Limits on Non-Standard Effects in Atmospheric Neutrino Oscillations

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Outline

- Introduction of Super-K experiment and events
- Sterile neutrino as an alternative to the standard $\nu_\mu - \nu_\tau$ mixing
  - $\nu_\mu - \nu_\tau$ mixing versus $\nu_\mu - \nu_s$ mixing
  - An admixture analysis
- Violations of Lorentz (LIV) and CPT (CPTV) invariance as alternatives to the standard $\nu_\mu - \nu_\tau$ mixing
  - Plausibility of LIV and allowed limits
  - Plausibility of CPTV and its allowed limits
- Summary and conclusions
Super-Kamiokande Collaboration

- Located in Kamioka town of Gifu prefecture, Japan
  - A 50 kt water Cherenkov detector
- 36 institutes from 5 different countries:
  - Japan (18)
  - US (12)
  - South Korea (3)
  - Poland (1)
  - China (1)
- ~140 collaborators
- Operating periods:
  - SK-I: 1996 - 2001 (1489 days, this analysis)
  - SK-II: 2003 - 2005
  - SK-III: 2006 -
Five Decades of Neutrino Energy

Number of events

$E_\nu$(GeV)

- e-like
- single ring $\mu$
- multi-ring $\mu$

- NC sub-GeV
- NC multi-GeV

- stopping $\mu$
- non-showering $\mu$
- showering $\mu$

- FC
- Multi-Ring
- PC STOP
- PC THRU
- UP $\mu$ STOP
- UP THRU
- UP SHOWER

~1GeV
~3GeV
~5GeV
~10GeV
~100GeV
~1TeV
Four Decades of Pathlengths

- large ranges of $L$ and $E$
- different matter densities
  $\Rightarrow$ advantages for exotic models
SK-I Atmospheric Neutrino Sample

- SK-I: 1489.2 days (12263.3 events) and 100 years MC
  - \( \nu_\mu - \nu_\tau \) model fits the data well
  - But what about other models?
- Fit alternative models and compare the chi-square values
- Put in non-standard effects and find allowed limits

\[ \chi^2/dof=384/376 \text{ (68\%)} \]
\[ \sin^2 2\theta = 1.0 \]
\[ \Delta m^2 = 2.5 \times 10^{-3} \text{eV}^2 \]
Oscillation Analysis

\[ \chi^2 = 2 \sum_{i=1}^{n} (N_{i}^{\text{exp}} - N_{i}^{\text{obs}} + N_{i}^{\text{obs}} \log \frac{N_{i}^{\text{obs}}}{N_{i}^{\text{exp}}}) + \sum_{j=1}^{m'} \frac{\varepsilon_{j}^2}{\sigma_{\text{sys}}^2} \]

\[ N_{i}^{\text{exp}} = (1 + \sum_{j=1}^{m} \varepsilon_{j} f_{j}^{i}) N_{i}^{\text{osc}} \]

\[ N_{i}^{\text{osc}} = \sum_{l} p_{\text{sur}} \text{ (model) } w_{\text{lifetime}} \]

- **Chisquare has 2 parts**
  - Data bins
  - Systematic uncertainties (Pull terms)

- Data bins use likelihood ratios as chi-square, i.e. Poisson errors

- Systematic uncertainty terms use Gaussian errors

- Find the minimum \( \chi^2 \) on a grid in the parameter space

\( \varepsilon_{j} \): pull values to systematic uncertainties

\( \sigma_{\text{sys}}^2 \): systematic uncertainties (normalization free)

\( f_{j}^{i} \): the response factor of the ith bin to \( \varepsilon_{j} \)

\( p_{\text{sur}} \text{ (model)} \): survival probability of the neutrino

\( w_{\text{lifetime}} \): livetime normalization factor
Must It Be Tau Neutrino?

- **If three flavors of neutrinos, no choice**
  - Super-K does not see excess of electron neutrinos
    - $\nu_{\mu} - \nu_e$ oscillation analysis gives a bad fit compared to $\nu_{\mu} - \nu_{\tau}$
  - Chooz and Palo Verde: no oscillate at the scale $\Delta m^2 \sim 10^{-3} \text{eV}^2$
  - LEP experiments: $Z$ decay width consistent with 3 neutrino flavors, $N_\nu = 2.992 \pm 0.020$

- **What about more neutrinos which do not interact with $Z$?**
  - Some neutrino mass models do require the existence of "sterile neutrinos" ($\nu_s$): do not have electric, strong or weak charge
  - Extra neutrinos, which must be sterile, can solve the LSND anomaly
Signatures of $\nu_\mu-\nu_\tau$ Oscillation

- Based on the definition, $\nu_\mu-\nu_\tau$ oscillation can be distinguished from $\nu_\mu-\nu_s$ oscillation in two ways

1. A trivial difference: neutral current events

![Diagram of $\nu_\mu, \nu_\tau$, $Z^0$, pions, and $\nu_s$: no interaction]

2. A subtle one: Matter Effect
1. NC Events

- Multi-ring events
- $E_{vis} > 400\text{MeV}$
  - Low energy events do not point well
- Brightest ring e-like

![Graph showing NC and CC events]

- $400\text{MeV} < E_{vis} < 1330\text{MeV}$
  - NC: 38%
  - CC$\mu$: 22%

- $E_{vis} > 1330\text{MeV}$
  - NC: 27%
  - CC$\mu$: 40%
2. Matter Effect

- If two neutrino flavors interact differently in matter

\[ P_{osc} = \sin^2 2\theta_M \sin^2 \frac{\Delta m_M^2 L}{4E}, \]

\[
\sin^2 2\theta_M = \frac{\sin^2 2\theta}{(2E\Delta V / \Delta m^2 - \cos 2\theta)^2 + \sin 2\theta^2} \\
\Delta m_M^2 = \Delta m^2 \sqrt{(2E\Delta V / \Delta m^2 - \cos 2\theta)^2 + \sin 2\theta^2}
\]

- \( \nu_\mu - \nu_s \): \( \nu_\mu \) and \( \nu_s \) interact with matter differently \( \Delta V = \mp \sqrt{2} G_F \frac{\rho_n}{2} \)

\( \Rightarrow \) matter effect \( \Rightarrow \) oscillation is suppressed

Survival probability \( \nu_\mu \) crossing Earth:
- \( \Delta m^2 = 2.5 \times 10^{-3} \text{eV}^2 \)
- \( \sin^2 2\theta = 1 \)
$\nu_\mu - \nu_\tau$ versus $\nu_\mu - \nu_s$

\begin{align*}
\nu_\mu - \nu_\tau: \quad & \chi^2_{\text{min}}/\text{dof} = 455/426 (40\%) \\
\nu_\mu - \nu_s: \quad & \chi^2_{\text{min}}/\text{dof} = 504/426 (4.0\%) \\
\hline
\Delta \chi^2 = 49 (7\sigma)
\end{align*}
## Detailed Comparisons

### Data Bins

<table>
<thead>
<tr>
<th>Data Sample</th>
<th>Contribution to $\Delta \chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC single ring sub-GeV e-like</td>
<td>1.3</td>
</tr>
<tr>
<td>FC single ring sub-GeV $\mu$-like</td>
<td>-0.1</td>
</tr>
<tr>
<td>FC single ring multi-GeV e-like</td>
<td>0.2</td>
</tr>
<tr>
<td>FC single ring multi-GeV $\mu$-like</td>
<td>-0.3</td>
</tr>
<tr>
<td>FC multi-ring sub-GeV NC</td>
<td>5.0</td>
</tr>
<tr>
<td>FC multi-ring multi-GeV e-like CC</td>
<td>0.4</td>
</tr>
<tr>
<td>FC multi-ring $\mu$-like</td>
<td>4.2</td>
</tr>
<tr>
<td>PC stopping</td>
<td>3.5</td>
</tr>
<tr>
<td>PC through going</td>
<td>3.5</td>
</tr>
<tr>
<td>Up$\mu$ stopping</td>
<td>11.6</td>
</tr>
<tr>
<td>Up$\mu$ non-showering</td>
<td>7.9</td>
</tr>
<tr>
<td>Up$\mu$ showering</td>
<td>-1.0</td>
</tr>
<tr>
<td>Total</td>
<td>35.8</td>
</tr>
</tbody>
</table>

### Pull terms

- $\nu - \nu$ vs $\mu - \nu$
- $\nu - \tau$

### Graphs

- **Up stopping $\mu$**
  - Number of Events vs Normalized Pulls
  - Graph showing data points and fitted curves for different pull terms.

- **cos$\theta$**
  - Graph showing distribution of $\cos \theta$ with data points and fitted curves.

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An Admixture Model

- Admixture is model dependent
- The particular model considered here is by Fogli et al, PRD 63(053008), 2001
  - based on 2+2 mass hierarchy
  - Constructing two superposition states:
    four-flavor mixing $\Rightarrow$ 2 two-flavor mixings

\[
\begin{pmatrix}
|v_1 > \\
|v_2 >
\end{pmatrix} =
\begin{pmatrix}
\cos \xi & \sin \xi \\
-\sin \xi & \cos \xi
\end{pmatrix}
\begin{pmatrix}
|v_e > \\
|v_s >
\end{pmatrix}
\]

Allowed portion of $v_s$
Allowed Admixture Level

25% admixture allowed at 90% C.L.
Well, End of the Story?

- Lorentz Invariance violation or CPT violation
  \[ \Rightarrow \text{modify the dispersion relation} \]
  \[ \Rightarrow \text{different energy states for the same momentum} \]
  \[ \Rightarrow \text{neutrino oscillation} \]

- Other causes of neutrino disappearance
  - Neutrino decay (K. Okumura’s talk)
  - Neutrino decoherence (K. Okumura’s talk)
  - Limits under study
Violation of Lorentz and CPT Invariance

  \[ L = a_{\mu AB} \bar{L}_A \gamma^\mu L_B + \frac{1}{2} i c_{\mu\nu AB} \bar{L}_A \gamma^\mu \vec{D}^\nu L_B \]
  - The first term violates both CPT (CPTV) and Lorentz invariance (LIV); the second term only violates Lorentz invariance
  - Two rotationally invariant cases (only time components non-zero)
    • Coleman and Glashow, PRD 59(116008), 1999
    • Barger et al, PRL 85(5055), 2000
The Test of Pure LIV

- Flavor eigenstates are superpositions of Maximum Attainable Velocity eigenstates ⇒ LxE oscillation
- If the LIV effect has energy dependence ⇒ a more general formula: \( P_{\text{osc}} = \sin^2 2\theta \sin^2 \kappa L / E^\alpha \)

LIV does not fit the atmospheric neutrino observation ⇒ how much is allowed?
LIV as a Sub-Dominant Effect

\[ P_{osc} = \sin^2 2\Theta \sin^2 \Omega \]

\[ \tan 2\Theta = \frac{1 + (E / E_c)^2 \sin 2\theta_v}{(E / E_c)^2 \cos 2\theta_v} \]

\[ \Omega = 1.27 \sqrt{(\Delta m^2 L / E)^2 \pm 4c_{TT} \sin 2\theta_v LE + 4(c_{TT} LE)^2} \]

\[ E_c = \frac{\sqrt{\Delta m^2}}{2c_{TT}} \]

Assuming maximal mixing between mass eigenstates and the best Super-K \( \Delta m^2 \)

- \( c_{TT} \): the difference of maximum attainable velocities; \( c_{TT} \Rightarrow 0 \), recovers standard osc
- \( \theta_v \): mixing angle between two different maximal attainable velocity eigenstates
- “+/-”: corresponds to the 0/\( \pi \) phase differences between the mass mixing matrix and the maximum attainable velocity one
Allowed LIV Limits

Best fit: \( c_{TT} = 0.053 \times 10^{-23} \sin^2 \theta_v = 0.093 \)

- \( c_{TT} < \sim 1.4 \times 10^{-24} \) at 90% C.L.
- Limits from other experiments:
  - MACRO: \( 6 \times 10^{-24} \) (neutrino)
  - cosmic ray energy spectrum: \( 10^{-15} \)
  - nuclear magnetic resonance frequencies: \( 10^{-22} \)

Best fit: \( c_{TT} = 0.06 \times 10^{-23} \sin^2 \theta_v = 0.0 \)
Studiees of CPTV

- An *ad hoc* model implementing CPTV: allow neutrinos and antineutrinos to have different mass squared splittings
  - To check whether LSND scale is allowed by Super-K atmospheric neutrino data

- CPTV as an sub-dominant effect to the standard $\nu_\mu - \nu_\tau$ oscillation
  - To study the allowed limit
**An *ad hoc* Model of CPT Violation**

- An *ad hoc* consideration inspired by the LSND result: does Super-K allow neutrinos and antineutrinos to have different mass squared splittings?
  - Super-K does have sensitivity due to their different fluxes and cross sections

- **Answer:** best fit far away from the LSND scale
- A limit on the CPT violation can then be set
CPTV as a Sub-Dominant Effect

- CPTV term $a_{0AB} \bar{L}_A \gamma^0 L_B$ has opposite contributions to neutrinos and antineutrinos.

$$P_{osc} = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2}{4E} \pm \frac{\Delta a}{2} \right)L$$

- Best fit: $\Delta a = 0$
- A limit of $\Delta a < 10^{-23}$ GeV is set at 90% C.L.

Other types of experiments:
- LSND: $\sim 10^{-19}$ GeV
- $K^0 - \bar{K}^0$ mass difference: $\sim 0.44 \times 10^{-18}$ GeV
Summary and Conclusions

- Compared to $\nu_\mu - \nu_\tau$ oscillation, $\nu_\mu - \nu_s$ oscillation model is excluded at $7\sigma$ level.
- An admixture analysis was carried out based on a 2+2 mass hierarchy model. At 90% C.L., up to 25% sterile neutrinos is allowed.
- Pure Lorentz Invariant violation effect is strongly disfavored. With the large ranges of pathlengths and energies of SK neutrinos, a limit $c_{TT} \leq 1.4 \times 10^{-24}$ is set at 90% C.L.
- LSND scale is not allowed by Super-K data assuming neutrinos and antineutrinos having different mass squared splittings.
- At 90% C.L., a limit on CPT violation is set: $\Delta a < 10^{-23}$ GeV.
Testing MaVaN

• Neutrinos gain mass only in high density matter (not in air or vacuum)

• Best Fit:
  \[ \chi^2 \text{MaVaN} = 194.4/178 \text{ d.o.f} \]
  \[ (\sin^2 2\theta, \Delta m^2) = (1.00, 2.19 \times 10^{-3} \text{ eV}^2) \]

  \[ \chi^2 \text{Standard} = 174.97/178 \text{ d.o.f} \]
  \[ (\sin^2 2\theta, \Delta m^2) = (1.00, 2.11 \times 10^{-3} \text{ eV}^2) \]

• Excluded at 4.4\sigma level

• A general form under study

\[ \Delta m^2 \rightarrow \Delta m^2 \left( \frac{\rho}{\rho_0} \right)^n \]