Physics at the Photon Linear Collider $^a$

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The physics prospects of the high energy Photon Linear Collider are reviewed, emphasizing its potential to study the symmetry breaking sector, including Higgs searches and precision anomalous $W$ couplings measurements.

1 Introduction

Using the process of Compton backscattering of laser light off electron beams from the linear collider one can obtain $\gamma\gamma$ and $\gamma e$ colliding beams with an energy and luminosity comparable to that in $e^+e^-$ collisions. The expected physics at the Photon Linear Collider (PLC) is very rich and complementary to that in $e^+e^-$ collisions. Since there exist several excellent extensive reviews on the subject only the issues concerning the electroweak physics based on recent progress that has been achieved since Photon’95 Conference in Sheffield are summarized here.

2 Higgs boson physics

Discovery and study of Higgs boson(s) will be of primary importance at future $pp$ and linear $e^+e^-$ and $\gamma\gamma$ colliders. The survey of the Higgs physics opportunities of PLC is simultaneously a very good example showing how the complete phenomenological portrait is obtained only by combining the complementary information available from these distinct types of machines.

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2.1 Measurements of the Higgs boson couplings

The most fundamental properties of the Higgs boson are its mass, its total width and its partial widths. Ideally, one would wish to determine, in a model-independent way, all of the tree-level and one-loop couplings of the $h^0$, its spin, parity, and $CP$ nature, and its total width. The total Higgs width, while certainly important in its own right, becomes even more so since it is required in order to compute many important partial widths, which provide the most direct means of verifying that the observed Higgs boson is or is not the $h_{SM}$.

While branching ratios, being the ratio of a partial width to the total width can not be unambiguously interpreted, any deviations of partial widths from SM predictions can be directly compared to predictions of alternative models such as the MSSM, the Non-Minimal Supersymmetric Standard Model, or the general two Higgs doublet model (2HDM).\[11\]

The predicted width, $\Gamma_{h_{SM}}^{\text{tot}}$, and branching ratios are plotted in Fig. 1 as a function of $m_{h_{SM}}$. For $m_{h_{SM}} \lesssim 2M_W$, $\Gamma_{h_{SM}}^{\text{tot}}$ is too small to be reconstructed in the final state and only indirect determination of $\Gamma_{h_{SM}}^{\text{tot}}$ is possible at NLC and LHC using a multiple step process; the best process depends upon the Higgs mass. In this respect $\gamma\gamma$ collider mode offers a unique possibility to produce the Higgs boson as an $s$-channel resonance decaying, for instance, into $bb$:

$$\gamma\gamma \rightarrow h^0 \rightarrow bb$$

and thereby measuring the rate for the Higgs boson production in $\gamma\gamma$ mode of...
the linear collider we can determine the value of the Higgs two-photon width itself. Assuming that 300-500 GeV linear collider will first start operating in $e^+e^-$ mode, the mass of the $h^0$ will already be known from the Bjorken reaction $e^+e^- \rightarrow Z^* \rightarrow Zh$, and the beam energy could be tuned so that the $\gamma\gamma$ luminosity spectrum peaks at $m_h$. The Higgs two-photon decay width is of special interest by itself since it appears at the one-loop level. Thus, any heavy charged particles which obtain their masses from electroweak symmetry breaking can contribute in the loop. Moreover, for $m_{h_{SM}} \lesssim 130 \text{ GeV}$ (i.e. in the MSSM $m_{h^0}$ range), the only known procedure for determining the total Higgs width $\Gamma_{h}^{\text{tot}}(h)$ is that based on the measurement of $\Gamma(h \rightarrow \gamma\gamma)$ in the reaction (1) as described in Ref. [1].

The following procedure could be used. First one should measure the cross section of the single Higgs production at PLC

$$\sigma(\gamma\gamma \rightarrow h^0 \rightarrow X) = \tau \frac{dL_{\gamma\gamma}}{d\tau} \frac{8\pi^2}{m_h^2} \Gamma(h^0 \rightarrow \gamma\gamma) \cdot BR(h^0 \rightarrow X)(1 + \lambda_1 \lambda_2)$$

and determine $\Gamma(h \rightarrow \gamma\gamma)BR(h \rightarrow b\bar{b})$. Here the effective photon-photon luminosity $L_{\gamma\gamma}$ is introduced, $\tau = m_h^2/s$. Then one can compute the two-photon width as a ratio

$$\Gamma(h \rightarrow \gamma\gamma) = \frac{\Gamma(h \rightarrow \gamma\gamma)BR(h \rightarrow b\bar{b})}{BR(h \rightarrow b\bar{b})}. \tag{3}$$

The branching ratio $BR(h \rightarrow b\bar{b})$ will also already be known from $e^+e^-$ annihilation. Indeed, measuring $\sigma(e^+e^- \rightarrow ZH)$ (in the missing mass mode) and $\sigma(e^+e^- \rightarrow ZH)BR(h \rightarrow b\bar{b})$ in $e^+e^-$ mode of the linear collider we can compute

$$BR(h \rightarrow b\bar{b}) = \frac{\sigma(e^+e^- \rightarrow ZH)BR(h \rightarrow b\bar{b})}{\sigma(e^+e^- \rightarrow ZH)} \tag{4} \text{,}$$

the error in the branching ratio is estimated at $\pm(5 \div 10)\%$. Finally, one can compute the total Higgs boson width

$$\Gamma_{h}^{\text{tot}}(h) = \frac{\Gamma(h \rightarrow \gamma\gamma)BR(h \rightarrow \gamma\gamma)}{BR(h \rightarrow \gamma\gamma)}, \tag{5}$$

using the $BR(h \rightarrow \gamma\gamma)$ determination(s) at NLC and LHC [1].

$$BR(h \rightarrow \gamma\gamma) = BR(h \rightarrow b\bar{b}) \frac{\sigma(e^+e^- \rightarrow Zh)BR(h \rightarrow \gamma\gamma)}{\sigma(e^+e^- \rightarrow Zh)BR(h \rightarrow b\bar{b})} \tag{6} \text{.}$$

The other alternative is to employ FMC $\mu^+\mu^-$ collisions at $\sqrt{s} \sim m_{h_{SM}}$ and directly measure $\Gamma_{h_{SM}}^{\text{tot}}$ by scanning.
\[ \text{BR}(h \rightarrow bb) \left[ \frac{\sigma(pp \rightarrow Wh) \text{BR}(h \rightarrow \gamma\gamma)}{\sigma(pp \rightarrow Wh) \text{BR}(h \rightarrow bb)} \right] \]

and compute in a model-independent way partial Higgs decay widths that are directly related to fundamental couplings

\[ \Gamma(h \rightarrow bb) = \Gamma_h^{\text{tot}} \text{BR}(h \rightarrow bb), \quad \Gamma(h \rightarrow gg) = \Gamma_h^{\text{tot}} \text{BR}(h \rightarrow gg) \ldots \quad (7) \]

The observable cross section for the $\gamma\gamma$ Higgs signal in the gluon fusion reaction at the LHC can depend quite strongly on the masses and couplings of the superpartners and Higgs bosons, particularly if they are not too heavy, and it varies from a few fb to more than 100 fb over the parameter space of the MSSM, even in the scenario that supersymmetry is not discovered at LEP2. 

Having measured $\text{BR}(h \rightarrow gg) \cdot \Gamma(h \rightarrow \gamma\gamma)$ (with an error of order $\pm 22\%$ at $m_{h,SM} = 120 \text{ GeV}$) and combining this number with the value of the Higgs total and two-photon decay width, measured in $\gamma\gamma$ and $e^+e^-$ experiments one can calculate the two-gluon Higgs branching ratio and partial width.

The main background to the $h^0$ production is the continuum production of $bb$ and $cc$ pairs. In this respect, the availability of high degree of photon beams circular polarization is crucial, since for the equal photon helicities ($\pm$) that produce spin-zero resonant states, the $\gamma\gamma \rightarrow q\bar{q}$ QED Born cross section is suppressed by the factor $m_q^2/s$. Another potentially dangerous backgrounds originate from the resolved-photon processes in which a gluon from the photon structure function produces $bb$, $cc$ pairs, and from the continuum production of $bb$ pairs accompanied by the radiation of additional gluon, calculated taking into account large QCD $\mathcal{O}(\alpha_s)$ radiative corrections, which are not suppressed even for the equal photon helicities. Virtual one-loop QCD corrections for $J_z = 0$ were found to be especially large due to the double logarithmic enhancement factor, so that the corrections are comparable or even larger than the Born contribution for the two-jet final topologies.

For small values of the cutoff $y_{cut}$, separating two and three-jet events, two-jet cross section, calculated to order $\alpha_s$, becomes even negative in the central region. Recently leading QCD corrections for $J_z = 0$ have been calculated at the two-loop level. The non-Sudakov form factor in the double logarithmic approximation, including the two-loop contribution, is given by

\[ \left. \frac{\sigma_{2\text{-loop}}}{\sigma_{\text{Born}}} \right|_{J_z=0} = 1 - 2\frac{\alpha_s}{\pi} \log^2 \left( \frac{s}{m_b^2} \right) + \frac{121}{108} \left( \frac{\alpha_s}{\pi} \right)^2 \log^4 \left( \frac{s}{m_b^2} \right). \quad (8) \]

The account of two-loop contribution makes cross section to be positive and the authors of Ref. argue that the higher order contributions are not so
anomalously large. Anyway, these detailed studies have shown that the Higgs signal can still be observed well above the background with the statistical error of the Higgs cross section at the 10 ± 30% level in the wide range of Higgs mass 60 ÷ 170 GeV. The net error on $\Gamma(h_{\text{SM}} \to \gamma\gamma)BR(h_{\text{SM}} \to b\bar{b})$ for $L = 50 \text{ fb}^{-1}$ is illustrated in Fig. 2. Thus, the error in the $m_{h_{\text{SM}}} \lesssim 120$ GeV mass region will be in the 8% ÷ 10% range, rising to 15% by $m_{h_{\text{SM}}} = 140$ GeV and peaking at 30% at $m_{h_{\text{SM}}} = 170$ GeV, as illustrated in Fig. 2.

![Figure 2: Accuracy with which $\Gamma(h_{\text{SM}} \to \gamma\gamma)BR(h_{\text{SM}} \to b\bar{b} \text{ or } WW, ZZ)$ can be measured at the PLC](image)

For the Higgs bosons heavier than $2M_Z$ the Higgs signal in $\gamma\gamma$ collisions can be observed in ZZ decay mode if one of the Z’s is required to decay to $l^+l^−$ to suppress the huge tree-level $\gamma\gamma \to W^+W^−$ continuum background. However, even though there is no tree-level ZZ continuum background, such a background due to the reaction $\gamma\gamma \to ZZ$ does arise at the one-loop level in the electroweak theory which makes the Higgs observation in the ZZ mode impossible for $m_h \gtrsim (350 \div 400)$ GeV. It was found that for $185 \lesssim m_h \lesssim 300$ GeV the ZZ mode will provide a 10-20% determination of the quantity $\Gamma(h \to \gamma\gamma) \cdot BR(h \to ZZ)$ (see Fig. 2).

The accuracies of the various measurements involved are a crucial issue. The errors for $\Gamma_{h_{\text{SM}}}^{\text{tot}}$ are tabulated in Table 1.

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For $m_{h_{\text{SM}}} \gtrsim 130$ GeV one can compute $\Gamma_{h_{\text{SM}}}^{\text{tot}} = \Gamma(h_{\text{SM}} \to WW^*)/BR(h_{\text{SM}} \to WW^*)$ using LHC data. Combined error for $\Gamma_{h_{\text{SM}}}^{\text{tot}}$ is quoted in the Table for this mass range.
Table 1: The errors for $\Gamma(h_{\text{SM}} \rightarrow \gamma\gamma)$ as determined using luminosity of $L = 50 \text{ fb}^{-1}$ accumulated in $\gamma\gamma$ collisions at $\sqrt{s}_{e^+e^-} \sim m_{h_{\text{SM}}}/0.8$. Approximate errors for Higgs total width, branching ratios, and couplings-squared are given for $L = 200 \text{ fb}^{-1}$ at $\sqrt{s} = 500 \text{ GeV}$ NLC. For $BR(h_{\text{SM}} \rightarrow \gamma\gamma)$ the NLC and LHC results are combined.

| Quantity             | Errors       |
|----------------------|--------------|
| $m_{h_{\text{SM}}}$(GeV) | 80 | 100 | 110 | 120 |
| $(\gamma\gamma h_{\text{SM}})^2/(bbh_{\text{SM}})^2$ | $\pm 42\%$ | $\pm 27\%$ | $\pm 24\%$ | $\pm 22\%$ |
| $BR(h_{\text{SM}} \rightarrow b\bar{b})$ | $\pm 5\%$ | $\pm 5\%$ | $\pm 5\%$ | $\pm 5\%$ |
| $BR(h_{\text{SM}} \rightarrow \gamma\gamma)$ | $\pm 15\%$ | $\pm 14\%$ | $\pm 13\%$ | $\pm 13\%$ |
| $(\gamma\gamma h_{\text{SM}})^2$ | $\sim \pm 12\%$ | $\sim \pm 12\%$ | $\sim \pm 12\%$ | $\sim \pm 12\%$ |
| $P_{\text{tot}}^h_{\text{SM}}$ | $\pm 19\%$ | $\pm 18\%$ | $\pm 18\%$ | $\pm 18\%$ |
| $(bbh_{\text{SM}})^2$ | $\pm 20\%$ | $\pm 19\%$ | $\pm 18\%$ | $\pm 18\%$ |
| $m_{h_{\text{SM}}}(\text{GeV})$ | 130 | 140 | 150 | 170 |
| $(\gamma\gamma h_{\text{SM}})^2/(bbh_{\text{SM}})^2$ | $\pm 23\%$ | $\pm 26\%$ | $\pm 35\%$ | $\sim \pm 20\%$ |
| $BR(h_{\text{SM}} \rightarrow b\bar{b})$ | $\pm 6\%$ | $\pm 9\%$ | $\sim 20\%$ |
| $BR(h_{\text{SM}} \rightarrow \gamma\gamma)$ | $\pm 13\%$ | $\pm 18\%$ | $\pm 35\%$ | $\sim \pm 20\%$ |
| $(\gamma\gamma h_{\text{SM}})^2$ | $\pm 15\%$ | $\pm 17\%$ | $\pm 31\%$ | $\sim \pm 20\%$ |
| $P_{\text{tot}}^h_{\text{SM}}$ | $\pm 13\%$ | $\pm 9\%$ | $\pm 10\%$ | $\pm 11\%$ |
| $(bbh_{\text{SM}})^2$ | $\pm 14\%$ | $\pm 11\%$ | $\pm 13\%$ | $\pm 23\%$ |
| $m_{h_{\text{SM}}}(\text{GeV})$ | 180 | 190 | 200 | 300 |
| $(ZZ h_{\text{SM}})^2$ | $\pm 4\%$ | $\pm 5\%$ | $\pm 6\%$ | $\pm 9\%$ |
| $(\gamma\gamma h_{\text{SM}})^2$ | $\pm 13\%$ | $\pm 12\%$ | $\pm 12\%$ | $\pm 22\%$ |
| $P_{\text{tot}}^h_{\text{SM}}$ | $\pm 13\%$ | $\pm 14\%$ | $\pm 15\%$ | $\pm 28\%$ |

2.2 Measurements of the Higgs boson CP-properties

The ability to control the polarizations of back-scattered photons provides a powerful means for exploring the CP properties of any single neutral Higgs boson that can be produced with reasonable rate at the Photon Linear Collider\textsuperscript{22}. A CP-even Higgs bosons $h^0$, $H^0$ couple to the combination $\vec{\epsilon}_1 \cdot \vec{\epsilon}_2 = -1/2 (1 + \lambda_1 \lambda_2)$, while a CP-odd Higgs boson $A^0$ couples to $\vec{\epsilon}_1 \times \vec{\epsilon}_2 \cdot \vec{k}_\gamma = \omega_\gamma/2i \lambda_1 (1 + \lambda_1 \lambda_2)$, where $\vec{\epsilon}_i$ and $\lambda_i$ are photon polarization vectors and helicities. The first of these structures couples to linearly polarized photons with the maximal strength if the polarizations are parallel, the letter if the polarizations are perpendicular. Moreover, if the Higgs boson is a mixture of CP-even and CP-odd states, as can occur e.g. in a general 2HDM with CP-violating neutral sector, the interference of these two terms gives rise to a CP-violating asymmetries\textsuperscript{22}. Two CP-violating ratios could contribute to linear order with respect to CP-violating couplings:

$$A_1 = \frac{|M_{++}|^2 - |M_{--}|^2}{|M_{++}|^2 + |M_{--}|^2}, \quad A_2 = \frac{2 Im(M^*_{--}M_{++})}{|M_{++}|^2 + |M_{--}|^2}$$

(9)
Since the event rate for Higgs boson production in $\gamma\gamma$ collisions is given by

$$dN = dL_{\gamma\gamma}dP S_{\gamma\gamma} \frac{1}{4}(|M_{++}|^2 + |M_{--}|^2) \times [(1 + \langle \xi_2 \tilde{\xi}_2 \rangle) + (\langle \xi_2 \rangle + \langle \tilde{\xi}_2 \rangle) A_1 + (\langle \xi_2 \tilde{\xi}_1 \rangle + \langle \xi_1 \tilde{\xi}_3 \rangle) A_2],$$

(10)

where $\xi_i, \tilde{\xi}_i$ are the Stokes polarization parameters, two CP-violating asymmetries could be observed. The first one is

$$A_{\text{circ}} = \frac{N_{++} - N_{--}}{N_{++} + N_{--}} = \frac{\langle \xi_2 \rangle + \langle \tilde{\xi}_2 \rangle}{1 + \langle \xi_2 \tilde{\xi}_2 \rangle} A_1,$$

(11)

where $N_{\pm\pm}$ correspond to the event rates for positive (negative) initial photon helicities. Experimentally the measurement of the asymmetry is achieved by simultaneously flipping the helicities of both of the initiating laser beams. Since the $A_{\text{circ}}$ is proportional to the imaginary part of the SM contribution to the $\gamma\gamma \rightarrow h^0$ amplitude, which is very small below $2M_W$ threshold, this asymmetry can be useful only for $m_h \gtrsim 2M_Z$. The asymmetry to be observed with linearly polarized photons is given by

$$A_{\text{lin}} = \frac{N(\chi = \pi/4) - N(\chi = -\pi/4)}{N(\chi = \pi/4) + N(\chi = -\pi/4)} = \frac{\langle \xi_3 \tilde{\xi}_1 \rangle + \langle \xi_1 \tilde{\xi}_3 \rangle}{1 + \langle \xi_2 \tilde{\xi}_2 \rangle} A_2,$$

(12)

$\chi$ is the angle between the linear polarization vectors of the photons. The attainable degree of linear polarization $l_{\gamma}$ at PLC depends on the value of $z_m = (\sqrt{s}_{\gamma\gamma})_{\text{max}}/2E_b$, which can be changed in the case of free electron laser. For $z_m = 0.82$ the degree of linear polarization is $l_{\gamma} \sim 0.33$ only, but $l_{\gamma} \gtrsim 0.8$ at $z_m \lesssim 0.5$. One finds that the asymmetries are typically larger than 10% and are observable for a large range of 2HDM parameter space if CP violation is present in the Higgs potential.

2.3 The discovery of the heavy states in extended Higgs models

The PLC potential to discover Higgs bosons is especially attractive in the search for heavy Higgs states in the extended models such as MSSM. The most important limitation of a $e^+e^-$ collider in detecting the MSSM Higgs bosons is the fact that they are produced only in pairs, $H^0 A^0$ or $H^+ H^-$ and the parameter range for which the production process, $Z^* \rightarrow H^0 A^0$ has adequate event rate is limited by the machine energy to $m_A \sim m_H \lesssim \sqrt{s_{ee}}/2 - 20$ GeV ($m_{A^0} \sim m_{A^0}$ for large $m_{A^0}$). At $\sqrt{s_{ee}} = 500$ GeV, this means $m_{A^0} \lesssim 230$ GeV. As $e^+e^- \rightarrow H^+ H^-$ is also limited to $m_{H^\pm} \sim m_{H^0} \lesssim (220\div 230)$ GeV, it could happen that only a rather SM-like $h^0$ is detected in $e^+e^-$ mode of the
linear collider, and none of the other Higgs bosons are observed. On the other hand, $H^0$ and $A^0$ can be singly produced as $s$-channel resonances in the $\gamma\gamma$ mode and PLC might allow the discovery of the $H^0$ and/or $A^0$ up to higher masses. Particularly interesting decay channels at moderate $\tan\beta$ and below $t\bar{t}$ threshold are $H^0 \rightarrow h^0h^0$ (leading to a final state containing four $b$ quarks) and $A^0 \rightarrow Zh^0$. These channels are virtually background free unless $m^0_h \sim m_W$, in which case the large $\gamma\gamma \rightarrow W^+W^-$ continuum background would have to be eliminated by $b$-tagging. Discovery of the $A^0$ or $H^0$ up to about $0.8\sqrt{s_{ee}}$ would be possible. For large $\tan\beta$, the detection of the $A^0$ or $H^0$ in the $b\bar{b}$ channel should be possible for masses $\leq 0.8\sqrt{s_{ee}}$, provided that effective luminosities as high as 200 fb$^{-1}$ can be accumulated.

![Figure 3: The cross sections of some processes in $\gamma\gamma$, $\gamma e$ and $e^+e^-$ collisions.](image)

3 Gauge boson physics

Without the discovery of a Higgs boson at LEP2, LHC or linear collider, the best alternative to study the symmetry breaking sector lies in the study of
the self-couplings of the $W$. The PLC will be the dominant source of the $W^+W^-$ pairs at future linear colliders due to the reaction $\gamma\gamma \rightarrow W^+W^-$ with the large cross section, that fast reaches at high energies its asymptotic value $\sigma_W = 8\pi\alpha^2/M_W^2 \approx 81$ pb, which is at least an order of magnitude larger than the cross section of $W^+W^-$ production in $e^+e^-$ collisions. With the rate of about 1–3 million of $W$ pairs per year PLC can be really considered as a $W$ factory and an ideal place to conduct precision tests on the anomalous triple \cite{23,24} and quartic \cite{25} couplings of the $W$ bosons.

The cross sections of main processes with the $W$ and $Z$ production at PLC within SM are shown in Fig. \ref{fig:SM}. When the energy increases, the cross sections of a number of higher-order processes become large enough.

In spite of enormous $WW$ event rates, prospects to improve the precision of the measurement of the $W$ mass at LEP2 seem to be quite limited. The reason is that the best estimated error on $M_W$ of $30 \div 40$ MeV \cite{27} is extracted from the direct reconstruction of invariant mass of the $W$ decay products by a kinematic fit using the constraints of energy and momentum conservation. Since the energy of colliding photons is not so precisely fixed this method would not be effective at the PLC.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{Figure_4}
\caption{The tri-dimensional bounds in the case of 4 different anomalous couplings for a fit at $\sqrt{s} = 500$ GeV. The ellipsoid represents the $e^+e^-$ constraints, while $\gamma\gamma$ bounds are shown as two band projections on the planes.}
\end{figure}

At $\sqrt{s} = 500$ GeV the benefits of the reaction $\gamma\gamma \rightarrow W^+W^-$ in precise anomalous $W$ coupling measurements are clearly visible \cite{25} in Fig. \ref{fig:4parafit}, since
when combined with the bounds from $e^+e^- \rightarrow W^+W^-$ the parameter space shrinks considerably. Since only one combination of triple anomalous couplings (corresponding to $W$ anomalous magnetic moment) contributes to the reaction $\gamma\gamma \rightarrow W^+W^-$ the allowed region is constrained to be between two planes, while $e^+e^- \rightarrow W^+W^-$ being sensitive to several anomalous couplings constrains the parameter space outside the ellipsoid.

With the natural order of magnitude on anomalous couplings, one needs to know the SM cross sections with a precision better than 1% to extract these small numbers. The predictions for $W$ pair production, including full electroweak radiative corrections in the SM are known with very little theoretical uncertainty at least for energies below 1 TeV.

Although the cross section of $WW$ production is much larger in $\gamma\gamma$ collisions, this fact itself is not to be considered as an obvious advantage of PLC. The reason is that although the anomalous contribution to the amplitude of longitudinal $WW$ pair production is enhanced by a factor of $s/M_W^2$ both in $\gamma\gamma$ for $J_z = 0$ and $e^+e^-$ collisions, the SM amplitude of $WW$ production at PLC is suppressed as $M_W^4/s$, so that the contribution of the interference term to the total cross section is decreasing as $1/s$ at PLC. On the contrary, in $e^+e^-$ collisions the anomalous contribution is enhanced, corresponding to non-decreasing cross section of $WW$ production. Recently the authors of Ref. have demonstrated that enhanced coupling could still be exploited in the $\gamma\gamma$ mode. Their clever idea is to reconstruct the non diagonal elements of the $WW$ polarization density matrix by analyzing the distributions of the decay products of the $W$’s, thereby achieving the improvement over simple counting rate method of more than an order of magnitude at $\sqrt{s} = 2$ TeV. However, although the benefits from $\gamma\gamma$ mode are evident at $\sqrt{s} = 500$ GeV (Fig. 4), at energies above 1 TeV combining results from $e^+e^-$ and $\gamma\gamma$ modes does not considerably reduce the bounds obtained from $e^+e^- \rightarrow W^+W^-$ alone. This is especially true for fits with one anomalous coupling. Qualitatively these results can be understood considering the ratio $S/\sqrt{B}$ as a measure of statistical significance of the anomalous coupling signal $S$ with respect to the SM background $B$. Since the total SM cross section is decreasing as $1/s$ in $e^+e^-$ collisions and is constant $\gamma\gamma$ collisions, while the enhanced anomalous cross section behaves like a constant we get

$$\frac{S(e^+e^- \rightarrow W^+W^-)}{\sqrt{B(e^+e^- \rightarrow W^+W^-)}} \propto \sqrt{s},$$

while $S(\gamma\gamma \rightarrow W^+W^-)/\sqrt{B(\gamma\gamma \rightarrow W^+W^-)} \propto 1$. If we take into account that anomalous couplings affect mostly the cross section in the central region,
where the SM cross section behaves like $\sigma(\gamma\gamma \rightarrow W^+W^-) \sim 8\pi\alpha^2/p_T^2$, we get

$$\frac{S(\gamma\gamma \rightarrow W^+W^-)}{\sqrt{B}(\gamma\gamma \rightarrow W^+W^-)} \propto p_T,$$

i.e. the same improvement at higher energy as for $e^+e^-$ collisions but only for large values of $p_T$ cut $p_T \sim s$, with which the cross section of $WW$ production in $\gamma\gamma$ collisions is not enhanced any more with respect to production in $e^+e^-$ collisions.

The process of $W$ production with the highest cross section in $\gamma e$ collisions, $\gamma e \rightarrow W\nu$, with the asymptotic cross section of $\sigma_{e\gamma \rightarrow WW} = \sigma_W/8\sin^2\theta_W \approx 43$ pb, is very sensitive to the admixture of right–handed currents in $W$ coupling with fermions and could be also used to constrain the anomalous magnetic moment of $W_2^{±}$. Another example of the asymmetry, that could be used for the measurement of the $W$-boson anomalous magnetic and quadrupole moments has been proposed recently and is given by the so called polarization asymmetry

$$A^{+-} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}},$$

where $\sigma_{\lambda,\lambda'}$ is the polarized cross section of the reaction $\gamma e \rightarrow W\nu$. Using a quantum loop expansion it was shown that there must be a center of mass energy where the polarization asymmetry possesses a zero. The position of the zero may be determined with sufficient precision to constrain the anomalous couplings of the $W$ to better than the 1% level at 500 GeV. At higher energies the precise measurements suffer from the same problems as those discussed for $W$ pair production in $\gamma\gamma$ collisions due to suppressed yield of $W_L$’s with respect to $W_T$’s.

At higher energy the effective $W$ luminosity becomes substantial enough to allow for the study of $W^+W^- \rightarrow W^+W^-$, $ZZ$ scattering in the reactions $\gamma\gamma \rightarrow WWWW$, $WWZZ$, when each incoming photon turns into a virtual $WW$ pair, followed by the scattering of one $W$ from each such pair to form $WW$ or $ZZ$. The result is that a signal of SM Higgs boson with $m_h$ up to 700 GeV (1 TeV) could be probed in these processes at 1.5 TeV (2 TeV) PLC, assuming integrated luminosity of 200 fb$^{-1}$ (300 fb$^{-1}$). However even larger luminosity is needed in order to extract the signal of enhanced $W_LW_L$ production in models of electroweak symmetry breaking without Higgs boson. The main problem is again large background from transverse $W_TW_TW_TW_T$, $W_TW_TW_TW_T$ production.
4 Conclusions

Photon Linear Collider based on $e^+e^-$ collider with $\sqrt{s} = 500$ GeV

- provides unique opportunities to measure $\Gamma(h^0 \rightarrow \gamma\gamma)$ up to $m_h \lesssim 350$ GeV, making possible with the use of NLC and LHC measurements to measure $\Gamma_{\text{tot}}(h^0)$ and Higgs boson partial widths;
- substantially extends NLC reach in discovering heavy Higgs states $H^0$, $A^0$ in extended Higgs models such as MSSM or 2HDM;
- can provide much more stringent bounds on $W$ anomalous couplings complementary to those in $e^+e^-$ collisions.

One can fully exploit PLC potential at higher energies $\sqrt{s_{\gamma\gamma}} \sim 1 \div 2$ TeV if luminosity much higher than in $e^+e^-$ collisions is achievable.\[1\]

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