Decays $\Phi^P \to \gamma Z, ZZ$ in the context of the Littlest Higgs Model

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Abstract. In this study we analyze the decay of the neutral pseudoscalar $\Phi^P$ predicted by the Littlest Higgs Model (LTHM), an extension of the Standard Model (SM) that seeks to solve the hierarchy problem. We focus our research in the decays $\Phi^P \to \gamma Z, ZZ$ at the one-loop level. Here, we analyze the branching ratios of these decays and the production cross section via gluon fusion as function of the new scale of energy $f$, which characterizes the scale of energy of the breaking of the global symmetry and whose values are restricted to the range of 2 to 4 TeV.

1. Introduction

The experimental collaborations in the LHC [1, 2] are seeking for a wide variety of exotic particles, in particular, new heavy scalar bosons. The LTHM is one of the most simple extensions of the Little Higgs models, since it only presents new degrees of freedom [3, 4, 5] at the scale of TeVs. In addition, it predicts a reduced spectrum of new scalar particles [6], which is not the case in other versions of these type of models. The Little Higgs models are interesting because they offer a possible explanation to the hierarchy problem of the SM. The LTHM represents another approach to the electroweak symmetry breaking pattern based on the dimensional deconstruction [6].

2. The Littlest Higgs Model

The LTHM is built using a nonlinear sigma model with $SU(5)$ global symmetry together with a gauged group $[SU(2)_1 \otimes U(1)_1] \otimes [SU(2)_2 \otimes U(1)_2]$ [6, 7]. Firstly, the $SU(5)$ group is spontaneously broken to the $SO(5)$ group at the energy scale $f$. Simultaneously, the $[SU(2)_1 \otimes U(1)_1] \otimes [SU(2)_2 \otimes U(1)_2]$ group is broken to its subgroup $SU_L(2) \otimes U_Y(1)$, being the latter the electroweak gauge group of the SM. At the scale $f$, the spontaneous global symmetry breaking is generated by the vacuum expectation value (VEV) of the $\Sigma$ field, identified as $\Sigma_0$. The structure of the $\Sigma$ field is given as follows

$$\Sigma = e^{i\Pi/f} \Sigma_0 e^{i\Pi^T/f},$$

(1)
with

\[
\Sigma_0 = \begin{pmatrix} 0_{2\times2} & 0_{2\times1} & 1_{2\times2} \\ 0_{1\times2} & 1 & 0_{1\times2} \\ 1_{2\times2} & 0_{2\times1} & 0_{2\times2} \end{pmatrix},
\]

(2)

and \( \Pi \) being the Goldstone boson matrix [7]. On the other hand, the effective Lagrangian invariant under the \([SU(2)_1 \otimes U(1)_1] \otimes [SU(2)_2 \otimes U(1)_2]\) group is composed of [7]

\[
\mathcal{L}_{LTHM} = \mathcal{L}_G + \mathcal{L}_F + \mathcal{L}_\Sigma + \mathcal{L}_Y - V_{CW},
\]

(3)

where \( \mathcal{L}_G \) represents the gauge bosons kinetic contributions, \( \mathcal{L}_F \) contains the fermion kinetic contributions, \( \mathcal{L}_\Sigma \) includes the nonlinear sigma model contributions of the LTHM and \( \mathcal{L}_Y \) encompasses the Yukawa couplings of fermions and pseudo-Goldstone bosons. The \( V_{CW} \) term is the Coleman-Weinberg potential [8]. For the nonlinear sigma sector, we have the Lagrangian density [7]

\[
\mathcal{L}_\Sigma = \frac{f^2}{8} \text{tr} [D_\mu \Sigma]^2,
\]

(4)

where the covariant derivative is

\[
D_\mu \Sigma = \partial_\mu \Sigma - i \sum_{j=1}^{2} \left[ g_j \sum_{a=1}^{3} W^a_{\mu j}(Q^a_j \Sigma + \Sigma Q^a_j^T) + g'_j B_{\mu j}(Y_j \Sigma + \Sigma Y_j^T) \right],
\]

(5)

being \( W^a_{\mu j} \) the gauge fields of the \( SU(2) \) group, the \( B_{\mu j} \) are the \( U(1) \) gauge fields, \( Q^a_j \) and \( Y_j \) are the generators of \( SU(2) \) and \( U(1) \) groups, respectively. The quantities \( g_j \) and \( g'_j \) are the coupling constants of the \( SU(2) \) and \( U(1) \) groups. After the spontaneous symmetry breaking around \( \Sigma_0 \), the mass eigenstates of the order of the energy scale \( f \) are generated. All the details of the LTHM and the corresponding Feynman rules can be found in Ref. [7].

3. Decays \( \Phi^P \to \gamma Z, ZZ \) at one-loop level

Because the main subject of this work is to analyze the one-loop level decays \( \Phi^P \to \gamma Z, ZZ \), we present some samples of Feynman rules involved in the calculation of the amplitudes [7]:

\[
\begin{align*}
\Phi^P \bar{u}u & \to - \frac{m_u}{\sqrt{2} v} \left( \frac{u}{f} - \sqrt{2} s_P \right) \gamma^5, \\
Z \bar{u}u & \to \frac{ig_\gamma}{2 c_W} (g^f_\gamma - g^f_A \gamma^5), \\
A \bar{u}u & \to ie Q_f \gamma_\mu,
\end{align*}
\]

(6)

where \( u \) denotes the up quark, \( g^f_\gamma \) and \( g^f_A \) are the weak charges given by

\[
\begin{align*}
g^f_\gamma &= T^f_3 - 2 Q_f s_W^2, \\
g^f_A &= T^f_3,
\end{align*}
\]

(7)

where \( T^f_3 = -\frac{1}{2} \) for the charged leptons and down type quarks, and \( T^f_3 = \frac{1}{2} \) for the up type quarks. Here \( s_W \equiv \sin \theta_W \) and \( c_W \equiv \cos \theta_W \), being \( \theta_W \) the weak angle. In addition, \( Q_f \) is the charge of the fermion in units of \( e \).
For the $\Phi^P \to \gamma Z$ process that involves fermions, this decay occurs through two triangle diagrams, as shown in Fig. 1. Thus, the amplitude is obtained as a result of the sum of the two contributions. Here the top quark provides the dominant contribution to the quantum fluctuation. So, for the $\Phi^P \to \gamma Z$ decay, the amplitude is

$$M(\Phi^P \to \gamma Z) = A^\gamma Z \epsilon^{\mu\nu\alpha\beta} k_1^\alpha k_2^\beta \epsilon_\mu^*(k_1) \epsilon_\nu^*(k_2),$$

(8)

where the form factor $A^\gamma Z$ is finite,

$$A^\gamma Z = \frac{g^2 N_C s_W (3 - 8 s_W^2)}{72 \sqrt{2} \pi^2 c_W f} m_t^2 C_0(1),$$

(9)

with $C_0(1) = C_0(m_Z^2, m_{\Phi^P}^2, 0, m_t^2, m_e^2, m_l^2)$ the Passarino-Veltman scalar function, $N_C$ is the color factor, 3 for quarks and 1 for leptons; $f$ is the scale of the global symmetry breaking, $m_t$ is the mass of the top quark. Thus, the decay width is

$$\Gamma(\Phi^P \to \gamma Z) = \frac{1}{32 \pi} \frac{m_{\Phi^P}^3}{m_Z^3} (m_{\Phi^P}^2 - m_Z^2)^3 |A^\gamma Z|^2.$$

(10)

Concerning to the $\Phi^P \to ZZ$ (see Fig. 2) decay, this also has two contributions, the amplitude is

$$M(\Phi^P \to ZZ) = A^{ZZ} \epsilon^{\mu\nu\alpha\beta} k_1^\alpha k_2^\beta \epsilon_\mu^*(k_1) \epsilon_\nu^*(k_2),$$

(11)

with the form factor $A^{ZZ}$ is

$$A^{ZZ} = \frac{g^2 N_C m_t^2}{144 \sqrt{2} \pi^2 s_W^2 (4 m_Z^2 - m_{\Phi^P}^2) f} \left[ \left( 4 (3 - 4 s_W^2) s_W^2 m_{\Phi^P}^2 + (3 - 8 s_W^2)^2 m_Z^2 \right) C_0(2) + 9 (B_0(1) - B_0(2)) \right] f,$$

(12)
being \( C_0(2) = C_0(m_Z^2, m_Z^2, m_{\Phi}^2, m_{\Phi}^2, m_t^2, m_t^2) \), \( B_0(2) = B_0(m_Z^2, m_t^2, m_t^2) \) and \( B_0(1) = B_0(m_{\Phi}^2, m_t^2, m_t^2) \). This amplitude is free of ultraviolet divergences, because the \( B_0 \) functions appear as a difference from each other in the equation (12), while \( C_0 \) is finite. The gauge structure for this process also satisfies electromagnetic gauge invariance. The decay width is

\[
\Gamma(\Phi^P \rightarrow ZZ) = \frac{1}{64} \frac{m_{\Phi}^2 - 4m_Z^2}{3} |A_{ZZ}|^2. \tag{13}
\]

In this work we also present a study for the production cross section for the pseudoscalar \( \Phi^P \) in the context of the LTHM at LHC, decaying into final states, \( \gamma Z \) and \( ZZ \). To carry out this task, we employ the Breit-Wigner resonant cross section \[9\]. The production cross section via gluon fusion can be computed by means of the branching ratios \( \text{Br}(\Phi^P \rightarrow gg) \) and \( \text{Br}(\Phi^P \rightarrow Y) \), where \( Y = \gamma Z, ZZ \). Thus, our Breit-Wigner cross section is

\[
\sigma(gg \rightarrow \Phi^P \rightarrow Y) = \frac{\pi \text{Br}(\Phi^P \rightarrow gg)\text{Br}(\Phi^P \rightarrow Y)}{m_{\Phi}^2}, \tag{14}
\]

where \( \sigma(gg \rightarrow \Phi^P \rightarrow Y) \) is estimated at the resonance of the pseudoscalar \( \Phi^P \).

\begin{figure}[h]
\centering
\begin{tabular}{cc}
\includegraphics[width=0.45\textwidth]{fig3a.png} & \includegraphics[width=0.45\textwidth]{fig3b.png} \\
(a) & (b)
\end{tabular}
\caption{(a) Decay widths for the \( \Phi^P \rightarrow \gamma Z, ZZ \) processes as a function of the \( f \) energy scale. (b) Branching ratios for the same decays on the \( f \) energy scale.}
\end{figure}

4. Results and conclusions

The numerical evaluation of the \( \Phi^P \rightarrow \gamma Z, ZZ \) processes was carried out using the programs FeynCalc \[10\] and LoopTools \[11\]. We stress that the energy scale \( f \) is the only free parameter with which we can play. Thus, in strict agreement with the electroweak precision observables of the SM, the energy scale \( f \) is found around 3 – 4 TeV at 99% C.L. \[12\]. However, we present our numerical analysis from \( f = 3 \) TeV to \( f = 4 \) TeV. For the decay widths of each process we have found: \( \Gamma(\Phi^P \rightarrow \gamma Z) \sim 10^{-7} \) GeV and \( \Gamma(\Phi^P \rightarrow ZZ) \sim 10^{-8} \) GeV for \( f = 2 \) TeV, as shown in Fig. 3. In addition, we have calculated its corresponding branching ratios that turned out to be \( \text{Br}(\Phi^P \rightarrow \gamma Z) \sim 10^{-7} \) and \( \text{Br}(\Phi^P \rightarrow ZZ) \sim 10^{-8} \) for \( f \) around 2 TeV (see Fig. 3). For the cross section, its behavior is depicted in the Fig. 4. In specific, \( \sigma(gg \rightarrow \Phi^P \rightarrow \gamma Z) \sim 10^{-7} \) fb and \( \sigma(gg \rightarrow \Phi^P \rightarrow ZZ) \sim 10^{-8} \) fb for \( f = 2 \) TeV.

It should be noted that our work presents preliminary results which in the future will serve us as a basis for a more complete study of the various modes of decay of \( \Phi^P \) in the context of the LTHM.
Figure 4: Cross section $\sigma(gg \rightarrow \Phi^P \rightarrow \gamma\gamma)$ as a function of the $f$ energy scale.

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