Analysis of oscillations with 3 and 3+N neutrinos

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I. Conventional three-neutrino oscillations

II. Models with extra sterile neutrinos

Summary

General three-neutrino framework

- Equation of motion: **6 parameters** (including Dirac and neglecting Majorana phases):

$$i\frac{d\vec{\nu}}{dt} = H\,\vec{\nu}; \qquad H = U_{\text{vac}} \cdot D_{\text{vac}} \cdot U_{\text{vac}}^{\dagger} \pm V_{\text{mat}};$$

$$U_{\text{vac}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \xcancel{\begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix};$$

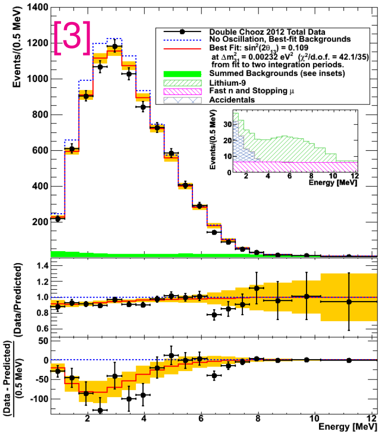
$$D_{\text{vac}} = \frac{1}{2E_\nu}\Big[\operatorname{diag}\left(0,\, \Delta m^2_{21},\, \Delta m^2_{31}\right) + \xcancel{m_1^2 I}\Big]; \qquad V_{\text{mat}} = \sqrt{2}G_F N_e \operatorname{diag}\left(1,\, 0,\, 0\right).$$

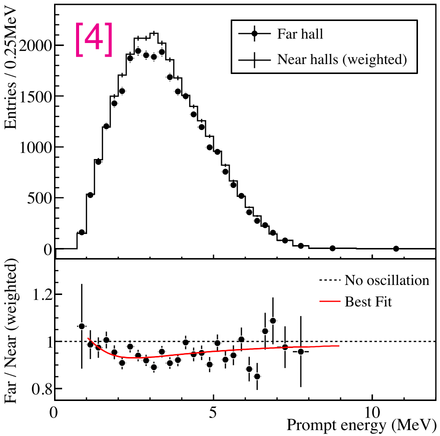
6 parameters $\Longleftrightarrow$ 6 types of experiments

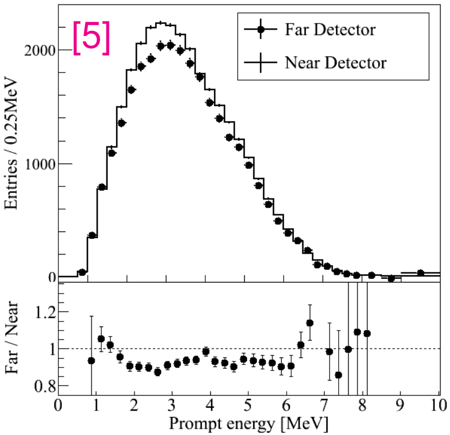
- **SOLAR** sector:
  - – solar experiments (mainly SNO) $\longrightarrow \theta_{12}$
  - – rector VLBL (KamLAND) $\longrightarrow \Delta m^2_{21}$
- **REACT** sector:
  - – rector LBL (Double-Chooz, Daya-Bay, Reno) $\longrightarrow \theta_{13}$
- **ATMOS** sector:
  - – atmospheric experiments (SK) $\longrightarrow \theta_{23}$
  - – accelerator LBL-DIS (Minos $\nu_\mu \to \nu_\mu$) $\longrightarrow \Delta m^2_{31}$
  - – accelerator LBL-APP (Minos $\nu_\mu \to \nu_e$, T2K) $\longrightarrow \delta_{\text{CP}}$

Reactor sector: the 2012 revolution

- Until summer 2011, only CHOOZ [1] and PALO-VERDE [2] **upper limits** available;
- since then: **positive signal** from DOUBLE-CHOOZ [3], DAYA-BAY [4], RENO [5];
- present status: $\underline{\theta_{13} \neq 0 \ @\ 9\sigma}$ after inclusion of the data presented at Neutrino 2012.







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[1] M. Apollonio *et al.* [CHOOZ], Eur. Phys. J. C **27** (2003) 331 [`hep-ex/0301017`].

[2] F. Boehm *et al.* [PALO-VERDE], Phys. Rev. D **64** (2001) 112001 [`hep-ex/0107009`].

[3] M. Ishitsuka [DOUBLE-CHOOZ], talk presented at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

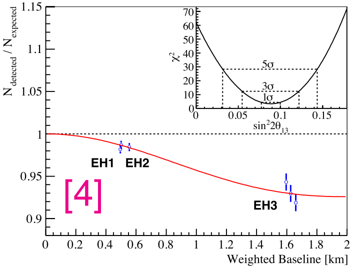
[4] D. Dwyer [DAYA-BAY], talk presented at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

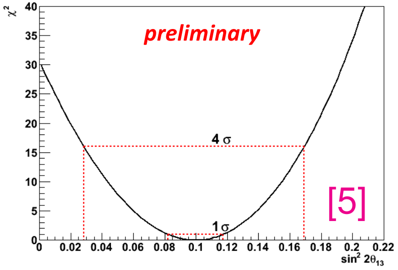
[5] S.H. Seo [RENO], talk presented at Neutrino Telescopes 2013, Venice, Italy, March 11-15, 2013.

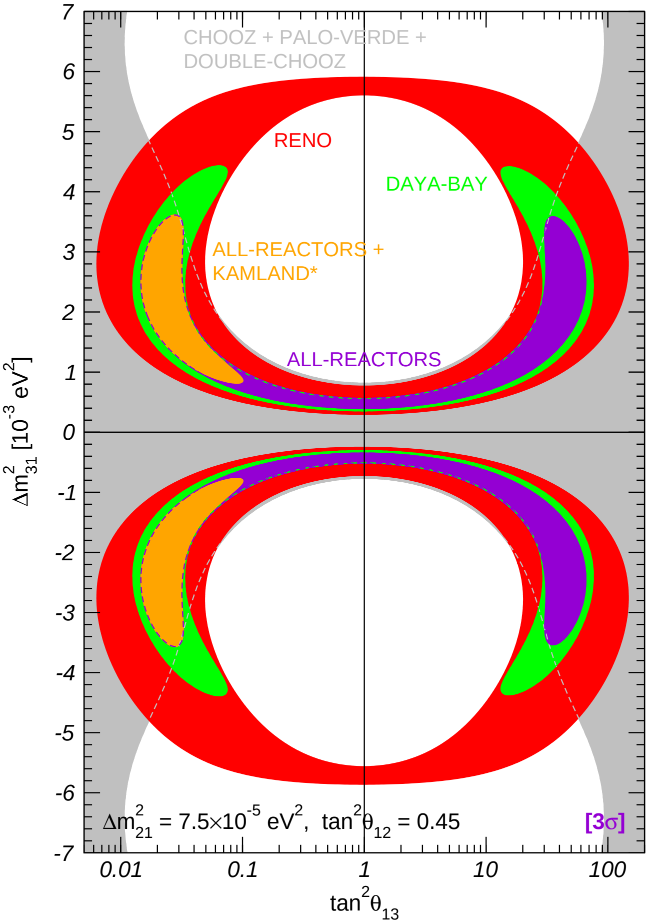
I. Conventional three-neutrino oscillations

Measuring Δm^2_{31} with reactors only

- Sizable deficit at the **far** detector ⇒ oscillations ⇒ **lower** bound on θ_{13} and Δm^2_{31};
- smaller deficit at the **near** detector ⇒ not-too-much oscillations ⇒ **upper** bound on Δm^2_{31};
- KamLAND spectrum ⇒ **upper** bound on θ_{13}.







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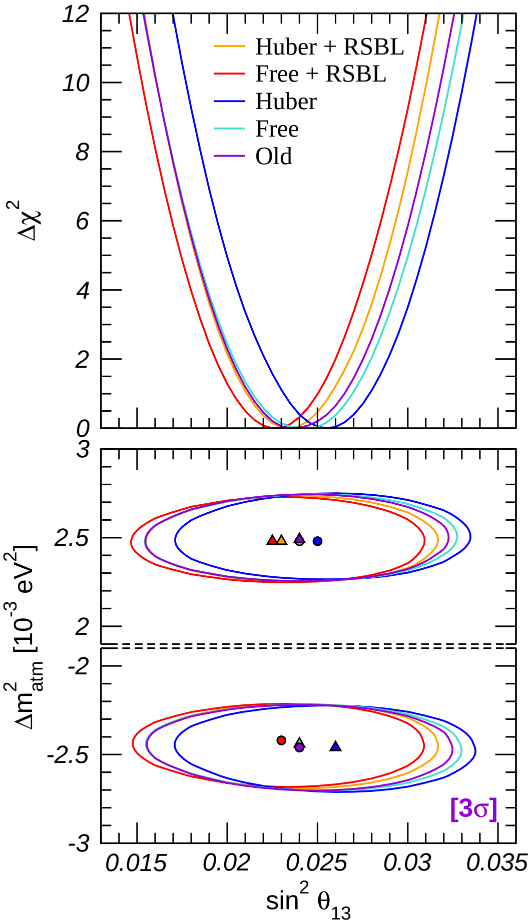
[4] D. Dwyer [DAYA-BAY], talk presented at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

[5] S.H. Seo [RENO], talk presented at Neutrino Telescopes 2013, Venice, Italy, March 11-15, 2013.

Impact of the reactor neutrino fluxes

- Analysis of reactor data require a precise knowledge of the reactor ν fluxes. We follow two approaches:
  - use the flux calculations presented in [7];
  - treat the fluxes as free parameters and fit them;
- The reactor fluxes in [6, 7] are quite **large**, hence they favor **large** suppression ⇒ **larger** θ_{13};
- including reactor short-baseline (RSBL) experiments in the fit [8] results in **smaller** fluxes ⇒ **smaller** θ_{13};
- once RSBL data are included, the specific prior on the reactor fluxes (fixed or free) has little impact;
- θ_{13} uncertainty from fluxes: $\delta(\sin^2\theta_{13}) = \pm 0.002$.



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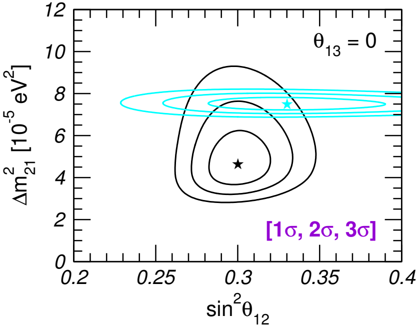
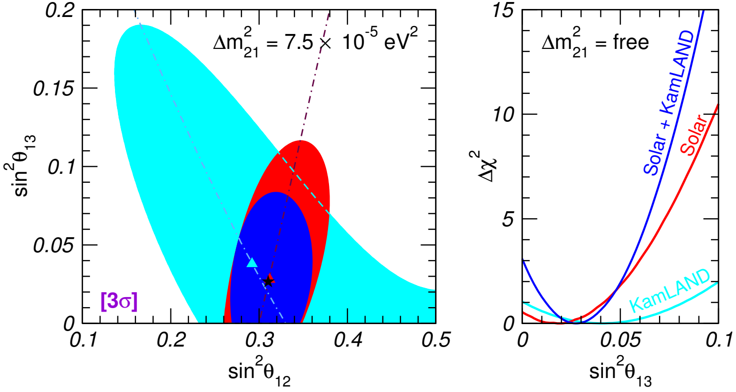
[6] Mueller *et al.*, PRC **83** (2011) 054615 [`arXiv:1101.2663`].
[7] Huber, PRC **84** (2011) 024617 [`arXiv:1106.0687`].
[8] Schwetz *et al.*, NJP **13** (2011) 063004 [`arXiv:1103.0734`].

I. Conventional three-neutrino oscillations

Solar sector: effect of θ_{13} on SOL & KAM data



- For $\theta_{13} = 0$, we have $\sin^2\theta_{12} = \begin{cases} 0.30 \text{ from solar data,} \\ 0.33 \text{ from KamLAND data;} \end{cases}$
- When θ_{13} increases:
  - KamLAND region definitely shifts to smaller θ_{12};
  - solar region slightly moves to larger θ_{12} (high-E data dominate over low-E ones);
- therefore, a non-zero value of θ_{13} reduces the tension between solar and KamLAND data [9, 10];
- new SNO (I+II+III) analysis favor smaller ϕ_{CC}/ϕ_{NC} ⇒ smaller θ_{12} from solar ⇒ tension with KamLAND is increased ⇒ larger θ_{13} is preferred.



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[9] G.L. Fogli *et al.*, Phys. Rev. Lett. **101** (2008) 141801 [`arXiv:0806.2649`].

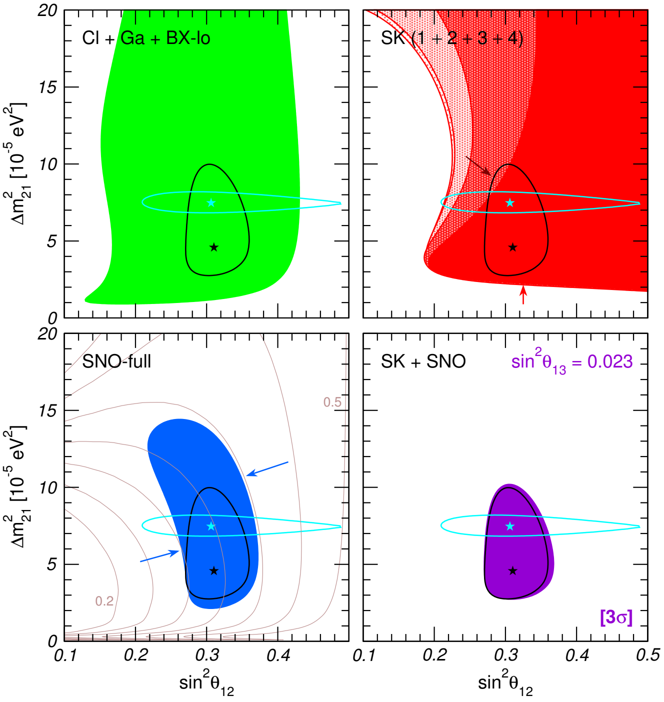
[10] T. Schwetz, M.A. Tortola, J.W.F. Valle, New J. Phys. **10** (2008) 113011 [`arXiv:0808.2016`].

Relevance of solar data in the determination of Δm^2_{21} and θ_{12}

- $P_{ee} = c^4_{13} P_\text{eff} + s^4_{13}$, $\quad i\dfrac{d\vec\nu}{dt} = \left[\dfrac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12}\end{pmatrix} \pm \sqrt{2} G_F N_e \begin{pmatrix} c^2_{13} & 0 \\ 0 & 0 \end{pmatrix}\right]\vec\nu$, $\quad \vec\nu = \begin{pmatrix}\nu_e \\ \nu_a\end{pmatrix}$;
- $\nu_\mu \equiv \nu_\tau \Rightarrow$ no sensitivity to θ_{23} and δ_CP;
- $\Delta m^2_{31} \approx \infty \Rightarrow$ specific Δm^2_{31} value irrelevant;

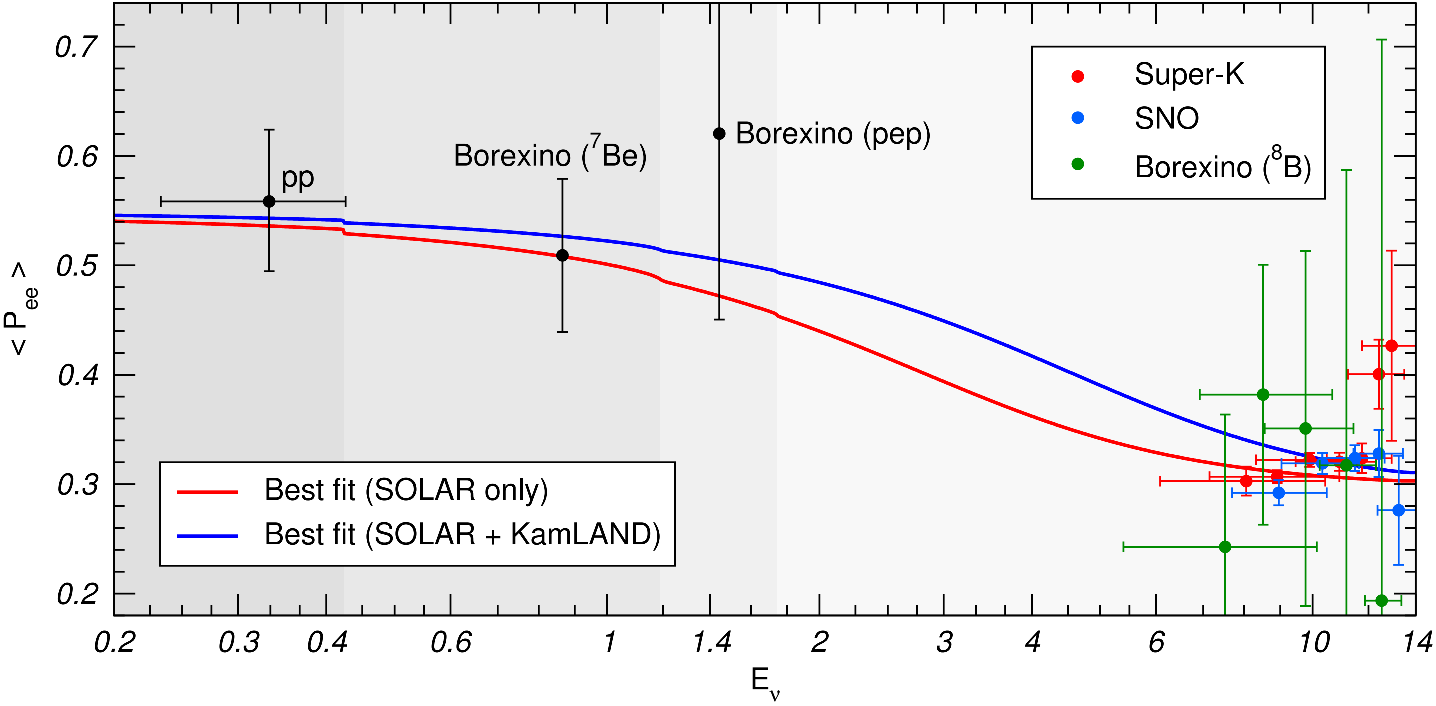
$\Rightarrow$ data only depend on Δm^2_{21}, θ_{12} and θ_{13};

- $P_{ee} \approx \begin{cases} \text{Kam: } \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12} \sin^2 \dfrac{\Delta m^2_{21} L}{4E}\right), \\ \text{low-E: } \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2 2\theta_{12}\right), \\ \text{high-E: } \cos^4\theta_{13} \sin^2\theta_{12}; \end{cases}$
- param's: $\begin{cases} \theta_{12} \text{ dominated by SNO;} \\ \Delta m^2_{21} \text{ dominated by KamLAND;} \end{cases}$
- solar region determined by high-E data, low-E contribution marginal;
- residual tension between solar and KamLAND not statistically significant.



Transition between vacuum and MSW regime in solar data

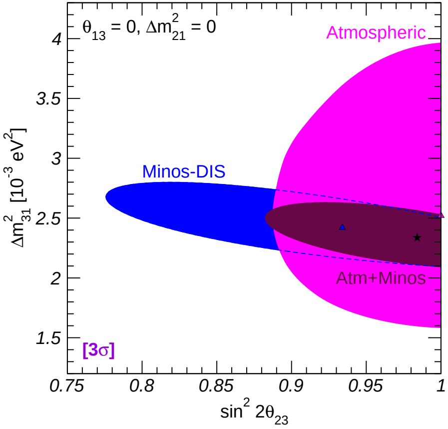
- Tension between solar and KamLAND related to non-observation of low-E turn-up.

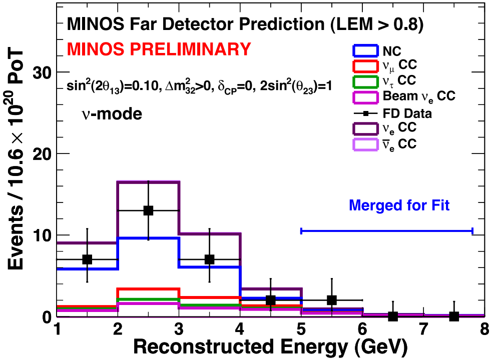


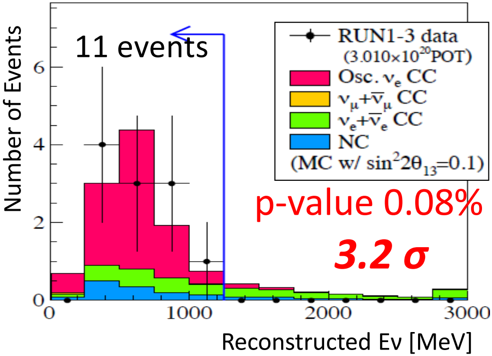
Atmospheric sector: general overview

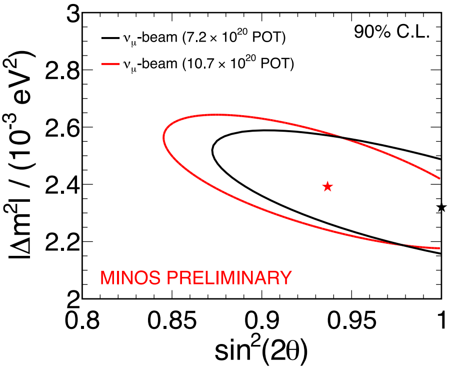
- Δm^2_{31} is now determined by Minos-DIS ($\nu_\mu \to \nu_\mu$) data;
- θ_{23} still dominated by SK atmospheric data;
- θ_{13} & δ_{CP} mostly visible in appearance ($\nu_\mu \to \nu_e$) data; hints of $\theta_{13} \neq 0$ from Minos-APP (2.1σ) and T2K (3.2σ);
- Δm^2_{21} effects visible but only at subleading level;

★ **new result**: Minos disappearance data now slightly favor non-maximal θ_{23} mixing.





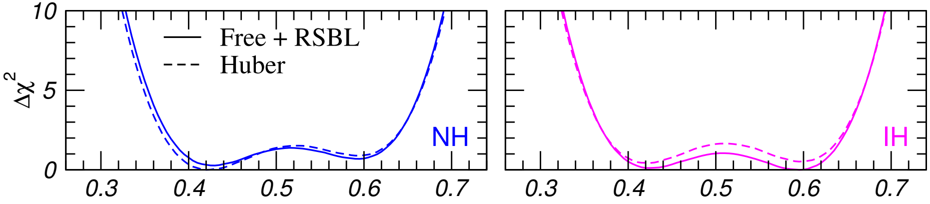


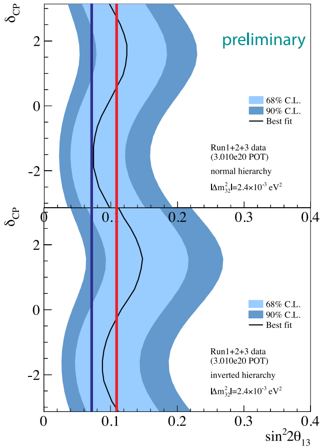


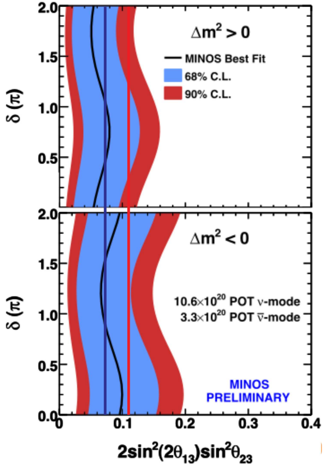
I. Conventional three-neutrino oscillations

Octant discrimination with REA+LBL data

- In principle, REA + LBL-APP + LBL-DIS can fix the octant [11]:
  - REACTORS: measure $\sin^2(2\theta_{\text{rea}}) \equiv \sin^2(2\theta_{13})$;
  - LBL-DIS: measure $\sin^2(2\theta_{\text{dis}})$, with $\sin^2\theta_{\text{dis}} \equiv \cos^2\theta_{13}\sin^2\theta_{23}$;
  - LBL-APP: measure $\sin^2(2\theta_{\text{app}}) \equiv \sin^2(2\theta_{13})\,2\sin^2\theta_{23}$ and δ_{CP};
- in practice, putting explicit numbers:
  - from REACTORS: $\sin^2(2\theta_{13}) \simeq 0.09$;
  - from LBL-DIS: $\sin^2(2\theta_{\text{dis}}) \simeq 0.96$ implies $\sin^2\theta_{23} = 0.41$ or 0.61;
  - hence, REA + LBL-DIS imply $\sin^2(2\theta_{\text{app}}) = 0.074$ or 0.110;
- both values of $\sin^2(2\theta_{\text{app}})$ are in similar agreement with LBL-APP.







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[11] G.L. Fogli *et al.*, Phys. Rev. D **86** (2012) 013012 [`arXiv:1205.5254`].

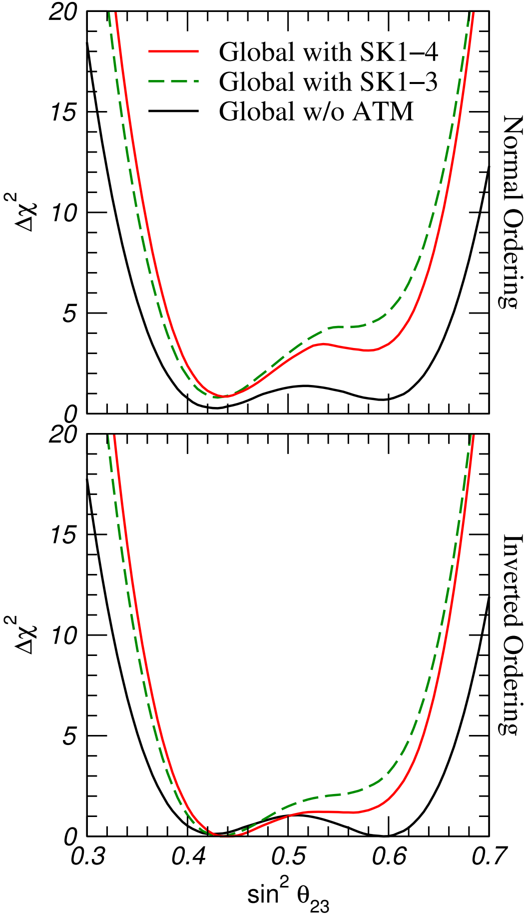
Octant and hierarchy: present status

θ_{23} octant

- Deviation of θ_{23} from maximal mixing **is a physical effect**, which follows from:
  - excess of events in sub-GeV e-like data;
  - zenith distorsion in multi-GeV e-like data;
- the effect is not statistically significant, but it is well understood and clearly visible;
- found also by other Fogli *et al.* [11], but **not** by SK.

Mass hierarchy

- Matter effects enhanced for larger θ_{13} ⇒ sensitive to specific range of θ_{13};
- no meaningful preference for NH or for IH.



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[11] G.L. Fogli *et al.*, PRD **86** (2012) 013012 [`arXiv:1205.5254`].

Neutrino oscillations: where we are

- Global 6-parameter fit (including $\delta_{\rm CP}$):
  - **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + Borexino;
  - **Atmospheric**: SK-1 + SK-2 + SK-3 + SK-4;
  - **Reactor**: KamLAND + Chooz + Palo-Verde + Double-Chooz + Daya-Bay + Reno;
  - **Accelerator**: Minos (DIS+APP) + T2K (DIS+APP);
- best-fit point and 1σ (3σ) ranges:

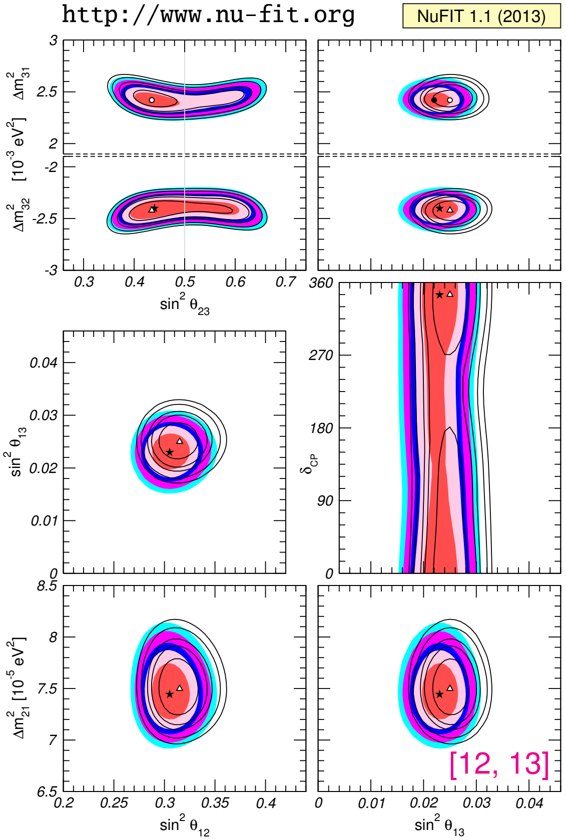
$$\theta_{12} = 33.57\,^{+0.77}_{-0.75}\,\left(^{+2.44}_{-2.19}\right), \quad \Delta m^2_{21} = 7.45\,^{+0.19}_{-0.16}\,\left(^{+0.60}_{-0.47}\right) \times 10^{-5}\ \text{eV}^2\,,$$

$$\theta_{23} = 41.4\,^{+3.5}_{-1.8}\,\left(^{+12.6}_{-4.7}\right), \quad \Delta m^2_{31} = \begin{cases} -2.403\,^{+0.062}_{-0.063}\,\left(^{+0.184}_{-0.193}\right) \times 10^{-3}\ \text{eV}^2\,, \\ +2.421\,^{+0.022}_{-0.023}\,\left(^{+0.191}_{-0.173}\right) \times 10^{-3}\ \text{eV}^2\,, \end{cases}$$

$$\theta_{13} = 8.75\,^{+0.42}_{-0.44}\,\left(^{+1.21}_{-1.46}\right), \quad \delta_{\rm CP} = 341\,^{+58}_{-46}\ \text{(any)}\,;$$

- neutrino mixing matrix:

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.515 \to 0.581 & 0.127 \to 0.173 \\ 0.218 \to 0.533 & 0.430 \to 0.719 & 0.591 \to 0.800 \\ 0.222 \to 0.534 & 0.431 \to 0.720 & 0.582 \to 0.793 \end{pmatrix}.$$



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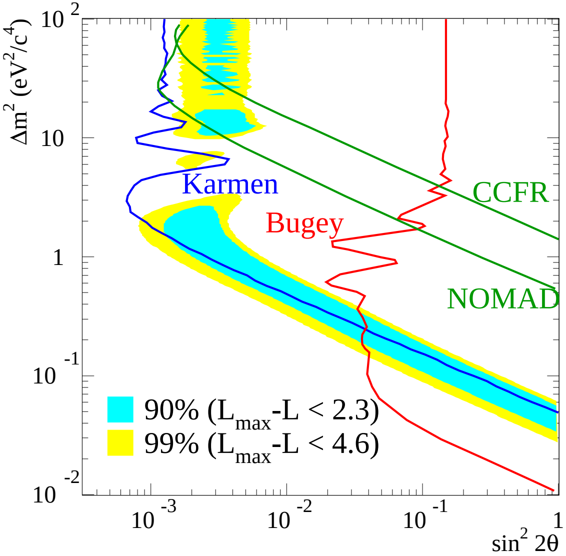
[12] M.C. Gonzalez-Garcia *et al.*, JHEP **12** (2012) 123 [`arXiv:1209.3023`].

[13] M.C. Gonzalez-Garcia *et al.*, NuFIT 1.1 (2013), `http://www.nu-fit.org`.

The LSND problem

- LSND observed $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam ($E_\nu \sim 30$ MeV, $L \simeq 35$ m);
- Karmen did not confirm the claim, but couldn't fully exclude it either;
- the signal is compatible with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations provided that $\Delta m^2 \gtrsim 0.1$ eV^2;
- on the other hand, other data give (at 3σ):

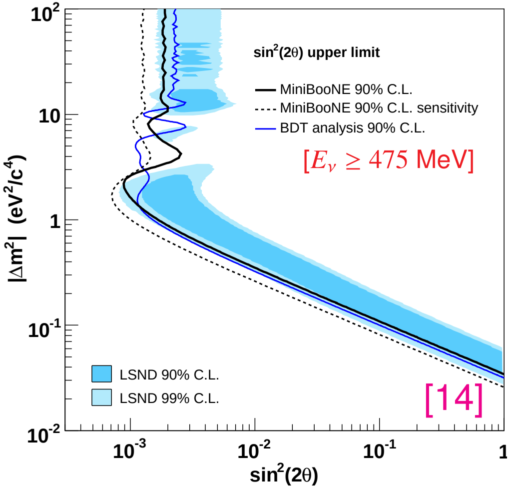
$$\Delta m^2_{\text{SOL}} \simeq 7.5 \pm 0.6 \times 10^{-5}\ \text{eV}^2\,,$$
$$\left|\Delta m^2_{\text{ATM}}\right| \simeq 2.4 \pm 0.3 \times 10^{-3}\ \text{eV}^2\,;$$



- in order to explain LSND with mass-induced neutrino oscillations one needs *at least one more* neutrino mass eigenstate;
- to check the LSND claim once and for all, the MiniBooNE experiment was built, with very different E_ν and L but similar L/E_ν.

MiniBooNE results: neutrino data

- Statistics: 5.58 (2007) $\to$ 6.46 (2008) $\times 10^{20}$ POT, then just improved analysis;
- is ν signal compatible with 2ν oscillations? $\begin{cases} \text{2007: } P_{\text{osc}} \simeq 1\% \Rightarrow \text{no it isn't [14];} \\ \text{2012: } P_{\text{osc}} \simeq 6\% \Rightarrow \text{maybe it is [15];} \end{cases}$
- do MB ν data rule out the LSND $\bar{\nu}$ signal? 2007: yes [14]; 2012: not really [15].



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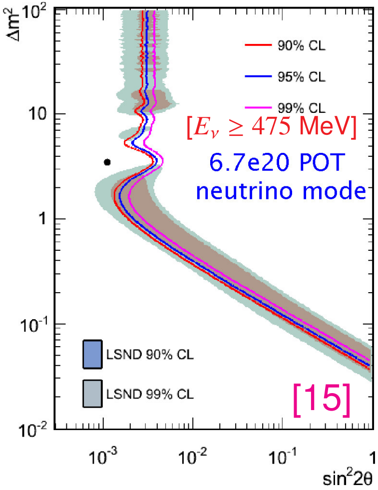

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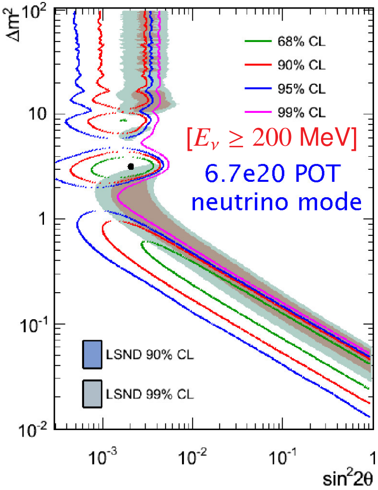

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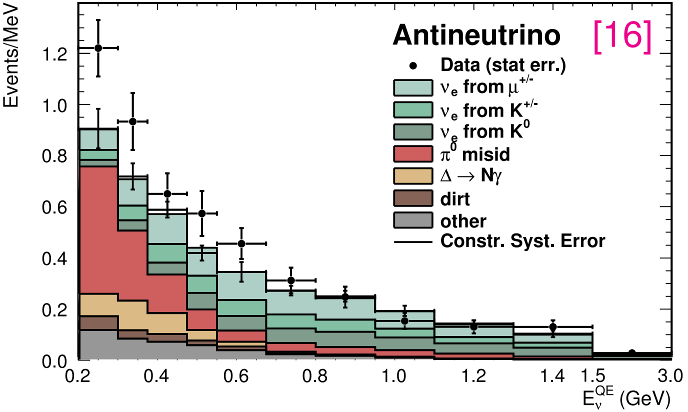
[14] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], Phys. Rev. Lett. **98** (2007) 231801 [`arXiv:0704.1500`].

[15] C. Polly, talk at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

MiniBooNE results: antineutrino data

- New data presented at Neutrino 2012, statistics doubled ($\rightarrow 11.27 \times 10^{20}$ POT) [15];
- compatibility with ν data: $\begin{cases} \text{low-energy excess increased} \Rightarrow \text{better agreement;} \\ \text{mid-energy excess reduced} \Rightarrow \text{better agreement;} \end{cases}$
- is $\bar{\nu}$ signal compatible with 2ν oscillations? $P_{\text{osc}} = 67.5\% \Rightarrow$ definitely yes [15, 16];
- is MB-$\bar{\nu}$ signal compatible with LSND? Yes, irrespective of the energy threshold.



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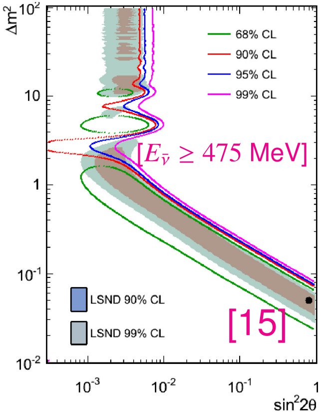

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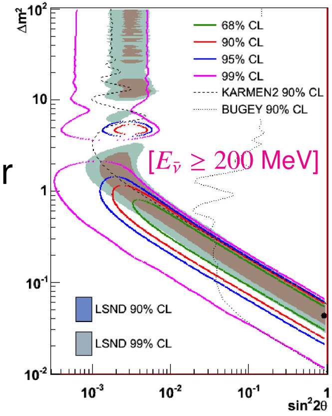

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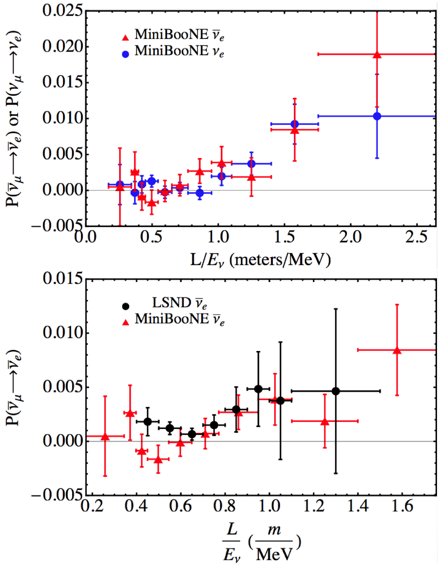
[15] C. Polly, talk at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

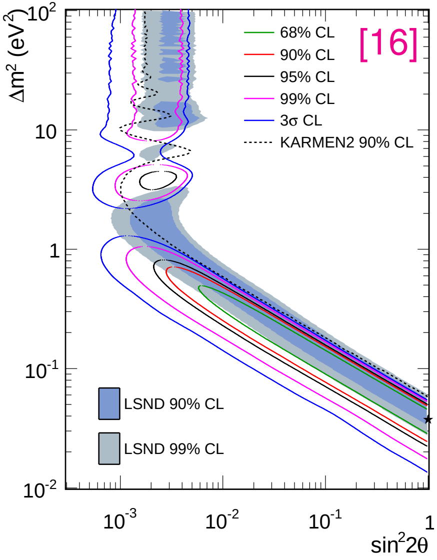
[16] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], `arXiv:1207.4809` [hep-ex].

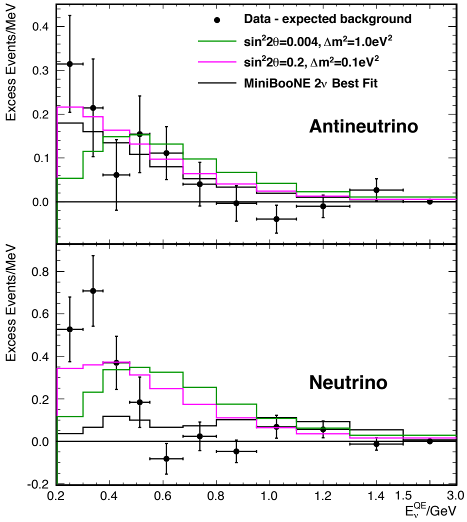
II. Models with extra sterile neutrinos

MiniBooNE results: global $\nu + \bar{\nu}$ appearance

- MiniBooNE ν and $\bar{\nu}$ no longer in open disagreement with LSND;
- however, dramatic change in interpretation **not** linked to dramatic change in data;
- problems still there ($P_{\text{osc}} \simeq 6.7\%$ [16]).







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[16] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], `arXiv:1207.4809` [hep-ex].

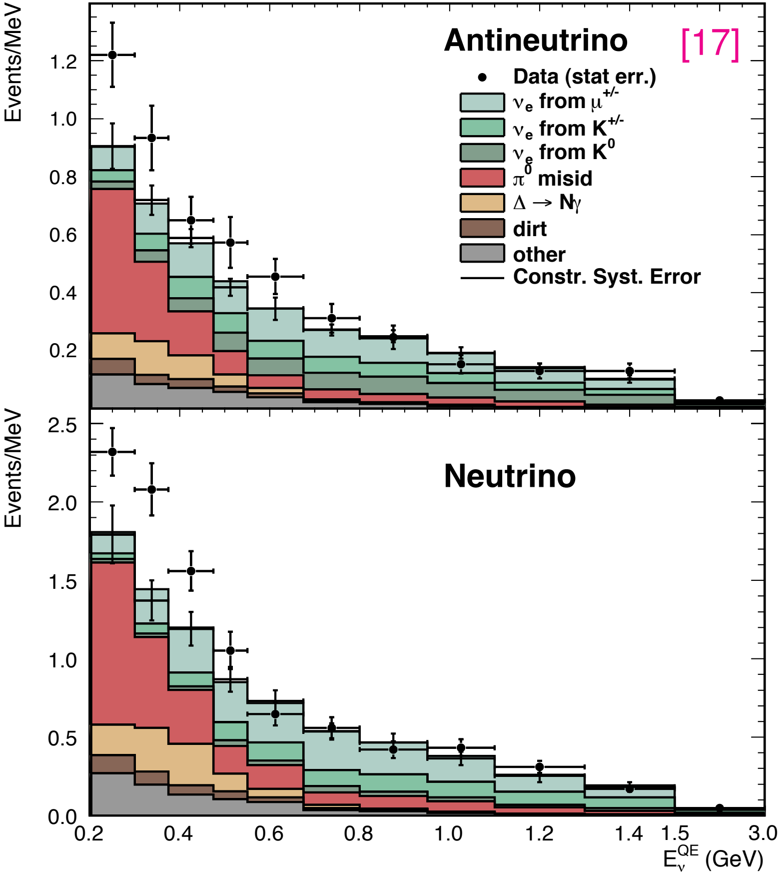
II. Models with extra sterile neutrinos

The MiniBooNE excess

- MiniBooNE observed an overall 3.8σ excess, mostly at low energy [17];
- although no longer *"in open disagreement"*, ν and $\bar{\nu}$ signals are not really equivalent either. For example:

$$P_{2\nu} = \begin{cases} 6.1\% & \text{for } \nu; \\ 67.5\% & \text{for } \bar{\nu}; \end{cases}$$

- former omission of low-energy ν bins ($E_\nu^{\text{QE}} < 475$ MeV) based on the hypothesis of **two-flavor oscillations**;
- is it possible to do something better about low-energy data in **more sophisticated** models?



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[17] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], Phys. Rev. Lett. **110** (2013) 161801 [`arXiv:1303.2588`].

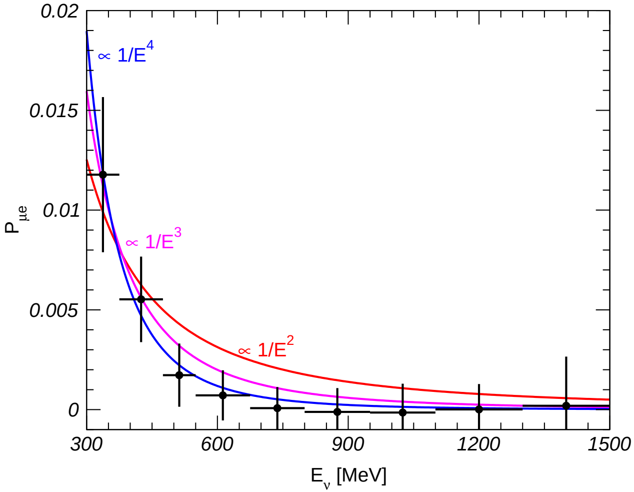
Explaining the MiniBooNE excess with two sterile neutrinos

- With *one* extra sterile neutrino, m_4:

$$P_{\mu e}^{4\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\phi_{41} \quad \text{with} \quad \phi_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}\,;$$

- for large energy $P_{\mu e}^{4\nu}$ drops as $1/E^2$;
- however, the low-energy MB excess is much sharper ($\sim 1/E^4$);

⇒ **it is very hard to account for the MB excess with only one extra sterile neutrino.**



- On the other hand, with *two* extra neutrinos, m_4 and m_5:

$$P_{\mu e}^{5\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2\phi_{51} + 8|U_{e4}U_{e5}U_{\mu 4}U_{\mu 5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} - \delta)\,;$$

- terms of order $1/E^2$ cancel if $\delta = \pi$ and $|U_{e4}\, U_{\mu 4}|\Delta m_{41}^2 = |U_{e5}\, U_{\mu 5}|\Delta m_{51}^2$;

⇒ **with two extra sterile states it is possible to fit the MB low-energy excess** [18].

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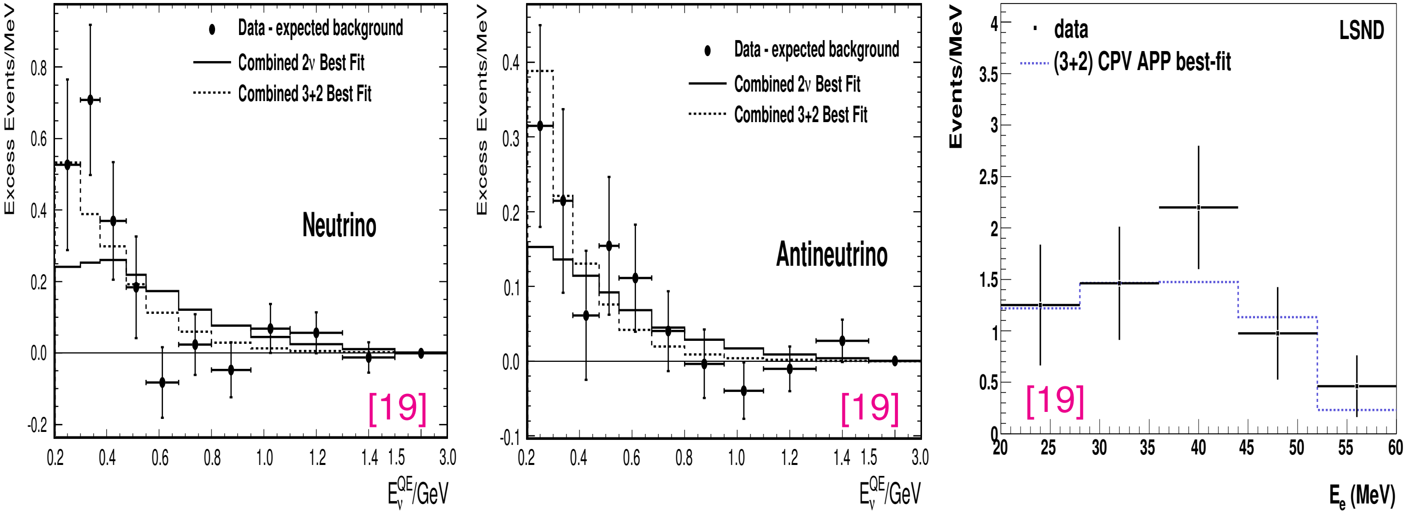
[18] M. Maltoni, T. Schwetz, Phys. Rev. **D76** (2007) 093005 [`arXiv:0705.0107`].

Reconciling MiniBooNE and LSND in (3+2) models



- **Trick**: use the CP phase $\delta = \arg(U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*)$ to differentiate ν (MB) from $\bar\nu$ (LSND):

$$P_{\mu e}^{5\nu} = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu5}|^2 \sin^2\phi_{51} + 8|U_{e4}U_{e5}U_{\mu4}U_{\mu5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} - \delta)\,;$$

- note that $\delta = \pi + \epsilon$ and $|U_{e4}\, U_{\mu4}|\Delta m^2_{41} \approx |U_{e5}\, U_{\mu5}|\Delta m^2_{51}$ to suppress MB probability [18].

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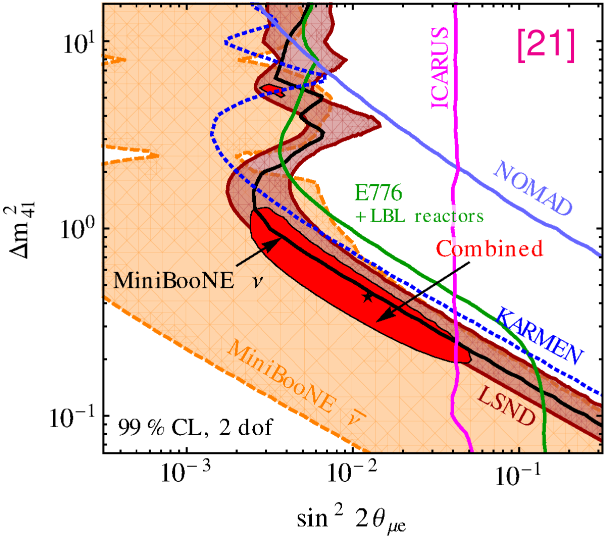
[18] M. Maltoni, T. Schwetz, Phys. Rev. **D76** (2007) 093005 [`arXiv:0705.0107`].

[19] J.M. Conrad, W.C. Louis, M.H. Shaevitz, Ann. Rev. Nucl. Part. Sci. **63** (2013) 45 [`arXiv:1306.6494`].

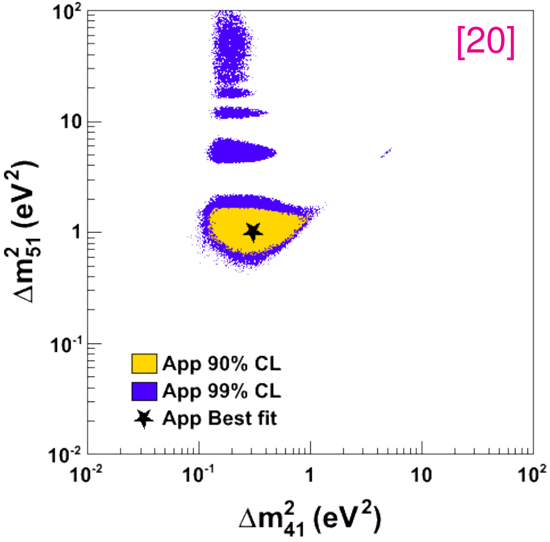
II. Models with extra sterile neutrinos

Fitting all $\nu_\mu \to \nu_e$ appearance data: (3+1) vs (3+2) models

(3+1)



(3+2)



- $\chi^2_{\text{min}}/\text{dof} = 87.9/(68-2) \Rightarrow \text{GOF} = 3.7\%$;
- $\chi^2_{\text{min}}/\text{dof} = 72.7/(68-5) \Rightarrow \text{GOF} = 19\%$;
- the improvement of (3+2) over (3+1) is $\chi^2_{(3+1),\text{app}} - \chi^2_{(3+2),\text{app}} = 15.2$ [21].

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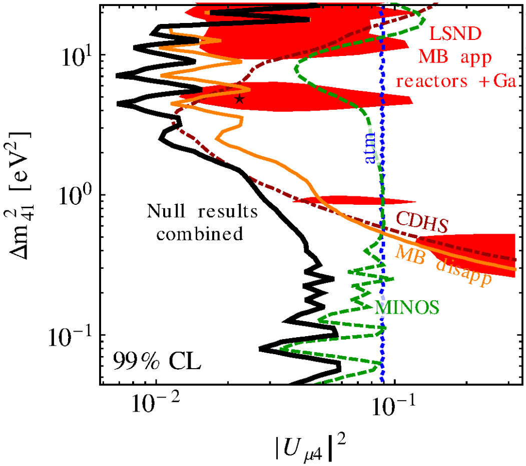
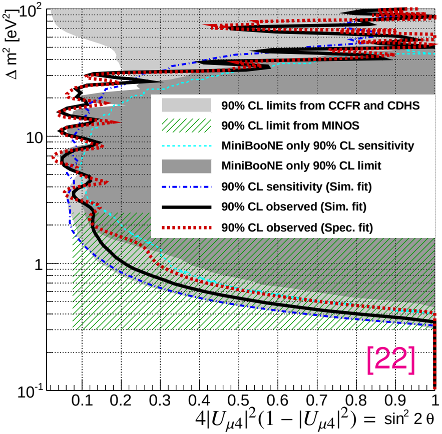
[20] J.M. Conrad *et al.*, Adv. High Energy Phys. **2013** (2013) 163897 [`arXiv:1207.4765`].

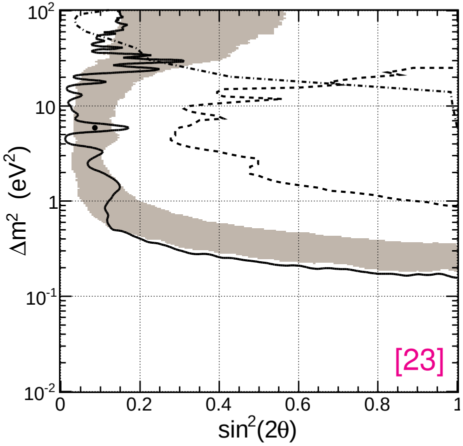
[21] J. Kopp, P.A.N. Machado, M. Maltoni, T. Schwetz, JHEP **05** (2013) 050 [`arXiv:1303.3011`].

ν_μ disappearance: combined MiniBooNE & SciBooNE analysis

- In addition to atmospheric and MINOS data, a combined analysis of MiniBooNE & SciBooNE data has recently been presented, for both ν [22] and $\bar{\nu}$ [23];
- no hint of ν_μ disappearance has been found in either case, thus strengthening the bound in the large-Δm^2 region ($\Delta m^2_{41} \gtrsim 1$ eV^2).







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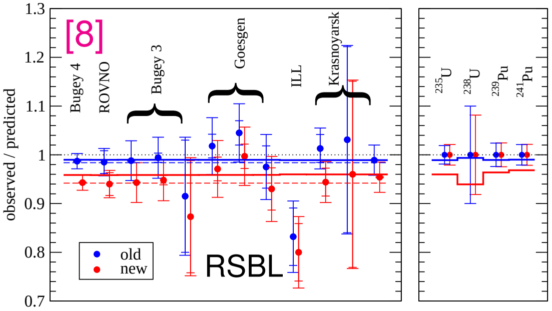
[22] K.B.M. Mahn *et al.* [SciBooNE & MiniBooNE collab], Phys. Rev. D **85** (2012) 032007 [`arXiv:1106.5685`].

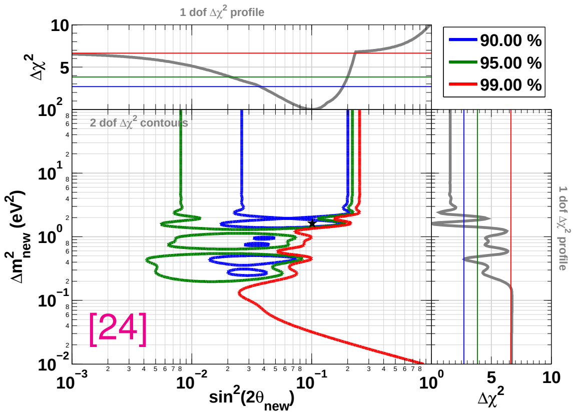
[23] G. Cheng *et al.* [MiniBooNE & SciBooNE collab], Phys. Rev. D **86** (2012) 052009 [`arXiv:1208.0322`].

ν_e disappearance: the reactor anomaly

- In [6, 7] the reactor $\bar{\nu}$ fluxes was reevaluated;
- the new calculations result in a small increase of the flux by about **3.5%**;
- hence, **all** reactor short-baseline (RSBL) finding no evidence are actually observing a deficit;
- this deficit **could** be interpreted as being due to SBL neutrino oscillations;
- no visible dependence on $L \Rightarrow \Delta m^2 \gtrsim 1~\text{eV}^2$;

⇒ new “hint” in favor of SBL oscillations, **independent** of LSND & MiniBooNE.





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[6] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [`arXiv:1101.2663`].

[7] P. Huber, Phys. Rev. C **84** (2011) 024617 [`arXiv:1106.0687`].

[8] T. Schwetz, M. Tortola, J.W.F. Valle, New J. Phys. **13** (2011) 063004 [`arXiv:1103.0734`].

[24] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [`arXiv:1101.2755`].

II. Models with extra sterile neutrinos

Disappearance data: present status

- As expected, the new reactor fluxes lead to a clear preference for $|U_{e4}|^2 \neq 0$;
- however, the upper bound on $|U_{e4}|^2$ is **not** dramatically reduced;
- combined with the limit on $|U_{\mu 4}|^2$, this implies an upper limit on $|U_{e4} U_{\mu 4}|$ $\Rightarrow$ tension with appearance data;
- for (3+2) models the situation is qualitatively the same, except that $|U_{e5}|$ and $|U_{\mu 5}|$ are also involved.

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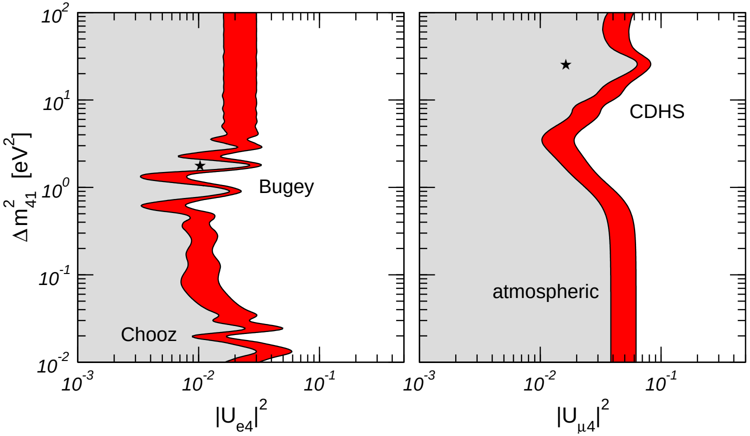
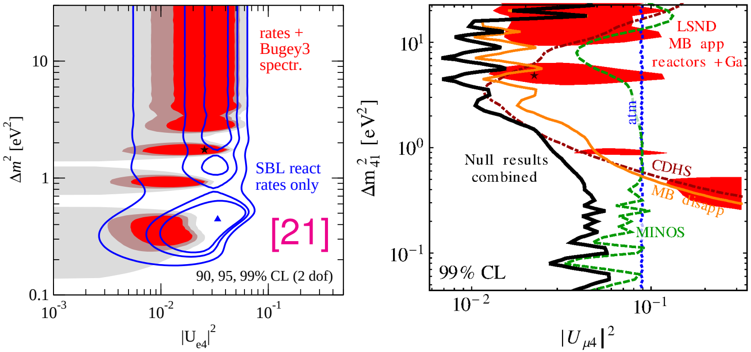
[21] J. Kopp, P.A.N. Machado *et al.*, JHEP **05** (2013) 050 [`arXiv:1303.3011`].

Old reactor fluxes



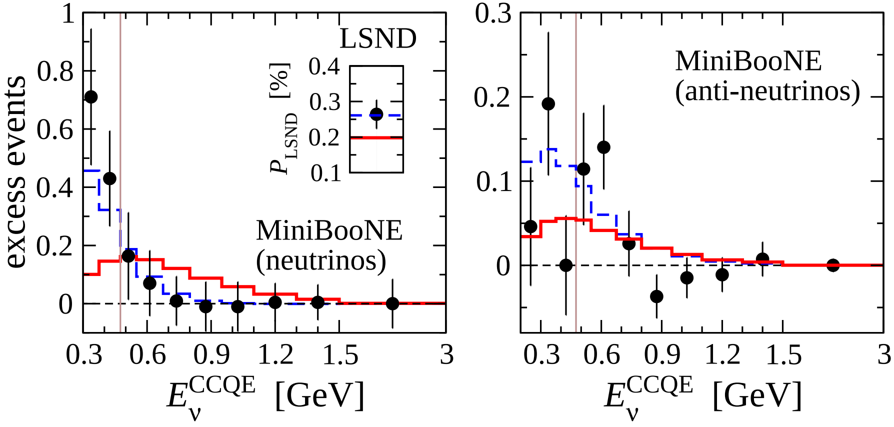
New reactor fluxes & MINOS

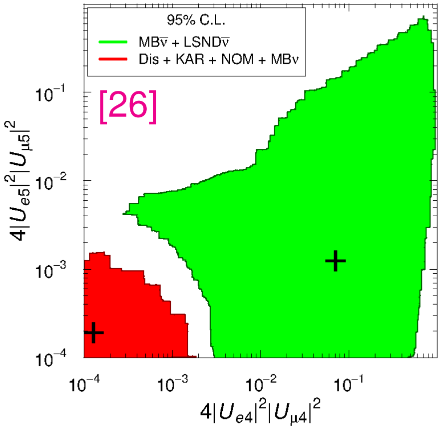


II. Models with extra sterile neutrinos

Status of (3+2) models from global data

- (3+2) models suffer from severe tension between APP and DIS data: PG=0.53% [25];
- the situation worsen when MiniBooNE low-E data are included: PG=0.0035% [21];
- (1+3+1) works slightly better (PG=0.21% [21]), but has stronger problems with cosmology since the sum of neutrino masses ($\sum m_\nu$) is larger.





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[21] J. Kopp, P.A.N. Machado, M. Maltoni, T. Schwetz, JHEP **05** (2013) 050 [`arXiv:1303.3011`].

[25] J. Kopp, M. Maltoni and T. Schwetz, Phys. Rev. Lett. **107** (2011) 091801 [`arXiv:1103.4570`].

[26] C. Giunti, M. Laveder, Phys. Rev. D **84** (2011) 073008 [`arXiv:1107.1452`].

Summary

- Most of the present data from solar, atmospheric, reactor and accelerator experiments are well explained by the 3ν oscillation hypothesis;
- however, a few experiments exhibit deviations from the “standard” 3ν scenario:
  - LSND observed an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam;
  - MiniBooNE mildly “confirm” this excess: $\begin{cases}\text{in both } \bar{\nu} \text{ mode and } \nu \text{ mode at low-E;} \\ \text{only in } \bar{\nu} \text{ mode at mid-E;}\end{cases}$
  - new fission $\bar{\nu}$ fluxes suggests that **all** SBL reactor experiments are observing a deficit;
- however, these “hints” for sterile neutrinos are **not** in agreement among them:
  - MiniBooNE asymmetry in $\nu/\bar{\nu}$ requires CP violation, hence at least **two sterile ν’s**;
  - (3+2) models reconcile APP data, but DIS ones still show strong tension;
  - attempts to include the low-E excess in the game further increase such tension;
  - new reactor fluxes reduce tension with DIS data only marginally;

⇒ **we are still quite far from the solution of the LSND puzzle!**