Phenomenology of neutrino oscillations

Part I: present experiments

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Padova, 31 May, 1 June 2006

Outline

- Introduction
- Determination of Δm^2_{21} and θ_{12}
  global solar (SNO, SK, GNO, SAGE, Homestake)
  and KamLAND data
- Determination of Δm^2_{31} and θ_{23}
  SK atmospheric ν data, K2K, first results from MINOS
- The bound on θ_{13} from global data
- The LSND puzzle

3-flavour oscillation parameters

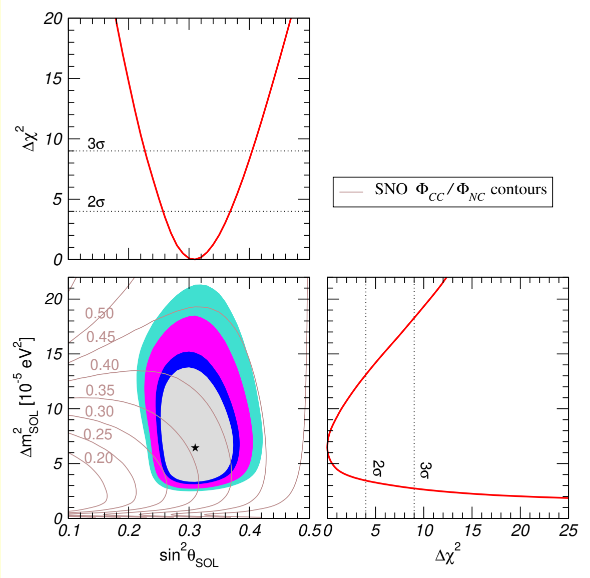
$$\begin{array}{cccc} & \Delta m^2_{31} & & \Delta m^2_{21} \\ U = & \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} & \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} & \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ & \text{“atmospheric”} & & \text{“solar”} \end{array}$$

known params.	bounded params.	unknown params.
$\lvert\Delta m^2_{31}\rvert$ $\sin^2\theta_{23}$ Δm^2_{21} $\sin^2\theta_{12}$	$\sin^2\theta_{13}$ $D_{23} \equiv \sin^2\theta_{23} - 0.5$	δ sign(Δm^2_{31})

The ’solar’ parameters Δm^2_{21}, θ_{12}

'Solar' parameters

global solar neutrino data:
Homestake,SAGE,GNO,SK,SNO



The SNO experiment:

$\nu_e + d \to p + p + e^-$

$\nu_x + d \to p + n + \nu_x$

SNO-II 391d nucl-ex/0502021

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023 \pm 0.03$$

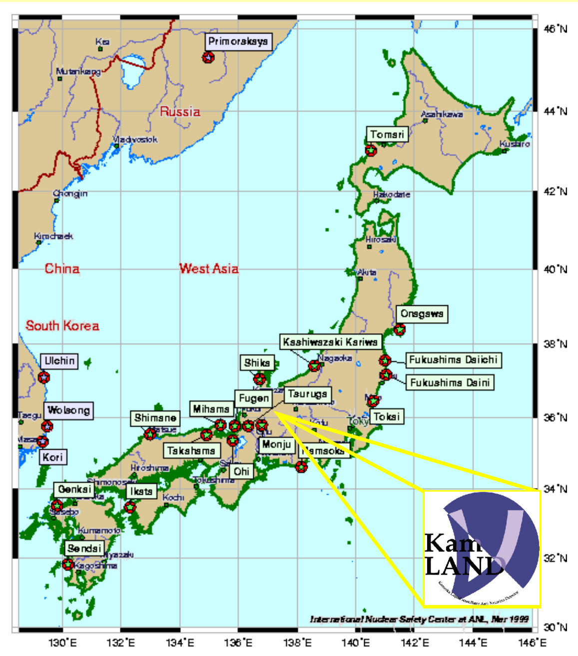
7σ evidence for a non-zer
$\nu_{\mu,\tau}$ flux from the sun

constraint on θ_{12}:

$$\frac{\phi_{CC}}{\phi_{NC}} \approx P_{ee}^{\text{SNO}} \approx \sin^2\theta_{12}$$

The KamLAND reactor neutrino experiment

Kamioka Liquid scinitillator Anti-Neutrino Detector

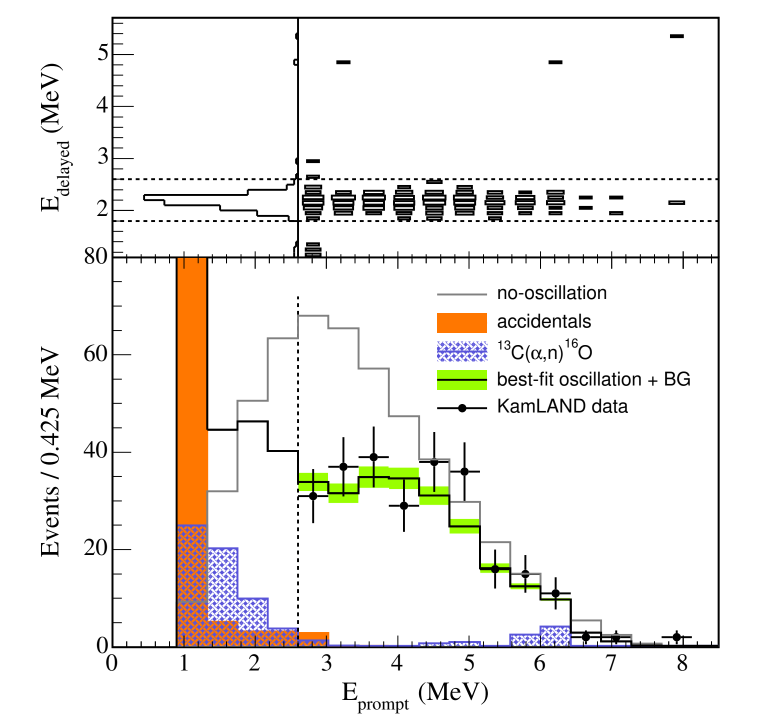


detection of $\bar{\nu}_e$ produced i
surrounding nuclear powe
plants

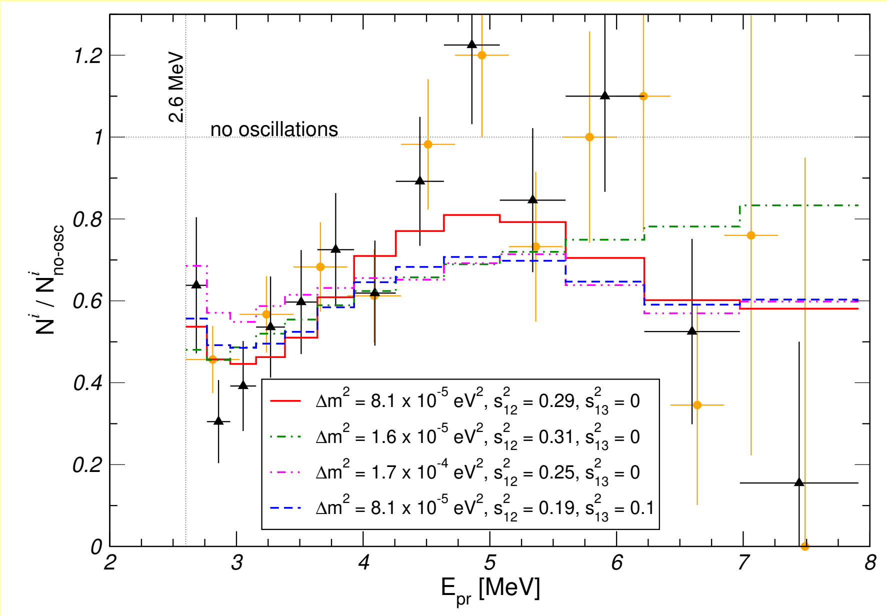
70 GW of nuclear powe
(7% of world total) is
generated at a distance
175 ± 30 km from Kamiok

258 events are observed,
365.2 ± 23.7 expected fo
no disappearance

The KamLAND energy spectrum



The KamLAND energy spectrum

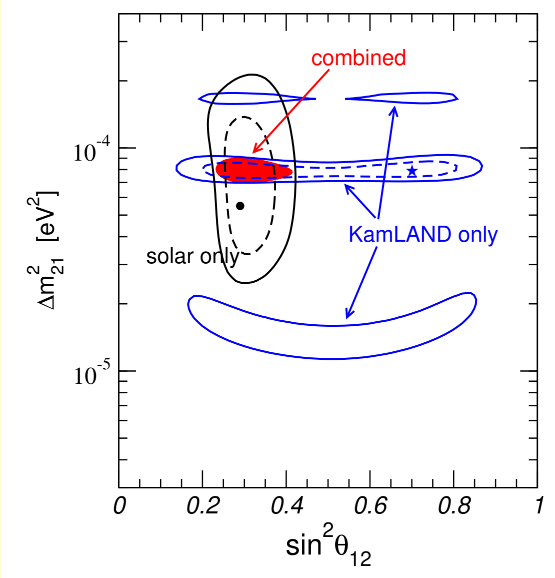


evidence for flux suppression and spectral distortion

equal bins in $1/E_{\rm pr}$ better than equal bins in $E_{\rm pr}$ $\Rightarrow$

KamLAND vs solar data

90% and 99.73% CL contours

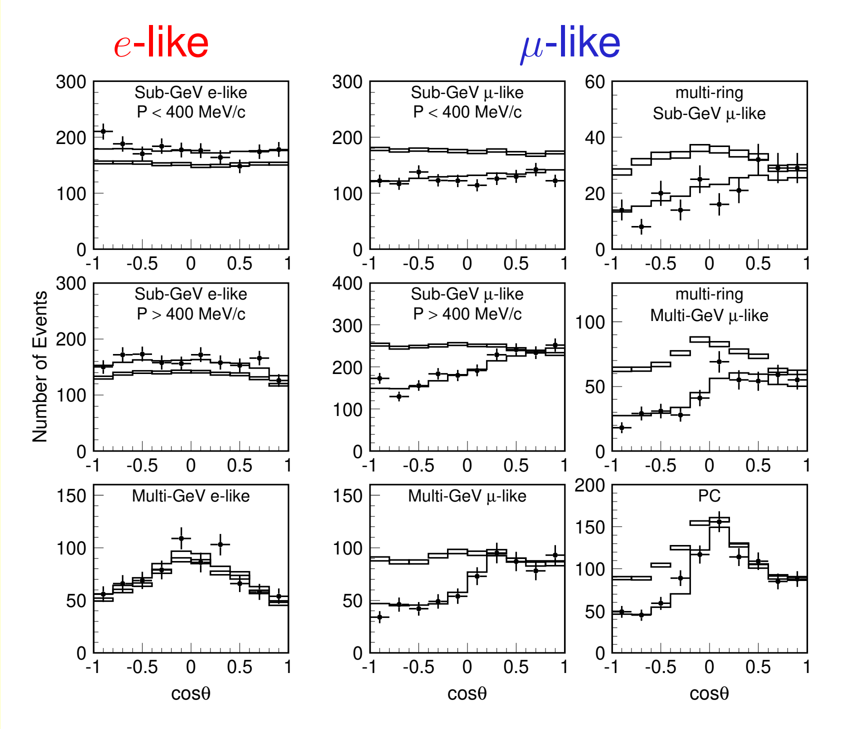


$$\Delta m^2 = 7.9 \pm 0.3 \times 10^{-5}\,\mathrm{eV}^2,\ \sin^2\theta_{12} = 0.31^{+0.02}_{-0.03}$$

The 'atmospheric' parameters Δm^2_{31}, θ_{23}

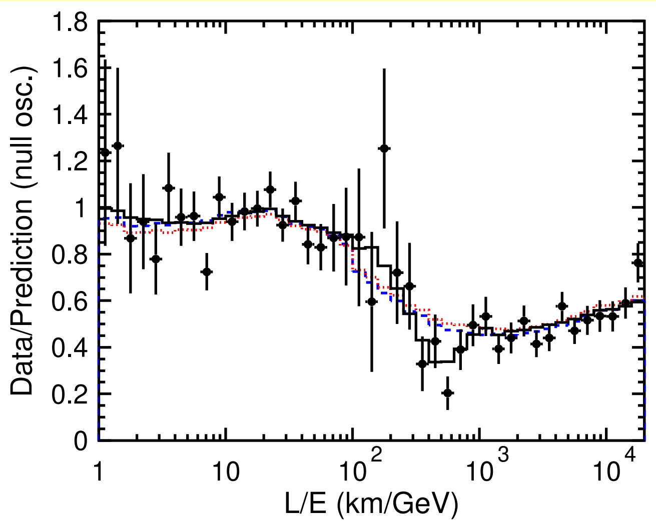
’Atmospheric’ parameters

Super-Kamiokande I atmospheric data hep-ex/0501064 $\Longrightarrow$



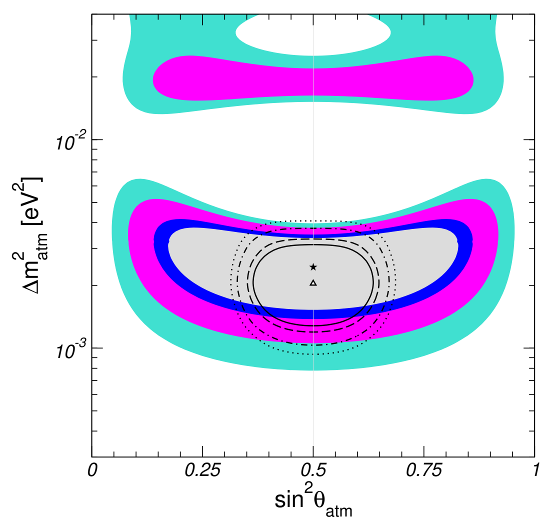
Oscillatory signal in atmospheric neutrinos

Super-K Coll., Phys. Rev. Lett. **93** (2004) 101801



$$P_{2\nu} = 1 - \sin^2 2\theta \, \sin^2 \left(\frac{\Delta m^2}{4} \frac{L}{E_\nu} \right)$$

'Atmospheric' parameters



best fit:

$\Delta m^2_{32} = 2.2 \times 10^{-3}\,\mathrm{eV}^2$
$\sin^2\theta_{23} = 0.5$

(K2K spectral analysis with 56 1-ring μ-like events)

K2K: 250 km from KEK to SK, 1.3 GeV neutrinos

108 events observed, $150.9^{+11.6}_{-10.0}$ expected for no osc

'Atmospheric' parameters

First results from MINOS

- NuMI beam produced at Fermilab
  98.5% $\nu_\mu + \bar\nu_\mu$, 6.5% $\bar\nu_\mu$, 1.5% $\nu_e + \bar\nu_e$
- mean energy of $\sim 3\,\mathrm{GeV}$
- far detector (5.4 kt) at Soudan Mine ($L = 735\,\mathrm{km}$)

oscillation maximum at $\sim 1.5\,\mathrm{GeV}$
for $\Delta m^2 = 2.5 \times 10^{-3}\,\mathrm{eV}^2$

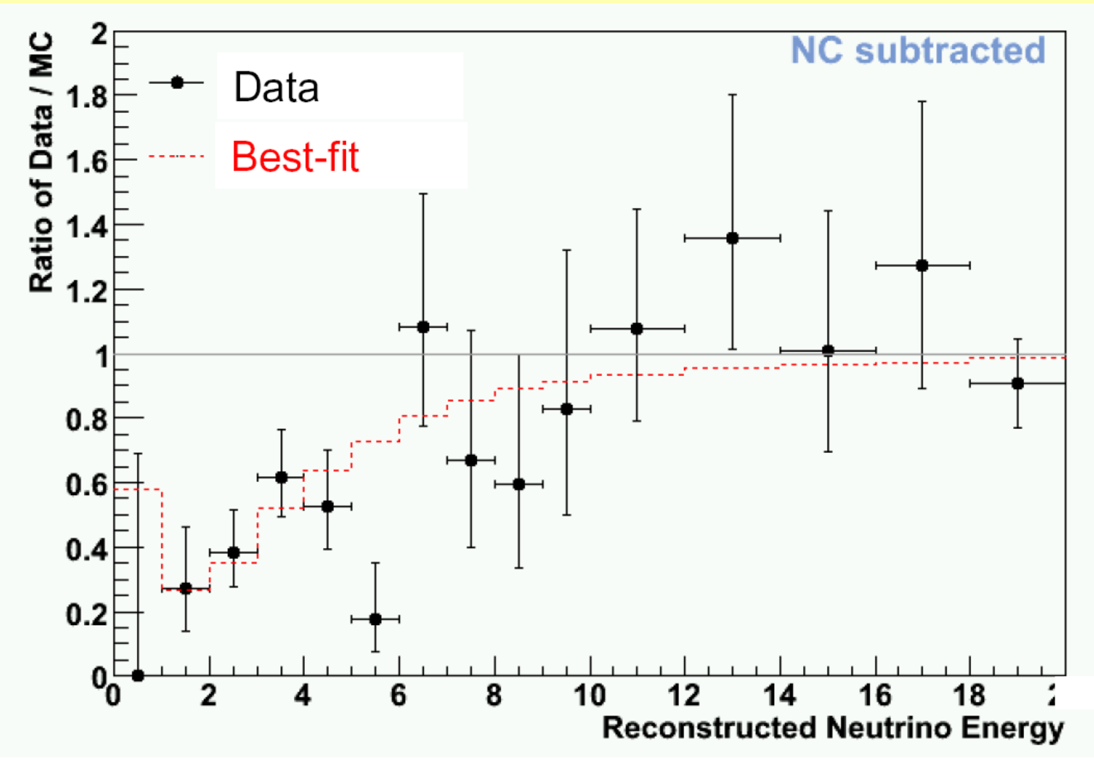
First results from MINOS

data taken from 20 May to 6 Dec 2005
(0.93×10^{20} p.o.t.)
presented in a talk at Fermilab on 30 March 2006

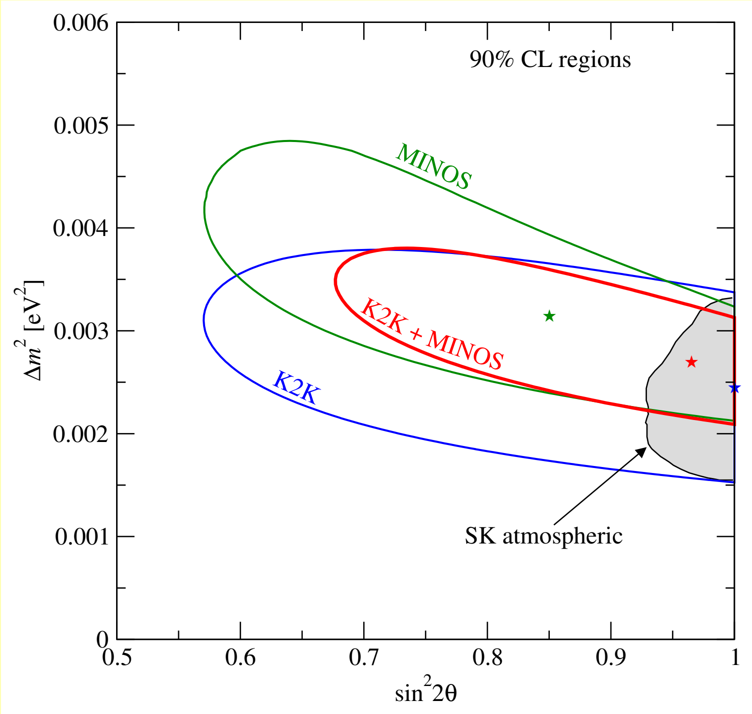
http://www-numi.fnal.gov/talks/results06.html

Data sample	observed	expected	ratio	significance
All CC-like events ($\nu_\mu+\bar{\nu}_\mu$)	204	298±15	0.69	4.1σ
ν_μ only (<30 GeV)	166	249±14	0.67	4.0σ
ν_μ only (<10 GeV)	92	177±11	0.52	5.0σ

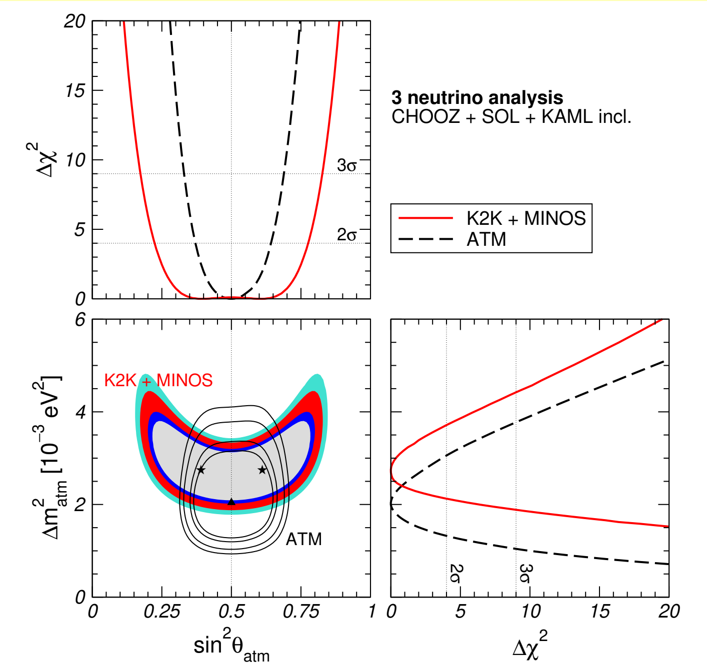
First results from MINOS



’Atmospheric’ parameters



’Atmospheric’ parameters

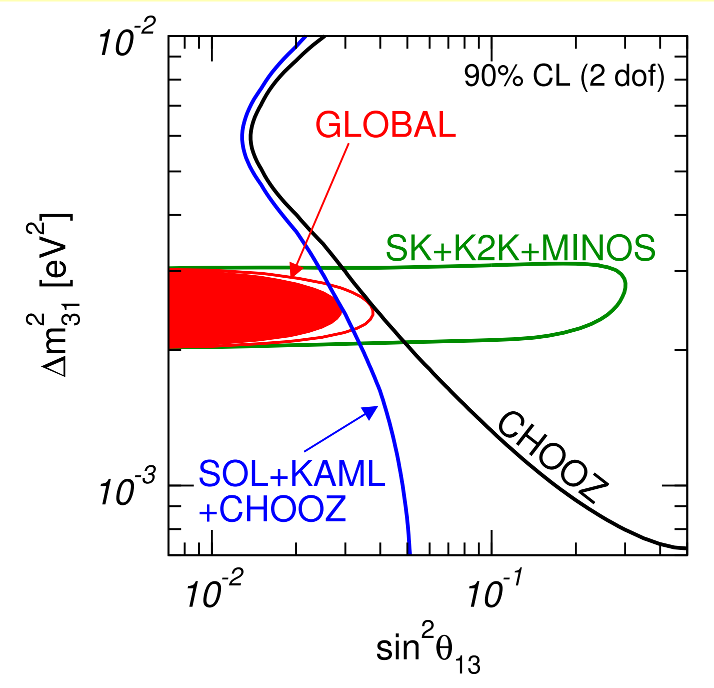


$\Delta m^2\ [10^{-3}\ \mathrm{eV}^2]$		
exp.	bf	3σ int.
SK	2.0	1.0-3.8
SK+K2K	2.2	1.4-3.3
SK+K2K +MINOS	2.5	1.8-3.3
$\sin^2\theta_{23}$		
SK	0.5	3.4-6.8

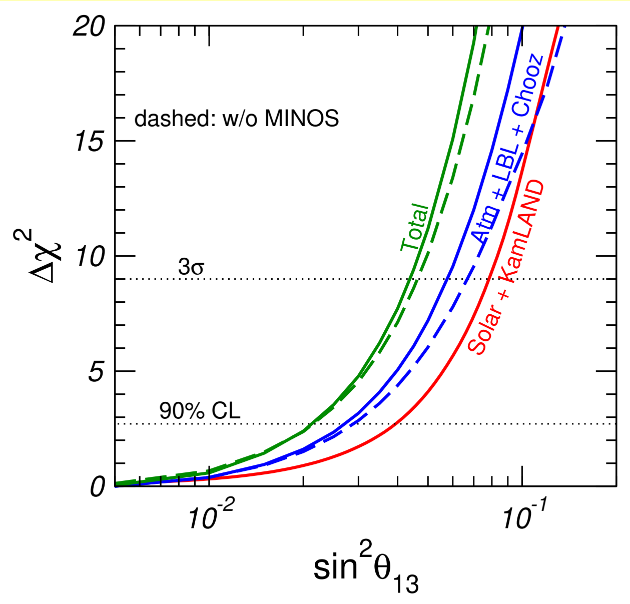
The bound on θ_{13}

The bound on θ_{13}

The bound on θ_{13} emerges from an interplay of the global data



The bound on θ_{13}



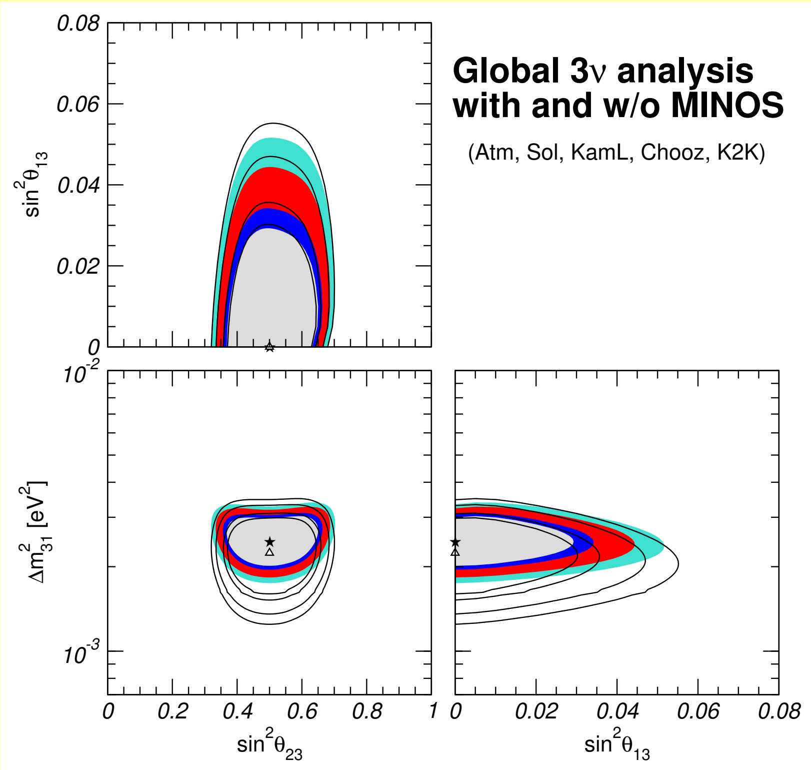
3σ bounds
with (w/o) MINOS:

Solar+KamLAND:
$\sin^2\theta_{13} < 0.079$

Atm+Chooz+LBL:
$\sin^2\theta_{13} < 0.058\,(0.067)$

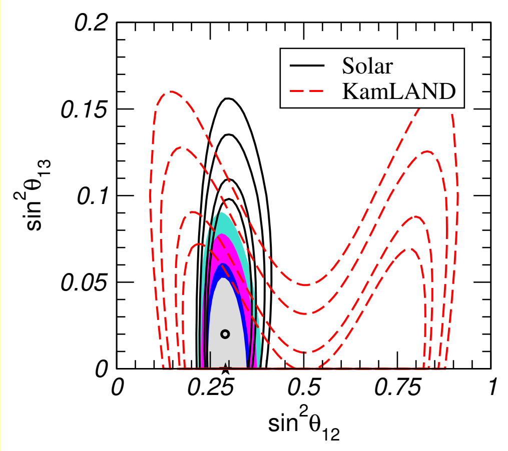
Global:
$\sin^2\theta_{13} < 0.044\,(0.046)$

The bound on θ_{13} and MINOS



The θ_{13} bound from KamLAND and Solar

complementarity between solar and KamLAND data



Maltoni et al., hep-ph/0405172

see also Goswami and Smirnov, hep-ph/0411359

KamLAND spectrum $\Rightarrow$

$$P_{\rm KL} \approx (1 - 2\sin^2\theta_{13}) \left(1 - \sin^2 2\theta_{12}\, \sin^2 \frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

$$P_{\rm Sol} \approx (1 - 2\sin^2\theta_{13}) \begin{cases} \sin^2\theta_{12} & \text{high } E_\nu \\ (1 - 0.5\sin^2 2\theta_{12}) & \text{low } E_\nu \end{cases}$$

Summary 3-flavour oscillation parameters

mass-squared differences:

parameter	bf$\pm1\sigma$	1σ acc.	3σ range
Δm^2_{21} [10^{-5}eV^2]	7.9 ± 0.3	4%	$7.1 - 8.9$
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2]	$2.5^{+0.2}_{-0.25}$	10%	$1.8 - 3.3$

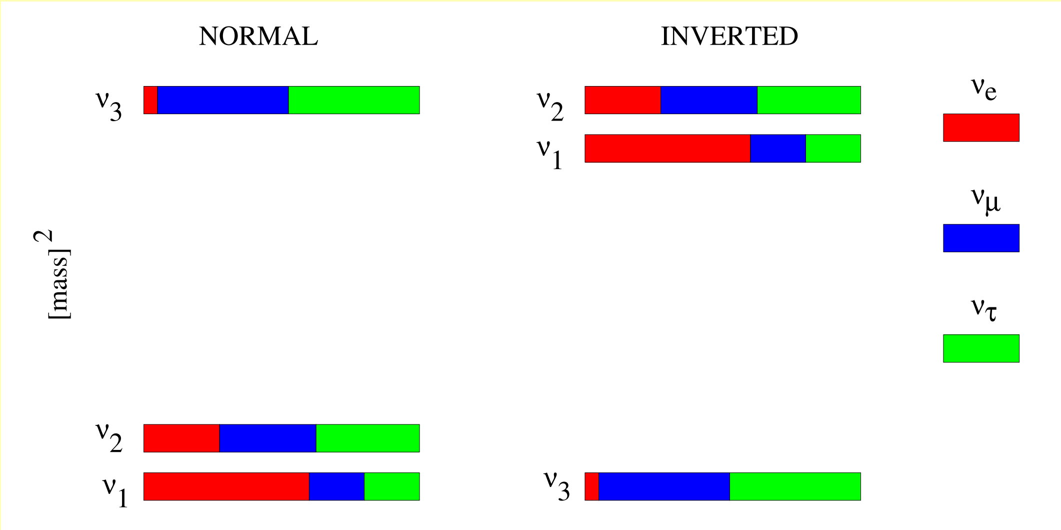
mixing angles:

parameter	bf$\pm1\sigma$	1σ acc.	3σ range
$\sin^2\theta_{12}$	$0.31^{+0.02}_{-0.03}$	9%	$0.24 - 0.40$
$\sin^2\theta_{23}$	$0.50^{+0.08}_{-0.07}$	16%	$0.34 - 0.68$
$\sin^2\theta_{13}$	–	–	≤ 0.044

updated from Maltoni, Schwetz, Tortola, Valle, hep-ph/0405172

The 3 neutrino mass spectrum

Two possibilities for the neutrino mass spectrum:



$\Delta m^2_{31} > 0$ $\quad\quad$ $\Delta m^2_{31} < 0$

3-flavour oscillations

Open questions:

- Is this basic picture correct?
  LSND hint, checked by MiniBooNE 2006
- Increase the precision on solar and atmospheric parameters (e.g. Is θ_{23} exactly 45°?)
- How small is θ_{13}?
- What is the value of the CP phase δ?
- Type of the neutrino mass ordering (sign of Δm^2_{31})

The LSND puzzle

$\Rightarrow$

The LSND signal

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu \xrightarrow{\text{oscillations}} \bar{\nu}_e$$

$$E_\nu \simeq 40 \text{ MeV}, \quad L \simeq 35 \text{ m}$$

The LSND result

evidence for $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ oscillations

Aguilar et al., PRD 64 (2001) 112007

$87.9 \pm 22.4 \pm 6.0$ excess events

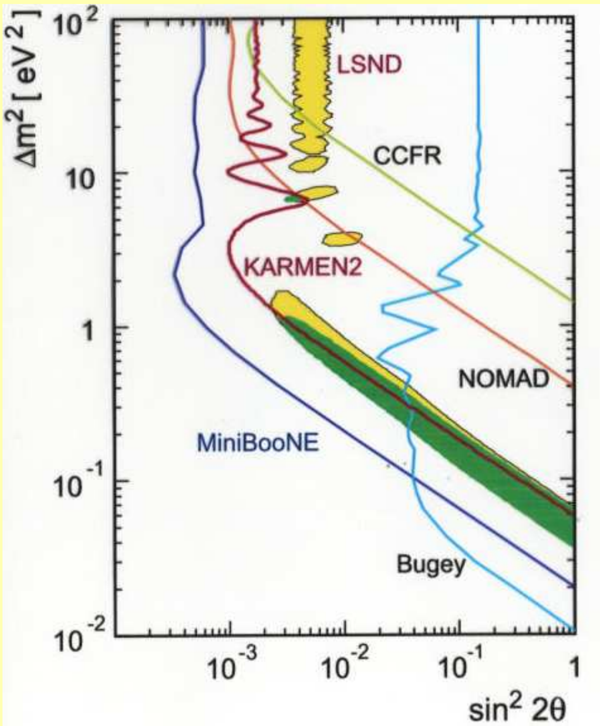
$P = (0.264 \pm 0.067 \pm 0.045)\%$

$\sim 3.3\sigma$ away from zero

$\Delta m^2 \sim$ **eV^2 not consistent with solar and atmospheric mass splittings for 3 neutrinos!**

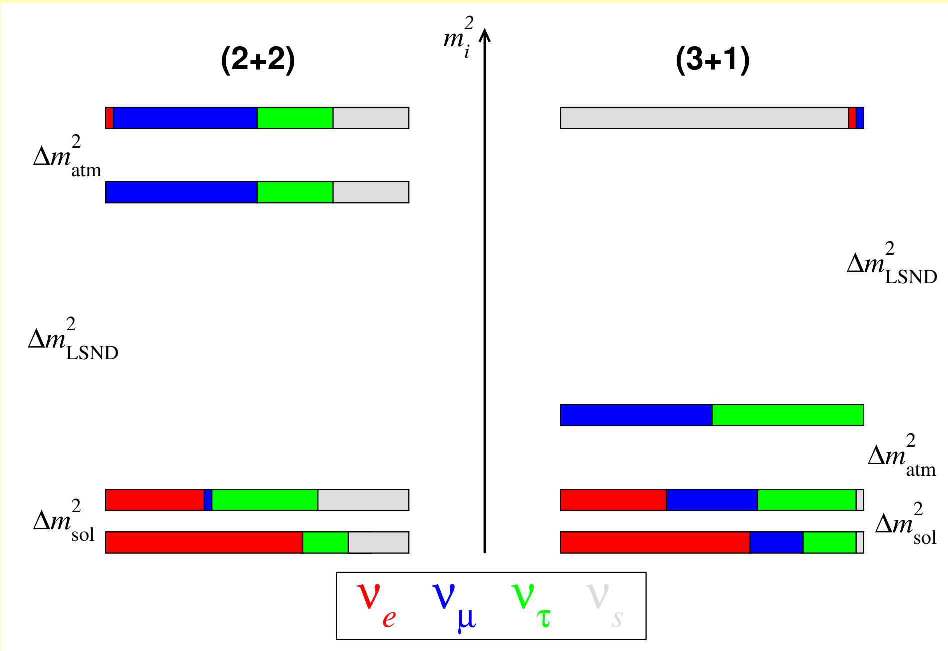
$\longrightarrow$ MiniBooNE

results: Neutrino 2006 (?)



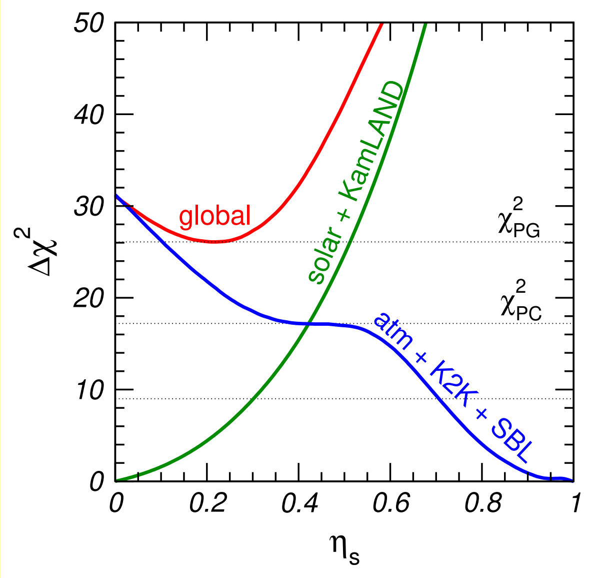
Adding a sterile neutrino

4-neutrino mass schemes:



(2+2): ruled out by solar and atmospheric data

Maltoni, Schwetz, Tortola, Valle, hep-ph/0207157, hep-ph/0405172



$\Delta\chi^2 = 26 \quad \rightarrow$ **(2+2) ruled out at the 5σ level** $\Rightarrow$

(3+1): strongly disfavoured by SBL data

disappearance experiments

Bugey, CDHS: $d_e,\ d_\mu \ll 1$

(3+1): $\sin^2 2\theta_{\rm LSND} = 4\, d_e d_\mu$

Bilenky, Giunti, Grimus, 96, 98;

Okada, Yasuda, 1997;

Barger *et al.*, 1998, 2000;

Bilenky, Giunti, Grimus, Schwetz, 1999;

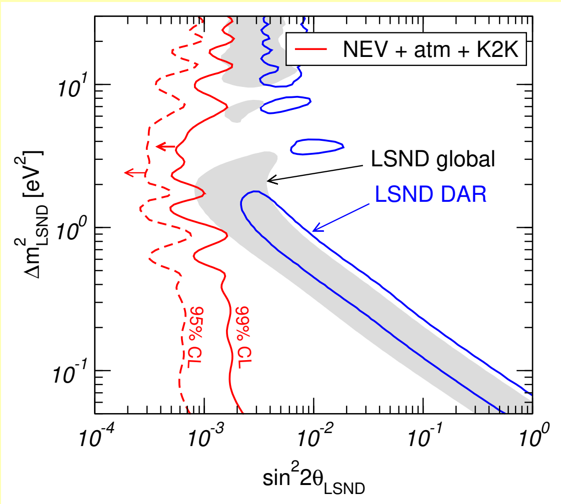
Giunti, Laveder, 2001;

Peres, Smirnov, 2001;

Grimus, Schwetz, 2001;

Maltoni, Schwetz, Valle, 2002

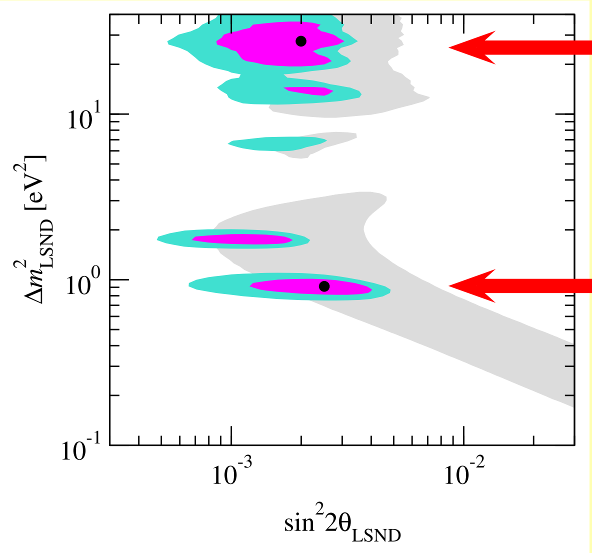
Maltoni, Schwetz, Tortola, Valle, hep-ph/0405172



$\Rightarrow$

5-neutrino oscillations

(3+2) mass schemes, Sorel, Conrad, Shaevitz, hep-ph/0305255



$\Delta m^2_{51} \sim 20$ eV^2

$\Delta m^2_{41} \sim 0.9$ eV^2

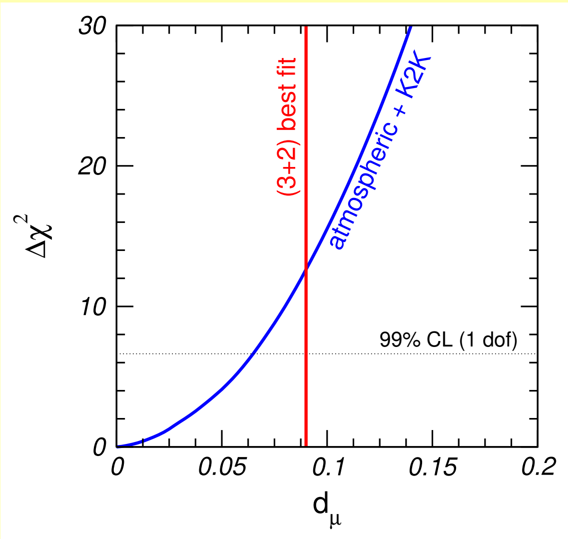
cosmology?

$\mathrm{PG}_{(3+2)} = 2.1\%$ $\mathrm{PG}_{(3+1)} = 0.032\%$

5-neutrino oscillations

Conflict with atmospheric neutrinos?

best fit: $U_{\mu 4} = 0.204,\ U_{\mu 5} = 0.224 \quad \to d_\mu = |U_{\mu 4}|^2 + |U_{\mu 5}|^2 \approx 0.09$



Maltoni, Schwetz, Tortola, Valle, hep-ph/0405172

More exotic proposals

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, Schwetz 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT violating quantum decoherence Barenboim, Mavromatos 04, 06
- mass varying neutrinos Kaplan, Nelson, Weiner 04; Zurek 04; Barger, Marfatia, Whisnant 05
- shortcuts of sterile neutrinos in extra dimensions Paes, Pakvasa, Weiler 05
- decaying sterile neutrinos Palomares-Riuz, Pascoli, Schwetz 05
- 3 neutrinos and Lorentz violation deGouvea, Grossmann 06

$\Rightarrow$

LSND and a decaying sterile neutrino

oscillation interpretation

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \xrightarrow{\text{oscillations}} \bar{\nu}_e$$

Palomares-Riuz, Pascoli, Schwetz, hep-ph/0505216

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$
$$\bar{\nu}_\mu \xrightarrow{|U_{\mu 4}|^2} \bar{\nu}_h$$
$$\bar{\nu}_h \xrightarrow{\text{decay}} \bar{\nu}_e + \Phi$$

The decay model

postulate heavy neutrino ν_h, which decays into light neutrinos ν_l and a scalar Φ

$$\mathcal{L} = -\sum_{l=1}^{3} g_l \, \bar{\nu}_{lL} \, \nu_{hR} \, \Phi + \text{h.c.}$$

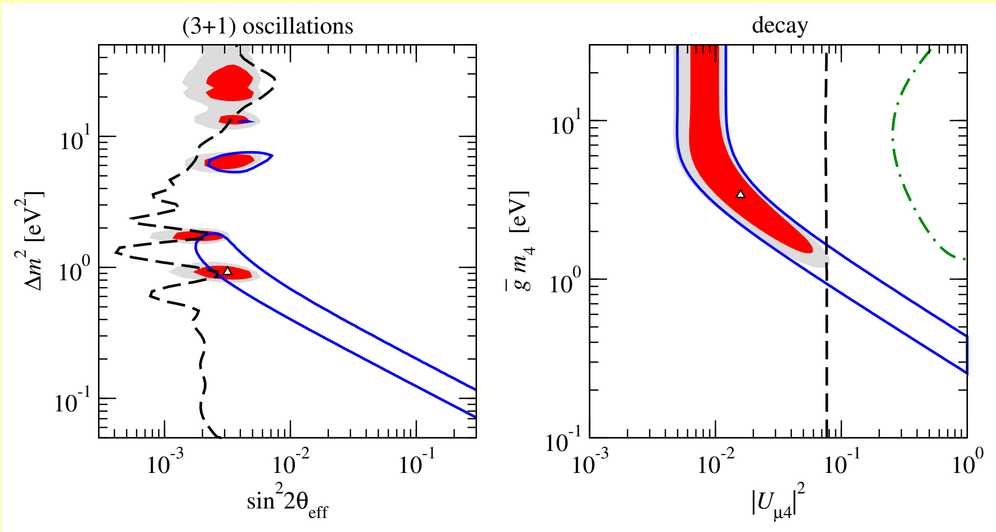
total decay rate of ν_h:

$$\Gamma = \frac{\bar{g}^2 m_h^2}{16\pi E_{\nu_h}} \qquad \text{with} \qquad \bar{g}^2 = \sum_l |g_l|^2$$

branching ratio for $\nu_h \to \nu_\alpha$:

$$R_\alpha \equiv \frac{|g_\alpha|^2}{\bar{g}^2} \qquad \text{with} \qquad g_\alpha = \sum_l U_{\alpha l} g_l$$

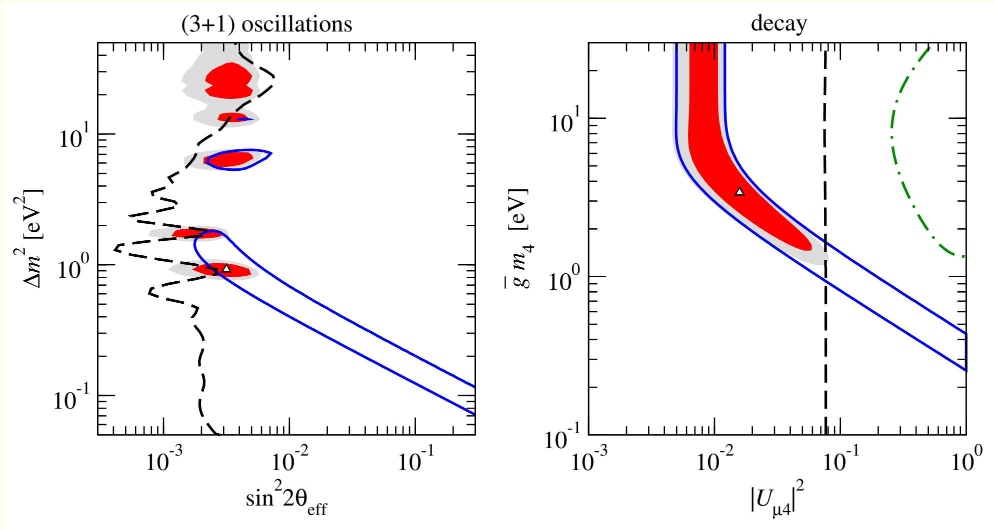
Reconciling LSND and no-evidence SBL data



$$P_{\rm osc} = 2|U_{e4}|^2 |U_{\mu 4}|^2 \left[1 - \cos\left(\frac{\Delta m^2}{2}\frac{L}{E}\right)\right]$$

$$P_{\rm dec} = \tfrac{1}{2}|U_{\mu 4}|^2 R_e \left[1 - \exp\left(-\frac{\bar{g}^2 m_h^2}{16\pi}\frac{L}{E}\right)\right] \qquad |U_{e4}|^2 = 0, \; R_e \sim 1$$

Reconciling LSND and no-evidence SBL data



LSND vs the rest:

PG$_{(3+1)}$ = 0.002%
PG$_{(3+2)}$ = 2.1%

PG$_{\rm decay}$ = 4.6%

LSND and a decaying sterile neutrino

the global best fit point:

$$|U_{\mu 4}|^2 = 0.016\,, \qquad \bar{g} m_h = 3.4\,\mathrm{eV}$$

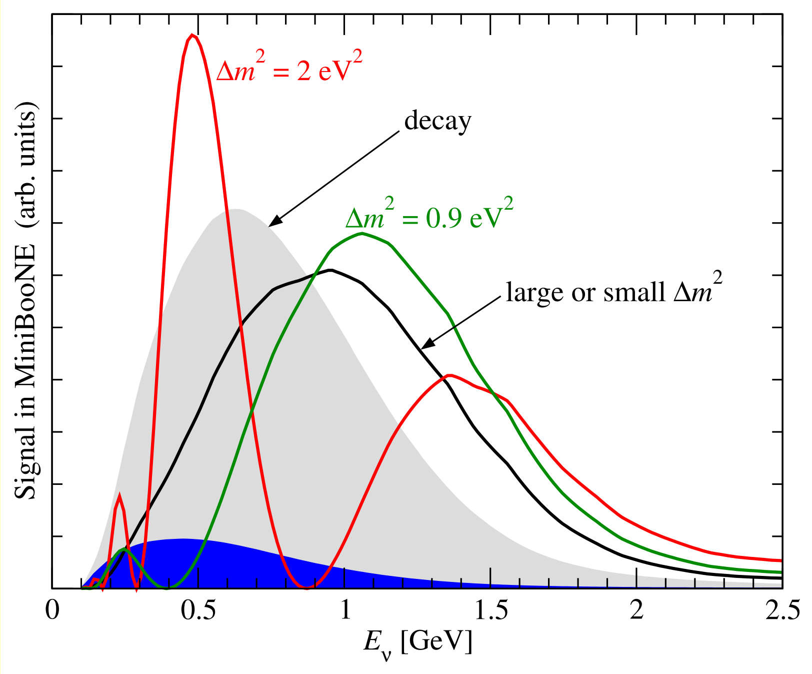
need $\bar{g} \sim 10^{-6} - 10^{-3}$, $m_h \sim \mathrm{keV} - \mathrm{MeV}$

oscillations in solar and KamLAND are un-affected

very small effects in atmospheric oscillations

the values for g, m_h, $|U_{\mu 4}|^2$ are consistent with various existing bounds

Predictions for MiniBooNE



Summary: LSND

The LSND signal remains an open issue

A confirmation from MiniBooNE would require new ideas (or the re-consideration of other SBL data)

For the rest of these lectures I will ignor LSND and consider only the standard 3-neutrino framework