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ANALYSIS OF THE PROCESS $e^+e^- \to H^0A^0$ IN IHDM IN THE PRESENCE OF A LINEARLY POLARIZED LASER FIELD

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We consider the process of neutral Higgs production from e^+e^- annihilation in Inert Higgs Doublet Model (IHDM) in the absence and presence of an external field. The latter is assumed to be a plane and monochromatic wave with linear polarization. In the theoretical framework, we present the analytic calculation of the lowest order differential cross section by using the scattering matrix approach and Dirac-Volkov formalism for charged incident particles. The total cross section is computed by performing a numerical integration of the differential cross section over the solid angle. The results obtained are analyzed and discussed for different centre of mass energies and laser parameters. We found that inserting a laser wave with linear polarization is a suitable mechanism to enhance the total cross-section of the process. Indeed, the probability of the process to occur increases with the presence of a linearly polarized laser field, especially with low frequency and high strength.

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1. INTRODUCTION

In 1917, the theoretical foundations of a laser field were established by Albert Einstein by introducing the concept of stimulated emission. This concept states that a photon can interact with an excited atom or molecule, and this causes the emission of another photon with the same properties such as phase, frequency, polarization and direction. However, the laser-matter interactions basis is theoretically well established from the atomic energy scale to high energy physics in both non-relativistic and relativistic regimes [1–4].

Recently, much interest is dedicated to the analysis of high-energy processes in the presence of an electromagnetic field. In [5–7], the process $e^+e^- \to \mu^+\mu^-$ is studied in the presence of a circularly polarized laser field by considering different laser geometries. The laser-assisted Higgs boson production is studied in the presence of a laser wave in the standard model [8–10] and beyond [11–13]. In [11], we studied the pair production of neutral Higgs bosons in IHDM via e^+e^- collisions in the presence of an electromagnetic field. As a result, we found that the circularly polarized laser wave reduces the cross-section of the process. In this respect, we investigate in this paper the neutral Higgs boson pair production inside a linearly polarized laser beam in IHDM. The choice of the IHDM model, which is a special case of the Two Higgs Doublet Model (THDM), is due to its interesting dark matter phenomenology [14].

2. OUTLINE OF THE THEORY

In this part, we perform an analytic calculation of the differential cross section for the process $e^+e^- \to H^0A^0$ in IHDM, which is one of the simplest extensions of the standard model (SM) [14]. In addition to the SM Higgs doublet H^1, the IHDM has an extra doublet H^2 which does not have a direct coupling to fermions, and it has no vev (vacuum expectation value). Therefore, H^2 may act as a dark matter

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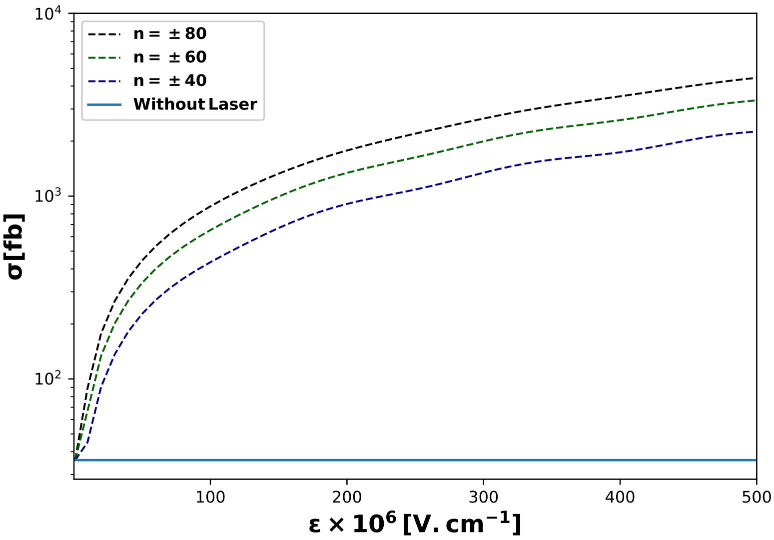

Fig. 1. Dependence of the laser-assisted total cross section on the laser amplitude for different numbers of transferred photons with $\sqrt{s} = 500$ GeV, $\omega = 1.17\,eV$ and $m_s = 120$ GeV

candidate. The Higgs coupling to gauge bosons can be derived from the covariant derivative of the Higgs doublet. We list in the following equation, the part of the Lagrangian needed for our study:

$$\mathcal{L}_{VS_iS_j,VVh^0} = = \Big(-ieA^\mu + ie\frac{(\cos^2_{\theta_W} - \sin^2_{\theta_W})}{2\cos_{\theta_W}\sin_{\theta_W}} Z^\mu \Big) H^+ \overleftrightarrow{\partial_\mu} H^- + + \frac{e}{2\cos_{\theta_W}\sin_{\theta_W}} Z^\mu H^0 \overleftrightarrow{\partial_\mu} A^0 + i\frac{eM_Z}{\cos_{\theta_W}\sin_{\theta_W}} h^0 Z^\mu Z_\mu. \quad (1)$$

2.1. Calculation of the total cross section in the absence of a laser field

In the absence of a laser field and by using the Feynman rules, the lowest-order scattering matrix element of the process $e^+e^- \to H^0A^0$ can be expressed as follows:

$$\mathcal{S}_{fi}(e^+e^- \to H^0A^0) = = \frac{-ie}{2\cos_{\theta_W}\sin_{\theta_W}} \int d^4x \int d^4y \Big[\bar{\psi}_{p_2,s_2}(x) \times \times \Big[\gamma_\mu(g_v^e - g_a^e\gamma^5)\Big] \psi_{p_1,s_1}(x) \times \times D^{\mu\nu}(x-y) \phi^*_{k_1}(y) \Big(\frac{e\overleftrightarrow{\partial_\nu}}{2\cos_{\theta_W}\sin_{\theta_W}} \Big) \phi^*_{k_2}(y) \Big], \quad (2)$$

where $g_v^e = -\frac{1}{2} + 2\sin^2_{\theta_W}$ ($g_a^e = -\frac{1}{2}$) is the vector (axial-vector) coupling constant. In this case, the incident electron and positron can be described by the Dirac state. $D^{\mu\nu}(x-y)$ is the propagator of the Z^*-boson [15]. The produced pair of Higgs particles are described by using the Klein-Gordon states. In the center of mass frame, the differential cross section can be derived as follows:

$$d\sigma = \frac{|\mathcal{S}_{fi}|^2}{VT} \frac{1}{|\mathcal{J}_{inc}|} \frac{1}{\varrho} V \int \frac{d^3k_1}{(2\pi)^3} V \int \frac{d^3k_2}{(2\pi)^3}, \quad (3)$$

where $|\mathcal{J}_{inc}| = (\sqrt{(p_1p_2)^2 - m_e^4}/E_1E_2V)$ is the current of incident particles, and $\rho = V^{-1}$ is the particles' density.

The cross section is unpolarized. Thus, we sum over the final spins and average over the initial ones, we integrate over d^3k_2 and $d|\mathbf{k}_1|$. To obtain the total cross section, the differential cross section is integrated over the solid angle $d\Omega = \sin(\theta)d\theta d\phi$, using $\int d\Omega(a + b\sin^2\theta) = 4\pi a + \frac{8\pi}{3}b$.

If we neglect the electron and positron's mass ($m_e \approx 0$), the expression of the total cross section will be as follows:

$$\sigma(e^+e^- \to H^0A^0) = = \frac{\alpha^2\pi}{192\cos^4_{\theta_W}\sin^4_{\theta_W}} \frac{(1 + (1 - 4\sin^2_{\theta_W})^2)}{(s - M_Z^2)^2} \times \Big[\Big(1 - \frac{(M_{A^0} + M_{H^0})^2}{s}\Big) \Big(1 - \frac{(M_{A^0} - M_{H^0})^2}{s}\Big) \Big]^3 \quad (4)$$

where $\alpha = \frac{e^2}{4\pi}$, and s is the centre of mass energy.

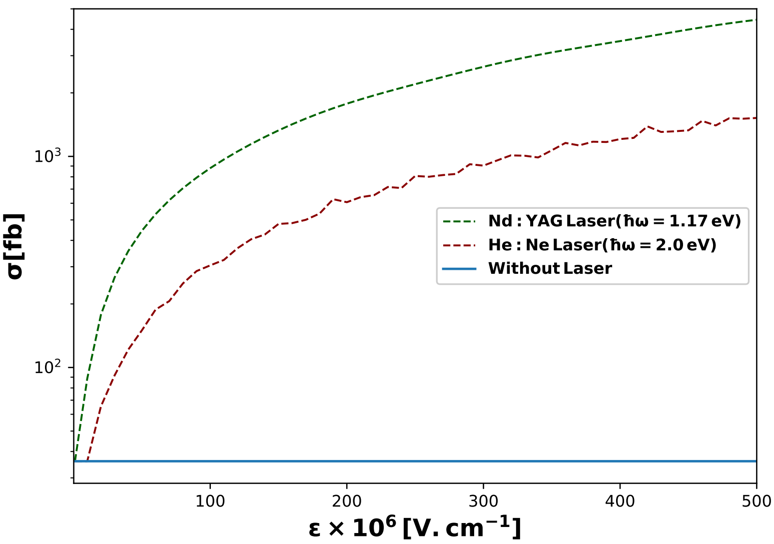

Fig. 2. Variation of the laser-assisted total cross section as a function of the laser amplitude for different laser sources with $\sqrt{s} = 500$ GeV, $n = \pm 80$ and $m_s = 120$ GeV

2.2. Calculation of the total cross section in the presence of a linearly polarized laser field

Inside an electromagnetic field, the scattering matrix element [15] of this process $e^+e^- \to H^0A^0$ can be expressed as follows:

$$S_{fi}(e^+e^- \to H^0A^0) = \\ = \frac{-ie}{2\cos_{\theta_W}\sin_{\theta_W}} \int d^4x \int d^4y \Big[\bar{\Psi}_{p_2,s_2}(x) \times \\ \times \Big[\gamma_\mu(g_v^e - g_a^e\gamma^5)\Big]\Psi_{p_1,s_1}(x) \times \\ \times D^{\mu\nu}(x-y)\phi^*_{k_1}(y)\Big(\frac{e\overleftrightarrow{\partial_\nu}}{2\cos_{\theta_W}\sin_{\theta_W}}\Big)\phi^*_{k_2}(y)\Big], \quad (5)$$

where $\Psi_{p_1,s_1}(x)$ and $\Psi_{p_2,s_2}(x)$ are respectively the Dirac-Volkov state [16] of the electron and positron inside the electromagnetic field with linear polarization. The classical four-potential is defined, in the case of a laser wave with linear polarization, as follows:

$$A_l^\mu(\phi) = a_l^\mu \cos(\phi) \qquad ; \qquad \phi = (k.x). \quad (6)$$

In equation (6), $a_l^\mu = (0,0,0,|a|)$ is the 4-vector polarization with $|a|^2 = (\varepsilon/\omega)^2$, where ε is the electromagnetic field amplitude, $\phi = (k.x)$ is its phase. The wave four-vector $k^\mu = (\omega,\omega,0,0)$ satisfies $(a_l.k) = 0$ where ω is the laser frequency. In the center of mass frame, the laser-assisted differential cross section can be derived from the equation (3) by replacing $\mathcal{S}_{fi}$ by S^n_{fi} which is given by equation (5). The current of incident particles in the presence of the laser field is expressed as $|J_{inc}| = (\sqrt{(q_1q_2)^2 - m_e^{*4}}/Q_1Q_2V)$. The differential cross section becomes as expressed in the following equation:

$$\frac{d\sigma_n}{d\Omega} = \frac{e^4}{256\cos^4_{\theta_W}\sin^4_{\theta_W}}\left[\frac{1}{(q_1+q_2+nk)^2 - M_Z^2}\right]^2 \times \\ \times \frac{1}{\sqrt{(q_1q_2)^2 - m_e^{*4}}}\left|\overline{M^n_{fi}}\right|^2 \frac{2|\mathbf{k_1}|^2}{(2\pi)^2 Q_{H^0}} \times \\ \times \frac{1}{\left|g'(|\mathbf{k}_1|)\right|_{g(|\mathbf{k}_1|)=0}}, \quad (7)$$

where the function $g'(|\mathbf{k}_1|)$ is defined as:

$$g'(|\mathbf{k}_1|) = -2\Big[\frac{E_1|\mathbf{k}_1|}{\sqrt{|\mathbf{k}_1|^2 + M^2_{H^0}}} - |\mathbf{p}_1|\cos\theta\Big] - \\ - \frac{e^2a^2}{2k.p_1}\Big[\frac{\omega|\mathbf{k}_1|}{\sqrt{|\mathbf{k}_1|^2 + M^2_{H^0}}} - \omega\cos\theta\Big] - \\ - 2\Big[\frac{E_2|\mathbf{k}_1|}{\sqrt{|\mathbf{k}_1|^2 + M^2_{H^0}}} + |\mathbf{p}_2|\cos\theta\Big] - \\ - \frac{e^2a^2}{2k.p_2}\Big[\frac{\omega|\mathbf{k}_1|}{\sqrt{|\mathbf{k}_1|^2 + M^2_{H^0}}} - \omega\cos\theta\Big] - \\ - 2n\Big[\frac{\omega|\mathbf{k}_1|}{\sqrt{|\mathbf{k}_1|^2 + M^2_{H^0}}} - \omega\cos\theta\Big]. \quad (8)$$

The quantity $\left|\overline{M^n_{fi}}\right|^2$ that appears in equation (7) can be evaluated as follows:

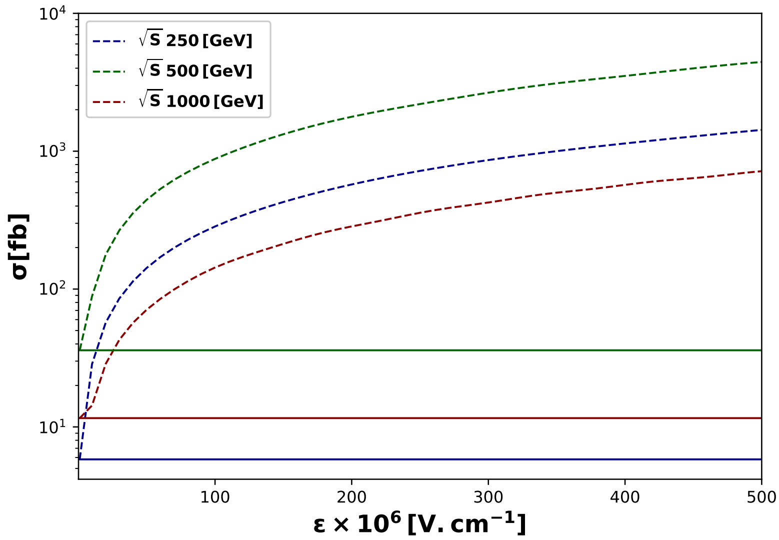

Fig. 3. Variation of the laser-assisted total cross section as a function of the laser amplitude for different centre of mass energies by taking $\omega = 1.17\,eV$, $n = \pm 80$ and $m_s = 120$ GeV

$$|\overline{M^n_{fi}}|^2 = \frac{1}{4}\sum_{n=-\infty}^{+\infty}\sum_s |M^n_{fi}|^2 = = \frac{1}{4}\sum_{n=-\infty}^{+\infty} Tr\Big[(\not{p}_2 + m_e)(k_1^\mu - k_2^\mu) \times \times \Gamma^n_\mu(\not{p}_1 - m_e)(k_1^\nu - k_2^\nu)\bar{\Gamma}^n_\nu\Big], \quad (9)$$

We have used the FeynCalc package [17,18] for the trace calculations in equation (9). To obtain the total cross section, the differential cross section is numerically integrated over the solid angle $d\Omega = \sin(\theta)d\theta d\phi$.

3. RESULTS AND DISCUSSION

In this part, we compute the total cross-section of the process $e^+e^- \to H^0A^0$ in the centre of mass frame in the absence and presence of a laser field. Then, we discuss and analyze the results obtained as a function of the laser parameters such as laser field strength ε, the frequency ω, and the number of transferred photons n. The electromagnetic field is assumed to be a linearly polarized wave where its direction is chosen along the x-axis. The initial electron-positron beam is considered to be co-propagating with the laser beam.

The produced Higgs-bosons are degenerate such that : $m_{A^0} = m_{H^0} = m_s$. The mass of the Z-boson and that of the electron are taken from PDG [19] as $m_Z = 91.1875$ GeV and $m_e = 0.511$ MeV.

We begin our discussion by comparing the total cross section of the process $e^+e^- \to H^0A^0$ in the presence of a laser field with its corresponding laser free cross section that is calculated by using both CalcHEP and MadGraph packages [20, 21]. At the limit of vanishing laser field ($n = 0$ and $\varepsilon = 0\,\mathrm{V{\cdot}cm^{-1}}$), the laser-assisted cross section has the same order of magnitude as the total cross section without laser. Besides, the obtained results are in good agreement with the result obtained in [14].

The variation of different summed laser-assisted total cross sections of the process $e^+e^- \to H^0A^0$ as a function of the laser field strength is illustrated in figure 1. The solid line represents the laser-free cross-section, and it does not depend on the laser strength. According to figure 1 and at $\sqrt{s} = 500$ GeV and $m_s = 120$ GeV, this laser-free total cross section is $\sigma_{wl} = 35.97$ fb.

However, the laser-assisted total cross section in the presence of linearly polarized laser wave increases with the increasing laser strength. The number of exchanged photons between the colliding system and the laser field is also important. Indeed, for a given laser strength, the laser-assisted total cross section is enhanced as far as we sum over a large number of exchanged photons.

For example, at $\varepsilon = 2 \cdot 10^8\,\mathrm{V{\cdot}cm^{-1}}$, we have successively $\sigma = 899.68$ fb, $\sigma = 1.3 \cdot 10^3$ fb and $\sigma = 1.7 \cdot 10^3$ fb for $n = \pm 40$, $n = \pm 60$ and $n = \pm 80$.

Consequently, the total cross section in the presence of a linearly polarized laser wave can be enhanced as long as we increase the strength of the laser field and/or by summing over a big range of transferred photons. The dependence of the laser-assisted total cross section on the laser frequency is shown in figure 2 where two laser sources are considered and which are the ND:YAG laser and He:Ne laser.

In this case, the total cross section inside a linearly polarized electromagnetic field is summed from -80 to $+80$, and it increases as well as the laser source has a low frequency. At $\varepsilon = 2 \cdot 10^8$ V·cm^{-1} for instance, $\sigma = 1.7 \cdot 10^3$ fb and $\sigma = 605.95$ fb for $\omega = 1.17\,eV$ and $\omega = 2\,eV$, respectively.

The luminosity (L) is interpreted as the ability of a particle collider to produce the required number of events (useful interactions), and it is defined as the proportionality factor between the total cross section (σ) and the number of events per second (dR/dt) as follows: $dR/dt = L \cdot \sigma$.

For the luminosity $L = 1.8 \cdot 10^{34}$cm$^{-2}s^{-1}$ and for $\sqrt{s} = 500$ GeV, $m_s = 120$ GeV, $\omega = 1.17\,eV$, and $\varepsilon = 10^8$V·cm^{-1}, the number of events per second is $7.79 \cdot 10^{-3}$, $1.16 \cdot 10^{-2}$ and $1.56 \cdot 10^{-2}$ for $n = \pm 40$, $n = \pm 60$ and $n = \pm 80$, respectively. These values of events' number in the presence of a laser field are larger than their corresponding value outside an external field and that is equal to $6.47 \cdot 10^{-4}$ at $\sqrt{s} = 500$ GeV. In addition, we have $dR/dt = 3.06 \cdot 10^{-2}$ and $1.09 \cdot 10^{-2}$ for $\omega = 1.17\,eV$ and $\omega = 2\,eV$, respectively.

Therefore a powerful laser source with a small frequency and high laser strength can enhance the number of events and also the total cross-section by several orders of magnitude as compared to the laser-free cross-section.

Figure 3 shows a comparison between the laser-free cross-section with its corresponding laser-assisted total cross-section as a function of laser strength for different centre of mass energies which are $\sqrt{s} = 250$ GeV, $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1000$ GeV. Indeed, for $m_s = 120$ GeV, this laser-free total cross-section is $\sigma = 5.817$ fb, $\sigma = 35.973$ fb and $\sigma = 11.581$ fb for $\sqrt{s} = 250$ GeV, $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1000$ GeV, respectively. These values are checked by using MadGraph and CalcHEP packages [20, 21].

Inside an electromagnetic field, the probability of the process to occur increases as far as the strength of the laser raises. In addition, this increasing process depends on the colliding centre of mass energy.

We remark that the laser-assisted total cross section is high for $\sqrt{s} = 500$ GeV as well as in the absence of the laser field. Another important remark is that in contrast to the laser-free total cross-section, the laser-assisted total cross-section is high in the case of $\sqrt{s} = 250$ GeV as compared to that of $\sqrt{s} = 1000$ GeV.

4. CONCLUSION

The process of neutral Higgs pair production in IHDM in the presence of a laser wave with linear polarization is investigated in this paper. The incident electron and positron are described by Dirac-Volkov states, while the produced Higgs bosons are considered as free states. The total cross section of the studied process is calculated within the scattering matrix approach. Then, we compute and analyze the obtained results for different laser parameters and centre of mass energies. We find that a laser wave with linear polarization has a great impact on the process as it enhances its number of events and hence its cross section. This enhancement depends on laser parameters and the colliding centre of mass energy. Indeed, the total cross-section of the process increases in the case of using an intense laser wave with low frequency and high strength. In addition, this total cross section can be enhanced significantly for $\sqrt{s} = 250$ GeV as compared to $\sqrt{s} = 1000$ GeV. Consequently, we assume that the linearly polarized laser field can be a great mechanism that may help in the discovery of dark matter candidates in IHDM.

The full text of this paper is published in the English version of JETP.

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