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Measurements of $\gamma\gamma \to higgs \to b\bar{b}$ cross sections for SM and MSSM at the TESLA Photon Collider.

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Abstract

Feasibility of the measurement of the Higgs-boson production at the Photon Collider at TESLA is studied, using the realistic gamma-gamma luminosity spectra and taking into account the crossing angle between beams and distribution of the primary vertex. The heavy quark background estimated using NLO QCD results, overlaying events $\gamma\gamma \to$ *hadrons* and $\gamma\gamma \to W^+W^-$ background are included. Detector simulation, realistic b-tagging and corrections for escaping neutrinos are performed. For the SM Higgs boson with mass of 120 to 160 GeV it is shown that the $\gamma\gamma \to h \to b\bar{b}$ cross section can be measured with a statistical accuracy of 2-9% after one year of the Photon Collider running. In case of MSSM, for heavy neutral Higgs bosons with masses 200-350 GeV, the statistical precision of the $\gamma\gamma \to A, H \to b\bar{b}$ cross-section measurement is estimated to be 11-23% for $\tan\beta = 7$, $M_2 = \mu = 200$ GeV.

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 Standard Model (SM).

The SM Higgs boson with a mass below ~ 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 between 120 and 160 GeV at the Photon Collider at TESLA.

In case of the minimal supersymmetric extension of the SM (MSSM) the photon collider will be able to cover the so called "LHC wedge" for moderate values of $\tan\beta$, $\tan\beta \sim 7$, and for masses of heavy neutral Higgs bosons above 200 GeV. In this parameter region Higgs bosons A and H can be discovered neither at LHC [2] nor at the first stage of e^+e^- linear colliders. Here we consider a SM-like scenario where the lightest Higgs boson h has properties of the SM-Higgs boson, while the heavy neutral Higgs bosons are nearly degenerated in masses and have negligible couplings to the gauge bosons W/Z. We take MSSM parameters as in [3], *i.e.* $\tan\beta = 7$, $M_2 = \mu = 200$ GeV, and consider the process $\gamma\gamma \to A, H \to b\bar{b}$ at the Photon Collider at TESLA for Higgs-boson masses $M_A = 200$, 250, 300 and 350 GeV. The MSSM Higgs bosons A, H with masses in this range are expected to decay into $b\bar{b}$ state with branching ratios from around 80% to 20%.

Both the signal and background events are generated according to the CompAZ [4] parametrization of luminosity spectrum. The overlaying events $\gamma\gamma \to$ *hadrons* are taken into account, for which we use the photon–photon luminosity spectra according to the full simulations [5]. All events are generated with proper crossing angle between beams and interaction point (IP) distribution. Our analysis incorporates a simulation of the detector response according to the program Simdet [6] and a realistic b-tagging [7]. For the first time in such analysis we consider background from process $\gamma\gamma \to W^+W^-$. This analysis supersedes our earlier results presented in [8, 9, 10, 11, 12, 13, 14, 15].

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 [16]. 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 a circular polarization $P_c = 100\%$, a longitudinal polarization for electrons is taken equal to $P_e = 85\%$. In considered case the luminosity spectrum is peaked at high energy and we 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 $\gamma\gamma \to hadrons$ also the low energy events have to be taken into account, since they contribute to overlaying events [1]. To simulate them we use the realistic $\gamma\gamma$ luminosity-spectra for the photon collider at TESLA [5], with the non-linear corrections and contribution from the higher order QED processes. For generation of the processes $\gamma\gamma \to h \to b\bar{b}$, $\gamma\gamma \to b\bar{b}(g)$, $c\bar{c}(g)$ and $\gamma\gamma \to W^+W^-$ we use the CompAZ parametrization [4] of the $\gamma\gamma$-luminosity spectrum.

The results presented in this paper were obtained for an integrated luminosity corresponding to one year of the Photon Collider running, as given by [5]. 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 assumed to be $L_{\gamma\gamma} = 410$ fb^{-1} (84 fb^{-1} for $W_{\gamma\gamma} > 80$ GeV). The total photon-photon luminosity increases with energy up to about 490 fb^{-1} for $\sqrt{s_{ee}} = 260$ GeV (used for $M_h = 160$ GeV). In case of MSSM for M_A from 200 to 350 GeV the total luminosity is 570–937 fb^{-1}, for corresponding e^-e^-–collision energies $\sqrt{s_{ee}} = 305$–473 GeV.

3 Details of the simulation

To calculate the total widths and branching ratios of the Higgs bosons we use the program Hdecay [17], where the higher order QCD corrections are included. For MSSM parameters we use values as in [3], $\tan\beta = 7$, $M_2 = \mu = 200$ GeV, with the contributions due to the decays and loops of supersymmetric 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 [18], 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 $\gamma\gamma \to b\bar{b}$, $c\bar{c}$ [19], and in addition the non-Sudakov form factor in the double-logarithmic approximation, calculated up to four loops [20].

The processes $\gamma\gamma \to \tau^+\tau^-$ and $\gamma\gamma \to hadrons$[1] were simulated as well. However, their influence has appeared to be negligible. In the present analysis we also made a first estimate[2] of the background from process $\gamma\gamma \to W^+W^-$ for which one expects a few millions of events per year for $\sqrt{s_{ee}} \gtrsim 300$ GeV.

A generation of events for all mentioned processes except $\gamma\gamma \to b\bar{b}(g)$, $c\bar{c}(g)$ was done with the Pythia 6.225 program [21]. A parton shower algorithm, implemented in Pythia, was used to generate the final-state particles.

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

[1] Hadron-like×hadron-like and hadron-like×direct photons interactions. Direct×direct part is considered separately and denoted as $\gamma\gamma \to b\bar{b}(g)$, $c\bar{c}(g)$.

[2] Unpolarized $\gamma\gamma \to W^+W^-$ cross section is used as for this process beams polarization is not included in Pythia.

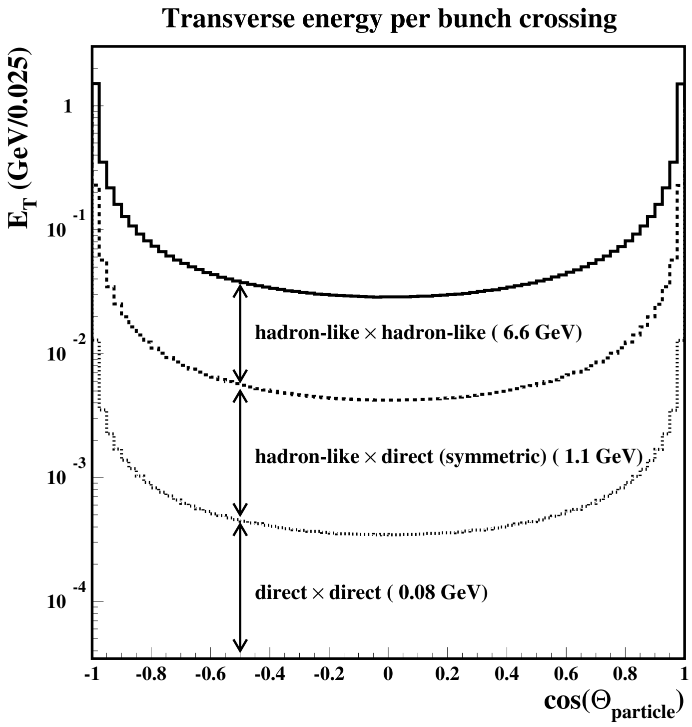

Figure 1: Average transverse energy, E_T, for $\gamma\gamma \to hadrons$ events per bunch crossing as a function of $\cos(\theta_{particle})$ where $\theta_{particle}$ is an angle between beam axis and the particle. Various components and their sums are indicated. Generation was done for $\sqrt{s_{ee}} = 210.5$ GeV.

Because of the large cross section, about one (two) $\gamma\gamma \to hadrons$ event(s)[3] is expected per bunch crossing at TESLA Photon Collider for $\sqrt{s_{ee}} = 210$–260 (305–473) GeV, with the nominal luminosity. If Higgs-boson production process takes place in the same bunch crossing, the additional particle flow can significantly influence the event reconstruction. We generate these overlaying events according to PYTHIA 6.225, including direct and hadron-like photon contributions. We use the full simulation of photon–photon spectra [5], 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 $\gamma\gamma \to b\bar{b}(g)$, $c\bar{c}(g), W^+W^-$ event $\gamma\gamma \to hadrons$ events are overlaid (added to the event record) according to the Poisson distribution.

4 Analysis

Processes contributing to the overlaying events have forward-peaked distributions, as shown in Fig. 1 (for $\sqrt{s_{ee}} = 210.5$ GeV). Therefore, to minimize the influence of these events on the signal measurement we ignore tracks and clusters with $|\cos(\theta_i)| > \cos(\theta^{DET}_{min}) = 0.85$ ($\theta^{DET}_{min} =$

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

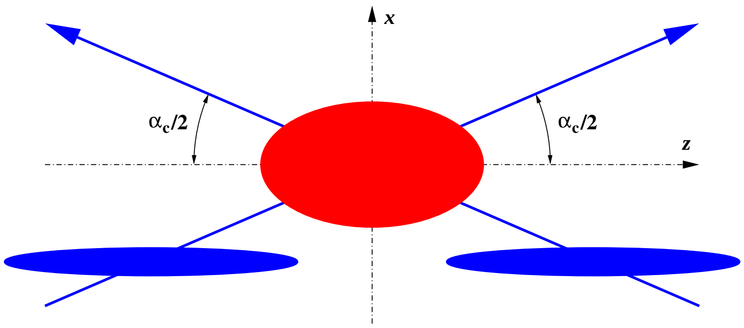

Figure 2: A scheme of the "crab-wise" bunch-bunch collision. Bunches (the blue ellipses) are tilted to preserve the luminosity. The resulting primary vertex distribution (the red ellipse) in the horizontal direction (x) is greater than it would be in case of collinear beams.

555 mrad; where the angle between the beam axis and a track/cluster, θ_i, is measured in the laboratory frame).

In simulation of all events we take into account that according to the present design of the linear collider the beams will collide with the relative angle $\alpha_c = 34$ mrad. After event reconstruction four-momenta of all jets are corrected for crossing angle by boosting them to the frame moving with the speed $\sin(\alpha_c/2)$.

In generation of the event samples we also take into account the Gaussian smearing of the interaction point with $\sigma_x = 3.6$ μm, $\sigma_y = 11$ nm and $\sigma_z = 0.21$ mm. Large spread of the primary vertex in the horizontal direction (x coordinate) is due to the so called "crab-wise" crossing of beams as shown schematically in Fig. 2.

The fast simulation program SIMDET version 4.01 [6] was used to model the performance of a TESLA detector. 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 optimized cuts are used to select the properly reconstructed $b\bar{b}$ events; exemplary values are given for $M_{higgs} = 120$ (300) GeV, respectively. :

1. Jets with relative low transverse momentum are rejected, as they mainly arise from overlaying events; in further steps of the analysis only jets with $p_T^{jet}/E_T > 0.1$ are considered where p_T^{jet} is the transverse momentum of the jet and E_T is the total transverse energy of all tracks and clusters.

2. For $\sqrt{s_{ee}} < 300$ GeV: number of selected jets should be 2 or 3 , so events with one additional jet due to a hard-gluon emission are also accepted.

3. For $\sqrt{s_{ee}} \geq 300$ GeV: only 2-jet events are accepted.

4. Since the Higgs bosons are expected to be produced almost at rest, the ratio of the

longitudinal momentum of accepted jets, $P_z^{\rm jets}$, to their total energy, $E^{\rm jets}$, fulfills condition $|P_z^{\rm jets}|/E^{\rm jets} < 0.12$ (0.07).

5. The requirement $|\cos\theta^{\rm jet}| < 0.71$ (0.65) is satisfied by all accepted jets where $\theta^{\rm jet}$ is an angle between jet axis and beam axis.

6. To suppress the $\gamma\gamma \to W^+W^-$ background, for $\sqrt{s_{ee}} \geq 300$ GeV (analysis of MSSM Higgs bosons) we also require that the ratio of the total transverse momentum to the total transverse energy should be less than 0.11; one jet has the mass lower than 70 GeV and one lower than 50 GeV; each jet has at least 7 tracks.[4]

For a realistic simulation of b-tagging the ZVTOP-B-HADRON-TAGGER package for the TESLA collider [7] was used. The package is based on the neural-network algorithm trained on the Z decays. For each jet the algorithm returns a "b-tag" value – the number between 0 and 1 corresponding to "b-jet" likelihood. For the final event selection we use the so called *higgs*-tagging which is based on the study of the signal to the background ratio, $N(\gamma\gamma \to higgs \to b\bar{b})/N(\gamma\gamma \to b\bar{b}(g),\, c\bar{c}(g))$, as a function of the two b-tag values.[5] The range of b-tag values optimal for $\gamma\gamma \to higgs \to b\bar{b}$ cross section measurement was found, separately for each beam energy. The result of the procedure for $M_h = 120$ GeV is shown in Fig. 3. Filled stars indicate the region of b-tag values accepted in the final selection of signal events. For comparison open stars show results of our earlier study [9, 10] where overlaying events were not included. Due to overlaying events contribution tighter b-tagging cuts have to be imposed.

As in our earlier analysis [8], to correct for escaping neutrinos we use the corrected invariant-mass variable, defined as:

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

We assume that the signal for Higgs-boson(s) production will be extracted by counting the number of $b\bar{b}$ events in the mass window around the peak, N_{obs}, and subtracting the expected background events, N_{bkgd}. One can calculate then the expected relative statistical error for the cross section $\sigma(\gamma\gamma \to higgs \to b\bar{b})$ in the following way:

$$\frac{\Delta\sigma(\gamma\gamma \to higgs \to b\bar{b})}{\sigma(\gamma\gamma \to higgs \to b\bar{b})} = \frac{\sqrt{N_{obs}}}{N_{obs} - N_{bkgd}}.$$

In Fig. 4 distributions of W_{corr} for production of SM Higgs boson for $M_h = 120$ GeV (left) and 160 GeV (right) are shown. The optimal windows for cross section measurement are indicated by arrows. Contributions from signal and heavy quark production background are shown. In case of $M_h = 160$ GeV the contribution from $\gamma\gamma \to W^+W^-$ background is also indicated.

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[4] Possible improvement in W^+W^- background reduction with dedicated jet reconstruction algorithm is under study.

[5] Only 2-jet events were considered in the algorithm optimization procedure, with additional cut $E_{vis} > 0.8 M_{higgs}$.

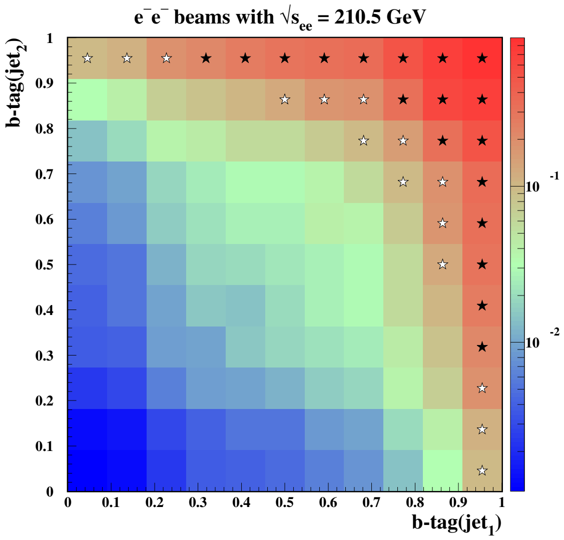

Figure 3: The range of b-tag values optimal for $\gamma\gamma \to higgs \to b\bar{b}$ cross section measurement for $M_h = 120$ GeV. Filled stars indicate the region of b-tag values accepted in the final selection of signal events. For comparison open stars show results of our earlier study [9, 10] where overlaying events were not included.

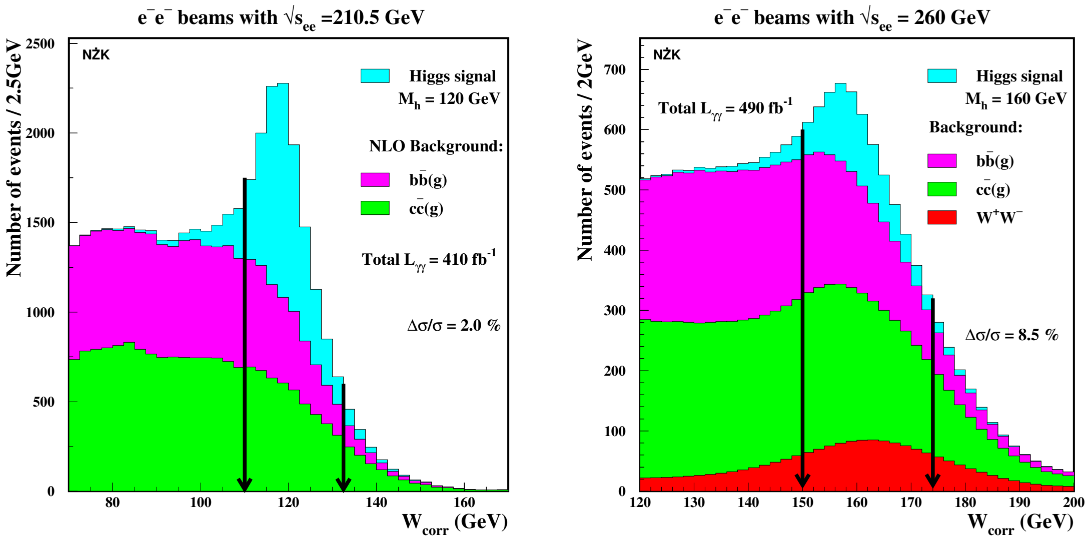

Figure 4: Distributions of W_{corr} for $M_h = 120$ GeV (left) and 160 GeV (right). For each case the optimal window for the cross section measurement is indicated by arrows. In case of $M_h = 160$ GeV contribution from $\gamma\gamma \to W^+W^-$ background is visible.

Summary of our results for the SM Higgs boson is shown in Fig. 5. For a comparison we present also our earlier results [9, 10, 13, 14, 11, 15], obtained with/without the overlaying events and with/without the beams crossing angle and the IP distribution. As contribution

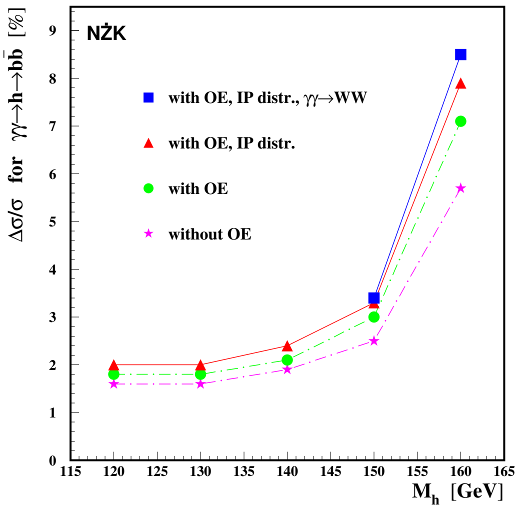

Figure 5: Statistical precisions of $\sigma(\gamma\gamma \to h \to b\bar{b})$ measurements for the SM Higgs boson with mass 120-160 GeV with/without overlaying events (OE) and with/without IP distribution and crossing angle. For two masses the $\gamma\gamma \to W^+W^-$ background is included. The lines are drawn to guide the eye.

of $\gamma\gamma \to W^+W^-$ background decreases below the W^+W^- threshold, it does not influence the measurement for $M_h < 150$ GeV.

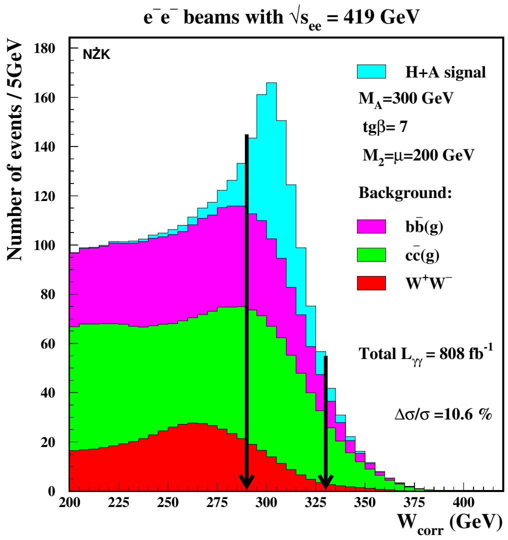

Figure 6: Distributions of W_{corr} for $M_A = 300$ GeV. The optimal window for cross section measurement is indicated by arrows. The contribution from $\gamma\gamma \to W^+W^-$ background is reduced by cuts on the number of jets, the number of tracks in each jet, the total transverse momentum and masses of jets.

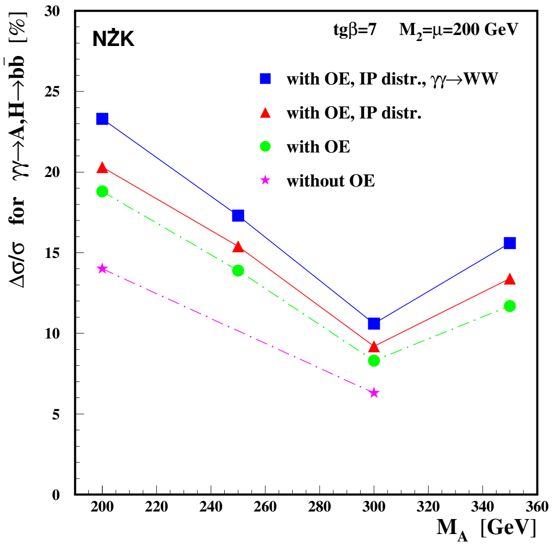

Figure 7: Precisions of $\sigma(\gamma\gamma \to A, H \to b\bar{b})$ measurement are shown for M_A = 200-350 GeV and $\tan\beta = 7$, $M_2 = \mu = 200$ GeVwith/without overlaying events (OE) and with/without IP distribution and crossing angle, as indicated in the plot. For all cases the $\gamma\gamma \to W^+W^-$ background is included. The points are connected with lines to guide the eye.

In Fig. 6 the distributions of W_{corr} for MSSM Higgs-bosons production for $M_A = 300$ GeV are shown with the optimal window for the cross section measurement indicated. The contribution of $\gamma\gamma \to W^+W^-$ background turned out to be on the acceptable level even without optimization of W^+W^- event reconstruction (*e.g.* by including the information about tracks/clusters at low angles).

Summary of results obtained for MSSM Higgs-bosons production is presented in Fig. 7. Our earlier results [10, 13, 14, 12, 15], obtained with/without overlaying events and with/without beam crossing angle and IP distribution, are also shown for a comparison.

5 Conclusions

We present an extension of our analysis of SM and MSSM Higgs-bosons production in the Photon Collider at TESLA, $\gamma\gamma \to higgs \to b\bar{b}$, with the NLO background calculations, corrections for escaping neutrinos, the realistic b-tagging and overlaying events. The new elements included in this analysis are the beam crossing angle, the primary vertex distribution and the preliminary estimate of $\gamma\gamma \to W^+W^-$ background. 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 2-9%.

For the MSSM Higgs bosons for $M_A \sim 300$ GeV the cross section $\sigma(\gamma\gamma \to A, H \to b\bar{b})$

can be measured with a statistical precision around 11%, while for other considered masses it is between 11% and 23%. The inclusion of $\gamma\gamma \to W^+W^-$ background worsens slightly the precision. However, there is still a possibility for a more efficient reconstruction of W^+W^- events what would allow to decrease even more the contribution of this background.

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