Phenomenology of the new physics coming from 2HDMs to the neutrino magnetic dipole moment.

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In several frameworks for leptons-sectors of two Higgs doublet models, we calculate the magnetic dipole moment for the different flavor types of neutrino. Computations are carried out by assuming a normal hierarchy for neutrino masses, and analyzing the process $\nu \rightarrow \nu \gamma$ with a charged Higgs boson into the loop. The analysis was performed by sweeping the charged Higgs mass and taking into account the experimental constraints for relevant parameters in Two Higgs Doublet Models with and without flavor changing neutral currents; obtaining magnetic dipole moments close to the experimental thresholds for tau neutrinos in type II and Lepton-specific cases. In the neutrino-specific scenario, the contribution of new physics could be sizeable to the current measurement for flavor magnetic dipole moment. This fact leads to excluding possible zones in the parameter space of charged Higgs mass and vacuum expectation value of the second doublet.

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I. INTRODUCTION

All elementary charged fermions in the Standard Model (SM) are Dirac fermions. Nevertheless, the nature of the neutrino is not yet definitely settled and depending on the model the neutrino can be either a Majorana or Dirac fermion. By discriminating the electromagnetic behavior of the neutrino, we could have an alternative resource (aside the neutrinoless double beta decay) to determine the nature of such a particle. Since neutrinos do not carry electric charge, they can participate in electromagnetic interactions by coupling with photons only via quantum corrections. Likewise, as it happens for other particles, electromagnetic properties of neutrinos can be described employing electromagnetic form factors (EFFs). For example, by the realization of their multipole moments, neutrinos can be sensitive to intense electromagnetic fields. Such intense fields can exist in nature indeed; it has been suggested that there could be sources of magnetic fields of order $(10^{13} - 10^{18})$ G, as it could be the case during a supernova explosion or in the vicinity of particular groups of neutron stars known as magnetars [1].

Several experiments have measured phenomenological constraints over neutrinos EFFs, particularly their Magnetic Dipole Moment (MDM), which in the most stringent bound the respective value should be less to $10^{-11} \mu_B$ [2–4]. The first prototypical model to take into account these experimental thresholds has been the SM with right-handed neutrinos (transforming as singlets of SM gauge group) to determine the nature of such a particle. Since neutrinos do not carry electric charge, they can participate in electromagnetic interactions by coupling with photons only via quantum corrections. Likewise, as it happens for other particles, electromagnetic properties of neutrinos can be described employing electromagnetic form factors (EFFs). For example, by the realization of their multipole moments, neutrinos can be sensitive to intense electromagnetic fields. Such intense fields can exist in nature indeed; it has been suggested that there could be sources of magnetic fields of order $(10^{13} - 10^{18})$ G, as it could be the case during a supernova explosion or in the vicinity of particular groups of neutron stars known as magnetars [1].

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Present limits on the scalar sector in the SM still allow the possibility of an extended Higgs sector, if the correspondent effects are weak enough in the current decay channels for the detection of the SM like scalar in the mass region around of 125 GeV [7]. We shall study one of the simplest extensions of the scalar sector of the SM, the so-called Two Higgs Doublet Model (2HDM) in which we add to the symmetry breaking sector of electroweak gauge group two Higgs doublets with the same quantum numbers of isospin and hypercharge. There are many motivations for this model. One of them is the fact that the SM with just one Higgs doublet is unable to generate a baryon asymmetry of the universe of sufficient size as well as plausible dark matter candidates, or to explain the mass hierarchy in the third generation of quarks. Two Higgs Doublet Models are possible scenarios to solve these problems, due to the flexibility of their scalar mass spectrum and the existence of additional sources of CP violation [8]. Also, in the Minimal Supersymmetric Standard Model (MSSM), a second doublet should be added to cancel chiral anomalies [9]; since scalars are represented by chiral multiplets together with spin 1/2 fields. Moreover, in MSSM, a minimal Higgs sector is unable to give the mass to the up type quarks and down type quarks simultaneously, because doublets of different chiralities cannot be coupled together in the Lagrangian. Thus, a second Higgs doublet must be introduced to endow all quarks with masses.
Furthermore, the origin of neutrino masses is still an open question in High energy physics. Explaining the smallness of neutrino masses in the SM demands to consider an effective operator involving a possible High energy scale for new physics related to perhaps a most fundamental theory. Indeed, 2HDMs could be invoked to describe the neutrino-hierarchy problem by the introduction of a Vacuum Expectation Value (VEV) for one of the doublets in the scale of neutrino masses. This approach can be achieved by the realization of 2HDM-neutrino specific, where fundamentals of the model are incorporated when the new doublet couples only to the neutrino sector [10–12].

When 2HDM is built up, the general form of Yukawa couplings among fermions and scalars compatible with gauge invariance have rare processes called Flavor Changing Neutral Currents (FCNCs). Experiments such as $K^0 - K^0$ mixing highly constrain flavor violation currents [13, 14]. The discrete symmetry $Z_2$ (e.g. $\Phi_1 \leftrightarrow -\Phi_2$) as an intrinsic parity is usually implemented in the 2HDM because it forbids mixing between the two doublets, which is the primary source of FCNCs. Moreover, this symmetry ensures a CP-conserving frame in the scalar sector when $Z_2$ symmetry extended to the Higgs potential. In the last point, the $Z_2$ transformation unfolds the 2HDM since its presence (absence) leads to different forms of the Yukawa couplings between fermions and Higgs bosons with (without) flavor natural conservation. Besides to this discrete symmetry, a continuous global symmetry like $U(1)$ could be incorporated to achieve this FCNC suppression. These symmetry implementations respect the so-called Weinberg-Glashow theorem: all fermions should be coupled at most to one doublet to avoid FCNCs naturally. In our description of neutrino MDMs, we consider three models with suppression of FCNCs at tree level (type I, II, flipped, lepton and neutrino-specific 2HDMs) and one model with that kind of couplings, i.e., the type III-2HDM.

As it was pointed out above, couplings of neutrinos with photons occur via loop diagrams. In the Standard Model (SM), the loop corrections have the form of vertex diagrams and vacuum polarization diagrams. When the SSB sector includes a second doublet, further corrections appear by replacing the vector bosons $W^\pm$ by charged Higgs bosons $H^\pm$. Our goal is to characterize the corrections to the EFF’s coming from the new physics and particularly in the region of parameters in which such factors become near to the threshold of experimental detection.

The structure of this paper is as follows. We discuss the general form of the EFF’s for neutrinos in section II. Subsequently, in section III we review the two Higgs doublet Model (2HDM) and its possible realizations to incorporate the neutrino masses. In section IV we include the neutrino-specific model with viable mass terms for neutrinos. We dedicate section V to study the behavior of the form factors for these different 2HDMs. In section VI we perform the correlations between the masses and the possibility of finding observable effects coming from EFF’s of the neutrino in the different frameworks of 2HDMs with natural flavor conservation and under the presence of FCNCs. Finally, section VII highlights our conclusions and remarks, as well as perspectives to implement these constraints in other models with new physics beyond SM.

II. THE ELECTROMAGNETIC FORM FACTORS (EFF’S)

In this section, we review the general structure of the electromagnetic interactions of Dirac and Majorana neutrinos in the one-photon approximation. To find all the EFF’s, we use the general expression for the electromagnetic current

$$\langle u(p,\lambda) | J^{EM}_\mu (x) | u(p',\lambda') \rangle = \pi(p,\lambda) \Lambda_{\mu} (l, q) u(p',\lambda'),$$

(1)

where $q_\mu = p'_\mu - p_\mu$, $l_\mu = p'_\mu + p_\mu$ are the four-momenta shown in Fig. 1, and $u(p,\lambda)$, $u(p',\lambda')$ are the initial and final fermion states respectively.

Figure 1: Effective coupling representation of two neutrinos with a photon.
Further, $\Lambda_\mu$ are matrices of couplings acting on the spinors. The matrices $\Lambda_\mu$ have some interesting properties [15–17]

- The first condition is that the arrangement $\Lambda_\mu$ must be a cuadrivector, i.e. must be Lorentz covariant.
- The second condition is hermiticity of the associated current, i.e., $J^{\mu EM}_\mu = J^{EM}_\mu$ which implies

$$\Lambda_\mu (l,q) = \gamma^0 \Lambda^\dagger_\mu (l,-q) \gamma^0.$$  \hspace{1cm} (2)

- The current conservation or gauge invariance $\partial^\mu J^{\mu EM}_\mu = 0$ gives

$$q^\mu \mathcal{P} (p', \lambda') \Lambda_\mu (l,q) u (p, \lambda) = 0.$$ \hspace{1cm} (3)

Finally, the most general expression for $\Lambda_\mu (l,q)$ reads

$$\Lambda_\mu (q) = F_Q (q^2) \gamma_\mu + [F_M (q^2) i + F_E (q^2) \gamma_5] a_{\mu} q^\nu + F_A (q^2) (q^2 \gamma_\mu - q_\mu q^0) \gamma_5,$$ \hspace{1cm} (4)

where $F_Q, F_M, F_E$ and $F_A$ represent the electric charge, magnetic dipole moment, electric dipole moment and anapole moment respectively.

The EFF’s show us how the particles couple with the photon at the tree level or in loop corrections. At the tree level, we got the electric charge and one part of the contribution coming from the magnetic dipole moment. Now, if we consider the interaction with an external field $A_{ext}^\mu$ in the form

$$\mathcal{L}_{ext} = -e A_{ext}^\mu J^{EM}_\mu,$$ \hspace{1cm} (5)

the so-called anomalous magnetic moment arises. Even uncharged particles may have a magnetic dipolar moment. However, for uncharged particles, all dipole moments only appear in loop corrections. Just like the anomalous magnetic moment, the electric dipole moment and the anapole moment can be non-zero even for an uncharged particle [18].

In a similar way to what happens to other particles, neutrinos can be described by EFF’s with vertex functions. For neutrinos, the magnetic and electric dipole moments are expected to be slight since they are likely proportional to the neutrino masses. For instance, the leading contribution to anomalous magnetic moment is [18]

$$a_{\nu_i} = -\frac{3G_F m_{\nu_i}}{4\sqrt{2}\pi^2} m_i.$$ \hspace{1cm} (6)

Consequently, the neutrino magnetic moment is

$$\bar{\mu}_{\nu_i} = \frac{e}{m_i} a_{\nu_i} s_{\nu_i} \Rightarrow \Lambda_{SM} \equiv \mu_{\nu_i} = \frac{3G_F e m_{\nu_i}}{4\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19} \left( \frac{m_{\nu_i}}{1 \text{ eV}} \right) \mu_B.$$ \hspace{1cm} (7)

This relation was derived for the first time in [19], where $\mu_B$ is the Bohr’s magneton. Other systematics, as the background field method and computations based on neutrino self-energy, have determined values in the same structure and the same order of magnitude for MDM of neutrino [20–22]. If neutrino couples to photons via such moments, the neutrino electromagnetic properties can be used to distinguish Majorana and Dirac neutrinos. For Dirac neutrinos, the most important moment is $F_M$ because the other terms vanish in a $CP$–conserving scenario with a Hermitian $J^{EM}_\mu$, and are highly suppressed owing to the soft violation of $CP$. On the other hand, for Majorana neutrinos only $F_A$ is possible because the other terms vanish due to the self-conjugate nature of Majorana neutrinos. Table I summarizes the contribution for the MDM of massive neutrinos (with effective flavor masses).

Constraints over neutrino MDMs are a result of scattering experiments (based on mainly on the distortion of the recoil of charged leptons energy spectrum) [28]. In these experiments, the flavor neutrino produced at some distance from the detector is a superposition of neutrino mass eigenstates. Therefore, the MDM measured is an effective value which takes into account neutrino mixing and the oscillations during the propagation between source and detector [16]. All computations shall be referred to an effective magnetic moment of a flavor neutrino without indication of a source-detector distance $L$. Indeed, it is implicitly understood that this value is small, such that the effective magnetic moment is independent of the neutrino energy and from the source detector distance [17]. In such case, the effective MDM is $\mu^{2}_{\nu_i} \approx \sum_{j=1}^{3} \sum_{j=1}^{3} U^*_{ij} (\mu_{ji} - i \epsilon_{ij} ) |^2$; being $\mu_{ji}$ and $\epsilon_{ij}$ the neutrino magnetic dipole moment and electric dipole moment respectively.
FCNCs are eliminated at the tree-level. Here neutrinos respectively.

and electric dipole moments, the effective magnetic moments of flavor neutrinos receive contributions only from the transition dipole moments. Nonetheless, flavor neutrinos can have effective magnetic moments ≤\(\beta\) values of 0

In a CP-conserving case, Majorana neutrinos have only transition elements (\(F_M, F_E\) are antisymmetric implying Majorana neutrinos do not have diagonal elements). Nonetheless, flavor neutrinos can have effective magnetic moments even if neutrinos are of Majorana nature. In this case, since massive Majorana neutrinos do not have diagonal magnetic and electric dipole moments, the effective magnetic moments of flavor neutrinos receive contributions only from the transition dipole moments.

Henceforth, we shall only be focused in Dirac neutrinos because considered models in the next section introduce right-handed neutrinos in such a way Lepton number is conserved. These scenarios based on different Yukawa sectors of 2HDMs lead us to elucidate as effective MDMs for flavor Dirac neutrinos arise regarding new physics parameters.

### III. THE TWO HIGGS DOUBLET MODEL WITH MASSIVE NEUTRINOS

Before introducing new physics effects in MDMs, we review several 2HDMs differentiating flavor properties; which are relevant in the form of interpreting electromagnetic properties for neutrinos. From a general point of view, in 2HDMs, the symmetry breaking \(SU(2)_L \times U(1)_Y \rightarrow U(1)_Q\) is implemented by introducing a new scalar doublet with the same quantum numbers of the first one. By counting the new degrees of freedom, 2HDMs contain five Higgs bosons in its spectrum [29]. In a CP-conserving scenario, the Higgs sector consists of Two Higgs CP-even scalars \((H^0, h^0)\), one CP-odd scalar \((A^0)\) and two charged Higgs bosons \((H^\pm)\). A key parameter of the model is the ratio between the vacuum expectation values, \(\tan \beta = v_2/v_1\), where \(v_1\) and \(v_2\) are the VEV’s of the Higgs doublets; with values of 0 ≤ \(\beta\) ≤ π/2.

There are several ways to incorporate neutrino masses within the SM or its extensions, to explain the observed neutrino oscillations. We shall use a simple form which consists of adding 3 right-handed singlets of neutrinos fields \((\nu_{jR})\) corresponding to each charged lepton, enforcing the conservation of lepton number on the Lagrangian. The most general gauge invariant Lagrangian that couples the Higgs fields to leptons reads

\[
-L_Y = \bar{\eta}_{ij} \nu_{iL}^\dagger \bar{\Phi}_1 \nu_{jR}^0 + \xi_{ij} \bar{\nu}_{iL}^\dagger \bar{\Phi}_2 \nu_{jR}^0 + \eta_{ij} \bar{\nu}_{iL}^\dagger \Phi_1 E_{jR}^0 + \xi_{ij} \bar{\nu}_{iL}^\dagger \Phi_2 E_{jR}^0 + h.c.,
\]  

(8)

where \(\Phi_{1,2}\) represents the Higgs doublets, and \(\bar{\Phi}_{1,2} = i \sigma_2 \Phi_{1,2}\); the superscript “0” indicates that the fields are not mass eigenstates yet, \(\eta_{ij}\) and \(\xi_{ij}\) are non diagonal 3 × 3 matrices with \((i,j)\); denoting family indices. \(E_{jR}^0\) denotes the three charged leptons and \(\nu_{iL}^0\); denotes the lepton weak isospin left-handed doublets. In (8) we have introduced non natural masses for Dirac neutrinos by considering singlets of right handed neutrinos \(\nu_{jR}\).

As was pointed before, it is customary to implement a discrete symmetry in the 2HDM to suppress some processes such as the Flavor Changing Neutral Currents (FCNC). In particular by demanding the \(Z_2\) symmetry

\[
\Phi_1 \rightarrow \Phi_1; \quad \Phi_2 \rightarrow -\Phi_2; \\
E_{jR} \rightarrow \mp E_{jR}; \quad \nu_{jR} \rightarrow -\nu_{jR},
\]  

(9)

FCNCs are eliminated at the tree-level. Here \(\nu_{jR}\) and \(E_{jR}\) denote right-handed singlets of the down and up types of leptons respectively.

The type I-2HDM

By taking \(E_{jR} \rightarrow -E_{jR}\), the Lagrangian (8) is reduced to the so-called type I-2HDM. In this scenario, only \(\Phi_2\) couples in the Yukawa sector and gives masses to all fermions. The lepton part of the Yukawa Lagrangian in this case

| \(l\) | Mass \(\left(\frac{m}{eV}\right)\) | Magnetic dipole moment \(A_{SM}\) |
|---|---|---|
| \(\nu_e\) | 0.06089 | \(1.948 \times 10^{-20} \mu_B\) |
| \(\nu_\mu\) | 0.06754 | \(2.161 \times 10^{-20} \mu_B\) |
| \(\nu_\tau\) | 0.07147 | \(2.287 \times 10^{-20} \mu_B\) |

Table I: Magnetic dipole moments of neutrinos in the SM scenario. Flavor effective masses are values compatible with central values for PMNS matrix [23] and with cosmological bounds [24, 25] and differences over masses for \(\nu_1, \nu_2\) and \(\nu_3\) eigenstates in normal ordering [26]. The effective values for masses, obtained in this way, satisfy the bounds for the average masses of the flavor eigenstates \(m_{\nu_e}, m_{\nu_\mu}, m_{\nu_\tau} < 2.5\ eV\ [27]\), and \(m_{\nu_\tau} < 2.05\ eV\ [26]\).
becomes

\[- \mathcal{L}_Y \text{ (type I)} = \eta_{i,j}^{E,0} l_{iL} \bar{\nu}_{jL}^0 + \xi_{i,j}^{E,0} l_{iL} \Phi_2 \nu_{jL}^0 + h.c., \quad (10)\]

and the contribution to the lepton sector coupling with $H^+$ yields

\[- \mathcal{L}_Y \text{ (type I)} = \frac{g \cot \beta}{\sqrt{2M_W}} \mathcal{P} \left( U_{PMNS} M_1^{diag} P_R - M_{\nu}^{diag} U_{PMNS} P_L \right) l H^+ + h.c., \quad (11)\]

where $P_{R,L} \equiv (1 \pm \gamma^5)/2$. Therefore, in a convenient chiral basis, vertices with $H^+$ have the following behavior

\[(aP_L + bP_R) = \frac{g \cot \beta}{\sqrt{2M_W}} \mathcal{P} \left( U_{PMNS} M_1^{diag} P_R - M_{\nu}^{diag} U_{PMNS} P_L \right) l H^+. \quad (12)\]

Working uniquely with the leptonic part, with the same couplings in the charged sector for type I-2HDM, is possible to describe another model without FCNCs, the so-called Flipped model. In the last scenario, leptons and up type quarks are coupled to $\Phi_2$, and $\Phi_1$ is just coupled to down type quarks; making type I- and Flipped models share the same couplings between leptons and the charged-Higgs [9].

The type II-2HDM

If we use $E_{jR} \rightarrow \bar{E}_{jL}$ we obtain the so-called 2HDM of type II. In this model $\Phi_1$ couples and gives masses to the charged lepton sector, while $\Phi_2$ couples and gives masses to the neutrino sector. Consequently, the lepton Yukawa Lagrangian becomes

\[- \mathcal{L}_Y \text{ (type II)} = \eta_{i,j}^{E,0} l_{iL} \bar{\nu}_{jL}^0 + \xi_{i,j}^{E,0} l_{iL} \Phi_2 \nu_{jL}^0 + h.c., \quad (13)\]

and the term of charged current of the Lagrangian with leptons gives

\[- \mathcal{L}_Y \text{ (type II)} = \frac{g}{\sqrt{2M_W}} \mathcal{P} \left( \cot \beta M_{\nu}^{diag} U_{PMNS} P_L + \tan \beta U_{PMNS} M_1^{diag} P_R \right) l H^+ + h.c. \]

Therefore, in an appropriate chiral basis, vertices for $H^+$ behave as

\[(aP_L + bP_R) = \frac{g}{\sqrt{2M_W}} \mathcal{P} \left( \cot \beta M_{\nu}^{diag} U_{PMNS} P_L + \tan \beta U_{PMNS} M_1^{diag} P_R \right) l H^+. \quad (14)\]

For the type II model, an interesting aspect is that the limits of the parameter space $(m_{H^+}, \tan \beta)$ are very similar to those obtained by considering the minimal supersymmetric scenario. Furthermore, since we are concerned only in lepton sectors, couplings with $H^\pm$ can also be extrapolated to the lepton specific-2HDM, where $\Phi_2$ couples to all quarks, while that $\Phi_1$ couples to right-handed leptons [30].

The type III-2HDM

When we take into account all terms in the Lagrangian (8), both doublets are coupled simultaneously to charged leptons and neutrinos

\[- \mathcal{L}_Y = \eta_{i,j}^{E,0} l_{iL} \bar{\nu}_{jL}^0 + \xi_{i,j}^{E,0} l_{iL} \Phi_2 \nu_{jL}^0 + \bar{\eta}_{i,j}^{E,0} l_{iL} \bar{\nu}_{jL}^0 \Phi_1 \nu_{jL}^0 + \bar{\xi}_{i,j}^{E,0} l_{iL} \bar{\nu}_{jL}^0 \Phi_2 \nu_{jL}^0 + h.c. \quad (15)\]

Choosing a basis where Yukawa couplings $\eta_i$ with $\Phi_1$ lead to fermion masses

\[\eta^\nu = \frac{\sqrt{2}}{v} M^\nu = \tilde{\eta}^\nu \cos \beta + \tilde{\xi}^\nu e^{-i\nu} \sin \beta, \quad (16)\]

\[\eta^E = \frac{\sqrt{2}}{v} M^E = \tilde{\eta}^E \cos \beta + \tilde{\xi}^E e^{i\nu} \sin \beta. \quad (17)\]
Meanwhile, Yukawa couplings $\xi_i$ with $\Phi_i$ lead to FCNC couplings

\begin{align}
\xi^\nu &= -\bar{\eta}^\nu \sin \beta + \bar{\xi}^\nu e^{-i\nu} \cos \beta, \\
\xi^E &= -\bar{\eta}^E \sin \beta + \bar{\xi}^E e^{i\nu} \cos \beta.
\end{align}

By a biunitary transformation involving $V_L^\nu, V_R^\nu, V_L^E$ and $V_R^E$ matrices, Yukawa couplings can be expressed in the basis of lepton masses, where $\bar{\eta}^\nu$ and $\bar{\eta}^E$ mass matrices will be diagonal and real

\begin{align}
\bar{\eta}^\nu &= \sqrt{\frac{\beta}{\nu}} M^\nu = V_L^\nu \bar{\eta}^\nu V_R^\nu, \quad M_{ij}^\nu = \delta_{ij} m_{i}^\nu; \\
\bar{\eta}^E &= \sqrt{\frac{\beta}{\nu}} M^E = V_L^E \bar{\eta}^E V_R^E, \quad M_{ij}^D = \delta_{ij} m_i^E,
\end{align}

and the remaining couplings are associated to FCNC matrices

\begin{align}
\bar{\xi}^\nu &= V_L^\nu \xi^\nu V_R^{\nu \dagger}, \\
\bar{\xi}^E &= V_L^E \xi^E V_R^{E \dagger}.
\end{align}

To write Lagrangian in Eq. (15) in terms of mass eigenstates, we should make a unitary transformation over singlets

\begin{align}
E_{L,R} &= V_{L,R}^E E_{L,R}, \\
\nu_{L,R} &= V_{L,R}^\nu \nu_{L,R}.
\end{align}

Performing a biunitary transformation, FCNC Lagrangian can be written by

\[ \mathcal{L}_{FCNC} = \bar{\xi}_{i,j}^{\nu} \bar{\nu}_{i} \bar{L}_{i} \bar{H}_{2} \nu_{j} + \bar{\xi}_{i,j}^{E} \bar{\nu}_{i} \bar{L}_{i} \bar{H}_{2} E_{j} + h.c., \]

where $V_{R}^{\nu,E}$ is completely unknown and FCNC matrices $\xi_{i,j}^{E,\nu}$ are arbitrary. Under specific conditions, we should make a parametrization with a hierarchical structure in an analog way for fermion masses. It is achieved by imposing a convenient texture for nondiagonal matrices [9], i.e. proposing that FCNC couplings should be of the order of the geometric mean of the masses

\[ \xi_{ij} = \lambda_{ij} \sqrt{\frac{2m_{i} m_{j}}{v}}, \]

where $\lambda_{ij}$ are of $O(1)$. This condition is the so-called Sher-Cheng anzats. In the lepton sector, the matrix texture taken would have the following structure [31-33].

\begin{align}
\xi^E &= \left(\begin{array}{ccc}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{array}\right)^{T} = \sqrt{\frac{2 \lambda_{i}}{v}} \left(\begin{array}{ccc}
0 & \sqrt{m_{e}m_{\mu}} & 0 \\
\sqrt{m_{e}m_{\mu}} & 0 & \sqrt{m_{\tau}m_{\mu}} \\
0 & \sqrt{m_{\tau}m_{\mu}} & m_{\tau} \\
\end{array}\right); \\
\xi^{\nu} &= \left(\begin{array}{ccc}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{array}\right)^{\nu} = \sqrt{\frac{2 \lambda_{i}}{v}} \left(\begin{array}{ccc}
0 & \sqrt{m_{\nu_{e}m_{\nu_{\mu}}}} & 0 \\
\sqrt{m_{\nu_{e}m_{\nu_{\mu}}}} & 0 & \sqrt{m_{\nu_{e}m_{\nu_{\tau}}}} \\
0 & \sqrt{m_{\nu_{e}m_{\nu_{\tau}}}} & m_{\nu_{\tau}} \\
\end{array}\right),
\end{align}

where we have made the extrapolation from charged lepton part to neutrino sector, by assuming the same mass hierarchy as in the charged lepton sector. Furthermore, textures have the assumption that $\lambda$‘s acting on the mass matrix are the same for all FCNC couplings.

In the Higgs basis, interactions among charged leptons $l$ and neutrinos $\nu_l$ arise from the following Lagrangian

\[ - \mathcal{L}_{Y \ (\text{type III})} = \bar{\nu}_{l} (U_{PMNS}^{E} \xi_{P}^{R} - \xi^{\nu} U_{PMNS}^{\nu} P_{L}) l H^{+} + h.c. \]

Under any assumption in the couplings in the type III-2HDM, the radical difference with other 2HDMs presenting FCNC suppression is that the magnetic dipole moment arises as a consequence of flavor neutral currents, but not directly from mass terms in the Lagrangian.
IV. NEUTRINO MASSES IN NEUTRINO SPECIFIC-2HDM

We have considered in this paper an extension of the Standard Model consisting of adding one extra Higgs doublet with the same quantum numbers as those for SM-doublet along with three right-handed neutrinos, which are singlets under the Standard Model SU(2) × U(1) gauge group. The VEV’s for both doublets belong in the same scale of energy. Neutrinos couple to doublets at the same energy scale that charged leptons yielding a hierarchical problem for fermions masses. Thus, in those scenarios and to take into account Dirac masses and explain MDMs, right-handed neutrinos are implemented in an unnatural way. We shall work on the so-called Neutrino specific-2HDM, where the tiny neutrino masses could arise using a small VEV, which implies fewer assumptions than fitting small masses or Yukawa couplings directly. In this framework, we intend to calculate electromagnetic form factors for neutrinos. For this model, it is customary to implement a U(1) global symmetry defined by

\[ \Phi_1 \to e^{i\phi} \Phi_1 \text{ and } \Phi_2 \to -\Phi_2. \]  

(30)

The most general Lagrangian in neutrino specific model reads

\[ \mathcal{L} = (D_{\mu} \Phi_1)^\dagger (D^\mu \Phi_1) + (D_{\mu} \Phi_2)^\dagger (D^\mu \Phi_2) - V_H + \mathcal{L}_Y + \mathcal{L}_\nu, \]

where \( V_H, \mathcal{L}_Y \) and \( \mathcal{L}_\nu \) denote the Higgs potential, Yukawa Lagrangian for quarks and charged leptons and Yukawa Lagrangian for the neutrino sector respectively. One interesting and straightforward model arising from this Lagrangian structure is the neutrino specific 2HDM, wherein Dirac neutrino masses are generated with the same SSB to the remaining fermions. Naturalness and smallness are circumvented by the fact that a doublet acquires one VEV in the same scale as the neutrino masses [10, 11]. To see this formally, we introduce a Higgs potential taking into account a softly broken U(1) symmetry using a \( \bar{m}_{12}^2 \) term, which has small radiative corrections as well as soft contributions to RGE’s [12]

\[ V_H = \bar{m}_{11}^2 \Phi_1^\dagger \Phi_1 + \bar{m}_{22}^2 \Phi_2^\dagger \Phi_2 - \left( \bar{m}_{12}^2 \Phi_1^\dagger \Phi_2 + h.c. \right) \\
+ \frac{1}{2} \lambda_1 \left( \Phi_1^\dagger \Phi_1 \right)^2 + \frac{1}{2} \lambda_2 \left( \Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \left( \Phi_1^\dagger \Phi_1 \right) \left( \Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left( \Phi_1^\dagger \Phi_2 \right) \left( \Phi_2^\dagger \Phi_1 \right). \]

(32)

We can settle \( \bar{m}_{12}^2 \) as real and positive without loss of generality, by re-phasing \( \Phi_2 \) and translating the excess phase into the Yukawa couplings, which is already, in general, a complex matrix taking into account possible CP violation phases. Note that even after the global U(1) is softly broken, lepton number survives as an accidental symmetry of the model. Neutrinoless double beta decay and Majorana neutrinos are thus absent.

On the other hand, it is worthwhile to discuss naturalness dependency in the scalar spectrum and radiative corrections for propagators. Likewise SM, the mass-squared parameters \( \bar{m}_{11}^2 \) and \( \bar{m}_{22}^2 \) in the Higgs potential (32) suffer from large radiative corrections with quadratic \( \Lambda^2 \) sensitivity to the high-scale cutoff of the theory, in the same way as the SM Higgs mass-squared parameter works. Hence, hierarchy problem is still present in this model. Nonetheless, it is possible to avoid it, by introducing this scalar sector in a model with strong dynamics (e.g. Composite Higgs Model) or SUSY in TeV scale. Due to smallness size demanded for \( \bar{m}_{12}^2 \), this problem can be circumvented even a TeV scale when mass scalar eigenstates \( H^0 \) and \( A^0 \) take appropriate values in the mass range of 400 – 600 GeV [34].

Mass eigenstates in this model can be achieved by the doubles parameterization

\[ \Phi_i = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+_i \\ \sqrt{2} \phi^i \end{pmatrix}. \]

(33)

Relations among quartic couplings and Higgs masses are 2

\[ 16\pi^2 \frac{d}{d \log \mu^2} \mu_{12}^2 = (2\lambda_3 + \lambda_4) \mu_{12}^2. \]

(1)

Hence its size is technically natural since radiative corrections to \( m_{12}^2 \) are proportional to \( \mu_{12}^2 \) itself and are only logarithmically sensitive to the cutoff.

\[ 2 \] By perturbativity grounds, we expect that small differences between \( m_{340}^2 \) and \( m_{440}^2 \) must be at most of the same order of \( v_2^2 \).
\begin{align}
m_{h_0}^2 &= \lambda_1 v^2, \\
m_{H^\pm}^2 &= m_{22}^2 + \frac{1}{2} \lambda_3 v^2, \\
m_{A,H}^2 &= m_{H^\pm}^2 + \frac{1}{2} \lambda_4 v^2.
\end{align}

This model behaves as a pseudo-inert 2HDM, where \( v_2 \ll v_1 \). The Yukawa Lagrangian in (31) with massive neutrinos (considering right-handed singlets of neutrinos) inspired on 2HDM reads

\[- L_Y = \xi_{ij}^\nu \bar{L} L \Phi_1 \nu R_j + \eta_{ij}^E \bar{L} L \Phi_1 E R_j + \eta_{ij}^D \bar{Q} L \Phi_1 U R_j + h.c., \]

where \( \Phi_i = i \sigma_2 \Phi_i \) is the conjugate of the Higgs doublet. Fermion doublets are defined by

\[ Q_L \equiv (u_L, d_L)^T \] and

\[ L_L \equiv (\nu_L, e_L)^T. \]

Here \( \Phi_1 \) is referred to the three down type weak isospin lepton (quark) singlets and \( \nu_R \) \((U_R)\) is referred to the three up type weak isospin neutrino (quark) singlets. The first part in (35) comes from right-handed neutrinos, while the second part is SM like. This can be considered as a Dirac addition for SM, where the small mass for neutrinos come from a small VEV in the second doublet. These right handed neutrinos \( \nu_R \) will pair up with the three left-handed neutrinos of the SM to form Dirac particles. Compatibility with a Higgs potential lead to define a \( U(1) \) charge acting only over the second doublet. Hence all SM fields hold unchanged. The Yukawa Lagrangian might also be generated from a \( U(1) \)-global symmetry from the following set of transformations

\[ \Phi_1 \rightarrow e^{i\varphi} \Phi_1 \text{ and } \Phi_2 \rightarrow - \Phi_2, \]

\[ E_{jR} \rightarrow e^{-i\omega} E_{jR} \text{ and } \nu_{jR} \rightarrow - \nu_{jR}, \]

\[ D_{jR} \rightarrow e^{-i\omega} D_{jR} \text{ and } U_{jR} \rightarrow e^{-i\varphi} U_{jR}. \]

with \( \omega = \varphi \) (which can be taken equal to zero as a particular case) generates neutrino-specific 2HDM. Moreover, it is possible to see that these transformations do not allow Majorana terms because of the presence of only right-handed singlets, i.e., \( \mathcal{L}_{Maj} = \eta^M (\nu_R^*) \Phi_2 U_R. \) The lepton sector of the Yukawa Lagrangian in its charged part reads

\[- L_Y (\text{neutrino specific}) = \sqrt{2 m_{\nu_i} v_2} \bar{\nu}_l (U_{PMNS} P_L) l H^+ + h.c. \]

V. RADIATIVE CORRECTIONS IN 2HDM

With all fundamentals for lepton charged Higgs sectors in different 2HDMs in mind, we study new physics contributions to neutrino-MDM. We begin our discussion with the background contribution in the SM with right-handed neutrinos. Figure 2 shows diagrams contributing to the neutrino electromagnetic vertex in SM+RH neutrinos.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{Loop contributions in SM to neutrino electromagnetic form factors.}
\end{figure}

Within the framework of a 2HDM with massive neutrinos, we should add three new types of contributions: two vertex corrections and one correction to the vacuum polarization displayed in Fig. 3. They arise by replacing \( W^\pm \) by \( H^\pm \) in the SM diagrams.

We can parametrize new physics effects by separating the contributions of SM and 2HDM

\[ \Lambda_{2HDM} = \Lambda_{SM} + \Delta \Lambda_{2HDM}, \]

where \( \Lambda_{SM} \) provides the contribution for MDM coming from the SM, given by Eq. (7). The new physics contribution \( \Delta \Lambda_{2HDM} \) splits into two diagrams: i) The first one associated with a vertex correction with two charged Higgs bosons...
and one charged lepton ($\Delta \Lambda_{2L \pm 1L}$) into the loop. ii) The second one is the vertex correction with two charged leptons and one charged Higgs boson ($\Delta \Lambda_{2L1H \pm}$) into the loop. Finally, the diagram in Fig. 3(g), does not contribute to MDM.

Figure 3(f) shows the vertex correction involving two charged Higgs bosons and one charged lepton into the loop ($2H^\pm 1L$). For this diagram, the general form of the contribution can be written as

$$
\Delta \Lambda^\alpha_{2H^\pm 1L} (q, l) = -e \int \frac{d^4k}{(2\pi)^4} \frac{(aP_L + bP_R) (2k^\alpha + p_1^2 + p_1^q) (cP_L + dP_R) (k + m_l)}{(k + p_1)^2 - m_{H^\pm}^2} (k^2 - m_l^2),
$$

(39)

where $a, b, c$ and $d$ are constants associated with the Feynman rules of the particular 2HDM. Finally, $\alpha$ is a Lorentz index.

On the other hand, the diagram in Fig. 3(c) with two leptons and one charged Higgs into the loop ($2L1H^\pm$), gives a contribution of the form

$$
\Delta \Lambda^\alpha_{2L1H^\pm} (q, l) = -e \int \frac{d^4k}{(2\pi)^4} \frac{(aP_L + bP_R) (k + p_1 + m_l) \gamma^\alpha (k + p_2 + m_l) (cP_L + dP_R)}{(k + p_1)^2 - m_l^2} (k^2 - m_{H^\pm}^2).
$$

(40)

Then by factorizing out these integrals in the form of Eq. (4), contribution from new physics to magnetic dipole moment is finally

$$
\Delta \Lambda_{2HDM} (q, l)_{FM} = 2\Delta \Lambda_{2H1L} (q, l)_{FM} + 2\Delta \Lambda_{2L1H} (q, l)_{FM}
$$

$$
= \frac{ei}{8\pi^2} \int_0^1 dx \int_0^1 dy \frac{1}{D_1} \left[ m_\nu (-1 + 3x - x^2) + m_l \left( \frac{1}{2} - x \right) \right] (ac + bd)
$$

$$
+ \frac{ei}{8\pi^2} \int_0^1 dx \int_0^1 dy \frac{1}{D_2} \left[ m_\nu (4x^2 - 5x + 2) (ad + bc) + m_l x (ac + bd) \right],
$$

(41)

where the number 2 comes from the inclusion of both $H^+$ and $H^-$ into the contributions. $D_1$ and $D_2$ are defined as

$$
D_1 = y^2 m_\nu^2 - 2x y m_\nu^2 + (m_\nu^2 - m_l^2 + m_{H^\pm}^2) y + x^2 m_\nu^2 + (m_\nu^2 - m_l^2 - m_{H^\pm}^2) x + m_{H^\pm}^2,
$$

$$
D_2 = y^2 m_\nu^2 - (m_{H^\pm}^2 - m_l^2 - m_\nu^2) y - 2x y m_\nu^2 + x^2 m_\nu^2 + (m_\nu^2 + m_l^2 - m_{H^\pm}^2) x + m_l^2.
$$

Using Yukawa Lagrangians for charged scalar sector described in sections III and IV, it is possible to extract the contributions for different models to charged Higgs-charged lepton and neutrino vertices, which are summarized in Tab. II.

VI. RESULTS AND ANALYSIS FOR MDM IN 2HDMS

Our analysis are based on constraints on charged Higgs masses. For either type I or II models, the experimental constraints on the possible values in the ($m_{H^\pm}$, tan $\beta$) parameter space come from processes such as $B_u \rightarrow \tau \nu$, $D_s \rightarrow \tau \nu$, $B \rightarrow D \tau \nu$, $K \rightarrow \mu \nu$, and BR ($B \rightarrow X_s \gamma$) [35].
Using the phenomenological constraints on the type I-2HDM, we take values of \( \tan \beta \) between \((2 - 90)\) and values of the charged Higgs mass of \( m_{H^\pm} = (100 - 900) \) GeV [36]. On the other hand, for the type II-2HDM, we have different allowed intervals of \( \tan \beta \) for different values of the charged Higgs mass: for \( m_{H^\pm} = 300 \) GeV the values of \( \tan \beta \) lie within the interval \((4 - 40)\), for \( m_{H^\pm} = 400 \) GeV, \( \tan \beta \) has the allowed interval of \((2 - 55)\). For \( m_{H^\pm} = 500 \) GeV the value of \( \tan \beta \) is between \((2 - 69)\) and for \( m_{H^\pm} = (700 - 900) \) GeV, \( \tan \beta \) is between \((1 - 70)\) [9, 36].

In the first three graphics of Fig. 4, we plot the electron, muon and tau neutrino MDM versus \( \tan \beta \) for the same charged Higgs masses as before for the type I and II 2HDMs. The horizontal lines in the electron neutrino case corresponds to the experimental upper limits for MDM coming from TEXONO 2007 (Taiwan Experiment On Neutrino) [37] which is \( \mu_{\nu_e} < 7.4 \times 10^{-11} \mu_B \) at 90% C.L., and GEMMA 2013. (Germanium Experiment for measurement of Magnetic Moment of Antineutrino) [38] which is \( \mu_{\bar{\nu}_e} < 2.9 \times 10^{-11} \mu_B \) at 90% C.L. In the case of muon neutrino the horizontal lines correspond to the experimental limits for MDM coming from LSND 2001 (Liquid Scintillating Neutrino Detector) [39] that yields \( \mu_{\nu_\mu} < 6.8 \times 10^{-10} \mu_B \) at 90% C.L., and BOREXino 2008 BOREXino is the Italian diminutive of BOREX (Boron solar neutrino experiment) [40] that gives \( \mu_{\nu_\mu} < 1.9 \times 10^{-10} \mu_B \) at 90% C.L. Finally the horizontal lines to tau neutrino correspond to the experimental limits for MDM coming from DONUT 2001 (Direct Observation of the NU Tau) [41] that gives \( \mu_{\nu_\tau} < 3.9 \times 10^{-7} \mu_B \) at 90% C.L., and BOREXino 2008 [40] whose upper limit is \( \mu_{\nu_\tau} < 1.5 \times 10^{-10} \mu_B \) at 90% C.L. [3].

We analyze magnetic dipolar moments for 2HDMs, taking the values for effective masses of each flavor neutrino considered in Tab I (which are respecting the cosmological bound and mass differences for \( \nu_1, \nu_2 \) and \( \nu_3 \) states in a normal ordering):

- Magnetic dipole moment of \( \nu_e \): For the type I and Flipped cases, the largest contributions come from lower values of \( \tan \beta < 10 \), that provides a scale for the MDM of at least four magnitude orders between \( 10^{-28} - 10^{-25} \) \( \mu_B \); being the most relevant for low values of charged Higgs masses. Hence, new physics from the type I-2HDM does not give a significant correction on SM effective operators \( \Lambda_{SM} \sim 2 \times 10^{-20} \mu_B \). Therefore, there are no regions of exclusions for the parameter space of type I from MDM’s analyses. As for the type II case, the most significant contributions are established by lower values of charged Higgs mass and higher values of \( \tan \beta \); our better case \( \tan \beta = 55 \) and a mass of charged Higgs of 400 GeV with a contribution close to \( 2 \times 10^{-22} \mu_B \). Even though this contribution is higher than the one of the type I-2HDM, they are still around of two orders of magnitude below of SM contribution.

Therefore, differences between both models start in one order of magnitude (for \( 1 < \tan \beta < 10 \)) and go up to at least seven orders of magnitude (for \( \tan \beta \gg 1 \)). The difference in behavior between both models with respect to \( \tan \beta \) is a consequence of couplings structure in the Yukawa sectors.

In the type III-2HDM, relevant contributions are located for \( \chi \rightarrow 1 \) and lower values of charged Higgs mass. For these values, the maximum achieved for \( \nu_e \)-MDM is three orders of magnitude below of SM contribution.

- Magnetic dipole moment of \( \nu_\mu \): Concerning MDM for electron neutrino, the value for a similar parameter space of new physics is at a higher scale, which lies between five to six orders of magnitude above. Fundamentally, these effects are slightly due to our assumption of a normal hierarchy for neutrinos. Despite contributions of the type II-2HDM overcome SM values, our better case \( \tan \beta = 55 \) and a mass of charged Higgs of 400 GeV with a contribution close to \( 1 \times 10^{-15} \mu_B \), avoiding possible exclusion regions in the parameter space of these theories. A similar case is presented in the type III-scenario (using Cheng-Sher anzats), where the best contribution is close to \( 10^{-17} \mu_B \) \((m_{H^\pm} = 300 \text{ Gev and } \lambda_1 \rightarrow 1)\).

\[ \text{Table II: Coefficients for } P_L \text{ and } P_R \text{ couplings present in the Magnetic Dipole Moment for type I,II,III and neutrino specific-2HDMs. In our numerical analyses, we shall use the accurate value for Fermi’s constant } G_F = \sqrt{2}g^2/8M_W^2 = 1.1663787(6) \times 10^{-5} \text{ GeV}^{-2}. \]

| Vertex couplings | Type I and Flipped | Type II and Lepton specific | Type III Neutrino specific |
|------------------|-------------------|----------------------------|---------------------------|
| \( a = c \)      | \( -2\sqrt{G_F m_{\nu_i} \cot \beta U_{k,i}} \) | \( -2\sqrt{G_F m_{\nu_i} \cot \beta U_{k,i}} \) | \( -2m_{\nu_i} U_{k,i} \) |
| \( b = d \)      | \( 2\sqrt{G_F m_{\nu_i} \cot \beta U_{k,i}} \) | \( -\xi_{k,i} U_{k,i} \) | \( \frac{2m_{\nu_i} U_{k,i}}{\xi_{k,i}} \) |

\[ \text{In a current study [28], an updated analysis of the neutrino magnetic moments was provided. Particularly, based on the most recent data from Borexino, a new limit on the effective neutrino magnetic moment has been obtained: } 3.1 \times 10^{-11} \mu_B \text{ at 90\% C.L.} \]
Figure 4: (Left) Contribution to the magnetic dipolar moment for $\nu_e, \nu_\mu, \nu_\tau$-neutrinos coming from type I (and Flipped), II (and Lepton-specific) 2HDMs with masses of charged Higgs sweeping between (100 – 900) GeV to type I, (300 – 900) GeV to type II to different values of $\tan\beta$ to each mass of charged Higgs. (Right) Contribution to the magnetic dipolar moment for neutrinos coming from type III-2HDM. Here we have taken the masses of charged Higgs sweeping between (300 – 800) and $\lambda_\nu, \lambda_1 \in [10^{-6}, 1]$. The horizontal dotted line makes reference to the experimental thresholds for each neutrino flavor at 90% C.L.
• Magnetic dipole moment of $\nu_\tau$: We can see that the scale for MDM increases by almost four orders of magnitude concerning muon neutrino contribution. For the type I and II 2HDMs, contributions are above of the standard model one. It owes to our anzats for mass behavior where tau neutrino is the heaviest, and also because of the tau lepton mass. For the type II model, the new physics contribution is only two orders of magnitude lower on the experimental threshold, for our better case $\tan \beta = 68$ and a mass of charged Higgs of 500 GeV with a contribution close to $8 \times 10^{-12} \mu_B$. The type III-scenario reproduces a best contribution close to $1 \times 10^{-14} \mu_B$ for our better case $\tan \beta = 68$ and a mass of charged Higgs of 500 GeV with a contribution close to $8 \times 10^{-12} \mu_B$. The type III-scenario reproduces a best contribution close to $1 \times 10^{-14} \mu_B$.

• Extracting relevant terms in Eq. (41), it is possible to estimate the discrepancies between SM and new physics coming from 2HDM through the following ratio for MDM contributions

$$R_\nu = \frac{\Delta \Lambda_{2HDM}^{\nu}}{\Lambda_{SM}^{\nu}} \sim O(1) \left( \frac{m_{l_i} m_{l_i}^2}{m_{H^\pm}} \right)^2. \quad (42)$$

Here $\Xi$ is related with the couplings attaching to lepton mass $m_{l_i}$ in each model, how is depicted in Tab. II. For instance, in the type II (or Lepton Specific) scenario the relative coupling is $\Xi_{II} = \tan \beta U_{i,k}$. Taking $\tan \beta = 10$, $m_{H^\pm} = 300$ GeV (with diagonal elements of $U_{PMNS}$ matrix and for the neutrino masses shown in Tab. I), we found for the type II-2HDM

$$R_{\nu}^{II} \sim \begin{cases} O \left( 10^{-3} \right) & \text{with } \nu_i = \nu_e, \\ O \left( 10^{-3} \right) & \text{with } \nu_i = \nu_\mu, \\ O \left( 10^7 \right) & \text{with } \nu_i = \nu_\tau. \end{cases}$$

• For the type I (or Flipped) case, it is just necessary to make the change $\tan \beta \rightarrow \cot \beta$ in the $\Xi$ couplings. For the same values in this parameter space, we get values for $R_{\nu}^{I}$ roughly belonging to four orders magnitude below to the corresponding contribution for the type II scenario.

• For the type III, the ratio for new physics effects is

$$R_{\nu}^{III} \sim \frac{m_{l_i} m_{l_i}^2}{G_F m_{\nu_j}}. \quad (43)$$

By taking Sher-Cheng anzats (included in the model dependent $\Xi$ coupling), and for values of $\lambda_l = 0.1$ and $m_{H^\pm} = 300$ GeV, the estimates give

$$R_{\nu}^{III} \sim \begin{cases} O \left( 10^{-4} \right) & \text{with } \nu_i = \nu_e, \\ O \left( 10^1 \right) & \text{with } \nu_i = \nu_\mu, \\ O \left( 10^4 \right) & \text{with } \nu_i = \nu_\tau. \end{cases}$$

It allows seeing as the structure used by anzats suppresses values of MDMs. Besides, the form of $R_{\nu}^{III}$ show us as higher values of parameters $\lambda$'s shall be the first couplings in to be constrained in future experiments. This fact will lead to new bounds to FCNC couplings in the lepton sector.

**Neutrino specific scenario**

In the neutrino specific scenario, the contribution to the MDM in each case of flavor neutrino is strongly sensitive to the VEV for the second doublet (which is the one giving mass to the neutrinos). The value of MDM is due to the structure of the coupling, that depends directly on the neutrino mass, weakened even more by the neutrino mass.
Figure 5: Contribution to the magnetic dipolar moment for (Left) electron and (Right) muon neutrinos coming from the neutrino specific-2HDM with masses of charged Higgs sweeping between (100 – 1000) GeV. The horizontal dotted lines make reference to the experimental thresholds for muon neutrino at 90% C.L. Blue line identifies the lower bound for vacuum expectation value \( v_2 \) based on Yukawa couplings perturbativity.

hierarchy used. These values are still far from the current experimental limits. Nevertheless, they are above of the SM contribution. Besides, in the case of \( \nu_e \) and \( \nu_\mu \), MDMs of type I and II 2HDMs are below of neutrino specific contributions. This effect is because the Yukawa structure of the neutrino specific model, which has the \( m_\nu/v_2 \) ratio; meanwhile for other models couplings between neutrinos and charged Higgs depend on the neutrino masses uniquely.

In the case of electron neutrino (see Fig. 5-Left), exists a significant contribution to the VEV of the second doublet less to 0.2 eV, which however is far from the experimental limits of about two orders of magnitude. Nevertheless, remaining contributions consistent with experimental thresholds are also above of the SM one by seven-nine orders of magnitude.

From Fig. 5-Right, we see as the contribution for \( \nu_\tau - \text{MDM} \) overpasses the SM-MDM in several order of magnitude. Experimental thresholds limit the MDM-value when \( v_2 < 0.18 \) eV and \( m_{H^-} = 100 \) GeV. Higher values of charged Higgs mass are allowed when \( v_2 \) is even lower. For instance, for \( m_{H^-} = 300 \) GeV, VEV suppressed satisfy \( v_2 < 0.075 \) eV.

Figure 6: Contribution to the magnetic dipolar moment for tau neutrinos coming from the neutrino specific-2HDM with masses of charged Higgs sweeping between (100 – 1000) GeV. Unitarity constraints from scattering processes put a limit value for charged Higgs close to 700 GeV [9]. The horizontal dotted lines make reference to the experimental thresholds for tau neutrino at 90% C.L. Blue line identifies the lower bound for vacuum expectation value \( v_2 \) based on Yukawa couplings perturbativity.
For tau neutrinos (see Fig. 6), we have one of the most promissory scenarios, due to the proximity of the experimental thresholds. These cases are only one order of magnitude below of measurements limits, for $v_2 < 1$ eV. Hence, Neutrino specific could be a plausible scenario where new physics could be constrained when the bound of MDM becomes enhanced employing new precision experiments for neutrino phenomenology.

To describe the discrepancies between new physics from neutrino specific model and SM contributions quantitatively, and quoting relation (42) for other 2HDM types, we define the ratio

$$R_{
u} = \frac{\Delta\mathcal{L}_{2HDM}}{\Delta\mathcal{L}_{SM}} \sim \frac{m_{12}^2}{m_{\nu}^2} \frac{m_{2}^2}{2\pi^2 G_F m_{\nu_i}}. \quad (44)$$

For $m_{H^\pm} = 300$ GeV and $v_2 = 0.1$ eV, we find for each type of neutrino

$$R_{\nu}^{\text{ns}} \sim \begin{cases} O \left(10^6\right) \text{ with } \nu_i = \nu_e, \\ O \left(10^8\right) \text{ with } \nu_i = \nu_\mu, \\ O \left(10^{10}\right) \text{ with } \nu_i = \nu_\tau. \end{cases}$$

However in these particular cases, as we approach near to the experimental threshold, Yukawa couplings are also reaching the perturbativity limit. Indeed, these limits are established to avoid divergences in the renormalization group equations. The reason is that the value of Yukawa coupling (square) cannot exceed the bound of 8π since beyond this limit the chance to find out some Landau pole in energy couplings evolution is significantly greater [42]. This value translates into a lower bound of $v_2$ for the respective neutrino mass present in the normal hierarchy. In the case of $\nu_\tau$, for instance, $v_{2\min} = 0.015$ eV. This VEV is the starting point of all scanings. Lower values of $v_2$ overpassing the threshold corrections are all non-perturbative contributions to MDM. Furthermore, in particular cases, contributions to MDMs can be constrained by threshold experimental limits, as for instance from $\nu_\tau$ contributions, the fact of $v_2 > 0.4$ eV for values are allowed at 90 % C.L. for all charged Higgs masses. By allowing smaller numbers of $v_2$ without to reach the perturbative limit, the constraints also exclude several values of charged Higgs masses.

From the latter points, we can see as the neutrino specific scenario is converted into a promising scenario to explain the MDMs and its intimate relation with neutrino mass.

**VII. CONCLUDING REMARKS**

The neutrino magnetic moment provides a tool for exploration of possible physics beyond the Standard Model. Although the value of the magnetic moment is suppressed by the smallness of the neutrinos masses, the contribution from new physics parameters (such as masses and mixing angles) could become relatively significant. In particular, for the 2HDMs, we evaluated the contributions coming from the insertion of the charged Higgs bosons into the loops. Our results show that for the type I and type II 2HDMs (scenarios without FCNC’s), the total contribution is located from the threshold of experimental detection in the case of electron neutrinos, obtaining a maximum contribution about three orders of magnitude below of the SM values (type II-2HDM). In the scenario of muon neutrinos, the total contribution produces comparable values with the SM contributions for the parameters of the model type I, with the higher contributions coming from the case of model type II. Finally, such values are much higher for tau neutrinos, but those contributions are much stronger for the model type II with tan $\beta \gg 1$ and $m_{H^\pm} = 500$ GeV. The last scenario for $\nu_\tau$—MDM is only two order of magnitude below of the threshold experimental given by BOREXINO experiment.

Despite the type-III 2HDM shows a new scenario to interpret MDM as a result of FCNCs, its contributions are tiny, even compared with the experimental threshold values. This effect is due to the suppression yielded by the Cheng-Sher Ansatzs which defined that FCNCs couplings satisfy the same hierarchical structure for leptonic mass matrices. This fact makes that FCNCs for neutrinos and charged leptons become suppressed by the same EW-scale.

Although the models without FCNCs converts into plausible scenarios for electromagnetic form factors, such frameworks are based on unnatural terms for neutrino masses. To circumvent this issue, we consider a simple 2HDM that incorporates viable masses for neutrinos. It is done by choosing a VEV in the eV scale (or even less) for the second doublet ($v_2$), which is coupled only to Dirac neutrinos. From this assumption, plausible masses could be explained if other parameters in the model, e.g. $m_{12}^2$, take appropriate values. Besides this neutrino-specific model has other phenomenological motivations (e.g. $\mu \rightarrow e\gamma$ decays, cosmology and neutrino phenomenology), in our case, this has been used to determine the nature of MDM and the relation with small sizable masses in the neutrino sector. For
instance, neutrino specific-2HDM gives characteristic scales up to $10^{-7} \mu B$ for $\nu_\tau$-MDM (even respecting the perturbative limit on Yukawa couplings). Higher values in MDM for the neutrino-specific model are due to Yukawa couplings structure, which scales with the ratio between neutrino mass and $v^2$. The last fact is a radical difference with the remaining Yukawa couplings structures of other considered 2HDMs. Under the assumption of normal ordering for neutrinos, these scales for MDMs are above of SM contributions and reach the threshold measurement, making of neutrino specific a great scenario to constrain new physics in future experiments.

An important aspect is the close relationship of MDMs with the neutrino mass and with the respectively charged lepton mass. In the type I-III 2HDMs, this can be clearly appreciated when the contribution due to the tau neutrino is compared concerning the muon and electron neutrinos ones, further strengthened by the normal hierarchy that we are assuming. Another relevant fact is that if we found magnetic dipole moment for neutrinos, such a measure would be highly sensitive to the type of 2HDM. However, at precision order we are working to neutrino MDMs, Lepton-specific analyses are the same that type II ones. Moreover, the flipped model shares the same remarks that case for type I-2HDM. Therefore, we have studied the influence on neutrinos-MDMs of all possible 2HDMs with natural flavor conservation.

In conclusion, $\nu_\tau$-MDM could be converted into a plausible framework to constrain new physics scenarios contributing to electromagnetic form factors. Particularly, in the light of future experiments for coherent neutrino-nucleus scattering, which are expected to improve all bounds on neutrino electromagnetic properties [28]. Particularly, and despite perturbativity could be in conflict with lower values of the natural VEV $v^2$, the neutrino specific model would be a significant benchmark to introduce these effects of new physics, at the same time that neutrino masses are at one viable scale. This mechanism leads to a well-motivated study of 2HDMs itself or implemented under more robust theories (e.g. $B-L$ gauge extended plus 2HDMs or SUSY models) containing a compatible explanation of smallness for neutrino masses and the influence of $CP$ phases in neutrino-phenomenology. In these scenarios, our results are also relevant in the regimen where new gauge bosons or new fermions in those theories become decoupled.

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