The $\Phi^0 \to \gamma Z$ decay in the Littlest Higgs Model

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Abstract. The existence of new particles with masses of the order of TeV's is a characteristic of several extended models. We study a heavy scalar particle decaying into γZ final states at the one-loop level in the Littlest Higgs Model. This process is analyzed in the context of the recent results reported by ATLAS and CMS Collaborations, concerning the observation of a resonance around 750 GeV. We analyze our results in a scenario where the energy scale f ranges from 2 TeV to 5 TeV. We found that the branching ratio for the $\Phi^0 \to \gamma Z$ decay is of the order of 10^{-7}, which mainly depends on a single parameter.

1. Introduction

The standard model of elementary particles (SM) is a theory whose predictions have been validated by current high energy physics experiments (HEP). However, it is not a complete theory because it does not offer solutions to certain fundamental problems such as: a consistent gravitational quantum theory, neutrino oscillations, matter-antimatter asymmetry, hierarchy problem, among others. In order to explain these shortcomings new theories beyond the SM are developed. The recent discovery of the Higgs boson by ATLAS and CMS experiments in the Large Hadron Collider (LHC) at CERN [1] opens the door to new questions and new projects in HEP. An example of these future projects is search for evidence of new physics beyond the SM where it involves the existence of particles whose masses would be within reach of the LHC. Recent preliminary observations suggest the presence of new scalar resonance decaying into two photons [2]. In fact, from the experimental analyses performed by ATLAS collaboration there are arguments to think that a new scalar resonance could be manifesting itself among 200 GeV and 1.7 TeV [2]. Thus, it is of particular interest the search for new neutral scalar bosons predicted by various Standard Model Extensions (SME). In this paper, we will concentrate on one of the so-called Little Higgs Models (LHM), namely, the Littlest Higgs model (LTHM). The LHM propose a solution to the hierarchy problem [3, 4, 5, 6, 7] and provide an alternative for the study of the electroweak symmetry breaking [3, 4] on the basis of dimensional deconstruction [8, 9], with feature of canceling quadratic divergences. The LTHM is particularly interesting since there are no new degrees of freedom beyond the SM under TeV scale along with its reduced spectrum of new scalar particles [4].

2. Littlest Higgs Model

The most economical version of the LHM is known as the LTHM [4, 5], which is based on a nonlinear sigma model with global symmetry $SU(5)$ alongside gauged group $[SU(2) \times U(1)]^2$ [4, 5]. The $SU(5)$ group breaks to $SO(5)$ at the energy scale f, which is constrained to be of the order of $2 - 4$ TeV [6]. At the same time, the $[SU(2) \times U(1)]^2$ group is broken to its subgroup $SU_L(2) \times U_Y(1)$, which corresponds to the SM electroweak gauge group. Owing to the breaking breaking pattern, 14 Goldstone bosons are generated, which transform under the $SU_L(2) \times U_Y(1)$ group as a real singlet $\mathbf{1}_0$, a real triplet $\mathbf{3}_0$, a complex doublet $\mathbf{2}_{\pm\frac{1}{2}}$ and a complex triplet $\mathbf{3}_{\pm 1}$ [4, 5]. The real singlet and the real triplet are absorbed by longitudinal components of the heavy gauge bosons, whereas the complex doublet and the complex triplet remain massless [5]. The complex triplet acquires a mass of the order of f by means of the Coleman-Weinberg potential when the global symmetry of the $SO(5)$ breaks down. The complex doublet is identifed as the SM Higgs field. The explicit form of the LTHM Lagrangian as well as the complete set of new particles, masses and new Feynman rules can be found in Ref. [5]. At the leading order in the LTHM, the masses of the new heavy scalar particles are degenerated, *i.e.*, $m_\Phi = \frac{\sqrt{2} m_H f}{\sqrt{1 - y_v^2 v}}$, where Φ can be any of the six new scalar bosons, in particular, we are interested in the physics of the new neutral scalar, denoted as Φ^0. Here, m_H is the Higgs boson mass and $y_v = 4v'f/v^2$, where v' is the vacuum expectation value (VEV) of the complex triplet and v is the electroweak energy scale. Moreover, there are another relevant parameters, namely, the coupling constants of the $SU(2)$ and $U(1)$ groups, which are g_j and g'_j for $j = 1, 2$, respectively, where $c \equiv g_1/\sqrt{g_1^2 + g_2^2}$ and $c' \equiv g'_1/\sqrt{g'^2_1 + g'^2_2}$. Typical values for the c parameters can be found in Refs. [5, 7]. Here, we will use $0.1 < c < 0.9$ and $c' = 1/\sqrt{2}$.

3. $\Phi^0 \to \gamma Z$ decay

In the LTHM, the $\Phi^0 \to \gamma Z$ decay is absent at the tree level, so the process is induced at one-loop level. To perform this calculation we take into account only the triangular diagrams mediated by the SM fermions. The contributions due to the charged gauge bosons are not considered because their couplings to Φ^0 are null. In the LTHM this decay is only mediated by SM quarks and a new heavy top quark [10]. In Fig 1, the Feynman diagrams that contribute to the $\Phi^0 \to \gamma Z$ decay are shown.

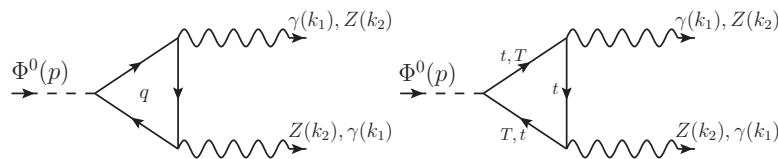**Figure 1.** Feynman diagrams contributing to the $\phi^0 \to \gamma Z$ decay at the one-loop level. Here, q symbolizes any SM quark, t is the top quark and T represents the heavy top quark.

The amplitude for the $\Phi^0 \to \gamma Z$ process can be expressed as

$$\mathcal{M}_{\Phi^0 \to \gamma Z} = A^{\gamma Z} \left(k_1 \cdot k_2 \, g^{\mu\nu} - k_1^\nu k_2^\mu \right) \epsilon_\mu(k_1) \epsilon_\nu(k_2), \tag{1}$$

where $\epsilon_\mu(k_1)$ and $\epsilon_\nu(k_2)$ are the polarization vectors for the photon and the Z boson, respectively. The $A^{\gamma Z}$ coefficient is given as

$$A^{\gamma Z} = \frac{egg_V m_{\Phi^0}^2 v y_t \{ C_a(y_Z - 1)(4t_t + y_Z - 1) + 2[(B_b - B_a + 1)y_Z - 1] \}}{4\sqrt{2} \, c_W f^2 (y_Z - 1)}, \tag{2}$$

where $B_a = B_0(m_{\Phi^0}^2, m_t^2, m_t^2), B_b = B_0(m_Z^2, m_t^2, m_t^2), B_c = B_0(m_{\Phi^0}^2, m_t^2, m_T^2), B_a = B_0(m_Z^2, m_t^2, m_T^2)$ and $C_a = m_{\Phi^0}^2 C_0(m_{\Phi^0}^2, m_Z^2, 0, m_t^2, m_t^2, m_t^2)$ denote Passarino-Veltman scalar functions. Here, $y_t = m_t^2/m_{\Phi^0}^2$ and $y_T = m_T^2/m_{\Phi^0}^2$. It is worth mentioning that the $A^{\gamma Z}$ coefficient is free of ultraviolet divergences, whereas the amplitude satisfies gauge invariance. The numerical evaluation was performed by using the LoopTools package [11].

Finally, we get the following decay width for $\Phi^0 \to \gamma Z$ process

$$\Gamma(\Phi^0 \to \gamma Z) = \frac{e^2 g^2 v^2 (y_Z - 1)|A^{\gamma Z}|^2}{16\pi c_W^2 \, f^2 \, m_{\Phi^0}}. \tag{3}$$
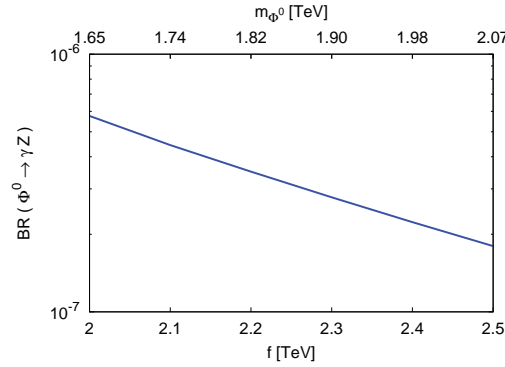

Figure 2. Branching ratio of the $\Phi^0 \to \gamma Z$ decay as a function of f parameter. On the upper x-axis, the value of the mass of the scalar particle Φ^0 is shown.

4. Results

Since the parameter space of the LTHM has been severely constrained by the Higgs discovery channels and electroweak precision observables [6], the $\Phi^0 \to \gamma Z$ decay could help to test this model. In this sense, a scenario where the mass of the scalar particle is assumed to be around 1 TeV is proposed. We begin our analysis by describing the behavior of the branching ratio for the $\Phi^0 \to \gamma Z$ process in the range 2 TeV $< f <$ 2.5 TeV, as it is shown in Fig. 2. For this interval of the energy scale f, the value of the mass of Φ^0 is $m_{\Phi^0} = 1.65$ TeV at $f = 2$ TeV and $m_{\Phi^0} = 2.07$ TeV with $f = 2.5$ TeV. The curve represents the branching ratio for the $\Phi^0 \to \gamma Z$ decay, which is of the order of 10^{-7}. For $f = 2$ TeV and $m_{\Phi^0} = 1.65$ TeV $Br(\Phi^0 \to \gamma Z) \approx 6 \times 10^{-7}$. It is important to mention that our results represent a preliminary study which must be enriched with a hypothetical analysis of the Φ^0 production at the LHC [10].

5. Conclusions

We have presented a brief description of the LTHM model. Our particular interest is the phenomenology of the scalar particle Φ^0 whose mass is assumed to be of the order of 1 TeV. However, although the space of parameters of this model has been severely restricted, there is a window to explore this scalar particle decaying into the final states γZ by using values for the parameter f between 2 TeV and 2.5 TeV. For these values of the energy scale f, the masses of Φ^0 are between 1.65 TeV and 2.07 TeV. For the process in question the corresponding branching ratio is of the order of 10^{-7}, which implies that this observable is very suppressed and it would be difficult to observe at the LHC in the near future.

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