Low-energy neutrino-electron scattering as a Standard Model probe : the potential of LENA as case study

E. A. Garcés* and O. G. Miranda†
Departamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, Apdo. Postal 17-740, 07000, Mexico DF, MEXICO

M. A. Tórtola‡ and J. W. F. Valle§
AHEP Group, Institut de Física Corpuscular – C.S.I.C./Universitat de València Edificio Institutos de Paterna, Apt. 22085, E–46071 Valencia, Spain

Several proposals for studying neutrinos with large detectors are currently under discussion. We suggest that they could provide a precise measurement of the electroweak mixing angle as well as a probe for new physics, such as non-standard neutrino interactions (NSI), and the electroweak gauge structure. We illustrate this explicitly for the case of the LENA proposal, either with an artificial radioactive source or by using the solar neutrino flux.

PACS numbers: 13.15.+g, 12.15.-y, 12.60.Cn, 14.60.St

I. INTRODUCTION

The historic discovery of neutrino oscillations [1] implies that neutrinos are massive and, therefore, the Standard Model of elementary particles should be extended [2]. The nature of the required new physics remains elusive but there are strong experimental and theoretical efforts to shed light on the correct roadmap.

A new generation of proposed large neutrino experiments involving different techniques such as liquid scintillators, water Cerenkov and liquid Argon detectors is currently under the R&D phase [3]. Experiments such as LENA [4], DAEdALUS [5] or MEMPHYS [6] could serve as multi-purpose experiments to improve our current knowledge of neutrino oscillation parameters as well as to test physics beyond the Standard Model (SM).

Low energy neutrino experiments provide a clean way to probe the weak mixing angle, for example in reactor neutrino experiments [7] or in arrays of water Cerenkov detectors [8], with an expected sensitivity in the range of few percent or less. While precise determinations of $\sin^2\theta_{\rm W}$ in the high energy regime exist, the situation changes when going to lower energies. Even for the case of neutrino nucleon scattering the NuTeV collaboration [9] reported a discrepancy of the expected value for $\sin^2\theta_{\rm W}$. Recent studies suggest the need for a re-estimation of the systematical errors [10, 11], leading to an error for $\sin^2\theta_{\rm W}$ of the order of $1-5\%$ [10, 11]. For the case of neutrino and anti-neutrino scattering off electrons this situation is worse and the current accuracy in the determination of the weak mixing angle is about $10-20\%$ [12–14].

It is also of great interest to investigate the potential sensitivity of low-energy neutrino electron scattering experiments to various types of new physics, such as non-standard interactions potentially associated to the mechanism of neutrino mass generation [15, 16] and/or new gauge bosons [17–19]. Indeed there have been suggestions in this direction [20], as well as proposals to test possible oscillations of active neutrinos into sterile ones [21].

Here we study the potential of the LENA proposal [4] towards an improved measurement of the the weak mixing

*Electronic address: egarces@fis.cinvestav.mx
†Electronic address: Omar.Miranda@fis.cinvestav.mx
‡Electronic address: mariam@ific.uv.es
§Electronic address: valle@ific.uv.es

angle. We focus on the case of an artificial radioactive neutrino source as has been considered in the proposal. We find that this experimental setup could bring an improvement in the sensitivity to $\sin^2\theta_{\rm W}$ in this range of energies. We also discuss how this setup could probe physics beyond the Standard Model. In case the LENA proposal will operate without the artificial neutrino source the potential sensitivity on the measurement of $\sin^2\theta_{\rm W}$ is reduced, although we speculate on the possible use of the Beryllium solar neutrino signal to make this measurement.

II. LENA POTENTIAL WITH AN ARTIFICIAL NEUTRINO SOURCE

Since the proposed LENA detector is 100 m long, one may, at least in principle, detect different neutrino rates at different distances from the source inside the detector [4]. Indeed, the LENA proposal has considered the possibility of using an artificial radioactive neutrino source to perform neutrino oscillation measurements at short baselines, especially oscillometry tests for sterile neutrino conversions. Here we focus on an alternative application of such a source, namely, the precise determination of the neutrino electron cross section and therefore (A) the possible determination of the electroweak mixing angle and also (B) the sensitivity to new physics such as NSI and/or additional neutral gauge bosons.

A. Sensitivity to the electroweak mixing angle

Although the weak mixing angle has been measured with extraordinary precision, this is not the case for leptonic processes, especially for the case of low energy experiments. To cite an example, a recent determination of this SM parameter from anti-neutrino electron scattering off electron reported the value [12] $\sin^2\theta_{\rm W} = 0.251 \pm 0.031(\text{stat}) \pm 0.024(\text{sys})$.

Within the Standard Model the $\nu_e e$ differential cross section is given by

$$\frac{d\sigma}{dT} = \frac{2G_F m_e}{\pi}[g_L^2 + g_R^2(1-\frac{T}{E_\nu})^2 - g_L g_R\frac{m_e T}{E_\nu^2},] \tag{1}$$

where G_F is the Fermi constant, m_e is the electron mass, T is the kinetic energy of the recoil electron and E_ν is the neutrino energy. The coupling constants g_L and g_R at tree level can be expressed as

$$g_L = \frac{1}{2} + \sin^2\theta_W \tag{2}$$
$$g_R = \sin^2\theta_W. \tag{3}$$

Radiative corrections to the $\nu_e e$ process could give a correction to these coupling constants of about 2% [22]. Throughout this paper we will write the tree level expressions in order to make the discussion more transparent, however, the radiative corrections will always be included in our computations following the expressions discussed in [22] with the more recent estimate for the weak mixing angle value $\sin^2\theta_W = 0.2313$ [1].

In order to obtain a better determination for $\sin^2\theta_{\rm W}$ we consider here the particular setup of a ^{51}Cr source of 5 MCi intensity with a monochromatic neutrino line at 747 keV, considered in the LENA proposal [4]. During the half-life of the source (28 days), the neutrino flux would give a signal of about 1.9×10^5 neutrinos.

We consider two different scenarios. In the first case we estimate the sensitivity by assuming the total number of events of the detector in the full recoil electron energy range from 200 to 550 keV , while in the second case we study the possibility of an analysis in seven bins of 50 keV width. That is, we take the neutrino events to be given by

$$N_i = n_e \phi_{Cr} \Delta t \int_{T_i}^{T_{i+1}} \int \frac{d\sigma}{dT} R(T,T') dT' dT, \tag{4}$$

where n_e is the number of electron targets, ϕ_{Cr} is the neutrino flux coming from the 5 MCi neutrino source, Δt is the 28 days time window which corresponds to the half-life of the source, and the resolution function $R(T,T')$ accounts

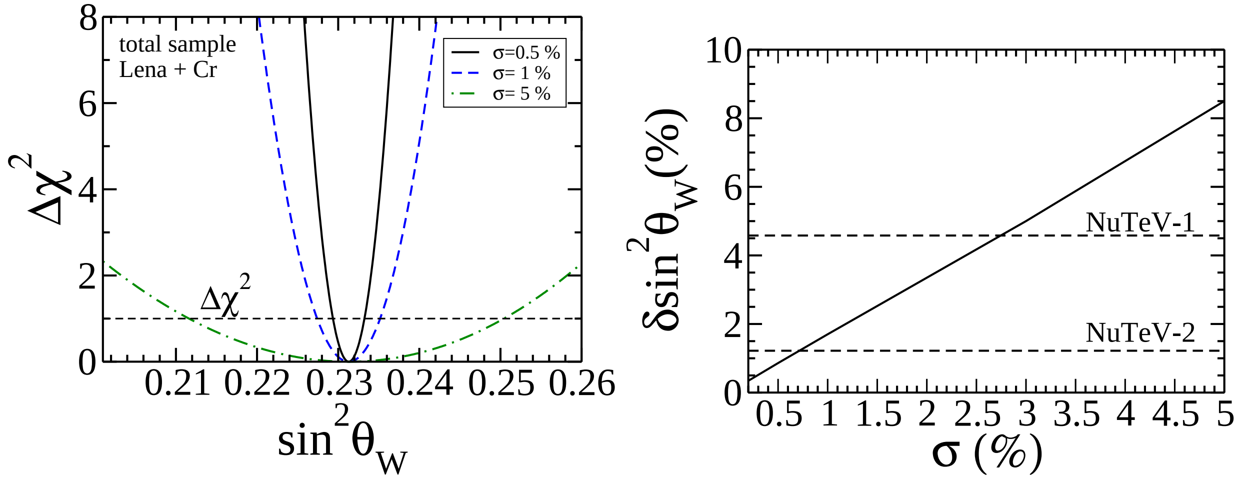

FIG. 1: Expected sensitivity to the electroweak mixing angle of a ^{51}Cr neutrino source with the LENA detector. We show the result of a simulated χ^2 analysis of the total number of events with a given total 'error' of 0.5, 1 and 5% (left panel). We also show the expected precision at 1σ (68.27 % CL) on $\sin^2\theta_{\rm W}$ as a function of a given percentual error (tilted line in right panel). Current NuTeV sensitivities associated to two evaluations of the systematical errors [10, 11] are also shown as horizontal lines.

for the distribution of the measured recoil electron energy, T, around the true energy T':

$$R(T,T') = \frac{1}{\sigma\sqrt{2\pi}}\exp[-\frac{(T-T')^2}{(2\sigma^2)}], \tag{5}$$

where $\sigma = 0.075\sqrt{T/MeV}$ is the expected energy resolution.

As already mentioned, we take two different scenarios. In the first one we consider the whole recoil electron energy window from 250 to 550 keV and therefore we have only one bin that collects all the 1.9×10^5 expected events, with a small statistical error, around 0.2%. In practice, one expects a larger error due to systematics and therefore, although we can not forecast the future precision of the experiment, we can perform our computation for different errors and determine the corresponding precision in the measurement of $\sin^2\theta_{\rm W}$.

To perform these computations we first assume that the detector will measure exactly the SM prediction and perform an ideal χ^2 analysis assuming a given error for the data. With this input we have performed a χ^2 analysis that gives us an idea of the sensitivity of LENA to a new measurement of the weak mixing angle with the help of the function

$$\chi^2 = \sum_i \frac{(N_i^{\rm theo} - N_i^{\rm exp})^2}{\sigma_i^2}, \tag{6}$$

where $N_i^{\rm theo}$ is the expected number of events for different values of $\sin^2\theta_{\rm W}$ for a given bin i, $N_i^{\rm exp}$ is the 'experimental' value given by the expected number of events for the SM prediction and σ_i^2 is the error per bin (which in this first scenario corresponds to one total bin). In order to estimate the future LENA sensitivity we have assigned different values to the error σ_i^2.

We show the results of our analysis in Fig. 1. In the left panel of this figure we can see the corresponding χ^2 function for three different values of the experimental error (0.5, 1 and 5 percent). The tilted line in the right panel indicates the expected sensitivity to the weak mixing angle at 1σ as a function of the assumed experimental error. In the same right panel we show the current NuTeV sensitivities corresponding to two evaluations of the systematical errors of the experiment [10, 11]. From the right panel one sees that an experimental error of the order of 2.5% would be required in order to improve the sensitivity obtained by the NuTeV-1 result, while only an experimental uncertainty smaller than 0.7% would improve the results given by the second NuTeV determination of the electroweak mixing angle.

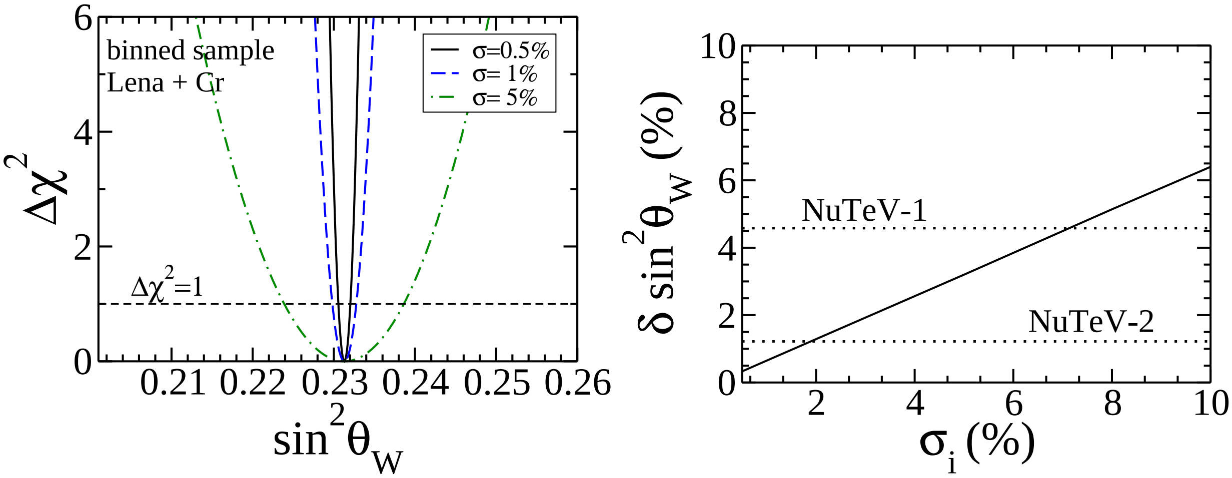

FIG. 2: Expected sensitivity to the electroweak mixing angle of a ^{51} Cr neutrino source with the LENA detector. We assume the data sample to be divided in seven bins of 50 keV each and an 'error' per bin of 0.5, 1 and 5% (left panel). The expected precision (at 68.27% CL) of the $\sin^2\theta_{\rm W}$ determination as a function of the given error in percent is given by the tilted line on the right panel. Current NuTeV sensitivities are indicated by the two horizontal lines [10, 11].

A second scenario under consideration is the case of a spectral binning in the recoil electron energy, T. Given the expected energy resolution in LENA here we imagine that the total sample is split into seven bins of 50 keV each. One performs a χ^2 analysis similar to the one developed in the previous case and we consider again different magnitudes for the error per bin (with the same error for any bin). We show the results in Fig. 2. One sees how in this case the prospects for a precise determination of the electroweak mixing parameter are substantially better than those obtained in Fig. 1. Moreover these results are less sensitive to potential uncertainties associated to the overall normalization of the neutrino flux which could arise, for example, in schemes with a light sterile neutrino. We also compare, as in Fig. 1, the current NuTeV sensitivities associated to two recent evaluations of the systematical errors of the experiment [10, 11]. One concludes that in this case an experimental error in the LENA detector of the order of 2% would suffice to improve the present sensitivity on the electroweak mixing angle given from the more precise calculations using the NuTeV measurements.

B. LENA sensitivity to new physics

Having seen how LENA detector has the potential to improve the sensitivity on the determination of the electroweak mixing angle we now turn to the possible search for new physics with LENA. For definiteness we first consider the sensitivity to the non-standard neutrino interaction (NSI) parameters that could be generically associated to the generation of neutrino mass through a low-scale seesaw mechanism [23–25] or through scalar-boson-mediation [26, 27].

We assume that a generic effective four-fermion NSI Lagrangian given as

$$-\mathcal{L}^{eff}_{\rm NSI} = \varepsilon^{fP}_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{f}\gamma^\rho P f)\,, \tag{7}$$

where G_F is the Fermi constant and $\varepsilon^{fP}_{\alpha\beta}$ parametrize the strength of the NSI. This term must be added to the Standard Model Lagrangian. For laboratory experiments f is a first generation SM fermion (e, u or d). The chiral projectors P denote $\{L, R = (1 \pm \gamma^5)/2\}$, while α and β denote the three neutrino flavors: e, μ and τ. Our aim is to obtain restrictions on the strength of the NSI parameters and compare them with those previously reported in the literature.

In order to illustrate the physics potential of LENA to this type of scenario we focus on the sensitivity to non universal NSI parameters for the interaction of neutrinos with electrons. The differential cross section for neutrino-

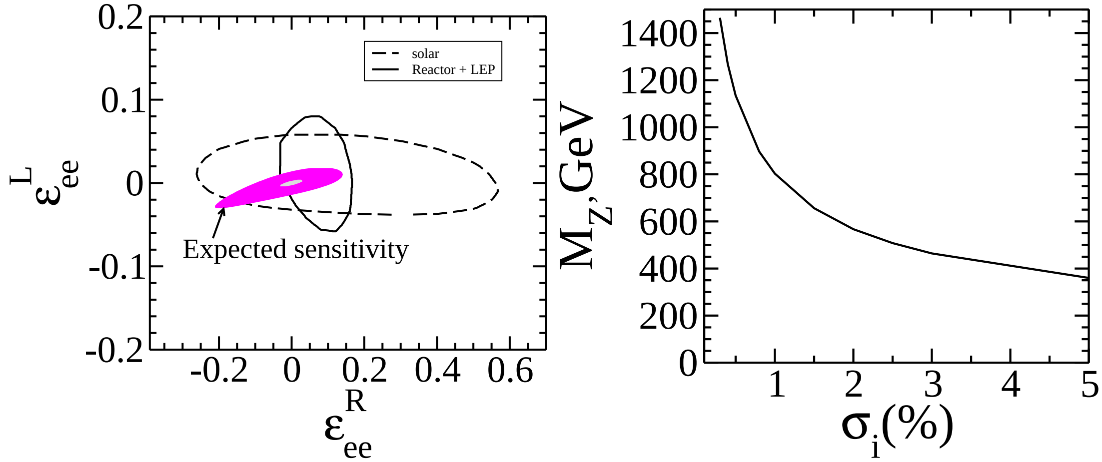

FIG. 3: Left panel: Expected LENA sensitivity at 90% CL to non-universal NSI using a ^{51} Cr neutrino source. The shaded areas correspond to a binned data sample divided in seven bins of 50 keV each and an 'error' per bin of either 1 (grey inner region) or 5% (magenta outer region). For comparison we show current limits to these parameters from an analysis coming from solar and KamLAND neutrino data [28] (dashed line) as well as from an analysis to the LEP and reactor data [29] (solid line). Right panel: Expected sensitivity at 90% CL to the mass of a new neutral gauge boson coupled to lepton number [18]. In both cases we fix the weak mixing angle as $\sin^2\theta_{\rm W} = 0.2313$.

electron scattering is therefore modified due to the presence of the new interactions. In particular, the coupling constants for the Eq. (1) will be modified to have the values

$$g_R \to g_R + \varepsilon_{ee}^R; \quad g_L \to g_L + \varepsilon_{ee}^L. \tag{8}$$

where in the Standard Model couplings $g_{L,R}$ we assume $\sin^2\theta_{\rm W} = 0.2313$ [1].

We have performed a χ^2 analysis, analogous to the one discussed above, in order to restrict the non universal NSI parameters. To this end we study the case of a ^{51} Cr source in combination with seven bins in LENA assuming an error of 0.5% and 5% in the measured number of events per bin. The results of our analysis are shown in Fig. 3 where we show the result for the case of non-universal NSI [1]. Current constraints, arising either from solar [28] or LEP+reactor neutrino experiments [29] are also displayed in the same figure, for comparison. One can see that even in the most pessimistic case the LENA sensitivity exceeds the current one. For instance, for a 5% error in the measured event number per bin the constraint on ε_{ee}^L would be below a few percent, while for the case of a 1% error the constraint on this parameter will lie below the percent level.

One can also apply these results to the case of specific theories beyond the Standard Model involving the presence of an additional relatively light neutral gauge boson, which may arise in a variety of scenarios, such as the E_6 gauge group [17–19]. As an example we take the χ model discussed in Ref. [18]. The results for the prospected sensitivity of the LENA proposal in this case are shown in the right panel of Fig. 3. One can see that a constraint in the range from 360 GeV to 1.1 TeV would be attainable depending on the statistics (the assumed error in the detected event number varying from 0.5% to 5%). It is therefore clear that for this type of models the sensitivity on the additional Z' gauge boson mass would be marginal in comparison with the reach expected at the Large Hadron Collider [30]. However one may have specific models that predict different couplings for leptons relative to quarks, suppressing the latter, for example in leptophilic scenarios [31, 32]. In this case our estimated LENA sensitivities would dominate. Similarly, the LENA proposal would also be useful in restricting models with trilinear R -parity violating couplings [33].

---

[1] Similar results may be obtained also for the flavour-changing case.

III. LENA POTENTIAL WITH SOLAR NEUTRINOS

Here we consider the possibility of performing similar analysis by using the solar neutrino data collected with the LENA detector, in the same manner as Borexino. However, in this case the signal would depend on the neutrino survival probability. Besides, as in Borexino [34], the counting per day in the detector includes the total signal from Beryllium neutrinos as well as from the background (C, Bi, Kr, etc) which can not be avoided.

Despite these difficulties we have tried to make a forecast of the sensitivity to the electroweak mixing angle assuming that LENA will be able to measure the solar neutrino signal in bins of 50 keV width. This seems attainable given the expected energy resolution of the detector. In order to obtain such a forecast we perform an analysis treating both the survival probability P_{ee} and the electroweak mixing angle $\sin^2\theta_{\rm W}$ as free parameters. In order to understand why one may reach a reasonable sensitivity on $\sin^2\theta_{\rm W}$ despite the dependence on the neutrino survival probability it is useful to see the expression for the number of events per bin,

$$N_i = n_e \phi_{Be} \Delta t \int_{T_i}^{T_{i+1}} \int \left(P_{ee} \frac{d\sigma^{\nu_e e}}{dT} + (1 - P_{ee}) \frac{d\sigma^{\nu_{\mu,\tau} e}}{dT} \right) R(T, T') dT' dT. \tag{9}$$

The differential cross section for the electron-neutrino is given by Eq. (1), while for muon or tau neutrinos one has a similar expression, but with different coupling constants [2]

$$\begin{aligned} g_L^{\nu_{\mu,\tau}} &= -\frac{1}{2} + \sin^2\theta_{\rm W} & (10)\\ g_R^{\nu_{\mu,\tau}} &= \sin^2\theta_{\rm W}. & (11) \end{aligned}$$

After some simple algebra one sees that the total number of events can be expressed as

$$N_i = n_e \phi_{Be} \Delta t \int_{T_i}^{T_{i+1}} \int \left(A(\sin^2\theta_{\rm W}) + B(\sin^2\theta_{\rm W}) T + C(\sin^2\theta_{\rm W}) T^2 \right) R(T, T') dT' dT, \tag{12}$$

where the coefficients A, B and C are given by

$$\begin{aligned} A(\sin^2\theta_{\rm W}) &= 2(\sin^2\theta_{\rm W})^2 - (1 - 2P_{ee}) \sin^2\theta_{\rm W} + \frac{1}{4}, \\ B(\sin^2\theta_{\rm W}) &= \frac{\sin^2\theta_{\rm W} m_e}{E^2} (\frac{1}{2} - \sin^2\theta_{\rm W} - P_{ee}) - \frac{2(\sin^2\theta_{\rm W})^2}{E}, \\ C(\sin^2\theta_{\rm W}) &= \frac{(\sin^2\theta_{\rm W})^2}{E}. \end{aligned} \tag{13}$$

One sees that the effect of the neutrino survival probability in the shape of the spectrum is minimal for the case of $P_{ee} \simeq 0.5$ which is close to the expected value in this region. Therefore, the main effect of P_{ee} will be to reduce the total number of events while the effect in the shape of the spectrum will be mild. For instance, the coefficient C of the quadratic term in T has no dependence on P_{ee}.

Notice also that for the ^{7}Be line we have in principle a fixed neutrino energy, $E_\nu = 0.862$ MeV, and therefore the survival probability is computed also for this energy value and hence there is no need to convolute the signal over an energy range. These features make the analysis more transparent.

Although it is difficult to forecast how well the LENA collaboration will measure the Beryllium line, we would like to give at least an estimate of the LENA sensitivity to the electroweak mixing parameter. To this end we proceed with a χ^2 analysis similar to the one introduced in the previous section, but given this time in terms of two parameters, the

---

[2] In order to make the analytical expressions more transparent we have omitted radiative corrections. However they are included in the numerical analysis.

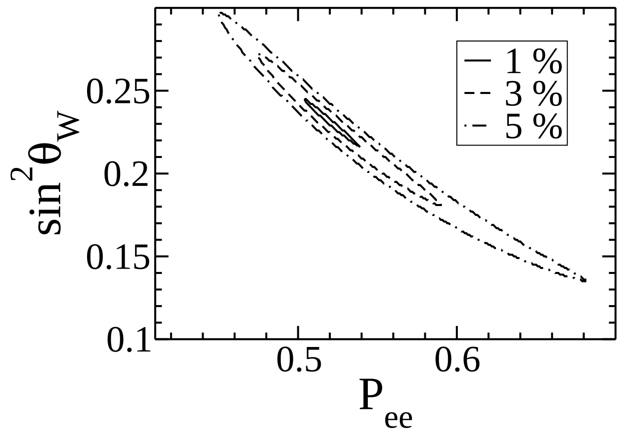

FIG. 4: Expected sensitivity (at 68.27% CL) of the LENA detector to the solar neutrino Beryllium signal, assuming a 50 keV recoil energy binning and an error per bin of 1, 3 and 5%.

electroweak mixing angle $\sin^2\theta_{\rm W}$ and the neutrino survival probability P_{ee}. In Fig. 4 we show the expected sensitivity to the neutrino survival probability and the electroweak mixing angle corresponding to a 50 keV recoil energy binning and an error of $1, 3$ and 5% for each bin. One can see that for a relatively precise determination of the Beryllium spectrum there will be a reasonable sensitivity to $\sin^2\theta_{\rm W}$. For instance, in the optimistic case of an error in the event number per bin of 1%, and despite the correlation with the survival probability, there would be a sensitivity to the electroweak mixing parameter of the order $\sim 6\%$.

IV. CONCLUSIONS

We have studied the potential of the LENA proposal for electroweak measurements in combination with a radioactive Chromium source. We showed how it could indeed provide a precise measurement of the electroweak mixing angle in a region of energy that is not easy to study with other experiments. We have also discussed some possible applications of LENA to probe physics beyond the Standard Model, such as non-standard neutrino interactions, and the possible existence of new electroweak neutral gauge bosons.

We also discussed the potential of the LENA detector for the solar Beryllium signal. Although in this case the goal will be more challenging, our results indicate that it would be worthwhile to perform a more realistic simulation of the LENA detector in order to determine more accurately its potential, by taking advantage of current Borexino spectral results. Although current data may be poor for this type of physics, they may be helpful to obtain better estimates of the future sensitivities attainable in LENA. Other proposals to probe the electroweak mixing parameter [7, 8, 35] have also been considered. The accuracy in the determination of the electroweak mixing parameter expected in LENA lies below the percent level for the most optimistic expectations on the systematical error. These results indicate that LENA holds good prospects, quite competitive with the alternatives.

V. ACKNOWLEDGMENTS

This work was supported by the Spanish MICINN under grants FPA2008-00319/FPA, FPA2011-22975 and MULTIDARK CSD2009-00064 (Consolider-Ingenio 2010 Programme), by Prometeo/2009/091 (Generalitat Valenciana), by the EU ITN UNILHC PITN-GA-2009-237920 and by CONACyT grant 166639 (Mexico). M. A. T. acknowledges financial support from CSIC under the JAE-Doc programme. O. G. M. is also supported by EPLANET.

---

[1] K. Nakamura *et al.*, Journal of Physics G: Nuclear and Particle Physics **37**, 075021 (2010).
[2] T. Schwetz, M. Tortola and J. W. F. Valle, New J.Phys. **13**, 109401 (2011); New J. Phys. **13**, 063004 (2011); for experimental references and other analyses see New J. Phys. **10**, 113011 (2008).
[3] LAGUNA Collaboration, A. Rubbia, Acta Phys. Polon. **B41**, 1727 (2010).
[4] LENA Collaboration, M. Wurm *et al.*, 1104.5620.
[5] DAEdALUS Collaboration, J. Alonso *et al.*, 1006.0260.
[6] MEMPHYS Collaboration, A. de Bellefon *et al.*, hep-ex/0607026.
[7] J. M. Conrad, J. M. Link and M. H. Shaevitz, Phys. Rev. **D71**, 073013 (2005).
[8] S. K. Agarwalla and P. Huber, JHEP **08**, 059 (2011).
[9] NuTeV collaboration, G. P. Zeller *et al.*, Phys. Rev. Lett. **88**, 091802 (2002).
[10] W. Bentz, I. C. Cloet, J. T. Londergan and A. W. Thomas, Phys. Lett. **B693**, 462 (2010).
[11] The NNPDF Collaboration, R. D. Ball *et al.*, Nucl.Phys. **B823**, 195 (2009).
[12] TEXONO collaboration, M. Deniz *et al.*, Phys. Rev. **D81**, 072001 (2010).
[13] LSND collaboration, L. B. Auerbach *et al.*, Phys. Rev. **D63**, 112001 (2001).
[14] J. Barranco, O. Miranda and T. Rashba, Phys.Lett. **B662**, 431 (2008).
[15] J. Schechter and J. W. F. Valle, Phys. Rev. **D22**, 2227 (1980).
[16] Constraints on NSI have been widely discussed. For an incomplete list, of relevance for electon-type (anti)-neutrinos see, e.g. M. Deniz *et al.* [TEXONO Collaboration], Phys. Rev. D **82** 033004 (2010); Z. Berezhiani and A. Rossi, Phys. Lett. B **535** 207 (2002); O. G. Miranda, M. A. Tortola and J. W. F. Valle, JHEP **0610** (2006) 008; S. Antusch, J. P. Baumann and E. Fernandez-Martinez, Nucl. Phys. B **810** 369 (2009); E. Fernandez-Martinez, M. B. Gavela, J. Lopez-Pavon and O. Yasuda, Phys. Lett. B **649** 427 (2007); S. Davidson, C. Pena-Garay, N. Rius and A. Santamaria, JHEP **0303** (2003) 011; S. Bergmann, M. M. Guzzo, P. C. de Holanda, P. I. Krastev and H. Nunokawa, Phys. Rev. D **62** 073001 (2000); for a review see M. Maltoni, T. Schwetz, M. A. Tortola and J. W. F. Valle, New J. Phys. **6** 122 (2004).
[17] R. N. Mohapatra and G. Senjanovic, Phys. Rev. **D23**, 165 (1981).
[18] J. W. F. Valle, Phys. Lett. **B196**, 157 (1987).
[19] E. K. Akhmedov et al, Phys. Rev. D **53** (1996) 2752; M. Malinsky, J. C. Romao and J. W. F. Valle, Phys. Rev. Lett. **95**, 161801 (2005).
[20] O. Miranda, V. Semikoz and J. W. F. Valle, Phys.Rev. **D58**, 013007 (1998).
[21] J. D. Vergados, Y. Giomataris and Y. N. Novikov, 1105.3654.
[22] J. N. Bahcall, M. Kamionkowski and A. Sirlin, Phys. Rev. **D51**, 6146 (1995).
[23] R. N. Mohapatra and J. W. F. Valle, Phys. Rev. **D34**, 1642 (1986).
[24] M. C. Gonzalez-Garcia and J. W. F. Valle, Phys. Lett. **B216**, 360 (1989).
[25] J. W. F. Valle, Phys. Lett. **B199**, 432 (1987).
[26] E. Roulet, Phys. Rev. **D44**, 935 (1991).
[27] M. M. Guzzo, A. Masiero and S. T. Petcov, Phys. Lett. **B260**, 154 (1991).
[28] A. Bolanos, O. G. Miranda, A. Palazzo, M. A. Tortola and J. W. F. Valle, Phys. Rev. **D79**, 113012 (2009).
[29] J. Barranco *et al.*, Phys. Rev. **D77**, 093014 (2008).
[30] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **700**, 163 (2011).
[31] P. J. Fox and E. Poppitz, Phys.Rev. **D79**, 083528 (2009).
[32] P. Ko and Y. Omura, Phys.Lett. **B701**, 363 (2011).
[33] E. M. Sessolo, F. Tahir and D. McKay, Phys.Rev. **D79**, 115010 (2009).
[34] G. Bellini *et al.*, Phys.Rev.Lett. **107**, 141302 (2011).
[35] A. Balantekin, J. de Jesus and C. Volpe, Phys.Lett. **B634**, 180 (2006).