LSND and MiniBooNE within (3+1) plus NSI

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Abstract. The recently observed event excess in MiniBooNE anti-neutrino data is in agreement with the LSND evidence for electron anti-neutrino appearance. We propose an explanation of these data in terms of a (3+1) scheme with a sterile neutrino including non-standard neutrino interactions (NSI) at neutrino production and detection. The interference between oscillations and NSI provides a source for CP violation which we use to reconcile different results from neutrino and anti-neutrino data. Our best fit results imply NSI at the level of a few percent relative to the standard weak interaction, in agreement with current bounds. We compare the quality of the NSI fit to the one obtained within the (3+1) and (3+2) pure oscillation frameworks.

Keywords: neutrino oscillations, sterile neutrinos, non-standard interactions
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Recently the MiniBooNE collaboration announced updated results of their search for $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions [1]. In the full energy range from 200 MeV to 3 GeV they find an excess of 43.2 ± 22.5 events over expected background. In the oscillation-sensitive region of 475 MeV to 1250 MeV the background-only-hypothesis has a probability of only 0.5% [1]. This result is consistent with the evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions reported by LSND [2], if interpreted in terms of effective two-flavour oscillations, see fig. 1. Any explanation of these hints for $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions at the scale of $E/L \sim 1$ eV^2 has to satisfy strong constraints from various experiments. First, no evidence for transitions has been found in MiniBooNE neutrino data above 475 MeV [3]. This suggests that CP (or even CPT) violation has to be invoked to reconcile neutrino and anti-neutrino data. Second, severe constraints exist for $\bar{\nu}_e$ [4, 5] and $\nu_\mu, \bar{\nu}_\mu$ [6, 7, 8, 9] disappearance at this scale, which have to be respected by any explanation of the $\bar{\nu}_\mu \to \bar{\nu}_e$ excesses.

The standard approach to the LSND problem is to introduce one or more sterile neutrinos at the eV scale. Adding one sterile neutrino one obtains the so-called (3+1) mass scheme. In this framework there is no CP violation at short baselines, and disappearance experiments strongly disfavour an explanation of the appearance signals, see for example [10]. This tension is illustrated in fig. 1. If two neutrino mass states at the eV scale are present [11, 12] ((3+2) scheme), the possibility of CP violation opens up [13], which allows to reconcile LSND and MiniBooNE neutrino data [14]. However, constraints from disappearance data still impose a challenge to the fit, and the overall improvement with respect to the (3+1) case is not significant [14, 15].

Here we report on an explanation of the global data based on a (3+1) neutrino scheme which is supplemented by non-standard interactions (NSI) of neutrinos [16]. Such new interactions may be induced by generic new

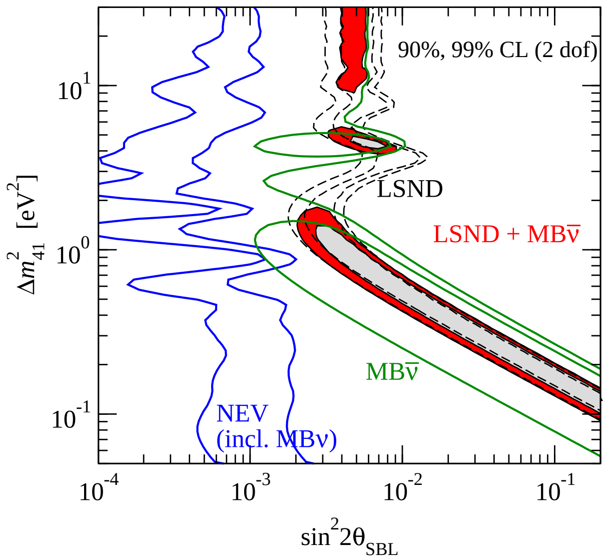

FIGURE 1. Constraint from no-evidence data (NEV) compared to the combined allowed regions from LSND and MiniBooNE $\bar{\nu}$ data (shaded) at 90% and 99% CL for (3+1) oscillations. We show also the individual regions from LSND and MiniBooNE $\bar{\nu}$ data.

physics beyond the Standard Model. Model-independent bounds on such new interactions are at the level of few $\times 10^{-2}$ compared to the standard 4-Fermi interaction strength set by G_F, see [17] and references therein. An observation of NSI at that level would be a remarkable sign of new physics.

Since the experiments considered here typically have rather short baselines (below 1 km), matter effects are very small and NSI affecting the propagation of neutrinos through matter will have a negligible impact. Therefore, we focus on charged-current (CC) like NSI, see for example [18, 19]. We assume that, in addition to the standard CC weak interactions, there exist non-standard CC-like interactions, whose Lagrangian can be parameterised at low energies as

$$\mathscr{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta} \varepsilon^{ff'}_{\alpha\beta} (\bar{f} P_{L,R} \gamma^\mu f')(\bar{l}_\alpha P_L \gamma_\mu \nu_\beta) + h.c.. \tag{1}$$

Here G_F is the Fermi constant, f and f' correspond to either quarks or leptons differing by one unit of electric charge and l_α corresponds to a charged lepton ($l_\alpha = e, \mu, \tau$). $P_{L(R)}$ denotes the projection operator on left-handed (right-handed) fields. The particular chirality structure assumed in eq. (1) allows for interference of standard and non-standard processes. The interactions in eq. (1) contribute to CC processes of neutrino emission and absorption. Thanks to the interference between NSI effects and oscillations with $\Delta m^2_{41} \sim 1$ eV^2 we obtain CP violation [19], even in the presence of only one mass scale. This effect is used to reconcile the indication for $\bar{\nu}_\mu \to \bar{\nu}_e$ in anti-neutrino experiments (LSND and MiniBooNE) with the absence of a signal in MiniBooNE neutrino data.

In [16] we have presented a general parameterisation of the relevant transition and survival probabilities in the presence of oscillations (within the one-mass scale approximation) and NSI, and we have identified particular combinations of mixing matrix elements $U_{\alpha 4}$ and NSI parameters $\varepsilon_{\alpha\beta}$ entering in the probabilities. This drastically reduces the number of independent parameters and allows us to perform a general fit to global short-baseline data.

We have considered two versions of the (3+1) NSI model. In the general case (denoted NSI^g) we make use of the fact that the neutrino production mechanism in LSND and in KARMEN [20] is muon decay (purely leptonic), whereas in all other experiments neutrino production and detection are semi-leptonic, involving transitions between u and d quarks. Therefore, in the presence of suitable NSI parameters we can decouple the transition probabilities in LSND and KARMEN from the rest of the data. In this case we obtain an excellent fit to the global data and the tension between appearance and disappearance experiments is resolved. For the global fit of appearance and disappearance data we find a χ^2 difference with respect to (3+1) oscillations of

$$\chi^2_{\rm min,(3+1)osc} - \chi^2_{\rm min,(3+1)NSI^g} = 18.5 \qquad (5\ \text{dof}), \tag{2}$$

where the number of dof corresponds to the additional 5 new parameters when extending the (3+1) oscillation scheme to NSI^g. The $\Delta\chi^2$ value corresponds to 99.76% CL. Hence, (3+1) oscillation can be excluded at the 3σ level compared to the NSI^g case. Let us mention that in this case MiniBooNE does not provide a direct test of LSND, since different combinations of parameters are relevant for them.

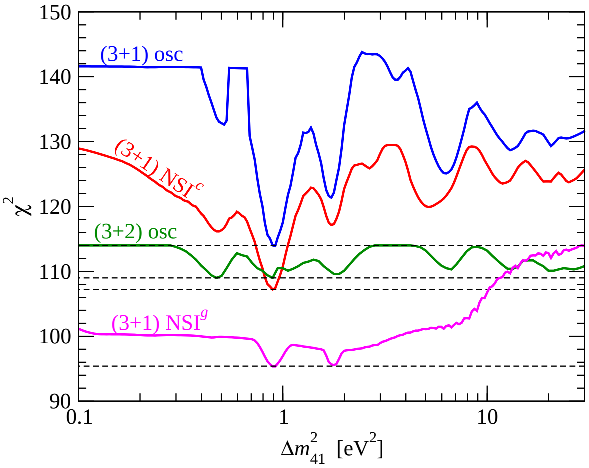

FIGURE 2. χ^2 of global data as a function of Δm^2_{41} for the (3+1) oscillation, (3+1) NSI^c, (3+1) NSI^g, and (3+2) oscillation models. In each case we minimise with respect to all parameters except Δm^2_{41}.

For the second version of the (3+1) NSI model we adopt the assumption that NSI involving the charged muon can be neglected. In this case exactly the same NSI parameters are relevant for LSND and KARMEN as for all other experiments. In this constrained model (NSI^c) we make use of the CP violation due to NSI–oscillation interference to reconcile neutrino and anti-neutrino data. We have shown that in the NSI^c model there is a factorisation between appearance and disappearance amplitudes, similar to that in the (3+1) oscillation scheme. Therefore, it is more difficult to satisfy constraints from disappearance experiments and some tension is left in the fit. However, also this model provides significant improvement of the global fit compared to the pure oscillation case:

$$\chi^2_{\rm min,(3+1)osc} - \chi^2_{\rm min,(3+1)NSI^c} = 6.9 \qquad (2\ \text{dof}), \tag{3}$$

where the number of dof corresponds to the two additional parameters of the (3+1) NSI^c model compared to (3+1) oscillations. Hence, the NSI case is favoured at 97% CL (slightly more than 2σ) compared to the pure oscillation case.

The relative quality of the fits of (3+1) oscillations, (3+2) oscillations, and the (3+1) NSI^c and NSI^g models is illustrated in fig. 2. We notice the clear improvement of the fit in the (3+1) NSI^g case compared to the other models. Let us mention also that in none of the scenarios considered here we can explain the MiniBooNE low energy excess of events when disappearance data are taken into account. Therefore, we follow the strategy of the MiniBooNE collaboration and exclude the data below 475 MeV from the analysis, relying on a separate explanation for this anomaly.

The values of the NSI parameters ε needed at our best fit points are in safe agreement with phenomenological bounds [17]. Typically we require ε's of order a few $\times 10^{-2}$. For example, the NSI^g scenario can be realized by taking the following ε's to be non-zero, and in agreement with the bounds from [17]: $|\varepsilon^{ud}_{\mu s}| \approx 0.05$, $|\varepsilon^{ud}_{e\mu}| \approx 0.011$, $|\varepsilon^{ev}_{\mu s}| \approx 0.03$, $|\varepsilon^{ev}_{\mu e}| \approx 0.01$.

The predictions of our model for future neutrino experiments are deviations from the standard three-flavour oscillation picture in both respects, sterile neutrino oscillations as well as NSI, see various related contributions at this conference. Several proposals to search for sterile neutrinos at the eV scale have been presented recently, e.g. [21, 22, 23, 24, 25, 26]. In [27] implications of sterile neutrinos for latest cosmological data have been investigated. Recent studies on NSI in the context of upcoming and far future experiments can be found, e.g., in [28, 29, 30, 31]. A specific prediction of our scenario are zero-distance effects in appearance searches [32, 33, 31], i.e., a non-zero transition probability even at zero distance from the neutrino source. Hence, the observation of an energy independent appearance probability at very short distances is a characteristic signature from this kind of models.

Our model may also provide a signature at the LHC. Typically, realising CC-like interactions as the ones from eq. (1) require a charged particle as mediator. The NSI parameters ε measure the strength of the new interactions relative to the standard weak interaction strength set by G_F. Therefore, from our fit results, $\varepsilon \sim 0.01$, one expects that the mass of a mediator for a dimension-6 operator should be roughly one order of magnitude larger than the W boson mass. Hence, one might expect charged particles to show up at the TeV scale, with good prospects to be observed at LHC. Let us mention, however, that the results of [34, 35] suggest that NSI at the level of 0.01 are difficult to obtain from dimension-6 operators without being in conflict with bounds on charged-lepton processes. As discussed there, a possibility to obtain such large NSI would be to go to dimension-8 operators and allow for some fine tuning.

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