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Light Higgs-boson production at the Photon Collider at TESLA with an improved background analysis

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Abstract

Measurement of the $\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})$ at the Photon Collider at TESLA is studied for the Standard Model Higgs boson with mass of 120 to 160 GeV. The NLO estimation of background, analysis of overlaying events, realistic b-tagging and corrections for escaping neutrinos were performed. We find that for M_h = 120-160 GeV the $\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})$ can be measured with a statistical accuracy of 2-7% after one year of the Photon Collider running.

1 Introduction

A search of 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 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 the 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 $\gamma\gamma \to h \to b\bar{b}$ for a Higgs-boson mass $M_h = 120$, 130, 140, 150 and 160 GeV at the 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]. For the first time in such study overlaying events $\gamma\gamma \to$ *hadrons* are taken into account, for which we use photon–photon luminosity spectra from a full simulation [2]. Our analysis incorporates a simulation of the detector response according to the program SIMDET [4] and – the next new element – a realistic b-tagging [5]. This analysis supersedes our earlier analyses presented in [6, 7, 8].

2 Photon–photon luminosity spectra

The Compton back-scattering of a laser light off high-energy electron beams is considered as a source of high energy, highly polarized photon beams [9]. According to the current design [1], the energy of the laser photons is assumed to be fixed for all considered electron-beam energies; laser photons are assumed to have circular polarization $P_c = 100\%$, electrons longitudinal polarization is $P_e = 85\%$. We use the luminosity spectrum peaked at high energy and assume that the energy of primary electrons is adjusted in order to enhance the signal at a particular mass.

In a generation of the processes $\gamma\gamma \to$ *hadrons* one has to take into account also the low energy events, since they contribute to overlaying events [1]. To simulate them we use the realistic $\gamma\gamma$ luminosity-spectra for the photon collider at TESLA [2], with the non-linear corrections and higher order QED processes. For generation of the processes $\gamma\gamma \to h \to b\bar{b}$ and $\gamma\gamma \to b\bar{b}(g)$, $c\bar{c}(g)$ we use the CompAZ parametrization [3] of the spectrum [2].

The results presented in this paper were obtained for an integrated luminosity corresponding to one year of the Photon Collider running, as given by [2]. For example, for $\sqrt{s_{ee}} = 210.5$ GeV, which is optimal for $M_h = 120$ GeV, the total photon–photon luminosity per year is $L_{\gamma\gamma} = 410$ fb^{-1} (84 fb^{-1} for $W_{\gamma\gamma} > 80$ GeV). The total photon-photon luminosity increases to about 490 fb^{-1} for $\sqrt{s_{ee}} = 260$ GeV (used for $M_h = 160$ GeV).

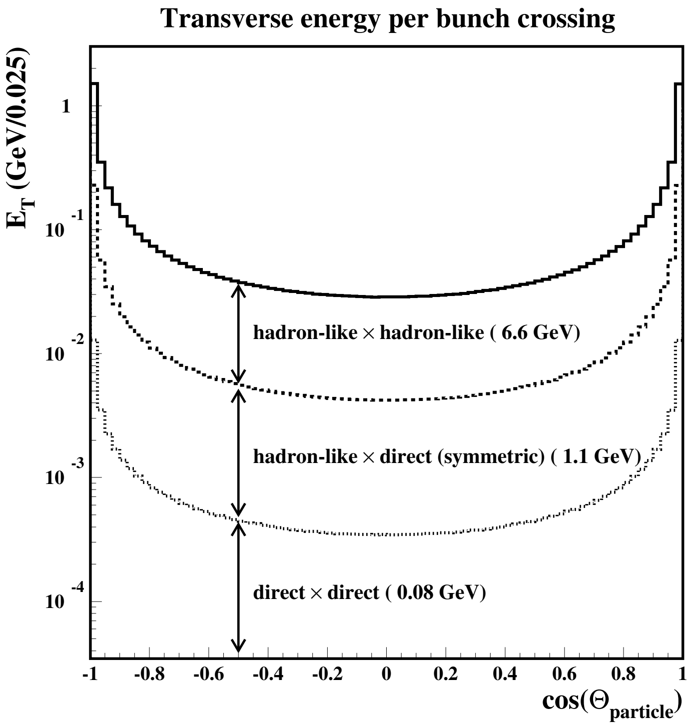

Figure 1: Angular distributions of transverse energy, E_T, for $\gamma\gamma \to$ *hadrons* events per bunch crossing. Various components and their sums are indicated. Generation was done for $\sqrt{s_{ee}} =$ 210.5 GeV [8].

3 Details of a simulation and the first results for $M_h = 120$ GeV

We calculated the total width and branching ratios of the SM Higgs boson, using the program HDECAY [10], where higher order QCD corrections are included. A generation of events was done with the PYTHIA 6.214 program [11]. A parton shower algorithm, implemented in PYTHIA, was used to generate the final-state particles.

The background events due to processes $\gamma\gamma \to b\bar{b}(g)$, $c\bar{c}(g)$ were generated using the program written by G. Jikia [12], where a complete NLO QCD calculation for the production of massive quarks is performed within the massive-quark scheme. The program includes exact one-loop QCD corrections to the lowest order (LO) process $\gamma\gamma \to b\bar{b}$, $c\bar{c}$ [13], and in addition the non-Sudakov form factor in the double-logarithmic approximation, calculated up to four loops [14].

For an estimation of systematic uncertainties in b-tagging simulation we also generated the background events, using the LO QED cross section for the processes $\gamma\gamma \to b\bar{b}$ and $\gamma\gamma \to c\bar{c}$, and including parton shower, as implemented in PYTHIA.

The fragmentation into hadrons for all processes was performed using the PYTHIA program.

Because of the large cross section, about one $\gamma\gamma \to hadrons$ event[1] is expected per bunch crossing at TESLA Photon Collider (for $\sqrt{s_{ee}}$ = 210-260 GeV, with nominal luminosity). We generate these events according to PYTHIA 6.214, including direct and hadron-like photon contributions. We use the full simulation of photon–photon spectra [2], rescaled to the chosen beam energy. For each considered collision energy, $\sqrt{s_{ee}}$, average number of $\gamma\gamma \to hadrons$ events per bunch crossing is calculated. Next, for each signal $\gamma\gamma \to h \to b\bar{b}$ or background $\gamma\gamma \to b\bar{b}(g)$, $c\bar{c}(g)$ event $\gamma\gamma \to hadrons$ events are overlaid (added to the event record) according to the Poisson distribution.

Processes contributing to the overlaying events have forward-peaked distributions, as is shown in Fig. 1 for $\sqrt{s_{ee}}$ = 210.5 GeV. Therefore, to minimize an influence of these events on the signal measurement we ignore tracks and clusters with $|\cos(\theta_i)| > \cos(\theta_{min}) = 0.9$ ($\theta_{min} = 450$ mrad; where the angle between the beam axis and a track/cluster, θ_i, is measured in the laboratory frame). Hadron-level studies performed with PYTHIA show that after this cut overlaying events contribute to the measured invariant mass below 5% in 90% of signal events. Below we use the θ_{min} cut only when overlaying events are included in the analysis.

The fast simulation program SIMDET version 4.01 [4] was used to model a TESLA detector performance.

Jets were reconstructed using the Durham algorithm, with $y_{cut} = 0.02$; the distance measure was defined as $y_{ij} = 2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})/E_{vis}^2$, where E_{vis} is the total energy measured in the detector.

The following cuts were used to select the $h \to b\bar{b}$ events:

1. since the Higgs bosons are expected to be produced almost at rest, we require that the ratio of the total longitudinal momentum of all observed particles to the total visible energy is $|P_z|/E_{vis} < 0.15$,
2. we select two- and three-jet events, $N_{jets} = 2, 3$, so that events with one additional jet due to a hard-gluon emission are also accepted,
3. for each jet we require $|\cos\theta_i| < 0.75$, $i = 1, ..., N_{jets}$.

We use "ZVTOP-B-Hadron-Tagger" package for the TESLA collider [5] for realistic b-tagging simulation. The package is based on the neural-network algorithm trained on the Z decays. For each jet it returns a "b-tag" value – the number between 0 and 1 corresponding to "b-jet" likelihood. At $\sqrt{s_{ee}}$ = 210.5 GeV, the signal to the background ratio, $N(\gamma\gamma \to b\bar{b}(g))/N(\gamma\gamma \to c\bar{c}(g))$, for selected 2-jet events, after additional cut $E_{vis} > 85$ GeV, was investigated as a function of two b-tag values, with and without overlaying events.

By accepting $\gamma\gamma \to b\bar{b}(g)$, $c\bar{c}(g)$ events above a given signal-to-background ratio, the $b\bar{b}$-tagging efficiency ε_{bb} was studied as a function of $c\bar{c}$-mistagging probability ε_{cc}, as shown in Fig. 2. For 3-jet events three possible pairs of jets were considered and the event was accepted

[1] We consider only photon–photon events with $W_{\gamma\gamma} > 4$ GeV.

if at least one pair gives the signal-to-background ratio above the cut. It was found that the cut corresponding to the efficiencies $\varepsilon_{bb} = 80\%$ and $\varepsilon_{cc} = 2.2\%$ is optimal for the $\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})$ measurement. For other considered electron-beam energies similar efficiencies were obtained (not shown). In the earlier analyses [12, 6] a fixed efficiency for the $b\bar{b}$-tagging, $\varepsilon_{bb} = 70\%$, and a fixed probability for a mistagging of the $c\bar{c}$ events, $\varepsilon_{cc} = 3.5\%$, were assumed (indicated in Fig. 2).

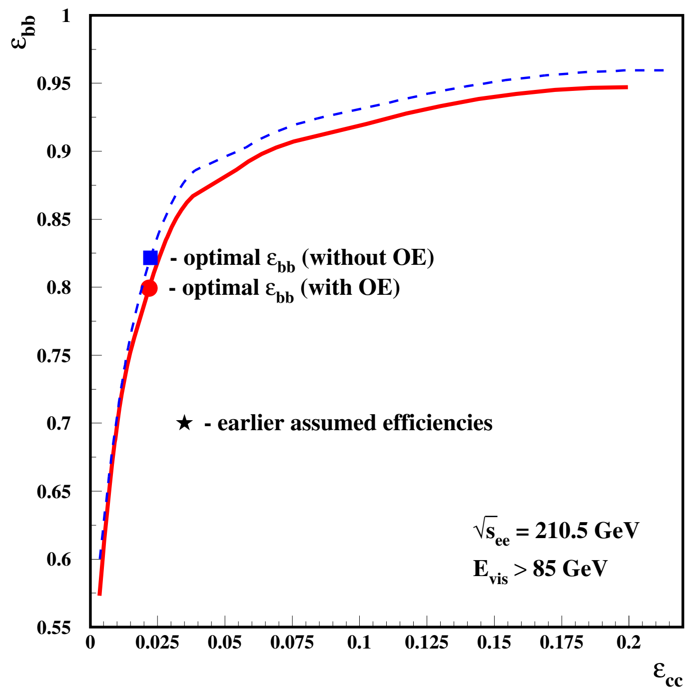

Figure 2: The $b\bar{b}$-tagging efficiency of $\gamma\gamma \to b\bar{b}(g)$ events, ε_{bb}, versus $c\bar{c}$-mistagging probability of $\gamma\gamma \to c\bar{c}(g)$ events, ε_{cc}, for $\sqrt{s_{ee}} = 210.5$ GeV with the additional cut $E_{vis} > 85$ GeV, without and with overlaying events. Optimal ε_{bb} (and ε_{cc}) from these simulations (square and dot) and the earlier estimate (star) are indicated.

In order to estimate possible influence of neglecting soft-gluon emissions in simulation of a NLO background, for which parton shower algorithm is not used, the efficiency of $b\bar{b}$-tagging was compared with an efficiency for the LO background simulation with PYTHIA (including parton shower) [7]. The overlaying events were not included in this investigation. Results of this analysis do not indicate any significant influence on the b-tagging. We obtain efficiencies of $\varepsilon_{bb} = 82.2\%\,(82.4\%)$ and $\varepsilon_{cc} = 2.2\%\,(2.3\%)$, for background events generated according to NLO cross-sections without parton shower (LO cross-sections with parton shower).

In Fig. 3 we show influence of a b-tagging on reconstructed invariant-mass distribution, W_{rec}, for the signal events $\gamma\gamma \to h \to b\bar{b}$. These results were obtained without overlaying events $\gamma\gamma \to$ *hadrons*. The low mass tail is due to the presence of events with escaping neutrinos (see [6] for more details). Contribution of these events can be suppressed by an additional cut

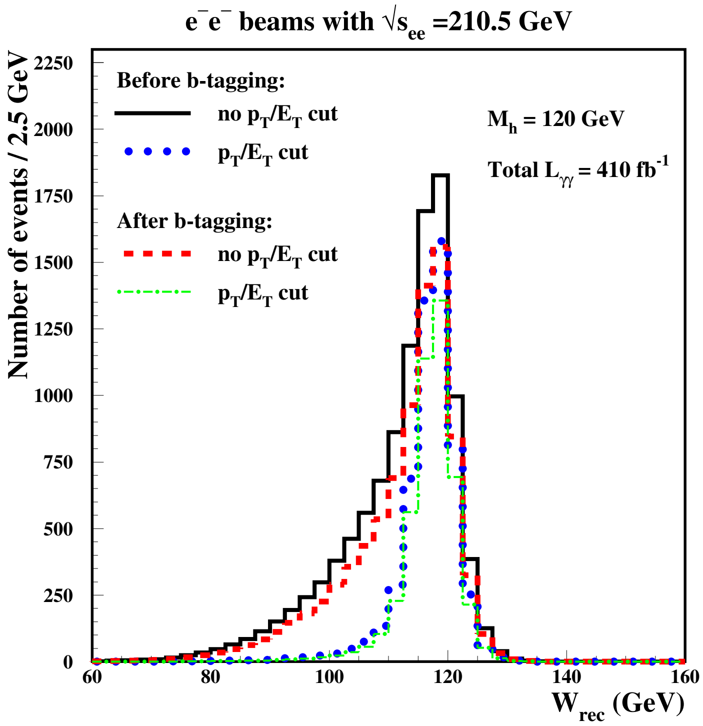

Figure 3: Reconstructed invariant mass, W_{rec}, distributions for selected $\gamma\gamma \to h \to b\bar{b}$ events, for $M_h = 120$ GeV. Distributions obtained before and after b-tagging, without and with an additional $P_T/E_T < 0.04$ cut are compared.

$P_T/E_T < 0.04$, where P_T and E_T are the absolute values of the total transverse momentum of an event, $\vec{P}_T$, and the total transverse energy, respectively. We see that b-tagging does not influence significantly the shape of the distributions.

In Fig. 4 we compare the invariant-mass distributions before and after taking into account the overlaying events. A mass resolution, derived from the Gaussian fit in the region from $\mu - \sigma$ to $\mu + 2\sigma$, is 3.5 and 6.1 GeV, respectively. Despite a quite high θ_{min} cut, the overlaying events result in a bigger tail above $W_{rec} = 120$ GeV. A small drop in a selection efficiency, resulting in the reduced number of events (from about 8520 to 7740 events), is observed. This is because the energy deposits from the $\gamma\gamma \to$ *hadrons* processes, remaining after the θ_{min} cut, "shift" jets nearer to the beam axis and the event can be rejected by the jet-angle cut. Moreover, the additional deposits and θ_{min}-cut deform jets, what slightly reduces the selection efficiency. To study this issue in details we plan to simulate in the future the signal events with various θ_{min} values.

After applying the selection cuts, b-tagging and rejecting low-angle deposits we obtain the distributions of the reconstructed $\gamma\gamma$ invariant mass, W_{rec}, shown in Fig. 5. The signal and NLO background contributions, $b\bar{b}(g)$ and $c\bar{c}(g)$, are shown separately.

Assuming that the signal for Higgs-boson production will be extracted by counting the

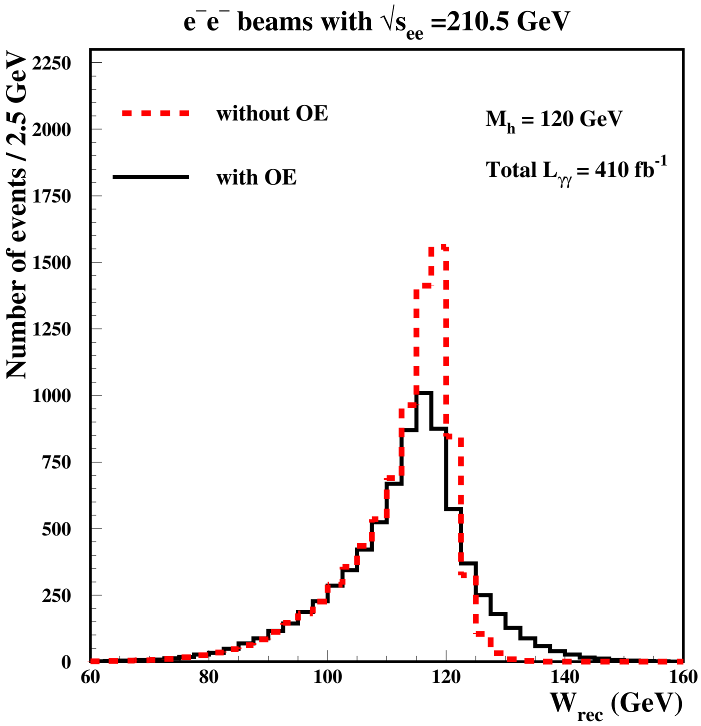

Figure 4: Reconstructed invariant-mass, W_{rec}, distributions for selected $\gamma\gamma \to h \to b\bar{b}$ events after b-tagging, for $M_h = 120$ GeV, obtained without and with overlaying events (OE).

number of $b\bar{b}$ events in the mass window around the peak, N_{obs}, and subtracting the expected background events, N_{bkgd}, we can calculate the expected relative statistical error for the cross section $\sigma(\gamma\gamma \to h \to b\bar{b})$ (or the partial width multiplied by the branching ratio $\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})$) in the following way:

$$\frac{\Delta\sigma(\gamma\gamma \to h \to b\bar{b})}{\sigma(\gamma\gamma \to h \to b\bar{b})} = \frac{\Delta\left[\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})\right]}{\left[\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})\right]} = \frac{\sqrt{N_{obs}}}{N_{obs} - N_{bkgd}}.$$

The accuracy expected for the Higgs-boson mass of 120 GeV, from the reconstructed invariant-mass distribution in the selected mass range between 102.5 and 142.5 GeV (see Fig. 5), is equal to 2.0%. It is in agreement with the results of a previous analysis [6]. Note however, that in the present analysis a loss of signal efficiency due to the overlaying events is compensated by a more effective b-tagging.

4 Final results for masses 120–160 GeV

As in [6], to correct for escaping neutrinos we use the corrected invariant mass, a variable defined as:

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

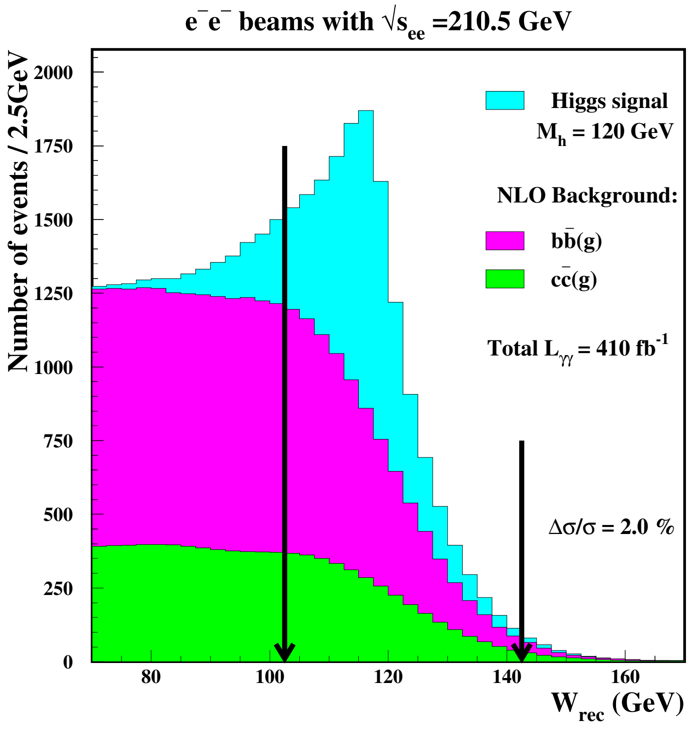

Figure 5: Reconstructed invariant-mass, W_{rec}, distributions for selected $b\bar{b}$ events. Contributions of the signal, for $M_h = 120$ GeV, and of the heavy-quark background, calculated in the NLO QCD, are shown separately. Arrows indicate the mass window, 102.5 to 142.5 GeV, optimized for the measurement of the $\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})$, which leads to the statistical precision of 2.0%.

In Fig. 6 the distributions of W_{corr} for the selected signal events, without and with overlaying events, are presented. The tail of events with invariant masses below ~ 110 GeV is much smaller than for the W_{rec}-distributions (compare with Fig. 4). The mass resolutions, derived from the Gaussian fits to the W_{corr}-distributions in the region from $\mu - 2\sigma$ to $\mu + \sigma$, are equal to 3.5 and 5.0 GeV, without and with overlaying events, respectively.

The distributions of the W_{corr}, obtained for the signal and background events, with overlaying events included, are shown in Fig. 7. The most precise measurement of the Higgs-boson cross section is obtained for the mass window W_{corr} between 110 and 150 GeV, as indicated by arrows. In the selected W_{corr} region one expects, after one year of the Photon Collider running at nominal luminosity, about 6900 reconstructed signal events and 8800 background events (i.e. $S/B \approx 0.8$). This corresponds to the statistical precision of:

$$\frac{\Delta\left[\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})\right]}{\left[\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})\right]} = 1.8\%.$$

We have performed a full simulation of signal and background events also for $M_h = 130$, 140,

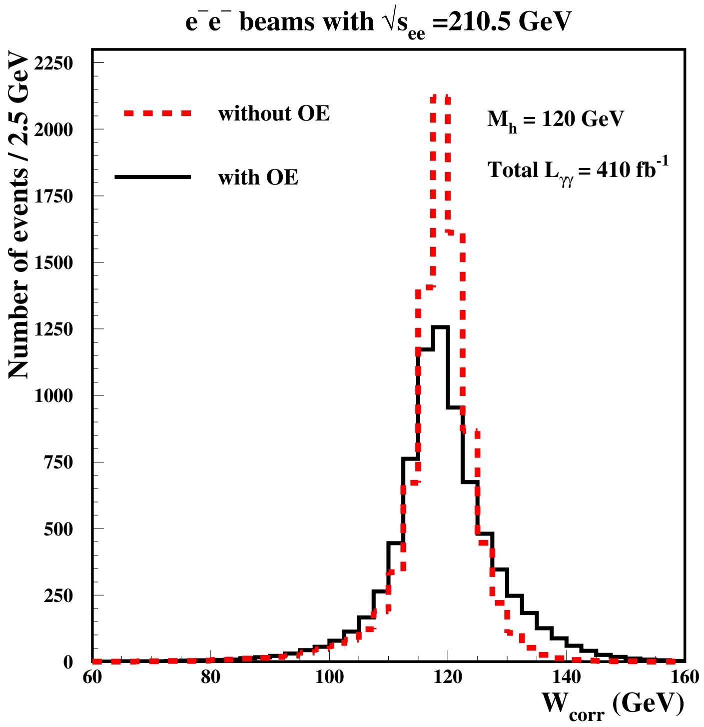

Figure 6: Corrected invariant mass, W_{corr}, distributions for selected $\gamma\gamma \to h \to b\bar{b}$ events after b-tagging, for $M_h = 120$ GeV, obtained without and with overlaying events (OE).

150 and 160 GeV choosing optimal e^-e^- beam energies for each Higgs-boson mass. Statistical precision of $\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})$ measurement was estimated in each case. It is equal to 1.8%, 2.1%, 3.0% and 7.1%, respectively. These results, together with described above result for $M_h = 120$ GeV, are presented in Fig. 8. For comparison our earlier results [8], obtained without overlaying events, are also shown.

5 Conclusions

We performed a realistic simulation of SM Higgs-boson production in the Photon Collider at TESLA, $\gamma\gamma \to h \to b\bar{b}$, with the NLO background, corrections for escaping neutrinos and – for the first time – with the realistic b-tagging and overlaying events. Our analysis shows that for $M_h =$ 120-160 GeV the two-photon width of SM Higgs boson can be measured with a statistical precision 1.8-7.1%.

The obtained accuracies are in a rough agreement with the results of a previous analysis, based on the idealistic Compton spectrum [12]. As shown in [6], the realistic photon–photon luminosity spectrum is more challenging for a precise determination of $\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})$. The precision of the measurement has been improved after applying a correction for escaping

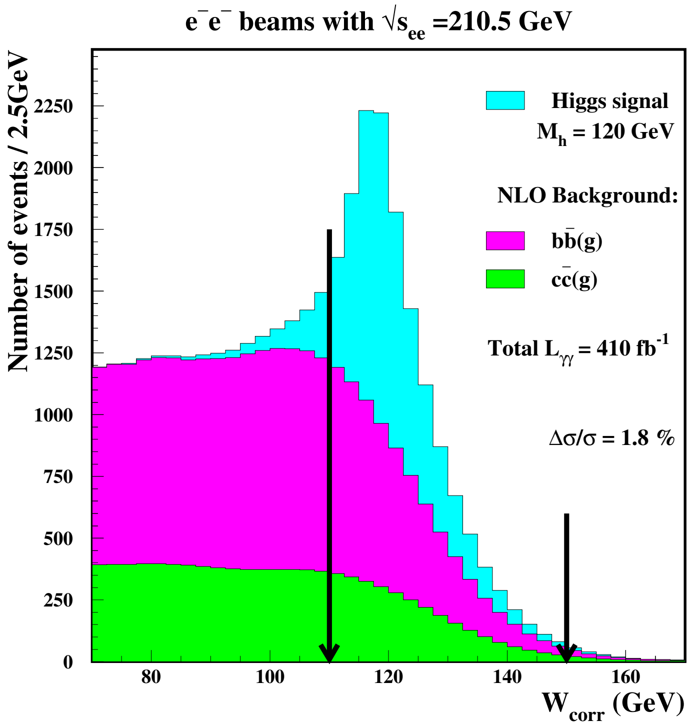

Figure 7: As in Fig. 5, for the corrected invariant mass, W_{corr}, distributions.

neutrinos and a mass-window cut. In the present analysis we include overlaying events and, as expected, the measurement precision decreases. However, a realistic b-tagging used here, resulting in a better $b\bar{b}$-tagging efficiency than estimated earlier, allows to counterbalance this effect.

The measurement discussed in this paper can be used to derive the partial width $\Gamma(h \to \gamma\gamma)$ [1]. For example, for a Higgs boson of $M_h = 120$ GeV we estimate a precision 1.8% on the measurement of $\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})$. Assuming that $\mathrm{Br}(h \to b\bar{b})$ will be measured at the e^+e^- Linear Collider with a precision 1.5% [15], the partial width $\Gamma(h \to \gamma\gamma)$ can be extracted with an accuracy of 2.3%. Using in addition the result from the e^+e^- Linear Collider for $\mathrm{Br}(h \to \gamma\gamma)$ [16], one can also extract Γ_{tot} with a precision of 10%.

For higher masses of the SM Higgs boson other decay channels should be considered, see e.g. [17].

Acknowledgments

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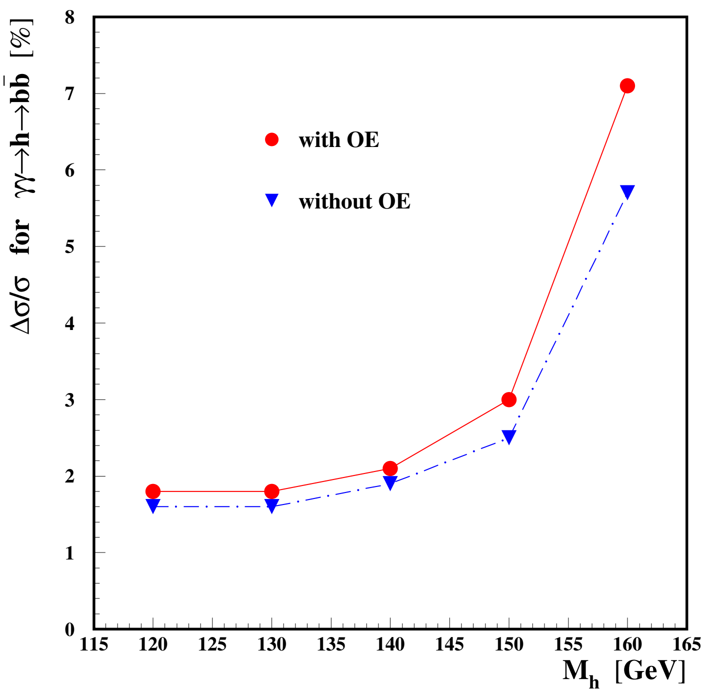

Figure 8: Statistical precisions of $\Gamma(h \to \gamma\gamma)\mathrm{Br}(h \to b\bar{b})$ measurements for the SM Higgs boson with mass 120-160 GeV with and without overlaying events (OE). The lines are drawn to guide the eye.

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