Sterile neutrino oscillations after first MiniBooNE results

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I. **Models with one extra sterile neutrino**

II. **Models with two or more sterile neutrinos**

Conclusions

The LSND problem

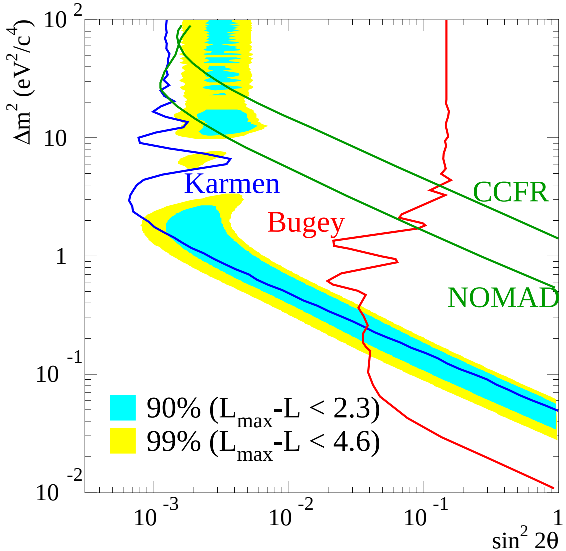
- LSND observed $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam ($E_\nu \sim 30$ MeV, $L \simeq 35$ m);

- 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):
  [Gonzalez-Garcia & MM, arXiv:0704.1800 v2]

$$\Delta m^2_{\text{SOL}} = 7.67^{+0.67}_{-0.61} \times 10^{-5}\ \text{eV}^2\,,$$

$$\Delta m^2_{\text{ATM}} = \begin{cases} -2.37^{+0.43}_{-0.46} \times 10^{-3}\ \text{eV}^2 & \text{(IH)}\,, \\ +2.46^{+0.47}_{-0.42} \times 10^{-3}\ \text{eV}^2 & \text{(NH)}\,; \end{cases}$$

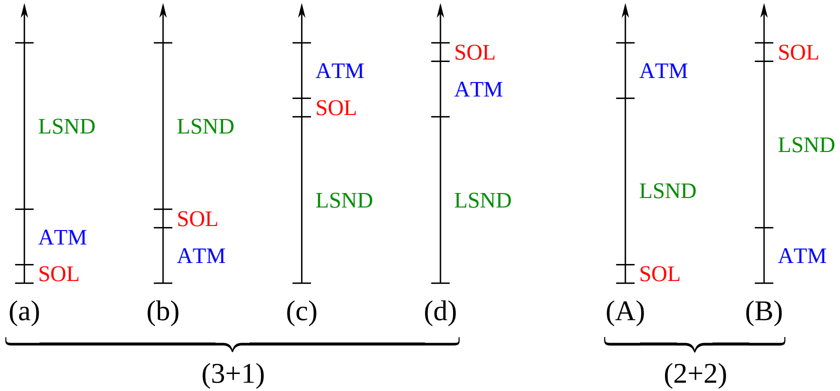


- in order to explain LSND with mass-induced neutrino oscillations one needs *at least one more* neutrino mass eigenstate;

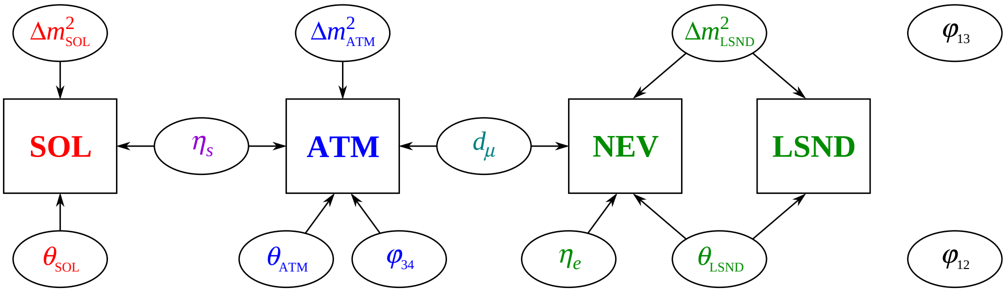
- **WARNING: having enough Δm^2 is not enough. To make sure that the model works, one has to check explicitly that all the experiments can be fitted simultaneously.**

Four neutrino mass models

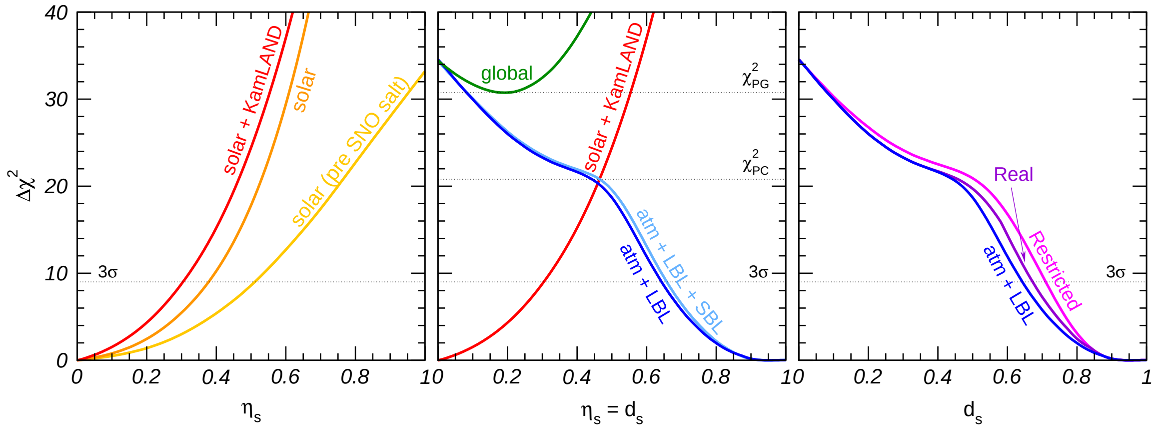
- Approximation: $\Delta m^2_{\text{SOL}} \ll \Delta m^2_{\text{ATM}} \ll \Delta m^2_{\text{LSND}} \Rightarrow$ 6 different mass schemes:



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



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



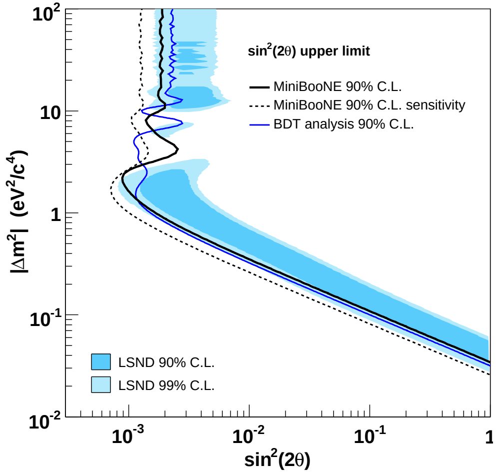
- in (2+2) models, the fractions of ν_s in solar (η_s) and atmospheric ($1 - d_s$) oscillations add to one $\Rightarrow$ $\boxed{\eta_s = d_s}$;
- 3σ allowed regions $\eta_s \leq 0.31$ (solar) and $d_s \geq 0.64$ (atmospheric) do not overlap; superposition occurs only above 4.6σ ($\chi^2_{\text{PC}} = 20.8$);
- the χ^2 increase due to the combination of solar and atmospheric data is $\chi^2_{\text{PG}} = 30.7$ (1 dof), corresponding to a PG $= 3 \times 10^{-8}$. [MM & Schwetz, PRD 68 (2003) 033020, hep-ph/0304176]

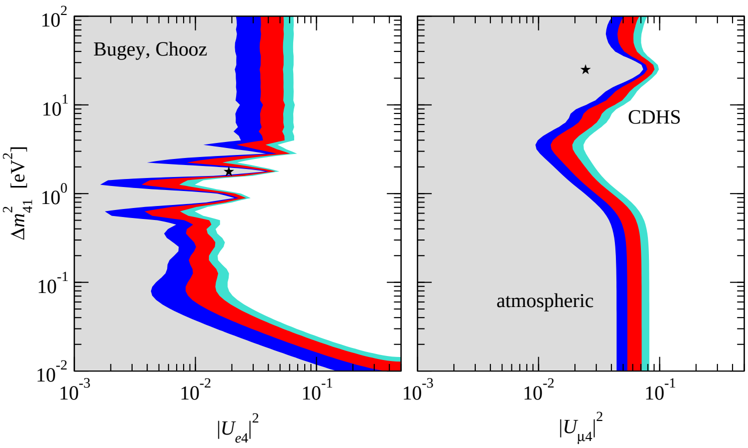
(3+1): tension between LSND and short-baseline data

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

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

- the MiniBooNE/LSND 2ν inconsistency fully applies;
- *disappearance* exper. bound $|U_{e4}|^2$ and $|U_{\mu 4}|^2$;





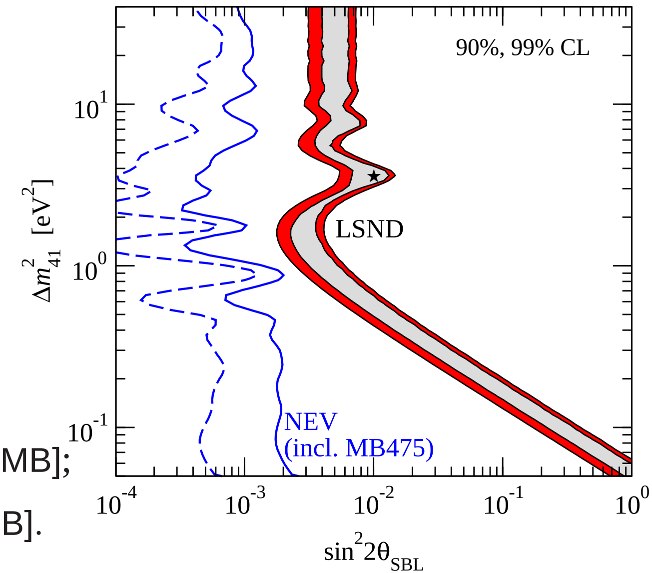
- LSND is in conflict:
  - with other *appearance* exp. (Karmen, Nomad, MB);
  - with *disappearance* experiments.

(3+1): ruled out by short-baseline data

- Three-fold disagreement:
  - LSND claims a signal;
  - NEV-APP reject its evidence;
  - NEV-DIS constraint the LSND angle;
- check: $\chi^2_{\text{PG}} = 24.8$ (4 dof) $\Rightarrow$ PG $= 6 \times 10^{-5}$;
- alternatively: compare LSND and NEV:

$\chi^2_{\text{PG}} = 20.9$ (2 dof) $\Rightarrow$ PG $= 3 \times 10^{-5}$ [before MB];

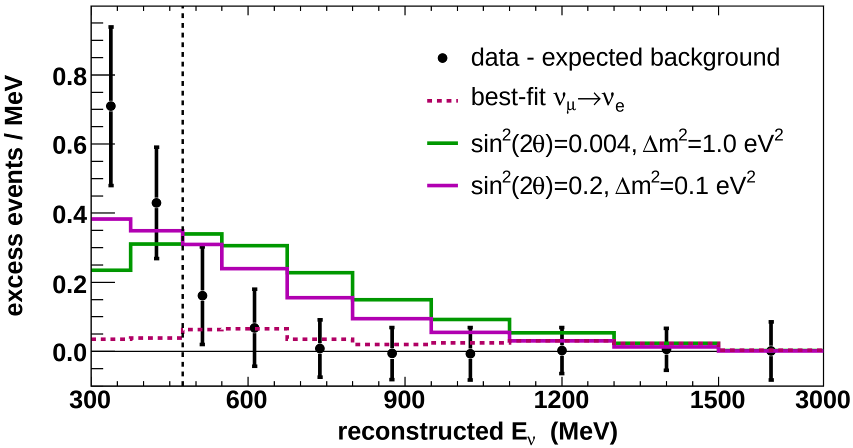
$\chi^2_{\text{PG}} = 24.7$ (2 dof) $\Rightarrow$ PG $= 4 \times 10^{-6}$ [after MB].



Summary of four-neutrino models

- Four-neutrino models **cannot** explain LSND. This was true even **before** MB.
- The negative MB result increases the tension in (3+1) models, now almost as bad as (2+2).

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.

[MB collaboration, arXiv:0704.1500, pag. 4]

- MiniBooNE observed a 3.6σ excess at low-energy;
- this excess is *incompatible* with 2ν oscillations;
- therefore, data with $E_\nu^{QE} < 475$ MeV have not been used to check LSND.

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

- From now on: consider both complete (MB300) and reduced (MB475) data sets.

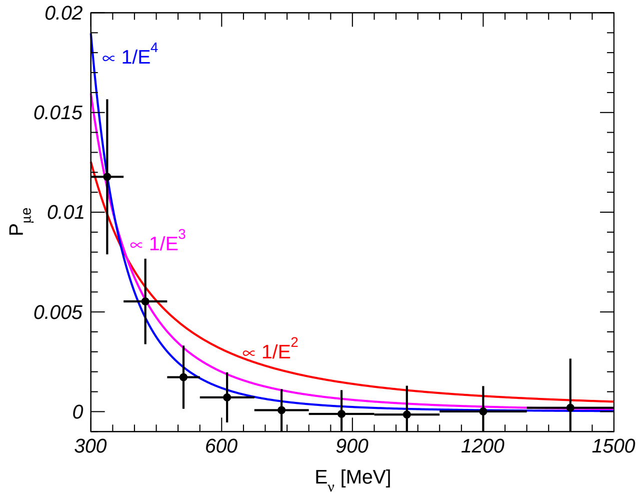
Explaining the MiniBooNE excess with two sterile neutrinos

- 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.**



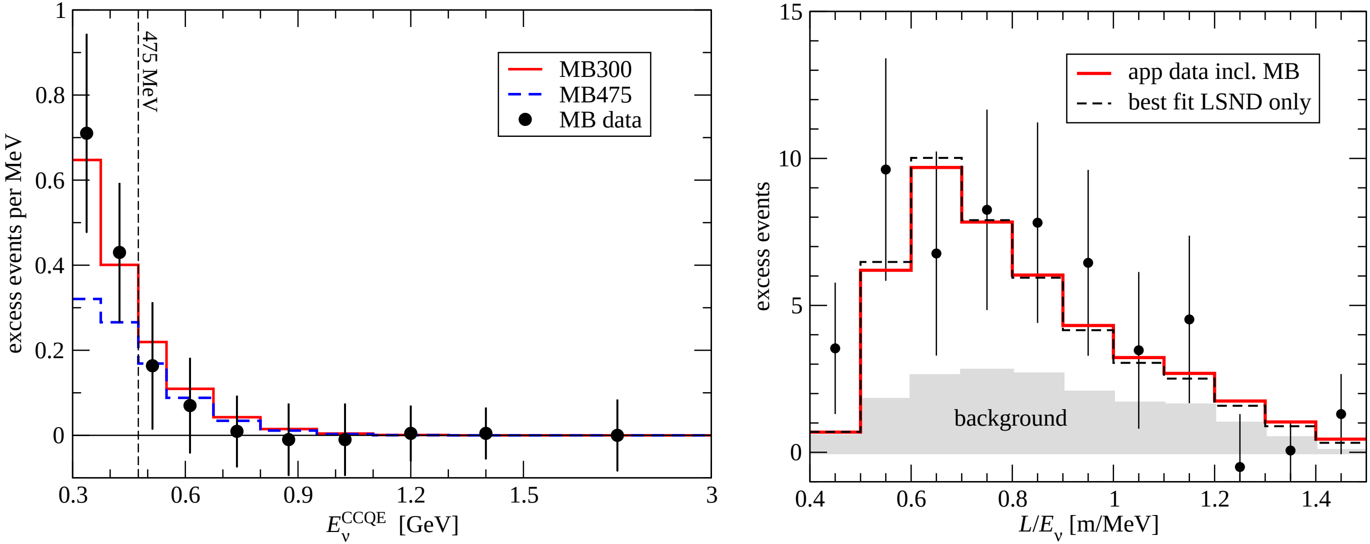
- On the other hand, with *two* extra neutrinos, m_4 and m_5:

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

- 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**.

Reconciling MiniBooNE and LSND in (3+2) models

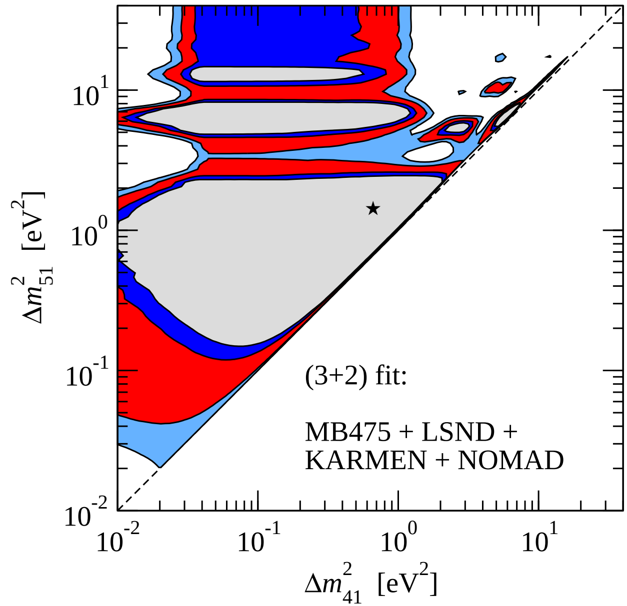


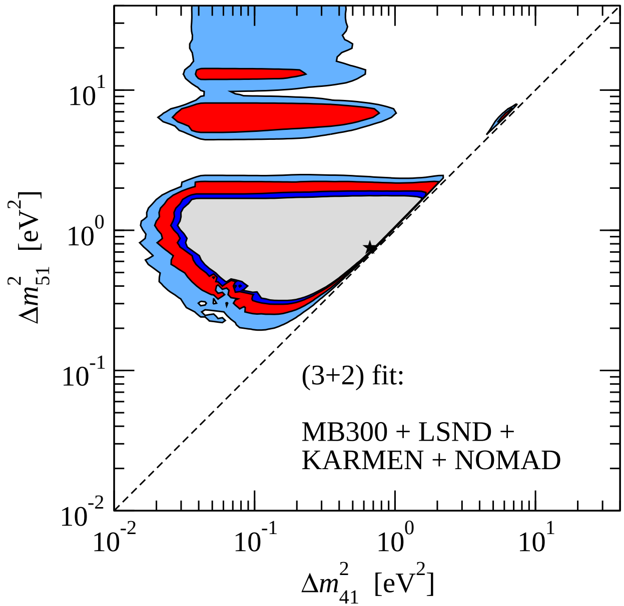
- **Trick**: use the CP phase $\delta = \arg(U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*)$ to differentiate ν (MB) from $\bar{\nu}$ (LSND):

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

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

Fitting all appearance data in (3+2) models





data set	$\lvert U_{e4}U_{\mu 4}\rvert$	Δm^2_{41}	$\lvert U_{e5}U_{\mu 5}\rvert$	Δm^2_{51}	δ	$\chi^2_{\text{min}}/\text{dof}$	gof
appearance (MB475)	0.044	0.66	0.022	1.44	1.12π	$16.9/(29-5)$	85%
appearance (MB300)	0.31	0.66	0.27	0.76	1.01π	$18.5/(31-5)$	85%

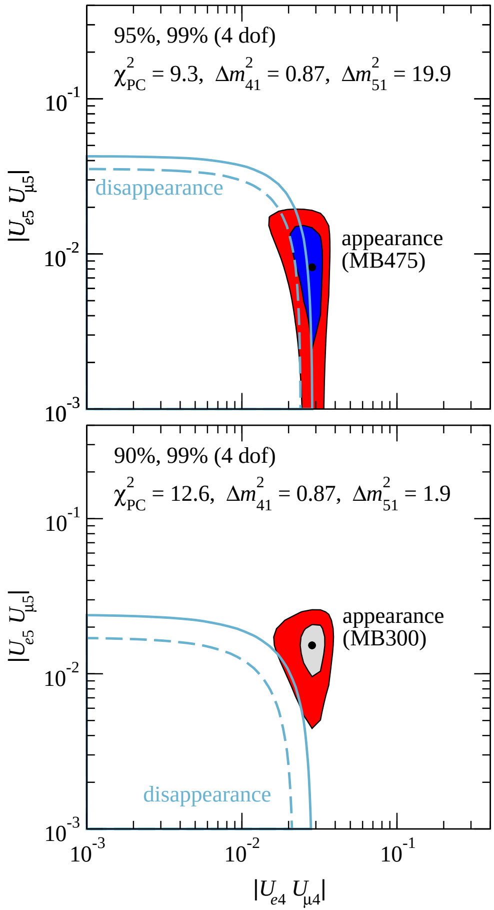
The doom of disappearance data

- 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) do!**

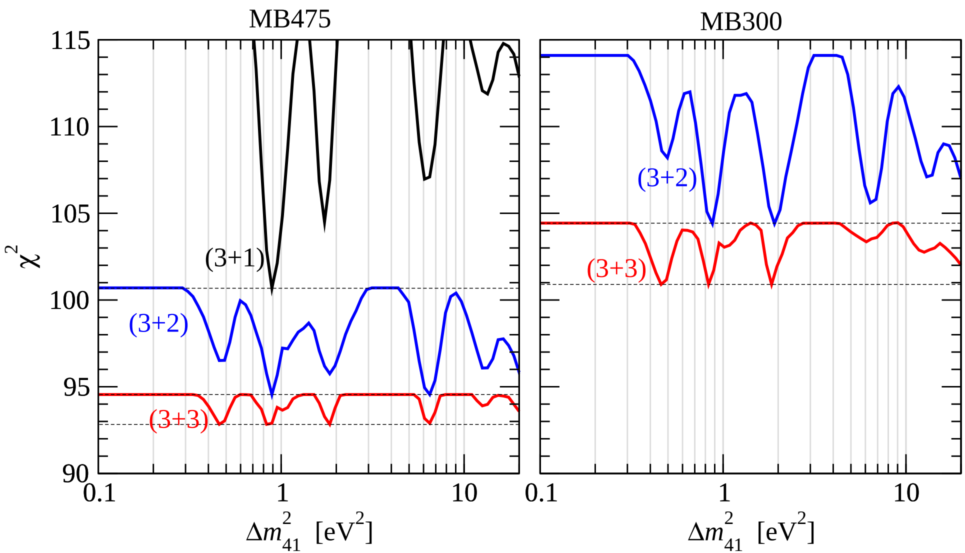
Adding a third sterile neutrino: (3+3) models

- Improvements:

— (3+1) → (3+2) [MB475]:
$\Delta\chi^2 = 6.1/4$ dof (81% CL)

— (3+2) → (3+3) [MB475]:
$\Delta\chi^2 = 1.7/4$ dof (21% CL)

— (3+2) → (3+3) [MB300]:
$\Delta\chi^2 = 3.5/4$ dof (52% CL)



- **(3+3) models do not offer qualitatively new effects with respect to (3+2) models; in particular, the improvement in χ^2 is very modest.**

Conclusions

- **(3+1)** four-neutrino schemes are strongly disfavored because:
  - recent MB data is incompatible with LSND at the 98% CL;
  - the tension between LSND and NEV SBL data becomes more severe due to MB. In particular, there is no overlap of the allowed regions for NEV and LSND at 99% CL, and the PG test implies inconsistency at the level of 4σ;
  - it is not possible to account for the low energy event excess in MB.
- **(3+2)** five-neutrino schemes
  - do provide a good fit to LSND and the recent MB data;
  - can account for the low energy event excess in MB;
  - fail to resolve the tension between appearance and disappearance data (according to the PG test at the level of 3σ for MB475 and 4σ for MB300).
- **(3+3)** six-neutrino schemes do not offer qualitatively new effects. In particular, the global χ^2 improves only marginally with respect to (3+2), and hence, the conflict between appearance and disappearance data remains.