SNOW 2006

Global fits to neutrino oscillation data

Thomas Schwetz
SISSA, Trieste

based on work in collaboration with M. Maltoni, M.A. Tortola, and J.W.F. Valle


T.S. is supported by an Intra-European Marie Curie fellowship of the European Commission within the 6th framework program
Outline

• Introduction
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- Determination of $\Delta m_{21}^2$ and $\theta_{12}$
  - global solar (SNO, SK, GNO, SAGE, Homestake)
  - and KamLAND data

The bound on $\theta_{13}$ from global data

Sub-leading effects in atmospheric neutrinos
  - implications for $\theta_{23}$ (deviations from maximal mixing)
  - and the bound on $\theta_{13}$

The LSND puzzle
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  - SK atmospheric $\nu$ data, K2K, first results from MINOS
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- The LSND puzzle
3-flavour oscillation parameters

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\quad \begin{pmatrix}
c_{13} & 0 & e^{-i\delta} s_{13} \\
0 & 1 & 0 \\
-e^{i\delta} s_{13} & 0 & c_{13}
\end{pmatrix}
\quad \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

“atmospheric”

“solar”
3-flavour oscillation parameters

\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

“atmospheric”

“solar”

<table>
<thead>
<tr>
<th>known params.</th>
<th>bounded params.</th>
<th>unknown params.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Delta m_{31}^2</td>
<td>$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$\Delta m_{21}^2$</td>
<td>$\text{sign}(\Delta m_{31}^2)$</td>
</tr>
<tr>
<td>$\Delta m_{21}^2$</td>
<td>$D_{23} \equiv \sin^2 \theta_{23} - 0.5$</td>
<td>$\sin^2 \theta_{12}$</td>
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</table>
The 'solar' parameters $\Delta m^2_{21}, \theta_{12}$
’Solar’ parameters

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

see also talk of A. McDonald
’Solar’ parameters

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

The SNO experiment:
\[ \nu_e + d \rightarrow p + p + e^- \]
\[ \nu_x + d \rightarrow p + n + \nu_x \]
\[ \frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023 \pm 0.030 \]

7σ evidence for a non-zero \( \nu_{\mu,\tau} \) flux from the sun

constraint on \( \theta_{12} \):
\[ \frac{\phi_{CC}}{\phi_{NC}} \approx P_{ee}^{SNO} \approx \sin^2 \theta_{12} \]

see also talk of A. McDonald
The KamLAND reactor neutrino experiment

Kamioka Liquid scinitillator Anti-Neutrino Detector

detection of $\bar{\nu}_e$ produced in surrounding nuclear power plants

70 GW of nuclear power (7% of world total) is generated at a distance $175 \pm 30$ km from Kamioka

258 events are observed, $365.2 \pm 23.7$ expected for no disappearance
The KamLAND energy spectrum

evidence for flux suppression and spectral distortion

Δm^2 = 8.1 \times 10^{-5} \text{eV}^2, s_{12}^2 = 0.29, s_{13}^2 = 0

Δm^2 = 1.6 \times 10^{-5} \text{eV}^2, s_{12}^2 = 0.31, s_{13}^2 = 0

Δm^2 = 1.7 \times 10^{-4} \text{eV}^2, s_{12}^2 = 0.25, s_{13}^2 = 0

Δm^2 = 8.1 \times 10^{-5} \text{eV}^2, s_{12}^2 = 0.19, s_{13}^2 = 0.1
characteristics of our KamLAND data analysis:

- equal bins in $1/E_{pr}$ instead of equal bins in $E_{pr}$
The KamLAND reactor neutrino experiment

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- include earth matter effects (few % effect)
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- improved anti-neutrino flux parameterization

The KamLAND reactor neutrino experiment

characteristics of our KamLAND data analysis:

- equal bins in $1/E_{pr}$ instead of equal bins in $E_{pr}$
- include earth matter effects (few % effect)
- improved anti-neutrino flux parameterization
  

- uncertainties from fluxes, flux shapes, reactor fuel composition, individual reactor powers
  
KamLAND vs solar data

90% and 99.73% CL contours

\[ \Delta m^2 = 7.9 \pm 0.3 \times 10^{-5} \text{ eV}^2, \quad \sin^2 \theta_{12} = 0.31^{+0.02}_{-0.03} \]
The 'atmospheric' parameters $\Delta m_{31}^2, \theta_{23}$
’Atmospheric’ parameters

Super-Kamiokande I atmospheric data  hep-ex/0501064
Oscillatory signal in atmospheric neutrinos


\[ P_{2\nu} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2}{4} \frac{L}{E_\nu} \right) \]
’Atmospheric’ parameters

![Diagram of atmospheric neutrino data from SK-I]

**best fit:**

\[
\Delta m_{32}^2 = 2.0 \times 10^{-3} \text{ eV}^2 \\
\sin^2 \theta_{23} = 0.5
\]

atmospheric neutrino data from SK-I

(re-analysis of Maltoni et al., hep-ph/0405172)
’Atmospheric’ parameters

\[ \Delta m_{32}^2 = 2.2 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 \theta_{23} = 0.5 \]

(K2K spectral analysis with 56 1-ring $\mu$-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
see talk of E. Falk Harris

- 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 $\sim 3$ GeV

- far detector (5.4 kt) at Soudan Mine ($L = 735$ km)
’Atmospheric’ parameters

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- mean energy of $\sim 3\text{ GeV}$

- far detector (5.4 kt) at Soudan Mine ($L = 735\text{ km}$)

Oscillation maximum at $\sim 1.5\text{ GeV}$
for $\Delta m^2 = 2.5 \times 10^{-3}\text{ eV}^2$
First results from MINOS

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

http://www-numi.fnal.gov/talks/results06.html
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<th>observed</th>
<th>expected</th>
<th>ratio</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>All CC-like events ((v_\mu+\bar{v}_\mu))</td>
<td>204</td>
<td>298±15</td>
<td>0.69</td>
<td>4.1σ</td>
</tr>
<tr>
<td>(v_\mu) only (&lt;30 \text{ GeV})</td>
<td>166</td>
<td>249±14</td>
<td>0.67</td>
<td>4.0σ</td>
</tr>
<tr>
<td>(v_\mu) only (&lt;10 \text{ GeV})</td>
<td>92</td>
<td>177±11</td>
<td>0.52</td>
<td>5.0σ</td>
</tr>
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First results from MINOS
’Atmospheric’ parameters

MINOS

K2K + MINOS

K2K

SK atmospheric

90% CL regions

$\Delta m^2$ [eV$^2$]

$\sin^2 2\theta$

’Atmospheric’ parameters

\[ \Delta m^2 \text{[10}^{-3} \text{eV}^2] \]

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<td>\text{SK+K2K +MINOS}</td>
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\[ \sin^2 \theta_{23} \]

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’Atmospheric’ parameters

![Graph showing atmospheric parameters](image)

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$\sin^2 \theta_{23}$

| SK | 0.5 | 3.4-6.8 |

The bound on $\theta_{13}$
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The bound on $\theta_{13}$ emerges from an interplay of the global data
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The bound on $\theta_{13}$

$$\Delta \chi^2$$ vs. $\sin^2 \theta_{13}$

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 $\theta_{13}$ and MINOS

Global 3ν analysis with and w/o MINOS
(Atm, Sol, KamL, Chooz, K2K)
The $\theta_{13}$ 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

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

\[
P_{\text{Sol}} \approx (1 - 2 \sin^2 \theta_{13}) \begin{cases} 
\sin^2 \theta_{12} & \text{high } E_\nu \\
(1 - 0.5 \sin^2 2\theta_{12}) & \text{low } E_\nu
\end{cases}
\]
Sub-leading effects in atmospheric neutrino data
Sub-leading effects in atmospheric neutrino data

Incomplete list:

Fogli, Lisi, Marrone, Palazzo, hep-ph/0506083
T. Kajita (Super-K), see e.g. talks at NuFact05, NuInt05
Sub-leading effects in atmospheric neutrinos

excess of electron-like events:

\[
\frac{N_e}{N_{e0}} - 1 \simeq (r s_{23}^2 - 1) P_{2\nu}(\Delta m_{31}^2, \theta_{13}) \quad \text{\(\theta_{13}\)-effects}
\]
\[
+ (r c_{23}^2 - 1) P_{2\nu}(\Delta m_{21}^2, \theta_{12}) \quad \text{\(\Delta m_{21}^2\)-effects}
\]
\[
- 2 s_{13} s_{23} c_{23} r \text{ Re}(A_{ee}^* A_{\mu e}) \quad \text{interference: \(\delta_{CP}\)}
\]

\[
r = r(E_{\nu}) \equiv \frac{F_{\mu}^0(E_{\nu})}{F_e^0(E_{\nu})} \quad r \approx 2 \quad \text{(sub-GeV)}
\]
\[
r \approx 2.6 - 4.5 \quad \text{(multi-GeV)}
\]
\( \theta_{13}\)-effects

\[
\frac{N_e}{N_e^0} - 1 \simeq (r \, s_{23}^2 - 1) \, P_{2\nu}(\Delta m_{31}^2, \theta_{13})
\]

resonant matter effect in \( P_{2\nu}(\Delta m_{31}^2, \theta_{13}) \)
for multi-GeV events \((r \approx 2.6 - 4.5)\)

normal hierarchy: enhancement for neutrinos
inverted hierarchy: enhancement for anti-neutrinos

detection cross sections are different for neutrinos
and anti-neutrinos

sensitivity to the neutrino mass hierarchy
$\theta_{13}$-effects

$$\frac{N_e}{N_e^0} - 1 \simeq (r s_{23}^2 - 1) P_{2\nu}(\Delta m_{31}^2, \theta_{13})$$

Bernabeu, Palomares-Ruiz, Petcov, hep-ph/0305152
\[ \frac{N_e}{N^0_e} - 1 \approx (r \ c_{23}^2 - 1) \ P_{2\nu}(\Delta m^2_{21}, \theta_{12}) \]

Peres, Smirnov, hep-ph/0309312

contours of \( \frac{N_e}{N^0_e} - 1 \)

relevant for sub-GeV events

sensitivity to the octant of \( \theta_{23} \)
Sub-leading effects in atmospheric neutrinos

Fogli et al., hep-ph/0506083

all 3 terms are important for sub-GeV, also the interference term depending on $\delta_{CP}$
multi-GeV are dominated by the $\theta_{13}$ term
effects at the level of few %
Sub-leading effects in atmospheric neutrinos

These effects can be explored in future Mt scale detectors, see talk of M. Maltoni, but...

Are these effects visible in present (SK-I) data?
Sub-leading effects in atmospheric neutrinos

These effects can be explored in future Mt scale detectors, see talk of M. Maltoni, but...

Are these effects visible in present (SK-I) data?

excess of sub-GeV $e$-like events
Sub-leading effects in atmospheric neutrinos

Currently there are three groups performing a 3-flavour analysis of SK data (to my knowledge):

- SK collaboration, hep-ex/0604011 ($\Delta m_{21}^2 = 0$)
  Talks by T. Kajita (including $\Delta m_{21}^2$)
- Bari group, E. Lisi et al., hep-ph/0506083 ($\delta_{CP} = 0, \pi$)
- M. Maltoni et al.
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- M. Maltoni et al.

In this context:

- Are there indications for non-maximal values of $\theta_{23}$?
- Is the bound on $\theta_{13}$ affected by these sub-leading effects?
Taking into account $\Delta m^2_{21}$

Gonzalez-Garcia, Maltoni, Smirnov, hep-ph/0408170
Is there an indication for a non-max $\theta_{23}$?

Super-K Coll. T. Kajita, NuFact05

Gonzalez-Garcia, Maltoni, Smirnov
hep-ph/0408170

Fogli et al.,
hep-ph/0506083

best fit: $\sin^2 \theta_{23} = 0.51$

max $\theta_{23}$: $\Delta \chi^2 \approx 0.1$

$\sin^2 \theta_{23} = 0.46$

$\Delta \chi^2 \approx 0.3$

$\sin^2 \theta_{23} = 0.44$

$\Delta \chi^2 \approx 0.8$
Is there an indication for a non-max $\theta_{23}$?

![Plot showing $\sin^2 \theta_{23}$ vs. $\sin^2 \theta_{13}$]

- $\Delta m_{\odot}^2 = 8 \times 10^{-5}$ eV$^2$
- $\Delta \chi^2 = 0.2, 0.5, 1, 4.6$ sub GeV 1-ring (e+\mu)
- SK + CHOOZ + K2K + MINOS
Is there an indication for a non-max $\theta_{23}$?
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SK + CHOOZ + K2K + MINOS

- sub GeV 1-ring ($e+\mu$)
  - $\chi^2 = 0.2, 0.5, 1, 4.6$
  - $\Delta m^2 = 8 \times 10^{-5} \text{ eV}^2$

- multi GeV 1-ring ($e+\mu$)
  - $\chi^2 = 0.2, 0.5, 1, 4.6$
  - $\Delta m^2 = 8 \times 10^{-5} \text{ eV}^2$

SK + CHOOZ + K2K + MINOS

- sub+multi GeV 1-ring
  - $\chi^2 = 0.2, 0.5, 1, 4.6$
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Is there an indication for a non-max $\theta_{23}$?

SK + CHOOZ + K2K + MINOS

$\Delta \chi^2 = 0.2, 0.5, 1, 4.6$
$\Delta m^2_{13} = 8 \times 10^{-5} \text{eV}^2$

$\Delta \chi^2 = 0.2, 0.5, 1, 4.6$
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Is there an indication for a non-max $\theta_{23}$?

sub-leading effects are

- significantly smaller than statistical and systematical uncertainties
- too small to account for the sub-GeV e-like excess

results depend on the fine-details of the analysis
Sub-leading effects in ATM and $\theta_{13}$

reference $\chi^2$ from Maltoni, Schwetz, Tortola, Valle
($\Delta m^2_{21} = 0$ and NH)
Sub-leading effects in ATM and $\theta_{13}$

$\Delta \chi^2$-
effects in ATM do contribute to the bound
Sub-leading effects in ATM and $\theta_{13}$

\[ \chi^2 \]

ATM+CHOOZ+K2K

- Black: systematics treatment from Kameda thesis
- Magenta: flux and CS systematics developed in Gonzalez-Garcia, Maltoni, hep-ph/0404085

90% CL

T. Schwetz, SNOW2006, Stockholm, 2 May 2006 – p.34
Sub-leading effects in ATM and $\theta_{13}$

$\Delta m^2_{21} \neq 0$ has an important impact on the bound
(shown for NH and IH, minimized over $\delta_{CP}$)
Sub-leading effects in ATM and $\theta_{13}$

Super-K $3\nu$ analysis from hep-ex/0604011 ($\Delta m^2_{21} = 0$)
big effect for NH
Sub-leading effects in ATM and $\theta_{13}$

comparison with Bari group

$(\Delta m^2_{21} \neq 0$, minimized over NH/IH, and $\delta_{CP} = 0, \pi)$
Sub-leading effects in ATM and $\theta_{13}$

![Graph showing sub-leading effects in ATM and $\theta_{13}$](image)

- Maltoni et al. [hep-ph/0405172]
- 2ν ATM
- different systematics
- with solar osc (NH)
- with solar osc (IH)
- SK 2ν
- SK 3ν NH
- SK 3ν IH
- Fogli et al., [hep-ph/0506083]
Sub-leading effects in ATM and $\theta_{13}$

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“systematic error” on bound: $\sin^2 \theta_{13} < (0.038 \pm 0.006)$ at $2\sigma$

effect of MINOS: shift of 0.003
Sub-leading effects in ATM and $\theta_{13}$

Fogli et al., hep-ph/0506083

$\delta_{CP} = \pi$

$\delta_{CP} = 0$

$\Delta \chi^2$

$\cos(\delta_{CP}) \sin \theta_{13}$

Bari: best fit: $\sin^2 \theta_{13} \approx 0.01$, $\Delta \chi^2 \approx 0.85$ for $\theta_{13} = 0$
Sub-leading effects in ATM and $\theta_{13}$

Bari: best fit: $\sin^2 \theta_{13} \approx 0.01$, $\Delta \chi^2 \approx 0.85$ for $\theta_{13} = 0$

Maltoni: best fit: $\sin^2 \theta_{13} \approx 0.005$, $\Delta \chi^2 \approx 0.16$ for $\theta_{13} = 0$
Sub-leading effects in ATM and $\theta_{13}$

Bari: best fit: $\sin^2 \theta_{13} \approx 0.01$, $\Delta \chi^2 \approx 0.85$ for $\theta_{13} = 0$

Maltoni: best fit: $\sin^2 \theta_{13} \approx 0.005$, $\Delta \chi^2 \approx 0.16$ for $\theta_{13} = 0$
The LSND puzzle
The LSND result

**evidence for** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ **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
The LSND result

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

results: Neutrino 2006 (?)
4-neutrino oscillations?
Adding a sterile neutrino

4-neutrino mass schemes:

(2+2)  \[ \Delta m^2_{\text{atm}} \]
\[ \Delta m^2_{\text{LSND}} \]
\[ \Delta m^2_{\text{sol}} \]

(3+1)  \[ \Delta m^2_{\text{atm}} \]
\[ \Delta m^2_{\text{LSND}} \]
\[ \Delta m^2_{\text{sol}} \]

\[ \nu_e, \nu_\mu, \nu_\tau, \nu_s \]
(2+2): ruled out by solar and atmospheric data

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$\Delta \chi^2 = 26 \quad \rightarrow \quad (2+2) \text{ ruled out at the } 5\sigma \text{ level}$
(3+1): strongly disfavoured by SBL data

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

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

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
(3+1): strongly disfavoured by SBL data

disappearance experiments
Bugey, CDHS: \( d_e, d_\mu \ll 1 \)

\[ (3+1): \quad \sin^2 2\theta_{\text{LSND}} = 4 \, d_e d_\mu \]

Bilenky, Giunti, Grimus, 96, 98;
Okada, Yasuda, 1997;
Barger \textit{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
# Global 4-neutrino analysis

<table>
<thead>
<tr>
<th></th>
<th>SOL</th>
<th>ATM</th>
<th>LSND</th>
<th>NEV</th>
<th>$\chi^2_{\text{PG}}$</th>
<th>parameter GOF (PG)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(3+1)</strong></td>
<td>0.0</td>
<td>0.4</td>
<td>5.7</td>
<td>10.9</td>
<td>17.0</td>
<td>$1.9 \times 10^{-3}$</td>
</tr>
<tr>
<td><strong>(2+2)</strong></td>
<td>5.3</td>
<td>20.8</td>
<td>0.6</td>
<td>7.3</td>
<td>33.9</td>
<td>$7.8 \times 10^{-7}$</td>
</tr>
</tbody>
</table>
More sterile neutrinos?
5-neutrino oscillations

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

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

\[ \Delta m_{51}^2 \sim 20 \text{ eV}^2 \]

\[ \Delta m_{41}^2 \sim 0.9 \text{ eV}^2 \]

\[ \text{PG}_{(3+2)} = 2.1\% \quad \text{PG}_{(3+1)} = 0.032\% \]
5-neutrino oscillations

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

\[ \Delta m_{51}^2 \sim 20 \text{ eV}^2 \]

\[ \Delta m_{41}^2 \sim 0.9 \text{ eV}^2 \]

cosmology?

\[ \text{PG}_{(3+2)} = 2.1\% \]

\[ \text{PG}_{(3+1)} = 0.032\% \]
5-neutrino oscillations

Conflict with atmospheric neutrinos?

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

Maltoni, Schwetz, Tortola, Valle, hep-ph/0405172
More ‘exotic’ proposals
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-Rius, Pascoli, Schwetz 05
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LSND and a decaying sterile neutrino
LSND and a decaying sterile neutrino

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

Dashed line indicates oscillations

\[ e^+ + \nu_e + \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]
LSND and a decaying sterile neutrino

oscillation interpretation

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ e^+ + \nu_e + \bar{\nu}_\mu \quad \text{oscillations} \]
\[ \rightarrow \bar{\nu}_e \]

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

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ e^+ + \nu_e + \bar{\nu}_\mu \]
\[ |U_{\mu 4}|^2 \]
\[ \rightarrow \bar{\nu}_h \quad \text{decay} \]
\[ \bar{\nu}_e + \Phi \]
The decay model

postulate heavy neutrino $\nu_h$, which decays into light neutrinos $\nu_l$ and a scalar $\Phi$

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

postulate heavy neutrino $\nu_h$, which decays into light neutrinos $\nu_l$ and a scalar $\Phi$

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

assume $m_{1,2,3} \lesssim m_\Phi \ll m_h \Rightarrow$ light neutrinos are stable
The decay model

postulate heavy neutrino $\nu_h$, which decays into light neutrinos $\nu_l$ and a scalar $\Phi$

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

total decay rate of $\nu_h$:

$$\Gamma = \frac{\bar{g}^2 m_h^2}{16\pi E_{\nu_h}}$$  

with  

$$\bar{g}^2 = \sum_l |g_l|^2$$

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

$$R_\alpha \equiv \frac{|g_\alpha|^2}{\bar{g}^2}$$  

with  

$$g_\alpha = \sum_l U_{\alpha l} g_l$$
Reconciling LSND and no-evidence SBL data

\[ P_{\text{osc}} = 2|U_{e4}|^2 |U_{\mu4}|^2 \left[ 1 - \cos \left( \frac{\Delta m^2}{2} \frac{L}{E} \right) \right] \]

\[ P_{\text{dec}} = \frac{1}{2} |U_{\mu4}|^2 R_e \left[ 1 - \exp \left( -\frac{\tilde{g}^2 m_h^2}{16\pi} \frac{L}{E} \right) \right] \]

\[ |U_{e4}|^2 = 0, \quad R_e \sim 1 \]
Reconciling LSND and no-evidence SBL data

LSND vs the rest:

\[ \text{PG}_{(3+1)} = 0.002\% \]
\[ \text{PG}_{(3+2)} = 2.1\% \]

\[ \text{PG}_{\text{decay}} = 4.6\% \]
Reconciling LSND and no-evidence SBL data

appearance vs disappearance:

\[ PG_{(3+1)} = 0.03\% \]

\[ PG_{\text{decay}} = 55\% \]
the global best fit point:

\[ |U_{\mu 4}|^2 = 0.016, \quad \bar{g} m_h = 3.4 \text{ eV} \]

need \( \bar{g} \sim 10^{-6} - 10^{-3} \), \( m_h \sim \text{keV} - \text{MeV} \)
LSND and a decaying sterile neutrino

the global best fit point:

\[ |U_{\mu4}|^2 = 0.016, \quad \bar{g}m_h = 3.4 \text{ eV} \]

need \( \bar{g} \sim 10^{-6} - 10^{-3}, \quad m_h \sim \text{keV} - \text{MeV} \)

oscillations in solar and KamLAND are un-affected

very small effects in atmospheric oscillations

the values for \( g, m_h, |U_{\mu4}|^2 \) are consistent with various existing bounds
Predictions for MiniBooNE

\[ \Delta m^2 = 2 \text{ eV}^2 \]

\[ \Delta m^2 = 0.9 \text{ eV}^2 \]

large or small \( \Delta m^2 \)

decay
Summary
### Summary: 3-flavour oscillation parameters

#### mass-squared differences:

<table>
<thead>
<tr>
<th>parameter</th>
<th>$bf \pm 1\sigma$</th>
<th>$1\sigma$ acc.</th>
<th>$3\sigma$ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{21}$ [10$^{-5}$ eV$^2$]</td>
<td>7.9 ± 0.3</td>
<td>4%</td>
<td>7.1 – 8.9</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{31}</td>
<td>$ [10$^{-3}$ eV$^2$]</td>
<td>2.5$^{+0.2}_{-0.25}$</td>
</tr>
</tbody>
</table>

#### mixing angles:

<table>
<thead>
<tr>
<th>parameter</th>
<th>$bf \pm 1\sigma$</th>
<th>$1\sigma$ acc.</th>
<th>$3\sigma$ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.31$^{+0.02}_{-0.03}$</td>
<td>9%</td>
<td>0.24 – 0.40</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.50$^{+0.08}_{-0.07}$</td>
<td>16%</td>
<td>0.34 – 0.68</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>–</td>
<td>–</td>
<td>$\leq 0.044$</td>
</tr>
</tbody>
</table>

very small correlations among the parameters

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

T. Schwetz, SNOW2006, Stockholm, 2 May 2006 – p.54
Summary: First results from MINOS
Two possibilities for the neutrino mass spectrum:

\[ \Delta m_{31}^2 > 0 \quad \text{NORMAL} \]

\[ \Delta m_{31}^2 < 0 \quad \text{INVERTED} \]
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)
Thanks to . . .

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Thank you for your attention!