Int J Theor Phys (2009) 48: 2679–2684
DOI 10.1007/s10773-009-0057-3

Two-Photon Channel in $B-L$ Models

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Received: 29 March 2009 / Accepted: 27 May 2009 / Published online: 30 May 2009

Abstract In this paper we examine the possibility of having an exception to the recent observation by L. Randall amd M. Wise, which states that "a significant branching ratios to both e^+e^- and $\gamma\gamma$ is possible only if new physics beyond that in the SM couples directly to electrons". We consider resonances decaying into diphotons and dielectrons final states predicted in $U(1)_{B-L}$ extensions of the SM. We find that these new resonances can't decay into e^+e^- and $\gamma\gamma$ final states with comparably measurable branching ratios although such resonances are directly coupled to electrons.

Keywords Diphton channel · $B-L$

1 Introduction

Heavy resonances predicted in a number of possible extensions to the Standard Model are interpreted as either extra gauge bosons or Kaluza-Klein excitations of graviton bosons. In experiments, graviton bosons can be distinguished from the Z' ones because of the spin-2 nature of the gravitons. Moreover, the possibility of having detected a Z' can be excluded only if a heavy resonance peak is observed in both the di-photon and di-electron final states channels [1]. Generally, in models where electrons have direct couplings to the SM gauge and Higgs bosons only, resonances can't decay to di-photon and di-electron final states with comparable branching ratios [2]. However, the Kaluza-Klein modes of graviton g_{KK} predicted in the Randall-Sundrum (RS) model are an outstanding exception [3]. In was shown recently that $Br(g_{kk} \to \gamma\gamma)/Br(g_{kk} \to e^+e^-) = 2$. In fact, this is not the only exception since the two-Higgs-Doublet-Models (2HDM) may also produce simultaneously e^+e^- and $\gamma\gamma$ final states with comparable rates from decays of neutral scalars as was shown recently [4].

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In this paper, we will examine the possibility of having another exception by considering models with new scalar fields that can decay into dielectron and diphoton with comparably measurable rates. In particular, we will concentrate on extensions of the SM with an extra Higgs singlet such as the low scale $U(1)_{B-L}$ extension of the standard models [5], based on the gauge group $G_{B-L} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$. In this class of models, an extra SM singlet scalar (extra Higgs) is predicted. The spin-0 neutral scalars predicted in these models couple to electron directly through Yukawa interactions. As we will see if one changes the free parameters of the model properly but within the current experimental limits, the rare diphoton decay can't be enhanced so that the extra scalar can decay into both e^+e^- and $\gamma\gamma$ final states with comparably measurable branching ratios. We also achieve the same results by considering the decay of the spin-1 extra gauge boson into e^+e^- and $\gamma\gamma$ channels.

This paper is organized as follows. In Sect. 2 we give a brief review on the minimal $B-L$ extension of the SM. Section 3 is devoted for studying the decay of the extra singlet scalar into e^+e^- and $\gamma\gamma$ final states. Finally we give our concluding remarks in Sect. 4.

2 Low Scale $U(1)_{B-L}$ Extension of the SM

The $B-L$ model under consideration is described by the following Lagrangian [5]

$$\begin{aligned}\mathcal{L}_{B-L} &= i\bar{l}D_\mu\gamma^\mu l + i\bar{e}_R D_\mu\gamma^\mu e_R + i\bar{\nu}_R D_\mu\gamma^\mu\nu_R \\ &\quad - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}C_{\mu\nu}C^{\mu\nu} \\ &\quad + (D^\mu\phi)(D_\mu\phi) + (D^\mu\chi)(D_\mu\chi) - V(\phi,\chi) \\ &\quad - \left(\lambda_e\bar{l}\phi e_R + \lambda_\nu\bar{l}\tilde{\phi}\nu_R + \frac{1}{2}\lambda_{\nu_R}\bar{\nu^c}_R\chi\nu_R + h.c.\right),\end{aligned} \tag{2.1}$$

where the covariant derivative D_μ is different from the SM one by the term $ig''Y_{B-L}C_\mu$. Here g'' is the $U(1)_{B-L}$ gauge coupling constant, Y_{B-L} is the $B-L$ charge, and $C_{\mu\nu} = \partial_\mu C_\nu - \partial_\nu C_\mu$ is the field strength of the $U(1)_{B-L}$. The λ_e, λ_ν and λ_{ν_R} refer to 3×3 Yakawa matrices. The interaction terms $\lambda_\nu l\tilde{\phi}\nu_R$ and $\lambda_{\nu_R}\bar{\nu^c}_R\chi\nu_R$ give rise to a Dirac neutrino mass term: $m_D \simeq \lambda_\nu v$ and a Majorana mass term: $M_R = \lambda_{\nu_R}v'$, respectively. $U(1)_{B-L}$ and $SU(2)_L \times U(1)_Y$ gauge symmetries are spontaneously broken by a SM singlet complex scaler field χ and a complex $SU(2)$ doublet of scalar fields ϕ, respectively.

The most general Higgs potential invariant under these symmetries is given by [5]

$$\begin{aligned}V(\phi,\chi) &= m_1^2\phi^\dagger\phi + m_2^2\chi^\dagger\chi + \lambda_1(\phi^\dagger\phi)^2 + \lambda_2(\chi^\dagger\chi)^2 \\ &\quad + \lambda_3(\chi^\dagger\chi)(\phi^\dagger\phi),\end{aligned} \tag{2.2}$$

where $\lambda_3 > -2\sqrt{\lambda_1\lambda_2}$ and $\lambda_1, \lambda_2 \geq 0$, so that the potential is bounded from below. For non-vanishing vacuum expectation values (vev's), we require $\lambda_3^2 < 4\lambda_1\lambda_2$, $m_1^2 < 0$ and $m_2^2 < 0$. The vev's, $|\langle\phi\rangle| = v/\sqrt{2}$ and $|\langle\chi\rangle| = v'/\sqrt{2}$, are then given by

$$v^2 = \frac{4\lambda_2 m_1^2 - 2\lambda_3 m_2^2}{\lambda_3^2 - 4\lambda_1\lambda_2}, \qquad v'^2 = \frac{-2(m_1^2 + \lambda_1 v^2)}{\lambda_3}.$$

Normally, one takes $v = 246$ GeV and constrains the other scale, v', by the lower bounds imposed on the mass of the extra neutral gauge boson.

The SM complex $SU(2)_L$ doublet and the extra complex scalar singlet arise in this class of models, give six scalar degrees of freedom. Only two physical degrees of freedom, (ϕ, χ), remain after the $B-L$ and electroweak symmetries are broken. The other four degrees of freedom are eaten by Z', Z and $W^{\pm}$ bosons.

There is a significant mixing between the two Higgs scalars where the mixing angle θ is defined by [5]

$$\tan 2\theta = \frac{|\lambda_3| v v'}{\lambda_1 v^2 - \lambda_2 v'^2}. \tag{2.3}$$

The masses of H and H' are therefore given by the following formula:

$$m^2_{H,H'} = \lambda_1 v^2 + \lambda_2 v'^2 \mp \sqrt{(\lambda_1 v^2 - \lambda_2 v'^2)^2 + \lambda_3^2 v^2 v'^2}. \tag{2.4}$$

H and H' are called light and heavy Higgs bosons, respectively. This mixing between the two Higgs bosons of this model modifies the usual couplings among the SM-like Higgs, H, and the SM fermions and gauge bosons. Moreover, new couplings are produced among the extra Higgs, H', and the SM particles:

$$\begin{aligned} g_{Hff} &= i\frac{m_f}{v}\cos\theta, & g_{H'ff} &= i\frac{m_f}{v}\sin\theta, \\ g_{HVV} &= -2i\frac{m_V^2}{v}\cos\theta, & g_{H'VV} &= -2i\frac{m_V^2}{v}\sin\theta, \\ g_{HZ'Z'} &= 2i\frac{m_C^2}{v'}\sin\theta, & g_{H'Z'Z'} &= -2i\frac{m_C^2}{v'}\cos\theta, \\ g_{H\nu_R\nu_R} &= -i\frac{m_{\nu_R}}{v'}\sin\theta, & g_{H'\nu_R\nu_R} &= i\frac{m_{\nu_R}}{v'}\cos\theta. \end{aligned} \tag{2.5}$$

These new couplings lead to a different Higgs phenomenology from the well known one, predicted by the SM.

3 Heavy Higgs Decay

Generally, the heavy Higgs particle tends to decay into the heaviest gauge bosons and fermions allowed by the phase space. Here, we consider two cases: $H' \to e^+e^-$ (Fig. 1) and $H' \to \gamma\gamma$ (Fig. 2).

The decay width into dielectron is directly proportional to the $H'ee$ coupling

$$\Gamma(H' \to e^+e^-) \approx m_{H'}\left(\frac{m_e}{v}\right)^2\left(1 - \frac{4m_e^2}{m_{H'}^2}\right)^{3/2}\sin^2\theta. \tag{3.1}$$

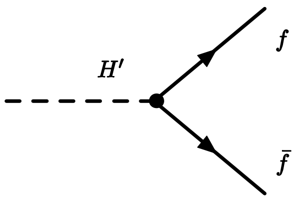
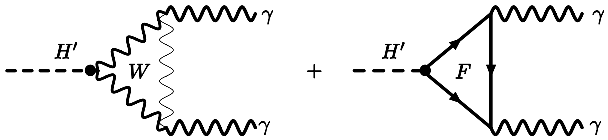


Fig. 1 The Feynman diagram for the Higgs boson decays into fermions

Fig. 2 Loop induced Heavy Higgs boson decays into two photons



On the other hand, the massless gauge bosons are not directly coupled to the extra Higgs boson, but they are coupled via W and charged fermions loops (Fig. 2). This implies that the decay widths are in turn proportional to the $H'WW$ and $H'ee$ couplings, hence they are relatively suppressed. The calculation of the diagrams shown in Fig. 2 reproduce the SM contribution expect for the coupling constants associated with the $H'WW$ and $H'ee$ vertices. The $H'WW$ and $H'ee$ contribution to $H' \to \gamma\gamma$ can be expressed as the SM result [6] with a modification given by

$$\Gamma(H' \to \gamma\gamma) = \frac{\alpha^2 m_H^3}{128\sqrt{2}\pi^3}\left|\sum_f N_c Q_f^2 A_f(\tau_f) + A_W(\tau_W)\right|^2, \tag{3.2}$$

where N_c is the color factor, Q_f is the electric charge of the fermion f, and

$$\tau_f = m_H'^2 v^2/4m_f^2 sin\theta^2, \qquad \tau_W = m_H'^2 v'^2/4m_W^2 cos\theta^2, \tag{3.3}$$

$$A_f(\tau) = 2[\tau + (\tau - 1)f(\tau)]/\tau^2, \tag{3.4}$$

$$A_W(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)]/\tau^2, \tag{3.5}$$

with

$$f(\tau) = \begin{cases} \arcsin^2(\sqrt{\tau}), & \tau \le 1, \\ -\frac{1}{4}[\log \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi]^2, & \tau > 1. \end{cases} \tag{3.6}$$

Now we examine the possibility of having H' decaying into e^+e^- and $\gamma\gamma$ with comparable rates. To enhance the loop-suppressed $\gamma\gamma$ channel, one has to enhance the $H'WW$ and $H'ee$ couplings. From (3.3), one finds that $H' \to \gamma\gamma$ is proportional to the mixing angle θ, the mass of the extra Higgs boson $m_{H'}$, and v' which are constrained experimentally. In Figs. 3 and 4, we present $\cos^2\theta$ as a function of $m_{H'}$ and v'. For all allowed values of θ and v', we have calculated the ratio $Br(H' \to e^+e^-)/Br(H' \to \gamma\gamma)$, and we see no significant difference between the results of the extra Higgs branching ratios in this model of $B - L$ extension and the SM ones. This result can be also generalized for all $U(1)_{B-xL}$ models.

4 Conclusions

We have provided an exception to the recent observation by L. Randall amd M. Wise, which states that a significant branching ratios to both e^+e^- and $\gamma\gamma$ is possible only if new physics beyond that in the SM couples directly to electrons. We have shown that the new resonances predicted in $U(1)_{B-L}$ extensions of the SM can't decay into e^+e^- and $\gamma\gamma$ final states with comparably measurable branching ratios although such resonances are directly coupled to electrons. A possible enchantment of the $\gamma\gamma$ decay width should be associated to the supersymmetric extension of the $B - L$ model.

Fig. 3 $\cos^2\theta$ as function of $m_{H'}$ and v'

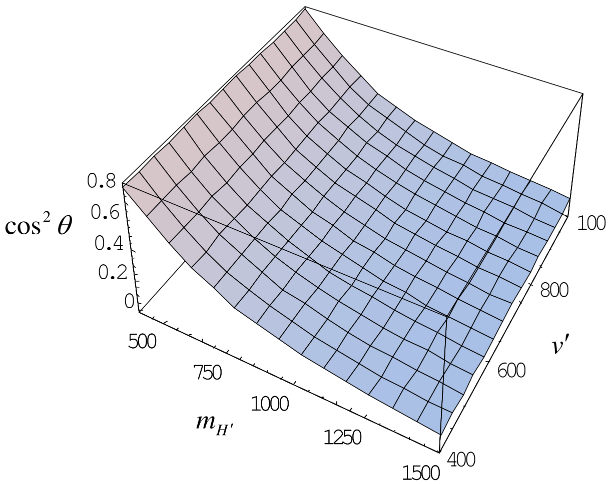
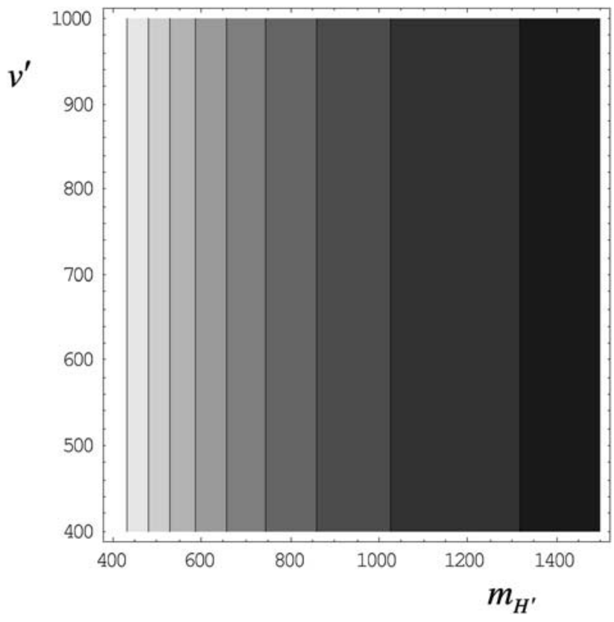


Fig. 4 Contour plot of $\cos^2\theta$ as function of $m_{H'}$ and v'



Acknowledgement W. Emam thanks the Department of Mathematical Sciences of the UAE University, where part of this work has be done, for their hospitality.

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