Phenomenology of sterile neutrinos

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Abstract. The indications in favor of short-baseline neutrino oscillations, which require the existence of one or more sterile neutrinos, are reviewed. In the framework of 3+1 neutrino mixing, which is the simplest extension of the standard three-neutrino mixing which can partially explain the data, there is a strong tension in the interpretation of the data, mainly due to an incompatibility of the results of appearance and disappearance experiments. In the framework of 3+2 neutrino mixing, CP violation in short-baseline experiments can explain the difference between MiniBooNE neutrino and antineutrino data, but the tension between the data of appearance and disappearance experiments persists because the short-baseline disappearance of electron antineutrinos and muon neutrinos compatible with the LSND and MiniBooNE antineutrino appearance signal has not been observed.

1. Introduction
From the results of solar, atmospheric and long-baseline neutrino oscillation experiments we know that neutrinos are massive and mixed particles (see [1]). There are two groups of experiments which measured two independent squared-mass differences ($\Delta m^2$) in two different neutrino flavor transition channels:

- Solar neutrino experiments (Homestake, Kamiokande, GALLEX/GNO, SAGE, Super-Kamiokande, SNO, BOREXino) measured $\nu_e \to \nu_\mu, \nu_\tau$ oscillations generated by $\Delta m^2_{\text{SOL}} = 6.2^{+1.1}_{-1.9} \times 10^{-5} \text{eV}^2$ and a mixing angle $\tan^2 \theta_{\text{SOL}} = 0.42^{+0.04}_{-0.02}$ [2]. The KamLAND experiment confirmed these oscillations by observing the disappearance of reactor $\nu_e$ at an average distance of about 180 km. The combined fit of solar and KamLAND data leads to $\Delta m^2_{\text{SOL}} = (7.6 \pm 0.2) \times 10^{-5} \text{eV}^2$ and a mixing angle $\tan^2 \theta_{\text{SOL}} = 0.44 \pm 0.03$ [2].

- Atmospheric neutrino experiments (Kamiokande, IMB, Super-Kamiokande, MACRO, Soudan-2, MINOS) measured $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance through oscillations generated by $\Delta m^2_{\text{ATM}} \simeq 2.3 \times 10^{-3} \text{eV}^2$ and a mixing angle $\sin^2 2\theta_{\text{ATM}} \simeq 1$ [3]. The K2K and MINOS long-baseline experiments confirmed these oscillations by observing the disappearance of reactor $\nu_\mu$ at distances of about 250 km and 730 km, respectively. The MINOS data give $\Delta m^2_{\text{ATM}} = 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{eV}^2$ and $\sin^2 2\theta_{\text{ATM}} > 0.90$ at 90% C.L. [4].

These measurements led to the current three-neutrino mixing paradigm, in which the three active neutrinos $\nu_e, \nu_\mu, \nu_\tau$ are superpositions of three massive neutrinos $\nu_1, \nu_2, \nu_3$ with respective masses $m_1, m_2, m_3$. The two measured squared-mass differences can be interpreted as

$$\Delta m^2_{\text{SOL}} = \Delta m^2_{21}, \quad \Delta m^2_{\text{ATM}} = |\Delta m^2_{31}| \approx |\Delta m^2_{32}|,$$  \hspace{1cm} (1)
with $\Delta m^2_{kj} = m_k^2 - m_j^2$. In the standard parameterization of the $3 \times 3$ unitary mixing matrix (see [1]) $\vartheta_{\text{SOL}} \simeq \vartheta_{12}$, $\vartheta_{\text{ATM}} \simeq \vartheta_{23}$ and $\sin^2 \vartheta_{13} < 0.035$ at 90% C.L. [5].

The completeness of the three-neutrino mixing paradigm was challenged in 1995 by the observation of a signal of short-baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations in the LSND experiment [6, 7], which would imply the existence of one or more squared-mass differences much larger than $\Delta m^2_{\text{SOL}}$ and $\Delta m^2_{\text{ATM}}$. The MiniBooNE experiment 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. The first results of the MiniBooNE experiment in neutrino mode did not show a signal compatible with that of LSND [8], but the results in antineutrino mode, presented in the summer of 2010 [9], show an excess of events over the background at approximately at the same $L/E$ of LSND. This result revived the interest in the possibility of existence of one or more neutrinos with masses at the eV scale which can generate squared-mass differences for short-baseline oscillations.

Figure 1 illustrates schematically the neutrino spectrum beyond three-neutrino mixing with one or more relatively heavy additional massive neutrinos which are mainly sterile.

Figure 1. Schematic description of the neutrino spectrum beyond three-neutrino mixing with one or more relatively heavy additional massive neutrinos which are mainly sterile.
Table 1. Values of $\chi^2$, number of degrees of freedom (NDF), goodness-of-fit (GoF) and best-fit values of the mixing parameters obtained in our 3+1 and 3+2 fits of short-baseline oscillation data. The last three lines give the results of the parameter goodness-of-fit test [43]: $\Delta \chi^2_{PG}$, number of degrees of freedom ($NDF_{PG}$) and parameter goodness-of-fit ($PGoF$).

|          | 3+1  | 3+2  |
|----------|------|------|
| $\chi^2_{min}$ | 100.2 | 91.6 |
| NDF      | 104  | 100  |
| GoF      | 59%  | 71%  |
| $\Delta m^2_{41}$ ($eV^2$) | 0.89 | 0.90 |
| $|U_{e4}|^2$       | 0.025 | 0.017 |
| $|U_{\mu 4}|^2$   | 0.023 | 0.019 |
| $\Delta m^2_{53}$ ($eV^2$) | 1.61 |   |
| $|U_{e5}|^2$       | 0.017 |   |
| $|U_{\mu 5}|^2$   | 0.0061 |   |
| $\eta$       | 1.51$\pi$ |   |
| $\Delta \chi^2_{PG}$ | 24.1 | 22.2 |
| NDF$_{PG}$    | 2    | 5    |
| PGoF          | $6 \times 10^{-6}$ | $5 \times 10^{-4}$ |

which may be an indication in the $\bar{\nu}_e \to \bar{\nu}_e$ channel of a signal corresponding to the $\bar{\nu}_\mu \to \bar{\nu}_e$ signal observed in the LSND and MiniBooNE experiments. Finally, there is a “Gallium neutrino anomaly” [26–31], consisting in a short-baseline disappearance of electron neutrinos measured in the Gallium radioactive source experiments GALLEX [32] and SAGE [33].

In the following, I consider in Sections 2 and 3 the cases of 3+1 [34–37] and 3+2 [38–41] neutrino mixing, respectively, following the discussion in [42]. Conclusions are drawn in Section 4.

2. 3+1 neutrino mixing

In this Section I consider the simplest extension of three-neutrino mixing with the addition of one massive neutrino. In 3+1 neutrino mixing [34–37] the effective flavor transition and survival probabilities in short-baseline (SBL) experiments are given by

$$
P_{\nu_{\alpha} \to \nu_{\beta}}^{SBL} = \sin^2 2\theta_{\alpha\beta} \sin^2 \left( \frac{\Delta m^2_{41} L}{4E} \right), \quad P_{\nu_{\alpha} \to \nu_{\alpha}}^{SBL} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \left( \frac{\Delta m^2_{41} L}{4E} \right),$$

for $\alpha, \beta = e, \mu, \tau, s$ and $\alpha \neq \beta$, with

$$
\sin^2 2\theta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2, \quad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2).
$$

Therefore:

1. All effective SBL oscillation probabilities depend only on the absolute value of the largest squared-mass difference $\Delta m^2_{41} = m_4^2 - m_1^2$.
2. All oscillation channels are open, each one with its own oscillation amplitude.
3. The oscillation amplitudes depend only on the absolute values of the elements in the fourth column of the mixing matrix, i.e. on three real numbers with sum less than unity, since the unitarity of the mixing matrix implies that $\sum_{\alpha} |U_{\alpha 4}|^2 = 1$. 

3
Figure 2. Left: exclusion curves obtained from the data of reactor $\bar{\nu}_e$ disappearance experiments (see [25]). Right: exclusion curves obtained from the data of the CDHSW $\nu_\mu$ disappearance experiment [44], and from atmospheric neutrino data (extracted from the analysis in [40]).

(4) CP violation cannot be observed in SBL oscillation experiments, even if the mixing matrix contains CP-violation phases, because neutrinos and antineutrinos have the same effective SBL oscillation probabilities. Hence, 3+1 neutrino mixing cannot explain the difference between neutrino [8] and antineutrino [9] oscillations observed in the MiniBooNE.

The dependence of the oscillation amplitudes in Eq. (3) on three independent absolute values of the elements in the fourth column of the mixing matrix implies that the amplitude of $^{(-)}\nu_\mu \to ^{(-)}\nu_e$ transitions is limited by the absence of large SBL disappearance of $^{(-)}\nu_e$ and $^{(-)}\nu_\mu$ observed in several experiments.

The results of reactor neutrino experiments constrain the value $|U_{e4}|^2$ through the measurement of $\sin^2 2\theta_{ee}$. Even taking into account the reactor antineutrino anomaly [25] discussed in the Introduction, the $\bar{\nu}_e$ disappearance is small and large values of $\sin^2 2\theta_{ee}$ are constrained by the exclusion curves in the left panel of Fig. 2. Since values of $|U_{e4}|^2$ close to unity are excluded by solar neutrino oscillations (which require large $|U_{e1}|^2 + |U_{e2}|^2$), for small $\sin^2 2\theta_{ee}$ we have

$$\sin^2 2\theta_{ee} \simeq 4|U_{e4}|^2. \quad (4)$$

The value of $\sin^2 2\theta_{\mu\mu}$ is constrained by the curves in the right panel of Fig. 2, which have been obtained from the lack of $\nu_\mu$ disappearance in the CDHSW $\nu_\mu$ experiment [44] and from the requirement of large $|U_{\mu1}|^2 + |U_{\mu2}|^2 + |U_{\mu3}|^2$ for atmospheric neutrino oscillations [40]. Hence, $|U_{\mu4}|^2$ is small and

$$\sin^2 2\theta_{\mu\mu} \simeq 4|U_{\mu4}|^2. \quad (5)$$

From Eqs. (3), (4) and (5), for the amplitude of $^{(-)}\bar{\nu}_\mu \to ^{(-)}\bar{\nu}_e$ transitions we obtain

$$\sin^2 2\theta_{\mu\mu} \simeq \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}. \quad (6)$$

Therefore, if $\sin^2 2\theta_{ee}$ and $\sin^2 2\theta_{\mu\mu}$ are small, $\sin^2 2\theta_{\mu\mu}$ is quadratically suppressed [34, 35]. This is illustrated in the left panel of Fig. 3, where one can see that the separate effects of the constraints on $\sin^2 2\theta_{ee}$ and $\sin^2 2\theta_{\mu\mu}$ exclude only the large-$\sin^2 2\theta_{\mu\mu}$ part of the region.
Figure 3. Left: exclusion curves in the \( \sin^2 2\theta_{\mu\tau} - \Delta m^2_{41} \) plane obtained from the separate constraints in Fig. 2 (blue and green lines) and the combined constraint given by Eq. (6) (red line) from disappearance experiments (Dis). Right: exclusion curve obtained with the addition of KARMEN [45] (KAR), NOMAD [46] (NOM) and MiniBooNE neutrino [8] (MB\(\nu\)) data (red line). In both figures the region enclosed by the dark-red lines is allowed by LSND and MiniBooNE antineutrino data.

allowed by LSND and MiniBooNE antineutrino data, whereas most of this region is excluded by the combined constraint in Eq. (6). As shown in the right panel of Fig. 3, the constraint becomes stronger by including the data of the KARMEN [45], NOMAD [46] and MiniBooNE neutrino [8] experiments, which did not observe a short-baseline \((\nu_\mu \rightarrow \nu_e)\) signal. Since the parameter goodness-of-fit [43] is \(6 \times 10^{-6}\) [42], 3+1 neutrino mixing is disfavored by the data. This conclusion has been reached recently in [42,47–49] and confirms the pre-MiniBooNE antineutrino results in [34–37,40,41,50].

However, in spite of the low value of the parameter goodness-of-fit it is not inconceivable to refuse to reject 3+1 neutrino mixing for the following reasons:

(A) It is the simplest scheme beyond the standard three-neutrino mixing which can partially explain the data.

(B) It corresponds to the natural addition of one new entity (a sterile neutrino) to explain a new effect (short-baseline oscillations). Better fits of the data require the addition of at least another new entity (in any case at least one sterile neutrino is needed to generate short-baseline oscillations).

(C) The minimum value of the global \(\chi^2\) is rather good: \(\chi^2_{\text{min}} = 100.2\) for 104 degrees of freedom.

(D) There is a marginal appearance–disappearance compatibility: \(\Delta \chi^2_{\text{PG}} = 9.2\) with 2 degrees of freedom, corresponding to PGoF = 1.0%.

(E) 3+1 mixing is favored with respect to 3+2 mixing by the Big-Bang Nucleosynthesis limit \(N_{\text{eff}} \leq 4\) at 95% C.L. obtained in [13].

Therefore, we consider the global fit of all data in the framework of 3+1 neutrino mixing, which yields the best-fit values of the oscillation parameters listed in Tab. 1.

Figure 4 shows the allowed regions in the \(\sin^2 2\theta_{\mu\tau} - \Delta m^2_{41}\), \(\sin^2 2\theta_{ee} - \Delta m^2_{31}\) and \(\sin^2 2\theta_{\mu\mu} - \Delta m^2_{31}\) planes and the marginal \(\Delta \chi^2\)s for \(\Delta m^2_{41}\), \(\sin^2 2\theta_{e\mu}\), \(\sin^2 2\theta_{e\tau}\) and \(\sin^2 2\theta_{\mu\mu}\).
baseline disappearance of neutrinos in LSND and MiniBooNE must correspond in any neutrino mixing scheme to enough small 
\(\sin^2\theta_{ee} - \Delta m^2_{31}\), \(\sin^2\theta_{ee} - \Delta m^2_{41}\) and \(\sin^2\theta_{\mu\mu} - \Delta m^2_{31}\) planes and marginal \(\Delta \chi^2\)'s obtained from the global fit in 3+1 neutrino mixing. The best-fit point is indicated 
based on a cross. Left: the isolated dark-blue long-dashed contours enclose the regions allowed at 3σ by the 
analysis of appearance data (LSND [7], KARMEN [45], NOMAD [46], MiniBooNE [8, 9]). Right: the 
isolated dark-red long-dashed lines delimit the region allowed at 99% C.L. by the Gallium anomaly [31].

3. 3+2 neutrino mixing
In 3+2 neutrino mixing [38–42, 47, 49] the relevant effective oscillation probabilities in short-
baseline experiments are given by

\[
P^{(\pm)}_{\nu_\alpha \rightarrow \nu_\beta} = 4|U_{\mu 4}|^2|U_{e 4}|^2 \sin^2 \phi_{41} + 4|U_{\mu 5}|^2|U_{e 5}|^2 \sin^2 \phi_{51} + 8\Omega \sin \phi_{41} \sin \phi_{51} \cos (\phi_{54} - \eta),
\]

\[
P^{(\pm)}_{\nu_\alpha \rightarrow \nu_\beta} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 \phi_{41} + |U_{\alpha 5}|^2 \sin^2 \phi_{51}) - 4|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2 \phi_{54},
\]

for \(\alpha, \beta = e, \mu\), with

\[
\phi_{kj} = \Delta m^2_{kj}L/4E, \quad \Omega = |U_{\mu 4}U_{e 4}U_{\mu 5}U_{e 5}|, \quad \eta = \arg(U^*_{e 4}U_{\mu 4}U_{e 5}U^*_{\mu 5}).
\]

Note the change in sign of the contribution of the CP-violating phase \(\eta\) going from neutrinos to antineutrinos, which allows us to explain the CP-violating difference between MiniBooNE neutrino and antineutrino data.

Figure 5 shows the marginal allowed allowed regions in the \(\Delta m^2_{31} - \Delta m^2_{32}\) plane obtained in our 3+2 global fit. The best-fit values of the mixing parameters are shown in Tab. 1.

The parameter goodness-of-fit obtained with the comparison of the fit of LSND and 
MiniBooNE antineutrino data and the fit of all other data is 5 \(\times 10^{-4}\). This is an improvement 
with respect to the 6 \(\times 10^{-6}\) parameter goodness-of-fit obtained in 3+1 mixing. However, the 
value of the parameter goodness-of-fit remains low and the improvement is mainly due to the 
increased number of degrees of freedom, as one can see from Tab. 1. The persistence of a bad 
parameter goodness-of-fit is a consequence of the fact that the \(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\) transitions observed 
in LSND and MiniBooNE must correspond in any neutrino mixing scheme to enough short-
baseline disappearance of \(\bar{\nu}_e\) and \(\bar{\nu}_\mu\) which has not been observed and there is an irreducible
tension between the LSND and MiniBooNE antineutrino data and the KARMEN antineutrino data. The only benefit of 3+2 mixing with respect to 3+1 mixing is that they allow to explain the difference between MiniBooNE neutrino and antineutrino data through CP violation. In fact, neglecting the MiniBooNE neutrino data we obtain $\Delta \chi^2_{PG} = 1.6$ with P GoF = $3 \times 10^{-4}$ in 3+1 mixing and $\Delta \chi^2_{PG} = 20.4$ with P GoF = $1 \times 10^{-3}$ in 3+2 mixing. In this case $\Delta \chi^2_{PG}$ is even lower in 3+1 mixing than in 3+2 mixing!

The tension between LSND and MiniBooNE antineutrino data and disappearance, KARMEN, NOMAD and MiniBooNE neutrino data is illustrated in the right panel of Fig. 5, which is the analogue for 3+2 mixing of the right panel in Fig. 3 in 3+1 mixing. In practice, in order to show the tension in a two-dimensional figure we have marginalized the $\chi^2$ over all the other mixing parameters, including the two $\Delta m^2_\alpha$.

4. Conclusions
In the framework of 3+1 neutrino mixing, there is a strong tension between LSND and MiniBooNE antineutrino data and disappearance, KARMEN, NOMAD and MiniBooNE neutrino data [42,47–49]. Since however the minimum value of the global $\chi^2$ is rather good, one may choose to consider as possible 3+1 neutrino mixing, which can partially explain the data, taking into account its simplicity and the natural correspondence of one new entity (a sterile neutrino) with a new effect (short-baseline oscillations).

In the framework of 3+2 neutrino mixing the tension between LSND and MiniBooNE antineutrino data and disappearance, KARMEN, NOMAD and MiniBooNE neutrino data is reduced with respect to the 3+1 fit, but it is not eliminated (see the right panel of Fig. 5). Moreover, the improvement of the parameter goodness of fit with respect to that obtained in the 3+1 fit is mainly due to the increase of the number of oscillation parameters, as one can see from Tab. 1. Hence it seems mainly a statistical effect.

In conclusion, I think that the interpretation of the indications in favor of short-baseline oscillations is uncertain and new experiments are needed in order to clarify the reasons of the tensions in the data and for leading us to the correct interpretation.
References

[1] Giunti C and Kim C W 2007 *Fundamentals of Neutrino Physics and Astrophysics* (Oxford: Oxford University Press) ISBN 978-0-19-850871-7

[2] Abe K et al. (Super-Kamiokande Collaboration) 2011 Phys. Rev. D 83 052010

[3] Ashie Y et al. (Super-Kamiokande Collaboration) 2005 Phys. Rev. D 71 112005

[4] Adamson P et al. (MINOS Collaboration) 2011 Phys. Rev. Lett. 106 181801

[5] Schwetz T, Tortola M and Valle J W F 2008 New J. Phys. 10 113011 (Preprint arXiv:0808.2016 [hep-ph])

[6] Athanassopoulos C et al. (LSND Collaboration) 1995 Phys. Rev. Lett. 75 2650–2653

[7] Aguilar A et al. (LSND Collaboration) 2001 Phys. Rev. D 64 112007 (Preprint hep-ex/0104049)

[8] Aguilar-Arevalo A A (MiniBooNE Collaboration) 2009 Phys. Rev. Lett. 102 101802

[9] Aguilar-Arevalo A A et al. (MiniBooNE Collaboration) 2010 Phys. Rev. Lett. 105 181801

[10] Schael S et al. (ALEPH, DELPHI, L3, OPAL, SLD Electroweak Working Group, SLD Electroweak Group, SLD Heavy Flavour Group) 2006 Phys. Rept. 427 257 (Preprint hep-ex/0509008)

[11] Cyburt R H, Fields B D, Olive K A and Skillman E 2005 Astropart. Phys. 23 313–323

[12] Izotov Y I and Thuan T X 2010 Astrophys. J. 710 L67–L71 (Preprint arXiv:1001.4440 [astro-ph.CO])

[13] Mangano G and Serpico P D 2011 Phys. Lett. B 701 296–299 (Preprint arXiv:1103.1261 [astro-ph.CO])

[14] Hamann J, Hannestad S, Raffelt G G, Tamborra I and Wong Y Y 2010 Phys. Rev. Lett. 105 181301

[15] Giusarma E et al. 2011 Phys. Rev. D 83 115023 (Preprint arXiv:1102.4774 [hep-ph.CO])

[16] Kristiansen J R and Elgaroy O 2011 (Preprint arXiv:1104.0704 [astro-ph.CO])

[17] de Holanda P C and Smirnov A Y 2011 Phys. Rev. D 83 113011 (Preprint arXiv:1012.5627 [hep-ph])

[18] Kusenko A 2009 Phys. Rept. 481 1–28 (Preprint arXiv:0906.2968 [hep-ph])

[19] Boyarsky A, Ruchayskiy O and Shaposhnikov M 2009 Ann. Rev. Nucl. Part. Sci. 59 191–214

[20] Mueller T A et al. 2011 Phys. Rev. C 84 054615 (Preprint arXiv:1101.2663 [hep-ex])

[21] Huber P 2011 Phys. Rev. C 84 024617 (Preprint arXiv:1106.0687 [hep-ph])

[22] Giunti C 2011 La Thuile 2011, NuTel 2011 and IFAE 2011 Preprint arXiv:1106.4479 [hep-ph]

[23] Mention G et al. 2011 Phys. Rev. D 83 073006 (Preprint arXiv:1101.2755 [hep-ex])

[24] Giunti C and Laveder M 2007 Mod. Phys. Lett. A 22 2499–2509 (Preprint hep-ph/0701352)

[25] Giunti C and Laveder M 2008 Phys. Rev. D 77 093002 (Preprint arXiv:0707.4593 [hep-ph])

[26] Acero M A, Giunti C and Laveder M 2008 Phys. Rev. D 78 073009 (Preprint hep-ph/0801352)

[27] Giunti C and Laveder M 2009 Phys. Rev. D 80 033005 (Preprint arXiv:0902.1992 [hep-ph])

[28] Giunti C and Laveder M 2010 Phys. Rev. D 82 053005 (Preprint arXiv:1005.4599 [hep-ph])

[29] Giunti C and Laveder M 2011 Phys. Rev. C 83 065504 (Preprint arXiv:1006.3244 [hep-ph])

[30] Sorel M, Conrad J and Shaevitz M 2004 Phys. Rev. D 70 073004 (Preprint hep-ph/0305255)

[31] Karagiorgi G et al. 2007 Phys. Rev. D 75 013011 (Preprint hep-ph/0609177)

[32] Maltoni M and Schwetz T 2008 Phys. Rev. D 77 053005 (Preprint arXiv:0705.0107 [hep-ph])

[33] Maltoni M and Schwetz T 2007 Phys. Rev. D 76 053005 (Preprint arXiv:0705.0107 [hep-ph])

[34] Maltoni M and Schwetz T 2006 Phys. Rev. D 76 053005 (Preprint arXiv:0705.0107 [hep-ph])

[35] Akhmedov E and Schwetz T 2010 JHEP 105 115 (Preprint arXiv:1007.4171 [hep-ph])

[36] Giunti C and Laveder M 2011 Phys. Rev. D 83 053006 (Preprint arXiv:1012.0267 [hep-ph])

[37] Kopp J, Maltoni M and Schwetz T 2011 Phys. Rev. Lett. 107 091801 (Preprint arXiv:1103.4570 [hep-ph])

[38] Maltoni M, Schwetz T, Tortola M A and Valle J W F 2002 Nucl. Phys. B 643 321–338