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Determining the flavour content of the low-energy solar neutrino flux

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Abstract: We study the sensitivity of the HELLAZ and Borexino solar neutrino experiments on discriminating the neutrino species ν_e, $\bar{\nu}_e$, $\nu_{\mu,\tau}$, $\bar{\nu}_{\mu,\tau}$, and ν_s using the difference in the recoil electron kinetic energy spectra in elastic neutrino-electron scattering. We find that one can observe a non-vanishing $\nu_{\mu,\tau}$ component in the solar neutrino flux, especially when the ν_e survival probability is low. Also, if the data turn out to be consistent with $\nu_e \leftrightarrow \nu_{\mu,\tau}$ oscillations, a $\bar{\nu}_e$ component can be excluded effectively.

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JHEP08(2000)025

Contents

1. Introduction **1**

2. Recoil electron kinetic energy spectrum **3**

3. Measuring a $\nu_{\mu,\tau}$ component in the solar neutrino flux **7**

4. Testing for the $\nu_e \leftrightarrow \nu_s$ or $\bar{\nu}_{e,\mu,\tau}$ hypotheses **11**

4.1 $\nu_e \leftrightarrow \nu_s$ 12

4.2 $\nu_e \leftrightarrow \bar{\nu}$, model-independent fit 13

4.3 $\nu_e \to \bar{\nu}$, SSM-dependent fit 16

5. Conclusions **18**

1. Introduction

The flux of solar neutrinos was first measured in the Homestake mine (see [1] and references therein) over thirty years ago. Since then, it was realized that the measured flux was significantly suppressed with respect to theoretical predictions. More recently, a handful of different experiments have also succeeded in measuring the solar neutrino flux [2]–[5]. All experiments measure a neutrino flux which is significantly suppressed with respect to the theoretical predictions of the most recent version of the Standard Solar Model (SSM) [6]. This thirty year old problem is what is referred to as the “solar neutrino puzzle”.

There are different types of solutions to the solar neutrino puzzle. At first sight, it appears natural to suspect that the SSM predictions for the solar neutrino flux are slightly off, and/or that the experiments have underestimated their systematic effects, given that detailed models of the Sun and neutrino experiments are highly non trivial. However, SSM independent analyses of the neutrino data (see [7] for a particularly nice and simple example), together with independent experimental evidence in favour of the SSM [6], seem to indicate that the above solution to the puzzle is strongly disfavoured.

The best solution to the solar neutrino puzzle involves extending the Standard Model of particle physics by assuming that the neutrinos have mass and that they mix, i.e. neutrino mass eigenstates are different from neutrino weak eigenstates. This possibility has become particularly natural in light of the recent strong evidence for ν_μ oscillations from the atmospheric neutrino data at SuperKamiokande [8].

JHEP08(2000)025

Nonetheless, in order to firmly establish that the solution to the solar neutrino puzzle involves physics beyond the Standard Model, it is necessary to come up with SSM independent, robust experimental evidence for, e.g. solar neutrino oscillations. Indeed, these "Smoking Gun" signatures of solar $\nu_e \leftrightarrow \nu_{\rm other}$ oscillations are among the present goals of the SuperKamiokande experiment, via the measurement of the day-night asymmetry of the solar neutrino data [9] and the recoil electron energy spectrum [10], and the SNO experiment [11], via the measurement of the charged to neutral current ratio, the day-night asymmetry of the data, and the recoil electron kinetic energy spectrum.

Other goals of this and the next generation of neutrino experiments are, if solar neutrino oscillations are established, to determine neutrino oscillation modes and measure masses and mixing angles. The current data allow for different ν_e oscillation modes and a handful of disconnected regions in the mass-mixing-angle parameter space (see [12, 13] for two-flavour analyses and also [14] for an extension to the "dark side" of the parameter space).

Experiments dedicated to measuring the flux of low-energy solar neutrinos ($E_\nu = O(100-1000)\,$keV) are going to be extremely useful, and perhaps crucial, in order to fully solve the solar neutrino puzzle. It was recently shown that future experiments (Borexino [15] and, perhaps, KamLAND [16]) dedicated to measuring the flux of ^{7}Be neutrinos (produced by $^7Be\,+\,e^- \rightarrow ^7 Li + \nu_e$ inside the Sun) should be able to establish or exclude the "just-so" solution [12] to the solar neutrino puzzle via the study of the seasonal variations of the neutrino flux [17], and establish or exclude the LOW MSW solution [13] via the study of the zenith angle dependence of their data [18]. Furthermore, the measurement of a sizable ^{7}Be neutrino flux would significantly disfavour the SMA MSW [13] solution to the solar neutrino puzzle, especially in the case of $\nu_e \leftrightarrow \nu_s$ oscillations (where ν_s is a sterile neutrino, i.e. a standard model singlet), and significantly constrain the SSM independent analysis, which require the flux of ^{7}Be neutrinos to be virtually absent [7]. Finally, we have shown [19] that, in the advent that the background rates at Borexino and/or KamLAND are exceptionally low, it should be possible to measure a non-zero component of $\nu_{\mu,\tau}$ in the solar neutrino flux by analysing the recoil electron kinetic energy spectrum.

Another exciting possibility is that of measuring the "fundamental" *pp*-neutrinos, which are produced in the interior of the Sun by proton-proton fusion ($p + p \rightarrow {}^2H + e^+ + \nu_e$) in a real time experiment. Future experiments, such as HELLAZ, HERON, LENS, etc. (see [20] for an overview) are being designed to do just that. The flux of *pp*-neutrinos is particularly constrained by the photon flux i.e. the Sun's luminosity, which, of course, is very well measured on the Earth. These lowest energy solar neutrinos ($E_\nu \lesssim 420\,$keV) are not only the most abundant ones, but also have the best known flux. Their energy spectrum is also very well known, since it is dictated by the particularly well studied $p + p$ nuclear fusion reaction. Among these proposed experiments, HELLAZ [21] will be able to determine the incoming neutrino

JHEP08(2000)025

energy in an event-by-event basis and have the unique opportunity of studying the solar neutrino spectrum and the recoil electron kinetic energy spectrum separately. Similar to what was shown for ^{7}Be neutrinos [19], the authors of [22] showed that HELLAZ may be able to measure a non-zero component of $\nu_{\mu,\tau}$ in the solar *pp*-neutrino flux by analysing the recoil electron kinetic energy spectrum independent of the SSM prediction for the solar neutrino flux.

In this paper we extend the analysis done in [19], and study the flavour composition of the flux of *pp* and ^{7}Be neutrinos using the recoil electron kinetic energy spectrum. In particular we will address the capability of future low-energy solar-neutrino experiments to see evidence for $\nu_{\mu,\tau}$ coming from the Sun, and, in light of such evidence, exclude more "exotic" oscillation scenarios, such as $\nu_e \leftrightarrow \nu_s$ or $\nu_e \leftrightarrow \bar{\nu}_{\rm any}$ oscillations.

Our presentation is organised as follows: section 2 describes the flavour dependent recoil kinetic energy distribution of events at Borexino and HELLAZ. Section 3 presents the technique for determining the presence of $\nu_{\mu,\tau}$ coming from the Sun, independent of the SSM prediction for the neutrino flux. We present simulations for both Borexino and HELLAZ and show how such a determination can be improved once we take the SSM prediction for the neutrino flux into account. Section 4 describes how the same procedure can be used to exclude the presence of antineutrinos or sterile neutrinos in the solar neutrino flux. In section 5, we conclude.

2. Recoil electron kinetic energy spectrum

In this section, we discuss the differences in the recoil electron kinetic energy spectra among different neutrino species. Low-energy solar neutrinos are detected via "ν" + $e^- \to$ "ν" + e^- elastic scattering in the experiments which will be considered here. By "ν" in the previous sentence, one actually means any of ν_e, ν_μ, ν_τ, $\bar{\nu}_e$, $\bar{\nu}_\mu$, or $\bar{\nu}_\tau$. Because ν_μ and ν_τ are indistinguishable as far as the reaction above is concerned, we will refer to both as ν_μ.

The kinetic energy distribution of the recoil electrons, for a given incoming neutrino energy E_ν is very well known and given by [23]

$$\frac{d\sigma(T,E_\nu)}{dT} = \frac{2G_F^2 m_e}{\pi}\left[A^2 + B^2\left(1-\frac{T}{E_\nu}\right)^2 - AB\frac{m_e T}{(E_\nu)^2}\right], \tag{2.1}$$

where m_e is the electron mass, T is the kinetic energy of the recoil electron, and G_F is the Fermi constant. The parameters A and B are given in table 1. The sign difference in the term 1/2 is a consequence of the presence (absence) of W-boson exchange and the interchange of A and B between neutrino and anti-neutrino cases is a consequence of the "handedness" of the weak interactions. Equation (2.1) is a tree-level expression, but higher order corrections are known to be very small [24], especially for the neutrino energies of interest, and will be neglected throughout.

species	A	B
ν_e	$\sin^2\theta_W + 1/2$	$\sin^2\theta_W$
$\bar{\nu}_e$	$\sin^2\theta_W$	$\sin^2\theta_W + 1/2$
$\nu_{\mu,\tau}$	$\sin^2\theta_W - 1/2$	$\sin^2\theta_W$
$\bar{\nu}_{\mu,\tau}$	$\sin^2\theta_W$	$\sin^2\theta_W - 1/2$

Table 1: Coefficients A, B in eq. (2.1) for different neutrino species.

Borexino (under construction) is an ultra-pure liquid scintillator tank which detects the scintillating light produced by the recoil electron absorbed by the medium. For more details see [15, 17]. It is sensitive to recoil electron kinetic energies greater than 250 keV, and is therefore sensitive to the (almost) monochromatic ^{7}Be neutrinos with $E_\nu = 862\,\text{keV}$. The expected resolution for the kinetic energy measurement varies from roughly 12%, for $T = T_{\text{min}} = 0.25\,\text{MeV}$, to 7% for $T = T_{\text{max}} = 0.66\,\text{MeV}$ [15]. They expect 53 events/day in the SSM (BP95) together with 19 background events/day with the anticipated radiopurity of the scintillator of 10^{-16} g/g for U/Th, 10^{-18} g/g for ^{40}K, and ^{14}C/^{12}C$= 10^{-18}$ and no radon diffusion. It is remarkable, however, that the München group of Borexino achieved a radiopurity for an organic liquid (Phenyl-ortho-xylylethane) better than 1.0×10^{-17} g/g [25]; this is an upper bound on the contamination, limited by the sensitivity of the neutron activation measurement and hence the actual radiopurity may be even better. In this paper, we ignore the background to the ^{7}Be solar neutrino signal at Borexino. This is probably an overoptimistic assumption, but could be realised in future upgrades given the above-mentioned achievement.

HELLAZ (proposed) is a large time projection chamber (TPC) filled with roughly $2000\,\text{m}^3$ of cool helium gas (~ 6 tons at 5 atmos, 77 K), which serves as the target for ν-e scattering. The recoil electron propagates in the gas medium before being absorbed, leaving a track of ionization electrons. These are then collected, yielding information about the kinetic energy and the flight direction of the recoil electron. HELLAZ is sensitive to recoil kinetic energies greater than $\sim 50\,\text{keV}$, and can therefore "see" most of the *pp*-neutrino spectrum. Most importantly, since not only the recoil kinetic energy of scattered electrons is measured but also their direction, it is possible to reconstruct the incoming neutrino energy, given that the position of the Sun in the sky is known, via the simple kinematic relation

$$T = m_e \frac{2\cos^2\theta}{(1 + m_e/E_\nu)^2 - \cos^2\theta}\,, \tag{2.2}$$

where θ is the recoil electron scattering angle with respect to the incoming neutrino direction in the laboratory frame. Incidently, from eq. (2.2) it is very easy to compute the maximum value of the recoil electron kinetic energy, $T_{\text{max}} = T(\theta = 0) = E_\nu/(1 + m_e/(2E_\nu))$. HELLAZ expects to measure the recoil electron kinetic energy with a resolution which varies roughly from 2% to 4% and the incoming neutrino energy with a resolution which varies between 5% and 12% [21]. They expect around 7 events/day from *pp* neutrinos in the SSM. The major sources of background at HELLAZ are radioactive impurities from ^{232}Th and ^{238}U in the structure of the TPC. However, because of the detector's total event reconstruction capabilities (including directional information), it is possible to measure the energy spectrum of the background (see [21] and references therein for further information), and separate it from the signal. This is done by looking at the energy spectrum of events in the backward hemisphere from the direction of the Sun, where solar neutrino induced events should not exist. One can also subtract events in this forward hemisphere by lookinkg at the data from 12 hours before, where the only assumption required is that the background energy spectrum is constant in time. Note that the project is still at the R&D stage and the "realistic" background situation is not well known.

The issue we would like to concentrate on is whether the shapes of the recoil electron kinetic energy distributions for different (anti)neutrino species are statistically different at Borexino and HELLAZ. With this in mind, figure 1 depicts the normalised distribution of events at HELLAZ (left) and Borexino (right).[1] In the case of Borexino, the data is binned into ten kinetic energy bins, between 250 keV and 650 keV. In the case of HELLAZ, the data is binned into 4×21 bins in $E_\nu \times T$. The bins have a width of 50 keV in the E_ν direction and central values of 245, 295, 345 and 395 keV, while in the T direction they have a width of 10 keV in the range from 50 to 260 keV. The bin sizes have been chosen such that they are roughly the same as the resolution of both detectors. In order to integrate over the incoming neutrino energy at HELLAZ, the (normalised) BP98 *pp*-spectrum presented at [26] was used.

Many important features of the recoil electron kinetic distributions are worthwhile to point out. First of all, it is quite clear that the spectrum produced by $\bar{\nu}_e$-e is much steeper than all the other ones.[2] Second, the ν_e and ν_μ generated spectra have opposite slopes when the neutrino energy is small enough, while their shapes start to look more and more similar as the neutrino energy increases. Finally, the spectra produced by ν_μ-e and $\bar{\nu}_\mu$-e scattering are extremely similar, especially at very low energies.

[1]In addition to *pp*-neutrinos, HELLAZ is also sensitive to ^{7}Be neutrinos, as well as the *pep*-neutrinos and the neutrinos coming from the CNO-cycle. ^{7}Be neutrinos can be clearly separated from *pp*-neutrinos, while the number of *pep* and CNO-cycle neutrino generated events is expected to be less than 10% that of *pp*-neutrinos. Borexino is sensitive to, in addition to ^{7}Be neutrinos (with $E_\nu = 862$ keV), a fraction of the *pep* and the CNO-cycle neutrinos, which produce approximately 10% as many events as ^{7}Be neutrinos. We assume throughout, for simplicity, that only *pp* (^{7}Be) neutrinos are detected at HELLAZ (Borexino).

[2]Some of these features were pointed out in [27].

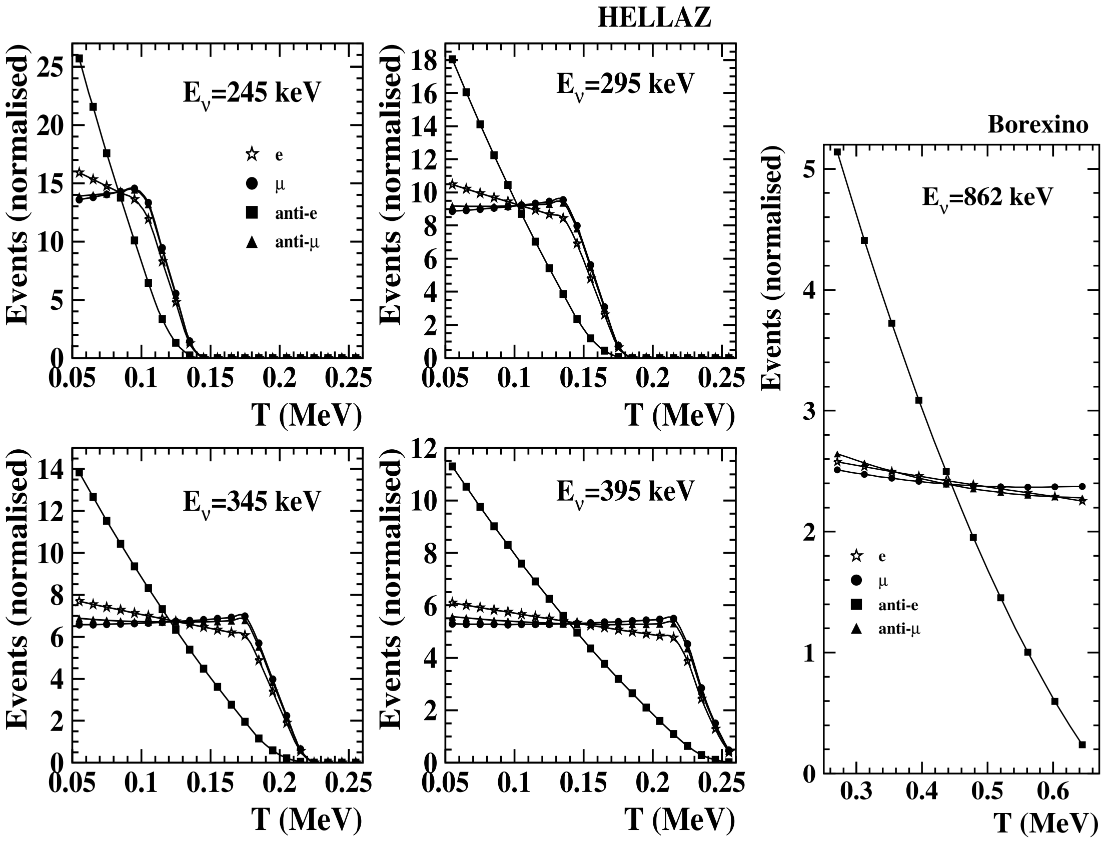

Figure 1: Normalised recoil electron kinetic energy distributions, for each of the 4 neutrino energy bins (see text) at HELLAZ (left) and for ^{7}Be neutrinos (right).

All of these features can be readily understood from eq. (2.1). First, it is convenient to write the expression for the normalised recoil electron kinetic energy distributions,

$$\frac{d\bar{\sigma}}{dy} = N\left[\frac{A}{B} + \frac{B}{A}(1-y)^2 - \frac{m_e}{E_\nu}y\right], \tag{2.3}$$

where $y = T/E_\nu$, and N is a normalisation constant, such that $\int d\bar{\sigma}/dT$ from $T_{\min}$ to $T_{\max}$ equals unity.

For ν_e, $A/B \sim 3$, while $B/A \sim 1/3$. For $\bar{\nu}_e$ the situation is reversed, while for both ν_μ and $\bar{\nu}_\mu$, $A/B \sim B/A \sim -1$.[3] Note, curiously enough, that the reason for the similarity between the ν_μ and $\bar{\nu}_\mu$ cases is simply due to the accidental fact that $\sin^2\theta_W$ is close to $1/4$.[4] This similarity is even more pronounced at very low energies, when the m_e/E_ν term dominates over the A/B and B/A terms.

[3]In this case, the normalisation constant N is negative.

[4]The fact that there is a sign difference between g_L and g_R for muon-type (anti)neutrinos is irrelevant, since these coefficients either appear as squares or as the product $g_L g_R$.

Keeping in mind that $0.59 \lesssim m_e/E_\nu \lesssim 2.3$ in the neutrino energy range of interest and $0 < y \le (1+m_e/2E_\nu)^{-1} < 1$, one may write approximate expressions

$$\left(\frac{d\bar{\sigma}}{dy}\right)_{\nu_e} \propto 3 - \frac{m_e}{E_\nu}y\,, \tag{2.4}$$

$$\left(\frac{d\bar{\sigma}}{dy}\right)_{\bar{\nu}_e} \propto 3(1-y)^2 - \frac{m_e}{E_\nu}y\,, \tag{2.5}$$

$$\left(\frac{d\bar{\sigma}}{dy}\right)_{\bar{\nu}_\mu} \propto \left(\frac{d\bar{\sigma}}{dy}\right)_{\nu_\mu} \propto 1 + (1-y)^2 + \frac{m_e}{E_\nu}y\,. \tag{2.6}$$

In the limit $m_e/E_\nu \ll 1$, all three distributions are quite different (see, e.g. figure 1*b* in [19]). The ν_e case is roughly flat, the $\bar{\nu}_e$ case ranges from 3 at $y=0$ to 0 at $y=1$ and the $\nu_\mu, \bar{\nu}_\mu$ case ranges from $3/2$ at $y=0$ to $3/4$ at $y=1$.

For $m_e/E_\nu \gtrsim 1$, things are slightly more complicated, but still easy to understand. For example, the slopes of the distributions for small values of y are, up to normalisation factors, $-m_e/E_\nu$, $-(6+m_e/E_\nu)$ and $+(m_e/E_\nu - 2)$ for ν_e, $\bar{\nu}_e$ and $\nu_\mu, \bar{\nu}_\mu$, respectively. It is then easy to note that the $\bar{\nu}_e$ slope is significantly more negative than the other two, and that, in the case of $\nu_\mu, \bar{\nu}_\mu$ the slope is actually positive if E_ν is small enough. This is indeed what one observes in figure 1.

As the incoming neutrino energy increases, the distributions generated by ν_e and $\nu_\mu, \bar{\nu}_\mu$ look more and more similar. One hint of this behaviour is that the slope of the ν_e case increases (decreases in absolute value), while the slope of the $\nu_\mu, \bar{\nu}_\mu$ decreases. One can easily estimate that for $0.9\,\text{MeV} \lesssim E_\nu \lesssim 1.0\,\text{MeV}$ the shapes of the ν_e and ν_μ induced recoil kinetic energy distributions are most similar. Indeed, for ^{7}Be neutrino energies, one can already note that the difference between the ν_e and the ν_μ cases is similar to the difference between the ν_μ and the $\bar{\nu}_\mu$ cases.

3. Measuring a $\nu_{\mu,\tau}$ component in the solar neutrino flux

In this section, we address the question whether the shapes of the recoil electron kinetic energy distributions presented in section 2 are *statistically different* at Borexino or HELLAZ. In the affirmative case, there is hope that one may be sensitive to a "contamination" of other neutrino types in the solar neutrino flux by analysing the shape of the recoil kinetic energy spectrum. We consider this an "appearance experiment" of the "wrong" types of neutrinos from the Sun. In this section we will only consider the case of $\nu_e \leftrightarrow \nu_\mu$ oscillations.

In the advent of neutrino oscillations, a mixture of different neutrino weak eigenstates reaches the Earth. Given an electron-type neutrino survival probability P_{ee}, a fraction P_{ee} of all the neutrinos arriving at the detector are ν_e, while a fraction $1-P_{ee}$ are ν_μ. The recoil electron kinetic energy distribution will, therefore, be given by

$$\frac{d\sigma(T,E_\nu)}{dT} = P_{ee} \times \left(\frac{d\sigma(T,E_\nu)}{dT}\right)_{\nu_e} + (1-P_{ee}) \times \left(\frac{d\sigma(T,E_\nu)}{dT}\right)_{\nu_\mu}. \tag{3.1}$$

Note that, in general, P_{ee} is a function of the neutrino oscillation parameters (the mass-squared differences of the neutrino mass eigenstates and the neutrino mixing angles) and the neutrino energy.

We simulate "data" at Borexino and HELLAZ for different values of P_{ee}. We use the distributions presented in section 2, while the flux of *pp* and ^{7}Be neutrinos are taken from the SSM [6]. In the case of Borexino, the energy dependence of P_{ee} is irrelevant, given the monochromatic nature of ^{7}Be neutrinos. In the case of HELLAZ, we assume that P_{ee} is constant inside each individual neutrino energy bin. Following the central idea presented in [19], we perform a χ^2 fit to the "data" using a linear combination of ν_e-e scattering and ν_μ-e scattering with arbitrary coefficients,

$$C_e \times \left(\frac{d\sigma(T, E_\nu)}{dT}\right)_{\nu_e} + C_\mu \times \left(\frac{d\sigma(T, E_\nu)}{dT}\right)_{\nu_\mu}, \qquad (3.2)$$

i.e. we perform a two parameter (C_e and C_μ) fit to the data. This measurement procedure is independent of the SSM prediction for the neutrino flux. Therefore, if a non-zero coefficient of the ν_μ-e scattering distribution is measured, one can claim to have detected evidence for neutrinos other than ν_e coming from the Sun. This "appearance" result certainly qualifies as a smoking gun signature for neutrino oscillations.

Figure 2 (long, thin error bars) depicts the measured value of $1 - P_{ee} = \frac{C_\mu}{C_e + C_\mu}$ in each of the neutrino energy bins defined in section 2 as a function of the input value of P_{ee}, for 5 years of simulated HELLAZ data. As was mentioned in the previous paragraph, the relevant information one should obtain from the plot is if the measured value of $1 - P_{ee} \propto C_\mu$ is statistically different from zero.

Figure 3 (right, long, thin error bars) depicts the measured value of $1 - P_{ee}$ as a function of the input value of P_{ee}, for two years of Borexino running. This is just a repetition of figure $2a$ in [19].[5] Figure 3 (left, long, thin error bars) depicts the result obtained at HELLAZ if all energy bins are used in the "data" analysis. This result is only meaningful if P_{ee} is roughly constant for neutrino energies ranging from 220 keV to 420 keV. This happens to be the case for most of the currently preferred regions of the two-neutrino oscillation parameter space, especially LMA, LOW and VAC solutions (see, e.g. [12]).[6] Clearly, the significance of the measurement is better than the one obtained for individual energy bins (figure 2).

Next, the same analysis as above is repeated, except that the SSM prediction for the solar neutrino flux is included in the χ^2 analysis. An uncertainty of 20% (5%) was assumed for the ^{7}Be (*pp*) neutrino flux. The theoretical error was considered gaussian

[5] In [19], a different variable, $P \equiv 1 - P_{ee}$, was used. Both results are, of course, equivalent.

[6] For the SMA solution, there is a sharp drop in P_{ee} at $E_\nu \simeq 0.4$ MeV, and the three lower bins can be combined without any problem. At HELLAZ, this will show up in the data, as the E_ν spectrum differs from the expected *pp*-neutrino spectrum, and hence is not a concern.

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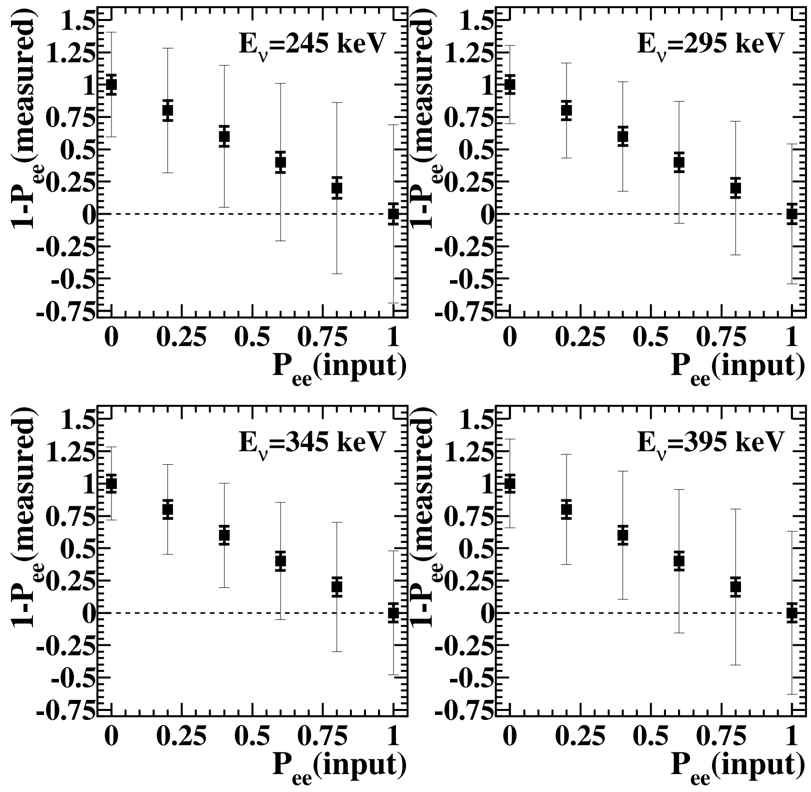

Figure 2: The "measured" value of $1 - P_{ee}$ as a function of the input value of P_{ee} for each of the 4 neutrino energy bins (see text), after 5 years of HELLAZ running. The long, thin error bars correspond to model-independent analyses based only on the electron recoil energy spectrum shape, while the short, thick ones correspond to analyses which include the SSM prediction for the solar *pp*-neutrino flux, with an (inflated) uncertainty of 5%.

for simplicity.[7] Note that the uncertainties assumed here are inflated with respect to the ones quoted in the SSM calculations [6] (9% and 1%, respectively), in order to render the results very conservative. Since the rates are very high both at Borexino and HELLAZ, the error bars are dominated by the uncertainties in the fluxes and hence they can be approximately scaled according to the assigned flux uncertainties.

The results are presented in figures 2 and 3 (short, thick error bars). The significance of the measured value of $1 - P_{ee}$ improves significantly, especially at HELLAZ, because of the small assigned uncertainty on the *pp*-neutrino flux. After five years of HELLAZ running, for example, one should be be able to determine a 1-sigma-away-from-zero ν_μ component in the *pp*-neutrino flux even for $P_{ee} \sim 0.9$. It is also noteworthy that in the case of the SMA MSW solution to the solar neutrino puzzle $P_{ee} \sim 0$ for ^{7}Be neutrinos, in which case a 4-sigma-away-from-zero evidence for ν_μ in the solar neutrino flux can be established in only two years of Borexino running! It

[7] This procedure follows the one used in [17]. The readers are referred to this article for details.

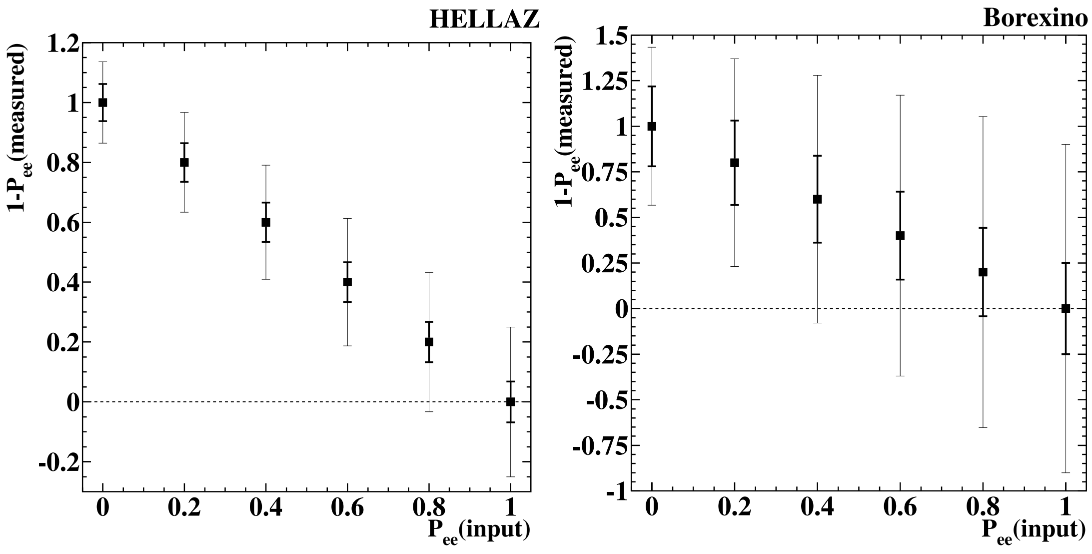

Figure 3: The "measured" value of $1 - P_{ee}$ as a function of the input value of P_{ee}, after 5 years of HELLAZ (left) and 2 years of Borexino running (right). P_{ee} is assumed to be constant for E_ν =220–420 keV in the case of HELLAZ. The long, thin error bars correspond to model-independent analyses based only on the electron recoil energy spectrum shape, while the short, thick ones correspond to analyses which include the SSM prediction for the solar pp (^{7}Be) neutrino flux, with an (inflated) uncertainty of 5% (20%).

is important to emphasise that using SSM predictions for the solar neutrino flux is a reasonable thing to do, especially for pp-neutrinos. As mentioned before, the flux of pp-neutrinos is very well known because it is tightly related to the flux of light coming from the Sun. It is, therefore, the neutrino flux which is least sensitive to detailed modelling of the Sun's innards.

Some comments are in order. First, only statistical uncertainties were considered, and there are no background events in our "data". As discussed in section 2, the assumption of a negligible background rate seems less than realistic at Borexino, but may be possible in future upgrades. However, as also discussed in section 2, the energy spectrum of the background can be measured and subtracted at HELLAZ. Note that the "realistic" background situation is still not well known at HELLAZ's present R&D stage, and studying of the impact of background subtraction on the spectrum analysis is beyond the scope of this paper. We have, therefore, neglected any effect of their background subtraction mechanism in our "data" analysis. If the real experimental data collected at either experiment contains a sizable number of background events, it is necessary to either subtract the background in a bin-by-bin basis or to somehow model the recoil kinetic energy distribution produced by background events. Analysing either of these procedures, however, is beyond the scope of this paper.

Second, the analysis which does not include the SSM flux predictions is completely model-independent (the only assumption being the electron recoil spectrum as predicted by the standard electroweak theory), while the one which includes the SSM flux predictions is model-dependent. Obviously, one obtains a much better determination of P_{ee} with the additional input of the SSM flux predictions. For establishing the "wrong neutrino component" in the solar neutrino flux as a smoking gun signature of the solar neutrino oscillations, the former approach is desired. However, for the purpose of determining the oscillation parameters, the energy dependence of the survival probability, and excluding other neutrino oscillation modes, such as $\nu_e \leftrightarrow \nu_s$ or $\nu_e \leftrightarrow \bar{\nu}_{e,\mu,\tau}$ (as will be discussed in section 4), it is reasonable to include the SSM predictions in the analysis.

Finally, we point out that the results we obtained for HELLAZ are similar to the ones obtained by J. Séguinot et al. [22]. Indeed, we chose neutrino energy bins at HELLAZ which coincide with the ones used in [22]. They also perform two different analyses of their simulated data, one which is independent of the SSM prediction for the solar neutrino flux, and one which assumes the SSM prediction for the flux. However, their data analysis procedure is somewhat different, and they do not take the theoretical uncertainty of the solar neutrino flux prediction into account.

4. Testing for the $\nu_e \leftrightarrow \nu_s$ or $\bar{\nu}_{e,\mu,\tau}$ hypotheses

Although it is most natural to assume that electron-type neutrinos oscillate into some linear combination of muon-type and tau-type neutrinos, there is a logical possibility that electron-type neutrinos might oscillate into standard model singlet sterile neutrinos [28], or, perhaps, into antineutrinos of all flavours[8] (see [27] and references therein). In this section, we will address the issue of excluding these solar neutrino oscillation modes *if the data collected at Borexino and HELLAZ are consistent with $\nu_e \leftrightarrow \nu_\mu$ oscillations.*

One can already address these "exotic" oscillation modes with the current experimental data. The flux of electron-type anti-neutrinos from the Sun is particularly constrained by the SuperKamiokande and the LSD experiments [30]: the 95% CL SuperKamiokande upper bound on the flux of $\bar{\nu}_e$ from the Sun with energies $\gtrsim 6.5\,\mathrm{MeV}$ is $\Phi_{\bar{\nu}_e} < 1.8\times10^5\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, or $\Phi_{\bar{\nu}_e}/\Phi^{^8\mathrm{B}}_{SSM} = 0.035$, where $\Phi^{^8\mathrm{B}}_{SSM}$ is the SSM prediction for the ^{8}B neutrino flux. KamLAND, being a dedicated detector for $\bar{\nu}_e$, will improve this bound further down to 0.1% of the SSM flux above reactor anti-neutrino energies ($E_\nu \gtrsim 8$ MeV) after one year of running [16]. There are, however, scenarios in which, for energies below the SuperKamiokande threshold, the $\nu_e \leftrightarrow \bar{\nu}_e$ mixing is quite large ([27] and references therein). Such a possibility can only be addressed by low-energy solar neutrino experiments.

[8]The original neutrino oscillation paper by Bruno Pontecorvo [29] did, after all, consider $\nu_e \leftrightarrow \bar{\nu}_e$!

Below, we discuss the exclusion of electron-type neutrino oscillations into sterile neutrinos or into one of the antineutrino types separately at Borexino and HELLAZ experiments.

4.1 $\nu_e \leftrightarrow \nu_s$

The $\nu_e \leftrightarrow \nu_s$ oscillation mode is allowed by the analysis of current solar neutrino data [13], even though in the case of the MSW solutions to the solar neutrino puzzle, only the equivalent of the SMA MSW solution exists at the 99% confidence level [13]. It is curious to note that, in the case of atmospheric neutrinos, the $\nu_\mu \leftrightarrow \nu_s$ hypothesis is currently somewhat disfavoured [31].

In the case of $\nu_e \leftrightarrow \nu_s$ oscillations, one expects the recoil electron kinetic energy spectrum to be exactly the same as the one generated by ν_e-e scattering, since ν_s do not interact with electrons. The only effect of the neutrino oscillations would be to suppress the expected number of events, i.e. the hypothesis of $\nu_e \leftrightarrow \nu_s$ oscillations is identical to assuming that the solar neutrino flux is, somehow, suppressed. Therefore, we attempt to fit the "data" simulated according to eq. (3.1) in section 3 (remember that the "data" is consistent with $\nu_e \leftrightarrow \nu_\mu$ oscillations) to the trial function eq. (3.2), where the piece which corresponds to C_μ vanishes identically. This is a one parameter χ^2 fit to C_e. Note that the only discrimination against ν_s is the recoil energy spectrum, because the rate can be always fitted with the free parameter C_e. The inclusion of the SSM flux prediction does not help in excluding the $\nu_e \rightarrow \nu_s$ oscillation because the free parameter C_e makes the predicted flux irrelevant.[9] Note that ^{7}Be neutrinos are predicted to have almost completely oscillated to ν_s for the (only available) SMA solution: $P_{ee} = 0.009^{+0.244}_{-0.005}$ [12].

Figure 4 depicts the value of χ^2 obtained when one attempts to fit the "data" to the sterile neutrino hypothesis, for 5 years of HELLAZ running (left) and 2 years of Borexino running (right). In the case of HELLAZ, we have assumed that P_{ee} is constant over the entire *pp*-neutrino energy range. The value of χ^2 is determined using the philosophy employed in [17], and should be compared to $N_{\rm bins} - 1$ ($N_{\rm bins}$ is the number of "data" bins). After 5 years of HELLAZ running, one should be able to exclude sterile neutrinos coming form the Sun at more than 99.9% confidence level (CL) if all electron-type neutrino have turned into muon-type neutrinos ($P_{ee} = 0$). After 2 years of Borexino running, the sterile neutrino hypothesis is only ruled out, at best, at the 89% CL.[10] The explanation for this is the fact that the recoil electron kinetic energy spectra are very different when one compares the ν_e-e and the

[9] One can "discover" ν_s by observing a nearly vanishing rate for ^{7}Be neutrinos. In the case of $\nu_e \leftrightarrow \nu_{\mu,\tau}$ oscillations, neutral-current scattering guarantees at least (when $P_{ee} = 0$) 21% of the SSM rate. For this purpose, one should rely on the SSM flux prediction.

[10] The situation does improve, of course, it more events are collected at Borexino. After 5 years of Borexino running, for example, one can exclude sterile neutrinos for $P_{ee} \lesssim 0.1$ at more than 95% CL.

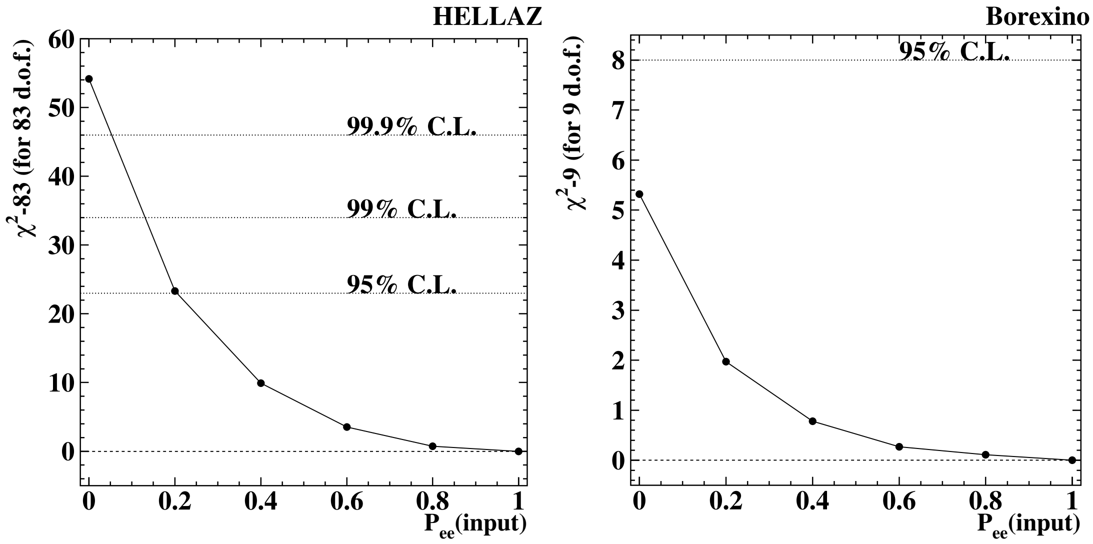

Figure 4: Minimum χ^2 values as a function of the input value of P_{ee}, obtained when one tries to fit the "data" (which is consistent with $\nu_e \leftrightarrow \nu_\mu$ oscillations and $P_{ee} = P_{ee}(\text{input})$) with a $\nu_e + \nu_s$ distribution (see text), for 5 years of HELLAZ (left) and 2 years of Borexino running (right). The dotted lines indicate the 95%, 99% and 99.9% exclusion confidence levels.

ν_μ-e scattering cases at very low energies, i.e. pp-neutrinos, and similar at $O(\text{MeV})$ energies, i.e. ^{7}Be neutrinos, as discussed in section 2. The exclusion CL decreases with increasing P_{ee}, and sterile neutrinos are excluded after 5 years of HELLAZ running only at the 77% CL for $P_{ee} = 0.4$.

4.2 $\nu_e \leftrightarrow \bar{\nu}$, model-independent fit

In the case of $\nu_e \leftrightarrow \bar{\nu}_{e,\mu}$ oscillations, we perform a two parameter fit to the "data" simulated as in section 3 to a linear combination of the ν_e-e and $\bar{\nu}_{e,\mu}$-e scattering recoil kinetic energy distributions. Figure 5 depicts the value of χ^2 obtained when such a fit is performed, for 5 years of Borexino and HELLAZ running. The value of χ^2 is to be compared to $N_{\text{bins}} - 2$ to determine exclusion confidence levels. As advertised in section 2, the ν_μ-e and $\bar{\nu}_\mu$-e scattering cases produce almost identical recoil kinetic energy spectra, and are almost undistiguishable at HELLAZ. At Borexino, however, the difference between ν_μ-e and $\bar{\nu}_\mu$-e scattering is similar to the difference between the ν_μ-e and ν_e-e cases, as mentioned in section 2 (see figure 1), and some discrimination seems possible. Furthermore, upon close inspection, one should note that the shape of the distribution produced due to ν_e-e scattering is more similar to the ν_μ-e case than the $\bar{\nu}_\mu$-e. Therefore, any $\bar{\nu}_\mu$ component in the trial function makes the value of χ^2 larger, i.e. the minimum of χ^2 is obtained when the coefficient of the $\bar{\nu}_\mu$ component

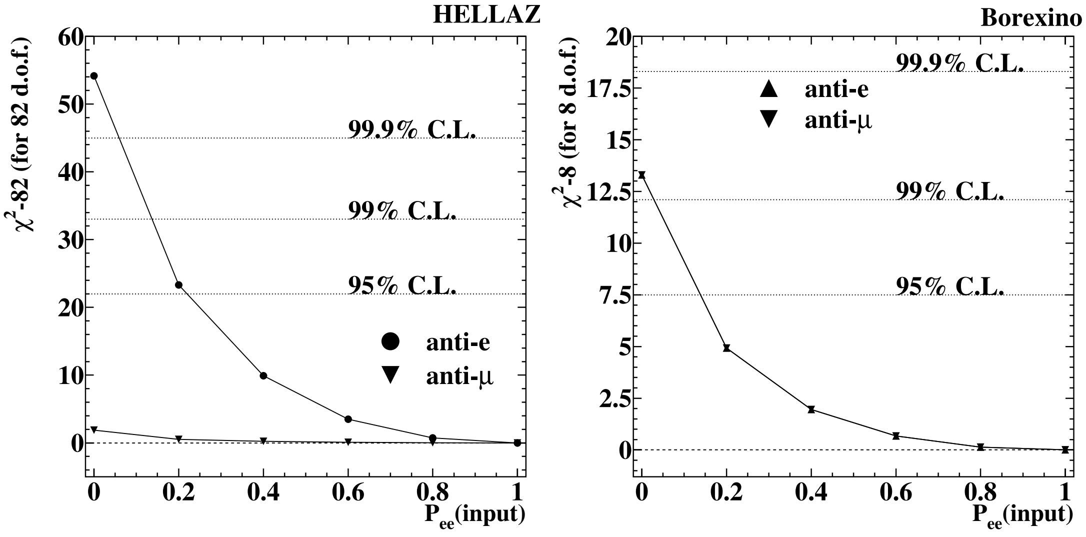

Figure 5: Minimum χ^2 values as a function of the input value of P_{ee}, obtained when fitting the "data" with a $\nu_e+\bar{\nu}$ distribution (see text). The fit does not include the SSM prediction for the solar neutrino flux and is for 5 years of HELLAZ (left) and Borexino running (right). The dotted lines indicate the 95%, 99% and 99.9% exclusion confidence levels.

is zero.[11] This is exactly what happens in the case of $\nu_e \leftrightarrow \bar{\nu}_e$ oscillations, at both experiments. Any $\bar{\nu}_e$ component in the flux makes the agreement between the theoretical function and the "data" worse, and again the best value of χ^2 is obtained when the coefficient of the $\bar{\nu}_e$-e scattering distribution is zero.

One can see from figure 5 that, after 5 years of HELLAZ data, $\bar{\nu}_e$ coming from the Sun can be ruled out at more than 95% CL if $P_{ee} \lesssim 0.2$, while $\nu_e \leftrightarrow \bar{\nu}_\mu$ oscillations are not constrained at all, even for $P_{ee} = 0$. After 5 years of Borexino data, both $\nu_e \leftrightarrow \bar{\nu}_\mu$ and $\nu_e \leftrightarrow \bar{\nu}_e$ oscillations are ruled out at more than 95% CL if $P_{ee} \lesssim 0.1$.

Even if the $\nu_e \leftrightarrow \bar{\nu}$ hypothesis cannot be ruled out at some reasonable CL, one may still be able to place upper limits on the flux of anti-neutrinos coming from the Sun. In the case of $\nu_e \leftrightarrow \bar{\nu}_e$ oscillations, it is straight-forward to place upper bounds on the flux of electron-type antineutrinos at both HELLAZ and Borexino. The 95% CL upper bounds on the $\bar{\nu}_e$ flux are depicted in figure 6. Of course, for $P_{ee} \lesssim 0.2$ (0.1) at HELLAZ (Borexino) the upper bound on the flux is meaningless, since the *hypothesis* of $\bar{\nu}_e$ is already ruled out at more than 95% CL. Note that the upper bounds on the antineutrino fluxes are normalised by the SSM prediction for the *pp*-neutrino flux $\Phi^{pp}_{SSM} = 5.94 \times 10^{10}$ cm^{-2}s^{-1} for the HELLAZ result, and the SSM prediction for the ^{7}Be neutrino flux $\Phi^{^7\mathrm{Be}}_{SSM} = 4.8 \times 10^9$ cm^{-2}s^{-1} for the Borexino result. For comparison, the 95% CL SuperKamiokande upper bound is

[11] We only allow non-negative coefficients of the distribution functions in the fits, for obvious reasons.

JHEP08(2000)025

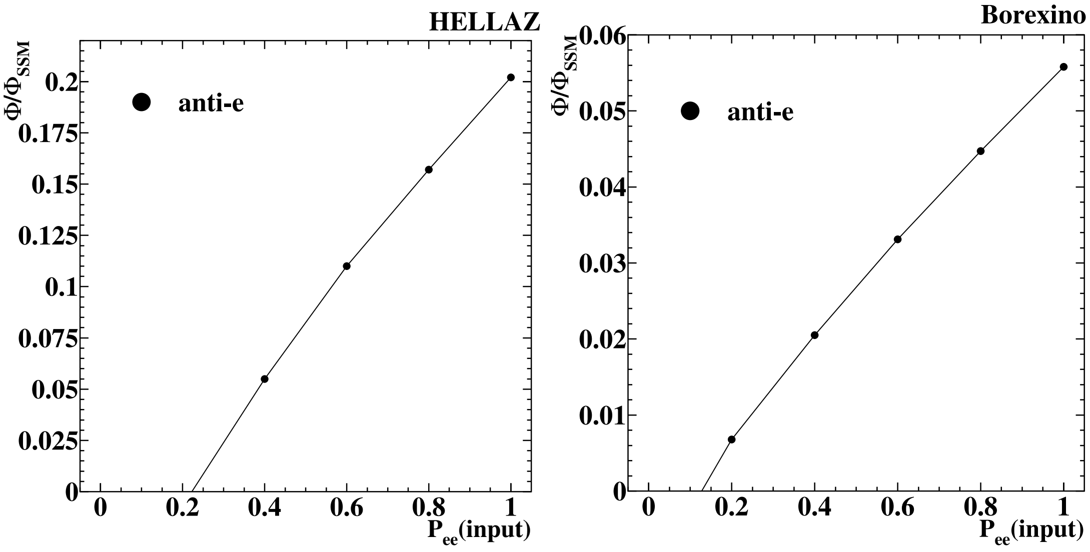

Figure 6: Upper limit on the flux of electron-type antineutrinos after 5 years of HELLAZ (left) and Borexino (right) running. The upper limits are normalised by Standard Solar Model (SSM) prediction for the *pp* (^{7}Be) neutrino flux at HELLAZ (Borexino).

Experiment	$\Phi_{\nu_\mu}/\Phi_{SSM}$	$\Phi_{\bar{\nu}_\mu}/\Phi_{SSM}$
HELLAZ	1.18	1.44
Borexino	1.62	3.77

Table 2: Model-independent 95% CL upper limits on the flux of solar muon-type neutrinos and antineutrinos, when the data after 5 years of HELLAZ/Borexino running is consistent with SSM predictions.

3.5% of the SSM flux, while KamLAND will improve it to 0.1% after one year of running. However, both of them are only for the ^{8}B neutrinos. Both the HELLAZ and (especially) the Borexino limits obtained from 5 years of "data" are competitive with the SuperKamiokande limit for lower energy neutrinos.

In the case of $\nu_e \leftrightarrow \bar{\nu}_\mu$ oscillations the situation is more ambiguous, especially at HELLAZ.[12] Not only are the minimum values of χ^2 very small, but in some cases (especially for small values of P_{ee}) a zero $\bar{\nu}_\mu$ flux is ruled out at more than 95% CL. In such cases, it seems that the reasonable thing to do is to measure the antineutrino flux, not determine upper limits! The only exception to this is the case $P_{ee} = 1$, when the data looks exactly like the SSM prediction, without neutrino oscillations. Indeed, one can not only set upper limits on the antineutrino fluxes, but should also set limits to the ν_μ flux. Such limits are presented in table 2.

It is worthwhile to comment that the information contained in figures 5, 6, and

[12] The same is true at Borexino if one assumes the SSM prediction of the total neutrino flux, as will be described later.

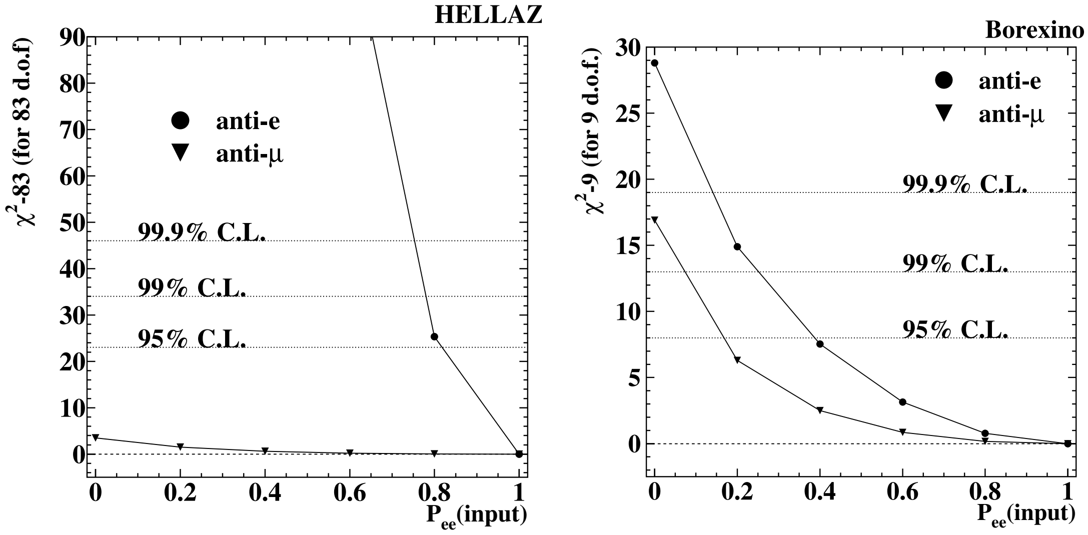

Figure 7: Minimum χ^2 values as a function of the input value of P_{ee}, obtained when fitting the "data" with a $\nu_e + \bar{\nu}$ distribution (see text). The fit assumes the SSM prediction for the solar neutrino flux with an (inflated) uncertainty of 2% (20%) for *pp* (^{7}Be) neutrinos, for 5 years of HELLAZ (left) and Borexino running (right). The dotted lines indicate the 95%, 99% and 99.9% exclusion confidence levels.

in table 2 is also valid for the case of any unknown source of solar antineutrinos of the electron and the muon-types, not only neutrino oscillations. This is because our "data" was analysed assuming that the total flux of solar neutrinos is unknown. We emphasise that P_{ee} is the survival probability of electron neutrinos assuming that they oscillate into active neutrinos, i.e. $\nu_e \leftrightarrow \nu_\mu$ oscillations.

4.3 $\nu_e \to \bar{\nu}$, SSM-dependent fit

Next, the same analysis can be repeated assuming that the solar neutrino flux is known within theoretical errors. Again, the value of χ^2 is computed[13] and compared with $N_{\rm bins}-2+1$ (the -2 corresponds to the two coefficients that are varied during the minimisation procedure and the $+1$ corresponds to the solar neutrino flux constraint). Figure 7 depicts the minimised values of χ^2 obtained with 5 years of HELLAZ (left) and Borexino (right) "data." The theoretical uncertainty on the *pp* (^{7}Be) neutrino flux was taken to be 2% (20%); we inflated the theoretical errors by roughly a factor of two from those in BP98.

A comparison between figures 5 and 7 reveals that the exclusion confidence levels increase, sometimes significantly. For example, after 5 years of HELLAZ one can exclude $\nu_e \leftrightarrow \bar{\nu}_e$ oscillations for virtually all values of P_{ee} at more than 99.9% CL. This is mostly because the $\bar{\nu}_e$ has a total cross section which is significantly larger than

[13]This procedure follows the one used in [17]. The readers are referred to this article for details.

Experiment	$\Phi_{\nu_\mu}/\Phi_{SSM}$	$\Phi_{\bar{\nu}_\mu}/\Phi_{SSM}$	$\Phi_{\bar{\nu}_e}/\Phi_{SSM}$
HELLAZ	0.14	0.14	0.13
Borexino	0.66	0.68	0.058

Table 3: 95% CL Upper limits on the flux of solar muon-type neutrinos and antineutrinos when the data after 5 years of HELLAZ/Borexino running is consistent with SSM predictions, assuming that the total *pp* (^{7}Be) neutrino flux is the one predicted by the SSM, with 2% (20%) (inflated) uncertainty.

ν_μ, and the oscillation $\nu_e \leftrightarrow \bar{\nu}_e$ cannot account for the large suppression in the event rate in the "data" (due to $\nu_e \leftrightarrow \nu_\mu$). Even the elusive $\nu_e \leftrightarrow \bar{\nu}_\mu$ case can be excluded at Borexino at more than 95% CL for $P_{ee} \lesssim 0.2$. Note that at HELLAZ the ability to discriminate between ν_μ and $\bar{\nu}_\mu$ is still quite limited. It is worthwhile to comment that, unlike in the case of model-independent fits in section 4.2, the minimum value of χ^2 is in general obtained for a non-zero coefficient of the $\bar{\nu}$-e scattering distribution. The reason for this is that, even though the shape of the $\bar{\nu}$-e scattering recoil electron kinetic energy distribution is "more wrong," the contribution to the overall cross section is smaller than the ν_e-e scattering case, and therefore one obtains values of the solar neutrino flux which are closer to the theoretical ones by having a finite $\bar{\nu}$ component, decreasing the value of χ^2.

Again, one may set upper limits on the antineutrino flux. As before, there is some ambiguity with regard to setting upper limits for the $\bar{\nu}_\mu$ flux, because for almost all values of $P_{ee} \neq 1$ at both experiments a zero flux is excluded at more than 95% CL. On the other hand, the $\nu_e \leftrightarrow \bar{\nu}_e$ oscillation hypothesis is almost completely ruled out by HELLAZ and the upper limits obtained at Borexino are not much better than the ones depicted in figure 6. For this reason, the equivalent of figure 6 in the case at hand is not presented.

Table 3 contains the obtained upper limits on the (anti)neutrino fluxes when $P_{ee} = 1$, i.e. when the data agrees with the predictions of the SSM. Unlike the case of a free total flux analysis, the results presented in table 3 assume that the total neutrino flux of neutrinos to be detected at HELLAZ and Borexino is the one predicted by the SSM, i.e. there is no "room" for other, yet unknown, low-energy solar neutrino sources. For this reason, of course, the bounds obtained are (in some cases) much more stringent.

Finally, as argued before, we emphasise that fixing the value of the solar neutrino flux to its SSM value is a reasonable thing to do, especially for *pp*-neutrinos. In these "exclusion analyses" such a procedure is even more natural, especially if one keeps in mind that a theoretical hypothesis, i.e. $\nu_e \leftrightarrow \nu_\mu$ oscillations plus the SSM computed values for the solar neutrino flux, has been "confirmed experimentally".

JHEP08(2000)025

5. Conclusions

In order to unambiguously solve the solar neutrino puzzle, and to establish the oscillations of solar neutrinos (if they occur), clear "smoking gun" signatures are required. Such signatures include a large day-night effect, anomalous seasonal variations, or an obvious distortion of the neutrino energy spectrum. Another unambiguous signature is a discrepancy between the number of charged current and neutral current events at SNO, which can be viewed as an "appearance" experiment of $\nu_{\mu,\tau}$. However, SNO can look for this "appearance" signature only for ^{8}B neutrinos with $E_\nu \gtrsim 6.5$ MeV and hence similar studies for lower energy neutrinos such as ^{7}Be and *pp* neutrinos, which are less sensitive to details of the solar model, are important.

We have argued in this paper that a careful analysis of the recoil kinetic energy spectrum at Borexino and HELLAZ serves as another "smoking gun" signature, in the sense that one may be able to infer, independent of the SSM prediction for the solar neutrino flux, the existence of $\nu_{\mu,\tau}$ coming from the Sun. It is worthwhile to emphasise that this is *different* from distortions in the incoming neutrino energy spectrum. In our case we are describing an "appearance" experiment, while the analysis of the neutrino energy spectrum is a (energy dependent) "disappearance" experiment.

It is important to point out that, in our simple simulations, no background events were included. While this is probably an oversimplification, radiopurity much better than previously anticipated has been demonstrated by Borexino [25], and one may hope to be in such a near-ideal situation in the future. The background situation of HELLAZ is not well understood at the current R&D stage, but they will be able to measure the rate and the energy spectrum of the background well and subtract it from the data. One should keep in mind that, even if the background rates are significant, the procedure we described may still be useful if the background can be successfully dealt with (one should not underestimate the ability and creativity of experimental physicists!).

We have also included in the analysis the SSM prediction of the flux of solar neutrinos. While the results obtained in this manner are model-dependent (they are not "smoking gun" signatures of neutrino oscillations), we found them very useful. This is a reasonable thing to do especially for *pp*-neutrinos, whose flux is constrained well by the solar luminosity. This additional input makes the measurement of the oscillation probability more precise.

Finally, we have argued that, *if the data collected at Borexino and HELLAZ is consistent with $\nu_e \leftrightarrow \nu_{\mu,\tau}$ oscillations*, one can try to exclude other neutrino oscillation modes ($\nu_e \leftrightarrow \nu_s$ and $\nu_e \leftrightarrow \bar{\nu}_{e,\mu,\tau}$) using the same procedure or, at least, to set upper limits on the flux of solar antineutrinos. Again we considered the possibility of constraining the solar neutrino flux to the SSM predicted value. The main result we obtained is that $\nu_e \leftrightarrow \bar{\nu}_e$ oscillations can, in general, be excluded, while the $\nu_e \leftrightarrow \bar{\nu}_{\mu,\tau}$

case is much more elusive. Nonetheless, Borexino should be able to exclude $\nu_e \leftrightarrow \bar{\nu}_{\mu,\tau}$ oscillations if the SMA MSW solution to the solar neutrino puzzle happens to be the correct one.

Acknowledgments

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