Status of neutrino oscillations with and without sterile neutrinos

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Hot topics in neutrino oscillations: a clue to physics beyond the Standard Model
Roma, Italy – December 5th, 2011

I. Conventional three-neutrino oscillations

General three-neutrino framework

- Equation of motion: **6** parameters (including CP-violating effects):

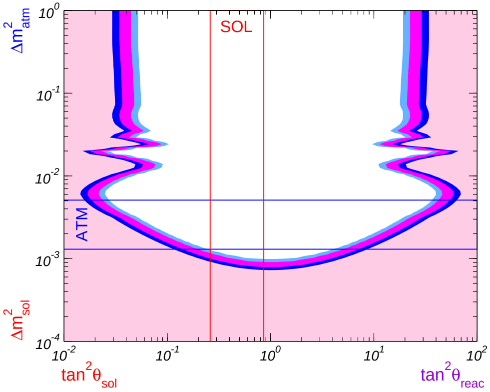
$$i\frac{d\vec{\nu}}{dt} = H\,\vec{\nu}; \qquad H = U_{\text{vac}} \cdot D_{\text{vac}} \cdot U_{\text{vac}}^{\dagger} \pm V_{\text{mat}};$$

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

$$D_{\text{vac}} = \frac{1}{2E_\nu}\,\text{diag}\,(0,\, \Delta m^2_{21},\, \Delta m^2_{31}); \qquad V_{\text{mat}} = \sqrt{2} G_F N_e\,\text{diag}\,(1,\, 0,\, 0)\,.$$

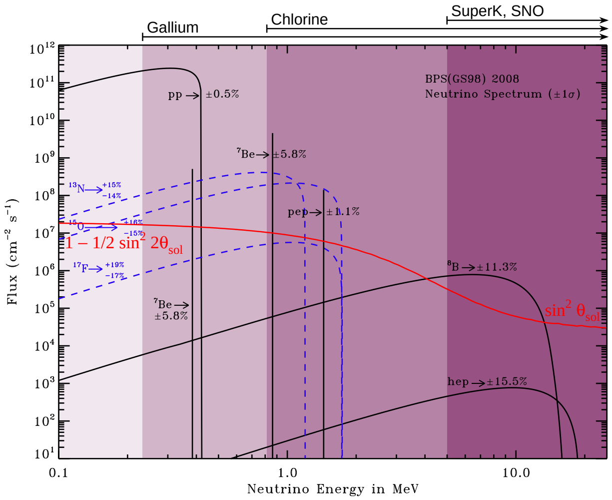
The hierarchy approximation

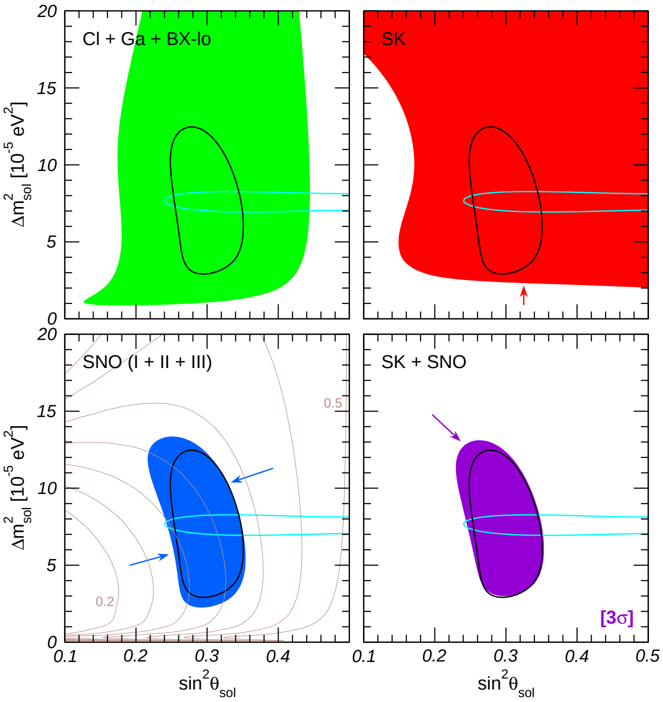
- From SOL and ATM data, we have $\Delta m^2_{21} \ll \Delta m^2_{31}$;
- **SOL**: $\Delta m^2_{31} \approx \infty \Rightarrow$ only **3** parameters: Δm^2_{21}, θ_{12}, θ_{13};
- **ATM**: $\Delta m^2_{21} \approx 0 \Rightarrow$ only **3** parameters: Δm^2_{31}, θ_{23}, θ_{13};
- CP-violating phase δ_{CP} disappears from equations;
- Chooz limit: $\theta_{13} \approx 0 \Rightarrow$ **SOL** and **ATM** decoupled.



Solar neutrinos: anatomy of the oscillation solution

- $\theta_{13} = 0 \Rightarrow$ $i\frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix}-\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12}\end{pmatrix} \pm \sqrt{2}\, G_F \begin{pmatrix} N_e & 0 \\ 0 & 0\end{pmatrix}\right]\vec{\nu}$, with $\vec{\nu} = \begin{pmatrix}\nu_e \\ \nu_a\end{pmatrix}$;
- Data:
  - low-E (Cl, Ga): $P_{ee} \approx 1 - \frac{1}{2}\sin^2 2\theta_{12}$,
  - high-E (SK, SNO): $P_{ee} \approx \sin^2\theta_{12}$;
- fit presently dominated by high-E.



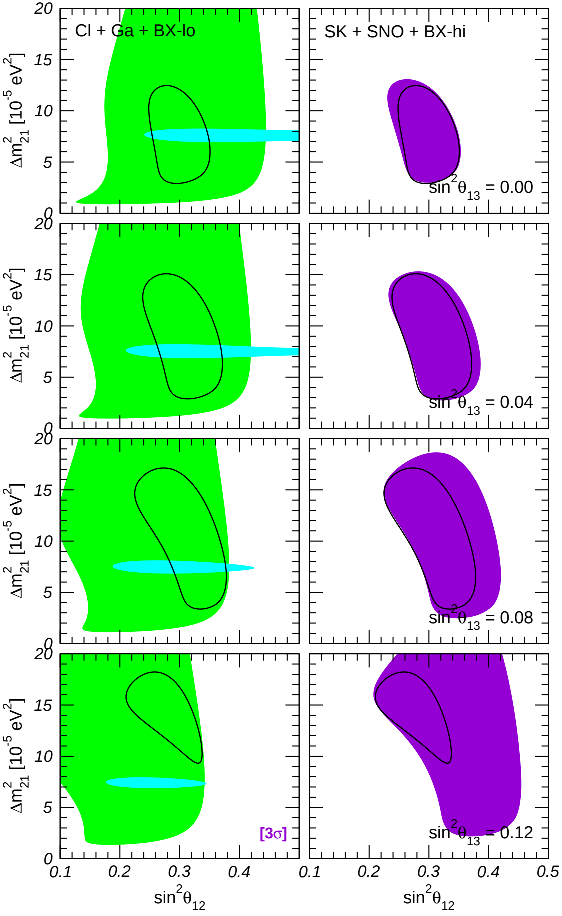


Bound on θ_{13} from solar & KamLAND

- $\nu_\mu \equiv \nu_\tau \Rightarrow$ 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};

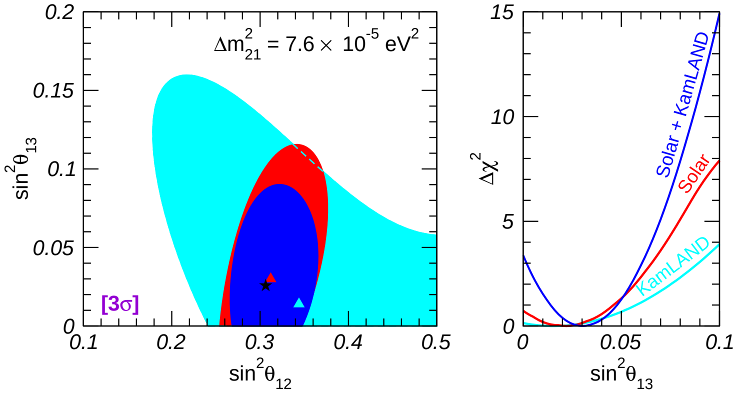
- $$P_{ee} \approx \begin{cases} \text{Kam: } \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12} \sin^2 \dfrac{\Delta m^2_{21} L}{4E}\right), \\ \text{low-E: } \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2 2\theta_{12}\right), \\ \text{high-E: } \cos^4\theta_{13} \sin^2\theta_{12}; \end{cases}$$
- as θ_{13} increases, $\cos^4\theta_{13}$ decreases and:
  - KamLAND and low-E data favor **smaller** θ_{12};
  - high-E data favor **larger** θ_{12} and Δm^2_{21};
  - Kam fit gets worse as osc. are suppressed;
- synergy between solar and KamLAND data: as θ_{13} increases, Δm^2_{21}: $\begin{cases}\text{increases in solar data;} \\ \text{remains stable in KamLAND;}\end{cases}$ hence, a tension appear.



I. Conventional three-neutrino oscillations

Hint for non-zero θ_{13} in solar and KamLAND data

- For $\theta_{13} = 0$, we have $\sin^2\theta_{12} = \left\{ \begin{matrix} 0.30 \text{ from Solar data} \\ 0.36 \text{ from KamLAND data} \end{matrix} \right\} \Rightarrow$ a tension appear;
- as we have just seen, when θ_{13} increases:
  - solar region slightly moves to larger θ_{12} (high-E data dominate over low-E ones);
  - KamLAND region definitely shifts to smaller θ_{12};
- therefore, a non-zero value of θ_{13} reduces the tension between solar and KamLAND data [1, 2];
- new SNO (I+II+III) analysis favor smaller $\phi_{\text{CC}}/\phi_{\text{NC}} \Rightarrow$ smaller θ_{12} from solar $\Rightarrow$ tension with KamLAND is increased $\Rightarrow$ larger θ_{13} is preferred.



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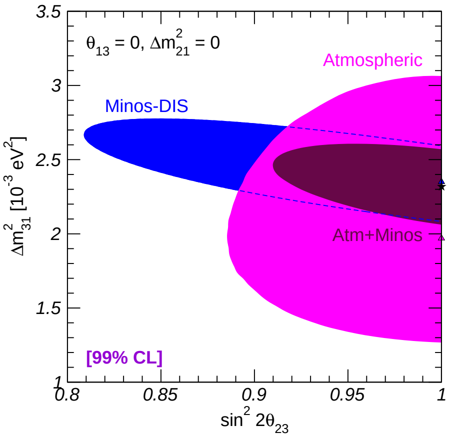
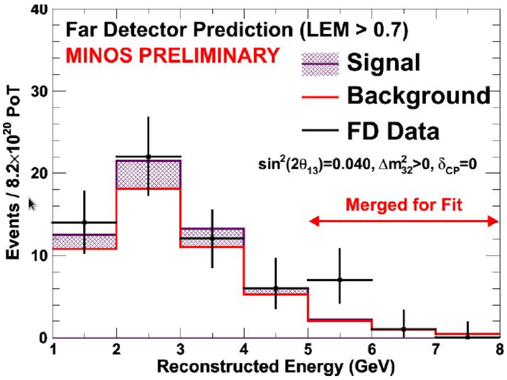
[1] G.L. Fogli *et al.*, Phys. Rev. Lett. **101** (2008) 141801 [`arXiv:0806.2649`].

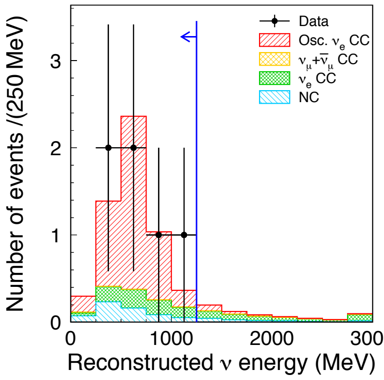
[2] T. Schwetz, M.A. Tortola, J.W.F. Valle, New J. Phys. **10** (2008) 113011 [`arXiv:0808.2016`].

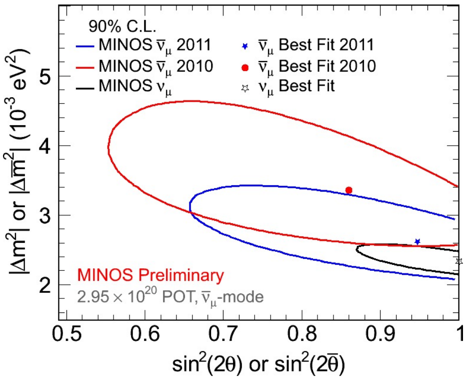
Atmospheric sector: the $\Delta m^2_{21} = 0$ limit

- Δm^2_{31} is now determined by Minos-DIS (ν_μ) data;
- θ_{23} still dominated by atmospheric data;
- θ_{13} mainly bounded by Chooz, with small atm contribution;
- hints of non-zero θ_{13} in ν_e appearance data, from Minos (1.6σ) and T2K (2.5σ);
- puzzling tension between Minos disappearance ν_μ and $\bar{\nu}_\mu$ data is now considerably reduced.





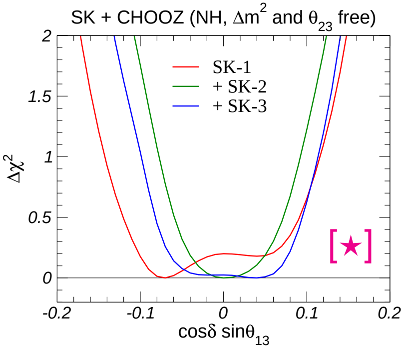


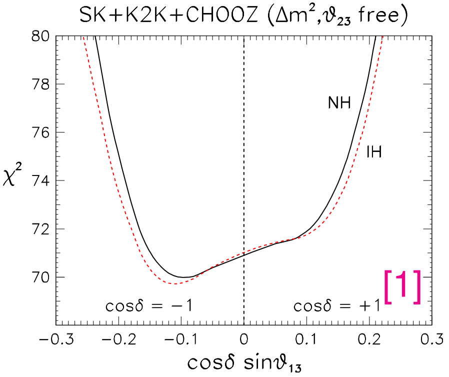


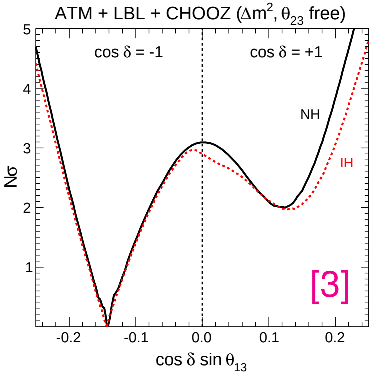
I. Conventional three-neutrino oscillations

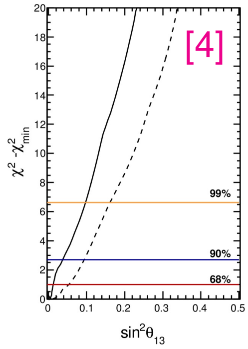
θ_{13} from SK atmospheric data

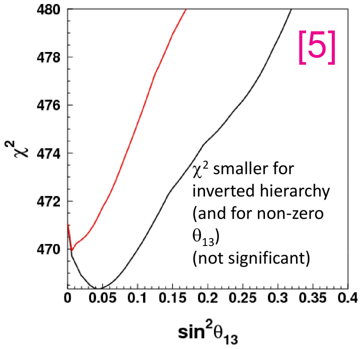
- Hint of non-zero θ_{13} in SK atmospheric data [1, 3];
- no such hint (or very weak one) from our simulation [★];
- ★ details of the simulation very important $\Rightarrow$ SK has final word;
- SK confirms $\theta_{13} = 0$ [4] but crucial Δm^2_{21} effects are neglected;
- preliminary full 3ν fit [5] suggests weak deviations for IH only.











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

[3] G.L. Fogli, E. Lisi, A. Marrone, A. Palazzo, A.M. Rotunno, `arXiv:1106.6028`.

[4] R. Wendell *et al.* [SK Collaboration], Phys. Rev. **D81** (2010) 092004 [`arXiv:1002.3471`].

[5] T. Kajita, talk presented at NOW 2010, 7/09/2010.

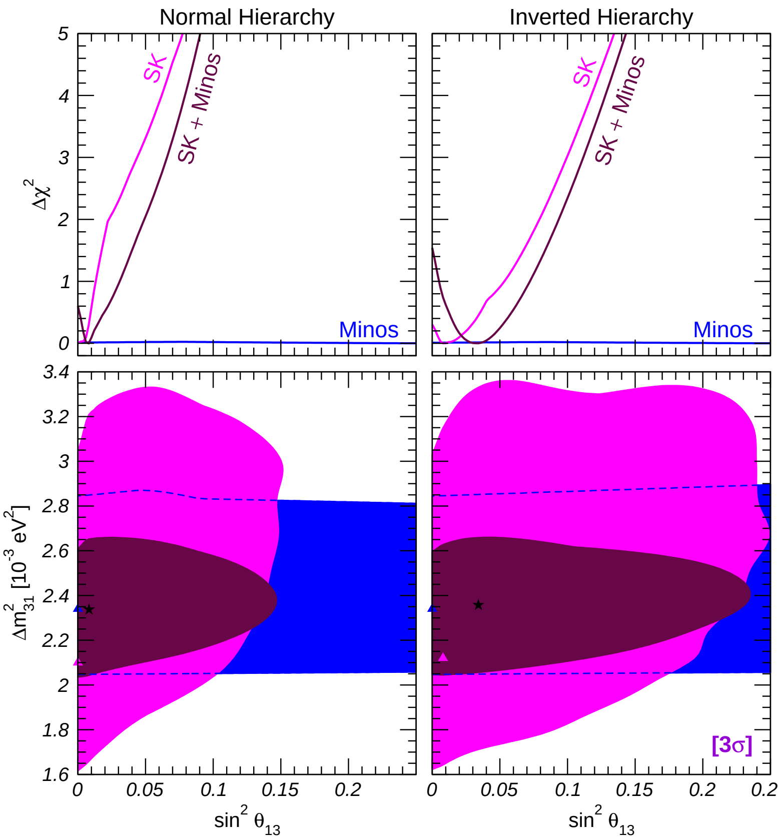
I. Conventional three-neutrino oscillations

θ_{13} from SK + Minos data

- For $\theta_{13} = 0$ we have:

$$\Delta m^2_{31} = \begin{cases} 2.10 \times 10^{-3}\ \text{eV}^2 \ \text{[SK]}, \\ 2.36 \times 10^{-3}\ \text{eV}^2 \ \text{[Minos]}; \end{cases}$$

- hence there is some tension between SK and Minos-DIS data;
- as θ_{13} increases:
  - SK region shifts to larger Δm^2_{31};
  - Minos-DIS region does not move;
- therefore, a non-zero value of θ_{13} reduces the tension between SK and Minos-DIS data [6, 7];
- effect is particularly relevant for IH.



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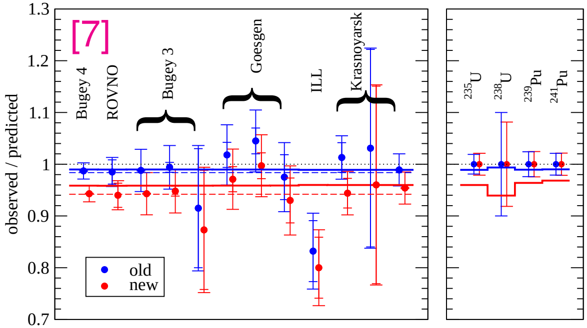
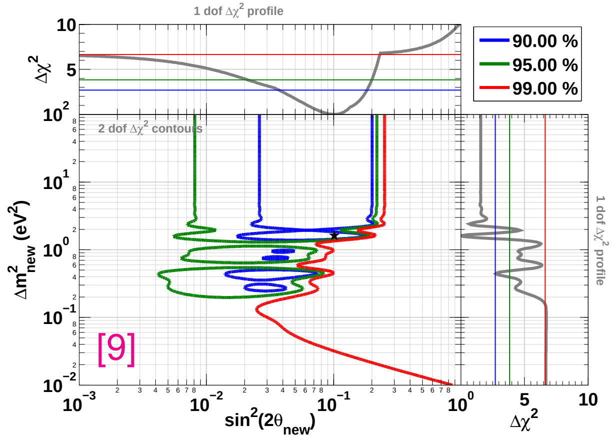
[6] M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, JHEP **04** (2010) 056 [`arXiv:1001.4524`].

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

The reactor neutrino anomaly

- In [8] the reactor $\bar{\nu}$ fluxes has been reevaluated;
- the new calculation results in a small increase of the flux by about **3.5%**;
- hence, **all** reactor experiments finding no evidence are actually observing a deficit;
- this deficit **could** be interpreted as being due to neutrino oscillations **but** requires $\Delta m^2 \gtrsim 1$ eV^2;
- if used within 3ν models, Chooz favor $\theta_{13} \neq 0$ **but** deficit of **other** SBL experiments unexplained;
- consistent approach [7]: fit also reactor fluxes (within errors) including **all** reactor data;
- this way "old" and "new" fluxes equivalent for θ_{13}.





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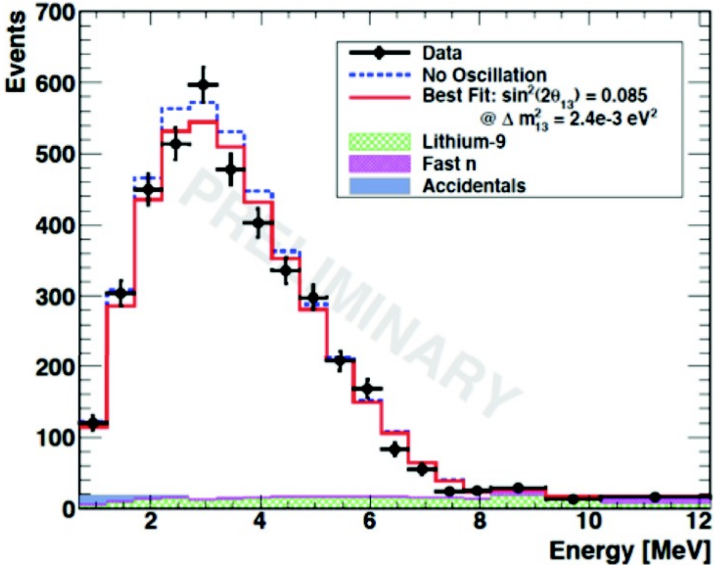
[7] T. Schwetz, M. Tortola, J.W.F. Valle, New J. Phys. **13** (2011) 063004 [`arXiv:1103.0734`].

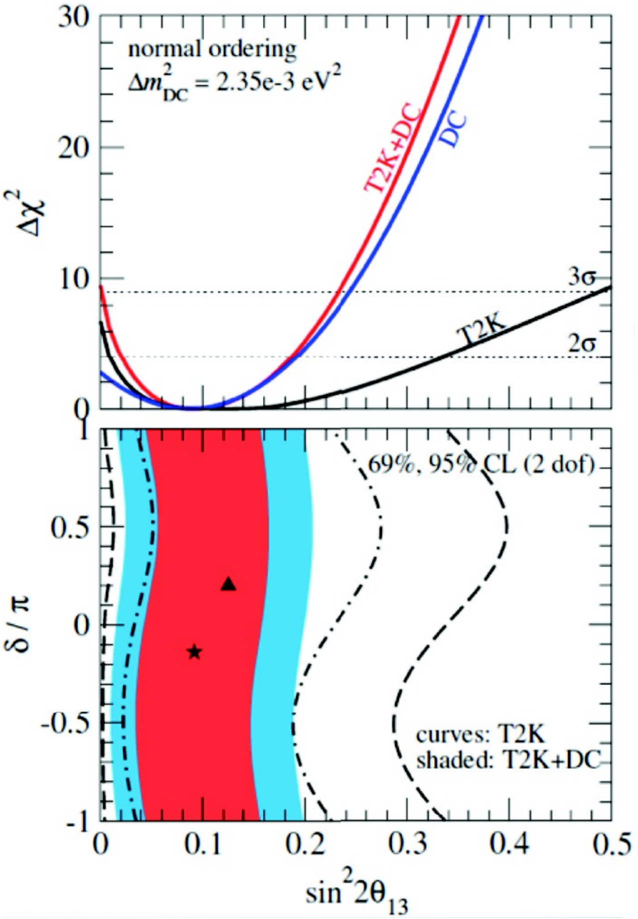
[8] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [`arXiv:1101.2663`].

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

The Double-Chooz experiment

- Reactor experiment (baseline: ≈ 1 km);
- no near-detector **yet** $\Rightarrow$ fix Φ_ν to Bugey-4;
- first data release: 1.7σ deficit observed.





Neutrino oscillations: where we are

- Global 6-parameter fit (including $\delta_{\rm CP}$):
  - **Solar**: Cl + Ga + SK-I + SNO-full (I+II+III) + BX-low + BX-high;
  - **Atmospheric**: SK-I + SK-II + SK-III;
  - **Reactor**: Chooz + KamLAND ~~+ Double-Chooz~~;
  - **Accelerator**: K2K + Minos-DIS + Minos-APP + T2K;
- BPS09(GS): best-fit and 1σ (3σ):

$$\theta_{12} = 34.4 \pm 1.0 \left(^{+3.3}_{-2.9}\right), \quad \Delta m^2_{21} = 7.58 \pm 0.20 \left(^{+0.59}_{-0.61}\right) \times 10^{-5}\ \text{eV}^2,$$

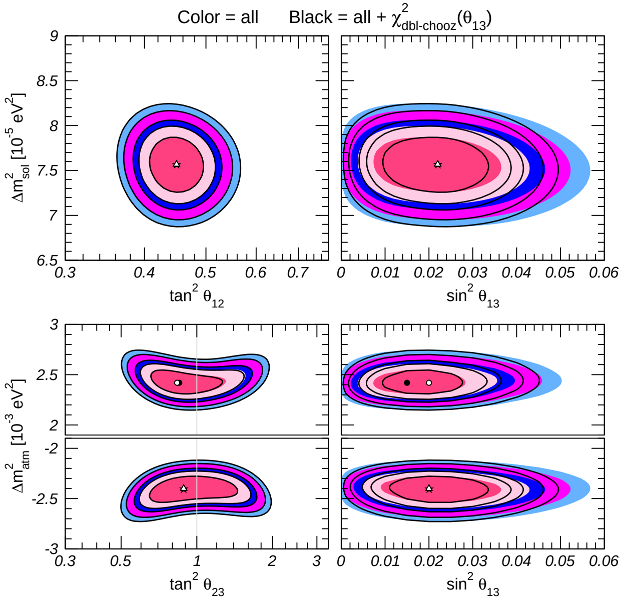
$$\theta_{23} = 42.1\,^{+6.5}_{-2.6} \left(^{+11.9}_{-6.5}\right), \quad \Delta m^2_{31} = \begin{cases} -2.34 \pm 0.09 \left(^{+0.26}_{-0.29}\right) \times 10^{-3}\ \text{eV}^2, \\ +2.44 \pm 0.09 \left(^{+0.29}_{-0.25}\right) \times 10^{-3}\ \text{eV}^2, \end{cases}$$

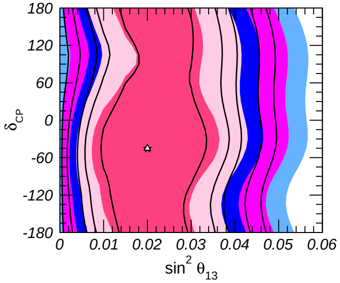
$$\theta_{13} = 7.4\,^{+2.3}_{-2.0}\ (\leq 12.8), \quad \delta_{\rm CP} = -45\,^{+75}_{-100}\ (\text{any});$$

- BPS09(AGSS): as above except:

$$\theta_{12} = 34.4 \pm 1.0 \left(^{+3.2}_{-2.8}\right), \quad \theta_{13} = 6.9\,^{+2.3}_{-1.8}\ (\leq 12.4);$$

Solar model	All	All+DC
BPS09(GS)	3.21σ	3.62σ
BPS09(AGSS)	3.07σ	3.49σ





- Fogli *et al.* [3]: $\sin^2\theta_{13} = 0.021 \pm 0.007$, with $\theta_{13} > 0$ at $\sim 3\sigma$ level.

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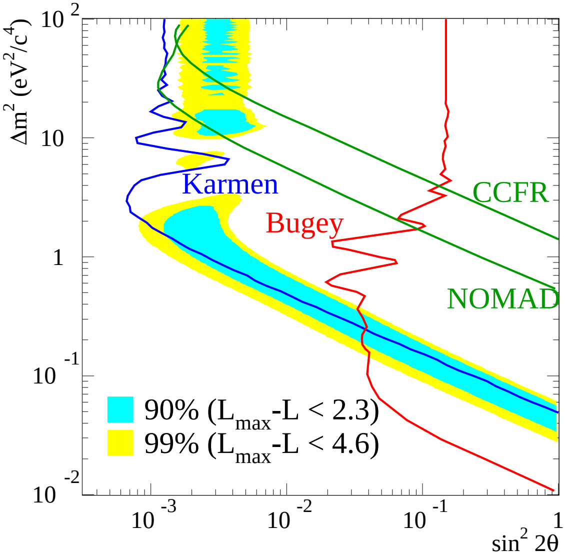
[3] G.L. Fogli, E. Lisi, A. Marrone, A. Palazzo, A.M. Rotunno, `arXiv:1106.6028`.

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):

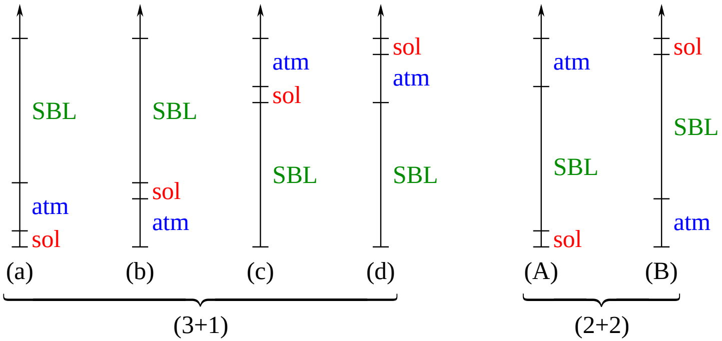
$$\Delta m^2_{\text{SOL}} \simeq 7.6 \pm 0.6 \times 10^{-5}\ \text{eV}^2\,,$$
$$\left|\Delta m^2_{\text{ATM}}\right| \simeq 2.4 \pm 0.4 \times 10^{-3}\ \text{eV}^2\,;$$



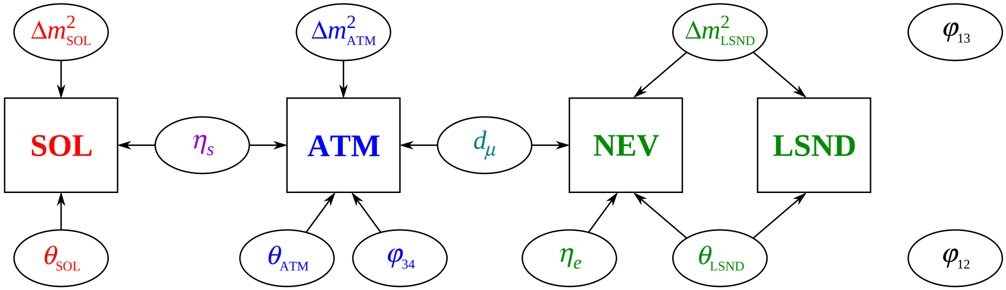
- in order to explain LSND with mass-induced neutrino oscillations one needs *at least one more* neutrino mass eigenstate;
- **WARNING: having enough Δm^2 is not enough. To make sure that the model works, one has to check explicitly that all the experiments can be fitted simultaneously.**

Four neutrino mass models

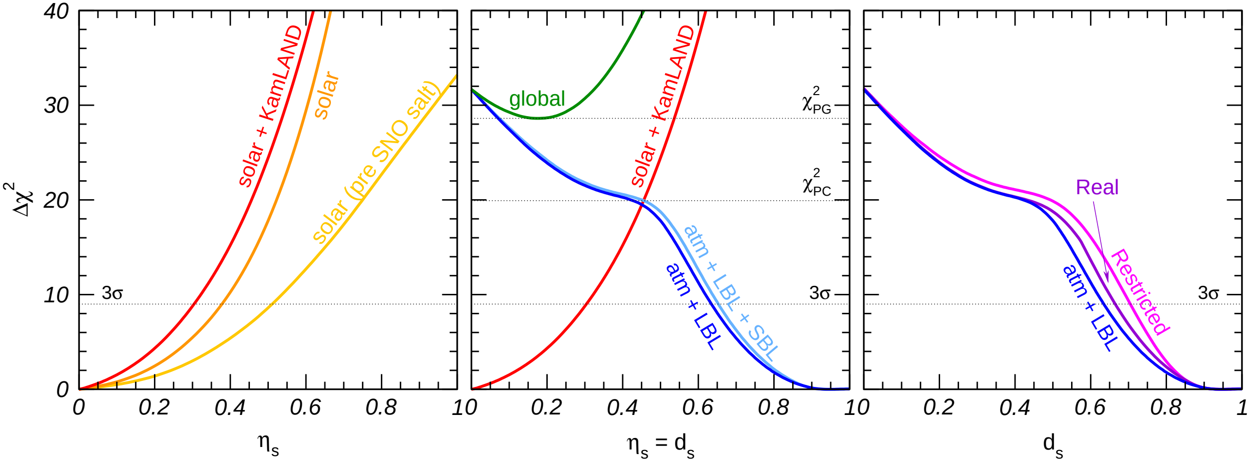
- Approximation: $\Delta m^2_{\text{SOL}} \ll \Delta m^2_{\text{ATM}} \ll \Delta m^2_{\text{LSND}} \Rightarrow$ 6 different mass schemes:



- 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 ⇒ $\boxed{\eta_s = d_s}$;
- 3σ allowed regions $\eta_s \leq 0.31$ (solar) and $d_s \geq 0.63$ (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 $= 9 \times 10^{-8}$ [10].

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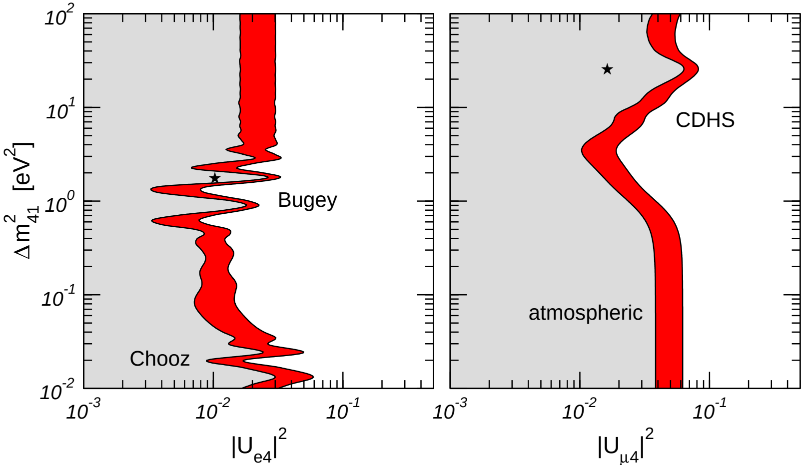
[10] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. **B643** (2002) 321 [`hep-ph/0207157`].

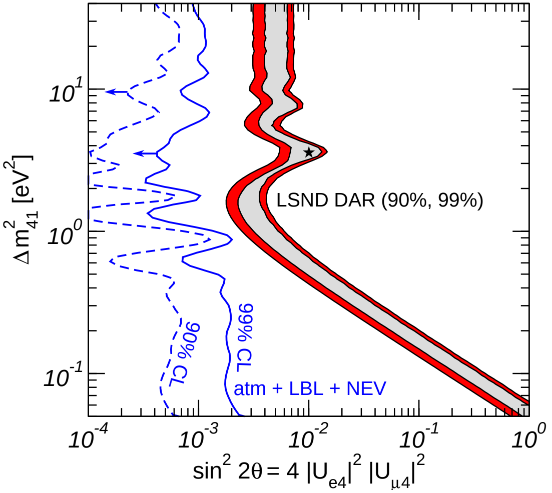
(3+1): tension between LSND and short-baseline data

- 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 [10]:
  - with other *appearance* experiments (Karmen & Nomad);
  - with all *disappearance* exp's.

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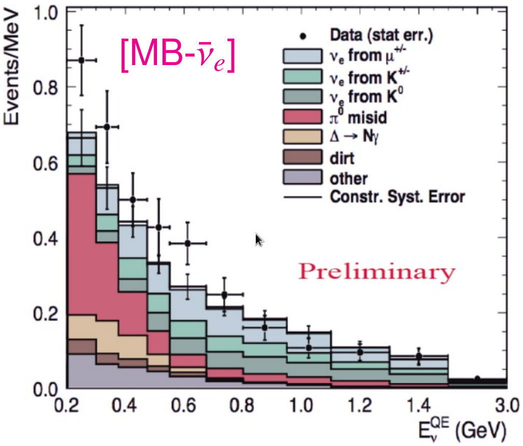
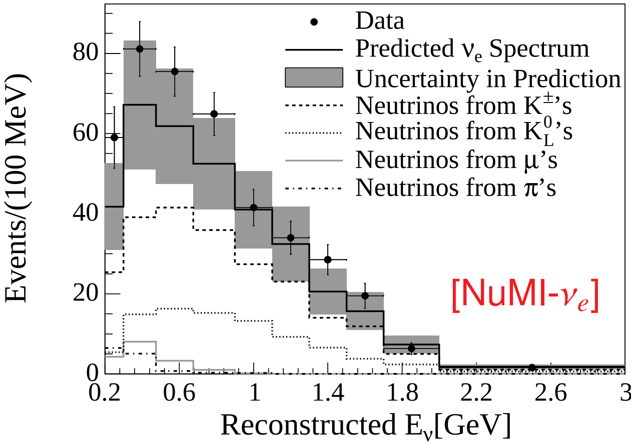
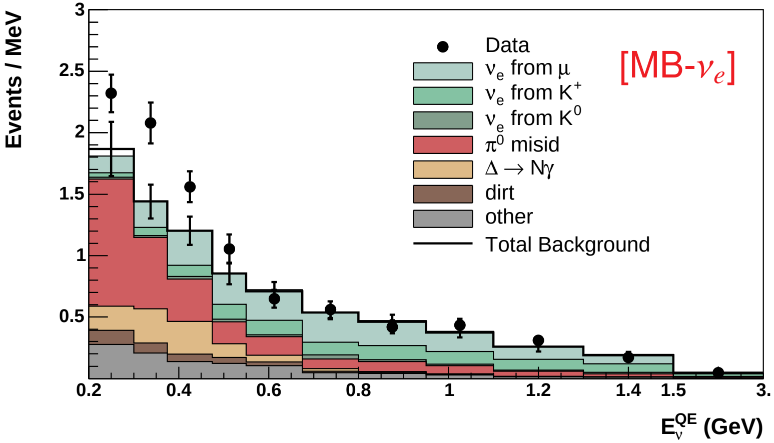
[10] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. **B643** (2002) 321 [`hep-ph/0207157`].

The MiniBooNE experiment

- 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, but not in $\bar\nu_e$;
  - mild mid-energy excess in $\bar\nu_e$, but not in ν_e.

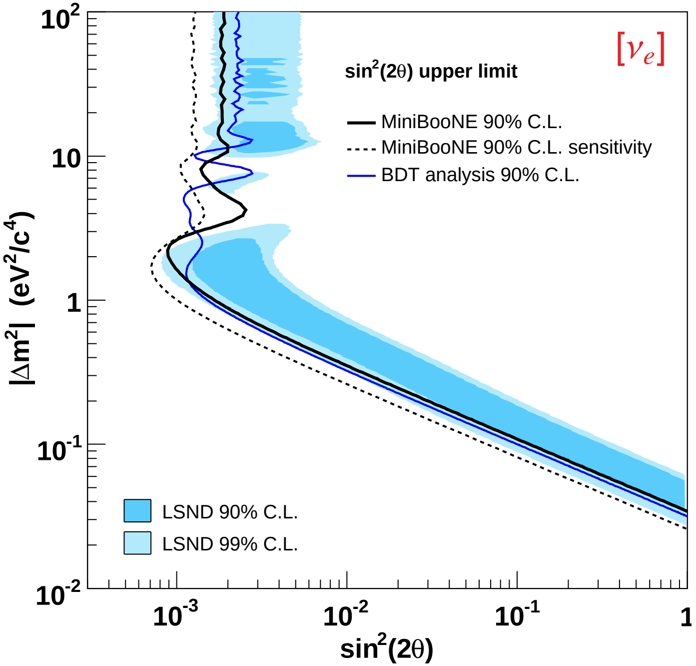


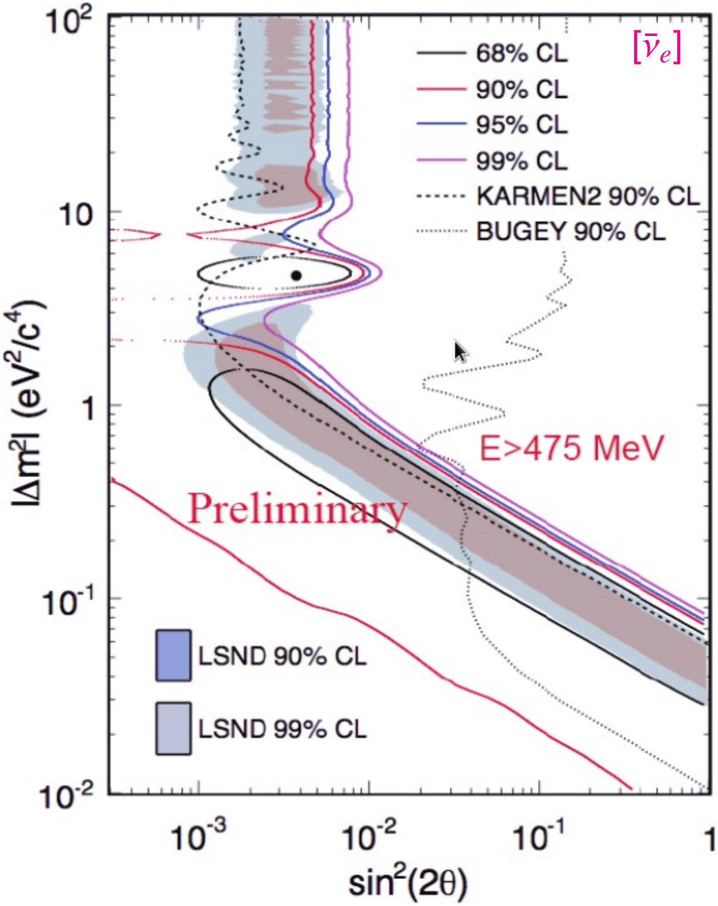




LSND vs MiniBooNE in (3+1)

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

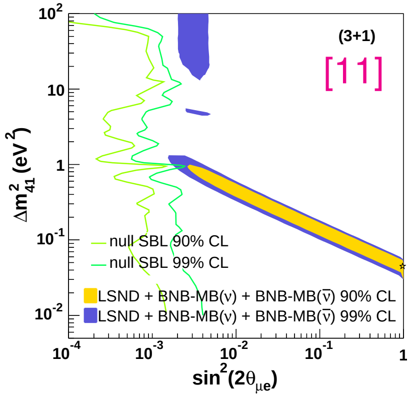




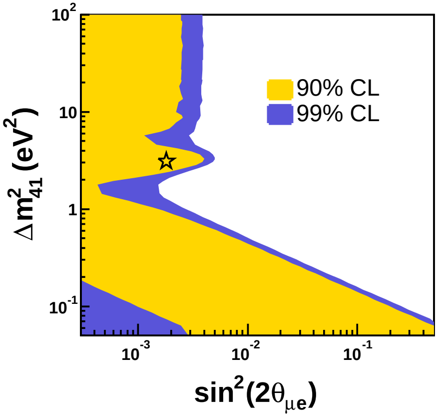
Status of (3+1) models after MiniBooNE

- (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.

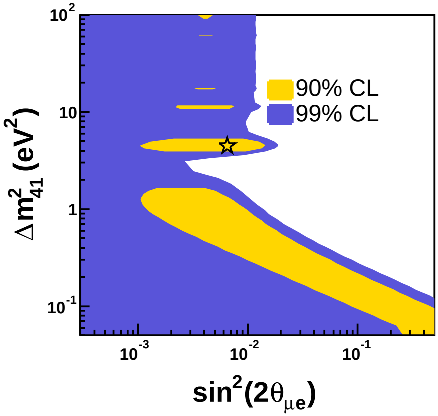
⇒ **(3+1) models are ruled out as explanation of SBL data.**



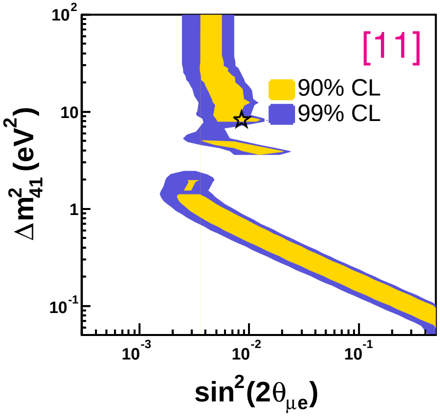
BNB-MB(ν)



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



LSND



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

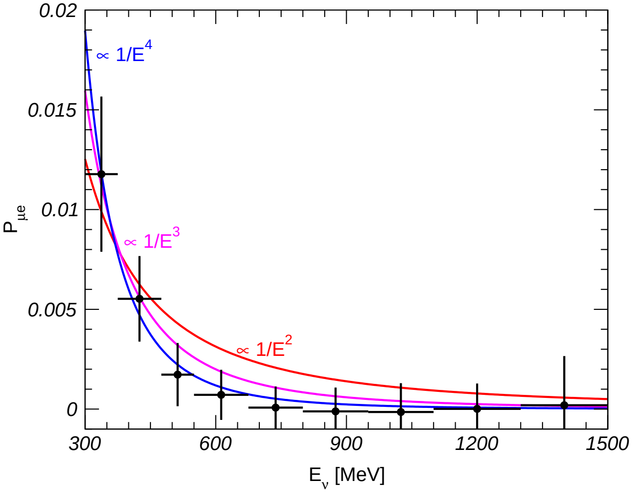
Explaining the MiniBooNE excess with two sterile neutrinos

- 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** [12].

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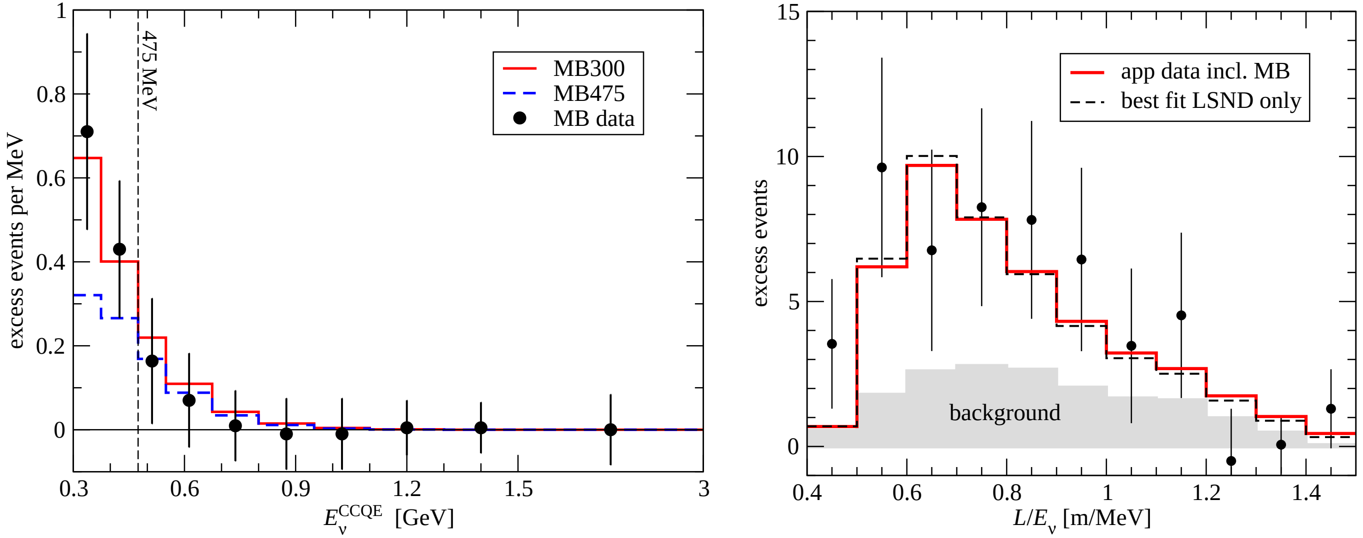
[12] M. Maltoni, T. Schwetz, Phys. Rev. **D76** (2007) 093005 [`arXiv:0705.0107`].

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 [12].

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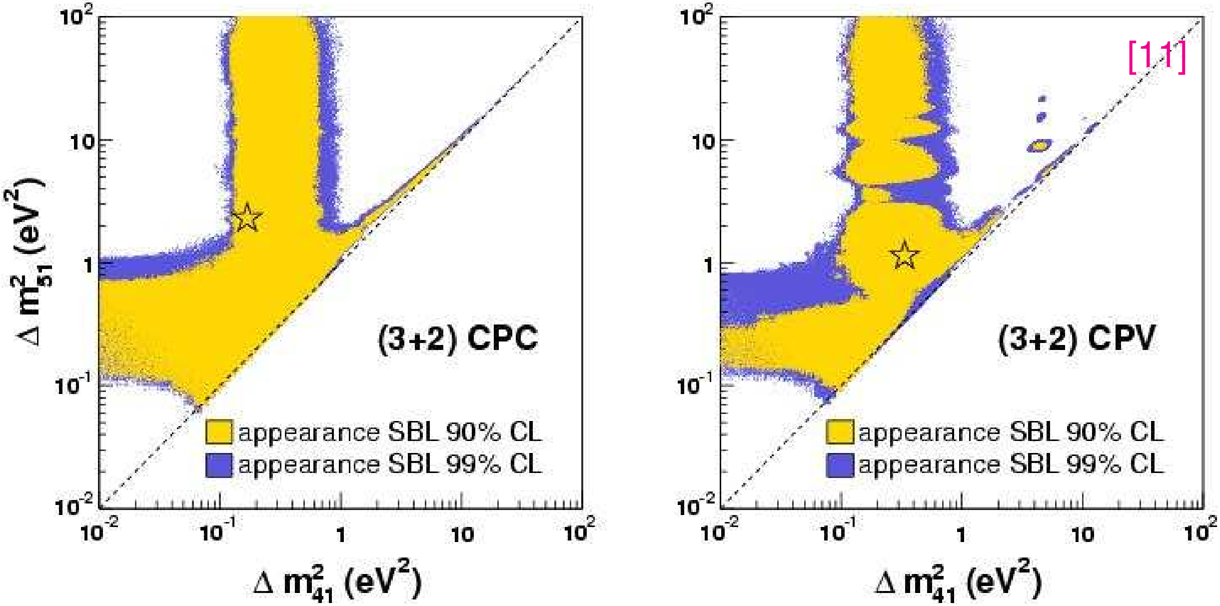
[12] M. Maltoni, T. Schwetz, Phys. Rev. **D76** (2007) 093005 [`arXiv:0705.0107`].

Fitting all appearance data in (3+2) models



data set	$\lvert U_{e4}U_{\mu4}\rvert$	Δm^2_{41}	$\lvert U_{e5}U_{\mu5}\rvert$	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. [11], which uses **old** MB-$\bar{\nu}$ data.

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

The doom of disappearance data

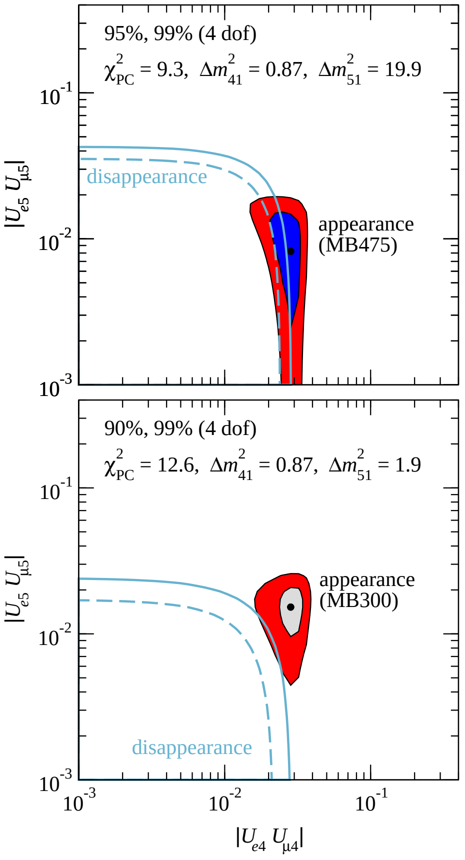
- As for (3+1) models, disappearance data imply bounds on $|U_{ei}|^2$ and $|U_{\mu i}|^2$ $(i = 4, 5)$;
- these bounds are in conflict with the large values of $|U_{ei} U_{\mu i}|$ required by appearance data;
- again, a tension between APP and DIS arises:

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

- 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) [12].**



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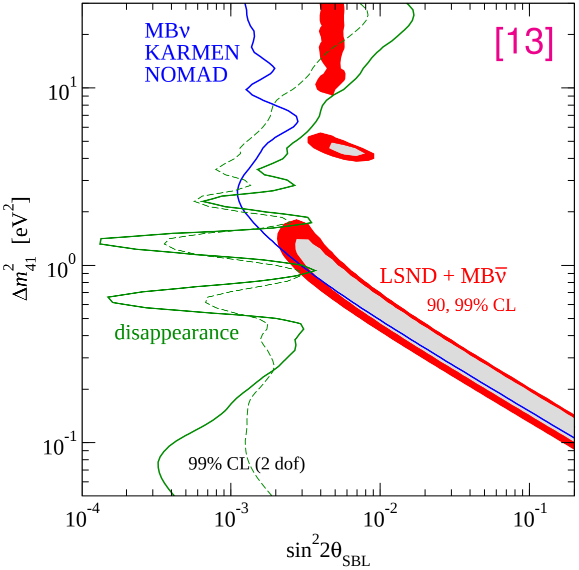
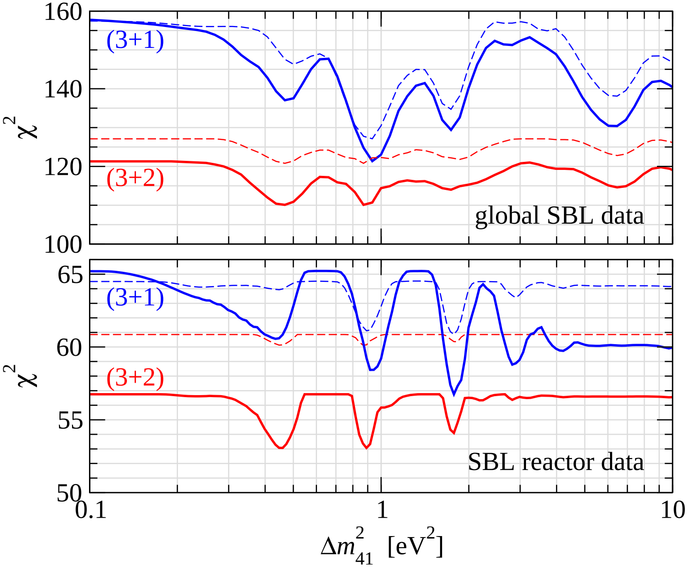
[12] M. Maltoni, T. Schwetz, Phys. Rev. **D76** (2007) 093005 [`arXiv:0705.0107`].

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: $\left\{ \begin{array}{l} \chi^2_{\text{PG}}/\text{dof} = 25.1/5 \to 19.9/5 \text{ for LSND + MB}(\bar{\nu}) \text{ vs NEV } (\Delta\chi^2_{\text{PG}} = 5.2); \\ \chi^2_{\text{PG}}/\text{dof} = 19.4/4 \to 14.7/4 \text{ for APP vs DIS } (\Delta\chi^2_{\text{PG}} = 4.7). \end{array} \right.$

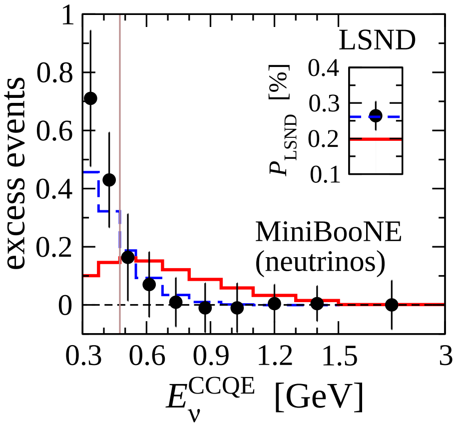


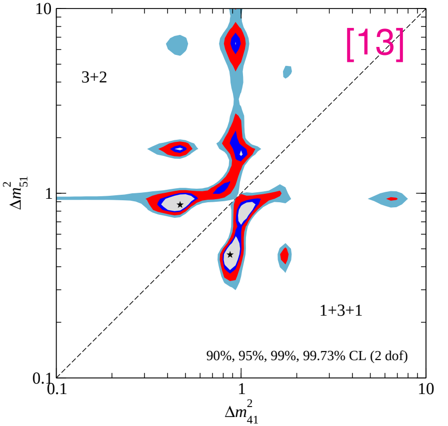


[13] J. Kopp, M. Maltoni, T. Schwetz, to appear in PRL [`arXiv:1103.4570`].

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.





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[13] J. Kopp, M. Maltoni, T. Schwetz, to appear in PRL [`arXiv:1103.4570`].

Summary

- Most of the present data from solar, atmospheric, reactor and accelerator experiments are well explained by the 3ν oscillation hypothesis;
- the "hint" for non-zero θ_{13} has now reached the 3σ **level**, summing up various contributions from solar+KamLAND, atmospheric+Minos-DIS, Minos-APP and T2K;

⇒ **the three-neutrino scenario is robust and provide a good description of most data.**

- Yet, a few experiments exhibit deviations from theis "new" standard 3ν scenario:
  - LSND observed an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam;
  - MiniBooNE mildly confirm this high-E excess in $\bar{\nu}$ mode, but not in ν mode;
  - MiniBooNE observes a strong low-E excess in ν mode, but not in $\bar{\nu}$ mode;
  - 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 tension;
  - new reactor fluxes reduce tension with DIS data, but **not** for MB low-E excess;

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