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Invisible Higgs boson decay in the littlest Higgs model with T-parity

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Abstract

We study the invisible decay of the Higgs boson into a pair of stable, heavy photons, $H \to A_H A_H$, in the littlest Higgs model with T-parity. For a symmetry breaking scale of $f = 450$ GeV, the branching ratio $H \to A_H A_H$ can be as high as 93% for Higgs masses below 150 GeV. For $f = 500$ GeV, the invisible branching ratio is about 75% in the Higgs mass range $135 - 150$ GeV and 10 (5.5)% for $m_H = 200$ (600) GeV. It drops to a few percent for f larger than 600 GeV. We have found regions in parameter space, allowed by the electroweak precision data, with such low values of f for 115 GeV $< m_H <$ 650 GeV.

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1 Introduction

One of the most crucial issues to be resolved in particle physics today is the mechanism behind electroweak symmetry breaking. In the Standard Model (SM) the symmetry is spontaneously broken by a fundamental Higgs boson which acquires a vacuum expectation value (vev). Since the Higgs mass is not protected by any symmetry, it turns out to be quadratically divergent as $\delta m_H^2 \sim \Lambda^2$, Λ being the cutoff scale for the SM. This leads to the well-known hierarchy or finetuning problem, whether the SM is embedded in some grand unified theory (where $\Lambda \sim 10^{16}$ GeV) or not (where a cutoff at the Planck scale $M_P \sim 10^{19}$ GeV must exist).

Then there is the so-called 'little hierarchy problem' [1]. We can view the SM as an effective field theory (EFT) with a cutoff Λ and parametrize new physics in terms of higher-dimensional operators which are suppressed by inverse powers of the cutoff. Precision tests of the SM at low energies and at LEP/SLC have not shown any significant deviations, which in turn translates into a cutoff of about $\Lambda \sim 5 - 10$ TeV which is slightly more than an order of magnitude above the electroweak scale.

An attractive set of solutions to this little hierarchy problem are the little Higgs models [2, 3]. In these models, the Higgs boson is a pseudo-Goldstone boson of a global symmetry which is spontaneously broken at a scale f. This symmetry protects the Higgs mass from getting quadratic divergences at one loop, even in the presence of gauge and Yukawa interactions. The electroweak symmetry is broken via the Coleman-Weinberg mechanism [4] and the Higgs mass is generated radiatively, which leads naturally to a light Higgs boson $m_H \sim (g^2/4\pi)f \approx$ 100 GeV, if the scale $f \sim 1$ TeV. In contrast to supersymmetric theories, here the new states at the TeV-scale which cancel the quadratic divergences arising from the top quark, gauge boson and Higgs boson loops, respectively, have the same spin as the corresponding SM particles. The little Higgs model can then be interpreted as an EFT up to a new cutoff scale of $\Lambda \sim 4\pi f \sim 10$ TeV.

Among the different versions of this approach, the littlest Higgs model [5] achieves the cancellation of quadratic divergences with a minimal number of new degrees of freedom. The global symmetry breaking pattern is $SU(5) \to SO(5)$ and an $SU(2)_i \times U(1)_i, i = 1, 2$, gauge symmetry is imposed, that is broken down at the scale f to the diagonal subgroup $SU(2)_L \times U(1)_Y$, which is identified with the SM gauge group. This leads to four heavy gauge bosons with masses $\sim f$ in addition to the SM gauge fields. The SM Higgs doublet is part of an assortment of pseudo-Goldstone bosons which result from the spontaneous breaking of the global symmetry. The multiplet of Goldstone bosons contains a heavy $SU(2)$ triplet scalar as well. Furthermore, a vectorlike heavy quark that can mix with the top is postulated. It turns out, however, that electroweak precision data put very strong constraints on the littlest Higgs model. Typically one obtains the bound $f \gtrsim 3 - 5$ TeV in most of the natural parameter space, unless specific choices are made for fermion representations or hypercharges [6]. Since f effectively acts as a cutoff for loops with SM particles, this reintroduces a little hierarchy between the Higgs boson mass and the scale f.

The constraints from electroweak precision data can be bypassed by imposing a discrete symmetry in the model, called T-parity [7]. In the littlest Higgs model with T-parity (LHT) [8], this discrete symmetry exchanges the two pairs of gauge groups $SU(2)_i \times U(1)_i, i = 1, 2$, forcing the corresponding gauge couplings to be equal $g_1 = g_2$ and $g'_1 = g'_2$. All SM particles, including the Higgs doublet, are even under T-parity, whereas the four additional heavy gauge bosons and the Higgs triplet are T-odd. The top quark has now two heavy fermionic partners, T_+ (T-even) and T_- (T-odd). For consistency of the model, one has to introduce an additional heavy, T-odd vector-like fermion for each left-handed SM quark and lepton field, see the original paper [8] and Refs. [9, 10] for details.

Two important phenomenological consequences of introducing T-parity are as follows. First, if T-parity is exact, the lightest T-odd particle, typically the heavy, neutral partner of the photon, A_H, is stable and can be a good dark matter candidate [9, 11, 12]. Secondly, in the LHT there are no tree-level corrections to electroweak precision observables and there is no dangerous Higgs triplet vev that violates the custodial symmetry of the SM grossly. This relaxes the constraints on the model from electroweak precision data and allows a relatively small value of f in certain regions of the parameter space. Thus T-parity opens up the possibility of seeing lighter new gauge bosons, scalars and fermions (whose masses are related to the parameter f) than has in general been thought possible in little Higgs scenarios.

In Ref. [10] it was shown that the LHT is compatible with electroweak precision data, even for scales as low as $f \sim 500$ GeV. Although such a low value of f may lead to additional constraints on the model (such as a strong degeneracy of the heavy, T-odd fermions, in order to avoid large flavor violations [13]) it is nevertheless an allowed scenario. Moreover, there are regions in parameter space where a Higgs boson with a mass of 800 GeV is allowed, due to a cancellation in the oblique T-parameter [14] between loops with a heavy Higgs boson and the heavy T-even partner T_+ of the top quark.

This raises the interesting possibility that a heavy or even intermediate mass Higgs boson could decay 'invisibly' into a pair of stable, heavy photons A_H. Such a possibility is facilitated by the fact that the state A_H can be quite light, with $M_{A_H} \approx g'f/\sqrt{5} \approx 0.15f$. Such T-odd particles can only be produced in pairs and lead to a signal of large missing transverse energy [7, 9], in a way similar to the minimal supersymmetric standard model (MSSM). The decay $H \to A_H A_H$ has already been mentioned briefly in Refs. [11, 15]. Ref. [11] obtained an invisible branching ratio of about 5% for $M_H \sim 170$ GeV, if the condition is imposed that the heavy photon A_H should constitute all of the dark matter in the universe. Ref. [15] studied the production and decay of the Higgs boson in the LHT at the LHC. However, the authors of Ref. [15] only considered scales $f \gtrsim 700$ GeV where the branching ratio is smaller than 1% and therefore they did not take this decay channel into account. Neither of these references did, however, consider constraints from electroweak precision data for Higgs masses larger than 115 GeV.

The aim of this paper is to show that there are certain regions in the parameter space of the LHT, compatible with electroweak constraints, where the invisible decay $H \to A_H A_H$ can have a substantial branching ratio. This ratio can be up to 95% for an intermediate mass Higgs, and from 20% down to a few percents for a Higgs boson of mass 200 GeV or above. Such a high invisible decay width is unlikely for the lightest neutral supersymmetric Higgs, in the allowed range of its mass, at least in the minimal version of the theory. Therefore this invisible Higgs boson decay might help to distinguish the LHT from the MSSM at present and future colliders. Of course, this spectacular difference is noticeable only in the limited region of the parameter space of the LHT, where $f \lesssim 600$ GeV.

The paper is organized as follows. In Section 2 we revisit the electroweak precision tests applied to the LHT. We then calculate in Section 3 the decay width $H \to A_H A_H$ and the corresponding branching ratio for a range of values of f allowed by the precision data. We briefly discuss the consequences of our findings for Higgs boson phenomenology at the Tevatron, the LHC and a future International Linear Collider (ILC). We summarize and conclude in Section 4.

2 Electroweak precision tests revisited

An analysis of the LHT in the light of the electroweak precision data has been performed in Ref. [10], based on the version of the model proposed in Ref. [9]. In the following, we will closely follow the notations and conventions of Ref. [10] and refer to Refs. [9, 10] and the original paper [8] for an introduction into the LHT. Ref. [10] identified the regions in the parameter space with a low symmetry breaking scale $f \sim 500$ GeV. However, such values of f are obtained only for a very light Higgs boson, $m_H = 113$ GeV. Since the T-odd heavy photon A_H has a mass of about 65 GeV for $f = 500$ GeV, the decay $H \to A_H A_H$ is kinematically not possible. On the other hand, in Ref. [10] some other regions in parameter space have been found where the Higgs boson is very heavy ($m_H \sim 800$ GeV). Such a Higgs boson could easily decay into a pair of heavy photons. In those regions, however, one also has $f \sim 1$ TeV. As we shall see in the next section, the decay width $\Gamma(H \to A_H A_H)$ scales approximately like $1/f^4$, so that the branching ratio is very small for $f > 700$ GeV.

In our bid to identify the allowed regions giving high invisible branching ratios, we have redone the electroweak fits, where we have found a small error in the program used in Ref. [10][1]. After correcting for this error, we obtain slightly different allowed regions in the parameter space. Although this does not affect

[1]We thank the authors of Ref. [10] for providing us with the code of their fitting program, which allowed us to track down the discrepancy.

the conclusions drawn in [10] in a qualitative manner, the allowed range of the Higgs mass goes up by about 100 GeV.

Our χ^2-fit is based on a parametrization [16] of new physics contributions to precision observables in terms of the oblique parameters S, T, U [14] and a correction to the left-handed $Zb\bar{b}$-vertex. The expressions for these quantities in the LHT have been calculated at one-loop in Ref. [10]. They depend on four parameters: the symmetry breaking scale f, the mass of the Higgs boson m_H, the ratio $R = \lambda_1/\lambda_2$ of the two couplings $\lambda_{1,2}$ that appear in the top-quark Lagrangian and a dimensionless number δ_c. For $f \gg v_{\rm SM}$, the mass of the top quark is given by $m_t = \lambda_1 v_{\rm SM}/\sqrt{R^2+1}$ and the mass of the heavy T-even partner T_+ of the top is $m_{T_+} = \lambda_2\sqrt{R^2+1}f$. Thus the parameter R is usually varied in the range $0 < R < 2$. The quantity $v_{\rm SM}$ is related to $v_{\rm LHT}$, the vev of the Higgs doublet in the LHT, generated radiatively by the Coleman-Weinberg mechanism, as follows: $v_{\rm SM} \equiv f\sqrt{1-\cos(\sqrt{2}v_{\rm LHT}/f)}$ [15]. Introducing $v_{\rm SM}$ allows one to express the light gauge boson masses and the Fermi constant as in the SM at tree level: $M_Z = \sqrt{g^2+g'^2}v_{\rm SM}/2$, $M_W = g v_{\rm SM}/2$ and $G_F = 1/(\sqrt{2}v_{\rm SM}^2)$, with $v_{\rm SM} \simeq 246$ GeV.

The parameter δ_c appears as the coefficient of a counterterm operator that absorbs divergences in the T-parameter at one-loop in the LHT. These divergences originate from the custodial $SU(2)$-violating tree-level mass splitting of the T-odd heavy W_H^3 and $W_H^\pm$ gauge bosons. The absolute value $|\delta_c|$ is assumed to be of order one and is varied here in the range $-5 < \delta_c < 5$, in accordance with Ref. [10].

In our fits we have considered the same 21 Z-peak and low-energy observables as in Ref. [10] (see also Ref. [16]). However, we have used the new data from the PDG 2006 [17]. Also, in accordance with the SM electroweak fits in Ref. [17], we have used the top quark mass $m_t = 172.7$ GeV. The reference value of the Higgs boson mass in the oblique parameters S, T, U has been taken as the best SM fit value $m_{H,ref} = 89$ GeV.

Figure 1 shows the constraints in the $f - m_H$ plane for $\delta_c = -3.5$ and four different choices of the parameter R. One observes that there are allowed regions in parameter space where the symmetry breaking scale f is roughly between $400 - 700$ GeV (or larger) and m_H is in the range $100 - 650$ GeV. Actually, in order to get allowed regions with values of $m_H > 500$ GeV, it seems that the scale f has to be bigger than about 600 GeV. The choice of the parameters, namely, $R \sim 1 - 1.3$, $\delta_c \sim -3.5$, is motivated by figures 5 and 6 in Ref. [10] where for $m_H = 113$ GeV small allowed values $f \lesssim 500$ GeV had been found. The modified contour plots obtained with our own program still have this feature. Varying δ_c between -4 and -3 leads to qualitatively similar conclusions. If $R \sim 1.1 - 1.3$, there are even allowed regions with low $f \sim 550$ GeV for positive values of $\delta_c \lesssim 3$, but only if the Higgs boson is not too heavy, i.e. $m_H \lesssim 250$ GeV.

If $R \lesssim 0.5$ there are allowed regions with a rather small Higgs mass, such as

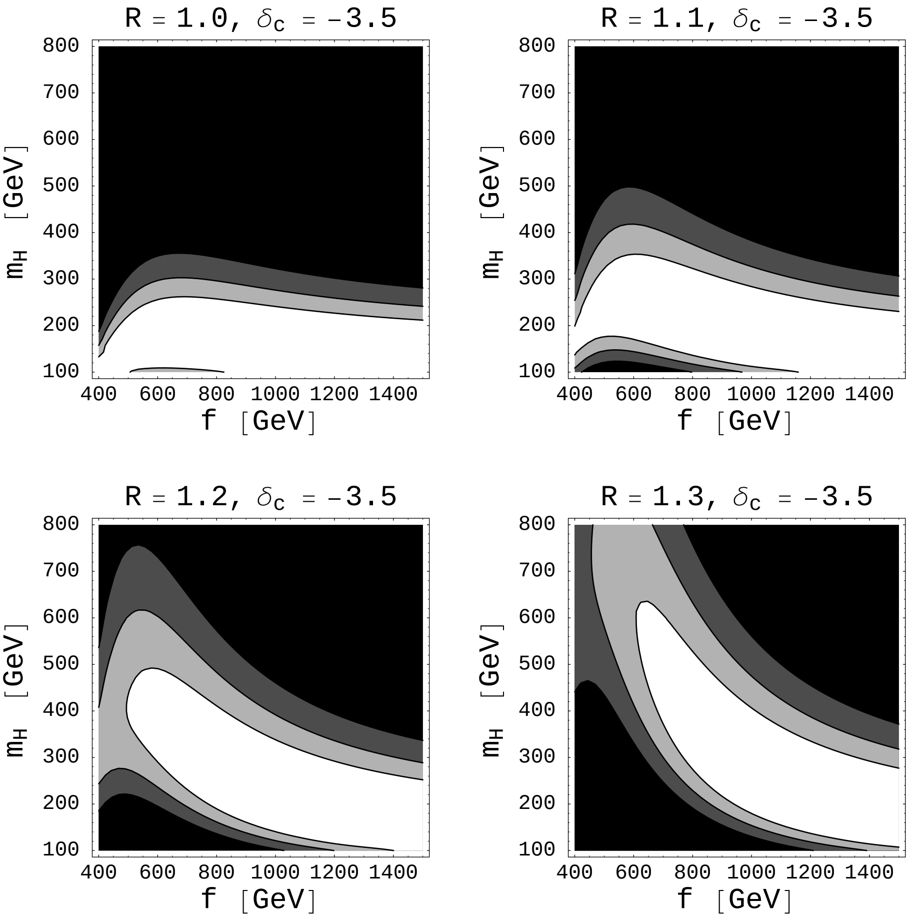


Figure 1: Exclusion contours in the plane of the Higgs mass m_H and the symmetry breaking scale f for $\delta_c = -3.5$ and four different values of R. From lightest to darkest, the contours correspond to the 95%, 99%, and 99.9% confidence level exclusion.

$m_H \sim 100 - 150$ GeV. This happens, however, only for $f > 700$ GeV, when the branching ratio $H \to A_H A_H$ will be smaller than one percent. On the other hand, for $R \gtrsim 2$, our electroweak fits show regions where very large Higgs masses such as $m_H > 1$ TeV are allowed. However, in those regions also $f > 1$ TeV, leading again to a very small branching ratio.

3 The invisible decay $H \to A_H A_H$: results and implications

The mass (squared) of the heavy T-odd photon A_H is given by

$$M_{A_H}^2 = \frac{g'^2 f^2}{5} - \frac{g'^2 v_{\rm SM}^2}{4}, \tag{1}$$

neglecting higher powers of $v_{\rm SM}^2/f^2$. It can be checked that keeping higher order terms in $M_{A_H}^2$ does not change our predictions qualitatively. Since the heavy photon, as the lightest T-odd state, is stable, there are no off-shell decays $H \to A_H^* A_H^*$ and the channel opens up only for $m_H \geq 2M_{A_H}$. The interaction $HA_{H\mu}A_H^\mu$ in the LHT is described by the Feynman rule $(-i/2)g'^2 v_{\rm LHT} g_{\mu\nu}$ [18, 9]. The decay width is then given by

$$\Gamma(H \to A_H A_H) = \frac{g'^4 v_{\rm LHT}^2}{2048\pi M_{A_H}^4} m_H^3 \beta_A \left(4 - 4a_A + 3a_A^2\right), \tag{2}$$

where $a_A = 1 - \beta_A^2 = 4M_{A_H}^2/m_H^2$. From Eq. (2) we see that the partial width scales like $1/M_{A_H}^4 \sim 1/f^4$. The quantity $v_{\rm LHT}$ is obtained from $v_{\rm SM}$ by inverting the relation given earlier.

As pointed out in Ref. [15], the couplings of the Higgs boson to the SM particles are subject to corrections in the LHT. Using the expressions for the couplings given in Ref. [15] one obtains for the partial decay widths of the Higgs boson into SM gauge bosons ($V = W, Z$) and into SM-fermions

$$\begin{aligned}
\Gamma(H \to VV)_{\rm LHT} &= \Gamma(H \to VV)_{\rm SM} \left(1 - \frac{1}{4}\frac{v_{\rm SM}^2}{f^2} - \frac{1}{32}\frac{v_{\rm SM}^4}{f^4}\right)^2, &(3)\\
\Gamma(H \to u\bar{u}, c\bar{c})_{\rm LHT} &= \Gamma(H \to u\bar{u}, c\bar{c})_{\rm SM} \left(1 - \frac{3}{4}\frac{v_{\rm SM}^2}{f^2} - \frac{5}{32}\frac{v_{\rm SM}^4}{f^4}\right)^2, &(4)\\
\Gamma(H \to d\bar{d})_{\rm LHT} &= \Gamma(H \to d\bar{d})_{\rm SM} \left(1 - \frac{1}{4}\frac{v_{\rm SM}^2}{f^2} + \frac{7}{32}\frac{v_{\rm SM}^4}{f^4}\right)^2, &(5)\\
\Gamma(H \to t\bar{t})_{\rm LHT} &= \Gamma(H \to t\bar{t})_{\rm SM} \left(1 - \frac{3 + 2R^2 + 3R^4}{4(1+R^2)^2}\frac{v_{\rm SM}^2}{f^2}\right)^2, &(6)
\end{aligned}$$

up to higher corrections in $v_{\rm SM}^2/f^2$. The expression for the decay into down-type quarks in Eq. (5) also applies to charged leptons. This interaction is model-dependent, since there are different ways [15] of introducing couplings of down-type quarks with the Higgs boson that are consistent with the cancellation of quadratic divergences and T-parity. Depending on the choice of the interaction terms, the expression for the coupling in Eq. (5) can numerically differ a little or considerably from the SM value. Since we are interested here in the effects of the invisible decay $H \to A_H A_H$, we have taken in Eq. (5) the couplings of "case A" from Ref. [15], where the decay width in the LHT is not much suppressed compared to the SM. For the evaluation of the decay mode $H \to t\bar{t}$ we will take $R = 1$ in Eq. (6).

The loop-induced decay $H \to gg$ gets further modified, since the additional T-even and T-odd fermions in the LHT can also run in the loop. It was shown in Ref. [15] that for fermion masses much heavier than the Higgs boson, the full

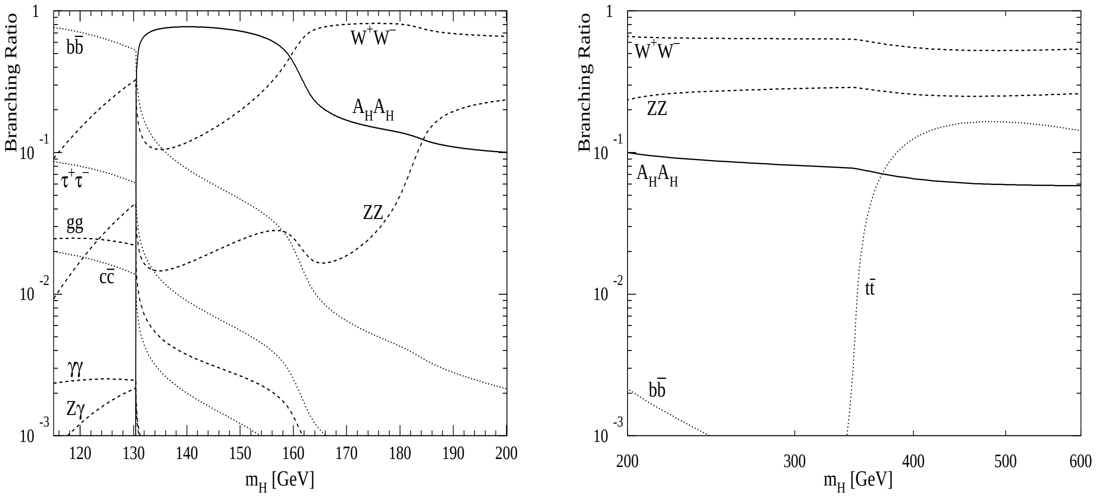


Figure 2: Branching ratios in the littlest Higgs model with T-parity for Higgs masses below 200 GeV (left panel) and above 200 GeV (right panel) for a symmetry breaking scale $f = 500$ GeV.

one-loop result can be well described by the approximate formula

$$\Gamma(H \to gg)_{\text{LHT}} = \Gamma(H \to gg)_{\text{SM}} \left(1 - 3\frac{v_{\text{SM}}^2}{f^2}\right). \tag{7}$$

In the decays $H \to \gamma\gamma$ and $H \to Z\gamma$, the W-boson loop dominates over the contribution from the top quark [19]. For the decay into two photons this is still true if the contributions from the heavy fermions in the LHT are taken into account [15]. We therefore simply rescale both decay widths with the same factor as in Eq. (3).

We have used the program HDECAY [20] to calculate the partial widths of the Higgs boson in the SM in the various channels. The program includes all relevant higher order QCD and electroweak corrections. The corresponding decay widths in the LHT have then been obtained in a simplified (and approximate) way by multiplying the SM results with the correction factors from Eqs. (3)–(7). Adding the new invisible decay mode $H \to A_H A_H$ from Eq. (2) leads to the total width of the Higgs boson in the LHT, which, as we shall see later, can change the total width by as much as an order of magnitude. We do not expect the conclusions we draw in the following to change qualitatively, if one were to include all radiative corrections within the LHT, e.g. not simply taking the tree-level expression (2) for the mode $H \to A_H A_H$ and rescaling the partial widths in the SM, Eqs. (3)–(7).

In Fig. 2 we have plotted for $f = 500$ GeV all branching ratios of the Higgs boson in the LHT that are larger than 10^{-3} in the mass range 115 GeV $< m_H <$ 600 GeV. One observes, that as soon as the decay $H \to A_H A_H$ is kinematically allowed, $m_H \geq 2M_{A_H} = 130$ GeV, we get a huge invisible BR($H \to A_H A_H$) of about 75% in the Higgs mass range $135 - 150$ GeV. The reason is that the Higgs boson couples to the heavy photons A_H with electroweak strength g' which is much larger than the Yukawa coupling to the bottom quarks. The decay width is also larger than the off-shell (three or four-body) decay $H \to W^{(*)}W^*$, unless that decay starts to grow around $m_H = 2M_W$. At $m_H = 159$ GeV we have BR($H \to A_H A_H$) $\approx$ BR($H \to WW$) = 47%. At $m_H = 200$ (600) GeV the invisible decay BR is still about 10 (5.5)%. We would like to stress that there are regions in parameter space where values of 115 GeV $< m_H <$ 600 GeV and $f = 500$ GeV are allowed by the electroweak data, see Fig. 1.

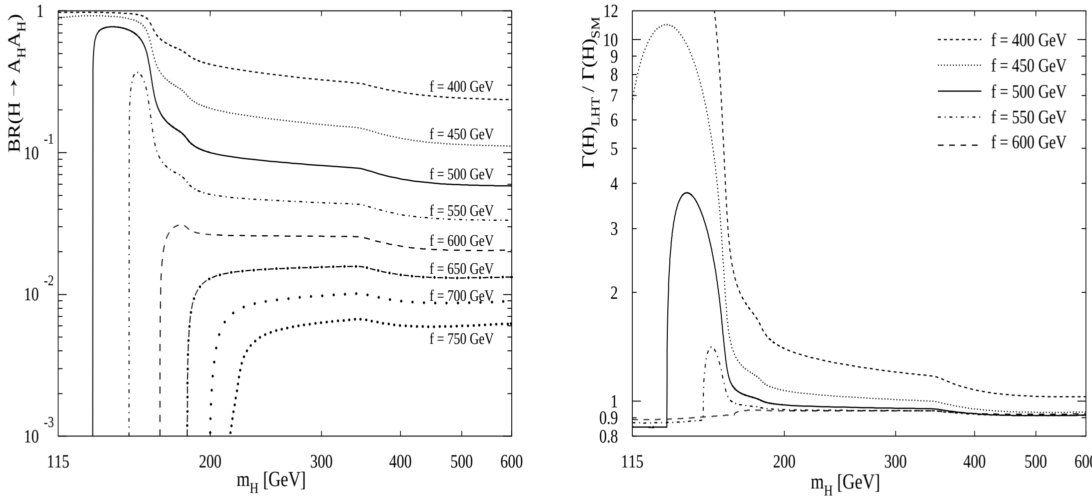
Below the threshold of 130 GeV, the same decay channels are open as in the SM, however, $H \to gg$ is highly suppressed in the LHT, see Ref. [15]. On the other hand, the branching ratio for $H \to \gamma\gamma$ for $m_H = 115$ GeV is about 2.3×10^{-3}, i.e. very close to the one in the SM. Since we have taken the fermion couplings in Eq. (5) from the "case A" proposed in Ref. [15], which differ not much from their SM values, there is no large enhancement of the $H \to \gamma\gamma$ mode as observed in that reference for the "case B". As soon as the decay $H \to A_H A_H$ is possible, all other branching ratios drop down considerably.

Note that we have not taken into account the off shell-decays $H \to W_H^* W_H^*$ and $H \to Z_H^* Z_H^*$ for Higgs masses larger than $M_{W_H} = M_{Z_H} = 317$ GeV for $f = 500$ GeV. We expect the corresponding branching ratios to be small below the two-particle threshold.

In Fig. 3(a) we show the invisible branching ratio $H \to A_H A_H$ as a function of the Higgs mass for different values of f in the range $400 - 750$ GeV. For $f = 400$ (450) GeV the branching ratio can be as large as 98 (93)% for Higgs masses below about 150 GeV. Although values of $f = 400$ GeV are allowed by the precision data (see Fig. 1), the calculation cannot be completely trusted there. For such low values of f, higher derivative terms in the low-energy expansion in the LHT model, generated at the scale $\Lambda \sim 4\pi f$, should be taken into account. It may be noted that values of $f \lesssim 400$ GeV have been discarded in Ref. [10] for this reason. In this sense $f \simeq 400$ GeV marks the lower end of the parameter space where the underlying framework is reliable.

For $f = 600$ GeV, the invisible branching ratio is $2 - 3\%$ for $m_H \gtrsim 169$ GeV, whereas it drops below 1% for $f \geq 700$ GeV. Since the $A_H A_H$-threshold for $f = 600$ GeV is about 167 GeV, i.e. above the WW-threshold, the on-shell decays into WW and later into ZZ overwhelm the invisible decay $H \to A_H A_H$. Note that for $f = 650$ GeV we have $M_{A_H} \approx M_Z$ and therefore $\Gamma(H \to A_H A_H) \approx \left(g'^2 c_W^2/g^2\right)^2 \Gamma(H \to ZZ)_{\text{SM}} \approx 0.05\, \Gamma(H \to ZZ)_{\text{SM}}$, i.e. the BR is 1.3% at $m_H =$ 200 GeV.

Figure 3(b) shows the ratio of the total decay width of the Higgs boson in the LHT, $\Gamma(H)_{\text{LHT}}$, to the total width in the SM, $\Gamma(H)_{\text{SM}}$, as a function of the Higgs mass for a subset of values of f used in Fig. 3(a). In contrast to earlier



(a) (b)

Figure 3: (a) Branching ratio for the invisible decay $H \to A_H A_H$ in the littlest Higgs model with T-parity for several values of the symmetry breaking scale f. (b) Ratio of the total decay width of the Higgs boson in the LHT, $\Gamma(H)_{\mathrm{LHT}}$, to the total decay width in the SM, $\Gamma(H)_{\mathrm{SM}}$, for different values of f. The curve for $f = 400$ GeV peaks at a value of about 35 for $m_H \approx 126$ GeV.

studies [21, 15] which always observed a reduction of the total decay width of the Higgs boson in the littlest Higgs model and in the LHT compared to the SM, we get a potentially huge enhancement of the decay width for values $f \leq 550$ GeV. For $f = (400, 450, 500, 550)$ GeV, the maximal enhancement factors of $(34.8, 11.0, 3.77, 1.41)$ that can be seen in Fig. 3(b) correspond to $\Gamma(H)_{\mathrm{LHT}} = (140, 51, 30, 33)$ MeV at $m_H = (125.8, 130.2, 140.5, 153.4)$ GeV. Note, however, that the width of the Higgs boson in the SM is very small for Higgs masses below the WW-threshold. Only for $f \geq 600$ GeV we obtain a reduction of the total width for the whole range of Higgs masses 115 GeV $< m_H <$ 600 GeV. The ratio $\Gamma(H)_{\mathrm{LHT}}/\Gamma(H)_{\mathrm{SM}}$ varies between 0.89 and 0.95 for values of $f = 600 - 750$ GeV.

A substantial branching ratio into the invisible channel not only makes the Higgs boson a rather interesting object but also helps in associating it with some specific types of non-standard physics. For example, in supersymmetric theories, the lightest neutral scalar can in principle decay into two lightest neutralinos, making it invisible. However, the branching ratio of such a decay is usually not very high, and is rather restricted in the regions of the parameter space allowed by LEP data, at least in those versions of the theory not too far from the minimal model. In our case, however, the invisible branching ratio can not only be appreciable but also may correspond to a Higgs boson that is heavier than what is allowed in a minimal supersymmetric framework. Thus this region of the parameter space may provide a test to distinguish the LHT from a supersymmetric scenario.

In the context of LEP, invisible Higgs boson decays have been studied earlier, and it has been concluded that a Higgs boson is identifiable in the channel $e^+e^- \to ZH$, with the H decaying invisibly, and the Z decaying into $q\bar{q}$ (acoplanar jets) or a lepton pair. The current limit [22] of $m_H > 114.4$ GeV at 95% confidence level for an invisible Higgs boson assumes SM production rates and a 100% invisible branching ratio. The small modification of the HZZ coupling in the LHT will not change this limit significantly. A hadron collider, on the other hand, will find it a more challenging task to unravel a Higgs boson that has a dominantly invisible decay mode. Channels such as associated production with gauge bosons, $pp \to WH, ZH$ [23] or top quarks $pp \to t\bar{t}H$ [24] have been suggested in this context. Another possibility is to consider Higgs production by weak boson fusion (WBF) [25] and look for final states with two energetic forward jets with a large rapidity gap and a large amount of missing energy in the gap. The efficacy of this search strategy has been discussed in the context of not only an invisible Higgs boson but also other types of new physics signals leading to invisible final states [26]. Combining WBF and associated production with Z might even allow the discovery at the Tevatron or in the early phase of LHC [27]. The biggest potential, however, lies in a linear collider [28], where an invisible Higgs boson is identifiable in the form of a peak recoiling against a Z-peak marked by a fermion-antifermion pair. The branching ratio of the Higgs boson decaying into the invisible channel can also be measured in this way, thus making it possible to probe the spectrum and new interactions of an LHT scenario (or any other theory that has similar effects).

4 Summary and conclusions

In this paper we have studied within the littlest Higgs model with T-parity, the decay of the Higgs boson into a pair of the heavy, T-odd partners of the photon, $H \to A_H A_H$. The neutral and stable heavy photons A_H will not leave any traces in the detector, thereby leading to an invisible decay mode of the Higgs boson with a missing energy signature. For Higgs masses between 115 and 650 GeV we have found regions in the parameter space, compatible with the latest electroweak precision data at 95% confidence level, where the symmetry breaking scale in the LHT can be quite low $f \sim 400 - 700$ GeV. Such values of f then lead to a substantial invisible branching ratio. For $f = 450$ GeV, the BR($H \to A_H A_H$) can be as high as 93% for Higgs masses below 150 GeV. The invisible decay takes over as soon as it is kinematically allowed. This is due to the fact that the interaction of the Higgs boson with the heavy photons A_H is governed by the gauge coupling g' which is much larger than the b-quark Yukawa coupling. Furthermore, the decay width $H \to A_H A_H$ scales like $1/M_{A_H}^4 \sim 1/f^4$. Because of phase space, it also dominates over the off-shell mode $H \to W^{(*)}W^*$, almost up to the $2M_W$ threshold. For $f = 500$ GeV, the BR($H \to A_H A_H$) is about 75% in the Higgs mass range $135 - 150$ GeV and 10 (5.5)% for $m_H = 200$ (600) GeV. For $f = 600$ GeV, the invisible branching ratio is $2 - 3\%$ above $m_H = 169$ GeV and it drops below one percent for $f \geq 700$ GeV. For $f = 450, 500$ and 550 GeV, respectively, the total decay width of the Higgs boson in the LHT can be enhanced by a factor of $11, 3.8$ and 1.4 (at $m_H = 130, 141$ and 153 GeV) compared with the SM.

Our analysis did not take into account the requirement that the heavy photon A_H has to constitute all of the dark matter in the universe. If such a condition is imposed then one may have to restrict oneself to values of $f \gtrsim 580$ GeV, which corresponds with Eq. (1) to $M_{A_H} \gtrsim 80$ GeV, see Refs. [9, 11, 12]. The invisible branching ratio $H \to A_H A_H$ including the bounds from dark matter has been evaluated in Ref. [11], however, without considering the constraints from electroweak precision data.

Such an invisible decay mode of the Higgs boson has been studied earlier in the context of several models of new physics beyond the Standard Model (e.g. MSSM, extra dimensions, ...). Although general procedures have been developed to detect such a signal at e^+e^- machines (LEP, ILC) and hadron colliders (Tevatron, LHC), this specific decay $H \to A_H A_H$ in the littlest Higgs model with T-parity certainly deserves detailed further studies which might help to determine the parameters of the LHT and to distinguish it from other models.

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