New Limits on Sterile Neutrino Mixing with Atmospheric Neutrinos

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What is a Sterile Neutrino?

Measurements at LEP tell us that the $Z^0$ couples to only 3 light neutrinos.
What is a Sterile Neutrino?

3 neutrinos $\rightarrow$ 2 mass splittings

$\nu_3$ $\nu_2$ $\nu_1$
What is a Sterile Neutrino?

3 neutrinos $\Rightarrow$ 2 mass splittings

$\nu_3$

$\nu_2$

$\nu_1$

$\Delta m^2_{\text{atm}}$

$\Delta m^2_{\text{sol}}$

4 neutrinos $\Rightarrow$ 3 mass splittings

$\nu_4$

$\nu_3$

$\nu_2$

$\nu_1$

$\Delta m^2_{\text{atm}}$

$\Delta m^2_{\text{sol}}$

$\Delta m^2_{???}$
What is a Sterile Neutrino?

3 neutrinos $\rightarrow$ 2 mass splittings

$\nu_3$

$\nu_2$

$\nu_1$

$\Delta m^2_{\text{atm}}$

$\Delta m^2_{\text{sol}}$

$\Delta m^2_{???}$

$\nu_3$

$\nu_2$

$\nu_1$

3 mass splittings $\rightarrow$ 4 neutrinos

One of which does not couple to the Z and so does not interact weakly, i.e. sterile
What is a Sterile Neutrino?

- One more neutrino adds 7 complex matrix elements
  - but not all independent.

- $1 \Delta m^2$, 3 “angles”, 2 phases – varying parameterizations
  - $|U_{e4}|^2, |U_{\mu4}|^2, |U_{\tau4}|^2$ or $\theta_{14}, \theta_{24}, \theta_{34}$

- One more neutrino adds 8 more parameters
Evidence of Sterile Neutrinos

\[ \Delta m^2 \gtrsim 0.1 - 10 \text{ eV}^2 \]

2-flavor approx.

\[ \sin^2 2\theta_{\mu e} = 4 |U_{e4}|^2 |U_{\mu 4}|^2 \]

Both \( |U_{e4}|^2 \) and \( |U_{\mu 4}|^2 \) must be > 0 for non-zero probability
Evidence of Sterile Neutrinos

Reactor $\bar{\nu}_e$ rate low at short distances

$|U_{e4}|^2 \approx 0.02$

$\Delta m^2 > 1 \text{ eV}^2$

2-flavor approx.

$\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2)$
What can Super-K tell us?

- 11 years of atmospheric neutrino data.
  - Covering a wide range of $L$ and $E$

- It is most useful because of what it is not sensitive to:

<table>
<thead>
<tr>
<th>The size of the sterile mass splitting</th>
<th>Oscillations appear “fast”</th>
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<tbody>
<tr>
<td>The number of sterile neutrinos</td>
<td>3+1 and 3+N models look the same</td>
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</table>
What can Super-K tell us?

- **Short-baseline-related:** $|U_{\mu 4}|^2$
  - Driven by new $\Delta m^2$
  - Creates fast oscillations across a wide range of $\nu_\mu$ samples

- **Atmospheric/long-baseline:** $|U_{\tau 4}|^2$
  - Accessible *only* at long distances
  - Oscillations into $\nu_s$ instead of $\nu_\tau$
  - Introduces a new matter effect

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50 kT Water

>13,000 PMTs
Super-K Sterile Model

• A fully generic sterile model is difficult computationally
  – Cannot calculate both active ($\nu_e$) and sterile (NC) matter effects together

• So, we need to perform 2 different fits:

| Fit for $|U_{\mu4}|^2$ | Fit for $|U_{\tau4}|^2$ |
|------------------------|------------------------|
| – $\nu_e$ matter effects only | – NC matter effects only |
| – Most accurate $|U_{\mu4}|^2$ limit | – Required for $|U_{\tau4}|^2$ |
| – No $|U_{\tau4}|^2$ limit | – Over-constrains $|U_{\mu4}|^2$ |
SK Analysis: Zenith Angle

- Look for change in flavor content vs. $L$
- Bin by angle and separate $\mu$ and $e$
  - isolate oscillations
  - other samples control systematics
- The original SK analysis was simple: up/down, $\mu/e$
Same philosophy, more samples
Most samples binned in angle & energy
Fully Contained
Sub-GeV

Partially
Contained
Multi-GeV

Up-going μ

100’s of MeV

Few GeV

1 TeV+

μ-like, e-like ($\nu_e/\bar{\nu}_e$), NC$\pi^0$-like

Low energy ->

Poor $\cos\theta_z$ resolution

Long tracks – all μ-like

Uncontained ->

Poor $E$ resolution
Oscillogram: Standard $3\nu$

$P(\nu_\mu \text{ to } \nu_\mu)$

- 40 km
- 700 km
- 6,200 km
- 12,800 km

Energy (GeV)

- FC Sub-GeV
- Multi-GeV

PC, Stop $\mu$

Through-going $\mu$

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Oscillogram: $|U_{\mu_4}|^2$ Fit

$P(\nu_\mu \to \nu_\mu)$

km

40 km

700 km

6,200 km

12,800 km

PC, Stop $\mu$

Through-going $\mu$

Through-going $\mu$

Lower survival probability

~everywhere
Fit for $|U_{\mu 4}|^2$

- Signature is extra disappearance in all $\mu$ samples
  - Correlated change at all energies, all $\cos \theta_z$
  - Sensitivity limited by $\mu/e$ flux uncertainty

Need to do 2 fits since we cannot calculate $\nu_e$ and NC matter effects simultaneously
Fit for $|U_{\mu 4}|^2$

$|U_{\mu 4}|^2 < 0.023$ at 90% C.L.

$|U_{\mu 4}|^2 < 0.034$ at 99% C.L.

As with similar experiments, no sterile-driven $\nu_\mu$ disappearance

Need to do 2 fits since we cannot calculate $\nu_e$ and NC matter effects simultaneously

PRD86, 052009 (2012)
PRL52, 1384 (1984)
Fit for $|U_{\mu 4}|^2$

$|U_{\mu 4}|^2 < 0.023$ at 90% C.L.

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As with similar experiments, no sterile-driven $\nu_\mu$ disappearance

Exclude much of the MiniBooNE appearance signal

Need to do 2 fits since we cannot calculate $\nu_e$ and NC matter effects simultaneously
Oscillogram: $|U_{\tau_4}|^2$ Fit

$P(\nu_\mu \text{ to } \nu_\mu)$

Potentially large changes introduced by sterile/NC matter effects

Distortion at long distances/high energies

Shift in $\Delta m^2$
Fit for $|U_{\tau 4}|^2$ (with $|U_{\mu 4}|^2$)

- Matter effects create shape distortion in PC/Up-$\mu$ zenith distribution
  - Less disappearance in most upward bins, still have extra disappearance in downward bins

Need to do 2 fits since we cannot calculate $\nu_e$ and NC matter effects simultaneously
$|U_{\tau 4}|^2 < 0.28$ at 99% C.L.

Favors $\mu$ to $\tau$ oscillations over $\mu$ to $s$

Lack of sterile matter effects places a strong constraint
- Note, $|U_{\mu 4}|^2$ is over-constrained in this fit

All comparisons from: ArXiv:1303.3011
Conclusions

• Atmospheric neutrinos provide a useful tool to study sterile oscillations
  – Wide range of $L/E$
  – Measurement independent of $\Delta m^2$ and $N_{\text{sterile}} > 1$

• No evidence of sterile neutrinos seen
  – No sterile-driven $\nu_\mu$ disappearance, consistent with other short- and long-baseline measurements
  – $\mu$ to $s$ oscillations strongly disfavored by the lack of sterile matter effects
3+N ≈ 3+1 for Super K

$$P_{\mu\mu} = (1 - |U_{\mu4}|^2)^2 P_{\mu\mu}^0 + \sum_{i \geq 4} |U_{\mu i}|^4$$

• The first sterile term:
  – Controls extra disappearance
  – Is the same for any $N_{\text{sterile}}$

• The second sterile term:
  – Fills in the minima
  – Varies for $N_{\text{sterile}}$

• Our experiment is much more sensitive to first term
  – Beam experiments, focusing on the first oscillation dip, are sensitive to the second term.
No Matter in 3ν

• At right are 2 sensitivities from the 2+1 fit

• The dashed is the normal fit, solid has sterile matter effects arbitrarily turned off

• $|U_{\mu 4}|^2$ limit is unaffected – it is independent of the sterile matter effects
When is $\Delta m_{41}^2$ no longer “large”? 

- When do the oscillations no longer appear fast?
  - This will be the worst at short L’s and large E’s, so let’s focus on Up-$\mu$ with $\cos \theta_z > -0.1$
  - Loop through all these events and calculate the mean of $\sin^2(\Delta m^2 L/4E)$ for various $\Delta m^2$

- Doing this, the approximation is valid down to $\sim 0.8$ eV$^2$
When is $\Delta m^2_{41}$ no longer “large”?

• However, the limit on $|U_{\mu 4}|^2$ is driven by the low $|U_{\tau 4}|^2$ region.
  – In this region, the dominant samples are Sub-GeV muons
  – Almost no power comes from Up–$\mu$

• For these samples, the “large” assumption is ~always valid so $|U_{\mu 4}|^2$ limit really is a vertical line in $\Delta m^2$ to a good approximation
Our Matter Effect Model

- The $\mu$ to $\mu$ probability is fairly simple:

$$P_{\mu\mu} = (1 - d_{\mu})^2 |\tilde{S}_{22}|^2 + d_{\mu}^2$$

- Get $|S_{22}|^2$ by diagonalizing the sum of the vacuum and matter Hamiltonians:

$$H^{(2)} = H_{sm}^{(2)} + H_s^{(2)} :$$

$$= \frac{\Delta m_{31}^2}{4E} \begin{pmatrix} -\cos 2\theta_{23} & \sin 2\theta_{23} \\ \sin 2\theta_{23} & \cos 2\theta_{23} \end{pmatrix} \pm \frac{G_F N_n}{\sqrt{2}} \begin{pmatrix} |\tilde{U}_{s2}|^2 & \tilde{U}_{s2}^* \tilde{U}_{s3} \\ \tilde{U}_{s2} \tilde{U}_{s3}^* & |\tilde{U}_{s3}|^2 \end{pmatrix}$$
Our Matter Effect Model

• This gives us a \(\sim\)familiar matter-effect probability

\[
|\tilde{S}_{22}|^2 = 1 - \sin^2(2\theta_m) \sin^2(f_m L)
\]

\[
f_m = \sqrt{A_{32}^2 + A_s^2 + 2A_{32}A_s (\cos(2\theta_{23}) \cos(2\theta_s) + \sin(2\theta_{23}) \sin(2\theta_s))}
\]

\[
E_{1,2}^m = \pm f_m
\]

\[
\sin 2\theta_m = \frac{A_{32} \sin(2\theta_{23}) + A_s \sin(2\theta_s)}{f_m}
\]

\[
A_{32} = \frac{\Delta m_{31}^2}{4E}
\]

\[
A_s = \pm \frac{G_F N_n}{2\sqrt{2}}
\]

\[
\sin 2\theta_s = \frac{2\sqrt{d_\mu d_\tau d_s}}{(1 - d_\mu)}
\]

\[
\cos 2\theta_s = \frac{d_\tau - d_\mu d_s}{(1 - d_\mu)}
\]
Oscillation probabilities with sterile neutrinos for SuperK with the following assumptions:

1 Assumptions and Definitions

- So far, the 3M matter matrix as based on this Hamiltonian:

\[ H \]

For the parameterization used:

\[ U = \begin{pmatrix} | & | & | \\ e & \mu & \nu \\ | & | & | \end{pmatrix} \]

For details, see Sects. 4.1 (1): $\|2\|_{\pm}$ and 4.1 (2): $\|2\|_{+}

- Only 1 additional sterile neutrino

\[ \begin{pmatrix} \mu \\ \\nu \\ \\nu \end{pmatrix} \]

is left generic.

\[ P_{\mu \mu} = (1 - d_{\mu})^2 |\tilde{S}_{22}|^2 + d_{\mu}^2 \]

\[ P_{\mu \tau} = (1 - d_{\mu})(1 - d_{\tau}) + (d_{\mu}(1 - d_{\mu}) - d_{s}(1 + d_{\mu})) |\tilde{S}_{22}|^2 - \sqrt{d_{\mu}d_{\tau}d_{s}}(\tilde{S}_{23}\tilde{S}_{22}^* + \tilde{S}_{23}^*\tilde{S}_{22}) \]

\[ P_{\mu \nu} = (1 - d_{\mu})(1 - d_{s}) + (d_{\mu}d_{s} - d_{\tau}) |\tilde{S}_{22}|^2 + \sqrt{d_{\mu}d_{\tau}d_{s}}(\tilde{S}_{23}\tilde{S}_{22}^* + \tilde{S}_{23}^*\tilde{S}_{22}) \]

\[ |\tilde{S}_{22}|^2 = 1 - \sin^2(2\theta_m) \sin^2(f_mL) \]

\[ (\tilde{S}_{23}\tilde{S}_{22}^* + \tilde{S}_{23}^*\tilde{S}_{22}) = -2 \sin(2\theta_m) \cos(2\theta_m) \sin^2(f_mL) \]
Our Parameters: $|U_{\mu4}|^2$

- Amount mixing between $\nu_\mu$ and the sterile mass state $\nu_4$
- Primary effect is extra $\nu_\mu$ disappearance at all path lengths
- Is directly comparable to SBL measurements of $\nu_\mu$ disappearance ($\theta_{\mu\mu}$) and indirectly to the MB/LSND appearance signal ($\theta_{\mu e}$)
- With more sterile neutrinos, becomes a more generic parameter $d_\mu$, but out limit is still applicable:

$$d_\mu = \frac{1 - \sqrt{1 - 4A}}{2},$$

$$A = (1 - |U_{\mu4}|^2 - |U_{\mu5}|^2 - |U_{\mu6}|^2)(|U_{\mu4}|^2 + |U_{\mu5}|^2 + |U_{\mu6}|^2)$$

$$+ |U_{\mu4}|^2 |U_{\mu5}|^2 + |U_{\mu4}|^2 |U_{\mu6}|^2 + |U_{\mu5}|^2 |U_{\mu6}|^2.$$

*Conrad, et. al. hep-ex:1207.4765*
Our Parameters: $|U_{\tau 4}|^2$

• Amount mixing between $\nu_\tau$ and the sterile mass state $\nu_4$

• Controls $\nu_\mu \rightarrow \nu_\tau$ vs. $\nu_\mu \rightarrow \nu_s$ fraction
  – Previous SK sterile measurements have implicitly limited this parameter

• This parameter \(\sim\) scales the size of sterile-NC matter effects

• Also responsible of NC disappearance over long baselines

• Private to long-baseline and atmospheric measurements
  – But still interesting for understanding atmospheric oscillations