Higgs Production and Decay in the Little Higgs Model

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Abstract

We analyse the consequences of the little Higgs model for double Higgs boson production at the LHC and for the partial decay width $\Gamma(H \rightarrow \gamma\gamma)$. In particular, we study the sensitivity of these processes in terms of the parameters of the model. We find that the little Higgs model contributions are proportional to $\left(\frac{v}{f}\right)^4$ and hence do not change significantly either single or double Higgs production at hadron colliders or $\Gamma(H \rightarrow \gamma\gamma)$ as compared to the standard model predictions. However, when interference and mixing effects are properly taken into account these contributions increase to be of the order of $\left(\frac{v}{f}\right)^2$.

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1 Introduction

The presence of quadratic divergences in the loop processes for the scalar Higgs boson self-energy in the standard model is responsible for the so-called hierarchy or fine-tuning problem. There is no natural way of protecting a light Higgs boson from getting GUT scale contributions. This problem is solved in supersymmetric extensions of the standard model, where the quadratic divergences are cancelled by supersymmetric partners of the existing particles \[1\]. The hierarchy problem is also absent in models in which the electroweak symmetry is dynamically broken, since the scalar particles are not fundamental in these models \[2\].

Recently a new model was proposed which can solve in a natural way the hierarchy problem of scalar Higgs boson in the standard model. In this class of models, called little Higgs models \[3\], the Higgs boson is a pseudo-Goldstone boson and its mass is protected by a global symmetry. The cancellations arise due to contributions of new particles with the same spin.

The phenomenology of these models has been discussed with respect to indirect effects on precision measurements and direct production of the new particles \[4\]. In this letter we study yet another phenomenological consequence, the contribution of new states to Higgs boson production and decay.

The little Higgs Lagrangian is given by the lowest order term of a non-linear sigma model based on a coset \(SU(5)/SO(5)\) symmetry:

\[
\mathcal{L}_\Sigma = \frac{1}{2} \frac{f^2}{4} \text{Tr} |\mathcal{D}_\mu \Sigma|^2, \tag{1}
\]

where the subgroup \([SU(2) \times U(1)]^2\) of \(SU(5)\) is promoted to a local gauge symmetry. The covariant derivative is defined as

\[
\mathcal{D}_\mu \Sigma = \partial_\mu \Sigma - i \sum_{j=1}^2 \left( g_j (W_j \Sigma + \Sigma W_j^T) + g'_j (B_j \Sigma + \Sigma B_j^T) \right). \tag{2}
\]

To linearize the theory, one can expand \(\Sigma\) in powers of \(1/f\) around its vacuum expectation
value $\Sigma_0$

$$
\Sigma = \Sigma_0 + \frac{2i}{f} \begin{pmatrix}
\phi^+ & \frac{h^*}{\sqrt{2}} & 0 \\
\frac{h}{\sqrt{2}} & 0 & \frac{h}{\sqrt{2}} \\
0 & \frac{h}{\sqrt{2}} & \phi
\end{pmatrix}_2 + O\left(\frac{1}{f^2}\right),
$$

(3)

where $h$ is a doublet and $\phi$ is a triplet under the unbroken $SU(2)$. The non-zero vacuum expectation value of the field $\langle \Sigma \rangle = \Sigma_0$ leads to the breaking of the global $SU(5)$ symmetry to $SO(5)$ and also breaks the local gauge symmetry $[SU(2) \times U(1)]^2$ into its diagonal subgroup, which is identified with the standard model $SU_L(2) \times U_Y(1)$ symmetry group.

Following the notation of Han et al. [4], we will denote the usual standard model gauge bosons mass eigenstates as $W_L^\pm$, $Z_L$ and $A_L$, where the subscript $L$ denotes light in order to distinguish from the heavy states with mass of order $f$, denoted by $W_H^\pm$, $Z_H$ and $A_H$.

The standard model fermions acquire their masses via the usual Yukawa interactions. However, in order to cancel the top quark quadratic contribution to the Higgs self-energy, a new-vector like color triplet fermion pair, $\tilde{t}$ and $\tilde{t}^c$, with quantum numbers $(3,1)_{Y_i}$ and $(\bar{3},1)_{-Y_i}$ must be introduced. Since they are vector-like, they are allowed to have a bare mass term which is chosen such as to cancel the quadratic divergence above scale $f$.

The coupling of the standard model top quark to the pseudo-Goldstone bosons and the heavy colored fermions in the littlest Higgs model is chosen to be

$$
\mathcal{L}_Y = \frac{1}{2} \lambda_1 f \epsilon_{ijk} \epsilon_{xy} \chi_i \Sigma_{jk} \Sigma_{ky} u_3^c + \lambda_2 f \tilde{t}\tilde{t}^c + h.c.,
$$

(4)

where $\chi_i = (b_3,t_3,\tilde{t})$ and $\epsilon_{ijk}$ and $\epsilon_{xy}$ are antisymmetric tensors. The new model-parameters $\lambda_1$, $\lambda_2$ are supposed to be of the order of unity.

In terms of the mass eigenstates $\tilde{t}^c$ and $u_3^c$, the term in the Lagrangian (4) which describes the coupling of the new fermion to the standard model (gauge eigenstate $^1$)

$^1$The standard model mass eigenstate Higgs will be denoted by $H$. The corrections due to the difference between gauge and mass eigenstates are small (of the order $v^2/f^2$) and will be neglected in this work. Likewise, we will neglect the mixing between $\tilde{t}$ and the top quark.
Higgs ($h^0$) is given by:

$$\mathcal{L}_{h-t} = \frac{\lambda_2^2}{\sqrt{\lambda_1^2 + \lambda_2^2} f} \left[ -\tilde{t} (h^+ h^- + h^0 h^{0*} + 2 \phi^{++} \phi^{--} + 2 \phi^+ \phi^- + 2 \phi^0 \phi^{0*} \tilde{t}) \right].$$  \hspace{1cm} (5)

Notice that only a quartic coupling $\tilde{t} h^0 h^{0*} \tilde{t}$ is generated.

Another vertex that will be relevant to our analysis is $HW_L W_L$ and $HW_H W_H$. It is an interesting characteristic of the model that they have opposite signs. It must be so in order to cancel quadratic divergences in the Higgs self-energy. Neglecting mixing terms of higher order in $v/f$ one has [4]:

$$HW_L^{\mu} W_{L\nu} \Rightarrow \frac{i}{2} g^2 v g_{\mu\nu}$$

$$HW_H^{\mu} W_{H\nu} \Rightarrow -\frac{i}{2} g^2 v g_{\mu\nu}$$  \hspace{1cm} (6)

We begin by investigating the changes in the partial width $\Gamma(H \to \gamma\gamma)$ arising in this model. The partial width can be written as [3]:

$$\Gamma(H \to \gamma\gamma) = \frac{G_F M_H^3}{8\sqrt{2}\pi} \left( \frac{\alpha}{\pi} \right)^2 |I|^2,$$  \hspace{1cm} (7)

where $|I|$ receives contributions from charged particles of spin $0, 1/2$ and $1$. In the little Higgs model, there is an additional contribution in the loop from the heavy vector boson $W_H^\pm$, which comes with the opposite sign of the usual $W_L^\pm$. One could think that this would result in a partial cancellation between these two contributions. However, since $M_{W_H} \approx \frac{f}{v} M_{W_L}$, the contribution of the $W_H^\pm$ is suppressed by a factor of roughly $\left(\frac{v}{f}\right)^4$.

Notice that the new heavy fermion does not contribute to this process and charged scalar contributions are naturally small, since it must arise from the Coleman-Weinberg effective potential in the scalar sector.

We now turn to Higgs boson production at the LHC in the little Higgs model. The contribution to single Higgs production via gluon-gluon fusion is unchanged since a Yukawa coupling of the type $\tilde{t} \bar{t} \nu H$ does not exist in the linearized Lagrangian. However, there is a contribution to Higgs pair production due to the quartic $\tilde{t} \bar{t} \nu H H$ term. We examine the
possibility of observing this new contribution in Higgs boson pair production at hadron accelerators.

Gluon-gluon fusion is the dominant mechanism of standard model Higgs boson pair production at the LHC \[6\]. There is a top quark triangle and a top quark box contributions. The differential partonic cross section in the standard model can be written as, in the heavy quark limit:

$$d\hat{\sigma}(gg \rightarrow HH) = \frac{G_F^2\alpha_s^2}{256(2\pi)^3} \left[2\frac{M_H^2}{s} - \frac{2}{3}\right]^2,$$

(8)

where \(\hat{t}\) is the momentum transfer between an initial state gluon and a final state Higgs boson. The total cross section is obtained by convoluting with the gluon distribution function:

$$\sigma(pp \rightarrow HH) = \int dx_1 dx_2 \ g(x_1, Q^2)g(x_2, Q^2)d\hat{\sigma}(gg \rightarrow HH)\theta(x_1 x_2 s - 4M_H^2),$$

(9)

where we have used the Cteq6l1 leading order gluon distribution function \[7\] with momentum scale \(Q^2 = \hat{s}\). For the LHC, with \(\sqrt{s} = 14\) TeV we obtain \(\sigma(pp \rightarrow HH) = 38\) fb for \(M_H = 120\) GeV. With an expected luminosity of \(10^{34}\) cm\(^{-2}\) s\(^{-1}\) \[8\] one would have of the order of 4000 events in one year.

In little Higgs models there is an extra contribution to this process shown in figure \[11\]. The amplitude for this process is given by:

$$\mathcal{M}(g^a g^b \rightarrow HH) = g_{HH\tilde{t}\tilde{t}} \frac{\alpha_s}{\pi} \frac{\hat{s}}{6m_t} \delta^{ab}(\varepsilon_1 \cdot \varepsilon_2),$$

(10)

where \(\varepsilon_{1,2}\) are the gluon polarization vectors and the relevant coupling constant is written as:

$$g_{HH\tilde{t}\tilde{t}} = -\frac{\lambda_1^2}{\sqrt{\lambda_1^2 + \lambda_2^2}} \frac{1}{f} \approx \frac{1}{\sqrt{2}f}.\$$

(11)

This leads to the parton level cross section contribution from the little Higgs model:

$$\hat{\sigma}_{LH}(gg \rightarrow HH) = \frac{g_{HH\tilde{t}\tilde{t}}^2\alpha_s^2\hat{s}}{9216\pi^3m_t^2} \sqrt{1 - \frac{4M_H^2}{\hat{s}}} \propto \frac{\hat{s}}{f^4}.$$  

(12)

The total cross section can be obtained by convoluting \(\hat{\sigma}_{LH}\) with the gluon distribution function. For \(M_H = 120\) and \(f = 2\) TeV, we obtain at the LHC the result \(\sigma_{LH} = 6 \times 10^{-3}\).
Figure 1: Little Higgs Model contribution to the Higgs boson pair production at LHC.

fb, 4 orders of magnitude smaller than the standard model. It only depends weakly on the Higgs mass and scales as $f^{-4}$. Since values of $f < 3.5$ TeV are excluded from precision measurements [4], we conclude that the contribution of the little Higgs to the pair production of the Higgs bosons seems to be unobservable at the LHC.

In conclusion, we have examined new contributions of the little Higgs model to production and decay of the Higgs boson. We have found that the corrections due to the new physics are at least of the order of $(\frac{v}{f})^4$. For $f > 3.5$ TeV, we expect small deviations of the order of $10^{-3}\%$, probably too small to be detected at future accelerators.

Note added: After this paper was completed, another paper on a similar subject appeared [9]. The authors of this paper correctly included in the analysis interference and mixing effects which when properly taken into account results in an increased contribution of the order of $(\frac{v}{f})^2$.

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