"Non-Standard" Neutrino Oscillations

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NeuTel XII
Venice, 2/07

"Exotic Explanations for Neutrino Anomalies"
1999 @ Neutel VIII

Revisit!

Then:

New Physics (other than mass-mixing)
to account for observations

But mass + mixing confirmed
for the observations

hence

Now: Constrains on New Physics
from current data & future expts.

- Non Standard Interactions (N.C.)

  FCNC & NUNC

  Solar
  Atm.
  Minos
  Future

- ν Decay

  New Bounds

- Lorentz Inv. Violations

  New Bounds + Future

- LSND explanations

  & Tests for them.

- New Neutral Cannent ν-interactions (new acronym NSI).

- FCNC & NUNC
  - Generally assumed $V-A$ but could be diffent
  - must have V or S for forward coherent scatt.

Typical term:

$$\varepsilon \cdot \frac{4G_F}{\sqrt{2}} \left\{ \bar{\nu}_{\alpha_L} \gamma_\mu \nu_{\beta_L} \bar{q}_L \gamma_\mu q_L + \cdots \right\}$$

$$\varepsilon'_\alpha \cdot \frac{4G_F}{\sqrt{2}} \left\{ \bar{\nu}_{\alpha_L} \gamma_\mu \nu_{\alpha_L} \bar{q}_L \gamma_\mu q_L \right\}, \quad \varepsilon'_\beta \text{ etc.}$$

similarly for leptons etc

e.g. $q = u, d$

Then: • fits to solar data with

$$\left\{ \begin{array}{ll} \varepsilon_u^{e\tau} \sim 10^{-2}, & (\varepsilon'_e - \varepsilon'_\tau)_q \sim 0.4 \\ \varepsilon_d^{e\tau} \sim 0.1, & (\varepsilon'_e - \varepsilon'_\tau)_q \sim 0.57 \end{array} \right\}$$

• fits to atm. data with

$\varepsilon_q^{e\tau} \sim 0.1 \quad (\varepsilon'_e - \varepsilon'_\tau)_q \sim 0.1 \quad$ (50-50).

Solar Neutrino Data analysed incl. NSI

Friedland
Lunardini
Miranda
Tortola
Valle
Pena-Garay

- Main Feature :
  - LMA parameters can shift
  - new LMA solutions appear. incl. dark side (?)
  - Observation of ^7Be & pep lines crucial to discriminate.

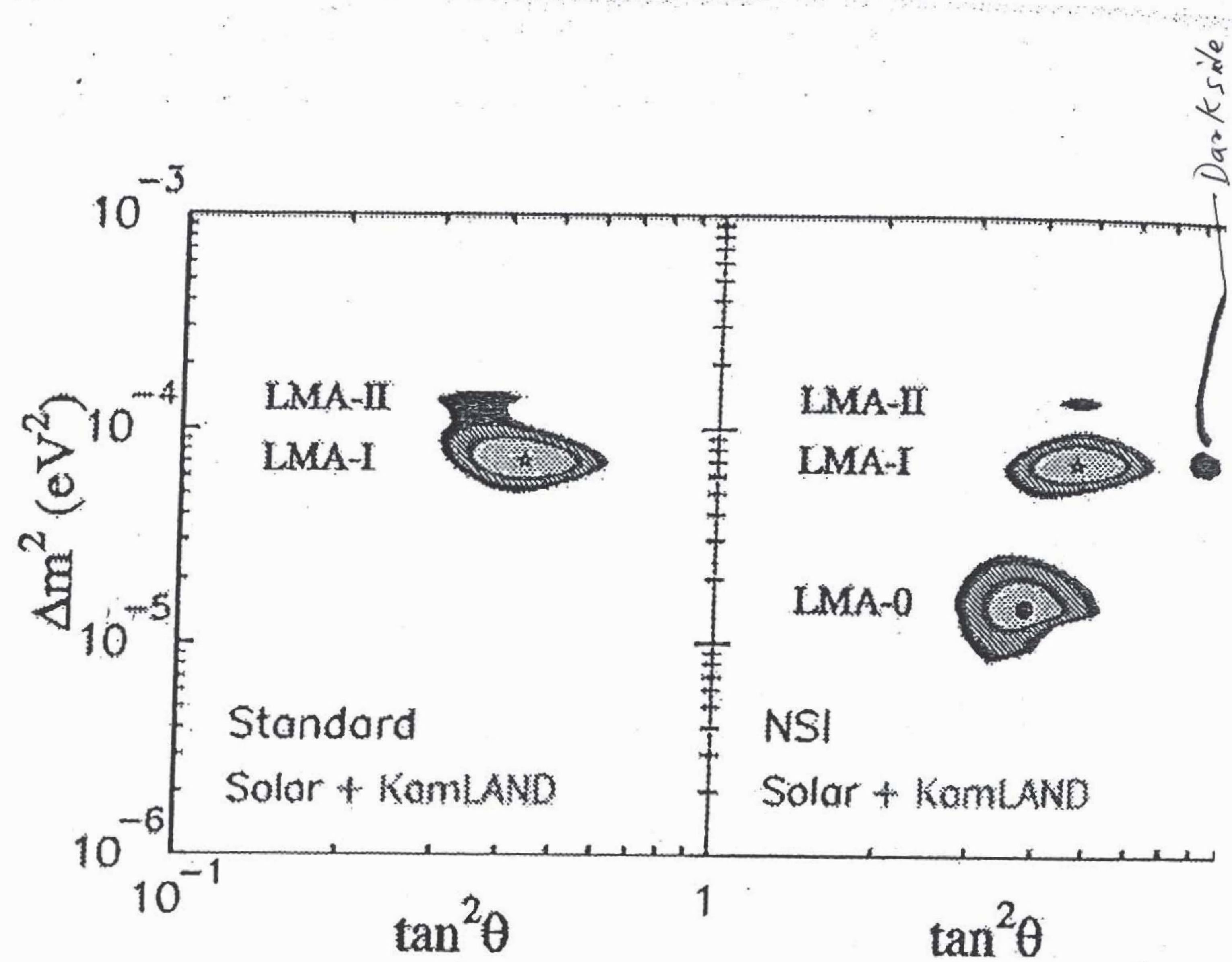
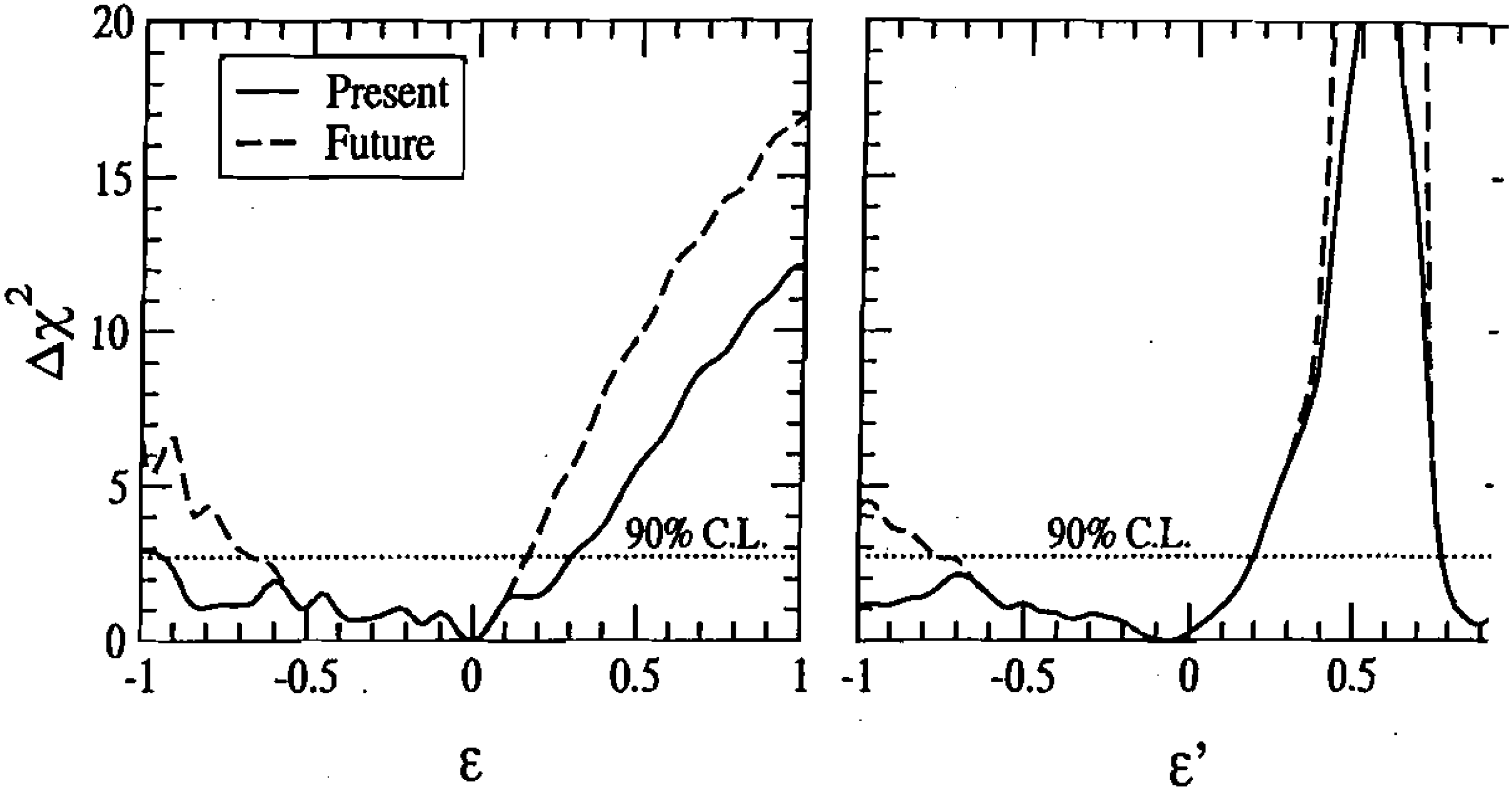


Fig. 2. Regions of Δm^2 and $\tan^2\theta$ allowed at 90, 95, 9 99.73% C.L. (2 d.o.f.) for SM interactions (left) and the NSI sc nario (right) described by Eqs. (3)–(6). For the latter we use $\underbrace{\epsilon^u_{11} = \epsilon^d_{11}}_{\varepsilon_{ee}^{\prime\,(u,d)}} = -0.065$, $\underbrace{\epsilon^u_{12} = \epsilon^d_{12}}_{\varepsilon_{e\mu}^{(d)}} = -0.15$.



: 3: Constraining NSI parameters: dependence of $\Delta\chi^2$ with respect to ε and ε', il
rent limits.

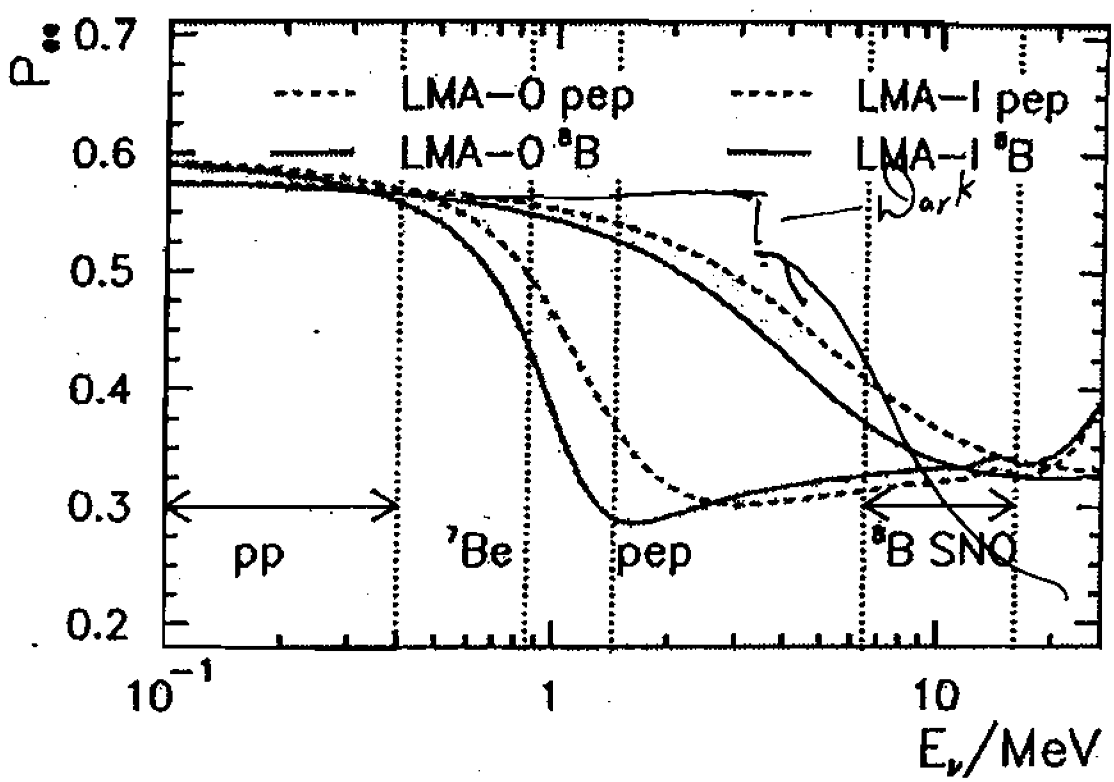


Fig. 3. The predicted KamLAND spectrum (top) and the time-averaged solar neutrino survival probability (bottom) for the LMA-0 best-fit point. For comparison, the standard LMA-I survival probability is also given. Refer to the text for details.

Atmospheric Data Analysed with NSI

{ Friedland, Lunardini, Maltoni (most recent)

- Main Features:
  - Best fit values for δm_A^2 and $\sin^2\theta_{23}$ shift
    - $\theta_{23} \rightarrow$ lower
    - $\delta m_A^2 \rightarrow$ higher

    } understood.
- large values for $\varepsilon_{e\tau}$ & $\varepsilon'_{\tau\tau}$ allowed (consistent with Solar)

  (assumed $\varepsilon_{e\mu} \to 0$)
- Tests: { more N.C. events at MINOS

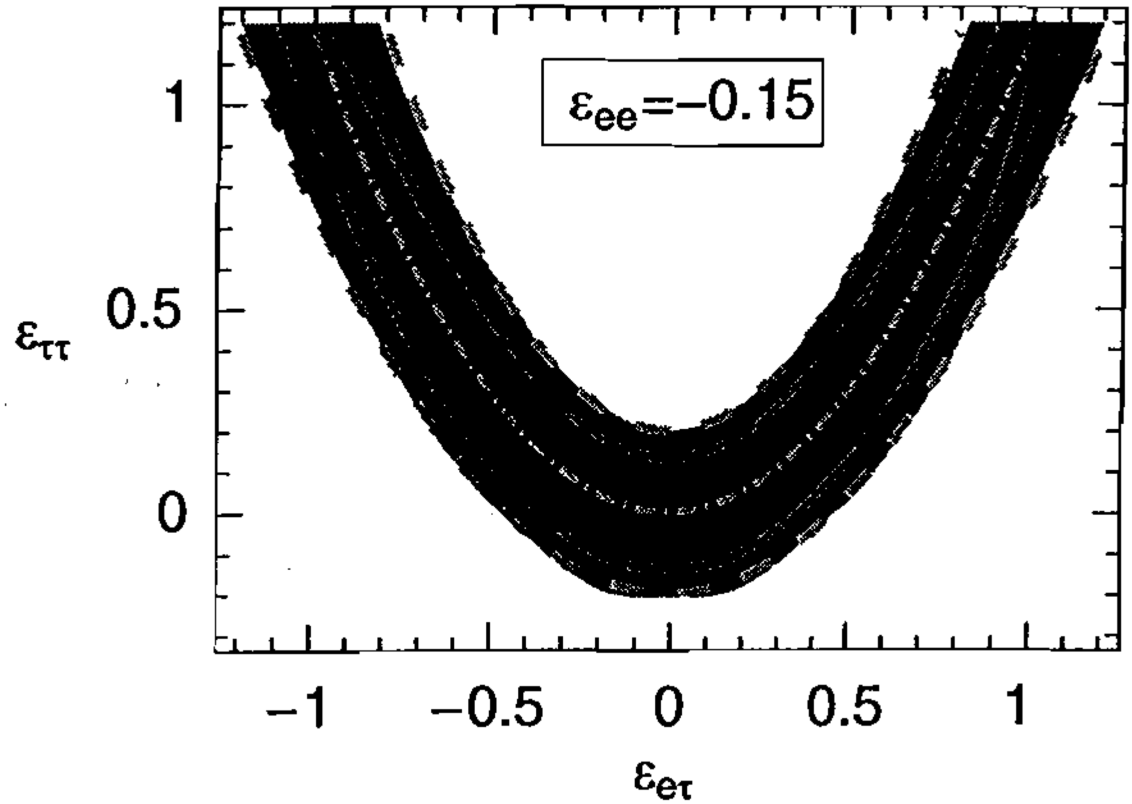


FIG. 1 (color online). A 2-D section ($\epsilon_{ee} = -0.15$) of the allowed region of the NSI parameters (shaded). We assumed $\Delta m^2_{\odot} = 0$ and $\theta_{13} = 0$, and marginalized over θ and Δm^2. The dashed contours indicate our analytical predictions. See text for details.

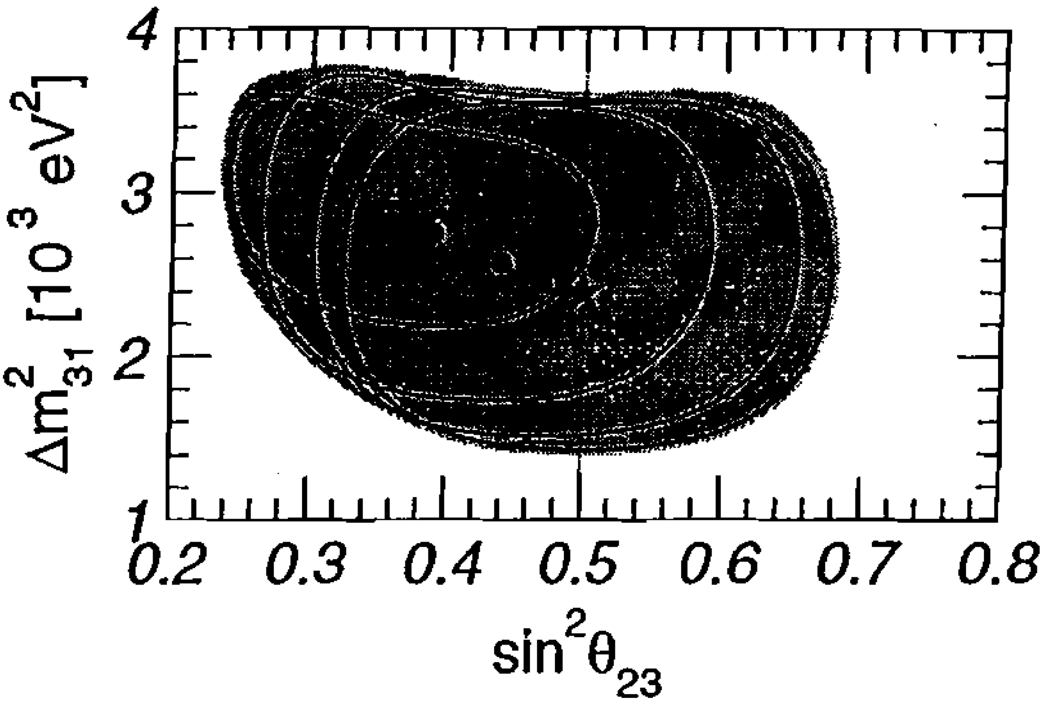


FIG. 2 (color online). The effect of the NSI on the allowed region and best-fit values of the oscillation parameters; see text for details.

Constraining NSI in $\nu_e e$ & $\bar{\nu}_e e$ scattering

J. Barranco, Miranda, Moura & Valle

- Use data from all expts (LSND, UCI, Rovno, MUNU)
- $\sin^2\theta_W$ well-known

New Bounds:

$$-1.6 < \varepsilon_{ee}^{\prime L}(e) < 0.12$$

$$-0.6 < \varepsilon_{ee}^{\prime R}(e) < 0.15$$

$$|\varepsilon_{e\tau}^{L}(e)| < 0.85$$

$$|\varepsilon_{e\tau}^{R}(e)| < 0.38$$

NSI @ MINOS

Kitazawa, Sugiyama, Yasuda
Friedland, Lunardini
Blennow, Ohlsson, Skrotzki

Two Main Effects

- Extraction of θ_{23} & δm_A^2

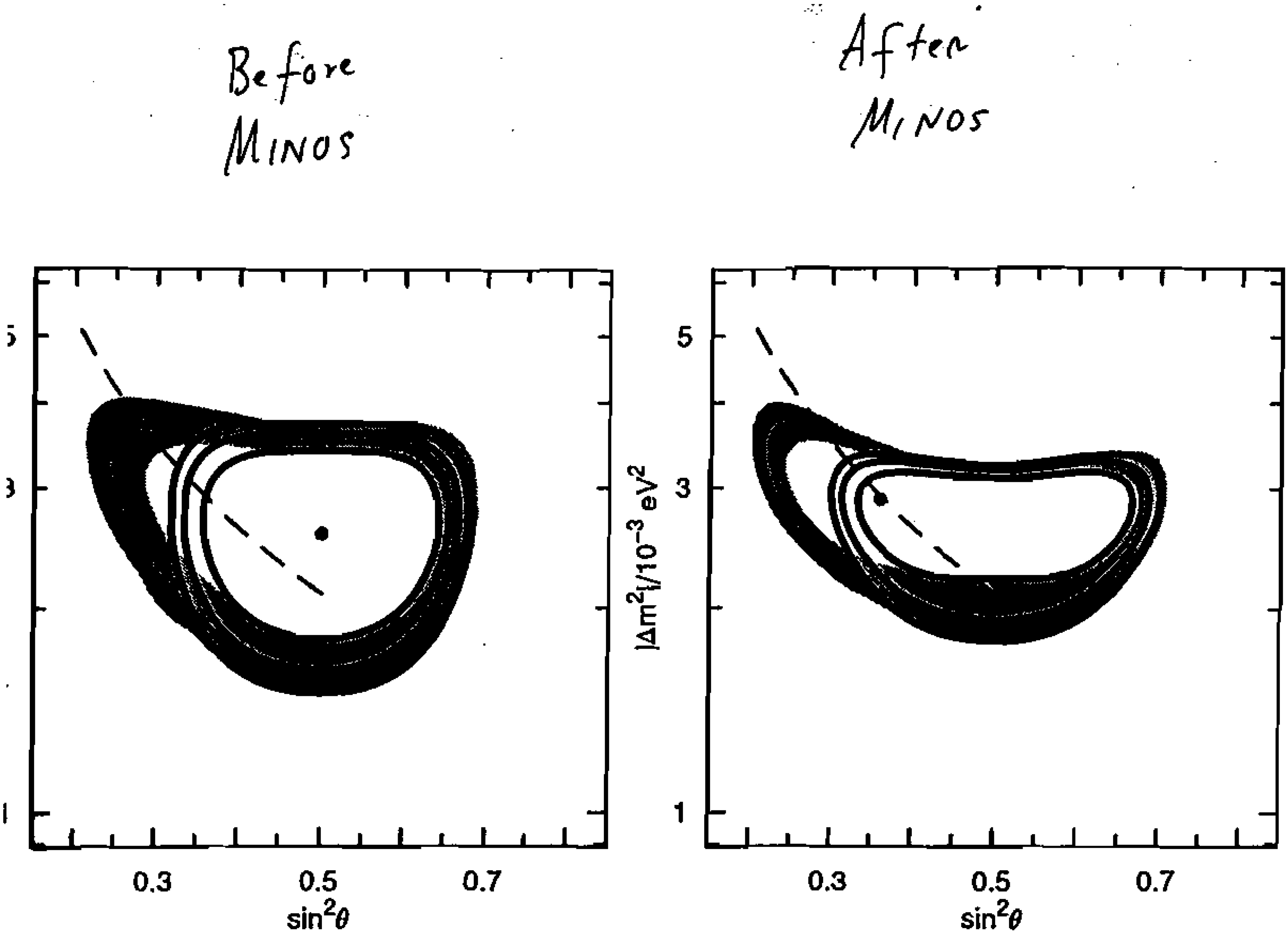
  Effect similar to atmospheric ν's.

- ν_e appearance and degeneracy of θ_{13} & $\varepsilon_{e\tau}$

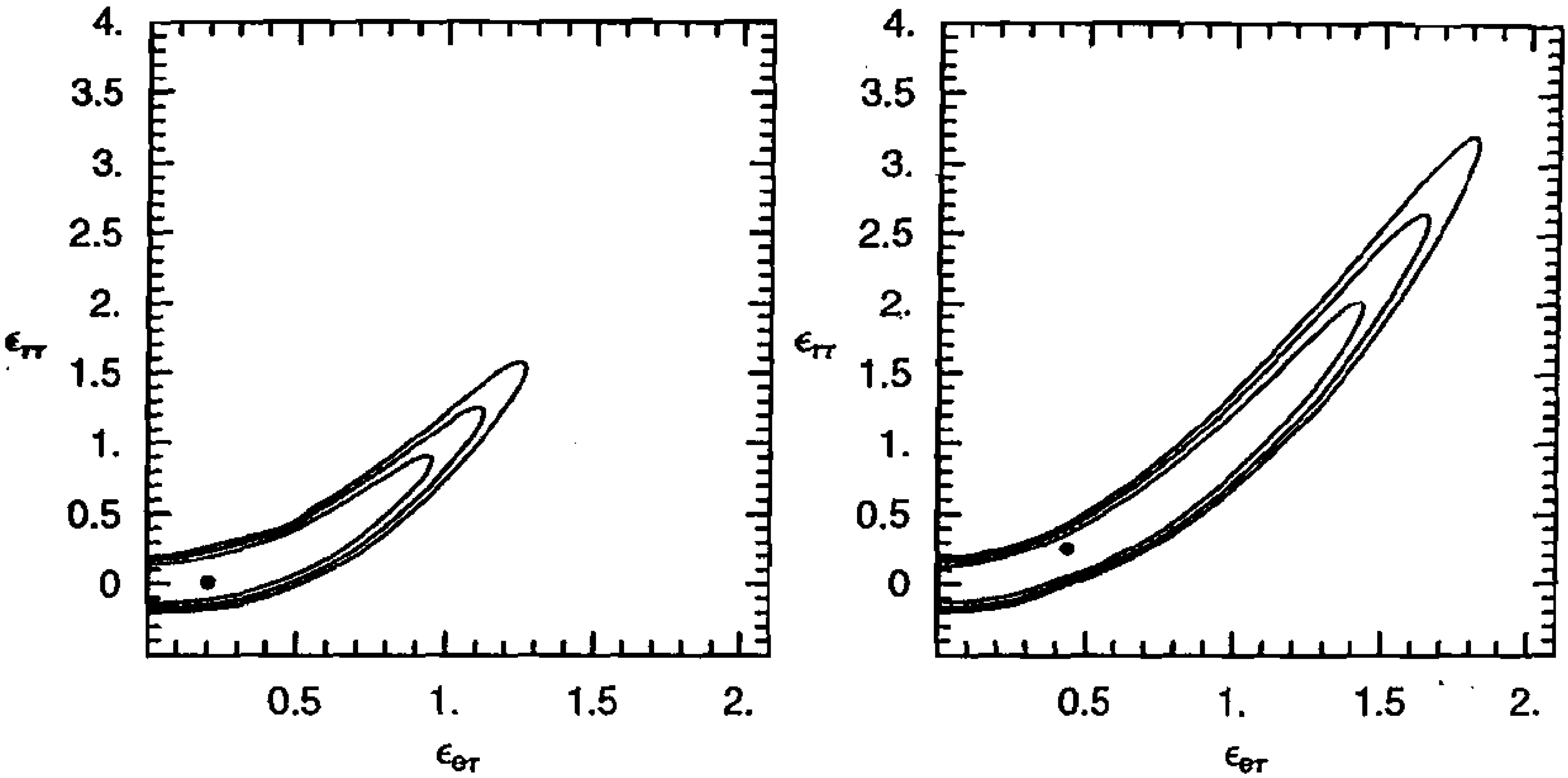
- Define $\tilde{U}_{e3} = U_{e3} + \varepsilon_{e\tau} \dfrac{2EV}{\delta m_A^2} \cos\theta_{23}$

Then $P_{\mu e} = 4|\tilde{U}_{e3}|^2 |\tilde{V}_{\mu 3}|^2 \sin^2\left(\dfrac{\delta \tilde{m}_{31}^2}{4E} L\right)$

$\Rightarrow$ Measuring $|\tilde{U}_{e3}|$ is not the same as measuring U_{e3}!

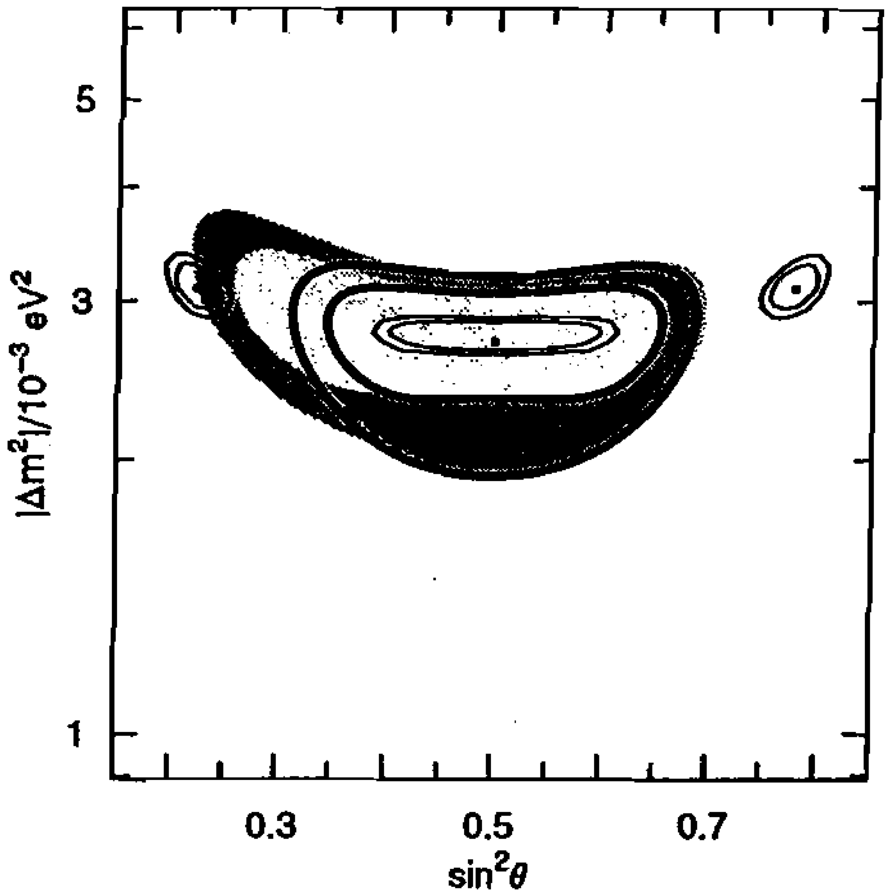


nline). Regions in the space $\Delta m^2 - \sin^2\theta$ allowed by the global fit before (left panel) and after (right pan
, with purely standard interactions (contours) and with NSI (filled areas). For both cases we plot the regions allo
l 3σ confidence levels for 2 degrees of freedom. We have marginalized also over the sign of Δm^2 and took
vated by one of the accelerator bounds (see [9]). The dashed line represents the possible positions of the best-fit p
data only in the space of the vacuum parameters for fixed θ_m and Δm_m^2, and varying NSI along the parabola (
$.1 \times 10^{-3}$ eV^2 and $\theta_m = \pi/4$, motivated by the best fit of atmospheric neutrinos alone [27].



lor online). Two sections of the allowed region in the three-dimensional space of the NSI couplings along
e contours refer to 95%, 99%, and 3σ confidence levels. The points of minimum of the χ^2 in this plane are also sl
panel refers to normal (inverted) mass hierarchy. The $\epsilon_{ee} < 0$ regions are symmetric with respect to those sho

FUTURE MINOS



IG. 3 (color online). Results of fits to simulated MINOS data ith statistics increased from the current 0.93×10^{20} to $25 \times$ 0^{20} protons on target (thin contours). 90% and 99% C.L. gions are shown. The "data" were simulated for two sets of SI and true oscillation parameters: (i) no NSI, $\sin^2\theta = 0.5$, and $m^2 = 2.7 \times 10^{-3}$ eV^2, (ii) $\epsilon_{ee} = 0$, $\epsilon_{\tau\tau} = 0.81$, $\epsilon_{e\tau} = 0.9$, n$2\theta = 0.27$, and $\Delta m^2 = 3.1 \times 10^{-3}$ eV^2. The fits were done 1 both cases in the assumption of no NSI. For reference, we also 1ow the regions allowed currently by all the data combined, at 0% and 99% C.L. with (filled area) and without NSI (thick ontours), as in Fig. 1. See text for details.

$\sin^2(2\theta_{12}) = 0.8$	$\Delta m_{21}^2 = 7 \cdot 10^{-5}$ eV^2
$\sin^2(2\theta_{13}) = 0.07$	$\Delta m_{31}^2 = 2.74 \cdot 10^{-3}$ eV^2
$\sin^2(2\theta_{23}) = 1$	$\delta = \frac{\pi}{2}$

TABLE I: The neutrino oscillation parameters used in the simulations.

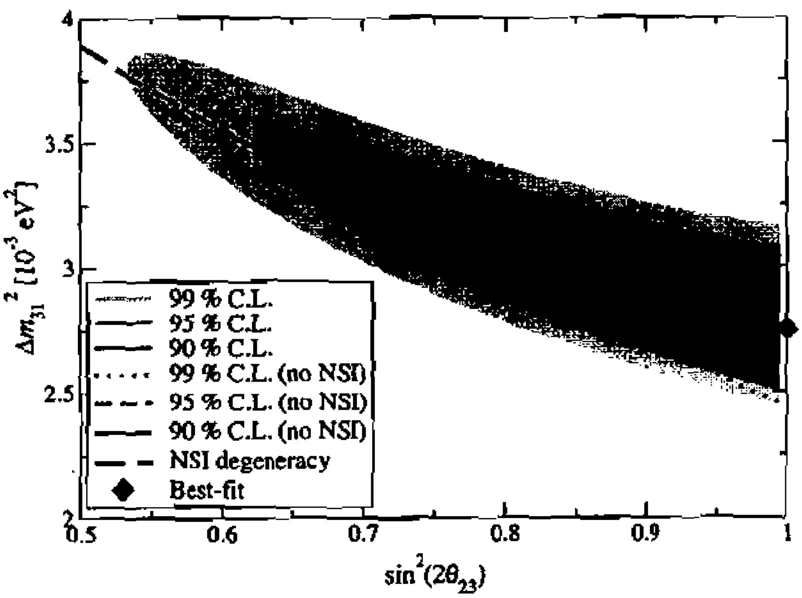


FIG. 2: Sensitivity limits in the $\sin^2(2\theta_{23})$–Δm_{31}^2 plane (2 d.o.f.) for the combined appearance and disappearance channels when allowing NSI compared with the sensitivity limits when not allowing NSI. The dashed blue curve marks the NSI degeneracy where $\Delta m_{31}^2 \sin(2\theta_{23}) = 2.74 \cdot 10^{-3}$ eV^2. The best-fit point corresponds to the parameter values used in the simulation.

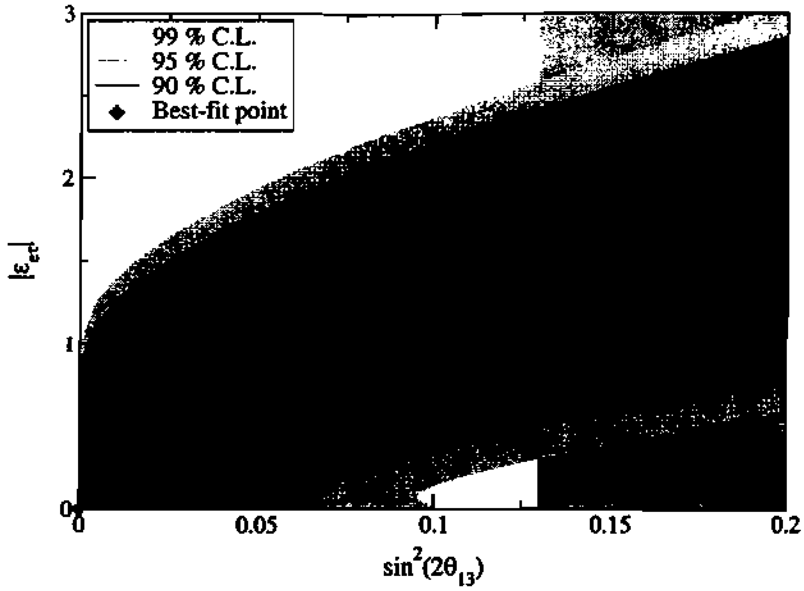


FIG. 3: The sensitivity limits in the $\sin^2(2\theta_{13})$-$|\varepsilon_{e\tau}|$ plane (1 d.o.f.) for the combined appearance and disappearance channels. The solid black curve corresponds to the minimum χ^2-value for given $\sin^2(2\theta_{13})$, while the dashed black curves are the $\bar{U}_{e3} = 0$ (assuming that the relative phase between the two contributions is π) curves using the approximation of Eq. (12) for 2 and 4 GeV, respectively. The corresponding approximation for $E \simeq 2.8$ GeV coincides with the solid black curve of the minimum χ^2. The shaded area shows the CHOOZ bound on $\sin^2(2\theta_{13})$ (at 95 % C.L.). The best-fit point corresponds to the parameter values used in the simulation.

θ_{13} – $\varepsilon_{e\tau}$ Degeneracy

Neutrino Decay

- $\nu_i \to \nu_j + \gamma$ (magnetic moment bounds $\Rightarrow \tau_\gamma$ too long to be interesting)

- $\nu_i \to \nu_j \nu_k \bar{\nu}_k$ (strong bounds on $\tau_{3\nu}$)

- $\nu_i \to \nu_j + \chi$ or $\to \bar{\nu}_j + \chi$ $\left\{ \begin{array}{l} \chi = \text{scalar} \\ \sim \text{majoron} \end{array} \right\}$

Then: Account for Atmospheric Data with $\tau_3 \sim 10^{-13}$ s/eV $\theta \sim 57^\circ$

Now: Decay Ruled out as explanation

Lifetime Limits

$\tau_{\bar{\nu}_1} > 10^{5}$ s/eV (SN 1987A)

$\tau_{\nu_2} > 10^{-4}$ s/eV (Lack of $\bar{\nu}_e$ (sun) in Kamland)

$\tau_{\nu_3} > 10^{-10}$ s/eV SK (Atm.)

Stronger Bounds Possible from Cosmology & High Energy Cosmic ν's.

• Lorentz Invariance Violation (LIV)

Very Simple Model of Spontaneous LIV (Coleman, Glashow) with a constant 4-vector : $\langle 0|V_\mu|0\rangle \rightarrow v_0$ ($\mu=0$).

$\rightarrow$ Each particle species has its own MAV v_i.

for massless ν's:

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta \sin^2\left(\tfrac{1}{2}\,\delta v\, L E\right)$$

$$(\delta E = E_1 - E_2 = \delta v p)$$

Then: Good fit to Atmospheric Data for $\theta \sim 45°$, $\delta v \sim 10^{-22}$

Also for Solar Data !!

Now:

Including δm^2, θ :

$$P_{\alpha\alpha} = 1 - \sin^2 2\Theta \sin^2 \Omega$$

$$2\Theta = \tan^{-1}(a_1/a_2)$$

$$\Omega = \sqrt{|a_1|^2 + |a_2|^2}$$

a_1 & a_2 functions of $(\delta m^2, \theta_m, \theta_v, L/E, \eta)$

(Glashow hep-ph/0407087)

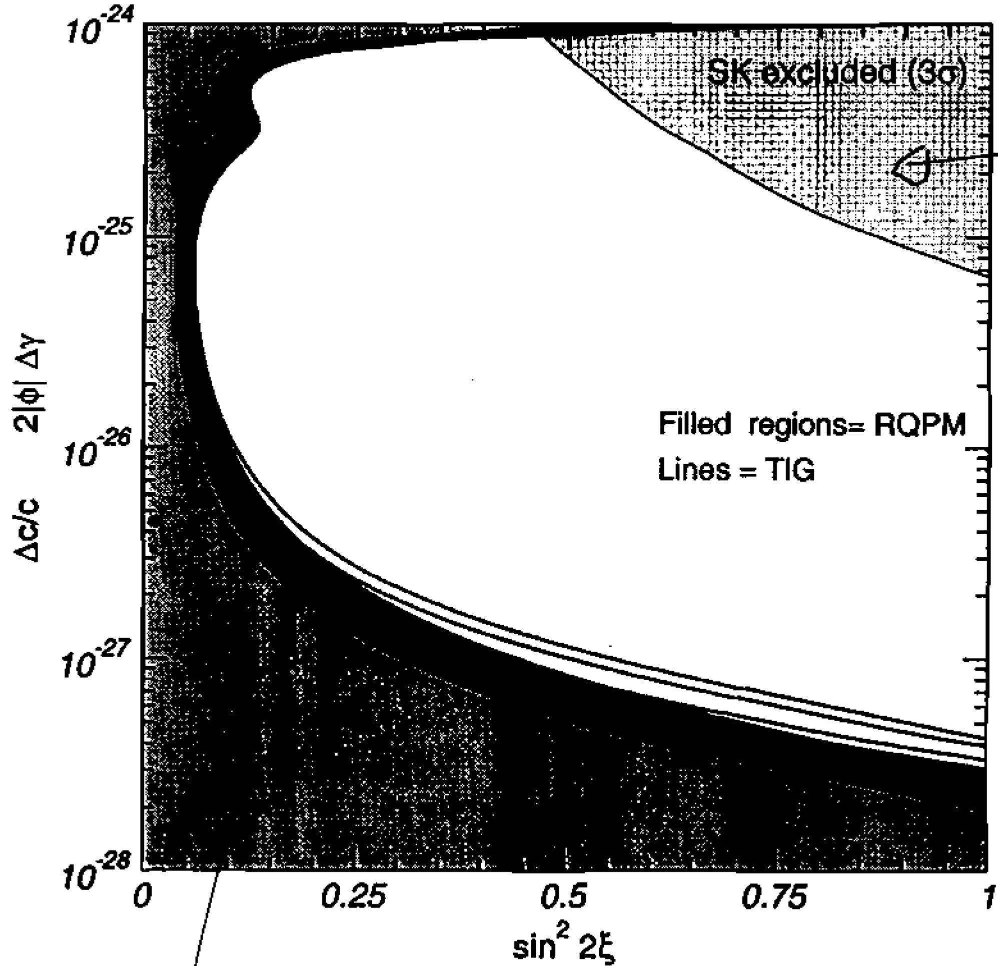
MACRO fit $\Rightarrow$

$$\delta v < 3 \cdot 10^{-25}$$

Super-K
(analysed by Gonzalez-Garcia, Maltoni, Halzen)

More General Elaborate versions of LIV due to A. Kostelecky $\longrightarrow$ see later.

Macro excluded



Sensitivity limits in the $\delta c/c, \xi_{\rm vli}$ at 90, 95, 99 and 3 σ CL. The hatched area in the upper rner is the present 3σ bound from the analysis of SK data in Ref. [26].

Sensitivity in ICE-CUBE

LSND

Summary Scorecard

Proposal	Problem	Viable?
3+1 sterile, 2+2 "	BUGEY + CDHS	×
Rare $\Delta L=2$ Decay Mode	TWIST value for ρ	×
CPTV	KamLand	×
Decoh/CPTV + 1 sterile		✓
3+2 sterile		✓
ν_{st} Decay		✓
ν_{st} in Bulk		✓
3ν + LIV (no sterile)		✓

TABLE I. Parameter values used in our analysis. These were extracted from a fit to all short-baseline neutrino oscillation experiments including LSND within the 3 + 2 scenario [15,20]. 1σ indicates a rough estimate of the 1 sigma allowed range for the different parameters.

	U_{e4}	$U_{\mu 4}$	U_{e5}	$U_{e\mu 5}$	Δm^2_{41} (eV^2)	Δm^2_{51} (eV^2)
Central value	0.121	0.204	0.036	0.224	0.92	22
1σ	0.015	0.027	0.034	0.018	0.08	2.4

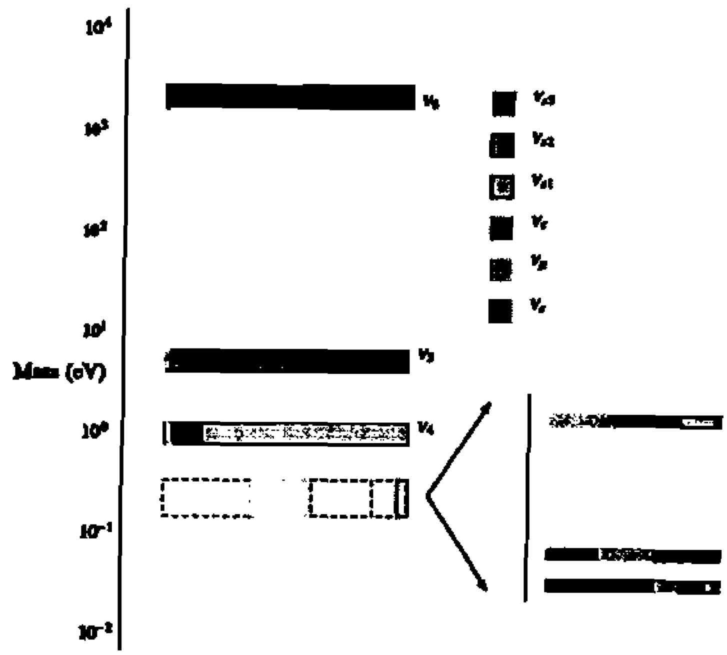


FIG. 1 (color online). Neutrino mass eigenstate spectrum along with the flavor composition of each state. This case accommodates all neutrino oscillation data, constraints from r-process nucleosynthesis in supernovae, and may help explain anomalous pulsar kicks (see text for details). While we choose to depict a normal hierarchy for the active neutrino states, an inverted active neutrino mass hierarchy would have yielded exactly the same physics (as far as the observables considered

Very Low Energy

See-Saw

RH ν's masses:

KeV → Dark Matter

10s of eV
~1 eV → Pulsar kicks etc

(3+2) for LSND!

de Gouvea, Jenkins, Vasudevan (2006).

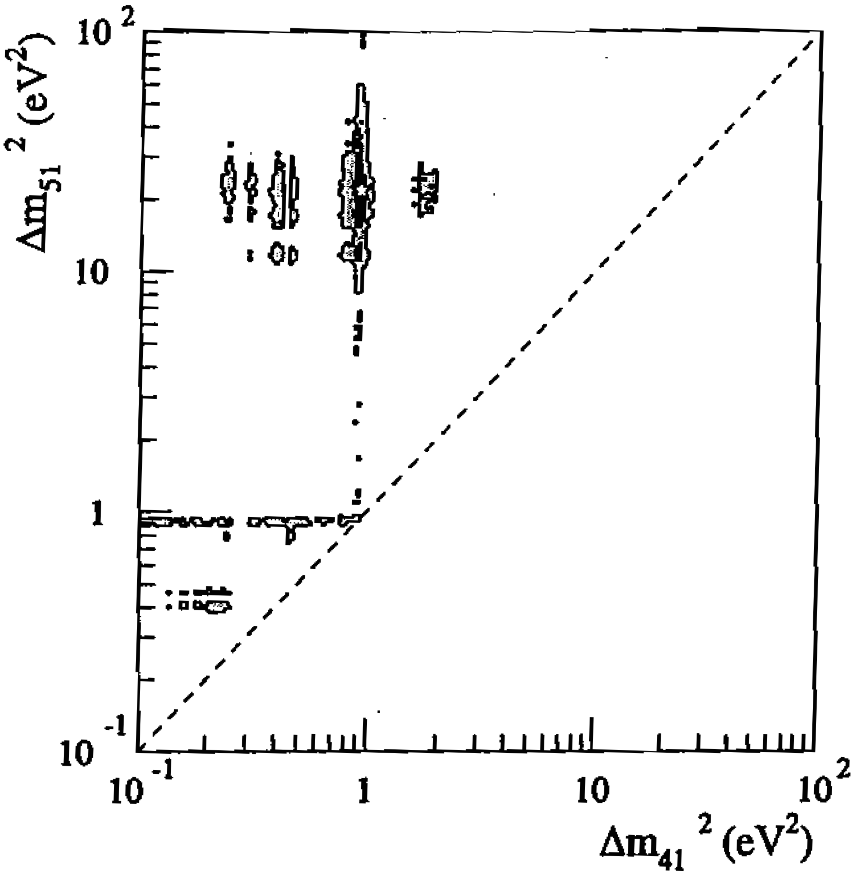


FIG. 7: Allowed ranges in $(\Delta m^2_{41}, \Delta m^2_{51})$ space for (3+2) models, for the combined NSBL+LSND analysis, assuming statistical compatibility between the NSBL and LSND datasets. The star indicates the best-fit point, the dark and light grey-shaded regions indicate the 90 and 99% CL allowed regions, respectively. Only the $\Delta m^2_{51} > \Delta m^2_{41}$ region is shown; the complementary region $\Delta m^2_{41} \geq \Delta m^2_{51}$ can be obtained by interchanging Δm^2_{41} with Δm^2_{51}.

(3+2) for LSND
Sorel, Conrad, Shaevitz (2006)

Palomares-Ruiz, Pascoli & Schwetz (2005)

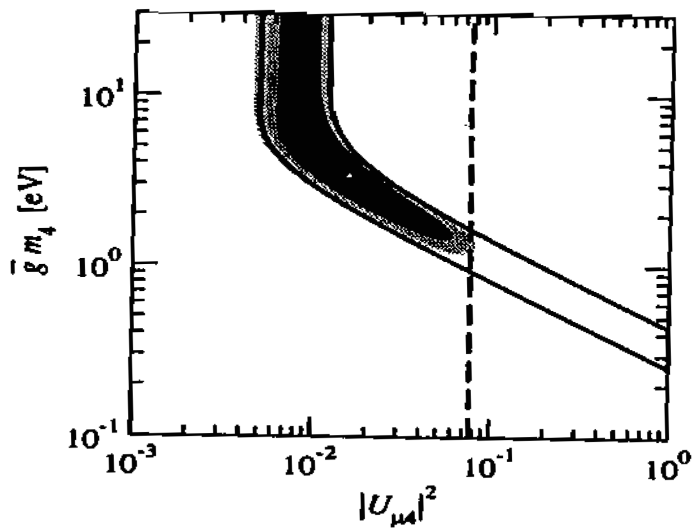


Figure 2. Allowed regions for LSND + KARMEN (solid) and SBL disappearance+atmospheric neutrino experiments (dashed) at 99% CL, and their combination (shaded regions) at 90% and 99% CL. From Ref. [12].

Decaying Sterile Neutrino

ν_μ mixes with ν_{st} $(U_{\mu 4})^2 \sim 0.01$

$\nu_{st} \longrightarrow \bar{\nu}_e + X$ $\quad c\tau_{\nu_{st}}(\text{Lab}) \sim 50\text{ m}$

$\tau_{\nu_{st}} \sim 10^{-14}\text{ s}$

$m_{\nu_{st}} \gtrsim$ few keV.

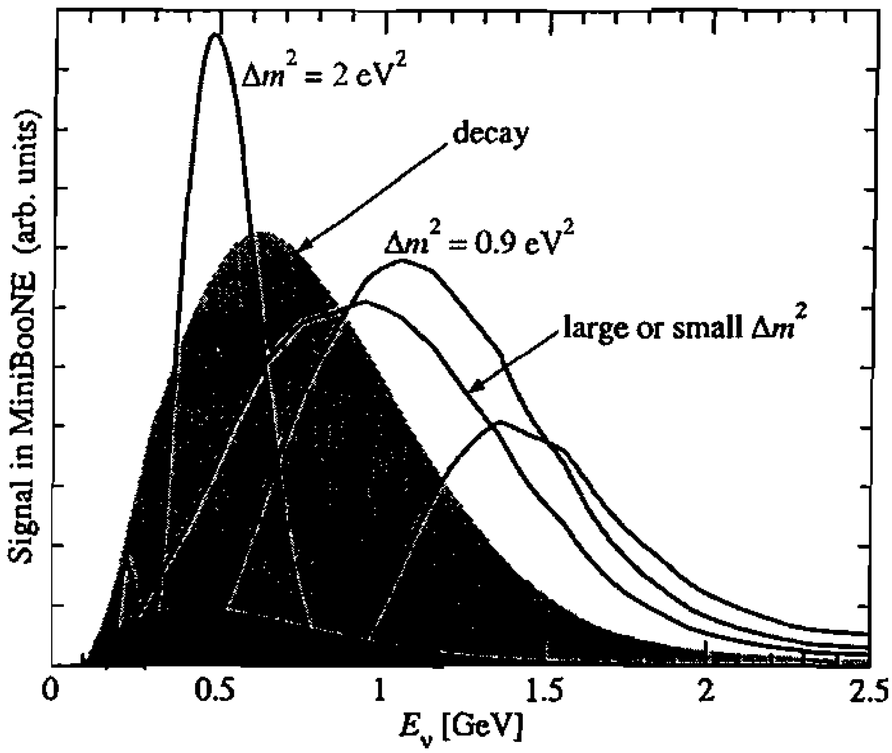


FIG. 4: Energy spectrum predicted for the ν_e appearance signal in MiniBooNE for decay with $\bar{g}m_4 = 3.4$ eV shaded region) and for various values of Δm^2 in the case of oscillations (solid curves). The blue/dark-shaded egion shows the contribution of $\bar{\nu}_e$ from the helicity changing decay.

Decaying Sterile Neutrino Signal
in Mini-Boone

3 flavors with Lorentz Violation for LSND

(Katori, Kostelecky, Tayloe 2006)

- So called "Tandem" Model
  (earlier version "Bicycle")

- $$H^{eff} \sim \begin{pmatrix} cE & a & a \\ a & 0 & a \\ a & a & m^2/2E \end{pmatrix}.$$

- CPT violated

- Solar data fit w.o. MSW
- Atm. data also fit well
- Kamland also fit well
- [CPTV visible at higher energies e.g. NOVA, T2K]

- LSND fit well
  ↳ prediction for MINI-BOONE

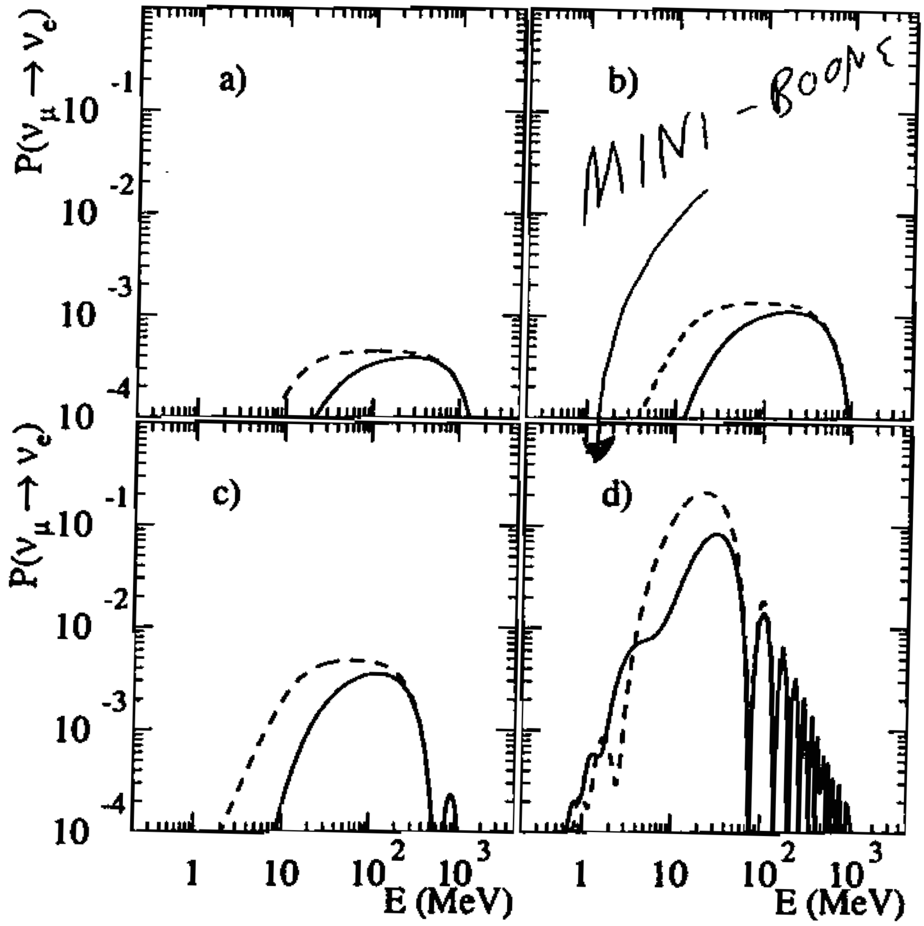


FIG. 7: Oscillation probabilities as a function of E for neutrinos (solid) and antineutrinos (dashed) in (a) KARMEN, (b) LSND, (c) the proposed OscSNS experiment, and (d) the currently running MiniBooNE experiment. The effects of experimental position and energy resolution are not shown.

Prediction for Mini-Boone of "Tandem" LIV Model

Bulk shortcuts and neutrino oscillations

30

Evolution equation in flavor space:

$\{\nu_\alpha = a\nu_e + b\nu_\mu\}$

$$i\frac{d}{dt}\begin{pmatrix}\nu_a(t)\\ \nu_s(t)\end{pmatrix} = H_F\begin{pmatrix}\nu_a(t)\\ \nu_s(t)\end{pmatrix}$$

Hamiltonian in the presence of bulk shortcuts:

$$H_F = +\frac{\delta m^2}{4E}\begin{pmatrix}\cos 2\theta & -\sin 2\theta\\ -\sin 2\theta & -\cos 2\theta\end{pmatrix} + \underbrace{E\,\frac{\epsilon}{2}\begin{pmatrix}-1 & 0\\ 0 & 1\end{pmatrix}}_{\text{Effective LIV in 4 Dim.}}$$

$\Rightarrow$ A Resonance exists at $E_{\rm res} = \sqrt{\frac{\delta m^2 \cos 2\theta}{2\epsilon}}$

$\rightarrow$ choose $E_{\rm res} = 30 - 400$ MeV $\leftrightarrow \epsilon \simeq 10^{-18} - 10^{-16}$

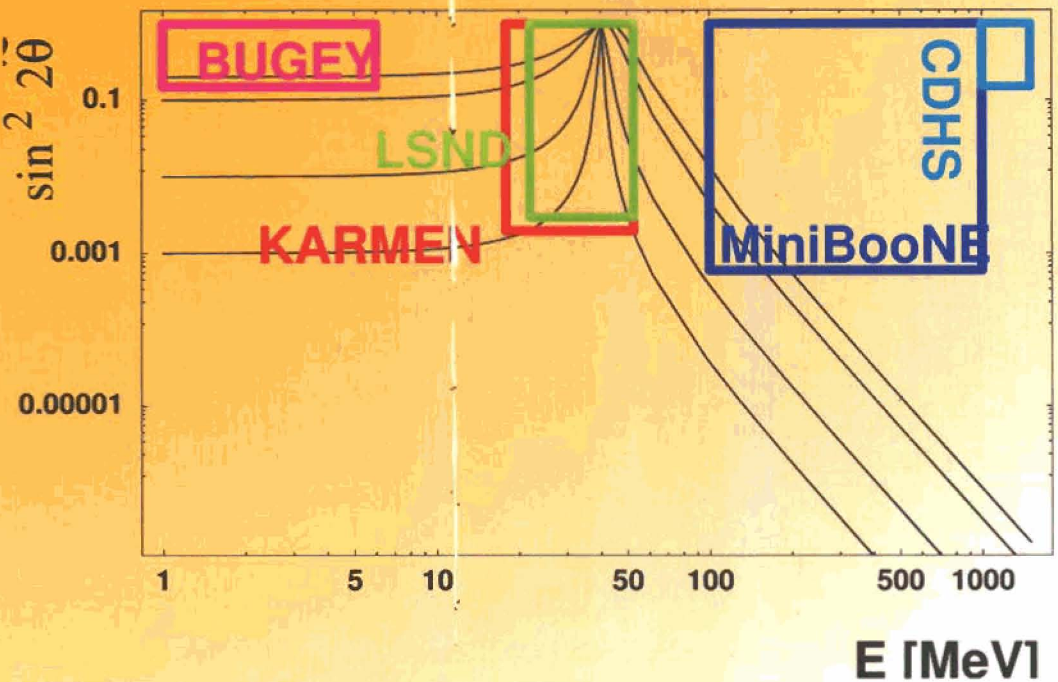
Päs, Pakvasa, Weiler, hep-ph/0504096

The active-sterile oscillation probability

$$\boxed{P_{as} = \sin^2 2\tilde{\theta}\ \sin^2(\delta H\, D/2)}$$

$$\sin^2 2\tilde{\theta} = \left[\frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2}\right] \qquad \delta H = \frac{\delta m^2}{2\,E}\sqrt{(\cos 2\theta - A)^2 + \sin^2 2\theta}$$

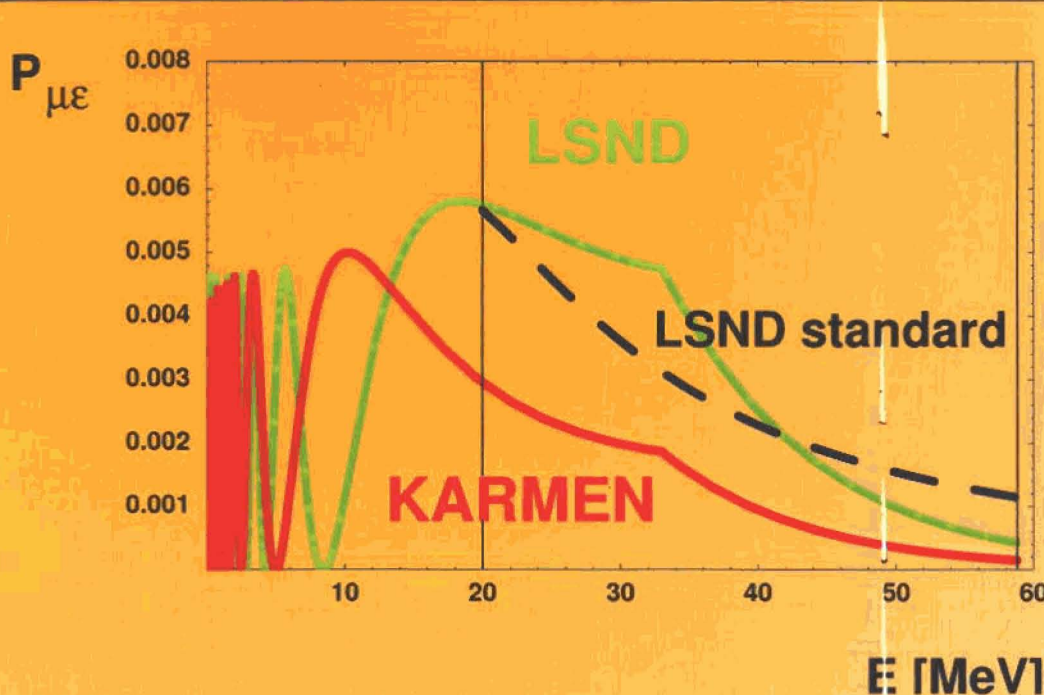
$$\boxed{A = (E/E_{\rm res})^2}$$

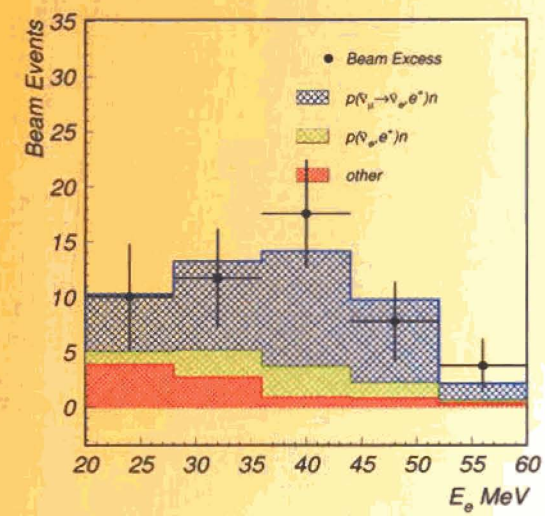


Oscillations at $E \gg E_{\rm res}$ (CDHS)are suppressed!

Päs, Pakvasa, Weiler, hep-ph/0504096

Scenario with low resonance energy



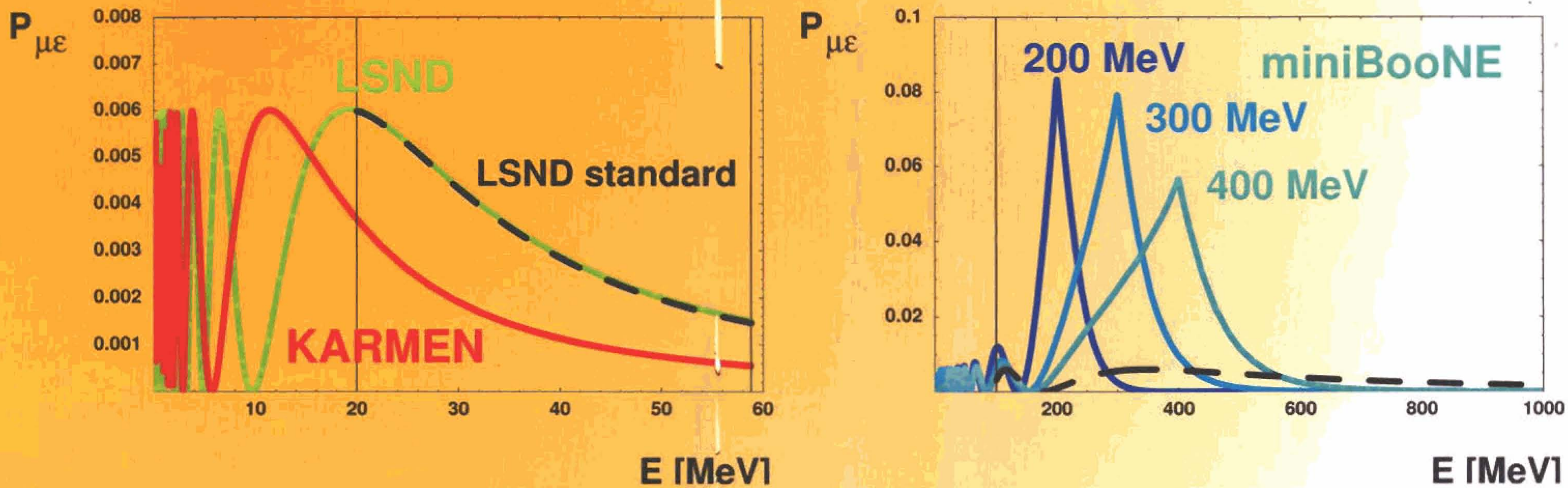


- $E_{\rm res} = 33$ MeV; $\sin^2\theta_* = 0.01$; $\sin^2 2\theta = 0.9$; $\delta m^2 = 0.7$ eV^2
- $P_{\rm LSND} > P_{\rm KARMEN}$

- good (better) fit of LSND spectrum
- no signal at miniBooNE!

Päs, Pakvasa, Weiler, hep-ph/0504096

Scenario with high resonance energy



- $E_{\rm res} = 200$ MeV, 300 MeV, 400 MeV; $\sin^2\theta_* = 0.1$; $\sin^2 2\theta = 0.45$; $\delta m^2 = 0.8$ eV^2
- good fit to LSND spectrum, $P_{\rm LSND} > P_{\rm KARMEN}$
- enhanced miniBooNE signal in the energy range 100-600 MeV

Päs, Pakvasa, Weiler, hep-ph/0504096

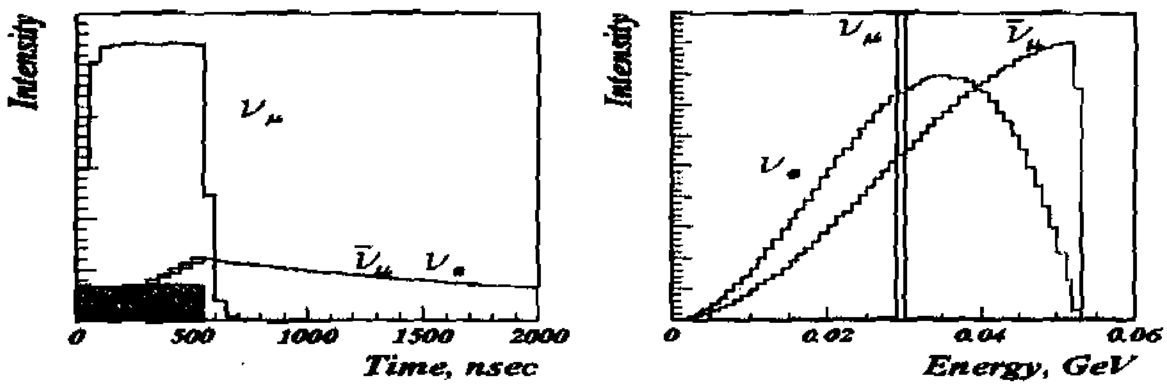


Figure 1: The neutrino time and energy spectra of the different neutrino species produced isotropically from a stopped pion source [17].

	FNAL (8 GeV)	FNAL (5 GeV)	SNS
P/yr	1.6×10^{22}	1.6×10^{22}	6.7×10^{22}
DAR $\nu(\nu/P)$	1.5	0.9	0.13
DAR $\nu(\nu/yr)$	7.3×10^{22}	4.4×10^{22}	2.9×10^{22}

Table 1: Proton intensities at FNAL and SNS. The numbers are taken from [18], assuming 3.15×10^7 s/yr operation.

Table 1 shows the expected proton rates for both SNS and FNAL beamlines, normalized to a full year of running, i.e. 3.15×10^7 seconds. The FNAL Proton Driver proposal is broken down into 8 GeV, 2 MW and 5 GeV, 1.25 MW beamlines. The FNAL 8 GeV option will provide about 2.5 times more protons per year than the SNS. However, the FNAL PD is only a proposal, while the SNS is under construction and will be operational by 2008. This makes the SNS a more timely option. Furthermore, the SNS is planning for 2014 an upgrade which will deliver 3 MW to two sources, making the interesting situation of multiple baselines with a single detector.

A key component of the sterile neutrino measurement is the physical size of the stopped pion source, which adds an uncertainty to the neutrino path length. For the SNS, the compact liquid mercury target will contribute approximately 25 cm (FWHM) to the neutrino path length uncertainty. The FNAL source size should be of similar dimensions to minimize neutrino path length uncertainties.

G. Garvey et al. (2005)

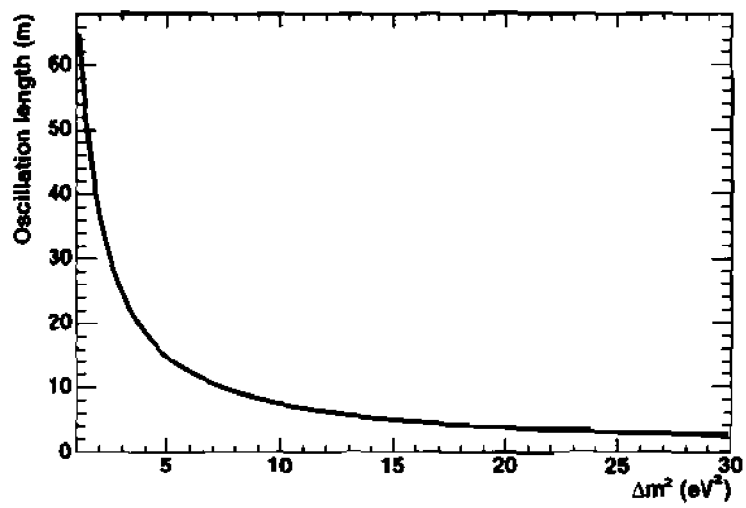


Figure 2: Oscillation length as a function Δm^2 where $E_{\nu_\mu} = 29.8$ MeV.

Neutral Current Disappearance Pattern
in a Two Detector Setup

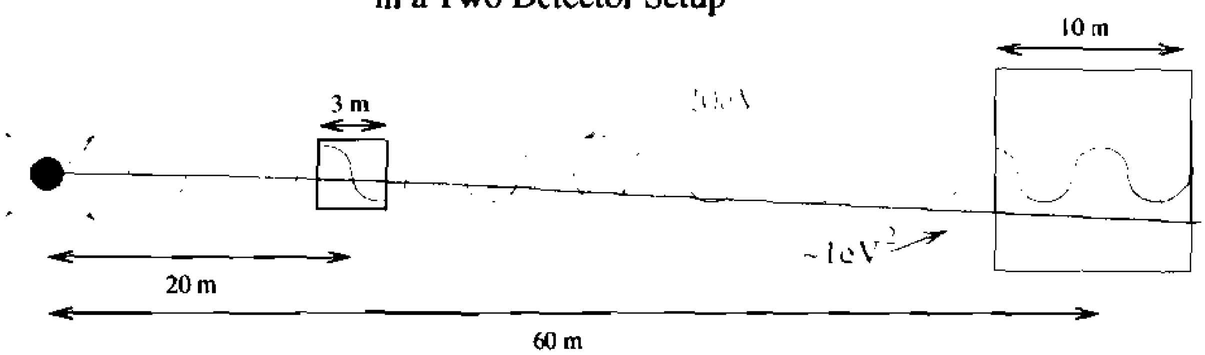


Figure 3: Neutral Current $\nu_x\ {}^{12}C \rightarrow \nu_x\ {}^{12}C^*(15.11)$ disappearance patterns for a two detector setup.

SNS or FNAL

Detector	Source Dist. (m)	FD Size (tons)	FD Length (m)	$\nu_\mu\ ^{12}C \rightarrow \nu_\mu\ ^{12}C^*$ events/yr
SNS Near	18	25	3	2056
SNS Far	60	500	10	3701
FNAL Near	10	116	5	77806
FNAL Far	100	1300	12	8720

Table 2: Estimated $\nu_\mu\ ^{12}\mathrm{C} \rightarrow \nu_\mu\ ^{12}\mathrm{C}^*(15.11)$ events per year at the SNS (1.4 MW) and FNAL (2 MW) sources, assuming 100% event reconstruction efficiency.

with limited statistics, getting a value of $(3.2 \pm 0.5_{\mathrm{stat}} \pm 0.4_{\mathrm{syst}}) \times 10^{-42}$ cm^2 [21], consistent with the calculated cross section.

For a proposed experiment at FNAL, we would not have space restrictions, allowing for larger near and far detectors. We assume a longer baseline, out to 100 m, and a detector mass of 2 ktons (8 m radius), which would be required to keep roughly the same statistics. This would give a fiducial mass of 1.3 ktons (7 m radius).

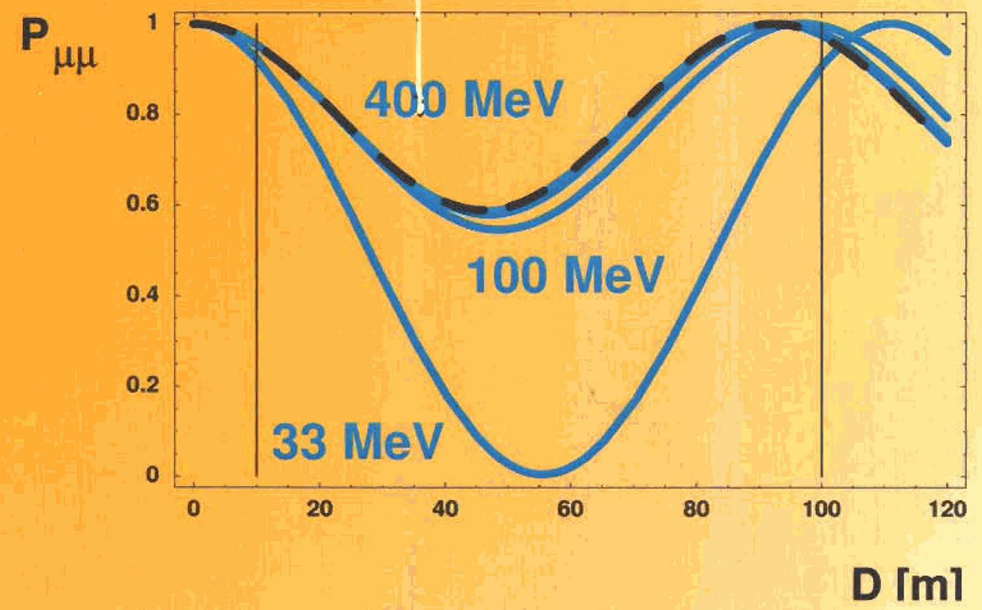
Table 2 shows the number of events expected per year for the $\nu_x\ ^{12}\mathrm{C} \rightarrow \nu_x\ ^{12}\mathrm{C}^*(15.11)$ reaction for the two possible configurations, one at SNS with 1.4 MW, and the other at FNAL with 2 MW. The event reconstruction efficiency was assumed to be 100%, as the 15.11 MeV gamma ray is relatively easy to detect.

A Monte Carlo calculation was performed to estimate the $\nu_x\ ^{12}\mathrm{C} \rightarrow \nu_x\ ^{12}\mathrm{C}^*(15.11)$ oscillation sensitivity, which includes smearing of 25 cm (FWHM) from the finite neutrino source size and 50 cm (FWHM) from the reconstructed position resolution for the 15.11 MeV gamma ray. Also included is background subtraction of charged current (CC) and neutral current (NC) events from $\bar{\nu}_\mu$ and ν_e in the beam window [14]. Because we can isolate a clean sample of these backgrounds in the time window after the beam, we will have an excellent estimation of their number and character, e.g. for the SNS far detector this is about 1300 events per year. This background increases the statistical error on the measured $\nu_\mu\ ^{12}\mathrm{C} \rightarrow \nu_\mu\ ^{12}\mathrm{C}^*(15.11)$ rate by at most 45%. The background contribution from cosmic rays is negligible because of the short duty factor of the beam.

Figures 4 and 5 show the (3+1) active-sterile neutrino oscillation sensitivity for a three year run at the SNS and FNAL proton driver with two detectors and a 5% normalization systematic errors. Both setups achieve a $\nu_\mu \rightarrow \nu_s$ oscillation sensitivity of 3σ for $\Delta m^2 > 0.4\,\mathrm{eV}^2$ and $\sin^2 2\theta > 0.05$. This sensitivity is desired if the LSND signal is due to active-sterile neutrino oscillations.

The oscillation sensitivity plots are generated from a simultaneous fit to both the L shape

Consequences for a stopped pion source at SNS

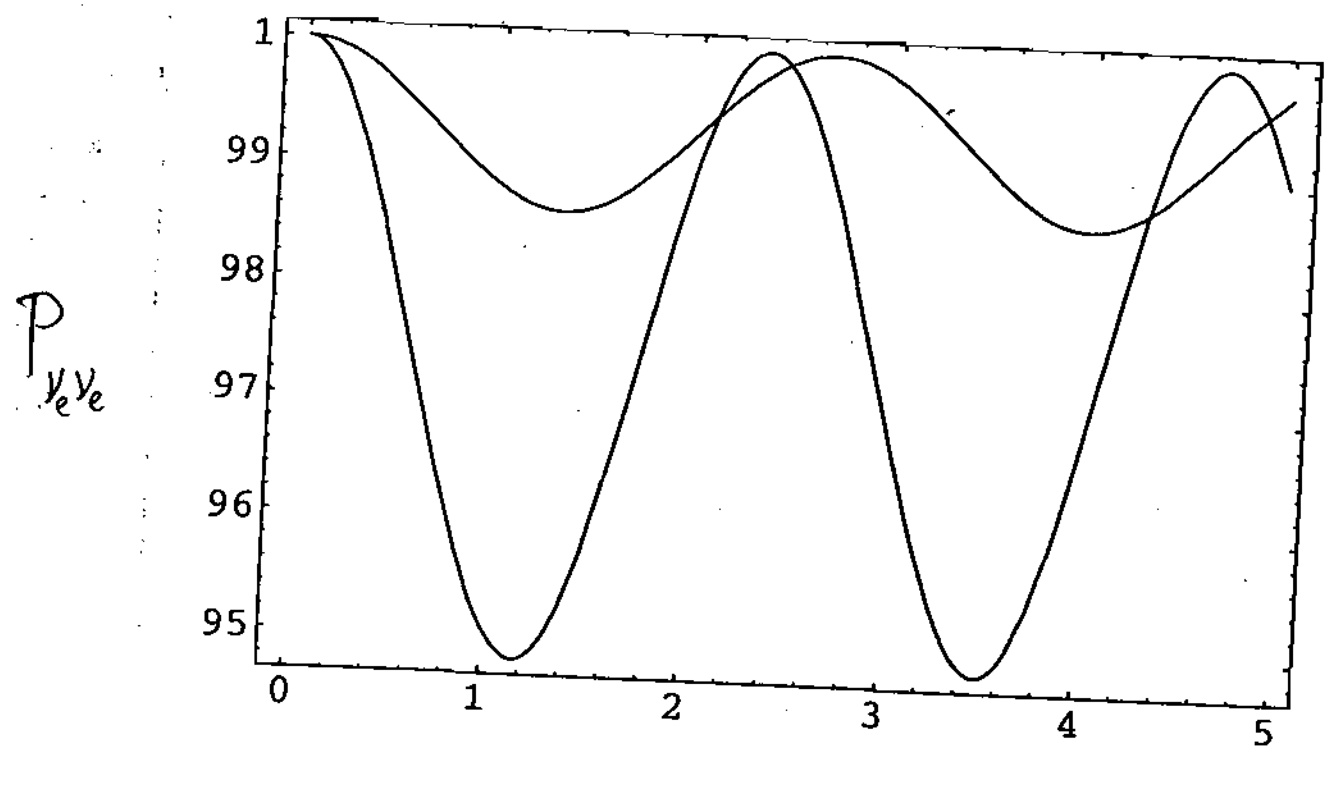


- $E_{\rm res} = 33$ MeV; $\sin^2\theta_* = 0.01$; $\sin^2 2\theta = 0.9$; $\delta m^2 = 0.7$ eV^2
- $E_{\rm res} = 100$ MeV, 200-400 MeV; $\sin^2\theta_* = 0.1$; $\sin^2 2\theta = 0.45$; $\delta m^2 = 0.8$ eV^2
- strongly enhanced ν_μ depletion signal

Päs, Pakvasa, Weiler, hep-ph/0504096

For sterile ν decay: $1 - (0.01$ to $0.03)$ [no L/E dependence]

Survival Probability for
a $E = 0.753$ MeV ν_e @LENS



- Sterile in Bulk
  short cut.
- for sterile ν decay $\quad P_{ee} = 1$ always.

Conclusions

- Exotic physics ruled out as dominant effects
- But can be sub-dominant

$\rightarrow$ slow, hard process to tighten the constraints or see a signal.

- For possible explanations of LSND

Many potential tests in

- Mini-boone ν_e spectrum
- $P_{\nu_\mu \to \nu_\mu}$
- $P_{\nu_e \to \nu_e}$.