Scalar-pseudoscalar interactions in neutrino-electron scattering

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Many extensions to the Standard Model imply the existence of new charged scalar Higgs bosons. We study the contribution of a general scalar or pseudoscalar coupling for the neutrino-electron scattering. We take a phenomenological approach in order to obtain model independent limits to the couplings that arise in this picture. We illustrate the reach of the constraints by studying the particular case of the type III two Higgs doublet model, where we have found new constraints to some elements of the Yukawa couplings mixing matrix ($|Y_{ee}| \leq 1 \times 10^{-1}$ and $|Y_{e\mu}| \leq 7 \times 10^{-2}$ at 90% CL).

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I. INTRODUCTION

The observation of a new boson at a mass of 125 GeV reported by ATLAS and CMS collaborations maintains the motivation to continue analyzing richer content in the scalar sector. An interesting proposal arises when one or more scalar fields are added to the scalar sector of the Standard Model (SM). One of the simplest and interesting proposals adds an additional doublet scalar field, named as Two Higgs Doublet Model (2HDM). As a result, new charged Higgs bosons are predicted which could give a sign of physics beyond the SM. This charged Higgs boson has been searched by ALEPH, DELPHI, L3 and OPAL collaborations in charged Higgs boson pair-production processes. Their results have excluded values for charged Higgs boson mass below 72.5 GeV or 80 GeV at 95% C.L. when the results are interpreted within 2HDM type I or type II, respectively. The latest experimental searches for channels $t \to H^\pm b$ and $H^\pm \to \tau \nu$ have been carried out by ATLAS and CMS. The CMS collaboration reports upper limits on the branching fraction $Br(t \to H^\pm b)$ in the range of 2-4% for charged Higgs boson masses between 80 GeV and 160 GeV. Moreover, ATLAS collaboration excluded the mixing angle $\beta$ of the charged scalar in the region $2 \leq \tan \beta \leq 6$ for charged Higgs boson masses between 90 GeV and 150 GeV in the MSSM benchmark scenario.

Other possible sources that could give clues to the existence of charged Higgs boson are the electron and neutrino scattering processes. The scattering among electrons and neutrinos plays an important role in particle physics since it is a purely leptonic process. As is well known, the Weinberg angle $\theta_W$ and the Fermi constant $G_F$ are measured with high precision in these leptonic weak interactions. Based on the SM, the only contributions for the $\nu - e$ or $\bar{\nu} - e$ scattering are given by the $W^\pm$ or $Z^0$ gauge bosons, which means purely weak interactions. The Higgs boson could participate at tree level if the neutrinos are considered with masses but its contribution is proportional to the neutrino masses which is neglected. However a charged Higgs boson contribution to the process could be considered without the neutrino masses assumption.

Beyond the SM framework, Non Standard Interactions (NSI) have been considered with vector, axial or tensor structure to electron neutrino scattering processes. Under this framework, the scalar or pseudoscalar structure has not been considered because its contribution is smaller. However, some authors give a phenomenological study with the possibility of scalar or pseudoscalar covariant neutral current interactions.

In this paper we are focused on a general analysis of scalar and pseudoscalar interactions that contribute to the (anti)neutrino-electron scattering processes. The paper is organized as follows: in Sec. II, we introduce the general formalism for the scalar-pseudoscalar interactions and derive the differential cross section for (anti)neutrino-electron scattering processes. In section III we discuss briefly the experimental data that we will use to obtain our constraints. Finally, in section IV we will show the numerical results for the general formalism and we will discuss the case of the 2HDM-type III.

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II. GENERAL CROSS SECTION

In order to have a model independent scalar-pseudoscalar interaction among leptons and charged Higgs bosons, we consider the effective Lagrangian

$$\mathcal{L}_{S,P} = \sum_{\alpha} \sum_{\beta} t_{\alpha}(Q_{S,P}) \nu_{\beta}, \quad (1)$$

where $(Q_{S,P})$ is a general operator with scalar and pseudoscalar interactions and $\alpha, \beta = e, \mu, \tau$. We will see in section IV that this expression will be useful for some extensions of the Standard Model.

With this effective Lagrangian, the amplitude for the $\nu_{\beta} - l_{\alpha}$ elastic scattering is given by the sum

$$\mathcal{M}_{\nu_{\beta} l_{\alpha}} = \mathcal{M}_{SM} + \mathcal{M}_{SP}, \quad (2)$$

where $\mathcal{M}_{SM}$ the usual amplitude of the Standard Model and $\mathcal{M}_{SP}$ the new scalar-pseudoscalar contribution that, assuming a low energy regime, is given by

$$\mathcal{M}_{SP} = \left( -\frac{i}{M_{\nu}^2} \right) \left( \bar{t}_{\alpha}(p') \nu_{\beta}(k) \bar{l}_{\alpha}(k') \nu_{\beta}(p) \right). \quad (3)$$

It is important to note that the two interference terms $\mathcal{M}_{SM}\mathcal{M}_{SP}^* \mathcal{M}_{SP} \mathcal{M}_{SM}^*$ contained in $|\mathcal{M}_{\nu_{\beta} l_{\alpha}}|^2$ give an important contribution to the result. In order to calculate these terms it is useful to make a Fierz reordering, using known techniques [11]. For the case of the operator $Q_{S,P}$, it is possible to find the general transformation

$$2i\alpha (a + b\gamma_5) \nu_{\beta} \bar{l}_{\beta} (c + d\gamma_5) l_{\alpha} = (a + b)(c + d) \left( t_{\alpha} P_R l_{\alpha} \bar{l}_{\beta} P_R \nu_{\beta} + \frac{1}{4} t_{\alpha} \sigma^{\mu \nu} P_R l_{\alpha} \bar{l}_{\beta} \sigma_{\mu \nu} P_R \nu_{\beta} \right)$$

$$+ (a + b)(c - d) t_{\alpha} \gamma^{\mu} P_R l_{\alpha} \bar{l}_{\beta} \gamma_{\mu} P_R \nu_{\beta} + (a - b)(c + d) t_{\alpha} \gamma^{\mu} P_R l_{\alpha} \bar{l}_{\beta} \gamma_{\mu} P_L \nu_{\beta}$$

$$+ (a - b)(c - d) \left( t_{\alpha} P_L l_{\alpha} \bar{l}_{\beta} P_L \nu_{\beta} + \frac{1}{4} t_{\alpha} \sigma^{\mu \nu} P_L l_{\alpha} \bar{l}_{\beta} \sigma_{\mu \nu} P_L \nu_{\beta} \right), \quad (4)$$

where $a, b, c, d$ are constants and $P_{L,R}$ the usual chiral projectors $\frac{1}{2}(1 \mp \gamma^5)$. Averaging over initial spin and summing over final spin, we have

$$|\mathcal{M}_{\nu_{\beta} l_{\alpha}}|^2 = 16G_F^2 \cdot m_e^2 \cdot E_{\nu}^2 \left\{ \left( g_{A} - g_{V} \right)^2 + 4 \left( \left| g_{S}^{\alpha, \beta} \right| + \left| g_{P}^{\alpha, \beta} \right| \right)^2 + 2 \left( g_{V} - g_{A} \right) \Re \left( g_{S}^{\alpha, \beta} - g_{P}^{\alpha, \beta} \right) \right\} (1 - y)^2$$

$$+ \left( g_{A} + g_{V} \right)^2 \left\{ \left( g_{V} - g_{A} \right)^2 + \left( g_{V} + g_{A} \right) \Re \left( g_{S}^{\alpha, \beta} - g_{P}^{\alpha, \beta} \right) \right\} \frac{m_{e} y}{E_{\nu}} \right\}, \quad (5)$$

where the $g_{V,A}$ are the Standard Model values for the vector and axial coupling constants, shown explicitly in Table II and $y = 1 - \frac{E_{\nu}'}{E_{\nu}}$, for $E_{\nu}'$ and $E_{\nu}$ the neutrino final and initial energies, respectively. With the help of previous formula it can be easily obtained that the neutrino-electron elastic cross section is

$$\frac{d\sigma_{\nu_{\beta} l_{\alpha}}}{dT} = \frac{2G_F^2 \cdot m_e}{\pi} \left\{ \frac{g_{S}^{\alpha, \beta} + \left( g_{S}^{\alpha, \beta} \right) + g_{P}^{\alpha, \beta} \right\} + g_{R} \Re \left( g_{S}^{\alpha, \beta} - g_{P}^{\alpha, \beta} \right) \left\{ 1 - \frac{T}{E_{\nu}} \right\}^2$$

$$- \left[ g_{L} g_{R} + \frac{1}{2} g_{L} \Re \left( g_{S}^{\alpha, \beta} - g_{P}^{\alpha, \beta} \right) \right] \frac{m_e T}{E_{\nu}^2} \right\}; \quad (6)$$

where $T$ is the electron recoil kinetic energy and $g_{L,R} = \frac{\nu \cdot B_{\nu \mu}}{2}$. Analogously, the antineutrino-electron elastic cross section can be obtained to be

$$\frac{d\sigma_{\bar{\nu}_{\beta} l_{\alpha}}}{dT} = \frac{2G_F^2 \cdot m_e}{\pi} \left\{ \frac{g_{S}^{\alpha, \beta} + \left( g_{S}^{\alpha, \beta} \right) + g_{P}^{\alpha, \beta} \right\} + g_{R} \Re \left( g_{S}^{\alpha, \beta} - g_{P}^{\alpha, \beta} \right) + g_{L} \left\{ 1 - \frac{T}{E_{\nu}} \right\}^2$$

$$- \left[ g_{L} g_{R} + \frac{1}{2} g_{L} \Re \left( g_{S}^{\alpha, \beta} - g_{P}^{\alpha, \beta} \right) \right] \frac{m_e T}{E_{\nu}^2} \right\}; \quad (7)$$

In the following we will study the dimensionless parameters $g_{S,P}^{\alpha, \beta}$ in muon and electron (anti)neutrino scattering. In general this parameters can be different in each case.
TABLE I: Standard Model couplings for $\nu_i e$ elastic scattering. $g_{V,A}$ are the same for the $\bar{\nu}_e e$ elastic scattering.

| Reaction                  | $g_V$                      | $g_A$ |
|---------------------------|----------------------------|-------|
| $\nu_e e \rightarrow \nu_e e$ | $2 \sin^2 \theta_W \pm \frac{1}{2}$ |       |
| $\nu_\mu e \rightarrow \nu_\mu e$ | $2 \sin^2 \theta_W - \frac{1}{2}$ |       |

III. ELASTIC NEUTRINO SCATTERING EXPERIMENTS

The cross sections computed in the previous section can be used to estimate the number of events expected in an (anti)neutrino electron scattering experiment. We will consider experiments that have measured the electron and muon neutrino scattering off electrons, both for neutrino and antineutrino channels.

The first experiment that we discuss in this section is the case of the CsI(Tl) detector in the neutrino reactor experiment TEXONO [12, 13]. The experimental resolution allows in this case a binned analysis of the data, the electron recoil energy is divided into ten energy bins, from 3 to 8 MeV. The expected number of events for energy bin is given by the following integral

$$N_i^{th} = \kappa \int_{T_i}^{T_{i+1}} \int_{E_{\nu}}^{E_{\nu}'} \chi_{\nu e}^2 (E_{\nu}) dE_{\nu} dT,$$

(8)

here $\kappa$ is a factor that includes the number of electron targets in the detector and the time exposure of the experiment, and $\chi_{\nu e}^2 (E_{\nu})$ is the antineutrino electron scattering cross section parameterized as in reference [13] for the specific radioactive isotope abundances in the Kuo Sheng 2.9 GW reactor [13]. We use for this analysis the differential antineutrino electron scattering cross section $(d\sigma/dT)$ shown in Eq. (7).

We can compute the theoretically expected number of events for a given values of $g_{e e}^S$ and $g_{e e}^P$ and perform a statistical analysis by using a $\chi^2$ function defined by

$$\chi^2 = \sum_{i=1}^{10} \frac{(N_i^{exp} - N_i^{th})^2}{\Delta_i^{stat}},$$

(9)

where $N_i^{exp}$ is the event rate for the $i^{th}$ bin measured by the experiment and $\Delta_i^{stat}$ is the associated statistical uncertainty.

A similar analysis can be done for the case of the electron neutrino scattering off electrons. In this case we can confront our theoretical estimates with the experimental result of the LSND experiment [10], that has reported the value of the total cross section for electron neutrino scattering off electron as $\sigma_{\nu e} = (10.1 \pm 1.1 \pm 1.0) \times E_{\nu} (\text{MeV}) \times 10^{-45}\text{cm}^2$. In this case we add the statistical and systematic errors in quadratures.

The same kind of statistical analysis can be done for the measurement of the muon neutrino-electron cross section reported by the CHARM II experiment [17]. As in the LSND case, in this experiment the total cross section is reported in the whole energy range, both for $\nu_\mu - e$ and $\bar{\nu}_\mu - e$ and, therefore, we will have two bins in the $\chi^2$ function.

IV. RESULTS AND DISCUSSION

In the previous sections we have showed the details of those computations in which are interested in. Here we show the results of our analysis and discuss our results.

For the case of the electron (anti)neutrino scattering, we have combined the results of the TEXONO and LSND analysis, described in the previous section, in order to obtain constraints on the parameter $g_{e e}^{S,P}$. The results are shown in Fig. 1. Although the allowed region appears to be large, it is important to notice that this is due to the strong correlation between the scalar and pseudoscalar couplings. Hence, despite the allowed region can have values of $g_{e e}^{S,P}$ as large as 1, this is only for the specific case of $g_{e e}^S \approx -0.5$. We can see that the constraints for one parameter at a time are more restrictive, given the regions $-0.15 \leq g_{e e}^S \leq 0.35$ for $g_{e e}^S = 0$ and $-0.35 \leq g_{e e}^S \leq 0.15$ for $g_{e e}^P = 0$. As we will discuss below, another important case will be that of $g_{e e}^S = g_{e e}^P$; the constraints for this particular case are shown in Fig. 2 where it is possible to see that $|g_{e e}^{S,P}| \leq 0.12$ at 90 % C.L.

Similarly, results for the muon (anti)neutrino scattering can be obtained by analyzing the CHARM II data. The results are shown in Fig. 3, also at 90 % C.L. As expected, this last case is more restrictive thanks to the better statistics of the muon neutrino experiments. In particular, if one consider one parameter at a time the constraint are stronger giving us the regions $-0.046 \leq g_{e e}^{S,P} \leq 0.045$ for $g_{e e}^S = 0$ and $-0.032 \leq g_{e e}^{S,P} \leq 0.036$ for $g_{e e}^P = 0$. As in the
FIG. 1: Parameter space allowed at 90% C.L. from the electron (anti)neutrino scattering off electrons. We have considered both the TEXONO and LSND results.

FIG. 2: Constraints from the electron (anti)neutrino scattering off electrons for the case $g_{ee}^P = g_{ee}^S$. We have considered both the TEXONO and LSND results.

previous analysis we have also computed the fit for the case where $g_{ee}^P = g_{ee}^S$, and we show this results in Fig. 4; in this case the allowed values are $|g_{ee}^P| \leq 0.06$ at 90% C.L.

As an application to a specific model we can consider the case of the 2HDM. The 2HDM contains a charged Higgs boson which has interactions with leptons as introduced previously. In order to write explicitly the general parameters $g_{S,P}$ we introduce the leptons and charged Higgs bosons interactions in 2HDM. The most general structure of the Yukawa Lagrangian for the leptons fields, can be written as follows:

$$L_{Yukawa}^{\text{leptons}} = \sum_a \sum_{\alpha,\beta} l_{L\alpha} Y_{a\alpha\beta} \phi_a e_{R\beta} + h.c.,$$

where $\alpha,\beta = e, \mu, \tau$ and $a = 1,2$ are indices for lepton flavors and Higgs doublets, respectively. $l_{Li}$ denotes the left handed leptons doublets and $e_{Rj}$ corresponds to the right handed singlets under $SU(2)_L$. The Higgs doublets are decomposed as follows:

$$\phi_a = \left( \frac{\varphi_a^+ + i\chi_a}{\sqrt{2}} \right),$$

where the vacuum expectation values $v_a$ are taken real and positive. One of the $v_a$ could have a phase $e^{i\xi}$ in a more general case, although this is outside the scope of our work. After getting a correct SSB the charged leptons mass
TABLE II: Explicit values for $g_{S,P}^\alpha$ obtained for the two Higgs doublet models [18].

| 2HDM   | $g_{S,P}^\alpha$                                      | $g_{S,P}^\beta$ |
|--------|------------------------------------------------------|-----------------|
| type I | $\sqrt{|m_{l_2}^2 \cos^2 \beta/4G_{FP} M_H^2|}$      | 0               |
| type II| $\sqrt{|m_{l_2}^2 \tan^2 \beta/4G_{FP} M_H^2|}$      | 0               |
| type III| $\frac{1}{\sqrt{2G_{FP} M_H^2}} \left( \frac{\sqrt{|m_{l_2}^2 \tan \beta - y_{ee} \sec \beta|}}{\sqrt{4G_{FP} M_H^2}} \right)^2$ | $\frac{\sqrt{m_{l_2} \sec \beta}}{\sqrt{4G_{FP} M_H^2}}$. |

matrix is given as

$$M_{\alpha\beta} = \sum_a v_a Y_{a\alpha\beta}$$  \hspace{1cm} (12)

Note that Eq. (12) relates the charged lepton mass matrix with the two matrices $Y_1$ and $Y_2$. Therefore we can choose $Y_1$ as a dependent variable. For the sake of simplicity from now on we will refer $Y_2 = Y$. As usual, we introduce the $\beta$ angle in order to relate the $\varphi_3^0$ with the physical $H^\pm$ and the Goldstone bosons $G^\pm$. Then, the interactions among leptons and $H^\pm$ is given by

$$L_{Hz} = \frac{\sqrt{2}}{v} \tan \beta H^+ \bar{\tau}_\alpha M_{\alpha\beta}^l P_R e_\beta + \frac{1}{\cos \beta} H^+ \bar{\tau}_\alpha Y_{\alpha\beta} P_R e_\beta$$

$$-\frac{\sqrt{2}}{v} \tan \beta H^- \bar{\tau}_a M_{\alpha\beta}^l P_L \nu_\beta + \frac{1}{\cos \beta} H^- \bar{\tau}_\alpha Y_{\alpha\beta}^l P_L \nu_\beta,$$  \hspace{1cm} (13)

where $P_{L,R} = \frac{1 \mp \gamma_5}{2}$. In literature, the 2HDM types are defined through the structure of Yukawa couplings [18]. The general couplings given in Eq. (10) denotes the 2HDM type III meanwhile the simplest versions named as type II or type I are defined for $Y_2 = 0$ or $Y_1 = 0$, respectively.

The specific cases of the 2HDM can be translated to the model independent approach discussed here. The corresponding values for $g_S$ and $g_P$ are shown in Table I. For these models the couplings are such that $g_S = g_P$.

Our model independent approach can be translated in the specific case of 2HDM and the phenomenological bounds to the $g_{S,P}^\alpha$ parameters could give some insight in the parameter space of $\tan^2 \beta$ and $M_{H^-}$. The 2HDM would be the particular case when $g_S = g_P$ and the table II shows explicitly values for the different model types.

In this particular case we will have $g_S = g_P$, and the values of these coupling constants are given in Table III.

From the comparison of these constants with the analytic expressions shown in Table I we can conclude that a constraint of $|Y_{ee}| < 7 \times 10^{-2}$ at 90% C.L. is reached when we consider a charged Higgs mass of 100 GeV [3] and $\tan \beta = 1$ while $|Y_{ee}| < 0.10$ at 90% C.L., for the same values of the Higgs mass and $\tan \beta$. These constraints are stronger than those coming from lepton flavor violation in the charged leptonic sector [19] where the following restrictions have been found $|Y_{\mu e}| < 0.39$ and $|Y_{ee}| < 0.71$. We can conclude then that, since we are dealing with tree level processes, we have been able to obtain a stronger bound. Moreover, the scattering that we are studying is a two body process where the contribution to new physics is only through charged current and, therefore there are less parameters involved in the process (there is no dependence on $\cos \alpha$ for example) and therefore the constraint is in some sense more robust.

It may also be interesting to obtain similar constraints for different mixings of the mixing matrix since in this case constraints could be more restrictive depending on the specific texture under study [21, 22].

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FIG. 3: Parameter space allowed at 90% C.L. from the CHARM muon (anti)neutrino scattering data.

FIG. 4: Constraints from the muon (anti)neutrino scattering off electrons, for the case $g_{e\mu}^p = g_{e\mu}^S$, from the CHARM muon (anti)neutrino scattering data.

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