Constraints on new physics from neutrinos

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Contents

Reference:

“Physics at a future Neutrino Factory and super-beam facility”, Int. Scoping Study Physics Working Group, Rept.Prog.Phys.72:106201,2009 (arXiv:0710.4947 [hep-ph])

- Chapter3: New physics (GUT, see-saw, extra dim.) to explain ν mass & mixings in SM+massive ν
- Chapter4: New physics to discuss possible deviation from SM+massive ν

1. Introduction for ν

(i) Notations for ν: different from those for quarks

Quarks (u, d, s, c, b, t): mass eigenstates

Charged leptons (e, μ, τ): mass eigenstates

Neutrinos (ν_e, ν_μ, ν_τ): **not** mass eigenstates

Neutrinos are defined as **flavor** eigenstates because we can observe them only by $\nu_\alpha + N \rightarrow \ell^-_\alpha + X$

Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Maki-Nakagawa-Sakata matrix

flavor eigenstates

mass eigenstates

In flavor eigenstates, flavor conversion (= ν oscillation) occurs.

(ii) 2 flavor oscillations in vacuum

$$\begin{cases} i\frac{d}{dx}\nu_1(x) = E_1\ \nu_1(x) \\ i\frac{d}{dx}\nu_2(x) = E_2\ \nu_2(x) \end{cases}$$

mass eigenstates

$$E_j \equiv \sqrt{\vec{p}^2 + m_j^2}$$

$$\begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \end{pmatrix} = U \begin{pmatrix} \nu_1(x) \\ \nu_2(x) \end{pmatrix}$$

flavor eigenstates

$$U \equiv \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

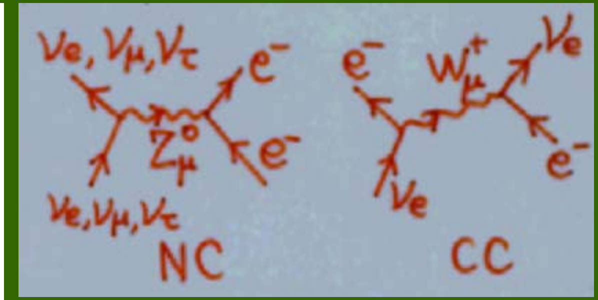
mixing matrix in vacuum

$$P(\nu_e \to \nu_\mu; L) \ = \ \sin^2 2\theta\ \sin^2\left(\frac{\Delta E L}{2}\right)$$

$$\Delta E \ = \ E_2 - E_1 \simeq \frac{m_2^2 - m_1^2}{2E} \equiv \frac{\Delta m^2}{2E}$$

(iii) 2 flavor oscillations in matter (MSW effect)

$$
\begin{aligned}
i\frac{d}{dx}\begin{pmatrix}\nu_e(x)\\ \nu_\mu(x)\end{pmatrix} &= \left[U\begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}U^{-1}+\begin{pmatrix}A & 0\\ 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e(x)\\ \nu_\mu(x)\end{pmatrix}\\
&= \tilde{U}(x)\begin{pmatrix}\tilde{E}_1 & 0\\ 0 & \tilde{E}_2\end{pmatrix}\tilde{U}^{-1}(x)\begin{pmatrix}\nu_e(x)\\ \nu_\mu(x)\end{pmatrix}
\end{aligned}
$$



$$(A \equiv \sqrt{2}G_F N_e(x))$$

For $\overline{\nu}$, A → -A

If N_e=const.

$$P(\nu_e \to \nu_\mu; L) = \sin^2 2\tilde{\theta}\, \sin^2\left(\frac{\Delta\tilde{E}L}{2}\right)$$

$$\tan 2\tilde{\theta} \equiv \frac{\Delta E \sin 2\theta}{\Delta E \cos 2\theta - A}$$

$$\Delta\tilde{E} = \left[(\Delta E \cos 2\theta - A)^2 + (\Delta E \sin 2\theta)^2\right]^{1/2}$$

even if θ in vacuum is small $\tilde{\theta}$ in matter could be large (MSW effect)

(iv) 3 flavor ν oscillation

MNS matrix (very different from CKM)

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cong \begin{pmatrix} c_{12} & s_{12} & \varepsilon \\ -s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \\ s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

Mixing angles & mass squared differences

$$\theta_{12} \cong \frac{\pi}{6}, \Delta m_{21}^2 \cong 8 \times 10^{-5} \mathrm{eV}^2$$ ← ν_{solar}+KamLAND (reactor)

$$\theta_{23} \cong \frac{\pi}{4}, |\Delta m_{32}^2| \cong 2.5 \times 10^{-3} \mathrm{eV}^2$$ ← ν_{atm}+K2K,MINOS (accelerators)

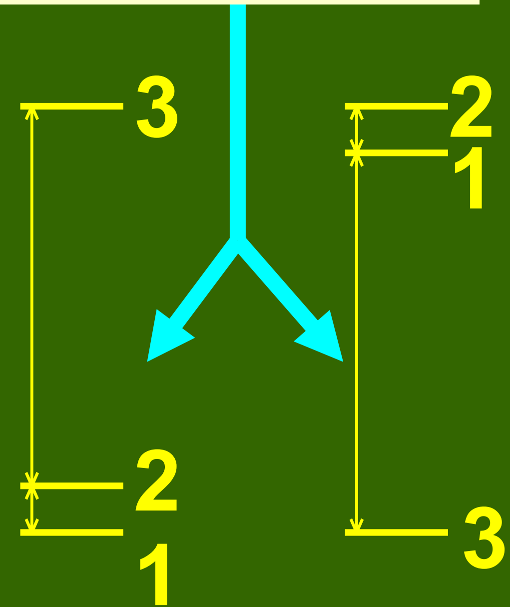
$$|\theta_{13}| \leq \sqrt{0.15}/2$$ ← CHOOZ (reactor)

(v) Unknown quantities in 3 flavor ν framework

- θ_{13} :only upper bound is known
- δ :undetermined

Next task is to measure θ_{13}, sign(Δm^2_{31}) and δ.

- Both mass hierarchies are allowed



normal hierarchy

$\Delta m^2_{32} > 0$

inverted hierarchy

$\Delta m^2_{32} < 0$

(vi) Future long baseline experiments

Ongoing & Near future experiments

Accelerator $\Rightarrow \theta_{13}, \mathrm{sgn}(\Delta m^2_{32})?, \delta?$

'06～ **MINOS** (FNAL→Soudan) L=730km, E ～10GeV

'08 ～ **OPERA･ICARUS** (CERN→GrandSasso) L=730km, E ～20GeV

'09 ～ **T2K** (JAERI→SK) L=295km, E ～1GeV **phase1** (0.75MW,22.5kt)

'14 ～ **NOνA** (FNAL→Ash River) L=810km, E ～1GeV (0.7MW,15kt)

Reactor $\Rightarrow \theta_{13}$

'09～ **Double CHOOZ**

'10～ **RENO**

'11～ **Daya Bay**

Far future experiments

Accelerator

'xx～ **T2K(K)** (JAERI→HK(+Korea)) L=295km(+1050km), E ～1GeV
phase2 (4MW,500kt)

'yy～ **ν factory** (?→?) L ～ 4000km+7500km, E ～25GeV

2. New physics & ν

New physics := Deviation from SM+massive ν

Most of discussions to date are **phenomenological**

Motivation: High precision measurements of ν oscillation in future experiments can be used also to probe **physics beyond SM** by looking at deviation from SM+massive ν

List of **New physics** to be discussed here

- Non-standard interactions in propagation
- Non-standard interactions at production/detection
- Unitarity violation due to heavy particles
- Sterile neutrinos

A word on exotic scenarios

- CPT invariance violation
- Presence of torsion
- Lorentz invariance violation
- Equivalence principle violation
- Decoherence
- Mass varying neutrinos

$$\overline{\theta}_{ij} \neq \theta_{ij} \qquad \Delta\overline{m}^2_{ij} \neq \Delta m^2_{ij}$$

$$P = \sin^2 2\theta \, \sin^2 (c\, L)$$

$$P = \sin^2 2\theta \, \sin^2 (c\, E L)$$

$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \times (1 - \exp(-\gamma_0 \frac{L}{E}) \times \cos(\frac{\Delta m^2 L}{2E}))$$

$$\Delta m^2 \rightarrow \Delta m^2 \times (\rho_e/\rho_0)^n$$

	Lorentz inv.
● (green)	✓
● (red)	×

None of them can be major cause for ν oscillations for ν_{atm} or ν_{sol} , although these may show up as small perturbation (at least killing them all completely is an experimentally challenge). → I will not discuss these scenarios here.

New physics which can be probed at a future long baseline neutrino experiments includes:

- **Non standard interactions in propagation**
- **Non standard interactions at production / detection**
- **Violation of unitarity due to heavy particles**
- **Schemes with light sterile neutrinos**

$$\sum_{\beta=e,\mu,\tau} P(\nu_\alpha \to \nu_\beta) = 1$$

Scenarios	3 flavor unitarity
NSI in propagation	✓
NSI at production / detection	✗
Violation of unitarity due to heavy particles	✗
Light sterile neutrinos	✗

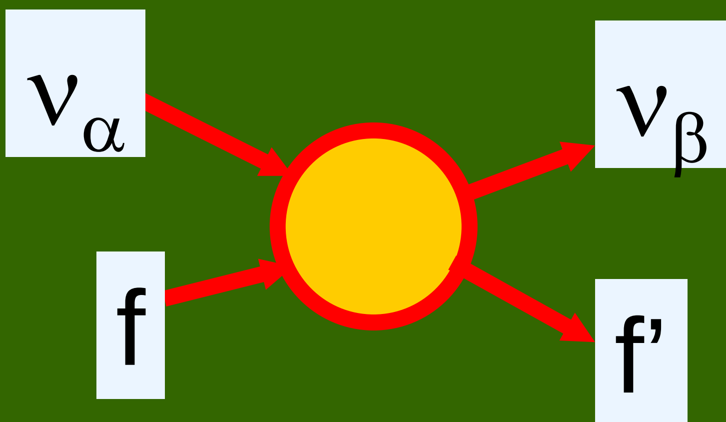
Scenarios	Phenomenological bound on deviation of unitarity
NSI at production / detection	O(1%)
Violation of unitarity due to heavy particles	O(0.1%)
Light sterile neutrinos	O(10%)

◆ (Except sterile ν) none of these scenarios has ever been supported experimentally.

◆ Even if LSND anomaly is excluded in the near future, light sterile ν could be phenomenologically even more promising than others.

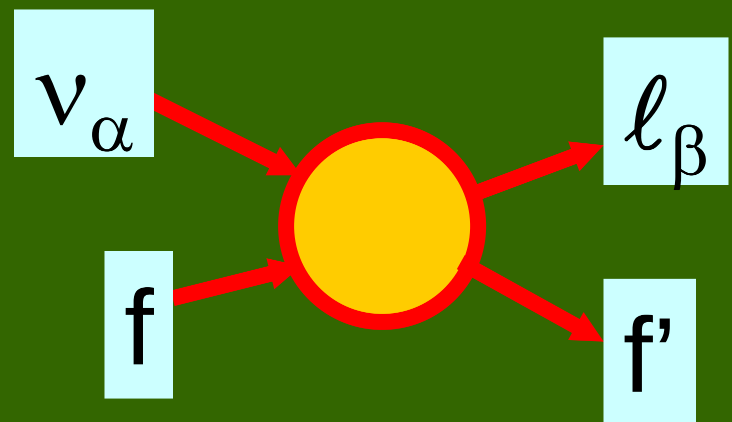
Phenomenological discussions on Non Standard Interactions (4-fermi exotic interactions)

$$\mathcal{L}_{\rm eff} = G_F\, \epsilon^{ff'}_{\alpha\beta}\; \bar{\nu}_\alpha \gamma^\rho \nu_\beta \bar{f} \gamma_\rho f'$$



neutral current

$$\mathcal{L}_{\rm eff} = G_F\, \epsilon^{ff'}_{\alpha\beta}\; \bar{\nu}_\alpha \gamma^\rho \ell_\beta \bar{f} \gamma_\rho f'$$



charged current

2-1. NSI in propagation (matter effect)

Correction from $\mathcal{L}_{\text{eff}} = G_F\, \epsilon_{\alpha\beta}^{ff'}\, \bar{\nu}_\alpha \gamma^\rho \nu_\beta \bar{f} \gamma_\rho f'$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\,\mathrm{diag}\,(E_1, E_2, E_3)\,U^{-1} + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$A \equiv \sqrt{2} G_F N_e$ $\quad N_e \equiv$ electron density

- **Mass matrix $\mathcal{M}$ is hermitian**
- **There are only 3 flavors**

Oscillation probability satisfies 3 flavor unitarity

Current bounds on the parameters of NSI in propagation

Davidson, Pena-Garay, Rius, Santamaria, JHEP 0303:011,2003

Biggio, Blennow, Fernandez-Martinez, JHEP 0908:090 ('09)

$$\begin{bmatrix} |\varepsilon_{ee}| < 4 & |\varepsilon_{e\mu}| < 0.3 & |\varepsilon_{e\tau}| < 3 \\ |\varepsilon_{e\mu}| < 0.3 & |\varepsilon_{\mu\mu}| < 0.07 & |\varepsilon_{\mu\tau}| < 0.3 \\ |\varepsilon_{e\tau}| < 3 & |\varepsilon_{\mu\tau}| < 0.3 & |\varepsilon_{\tau\tau}| < 20 \end{bmatrix}$$

$\varepsilon_{e\mu}$, $\varepsilon_{\mu\mu}$, $\varepsilon_{\mu\tau}$: Bounds $\sim O(10^{-1})$

ε_{ee} , $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$: Bounds $\sim O(1)$

Constraint from ν_{atm}

Friedland- Lunardini, PRD72 ('05) 053009

$$\varepsilon_{\tau\tau} \cong |\varepsilon_{e\tau}|^2 / (1 + \varepsilon_{ee}) \quad (*)$$

ε_{ee} , $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$ **$\sim O(1)$ are consistent with all data w/ Eq. (*)**

2-2. NSI at source and detector

Grossman, Phys. Lett. B359, 141 (1995)

Possible processes with $\mathcal{L}_{\rm eff} = G_F\,\epsilon^{ff'}_{\alpha\beta}\,\bar{\nu}_\alpha\gamma^\rho\ell_\beta\bar{f}\gamma_\rho f'$

● NP at source

$$\mu^+ \to e^+ + \overline{\nu}_\mu + \nu^s_\mu$$

$$\nu^s_e = \nu_e + \epsilon^s_{e\mu}\nu_\mu$$

Effective eigenstate

$$\begin{pmatrix} \nu^s_e \\ \nu^s_\mu \end{pmatrix} = \begin{pmatrix} 1 & \epsilon^s_{e\mu} \\ -\epsilon^s_{e\mu} & 1 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

● NP at detector

$$\nu^d_\mu + n \to \mu^- + p$$

$$\nu^d_\mu = \nu_\mu - \epsilon^d_{e\mu}\nu_e$$

Effective eigenstate

$$\begin{pmatrix} \nu^d_e \\ \nu^d_\mu \end{pmatrix} = \begin{pmatrix} 1 & \epsilon^d_{e\mu} \\ -\epsilon^d_{e\mu} & 1 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

Oscillation probability breaks 3 flavor unitarity

Direct bounds on prod/det NSI

From μ, β, π decays and zero distance oscillations

$$2\sqrt{2}G_F\varepsilon^{ud}_{\alpha\beta}\left(\bar{l}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{u}\gamma_\mu P_{L,R}d\right) \qquad 2\sqrt{2}G_F\varepsilon^{\mu e}_{\alpha\beta}\left(\bar{\mu}\gamma^\mu P_L\nu_\beta\right)\left(\bar{\nu}_\alpha\gamma_\mu P_L e\right)$$

$$\left|\varepsilon^{ud}\right| < \begin{pmatrix} 0.042 & 0.025 & 0.042 \\ 2.6\cdot10^{-5} & 0.1 & 0.013 \\ 0.087 & 0.013 & 0.13 \end{pmatrix} \qquad \left|\varepsilon^{\mu e}\right| < \begin{pmatrix} 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \end{pmatrix}$$

Bounds ~O(10^{-2})

C. Biggio, M. Blennow and EFM 0907.0097

2-3. Violation of unitarity due to heavy particles (Minimal Unitarity Violation)

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP0610,084, '06

In generic see-saw models, after integrating out ν_R, the kinetic term gets modified, and unitarity is expected to be violated.

$$L = \frac{1}{2}\left(i\overline{\nu}_\alpha \partial K_{\alpha\beta}\nu_\beta - \overline{\nu}^c{}_\alpha M_{\alpha\beta}\nu_\beta\right) - \frac{g}{\sqrt{2}}\left(W^+_\mu \bar{l}_\alpha \gamma^\mu P_L \nu_\alpha + h.c.\right) + \ldots$$

rescaling ν

$$L = \frac{1}{2}\left(i\overline{\nu}_i \partial \nu_i - \overline{\nu}^c{}_i m_{ii}\nu_i\right) - \frac{g}{\sqrt{2}}\left(W^+_\mu \bar{l}_\alpha \gamma^\mu P_L N_{\alpha i}\nu_i\right) + \ldots$$

N: non-unitary

$N \equiv HU$

$\eta = H - 1$: deviation from unitarity

Current bounds on the parameters of unitarity violation

- Without considering mixing bounds (90 % CL)

$$|\eta_{\alpha\beta}| < \begin{pmatrix} 2.0 \times 10^{-3} & 0.6 \times 10^{-4} & 0.8 \times 10^{-2} \\ 0.6 \times 10^{-4} & 0.8 \times 10^{-3} & 0.5 \times 10^{-2} \\ 0.8 \times 10^{-2} & 0.5 \times 10^{-2} & 2.7 \times 10^{-3} \end{pmatrix}$$

- Including mixing bounds (90 % CL)

$$|\eta_{\alpha\beta}| < \begin{pmatrix} 2.0 \times 10^{-3} & 0.6 \times 10^{-4} & 1.6 \times 10^{-3} \\ 0.6 \times 10^{-4} & 0.8 \times 10^{-3} & 1.1 \times 10^{-3} \\ 1.6 \times 10^{-3} & 1.1 \times 10^{-3} & 2.7 \times 10^{-3} \end{pmatrix}$$

Blennow @ NSI workshop at UAM 2009-12-10

Bounds ~O(10^{-3})

2-4. Light sterile neutrinos

LSND('93-'98,LANL)
L～30m, E～50MeV

→ $\Delta m^2 \sim O(1)\ eV^2$ $\bar{\nu}_\mu \to \bar{\nu}_e$

Because of the hierarchy: $\Delta m^2_{sol} << \Delta m^2_{atm} << \Delta m^2_{LSND}$

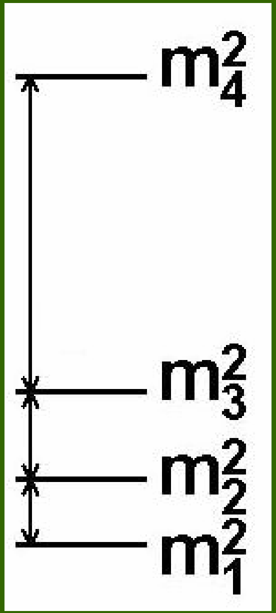
N_ν=3 schemes can't explain LSND.

$$\Delta m^2_{21} = \Delta m^2_{sol}, \Delta m^2_{32} = \Delta m^2_{atm}$$

N_ν=4 schemes may be able to explain all.

LEP → 4^{th} ν has to be sterile

$$\Delta m^2_{21} = \Delta m^2_{sol}, \Delta m^2_{32} = \Delta m^2_{atm}, \Delta m^2_{43} = \Delta m^2_{LSND}$$



(3+1)-scheme

(3+1)-scheme is the simplest to explain potentially LSND/MiniBooNE

To test LSND, MiniBooNE has been running @ FNAL

(3+1)-scheme w/ LSND has tension w/ short baseline reactor/accelerator ν experiments:

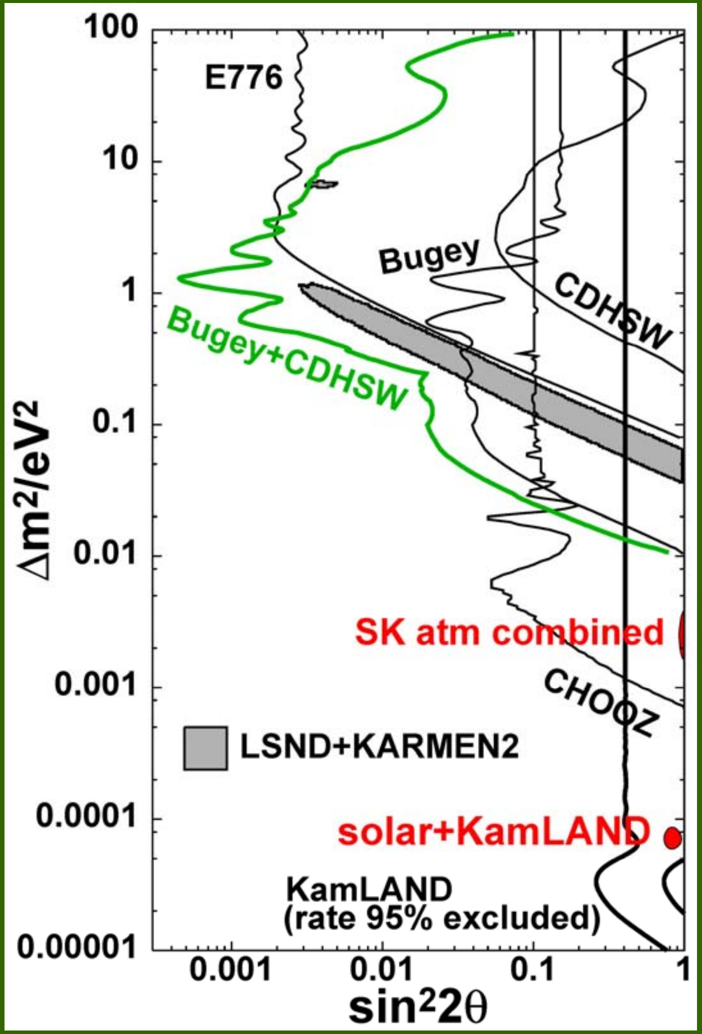
Negative result of CDHSW (~'80-'83, L=130m, 885m, E∼1GeV, $\nu_\mu \to \nu_\mu$)

+

Negative result of Bugey (~'94, L=15m, 40m, 95m, E∼4MeV, $\bar{\nu}_e \to \bar{\nu}_e$)

⇩

Upper bound on oscillation probability for $\bar{\nu}_\mu \to \bar{\nu}_e$

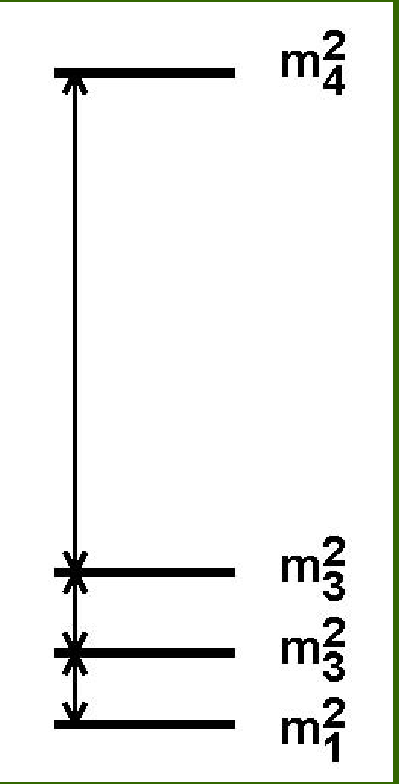


$$\sin^2 2\theta_{\rm LSND}(\Delta m^2) < \frac{1}{4}\sin^2 2\theta_{\rm Bugey}(\Delta m^2)\sin^2 2\theta_{\rm CDHSW}(\Delta m^2)$$

Okada-OY, Int. J. Mod. Phys. A12, 3669,'97

But there is no overlap between LSND and left side of Bugey+CDHSW

If we forget about LSND, then (3+1)-scheme is a possible scenario, provided that the mixing angles satisfy all the constraints of the negative results (w/ less motivation).



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$U = R_{34}(\theta_{34}, 0)\, R_{24}(\theta_{24}, 0)\, R_{23}(\theta_{23}, \delta_3)\, R_{14}(\theta_{14}, 0)\, R_{13}(\theta_{13}, \delta_2)\, R_{12}(\theta_{12}, \delta_1)$$

θ_{34} : ratio of $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ in ν_{atm}

θ_{24} : ratio of $\sin^2(\frac{\Delta m^2_{\rm atm} L}{4E})$ and $\sin^2(\frac{\Delta m^2_{\rm SBL} L}{4E})$ in ν_{atm}

θ_{14} : mixing angle in $\nu_{reactor}$ at L=O(10m)

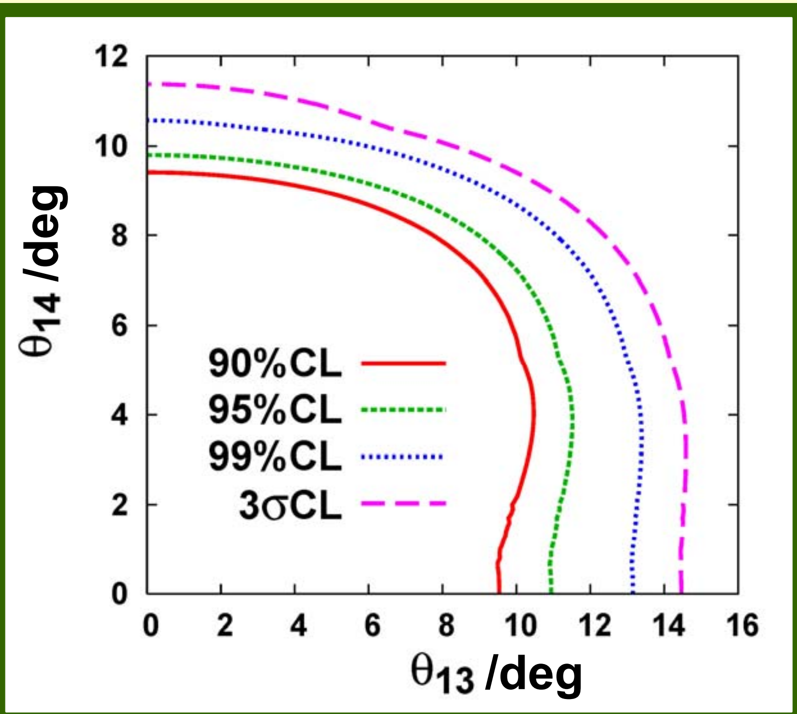
Constraints from ν_{atm} and SBL

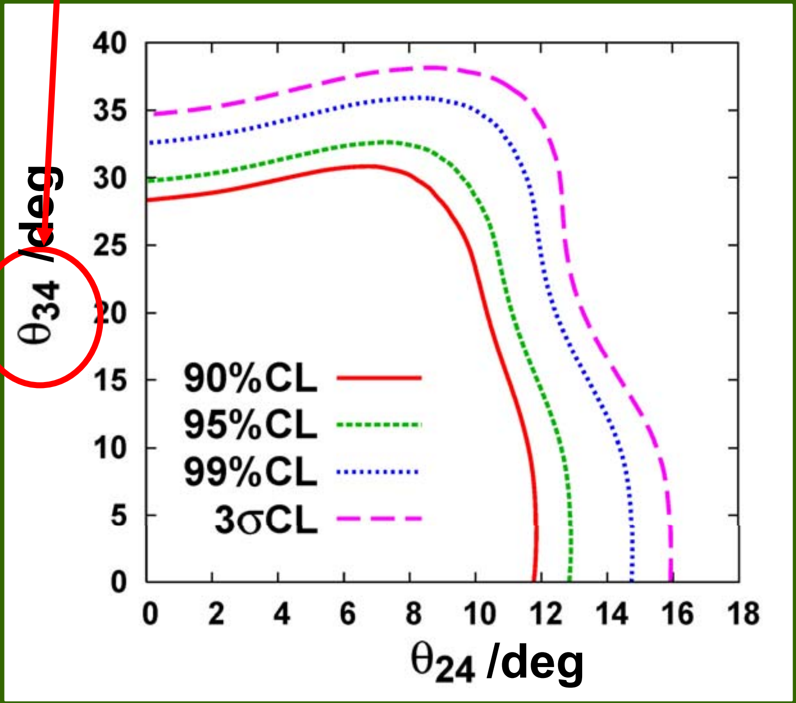
Donini-Maltoni-Meloni-Migliozzi-Terranova, JHEP 0712:013,'07

$$U = R_{34}(\theta_{34})\ R_{24}(\theta_{24})\ R_{23}(\theta_{23},\ \delta_3)\ R_{14}(\theta_{14})\ R_{13}(\theta_{13},\ \delta_2)\ R_{12}(\theta_{12},\ \delta_1)$$

Assumption on rapid oscillations in ν_{atm}: $\Delta m^2_{41} > 0.1\ eV^2$

θ_{34} : could be relatively large



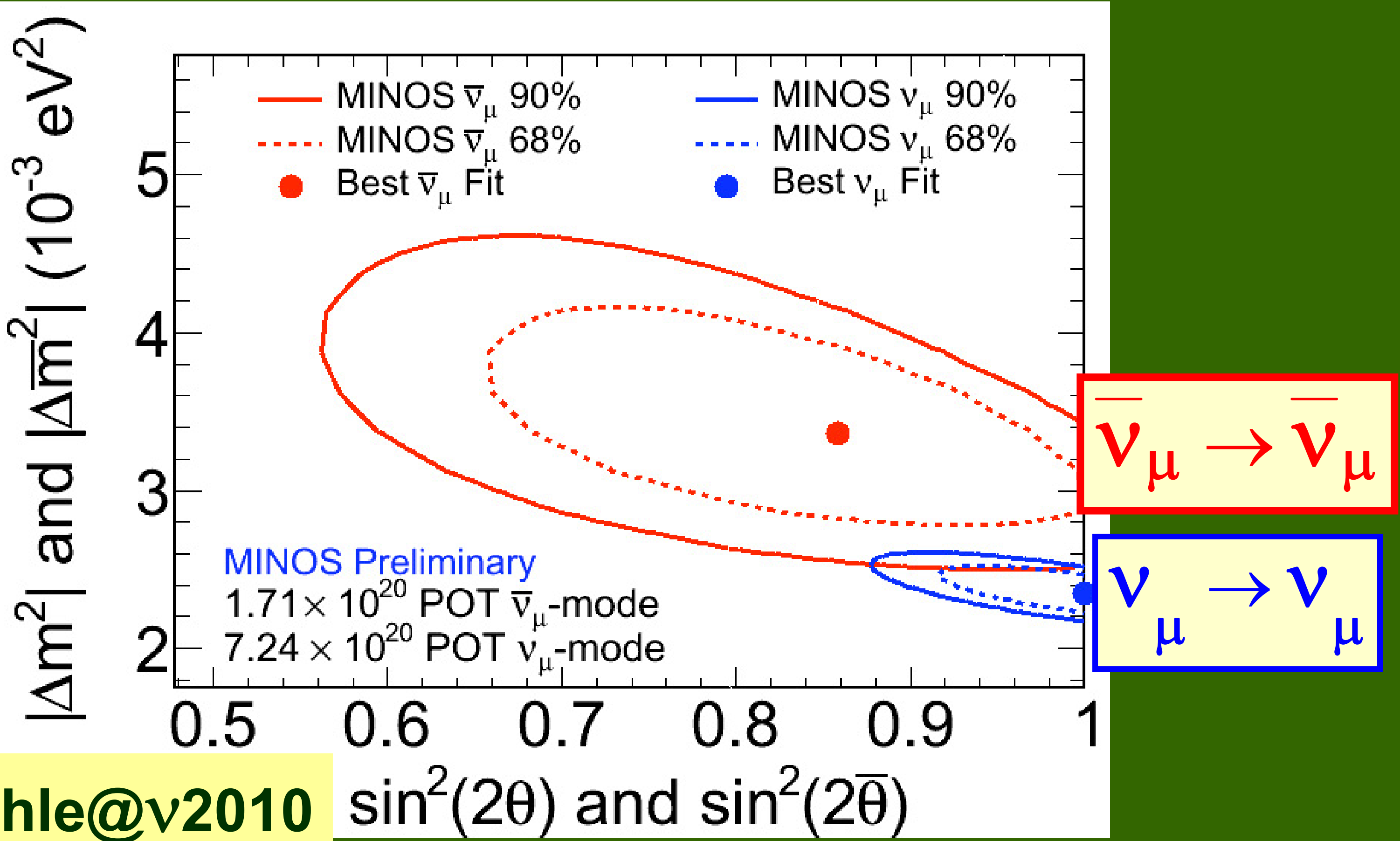


3. Anomalies @ν2010

(1) Anomaly #1@ν2010

MINOS (FNAL→Soudan, MN)
L=730km, E～4GeV

Oscillation parameters seem to be different for ν & $\bar{\nu}$: this can't be explained by standard 3ν oscillation)



P. Vahle@ν2010

What can this be?

- CPT violation? Probably not.
- Just statistics? Combining the data will probably produce a decent χ^2. But that is a weak test. Is there a parametric hypothesis?
- *"Within standard neutrino mixing, disappearance probabilities for neutrinos and antineutrinos are identical, by CPT conservation!"* (G. Karagiorgi). However, not true when matter is present.
- Could this mean that θ_{13} is showing up??

H. Robertson@ν2010

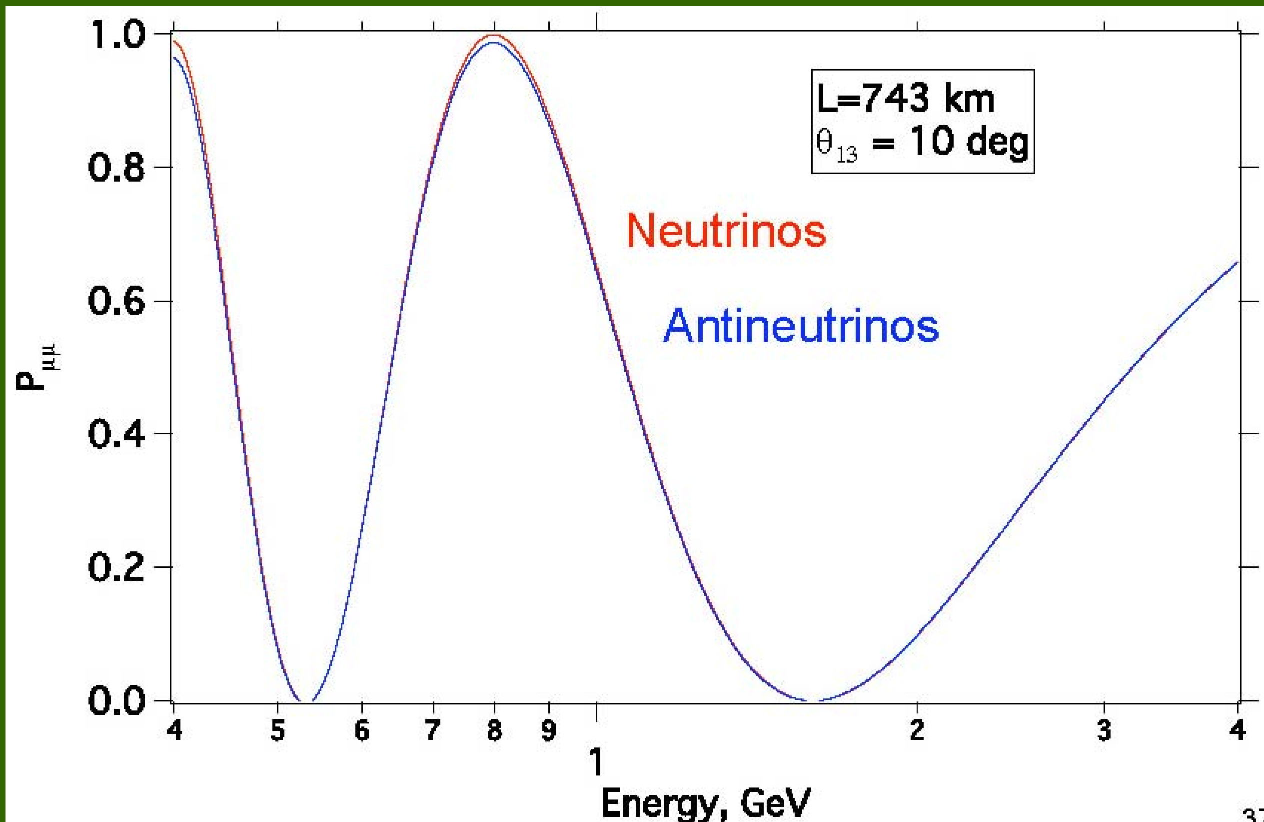
standard 3ν oscillation

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\,\mathrm{diag}\,(E_1, E_2, E_3)\,U^{-1} + A\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

When θ_{13} is small, ν_e decouples
$\rightarrow 1 - P_{\mu\mu} \doteqdot P_{\mu\tau}$: vacuum oscillation

This is supported by ν_{atm}

This anomaly might be explained by non-standard interaction in propagation.

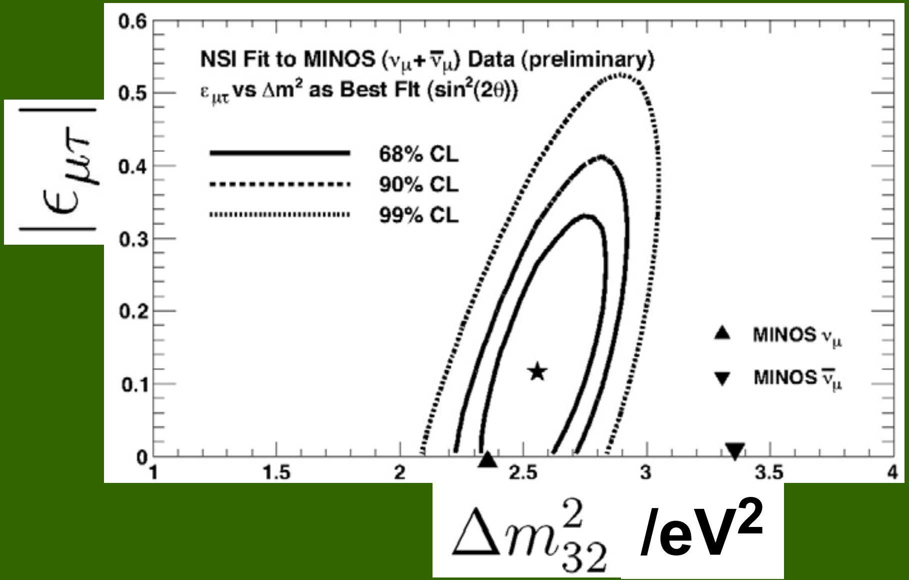


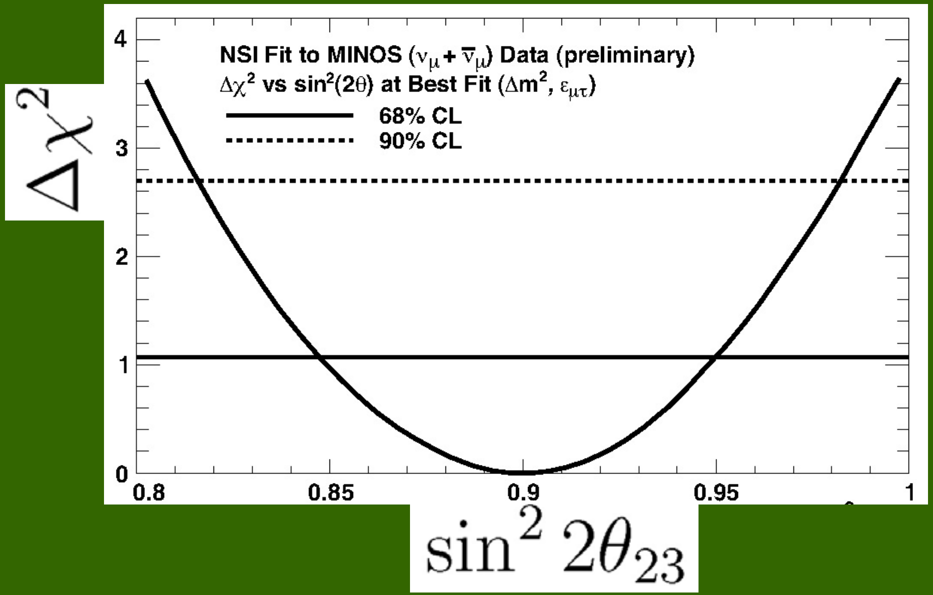
Non-standard interaction in propagation

Mann, Cherdack, Musial, Tomas, Kafka, Arxiv:1006.5720v1

$$A\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & \epsilon_{\mu\tau}\\ 0 & \epsilon_{\tau\mu} & 0\end{pmatrix}$$

2 flavor analysis w/ ν_μ & ν_τ & θ_{13}=0

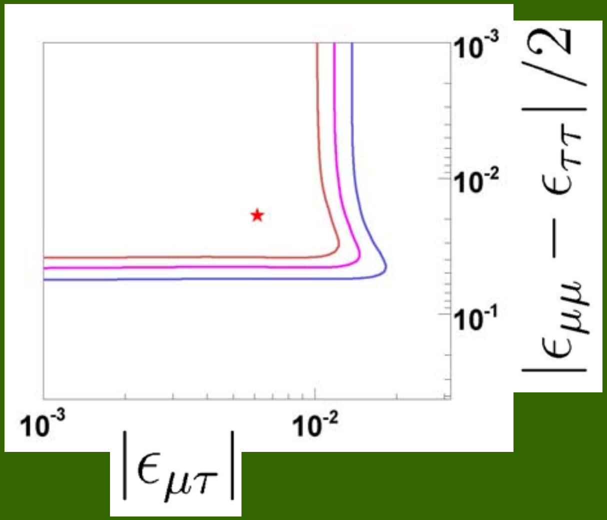




However, $|\varepsilon_{\mu\tau}|\sim 0.1$ is probably inconsistent w/ ν_{atm}.

Mitsuka, PoS NUFACT08, 059 ('08)

$$|\epsilon_{\mu\tau}| \lesssim 0.01$$



(2) Anomaly #2@ν2010

MiniBooNE(FNAL)
L～0.5km, E～0.5GeV

Oscillation w/ $\Delta m^2 \sim O(1) eV^2$ for $\bar{\nu}$: this can't be explained by standard 3 ν oscillation

cf. LSND('93-'98,LANL)
L～30m, E～50MeV

→ $\Delta m^2 \sim O(1)\ eV^2$ $\bar{\nu}_\mu \to \bar{\nu}_e$

Summary of MiniBooNE (R. Van der Water@ν2010)

1) **Neutrino Mode**: $\nu_\mu \to \nu_e$

a) E < 475 MeV: An unexplained 3σ electron-like excess.

b) E > 475 MeV: A two neutrino fit is inconsistent with LSND at the 90% CL.

inconsistent with LSND oscillation

2) **Anti-neutrino Mode**: $\bar{\nu}_\mu \to \bar{\nu}_e$

a) E < 475 MeV: A small 1.3σ electron-like excess.

b) E > 475 MeV: An excess that is 3.0% consistent with null. Two neutrino oscillation fits consistent with LSND at 99.4% CL relative to null.

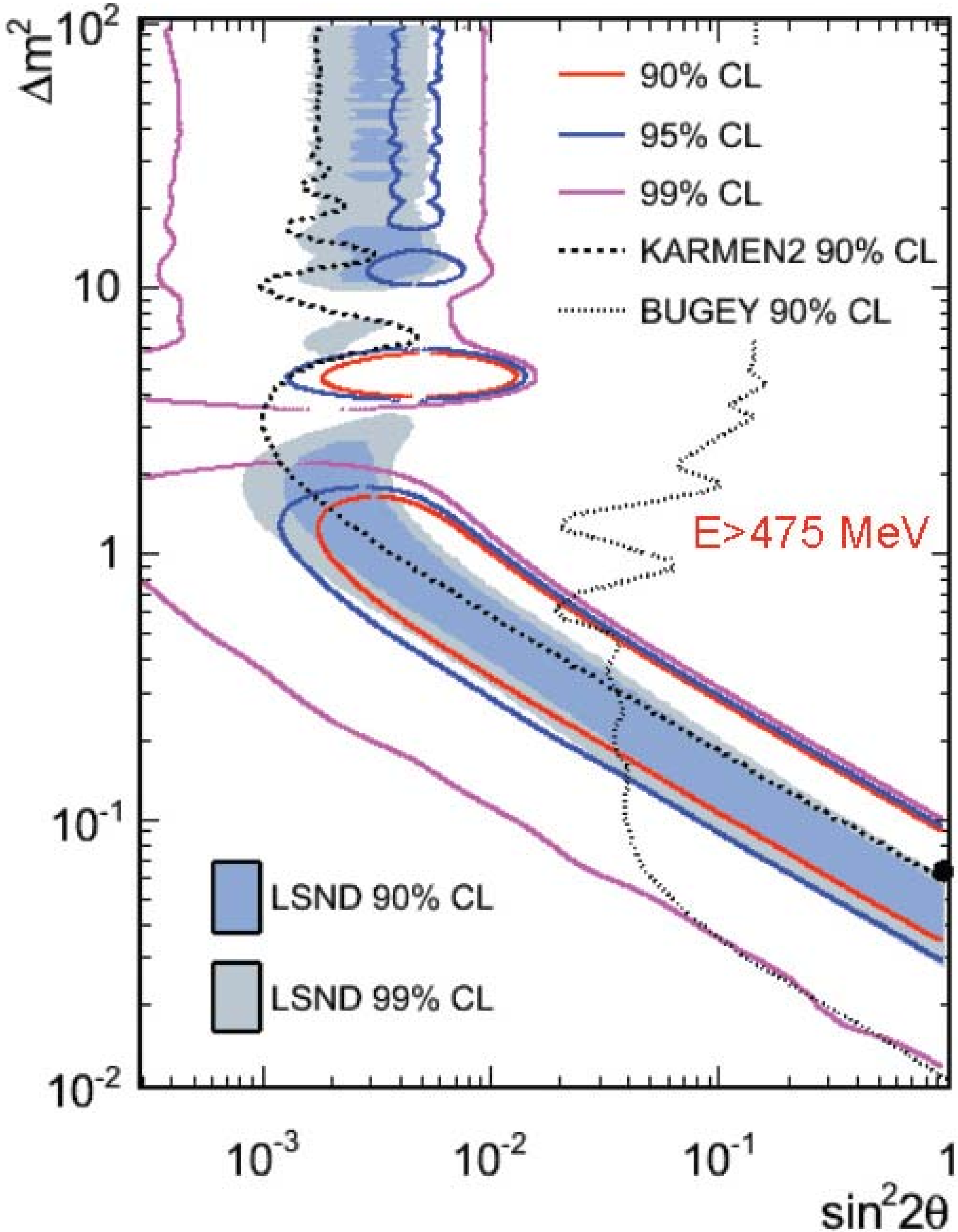
consistent with LSND oscillation

Updated Antineutrino mode MB results for E>475 MeV
(official oscillation region)

- Results for 5.66E20 POT
- Maximum likelihood fit.
- Null excluded at 99.4% with respect to the two neutrino oscillation fit.
- Best Fit Point
  $(\Delta m^2, \sin^2 2\theta) =$
  $(0.064\ eV^2, 0.96)$
  $\chi^2/NDF = 16.4/12.6$
  $P(\chi^2) = 20.5\%$
- Results to be published.

MiniBooNE

R. Van der Water



(3+2)-scheme

Sorel, Conrad, Shaevitz, PRD70,073004,'04

LSND($\bar{\nu}_\mu \to \bar{\nu}_e$): affirmative

MiniBOONE($\nu_\mu \to \nu_e$): negative

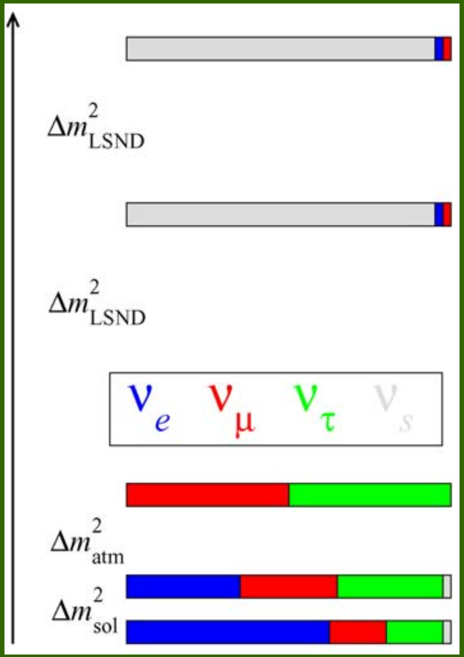
difference between ν & $\bar{\nu}$ may offer a promising fit

(3+2)-scheme w/ CP phase δ

$$\begin{aligned} P_{\nu_\mu \to \nu_e} &= 4\,|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} \\ &+ 4\,|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51} \\ &+ 8\,|U_{e4} U_{\mu 4} U_{e5} U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta) \end{aligned}$$

with the definitions

$$\phi_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}, \qquad \delta \equiv \arg\left(U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*\right).$$



(3+2)-scheme also has tension w/ short baseline reactor/accelerator ν experiments

3. Summary

- A brief review was given on new physics in ν phenomenology.
- Like B factories, the future neutrino experiments with high precision will be able to see deviation from SM.
- So far there is no experimental evidence to suggest CPT/Lorentz invariance violation.
- The anomalies @ ν2010 may or may not be explained by new physics.

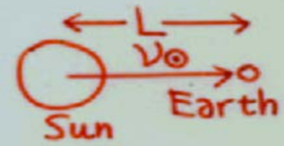
Backup slides

3 flavor ν oscillation

KamLAND(reactor) $\bar{\nu}_e \to \bar{\nu}_e$

- solar ν $\nu_e \to \nu_e$

① flux of $\nu_\odot$ observed on the Earth is lower than theoretical predictions



GALLEX-GNO, SAGE (Ga), Homestake (Cl), Kamiokande, SK (H_2O), SNO (D_2O)

② data/th depends on exps.

Large Mixing Angle solution

$\theta_{12} \cong \pi/6$

$\Delta m^2_{21} = 8 \times 10^{-5}\,\mathrm{eV}^2$

- atmospheric ν $\nu_\mu \to \nu_\mu,\ \bar{\nu}_\mu \to \bar{\nu}_\mu$

naive expectation from

$\pi^+ \to \mu^+ + \nu_\mu$, $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

$\pi^- \to \mu^- + \bar{\nu}_\mu$, $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

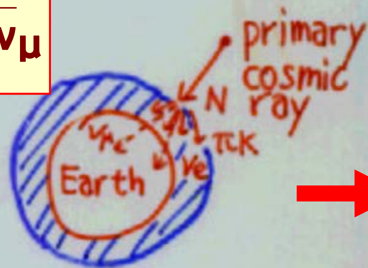
leads to

$\#(\nu_\mu + \bar{\nu}_\mu)/\#(\nu_e + \bar{\nu}_e) \simeq 2$

but observations show

① $\#(\nu_\mu + \bar{\nu}_\mu)/\#(\nu_e + \bar{\nu}_e) \simeq 1.3$

② data/th depends on zenith angle



Kamiokande
IMB
SK
Soudan2
MACRO

maximal mixing

$\theta_{23} \cong \pi/4$

$|\Delta m^2_{32}| = 2.5 \times 10^{-3}\,\mathrm{eV}^2$

K2K $\nu_\mu \to \nu_\mu$

CHOOZ (reactor) $\bar{\nu}_e \to \bar{\nu}_e$

$L \sim 1\,\mathrm{km}$, $E_\nu \sim 3\,\mathrm{MeV}$

$\left|\frac{\Delta m^2_{21} L}{4E}\right| = \left|\frac{\Delta m^2_\odot L}{4E}\right| \ll 1$

$\Delta m^2|_{N_\nu=2} \equiv \Delta m^2_{32}$

$N_\nu = 3$

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - 4|U_{e3}|^2(1-|U_{e3}|^2)\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$4|U_{e3}|^2(1-|U_{e3}|^2) = \sin^2 2\theta_{13}$

small mixing

$\sin^2 2\theta_{13} < 0.15$

● Oscillation probability w/ NP in propagation

$$\mathcal{M} \equiv U\,\mathrm{diag}(E_j)\,U^{-1} + \mathcal{A} = \tilde{U}\,\mathrm{diag}(\tilde{E}_j)\,\tilde{U}^{-1}$$

$$\mathcal{A} \equiv A \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

$$A \equiv \sqrt{2} G_F N_e$$

$$N_e \equiv \text{electron density}$$

$$P(\nu_\alpha \to \beta) = \left| \left[\tilde{U} \exp\left\{ -i\,\mathrm{diag}(\tilde{E}_j) L \right\} \tilde{U}^{-1} \right]_{\beta\alpha} \right|^2$$

- Mass matrix $\mathcal{M}$ is hermitian
- There are only 3 flavors

Oscillation probability satisfies 3 flavor unitarity

Oscillation probability w/ NP @ source/detector

$$\mathcal{M} \equiv U\,\mathrm{diag}(E_j)\,U^{-1} + \mathcal{A}_0 = \tilde{U}_0\,\mathrm{diag}(\tilde{E}_j^0)\,\tilde{U}_0^{-1}$$

$$\mathcal{A}_0 \equiv A \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$P(\nu_\alpha \to \beta) = \left| \left[U^d \tilde{U}_0 \exp\left\{ -i\mathrm{diag}(\tilde{E}_j^0) L \right\} \tilde{U}_0^{-1} (U^s)^{-1} \right]_{\beta\alpha} \right|^2$$

- There are only 3 flavors
- But matrix $U^d \mathcal{M} (U^s)^{-1}$ is not hermitian

↓

Oscillation probability does not satisfy 3 flavor unitarity

Off-diagonals from mixing with heavy states

- If NU is due to some mixing with heavy states, then ε is negative semi-definite
- In particular this implies

Antusch, Baumann, Fernandez-Martinez, NPB810(2009)369, 0807.1003

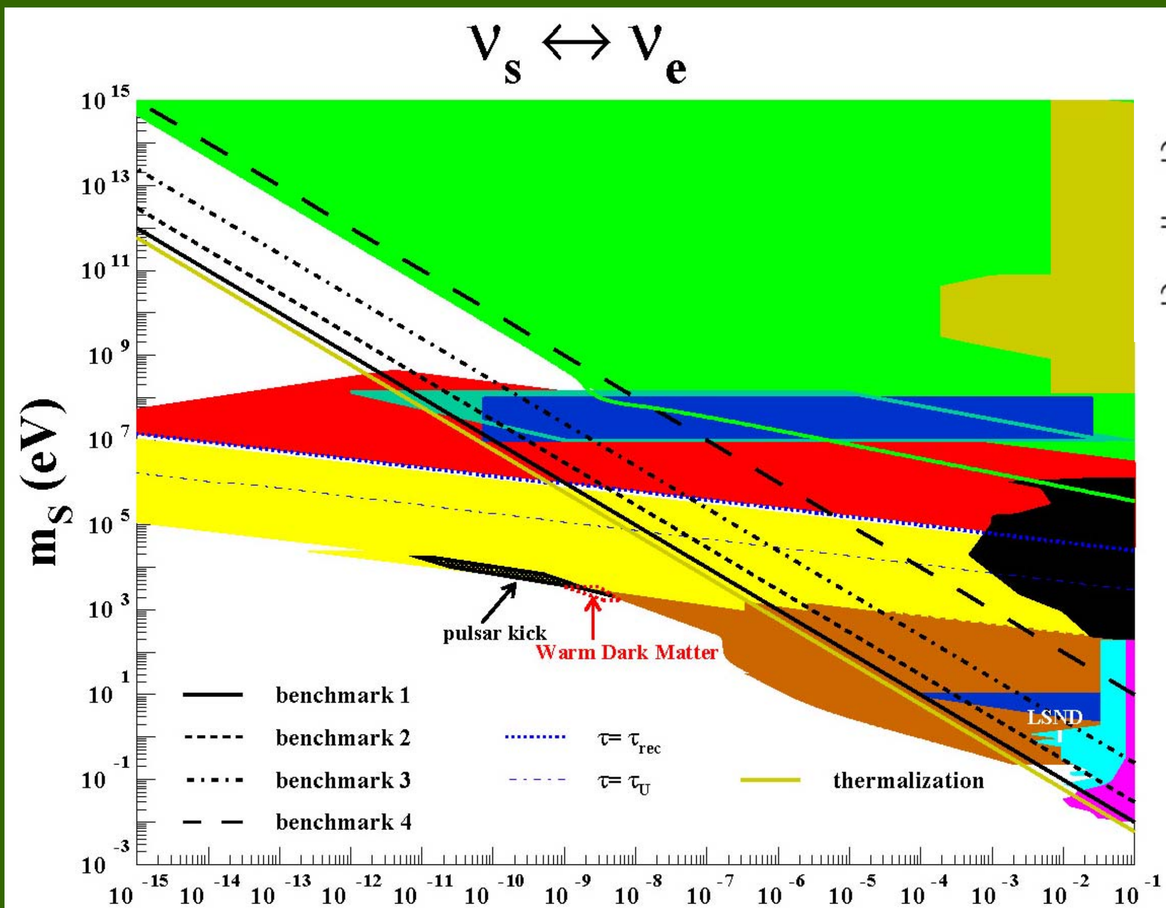
$$|\varepsilon_{\alpha\beta}|^2 \leq |\varepsilon_{\alpha\alpha}\varepsilon_{\beta\beta}|$$

as well as

$$\varepsilon_{\alpha\alpha} < 0$$

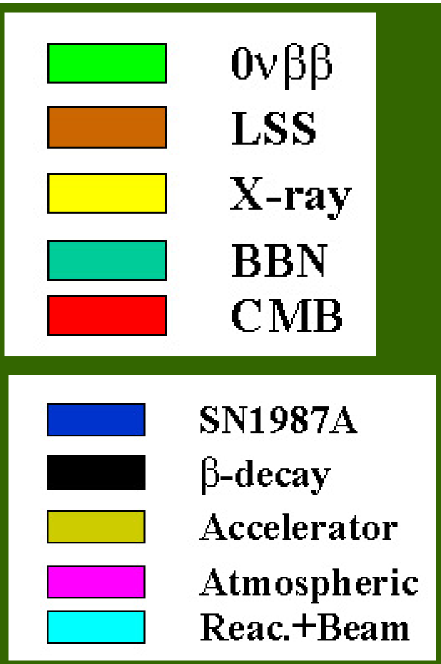
Cosmological constraints on light sterile neutrinos

Smirnov & Zukanovich -Funchal, Phys.Rev.D74:013001,2006

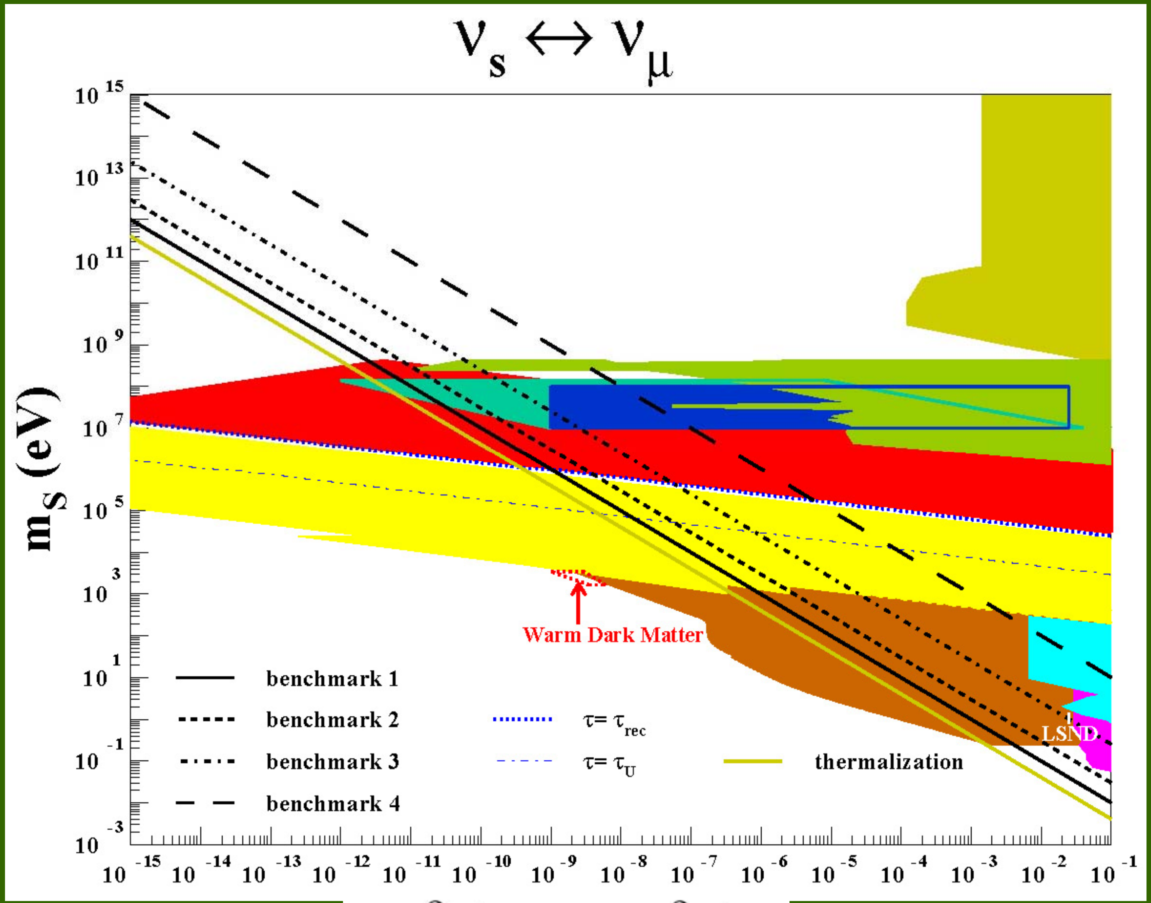


$\sin^2\theta_S \simeq \sin^2\theta_{14}$

$$
\begin{aligned}
&P(\nu_e \to \nu_s) \\
\simeq\ & 4|U_{e4}U_{s4}|^2 \sin^2(\Delta m^2_{41} L/4E) \\
=\ & c^2_{24}c^2_{34}\sin^2 2\theta_{14}\sin^2(\Delta m^2_{41} L/4E) \\
\simeq\ & \sin^2 2\theta_{14}\sin^2(\Delta m^2_{41} L/4E)
\end{aligned}
$$



Smirnov & Zukanovich -Funchal, Phys.Rev.D74:013001,2006



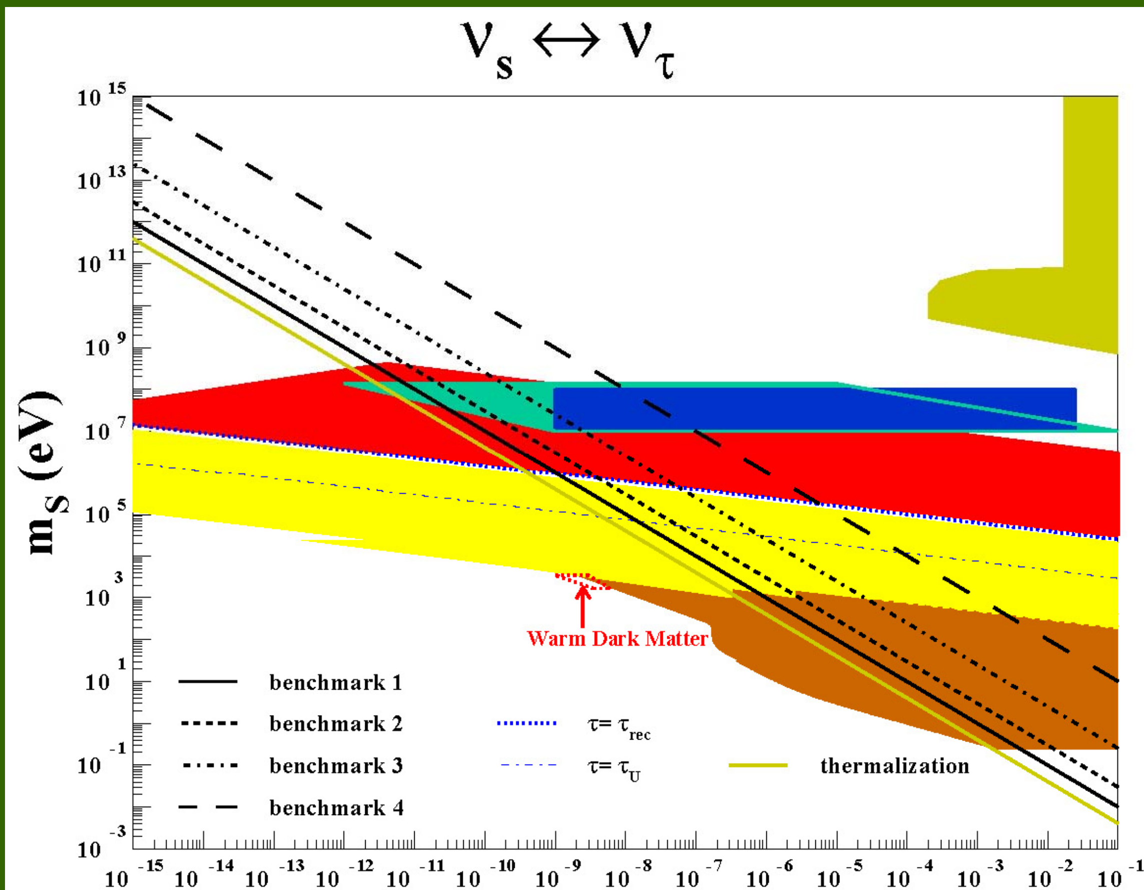
$\sin^2\theta_S \simeq \sin^2\theta_{24}$

$$
\begin{aligned}
& P(\nu_\mu \to \nu_s) \\
\simeq\ & 4|U_{\mu 4}U_{s4}|^2 \sin^2(\Delta m_{41}^2 L/4E) \\
=\ & c_{14}^4 c_{34}^2 \sin^2 2\theta_{24} \sin^2(\Delta m_{41}^2 L/4E) \\
\simeq\ & \sin^2 2\theta_{24} \sin^2(\Delta m_{41}^2 L/4E)
\end{aligned}
$$

- LSS
- X-ray
- BBN
- CMB

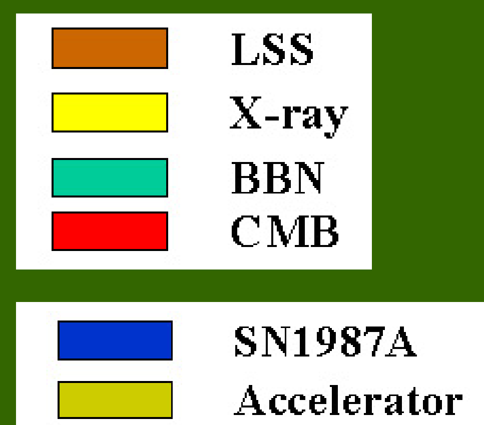
- SN1987A
- Accelerator
- Decays
- Atmospheric
- Beam

Smirnov & Zukanovich -Funchal, Phys.Rev.D74:013001,2006



$$\sin^2\theta_S \simeq \sin^2\theta_{34}$$

$$
\begin{aligned}
& P(\nu_\tau \to \nu_s) \\
\simeq\ & 4|U_{\tau 4}U_{s4}|^2 \sin^2(\Delta m^2_{41} L/4E) \\
=\ & c^4_{24} \sin^2 2\theta_{34} \sin^2(\Delta m^2_{41} L/4E) \\
\simeq\ & \sin^2 2\theta_{34} \sin^2(\Delta m^2_{41} L/4E)
\end{aligned}
$$



CPT and Lorentz invariance violation

If the major cause of ν oscillations come from a force which is mediated by a spin J particle, then oscillation probability behaves as

OY gr-qc/9403023v1

$$\mathrm{Prob}(J=0) = \sin^2 2\theta \sin^2\left(\frac{\text{const.}\times L}{E}\right)$$

$$\mathrm{Prob}(J=1) = \sin^2 2\theta \sin^2(\text{const.}\times L)$$

$$\mathrm{Prob}(J=2) = \sin^2 2\theta \sin^2(\text{const.}\times EL)$$

- $J=0$: the same as osc. from mass
- $J=1$: Lorentz inv. Violation, torsion
- $J=2$: equivalence principle violation

CPT invariance violation

Murayama-Yanagida, PL B520 (2001) 263

$$\overline{\theta}_{ij} \neq \theta_{ij} \qquad \Delta\overline{m}^2_{ij} \neq \Delta m^2_{ij}$$

None of them can be major cause for ν oscillations, although these may show up as small perturbation (at least killing them all completely is an experimentally challenge).

MaVaN (Mass Varying Neutrino) model

Neutrino dark energy scenario

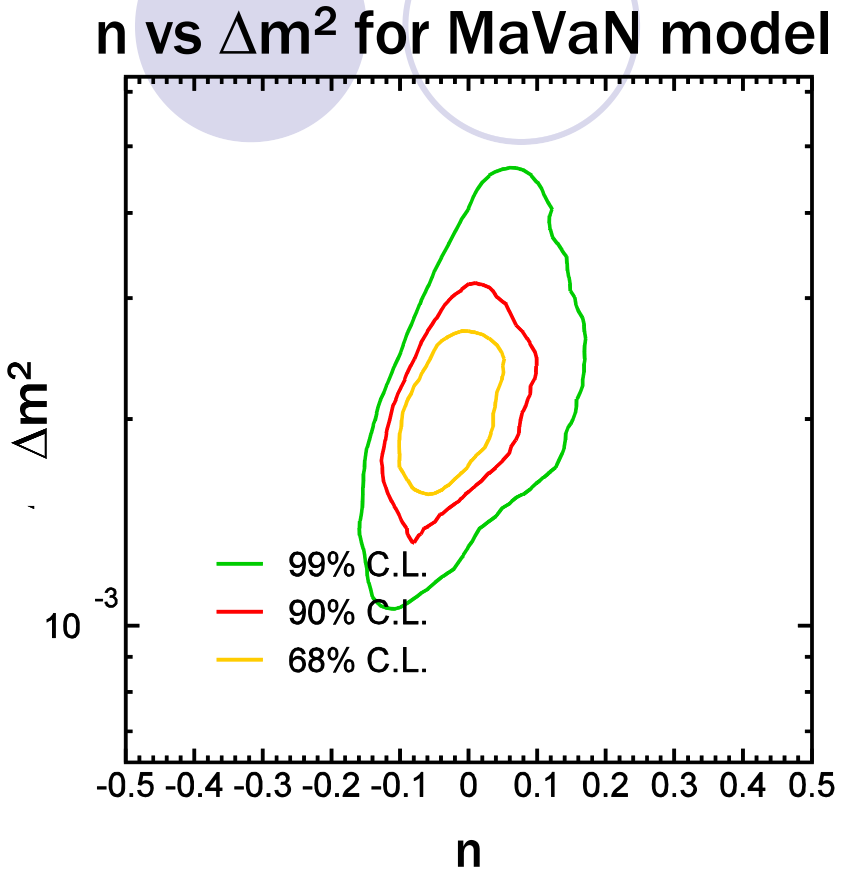
- Relic neutrinos of which masses varied by ambient neutrino density (A.Nelson et al. 2004)
- Possibly their masses also varied by matter density or electron density beyond the MSW effect

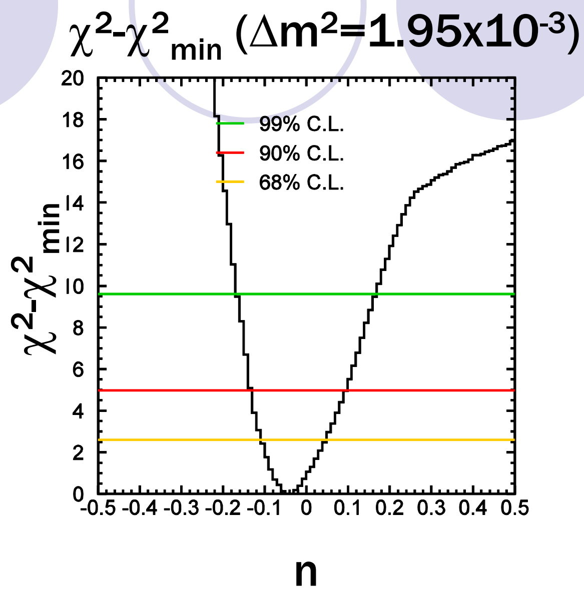
Check additional matter effect in atmospheric data

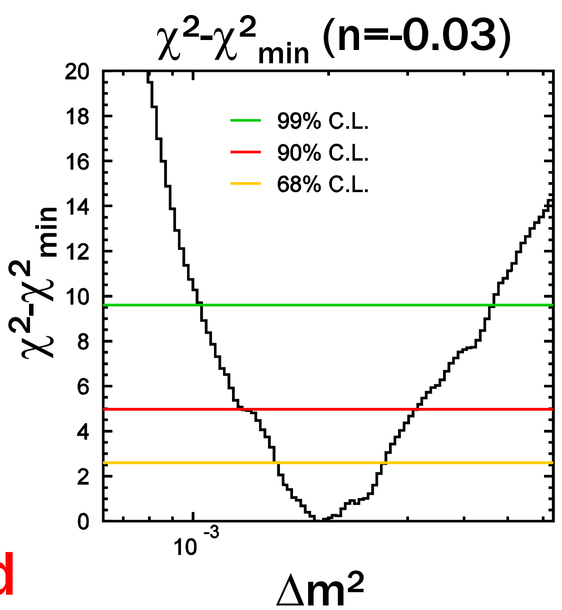
- $\Delta m^2 \rightarrow \Delta m^2 \times (\rho_e/\rho_0)^n$ (ρ_0=1.0mol/cm^3)

  mass varying with electron denstiy
- 2 flavor Zenith angle analysis
- assuming $\sin^2 2\theta$=1.0
- SK-I dataset

Result for MaVaN-type matter effect







Best fit : $\Delta m^2 = 1.95 \times 10^{-3} eV^2$

$n=-0.03$

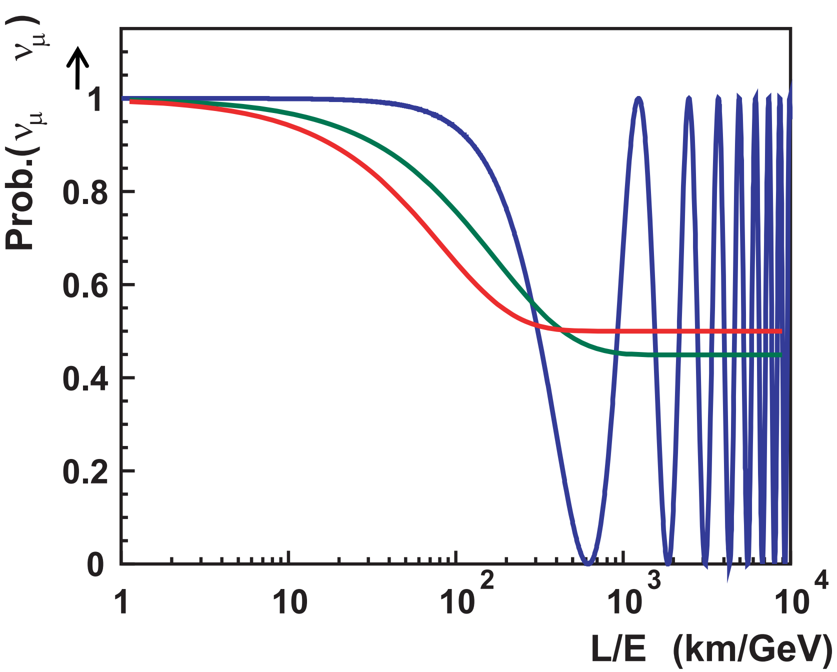
$\chi^2=172.2/178$ dof

MaVaN type models tested are disfavored

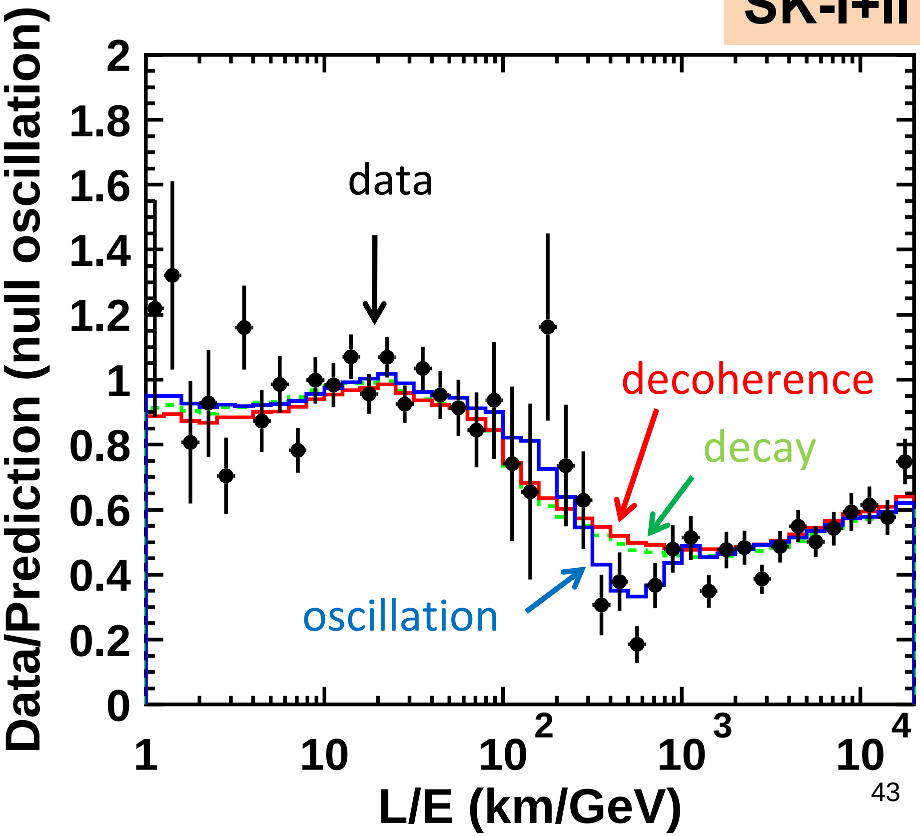
L/E oscillation analysis

Neutrino oscillation :	χ^2_{osc} = 83.9/82 d.o.f
Neutrino decay :	χ^2_{dcy} = 107.1/82 d.o.f, $\Delta\chi^2 = 23.2$ (4.8σ)
Neutrino decoherence :	χ^2_{dec} = 112.5/82 d.o.f, $\Delta\chi^2 = 27.6$ (5.3σ)

survival probability

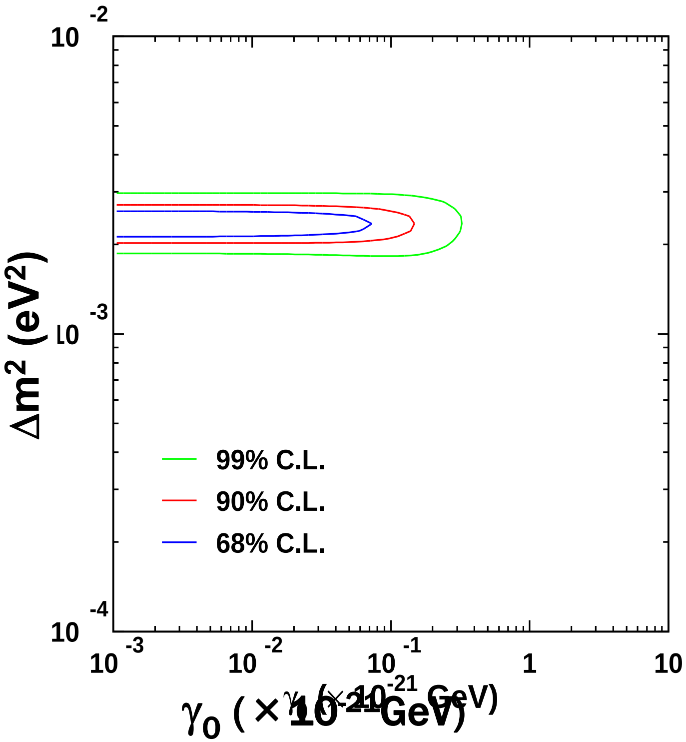


SK-I+II



oscillation+decoherence

$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \times \left(1 - \exp\left(-\gamma_0 \frac{L}{E}\right) \times \cos\left(\frac{\Delta m^2 L}{2E}\right)\right)$$



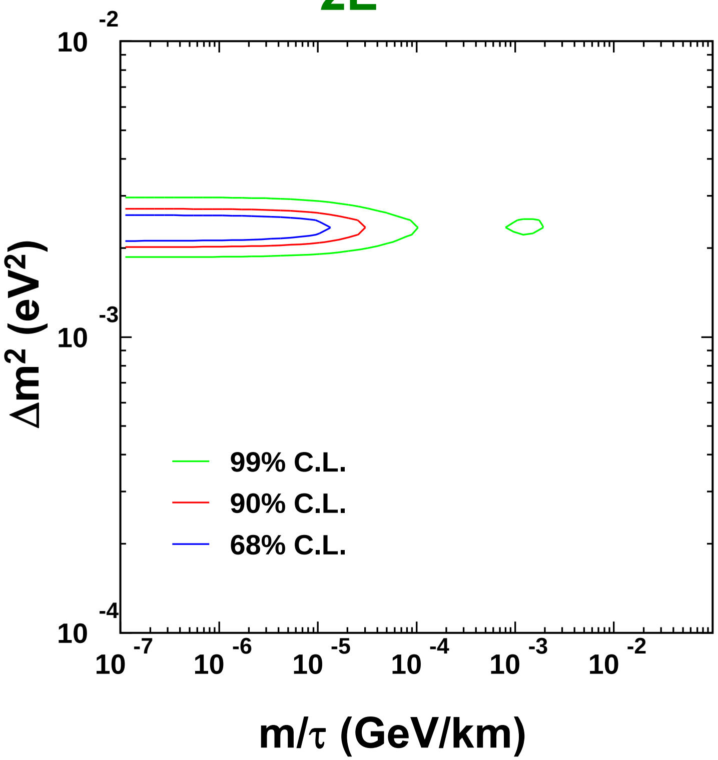
χ^2_{min} = 83.8/81 d.o.f

$(\gamma^0, \Delta m^2, \sin^2 2\theta)$ = (0 GeV, 2.4×10^{-3}eV^2, 1.0)

$\gamma_0 < 1.4\times10^{-22}$GeV (90%C.L.)

oscillation+decay

$$P_{\mu\mu} = \sin^4\theta + \cos^4\theta \times \exp\left(-\frac{m}{\tau}\frac{L}{E}\right) + 2\sin^2\theta\cos^2\theta \times \exp\left(-\frac{mL}{2\tau E}\right) \times \cos\left(\frac{\Delta m^2 L}{2E}\right)$$



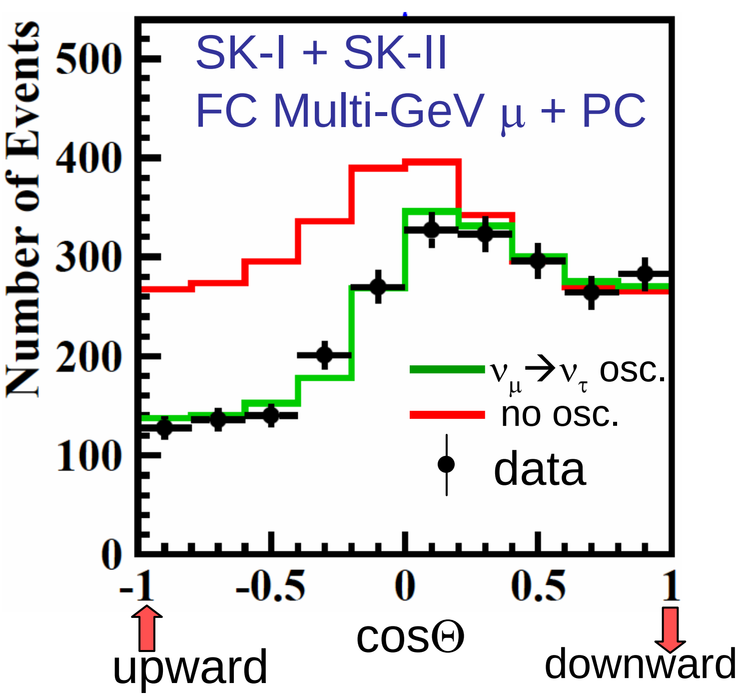
χ^2_{min} = 83.8/81 d.o.f

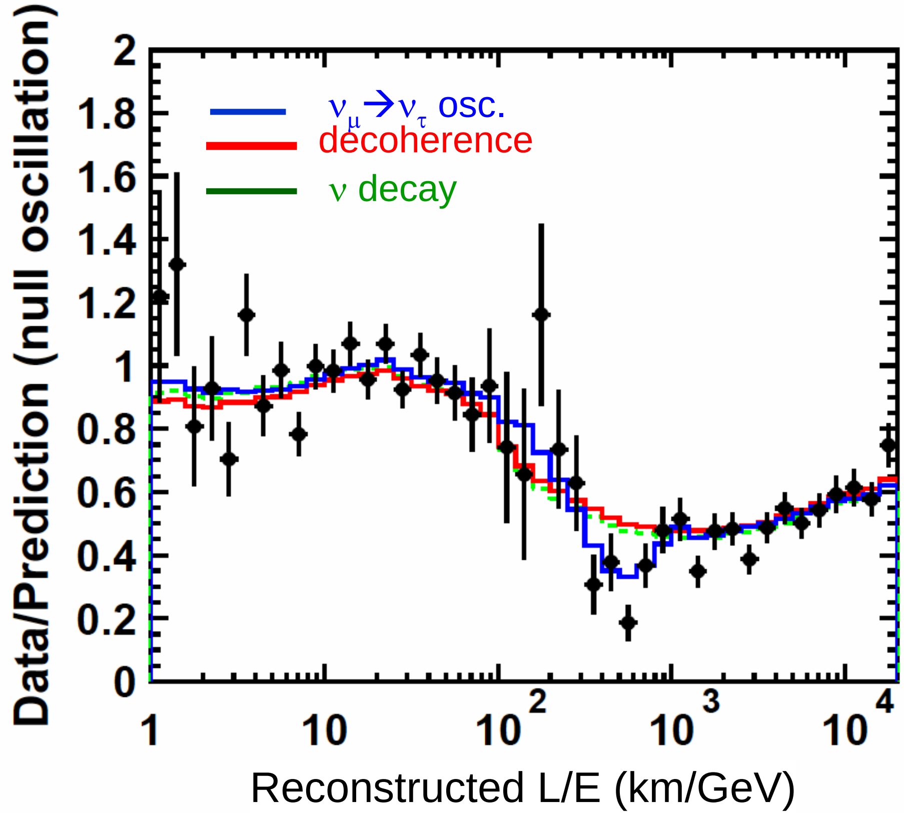
$(m/\tau, \Delta m^2, \cos^2\theta)$ = (0 GeV/km, 2.4×10^{-3}eV^2, 0.5)

$m/\tau < 3.2\times10^{-5}$GeV/km (90%C.L.)

New physics on Neutrinos using atmospheric neutrinos

Observed deficit of atmospheric muon neutrinos is well explained by Neutrino oscillation due to neutrino mass differences.





New physics can be explain the observed deficit pattern ?

$\nu_\mu \rightarrow \nu_\tau$ osc. : χ^2_{min} = 83.9/83 dof

decoherence : χ^2_{min} = 112.5/83 dof, $\Delta\chi^2$=23.2(5.3σ)

ν decay : χ^2_{min} = 107.1/83 dof $\Delta\chi^2$=27.6(4.8σ)

J. Kameda, Summary of searches for exotic phenomena with SK

Neutrino oscillations due to "New Physics"

Several classes of the theories predicts neutrino oscillation with a different energy dependence of the probability:

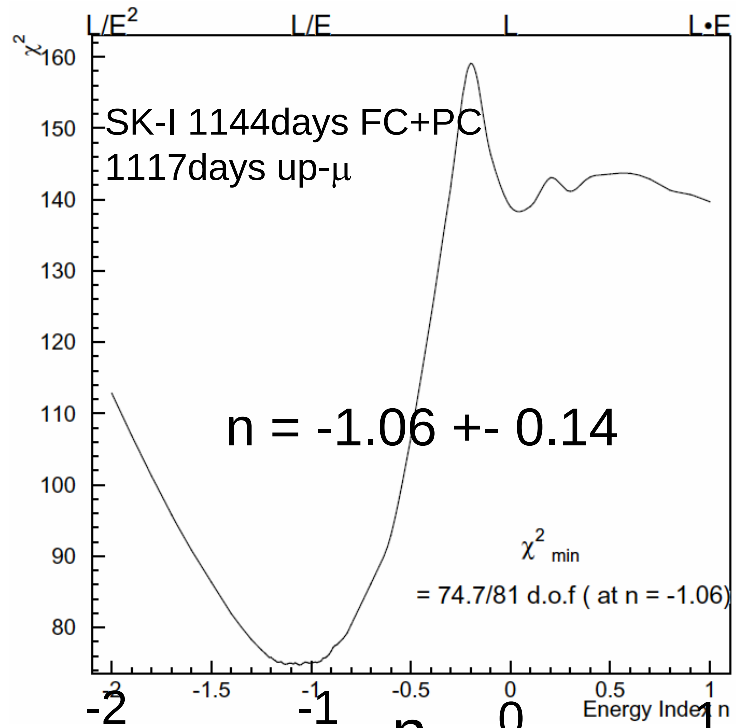
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\Theta \sin^2(a \cdot \mathrm{L} \cdot \mathrm{E}^n)$$

Θ:mixing angle, Lν:ν flight length, Eν: ν Energy, a: oscillation parameter

Models and Eν dependence:

L (n= 0) : CPT violation
LE (n= 1) : Lorentz inv. violation, Equiv. Principle violation
L/E (n=-1) : mass difference ("standard" picture)

"Standard" scenario is a most favored one. Pure CPT violation, LIV violation cannot explain the observed data.



J. Kameda, Summary of searches for exotic phenomena with SK