Light Higgs Production at a Photon Collider [1]

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Abstract

We present a preliminary study of the production of a light Higgs boson with a mass between 120 and 160 GeV in photon-photon collisions at a Compton collider. The event generator for the backgrounds to a Higgs signal due to $\overline{\rm b}$b and $\overline{\rm c}$c heavy quark pair production in polarized $\gamma\gamma$ collisions is based on a complete next-to-leading order (NLO) perturbative QCD calculation. For $J_z = 0$ the large double-logarithmic corrections up to four loops are also included. It is shown that the two-photon width of the Higgs boson can be measured with high statistical accuracy of about $2-10\%$ for integrated $\gamma\gamma$ luminosity in the hard part of the spectrum of 43 fb^{-1}. From this result the total Higgs boson width can be derived in a model independent way.

Key words: Higgs, Photon Collider

1 Introduction

The experimental discovery of the Higgs boson is crucial for understanding the mechanism of electroweak symmetry breaking. The search for Higgs particles is one of the main goals for LEP2 and the Tevatron and will be one of the major motivations for the future Large Hadron Collider (LHC) and Linear e^+e^- Collider (LC). Once the Higgs boson is discovered, it will be of primary importance to determine its tree-level and one-loop induced couplings, spin, parity, CP-nature, and its total width in a model independent way. In this respect, the $\gamma\gamma$ Compton Collider option of the LC offers a unique possibility to produce the Higgs boson as an s-channel resonance decaying into $\overline{\rm b}$b, WW*

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or ZZ and thereby to measure the two-photon Higgs width. This partial width is of special interest, since it first appears at the one-loop level so that all heavy charged particles which obtain their masses from electroweak symmetry breaking contribute to the loop. Moreover, the contributions of very heavy particles do not decouple. In addition, combined measurements of $\Gamma(\mathrm{h} \rightarrow \gamma\gamma)$ and $\mathrm{BR}(\mathrm{h} \rightarrow \gamma\gamma)$ at the LC provide a model independent measurement of the total Higgs width [1].

The lower bound on m_h from direct searches at LEP is 113.5 GeV at 95% CL [2]. A recent global analysis of precision electroweak data [3] suggests that the Higgs boson is light, yielding $m_\mathrm{h} = 62^{+53}_{-30}$ GeV. This fact is in remarkable agreement with the well known upper bound of $\sim$ 130 GeV for the lightest Higgs boson mass in the minimal version of supersymmetric theories, the Minimal Supersymmetric Standard Model (MSSM) [4]. For this case of a light Higgs boson the results of Monte Carlo simulations of Higgs production in $\gamma\gamma$ collisions with final decay to $\mathrm{\overline{b}b}$ quark pairs will be presented here. Similar studies as presented here but without detector simulation can be found in [5] but without detector simulation and in [6] but without taking into account higher order double logarithmic corrections. Since the current upper bound on the Higgs mass from radiative corrections is $m_\mathrm{h} < 170$ GeV at 95% CL [3], one can still hope to measure the two-photon Higgs width at the 300-500 GeV LC for heavier Higgs masses by studying its production in $\gamma\gamma$ collisions and final decays into WW^* [7] or ZZ [8] states.

The accuracy of the $\Gamma(\mathrm{h} \rightarrow \gamma\gamma)$ measurements to be reached can be inferred from the results of the studies of the coupling of the lightest SUSY Higgs boson to two photons in the decoupling regime [9]. It was shown that in the decoupling limit, where all other Higgs bosons are very heavy and no supersymmetric particle has been discovered at LHC or LC, chargino and top squark loops can generate a sizable difference between the standard and the SUSY two-photon Higgs couplings. Typical deviations are at the few percent level. Top squarks heavier than 250 GeV can induce deviations even larger than $\sim$ 10% if their couplings to the Higgs boson are large.

2 Signal and background

The cross-section of resonant Higgs production at a $\gamma\gamma$ Collider is proportional to the product

$$\sigma(\gamma\gamma \rightarrow \mathrm{h}^0 \rightarrow \mathrm{X}) = \mathrm{z}\frac{\mathrm{dL}_{\gamma\gamma}}{\mathrm{dz}}\frac{4\pi^2}{\mathrm{M}^3_{\mathrm{h}^0}}\Gamma(\mathrm{h}^0 \rightarrow \gamma\gamma) \cdot \mathrm{BR}(\mathrm{h}^0 \rightarrow \mathrm{X})(1+\lambda_1\lambda_2) \quad (1)$$

Here the effective photon-photon luminosity $L_{\gamma\gamma}$ is introduced (see the next section). $\lambda_{1,2}$ are mean high energy photon helicities.

The Standard Model (SM) Higgs branching ratios and the Higgs total width are calculated with the help of the program HDECAY [10]. The program includes the full massive NLO corrections for $\mathrm{h} \to \overline{\mathrm{q}}\mathrm{q}$ decays close to the thresholds as well as the massless $\mathcal{O}(\alpha_s^3)$ corrections far above the thresholds. For the Higgs signal only two-particle final states are generated, since the Parton Shower (PS) algorithm of JETSET is used to simulate three and higher particle final states.

The main background to h production is the continuum production of $\overline{\mathrm{b}}\mathrm{b}$ and $\overline{\mathrm{c}}\mathrm{c}$ pairs. In this respect, the availability of high degree of photon beams circular polarization is crucial, since for the equal photon helicities ($\pm\pm$) producing spin-zero resonant states, the $\gamma\gamma \to \overline{\mathrm{q}}\mathrm{q}$ QED Born cross-section is suppressed by the factor m_q^2/s [11]:

$$\frac{d\sigma^{\mathrm{Born}}(J_z=0)}{dt} = \frac{12\pi\alpha^2 Q_\mathrm{q}^4}{s^2} \frac{m_\mathrm{q}^2 s^2 (s - 2m_\mathrm{q}^2)}{t_1^2 u_1^2} \tag{2}$$

and

$$\frac{d\sigma^{\mathrm{Born}}(J_z=\pm 2)}{dt} = \frac{12\pi\alpha^2 Q_\mathrm{q}^4}{s^2} \frac{(t_1 u_1 - m_\mathrm{q}^2 s)(u_1^2 + t_1^2 + 2m_\mathrm{q}^2 s)}{t_1^2 u_1^2}. \tag{3}$$

Here m_q is the quark mass, Q_q its charge, and $t_1 = t - m_\mathrm{q}^2$, $u_1 = u - m_\mathrm{q}^2$.

Virtual one-loop QCD corrections for $J_z = 0$ are found to be especially large due to the double-logarithmic enhancement factor, so that the corrections are comparable or even larger than the Born contribution for the two-jet final topologies [12]. For small values of the cutoff y_{cut} separating two and three-jet events, the two-jet cross-section calculated to order α_s becomes negative in the central region. Recently leading double-logarithmic QCD corrections for $J_z = 0$ have been resummed to all orders [13,5]. Taking into account non-Sudakov form factors to higher orders makes the cross-section well defined and positive definite in all regions of the phase space.

The simulation program includes exact one-loop QCD corrections to heavy quark production in $\gamma\gamma$ collisions [12] and the non-Sudakov form factor in the double-logarithmic approximation through four loops [13]:

$$\frac{\sigma_{\mathrm{virt}}^{\mathrm{DL}}}{\sigma_{\mathrm{Born}}} \sim 1 + 6\mathcal{F} + \frac{1}{6}\left(56 + 2\frac{C_A}{C_F}\right)\mathcal{F}^2 + \tag{4}$$

$$\frac{1}{90}\left(94+90\frac{C_A}{C_F}+2\frac{C_A^2}{C_F^2}\right)\mathcal{F}^3+\frac{1}{2520}\left(418+140\frac{C_A}{C_F}+238\frac{C_A^2}{C_F^2}+3\frac{C_A^3}{C_F^3}\right)\mathcal{F}^4$$

where $\mathcal{F} = -C_F\frac{\alpha_s}{4\pi}\log^2\frac{m_q^2}{s}$ is the one-loop hard form factor. Since it is a non-trivial task to write down an event generator including both NLO corrections and the Parton Shower algorithm, we do not use any Parton Shower for background $\overline{\mathrm{b}}\mathrm{b}$ and $\overline{\mathrm{c}}\mathrm{c}$ production. So the experimental value of the y_{cut} parameter should not be chosen too small, otherwise resummed Sudakov corrections are needed. Two-parton ($\overline{\mathrm{b}}\mathrm{b}$, $\overline{\mathrm{c}}\mathrm{c}$, and $\overline{\mathrm{b}}\mathrm{bg}$, $\overline{\mathrm{c}}\mathrm{cg}$ with $y_{\mathrm{cut}} < 0.01$) and three-parton ($\overline{\mathrm{b}}\mathrm{bg}$, $\overline{\mathrm{c}}\mathrm{cg}$ with $y_{\mathrm{cut}} > 0.01$) final states are generated separately and the JETSET [14] string fragmentation algorithm is applied afterwards. The event generator both for the Higgs signal and heavy quark background is implemented using the programs BASES/SPRING [15].

3 $\gamma\gamma$ luminosity

The original polarized photon energy spectra [16] are used assuming 100% laser and 85% electron beam polarizations with $2\lambda_e^{1,2}\lambda_\gamma^{1,2} = -0.85$. The Parameter $x = \frac{4E_e\omega_0}{m_e^2}$ is taken to be 4.8. Assuming that the Higgs boson will already have been discovered at LEP, the LHC and/or the LC and that its mass will be known, we tune the ee collision energy $\sqrt{s}_{\mathrm{ee}}$ to be $\sqrt{s}_{\mathrm{ee}} = m_{\mathrm{h}}/0.8$ so that the Higgs mass corresponds to the peak of the photon-photon luminosity spectrum $z\frac{dL_{\gamma\gamma}}{dz}$, $z = 0.8$, where

$$z = \frac{W_{\gamma\gamma}}{2E_e}, \quad z_{\max} = \frac{x}{x+1} = 0.83.$$

We assume a total integrated $\gamma\gamma$ luminosity of $L_{\gamma\gamma}(0 < z < z_{\max}) = 150$ fb^{-1} with idealized Compton spectra [16]. Realistic simulations of the $\gamma\gamma$ luminosity [17] taking into account beamstrahlung, coherent pair creation and interaction between charged particles show that idealized spectra [16] will be strongly distorted in the low energy part of the spectrum. However, in the hard part of the spectrum which is relevant for our simulation, the idealized spectra represent a very good approximation [17]. The luminosity in the hard part of the spectrum is $L_{\gamma\gamma}(0.65 < z < z_{\max}) = 43$ fb^{-1} which corresponds to the integrated geometric luminosity of $\mathrm{e}^-\mathrm{e}^-$ collisions of $L_{\mathrm{ee}} \approx 400$ fb^{-1} [3].

[3] According to the present understanding [18,19] L_{ee} at TESLA in the Higgs region can be about $L_{\mathrm{e^+e^-}}(500$ GeV), where "nominal" $L_{\mathrm{e^+e^-}}(500\text{ GeV}) = 3\times10^{34}$ cm^{-2}s^{-1}.

4 Cross-sections

In Table 1 the cross-sections for the Higgs signal and for the background calculated without detector simulation are given. Both quark jets are assumed to satisfy a $|\cos\theta| < 0.9$ cut. The resolved photon contribution to the $\overline{\mathrm{b}}\mathrm{b}$ background is found to be negligible. It is therefore not included in the subsequent detector simulation analysis.

5 Results of the Monte Carlo simulation

The Monte Carlo simulation of the fragmentation is done with JETSET [14]. Signal and background are studied using the fast detector simulation program SIMDET [20] for a typical TESLA detector. Jets are reconstructed using the Durham algorithm with $y_{\mathrm{cut}} = 0.02$. b tagging is not simulated and b tagging efficiencies of 70% for $\overline{\mathrm{b}}\mathrm{b}$ events and 3.5% for $\overline{\mathrm{c}}\mathrm{c}$ events are used instead [21]. These efficiencies are based on double-tagging of b jets to suppress $\overline{\mathrm{c}}\mathrm{c}$ events by a factor of 20 which is large enough to overcome the enhancement factor of approximately 16 due to the larger c quark charge. The c rejection and the b tagging efficiency depend very much on the inner radius of the tracking detector [22].

The jet multiplicities for a Higgs signal with $m_{\mathrm{h}} = 120$ GeV and for the heavy quark background at the detector level are shown in Fig. 1. The three-jet rates are comparable for signal and background. Applying a jet multiplicity cut ($n_{\mathrm{jet}} = 2$) will therefore not improve significantly the signal to background ratio for the chosen y_{cut} value. Another advantage of not applying a jet multiplicity cut is due to the fact that no resummation of Sudakov logarithms was done for the heavy quark background. If no jet multiplicity cut is used, Sudakov logarithms are not present.

The t-channel background processes are forward peaked and the NLO order corrections even increase this effect, whereas the s-channel signal process has an isotropic angular distribution. The following cuts are therefore used to suppress background:

(i) Events where quark jets are scattered at a small angle are rejected by requiring for the thrust angle $|\cos\theta_{\mathrm{T}}| < 0.7$ (see Fig. 2).

(ii) Since the Higgs boson is produced at the peak of the photon-photon luminosity spectrum almost at rest, a cut on the longitudinal momentum component of the event divided by the ee centre-of-mass energy, $|p_{\mathrm{z}}|/\sqrt{s}_{\mathrm{ee}} < 0.1$, further reduces the background.

(iii) Most background events are produced at the lower energy tail of the photon-photon luminosity distribution. A cut on the total visible energy, $E_{\mathrm{vis}}/\sqrt{s_{\mathrm{ee}}} > 0.6$, eliminates most soft background events.

The invariant mass distributions for the combined $\overline{\mathrm{b}}\mathrm{b}(\mathrm{g})$ and $\overline{\mathrm{c}}\mathrm{c}(\mathrm{g})$ background, and for the Higgs signal are shown in Fig. 3 after applying these cuts. The relative statistical error is calculated using

$$\frac{\Delta\Gamma(\mathrm{h}\to\gamma\gamma)}{\Gamma(\mathrm{h}\to\gamma\gamma)} = \frac{\sqrt{N_{\mathrm{obs}}}}{N_{\mathrm{obs}} - N_{\mathrm{BG}}},$$

where N_{obs} is the sum of the signal and background events and N_{BG} the number of background events. It lies in the range

$$\frac{\Delta[\Gamma(\mathrm{h}\to\gamma\gamma)\mathrm{BR}(\mathrm{h}\to\overline{\mathrm{b}}\mathrm{b})]}{[\Gamma(\mathrm{h}\to\gamma\gamma)\mathrm{BR}(\mathrm{h}\to\overline{\mathrm{b}}\mathrm{b})]} \approx 2 - 10\%$$

in the Higgs mass range between 120 and 160 GeV.

Systematic errors would include the modelling of the b-tagging and the precise determination of the background shape. The background shape could be studied without relying on the theoretical predictions by running the collider at an energy below the Higgs production threshold, since the light Higgs boson is expected to be very narrow.

Assuming that at the $\mathrm{e}^+\mathrm{e}^-$ linear collider (or at a high luminosity $\gamma\gamma$ collider) the $\mathrm{h}\to\overline{\mathrm{b}}\mathrm{b}$ and $\mathrm{h}\to\gamma\gamma$ branching ratios can be measured with an accuracy of

$$\frac{\Delta\mathrm{BR}(\mathrm{h}\to\overline{\mathrm{b}}\mathrm{b})}{\mathrm{BR}(\mathrm{h}\to\overline{\mathrm{b}}\mathrm{b})} = 2 - 3\% \quad \text{and} \quad \frac{\Delta\mathrm{BR}(\mathrm{h}\to\gamma\gamma)}{\mathrm{BR}(\mathrm{h}\to\gamma\gamma)} = 10 - 15\%$$

the total width of the Higgs boson can be calculated using

$$\Gamma_{\mathrm{h}} = \frac{[\Gamma(\mathrm{h}\to\gamma\gamma)\mathrm{BR}(\mathrm{h}\to\overline{\mathrm{b}}\mathrm{b})]}{[\mathrm{BR}(\mathrm{h}\to\gamma\gamma)][\mathrm{BR}(\mathrm{h}\to\overline{\mathrm{b}}\mathrm{b})]}$$

to an accuracy dominated by the expected error on $\mathrm{BR}(\mathrm{h}\to\gamma\gamma)$.

The influence of the values of the b tag efficiencies for $\overline{\mathrm{b}}\mathrm{b}$ and $\overline{\mathrm{c}}\mathrm{c}$ events on the accuracy of two-photon Higgs width was also studied. b and c tag efficiencies were taken from a parametrisation by Battaglia [21]. In the region of b tag efficiencies from 50% to 90% the relative error on $\Gamma(\mathrm{h}\to\gamma\gamma)\mathrm{BR}(\mathrm{h}\to\overline{\mathrm{b}}\mathrm{b})$ is quite stable.

6 Conclusions

Our preliminary results show that the two-photon width of the Higgs boson can be measured at the photon-photon collider with high statistical accuracy of about 2-9% for the Higgs mass range between 120 GeV and 160 GeV. At such an accuracy one can discriminate between the SM Higgs particle and the lightest scalar Higgs boson of the MSSM in the decoupling limit, where all other Higgs bosons are very heavy and no supersymmetric particle has been discovered at the e^+e^- LC. Due to the large charm production cross-section in $\gamma\gamma$ collisions, excellent b tagging is required.

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Table 1
Cross-sections for the Higgs signal and for the background from direct heavy quark production in $\gamma\gamma$ collisions. The $\gamma\gamma \to \overline{\mathrm{b}}\mathrm{b(g)}, \overline{\mathrm{c}}\mathrm{c(g)}$ background was simulated for $\gamma\gamma$ invariant masses larger than W_{min}. A cut $\cos\theta < 0.9$ was applied. To calculate the event rates cross sections should be multiplied by the total luminosity $L_{\gamma\gamma}(0 < z < z_{\mathrm{max}})$ defined in Section 3.

m_{h} (GeV)	$\sqrt{s_{\mathrm{ee}}}$ (GeV)	$\mathrm{BR}(\mathrm{h} \to \overline{\mathrm{b}}\mathrm{b})$ (%)	$\sigma(\gamma\gamma \to \mathrm{h} \to \overline{\mathrm{b}}\mathrm{b})$ (pb)	W_{min} (GeV)	$\sigma_{\bar{\mathrm{b}}\mathrm{b(g)}}$ (pb)	$\sigma_{\bar{\mathrm{c}}\mathrm{c(g)}}$ (pb)
120	152.0	68	0.140	80	0.69	10.93
140	177.0	34	0.089	90	0.57	8.87
160	202.5	3.8	0.018	105	0.41	6.19

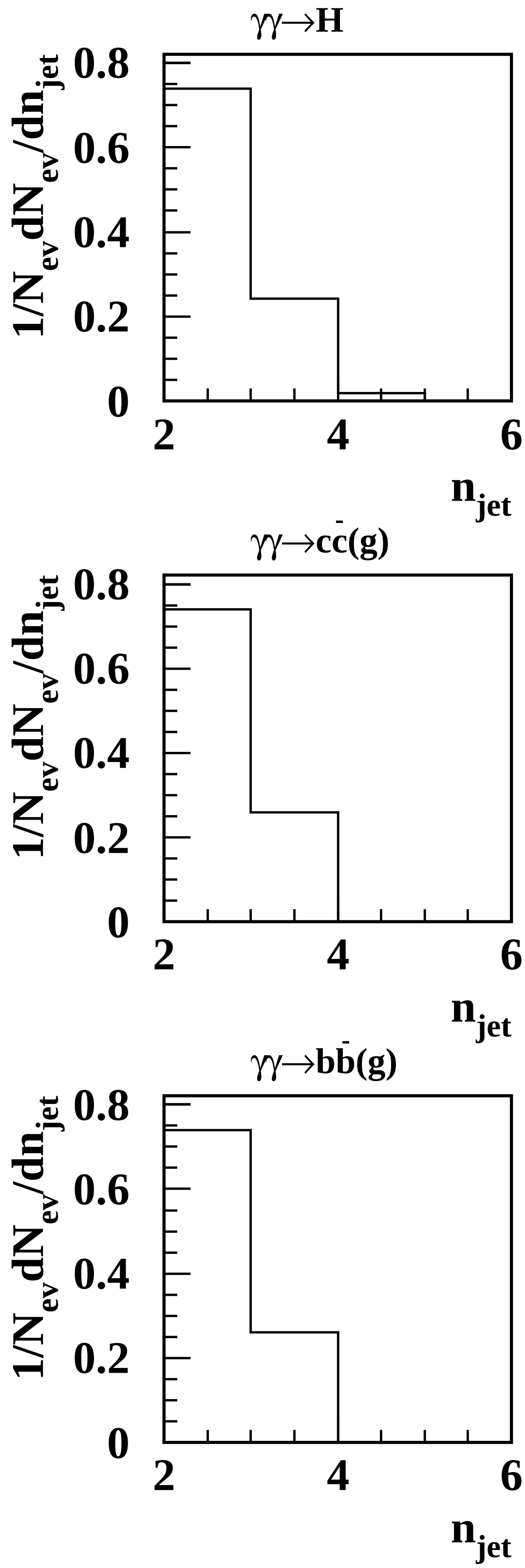

Fig. 1. Jet multiplicities for two- and three-parton event (detector level).

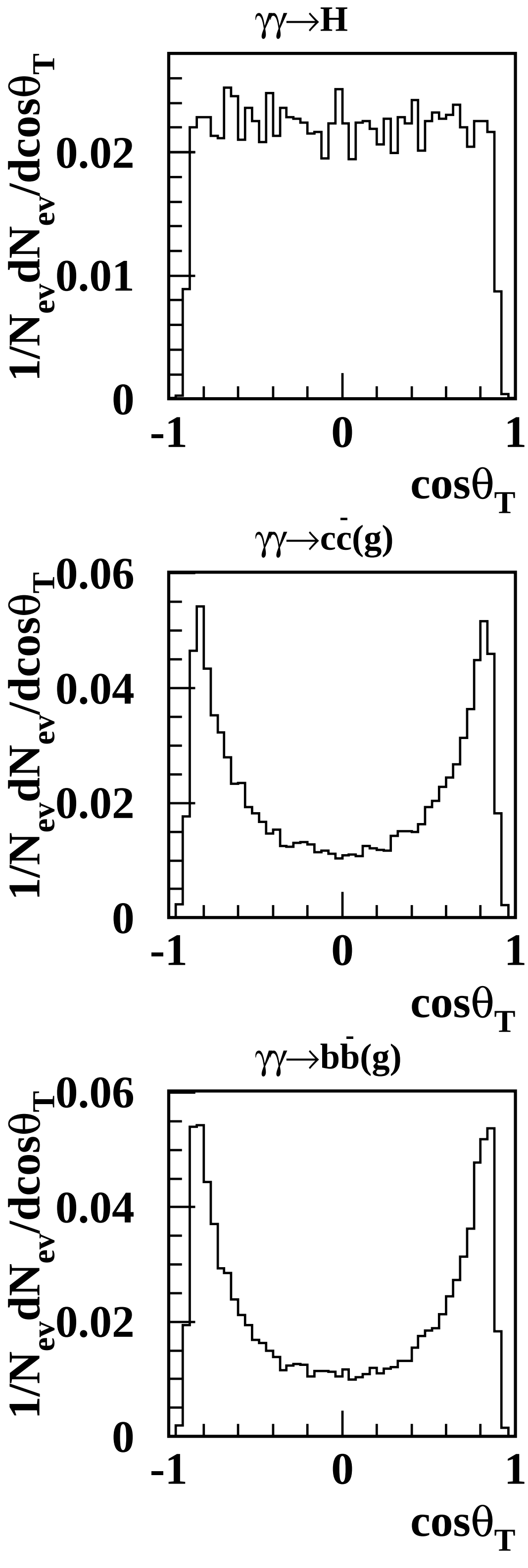

Fig. 2. Distribution of the thrust angle $\cos\theta_T$ for two- and three-parton events (detector level).

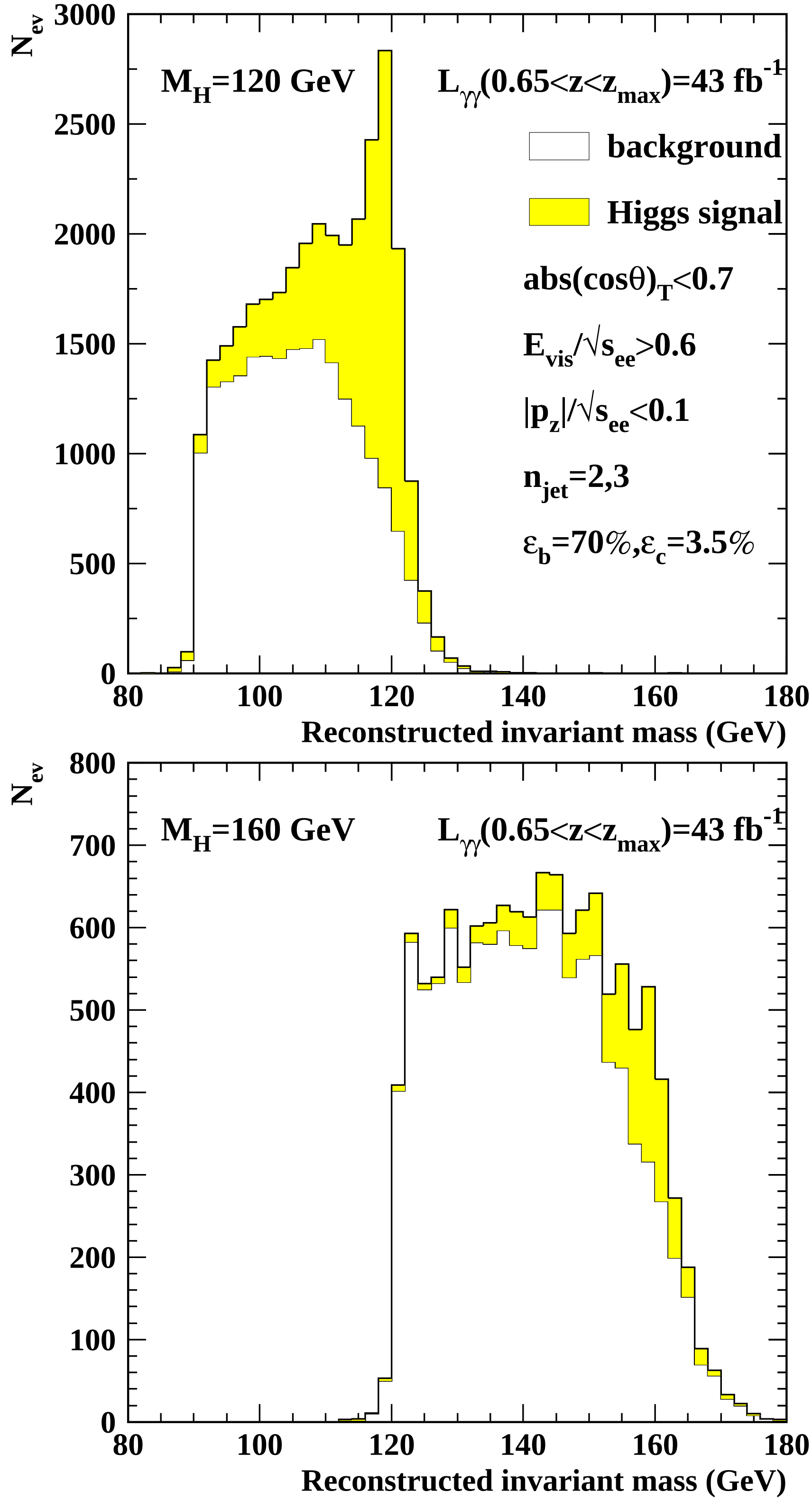

Fig. 3. Mass distributions for Higgs signal and heavy quark background for a) $m_{\rm h} = 120$ GeV and b) $m_{\rm h} = 160$ GeV (detector level).