Sterile Neutrino Oscillations and CP Violation Implications for MiniBooNE

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Abstract. These proceedings provide a summary of results from a combined analysis of short-baseline (SBL) oscillation data, including data from LSND and MiniBooNE, under a 3 active + 2 sterile neutrino oscillation hypothesis. The analysis is done within both a CP-conserving (CPC) and a CP-violating (CPV) framework. The implications for any possible leptonic CP violation that is allowed by a combined analysis of the null-SBL and LSND experiments are discussed in relation to the MiniBooNE experiment.

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Sterile neutrinos, unlike the three SM (active) neutrinos, do not interact through standard weak couplings. Their existence has been motivated experimentally by the LSND signature [1]. In this case, neutrinos with masses of order 1 eV and with very small active flavor content can participate in neutrino oscillations.

CONSTRAINTS FROM SHORT-BASELINE EXPERIMENTS

The oscillation parameters for sterile neutrino models are well constrained by the null SBL experiments (see, for example, [2]). The results presented in this talk reflect constraints on ν_μ disappearance from CCFR84[3] and CDHS[4]; ν_e disappearance from Bugey[5] and Chooz[6]; and $\nu_\mu \to \nu_e$ appearance from KARMEN2[7], and NOMAD[8].

Based on the combined analysis of the above oscillation data, including LSND, we estimate the range of fundamental parameters in (3+2) sterile neutrino models, following a similar analysis to that in Ref. [9], with the exception that MiniBooNE data has been added to the analysis to further constrain oscillation parameters.

The MiniBooNE experiment, which was designed to directly test the LSND result, has recently reported its first results from data collected during its neutrino running mode [10]. The results show that MiniBooNE is incompatible with LSND within a CPT/CP-conserving two-neutrino oscillation hypothesis at the 90% CL. This, however, could be interpreted as a call for a more complicated oscillation scenario in order to reconcile the two results. Furthermore, MiniBooNE has observed a significant excess of ν_e-like events at low energies. Because of this low-energy excess, and since within the scope of a (3+2) oscillation scenario with CP violation it is possible to reconcile MiniBooNE and LSND [11], we find it necessary and interesting to perform this analysis with MiniBooNE data over the full MiniBooNE energy range (0.3-3 GeV).

The MiniBooNE data is fitted according to two separate hypotheses: one where only $\nu_\mu \to \nu_e$ appearance is allowed in order to describe the MiniBooNE data, and one where both $\nu_\mu \to \nu_e$ appearance and ν_μ and ν_e disappearance is allowed.

(3+2) STERILE NEUTRINO OSCILLATION FORMALISM

In (3+2) oscillation models, the disappearance and appearance oscillation probabilities used to describe SBL oscillation data are given by Eqs. (1) and (2) [9].

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2) \cdot (|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) + |U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 x_{54}] \quad (1)$$

$$P(\nu_\alpha \to \nu_{\beta \neq \alpha}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 x_{41} + 4|U_{\alpha 5}|^2 |U_{\beta 5}|^2 \sin^2 x_{51} + 8|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \sin x_{41} \sin x_{51} \cos(x_{54} + \phi_{45}) \quad (2)$$

To obtain the above expressions, one assumes $x_{21} \approx x_{31} \approx 0$. The subscripts 4 and 5 represent the fourth and fifth sterile neutrino mass eigenstates; $\alpha = e, \mu$, making the above expressions relevant to SBL ν_e and ν_μ oscillations. The CP-violating phase ϕ_{45} defined as:

$$\phi_{45} = arg(U^*_{\mu 5} U_{e5} U_{\mu 4} U^*_{e4}) \quad (3)$$

For antineutrino oscillations one substitutes $\phi_{45} \to -\phi_{45}$. It should be noted that the (3+2) scenario is the

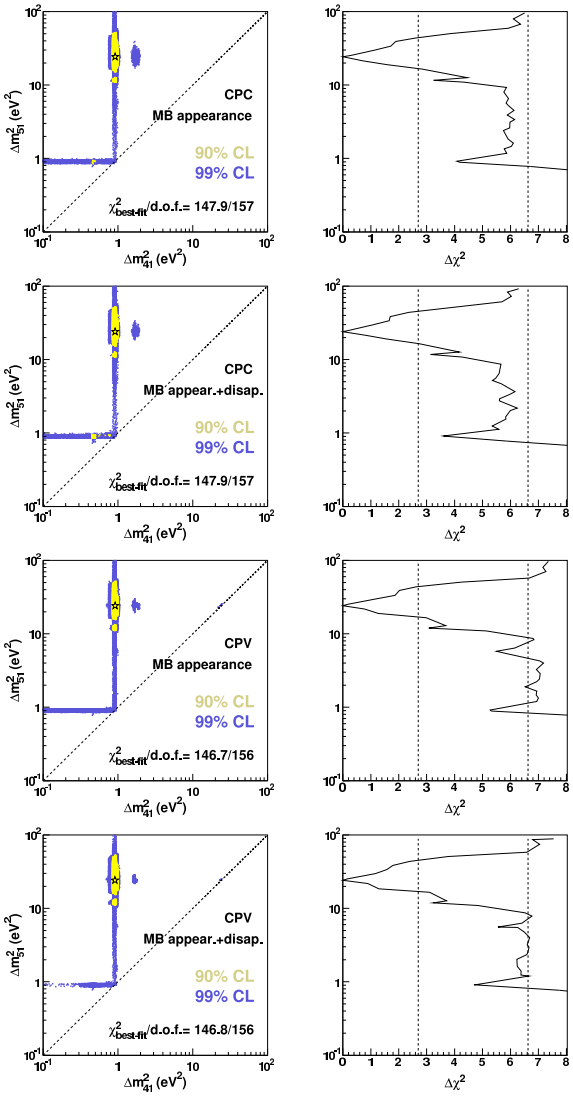

FIGURE 1. Allowed regions at 90% and 99% CL in $(\Delta m^2_{41}, \Delta m^2_{51})$ space from combined fits of appearance and disappearance experiments. See text for details.

most minimal sterile neutrino model that allows for CP violation studies at SBL oscillation experiments [9].

(3+2) OSCILLATION ANALYSIS AND RESULTS

The details of the method and assumptions followed in the analysis can be found in [9].

We implement constraints from MiniBooNE by comparing the ratio of ν_e-like to ν_μ-like predicted events after having applied relevant oscillation probabilities, to a ratio of ν_e-like to ν_μ-like observed events, as a function of reconstructed neutrino energy (8 bins). Events defined as ν_e-like include intrinsic ν_e background events, ν_μ-induced events that are mis-identified as ν_e events, and ν_e events resulting from any ν_μ's that have oscillated into ν_e's according to the appearance oscillation probability in Eq. (2). Events defined as ν_μ-like include ν_μ CCQE events only. This method allows for constraining both $\nu_\mu \to \nu_e$ oscillations, and ν_μ and ν_e disappearance with the MiniBooNE dataset, by letting the intrinsic ν_e events, and mis-identified ν_μ and ν_μ CCQE events to disappear according to Eq. (1), where $\alpha = e$, and $\alpha = \mu$, respectively. To allow only $\nu_\mu \to \nu_e$ oscillations to describe the MiniBooNE data, the above disappearance oscillation probabilities are set equal to 1 in the calculation of the MiniBooNE signal prediction, independent of the oscillation parameters. The MiniBooNE χ^2 contribution to the total χ^2 is formed using the full MiniBooNE fractional covariance matrix, including statistical+all systematic errors as in [10], scaled according to the MiniBooNE signal prediction.

Figure (1) shows results from combined fits of both appearance and disappearance experiments. The top two rows show the allowed regions in $(\Delta m^2_{41}, \Delta m^2_{51})$ space (left), and the χ^2_{min} projection as a function of Δm^2_{51} (right), under a CP-conserving scenario; the bottom two rows illustrate the same parameters under a CP-violating scenario. In rows 1 and 3, only $\nu_\mu \to \nu_e$ oscillations are allowed to describe the MiniBooNE dataset; in rows 2 and 4, both $\nu_\mu \to \nu_e$ oscillations and ν_μ and ν_e disappearance are allowed. The best-fit χ^2 and number of degrees of freedom for each case is shown in the bottom right-hand side of the left panels.

From this figure, it is evident that allowing ν_μ and ν_e disappearance along with $\nu_\mu \to \nu_e$ oscillations to describe MiniBooNE data does not seem to either favor or disfavor combined fits, compared to allowing just $\nu_\mu \to \nu_e$ oscillations. Finally, there seems to be no significant difference in preference of a CPV rather than a CPC scheme. The best fit model parameters are summarized in Tab. (1).

Not shown in these proceedings are the allowed regions obtained when considering appearance-only experiments. In that case, the allowed regions expand considerably compared to the combined appearance and disappearance experiment analysis. The obtained $\chi^2(d.o.f.)$ is 52.6(52) and 52.3(51) for the CPC and CPV hypothesis, respectively. (Here, only $\nu_\mu \to \nu_e$ oscillations are allowed for MiniBooNE).

CP VIOLATION IMPLICATIONS FOR MINIBOONE

Figure (2) shows the expected asymmetry in oscillation probability to be measured in neutrino and antineutrino

TABLE 1. Comparison of best-fit values for (3+2) CPC and CPV model parameters in a combined SBL analysis. (MiniBooNE dataset description assumes both appearance and disappearance). Mass splittings are shown in eV^2.

Model	χ^2 $(d.o.f.)$	Δm^2_{41}	Δm^2_{51}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	ϕ_{45}
CPC	147.9(157)	0.91	24	0.13	0.15	0.07	0.16	0
CPV	146.8(156)	0.91	24	0.12	0.14	0.07	0.17	1.72π

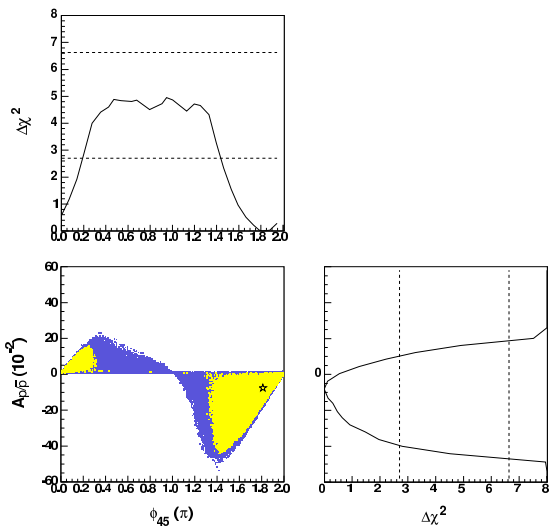

FIGURE 2. Expected MiniBooNE oscillation probability asymmetry measurement as a function of the CPV phase ϕ_{45} from short-baseline results. Light gray: 90% CL allowed region; dark gray: 99% CL allowed region.

running modes at MiniBooNE, $A_{p/\bar{p}}$, as a function of the CPV phase ϕ_{45}, from Ref. [9]. The allowed regions are obtained using constraints from the null-SBL and LSND experiments assuming a (3+2) oscillation scenario. The figure shows that all values for the CP-phase ϕ_{45} are presently allowed at the 99% confidence level, with small degrees of CP violation being marginally preferred. The bottom left plot shows that large (up to 50%) CP asymmetry is possible, but not required, for maximal CP violation ($\phi_{45} = \pi/2$ or $3\pi/2$).

A significant departure from zero in the asymmetry observable $A_{p/\bar{p}}$ could naturally be interpreted as a manifestation of leptonic CP violation. The MiniBooNE expected asymmetry predicted by the (3+2) CPV best-fit model parameters shown in Tab. (1) corresponds to $(\phi_{45}, A_{p/\bar{p}})$ = $(1.72\pi$,-12%). Such measurement at MiniBooNE would have a significance of approximately one sigma assuming that 6×10^{20} protons on target (POT) are delivered in both neutrino and antineutrino running mode. So far MiniBooNE has collected data for 7.0×10^{20} POT in neutrino mode, and 2.4×10^{20} POT in antineutrino mode. The MiniBooNE collaboration has recently submitted a proposal to the Physics Advisory Committee at Fermilab requesting an extension of the MiniBooNE antineutrino run, and is currently awaiting approval.

CONCLUSIONS

In conclusion, both CP-conserving and CP-violating (3+2) oscillations are possible and equally preferred by a combined analysis of SBL experiments, including LSND and MiniBooNE. However, if CP violation occurs within the context of (3+2) sterile neutrino models, MiniBooNE could observe a large asymmetry in oscillation probability during its neutrino and antineutrino running modes. Thus, not only is the MiniBooNE data important in addressing the viability of sterile neutrino models, but also a longer MiniBooNE antineutrino run would allow for more detailed studies of a possible CPV scenario, and a more confident determination of a possible CPV phase.

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