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PHOTON AND GLUON-FUSION AS A PROBE[⋆] OF HIGGS-SECTOR CP VIOLATION

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Abstract

We discuss the advantages of polarized photon and gluon beams for testing CP violation induced in the neutral-scalar sector of the two-Higgs-doublet extension of the Standard Model. We demonstrate that the ability to polarize the photons produced by back-scattering laser beams, at a TeV-scale linear e^+e^- collider, could make it possible to determine whether or not a neutral Higgs boson produced in photon-photon collisions is a CP eigenstate. Asymmetries that are non-zero only if the Higgs boson is a CP mixture are defined and calculated. We also show that the same source of CP violation can be directly probed using gluon-gluon collisions at the SSC or LHC. We point out that the possibility of measuring the high-energy photon helicity would be very useful in tests of CP violation induced by the neutral-scalar sector.

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An important issue for understanding electroweak symmetry breaking and physics beyond the Standard Model (SM) is whether or not CP is violated in the Higgs sector. For instance, both spontaneous and explicit CP violation are certainly possible in the context of a general two-Higgs-doublet model (2HDM).[1] In a CP-conserving 2HDM, there are three neutral Higgs bosons: two CP-even scalars, h^0 and H^0 ($m_h^0 \leq m_H^0$), and one CP-odd scalar, A^0. If the scalar sector of the 2HDM is CP-violating, there will simply be three mixed states, $\phi_{i=1-3}$, with undefined CP parity. In cases considered in the literature CP violation appears usually as one-loop effect; consequently, it must be quite small and therefore difficult to observe. We wish to contrast the above rather significant difficulties with the situation that arises in collisions of polarized photons[2] or polarized gluons.[3] We first concentrate on the former case. High luminosity for such collisions is possible using back-scattered laser beams at a TeV-scale linear e^+e^- collider.[4,5]

The basic physics behind our techniques is well-known.[1] A CP-even scalar couples to $\gamma_1\gamma_2$ via $F_{\mu\nu}F^{\mu\nu}$, yielding (in the centre of mass of the two photons) a coupling strength proportional to $\mathbf{e}\cdot\widetilde{\mathbf{e}}$, while a CP-odd scalar couples via $F_{\mu\nu}\widetilde{F}^{\mu\nu}$, implying a coupling proportional to $(\mathbf{e}\times\widetilde{\mathbf{e}})_z$. [Quantities without (with) a tilde belong to γ_1 (γ_2).] We write the general amplitude for a mixed-CP state ϕ to couple to $\gamma\gamma$ as $M = \mathbf{e}\cdot\widetilde{\mathbf{e}}\, e + (\mathbf{e}\times\widetilde{\mathbf{e}})_z\, o$, where e (o) represents the CP-even (-odd) coupling strength. Then the helicity amplitude squares and interferences of interest are:

$$\begin{aligned} |M_{++}|^2 + |M_{--}|^2 &= 2(|e|^2 + |o|^2), \qquad & 2\mathrm{Re}\,(M^*_{--}M_{++}) &= 2(|e|^2 - |o|^2), \\ |M_{++}|^2 - |M_{--}|^2 &= -4\mathrm{Im}\,(eo^*), \qquad & 2\mathrm{Im}\,(M^*_{--}M_{++}) &= -4\mathrm{Re}\,(eo^*). \end{aligned} \tag{1}$$

It is useful to define the three ratios:

$$\mathcal{A}_1 \equiv \frac{|M_{++}|^2 - |M_{--}|^2}{|M_{++}|^2 + |M_{--}|^2}, \quad \mathcal{A}_2 \equiv \frac{2\mathrm{Im}\,(M^*_{--}M_{++})}{|M_{++}|^2 + |M_{--}|^2}, \quad \mathcal{A}_3 \equiv \frac{2\mathrm{Re}\,(M^*_{--}M_{++})}{|M_{++}|^2 + |M_{--}|^2}. \tag{2}$$

Note that $\mathcal{A}_1 \neq 0$, $\mathcal{A}_2 \neq 0$, and $|\mathcal{A}_3| < 1$ only if *both* the even and odd CP couplings e and o are present. For a CP-even (-odd) eigenstate $\mathcal{A}_1 = \mathcal{A}_2 = 0$ and $\mathcal{A}_3 = +1$ (-1). It turns out that fully circular polarization (P_c) for the initial laser photon and maximal average helicity (λ_e) for the incoming electron yield the best photon energy spectrum for the study of a Higgs boson and nearly 100% circular polarization for the back-scattered photon's polarization for most photon energies. The most straightforward method to measure $\mathcal{A}_1$ would be to compare the production rate for (λ_e, P_c) and for those with reversed signs, which would correspond to $(++)$ and $(--)$ photon modes.

A convenient, explicit form for the number of Higgs-boson events is obtained by normalizing to the two-photon decay width of the Higgs boson obtained after summing over final-state photon polarizations. From Refs. [6] and [7] the number of Higgs bosons, N_ϕ, produced after averaging over colliding photon polarizations is:

$$\begin{aligned} N_\phi &= \left.\frac{dL_{\gamma\gamma}}{dW}\right|_{W=m_\phi} \frac{4\pi^2\Gamma(\phi\to\gamma\gamma)}{m_\phi^2} \\ &\simeq 1.54\times 10^4 \left(\frac{L_{ee}}{\mathrm{fb}^{-1}}\right)\left(\frac{E_{ee}}{\mathrm{TeV}}\right)^{-1}\left(\frac{\Gamma(\phi\to\gamma\gamma)}{\mathrm{keV}}\right)\left(\frac{m_\phi}{\mathrm{GeV}}\right)^{-2} F(m_\phi), \end{aligned} \tag{3}$$

where $F(W) = (E_{ee}/L_{ee})dL_{\gamma\gamma}/dW$ is a slowly varying function whose value depends upon details of the machine design, but is $\mathcal{O}(1)$. In Eq. (3), E_{ee} and L_{ee} are the e^+e^- machine energy and integrated luminosity. For the case of interest, where photons are polarized, the expressions for N_ϕ in Eq. (3) are multiplied by $(1 + \langle\zeta_2\widetilde{\zeta}_2\rangle(m_\phi))$, where $\zeta_2, \widetilde{\zeta}_2$ are the corresponding Stokes parameters.

We now turn to estimating the observability of the Higgs boson and the associated polarization asymmetries. In our normalization conventions we compute $\Gamma(\phi\to\gamma\gamma)$ as:

$$\Gamma(\phi\to\gamma\gamma) = \frac{\alpha^2 g^2}{1024\pi^3}\frac{m_\phi^3}{m_W^2}\left(|e|^2 + |o|^2\right), \tag{4}$$

where

$$e = \sum_i S^i_\phi, \quad o = \sum_i P^i_\phi, \tag{5}$$

and S^i_ϕ, P^i_ϕ represent CP-even, CP-odd triangle contributions of type i. The only non-zero P^i_ϕ's derive (at the one-loop triangle diagram level) from i = charged fermion. Although our computations include fermion loops from all quarks and leptons, we illustrate e and o by displaying the expressions keeping only b, t, W, and H^+ triangles. In this case, we have

$$\begin{aligned} e &= N_c e_t^2 s_{t\bar t} F^s_{1/2}(\tau_t) + N_c e_b^2 s_{b\bar b} F^s_{1/2}(\tau_b) + s_{W^+W^-} F_1(\tau_{W^+}) + s_{H^+H^-} F_0(\tau_{H^+}), \\ o &= N_c e_t^2 p_{t\bar t} F^p_{1/2}(\tau_t) + N_c e_b^2 p_{b\bar b} F^p_{1/2}(\tau_b), \end{aligned} \tag{6}$$

where $N_c = 3$ for quarks, $e_t = 2/3$ and $e_b = -1/3$ are the t and b fractional charges, and $\tau_i \equiv 4m_i^2/m_\phi^2$. The F_i's are those defined in Appendix C of Ref. [1]. The reduced CP-even (scalar, s) and CP-odd (pseudoscalar, p) couplings are given by

$$\begin{gathered} s_{t\bar t} = \frac{u_2}{\sin\beta}, \quad p_{t\bar t} = -u_3\cot\beta, \quad s_{b\bar b} = \frac{u_1}{\cos\beta}, \quad p_{b\bar b} = -u_3\tan\beta, \\ s_{W^+W^-} = u_2\sin\beta + u_1\cos\beta. \end{gathered} \tag{7}$$

Reduced couplings for the charged leptons follow those for $b\bar b$, while in Eq. (6) one would have $N_c = 1$ and charge -1. In the above, the u_i specify the eigenstate ϕ in the Φ_i basis of Ref. [8] (see Ref. [9] for more details). In Eq. (7) we gave no expression for $s_{H^+H^-}$, since it is expected to be small and therefore has been neglected.[2]

We will not attempt to study the backgrounds in detail here. Instead, we will use the results of Refs. [6] and [7] to estimate that a Higgs boson could be seen if its polarization-averaged event rate is such that there are at least 80 $b\bar b$ decays, or 80 $t\bar t$ decays, or 20 clean ZZ (with one $Z\to l^+l^-$) decays.

For the illustration we will adopt a machine energy of $E_{ee} = 0.5$ TeV, an integrated luminosity of $L_{ee} = 20\ \mathrm{fb}^{-1}$, and use the rough value of $F(W) \simeq 1$ in Eq. (3) in computing event rates. We will search for the values of $|\mathcal{A}_1|$, $|\mathcal{A}_2|$, and $|\mathcal{A}_3|$ that maximize the observability of CP violation, subject to the minimum event number requirements stated above. This search is performed separately for each of the observables by randomly scanning over all allowed u_i values. We will present our results as functions of m_ϕ for various values of m_t and $\tan\beta$. The statistical significance, N^1_{SD}, of event number differences deriving from the $\mathcal{A}_1$ is $N^1_{SD} \equiv \sqrt{2N}|\mathcal{A}_1|$. For the statistical significance $N^{2,3}_{SD}$ corresponding to $\mathcal{A}_{2,3}$, see Ref. [2].

Let us now discuss the asymmetry observables corresponding to these maximal N_{SD} values, (see Fig. 1). We focus on $\mathcal{A}_1$. The $|\mathcal{A}_1|$ is generally small and decreases with increasing m_ϕ for $m_\phi < 2m_W$. This is because the only significant imaginary contribution to the sum of loop

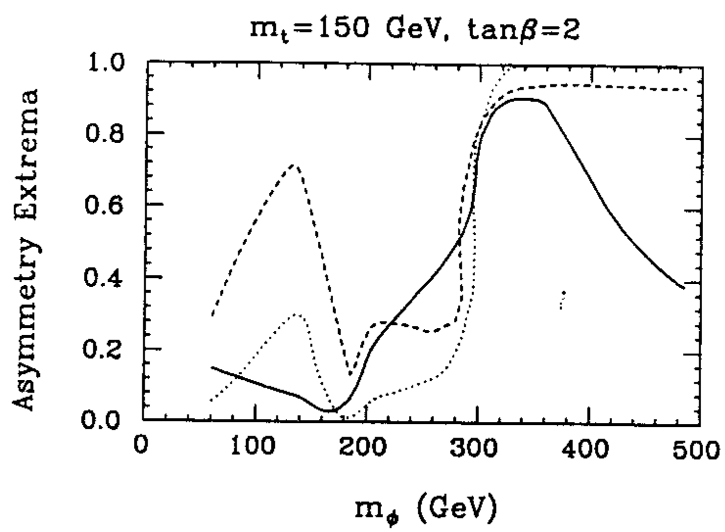

Figure 1: The values for $|\mathcal{A}_1|$ (———), for $|\mathcal{A}_2|$ (– – – –), and for $(1-|\mathcal{A}_3|)$ (· · · ·), which yield the largest statistical significances, N^1_{SD}, N^2_{SD}, and N^3_{SD}, respectively (see text and Ref. [2]), as a function of m_ϕ. We have taken $\tan\beta = 2$ and $m_t = 150$ GeV.

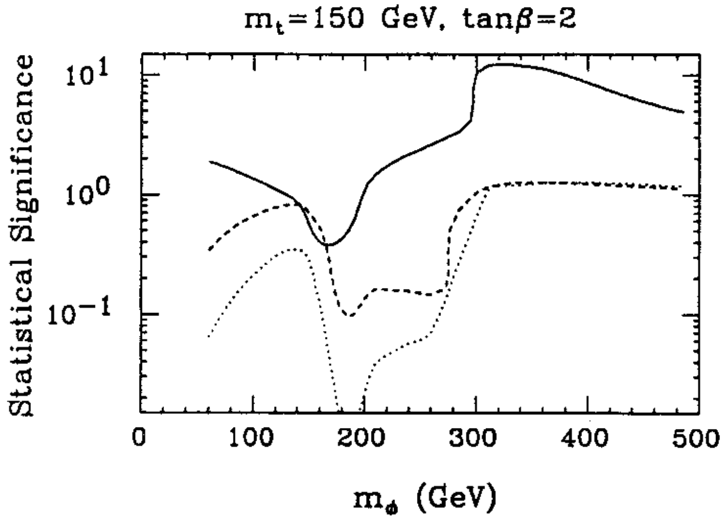

Figure 2: The maximum statistical significances N^1_{SD}, N^2_{SD}, and N^3_{SD}, for observing $|\mathcal{A}_1|$ (———), $|\mathcal{A}_2|$ (– – – –), and $(1-|\mathcal{A}_3|)$ (· · · ·), (for $N^{2,3}_{SD}$ see Ref. [2]) respectively, as a function of m_ϕ. We have taken $\tan\beta = 2$ and $m_t = 150$ GeV.

amplitudes comes from the b loop, and this imaginary part declines in magnitude as $\tau_b \ln(4/\tau_b)$. In this region, maximal statistical significance is achieved for values of $u_3 \gtrsim 0.6$, and if u_1 and u_2 have the same sign. The latter implies that the ϕWW coupling is not small, thereby keeping the basic production rate significant (recall that the W loop generally dominates). Once m_ϕ is above the W^+W^- threshold, a much larger imaginary part for the CP-even amplitude e is possible. In order to maximize interference, preferred values of u_3 remain large. Further, u_1 and u_2 continue to have the same sign; this allows for a large W-loop imaginary part, large basic production cross section, and large $\phi \to ZZ$ branching ratio. Not surprisingly, the best signal is in the ZZ channel for $2m_Z < m_\phi < 2m_t$. As m_ϕ passes beyond $2m_t$, for this case where m_t is significantly larger than m_W it is easier to achieve a large t-loop imaginary part than a W-loop one; effectively the $\mathcal{A}_1$ increases.

In summary, of the three possible CP-sensitive polarization asymmetries, $\mathcal{A}_1$ provides the best opportunities for studying the CP properties of a neutral Higgs boson produced in $\gamma\gamma$ collisions of polarized back-scattered laser photons. A non-zero value for $\mathcal{A}_1$ requires that the $\phi\gamma\gamma$ coupling have an imaginary part, as well as both CP-even and CP-odd contributions.

Hereafter we will show that the CP nature of a neutral Higgs boson (ϕ) could also be probed by the difference between its production rates through gluon-gluon fusion processes for colliding proton beams of opposite polarizations. The proposed asymmetry is closely analogous to that developed previously for collisions of polarized back-scattered laser beams. We compute the magnitude of the asymmetry that can be expected at the SSC in the context of a general 2HDM for a variety of models of the polarized gluon distribution function, $\Delta g(x)$. For all but extremely conservative $\Delta g(x)$ choices, large asymmetries are possible since the gg coupling to the CP-even and CP-odd components of the ϕ are generically comparable (both arising at one loop). Indeed, we find that asymmetries larger than 10% are quite typical; these would be observable in the $\phi \to ZZ \to l^+l^-X$ final state after 1 to 3 years of running.[3]

The procedure for computing the $gg \to \phi$ cross section in leading order is well-known.[1] Crucial to our discussion is the degree of polarization that can be achieved for gluons at the SSC. The amount of gluon polarization in a positively-polarized proton beam, defined by the standard structure function difference $\Delta g(x) = g_+(x) - g_-(x)$, is not currently known with any certainty.

We shall employ a variety of models that have appeared in the literature. In one extreme, also considered in Ref. [10], we assume that $\Delta g(x) = 0$ at all x when $Q^2 = 10$ GeV^2. The Q^2 evolution will retain $\Delta g \equiv \int_0^1 \Delta g(x)\,dx = 0$ (i.e. gluons never carry any portion of the proton's spin), but $\Delta g(x)$ will develop substantial oscillations at the large Q values of interest for Higgs-boson production. Another extreme is to assume that none of the proton's spin can be carried by strange quarks. This is the second case considered in Ref. [10], and leads to large Δg: $\Delta g \sim 4.5$ at $Q^2 = 10$ GeV^2.[11] Aside from numerical differences, this is also the choice considered in Ref. [11]. We shall label this case (2). We employ the detailed $\Delta g(x)$ form given in Ref. [10]. We also compute results for an intermediate choice, case (3), of $\Delta g \sim 2$ (at $Q^2 = 10$ GeV^2) considered in Ref. [10], using their parametrization for $\Delta g(x)$. Two additional $\Delta g(x)$ parametrizations have also been employed. These are: the Berger-Qiu parametrization[12] $\Delta g(x) = g(x)$ $(x > x_c)$, $\Delta g(x) = \frac{x}{x_c} g(x)$ $(x < x_c)$, where $x_c \sim 0.2$ yields a value of $\Delta g \sim 2.5$ at $Q^2 = 10$ GeV^2, case (4); and the rather modest $\Delta g(x)$ proposal of Ref. [13], with $\Delta g \sim 0.2$ at $Q^2 = 10$ GeV^2, case (5). In obtaining results for Higgs-boson production, we have computed the evolved $\Delta g(x)$ starting with the $Q^2 = 10$ GeV^2 inputs specified in cases (1–5), using a standard polarized structure function evolution.

The asymmetry we compute is simply $A \equiv [\sigma_+ - \sigma_-]/[\sigma_+ + \sigma_-]$, where $\sigma_\pm$ is the cross section for Higgs-boson production in collisions of an unpolarized proton with a proton of helicity $\pm$, respectively. The numerator $[\sigma_+ - \sigma_-]$ is proportional to the integral over x_1 and x_2 (with $x_1 x_2 = m_\phi^2/s$) of $g(x_1)\Delta g(x_2)\left[|\mathcal{M}_{++}|^2 - |\mathcal{M}_{--}|^2\right]$, while $\sigma_+ + \sigma_-$ is determined by the integral of $g(x_1)g(x_2)\left[|\mathcal{M}_{++}|^2 + |\mathcal{M}_{--}|^2\right]$. $\mathcal{M}_{ii}$ is the gluon analogy of the M_{ii} defined for photons. (We have assumed that it is proton 2 that is polarized. Distribution functions will be evaluated at $Q = m_\phi$.) Now, $|\mathcal{M}_{++}|^2 - |\mathcal{M}_{--}|^2$ vanishes for a CP eigenstate, but can be quite large in a general 2HDM. We find $|\mathcal{M}_{++}|^2 - |\mathcal{M}_{--}|^2 \propto -4\mathrm{Im}(\mathcal{E}\mathcal{O}^*)$ and $|\mathcal{M}_{++}|^2 + |\mathcal{M}_{--}|^2 \propto 2\left(|\mathcal{E}|^2 + |\mathcal{O}|^2\right)$, where $\mathcal{E}$ ($\mathcal{O}$) represents the gg coupling to the CP-even (-odd) component of ϕ. These depend upon the reduced CP-even (scalar, s) and CP-odd (pseudoscalar, p) couplings given by Eq. (7).

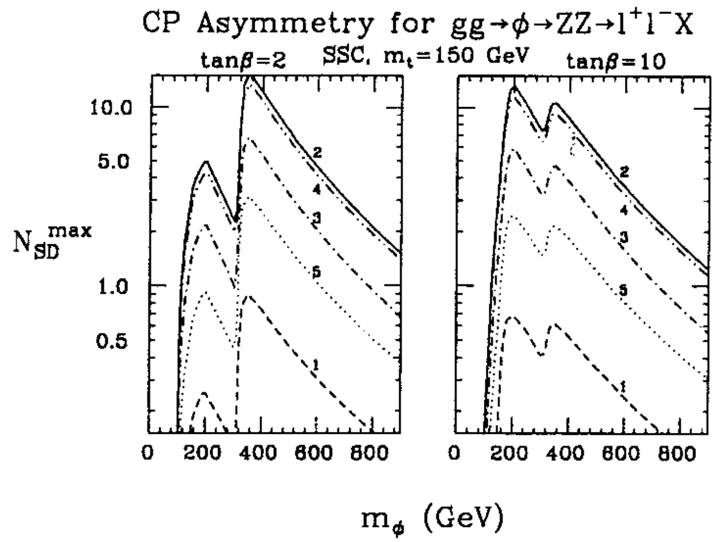

Figure 3: Maximal statistical significance, N_{SD}^{max}, achieved for the asymmetry signal in the $\phi \to ZZ \to l^+l^-X$ channel as a function of m_ϕ at the SSC with $L = 10$ fb^{-1}. The curves for different $\Delta g(x)$ choices are labelled by the case number, 1–5.

To obtain a numerical indication of the observability of A, we assume that ϕ can be best detected in the $\phi \to ZZ \to l^+l^-X$ modes (where $l = e, \mu$ and we include all possible X — $X = l^+l^-, \tau\overline{\tau}, q\overline{q}, \nu\overline{\nu}$ — so that the net branching ratio for $ZZ \to l^+l^-X$ is ~ 0.134). We compute the statistical significance of the asymmetry signal as $N_{SD} \equiv (N_+ - N_-)/\sqrt{N_+ + N_-}$, where N_+ (N_-) is the number of events predicted for positive (negative) proton polarization in the $ZZ \to l^+l^-X$ mode. Since $\Delta g(x) \to g(x)$ at large x, we impose a cut on the Higgs-boson events designed to enhance the importance of large x_2 in the convolution integrals contributing to the numerator and denominator of the asymmetry A.[3] Finally, we search (at fixed $\tan\beta = v_2/v_1$) for the parameters of the most general CP-violating 2HDM which yield the largest achievable statistical significance N_{SD}^{max}.

Our ability to detect A may be either better or worse than that illustrated in Fig. 3 , since we have neglected the effects of non-perfect proton polarization, limited acceptance efficiency and ZZ continuum background. For a more complete discussion, see Ref. [3].

Finally, it should not be forgotten that all our predictions are based upon the assumption that the heaviest coloured fermion that acquires its mass via the Higgs mechanism is the top quark. For $m_\phi > 2m_t$, the addition of a new generation of quarks yields a large increase in the observability of A (not to mention the observability of the ϕ in the first place).

In conclusion, we emphasize that the ability to polarize one of the proton beams at the SSC or LHC will provide a unique opportunity for determining the CP nature of any observed neutral Higgs boson.

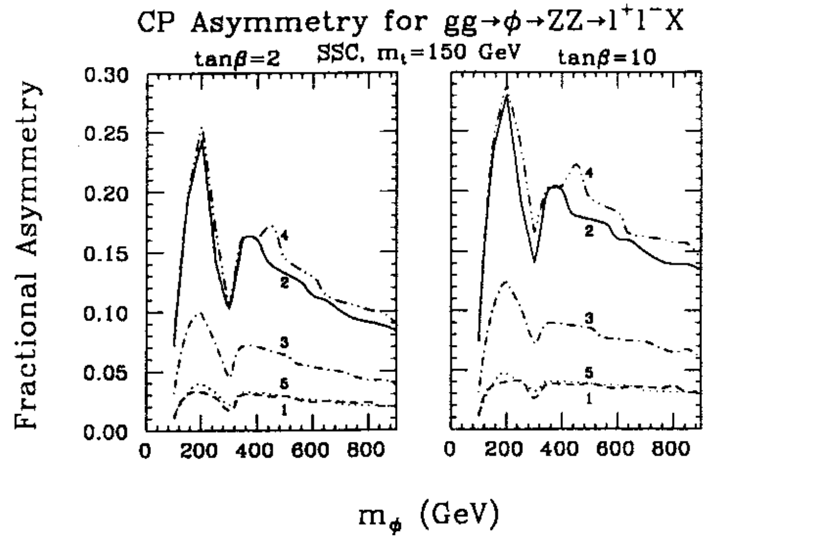

Figure 4: Fractional asymmetry, A, for which N_{SD} is maximal, as a function of m_ϕ at the SSC with $L = 10$ fb^{-1}. The curves for different $\Delta g(x)$ choices are labelled by the case number, 1–5.

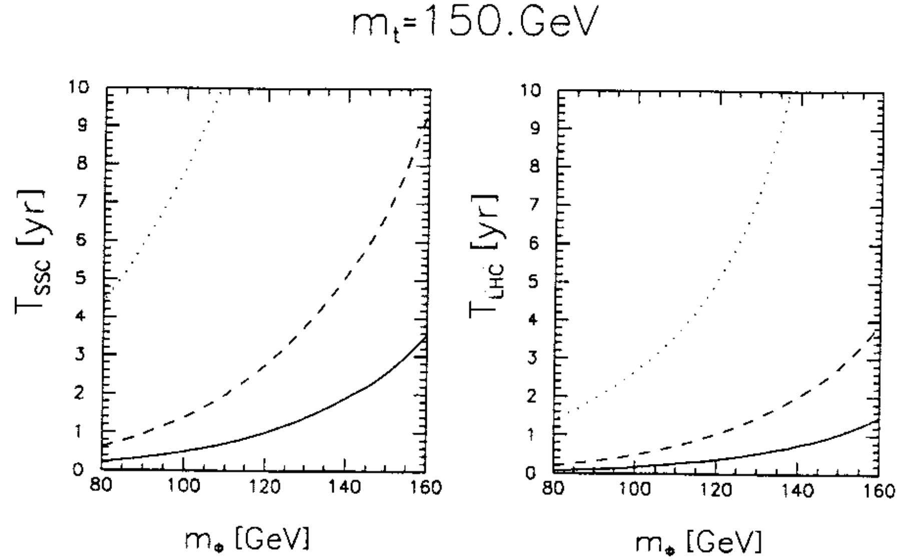

Figure 5: We plot the number of years required at the SSC (10 fb^{-1}) or LHC (100 fb^{-1}) to observe $A_{\phi\to\gamma\gamma}$ at the 3σ level for $\tan\beta = 2$ ($\cdot\cdot\cdot\cdot$), 10 ($-\ -\ -$), and 20 (——), for $m_t = 150$ GeV.

Finalizing, we would like to point here at another interesting scenario. Assume first (unfortunately quite unrealistically) that we can measure helicities of high-energy photons (with an energy of the order of 100 GeV). Now, instead of producing Higgs bosons in collisions of polarized photons or gluons, let us consider the standard Higgs-boson production mechanism for a pp collider (gg or bb fusion) followed by its decay into *polarized* photons. Providing we can control the photons polarization, it turns out to be a very effective way to observe CP violation induced by the Higgs sector. Using results obtained for the Higgs-boson production, one can easily calculate the asymmetry $\mathcal{A}_{\phi\to\gamma\gamma} = (|M'_{++}|^2 - |M'_{--}|^2)/(|M'_{++}|^2 + |M'_{--}|^2)$, where M'_{ii} stands for the amplitude for the production of two photons with indicated helicities through Higgs-boson exchange at a pp collider. Since Higgs-boson production at the SSC and LHC is going to be very substantial, this method could be extremely effective, providing one can control the helicity of final photons. Statistical significance for that case is $N_{SD} = \sqrt{N_\phi BR(\phi \to \gamma\gamma)}\mathcal{A}_{\phi\to\gamma\gamma}$, where N_ϕ is the total number of produced Higgs bosons. In Fig. 5 we present the minimal time necessary to observe $\mathcal{A}_{\phi\to\gamma\gamma}$ at the 3σ level ($T[\mathrm{yr}] > (3/N_{SD})^2$). Although we have not included any experimental details and backgrounds, it is clear from the figure that it may be a very promising method to observe CP violation induced by the scalar sector.

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