Journal of Modern Physics, 2012, 3, 1835-1839
http://dx.doi.org/10.4236/jmp.2012.312229 Published Online December 2012 (http://www.SciRP.org/journal/jmp)

Branching Ratios from $H \to \gamma\gamma$ and $H \to Z\gamma$ with a 125 GeV Higgs Boson

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Received July 1, 2012; revised October 19, 2012; accepted November 1, 2012

ABSTRACT

Motivated by the recent result reported from LHC on the di-photon search from the Standard Model (SM) Higgs boson, we obtain limits on the anomalous couplings $H\gamma\gamma$ and $HZ\gamma$. We also perform a calculation at tree level of the decay widths as well as of the branching ratios for the reactions $H \to \gamma\gamma$ and $H \to Z\gamma$ in the context of effective lagrangian for Higgs boson masses $115 \leq M_H \leq 130$ GeV. We find that the decay widths and branching ratios from these reactions enhanced significantly due to the anomalous $H\gamma\gamma$ and $HZ\gamma$ vertex, which would lead to measurable effects in Higgs signals at the LHC. Moreover, our results complement other studies on the channels $H \to \gamma\gamma$ and $H \to Z\gamma$.

Keywords: Standard Model Higgs Boson; Models beyond the Standard Model

1. Introduction

Recently, the Large Hadron Collider (LHC) of the European Center for Nuclear Research (CERN), has collected valuable data on the Higgs boson of the standard model of electroweak and strong interactions. Both ATLAS and CMS collaborations at LHC have performed a combined search [1] on Higgs boson. The main production channels used by both collaborations are: $H \to \gamma\gamma$, $H \to ZZ^* \to 4l$ and $H \to WW^* \to 2\nu 2l$. These experiments have reported an excess of events in channel research for an invariant mass $m \approx 125$ GeV with a confidence level of 2σ to 3σ, which could be the first evidence of existence of the Higgs boson.

In the Standard Model (SM) of electroweak interactions there are no couplings at the tree level among three neutral bosons such as $H\gamma\gamma$ and $HZ\gamma$. These couplings only appear at the one-loop level through fermion and charged vector bosons [2-4]. In the SM it is dominated by W gauge boson and top quark loops and the branching ratio for the decay modes $H \to \gamma\gamma$ and $H \to Z\gamma$ reaches its maximumvalue of order 10^{-3} for an intermediate mass Higgs boson ($115 \leq M_H \leq 140$ GeV) [4]. The decay $H \to \gamma\gamma$ is induced at one loop in the context of the standard model, and this channel is one of the main means of production in the next generation of linear colliders. This decay is also attractive in the LHC because it does not suffer from the uncertainty caused by the reconstruction of the jets, as in other decay channels. The study of these vertex $H \to \gamma\gamma$ and $H \to Z\gamma$ has attracted much attention because their strength can be sensitive to scales beyond the SM. The interest in this type of couplings thus lies in the additional contributions that may appear in extensions of the SM, for example, new charged scalar and vector bosons in Left-Right (L-R) symmetric gauge models [5], or Two Higgs Doublet Models (THDM) [6,7], as well as charginos and neutralinos in the Minimal Supersymmetric Standard Model (MSSM) [6,7]. The SM and LR symmetric models predict an anomalous $HZ\gamma$ vertex of order 10^{-4} [2,4], the MSSM may induce a suppression effect [6,7] but an effective lagrangian approach leaves room for an enhancement effect [6,8-10]. These models arise as an interesting alternative to analyze the couplings at the tree level among three neutral bosons such as $H\gamma\gamma$ and $HZ\gamma$. Sukanta Dutta, Kaoru Hagiwara and Yu Matsumoto [10] have proposed a model based on the effective lagrangian of the Higgs and the gauge bosons with operators up to mass dimension six. Detailed discussions on effective lagrangian can be found in the literature [6-9,11].

The sensitivity to the $H\gamma\gamma$ and $HZ\gamma$ vertex has been studied in processes such as $e^-\gamma \to e^-H$, $e^+e^- \to H\gamma$ [4,9,12] and $e^+e^- \to \tau^+\tau^-\gamma$ [13], rare Z and H decays [14-16], pp collisions via the basic interaction $qq \to qqH$ [16] and the annihilation process $e^+e^- \to HZ$ [9,17,18].

Our aim in the present paper is to analyze the reactions $H \to \gamma\gamma$ and $H \to Z\gamma$ in the framework of the effective lagrangian [10]. In this paper, we take advantage of this formalism with anomalous couplings $H\gamma\gamma$ and $HZ\gamma$ to obtain limits on $h_{1,2}^{\gamma\gamma}h_{1,2}^{Z\gamma}$. We also perform a calculation at tree level on the decay widths and branching ratios from reactions $H \to \gamma\gamma$ and $H \to Z\gamma$.

The paper is organized as follows: in Section 2 we present the calculation of the reactions $H \to \gamma\gamma$ and $H \to Z\gamma$ and in Section 3 we present our results and conclusions.

2. Decay Widths and Branching Ratios from $H \to \gamma\gamma$ and $H \to Z\gamma$

In this section we present the decay widths of the reactions $H \to \gamma\gamma$ and $H \to Z\gamma$ in the context of the effective lagrangian given in Ref. [10].

2.1. Decay Width of $H \to \gamma\gamma$

We calculate the decay width for the reaction $H \to \gamma\gamma$ using the terms that describe the *HVV* couplings in the effective lagrangian given in Equation (11) of Ref. [10]. From this lagrangian the Feynman rule for

$$V_1^{\mu}(p_1) - V_2^{\nu}(p_2) - H(p_H)$$

vertex is given by [10]

$$\Gamma_{\mu\nu}^{HV_1V_2}(p_H, p_1, p_2) = g_Z M_Z^2 \left[h_1^{V_1V_2} g_{\mu\nu} + \frac{h_2^{V_1V_2}}{M_Z^2} p_{2\mu} p_{1\nu} \right], \quad (1)$$

where M_Z is the Z boson mass, $g_z = e/\cos\theta_W$ and $p_1 + p_2 + p_H = 0$ as shown in **Figure 1** of Ref. [10]. In Equation (1) V_1 and V_2 can be

$$(V_1V_2) = (ZZ), (Z\gamma), (\gamma Z), (W^+W^-) \text{ or } (W^-W^+).$$

The coefficients $h_i^{V_1V_2}(p_1, p_2)$ are

$$h_1^{\gamma\gamma}(p_1, p_2) = \frac{p_1^2 + p_2^2 - M_H^2}{M_Z^2} c_{2\gamma\gamma},$$
$$h_2^{\gamma\gamma}(pp_1, p_2) = 2c_{2\gamma\gamma}, \quad (2)$$

for the $H\gamma\gamma$ couplings,

$$h_1^{Z\gamma}(p_1, p_2) = \frac{p_1^2 + p_2^2 - M_H^2}{M_Z^2} c_{2Z\gamma} - \frac{p_1^2 - p_2^2 - M_H^2}{M_Z^2} c_{3Z\gamma},$$
$$h_1^{Z\gamma}(p_1, p_2) = \frac{p_1^2 + p_2^2 - M_H^2}{M_Z^2} c_{2Z\gamma} - \frac{-p_1^2 + p_2^2 - M_H^2}{M_Z^2} c_{3Z\gamma}, \quad (3)$$
$$h_2^{Z\gamma}(p_1, p_2) = h_2^{\gamma Z}(p_1, p_2) = 2(c_{2Z\gamma} - c_{3Z\gamma}),$$

for the $HZ\gamma$ couplings. A interesting characteristic of this model is that the coefficients $h_1^{V_1V_2}$ and $h_2^{V_1V_2}$ are the only additional parameters.

The respective transition amplitude for the reaction $H \to \gamma\gamma$ is thus given by

$$M(H \to \gamma\gamma) = \Gamma_{\mu\nu}^{H\gamma\gamma}(p_H, p_1, p_2)\varepsilon^{\mu}(p_1, \lambda_1)\varepsilon^{\nu}(p_2, \lambda_2), \quad (4)$$

where $\varepsilon^{\mu}(p_1, \lambda_1)$ and $\varepsilon^{\nu}(p_2, \lambda_2)$ are the polarization vectors of the photons and $\Gamma_{\mu\nu}(p_H, p_1, p_2)$ is given in Equation (1). While the square of the transition amplitude for the reaction $H \to \gamma\gamma$ is

$$\sum_{\lambda} |M|^2 = g_Z^2 M_Z^2 \left[4\left(h_1^{\gamma\gamma}\right)^2 - \frac{M_H^4}{2M_Z^4}\left(h_2^{\gamma\gamma}\right)^2 \right], \quad (5)$$

The decay width in the context of effective lagrangian is given by

$$\Gamma(H \to \gamma\gamma) = \frac{g_Z^2 M_Z^2}{16\pi M_H} \left[4\left(h_1^{\gamma\gamma}\right)^2 - \frac{M_H^4}{2M_Z^4}\left(h_2^{\gamma\gamma}\right)^2 \right]. \quad (6)$$

In the standard model at tree level, the decay width is zero. Evaluating the limit when the coefficients $h_1^{\gamma\gamma}\left(h_2^{\gamma\gamma}\right) \to 0$ the terms that depend on $h_1^{\gamma\gamma}$ and $h_2^{\gamma\gamma}$ in (6) are zero and the results of the SM are recovered.

2.2. Decay Width of $H \to Z\gamma$

Following a similar procedure as in the case of the decay $H \to \gamma\gamma$, the expression for the square of the amplitude of transition of $H \to Z\gamma$ is

$$\sum_{\lambda} |M|^2 = g_Z^2 M_Z^2 \left[3\left(h_1^{Z\gamma}\right)^2 - \frac{\left(h_2^{Z\gamma}\right)^2}{4M_Z^4}\left(M_H^2 - M_Z^2\right)^2 \right], \quad (7)$$

while the corresponding decay width is given by

$$\Gamma(H \to Z\gamma) = \frac{g_Z^2 M_Z^2}{64\pi M_H^3}\left(M_H^2 - M_Z^2\right)\left[12\left(h_1^{Z\gamma}\right)^2 - \left(\frac{M_H^2 - M_Z^2}{M_Z^2}\right)^2 \left(h_2^{Z\gamma}\right)^2 \right]. \quad (8)$$

Using the fact that for on-shell particles, only one of the form factors given in Equation (1) contributes to the decay width [6], Equation (8) can be expressed by

$$\Gamma(H \to Z\gamma) = \frac{g_Z^2}{8\pi} \frac{M_Z^2\left(M_H^2 - M_Z^2\right)}{M_H^3}\left(h_1^{Z\gamma}\right)^2. \quad (9)$$

3. Results and Conclusions

For the numerical computation of the reactions $H \to \gamma\gamma$ and $H \to Z\gamma$ in the context of effective lagrangian and anomalous couplings $H\gamma\gamma$ and $HZ\gamma$, we have adopted the following parameters: the angle of Weinber $\sin^2\theta_W = 0.232$, the mass (m_b = 4.5 GeV) of the bottom quark, the mass (M_Z = 91.2 GeV) of the Z boson and the mass ($115 \le M_H \le 130$ GeV) of the Higgs boson [19], we obtain the decay widths

$$\Gamma = \Gamma\left(h_1^{\gamma\gamma}, h_2^{\gamma\gamma}, M_H\right),$$

$$\Gamma = \Gamma\left(h_1^{Z\gamma}, h_2^{Z\gamma}, M_H\right)$$

and the branching ratios, respectively. The branching ratio for the decay modes $H \to \gamma\gamma$ and $H \to Z\gamma$ reaches its maximum value of order 10^{-3} for an intermediate-mass Higgs boson of $115 \le M_H \le 130$ GeV [4,19-21]. Taking this into consideration, we obtain limits on $\left(h_1^{\gamma\gamma}, h_2^{\gamma\gamma}\right)$ and $\left(h_1^{Z\gamma}, h_2^{Z\gamma}\right)$ as a function of M_H.

To illustrate our results we obtain limits on $h_{1,2}^{\gamma\gamma}$ and calculate the decay width and the branching ratio for the reaction $H \to \gamma\gamma$ for different values of M_H in **Table 1**. In **Figure 1** we plot the decay width of the reaction $H \to \gamma\gamma$ as a function of the Higgs boson mass M_H and for the values of the anomalous couplings $h_1^{\gamma\gamma}$ and $h_2^{\gamma\gamma}$ given in **Table 1**. We observed from this figure that the decay width decreases with an increase in the Higgs boson mass and increases for $h_1^{\gamma\gamma}$ and $h_2^{\gamma\gamma}$ given. The $Br(H \to \gamma\gamma)$ is plotted in **Figure 2** and we apply our limits obtained in **Table 1** for $h_1^{\gamma\gamma}$ and $h_2^{\gamma\gamma}$. We notice an improvement of about an order of magnitude with respect to the result obtained by the SM [19].

In the case of the reaction $H \to Z\gamma$ we obtain limits on $h_{1,2}^{Z\gamma}$ and calculate the decay width and the branching ratio for different values of M_H in **Table 2**. We plot the decay width in **Figure 3** as a function of the Higgs boson mass M_H for the values of $h_1^{Z\gamma} = 0.042, 0.045, 0.047$ given in **Table 2**. We observe in this figure that the decay width of the reaction $H \to Z\gamma$ decreases with an increase in the Higgs bosons mass M_H, and increases to $h_1^{Z\gamma}$ given.

In **Figure 4** we show the branching ratio for the decay $\Gamma(H \to Z\gamma)$ using the Equation (9) and our limits obtained for the coupling $h_1^{Z\gamma}$. We note an improvement of about an order of magnitude with respect to that obtained by the L3 Collaboration from the process $e^+e^- \to H\gamma$ [20] and about two order of magnitude with respect to that obtained in the standard model for the reaction $\Gamma(H \to Z\gamma)$ [19].

The decay $H \to \gamma\gamma$ is induced at one loop in the context of the standard model, and although the width of the decay $H \to \gamma\gamma$ is small, this channel is one of the main means of production in the next generation of linear colliders. This decay is also attractive in the LHC because it does not suffer from the uncertainty caused by the reconstruction of the jets, as in other decay channels.

It has been found that the reaction $H \to Z\gamma$ with polarized beams may lead to the best sensitivity to the $HZ\gamma$ vertex [17] while an anomalous $HZ\gamma$ coupling may enhance Higgs decay widths by several orders of magnitude that would lead to measurable effects in Higgs signals at the LHC [16].

In conclusion, we have analyzed the decay widths and the branching ratios from $H \to \gamma\gamma$ and $H \to Z\gamma$ with anomalous couplings $h_{1,2}^{\gamma\gamma}$ and $h_{1,2}^{Z\gamma}$. Our results in this case are consistent with those reported in the literature [19] with one and two order of magnitude better than the limits obtained for the same reactions by the L3 Collaboration [21] and the standard model [19]. In addition, while these results have never been reported in the literature before, they complement other studies on the channels $H \to \gamma\gamma$ and $H \to Z\gamma$ and could be of relevance for the scientific community.

Table 1. Sensitivities achievable at 95% C. L. for the $H\gamma\gamma$ vertex, decay width and branching ratios for the reaction $H \to \gamma\gamma$ for different values of M_H.

M_H GeV	$h_1^{\gamma\gamma}$	$h_2^{\gamma\gamma}$	$\Gamma(H \to \gamma\gamma)$ MeV	$\Gamma\left(H \to b\bar{b}\right)$ MeV	$Br(H \to \gamma\gamma)$
115	0.0027	0.0026	1.53×10^{-2}	3.98	3.84×10^{-3}
125	0.003	0.00235	1.79×10^{-2}	4.33	4.14×10^{-3}
130	0.0031	0.0023	1.86×10^{-2}	4.52	4.01×10^{-3}

Table 2. Sensitivities achievable at 95% C. L. for the $HZ\gamma$ vertex, decay width and branching ratios for the reaction $H \to Z\gamma$ for different values of M_H.

M_H GeV	$h_1^{Z\gamma}$	$h_2^{Z\gamma}$	$\Gamma(H \to Z\gamma)$ MeV	$\Gamma\left(H \to b\bar{b}\right)$ MeV	$Br(H \to Z\gamma)$
115	0.042	0.045	1.48	3.98	0.366
125	0.045	0.072	1.94	4.33	0.448
130	0.047	0.081	2.21	4.52	0.490

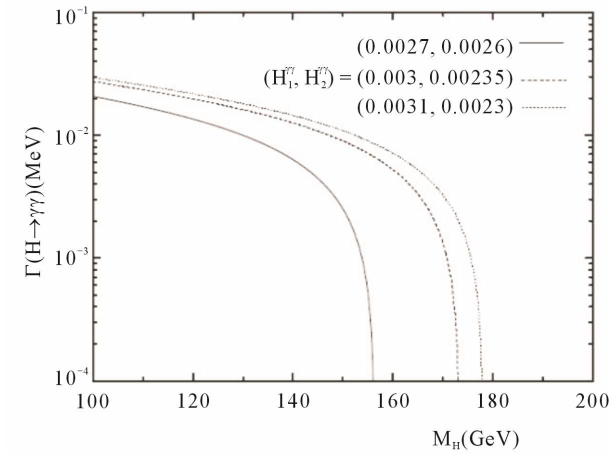

Figure 1. Higgs boson decay width as a function of the Higgs boson mass M_H and different values of $h_{1,2}^{\gamma\gamma}$.

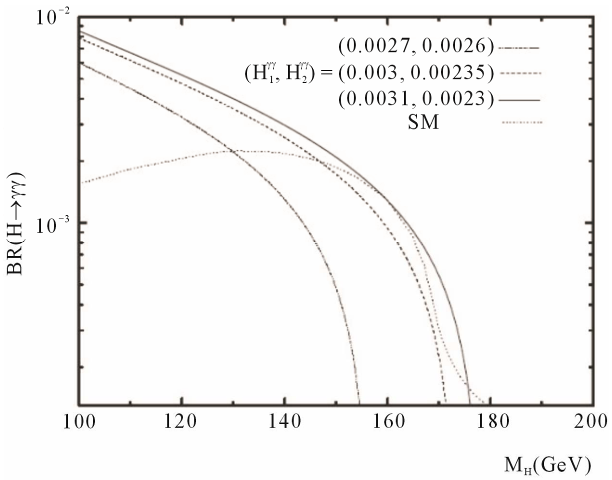

Figure 2. The branching ratio for the reaction $H \to \gamma\gamma$ as a function of the Higgs boson mass M_H and different values of $h_{1,2}^{\gamma\gamma}$.

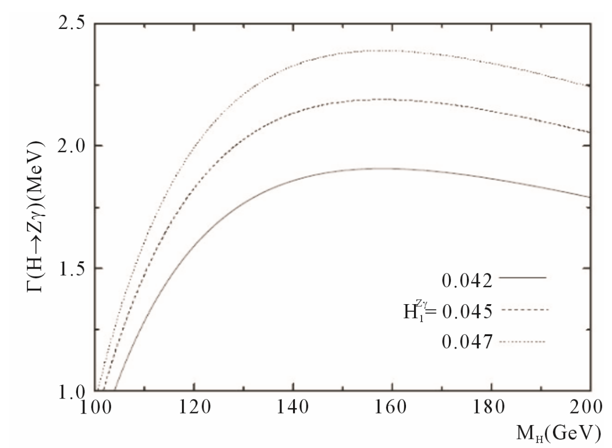

Figure 3. Higgs boson decay width as a function of the Higgs boson mass M_H and different values of $h_{1,2}^{Z\gamma}$.

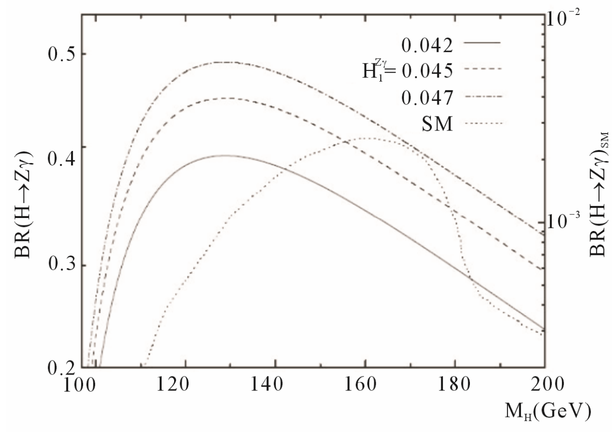

Figure 4. The branching ratio for the reaction $H \to Z\gamma$ as a function of the Higgs boson mass M_H and different values of $h_{1,2}^{Z\gamma}$.

4. Acknowledgements

We acknowledge support from CONACyT, SNI and PROMEP (México).

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