Sterile Neutrinos and Short-Baseline $\bar{\nu}_{\mu} \to \bar{\nu}_{e}$ Oscillations

Carlo Giunti

INFN, Sezione di Torino

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Standard Model

- Neutrinos are the only massless fermions
- Neutrinos are the only fermions with only left-handed component ν_L

Extension of the SM: Massive Neutrinos

- Simplest extension: introduce right-handed component ν_R
- Neutrinos become massive
- Dirac mass $m_{\text{D}} \overline{\nu_R} \nu_L$ $+$ Majorana mass $m_{\text{M}} \overline{\nu_R^c} \nu_R$
- It is likely that right-handed neutrinos are connected with new physics beyond the Standard Model

Sterile Neutrinos

- Light right-handed antineutrinos are called sterile neutrinos

$$\nu_R^c \rightarrow \nu_s \qquad \text{(left-handed)}$$

- Sterile means no standard model interactions
- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos
  - Indirect evidence through combined fit of data
- Extremely interesting and powerful window on new physics beyond the Standard Model

How many Sterile Neutrinos?

$e^+e^- \to Z \to \nu\bar{\nu} \quad \Rightarrow \quad \nu_e \ \nu_\mu \ \nu_\tau$ 3 active flavor neutrinos

mixing $\Rightarrow$ $\nu_{\alpha L} = \sum_{k=1}^{N} U_{\alpha k} \nu_{kL}$ $\alpha = e, \mu, \tau$

$N \geq 3$

no upper limit!

Mass Basis: $\nu_1 \quad \nu_2 \quad \nu_3 \quad \nu_4 \quad \nu_5 \quad \cdots$

Flavor Basis: $\nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_{s_1} \quad \nu_{s_2} \quad \cdots$

ACTIVE STERILE

Solar and Atmospheric Neutrino Oscillations

Solar
$\nu_e \to \nu_\mu , \nu_\tau$

Reactor
$\bar{\nu}_e$ disappearance

Homestake
Kamiokande
GALLEX/GNO & SAGE
Super-Kamiokande
SNO
BOREXino

(KamLAND)

→

$$\Delta m^2_{\text{SOL}} \simeq 7.6 \times 10^{-5} \, \text{eV}^2$$

$$\sin^2 \vartheta_{\text{SOL}} \simeq 0.32$$

Atmospheric
$\nu_\mu \to \nu_\tau$

Accelerator
ν_μ disappearance

Kamiokande
IMB
Super-Kamiokande
MACRO
Soudan-2

(K2K & MINOS)

→

$$\Delta m^2_{\text{ATM}} \simeq 2.4 \times 10^{-3} \, \text{eV}^2$$

$$\sin^2 \vartheta_{\text{ATM}} \simeq 0.50$$

Two scales of $\Delta m^2 \iff$ Three-Neutrino Mixing

$$\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.6 \times 10^{-5} \, \text{eV}^2$$

$$\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq 2.4 \times 10^{-3} \, \text{eV}^2$$

- New Short-BaseLine Oscillations: $\frac{L}{E} \lesssim 1 \, \frac{\text{m}}{\text{MeV}} \quad \Longrightarrow \quad \Delta m^2_{\text{SBL}} \gtrsim 1 \, \text{eV}^2$
- Necessary introduction of at least one new massive neutrino: 4-ν Mixing

Mass Basis: $\nu_1 \quad \nu_2 \quad \nu_3 \quad \nu_4$

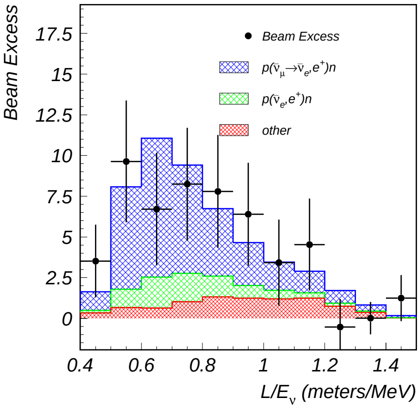
Flavor Basis: $\nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_s$

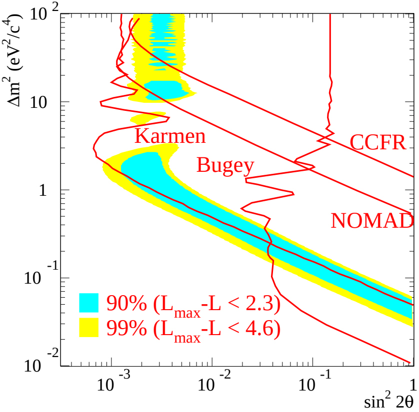
$$\Delta m^2_{\text{SBL}} = \Delta m^2_{41}$$

LSND

[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_{\mu} \to \bar{\nu}_{e}$ $\quad L \simeq 30\,\text{m}$ $\quad 20\,\text{MeV} \leq E \leq 200\,\text{MeV}$

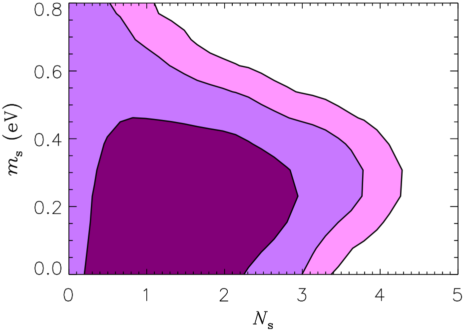




$\Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2$ $\quad (\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}})$

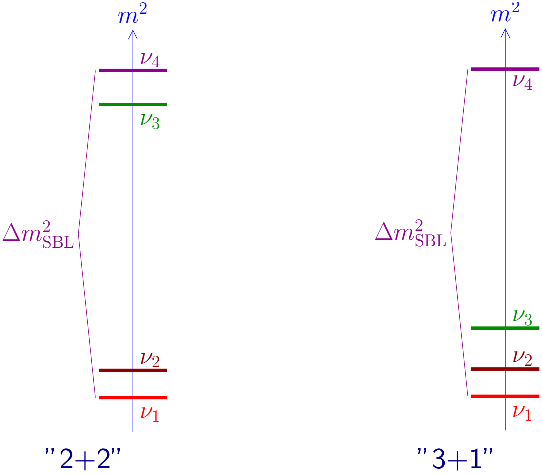
Cosmology

- CMB and LLS in ΛCDM: [Hamann, Hannestad, Raffelt, Tamborra, Wong, arXiv:1006.5276]



- BBN: $N_s = 0.68^{+0.80}_{-0.70}$ [Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440]

Four-Neutrino Schemes: 2+2 and 3+1



SBL Oscillation Probabilities in 3+1 Schemes

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

No CP Violation!

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

Perturbation of 3ν Mixing

$$|U_{e4}|^2 \ll 1 \,, \quad |U_{\mu 4}|^2 \ll 1 \,, \quad |U_{\tau 4}|^2 \ll 1 \,, \quad |U_{s4}|^2 \simeq 1$$

$$U = \left(\begin{array}{ccc|c|} \cline{4-4} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \\ \cline{4-4} \end{array}\right)$$

↑

SBL

$$\sin^2 2\vartheta_{\alpha\alpha} \ll 1$$

$$\Downarrow$$

$$|U_{\alpha 4}|^2 \simeq \frac{\sin^2 2\vartheta_{\alpha\alpha}}{4}$$

- ν_e disappearance experiments:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

- ν_μ disappearance experiments:

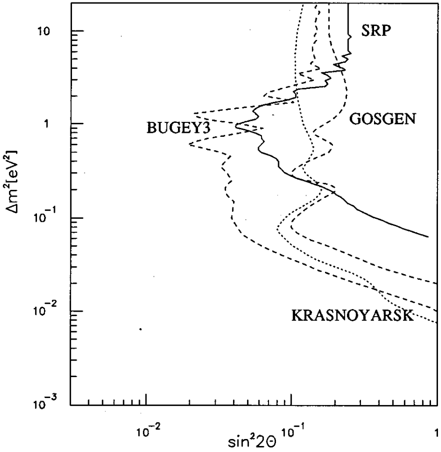
$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 \left(1 - |U_{\mu4}|^2\right) \simeq 4|U_{\mu4}|^2$$

- $\nu_\mu \to \nu_e$ experiments:

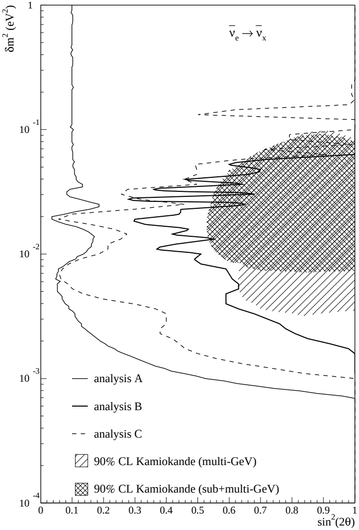
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ $\Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

$\bar{\nu}_e$ Disappearance

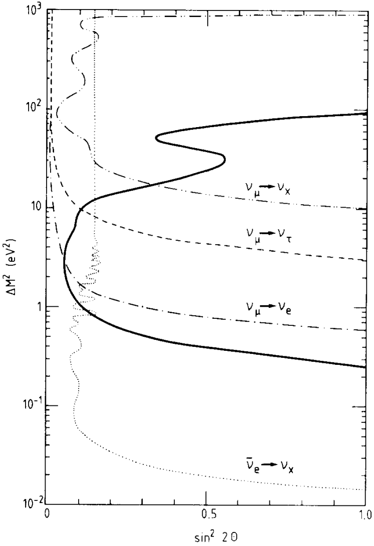


[Savannah River (SRP), PRD 53 (1996) 6054]

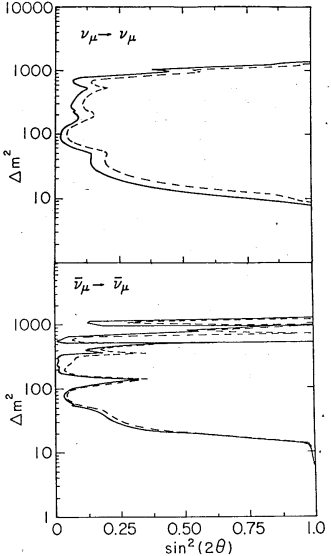


[CHOOZ, Eur. Phys. J. C27 (2003) 331, hep-ex/0301017]

ν_μ and $\bar{\nu}_\mu$ Disappearance

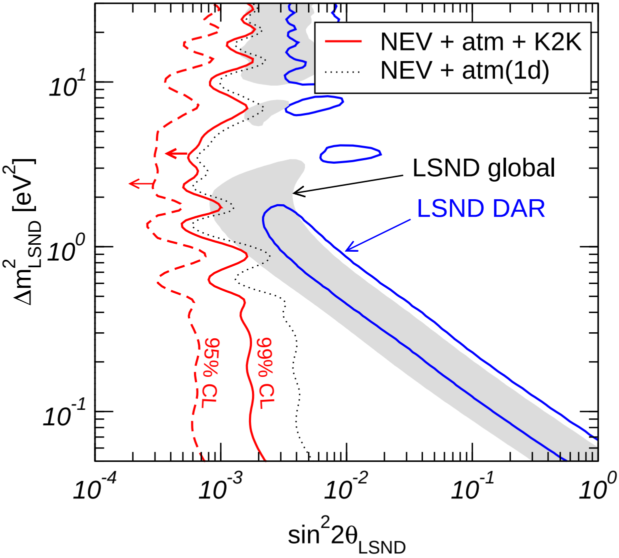


[CDHSW, PLB 134 (1984) 281]



[CCFR, Z. Phys. C 27 (1985) 53]

$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ in 3+1 Schemes

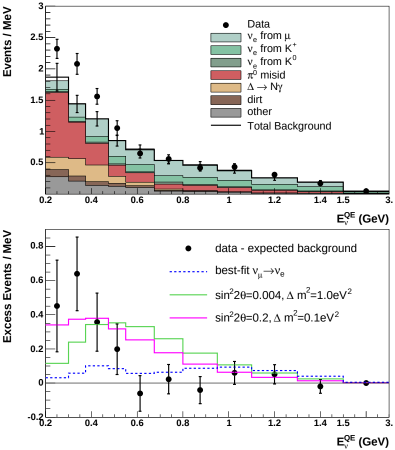


[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

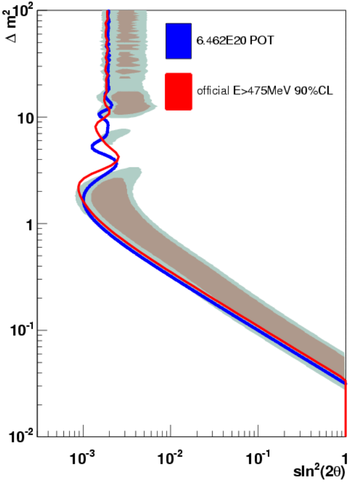
MiniBooNE Neutrinos

[PRL 98 (2007) 231801]

$\nu_\mu \to \nu_e$ $L \simeq 541\,\text{m}$ $475\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$



[PRL 102 (2009) 101802, arXiv:0812.2243]



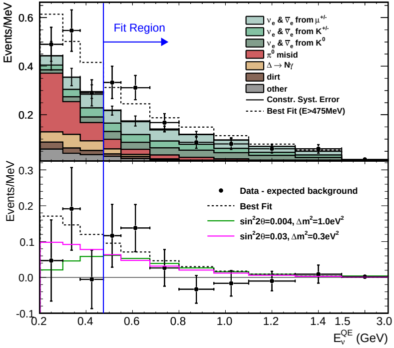
[arXiv:0901.1648]

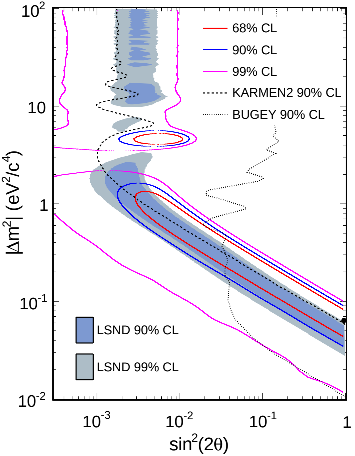
Low-Energy Anomaly!

MiniBooNE Antineutrinos

[arXiv:1007.1150]

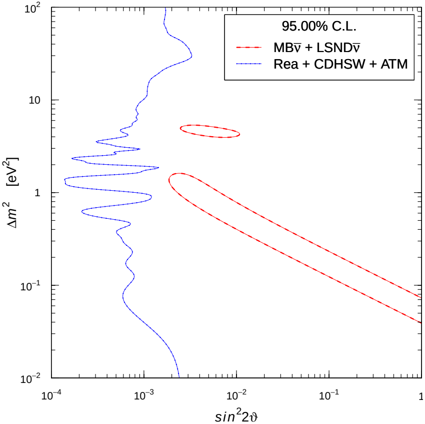
$\bar{\nu}_\mu \to \bar{\nu}_e$ $L \simeq 541\,\text{m}$ $475\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$



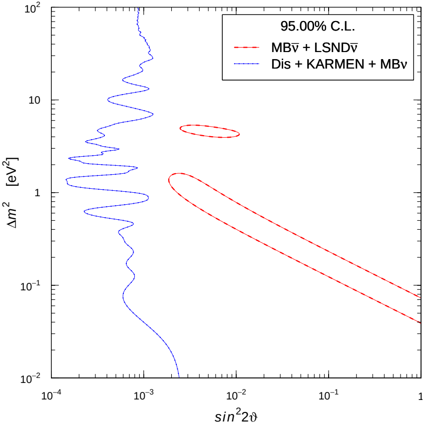


Agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal!

Similar L/E but different L and E $\Longrightarrow$ Oscillations!



PGoF = 0.11%

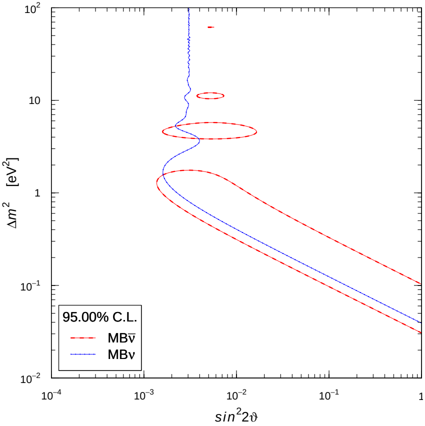


PGoF = 0.0095%

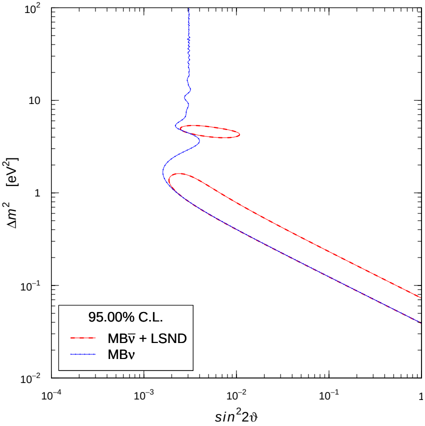
3+1 Schemes

Strong tension between LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ and

- $\bar{\nu}_e$ (Bugey) + $\overset{(-)}{\nu}_\mu$ (CDHSW+ATM) disappearance limits
- KARMEN $\bar{\nu}_\mu \to \bar{\nu}_e$ and MiniBooNE $\nu_\mu \to \nu_e$



PGoF = 2.0%

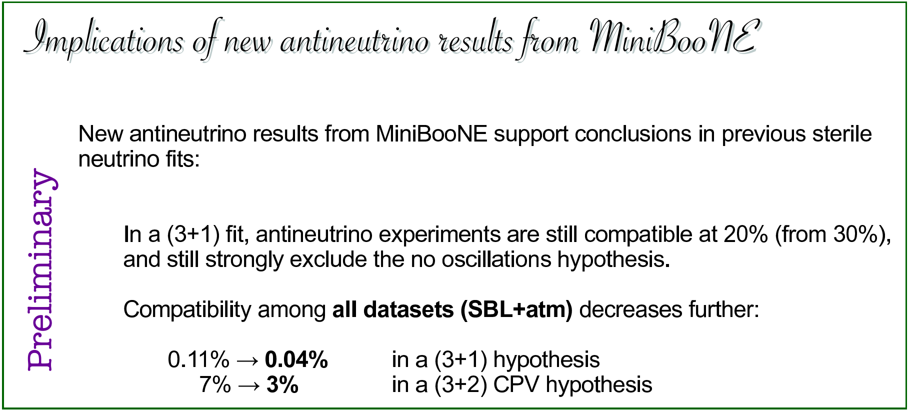


PGoF = 0.27%

3+1 Schemes: Strong tension between

- LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$
- MiniBooNE $\nu_\mu \to \nu_e$

CP Violation: 3+2 Five-Neutrino Mixing?



Implications of new antineutrino results from MiniBooNE

Preliminary

New antineutrino results from MiniBooNE support conclusions in previous sterile neutrino fits:

In a (3+1) fit, antineutrino experiments are still compatible at 20% (from 30%), and still strongly exclude the no oscillations hypothesis.

Compatibility among **all datasets (SBL+atm)** decreases further:

0.11% → **0.04%**	in a (3+1) hypothesis
7% → **3%**	in a (3+2) CPV hypothesis

[Georgia Karagiorgi, Neutrino 2010, 14 June 2010]

Other Approaches

- Evgeny Akhmedov, Thomas Schwetz, arXiv:1007.4171, "MiniBooNE and LSND data: non-standard neutrino interactions in a (3+1) scheme versus (3+2) oscillations": 1 or 2 sterile neutrinos and non-standard interactions

- Sergei Gninenko, arXiv:1009.5536, "A resolution of puzzles from the LSND, KARMEN, and MiniBooNE experiments": radiative decay of a heavy sterile neutrino

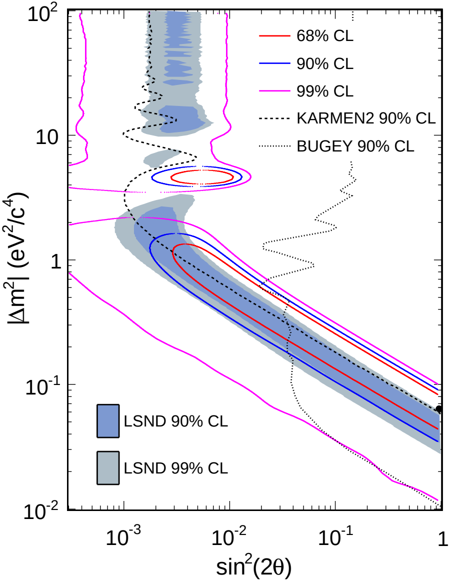
- Ann E Nelson, arXiv:1010.3970, "Effects of CP Violation from Neutral Heavy Fermions on Neutrino Oscillations, and the LSND/MiniBooNE Anomalies": heavy sterile neutrinos and non-unitarity of mixing matrix

All these possibilities involve sterile neutrinos!

CPT Violation?

- Masses and mixing of neutrinos and antineutrinos may be different
- In CDHSW mainly ν_μ's
- No limit on SBL $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions from disappearance experiments

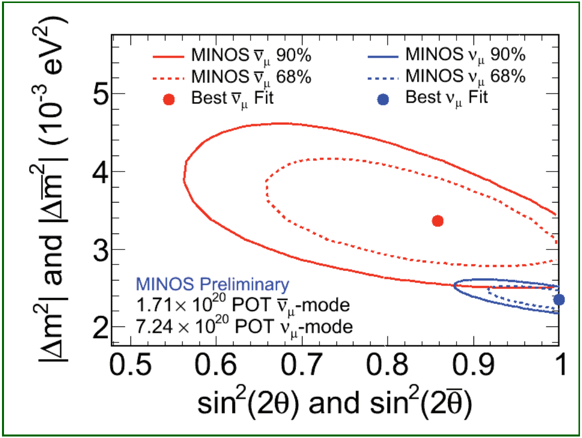
  [Barger, Marfatia, Whisnant, PLB 576 (2003) 303]
- LSND and MiniBooNE allowed regions are limited only by KARMEN and Bugey



MINOS Hint of CPT Violation

LBL ν_μ disappearance $E \sim 3\,\mathrm{GeV}$

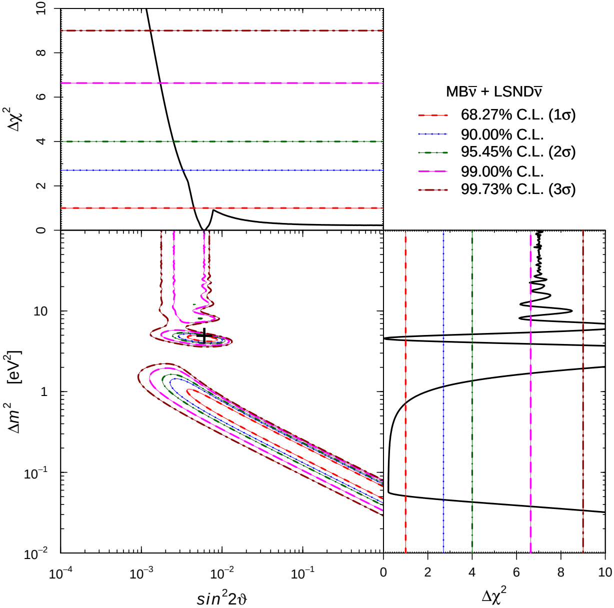
Near Detector at 1.04 km Far Detector at 734 km



[MINOS, Neutrino 2010, 14 June 2010]

Phenomenological Approach: Consider $\bar{\nu}$'s Only

$\bar{\nu}_\mu \to \bar{\nu}_e$



$\chi^2_{\text{min}} = 14.7$

$\text{NdF} = 18$

$\text{GoF} = 68\%$

$\sin^2 2\vartheta = 0.006$

$\Delta m^2 = 4.57\,\text{eV}^2$

Parameter Goodness-of-Fit

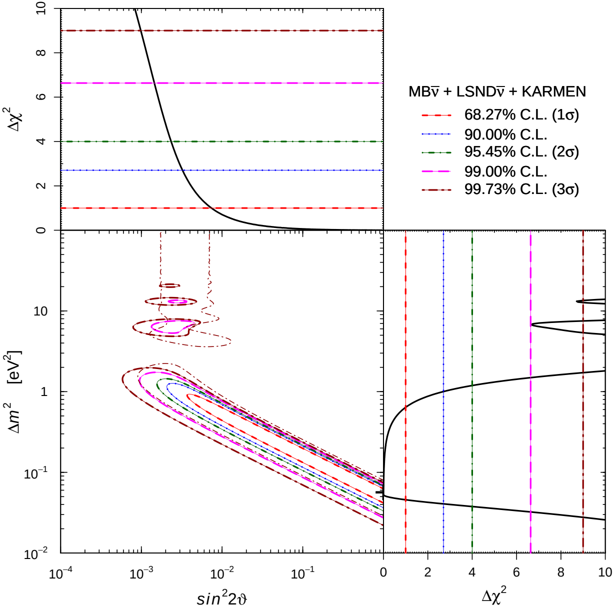
$\Delta\chi^2_{\text{min}} = 1.6$

$\text{NdF} = 2$

$\text{GoF} = 44\%$

[Giunti, Laveder, arXiv:1010.1395]

$\bar{\nu}_\mu \to \bar{\nu}_e$



$\chi^2_{\text{min}} = 25.7$

$\text{NdF} = 26$

$\text{GoF} = 48\%$

$\sin^2 2\vartheta = 1.00$

$\Delta m^2 = 0.052\,\text{eV}^2$

Parameter Goodness-of-Fit

$\Delta\chi^2_{\text{min}} = 6.3$

$\text{NdF} = 4$

$\text{GoF} = 18\%$

[Giunti, Laveder, arXiv:1010.1395]

Conservation of Probability

$$\sum_{\alpha} P_{\bar{\nu}_{\alpha} \to \bar{\nu}_{e}} = 1$$

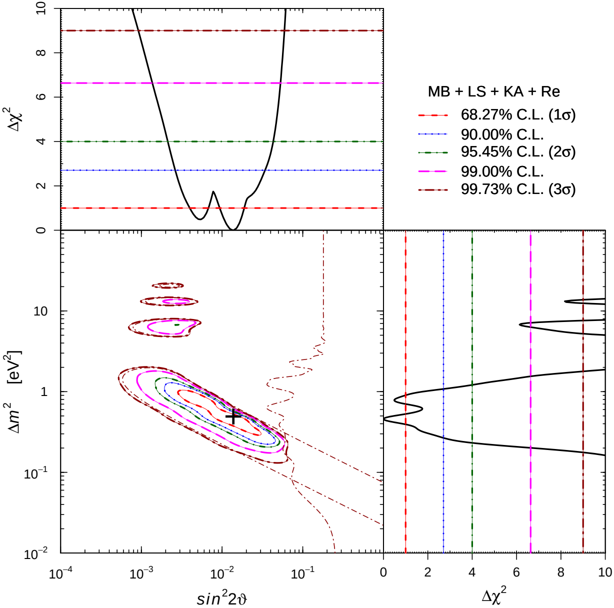
$$P_{\bar{\nu}_{e} \to \bar{\nu}_{e}} + P_{\bar{\nu}_{\mu} \to \bar{\nu}_{e}} + P_{\bar{\nu}_{\tau} \to \bar{\nu}_{e}} + P_{\bar{\nu}_{s} \to \bar{\nu}_{e}} = 1$$

$$P_{\bar{\nu}_{\mu} \to \bar{\nu}_{e}} = 1 - P_{\bar{\nu}_{e} \to \bar{\nu}_{e}} - P_{\bar{\nu}_{\tau} \to \bar{\nu}_{e}} - P_{\bar{\nu}_{s} \to \bar{\nu}_{e}}$$

$$\boxed{P_{\bar{\nu}_{\mu} \to \bar{\nu}_{e}} \leq 1 - P_{\bar{\nu}_{e} \to \bar{\nu}_{e}}}$$

Reactor $\bar{\nu}_e$ disappearance bound is unavoidable!

$\bar{\nu}_\mu \to \bar{\nu}_e$ and $\bar{\nu}_e \to \bar{\nu}_e$



$\chi^2_{\rm min} = 77.3$

$\mathrm{NdF} = 82$

$\mathrm{GoF} = 63\%$

$\sin^2 2\vartheta = 0.014$

$\Delta m^2 = 0.46\,\mathrm{eV}^2$

Parameter Goodness-of-Fit

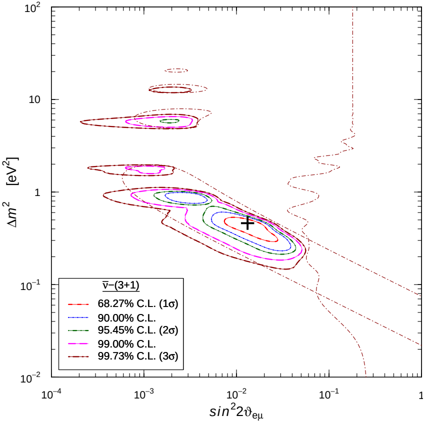
$\Delta\chi^2_{\rm min} = 3.0$

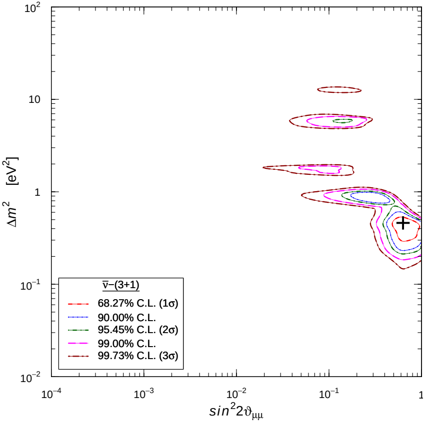
$\mathrm{NdF} = 2$

$\mathrm{GoF} = 22\%$

[Giunti, Laveder, arXiv:1010.1395]

Antineutrino Oscillations in 3+1 Schemes





$$\chi^2_{\text{min}} = 77.5 \qquad \text{NdF} = 82 \qquad \text{GoF} = 62\%$$

$$\Delta m^2 = 0.43\,\text{eV}^2 \qquad \sin^2 2\vartheta_{e\mu} = 0.013$$

$$\sin^2 2\vartheta_{ee} = 0.017 \qquad \sin^2 2\vartheta_{\mu\mu} = 0.63$$

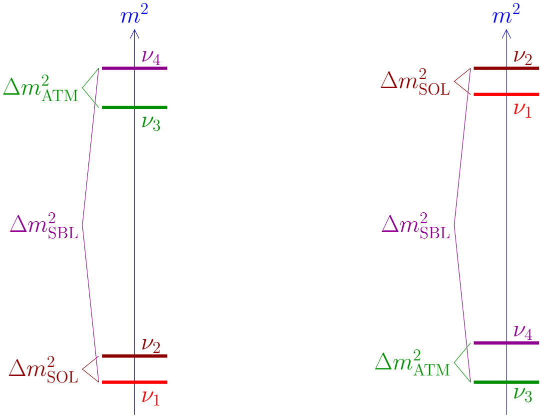
Prediction: large SBL $\bar{\nu}_\mu$ disappearance at $0.1 \lesssim \Delta m^2 \lesssim 1\,\text{eV}^2$

Conclusions

- Existence of sterile neutrinos is a very interesting possibility: powerful window on new physics beyond the Standard Model
- ΛCDM cosmology and BBN hint at $N_s > 0$
- Impressive LSND and MiniBooNE agreement on $\bar{\nu}_\mu \to \bar{\nu}_e$ signal
- Two experimental tensions:
    - LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ vs MiniBooNE $\nu_\mu \to \nu_e$
    - LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ vs $\bar{\nu}_e$ and ν_μ disappearance limits
- Interpretation of experimental results is difficult:
    - 3+1 Four-Neutrino Mixing is strongly disfavored (no CP violation)
    - CP violation $\Longrightarrow$ 3+2 Five-Neutrino Mixing or more?
    - CPT violation?
    - . . . ?
- New short-baseline neutrino oscillation experiments are needed!

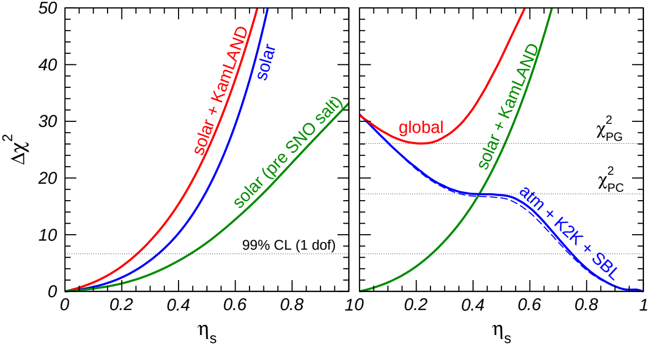
Backup Slides

2+2 Four-Neutrino Schemes



"normal" "inverted"

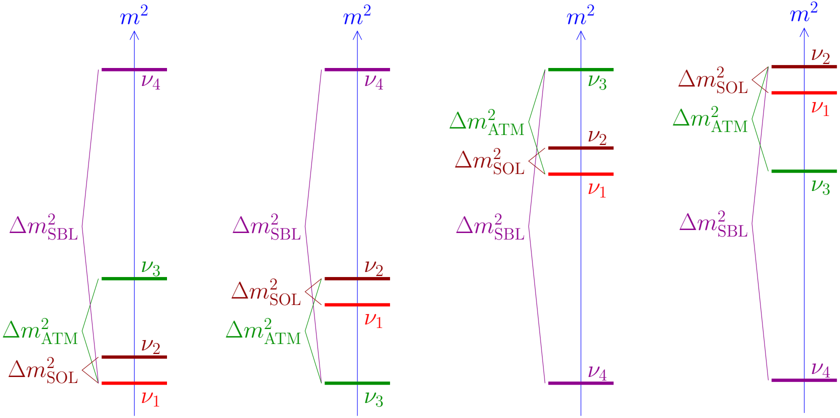
2+2 Schemes are strongly disfavored by solar and atmospheric data



[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

$$\eta_s = |U_{s1}|^2 + |U_{s2}|^2 \qquad 99\%\ \text{CL:} \begin{cases} \eta_s < 0.25 & \text{(solar + KamLAND)} \\ \eta_s > 0.75 & \text{(atmospheric + K2K)} \end{cases}$$

3+1 Four-Neutrino Schemes



"normal" "3ν-inverted" "4ν-inverted" "fully-inverted"

Perturbation of 3-ν Mixing

$|U_{e4}|^2 \ll 1$ $|U_{\mu 4}|^2 \ll 1$ $|U_{\tau 4}|^2 \ll 1$ $|U_{s4}|^2 \simeq 1$