New sources of CP violation

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Abstract. We present a short review of CP-violating effects induced by radiative corrections in a framework of extensions of the Standard Model: (EM, Weak, Chromo) electric dipole moments of heavy fermions, trilinear neutral gauge boson couplings and decays of the Higgs boson. We show that in order to induce CP-violating effects, non-diagonal couplings with complex coupling constant are required and the respective CP-odd term is proportional to the imaginary part of the product of coupling constants involved in the process, which is mathematically consistent with the respective CP-odd Lagrangian.

1. Introduction
In the universe observed there exists an evident matter-antimatter asymmetry, which is also known as baryon asymmetry in particle physics. But, the Standard Model (SM) fails to provide an explanation to the baryon asymmetry in the universe. However, it is assumed that the matter and antimatter were created in equal amounts after the Big-Bang. Then, to explain this asymmetry in a way consistent with the CPT theorem, the baryogenesis mechanism was proposed. According to Sakharov’s criteria, there are three conditions required for the baryogenesis:

• At least one B-number violating process.
• Charge conjugation (C) and Charge-Parity (CP) violation.
• Interactions outside of thermal equilibrium.

The non-conservation of CP symmetry is thus a necessary requirement for the baryon asymmetry to occur. CP violation could be included in the SM in three different ways; through the strong interactions that is known as the Strong CP problem, if neutrinos are massive and finally by the complex phase of the CKM matrix. Small amounts of CP violation in neutral mesons decays have been measured, but unfortunately, it is not enough to explain the baryon asymmetry, so it is important the study of new sources of CP violation beyond the SM.

Theoretically speaking, we show that in order to induce an electric dipole moment, the CP-odd part of the trilinear neutral gauge boson couplings and Higgs to gauge boson decays, are necessary non-diagonal couplings and complex coupling constants in some SM extensions. Additionally, we show that the respective CP source is proportional to the imaginary part of the product of the coupling constants, which is mathematically consistent with the non-conservation of the respective discrete symmetries.

The paper is organized as follows: in Sec. 2, we define the mathematical properties of the electric dipole moments, and we mention some examples in some SM extensions. In Sec. 3, we
show the general mathematical structure of the trilinear neutral gauge boson couplings, and we mention some contributions to the CP-odd part of the $ZZ^*\gamma$ and $ZZZ^*$ couplings. In Sec. 4, we present a study of the CP violation in Higgs boson decays to gauge bosons, we examined their experimental potential in LHC. Finally, we present our conclusions in the Sec. 5.

2. Electric Dipole Moments
In general, the magnetic (MDM) and electric (EDM) dipole moments induced by a neutral gauge boson $V = \gamma, Z, G$ can be described through the following interaction Lagrangian:

$$\mathcal{L}^\text{spin-1/2} = -\frac{i}{2} \bar{f} \gamma_\mu f \left( e d_f F^{\mu\nu}_{\gamma} + g d_f F^{\mu\nu}_Z + g_3 d_f F^{\mu\nu}_G \right) + \frac{1}{4 m_f} \bar{f} \gamma_\mu f \left( e a_f F^{\mu\nu}_W + g a_f F^{\mu\nu}_W + g_3 a_f F^{\mu\nu}_G \right),$$

where $F^{\mu\nu}_V$, $Z^{\mu\nu}$ and $G^{\mu\nu}$ are the strength tensors associated to a neutral gauge boson $V$, while $g_V = e, g, g_3$ is the respective charge induced by the $V$ boson. The Lorentz structure associated with $d^V$ violate parity and time-reversal symmetry, and due to the CPT theorem is equivalent to CP violation. The MDM and EDM arise at the loop level and can be extracted from the matrix element $i g_V \bar{u}(p') \Gamma_V^\mu u(p)$, where $\Gamma_V^\mu$ is given by:

$$\Gamma_V^\mu(q^2) = F^V_A(q^2) (\gamma_\mu \gamma_5 q^\nu - 2 m_f \gamma_\mu q^\nu) + F^V_1(q^2) \gamma_\mu q^\nu + F^V_2(q^2) \sigma_{\mu\nu} q^\nu + F^V_3(q^2) \sigma_{\mu\nu} q^\nu,$$

with $q = p' - p$ is the four-momentum of the gauge boson $V$, $m$ is the mass of the fermion $f$ and $F^V_k(q^2)$ are an one-loop form factors. Thus, the MDM and the EDM are defined as:

$$d_f^V = -F^V_3(q^2 = m_f^2)$$

$$d_f' = -e F^V_3(q^2 = m_f^2)$$

respectively, where $m_f$ is the rest mass of the neutral gauge boson. The MDMs are induced at one-loop level in the SM, but the EDMs are induced at multi-loop level and therefore are very suppressed in the SM framework. However, in general the MDM and EDM are proportional to the mass of the fermion in question [1]; therefore the respective values for the tau lepton, bottom and top quarks are expected to be greater than the other fermions. However, the lifetimes of tau and top quark are very short to measure their interaction with an electromagnetic field. Then, the current bound have been measured indirectly, this is, through deviations from the SM cross section of decay and production process associated with those fermions [2, 3, 4, 5, 6]. Nonetheless, the electromagnetic EDM of the tau lepton also can be proved using radiative $\tau \to \ell\gamma\nu\bar{\nu}$ decay at high-luminosity $B$ factories [7]. But in general, the tau lepton decays provide opportunities to search effects of new physics [8]. In the next subsections we go to analyze qualitatively some results of EDMs in several SM extensions.

2.1. Electromagnetic electric dipole moment
The electromagnetic case is the well known EDM and the associate gauge boson is the photon; for a charged lepton we have experimental bounds given in the Table 1.

Theoretical prediction in SM for the tau lepton is $d_\text{SM}^\tau < 10^{-34}$ cm [12], but the EDMs for the other charged leptons are more suppressed. However, in some SM extensions is possible to obtain predictions competitive with the experimental bound, and less suppressed than the SM
2.2. Weak electric dipole moment

The weak EDM is associated with the $Z^0$ boson, and it is the generalization of the electromagnetic case; mathematically speaking, with the appropriate change in the free parameters, we can obtain the usual EDM induced by the photon. On the other hand, due to the extremely short range of the weak interaction, the best possibility to measure a weak EDM is only by the deviation from the SM cross section for the production of heavy fermions, such as the tau lepton and top quark. Nevertheless, the weak EDM remain almost unexplored predictions. An example is the called Unparticle framework [13], which has been explored by CMS at the LHC[14, 15, 16]. In this model the non-diagonal coupling with fermions is induced at tree level and it is an important ingredient to induce CP violations effects. For the case of spin-1 unparticle $O^\mu_U$, the effective lagrangian is given by:

$$\mathcal{L}_{dV} = \frac{\lambda^{ij}_V}{\Lambda_U} \bar{f}_i \gamma_{\mu} f_i O^\mu_U + \frac{\lambda^{ij}_A}{\Lambda_d} \bar{f}_i \gamma_{\mu} \gamma_5 f_i O^\mu_U,$$

and the respective propagator can be written as:

$$\Delta^{\mu\nu}_u(p^2) = \frac{A_{dU}}{2 \sin(d_{dU} \pi)} (-p^2 - i\epsilon)^{d_{dU}-2} [ - g^{\mu\nu} + \frac{p^\mu p^\nu}{p^2} ],$$

where $\Lambda_U$ and $d_{dU}$ are the scale energy and dimension of the unparticle, respectively, while $p$ is the 4-momentum of the unparticle and $\lambda^{ij}_A$ is a complex coupling constant. A detailed discussion of the eqs. (5) and (6) can be found in [17]. Then, after resolving the one-loop integral, the authors of the reference [18] have obtained the following results for the EDM:

$$d^{\mu}_{\ell} = \frac{e A_{dU}}{32 \pi^2 \sin(\pi d_{dU}) m_{\ell}} \left( \frac{m_{\ell}^2}{\Lambda_U^2} \right)^{d_{dU}-1} \sum_{j=e,\mu,\tau} \text{Im}(\lambda^{ij}_V \lambda_{A}^{* ij}) g_{V,A}(\sqrt{m_{\ell}}, d_{dU}),$$

the explicit form of $g_{V,A}(\sqrt{m_{\ell}}, d_{dU})$ is given in [18], where $\sqrt{m_{\ell}} = m_j/m_i$. It is very interesting to note that this result is proportional to $m_{\ell}^{2(d_{dU}-1)}/m_i$ and to the imaginary part of the product of the vector and the axial coupling constants, such as we mentioned in the introduction. For selected values of the free parameters, the numerical result for the muon is $d^{\mu}_{\mu} \simeq (10^{-17} - 10^{-22}) \text{Im}(\lambda^{\mu\nu}_V \lambda_{A}^{* \mu\nu}) e \text{cm}$ for the range of $1.1 < d_{dU} < 1.9$. Further, we note that there is not EDM contribution if all the coupling constants are real numbers.

On the other hand, the contribution of spin-0 unparticles to EDM of the tau lepton is $d^{\mu}_{\tau} \simeq \text{Im}(\lambda^{\tau\mu}_V \lambda_{A}^{S \mu\nu})(0.69 + 3.17i) \times 10^{-20} e \text{cm}$ for $\Lambda_U = 10 \text{ TeV}$ [19]. Other contributions to tau lepton have been reported in the MSSM with an additional vector-like multiplet [20], and renormalizable scalar leptoquark interactions [21]. But theoretically speaking they have common aspects, these contributions were induced by non-diagonal couplings and they are proportional to the imaginary part of the product of the coupling constant.

### Table 1.

| lepton | $d_\ell$ |
|--------|----------|
| $e$ [9] | $d_e < (1.6 \pm 7.4) \times 10^{-25} e \text{cm}$ |
| $\mu$ [10] | $d_\mu < (-0.1 \pm 0.9) \times 10^{-19} e \text{cm}$ |
| $\tau$ [11] | $-0.22 < \text{Re}(d_\tau)/10^{-16} e \text{cm} < 0.45$ $-0.25 < \text{Im}(d_\tau)/10^{-16} e \text{cm} < 0.008$ |

**Notes:**

- $\Lambda_U$ is a scale energy and $d_{dU}$ is the dimension of the unparticle.
- $\lambda^{ij}_V$ and $\lambda^{ij}_A$ are coupling constants.
- $g_{V,A}$ is a function of $\sqrt{m_{\ell}}$ and $d_{dU}$.
- The results are given in electron cm for $1.1 < d_{dU} < 1.9$. Other contributions to tau lepton have been reported in the MSSM with an additional vector-like multiplet and renormalizable scalar leptoquark interactions. But theoretically speaking they have common aspects, these contributions were induced by non-diagonal couplings and they are proportional to the imaginary part of the product of the coupling constant.
up to date, where the experimental current bounds were obtained in the $e^+e^- \rightarrow \tau^+\tau^-$ process by the ALEPH collaboration [4]. These bounds are the following:

\[ \text{Re}(d_W^\tau) < 0.5 \times 10^{-17} \text{ cm}, \]  
\[ \text{Im}(d_W^\tau) < 1.1 \times 10^{-17} \text{ cm}, \]  

and the SM prediction is $d_{\tau}^W < 8 \times 10^{-34}$ cm [22]. Nonetheless, some SM extensions can give predictions much larger than the SM value. An example is the renormalizable Leptoquark interactions framework [23, 24]. In this context, the model with a scalar leptoquark doublet $R_2^T = (R_2^+, R_2^-)$ with quantum numbers $\{3; 2; 7/6\}$ under the $SU(3) \times SU(2) \times U_Y(1)$ gauge group has the following effective Lagrangian interaction [25, 26]:

\[ \mathcal{L}_{F=0} = e^i(\lambda_{ij}^L P_L + \lambda_{ij}^R P_R) u_j^i S_1^i + e^j \lambda_{ij}^R P_R d_j^R S_2^i + H.c., \]  

where $S_1 = R_2^+$ and $S_2 = R_2^-$ are scalar leptoquarks with electric charge $5/3$ and $2/3$, respectively. While, $\lambda_{ij}^L$ and $\lambda_{ij}^R$ are complex coupling constants again. Further, the leptoquark coupling with the photon and $Z^0$ boson are extracted from the respective leptoquark kinetic Lagrangian. Then, the contribution to the weak EDM of the fermion $f_i$ can be written as [21]:

\[ d_i^W = \frac{3e}{32m_i s_W c_W \pi^2} \text{Im}(\lambda_{ij}^L \lambda_{ij}^R^* G(x_i, x_j, x_Z)), \]  

where $x_A = m_A^2/m_S^2$ with $m_{S_k}$ the leptoquark mass and $m_A$ the mass of any fermion or the $Z^0$ boson; furthermore, the explicit form of the $G(x_i, x_j, x_Z)$ function can be found in [21]. The importance of the equation (11) is that the weak EDM is proportional to the external fermion mass and to the imaginary part of the product of left and right handed coupling constants. Then, the coupling constants should be complex to obtain nonzero weak EDM, such as the $F_3^Z(m_Z^2)$ form factor was necessary to have non-diagonal interactions.

2.3. Chromo electric dipole moment

Since the gluon does not have rest mass, mathematically the chromo EDM is a variation of the electromagnetic EDM, with the difference that the chromo EDM is induced only in fermions with color charge. Additionally, because most quarks are confined in a compound state, the experimental measurement of these properties is done indirectly, and the best possibilities are associated with the heavy quarks. For the top quark the most recent bound to chromo EDM has been obtained with the Higgs boson production at the LHC, where the bound is $|d_t| < 4.8 \times 10^{-16}$ cm [30]. The SM prediction is negligibly small, i.e $d_t < 10^{-30}$ cm [31]. To induce a chromo EDM less suppressed, we can use the Two Higgs Doublet Model (THDM) with a sequential fourth family [32]. In this version of THDM, the fourth family interacts only with the heavy scalar bosons, and thus the theoretical prediction for Higgs boson production in the LHC remains unchanged. In this model we have also non-diagonal couplings given by the following Lagrangian:

\[ \mathcal{L}_{FV} = \frac{g}{2m_W} f_j^\phi \bar{f}_i \left[ g_\phi^0 + g_\phi^\gamma \gamma_5 \right] f_j \phi^0, \]  

\[ (12) \]
here the scalar \((g_φ^s)\) and pseudo-scalar \((g_φ^p)\) couplings are mathematical structures that are composed by fermion masses and complex mixing matrices \(^1\). Then, the contribution to chromo EDM of the top quark can be written as \([34]\):

\[
d_1^φ = -\text{Im}(G_φ^s G_p^{φφ}) \frac{m_t^2 g_φ^s f_φ^p v}{24\pi^2 m_W^2} \int_0^1 \frac{x^2 dx}{x r_t^2 - (x - 1)(x - r_φ^2)}
\]

where \(r_k = m_k/m_t\), \(G_φ^s, G_p^{φφ} = g_φ^s, g_φ^p/m_t\) and \(φ = H^0, A^0, H^±\). Furthermore, we can observe that this result is proportional to \(\text{Im}(G_φ^s G_p^{φφ})\) and \(m_t^2\), such as the electromagnetic and weak cases. For neutral heavy scalar bosons the numerical result is around of \(10^{-24}\) e cm, where they set \(m_t' = 600\) GeV and \(m_φ = 300\) GeV \([34]\). Another results for the chromo EDM can be found for Models with Vector Like Multiplets \([35]\) and THDM with CP violation \([36]\).

**Figure 1.** Diagram for the vertex function \(ie \Gamma_{VVV}^i\) for the \(VVV\) couplings, all momenta are outgoing.

### 3. Trilinear neutral gauge boson coupling

In SM the triple coupling \(VV+V− (V = Z, γ)\) is the only interaction between electroweak gauge bosons at tree level. On the other hand, by Landau-Yang’s theorem the trilinear neutral gauge boson couplings (TNGBCs) \(VVV\) are induced only at one-loop level, with at least one off-shell neutral gauge boson. In this context, the different TNGBs are \(ZZγ, ZZγ \) and \(ZZZ\), while the \(γγγ\) coupling is forbidden by Furry’s theorem. Then for one off-shell neutral gauge boson there are four types of TNGBCs, which are described for the vertices \(VVVγ\) and \(ZZVγ\). The respective effective Lagrangians for each coupling are given for \([37]\):

\[
\mathcal{L}_{VVVγ} = \frac{\alpha}{m_Z^2} \left\{ - [h_1^Z(∂α F_{αβ}) + h_2^Z(∂α Z_{μα})]Z_β F_{μβ} \\
- \frac{1}{m_Z^2} \left[ h_3^Z(∂α Z_{μα}) Z_β + h_4^Z(∂α Z_{μα}) Z_β F_{μα} \right] \right\},
\]

\[
\mathcal{L}_{ZZVγ} = \frac{\alpha}{m_Z^2} \left\{ - [f_1^Z(∂α F_{αβ}) + f_2^Z(∂α Z_{μα})]Z_β F_{μβ} \\
+ [f_3^Z(∂α F_{αβ}) + f_4^Z(∂α Z_{μα})]Z_β F_{μα} \right\},
\]

\(^1\) For more details see \([33]\).
here $h_Y^V$ and $f_Y^V$ are one-loop form factors, while $\tilde{V}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta} V^{\alpha\beta}/2$ with $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$ standing for the strength tensor of the neutral gauge boson. The operators associated with $h_Y^Z$ and $h_F^Z$ have dimension eight, and the remaining ones are of dimension six. Furthermore, the Lorentz structure associated with $h_Y^Z$ and $f_Y^Z$ are CP-odd, $h_F^Z$ and $f_F^Z$ are CP-even. Then, from the effective Lagrangians (14) and (15) we obtain the respective vertex functions and they respect Lorentz covariance, Bose symmetry and $U_{em}(1)$ gauge invariance, which are given by [38, 39]:

$$\Gamma_{Z^V \gamma}(p_1, p_2, q) = i \frac{(p_1^2 - m_V^2)}{m_V^2} \left[ h_Y^V(q^\alpha g^{\alpha\mu} - q^\alpha g^{\beta\mu}) + \frac{h_F^V}{m_Z^2} p_2^\alpha \left((q \cdot p_2) g^{\beta\mu} - q^\beta p_2^\mu \right) \right] - \frac{h_F^V}{m_Z^2} \epsilon^{\beta\alpha\rho\sigma} p_2^\rho q_\sigma \right],$$

(16)

$$\Gamma_{Z^Z \gamma}(p_1, p_2, q) = i \frac{(q^2 - m_V^2)}{m_Z^2} \left[ f_Y^V(q^\alpha g^{\beta\mu} + q^\beta g^{\alpha\mu}) - f_F^V \epsilon^{\mu\alpha\beta\rho}(p_1 - p_2)_\rho \right].$$

(17)

where the four-momenta of the gauge bosons are defined in Figure 1. Thus, the CP-odd form factor parameterizes the effect of the CP-violation in the TNGBs. At one-loop level in the SM only the CP-even part is induced via fermion triangle [39], but to induce the CP-odd parts other theoretical mechanisms are necessary. One possible theoretical framework is a renormalizable effective theory with several physical charged scalar bosons, which includes non-diagonal couplings. In this context, the Lagrangian describing the non-diagonal coupling between the $Z^0$ boson and the charged scalar bosons can be written as:

$$\mathcal{L}_{FV} = i \sum_{i \neq j} g_{ij}^Z Z^\mu \Phi_i^+ \overrightarrow{\partial}_\mu \Phi_j^- + H.c.$$ 

(18)

where $g_{ij}^Z$ is a complex coupling constant. The diagonal coupling $\gamma \Phi_i^+ \Phi_j^-$ has the usual gauge invariant interaction for a scalar sector of any renormalizable theory. Then, the CP-odd part of the TNGBs can be induced via the non-diagonal interaction (18). In the next sub-sections we show some results reported previously for the $ZZ^\star \gamma$ and $ZZZ^\star$ couplings.

### 3.1. $ZZ^\star \gamma$ coupling

To induce this vertex four diagrams are necessary, where two diagrams are required by Bose symmetry, whereas two diagrams involve the exchange of the virtual scalar bosons and they are necessary to cancel out ultraviolet divergences. Thus, after the transversality and mass-shell conditions for the gauge bosons are considered, the results are the following [40]:

$$h_Y^Z = \frac{m_Z^2 g_{ij}^Z \text{Im}(g_{ij}^Z g_{ji}^{Z^\star})}{12\pi^2 (m_Z^2 - p_j^2)} \left[ (m_i^2 - m_j^2)(m_Z^2 - p_j^2) - 2(m_i^2 - p_j^2)[m_i^2 B_{ij}(0) - m_j^2 B_{jj}(0)] \right] - (m_i^2 - m_j^2) \left[ (m_Z^2 - p_j^2) B_{ij}(0) + 3(m_i^2 + p_j^2) B_{ij}(0) - 6m_Z^2 B_{ij}(m_Z^2) \right] + 3(m_Z^2 - p_j^2) \left[ m_j^2(m_i^2 - m_j^2 - m_Z^2) C_{ij}(p_j^2) + m_i^2(m_i^2 - m_j^2 + m_Z^2) C_{ji}(p_j^2) \right].$$

(19)

$$h_F^Z = \frac{m_Z^4 g_{ij}^Z \text{Im}(g_{ij}^Z g_{ji}^{Z^\star})}{12\pi^2 (m_Z^2 - p_j^2)} \left[ 2(m_i^2 - m_j^2)(m_Z^2 - p_j^2) - 4(m_i^2 - p_j^2)[m_i^2 B_{ij}(0) - m_j^2 B_{jj}(0)] \right] - (m_i^2 - m_j^2) \left[ (m_Z^2 - p_j^2) B_{ij}(0) + 3(m_i^2 + p_j^2) B_{ij}(0) - 3(3m_Z^2 + p_j^2) B_{ij}(0) \right] + 3(m_Z^2 - p_j^2) \left[ m_j^2(2m_i^2 - m_j^2 - m_Z^2 - p_j^2) C_{ij}(p_j^2) + m_i^2(2m_i^2 - 2m_j^2 + m_Z^2 + p_j^2) C_{ji}(p_j^2) \right].$$

(20)
where \( p_2 \) is the four-momentum of the off-shell \( Z^0 \) boson, \( m_{i,j} \) is the mass of the charged scalar boson and it was introduced the shorthand notation in terms of Passarino-Veltman scalar functions. We note that this result also is proportional to \( \text{Im}(g^2_{ij}g^2_{ji}) \), and it is evident that it vanishes when \( i = j \). The numerical results for values above 300 \( \text{GeV} \), for the charged scalar bosons are \( |h^Z_{ij}| \propto 10^{-5} - 10^{-4} \) and \( |h^Z_{ij}| \propto 10^{-7} - 10^{-6} \).

The CP-violating vertices \( ZZ^*\gamma \) and \( Z\gamma^*\gamma \) may induce CP-odd asymmetries in the radiative decay \( Z \to \mu^+\mu^-\gamma \) that could be used to set bounds on these vertices [41].

3.2. \( ZZ^* \) coupling

For this coupling twelve diagrams are necessary, and in order to satisfy the Bose symmetry \( 3! = 6 \) diagrams are required, and it corresponds to the different permutations of the \( Z^0 \) bosons. Additionally, six diagrams involve the exchange of the virtual scalar bosons that are added to cancel out ultraviolet divergences. Then, after the Passarino-Veltman method is applied, the result is the following:

\[
f^Z_{ij} = \frac{m^2_{Z} g^Z_{ij} \text{Im}(g^Z_{ij}g^Z_{ji})}{24\pi^2 s_W q^2 (q^2 - m_Z^2)(q^2 - 4m_Z^2)} \Xi(q^2, m_i^2, m_j^2)
\]  \( \text{(21)} \)

where \( q \) is the four momentum of the off-shell \( Z^0 \) boson and the explicit form of \( \Xi(q^2, m_i^2, m_j^2) \) can be found in [40]. We see the same properties for the \( ZZ^*\gamma \) coupling; the form factor (21) is proportional to \( \text{Im}(g^2_{ij}g^2_{ji}) \) and the \( \Xi(q^2, m_i^2, m_j^2) \) function vanishes when \( i = j \). The numerical result is around \( |f^Z_{ij}| \propto 10^{-6} - 10^{-5} \) for the same values of the scalar bosons in the previous case.

To study the TNGBCs, the experimentalists focused their attention on pair production of neutral gauge bosons; but in the SM the non-resonant neutral diboson production proceeds mainly through quark-antiquark (electron-positron) \( t \) – and \( u \) – channel scattering diagrams, though also a contribution about of the 6\% proceeds via gluon-gluon fusion into box quark loops in hadronic processes. On the other hand, the SM offers precise predictions of production rates associated with self-interactions of the neutral gauge bosons [42]. Then the production of neutral gauge bosons not only provides an important background for the studies of the Higgs boson, it also allows to test the electroweak sector of the SM. Consequently, with precise measurements of the cross sections of production of neutral diboson, any observed deviation from the SM prediction would be an indication of new SM physics, such as the TNGBCs. But up to now, the measured total cross section is statistically consistent with the respective SM prediction [43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53] and therefore, no evidence of NTGBCs has been found. Nevertheless, all results of the analysis have been used to set limits on NTGBCs at the 95\% confidence level. Particularly, the most stringent limits to date on CP-violating form factors are shown in the table 2.

| Experiment     | limits          |
|----------------|-----------------|
| DELPHI [53]    | \(|h^Z_{ij}| < 0.23\) |
| L3 [52]        | \(-0.087 < h^Z_{ij} < 0.079\) |
| CMS [43]       | \(-0.00117 < f^Z_{ij} < 0.00110\) |
| CMS [43]       | \(-0.00133 < f^Z_{ij} < 0.00132\) |

Table 2. The most stringent limits up to date on CP-violating NTGBCs.

4. Higgs to gauge boson decays

In the SM, the Higgs mechanism generates the masses of the electroweak gauge bosons, while the photon and gluon remain massless. Consequently, at tree level the Higgs boson interact only
with $W^\pm$ and $Z^0$. The Lagrangian for this interaction is the following:

$$\mathcal{L}_{\text{tree}} = g m_W h W^\dagger \mu W^\mu + \frac{g m_Z}{2 c_W} h Z^\dagger \mu Z^\mu,$$

(22)

these interactions have been observed since discovery of Higgs boson, and they are statistically consistent with the SM [54, 55, 56, 57]. However, the Higgs boson decay into a photon pair was also measured by ATLAS [54] and CMS [55] collaborations. Additionally, the Higgs boson production at the LHC is dominated by the gluon fusion process [58]. Although the coupling of the Higgs boson with photons and gluons is absent at tree level in the SM, these interactions are induced at one-loop level and they are also consistent with the SM [54, 55, 56, 57]. Nevertheless, at one-loop level new contributions may arise in some SM extension and they are called anomalous couplings. The Lagrangian for these interactions has four and six dimension operators and is given by:

$$\mathcal{L}_{\text{eff}}^{VV} = g m_V a_1^V h V^\mu V^\mu + a_2^V h V^\mu V^{\mu
u} + a_3^V h V^\mu V^{\mu
u},$$

(23)

here $V = \gamma, Z^0, W, G$ and $a_1^V$ is an one-loop form factor, while $\tilde{V}_{\mu\nu} = \epsilon^{\mu\nu\alpha\beta} V_{\alpha\beta}$ and the operator $Z_{\mu\nu}(Z'\partial^\mu h - Z^\nu\partial^\mu h)$ is related with $a_1^V$ and $a_3^V$ terms. On the other hand, the Lorentz structures associated to $a_{1,2}^2$ are CP-even and for $a_1^V$ is CP-odd. Therefore, a nonzero $a_3^V$ form factor parameterizes the effect of CP-violation in the interactions of the Higgs boson with gauge bosons. Then from (23), the vertex function for the coupling $hV^\mu(p_1)V^{\nu}(p_2)$ is the following:

$$\Gamma^{\mu\nu} = g m_V a_1^V g^{\mu\nu} + a_2^V (p_1 \cdot p_2 g^{\mu\nu} - p_2^\mu p_1^\nu) + a_3^V \epsilon^{\mu\nu\alpha\beta} p_{1\alpha} p_{2\beta},$$

(24)

where $a^Z$ is a correction of the respective tree-level coupling, while that $a^V_2$ explain the gluon fusion and Higgs boson decay into a photon pair at LHC. Further, in the SM the $a_1^Z$ and $a_2^V$ can be induced through a loop involving top or bottom quarks, but to induce $a_3^V$ form factor is necessary some additional theoretical mechanisms.

A possibility consists in considering flavor changing neutral currents (FCNC). But the FCNC is induced only at one-loop in some SM extensions and since the photon and the gluon are massless, the FCNC associated with these gauge bosons are very suppressed. Then the best opportunity resides in the $Z^0$ boson. However, considering an effective lagrangian for the $Z^0\ell_i\ell_j$ coupling, that includes both vector and axial complex coupling constants, the results for $a_2^V$ is extremely suppressed [62]. The importance of this analysis is that the result is proportional to $\text{Im}(g_V^i g_A^j)$, and vanishes when we consider diagonal couplings. From the experimental side, the CMS collaboration has been exploring the $a_3^V$ coupling in different Higgs boson decays to neutral diboson [63, 64, 65]. In those experimental analysis the effective fractional cross sections $f_{a_i}$ and phases $\phi_{a_i}$ are defined as follows:

$$f_{a_i} = |a_i|^2 \sum_j |a_j|^2 \sigma_j,$$

(25)

$$\phi_{a_i} = \text{arg}(a_i/a_1).$$

(26)

Where $\sigma_j$ is the cross section for the $h \to ZZ/\gamma\gamma^*/\gamma^*\gamma^* \to 2\ell 2\mu$ process. Thus, from the combined Run 1 and Run 2 analysis, the current results are $f_{a_3} = 0.00^{+0.26}_{-0.06}$ with 68% C.L., and $-0.38 < \cos(\phi_{a_3}) < 0.46$ with 95% C.L. [63].

$^2$ BR($\tau \to \mu\gamma$)< $4.4 \times 10^{-8}$, BR($\tau \to e\gamma$)< $3.3 \times 10^{-8}$ [59] and BR($\mu \to e\gamma$)< $4.2 \times 10^{-13}$ [60].

$^3$ BR($Z^0 \to e\mu$)< $1.7 \times 10^{-6}$, BR($Z^0 \to e\tau$)< $9.8 \times 10^{-6}$ and BR($Z^0 \to \mu\tau$< $1.2 \times 10^{-5}$) [61].
5. Conclusions
In this report we have shown that the radiative corrections are a powerful tool to study new sources of CP-violation. In this context, we have explored the mathematical potential of the electric dipole moments, trilinear neutral gauge boson couplings and Higgs to gauge boson decays. These sources can be induced in some SM extension framework, and we showed that in order to induce the respective source of CP-violation non-diagonal couplings are necessary. Additionally, we showed that the respective CP-odd term is proportional to the imaginary part of the product of the coupling constants, which is necessary to obtain nonzero results and is consistent with the Lorentz structure of the respective Lagrangian.

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