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BRIEF REPORTS

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Production of Z-Higgs boson pairs at photon linear colliders

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We study the associated production of Z and standard model Higgs bosons in high energy $\gamma\gamma$ collisions with the photons originating from Compton laser backscattering. According to our results, within the framework of the standard model, this process will give rise only to very few events for a yearly integrated luminosity of 10 fb^{-1}, even at very high energies.

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Experiments at future linear e^+e^- colliders, such as the next linear collider (NLC), will be able to investigate in detail the interactions of gauge bosons, fermions, and scalars. In particular, one of the prime targets is the study of the interactions of the Higgs boson, for which the $\gamma\gamma$ mode of the collider seems especially suitable [1–3]. By using the old concept of Compton laser backscattering [4], it is feasible to obtain very energetic photons from an electron beam: The scattering of a laser with few eV against an electron beam can give rise to a scattered photon beam carrying almost all the parent electron energy with similar luminosity [5]. This mechanism can be used at the NLC [6] which has a projected center of mass energy of 500–1000 GeV with a yearly integrated luminosity around 10 fb^{-1}. At the NLC operating in the $\gamma\gamma$ mode, Higgs bosons can be produced via one-loop triangle diagrams [1], or in association with a W-boson pair ($\gamma\gamma \to W^+W^-H$) [2] or a top-quark pair ($\gamma\gamma \to t\bar{t}H$) [3].

Our aim in this note is to study the associated production of Higgs and Z bosons in $\gamma\gamma$ collisions, $\gamma\gamma \to ZH$, which occurs at the one-loop level within the scope of standard model. There are several other interesting processes that take place at photon colliders at the one-loop level, such as photon-photon scattering [7], the production of Z pairs [8], γZ pairs [9], and Higgs boson pairs [10]. Our calculation complements the literature for the evaluation of one-loop processes in $\gamma\gamma$ collisions.

In the standard model, the process $\gamma\gamma \to ZH$ occurs, *a priori*, via lepton, quark, and W boson loops. Nevertheless, because of the C-conserving couplings of the bosonic sector, the contribution of the W loops vanishes since the initial (final) state is C even (odd). Therefore this reaction takes place only through the fermionic triangle and box one-loop diagrams involving the axial couplings of the Z. This implies that the helicity amplitude ($T^{\gamma\gamma}$) for this process can be readily obtained from the known result (T^{gg}) for the reaction $gg \to ZH$ [11,12] through the replacement

$$\alpha_s\, T^{gg}_{\lambda_1,\lambda_2,\lambda_3}(s,t,u)\, \delta^{ab} \longrightarrow 2N_c Q_f^2 \alpha_{\rm em}\, T^{\gamma\gamma}_{\lambda_1,\lambda_2,\lambda_3}(s,t,u)\,, \qquad (1)$$

where $N_c = 3$ is the number of colors, and Q_f is the charge of the fermion running in the loop. λ_1 and λ_2 are the helicities of the photons while λ_3 is the helicity of the Z boson. In our calculations we used the expression given in Ref. [11] for the amplitude T^{gg}.

In the helicity basis, there are 12 possible helicity configurations; however, due to CP invariance and Bose symmetry, only five of them give rise to independent contributions. Denoting by $\sigma_{\lambda_1\lambda_2\lambda_3}$ the contribution to the elementary cross section from the helicity configuration $\{\lambda_1, \lambda_2, \lambda_3\}$, we have

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$$\begin{aligned}
&\hat{\sigma}_{+++} = \hat{\sigma}_{---} \ , \\
&\hat{\sigma}_{++0} = \hat{\sigma}_{--0} \ , \\
&\hat{\sigma}_{++-} = \hat{\sigma}_{--+} \ , \\
&\hat{\sigma}_{+--} = \hat{\sigma}_{-++} = \hat{\sigma}_{-+-} = \hat{\sigma}_{+-+} \ , \\
&\hat{\sigma}_{+-0} = \hat{\sigma}_{-+0} \ .
\end{aligned} \tag{2}$$

In Fig. 1, we plot the five independent contributions as a function of the center-of-mass energy of the $\gamma\gamma$ system. The triangle loops contribute only to the $J_z = 0$ amplitudes ($+ + 0$ and $- - 0$), while the box diagrams contribute to all of them. In spite of the interference between the triangle and the box contributions being destructive [11], the largest polarized cross section comes from the $+ + 0$ helicity configuration.

Figure 2 shows the behavior of the unpolarized elementary cross section,

$$\hat{\sigma} = \frac{1}{4} \sum_{\lambda_1\lambda_2\lambda_3} \hat{\sigma}_{\lambda_1\lambda_2\lambda_3} , \tag{3}$$

for the subprocess $\gamma\gamma \to ZH$ as a function of the center-of-mass energy of the $\gamma\gamma$ system for two different values of the top quark mass. Since the Z boson couples axially with the fermions in the loop, the contribution of a degenerated family to this process vanishes. In fact, the invariant amplitude in this limit is proportional to

$$I_\ell Q_\ell^2 + N_c I_{\rm up} Q_{\rm up}^2 + N_c I_{\rm down} Q_{\rm down}^2 = 0 \ , \tag{4}$$

where I_f is the weak isospin of the fermion f. Therefore the cross section increases as the mass splitting inside a generation increases. In consequence, as we could expect, for a fixed value of the Higgs boson mass, the cross section at high energies is larger for a heavier top quark. Moreover, the elementary cross section exhibits peaks around the threshold for the production of the fermions – that is, for the center-of-mass energies around twice the fermion masses.

In order to evaluate the total cross section for the ZH production in a $\gamma\gamma$ collider, we must fold the photon luminosity with the subprocess elementary cross section, i.e.,

$$\sigma(s) = \int_{z_{\rm min}}^{z_{\rm max}} dz \ \frac{d\mathcal{L}_{\gamma\gamma}}{dz} \ \hat{\sigma}(\hat{s} = z^2 s) \ , \tag{5}$$

where $\sqrt{s}$ ($\sqrt{\hat{s}}$) is the center-of-mass energy of the e^+e^- ($\gamma\gamma$) system, and

$$\frac{d\mathcal{L}_{\gamma\gamma}}{dz} = 2z \int_{z^2/y_{\rm max}}^{y_{\rm max}} \frac{dy}{y} F_L(x,y) F_L(x, z^2/y) \ . \tag{6}$$

We assumed that the backscattered photon beam is not polarized and employed the spectrum of backscattered photons $F_L(x,y)$ given in Ref. [5] with $x = 4.8$ in order to maximize the available energy of the photons and to avoid unwanted e^+e^- pair production, which leads to a reduction of the $\gamma\gamma$ luminosity.

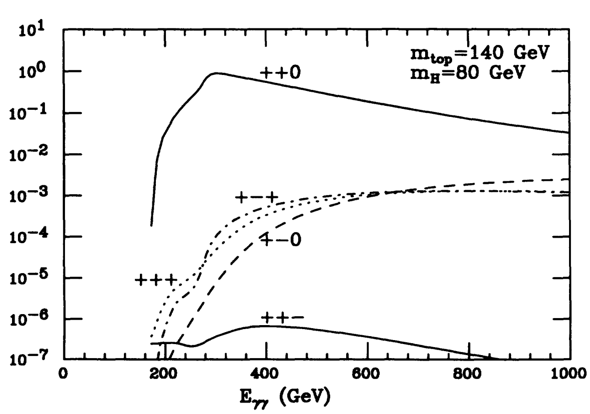

FIG. 1. Contributions to the elementary cross section $\hat{\sigma}(\gamma\gamma \to ZH)$ from each helicity amplitude as a function of the center-of-mass energy $E_{\gamma\gamma}$ assuming $M_H = 80$ and 140 GeV.

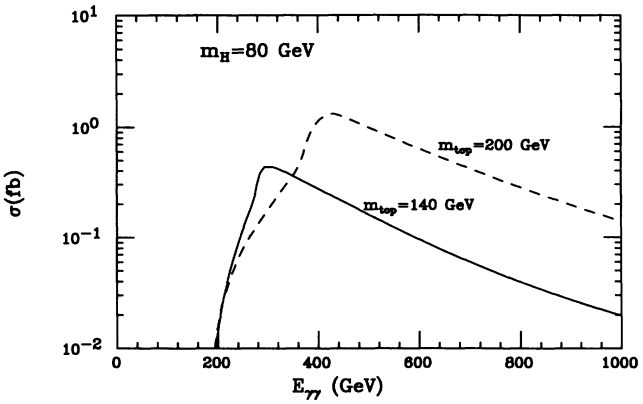

FIG. 2. Unpolarized elementary cross section $\hat{\sigma}(\gamma\gamma \to ZH)$ as a function of the center-of-mass energy $E_{\gamma\gamma}$ assuming $M_H = 80$ GeV. The solid (dashed) line corresponds to $m_{\rm top} = 140$ (200) GeV.

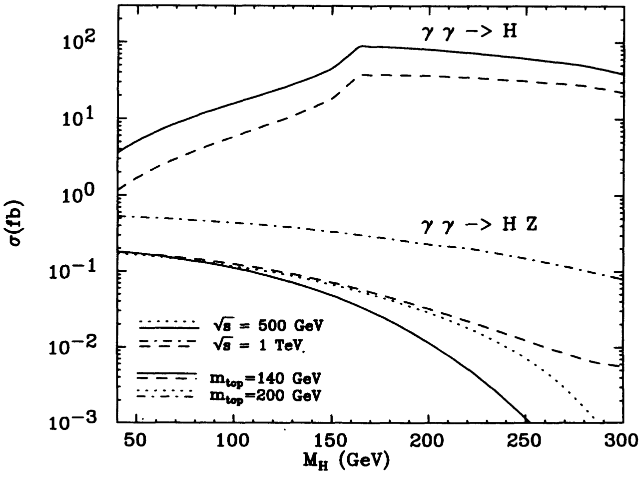

FIG. 3. Total cross section $\sigma(\gamma\gamma \to ZH)$ as a function of the Higgs boson mass (M_H) for $\sqrt{s} = 500$ and 1000 GeV and $m_{\rm top} = 140$ and 200 GeV (four lower curves). For the sake of comparison we also plotted the cross section of the process $\gamma\gamma \to H$ for $\sqrt{s} = 500$ GeV and 1 TeV (upper curves).

In Fig. 3 we plot the results for the total cross section for $\gamma\gamma \to ZH$ as a function of the Higgs boson mass (M_H)

at $\sqrt{s} = 500$ and 1000 GeV. From this figure it is clear that the cross section grows as the value of m_{top} and/or $\sqrt{s}$ increases. This behavior can be easily related to the subprocess elementary cross section given in Fig. 2 and to the available phase space for ZH production. Therefore, within the framework of the standard model, this process will give rise only to very few events for a yearly integrated luminosity of 10 fb^{-1}, even at very high energies. For the sake of comparison, we also plot the cross section for the lower order process $\gamma\gamma \to H$ [1] which is a factor 10–1000 times larger than the cross section for the ZH production. In principle, the process ZH could be used as a possible signature for invisibly decaying Higgs bosons in $\gamma\gamma$ collisions [13] since in this mode the $\gamma\gamma \to H$ production mechanism would lead to no visible signature. However, because of the low event rate, it is not possible to look for invisibly decaying Higgs bosons since the signal will be immersed in a large $\gamma\gamma \to ZZ$ background, whose cross section [8] is about 300 (1000) times larger than the ZH one, for $m_H = m_Z$ for $\sqrt{s} = 500$ GeV (1 TeV) and $m_{\text{top}} = 140$ GeV. The larger size of the ZZ cross section is due to the contribution from W loops and, as expected, the fermion-loop contributions to the ZZ and ZH processes are of the same order of magnitude (see the dotted curve in Fig. 3(b) of the first reference in [8]).

In order to access the effect of new charged particles that might exist, we also analyzed this process taking into account a fourth sequential generation of fermions. For most values of the allowed parameter space, this modification leads to a slight increase in the total cross section that is of the order of 10%. This is due to the fact that the elementary cross section is significantly modified only for the center-of-mass energies above the threshold for the production of the new fermions and the limited available phase space in this energy regime. An interesting scenario that might increase dramatically the event rate for the ZH production is the enlargement of the Higgs sector, e.g., two doublet models. In this case, there will be contributions from bosonic W loops for the associate production of a Z and a pseudoscalar Higgs boson and it is expected, as in the Z pair production [8], that this will dominate over the fermionic one.

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[1] O. J. P. Éboli, M. C. Gonzalez-Garcia, F. Halzen, and D. Zeppenfeld, Phys. Rev. D **48**, 1430 (1993); J. F. Gunion and H. E. Haber, *ibid.* **48**, 5109 (1993).

[2] M. Baillargeon and F. Boudjema, Phys. Lett. B **317**, 371 (1993).

[3] E. Boos, I. Ginzburg, K. Melnikov, T. Sack, and S. Shichanin, Z. Phys. C **56**, 487 (1992); K. Cheung, Phys. Rev. D **47**, 3750 (1993).

[4] F. R. Arutyunian and V. A. Tumanian, Phys. Lett. **4**, 176 (1963); R. H. Milburn, Phys. Rev. Lett. **10**, 75 (1963); see also C. Akerlof, University of Michigan Report No. UMHE 81-59, 1981 (unpublished).

[5] I. F. Ginzburg, G. L. Kotkin, V. G. Serbo, and V. I. Telnov, Nucl. Instrum. Methods **205**, 47 (1983); **219**, 5 (1984); V. I. Telnov, *ibid.* **A294**, 72 (1990).

[6] R. B. Palmer, Annu. Rev. Nucl. Part. Sci. **40**, 529 (1990).

[7] X.-D. Jiang and X.-J. Zhou, Phys. Rev. D **47**, 214 (1993); F.-X. Dong, X.-D. Jiang, and X.-J. Zhou, *ibid.* **47**, 5169 (1993); G. V. Jikia and A. Tkabladze, Phys. Lett. B **323**, 453 (1994).

[8] G. V. Jikia, Phys. Lett. B **298**, 224 (1993); Nucl. Phys. **B405**, 24 (1993); M. S. Berger, Phys. Rev. D **48**, 5121 (1993); D. A. Dicus and C. Kao, *ibid.* **49**, 1265 (1994).

[9] G. Jikia and A. Tkabladze, Report No. IFVE 93-151 (hep-ph 9312274) (unpublished).

[10] G. V. Jikia and Yu. F. Pirogov, Phys. Lett. B **283**, 135 (1992); G. V. Jikia, Nucl. Phys. **B412**, 57 (1994).

[11] B. A. Kniehl, Phys. Rev. D **42**, 2253 (1993).

[12] D. A. Dicus and C. Kao, Phys. Rev. D **38**, 1008 (1988); **42**, 2412(E) (1990).

[13] A. Lopez-Fernandez, J. C. Romão, F. de Campos, and J. W. F. Valle, Phys. Lett. B **312**, 240 (1993); O. J. P. Éboli, M. C. Gonzalez-Garcia, A. Lopez-Fernandez, S. F. Novaes, and J. W. F. Valle, U. W. Madison Report No. MAD/PH/810, (hep-ph 9312278) [Nucl. Phys. (to be published)].