Higgs Search in the $WW^*$ Decay Mode at Photon Linear Colliders

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Abstract

We present the results of calculations for the process $\gamma\gamma \rightarrow W + 2\text{ fermions}$ at a future Photon Linear Collider (PLC). The calculations include at the same time the next-to-leading order Higgs signal and the complete tree level gauge boson background. We present numerical results in the intermediate mass Higgs region $140 \text{GeV} < M_H < 2M_W$. We propose strategies for the determination of Higgs properties using the leptonic and hadronic final states for both polarized and unpolarized photon beams.

1 Introduction

The search for a Higgs boson, the last unobserved particle predicted by the minimal electro-weak Standard Model (SM), is a primary objective for experiments at operating colliders, as well as for the planning of future colliders. The potential discovery of a fundamental Higgs particle—either at a
hadron collider (Tevatron, LHC) or at a \( e^+e^- \)-collider (LEP2, Next Linear Collider)—will initiate detailed studies and measurements of its properties like spin, parity, decay branching fractions, total width, and the couplings with gauge bosons and fermions. Any deviation of these results from the SM predictions will be a signature of new physics beyond the SM.

Electro-weak precision tests at LEP1 are sensitive to the symmetry breaking sector and a fundamental Higgs through radiative corrections to the electro-weak observables. The minimal SM and the most popular extensions (supersymmetry) favour a neutral Higgs boson in the intermediate-mass region between \( M_Z \) and just above \( 2M_Z \). In this mass range, the search for the Higgs boson and the study of its properties are delicate phenomenological and experimental problems, mostly because of large irreducible backgrounds.

In fact, the complementary information provided by different colliders has to be used \( [1, 2] \) and a Photon Linear Collider (PLC) hosted at a \( e^+e^- \) Linear Collider \( [3] \) plays an important rôle in this context. For example, the total Higgs width \( \Gamma_{H}^{\text{tot}} \), which is related directly to the fundamental couplings, can be determined in a model-independent way by simultaneously using results from various machines \( [4] \). This procedure combines the branching ratios \( \text{BR}(H^{0} \rightarrow b\bar{b}) \) and \( \text{BR}(H^{0} \rightarrow \gamma\gamma) \), measured at an \( e^+e^- \) or hadron machine, with the width \( \Gamma(H^{0} \rightarrow \gamma\gamma) \) measured at the PLC. The detailed study of the \( \gamma\gamma H^{0} \) vertex at the required precision is only possible at the PLC.

In the intermediate Higgs mass range \( 140 \text{ GeV} < M_H < 2M_Z \), the dominant decay mode is into \( WW \) pairs. This final state is contaminated by a huge tree level gauge boson background and it is generally expected that it will be very difficult to use for Higgs physics at a PLC \( [5] \).

Recently, this question has been reanalysed \( [6] \) with the conclusion that both the \( WW^* \) and \( WW \) modes can be used if a reasonable (on the order of \( 10 \text{ GeV} \)) resolution for \( WW \) invariant mass can be achieved experimentally. However, the calculations in \( [6] \) are based on on-shell matrix elements continued from above the \( WW \) pair production threshold. This method gives the correct signal to background (S/B) ratio above the threshold, of course. However, as will be shown below, it overestimates the S/B ratio significantly below the threshold. Indeed, it has already been pointed out \( [7] \) that the correct background rate below the \( WW \) threshold is dominated by the contribution of nonresonant diagrams. In the present paper we investigate the possibilities for searching for the Higgs boson in that mass range from about \( 140 \text{ GeV} \) to \( 2M_W \) at a PLC in more detail.

After a short discussion of Higgs production at a PLC in section \( [2] \), we present in this paper an analysis for the Higgs signal process including all
important corrections (cf. section 3.1)

\[ \gamma \gamma \rightarrow H^0 \rightarrow W + 2 \text{fermions} \] (1a)

together with the complete tree level calculation of the corresponding background process

\[ \gamma \gamma \rightarrow W + 2 \text{fermions} \] (1b)

which includes the subsequent decay of the \(W^*\) into quark or lepton pairs as well as all other SM contributions. In the remainder of the paper, we will often write \(\gamma \gamma \rightarrow WW^*\) for brevity. In section 3 we present numerical results for these cross sections and we investigate two extreme scenarios for the operation of a PLC in section 4. We conclude in section 5.

2 Higgs Searches at a Photon Linear Collider

The optimal strategy for the Higgs search and the experimental determination of its properties at any collider depends strongly on the value of the Higgs mass under consideration. At the PLC we can distinguish three mass ranges for the search for the intermediate mass Higgs that require different approaches.

2.1 Light Higgs: \(M_H < 140 \text{GeV}\)

In the mass range below 140 GeV, a Higgs boson decays predominantly into \(b\bar{b}\) and the Higgs signal at a PLC can be extracted from the background using highly polarized photon beams (cf. one of the latest studies \[8\] where the two loop QCD corrections have been taken into account). For collider energies up to about 300 – 400 GeV, the background from resolved photon processed remains small enough \[9\]. The potentially large four-fermion background like \(\gamma \gamma \rightarrow e^+e^-b\bar{b}\) where the \(e^+e^-\) pair is lost in the beam pipe can be suppressed by a proper cut using the different kinematics of the signal \[10\]. In this case highly polarized photon beams are not sufficient for rejecting the background, because the initial photon polarization is shared among the polarizations of the four final state fermions and therefore no strong suppression of \(b\bar{b}\) production occurs.

2.2 Heavy Higgs: \(M_H > 2M_Z\)

In the mass range above \(2M_Z\), the dominant Higgs decay mode into \(W\)-pairs is obscured by the huge tree level background \(\gamma \gamma \rightarrow WW\) \[5\]. It is possible
to utilize the interference of the Higgs signal with the $WW$ background \cite{11}, which manifests itself as a resonant dip in the $WW$ invariant mass distribution for Higgs studies. However, in this case a more detailed simulation of the four-fermion final state, including all tree level diagrams is mandatory. Alternatively, one can use the $ZZ$ mode with semileptonic four-fermion final states consisting of one neutral lepton pair and two jets \cite{5,12}. But the one-loop $\gamma\gamma \rightarrow ZZ$ background becomes important when the Higgs mass exceeds about $350 - 400$ GeV \cite{13,14} and makes a search for the Higgs even more problematic in this region.

### 2.3 Intermediate Mass Higgs: $140$ GeV < $M_H$ < $2M_Z$

In the remaining region for the Higgs mass from 140 GeV to $2M_Z$, the determination of the Higgs properties is a challenging experimental task. Here, the decay mode of Higgs to $WW$ dominates as well, but it is plagued by a huge tree level background. Nevertheless, it has been shown in \cite{6} that a signal can be extracted for Higgs masses above the $W$ pair production threshold.

In the remainder of this paper, we will discuss the $WW^*$ final state for Higgs masses below the $WW$ threshold in more detail. Despite the fact that the S/B ratio has been overestimated significantly in \cite{6}, we will present strategies for measuring Higgs properties in this region as well.

### 3 Cross Section and Background for $\gamma\gamma \rightarrow \bar{\nu}\mu^-W^+$ and $\gamma\gamma \rightarrow \bar{u}dW^+$

#### 3.1 Calculational Procedures

The SM tree-level diagrams contributing to the background process $\gamma\gamma \rightarrow WW^*$ for the quark pair final state $\bar{u}dW^+$ are shown in figure 1 and for the semileptonic final state $\bar{\nu}\mu^-W^+$ in figure 2. Only hadronic decays of the $W$ will be selected to allow for invariant mass cuts.

The calculations were performed using the software package CompHEP Version 3.2 \cite{15} for unpolarized and polarized photon beams. In the polarized case, the unpolarized initial state matrix $\sum \epsilon^\mu \epsilon^{*\nu} = -g^{\mu\nu}$ in Feynman gauge is replaced by the axial gauge expressions

$$T^\mu_\lambda = \frac{1}{2} \left[ -g^{\mu\nu} + \frac{p^\mu p'^\nu + p'^\mu p^\nu}{pp'} + i\lambda \epsilon^{\mu \nu \rho \sigma} p^\rho p'^\sigma \right]$$

where $p$ and $p'$ are the light-like Lorentz momenta of the incoming photons with $pp' = s_{\gamma\gamma}/2$ and $\lambda = \pm 1$ is the helicity, with the convention $\epsilon^{0123} = +1.$
Figure 1: Feynman diagrams for $\gamma\gamma \rightarrow \bar{u}dW^+$. 

Figure 2: Feynman diagrams for $\gamma\gamma \rightarrow \bar{\nu}\mu^{-}W^+$. 

In order to calculate the Higgs signal contribution, the effective $H\gamma\gamma$ vertex has been implemented in CompHEP. In addition, all important corrections have been included: NLO and NNLO QCD corrections to the running quark masses [16] as well as the three particle partial Higgs decay width $\Gamma_{H \to WW^*}$ with $W^* \to 2$ fermions [17]. The accuracy of the implementation of the $H\gamma\gamma$ vertex has been verified by finding very good agreement with the results from the program HDECAY [18].

3.2 Background Cross Section

Figure 3 shows the background cross section $\gamma\gamma \to WW^*$ together with the leptonic and quark subsets for $p_\perp$-cuts of 10 and 20 GeV on both fermions as a function of the photon-photon energy $\sqrt{s_{\gamma\gamma}}$. As expected, the cross sections...
vary strongly with the energy $\sqrt{s_{\gamma\gamma}}$ in the threshold region from 140 GeV to $2M_W$. Therefore, a careful consideration of the background and signal rates is mandatory.

4 Scenarios for the Higgs Search in the $WW^*$ Mode at a PLC below the $WW$ Threshold

Depending on the advances in technology, it will be possible to operate a future PLC in a variety of modes (see [3] for a recent review). In order to cover a wide range of options, we consider two extreme scenarios: scenario I is a more conservative wide-band PLC and scenario II is a technically more demanding narrow-band PLC.

- In the technically most conservative scenario I, laser backscattering is used to turn a first stage $e^+e^-$ Next Linear Collider operating at the $t\bar{t}$ threshold 360 GeV into a PLC with colliding $\gamma\gamma$ beams. A rather broad photon energy spectrum with a maximum energy at $\approx 80\%$ of the incident electron energy is expected for the colliding photons, which will be unpolarized.

- In the technically more challenging scenario II, the energy of the electron beam, the frequency of the laser, the respective polarizations and the geometry of the conversion and interaction region are tuned to produce highly polarized colliding $\gamma\gamma$ beams with energy and luminosity comparable to the underlying $e^+e^-$ machine [3]. The accelerator parameters can be chosen so that the differential $\gamma\gamma$ luminosity has a peak at a particular energy (e.g. at $\sqrt{s_{\gamma\gamma}} = M_H$) with a width of approximately 15% [3].

Until realistic energy spectra for the photons can be made available by accelerator physicists, we use a simple step function of appropriate width for our simulations. We do not expect our conclusions to depend sensitively on the shape of the spectrum. In a real analysis, a spectrum determined experimentally from a reference process will be used.

Obviously, scenario II is best suited for studying Higgs properties, provided that the Higgs mass will be known at the start of the operation of a PLC. In fact, if Nature has chosen an intermediate mass Higgs for electroweak symmetry breaking, it is likely that its mass will have been determined by $e^+e^-$- or hadron-machines at the time a PLC can be commissioned. Nevertheless, we will consider the wide-band scenario I as well, in order to show
\[ \gamma \gamma \rightarrow H^0 \rightarrow \bar{\nu}\mu^- W^+ \]

| \( \gamma \gamma \rightarrow \bar{\nu}\mu^- W^+ \) | BG/fb |
|---------------------------------|--------|
| no \( p_\perp \)-cut            | 1.64   |
| \( p_\perp > 10 \) GeV        | 1.26   |
| \( p_\perp > 20 \) GeV        | 0.43   |

Table 1: Cross sections for \( \gamma \gamma \rightarrow \bar{\nu}\mu^- W^+ \) with different \( p_\perp \)-cuts, assuming a Compton backscattering \( \gamma \)-spectrum (scenario I).

what could be achieved with a technically more conservative design and in order to gauge the gain in physics results provided by scenario II.

### 4.1 Scenario I: Wide-Band PLC

Considering the semileptonic case first, we obtain in scenario I, with a broad \( \gamma \) spectrum up to \( \sqrt{s_{\gamma\gamma}} = 0.8 \times 360 \) GeV, the cross sections in table 1, for a Higgs mass of \( M_H = 140 \) GeV. The cross sections for the Higgs signal \( \gamma \gamma \rightarrow H^0 \rightarrow \bar{\nu}\mu^- W^+ \) and the background \( \gamma \gamma \rightarrow \bar{\nu}\mu^- W^+ \) are given for various \( p_\perp \)-cuts. We have neglected the additional irreducible four-fermion background from the hadronic decay of the \( W \) boson. In the semileptonic channel, this decreases the S/B ratio only marginally compared to the huge background coming mostly from the invariant mass region above the \( WW \) threshold. This region can not be cut out, because the indeterminate photon energy and the “lost” neutrino conspire to make a full kinematical reconstruction impossible.

In table 1, we observe that the S/B ratio is prohibitively small, irrespective of the \( p_\perp \)-cut on the \( \mu \) and on the missing transversal momentum. An additional cut, \( p_\perp < 50 \) GeV, on the transversal momenta of \( \mu \) and \( W \) and on the missing transversal momentum improves the S/B ratio by a factor of two only (see figure 4 and the discussion of the hadronic final states below), which is insufficient for establishing a signal. Therefore, we have to conclude that it appears to be hopeless to find the Higgs signal in the semileptonic final state for scenario I.

Turning our attention to the hadronic final state \( \gamma \gamma \rightarrow \bar{u}dW^+ \), we obtain the cross sections shown in table 2 for three different Higgs masses. If only the canonical cuts from the Linear Collider studies [1] are used, the S/B ratio is as prohibitively small as in the semileptonic case. These cuts correspond to the most inclusive coverage of a realistic detector: a minimum energy of
| cuts      | $M_H = 140$ GeV | $M_H = 150$ GeV | $M_H = 160$ GeV |
|-----------|----------------|----------------|----------------|
|           | signal/fb      | BG/fb          | signal/fb      | BG/fb          | signal/fb      | BG/fb          |
| canonical | 4.4 7286.0     | 7.6 7286.0     | 13.6 7286.0    |
| optimized | 3.4 3.9        | 6.4 8.1        | 12.1 94.4      |

Table 2: Cross sections for $\gamma\gamma \rightarrow \bar{u}dW^+$, assuming a Compton backscattering $\gamma$-spectrum (scenario I). See the text for a description of canonical and optimized cuts.

3 GeV for the jets, a minimum angle of 10 degrees from either beam for each jet and a minimum jet/jet invariant mass of 10 GeV.

The S/B ratio can be improved dramatically by applying additional $p_T$-cuts and, most significantly, by invariant mass cuts. Figures 4a and 4b show the $p_T$-distributions of the jets and the $W$-boson produced both by a 150 GeV Higgs signal and by the corresponding background (see figure 1). These distributions suggest a transversal momentum cut of $p_T < 50$ GeV. In fact, this value can be understood from looking at the kinematics of a three-body decay of an on-shell Higgs. There the transversal momentum of particle 1 is bounded by

$$p_{\perp,1} \leq \frac{\sqrt{(M_H^2 - (m_1 + m_{23})^2)(M_H^2 - (m_1 - m_{23})^2)}}{2M_H}$$

where $m_{23}$ is the invariant mass of the other two particles. In the extreme case $m_{jj} = 0$ we find for example $p_{\perp,W} \leq (M_H^2 - M_W^2)/(2M_H)$ which is $\approx 54$ GeV for a 150 GeV Higgs.

Using a transverse momentum cut of 10 GeV $< p_{\perp} < 50$ GeV on either jet and the $W$-boson, we find the invariant mass distributions for signal and background, shown in figure 4c. Obviously, a cut on the invariant mass of $M_H - 5$ GeV $< M_{\gamma\gamma} < M_H + 5$ GeV brings the signal to the level of the background. This cut can be applied because, as mentioned in the introduction, we assume that the Higgs mass will have been determined by the time a PLC is commissioned. However, it should be noted from table 2 that the S/B ratio of nearly one for a Higgs mass at 140 GeV deteriorates when $M_H$ approaches the $WW$ threshold.

The fully hadronic final state suffers from additional combinatorial background, since the four jets can not be assigned unambiguously. Therefore a more detailed analysis using a full four-fermion calculation will have to be performed in the future. However, since we assume one of the $W$’s to be
Figure 4: Differential cross section for $\gamma\gamma \rightarrow \bar{u}dW^+$. Note that the differential distributions are identical for $\gamma\gamma \rightarrow \bar{\nu}\mu^-W^+$, only the normalization changes.
\[ M_H = 140 \text{ GeV} \]
\[ M_H = 150 \text{ GeV} \]
\[ M_H = 160 \text{ GeV} \]

| cuts | \( \gamma \gamma \rightarrow \bar{u}dW^+ \) | \( \gamma \gamma \rightarrow \bar{\nu}\mu^-W^+ \) |
|------|------------------|------------------|
|       | signal/fb BG/fb | signal/fb BG/fb |
| canonical | 221.2 122.3 | 309.4 262.2 | 566 1097 |
|        | (110.6) (179.2) | (154.7) (429.2) | (283) (2493) |
| \( p_\perp > 20 \text{ GeV} \) | 56.6 10.2 | 143.4 42.8 | 422 471 |
| \( m_{Wud} \pm 5 \text{ GeV} \) | (28.3) (19.6) | (71.7) (82.0) | (211) (1139) |
| \( p_\perp > 20 \text{ GeV} \) | 20.0 3.2 | 50.2 25.1 | 148.8 250 |
|        | (10.0) (6.5) | (25.1) (53.7) | (74.4) (593) |

Table 3: Cross sections for \( \gamma \gamma \rightarrow \bar{u}dW^+ \) and \( \gamma \gamma \rightarrow \bar{\nu}\mu^-W^+ \), assuming a narrow-band PLC (scenario II). The numbers without brackets correspond to fully polarized ((++) or (−−)) photon beams. For comparison, the numbers corresponding to unpolarized beams are given in brackets.

On-shell, an invariant mass cut on one pair of jets will have rejected most of the combinatorics.

### 4.2 Scenario II: Narrow-Band PLC

Scenario II assumes the technical feasibility [3] of producing a narrow photon spectrum around a previously measured Higgs mass. For the numerical illustrations we have chosen again Higgs masses of 140, 150 and 160 GeV.

We expect that the narrow photon energy spectrum reduces the background cross section substantially and increases the signal at the same time. This expectation is confirmed by the numerical results shown in table 3. Since the energy is fixed at the Higgs mass by the experimental conditions, we can now use also the semileptonic channel, which we had to disregard in scenario I, because the incomplete kinematical information did not allow invariant mass cuts.

In addition, the photons will be highly polarized in scenario II such that states with \( J_z = 0 \) are strongly enhanced [3]. Higgs bosons are produced only from photon helicities of (++) and (−−) that correspond to states with \( J_z = 0 \). For fully polarized photon beams, the Higgs signal cross section is enriched by a factor of two (see [3]) whereas the background is suppressed.
with respect to the unpolarized case. Close to the threshold, we can estimate this suppression factor simply [6] by comparing the \( W \) pair production cross section just above the \( WW \) threshold in the polarized \((J_z = 0)\) and unpolarized case. The cross sections read [19, 20]

\[
\sigma_{\gamma\gamma\to W^+W^-}^{\text{unpol}} = \frac{\pi\alpha^2}{2M^2}\beta \left[ 22 - 9\beta^2 + 3\beta^4 - \frac{3(1 - \beta^2)^2(1 + \beta^2)}{2\beta} \log \left| \frac{1 + \beta}{1 - \beta} \right| \right] \\
\sigma_{\gamma\gamma\to W^+W^-}^{J_z=0} = \frac{\pi\alpha^2}{2M^2}\beta(1 + 3\beta^2)(3 + \beta^2) \left[ 1 + \frac{1 - \beta^2}{2\beta} \log \left| \frac{1 + \beta}{1 - \beta} \right| \right]
\]

(4a)

with the velocity \( \beta = \sqrt{1 - 4M^2/s_{\gamma\gamma}} \). Close to threshold, these cross sections are proportional to \( \beta \). The coefficients, \( 19/2 \) in the unpolarized case and \( 3 \) in the polarized case, result in a suppression of \( W \) pair production close to threshold through photon polarization by \( 19/6 \approx 3 \). The explicit calculation including all tree diagrams and cuts shows a suppression factor varying from 2.5 to 1.5 as the Higgs mass moves down from the \( WW \) threshold (cf. table 3).

The results of the complete calculation in table 3 show that the S/B ratio is smaller than estimated in [6]. If only the very inclusive canonical cuts are applied, the S/B ratio varies from 1.8 for a 140 GeV Higgs mass to 0.5 for a 160 GeV Higgs mass close to the \( WW \) threshold. This is smaller than the values estimated in [6] by factors of 4 and 1.7, respectively. Of course, if \( p_{\perp} \)-cuts on jets, leptons and the \( W \)-boson are applied, as well as the invariant mass cut in the case of the hadronic final state, the S/B ratio improves just like in scenario I. However, we should stress that even for the most stringent cuts, the S/B ratio approaches only 5.6 for a 140 GeV Higgs mass, which remains below the 8 estimated in [6] without any cuts.

In any case, the S/B ratio with optimized cuts is sufficiently large and approaches unity for the hadronic final state, even for a Higgs mass of 160 GeV close to the \( WW \) threshold.

In addition to the improved S/B ratio, the signal cross sections are also 10 times larger in the narrow-band scenario II than in scenario I. Assuming a luminosity of 30–50 fb\(^{-1}\) year\(^{-1}\) [3], we can expect sufficient statistics at a PLC operating in scenario II.

### 5 Conclusions

We have investigated the options for extracting a signal for an intermediate mass Higgs in the process \( \gamma\gamma \to W + 2\) fermions at a future Photon Linear Collider (PLC). The more realistic signal to background (S/B) ratios are
significantly smaller than those obtained earlier [6] for $\gamma\gamma \rightarrow W^*W$. The S/B ratio is of course most favourable for a narrow band PLC with energies tuned to the Higgs mass. For a wide band PLC the hadronic final state provides enough kinematical information to raise the S/B ratio close to unity.

If a PLC can be constructed [3], it will therefore play an important part in determining the properties of an intermediate mass Higgs boson in general and in measuring the $\gamma\gamma H^0$ vertex in particular.

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