The effects of a strongly interacting Higgs sector on $\gamma \gamma \rightarrow W^+_L W^-_L, Z^0_L Z^0_L$ scattering

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We study the effects of a strongly interacting Higgs sector on the amplitudes for $\gamma \gamma \rightarrow W^+_L W^-_L, Z^0_L Z^0_L$ by unitarizing the $W^+_L W^-_L, Z^0_L Z^0_L, \gamma \gamma$ system using the $K$–matrix technique. Unitarization produces substantial corrections to the cross sections for gauge boson pair production by photon fusion when $m_H \gtrsim 5 - 10$ TeV.

PACS numbers: 13.85.Qk, 14.80.Er, 14.80.Gt
I. INTRODUCTION

The possibility of producing high-luminosity photon beams by backscattering laser beams from high energy polarized electrons has prompted theoretical investigations suggesting that the photon fusion processes

$$\gamma \gamma \rightarrow W_L^+ W_L^- , Z_L^0 Z_L^0 ,$$

(1)
can be used to probe the Higgs sector of the standard model [1] as well as to explore the symmetry breaking sector of its non-linear Chiral Lagrangian generalizations [2]. It has also been shown that the photon fusion processes of Eq.(1) can be used in the search for ultraheavy fermions at high energy hadron colliders [3]. In either case, the $$W_L^+ W_L^-$$ and $$Z_L^0 Z_L^0$$ signals receive large contributions from one-loop diagrams containing $$W_L^\pm , Z_L^0$$ and Higgs bosons, $$H$$ [1].

In this paper, we examine the effect of a strongly interacting Higgs sector on the photon fusion by unitarizing the s-wave amplitudes for $$W_L^+ W_L^- , Z_L^0 Z_L^0$$ and $$\gamma \gamma$$ scattering using the $$K$$-matrix formalism [4,5]. It is then possible to increase the longitudinal coupling strength $$\lambda = g^2 m_H^2 / 8 m_W^2$$ by varying $$m_H$$. Additionally, the Higgs width is introduced in a manner which preserves the Goldstone-boson equivalence theorem [6–8].

II. UNITARIZATION

We define the $$3 \times 3$$, $$J = 0$$, $$t$$-matrix as

$$t_0 = \begin{pmatrix}
    a + b & \frac{a}{\sqrt{2}} & \frac{\varepsilon}{\sqrt{2}} \\
    \frac{a}{\sqrt{2}} & \frac{1}{2} a + b & \frac{\varepsilon a}{2} \\
    \frac{\varepsilon d}{\sqrt{2}} & \frac{\varepsilon a}{2} & \frac{\varepsilon^2 f}{2}
\end{pmatrix},$$

(2)

where $$\varepsilon = \alpha / 2 \pi$$. The rows and columns of $$t_0$$ are labeled by $$W_L^+ W_L^- , Z_L^0 Z_L^0 / \sqrt{2}$$ and $$\gamma \gamma / \sqrt{2}$$, and the Born level partial wave projections $$a$$ and $$b$$ are given by [4].
a = -\frac{\lambda}{8\pi} \frac{s}{s - m^2_H} \quad (3)

b = -\frac{\lambda}{8\pi} \left(1 - \frac{m^2_H}{s} \ln(1 + \frac{s}{m^2_H})\right) \quad (4)

In Ref. [1], it is shown that the one-loop $\gamma \gamma \to Z^0_L Z^0_L$ amplitude is proportional to $a$ for $m^2_W \to 0$. For the $\gamma \gamma \to W^+_L W^-_L$ case, the one-loop correction to the s-wave amplitude is also real for $m^2_W \to 0$, since the Born amplitude vanishes in this limit. However, explicit calculations show that the Born term, though proportional to $m^2_W$, is not negligible for interesting values of the $\gamma \gamma$ center of mass energy $\sqrt{s}$. Consequently, the s-wave amplitude $d$ is taken to be

\[ d = 2\pi \frac{m^2_W}{\beta_W s} \ln\left(\frac{1+\beta_W}{1-\beta_W}\right) - \frac{\lambda}{8\pi} \frac{s}{s - m^2_H} \]

\[ -\frac{\lambda}{8\pi} \left(1 + \frac{2m^2_H}{s} \left(\text{Li}_2\left(-\frac{s}{m^2_H}\right) + \left(1 + \frac{s}{m^2_H}\right) \ln(1 + \frac{s}{m^2_H}) - 1\right)\right) \quad (5)\]

Since we are only interested in effects of order $\alpha$ and $\alpha \lambda$, we can ignore the photon-photon partial wave amplitude $f$ [1]. We also consider the case of photons with helicity $\lambda_\gamma = 1$, which is appropriate for the case of backscattered laser photons.

Including terms through order $\alpha^2$, the eigenvectors of the matrix $t_0$ are

\[ \xi_1 = \left(\frac{\sqrt{2}}{3} (1 - \frac{1}{6} \frac{y^2}{c^2} - \frac{2}{3} \frac{x y}{a c} ), \frac{1}{\sqrt{3}} (1 - \frac{1}{6} \frac{y^2}{c^2} + \frac{4}{3} \frac{x y}{a c} ), \frac{1}{\sqrt{3}} \frac{y}{c}\right), \quad (6)\]

\[ \xi_2 = \left(\frac{1}{\sqrt{3}} (1 - \frac{1}{3} \frac{x^2}{b^2} + \frac{4}{3} \frac{x y}{a b} ), -\frac{\sqrt{2}}{\sqrt{3}} (1 - \frac{1}{3} \frac{x^2}{b^2} - \frac{2}{3} \frac{x y}{a b} ), -\frac{\sqrt{2}}{\sqrt{3}} \frac{x}{b}\right), \quad (7)\]

\[ \xi_3 = \left(\frac{\sqrt{2}}{3} \left(\frac{x}{b} - \frac{y}{c}\right), -\frac{2}{3} \frac{x}{b} + \frac{1}{3} \frac{y}{c}, (1 - \frac{1}{6} \frac{y^2}{c^2} - \frac{1}{3} \frac{x^2}{b^2}\right), \quad (8)\]

where $c = \frac{3}{2} a + b$, $x = \frac{1}{2} \varepsilon (a - d)$ and $y = \frac{1}{2} \varepsilon (a + 2 d)$. It is easy to check that if $U$ is the matrix whose columns consist of $\xi_1$, $\xi_2$ and $\xi_3$, the product $U^T t_0 U$ is diagonal. The corresponding eigenamplitudes are

\[ \lambda_1 = c + \frac{1}{3} \frac{y^2}{c}, \quad (9)\]

\[ \lambda_2 = b + \frac{2}{3} \frac{x^2}{b}, \quad (10)\]

\[ \lambda_3 = -\frac{2}{3} \frac{x^2}{b} - \frac{1}{3} \frac{y^2}{c}. \quad (11)\]
To obtain the $K$-matrix unitarized amplitudes, the $\lambda_i$ are replaced by

$$\lambda_i \rightarrow \lambda_i^K = \frac{\lambda_i}{1 - i \lambda_i}, \quad (12)$$

and the diagonal $t$-matrix is transformed back to the basis of physical states with the aid of the matrix $U$.

III. RESULTS

Proceeding in the manner outlined in Sec. (II), the unitarized s-wave amplitudes for the production of $W_L$ and $Z^0_L$ pairs are

$$a_0^K(\gamma \gamma \rightarrow W^+_L W^-_L) = \frac{2}{3} \left( \frac{y}{1 - i (c + \frac{1}{3} y^2 \frac{x}{c})} - \frac{x}{1 - i (b + \frac{2}{3} \frac{x^2}{b})} \right), \quad (13)$$

$$a_0^K(\gamma \gamma \rightarrow Z^0_L Z^0_L) = \frac{2}{3} \left( \frac{y}{1 - i (c + \frac{1}{3} y^2 \frac{x}{c})} + 2 \frac{x}{1 - i (b + \frac{2}{3} \frac{x^2}{b})} \right), \quad (14)$$

where we have dropped terms of order $\alpha^3$, and removed the symmetry factors associated with the identity of the $\gamma$’s and $Z^0_L$’s. Taking into account the definitions of $a$, $b$ and $d$, it can be seen that, at the Higgs pole, the unitarized amplitudes introduce a width which is equal to the sum of $\Gamma(H \rightarrow W^+_L W^-_L)$, $\Gamma(H \rightarrow Z^0_L Z^0_L)$ and $\Gamma(H \rightarrow \gamma \gamma)$.

The cross sections obtained from these amplitudes are displayed in Figs. (1-3). For Higgs masses of .7 TeV and 1.0 TeV, the cross sections are in good agreement with those of Ref. [1]. This is consistent with the situation found for the unitarized gauge boson scattering amplitudes [4,5]. When $m_H$ exceeds a few TeV, the unitarized amplitudes rise less rapidly than those presented in Ref. [1], and the maximum cross section for large $m_H$ is about a factor of three smaller. Fig. (3) shows the contribution of the one-loop correction to the cross section for $\gamma \gamma \rightarrow W^+_L W^-_L$ scattering. A comparison of this figure with the result for the complete amplitude, Fig.(2), shows that the Born and one-loop amplitudes interfere substantially.
In conclusion, we find that unitarity corrections to the cross sections for $\gamma \gamma \rightarrow Z_L^0 Z_L^0$ and $\gamma \gamma \rightarrow W_L^+ W_L^-$ are large for $m_H \gtrsim 5$ TeV. Nevertheless, in the large $m_H$ limit there is still a cross section on the order of several femtobarns for either of these processes. This implies that searches for ultraheavy fermions which make use of photon fusion [3] must take into account the sources of gauge boson pairs discussed here.

ACKNOWLEDGMENTS

One of us (WWR) wishes to thank the Center for Particle Physics at the University of Texas for its hospitality during the initial stages of this work. This research was supported in part by the National Science Foundation under Grant 90–06117 and by the U. S. Department of Energy under Contract No. DE–FG02–85ER40200.
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FIGURES

FIG. 1. The s-wave total cross section for $\gamma\gamma \rightarrow Z_L^0 Z_L^0$ is plotted for $m_H = .7, 1.0$ and $10$ TeV.

FIG. 2. The s-wave total cross section for $\gamma\gamma \rightarrow W_L^+ W_L^-$ including the Born and one-loop contributions is plotted for $m_H = .7, 1.0$ and $10$ TeV, with $|\cos\theta| \leq \cos(\pi/6)$.

FIG. 3. Same as Fig.(2) except that only the one-loop contribution is included.