Double Higgs Production at a Photon Collider

Abdesslam Arhrib[1,2], *Rachid Benbrik*[2,3,4], *Chuan-Hung Chen*[3,4] *and Rui Santos*[5]

[1] Faculté des Sciences et Techniques, Université Abdelmalek Essaâdi, B.P. 416, Tangier, Morocco
[2]LPHEA, Faculté des Sciences-Semlalia, B.P. 2390 Marrakesh, Morocco
[3] Department of Physics, National Cheng Kung University, Taiwan 701, Taiwan
[4] National Center for Theoretical Physics, Taiwan 701, Taiwan
[5] NExT Institute and School of Physics and Astronomy, University of Southampton Highfield, Southampton SO17 1BJ, UK

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We study double Higgs production in photon-photon collisions in the framework of two Higgs Doublet Models. We show that the fusion processes $\gamma\gamma \to S_i S_j$, $S_i = h^0, H^0, A^0$, can be enhanced by threshold effects in the region $E_{\gamma\gamma} \approx 2m_{H^\pm}$. We have scanned the allowed parameter space of the two Higgs Doublet Model and found a vast region where the cross section is two orders of magnitude above the Standard Model cross section. We further show that the Standard Model experimental analysis can be used to discover or to constraint the two Higgs doublet model parameter space.

1 Introduction

With the eminent start of CERN's Large Hadron Collider (LHC), enthusiasm is growing in the particle physics community with the prospect of finding the scalar responsible for electroweak symmetry breaking. If the Higgs is found, the next task will be to identify the underlying model and in many cases, a complete identification can only be completed with the help of a $\gamma\gamma$ collider [1, 2]. Since photons couple directly to all fundamental fields carrying electromagnetic charge, $\gamma\gamma$ collisions provide a comprehensive means of exploring virtual aspects of the Standard Model (SM) and its extensions [3]. The production mechanism in hadron and e^+e^- machines are often more complex and model-dependent.

Neutral Higgs bosons are primarily produced in $\gamma\gamma$ collisions via $\gamma\gamma \to (h^0, H^0, A^0)$ [4, 5, 6, 7] However, triple and quartic Higgs couplings can only be explored through Higgs boson pair production processes. 2HDM triple Higgs couplings could be measured at e^+e^- colliders [8]. At photon-photon colliders, the cross section for neutral Higgs boson pair production has been calculated in [9, 10] in the SM and found to be rather small. In the 2HDM, the authors of [11, 12] found that the cross section for $\gamma\gamma \to h^0h^0$ can be substantially enhanced relative to the SM one in the decoupling limit.

In this work, we present a complete calculation of pair production of all neutral Higgs bosons at the one loop level in the 2HDM. We study the Higgs self couplings effects on the $\gamma\gamma \to h^0h^0$ and $\gamma\gamma \to A^0A^0$ cross sections and briefly comment on the $\gamma\gamma \to h^0A^0$, $\gamma\gamma \to h^0H^0$, $\gamma\gamma \to H^0A^0$ and $\gamma\gamma \to H^0H^0$ production modes. This exhausts all possible neutral scalar production processes in the 2HDM. A measurement of these processes could shed some light on the 2HDM triple Higgs couplings. However, even if the situation regarding a measurement of the vertex is not clear because no peak is detected, a vast region of the 2HDM parameter space will be excluded. For a more detailed version of this study see [13].

2 The CP-conserving 2HDM

The 2HDM potential used in this work is an eight parameter potential invariant under the Z_2 discrete symmetry $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$ except for the soft breaking term $[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}]$. The vacuum structure is chosen such that the potential does not break CP spontaneously and the potential is written as

$$\begin{aligned} V(\Phi_1, \Phi_2) &= m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 + (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ &+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2}\lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}] \,, \end{aligned} \tag{1}$$

where Φ_i, $i = 1, 2$ are complex $SU(2)$ doublets and all parameters are real. After symmetry breaking, we end up with two CP-even Higgs states usually denoted by h^0 and H^0, one CP-odd state, A^0, two charged Higgs boson, $H^\pm$ and three Goldstone bosons. Because $v^2 = v_1^2 + v_2^2$ is fixed by $v^2 = (2\sqrt{2}G_F)^{-1}$, there are 7 independent parameters we can choose. We adopt as independent parameters, m_{h^0}, m_{H^0}, m_{A^0}, $m_{H^\pm}$, $\tan\beta = v_2/v_1$, α and m_{12}^2. The angle β is the rotation angle from the group eigenstates to the mass eigenstates in the CP-odd and charged sector. The angle α is the corresponding rotation angle for the CP-even sector. The Yukawa Lagrangian is a straightforward generalization of the SM one. The need to avoid tree-level flavor changing neutral currents (FCNCs) lead us to extend the Z_2 symmetry to fermions. It suffices that fermions of a given electric charge couple to no more than one Higgs doublet [14]. This can be accomplished naturally by imposing on all fields appropriate discrete symmetries that forbid the unwanted FCNC couplings. There are essentially four ways of doing this [15]: type I is the model where only the doublet ϕ_2 couples to all fermions; type II is the model where ϕ_2 couples to up-type quarks and ϕ_1 couples to down-type quarks and leptons; in a Type III model ϕ_2 couples to all quarks and ϕ_1 couples to all leptons; a Type IV model is instead built such that ϕ_2 couples to up-type quarks and to leptons and ϕ_1 couples to down-type quarks.

In our analysis we took into account all available experimental and constraints on the 2HDM parameter space. LEP direct searches give us a lower bound for particle masses (see [16] for details) except in some particular scenarios. In a general 2HDM all bounds on the Higgs masses, with the exception of the charged Higgs, can be avoided with a suitable choice of the angles and m_{12}. The extra contributions to the $\delta\rho$ parameter from the Higgs scalars [17] should not exceed the current limit from precision measurements [16]: $|\delta\rho| \lesssim 10^{-3}$. As this extra contribution to $\delta\rho$ vanishes when $m_{H^\pm} = m_{A^0}$, we demand either a small splitting between $m_{H^\pm}$ and m_{A^0} or a combination of parameters that produces the same effect. The constraint from the $B \to X_s\gamma$ branching ratio [18] gives a lower bound on the charged Higgs mass, $m_{H^\pm} \gtrsim 295\ GeV$, in 2HDM type II and III. These bounds do not apply to models type I and IV. Values of $\tan\beta$ smaller than ≈ 1 are disallowed both by the constraints coming from $Z \to b\bar{b}$ and from $B_q\bar{B}_q$ mixing [18]. Finally, we take into account the following theoretical constraints: perturbative unitarity as defined in [19, 20], vacuum stability conditions [21] that assure that the potential is bounded from below and perturbativity on the couplings, that is, $|\lambda_i| \leq 8\pi$ for all i. Finally we note that all 2HDM are protected against charge and CP-breaking [22].

3 Results and discussion

The processes $\gamma\gamma \to S_i S_j$, $S_{i,j} = h^0, H^0, A^0$ occur only at one-loop level. This makes them sensitive to virtual gauge bosons, fermions and especially charged Higgs particles. We have calculated all production modes but have paid particular attention to the $\gamma\gamma \to h^0 h^0$ mode. The one-loop amplitudes were generated and calculated with the packages FeynArts [23] and FormCalc [24]. The scalar integrals were evaluated with LoopTools and the CUBA library [25]. A cut of approximately 6^o relative to the beam axis was set on the scattering angle in the forward and backward directions. In our numerical analysis, we used $m_t = 171$ GeV, $m_b = 4.7$ GeV, $m_Z = 91.187$ GeV, $m_W = 80.45$ GeV, the Weinberg angle s_W is defined in the on-shell scheme as $s_W^2 = 1 - m_W^2/m_Z^2$ and $\alpha_{ew} = 1/137.035$.

3.1 The general 2HDM

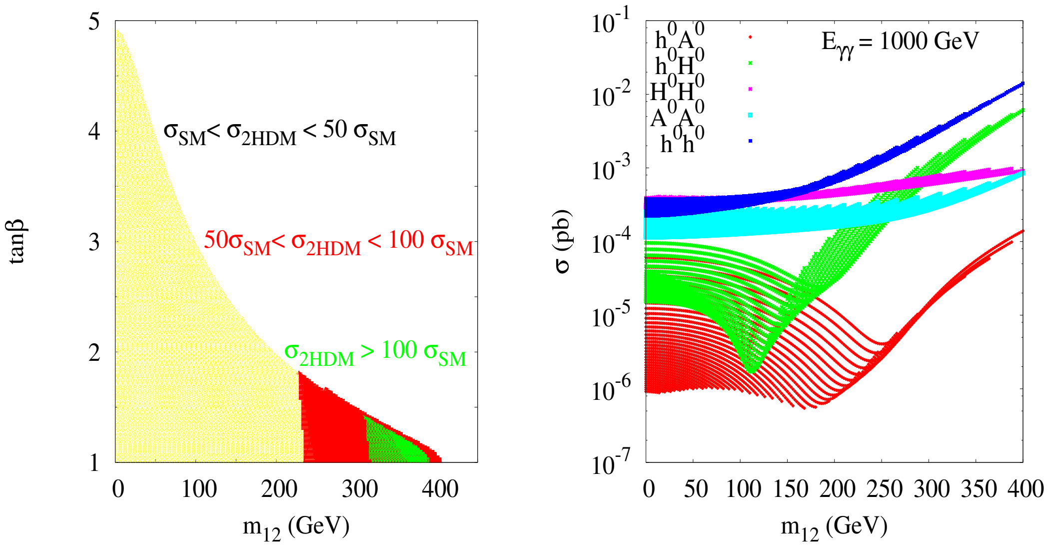

Figure 1: On the left panel we show the allowed region in the $(\tan\beta,\, m_{12})$ plane and the values of $\sigma(\gamma\gamma \to h^0 h^0)$ when compared to the SM ones, with $m_{h^0} = 115$ GeV, $m_{A^0} = 270$ GeV, $m_{H^\pm} = 350$ GeV, $m_{H^0} = 2m_{h^0}$, $E_{\gamma\gamma} = 500$ GeV, $-1 \leq \sin\alpha \leq 1$ and $1 \lesssim \tan\beta \lesssim 10$. On the right panel, we present $\sigma(\gamma\gamma \to S_i S_j)$, with $S_{i,j} = h^0, H^0, A^0$ as a function of m_{12}. We have taken $m_{h^0} = 115$ GeV, $m_{A^0} = m_{H^0} = 160$ GeV, $m_{H^\pm} = 250$ GeV, $\sin\alpha = -0.4$, $1 \lesssim \tan\beta \lesssim 10$ and $E_{\gamma\gamma} = 500$ GeV.

The very detailed parton-level study [10] concluded that for a 350 GeV center of mass energy photon collider and a Higgs mass of 120 GeV, an integrated $\gamma\gamma$ luminosity of 450 fb^{-1} would be needed to exclude a zero trilinear Higgs boson self-coupling at the 5σ level, considering only the statistical uncertainty. If one assumes the luminosity based on the TESLA design report [26] we conclude that this is an attainable luminosity in less than two years. A more recent study, although not as optimist, reaches similar conclusions [27]. Therefore, we have decided to perform a comprehensive scan of the parameter space of the 2HDM looking for regions where the 2HDM dominate over the SM, that is, $\sigma_{2HDM}(\gamma\gamma \to h^0h^0) > \sigma_{SM}(\gamma\gamma \to h^0h^0)$, together with all theoretical and experimental constraints.

The results of this scan are shown in Fig. 1. From the left scan we conclude that to have m_{12} large, unitarity constraints require $\tan\beta$ to be rather small. It is clear that in order to have a 2HDM cross section for $\gamma\gamma \to h^0h^0$ much larger than the corresponding SM one, a large m_{12} is needed together with a small value for $\tan\beta$. In the right panel of Fig. 1 we present the cross section $\sigma(\gamma\gamma \to S_iS_j)$, $S_{i,j} = h^0, H^0, A^0$ as a function of m_{12}. All processes stand a chance of being observed at a gamma-gamma collider - for large values of m_{12} all processes can be above the SM cross section of double Higgs production. The main enhancement factor for all cross section is the virtual charged Higgs bosons exchange, particularly relevant near the threshold region $E_{\gamma\gamma} = 2m_{H\pm}$. The only difference between the mixed final states and the h^0h^0 and the A^0A^0 ones, is the absence of the H^0 resonant effect, since it can not decay neither to h^0H^0 nor to H^0H^0. The situation is the same as in the SM. If $m_{h^0} \approx m_{H^0}$ all processes h^0h^0, h^0H^0 and H^0H^0 can be of the same order of magnitude and may reach 0.1 pb. If the CP-even Higgs is heavy, phase space suppression occurs and the cross sections for h^0H^0 and H^0H^0 production are smaller.

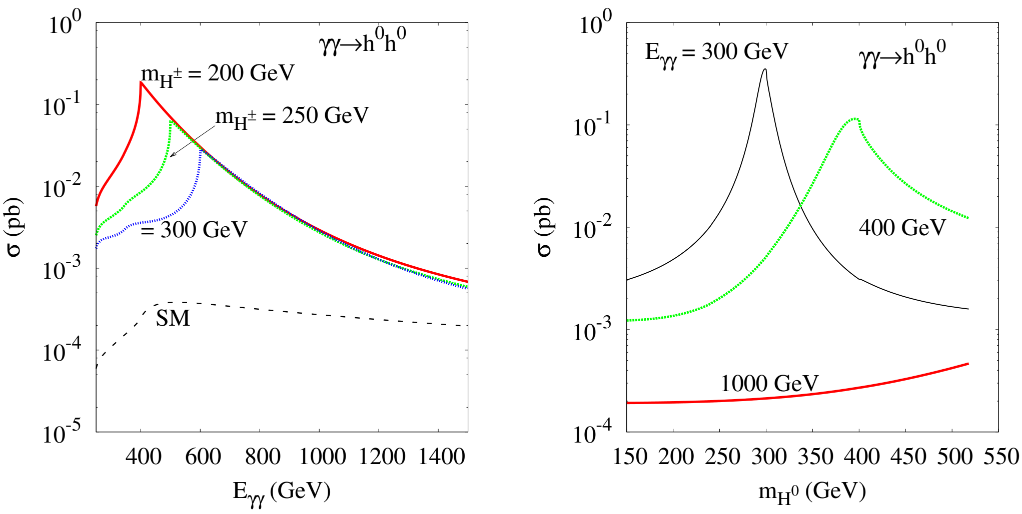

Figure 2: $\sigma(\gamma\gamma \to h^0h^0)$ as a function of the center of mass energy (left) and as a function of the heavy Higgs mass m_{H^0} (right) in the 2HDM. In the left panel the parameters are $m_{h^0}, m_{H^0}, m_{A^0}, m_{12} = 120, 200, 120, 300$ GeV, $\sin\alpha = -0.86$ and $\tan\beta = 1$. In the right panel the values are $m_{h^0}, m_{H^\pm}, m_{A^0}, m_{12} =$ 120, 250, 150, 200 GeV, $\sin\alpha = 0.9$ and $\tan\beta = 1.5$.

In Fig. 2 we present the total cross section for $\gamma\gamma \to h^0h^0$ as a function of the center of mass energy for several values of the charged Higgs mass and as a function of the heavy CP-even Higgs boson for different center of mass energies. These show the two most distinctive features of double h^0 production. First, there is an enhancement when $E_{\gamma\gamma} \approx 2m_{H\pm}$ - the cross section is largest when $\gamma\gamma \to H^+H^-$ is closed and subsequently suppressed when this threshold is crossed. This behavior is shown in the left panel of Fig. 2 where the cross section can reach 0.2 pbarn. In the left panel of Fig. 2 we show the total cross section for $\gamma\gamma \to h^0h^0$ as a function the heavy Higgs mass for several values of the center of mass energy. Once the center of mass energy is close to m_{H^0}, one can see in both plots the effect of the resonance of the heavy CP-even Higgs. In both cases, the cross sections can reach 0.1 pb near the resonance $E_{\gamma\gamma} \approx m_{H^0}$.

3.2 Decoupling limit

The decoupling regime of the 2HDM is a scenario where the light Higgs couples to the SM particles, fermions and gauge bosons, with exactly the same strength as the SM Higgs. The triple self Higgs coupling is also the SM one and the triple Higgs coupling $\lambda^{(0)}_{h^0 h^0 H^0}$ vanishes at tree-level, so that the heavy Higgs cannot contribute to the process $\gamma\gamma \to h^0 h^0$ and the result is independent of the mass m_{H^0}. All other Higgs are taken to be heavy. In the 2HDM, the decoupling limit can be achieved by taking the limit $\alpha \to \beta - \pi/2$.

There are mainly two non-decoupling effects that have a measurable impact on the cross section. One comes from the $\lambda^{2HDM}_{h^0 H^+ H^-}$ coupling and is present already at tree level. This is the case discussed in [11], where was shown that, at the 1-loop level, m^2_{12} and the charged Higgs mass are the parameters that regulate the non-decoupling effects. There is an very important contribution from the m_{12} parameter in the vertex that acts constructively for $m^2_{12} > 0$ and destructively for $m^2_{12} < 0$. The second comes from the one-loop corrections to the triple Higgs self-coupling $\lambda_{h^0 h^0 h^0}$ as described in Ref. [28] and was discussed in [12]. To account for this effect, in the calculation of the $\gamma\gamma \to h^0 h^0$ cross section, one should replace the $\lambda^{(0)}_{h^0 h^0 h^0}$ coupling by its effective coupling which corresponds, in this limit, to an effective 2-loop 2HDM contribution. In this scenario non-decoupling effects have their origin in the large values of the remaining Higgs masses. In this section we will combine the effects of ref. [11] and ref. [12] to show that even in the limit when the cross sections is reduced, there are still regions where the 2HDM Higgs h^0 could be disentangled from the SM h_{SM}.

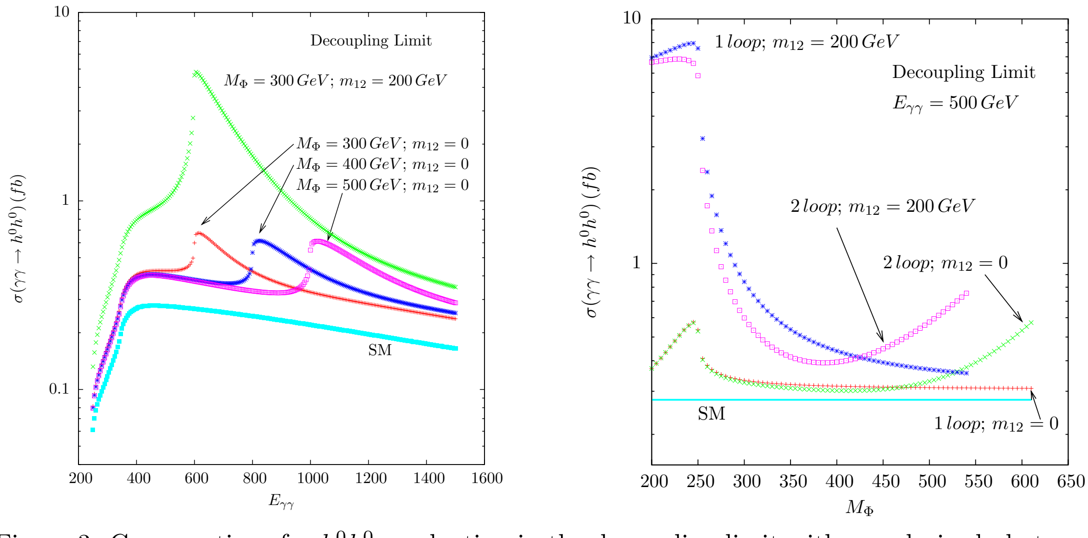

Figure 3: Cross sections for $h^0 h^0$ production in the decoupling limit with unpolarized photons. On the right we show the loop contributions to the total cross section as a function of m_Φ and for two values of m_{12}, 0 and 200 GeV. On the left panel the cross section as a function $E_{\gamma\gamma}$ is shown for different values of m_Φ and m_{12}. The light Higgs mass is $m_{h^0} = 120\ GeV$.

In the left panel of Fig. 3 we show the cross section for $\gamma\gamma \to h^0h^0$ as a function of $E_{\gamma\gamma}$ for m_Φ = 300, 400 and 500 GeV with $m_{12} = 0$ together with the case where $m_{12} = 200$ GeV and $m_\Phi = 300$ GeV. The coupling $h^0h^0h^0$ is taken at the tree-level and therefore the non-decoupling effects are only due to the charged Higgs mass threshold, $E_{\gamma\gamma} = 2\ m_\Phi$. This effect is enhanced for higher values of m_{12}. As shown in the plot, for a charged Higgs mass of 300 GeV and $m_{12} = 200\,GeV$ the cross section can reach 5 fbarn and this value grows with m_{12}. In the right panel of Fig. 3 we display the cross section of $\gamma\gamma \to h^0h^0$ as a function m_Φ. Here, besides the SM value we plot four different scenarios. The one-loop case with $m_{12} = 0$ and $m_{12} = 200\,GeV$ and the two-loop case with the higher order corrections for the same two values of m_{12}. One can see that the cross section enhancement due to the large corrections in $\lambda^{eff}_{h^0h^0h^0}$ take place only for large m_Φ if $m_{12} = 0$. As m_{12} grows the cross section grows as described in the left panel, but on top of that we get an extra enhancement due to the higher order corrections. Largest values of the cross section, that can reach 10 fbarn, are attained for the low mass region in m_Φ. We note that the cut on m_Φ at 610 GeV for $m_{12} = 0$ and on m_Φ at 550 GeV for $m_{12} = 200$ GeV is due to unitarity constraints.

4 Conclusions

In this section we sum up the main points of this work (see [13]):

- We have shown that the cross section for $\gamma\gamma \to h^0h^0$ can be more than 100 times larger than the corresponding SM one in vast regions of the parameters space. The parameter space will easily be probed for the largest allowed values of $\tan\beta$, m_{12}^2 and $|\sin\alpha|$. A light charged Higgs, that is, below the collider center of mass energy, is preferred. A variable energy collider would be a good option to detect the heavy Higgs resonance. We have shown that even with a charged Higgs mass of the order of 300 GeV, in agreement with $b \to s\gamma$, the cross section can have a substantial enhancement. In case of 2HDM type I, where a light charged Higgs is allowed the cross section could be 3 order of magnitude above the SM results;

- The analysis in [10] shows that the SM Higgs triple coupling could be probed at a photon collider. As described before, their analysis is mainly based on an invariant mass cut, on the identification of at least 3 jets as originating from b-quarks and on a the polar angle cut $|\cos\theta_b| < 0.9$. We have shown that the inclusion of the new 2HDM diagrams do not change the angular distribution so that the same cut could be applied. Moreover, for most Yukawa versions of the model and for most of the allowed parameter space, $BR(h \to b\bar{b})$ is at least the SM one if not larger. Because the invariant mass cut is the same, the analysis can be applied directly to the 2HDM case. Therefore, when a complete experimental analysis is completed for the SM, it is ready to be used to constraint the 2HDM parameter space. For heavier h^0 and for final states other then $b\bar{b}$ the analysis has to be redone. Finally we have shown that all the different final states stand a chance of being probed at a gamma gamma collider especially for large values of m_{12}.

- Although other regions give rise to higher cross sections, the very interesting case of the 2HDM decoupling limit can also be probed at the photon collider. The importance of the sign of m_{12}^2 was studied in a more general context. Clearly, positive m_{12}^2 (in our notation) can lead to large non-decoupling effects.

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References

[1] J. Brau *et al.* [ILC Collaboration], arXiv:0712.1950 [physics.acc-ph]; A. Djouadi, J. Lykken, K. Monig, Y. Okada, M. J. Oreglia and S. Yamashita, arXiv:0709.1893 [hep-ph]; N. Phinney, N. Toge and N. Walker, arXiv:0712.2361 [physics.acc-ph]; T. Behnke *et al.* [ILC Collaboration], arXiv:0712.2356 [physics.ins-det].

[2] V. I. Telnov, Acta Phys. Polon. **B37** 633 (2006).

[3] E. Boos *et al.*, Nucl. Instrum. Meth. **A472** 100 (2001).

[4] J. F. Gunion and H. E. Haber, Phys. Rev. **D48** 5109 (1993).

[5] D. L. Borden, D. A. Bauer and D. O. Caldwell, Phys. Rev. **D48**, 4018 (1993); D. L. Borden, V. A. Khoze, W. J. Stirling and J. Ohnemus, Phys. Rev. **D50**, 4499 (1994).

[6] M. M. Muhlleitner, M. Kramer, M. Spira and P. M. Zerwas, Phys. Lett. **B508** 311 (2001); M. M. Muhlleitner, arXiv:hep-ph/0008127.

[7] D. M. Asner, J. B. Gronberg and J. F. Gunion, Phys. Rev. **D67**, 035009 (2003).

[8] R. N. Hodgkinson, D. Lopez-Val and J. Sola, arXiv:0901.2257 [hep-ph]; A. Arhrib, R. Benbrik and C. W. Chiang, Phys. Rev. **D77**, 115013 (2008); G. Ferrera, J. Guasch, D. Lopez-Val and J. Sola, Phys. Lett. **B659** 297 (2008); M. N. Dubinin and A. V. Semenov, Eur. Phys. J. **C28** 223 (2003).

[9] G. V. Jikia and Yu. F. Pirogov, Phys. Lett. **B283** 135 (1992); G. V. Jikia, Nucl. Phys. **B412** 57 (1994).

[10] R. Belusevic and G. Jikia, Phys. Rev. **D70** 073017 (2004).

[11] F. Cornet and W. Hollik, Phys. Lett. **B669** 58 (2008).

[12] E. Asakawa, D. Harada, S. Kanemura, Y. Okada and K. Tsumura, Phys. Lett. **B672** 354 (2009) 354.

[13] A. Arhrib, R. Benbrik, C. H. Chen and R. Santos, arXiv:0901.3380 [hep-ph].

[14] S. L. Glashow and S. Weinberg, Phys. Rev. **D15** 1958 (1977).

[15] V. D. Barger, J. L. Hewett and R. J. N. Phillips, Phys. Rev. **D41** 3421 (1990).

[16] C. Amsler *et al.* [Particle Data Group], Phys. Lett. **B667** 1 (2008).

[17] A. Denner, R. J. Guth, W. Hollik and J. H. Kuhn, Z. Phys. **C51** 695 (1991).

[18] A. Wahab El Kaffas, P. Osland and O. Magne Ogreid, Phys. Rev. **D76**, 095001 (2007).

[19] S. Kanemura, T. Kubota and E. Takasugi, Phys. Lett. **B313**, 155 (1993).

[20] A. G. Akeroyd, A. Arhrib and E. M. Naimi, Phys. Lett. **B490**, 119 (2000); A. Arhrib, arXiv:hep-ph/0012353; J. Horejsi and M. Kladiva, Eur. Phys. J. **C46**, 81 (2006)

[21] N. G. Deshpande and E. Ma, Phys. Rev. **D18** 2574 (1978).

[22] P. M. Ferreira, R. Santos and A. Barroso, Phys. Lett. **B603** 219 (2004), [Erratum-ibid. **B629** 114 (2005)].

[23] T. Hahn, Comput. Phys. Commun. **140** 418 (2001); T. Hahn, C. Schappacher, Comput. Phys. Commun. **143** 54 (2002); J. Küblbeck, M. Böhm, A. Denner, Comput. Phys. Commun. **60** 165 (1990).

[24] T. Hahn and J. I. Illana, arXiv:0708.3652 [hep-ph]; T. Hahn and J. I. Illana, Nucl. Phys. Proc. Suppl. **160** 101 (2006); T. Hahn, M. Perez-Victoria, Comput. Phys. Commun. **118**, 153 (1999); T. Hahn and J. I. Illana, arXiv:0708.3652 [hep-ph]. T. Hahn, Nucl. Phys. Proc. Suppl. **89**, 231 (2000).

[25] G. J. van Oldenborgh, Comput. Phys. Commun. **66**, 1 (1991); T. Hahn, Acta Phys. Polon. **B30**, 3469 (1999); T. Hahn, Comput. Phys. Commun. **168** 78 (2005); T. Hahn, Nucl. Instrum. Meth. **A559** 273 (2006).

[26] B. Badelek *et al.* [ECFA/DESY Photon Collider Working Group], Int. J. Mod. Phys. A **A19** 5097 (2004).

[27] N. Maeda *et al.*, Presented at TILC09, Tsukuba, Japan.

[28] S. Kanemura, S. Kiyoura, Y. Okada, E. Senaha and C. P. Yuan, Phys. Lett. **B558** 157 (2003) S. Kanemura, Y. Okada, E. Senaha and C. P. Yuan, Phys. Rev. **D70** 115002 (2004).