The SM Higgs boson production $\gamma\gamma \rightarrow h \rightarrow b\bar{b}$ at the Photon Collider at TESLA

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Abstract

Measurement of the $\Gamma(h \rightarrow \gamma\gamma)\text{Br}(h \rightarrow b\bar{b})$ at the photon collider at TESLA is studied for a Standard Model Higgs-boson with mass $m_h = 120$ GeV. The main background due to the process $\gamma\gamma \rightarrow Q\bar{Q}(g)$, where $Q = b, c$, is estimated using the NLO QCD program (G. Jikia) and the obtained results are compared with the corresponding LO estimate. Using a realistic luminosity spectrum and performing a detector simulation with the SIMDET program we find that the $\Gamma(h \rightarrow \gamma\gamma)\text{Br}(h \rightarrow b\bar{b})$ can be measured with an accuracy better than 2% after one year of Photon Collider running.
1 Introduction

A search of the last missing member of the Standard Model (SM) family, the Higgs boson, is among the most important tasks for the present and future colliders. Once the Higgs boson is discovered, it will be crucial to determine its properties with a high accuracy. A photon collider option of the TESLA $e^+e^-$ collider [1] offers a unique possibility to produce the Higgs boson as an s-channel resonance. The neutral Higgs boson couples to the photons through a loop with massive charged particles. This loop induced $h\gamma\gamma$ coupling is sensitive to contributions of new particles, which appear in various extensions of the SM.

The SM Higgs boson with a mass below $\sim 140$ GeV is expected to decay predominantly into the $b\bar{b}$ final state. Here we consider the process $\gamma\gamma \rightarrow h \rightarrow b\bar{b}$ for the Higgs-boson mass $m_h = 120$ GeV, to be realized at a photon collider at TESLA. Both, the signal and background events are generated according to a realistic photon-photon luminosity spectrum [2], parametrized by a CompAZ model [3]. Our analysis incorporates a simulation of the detector response according to the program SIMDET [4].

2 Photon-photon luminosity spectrum

The Compton backscattering of a laser light off a high energy electron-beam is considered as a source of high energy, highly polarised photons for a $\gamma\gamma$ collider [5]. A simulation of the realistic $\gamma\gamma$ luminosity spectra at the photon collider at TESLA, taking into account nonlinear corrections and higher order QED processes, has become available recently [2]. In this simulation, according to the current design [1], an energy of the laser photons $\omega_L$ is assumed to be fixed, for all considered electron-beam energies.

In the analysis we use the CompAZ parametrization [3] of the spectrum [2] to generate energies of the colliding photons. We assume that the energy of primary electrons can be adjusted in order to enhance the signal, which corresponds to the projection of the total $\gamma\gamma$ angular momentum on a collision (z) axis, $J_z$, equal to zero. For $\sqrt{s_{ee}} = 2E_e = 210$ GeV we obtain a peak of the $J_z = 0$ component of the photon-photon luminosity spectra at the invariant mass of the two colliding photons $W_{\gamma\gamma}$ equal to the considered mass of the Higgs boson $m_h = 120$ GeV.

The luminosity spectrum are shown in Fig. 1. The lowest invariant mass of the two colliding photons used in the generation of events, is equal to $W_{\gamma\gamma\min} = 80$ GeV. For the assumed $\sqrt{s_{ee}}$ value, the maximum invariant mass for the colliding photons, each being produced in a single Compton scattering, is equal to $W_{\max 1} = 131.2$ GeV. However, there is also a small contribution from the events which correspond the interaction of an initial electron with two laser photons (higher order effect). This gives a higher maximal invariant mass of the produced energetic photon-beams, namely $W_{\max 2} = 161.5$ GeV. The results presented in this paper were obtained assuming the integrated luminosity of the primary $e^-e^-$ beams $L_{\text{geom}} = 502$ fb$^{-1}$, as expected for one year of the photon collider running [2]. The resulting $\gamma\gamma$ luminosity is expected to be
$e^+e^-$ beams with $\sqrt{s_{ee}} = 210$ GeV

$J_\gamma = 0, 2$

$J_\gamma = 0$

$J_\gamma = 2$

$W_{\max 1} = 131.2$ GeV

$W_{\max 2} = 161.5$ GeV

$W_{\gamma\gamma} = 80.0$ GeV

Figure 1: Photon-photon luminosity spectrum for $\sqrt{s_{ee}} = 210$ GeV, obtained with CompAZ parametrization of the Telnov’s simulation, as a function of the invariant mass of two colliding photons $W_{\gamma\gamma}$. The contributions of states with the total $\gamma\gamma$ angular momentum projected on a collision ($z$) axis, $J_z = 0$ and $J_z = \pm 2$, are indicated.

then: $L_{\gamma\gamma} = 409$ fb$^{-1}$ or 84 fb$^{-1}$ for $W_{\gamma\gamma} > 80$ GeV.

In the earlier analyses, for instance in [6], spectra derived from the lowest order QED calculation for the Compton scattering were used, with a fixed parameter $x = \frac{4E_{e\gamma}}{m_\gamma^2}$ equal to 4.8. The realistic spectrum [2], parametrized by the CompAZ model, differs significantly from a spectrum of the high energy photons used in [6] what is shown in Fig. 2. The comparison is made for two combinations of the helicities of two colliding photons, $(\pm, \pm)$ and $(\pm, \mp)$, with the total angular momentum projected on a collision ($z$) axis equal to 0 and $\pm 2$, respectively (denoted in the figures as $J_z = 0$ and $J_z = 2$).

3 Details of a simulation and first results

The total width and branching ratios of the SM Higgs boson were calculated with the program HDECAY [7], where a higher order QCD corrections are included. A generation of the events was done with the PYTHIA 6.205 program [8], with the parameters for a Higgs boson as in the HDECAY. A parton shower algorithm, implemented in the PYTHIA, was used to generate the
Figure 2: Photon-photon luminosity spectra used in the analysis of the SM Higgs-boson production with mass $m_h = 120$ GeV, as a function of the invariant mass of two colliding photons $W_{\gamma\gamma}$. The spectrum used here, as obtained from CompAZ parametrization based on Telnov simulation, (hashed area) is compared with a spectrum derived from the lowest order QED predictions for the Compton scattering, used in the earlier analysis (lines). Total luminosity distribution ($J_z = 0, \pm 2$) and the $J_z = 0$ contribution are shown, separately.

The background events due to processes $\gamma\gamma \rightarrow b\bar{b}(g)$, $c\bar{c}(g)$ were generated using the program written by G. Jikia [6], where a complete NLO QCD calculation for the production of the massive quarks is performed within the massive-quark scheme. The program includes an exact one-loop QCD corrections to the lowest order (LO) process $\gamma\gamma \rightarrow b\bar{b}$, $c\bar{c}$ [9] and in addition the non-Sudakov form-factor in the double-logarithmic approximation, calculated up to four loops [10].

For a comparison we generated also the LO background events, using the QED Born cross section for the process $\gamma\gamma \rightarrow b\bar{b}$, $c\bar{c}$, as implemented in the PYTHIA\footnote{For a consistency with the Jikia’s program, we use a fixed electromagnetic coupling constant equal to $\alpha_{em} \approx 1/137.$}, including in addition a parton shower.

The fragmentation into hadrons was performed using the PYTHIA program. A fast simulation for a TESLA detector, the program SIMDET version 3.01 [4], was used to model a detector
performance. The jets were reconstructed using the Durham algorithm, with $y_{\text{cut}} = 0.02$; the distance measure was defined as $y_{ij} = 2 \min(E_i^2, E_j^2)(1 - \cos \theta_{ij})/E_{\text{vis}}^2$, where $E_{\text{vis}}$ is defined as the total energy measured in the detector.

The double b-tag was required for selection of the signal $h \rightarrow b\bar{b}$ events. Since a flavour tagging simulation is not included in the SIMDET program, we assume, following the approach used in [6], a fixed efficiency for the $bb$-tagging, equal to $\varepsilon_{bb} = 70\%$, and a fixed probability for a mistagging of the $cc$ events, a main background to the $b\bar{b}$ events, equal to $\varepsilon_{cc} = 3.5\%$.

The following cuts were used in order to select properly reconstructed $b\bar{b}$ events:

1. the total visible energy $E_{\text{vis}}$ greater than 90 GeV,
2. since the Higgs boson is expected to be produced almost at rest, the ratio of the total longitudinal momentum of all observed particles to the total visible energy is taken to be $|P_z|/E_{\text{vis}} < 0.1$,
3. we take number of jets $N_{\text{jets}} = 2, 3$, so that events with one additional jet due to hard gluon emission are accepted,
4. for each jet, $i = 1, ..., N_{\text{jets}}$, we require $|\cos \theta_i| < 0.75$, where $\cos \theta_i = p_{zi}/|\vec{p}_i|$.

Using the above cuts we obtain the distributions of the reconstructed $\gamma\gamma$ invariant mass $W_{\text{rec}}$ for a signal and for a background, shown in Fig. 3. The $J_z = 0$ and $J_z = \pm 2$ contributions from the NLO background, with $bb(g)$ and with $cc(g)$ final states, are shown separately. For a comparison the estimated LO background is presented as well (dotted line). Note that the NLO background contribution is approximately two times larger than the LO one. This is mainly due to the $J_z = 0$ component, which is strongly suppressed in the LO case, however it gives a large contribution in the case of NLO, especially pronounced in the high $W_{\gamma\gamma}$ part of the signal peak. More detailed comparison of the LO and NLO background estimations is presented in the Appendix A.

4 Final results

Assuming that the signal for a Higgs-boson production will be extracted by counting the $b\bar{b}$ events in the mass window around the peak, and subtracting the expected in this window background events, we can calculate the expected relative statistical error for the partial width multiplied by the branching ratio, $\Gamma(h \rightarrow \gamma\gamma)\text{Br}(h \rightarrow b\bar{b})$, in the following way:

$$\frac{\Delta \left[ \Gamma(h \rightarrow \gamma\gamma)\text{Br}(h \rightarrow b\bar{b}) \right]}{\left[ \Gamma(h \rightarrow \gamma\gamma)\text{Br}(h \rightarrow b\bar{b}) \right]} = \frac{\sqrt{N_{\text{obs}}}}{N_{\text{obs}} - N_{\text{bkgd}}},$$

The accuracy expected for the considered quantity $\Gamma(h \rightarrow \gamma\gamma)\text{Br}(h \rightarrow b\bar{b})$, if estimated from the reconstructed invariant-mass distribution obtained for the Higgs-boson mass of 120 GeV in
For comparison:

LO Background:

Figure 3: Reconstructed invariant mass $W_{rec}$ distributions for the selected $b\bar{b}$ events. Contributions of the signal due to the Higgs boson with a mass $m_h = 120$ GeV and of the heavy quark background calculated in the NLO QCD are indicated. For a comparison the LO background estimate is also plotted (dots). Arrows indicate the mass window optimized for the measurement of the $\Gamma(h \rightarrow \gamma\gamma)\text{Br}(h \rightarrow b\bar{b})$.

the selected mass range between $W_{rec}=106$ and 126 GeV (see Fig. 3), is equal to 1.9%. It is in agreement with the result of previous analysis [6].

A long tail in the reconstructed mass $W_{rec}$ distribution obtained for the $h \rightarrow b\bar{b}$ events, seen in Fig. 3, is due to the escaping neutrinos, which mainly originate in the semileptonic decays of the $D$ and $B$-mesons. This tail can be effectively suppressed by applying an additional cut on $P_T/E_T$, where $P_T$ and $E_T$ are the absolute value of the total transverse momentum of an event and the total transverse energy, respectively.\(^2\) It relies on demanding the $P_T/E_T$ to be small. The $W_{rec}$ distribution for the $h \rightarrow b\bar{b}$ events obtained by applying various $P_T/E_T$ cuts is shown in Fig. 4. In this figure we use different colors to denote various total energy of neutrinos in the event $E_{\nu{s}}$. The effects due to the detector resolution influence a shape of the distribution for $W_{rec} > m_h$, whereas for a lower $W_{rec}$ a significant effect of the escaping neutrinos is observed in the distribution. By applying a realistic $P_T/E_T$ cut, e.g. $P_T/E_T < 0.04$, a mass resolution, derived from the Gaussian fit in the region from $\mu - \sigma$ to $\mu + 2\sigma$, better than 2 GeV can be obtained.

\(^2\)\(\vec{P}_T\) ($E_T$) is calculated as a vector (scalar) sum of the transverse momenta $\vec{p}_T^i = (p_{x}^i, p_{y}^i, 0)$ (the transverse energies $E_{T}^i = E^i \sin \theta^i$) over all particles which belong to an event.
Figure 4: Reconstructed invariant mass $W_{\text{rec}}$ distributions for $\gamma\gamma \rightarrow h \rightarrow b\bar{b}$ events, for various cuts on the ratio $P_T/E_T$. Contributions of events with a different total energy of neutrinos in the event $E_{\nu s}$ are indicated by different colors. Parameters $\mu$ and $\sigma$ are obtained from the Gaussian fit in the region $(\mu - \sigma, \mu + 2\sigma)$.

Shown in Fig. 5 is the $W_{\text{rec}}$ distribution obtained by applying a cut: $P_T/E_T < 0.04$. The relative accuracy expected for the $\Gamma(h \rightarrow \gamma\gamma)\text{Br}(h \rightarrow b\bar{b})$ measurement, calculated in the $W_{\text{rec}}$ mass range between 114 and 124 GeV (as indicated by arrows in the figure), is equal to 2.2%. We conclude that the $P_T/E_T$ cut improves a mass resolution but it worsens a statistical significance of the measurement.

We have found a method which allows to increase a signal to background ratio without reducing the event statistics. We assume, that the measured missing transverse momentum is due to a single neutrino emitted perpendicularly to the beam line.$^3$ Then, we introduce the corrected, reconstructed invariant mass, namely:

$$W_{\text{corr}} \equiv \sqrt{W_{\text{rec}}^2 + 2P_T(E_{\text{vis}} + P_T)}, \quad (1)$$

$^3$Due to a large spread of the photon beam energy no constraints can be imposed on the longitudinal momentum.
Figure 5: As in Fig. 3, for the reconstructed invariant mass $W_{\text{rec}}$ distributions for the selected $b\bar{b}$ events, obtained by applying an additional cut on the ratio of the total transverse momentum and total transverse energy, $P_T/E_T < 0.04$.

The distributions of the $W_{\text{corr}}$, obtained for the signal and background events, are shown in Fig. 6. The most precise measurement of the Higgs-boson production cross section is obtained using the mass window: $W_{\text{corr}}$ between 115 and 128 GeV, as indicated by arrows. In the selected $W_{\text{corr}}$ region one expects, after one year of Photon Collider running at nominal luminosity, about 5900 reconstructed signal events and 4600 background events (i.e. $S/B \approx 1.3$). This corresponds to the expected relative statistical precision of the measurement:

$$\frac{\Delta \left[ \Gamma(h \rightarrow \gamma\gamma) Br(h \rightarrow b\bar{b}) \right]}{\Gamma(h \rightarrow \gamma\gamma) Br(h \rightarrow b\bar{b})} = 1.7\%.$$

5 Conclusions

Our analysis shows that for the SM Higgs boson with a mass around 120 GeV the two-photon width for the $b\bar{b}$ final state can be measured in the photon collider at TESLA with a precision better than 2%. If the reconstructed invariant mass of the event is corrected for the energy of escaping neutrinos from $D$ and $B$ meson decays, we achieve the precision of the measurement of the $\Gamma(h \rightarrow \gamma\gamma) Br(h \rightarrow b\bar{b})$ equal to 1.7%. The obtained accuracy is in an agreement with
the result of previous analysis, based on the idealistic Compton spectrum [6]. Note however, that used by us realistic photon-photon luminosity spectrum is more challenging for a precision measurement of the Higgs boson width $\Gamma(h \rightarrow \gamma\gamma)$.

This analysis of the SM Higgs-boson production $\gamma\gamma \rightarrow h \rightarrow b\bar{b}$ will be extended to higher masses, up to about 160 GeV in the forthcoming paper. For even higher masses of the SM Higgs boson one should consider other decay channels, see e.g. [11].

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Appendix: Comparison of the LO and NLO background estimates

As it is well known, see e.g. [9, 10], the NLO corrections for the background process $\gamma\gamma \rightarrow b\bar{b}$ are large. Whereas the LO background is strongly suppressed for a dominant $J_z = 0$ contribution, this suppression is removed for the higher order process, with an additional gluon in the final state. As an example, we show in Fig. 7 the ratios of the corresponding NLO and LO results for the $W_{rec}$ distribution for the process $\gamma\gamma \rightarrow b\bar{b}(g)$ for different values of $N_{jets}$ and $J_z$. In each case one observes large differences between the NLO and LO results, both in the shape and in the normalization. As the precise determination of the background shape is crucial for a reliable estimation of the Higgs-boson width, we conclude that a rescaling the LO estimates can not be recommended as a substitute of the full NLO background analysis.

Figure 7: Ratio of the NLO to LO results for the reconstructed invariant mass $W_{rec}$ distribution for the background process $\gamma\gamma \rightarrow b\bar{b}(g)$. 
References


