Sterile neutrinos

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What is ν?
Invisibles 2012 and Alexei Smirnov Fest

GGI, Firenze, Italy – June 28th, 2012

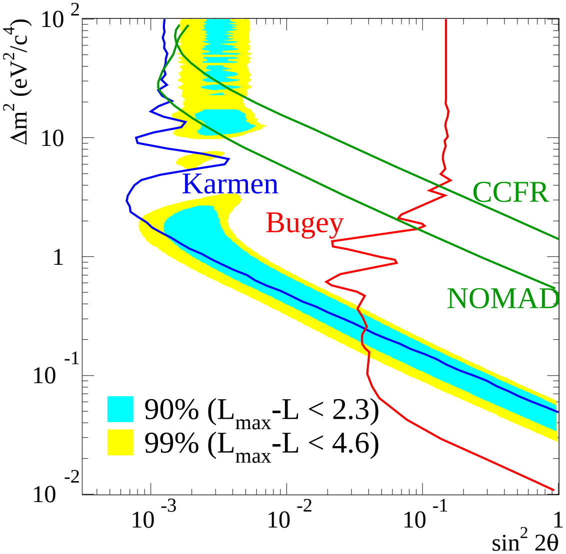
I. The LSND experiment and four-neutrino models

II. MiniBooNE and models with two sterile neutrinos

III. A word on MiniBooNE data after Neutrino 2012

Summary

The LSND problem



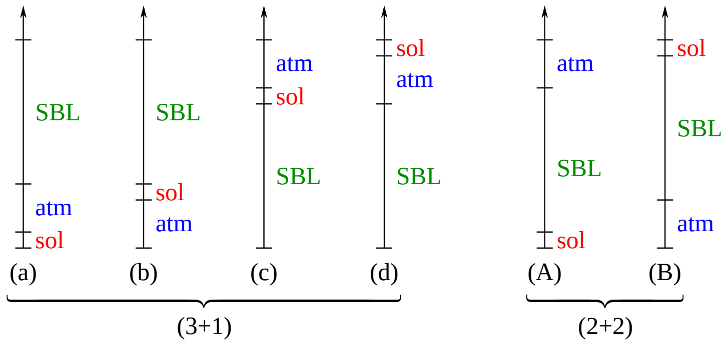
- LSND observed $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam ($E_\nu \sim 30$ MeV, $L \simeq 35$ m);
- Karmen did not confirm the claim, but couldn't fully exclude it either;
- the signal is compatible with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations provided that $\Delta m^2 \gtrsim 0.1$ eV^2;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

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

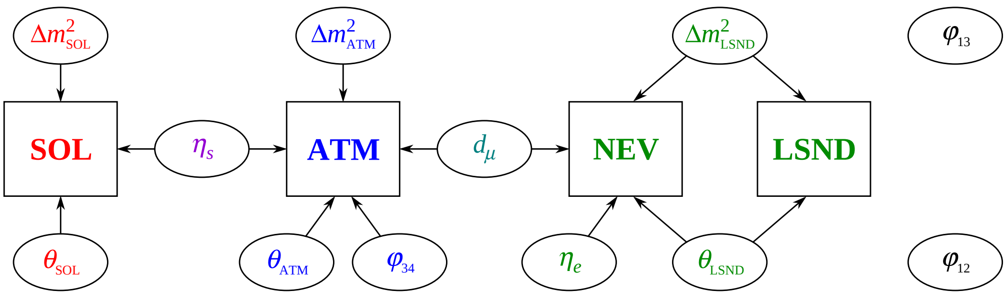
- in order to explain LSND with mass-induced neutrino oscillations one needs *at least one more* neutrino mass eigenstate;
- **WARNING: having enough Δm^2 is not enough. To make sure that the model works, one has to check explicitly that all the experiments can be fitted simultaneously.**

Four neutrino mass models

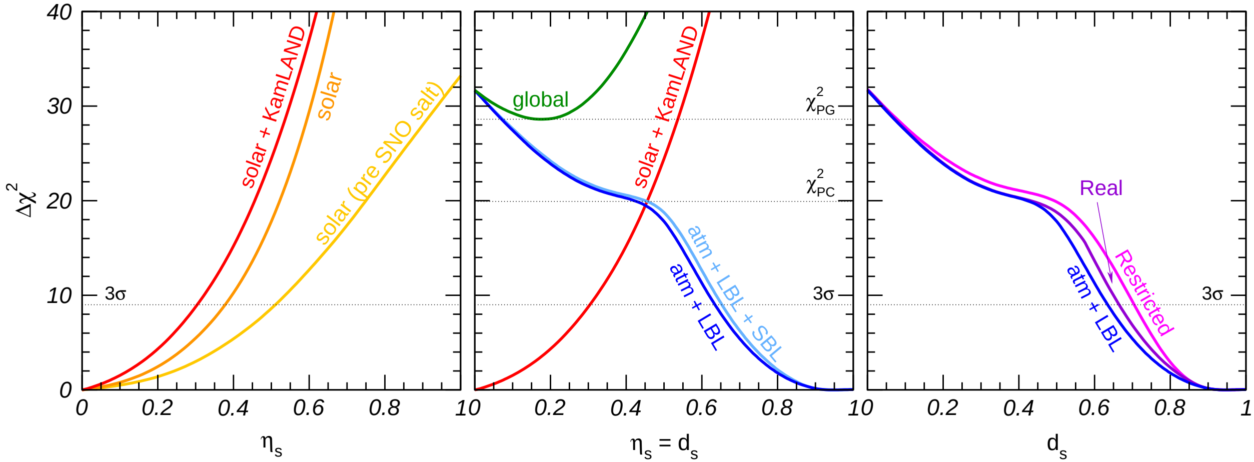
- Approximation: $\Delta m^2_{\text{SOL}} \ll \Delta m^2_{\text{ATM}} \ll \Delta m^2_{\text{LSND}} \Rightarrow$ 6 different mass schemes:



- Total: 3 Δm^2, 6 angles, 3 phases. Different set of experimental data *partially decouple*:



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



- in (2+2) models, fractions of ν_s in solar (η_s) and atmos ($1 - d_s$) add to one $\Rightarrow$ $\boxed{\eta_s = d_s}$;
- 3σ allowed regions $\eta_s \le 0.31$ (solar) and $d_s \ge 0.63$ (atmos) do not overlap; superposition occurs only above 4.5σ ($\chi^2_{\text{PC}} = 19.9$);
- the χ^2 increase from the combination of solar and atmos data is $\chi^2_{\text{PG}} = 28.6$ (1 dof), corresponding to a PG $= 9 \times 10^{-8}$ [1].

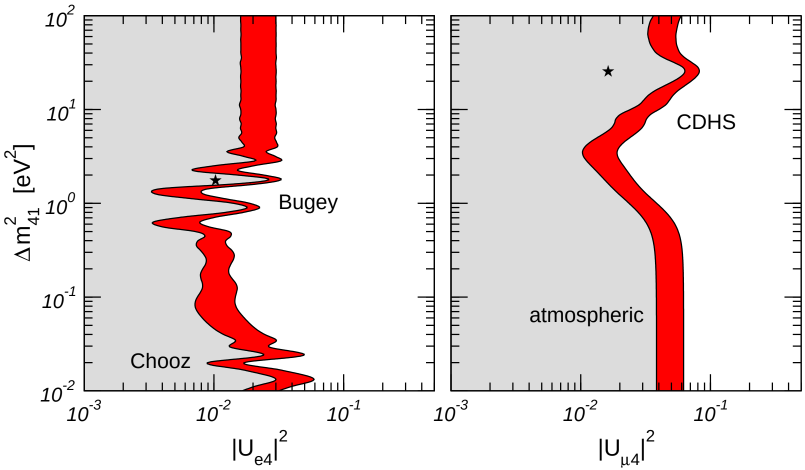
[1] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. **B643** (2002) 321 [hep-ph/0207157].

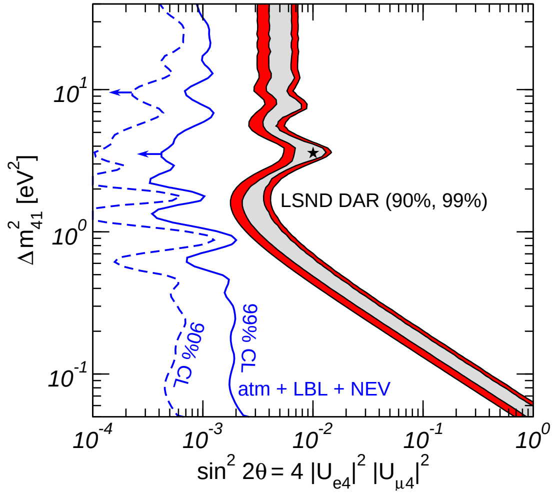
(3+1): tension between LSND and short-baseline data

- In (3+1) schemes the SBL *appearance* probability is effectively 2ν oscillations:

$$P_{\mu e} = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2_{41} L}{4E}, \qquad \sin^2 2\theta = 4\,|U_{e4}|^2\,|U_{\mu 4}|^2\,;$$

- *disappearance* experiments bound $|U_{e4}|^2$ and $|U_{\mu 4}|^2$;



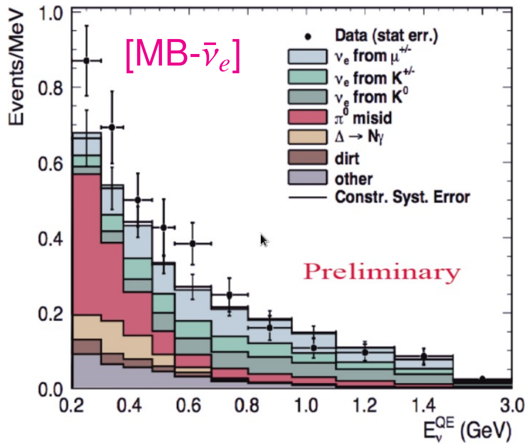


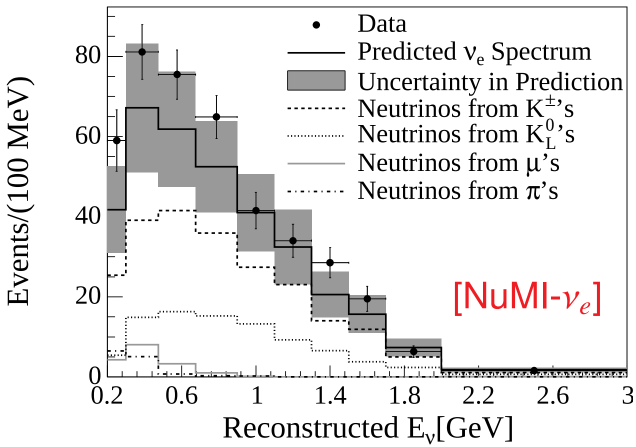
- LSND is in conflict [1]:
  - with other *appearance* experiments (Karmen & Nomad);
  - with all *disappearance* exp's.

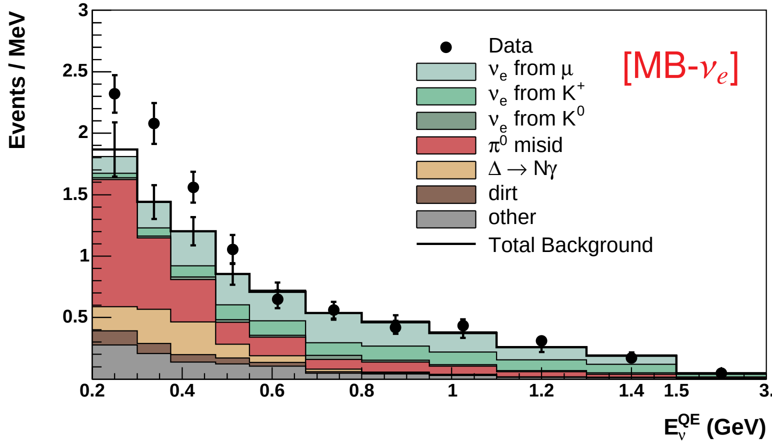
[1] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. **B643** (2002) 321 [hep-ph/0207157].

The MiniBooNE experiment (≤ 5/2012)

- E_ν and L very different from LSND (but similar L/E_ν) $\Rightarrow$ can check **the oscillation solution** of the LSND problem, **not** the signal itself;
- very peculiar results:
  - strong low-energy excess in ν_e, mild in $\bar\nu_e$;
  - mild mid-energy excess in $\bar\nu_e$, but not in ν_e.

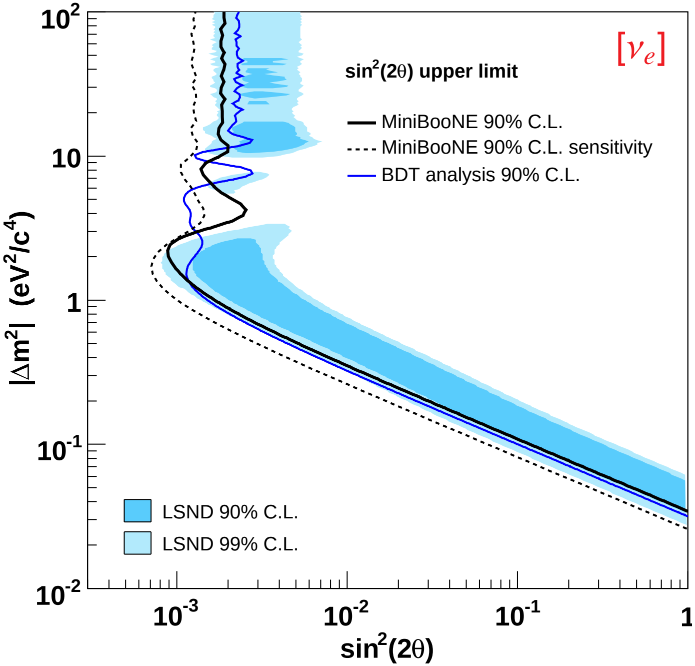


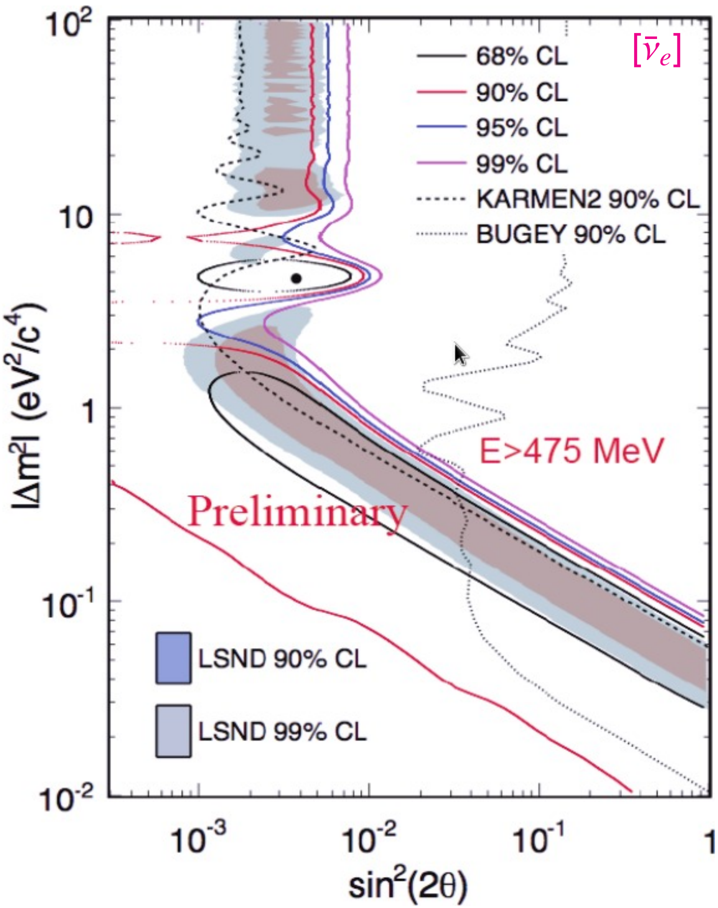




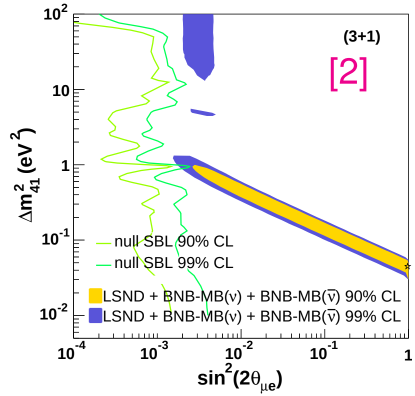
LSND vs MiniBooNE in (3+1)

- ν_e: no signal $\Rightarrow$ **excludes** LSND;
- $\bar{\nu}_e$: signal $\Rightarrow$ **mildly confirms** LSND.





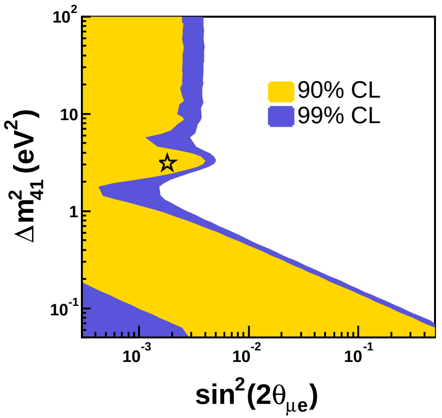
Status of (3+1) models after MiniBooNE



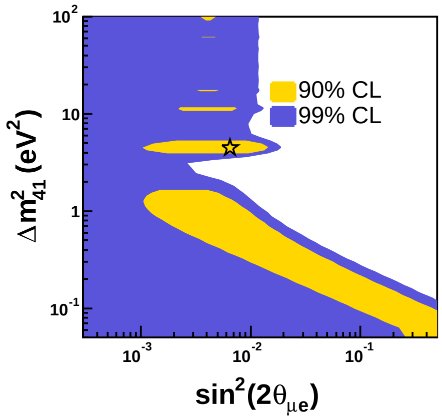
- (3+1) four-neutrino schemes fail because:
  - can't reconcile *appearance* and *disappearance* data;
  - can't explain the different ν_e (MB) and $\bar{\nu}_e$ (LSND) results;
  - can't account for the low-energy ν_e event excess in MB.

⇒ **(3+1) models are ruled out as explanation of SBL data.**

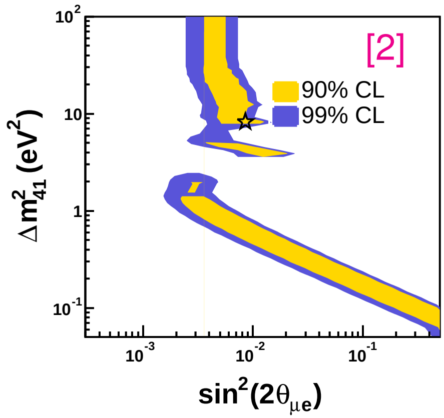
BNB-MB(ν)



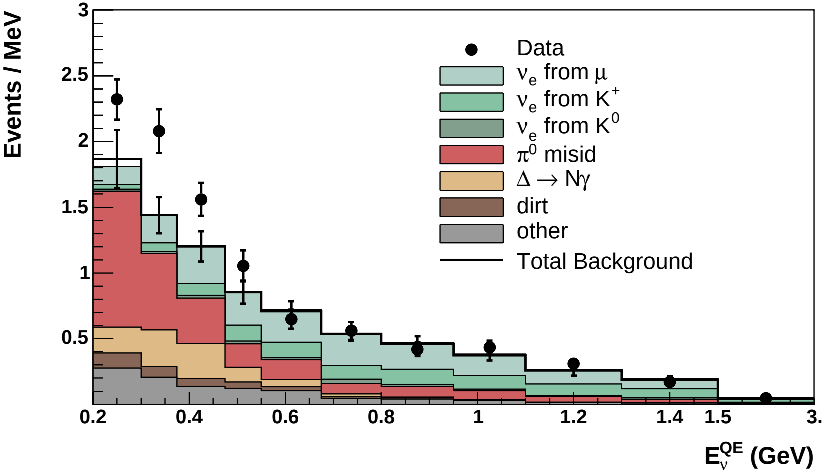
BNB-MB($\bar{\nu}$) [OLD]



LSND



[2] G. Karagiorgi *et al.*, Phys. Rev. **D80** (2009) 073001 [arXiv:0906.1997].



The MiniBooNE excess

With the analysis cuts set, a signal-blind test of data-MC agreement in the signal region was performed. The full two-neutrino oscillation fit was done in the range $300 < E_\nu^{QE} < 3000$ MeV and, with no information on the fit parameters revealed, the sum of predicted background and simulated best-fit signal was compared to data in several variables, returning only the χ^2. While agreement was good in most of the comparisons, the E_{vis} spectrum had a χ^2 probability of only 1%. This triggered further investigation of the backgrounds, focusing on the lowest energies where ν_μ-induced backgrounds, some of which are difficult to model, are large. As part of this study, one more piece of information from the signal region was released: unsigned bin-by-bin fractional discrepancies in the E_{vis} spectrum. While ambiguous, these reinforced suspicions about the low-energy region. Though we found no specific problems with the background estimates, it was found that raising the minimum E_ν^{QE} of the fit region to 475 MeV greatly reduced a number of backgrounds with little impact on the fit's sensitivity to oscillations. We thus performed our oscillation fits in the energy range $475 < E_\nu^{QE} < 3000$ MeV and opened the full data set.

- MiniBooNE observed a 3.0σ excess at low-E [3];
- this excess is *incompatible* with 2ν oscillations;
- therefore, data with $E_\nu^{QE} < 475$ MeV have not been used to check LSND.

⇒ Omission of low-energy bins in based on the hypothesis of **two-flavor oscillations**!

- Is it possible to do something about these data in **more sophisticated** models?

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

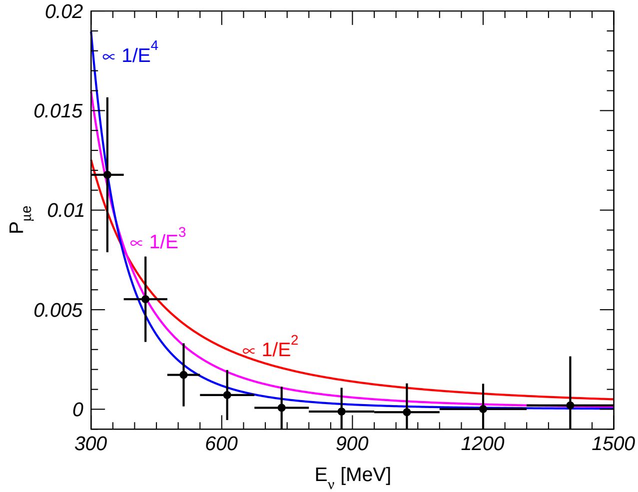
Explaining the MiniBooNE excess with two sterile neutrinos

- With *one* extra sterile neutrino, m_4:

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

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

⇒ **it is not possible 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:

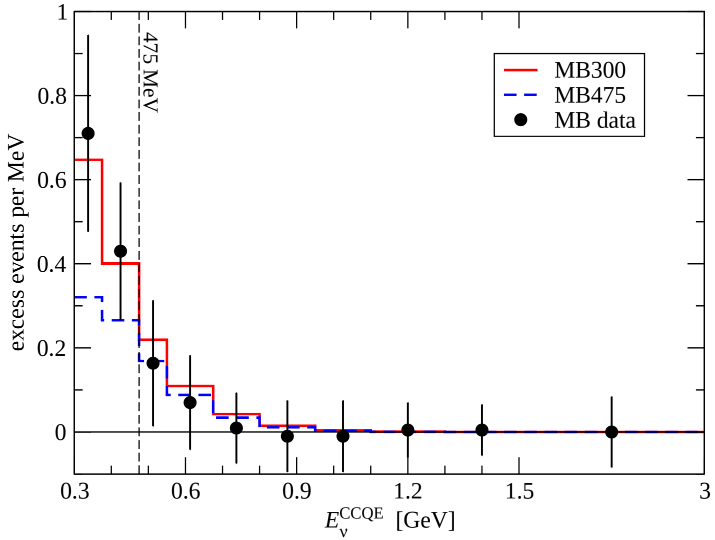
$$P^{5\nu}_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2\phi_{51} + 8|U_{e4}U_{e5}U_{\mu 4}U_{\mu 5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} - \delta);$$

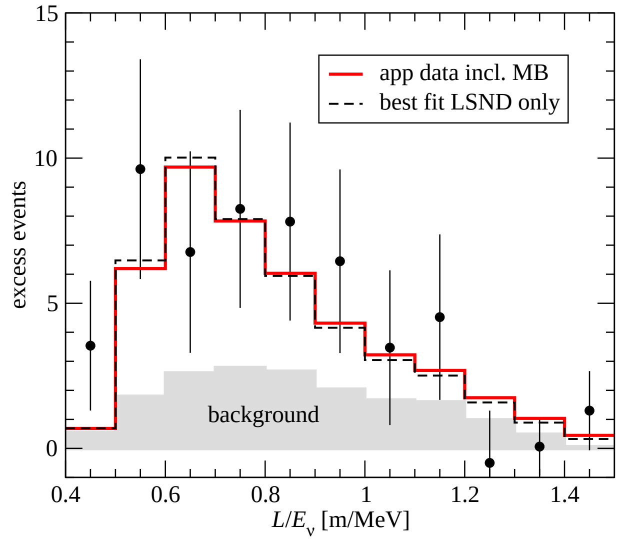
- terms of order $1/E^2$ cancel if $\delta = \pi$ and $|U_{e4}\, U_{\mu 4}|\Delta m^2_{41} = |U_{e5}\, U_{\mu 5}|\Delta m^2_{51}$;

⇒ **with two extra sterile states it is possible to fit the MB low-energy excess** [4].

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

Reconciling MiniBooNE and LSND in (3+2) models





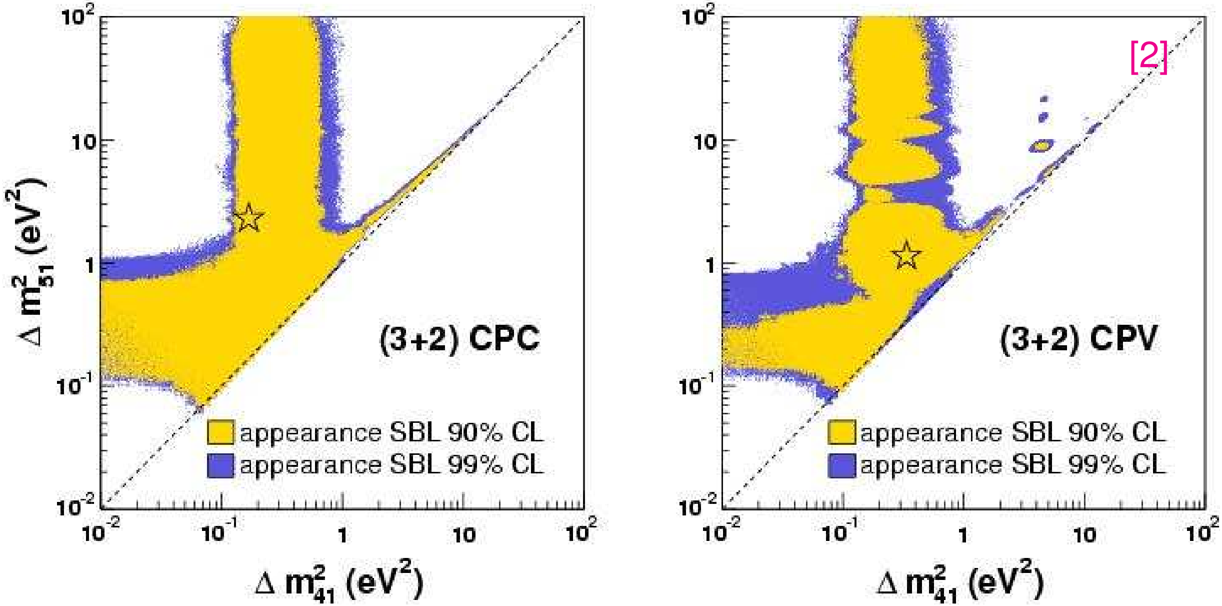
- **Trick**: use the CP phase $\delta = \arg(U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*)$ to differentiate ν (MB) from $\bar{\nu}$ (LSND):

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

- note that $\delta = \pi + \epsilon$ and $|U_{e4}\, U_{\mu 4}|\Delta m_{41}^2 \approx |U_{e5}\, U_{\mu 5}|\Delta m_{51}^2$ to suppress MB probability [4].

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

Fitting all appearance data in (3+2) models



data set	$\|U_{e4}U_{\mu4}\|$	Δm^2_{41}	$\|U_{e5}U_{\mu5}\|$	Δm^2_{51}	δ	χ^2_{min}/dof	gof
appearance (CPC)	0.12	0.18	0.006	2.31	–	95.8/86	22%
appearance (CPV)	0.080	0.39	0.029	1.10	1.1π	82.5/85	56%

NOTE: data taken from Ref. [2], which uses **old** MB-$\bar{\nu}$ data.

[2] G. Karagiorgi *et al.*, Phys. Rev. **D80** (2009) 073001 [arXiv:0906.1997].

The doom of disappearance data

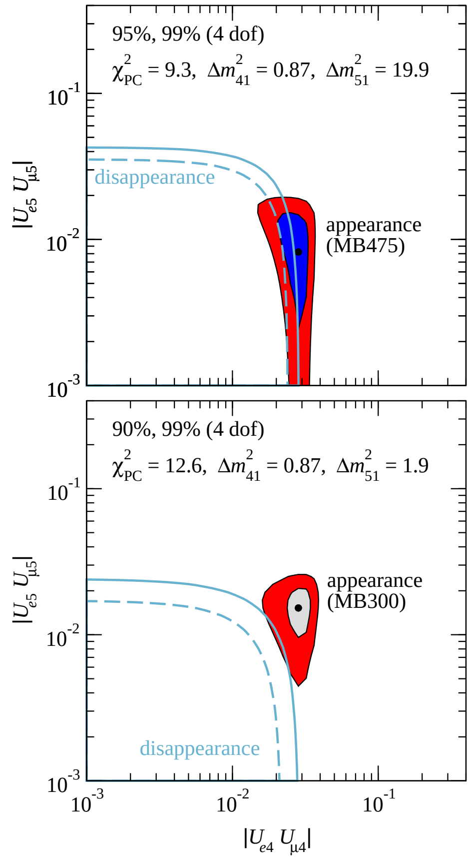
- As for (3+1) models, disappearance data imply bounds on $|U_{ei}|^2$ and $|U_{\mu i}|^2$ $(i = 4, 5)$;
- these bounds are in conflict with the large values of $|U_{ei} U_{\mu i}|$ required by appearance data;
- again, a tension between APP and DIS arises:

$$\chi^2_{\text{PG}} = 17.5 \text{ (4 dof)} \Rightarrow \text{PG} = 1.5 \times 10^{-3} \quad \text{[no MB]};$$
$$\chi^2_{\text{PG}} = 17.2 \text{ (4 dof)} \Rightarrow \text{PG} = 1.8 \times 10^{-3} \quad \text{[MB475]};$$
$$\chi^2_{\text{PG}} = 25.1 \text{ (4 dof)} \Rightarrow \text{PG} = 4.8 \times 10^{-5} \quad \text{[MB300]};$$

- alternatively, compare LSND and NEV as in (3+1):

$$\chi^2_{\text{PG}} = 19.6 \text{ (5 dof)} \Rightarrow \text{PG} = 1.5 \times 10^{-3} \quad \text{[before MB]};$$
$$\chi^2_{\text{PG}} = 21.2 \text{ (5 dof)} \Rightarrow \text{PG} = 7.4 \times 10^{-4} \quad \text{[after MB]}.$$

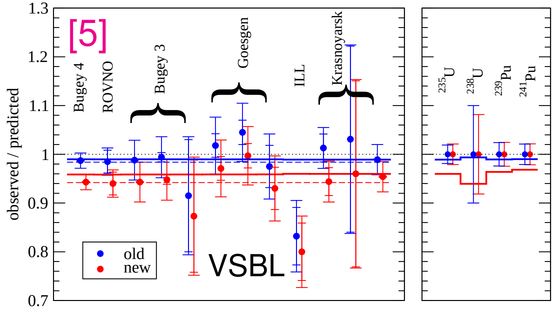
⇒ **Conclusion: (3+2) models fail exactly as (3+1) [4].**

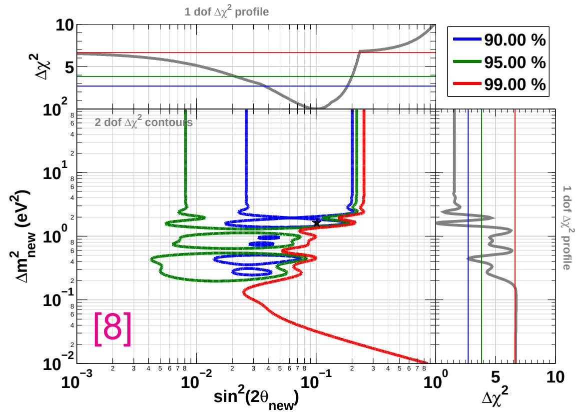


[4] M. Maltoni, T. Schwetz, Phys. Rev. **D76** (2007) 093005 [arXiv:0705.0107].

The reactor neutrino anomaly

- In [6, 7] the reactor $\bar{\nu}$ fluxes has been reevaluated;
- the new calculations result in a small increase of the flux by about **3.5%**;
- hence, **all** reactor short-baseline (RSBL) exp. finding no evidence are actually observing a deficit;
- this deficit **could** be interpreted as being due to SBL neutrino oscillations;
- deficit independent of $L \Rightarrow \Delta m^2 \gtrsim 1$ eV^2;
- impact on previous results:
  - 4ν: small (4ν dead anyway);
  - 5ν: important.



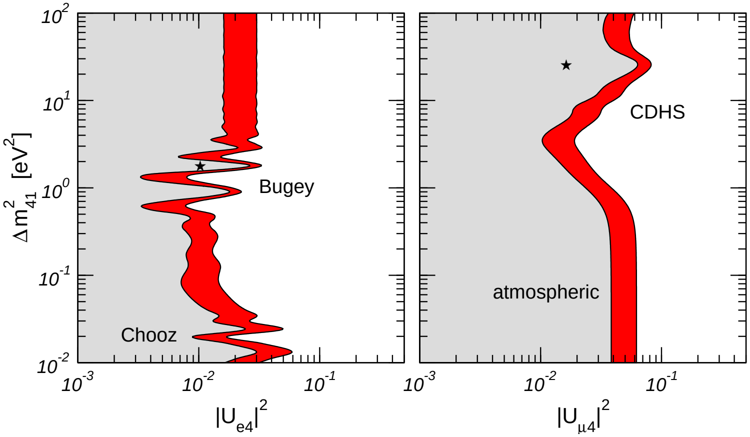


[5] T. Schwetz, M. Tortola, J.W.F. Valle, New J. Phys. **13** (2011) 063004 [arXiv:1103.0734].
[6] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [arXiv:1101.2663].
[7] P. Huber, Phys. Rev. C **84** (2011) 024617 [arXiv:1106.0687].
[8] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [arXiv:1101.2755].

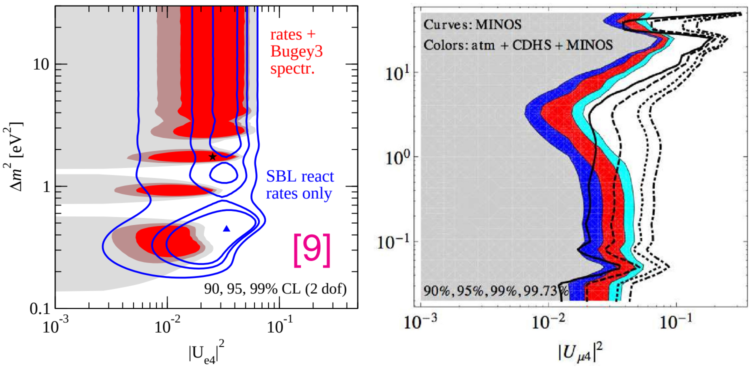
Can the reactor neutrino anomaly save the day?

- 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;
- morever, the bound on $|U_{\mu 4}|^2$ from atmospheric data is now independently confirmed by MINOS;
- all together, there is **no** reason to expect an impressive weakening of the disappearance bound.

Old reactor fluxes



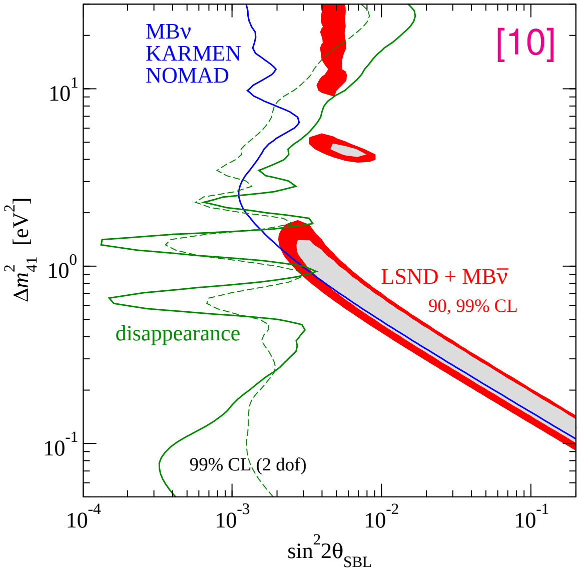
New reactor fluxes & MINOS

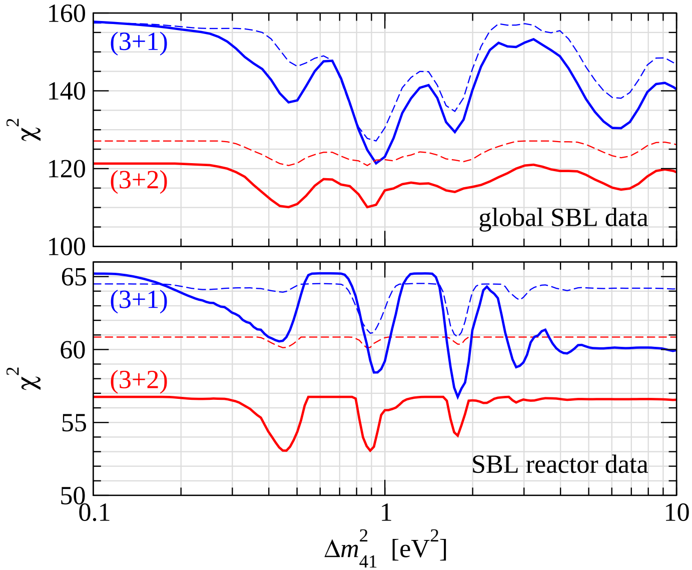


[9] T. Schwetz, talk at Neutrino Conference, Kyoto, Japan, June 3-9, 2012.

Impact of the new reactor fluxes

- (3+1)models: $\chi^2_{\text{PG}}/\text{dof} = 24.2/2 \to 21.5/2$ for LSND + MB($\bar\nu$) vs NEV ($\Delta\chi^2_{\text{PG}} = 2.7$);
- (3+2) models: $\begin{cases} \chi^2_{\text{PG}}/\text{dof} = 25.1/5 \to 19.9/5 \text{ for LSND + MB}(\bar\nu) \text{ vs NEV } (\Delta\chi^2_{\text{PG}} = 5.2); \\ \chi^2_{\text{PG}}/\text{dof} = 19.4/4 \to 14.7/4 \text{ for APP vs DIS } (\Delta\chi^2_{\text{PG}} = 4.7). \end{cases}$

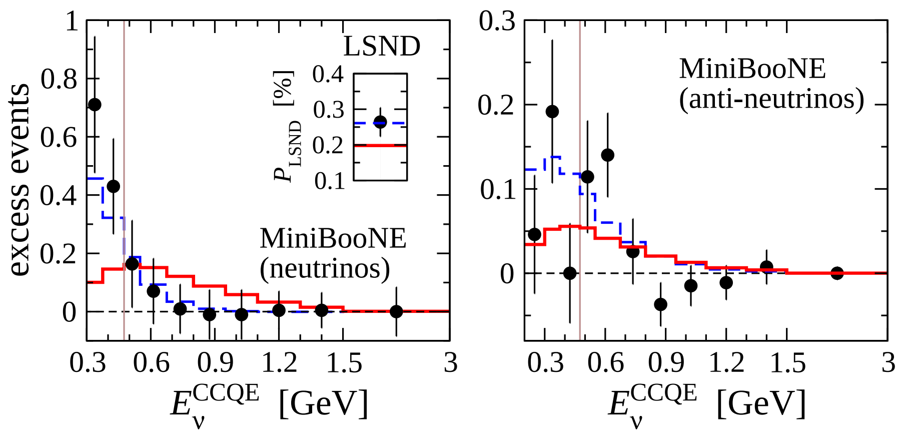


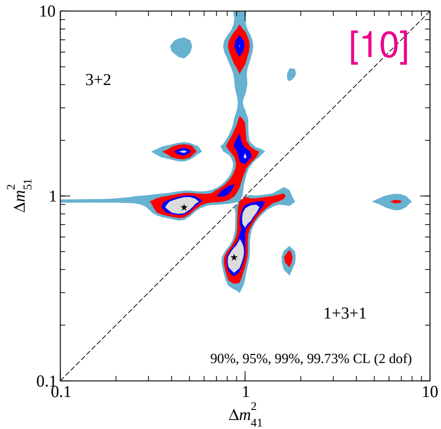


[10] J. Kopp, M. Maltoni and T. Schwetz, Phys. Rev. Lett. **107** (2011) 091801 [arXiv:1103.4570].

Status of (3+2) models with the new reactor fluxes

- (3+2) models experience substantial improvement, but tension with disappearance data remains considerably strong: PG=0.53%;
- situation becomes more critical if the MiniBooNE low-E excess is included, since larger mixing angles are required;
- (1+3+1) works slightly better, but has stronger problems with cosmology since the sum of neutrino masses ($\sum m_\nu$) is larger.

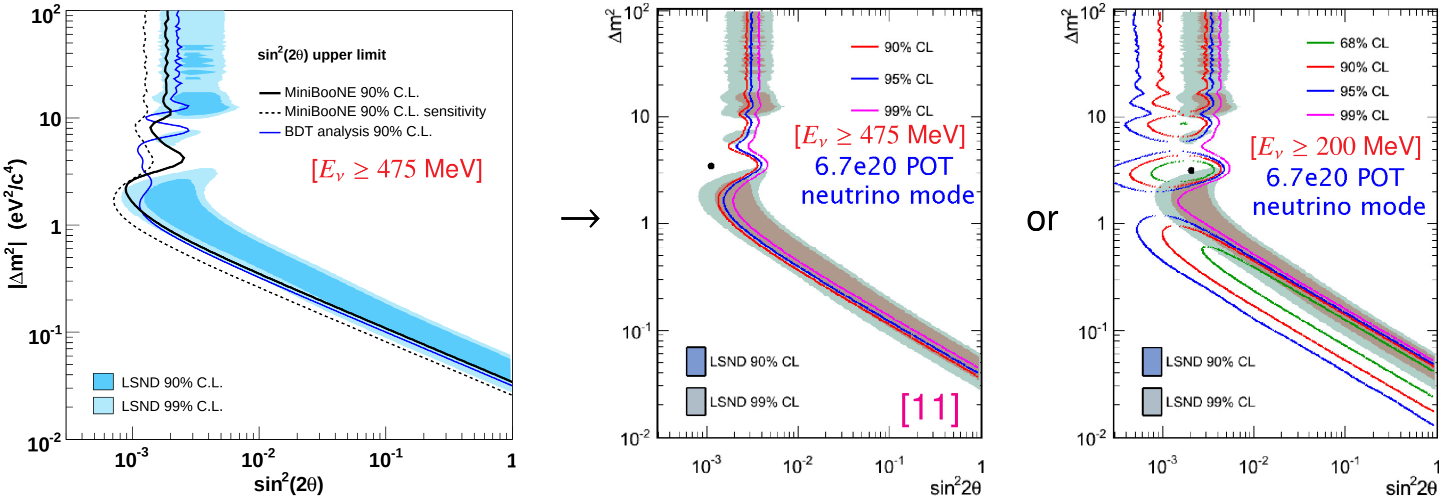




[10] J. Kopp, M. Maltoni and T. Schwetz, Phys. Rev. Lett. **107** (2011) 091801 [arXiv:1103.4570].

MiniBooNE: neutrino data

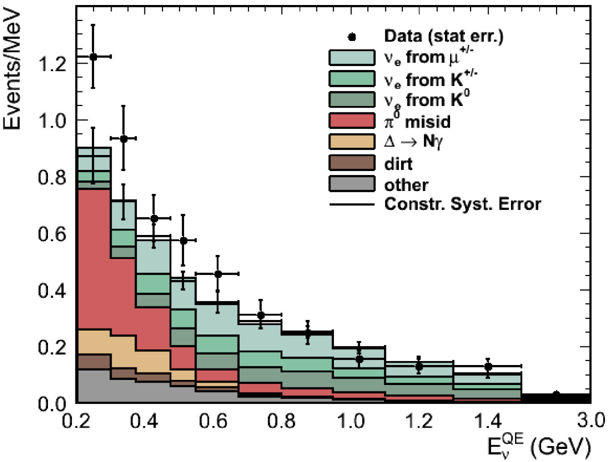
- No new data, but improved analysis. Full details: [→ Steve Brice's talk];
- is ν signal compatible with 2ν oscillations? $\begin{cases} \text{2007: } P_\text{osc} \simeq 1\% \Rightarrow \text{no it isn't [3];} \\ \text{2012: } P_\text{osc} \simeq 6\% \Rightarrow \text{maybe it is [11];} \end{cases}$
- do MB ν data rule out LSND $\bar{\nu}$ signal in (3+1)? 2007: yes [3]; 2012: not really [11].



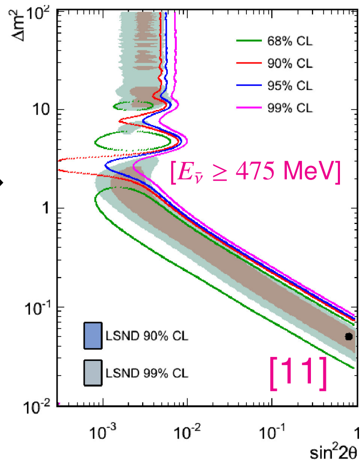
[3] A.A. Aguilar-Arevalo *et al.*[MiniBooNE collab], Phys. Rev. Lett. **98** (2007) 231801 [arXiv:0704.1500].
[11] C. Polly, talk at Neutrino Conference, Kyoto, Japan, June 3-9, 2012.

MiniBooNE: antineutrino data

- New data presented at Neutrino 2012, statistics doubled [11];
- compatibility with ν data: { low-energy excess increased $\Rightarrow$ better agreement; mid-energy excess reduced $\Rightarrow$ better agreement;
- is $\bar{\nu}$ signal compatible with 2ν oscillations? $P_{\text{osc}} = 67\%$ $\Rightarrow$ definitely yes [11];
- is MB-$\bar{\nu}$ signal compatible with LSND? Yes, irrespective of the energy threshold.



$\Rightarrow$



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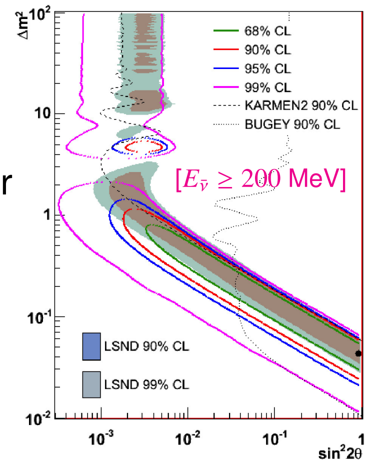
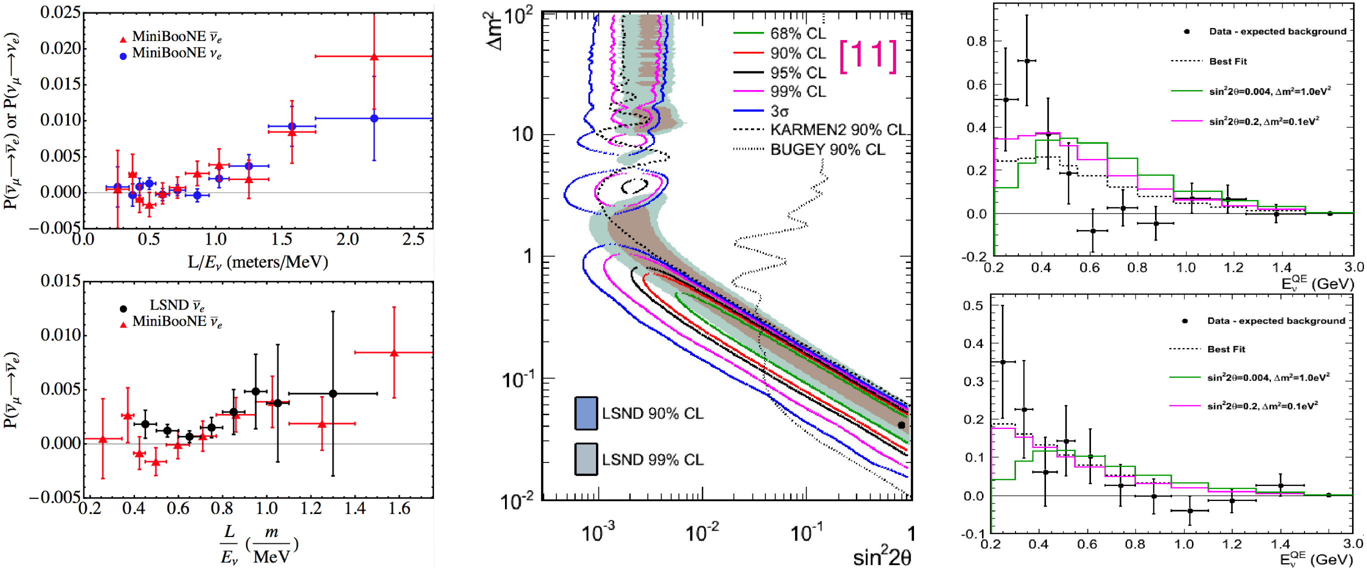


[11] C. Polly, talk at Neutrino Conference, Kyoto, Japan, June 3-9, 2012.

MiniBooNE: global $\nu + \bar{\nu}$ appearance analysis in (3+1)

- MiniBooNE ν and $\bar{\nu}$ no longer in open disagreement with LSND within (3+1) models;
- however, dramatic change in interpretation **not** linked to dramatic change in data;
- problems still there ($P_{\text{osc}} \simeq 6.7\%$ [11]) $\Rightarrow$ no great change expected in our conclusions.



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

- 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;
- efforts to produce an updated global analysis are presently under way [12];

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

[12] J. Kopp, P. Machado, M. Maltoni, T.Schwetz, work in progress.