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# Contribution to the neutrino magnetic moment coming from 2HDM in presence of magnetic fields.

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The confirmation of the neutrino mass by oscillation phenomena converts the study of the magnetic dipole moment (MDM) of the neutrino, in vacuum and regions where existing external magnetic fields, a topic of particular interest from the theoretical point of view. The MDM has an implicit relation with neutrino masses, and this is a possible benchmark from new physics in the solution of open questions in neutrino physics. Besides we know that this kind of phenomena has significant consequences on cosmology and astrophysics, e.g., under the influence of combined effects of neutrinos in the compact objects formation and evolution of primordials magnetic fields. We calculate and analyze such effects introducing charged Higgs bosons based on the parameter space of several 2HDMs with and without flavor conservation in neutral currents.

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## 1. The electromagnetic form factors (EFF's)

To examine the electromagnetic form factors is necessary analyzing the interaction of the particle with the photon. The general expression to the electromagnetic current in the vertex $\Lambda_\mu(l,q)$ is [1]:

$$\Lambda_\mu(l,q) = F_Q(q^2)\gamma_\mu + F_M(q^2)\, i\sigma_{\mu\nu}q^\nu + F_E(q^2)\,\sigma_{\mu\nu}q^\nu\gamma_5 + F_A(q^2)\left(q^2\gamma_\mu - q_\mu \not{q}\right)\gamma_5, \tag{1.1}$$

where $F_Q(q^2)$ corresponds to the factor of electric charge, $F_M(q^2)$ is associated with the anomalous magnetic moment, $F_E(q^2)$ is the electric dipole moment, and $F_A(q^2)$ is called anapolar moment. When we consider neutrino masses, the MDM value of neutrino in the vacuum is $\mu_{\nu_\alpha} = 3.2\times 10^{-19}\mu_B(m_{\nu_\alpha}/1\text{ eV})$, where $\mu_B = e/2m_e$ is the Bohr magneton.

When we take into account an external magnetic field with massive neutrinos, the computation of the electromagnetic form factors can make it by the self energy compation using the proper-time (Schwinger) formalism [2]. The Feynman diagrams contributing to the neutrino Self-Energy are depicted in figure 1. The double lines represent the interaction with the magnetic field.

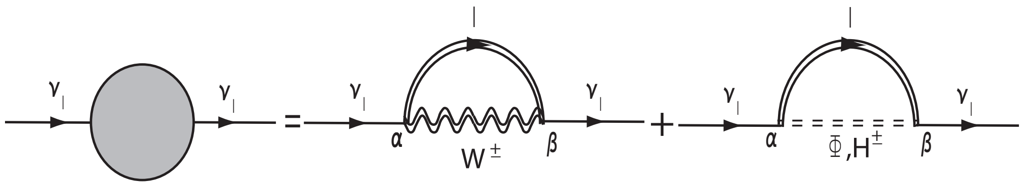


**Figure 1:** *Feynman diagram representing the contribution to self-energy due to a constant and uniform magnetic field, the double line corresponds to lepton charged l, the $W^\pm$ boson, the charged Goldstone boson $\Phi$, and the charged Higgs boson $H^\pm$ in an external magnetic field.*

The new structure to the gauge bosons $G_B(p)$, Goldstone bosons $D(p)$, Higgs charged $D_H(p)$ and fermions $S_B^F(p)$ propagators due to the presence of an external magnetic field are described respectively by

$$G_B(p) = -\frac{ig_{\alpha\beta}}{p^2-m_W^2} - \frac{2\beta\varphi}{\left(p^2-m_W^2\right)^2} + \mathscr{O}\left(\beta^2\right),\quad D(p) = \frac{i}{p^2-m_W^2} + \mathscr{O}\left(\beta^2\right),$$

$$D_H(p) = \frac{i}{p^2-m_{H^\pm}^2} + \mathscr{O}\left(\beta^2\right),\quad S_B^F(p) = \frac{i(m-\not{p})}{p^2-m^2} + \beta\frac{\left(m-\not{p}_\parallel\right)}{2\left(p^2-m^2\right)^2}(\gamma\varphi\gamma) + \mathscr{O}\left(\beta^2\right). \tag{1.2}$$

where $\beta = eB$ and $\varphi^{\alpha\eta} = F^{\alpha\eta}/B$ is the dimensionless electromagnetic field tensor normalized to $B$, with the Lorentz indices of tensors are contracted as $\gamma\varphi\gamma = \gamma_\alpha\varphi^{\alpha\beta}\gamma_\beta$ and dual tensor $\tilde{\varphi}^{\alpha\eta} = \frac{1}{2}\varepsilon^{\alpha\eta\zeta\vartheta}\varphi_{\zeta\vartheta}$. The self-energy operator has the following Lorentz structure [2]

$$\sum(p) = \left[a_L\not{p} + b_L\not{p}_\parallel + c_L(p\tilde{\varphi}\gamma)\right]P_L + \left[a_R\not{p} + b_R\not{p}_\parallel + c_R(p\tilde{\varphi}\gamma)\right]P_R + m_\nu\left[K_1 + iK_2(\gamma\varphi\gamma)\right]. \tag{1.3}$$

where $p^\mu = p_\parallel^\mu + p_\perp^\mu = \left(p^0,0,0,p^3\right) + \left(0,p^1,p^2,0\right)$. The terms that represent the contibution to MDM have the structure [3]

$$\mu_{\nu_l}^B = \frac{m_\nu}{2B}\left(c_L - c_R + 4K_2\right), \tag{1.4}$$

the result of this contribution calculated by the self-energy is

$$\mu_{\nu_l}^B = \mu_{\nu_l}\frac{1}{(1-\lambda_l)^3}\left(1 - \frac{7}{2}\lambda_l + 3\lambda_l^2 - \lambda_l^2\ln\lambda_l - \frac{1}{2}\lambda_l^3\right), \tag{1.5}$$

where $\lambda_l = m_l^2/m_W^2$. The MDM in the vacuum and in presence of a magnetic field are described in table 1.

| | $m_\nu\,[eV]$ | $\mu_\nu\,[\mu_B]$ | $\mu_\nu^B\,[\mu_B]$ |
|---|---|---|---|
| $\nu_e$ | 0.06089 | $1.948\times10^{-20}$ | $1.948\times10^{-20}$ |
| $\nu_\mu$ | 0.06754 | $2.161\times10^{-20}$ | $2.161\times10^{-20}$ |
| $\nu_\tau$ | 0.07147 | $2.287\times10^{-20}$ | $2.286\times10^{-20}$ |

**Table 1:** *MDM of the neutrinos in the vacuum and with magnetic fields. The values of the effective flavor masses are compatible with cosmological bounds and the masses for eigenstates in normal ordering.*

## 2. Contributions to MDM comming from 2HDM with $\vec{B}$

To include the contribution to MDM owing to 2HDM, we take into account the RS of fig. 1. Using the propagators of Eqs. (1.2) and writing the respective vertices like $aP_L + bP_R$, we got

$$\sum_{H^\pm}(p) = i\int \frac{d^4k}{(2\pi)^4}\left(aP_L+bP_R\right)S_B^F(p-k)\left(cP_R+dP_L\right)D_B(k). \tag{2.1}$$

Factorizing the terms $c_L, c_R$ and $K_2$ like in Eq. (1.4), the contribution to the MDM of neutrinos is

$$\left(\mu_{\nu_l}^B\right)_{H^\pm} = \frac{\sqrt{2}}{3G_f}\mu_{\nu_l}\int_0^1 dx\frac{2\left(x^2-3x+2\right)\left(b^2+a^2\right)+(1-x)\frac{m_l}{m_\nu}ab}{m_\nu^2x^2+\left(m_l^2-m_\nu^2-m_{H^\pm}^2\right)x+m_{H^\pm}^2}, \tag{2.2}$$

where the constants $a$ and $b$ are model dependent as showed in table 2. The results of Eq.(2.2) are displayed in figure 2.

| Vertex | Type I or Flipped 2HDMs | Type II or Lepton Specific 2HDMs | Type III 2HDM |
|---|---|---|---|
| $a$ | $-2^{\frac{3}{4}}\sqrt{G_F}m_{\nu_l}\cot\beta U_{k,i}$ | $2^{\frac{3}{4}}\sqrt{G_F}m_{\nu_l}\cot\beta U_{k,i}$ | $-\lambda_\nu\xi_{i,k}^\nu U_{k,i}$ |
| $b$ | $2^{\frac{3}{4}}\sqrt{G_F}m_l\cot\beta U_{i,k}$ | $2^{\frac{3}{4}}\sqrt{G_F}m_l\tan\beta U_{i,k}$ | $\lambda_l U_{i,k}\xi_{k,i}^E$ |

**Table 2:** *Couplings for $P_L$ and $P_R$ in the MDM for type I (Flipped), II (Lepton Specific), III-2HDMs.*

## 3. Concluding remarks

The contribution to the MDM due to the presence of magnetic fields is below the SM contribution for all models (with and without natural flavor conservation). Furthermore, as our recent work has showed [4], contributions from magnetic fields are less than those obtained in the vacuum for the models considered. As it happens in analyses from vacuum for MDM, there is a strong relationship among MDM, neutrino and charged lepton masses. We can see this comparing the MDM contributions due to the tau neutrino regarding the muon and electron neutrinos in fig. 2.

## References

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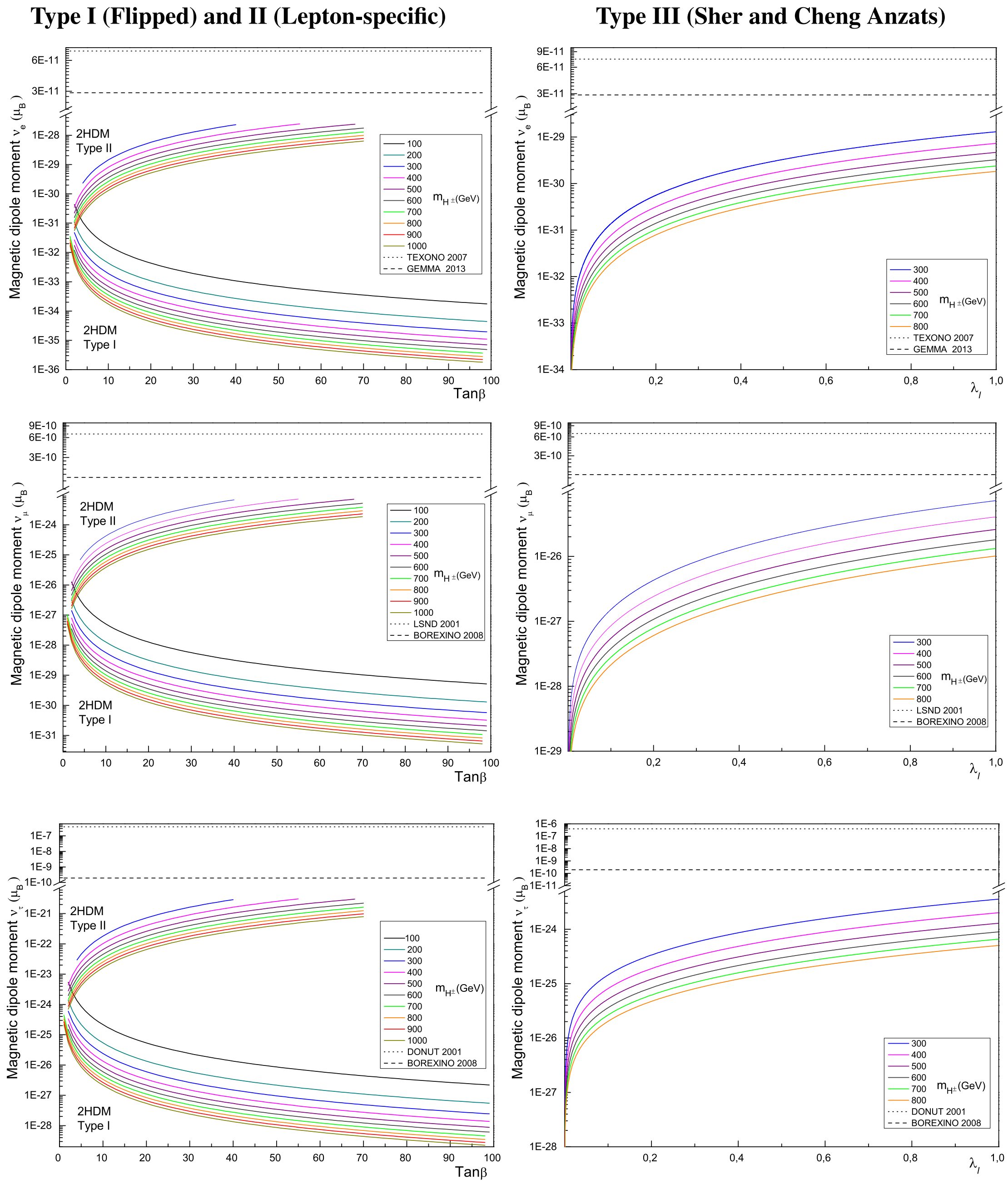


**Figure 2:** *(**Left**) Contribution to the magnetic dipolar moment in presence of magnetic fields for* $\nu_e, \nu_\mu, \nu_\tau$*-neutrinos coming from type I (and Flipped), II ( and Lepton-specific) 2HDMs with masses of charged Higgs sweeping between* $(100-900)$ *GeV to type I,* $(300-900)$ *GeV 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 $\lambda_\nu, \lambda_l \in [10^{-6}, 1]$. *The horizontal dotted line makes reference to the experimental thresholds for each neutrino flavor at* 90% *C.L..*