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Sterile neutrinos after the first MiniBooNE results

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Abstract. In view of the recent results from the MiniBooNE experiment we revisit the global neutrino oscillation fit to short-baseline neutrino data by adding one, two or three sterile neutrinos with eV-scale masses to the three Standard Model neutrinos. We find that four-neutrino oscillations of the (3+1) type, which have been only marginally allowed before the recent MiniBooNE results, become even more disfavored with the new data. In the framework of so-called (3+2) five-neutrino mass schemes the MiniBooNE results can be nicely reconciled with the LSND appearance evidence thanks to the possibility of CP violation available in such oscillation schemes; however, the tension between appearance and disappearance experiments represents a serious problem in (3+2) schemes, so that these models are ultimately not viable. This tension remains also when a third sterile neutrino is added, and we do not find a significant improvement of the global fit in a (3+3) scheme.

1. Introduction

Recently the first results from the MiniBooNE (MB) experiment [1, 2] at Fermilab have been released on a search for $\nu_\mu \to \nu_e$ appearance with a baseline of 540 m and a mean neutrino energy of about 700 MeV. The primary purpose of this experiment is to test the evidence of $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions reported by the LSND experiment at Los Alamos [3] with a very similar L/E range. Reconciling the LSND signal with the other evidence for neutrino oscillations is a long-standing challenge for neutrino phenomenology, since the mass-squared differences required to explain the solar, atmospheric and LSND experimental results in terms of neutrino oscillations differ from one another by various orders of magnitude. Consequently, there is no consistent way to explain all these three signals invoking only oscillations among the three known neutrinos. Therefore, in order to explain the LSND anomaly one had to invoke an extension of the three-neutrino mixing scenario, introducing either a mechanism to generate at least a third mass-square difference, or a new form of flavor transition beyond oscillations. In this talk we will concentrate on the first possibility, starting from models with one extra sterile neutrino (Sec. 2) and then considering models with two and three sterile neutrino states (Sec. 3).

2. Four-neutrino mixing

In four-neutrino models, one extra sterile state is added to the three weakly interacting ones. The relation between the flavor and the mass eigenstates can be described in terms of a 4×4 unitary matrix U, which generalizes the usual 3×3 leptonic matrix of the Standard Model. There are six possible four-neutrino schemes that can accommodate the results from solar and atmospheric neutrino experiments and contain a third much larger Δm^2. They can be divided

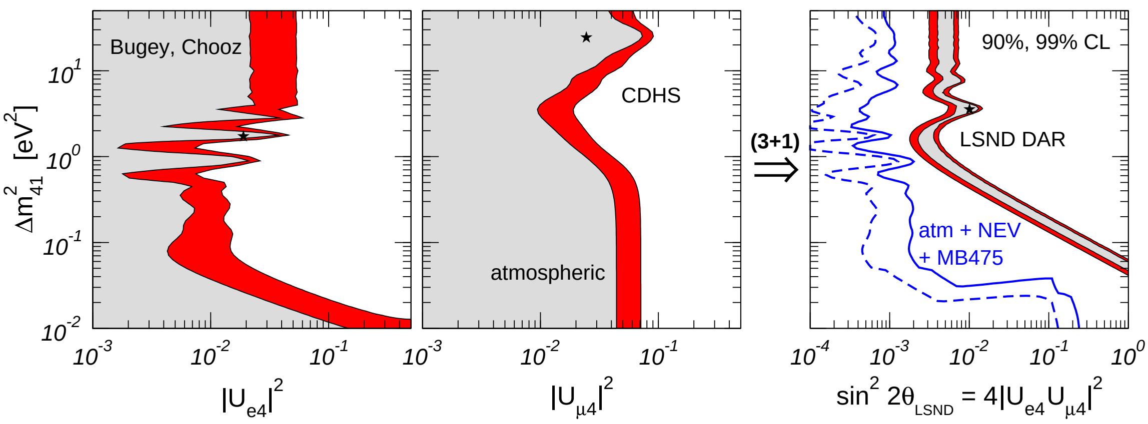

Figure 1. Bounds on $|U_{e4}|^2$ (left panel), on $|U_{\mu4}|^2$ (middle panel) and on $\sin^2 2\theta$ (right panel) in (3+1) schemes, as a function of Δm^2_{41}. Different contours correspond to 90% and 99% CL.

into two classes: (3+1) and (2+2). In the (3+1) schemes, there is a group of three close-by neutrino masses that is separated from the fourth one by the larger gap. In (2+2) schemes, there are two pairs of close masses separated by the large gap. While different schemes within the same class are presently indistinguishable, schemes belonging to different classes lead to very different phenomenological scenarios.

A characteristic feature of (2+2) schemes is that the extra sterile state cannot be simultaneously decoupled from *both* solar and atmospheric oscillations. To understand why, let us define $\eta_s = \sum_{i\,\in\,\text{SOL}} |U_{si}|^2$ and $c_s = \sum_{j\,\in\,\text{ATM}} |U_{sj}|^2$, where the sums in i and j run over mass eigenstates involved in solar and atmospheric neutrino oscillations, respectively. Clearly, the quantities η_s and c_s describe the fraction of sterile neutrino relevant for each class of experiment. Results from atmospheric and solar neutrino data imply that in both kind of experiments oscillation takes place mainly between active neutrinos. Specifically, from Fig. 46 of Ref. [4] we get $\eta_s \le 0.31$ and $c_s \le 0.36$ at the 3σ level. However, in (2+2) schemes unitarity implies $\eta_s + c_s = 1$. A statistical analysis using the *parameter goodness of fit* (PG) proposed in [5] gives $\chi^2_{\text{PG}} = 30.7$ for 1 d.o.f., corresponding to a 5.5σ rejection ($\text{PG} = 3 \times 10^{-8}$) of the (2+2) hypothesis. These models are therefore ruled out at a very high confidence level, and in the rest of this talk we will not consider them anymore.

On the other hand, (3+1) schemes are not affected by this problem. Although the experimental bounds on η_s and c_s quoted above still hold, the condition $\eta_s + c_s = 1$ no longer applies. For what concerns neutrino oscillations, in (3+1) models the mixing between the sterile neutrino and the three active ones can be reduced at will, and in particular it is possible to recover the usual three-neutrino scenario as a limiting case. However, as widely discussed in the literature (see, *e.g.*, Ref. [6] and references therein) these models are strongly disfavored as an explanation of LSND by the data from other short-baseline (SBL) laboratory experiments. In the limit $\Delta m^2_{\text{LSND}} \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$ the probability $P_{\nu_\mu \to \nu_e}$ which is relevant for LSND as well as for KARMEN [7], NOMAD [8] and MiniBooNE is driven by the large Δm^2_{41}, and is given by

$$P_{\nu_\mu \to \nu_e} = P_{\bar\nu_\mu \to \bar\nu_e} = 4\,|U_{e4} U_{\mu4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}\,, \tag{1}$$

where L is the distance between source and detector. The LSND, KARMEN, NOMAD and MiniBooNE experiments give allowed regions in the $(\Delta m^2_{41},\, |U_{e4} U_{\mu4}|^2)$ plane which can be directly obtained from the corresponding two-neutrino exclusion plots [2, 3, 7, 8]. At the light of the recent MiniBooNE result which is consistent with no oscillations above 475 MeV, practically all the LSND region is now excluded. In addition, further constraints on $|U_{e4}U_{\mu4}|^2$ can be obtained by combining together the bounds on $|U_{e4}|$ and $|U_{\mu4}|$ derived from reactor and accelerator experiments (mainly Bugey [9] and CDHS [10]) as well as solar and atmospheric data. These bounds are plotted in the two leftmost panels of Fig. 1 as a function of Δm^2_{41}. A detailed and statistically meaningful evaluation of the final combined limit, including the results of atmospheric and long-baseline data together with all the short-baseline experiments observing *no evidence* (NEV), has been presented in Ref. [11] and is summarized in the right panel of Fig. 1. Using the PG test discussed above we find $\chi^2_{\text{PG}} = 24.7$ for 2 d.o.f., corresponding to a 4.6σ rejection (PG $= 4 \times 10^{-6}$) of the (3+1) hypothesis. These results show that (3+1) schemes are now ruled out as a possible explanation of LSND [11]. In addition, it should be noted that the low-energy excess observed by MiniBooNE at $E_\nu \leq 475$ MeV cannot be explained in terms of oscillations with only one large mass-squared difference, thus adding another problem to these models in case this excess is confirmed to be a real signal.

3. Five-neutrino and six-neutrino mixing

Five-neutrino schemes of the (3+2) type are a straight-forward extension of (3+1) schemes. In addition to the cluster of the three neutrino mass states accounting for "solar" and "atmospheric" mass splittings now two states at the eV scale are added, with a small admixture of ν_e and ν_μ to account for the LSND signal. In the Appendix of Ref. [12] it was suggested that such models could somewhat relax the tension existing between short-baseline experiments and the LSND data. In Ref. [13] a complete analysis was performed, finding that indeed the disagreement between LSND and null-result experiments is reduced. Here we will reconsider this possibility at the light of the new MiniBooNE data. As explained in Ref. [2], MiniBooNE found no evidence of oscillations above 475 MeV, whereas below this energy a 3.6σ excess of $96 \pm 17 \pm 20$ events is observed. Whether this excess comes indeed from $\nu_\mu \to \nu_e$ transitions or has some other origin is under investigation [2]. Lacking any explanation in terms of backgrounds or systematical uncertainties, we will present the results obtained using both the full energy range from 300 MeV to 3 GeV ("MB300") and for the restricted range from 475 MeV to 3 GeV ("MB475").

As for (3+1) models, in (3+2) schemes the *appearance* data (LSND, KARMEN, NOMAD, and MiniBooNE) can be described using the SBL approximation $\Delta m^2_{\text{SOL}} \approx 0$ and $\Delta m^2_{\text{ATM}} \approx 0$, in which case the relevant transition probability is given by

$$P_{\nu_\mu \to \nu_e} = 4\,|U_{e4}U_{\mu4}|^2 \sin^2\phi_{41} + 4\,|U_{e5}U_{\mu5}|^2 \sin^2\phi_{51} + 8\,|U_{e4}U_{\mu4}|\,|U_{e5}U_{\mu5}| \sin\phi_{41}\sin\phi_{51}\cos(\phi_{54} - \delta)\,, \quad (2)$$

with the definitions $\phi_{ij} \equiv \Delta m^2_{ij} L/4E$ and $\delta \equiv \arg(U^*_{e4}U_{\mu4}U_{e5}U^*_{\mu5})$. Eq. (2) holds for neutrinos (NOMAD and MB); for anti-neutrinos (LSND and KARMEN) one has to replace $\delta \to -\delta$. Note that Eq. (2) is invariant under the transformation $4 \leftrightarrow 5$ and $\delta \leftrightarrow -\delta$, and depends only on the combinations $|U_{e4}U_{\mu4}|$ and $|U_{e5}U_{\mu5}|$. An important observation is that non-trivial values of the complex phase δ lead to CP violation, and hence in (3+2) schemes much more flexibility is available to accommodate the results of LSND (anti-neutrinos) and MB (neutrinos). In Fig. 2 we show the prediction for MB and LSND at the best fit points of the combined MB, LSND, KARMEN, NOMAD analysis. As can be seen from this figure, MB data can be fitted very well while simultaneously explaining the LSND evidence. Furthermore, in this case also the low energy MB data can be explained, and therefore, in contrast to (3+1) schemes, (3+2) oscillations offer an appealing possibility to account for this excess. For both MB475 and MB300 a goodness-of-fit of 85% is obtained, showing that MB is in very good agreement with global SBL appearance data including LSND.

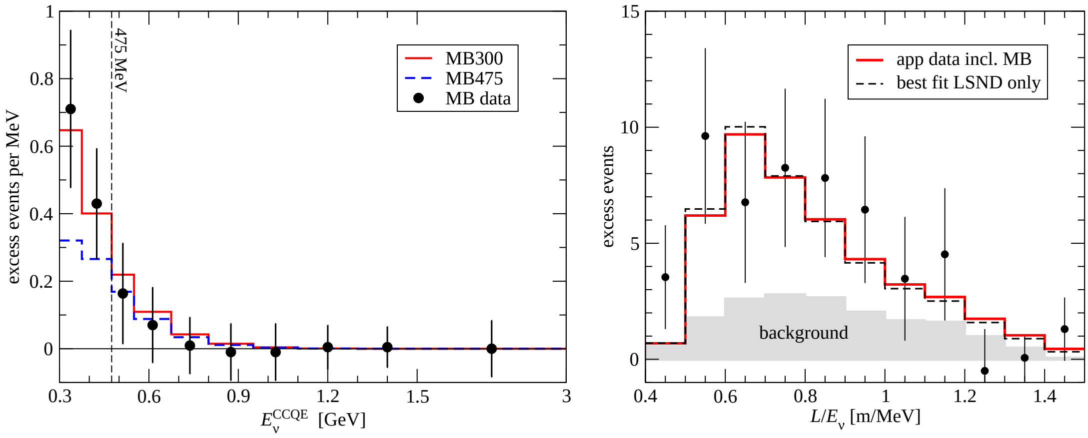

Figure 2. Spectral data for the MiniBooNE (left) and LSND (right) experiments, calculated at the best fit point of a combined fit of LSND, KARMEN, NOMAD and MB in (3+2) schemes.

On the other hand, once *disappearance* data are included in the analysis, the quality of the fit decreases considerably. Indeed, even in (3+2) schemes short-baseline experiments pose stringent bounds on the mixing angles $|U_{ei}|$ and $|U_{\mu i}|$, in close analogy with (3+1) models described in Sec. 2 and shown in the two leftmost panels of Fig. 1. Since rather large values of $|U_{e4}U_{\mu 4}|$ and $|U_{e5}U_{\mu 5}|$ are needed to account for the negative result of MiniBooNE as well as the positive signal of LSND, one expects that reconciling appearance and disappearance data will be a problem also within (3+2) models. This tension is illustrated in Fig. 3, where the projections of the allowed regions in the plane of the appearance amplitudes $|U_{e4}U_{\mu 4}|$ and $|U_{e5}U_{\mu 5}|$ are shown. Indeed the opposite trend of the two data sets is clearly visible, especially when the low energy excess in MB is included (right panel). In order to quantify this disagreement one can apply the PG test to appearance versus disappearance data without MB, with MB475, and with MB300:

$$\text{APP vs DIS:} \quad \begin{cases} \chi^2_{\rm PG} = 17.5\,, & \text{PG} = 1.5\times 10^{-3} \quad \text{(no MB)}, \\ \chi^2_{\rm PG} = 17.2\,, & \text{PG} = 1.8\times 10^{-3} \quad \text{(MB475)}, \\ \chi^2_{\rm PG} = 25.1\,, & \text{PG} = 4.8\times 10^{-5} \quad \text{(MB300)}. \end{cases} \tag{3}$$

From these numbers we conclude that also in (3+2) schemes the tension between appearance and disappearance experiments is quite severe. If MB475 is used the result is very similar to the pre-MiniBooNE situation implying inconsistency at about 3.1σ, whereas in case of the full MB300 data the tension becomes significantly worse (about 4σ), since appearance data are more constraining because of the need to accommodate LSND as well as the MB excess at low energies.

Finally, since there are three active neutrinos it seems natural to consider also the case of three sterile neutrinos. If all three additional neutrino states have masses in the eV range and mixings as relevant for the SBL experiments under consideration, such a model will certainly have severe difficulties to accommodate standard cosmology [14]. Besides this fact, the results of the search performed in Ref. [11] show that there is only a marginal improvement of the fit by 1.7 units in χ^2 for MB475 (3.5 units for MB300) with respect to (3+2), to be compared with four additional parameters in the model. Hence, the conclusion is that here are no qualitatively new effects in the (3+3) scheme. The conflict between appearance and disappearance data remains a problem, and the additional freedom introduced by the new parameters does not relax significantly this tension.

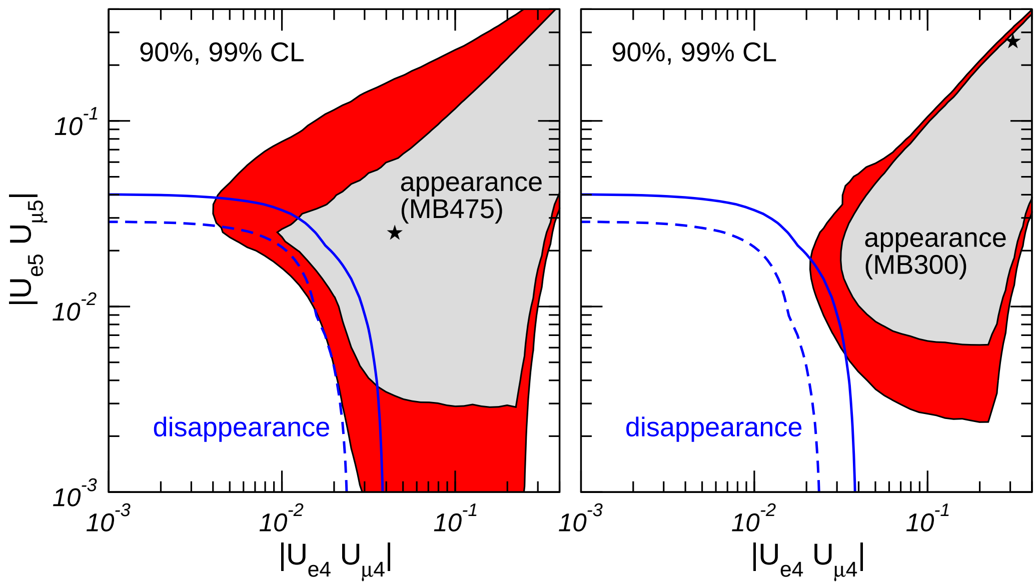

Figure 3. Allowed regions at 90% and 99% CL in (3+2) schemes from the analysis of appearance and disappearance data, projected onto the plane of $|U_{e4}U_{\mu 4}|$ and $|U_{e5}U_{\mu 5}|$.

4. Conclusions

We have considered the global fit to short-baseline neutrino oscillation data including the recent data from MiniBooNE, in the framework of (3+1), (3+2) and (3+3) oscillation models. Four-neutrino models are ruled out since (a) the don't allow to account for the low energy event excess in MB, (b) MiniBooNE result cannot be reconciled with LSND, and (c) there is severe tension between *appearance* and *disappearance* experiments. Five-neutrino models provide a nice way out for problems (a) and (b), but fail to resolve (c). Similarly, six-neutrino models do not offer qualitatively new effects with respect to (3+2). In all cases we find severe tension between different sub-samples of the data, hence we conclude that at the light of present experimental results it is *not* possible to explain the LSND evidence in terms of sterile neutrinos.

Acknowledgments

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