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Pseudoscalar boson and SM-like Higgs boson production at ILC in the left–right twin Higgs model

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ABSTRACT

Besides the SM-like Higgs boson h, the left–right twin Higgs(LRTH) model predicts the existence of the neutral pseudoscalar boson ϕ^0. In this Letter, we study the pair production of the pseudoscalar boson ϕ^0 and SM-like Higgs bosons h at the International Linear Collider (ILC). We find that the production cross section of the process $e^+e^- \to h\phi^0$ are at the level of 10^{-1} fb with reasonable parameter values, However, the resonance production cross section can be significantly enhanced, which can reach several hundreds fb. In some favorable case (for example, small values of f and m_{ϕ^0}), the SM backgrounds are nowhere an issue by applying suitable cut on the $b\bar{b}$ invariant mass spectrum. The ILC provides an idea environment for discovering the pseudoscalar boson and measuring its properties.

1. Introduction

Despite all its success against precision tests so far, the standard model (SM) is widely considered as the low-energy effective approximation of a fundamental theory. Most extensions of the SM require the introduction of extended Higgs sector to the theory. Many models of new physics beyond the SM predict the existence of neutral or charged scalar particles. These new particles might produce observable signatures in the current or future high energy experiments different from the case of the SM Higgs boson. Any visible signal from the new scalar particles will be evidence of new physics beyond the SM. So far, many works have been contributed to studies of the neutral Higgs boson pair production at the high energy collider in the model independent [1], in the SM [2], and in many new physics models, such as little Higgs models [3], supersymmetric models [4], top condensation models [5] and models of universal extra dimensions [6].

The twin Higgs mechanism has been proposed as a solution to the little hierarchy problem [7–9]. The twin Higgs mechanism can be implemented in left–right models with the discrete symmetry being identified with left–right symmetry [8]. The left–right twin Higgs (LRTH) model contains $U(4)_1 \times U(4)_2$ global symmetry as well as $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge symmetry. The global $U(4)_1(U(4)_2)$ symmetry is spontaneously broken down to its subgroup $U(3)_1(U(3)_2)$ with non-zero vacuum expectation values (VEV) as $\langle H \rangle = (0, 0, 0, f)$ and $\langle \hat{H} \rangle = (0, 0, 0, \hat{f})$. The Higgs VEVs also break $SU(2)_R \times U(1)_{B-L}$ down to the SM $U(1)_Y$. The phenomenology of the LRTH model has been widely studied [10–14].

In many cases, the International Linear Collider (ILC) can significantly improve the LHC measurements [15]. If a Higgs boson is discovered, it will be crucial to determine its couplings with high accuracy, to understand the so-called mechanism of electroweak symmetry breaking. In the SM, the cross section of pair production of the Higgs boson at the ILC which proceeds via the t- and u-channel exchanges of the electron at tree level, is suppressed by powers of $(m_e/m_W)^2$. It has been shown that the one loop contributions to the process $e^+e^- \to hh$ is larger than the tree level one, but is also rather small [16]. However, some of new physics models might enhance the cross section in the ILC [17, 18]. In addition to the SM-like Higgs boson h, the LRTH model predicts one neutral Higgs boson ϕ^0 which is a pseudoscalar. The light neutral Higgs boson ϕ^0 decays dominantly into $b\bar{b}$ and gg, which has been studied in Ref. [19]. At LHC, the huge QCD backgrounds make it essentially impossible to discover the signatures $q\bar{q}(gg) \to h\phi^0 \to b\bar{b}b\bar{b}$ (or $b\bar{b}gg$). The decay $h \to WW$ is dominant for $m_h > 150$ GeV, and the decay $h \to ZZ$ is subdominant for $m_h > 160$ GeV. Here the largest mode $b\bar{b}WW$ from the decays $h \to WW$ and $\phi^0 \to b\bar{b}$ has huge background $q\bar{q} \to t\bar{t} \to b\bar{b}WW$, so the mode is also not optimistic [20]. The leptonic final states from Higgs decay might make this channel useful for ϕ^0 discovery. However, the ILC will open an ideal window to detect the pseudoscalar boson ϕ^0 and study its properties. Thus, in this Letter, we will perform a comprehensive study for the neutral Higgs boson pair $h\phi^0$ production at ILC.

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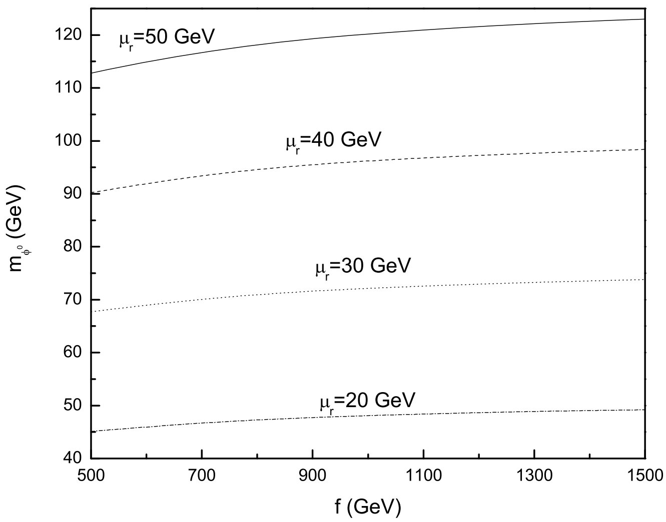

Fig. 1. Typical values for the neutral pseudoscalar mass as a function of the symmetry breaking scales f for different values of the mass parameter μ_r.

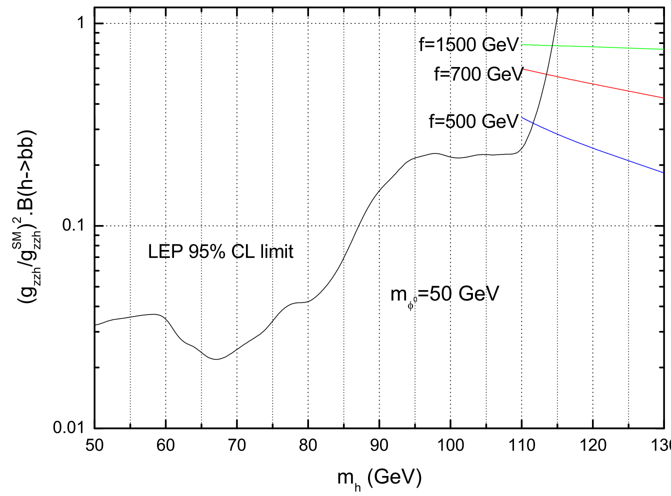

Fig. 2. Upper bounds on $[g_{ZZh}/g_{ZZh}^{SM}]^2 \times Br(h \to b\bar{b})$ established by the LEP Collaborations, and the corresponding values in the LRTH model for $m_{\phi_0} = 50$ GeV.

This Letter is organized as follows. In Section 2, we give a briefly review of the LRTH model, and then give the relevant couplings which are related to our calculation. Sections 3 is devoted to the computation of the production cross sections of the processes $e^+e^- \to h\phi^0$. Some phenomenological analysis are also included in this section. The conclusions are given in Section 4.

2. Left–right twin Higgs model

The details of the LRTH model as well as the particle spectrum, Feynman rules, and some phenomenology analysis have been studied in Ref. [10]. In this section we will briefly review the essential features of the LRTH model and focusing on particle content and the couplings relevant to our computation.

In LRTH model, the global symmetry is $U(4)_1 \times U(4)_2$ with a locally gauged $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ subgroup. Two Higgs fields, H and $\hat{H}$, are introduced and each transforms as $(4,1)$ and $(1,4)$ respectively under the global symmetry. They are written as

$$H = \begin{pmatrix} H_L \\ H_R \end{pmatrix}, \qquad \hat{H} = \begin{pmatrix} \hat{H}_L \\ \hat{H}_R \end{pmatrix}, \tag{1}$$

where $H_{L,R}$ and $\hat{H}_{L,R}$ are two component objects which are charged under $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. After the re-parametrization of the fields, there are one neutral pseudoscalar ϕ^0, a pair of charged scalar $\phi^\pm$, the SM-like Higgs boson h, and a $SU(2)_L$ doublet $\hat{h} = (\hat{h}_1^+, \hat{h}_2^0)$.

In the LRTH model, the masses of the heavy gauge bosons can be written as [10]:

$$m_{W_H}^2 = \frac{1}{2} g_2^2 \left(\hat{f}^2 + f^2 \cos^2 x\right), \tag{2}$$

$$m_{Z_H}^2 = \frac{g_1^2 + g_2^2}{g_2^2} \left(m_{W_H}^2 + m_W^2\right) - m_Z^2, \tag{3}$$

where $x = v/(\sqrt{2} f)$ and v is the electroweak scale, the values of f and $\hat{f}$ are interconnected once we set $v = 246$ GeV. g_1 and g_2 are the gauge coupling constants of the $U(1)_{B-L}$ and $SU(2)_{L,R}$, respectively, which can be written as:

$$g_1 = \frac{e}{\sqrt{\cos 2\theta_W}}, \qquad g_2 = \frac{e}{S_W}. \tag{4}$$

Table 1
The decay branching ratio $Z_H \to h\phi^0$ and the parameters used in this Letter in the LRTH model for $M = 150$ GeV, $m_h = m_{\phi^0} = 120$ GeV.

f (GeV)	500	600	700
m_{Z_H} (GeV)	1294	1662	2030
$\Gamma(Z_H)$ (GeV)	26.9	35.1	44.6
$BR(Z_H \to h\phi^0)$	0.53%	0.37%	0.28%

Where $S_W = \sin\theta_W$ and θ_W is the Weinberg angle. At the leading order, the two-body decay channels of the neutral gauge boson Z_H mainly contain $Z_H \to f\bar{f}$, where f is any of the SM quarks or leptons [10,21].

The neutral Higgs boson ϕ^0 get mass from both the soft left–right symmetry breaking μ term and the one-loop radiative correction, which can be written as [10]

$$m_{\phi^0}^2 = \frac{\mu_r^2}{(\hat{f}^2 + f^2 \cos^2 x)} f \hat{f} \left[\frac{\hat{f}^2 (\cos x + \frac{\sin x}{x}(3 + x^2))}{f^2 (\cos x + \frac{\sin x}{x})^2} + 2\cos x + \frac{f^2 \cos^2 x (1 + \cos x)}{2\hat{f}^2} \right]. \tag{5}$$

The value of μ_r cannot be too large, since otherwise the fine-tuning of the SM-like Higgs boson mass becomes severe. In our analysis, we pick μ_r to be small, as the current experimental bound on the mass of ϕ^0 is fairly weak. As shown in Fig. 1, for $\mu_r < 30$ GeV, the mass of m_{ϕ^0} is smaller than 70 GeV.

It has been shown [22,23] that, the Higgs boson can dominantly decay into a pair of pseudoscalar boson in the case $m_h > 2m_{\phi^0}$. Thus, one may expect that the LEP bound on the Higgs mass can be loosened to some extent. The four LEP Collaborations [24] searched for the Higgs boson via $e^+e^- \to Zh \to (l^+l^-, q\bar{q}, \nu\bar{\nu}) + b\bar{b}$. Here the main decay mode of the SM Higgs boson in $b\bar{b}$ dominates the width of the Higgs boson for most of the mass range. The mass bound on the SM Higgs boson is 114.4 GeV [24]. In the LRTH model, one anticipates that the LEP bound on m_h would be reduced, because of (i) sizable decay rate of $h \to \phi^0\phi^0$ such that $Br(h \to b\bar{b})$ is substantially reduced as shown in Ref. [23], and (ii) the reduced coupling g_{ZZh} in the LRTH model [10]. In Fig. 2, we present the prediction of $[g_{ZZh}/g_{ZZh}^{SM}]^2 \times Br(h \to b\bar{b})$ for $m_{\phi_0} = 50$ GeV and compare to the 95% C.L. upper limit obtained by the LEP Collaborations. We find that the $f = 1500$ GeV case is safe because the minimum value of m_h predicted is already above