

The Lorentz and CPT violating effects on $H^0 \rightarrow f^+ f^-$ (ZZ, W^+W^-) decays.

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Abstract

We study the Lorentz and CPT violating effects on the ratio $\frac{BR_{LorVio}}{BR_{SM}}$ where BR_{LorVio} (BR_{SM}) is the branching ratios coming from the Lorentz violating effects (the SM), for the decays $H^0 \rightarrow f^+ f^-$ ($f =$ quarks and charged leptons) and $H^0 \rightarrow ZZ$ (W^+W^-). We observe that these new effects are too small to be detected, especially for $f^+ f^-$ output, since the corresponding coefficients are highly suppressed at the low energy scale.

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1 Introduction

The CP even Higgs boson (H^0) is essential in the existence of the standard model (SM) of electroweak interactions. Therefore, its possible detection in future collider experiments is one of the main goals of physicists to test the SM and to get strong information about the mechanism of the electroweak symmetry breaking, the Higgs mass and the top Higgs Yukawa coupling.

The light Higgs boson, $m_{H^0} \leq 130 \text{ GeV}$, mainly decays into $b\bar{b}$ pair [1]. However its detection is difficult due to the QCD background and the $t\bar{t}H^0$ channel, where the Higgs boson decays to $b\bar{b}$, is one of the promising one [2]. For a heavier Higgs boson $m_{H^0} \sim 180 \text{ GeV}$, the suitable production exists via gluon fusion and the leading decay mode is $H^0 \rightarrow WW \rightarrow l^+l'^-\nu_l\nu_{l'}$ [3, 4]. In [4], it is stated that this decay mode gives three order times larger events compared to the mode $H^0 \rightarrow ZZ^* \rightarrow l^+l^-l'^+l'^-$.

Besides the quark or lepton flavor conserving decays of H^0 , the flavor violating (FV) H^0 decays have been studied in series of works in the literature. $H^0 \rightarrow \tau\mu$ decay is an example for lepton FV (LFV) decays and it has been studied in [5, 6]. In [5], a large branching ratio (BR), at the order of magnitude of $0.1 - 0.01$, has been estimated in the framework of the 2HDM. In [6], its BR was obtained in the interval $0.001 - 0.01$ for the Higgs mass range $100 - 160(\text{GeV})$, for the LFV parameter $\lambda_{\mu\tau} = 1$. The observable CP violating asymmetries in the leptonic flavor changing H^0 decays with BR s of the order of $10^{-6} - 10^{-5}$ has been examined in [7]. The LFV $H^0 \rightarrow l_i l_j$ decay has been studied also in [8].

The present work is devoted to the Lorentz and CPT violating effects on the BR and the ratio $\frac{BR_{LorVio}}{BR_{SM}}$, where BR_{LorVio} (BR_{SM}) is the BR s coming from the Lorentz violating effects (the SM) for the decays $H^0 \rightarrow f^+f^-$ ($f =$ quarks and charged leptons) and $H^0 \rightarrow ZZ (W^+W^-)$.

The Lorentz and CPT symmetry violations exist in the extended theories like the string theory [9], the non-commutative theories [10], which are more fundamental and exist at higher scales. In such scales, there are signals that the Lorentz and CPT symmetries are broken [11]. However, the small violations of these symmetries can appear at the low energy level and in the SM of particle physics, which is the low energy limit of more fundamental theories, such tiny effects are switched on. In [12, 13], the general Lorentz and CPT violating extension of the SM is obtained. The source of these new effects are the coefficients which can arise from the expectation values in the string theories or some coefficients in the noncommutative field theories [10], existing at the Planck scale [9, 10]. In addition to string theory and noncommutative geometry, space-time-varying scalar couplings can also lead to Lorentz-violating effects

described by the SM extensions [14].

The general Lorentz and CPT violating effects have been studied in Quantum Electro Dynamics (QED) extensions [15, 16], in Maxwell-Chern-Simons model [17], in the noncommutative space time [18], in Wess-Zumino model [19] and the theoretical overview of Lorentz and CPT violation has been done in [20]. In [21, 22, 23], some of these coefficients has been restricted using the experiments and in [24] it was pointed that threshold analyzes of ultra- high-energy cosmic rays could also be used for Lorentz and CPT-violation searches.

There are also some phenomenological works done on the the Lorentz and CPT violating effects in the SM extension. In [25], the Lorentz and CPT violating effects on the BR and the CP violating asymmetry A_{CP} for the lepton flavor violating (LFV) interactions $\mu \rightarrow e\gamma$ and $\tau \rightarrow \mu\gamma$ has been analyzed in the model III version of the two Higgs doublet model (2HDM) and the relative behaviors of the new coefficients on these physical parameters have been studied. In [26] these effects on the BR and on the possible CPT violating asymmetry (A_{CPT}) for the $Z \rightarrow l^+l^-$ ($l = e, \mu, \tau$) decay have been examined.

In this work, we predict the ratios $\frac{BR_{LorVio}}{BR_{SM}}$ for $H^0 \rightarrow f^+f^-(ZZ, W^+W^-)$ decays and we get the small numbers of the order of 10^{-33} (10^{-16}) at most, since the natural suppression scale for Lorentz-CPT violating coefficients can be taken as the ratio of the light one, of the order of the electroweak scale, to the one of the order of the Planck mass [22]. For the $H^0 \rightarrow f^+f^-$ decay this ratio is highly suppressed since the Lorentz violating effects enters into expressions as the corresponding coefficient square. We also study the relative magnitudes the BR s of the decays $H^0 \rightarrow ZZ$ and $H^0 \rightarrow W^+W^-$ in the case that only the Lorentz violating effects are taken into account. We observe that the Lorentz violating effects are tiny and it is not possible to detect in the present experiments.

The paper is organized as follows: In Section 2, we present the theoretical expression for the decay width Γ , for the $H^0 \rightarrow f^+f^-$ ($f =$ quarks and charged leptons) and $H^0 \rightarrow ZZ (W^+W^-)$ decays, with the inclusion of the Lorentz and CPT violating effects. Section 3 is devoted to discussion and our conclusions.

2 The Lorentz and CPT violating effects on $H^0 \rightarrow f^+f^-$ and $H^0 \rightarrow ZZ (W^+W^-)$ decays.

In this section we present the Lorentz and CPT violating effects on the BR of the Higgs decays, $H^0 \rightarrow f^+f^-$ ($f =$ quarks and charged leptons) and $H^0 \rightarrow ZZ (W^+W^-)$ in the SM extension. For these decays, the Lorentz and CPT violating effects enter into calculations at tree level

similar to the main contribution coming from the SM. The tiny Lorentz-CPT violating effects are regulated by the new coefficients which have small numerical values and their natural suppression scale reaches to, at most, the ratio of the mass in the electroweak scale to the one in the Planck scale .

The lagrangian which is responsible for the $H^0 \rightarrow f^+ f^-$ decay is the Yukawa lagrangian and, in the SM, it reads

$$\mathcal{L}_Y = \eta_{ij}^U \bar{Q}_{iL} \tilde{\phi} U_{jR} + \eta_{ij}^D \bar{Q}_{iL} \phi D_{jR} + \eta_{ij}^E \bar{l}_{iL} \phi E_{jR} + h.c. , \quad (1)$$

where L and R denote chiral projections $L(R) = 1/2(1 \mp \gamma_5)$ and ϕ is the Higgs scalar doublet. Here $\eta_{ij}^{U,D,E}$, are the Yukawa matrices and U (D,E) denotes up quarks (down quarks, charged leptons). The additional part due to the Lorentz violating effects can be represented by the CPT-even lagrangian [12]

$$\mathcal{L}_Y^{LorVio} = \frac{1}{2} \left(H_{ij}^{U,\mu\nu} \bar{Q}_{iL} \tilde{\phi} \sigma_{\mu\nu} U_{jR} + H_{ij}^{D,\mu\nu} \bar{Q}_{iL} \phi \sigma_{\mu\nu} D_{jR} + H_{ij}^{E,\mu\nu} \bar{l}_{iL} \phi \sigma_{\mu\nu} E_{jR} \right) + h.c. , \quad (2)$$

where the coefficients $H^{\mu\nu}$ are dimensionless and antisymmetric.

Using the well known expression defined in the H^0 boson rest frame

$$d\Gamma = \frac{(2\pi)^4}{2 m_{H^0}} \delta^{(4)}(p_{H^0} - q_1 - q_2) \frac{d^3 q_1}{(2\pi)^3 2 E_1} \frac{d^3 q_2}{(2\pi)^3 2 E_2} \times |M|^2(p_{H^0}, q_1, q_2) \quad (3)$$

where p_{H^0} (q_1, q_2) is the four momentum vector of H^0 boson (fermion, anti-fermion), and M is the matrix element of the process $H^0 \rightarrow f^+ f^-$, we get

$$\begin{aligned} \Gamma_{SM}^{ff} &= \frac{G_F}{4\sqrt{2}\pi} m_{H^0}^3 x_f (1 - 4x_f)^{\frac{3}{2}} \\ \Gamma_{LorVio}^{ff} &= -\frac{3 m_{H^0}}{8\pi} x_f (1 - 4x_f)^{\frac{1}{2}} \left(|H|^2 + |H^\dagger|^2 \right). \end{aligned} \quad (4)$$

Here the parameter x_f is $x_f = \frac{m_f^2}{m_{H^0}^2}$ and $|H^{(\dagger)}|^2 = H_{\mu\nu}^{(\dagger)} H^{(\dagger)\mu\nu}$. Notice that the Lorentz violating effects enter into expressions quadratic in coefficient $|H|$ and therefore it is highly suppressed in the calculation of the decay width Γ .

Now we will present the decay widths of the decays $H^0 \rightarrow ZZ$ and $H^0 \rightarrow W^+ W^-$ including the possible Lorentz-CPT violating effects in the SM extension.

The SM lagrangian which drives the $H^0 \rightarrow ZZ$ ($W^+ W^-$) decay is the so called kinetic term,

$$\mathcal{L}_K = (D_\mu \phi)^\dagger D^\mu \phi , \quad (5)$$

where D_μ is the covariant derivative, $D_\mu = \partial_\mu + \frac{ig}{2}\tau \cdot W_\mu + \frac{ig'}{2}YB_\mu$, τ is the Pauli spin matrix, Y is the weak hypercharge, B_μ (W_μ) is the $U(1)_Y$ ($SU(2)_L$ triplet) gauge field. The lagrangian responsible for the Lorentz violating effects to these decays can be divided into CPT-odd and CPT-even parts [12]:

$$\begin{aligned}\mathcal{L}_K^{CPT-even} &= \frac{1}{2}k_{\phi\phi}^{\mu\nu}(D_\mu\phi)^\dagger D_\nu\phi + h.c - \frac{1}{2}k_{\phi B}^{\mu\nu}\phi^\dagger\phi B_{\mu\nu} - \frac{1}{2}k_{\phi W}^{\mu\nu}\phi^\dagger W_{\mu\nu}\phi, \\ \mathcal{L}_K^{CPT-odd} &= ik_\phi^\mu\phi^\dagger D_\mu\phi + h.c.\end{aligned}\quad (6)$$

Here the coefficient $k_{\phi\phi}$ ($k_{\phi B}$, $k_{\phi W}$) is dimensionless (have dimension of mass and real antisymmetric) and the CPT-odd coefficient k_ϕ has dimensions of mass. $B_{\mu\nu}$ and $W_{\mu\nu}$ are the field tensors which are defined in terms of the gauge fields B_μ and W_μ ,

$$\begin{aligned}B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu, \\ W_{\mu\nu} &= \partial_\mu W_\nu - \partial_\nu W_\mu + ig[W_\mu, W_\nu].\end{aligned}\quad (7)$$

Finally the decay widths for the decays $H^0 \rightarrow ZZ$ and $H^0 \rightarrow W^+W^-$ read

$$\begin{aligned}\Gamma_{SM}^{ZZ} &= \frac{G_F}{16\sqrt{2}\pi} m_{H^0}^3 (1 - 4x_Z + 12x_Z^2)(1 - 4x_Z)^{\frac{1}{2}} \\ \Gamma_{SM}^{WW} &= \frac{G_F}{8\sqrt{2}\pi} m_{H^0}^3 (1 - 4x_W + 12x_W^2)(1 - 4x_W)^{\frac{1}{2}} \\ \Gamma_{LorVio}^{ZZ} &= \frac{G_F}{8\sqrt{2}\pi} m_{H^0}^3 (1 - x_Z + 6x_Z^2)(1 - 4x_Z)^{\frac{1}{2}} |k_{\phi\phi}^{Sym}| \\ \Gamma_{LorVio}^{WW} &= \frac{G_F}{4\sqrt{2}\pi} m_{H^0}^3 (1 - x_W + 6x_W^2)(1 - 4x_W)^{\frac{1}{2}} |k_{\phi\phi}^{Sym}|,\end{aligned}\quad (8)$$

where $x_{Z(W)} = \frac{m_{Z(W)}^2}{m_{H^0}^2}$. Here we use the parametrization

$$k_{\phi\phi}^{\mu\nu} = \delta^{\mu\nu} |k_{\phi\phi}^{Sym}| + k_{\phi\phi}^{ASym\mu\nu}.\quad (9)$$

Notice that we take only the additional part of the decay width which is linear in the Lorentz violating coefficients. Eq. (8) shows that Γ_{LorVio}^{ZZ} and Γ_{LorVio}^{WW} depends on the CPT even $k_{\phi\phi}^{Sym}$ coefficient.

3 Discussion

Even if the SM is invariant under Lorentz and CPT transformations, the small violations of Lorentz and CPT symmetry, possibly coming from an underlying theory at the Planck scale, can arise in the extensions of the SM. In this section, we study the Lorentz and CPT violating

effects on the ratios $\frac{BR_{LorVio}}{BR_{SM}}$ where BR_{LorVio} (BR_{SM}) is the BR 's coming from the Lorentz violating effects (the SM) for the decays $H^0 \rightarrow f^+ f^-$ ($f =$ quarks and charged leptons) and $H^0 \rightarrow ZZ$ ($W^+ W^-$). As a final work, we analyze the ratio $R = \frac{BR_{ZZ}}{BR_{WW}}$, where BR_{ZZ} (BR_{WW}) is the BR for the decay $H^0 \rightarrow ZZ$ (WW), to observe the relative magnitudes of BR s in the SM and in the SM extension including only the Lorentz violating effects.

Since the natural suppression scale for these coefficients can be taken as the ratio of the light one $m_{f,W,Z}$ to the one of the order of the Planck mass, the coefficients which carry the Lorentz and CPT violating effects are in the the range of $10^{-23} - 10^{-17}$ [22]. Here the first (second) number represent the electron mass m_e ($m_{EW} \sim 250 GeV$) scale.

First we analyze the ratio $R = \frac{BR_{LorVio}}{BR_{SM}}$ for $H^0 \rightarrow f^+ f^-$ ($f =$ quarks and charged leptons) decays. Since the Lorentz violating effects enters into expressions quadratic in coefficient $|H|$ (see eq. (4)), the ratio R is at most at the order of the magnitude of 10^{-33} for the range of the coefficient $|H|$, $10^{-20} \leq |H| \leq 10^{-17}$ and for the fixed value of the Higgs mass $m_{H^0} = 100 GeV$. This is an extremely small number and there is no phenomenological interest.

Now, we start to study the same ratio for the decays $H^0 \rightarrow ZZ$ and $H^0 \rightarrow W^+ W^-$.

In Fig. 1, we present the magnitude of the coefficient $|k_{\phi\phi}^{Sym}|$ dependence of the ratio $R = \frac{BR_{LorVio}}{BR_{SM}}$ for the fixed value of the Higgs mass $m_{H^0} = 200 GeV$, for the decay $H^0 \rightarrow ZZ$ (WW). Here solid (dashed) line represents the dependence of R to the coefficient $|k_{\phi\phi}^{Sym}|$ for the ZZ (WW) output. Here it is observed that this ratio is at most at the order of the magnitude of 10^{-16} for the larger values of the coefficient $|k_{\phi\phi}^{Sym}| \sim 10^{-17}$. This figure shows that the ratio R for the ZZ output is slightly larger compared to the one for the WW output. The Lorentz violating effects strongly depends on the magnitude of the parameter $|k_{\phi\phi}^{Sym}|$ and in the expected region $10^{-20} \leq |k_{\phi\phi}^{Sym}| \leq 10^{-17}$, they are too small to detect in the experiments.

Fig. 2, represents the Higgs mass m_{H^0} dependence of the ratio $R = \frac{BR_{LorVio}}{BR_{SM}}$ for the fixed value of the Lorentz violating parameter $|k_{\phi\phi}^{Sym}| = 10^{-20}$, for the decay $H^0 \rightarrow ZZ$ (WW). Here solid (dashed) line represents the dependence of R to m_{H^0} for the ZZ (WW) output. This ratio decreases with the increasing values of m_{H^0} and the ratio R for the ZZ output is slightly larger compared to the one for the WW output, for different m_{H^0} .

Fig. 3 is devoted to the Higgs mass m_{H^0} dependence of the ratio $R = \frac{BR_{ZZ}}{BR_{WW}}$ for the fixed value of the parameter $|k_{\phi\phi}^{Sym}| = 10^{-20}$. Here BR_{ZZ} (BR_{WW}) is the BR for the decay $H^0 \rightarrow ZZ$ (WW) and the solid (dashed) line represents the m_{H^0} dependence of R for the SM (the Lorentz Violating part). It is observed that the ratio R has the value $R \sim 0.4$ for the SM case. This ratio larger in the case that only the Lorentz violating part is taken into account

and it reaches the numerical value $R \sim 0.6$.

As a summary, we analyze the ratio $R = \frac{BR_{LorVio}}{BR_{SM}}$ for $H^0 \rightarrow f^+ f^- (ZZ, W^+ W^-)$ decays. This ratio is 10^{-33} for $f^+ f^-$ output and it is comparably larger for $W^+ W^-$ and ZZ output, namely at the order of the magnitude of 10^{-16} , in the expected range of the Lorentz violating coefficient under consideration. The ratio R decreases with the increasing values of m_{H^0} and it is slightly larger for the ZZ output compared to the WW one. Furthermore, we calculated the ratio $R = \frac{BR_{ZZ}}{BR_{WW}}$ for the fixed value of the Lorentz violating parameter $|k_{\phi\phi}^{Sym}| = 10^{-20}$ and observe that it is of the order of 0.6 (0.4) for the Lorentz violating (the SM) part.

This analysis shows that it is not possible to detect the Lorentz violating effects for the Higgs decays under consideration in the present experiments.

4 Acknowledgement

This work has been supported by the Turkish Academy of Sciences in the framework of the Young Scientist Award Program. (EOI-TUBA-GEBIP/2001-1-8)

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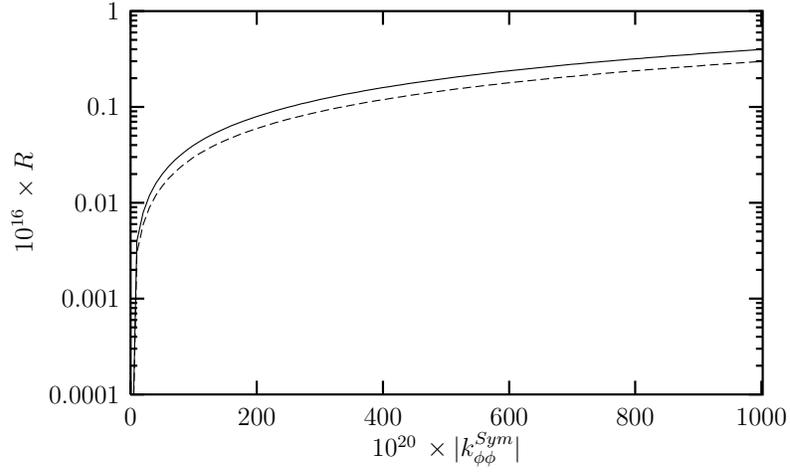


Figure 1: The magnitude of the coefficient $|k_{\phi\phi}^{Sym}|$ dependence of the ratio $R = \frac{BR_{LorVio}}{BR_{SM}}$ for the fixed value of the Higgs mass $m_{H^0} = 200 GeV$, for the decay $H^0 \rightarrow ZZ (WW)$. Here solid (dashed) line represents the dependence of R to the coefficient $|k_{\phi\phi}^{Sym}|$ for the $ZZ (WW)$ output..

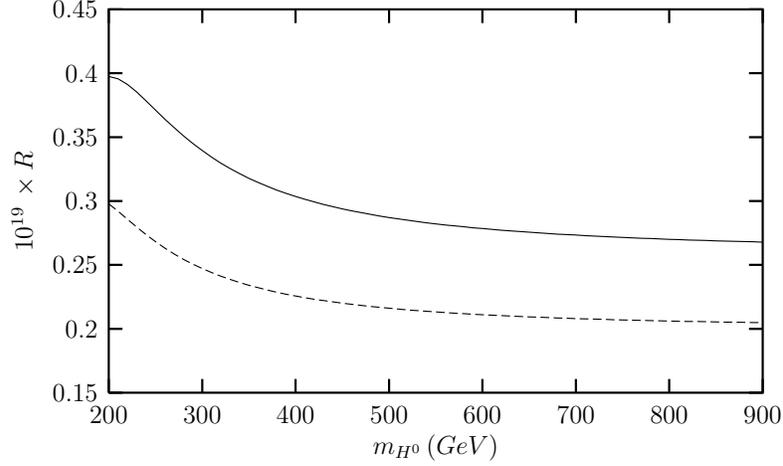


Figure 2: The Higgs mass m_{H^0} dependence of the ratio $R = \frac{BR_{LorVio}}{BR_{SM}}$ for the fixed value of the coefficient $|k_{\phi\phi}^{Sym}| = 10^{-20}$, for the decay $H^0 \rightarrow ZZ(WW)$. Here solid (dashed) line represents the dependence of R to m_{H^0} for the $ZZ(WW)$ output.

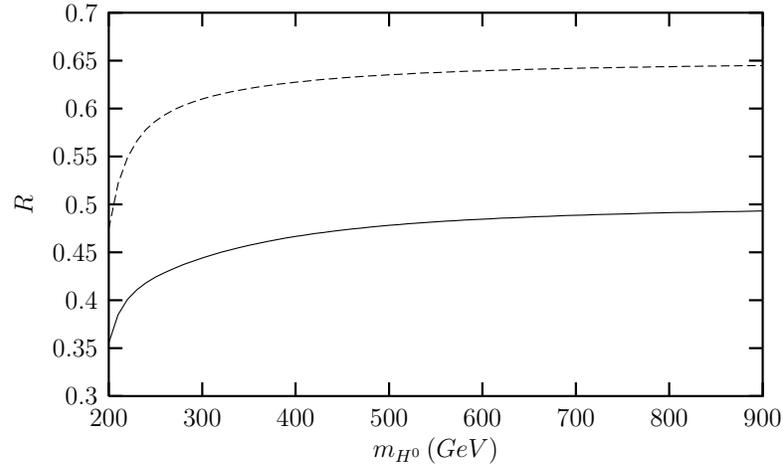


Figure 3: The Higgs mass m_{H^0} dependence of the ratio $R = \frac{BR_{ZZ}}{BR_{WW}}$ for the fixed value of the coefficient $|k_{\phi\phi}^{Sym}| = 10^{-20}$. Here the solid (dashed) line represents the m_{H^0} dependence of R for the SM (the Lorentz Violating part).