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Direct test of the MSW effect by the solar appearance term in beam experiments

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Abstract

We discuss if one can verify the MSW effect in neutrino oscillations at a high confidence level in long-baseline experiments. We demonstrate that for long enough baselines at neutrino factories, the matter effect sensitivity is not suppressed by $\sin^2 2\theta_{13}$ because it is driven by the solar oscillations in the appearance probability. Furthermore, we show that for the parameter independent direct verification of the MSW effect at long-baseline experiments, a neutrino factory with a baseline of at least 6000 km is needed.

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1. Introduction

It is now widely believed that neutrino oscillations are modified by matter effects, which is often referred to as the Mikheev–Smirnov–Wolfenstein (MSW) effect [1–3]. In this effect, the coherent forward scattering in matter by charged currents results in phase shifts in neutrino oscillations. The establishment of the LMA (large mixing angle) solution in solar neutrino oscillations by the combined knowledge from SNO [4], KamLAND [5], and the other solar neutrino experiments has lead to "indirect" evidence for the MSW effect within the Sun. A more direct test of these matter effects would be the "solar day–night effect" (see Ref. [6] and references therein), where the solar neutrino flux can (during the night) be enhanced through matter effects in the Earth due to regeneration effects [7]. So far, the solar day–night effect has not been discovered at a high confidence level by Super-Kamiokande and SNO solar neutrino measurements [8,9]. Similar tests could be performed with supernova neutrinos [10], which, however, have a strong (neutrino flux) model, detector position(s), and θ_{13}

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dependence [11]. In addition, strong matter effects can also occur in atmospheric neutrino oscillations in the Earth [12,13]. Since the muon neutrino disappearance probability is, to first order in $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin\theta_{13}$, not affected by Earth matter effects [14], testing the matter effects in atmospheric neutrinos is very difficult. However, the appearance signal of future long-baseline experiments is supposed to be very sensitive towards matter effects in atmospheric neutrino oscillations (see, for example, Refs. [15–19]). This makes the long-baseline test one natural candidate to directly discover the MSW effect at a very high confidence level. So far, the matter effect sensitivity has been widely believed to be suppressed by $\sin^2 2\theta_{13}$, since the contributions of the solar terms in the appearance probability have been neglected (see, for example, Ref. [16]). In this Letter, we study the idea to test the MSW effect by exactly these solar neutrino oscillations in beam experiments.

2. Theoretical idea

For long-baseline beam experiments, the electron or muon neutrino appearance probability P_{app} (one of the probabilities $P_{e\mu}$, $P_{\mu e}$, $P_{\bar{e}\bar{\mu}}$, $P_{\bar{\mu}\bar{e}}$) is very sensitive to matter effects, whereas the disappearance probability $P_{\mu\mu}$ (or $P_{\bar{\mu}\bar{\mu}}$) is, to first order, not. The appearance probability can be expanded in the small hierarchy parameter $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ and the small $\sin 2\theta_{13}$ up to the second order as [14,20,21]:

$$\begin{aligned} P_{\mathrm{app}} \simeq{}& \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\varDelta]}{(1-\hat{A})^2} \\ &\pm \alpha \sin 2\theta_{13} \sin\delta_{\mathrm{CP}} \sin(\varDelta)\xi(\hat{A},\varDelta) \\ &+ \alpha \sin 2\theta_{13} \cos\delta_{\mathrm{CP}} \cos(\varDelta)\xi(\hat{A},\varDelta) \\ &+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\varDelta)}{\hat{A}^2}. \end{aligned} \tag{1}$$

Here $\varDelta \equiv \Delta m^2_{31} L/(4E)$, $\xi(\hat{A},\varDelta) = \sin 2\theta_{12} \cdot \sin 2\theta_{23} \cdot \sin(\hat{A}\varDelta)/\hat{A} \cdot \sin[(1-\hat{A})\varDelta]/(1-\hat{A})$, and $\hat{A} \equiv \pm(2\sqrt{2}G_{\mathrm{F}} n_e E)/\Delta m^2_{31}$ with G_{F} the Fermi coupling constant and n_e the electron density in matter. The sign of the second term is positive for $\nu_e \to \nu_\mu$ or $\nu_{\bar{\mu}} \to \nu_{\bar{e}}$ and negative for $\nu_\mu \to \nu_e$ or $\nu_{\bar{e}} \to \nu_{\bar{\mu}}$. The sign of $\hat{A}$ is determined by the sign of Δm^2_{31} and choosing neutrinos (plus) or antineutrinos (minus). Note that the matter effect in Eq. (1) enters via the matter potential $\hat{A}$, where the equation reduces to the vacuum case for $\hat{A} \to 0$ (cf. Ref. [14]).

Since $\sin^2 2\theta_{13} > 0$ has not yet been established, any suppression by $\sin^2 2\theta_{13}$ would be a major disadvantage for a measurement. Therefore, let us investigate the interesting limit $\sin^2 2\theta_{13} \to 0$. In this limit, only the fourth term in Eq. (1) survives, which is often referred to as the "solar term", since the appearance signal in the limit $\theta_{13} \to 0$ corresponds to the contribution from the solar neutrino oscillations. It would vanish in the two-flavor limit (limit $\alpha \to 0$) and would grow proportional to $\left(\Delta m^2_{21} L/(4E)\right)^2$ in vacuum (limit $\hat{A} \to 0$), as one expects from the solar neutrino contribution in the atmospheric limit. Note that this term is equal for the normal and inverted mass hierarchies, which means that it cannot be used for the mass hierarchy sensitivity. In order to show its effect for the matter effect sensitivity compared to vacuum, we use $\Delta P \equiv P^{\mathrm{matter}}_{\mathrm{app}} - P^{\mathrm{vac}}_{\mathrm{app}}$. We find from Eq. (1)

$$\Delta P^{\theta_{13}\to 0} \simeq \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \times \varDelta^2 \left(\frac{\sin^2(\hat{A}\varDelta)}{\hat{A}^2\varDelta^2} - 1 \right). \tag{2}$$

Thus, this remaining effect does not depend on $\sin^2 2\theta_{13}$ and strongly increases with the baseline. In particular, the function $\sin^2(\hat{A}\varDelta)/(\hat{A}^2\varDelta^2)$ is maximal (i.e., unity) for $\hat{A}\varDelta \to 0$ and has its first root for $\hat{A}\varDelta = \pi$ at the "magic baseline" $L \sim 7500$ km.[1] In the Earth, where Eq. (1) is valid because of the approximation $\Delta m^2_{21} L/(4E) \ll 1$, we therefore have $\Delta P^{\theta_{13}\to 0} < 0$. This means that the matter effects will suppress the appearance probability, where maximal suppression is obtained at the magic baseline. For short baselines, the expansion in $\varDelta$ shows that $\Delta P^{\theta_{13}\to 0} \propto L^4$ strongly grows with the baseline, and for very long baselines, the bracket in Eq. (2) becomes close to -1, which means that $\Delta P^{\theta_{13}\to 0} \propto L^2$. Thus,

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[1] At the magic baseline [22], the condition $\sin(\hat{A}\varDelta) = 0$ makes all terms but the first in Eq. (1) disappear in order to allow a "clean" (degeneracy-free) measurement of $\sin^2 2\theta_{13}$. Note that the argument $\hat{A}\varDelta$ evaluates to $\sqrt{2}/2 G_{\mathrm{F}} n_e L$ independent of E and Δm^2_{31}, which means that it only depends on the baseline L.

we expect to be able to test the matter effect even for vanishing θ_{13} if the baseline is long enough.[2]

There is, however, another important ingredient in these qualitative considerations: the statistics has to be good enough to detect the term suppressed by α^2. For the current best-fit values, α^2 evaluates to $\sim 10^{-3}$. One can easily estimate that the statistics of superbeams will normally be too low to measure the solar term for this value of α^2 to a high accuracy: let us compare the first and fourth terms in Eq. (1), which are suppressed by $\sin^2 2\theta_{13}$ and α^2, respectively. If one assumes that the other factors in the first and fourth terms are of order unity (at least for $\Delta \sim \pi/2$ close to the first oscillation maximum), one can estimate for a specific experiment that the contribution from the α^2-term only becomes significant if the $\sin^2 2\theta_{13}$-sensitivity limit of this experiment is much better than α^2. This condition is, in general, not satisfied for the proposed superbeams[3] and could only be circumvented by a very long baseline, where the probability difference in Eq. (2) grows $\propto L^2$. For example, the NOνA superbeam in the simulation of Ref. [23] would only lead to about four events with almost no dependence on the matter effect for $\theta_{13} \to 0$ (dominated by the intrinsic beam background). For neutrino factories, however, this order of α^2 should be accessible for long enough baselines. For example, for the neutrino factory NuFact-II of Ref. [24] at a baseline of 6000 km, we find for $\theta_{13} \to 0$ about 90 events in matter compared to 421 in vacuum, which (for fixed oscillation parameters) would mean a highly significant effect.

Since is well known that (among others) the correlations with $\sin^2 2\theta_{13}$ and δ_{CP}, as well as intrinsic degeneracies highly affect any appearance measurement in large regions of the parameters space (see, e.g., Refs. [24,25]), it cannot be inferred from this statistical estimate that the matter effect can really be established at a high confidence level. This means that the drop in the event rate could be faked by the change of another oscillation parameter value. Hence, a complete analysis is necessary to test this idea quantitatively.

3. Quantitative test

In order to test the matter effect sensitivity, we use a three-flavor analysis of neutrino oscillations, where we take into account statistics, systematics, correlations, and degeneracies [25–28]. The analysis is performed with the $\Delta\chi^2$ method using the GLoBES software [29]. We test the hypothesis of vacuum oscillations, i.e., we compute the simulated event rates for vacuum and a normal mass hierarchy. Note that there is not a large dependence on the mass hierarchy in vacuum, though the event rates depend (even in vacuum) somewhat on the mass hierarchy by the third term in Eq. (1) (if one is far enough off the oscillation maximum). We then test this hypothesis of vacuum oscillations by switching on the (constant) matter density profile and fit the rates to the simulated ones using the $\Delta\chi^2$ method. In order to take into account correlations, we marginalize over all the oscillation parameters and test both the normal and inverted hierarchies. As a result, we obtain the minimum $\Delta\chi^2$ for the given set of true oscillation parameters which best fit the vacuum case.

We assume that each experiment will provide the best measurement of the leading atmospheric oscillation parameters at that time, i.e., we use the information from the disappearance channels simultaneously. However, we have tested for this study that the disappearance channels do not significantly contribute to the matter effect sensitivity.[4] Furthermore, for the leading solar parameters, we take into account that the ongoing KamLAND experiment will improve the errors down to a level of about 10% on each Δm^2_{21} and $\sin 2\theta_{12}$ [30,31]. As experiments, we mainly use neutrino factories based upon the representative NuFact-II from Ref. [24]. In its standard configuration, it uses muons with an energy of 50 GeV, 4 MW target power (5.3×10^{20} useful muon decays per year), a baseline

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[2] Note that the absolute statistical error is proportional to $\sqrt{N}$, where N is the event rate. Thus, the relative error $\Delta N/N \propto 1/\sqrt{N} \propto L$, because of $N \propto 1/L^2$. The statistical error therefore grows slower than the event rate coming from the solar signal, which means that one does not expect a suppression of the MSW effect sensitivity with increasing baseline length within the Earth.

[3] In fact, for superbeams, the background from the intrinsic (beam) electron neutrinos limits the performance, which means that increasing the luminosity would not solve this problem.

[4] In fact, the disappearance channels alone could resolve the matter effects for very large L and large $\sin^2 2\theta_{13}$. However, in this region, the relative contribution of the disappearance $\Delta\chi^2$ to the total one is only at the percent level.

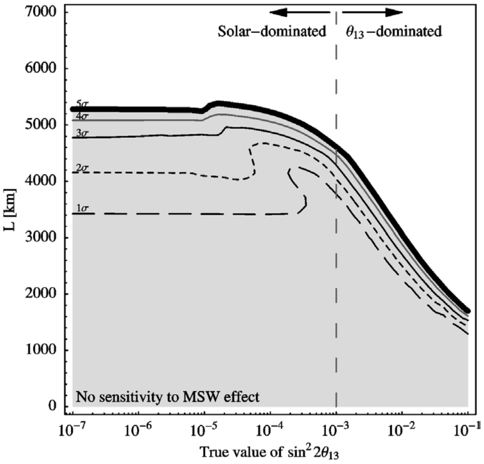

Fig. 1. Sensitivity to the MSW effect for NuFact-II as function of the true value of $\sin^2 2\theta_{13}$ and the baseline L. For the simulated oscillation parameters, the current best-fit values, $\delta_{\mathrm{CP}} = 0$, and a normal mass hierarchy are assumed, whereas the fit parameters are marginalized. Sensitivity is given at the shown confidence level on the upper sides of the curves.

of 3000 km, and a magnetized iron detector with a fiducial mass of 50 kt. We choose a symmetric operation with 4 yr in each polarity. For the oscillation parameters, we use, if not stated otherwise, the current best-fit values $\Delta m_{31}^2 = 2.5 \times 10^{-3}\ \mathrm{eV}^2$, $\sin^2 2\theta_{23} = 1$, $\Delta m_{21}^2 = 8.2 \times 10^{-5}\ \mathrm{eV}^2$, and $\sin^2 2\theta_{12} = 0.83$ [32–35]. We only allow values for $\sin^2 2\theta_{13}$ below the CHOOZ bound $\sin^2 2\theta_{13} \lesssim 0.1$ [36] and do not make any special assumptions about δ_{CP}. However, we will show in some cases the results for chosen selected values of δ_{CP}.

We show in Fig. 1 the sensitivity to the MSW effect for NuFact-II as function of the true values of $\sin^2 2\theta_{13}$ and the baseline L, where $\delta_{\mathrm{CP}} = 0$ and a normal mass hierarchy are assumed. The sensitivity is given above the curves at the shown confidence levels. Obviously, the experiment can verify the MSW effect for long enough baselines even for $\sin^2 2\theta_{13} = 0$, i.e., where the solar term dominates. The vertical dashed line separates the region where this measurement is dominated by the first term (θ_{13}-dominated) and the fourth term (solar-dominated) in Eq. (1). It is drawn for $\sin^2 2\theta_{13} = 10^{-3} \sim \alpha^2$, i.e., in this region all the terms of Eq. (1) have similar magnitudes. Obviously, the performance in the θ_{13}-dominated (atmospheric oscillation-dominated) regime is much better than the one in the solar-dominated regime, because the θ_{13}-terms provide information on the matter effects in addition to the solar term. In this figure, the curves are shown for different selected confidence levels. However, in order to really establish the effect, a minimum 5σ signal will be necessary. Therefore, we will only use the 5σ curves below.

In order to discuss the most relevant parameter dependencies and to compare the matter effect and mass hierarchy sensitivities, we show in Fig. 2 these sensitivities for two different values of δ_{CP}. As we have tested, the true value of δ_{CP} is one of the major impact factors for these measurements. In addition, the mass hierarchy sensitivity is modified by a similar amount for a simulated inverted instead of normal mass hierarchy, whereas the matter effect sensitivity does not show this dependence (because the reference rate vector is computed for vacuum). As far as the dependence on Δm_{21}^2 is concerned, we have not found any significant dependence of the MSW effect sensitivity within the current allowed 3σ range $7.4 \times 10^{-5}\ \mathrm{eV}^2 \lesssim \Delta m_{21}^2 \lesssim 9.2 \times 10^{-5}\ \mathrm{eV}^2$ [33]. Hence, we show in Fig. 2 the selected two values of δ_{CP} for estimates of the (true) parameter dependencies, since there are no major qualitative differences.

As one can see from this figure, the behavior of the MSW sensitivity for short baselines and large $\sin^2 2\theta_{13}$ is qualitatively similar to the one of the mass hierarchy sensitivity, because both measurements are dominated by the θ_{13}-terms of Eq. (1). However, the difference between the normal and inverted hierarchy matter rates is about a factor of two larger than the one between vacuum and matter rates (for any mass hierarchy). Thus, for large $\sin^2 2\theta_{13}$, the mass hierarchy sensitivity is better than the MSW sensitivity (better means that it works for shorter baselines). Note that the solar (fourth) term in Eq. (1) is not dependent on the mass hierarchy, which means that there is no mass hierarchy sensitivity for small values of $\sin^2 2\theta_{13}$.

For the MSW effect sensitivity, one can easily see from both panels of Fig. 2 that for $\sin^2 2\theta_{13} \gtrsim 0.05$ a baseline of 3000 km would be sufficient, because in this case the θ_{13}-signal is strong enough to provide information on the matter effects. However, in this case, $\sin^2 2\theta_{13}$ will be discovered by a superbeam and it is unlikely that a neutrino factory will be built. For smaller values $\theta_{13} < 0.01$, longer baselines will be necessary. In particular, to have sensitivity to the mat-

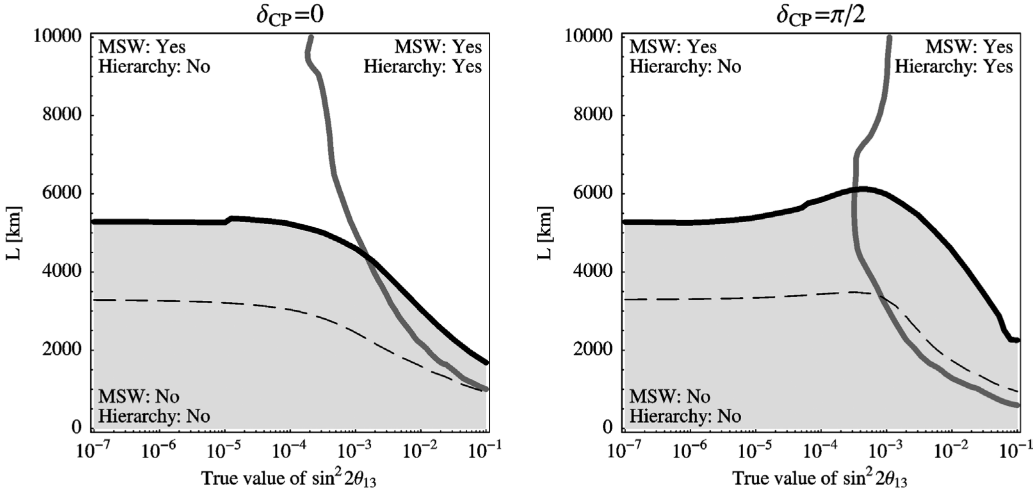

Fig. 2. The sensitivity to the MSW effect (black curves) and to the mass hierarchy (gray curves) for NuFact-II as function of the true value of $\sin^2 2\theta_{13}$ and the baseline L (5σ only). For the simulated oscillation parameters, the current best-fit values, $\delta_{\rm CP}=0$ (left) or $\delta_{\rm CP}=\pi/2$ (right), and a normal mass hierarchy are assumed, whereas the fit parameters are marginalized over (solid curves). Sensitivity to the respective quantity is given on the upper/right side of the curves. The dashed curves correspond to the MSW effect sensitivity without correlations, i.e., for all the fit parameters fixed. For the computation of the mass hierarchy sensitivity, we determine the minimum $\Delta\chi^2$ at the $\mathrm{sgn}(\Delta m^2_{31})$-degeneracy [25]. In addition, we assume a constant matter density profile with 5% uncertainty, which takes into account matter density uncertainties as well as matter profile effects [37–39].

ter effect independent of the true parameter values, a neutrino factory baseline $L \gtrsim 6000$ km is a prerequisite. Therefore, this matter effect test is another nice argument for at least one very long neutrino factory baseline. Note that one can read off the impact of correlations with the oscillation parameters from the comparison between the dashed and solid black curves in Fig. 2. If one just fixed all the oscillation parameters, one would obtain the dashed curves. In this case, one could come to the conclusion that a shorter baseline would be sufficient, which is not true for the complete marginalized analysis.

As we have discussed in Section 2, the MSW test is very difficult for superbeams. For the combination of T2K, NOνA, and Reactor-II from Ref. [23], it is not even possible at the 90% confidence level for $\sin^2 2\theta_{13}=0.1$ at the CHOOZ bound. However, for a very large superbeam upgrade at very long baselines, there would indeed be some sensitivity to the matter effect even for vanishing θ_{13}. For example, if one used the T2HK setup from Ref. [24] and (hypothetically) put the detector to a longer baseline, one would have some matter effect sensitivity at the 3σ confidence level for selected baselines $L \gtrsim 5500$ km. For the "magic baseline" $L \sim 7500$ km, one could even have a 4σ signal, but 5σ would hardly be possible.

4. Summary and discussion

We have investigated the potential of long-baseline experiments to test the matter effect (MSW effect) in neutrino oscillations. In particular, we have discussed under what conditions one can directly verify this MSW effect compared to vacuum oscillations at a high confidence level. We have found that, for long enough baselines $L \gtrsim 6000$ km and good enough statistics, the solar term in the appearance probability is sensitive to matter effects compared to vacuum, which means that the MSW effect sensitivity is not suppressed by $\sin^2 2\theta_{13}$ anymore. Note that the solar term is not sensitive to the mass hierarchy at all, but it is reduced in matter compared to vacuum. We have demonstrated that a neutrino factory with a sufficiently long baseline would have good enough statistics for a 5σ MSW effect discovery independent of $\sin^2 2\theta_{13}$, where the solar term becomes indeed statistically accessible. However, a very long baseline superbeam upgrade, such as a T2HK-like experiment at the "magic

Table 1
Different methods to test the MSW effect: source and method (in which medium the MSW effect is tested), the suppression of the effect by θ_{13}, the potential confidence level reach (including reference, where applicable), and comments/assumptions which have led to this estimate

Source/Method (where tested)	θ_{13}-suppressed	Reach [Ref.]	Comments/Assumptions
Solar ν/Sun	No	6σ [40]	MSW effect in Sun; by comparison between vacuum and matter (existing solar ν experiments)
Solar ν/Earth (“day–night”)	No	4σ [41]	By large Water Cherenkov detector used for proton decay
SN ν/Earth, one detector	No	n/a [11]	Observation as “dips” in spectrum, but no observation guaranteed (because of flux uncertainties); effects depend on $\sin^2 2\theta_{13}$; HyperK-like detector needed
SN ν/Earth, two detectors	No	4σ–5σ [10]	For SN distance 10 kpc, $E_B = 3 \times 10^{53}$ ergs; at least two Super-K size detectors, depends on their positions
Atmospheric ν/Earth	**Yes**	4σ [42]	Estimate for 100 kt magn. iron detector computed for $\sin^2 2\theta_{13} = 0.1$
Superbeam/Earth $L \lesssim 5500$ km	**Yes**	2σ	Estimate for T2HK-like setup for $\sin^2 2\theta_{13} \gtrsim 0.05$ at $L = 3000$ km; strongly depends on $\sin^2 2\theta_{13}$ and δ_{CP}
Superbeam/Earth $L \gtrsim 5500$ km	No	$\sim 3\sigma$–4σ	Estimate for T2HK-like setup independent of $\sin^2 2\theta_{13}$
ν-factory/Earth $L \lesssim 6000$ km	**Yes**	5σ	Reach for $\sin^2 2\theta_{13} \gtrsim 0.05$ at $L = 3000$ km ($\delta_{\mathrm{CP}} = \pi/2$); strongly depends on $\sin^2 2\theta_{13}$ and δ_{CP}
ν-factory/Earth $L \gtrsim 6000$ km	No	5σ–8σ	Range depending on δ_{CP} for $L = 6000$ km; for $L \gg 6000$ km much better reach, such as $\sim 12\sigma$ for $L = 7500$ km

baseline” $L \sim 7500$ km, could have some sensitivity to the solar appearance term at the 4σ confidence level.

As most important implication, the matter effect sensitivity it is another argument for at least one very long neutrino factory baseline, where the other purposes of such a baseline could be a “clean” (correlation- and degeneracy-free) $\sin^2 2\theta_{13}$-measurement at the “magic baseline” [22] and a very good mass hierarchy sensitivity for large enough $\sin^2 2\theta_{13}$. The verification of the MSW effect would be a little “extra” for such a baseline. In addition, note that the mass hierarchy sensitivity assumes that the matter effects are present, which means that some more evidence for the MSW effect would increase the consistency of this picture.

Eventually, the absence of the $\sin^2 2\theta_{13}$-suppression in the solar appearance term means that the direct MSW test at a beam experiment could be competitive with others methods, for a summary, see Table 1. However, it could be also partly complementary: if $\sin^2 2\theta_{13}$ turned out to be large, it is the atmospheric oscillation frequency which would be modified by matter effects and not the solar one. Furthermore, the MSW effect in Earth matter could be a more “direct” test under controllable conditions, because the Earth’s mantle has been extensively studied by seismic wave geophysics. Note that for atmospheric neutrinos, this test is much harder, an example can be found in Ref. [42].

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