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Measurement of the MSSM Higgs-bosons production in $\gamma\gamma \to A, H \to b\bar{b}$ at the Photon Collider at TESLA

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Abstract

Results from a realistic simulation of the heavy MSSM Higgs-bosons A and H production, $\gamma\gamma \to A, H \to b\bar{b}$, at the Photon Collider at TESLA are reported. In the scenario where a light SM-like Higgs boson h exists, we study (following M. Mühlleitner et al. [1]) Higgs bosons A and H for masses $M_A = 200, 250, 300, 350$ GeV and $\tan\beta = 7$. This scenario corresponds to parameters region not accessible at LHC or at the first stage of the e^+e^- collider. NLO estimation of background, analysis of overlaying events, realistic b-tagging and corrections for escaping neutrinos were performed. The statistical precision of the cross-section measurement is estimated to be 8-20%.

1 Introduction

A photon collider option of the TESLA collider [2] 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 higgs-$\gamma\gamma$ coupling is sensitive to contributions of new particles, which appear in various extensions of the Standard Model (SM). Besides precision measurements, a photon collider is a candidate for the discovery machine [3].

In case of Minimal Supersymmetric extension of the SM (MSSM) the photon collider will be able to cover so called "LHC wedge" around intermediate values of $\tan\beta$, $\tan\beta \sim 7$, and for heavy neutral Higgs-bosons masses above 200 GeV, which will be inaccessible at LHC [4] and at the first stage of e^+e^- linear colliders.

In our analysis, we consider a SM-like scenario where the lightest Higgs boson h has properties of the SM-Higgs boson, while heavy neutral Higgs bosons are degenerated in mass and have negligible couplings to the gauge bosons W/Z. We take MSSM parameters as in [1], 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%.

The preliminary results for the MSSM Higgs-bosons were presented in [5]. In our previous works [6, 7] we have considered a light SM Higgs-boson production at the Photon Collider at TESLA. The background treatment introduced in that analysis we apply now for the MSSM Higgs-bosons. Both, the signal and background events are generated according to a realistic photon–photon luminosity spectrum [8], parametrized by a CompAZ model [9]. This study takes into account overlaying events $\gamma\gamma \to$ *hadrons* for which full simulated photon–photon luminosity spectra [8] are used. We simulate the detector response according to the program SIMDET [10] and perform a realistic b-tagging [11].

2 Photon–photon luminosity spectra

The Compton back-scattering of a laser light off the high-energy electron beams is considered as a source of the highly energetic, highly polarized photon beams [12]. In photon–photon beams simulations for a photon collider option at TESLA, according to the current design [2], the energy of the laser photons is assumed to be fixed for all considered electron-beam energies; the laser photons are assumed to have circular polarization $P_c = 100\%$, while the electrons longitudinal polarization is $P_e = 85\%$. 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*, one has to take into account also the low energy events, since they contribute to overlaying events. To simulate them the realistic $\gamma\gamma$-

luminosity spectra for the photon collider at TESLA [8] are used, with the non-linear corrections and higher order QED processes. For generation of the processes $\gamma\gamma \to A, H \to b\bar{b}$ and $\gamma\gamma \to b\bar{b}(g)$, $c\bar{c}(g)$ we use the CompAZ parametrization [9] of the $\gamma\gamma$-luminosity spectrum [8].

The results presented in this paper were obtained for an integrated luminosity expected for one year of the photon collider running for TESLA collider [8]. For example with $\sqrt{s_{ee}} = 419$ GeV – the optimal choice for $M_A = 300$ GeV – the total photon–photon luminosity per year is $L_{\gamma\gamma} = 808$ fb^{-1}. The total photon-photon luminosity increases with energy from about 570 fb^{-1} for $\sqrt{s_{ee}} = 305$ GeV ($M_A = 200$ GeV) to about 937 fb^{-1} for $\sqrt{s_{ee}} = 473$ GeV ($M_A = 350$ GeV).

3 Details of a simulation and the first results for $M_A = 300$ GeV

To calculate the total widths and branching ratios of the MSSM Higgs bosons H and A we use the program HDECAY [13] with MSSM parameters as in [1], i.e. $\tan\beta = 7$, $M_2 = \mu = 200$ GeV, and including decays and loops of supersymmetric particles.

In a generation of the signal events both A and H are included, due to their degeneracy in mass. This was done with the PYTHIA 6.214 program [14]. 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 [15], 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 $\gamma\gamma \to b\bar{b}$, $c\bar{c}$ [16], and in addition the non-Sudakov form factor in the double-logarithmic approximation, calculated up to four loops [17].

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

Because of a large cross section, about two $\gamma\gamma \to$ *hadrons* events[1] are expected on average per bunch crossing at the TESLA Photon-Collider (for $\sqrt{s_{ee}} \approx 400$ GeV, at nominal luminosity). We generate these events according to PYTHIA 6.214and convolute with results of a full simulation of the photon–photon luminosity spectra [8], rescaled for the chosen beam energy. For each considered e^-e^- energy, $\sqrt{s_{ee}}$, an average number of the $\gamma\gamma \to$ *hadrons* events per a bunch crossing is calculated. Then, for every signal $\gamma\gamma \to A, H \to b\bar{b}$ or background $\gamma\gamma \to b\bar{b}(g)$, $c\bar{c}(g)$ event, the $\gamma\gamma \to$ *hadrons* events are overlaid (added to the event record) according to the Poisson distribution.

Program SIMDET version 4.01 [10] was used to simulate a detector performance. Because $\gamma\gamma \to$ *hadrons* process has a forward-peaked distribution (see for example [5]) we decrease the influence of overlaying events by ignoring tracks and clusters with $|\cos(\theta_i)| > \cos(\theta_{min}) = 0.9$ ($\theta_{min} = 450$ mrad; the polar angle is measured in the laboratory frame). This cut is used only

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

when overlaying events are included in the analysis.

The 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 defined as the total energy measured in the detector.

The following selection cuts were used to select the signal events, $\gamma\gamma \to A, H \to b\bar{b}$:

- 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 $|P_z|/E_{vis} < 0.15$,
- 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,
- 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 [11] 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. In order to optimize the signal cross-section measurement, we choose the two-dimensional cut on b-tag values for 2-jet events. For 3-jet events three possible pairs of jets were considered and the event was accepted if at least one pair passed the $b\bar{b}$ cut. It was found that the cut optimal for $\sigma(\gamma\gamma \to A, H \to b\bar{b})$ measurement, including effects of overlaying events, corresponds to the $b\bar{b}$-tagging efficiency $\varepsilon_{bb} = 79\%$ and $c\bar{c}$-mistagging probability $\varepsilon_{cc} = 3.6\%$. However, if overlaying events are not included then the best choice corresponds to the efficiences $\varepsilon_{bb} = 72\%$ and $\varepsilon_{cc} = 1.7\%$.

The invariant-mass distributions for the $\gamma\gamma \to A \to b\bar{b}$ events after b-tagging, before and after taking into account overlaying events (OE), are compared in Fig. 1 for $M_A = 300$ GeV. The mass resolutions from the Gaussian fits, in the region $\mu - \sigma$ to $\mu + 2\sigma$, to both distributions are 8 and 20 GeV, respectively. The same resolutions are obtained for the selected $\gamma\gamma \to H \to b\bar{b}$ events (not shown). As the expected mass difference between H and A is of the order of 1 GeV, it will not be possible to separate signals of scalar and pseudoscalar Higgs boson using the the invariant-mass distribution. In the following we will consider a simultaneous measurement of the total cross section for both processes $\gamma\gamma \to A \to b\bar{b}$ and $\gamma\gamma \to H \to b\bar{b}$.

Despite our choice of a $b\bar{b}$ selection cut which corresponds to the greater $b\bar{b}$-tagging efficiency than for the simulation without overlaying events, we observe a 16% drop of number of events (from about 440 to 370 events) for simulation which includes overlaying events. This is because 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 slightly what reduces a selection efficiency.

After applying selection cuts described above and including b-tagging, we obtain the distributions of the reconstructed $\gamma\gamma$ invariant mass, W_{rec}, shown in Figs. 2. The $H \to b\bar{b}$ and

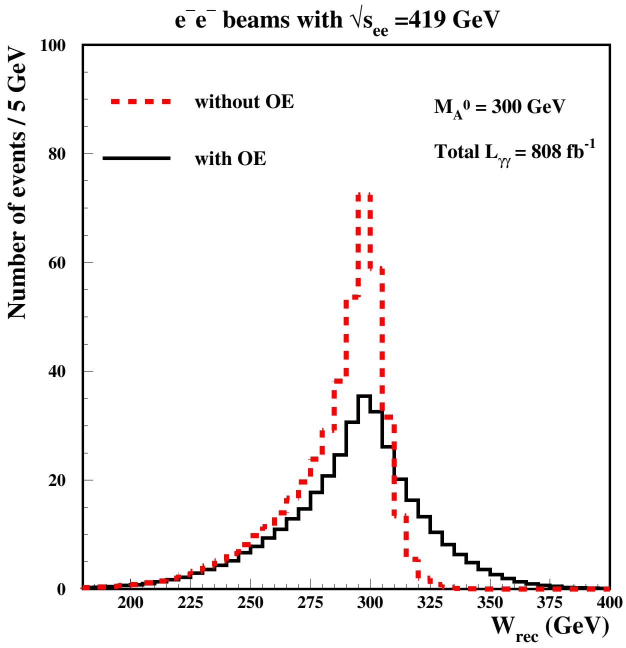


Figure 1: Reconstructed invariant-mass, W_{rec}, distributions for selected $\gamma\gamma \to A \to b\bar{b}$ events for $M_A = 300$ GeV, after b-tagging, without and with overlaying events (OE).

$A \to b\bar{b}$ signal, and the NLO background contributions, $b\bar{b}(g)$ and $c\bar{c}(g)$, are shown separately. Result obtained before (upper plot) and after (lower plot) taking into account overlaying events are compared. We observe that the overlaying events significantly smear out the Higgs-boson signal.

Assuming that the signal for the Higgs-bosons 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}, we can calculate the expected relative statistical error for the cross section $\sigma(\gamma\gamma \to A, H \to b\bar{b})$ in the following way:

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

For Higgs-boson mass of 300 GeV, after taking into account overlaying events, the accuracy of 9.3% is expected for the reconstructed invariant-mass window between 275 and 405 GeV (see Fig. 2).

4 Final results for masses 200–350 GeV

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

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

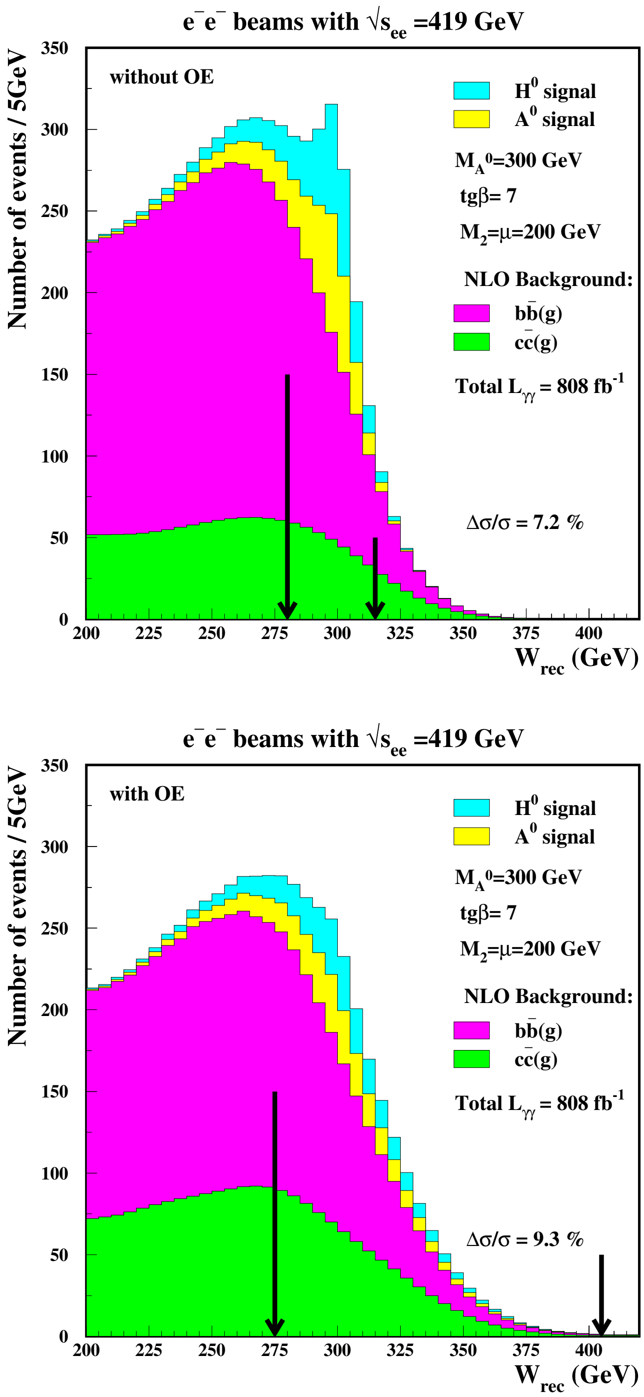


Figure 2: Distribution of the reconstructed invariant mass, W_{rec}, for the selected $b\bar{b}$ events (M_A = 300 GeV) before (upper plot) and after (lower plot) taking into account overlaying events (OE). Contributions of the H and A signal and of the heavy-quark background are shown separately. Arrows indicate the mass windows optimized for the measurement of $\sigma(\gamma\gamma \to A, H \to b\bar{b})$.

In Fig. 3 the distributions of W_{corr} for the selected $\gamma\gamma \to A \to b\bar{b}$ events, obtained without and with overlaying events, are presented. The tail of events with the invariant masses below ~ 280 GeV is much smaller than for W_{rec} (compare with Fig. 1). The mass resolutions, derived from the Gaussian fits to the W_{corr} distributions in the region from $\mu - 2\sigma$ to $\mu + \sigma$, without and with overlaying events, are equal to 8 and 13 GeV, respectively. For $\gamma\gamma \to H \to b\bar{b}$ events we obtain a very similar distribution, as seen in Fig. 4.

The W_{corr} distributions, obtained for the signal and background events, are shown in Figs. 5. Results obtained before (upper plot) and after (lower plot) taking into account overlaying events (OE) are compared. If overlaying events are included, the most precise measurement of the Higgs-boson cross section is obtained for the W_{corr} mass window between 290 and 415 GeV, as indicated by arrows. In the selected W_{corr} region one expects, after one year of the Photon Collider running at the nominal luminosity, about 610 reconstructed signal events and 2000 background events (i.e. $S/B \approx 0.3$). This corresponds to the measurement with the expected relative statistical precision of 8.3%.

We have performed also a full simulation of the signal and background events for $M_A = 200$, 250 and 350 GeV, choosing for each mass an optimal e^-e^- beam energy. In Fig. 6 a statistical precision of $\sigma(\gamma\gamma \to A, H \to b\bar{b})$ measurement for all considered masses are presented. For comparison also our earlier estimates [5], obtained without overlaying events, are shown.

5 Conclusions

In this paper we present results of a full simulation of a signal due to the heavy MSSM Higgs bosons A and H decaying into $b\bar{b}$ and background events for the Photon Collider at TESLA. We study masses $M_A = 200$, 250, 300 and 350 GeV, and for each mass we choose an optimal e^-e^- beam energy. Following [1], we study parameters of the MSSM, which correspond to the "LHC wedge", for which A and H are almost degenerate in mass. We performed a realistic simulation with the NLO background, corrections for escaping neutrinos, with realistic b-tagging and taking into account overlaying events, as in our SM-Higgs analysis [7].

Our analysis shows that, for the MSSM Higgs-bosons at $M_A \sim 300$ GeV, the cross section $\sigma(\gamma\gamma \to A, H \to b\bar{b})$ can be measured with a statistical precision around 8%, for other masses it is lower – from 10% till 20%. Although this result is less optimistic than the earlier estimate [1], it is still true that a photon–photon collider gives opportunity of a precision measurement of $\sigma(\gamma\gamma \to A, H \to b\bar{b})$, assuming that we know the mass of a Higgs boson(s). The issue arises how to distinguish (separate) A from H. To get a reliable answer to this question an additional study is needed. We confirm results of [15] which indicated that the reconstructed mass resolutions (without including overlaying events) are greater than ~ 2 GeV. A discovery of MSSM Higgs-bosons requires energy scanning or a run with a broad luminosity spectrum, perhaps followed by the run with a peaked one [3].

We conclude, that there is still a room for an optimization of θ_{min} cut to minimize an influence of overlaying events, which may increase a statistical precision.

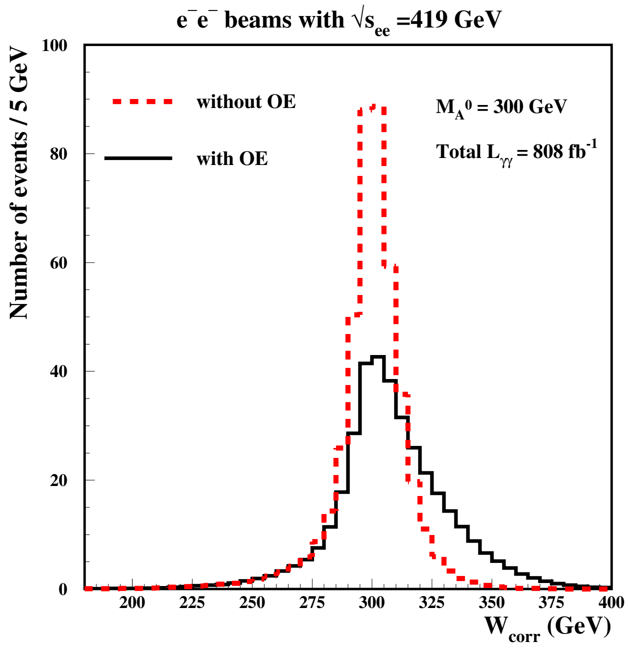


Figure 3: Corrected invariant mass, W_{corr}, distributions for the selected $\gamma\gamma \to A \to b\bar{b}$ events for $M_A = 300$ GeV, after b-tagging, obtained without and with overlaying events (OE).

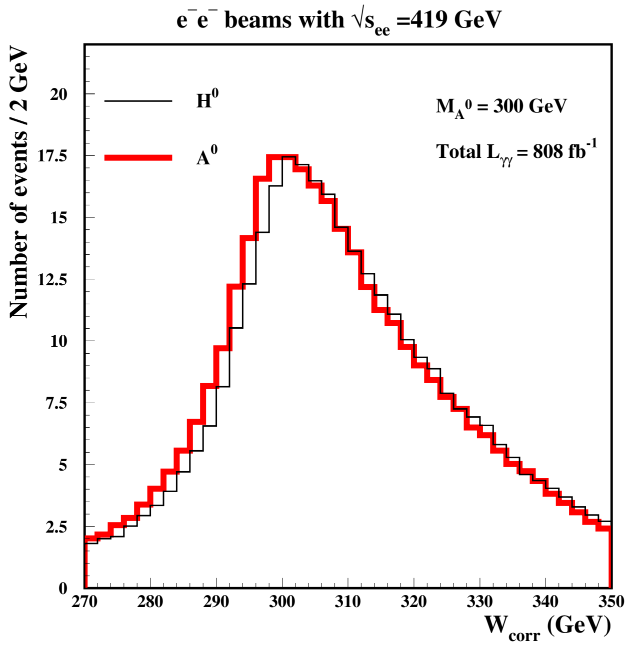
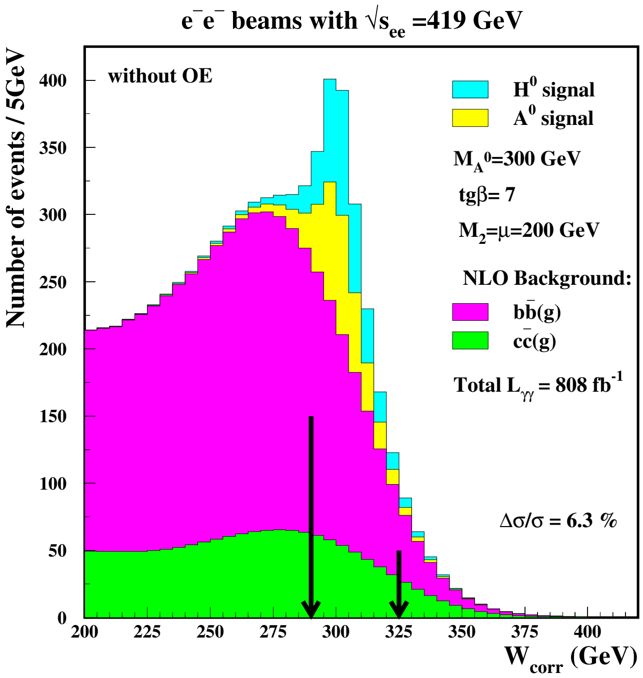


Figure 4: Corrected invariant mass, W_{corr}, distributions for the selected $\gamma\gamma \to H \to b\bar{b}$ and $\gamma\gamma \to A \to b\bar{b}$ events for $M_A = 300$ GeV, after b-tagging, with overlaying events.



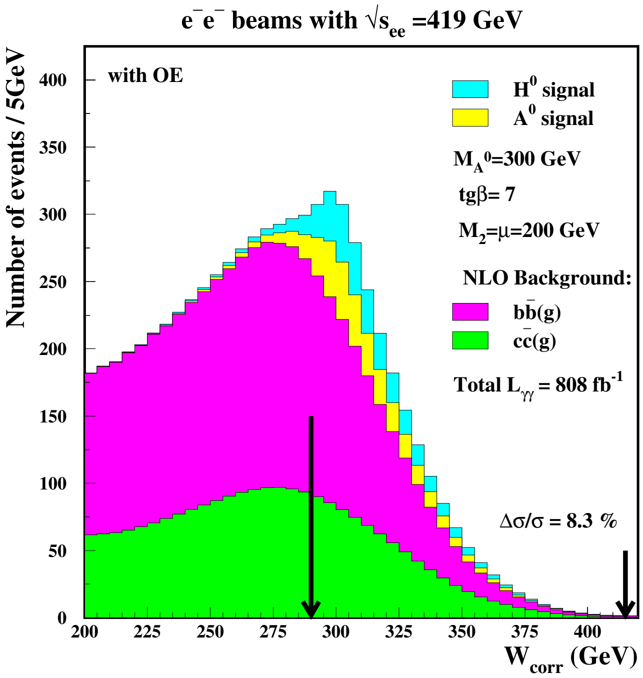


Figure 5: As in Figs. 2, for the corrected invariant-mass, W_{corr}, distributions.
The statistical precision is 6.3% without overlaying events (upper plot) and 8.3% with overlaying events (lower plot).

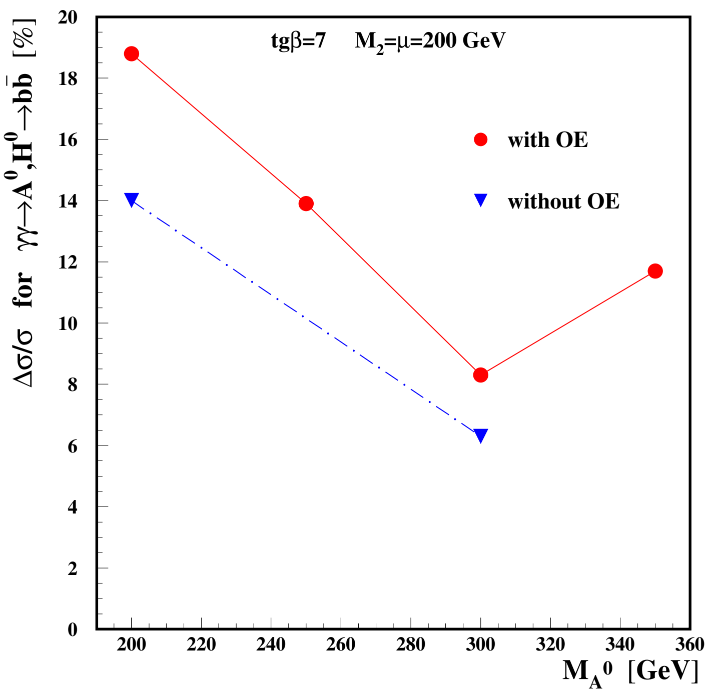


Figure 6: Precisions of $\sigma(\gamma\gamma \to A, H \to b\bar{b})$ measurement are shown for M_A = 200-350 GeV and $\tan\beta = 7$, $M_2 = \mu = 200$ GeV; with and without overlaying events (OE), as indicated in the plot. The points are connected with lines to guide the eye.

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