Decay of a pseudoscalar into two photons

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Abstract. The existence of new particles whose masses could be found in the region of TeVs are predicted by extensions of the Standard Model, one of these is the Littlest Higgs model, where it is proposed the existence of a new neutral massive pseudoscalar particle. In this context we analyze the $\Phi^P \rightarrow \gamma\gamma$ decay, where $\gamma$ symbolizes the photon and $\Phi^P$ is the pseudoscalar particle predicted by this model.

1. Introduction

Currently, the ATLAS \cite{1} and CMS \cite{2} Collaborations continue with the search for new particles, such as the Randall-Sundrum spin-2 boson or new heavy scalar particles \cite{3,4}. In this sense, there are several models that predict the existence of more scalar particles, such as the two-Higgs doublet models (2HDMs) \cite{5,6}, three-Higgs doublet model (3HDM) \cite{7}, Higgs-singlet extension model \cite{8}, little Higgs models (LHMs) \cite{9}, etc. Among the large variety of LHMs, we will focus on the simplest model, which is the Littlest Higgs model (LTHM) because it does not contain new degrees of freedom below the TeVs scale. Particularly, the LTHM has a reduced particle spectrum and does not consider additional discrete symmetries. Within this model, it is proposed to study the $\Phi^P \rightarrow \gamma\gamma$ decay at one loop level, since the coupling $\Phi^P\gamma\gamma$ is not present at the tree level. In particular, we are interested in estimating the branching ratio of this process as a function of the parameter $f$. In the same context, a rough analysis for the production cross section of the $\Phi^P$ boson via gluon fusion at LHC is presented.

2. The LTHM model

The LTHM model is constituted by a nonlinear sigma model with $SU(5)$ global symmetry together with the gauge group $[SU(2)_1 \times U(1)_1] \times [SU(2)_2 \times U(1)_2]$ \cite{10,11}, where the $SU(5)$ group is spontaneously broken to $SO(5)$ at the energy scale $f$, which is of the order of TeV. At the same time, the $[SU(2)_1 \times U(1)_1] \times [SU(2)_2 \times U(1)_2]$ group is also broken to its subgroup $SU(2)_L \times U(1)_Y$, which is identified as the electroweak gauge group of the Standard Model (SM) \cite{11,12}. Due to the global symmetry breaking 14 Goldstone bosons are generated, which are transformed under the $SU_L(2) \times U_Y(1)$ group as a real singlet $1_0$, a real triplet $3_0$, a complex doublet $2_{\pm 1/2}$ and a complex triplet $3_{\pm 1}$ \cite{11}. The real singlet and the real triplet are absorbed by longitudinal components of the gauge bosons at the energy scale $f$, while the complex doublet...
and the complex triplet remain massless [11].

On the other hand, the mass of the new pseudoscalar particle $\Phi^P$ is given by [11]

$$m_\Phi = \sqrt{\frac{2m_H f}{\sqrt{1 - y_v^2 v}}}.$$  \hspace{1cm} (1)

where $y_v = 4v'f/v^2$, being $v$ and $v'$ the vacuum expectation values of the doublet and triplet, respectively. This mass expression is definite positive if the following relation is satisfied

$$\frac{v'^2}{v^2} < \frac{v^2}{16f^2}.$$  \hspace{1cm} (2)

3. The $\Phi^P \to \gamma\gamma$ process

The Feynman rules involved in the $\Phi^P \to \gamma\gamma$ decay are summarized in Table 1 [11].

| $\Phi^P \bar{u}u$ | $\bar{u}A_{\mu}$ |
|------------------|------------------|
| $-\frac{ie}{\sqrt{2}}(\bar{u} - \sqrt{2}s_\rho)\gamma^\mu$ | $-ieQ_\alpha\gamma^\mu$ |

Table 1. LTHM and SM couplings.

The Feynman diagrams corresponding to the $\Phi^P \to \gamma\gamma$ decay are shown in Fig. 1, where inside the loops are circulating quarks of the SM.

![Figure 1: Decay $\Phi^P \to \gamma\gamma$.](image)

The kinematic conditions of this decay are: $k_1^2 = k_2^2 = 0$, $k_1 \cdot k_2 = m^2_{\Phi^P}$, and $p^2 = m^2_{\Phi^P}$, where $p$ is the four-moment of $\Phi^P$, $k_1$ and $k_2$ are the four-moments of the photons. Considering the above and after the application of the Passarino-Veltman reduction scheme, the amplitude of the decay takes the form

$$M(\Phi^P \to \gamma\gamma) = A^{\gamma\gamma} e^{\mu_\alpha\beta} k_{1\alpha} k_{2\beta} \epsilon_{\mu}(k_1) \epsilon_{\nu}(k_2),$$  \hspace{1cm} (3)

where the Levi-Civita tensor is a distinctive feature of the pseudoscalar nature of this process [14].

The form factor is

$$A^{\gamma\gamma} = \frac{-g^2 N_C s_W^2 m_t^2 C_0(0,0,m^2_{\Phi^P},m^2_t,m^2_1,m^2_2)}{9\sqrt{2} f \pi^2},$$  \hspace{1cm} (4)

where $C_0(0,0,m^2_{\Phi^P},m^2_t,m^2_1,m^2_2)$ is the three-point Passarino-Veltman scalar function, $m_t$ is the top quark mass, $N_C = 3$ is the color factor due to quarks circulating in the loop, and $s_W \equiv \sin \theta_W$ being $\theta_W$ the weak mixing angle. The form factor is free of ultraviolet divergences and its corresponding Lorentz structure satisfies gauge invariance.
4. Analysis of the results

After using the decay width formula [13], and after performing some algebraic operations we find that the decay width for our decay is

$$\Gamma(\Phi^P \rightarrow \gamma \gamma) = \frac{1}{64\pi} |A_{\gamma\gamma}|^2 m_{\Phi^P}. \quad (5)$$

In this work we use the LoopTools [15] software for the numerical evaluation of the decay width $\Gamma(\Phi^P \rightarrow \gamma \gamma)$. Before continuing the analysis of results, we recall that $m_{\Phi^P}$ is a function of the energy scale $f$ in which the global symmetry is broken. Note that this energy scale is the only free parameter for testing. This symmetry breaking scale is constrained by the experimental data to $2 \leq f \leq 4$ TeV [16]. Thus, the $m_{\Phi^P}(f)$ quantity is a monotonous increasing function, being restricted to $1.66 \leq m_{\Phi^P}(f) \leq 3.32$ TeV. In Fig. 2(a) is shown the behavior of $\Gamma(\Phi^P \rightarrow \gamma \gamma)$ as a function of the energy scale $f$, we can clearly see that the decay width is entirely of the order of $10^{-7}$ in the interval $2 \leq f \leq 4$ TeV. In Fig. 2(b) is presented the corresponding branching ratio as a function of the energy scale $f$, it is observed that the branching ratio is of the order of $10^{-7}$, for interval $2$ TeV $\leq f \leq 2.7$ TeV. It should be noted that the total decay width $\Gamma_{\Phi^P}$ is conformed by the channels $ZH$, $WWZ$, $WWH$, $tt$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{(a) $\Gamma(\Phi^P \rightarrow \gamma \gamma)$ and (b) $\text{Br}(\Phi^P \rightarrow \gamma \gamma)$ as a function of the $f$ parameter.}
\end{figure}

4.1. Production of the heavy neutral pseudoscalar boson

Here we develop a rough study for the production cross section of the scalar $\Phi^P$ at LHC. To carry out this, we use the Breit-Wigner resonant cross section [17]. In this way, the production cross section via gluon fusion can be computed through the branching ratios $\text{Br}(\Phi^P \rightarrow gg)$ and $\text{Br}(\Phi^P \rightarrow \gamma \gamma)$. Therefore, our Breit-Wigner cross section is written as

$$\sigma(gg \rightarrow \Phi^P \rightarrow \gamma \gamma) = \frac{\pi}{12} \frac{\text{Br}(\Phi^P \rightarrow gg) \text{Br}(\Phi^P \rightarrow \gamma \gamma)}{m_{\Phi^P}^2}. \quad (6)$$
where \( \sigma(gg \rightarrow \Phi^P \rightarrow \gamma \gamma) \) is estimated at the resonance of the \( \Phi^P \) boson [17]. The branching ratio of the \( \Phi^P \rightarrow gg \) process is

\[
\text{Br}(\Phi^P \rightarrow gg) = \frac{1}{8\pi} \frac{|A_{gg}|^2 m_{\Phi^P}^3}{\Gamma_{\Phi^P}}, \tag{7}
\]

with \( A_{gg} = \frac{g^2}{8\sqrt{2\pi f}} m_f^2 C_0(m_{\Phi^P}, 0, 0, m_f^2, m_f^2, m_f^2) \), being \( \Gamma_{\Phi^P} \) the total decay width of \( \Phi^P \).

Figure 3. Cross section of \( gg \rightarrow \Phi^P \rightarrow \gamma \gamma \) as a function of \( f \).

In Fig. 3 we show the Breit-Wigner cross section for the \( \Phi^P \) production as a function of the \( f \) parameter from 2 TeV to 4 TeV. The expected integrated luminosity of the LHC at the last stage of operation is planned to be around 3000 fb\(^{-1}\) [18]. In this context, from our results shown in Fig. 3, the corresponding \( \sigma(gg \rightarrow \Phi^P \rightarrow \gamma \gamma) \) is \( 6.077 \times 10^{-7} \) fb for \( f = 2 \) TeV, which implies that this observable related with the \( \Phi^P \rightarrow \gamma \gamma \) is very suppressed and it would be difficult to observe at the LHC.

5. Conclusions

The LTHM is constituted by a nonlinear sigma model together with a \( SU(5) \) global symmetry and a subgroup of gauge \([SU(2)_1 \times U(1)_1] \times [SU(2)_2 \times U(1)_2]\) , where the presence of new particles with masses of the order of several TeVs is predicted. From all new particles, a new neutral pseudoscalar particle, \( \Phi^P \), is the object of analysis in this work. We have established a study region from 2 TeV to 4 TeV for the energy scale \( f \), which represents a mass range for \( m_{\Phi^P} \) between 1.66 TeV and 3.32 TeV, respectively. In this energy range, the width decay found for the \( \Phi^P \rightarrow \gamma \gamma \) process is of the order of \( 10^{-7} \) GeV, while the branching ratio computed is of the order of \( 10^{-7} \) on the range \( 2 \) TeV \( < f < 2.7 \) TeV. Finally, an estimate for the production cross section of the \( \Phi^P \) boson via gluon fusion was implemented. For \( f = 2 \) TeV, the \( \sigma(gg \rightarrow \Phi^P \rightarrow \gamma \gamma) \sim 10^{-7} \) fb, which implies that this observable is very suppressed and it would be difficult to observe at the LHC.

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