

Status of Light Sterile Neutrinos

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We review the results of the global analyses of short-baseline neutrino oscillation data in 3+1 and 3+2 neutrino mixing schemes with one or two light sterile neutrinos. The implications for neutrinoless double- β decay are briefly discussed.

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1. Introduction

Neutrino oscillations have been measured with high accuracy in solar, atmospheric and long-baseline neutrino oscillation experiments (see Refs. [1–3]), in agreement with the standard three-neutrino mixing paradigm (3ν), in which the three active neutrinos ν_e, ν_μ, ν_τ are superpositions of three massive neutrinos ν_1, ν_2, ν_3 with respective masses m_1, m_2, m_3 (see Refs. [4, 5]). There are two independent squared-mass differences, the small solar $\Delta m_{\text{SOL}}^2 \simeq 7.5 \times 10^{-5} \text{eV}^2$ and the larger atmospheric $\Delta m_{\text{ATM}}^2 \simeq 2.3 \times 10^{-3} \text{eV}^2$, which can be interpreted as $\Delta m_{\text{SOL}}^2 = \Delta m_{21}^2$ and $\Delta m_{\text{ATM}}^2 = |\Delta m_{31}^2| \simeq |\Delta m_{32}^2|$, with $\Delta m_{kj}^2 = m_k^2 - m_j^2$.

The completeness of the 3ν mixing paradigm has been challenged by the following indications in favor of short-baseline neutrino oscillations, which require the existence of at least one additional squared-mass difference, $\Delta m_{\text{SBL}}^2 \gg \Delta m_{\text{ATM}}^2$ (see the review in Ref. [6]):

1. The reactor antineutrino anomaly [7], which is a deficit of the rate of $\bar{\nu}_e$ observed in several short-baseline reactor neutrino experiments in comparison with that expected from a new calculation of the reactor neutrino fluxes [8, 9]. The statistical significance is about 2.8σ .
2. The Gallium neutrino anomaly [10–14], consisting in a short-baseline disappearance of ν_e measured in the Gallium radioactive source experiments GALLEX [15] and SAGE [16] with a statistical significance of about 2.9σ .
3. The LSND experiment, in which a signal of short-baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations has been observed with a statistical significance of about 3.8σ [17, 18].

In this review, we consider 3+1 [19–22] and 3+2 [23–26] neutrino mixing schemes in which there are one or two additional massive neutrinos at the eV scale¹ and the masses of the three standard massive neutrinos are much smaller. Since from the LEP measurement of the invisible width of the Z boson we know that there are only three active neutrinos (see Ref. [6]), in the flavor basis the additional massive neutrinos correspond to sterile neutrinos [32], which do not have standard weak interactions.

The possible existence of sterile neutrinos is very interesting, because they are new particles which could give us precious information on the physics beyond the Standard Model (see Refs. [33, 34]). The existence of light sterile neutrinos is also very important for astrophysics (see Ref. [35]) and cosmology (see Refs. [36–39]).

In the 3+1 scheme, the effective probability of $\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$ transitions in short-baseline experiments has the two-neutrino-like form [20]

$$P_{\nu_\alpha \rightarrow \nu_\beta}^{(-) \quad (-)} = \delta_{\alpha\beta} - 4|U_{\alpha 4}|^2 (\delta_{\alpha\beta} - |U_{\beta 4}|^2) \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right), \quad (1.1)$$

where U is the mixing matrix, L is the source-detector distance, E is the neutrino energy and $\Delta m_{41}^2 = m_4^2 - m_1^2 = \Delta m_{\text{SBL}}^2 \sim 1 \text{eV}^2$. The electron and muon neutrino and antineutrino appearance and disappearance in short-baseline experiments depend on $|U_{e4}|^2$ and $|U_{\mu 4}|^2$, which determine the amplitude $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2$ of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions, the amplitude $\sin^2 2\vartheta_{ee} =$

¹It is interesting to consider also the 3+1+1 scheme [27–31], in which one of the two additional massive neutrinos is much heavier than the eV scale.

$4|U_{e4}|^2(1-|U_{e4}|^2)$ of $\bar{\nu}_e$ disappearance, and the amplitude $\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2(1-|U_{\mu4}|^2)$ of $\bar{\nu}_\mu$ disappearance.

Since the oscillation probabilities of neutrinos and antineutrinos are related by a complex conjugation of the elements of the mixing matrix (see Ref. [4]), the effective probabilities of short-baseline $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions are equal. Hence, the 3+1 scheme cannot explain a possible CP-violating difference of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions in short-baseline experiments. In order to allow this possibility, one must consider a 3+2 scheme, in which, there are four additional effective mixing parameters in short-baseline experiments: $\Delta m_{51}^2 \geq \Delta m_{41}^2$, $|U_{e5}|^2$, $|U_{\mu5}|^2$ and $\eta = \arg[U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*]$ (see Refs. [5, 6, 40]). Since this complex phase appears with different signs in the effective 3+2 probabilities of short-baseline $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions, it can generate measurable CP violations.

2. Global fits of short-baseline neutrino oscillations

Updated global fits of short-baseline neutrino oscillation data have been presented in Refs. [6, 31, 41]. These analyses take into account the final results of the MiniBooNE experiment, which was made in order to check the LSND signal with about one order of magnitude larger distance (L) and energy (E), but the same order of magnitude for the ratio L/E from which neutrino oscillations depend. Unfortunately, the results of the MiniBooNE experiment are ambiguous, because the LSND signal was not seen in neutrino mode ($\nu_\mu \rightarrow \nu_e$) [42] and the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal observed in 2010 [43] with the first half of the antineutrino data was not observed in the second half of the antineutrino data [44]. Moreover, the MiniBooNE data in both neutrino and antineutrino modes show an excess in the low-energy bins which is widely considered to be anomalous because it is at odds with neutrino oscillations [45, 46]².

In the following we summarize the results of the update in Ref. [6] of the global fit of short-baseline neutrino oscillation data presented in Ref. [31]. We consider three groups of experiments:

- (A) The $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance data of the LSND [18], MiniBooNE [44], BNL-E776 [49], KARMEN [50], NOMAD [51], ICARUS [52] and OPERA [53] experiments.
- (B) The $\bar{\nu}_e$ disappearance data described in Ref. [14], which take into account the reactor [7–9] and Gallium [10–13, 54] anomalies. We extended the data set considered in Ref. [14] by including the Daya Bay measurement of the reactor electron antineutrino flux at the near detector [55] and the results of the Chooz [56], Palo Verde [57] and Double Chooz [58, 59] reactor experiments, as suggested in Ref. [60].
- (C) The constraints on $\bar{\nu}_\mu$ disappearance obtained from the data of the CDHSW experiment [61], from the analysis [25] of the data of atmospheric neutrino oscillation experiments³, from the analysis [45] of the MINOS neutral-current data [64] and from the analysis of the SciBooNE-MiniBooNE neutrino [65] and antineutrino [66] data.

²The interesting possibility of reconciling the low-energy anomalous data with neutrino oscillations through energy reconstruction effects proposed in Ref. [47, 48] still needs a detailed study.

³The IceCube data, which could give a marginal contribution [62, 63], have not been considered because the analysis is too complicated and subject to large uncertainties.

	3+1 LOW	3+1 HIG	3+1 noMB	3+1 noLSND	3+2 LOW	3+2 HIG
χ^2_{\min}	306.0	276.3	251.2	291.3	299.6	271.1
NDF	268	262	230	264	264	258
GoF	5%	26%	16%	12%	7%	28%
$(\chi^2_{\min})_{\text{APP}}$	98.9	77.0	50.9	91.8	86.0	69.6
$(\chi^2_{\min})_{\text{DIS}}$	194.4	194.4	194.4	194.4	192.9	192.9
$\Delta\chi^2_{\text{PG}}$	13.0	5.3	6.2	5.3	20.7	8.6
NDF_{PG}	2	2	2	2	4	4
GoF_{PG}	0.1%	7%	5%	7%	0.04%	7%
$\Delta\chi^2_{\text{NO}}$	49.2	47.7	48.1	11.4	55.7	52.9
NDF_{NO}	3	3	3	3	7	7
$n\sigma_{\text{NO}}$	6.4σ	6.3σ	6.4σ	2.6σ	6.1σ	5.9σ

Table 1: Results of the fit of short-baseline data [6, 31] taking into account all MiniBooNE data (LOW), only the MiniBooNE data above 475 MeV (HIG), without MiniBooNE data (noMB) and without LSND data (noLSND) in the 3+1 and 3+2 schemes. The first three lines give the minimum χ^2 (χ^2_{\min}), the number of degrees of freedom (NDF) and the goodness-of-fit (GoF). The following five lines give the quantities relevant for the appearance-disappearance (APP-DIS) parameter goodness-of-fit (PG) [67]. The last three lines give the difference between the χ^2 without short-baseline oscillations and χ^2_{\min} ($\Delta\chi^2_{\text{NO}}$), the corresponding difference of number of degrees of freedom (NDF_{NO}) and the resulting number of σ 's ($n\sigma_{\text{NO}}$) for which the absence of oscillations is disfavored.

Table 1 summarizes the statistical results obtained from global fits of the data above in the 3+1 and 3+2 schemes [6, 31]. In the LOW fits all the MiniBooNE data are considered, including the anomalous low-energy bins, which are omitted in the HIG fits. There is also a 3+1-noMB fit without MiniBooNE data and a 3+1-noLSND fit without LSND data.

From Tab.1, one can see that in all fits which include the LSND data the absence of short-baseline oscillations is disfavored by about 6σ , because the improvement of the χ^2 with short-baseline oscillations is much larger than the number of oscillation parameters.

In all the 3+1 and 3+2 schemes the goodness-of-fit in the LOW analysis is significantly worse than that in the HIG analysis and the appearance-disappearance parameter goodness-of-fit is much worse. This result confirms the fact that the MiniBooNE low-energy anomaly is incompatible with neutrino oscillations, because it would require a small value of Δm^2_{41} and a large value of $\sin^2 2\vartheta_{e\mu}$ [45, 46], which are excluded by the data of other experiments (see Ref. [31] for further details)⁴. Note that the appearance-disappearance tension in the 3+2-LOW fit is even worse than that in the 3+1-LOW fit, since the $\Delta\chi^2_{\text{PG}}$ is so much larger that it cannot be compensated by the additional degrees of freedom⁵. Therefore, we think that it is very likely that the MiniBooNE low-energy anomaly has an explanation which is different from neutrino oscillations and the HIG fits

⁴One could fit the three anomalous MiniBooNE low-energy bins in a 3+2 scheme [40] by considering the appearance data without the ICARUS [52] and OPERA [53] constraints, but the required large transition probability is excluded by the disappearance data.

⁵This behavior has been explained in Ref. [68]. It was found also in the analysis presented in Ref. [41].

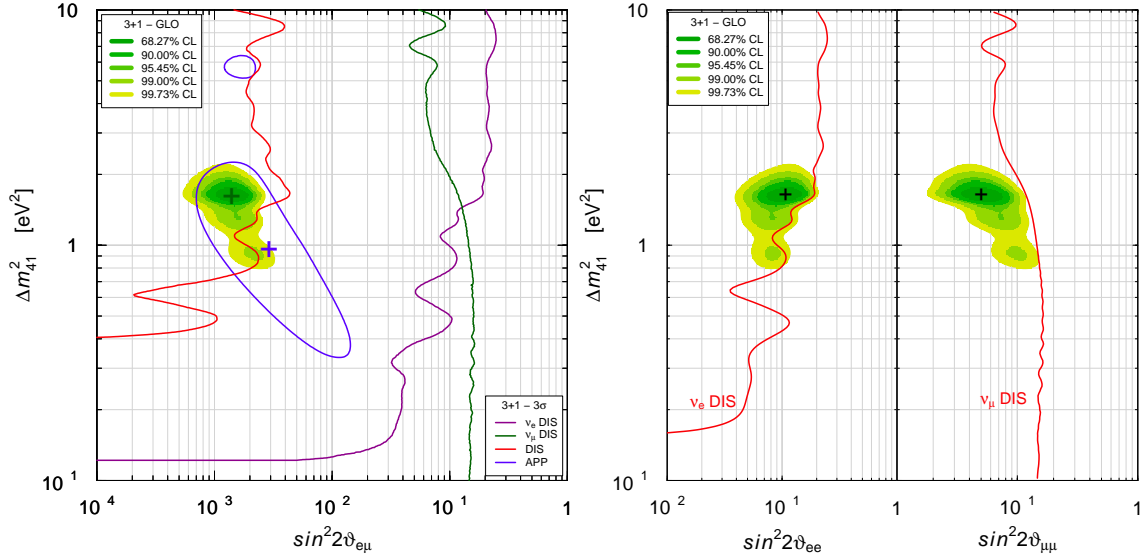


Figure 1: Allowed regions in the $\sin^2 2\vartheta_{e\mu}-\Delta m_{41}^2$, $\sin^2 2\vartheta_{ee}-\Delta m_{41}^2$ and $\sin^2 2\vartheta_{\mu\mu}-\Delta m_{41}^2$ planes obtained in the global (GLO) 3+1-HIG fit [6, 31] of short-baseline neutrino oscillation data compared with the 3σ allowed regions obtained from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ short-baseline appearance data (APP) and the 3σ constraints obtained from $\bar{\nu}_e$ short-baseline disappearance data (ν_e DIS), $\bar{\nu}_\mu$ short-baseline disappearance data (ν_μ DIS) and the combined short-baseline disappearance data (DIS). The best-fit points of the GLO and APP fits are indicated by crosses.

are more reliable than the LOW fits.

The 3+2 mixing scheme was considered to be interesting in 2010 when the MiniBooNE neutrino [42] and antineutrino [43] data showed a CP-violating tension, but this tension almost disappeared in the final MiniBooNE data [44]. In fact, from Tab.1 one can see that there is little improvement of the 3+2-HIG fit with respect to the 3+1-HIG fit, in spite of the four additional parameters and the additional possibility of CP violation. Moreover, since the p-value obtained by restricting the 3+2 scheme to 3+1 disfavors the 3+1 scheme only at 1.1σ [6, 31], we think that considering the larger complexity of the 3+2 scheme is not justified by the data⁶.

Figure 1 shows the allowed regions in the $\sin^2 2\vartheta_{e\mu}-\Delta m_{41}^2$, $\sin^2 2\vartheta_{ee}-\Delta m_{41}^2$ and $\sin^2 2\vartheta_{\mu\mu}-\Delta m_{41}^2$ planes obtained in the 3+1-HIG fit of Ref. [6, 31]. These regions are relevant, respectively, for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance, $\bar{\nu}_e$ disappearance and $\bar{\nu}_\mu$ disappearance searches. The corresponding marginal allowed intervals of the oscillation parameters are given in Tab.2. Figure 1 shows also the region allowed by $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance data and the constraints from $\bar{\nu}_e$ disappearance and $\bar{\nu}_\mu$ disappearance data. One can see that the combined disappearance constraint in the $\sin^2 2\vartheta_{e\mu}-\Delta m_{41}^2$ plane excludes a large part of the region allowed by $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance data, leading to the well-known appearance-disappearance tension [40, 41, 45, 46, 68–71] quantified by the parameter goodness-of-fit in Tab.1.

It is interesting to investigate what is the impact of the MiniBooNE experiment on the global analysis of short-baseline neutrino oscillation data. With this aim, we consider two additional 3+1

⁶See however the somewhat different conclusions reached in Ref. [41].

CL	Δm_{41}^2 [eV ²]	$\sin^2 2\vartheta_{e\mu}$	$\sin^2 2\vartheta_{ee}$	$\sin^2 2\vartheta_{\mu\mu}$
68.27%	1.57 – 1.72	0.0011 – 0.0018	0.085 – 0.13	0.039 – 0.066
90.00%	1.53 – 1.78	0.00098 – 0.0020	0.071 – 0.15	0.032 – 0.078
95.45%	1.50 – 1.84	0.00089 – 0.0021	0.063 – 0.16	0.03 – 0.085
99.00%	1.24 – 1.95	0.00074 – 0.0023	0.054 – 0.18	0.025 – 0.095
99.73%	0.87 – 2.04	0.00065 – 0.0026	0.046 – 0.19	0.021 – 0.12

Table 2: Marginal allowed intervals of the oscillation parameters obtained in the global 3+1-HIG fit of short-baseline neutrino oscillation data [6, 31].

fits [6, 31]: a 3+1-noMB fit without MiniBooNE data and a 3+1-noLSND fit without LSND data. From Tab.1 one can see that the results of the 3+1-noMB fit are similar to those of the 3+1-HIG fit and the exclusion of the case of no-oscillations remains at the level of 6σ . On the other hand, in the 3+1-noLSND fit, without LSND data, the exclusion of the case of no-oscillations drops dramatically to 2.6σ . In fact, in this case the main indication in favor of short-baseline oscillations is given by the reactor and Gallium anomalies which have a similar statistical significance [14]. Therefore, it is clear that the LSND experiment is still crucial for the indication in favor of short-baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions and the MiniBooNE experiment has been rather inconclusive.

3. Neutrinoless double- β decay

The existence of massive neutrinos at the eV scale can be probed in β -decay experiments [73–79] and in neutrinoless double- β decay experiments [14, 72, 80–88]. Here we discuss briefly only neutrinoless double- β decay, which in the case of 3+1 mixing depends on the effective Majorana mass

$$|m_{\beta\beta}| = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3 + |U_{e4}|^2 e^{i\alpha_4} m_4 \right|, \quad (3.1)$$

with three completely unknown complex phases $\alpha_2, \alpha_3, \alpha_4$ which can generate cancellations between the different mass contributions. Figure 2 shows the range of allowed values of $|m_{\beta\beta}|$ as a function of the lightest neutrino mass in the cases of 3 ν and 3+1 mixing with Normal and Inverted Ordering of the three lightest neutrinos [72]. The 3 ν mixing parameters have been taken from Ref. [89] and the sterile neutrino mixing is that obtained in the 3+1-HIG global fit of short-baseline neutrino oscillation data discussed in Section 2.

From Fig.2 one can see that the presence of an additional massive neutrinos at the eV scale can change dramatically the predictions for the possible range of values of $|m_{\beta\beta}|$ [14, 72, 80–88].

4. Conclusions

In conclusion, the results of the global fit of short-baseline neutrino oscillation data [6, 31] show that the data can be explained by 3+1 neutrino mixing and this simplest scheme beyond three-neutrino mixing cannot be rejected in favor of the more complex 3+2 scheme. The low-energy MiniBooNE anomaly cannot be explained by neutrino oscillations in any of these schemes. Moreover, the only substantial indication in favor of short-baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance is still

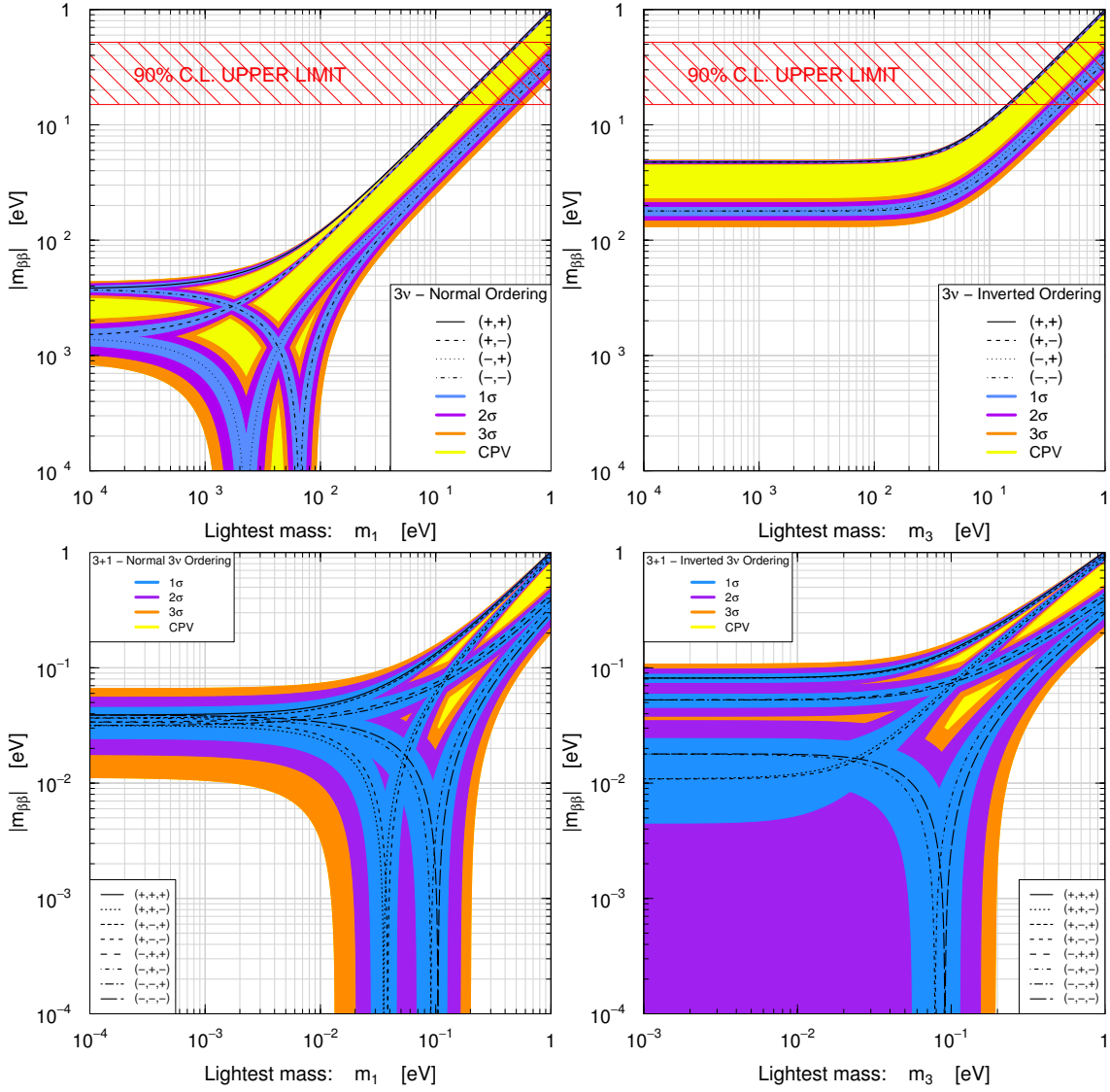


Figure 2: Value of the effective Majorana mass $|m_{\beta\beta}|$ as a function of the lightest neutrino mass in the cases of 3ν and 3+1 mixing with Normal and Inverted Ordering of the three lightest neutrinos [72]. The signs in the legends indicate the signs of $e^{i\alpha_2}, e^{i\alpha_3}, e^{i\alpha_4} = \pm 1$ for the cases in which CP is conserved. The intermediate yellow regions are allowed only in the case of CP violation.

given by the old LSND data and the MiniBooNE experiment has been inconclusive. Hence new experiments are needed in order to check this signal [90–98].

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