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THE SM HIGGS BOSON PRODUCTION IN $\gamma\gamma \to h \to b\bar{b}$ AT THE PHOTON COLLIDER AT TESLA

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Measuring the $\Gamma(h \to \gamma\gamma)$ BR$(h \to b\bar{b})$ decay at the photon collider at TESLA is studied for a Standard Model Higgs boson of mass $m_{\mathrm{h}} = 120$ GeV. The main background due to the process $\gamma\gamma \to Q\overline{Q}(g)$, where $Q = b, c$, is estimated using the NLO QCD program (G. Jikia); the results obtained 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 $\Gamma(h \to \gamma\gamma)BR(h \to b\bar{b})$ decay can be measured with an accuracy better than 2% after one year of photon collider running.

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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 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 ~ 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 of $m_{\rm h} = 120$ GeV 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 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 high-energy electron beams is considered as a source of high energy, highly polarized photon beams [5]. A simulation of the realistic $\gamma\gamma$ luminosity spectra for the photon collider at TESLA, taking into account non-linear corrections and higher order QED processes, has become available recently [2]. In this simulation, according to the current design [1], the energy of the laser photons $\omega_{\rm L}$ is assumed to be fixed for all considered electron beam energies.

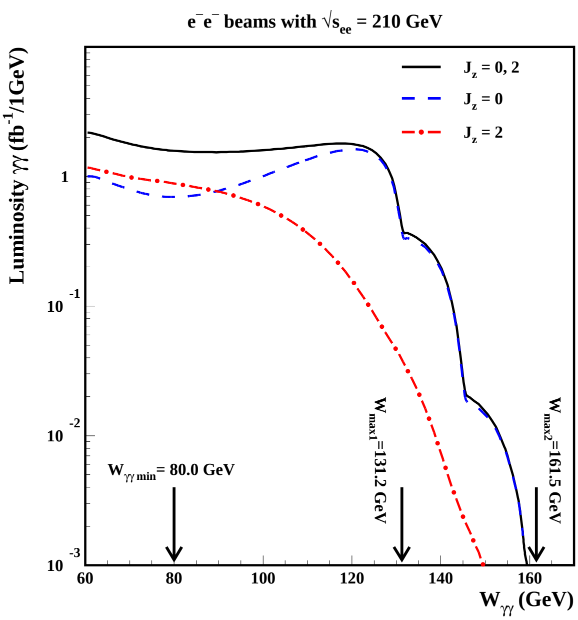

Fig. 1. Photon–photon luminosity spectra for $\sqrt{s_{ee}} = 210$ GeV, obtained with CompAZ parametrization of Telnov's simulation, as a function of the invariant mass of two colliding photons $W_{\gamma\gamma}$. The contributions of states with the total $\gamma\gamma$ angular momentum projected on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

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. Our signal production of a scalar particle corresponds to the case where projection of the total $\gamma\gamma$ angular momentum on a collision (z) axis J_z is 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, *i.e.* $m_{\rm h} = 120$ GeV.

The luminosity spectra are shown in Fig. 1. The lowest invariant mass of the two colliding photons used in our generation of events is equal to $W_{\gamma\gamma\,\rm min} = 80$ GeV. For the assumed $\sqrt{s_{ee}}$ value, the maximum invariant mass for the colliding photons, each produced in a single Compton scattering, is equal to $W_{\rm max\,1} = 131.2$ GeV. However, there is also a small contribution from the events, which correspond to 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 $W_{\rm max\,2} = 161.5$ GeV. The results presented in this paper were obtained for an inte-

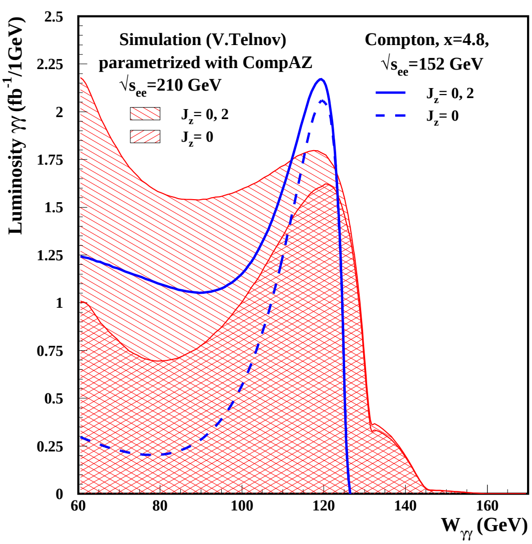

Fig. 2. Photon–photon luminosity spectra used in the analysis of the SM Higgs boson production with mass $m_{\rm h} = 120$ GeV, as a function of the invariant mass of two colliding photons $W_{\gamma\gamma}$. The spectrum used here, as obtained from CompAZ parametrization based on Telnov simulation (hatched areas), is compared with a spectrum derived from the lowest order QED predictions for the Compton scattering, used in the earlier analysis (lines). The total luminosity distribution ($J_z = 0, \pm 2$) and the $J_z = 0$ contribution are shown, separately.

grated luminosity of the primary e^-e^- beams equal to $L_{ee}^{\rm geom} = 502\ {\rm fb}^{-1}$, expected for one year of the photon collider running [2]. The resulting $\gamma\gamma$ luminosity is then expected to be: $L_{\gamma\gamma} = 409\ {\rm fb}^{-1}$, or $84\,{\rm fb}^{-1}$ for $W_{\gamma\gamma} > 80\,{\rm GeV}$.

In the earlier analysis, for instance in [6], the spectra that were used had been derived from the lowest order QED calculation for the Compton scattering, with a fixed parameter $x = 4E_e\omega_{\rm L}/m_e^2$ equal to 4.8. The realistic spectrum [2], parametrized by the CompAZ model, differs significantly from the spectrum of the high-energy photons used in [6], which 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 ± 2, respectively.

3. Details of a simulation and the first results

We calculate the total width and branching ratios of the SM Higgs boson, using the program HDECAY [7], where higher order QCD corrections are included. A generation of 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 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 Jikia [6], 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 $\gamma\gamma \to b\bar{b}$, $c\bar{c}$ [9], and in addition the non-Sudakov form factor in the double-logarithmic approximation, calculated up to four loops [10].

For a comparison we generate also the LO background events, using the QED Born cross section for the processes $\gamma\gamma \to b\bar{b}$ and $\gamma\gamma \to c\bar{c}$, including in addition a parton shower, as implemented in PYTHIA[1].

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

The double b-tag was required to select the signal $h \to b\bar{b}$ events. Since no suitable flavor-tagging package exists for the SIMDET 3.01 program[2],

[1] For consistency with Jikia's program, we use a fixed electromagnetic coupling constant equal to $\alpha_{\rm em} \approx 1/137$.

[2] The b-tagging code adapted for the new version of SIMDET 4.01 [11] should become available soon [12].

we assume, following the approach used in [6], a fixed efficiency for the $b\bar{b}$-tagging, equal to $\varepsilon_{bb} = 70\%$, and a fixed probability for a mistagging of the $c\bar{c}$ events, a main background to the $b\bar{b}$ events, equal to $\varepsilon_{cc} = 3.5\%$.

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

1. a total visible energy $E_{\rm vis}$ 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 $|P_z|/E_{\rm vis} < 0.1$,
3. a number of jets $N_{\rm jets} = 2, 3$, so that events with one additional jet due to hard-gluon emission are accepted,
4. for each jet, $i = 1, \ldots, N_{\rm jets}$, we require $|\cos\theta_i| < 0.75$, where $\cos\theta_i = p_{z\,i}/|\overrightarrow{p_i}|$.

Using the above cuts, we obtain the distributions of the reconstructed $\gamma\gamma$ invariant mass $W_{\rm rec}$ 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

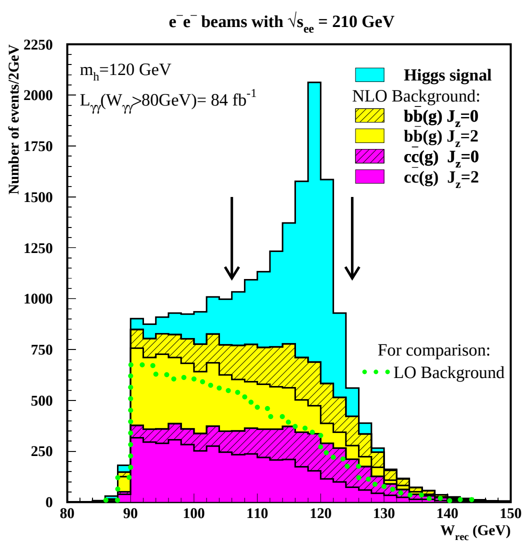

Fig. 3. Reconstructed invariant mass $W_{\rm rec}$ distributions for the selected $b\bar{b}$ events. Contributions of the signal, due to the Higgs boson with a mass $m_{\rm h} = 120$ GeV, and of the heavy-quark background, calculated in the NLO QCD, are indicated. For comparison, the LO background estimate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

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 in the case of NLO it gives a large contribution, especially pronounced in the high-$W_{\gamma\gamma}$ part of the signal peak. A more detailed comparison of the LO and NLO background estimations is presented in the Appendix. Other background contributions, from the resolved photon(s) interactions and the overlaying events, were found to be negligible [13].

4. Final results

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

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

The accuracy expected for the considered quantity $\Gamma(h \to \gamma\gamma)\mathrm{BR}(h \to b\bar{b})$, if estimated from the reconstructed invariant-mass distribution obtained for the Higgs boson mass of 120 GeV in the selected mass region, between 106 and 126 GeV (see Fig. 3), is equal to 1.9%. It is in agreement with the result of a previous analysis [6].

A long tail in the reconstructed mass W_{rec} distribution obtained for the $h \to b\bar{b}$ events seen in Fig. 3 is due to the escaping neutrinos, which mainly originate in the semi-leptonic decays of the D- and B-mesons. This tail can be effectively suppressed by applying an additional cut on $P_{\mathrm{T}}/E_{\mathrm{T}}$, where P_{T} and E_{T} are the absolute values of the total transverse momentum of an event $\vec{P}_{\mathrm{T}}$ and the total transverse energy, respectively[3]. The cut relies on demanding the $P_{\mathrm{T}}/E_{\mathrm{T}}$ to be small. The W_{rec} distributions for the $h \to b\bar{b}$ events obtained by applying various $P_{\mathrm{T}}/E_{\mathrm{T}}$ cuts are shown in Fig. 4. In this figure we use different colors to denote the different total energies of neutrinos in the event, $E_{\nu s}$. The effects due to the detector resolution influence a shape of the distribution for $W_{\mathrm{rec}} > m_{\mathrm{h}}$, whereas for a lower W_{rec} one observes a significant effect of the escaping neutrinos in the distribution. By applying a realistic $P_{\mathrm{T}}/E_{\mathrm{T}}$ cut, *e.g.* $P_{\mathrm{T}}/E_{\mathrm{T}} < 0.04$, we can obtain a mass resolution, derived from the Gaussian fit in the region from $\mu - \sigma$ to $\mu + 2\sigma$, better than 2 GeV.

[3] $\vec{P}_{\mathrm{T}}$ (E_{T}) is calculated as a vector (scalar) sum of the transverse momenta $\vec{p}^{\,i}_{\mathrm{T}} = (p^i_x, p^i_y, 0)$ (the transverse energies $E^i_{\mathrm{T}} = E^i \sin\theta_i$) over all particles that belong to an event.

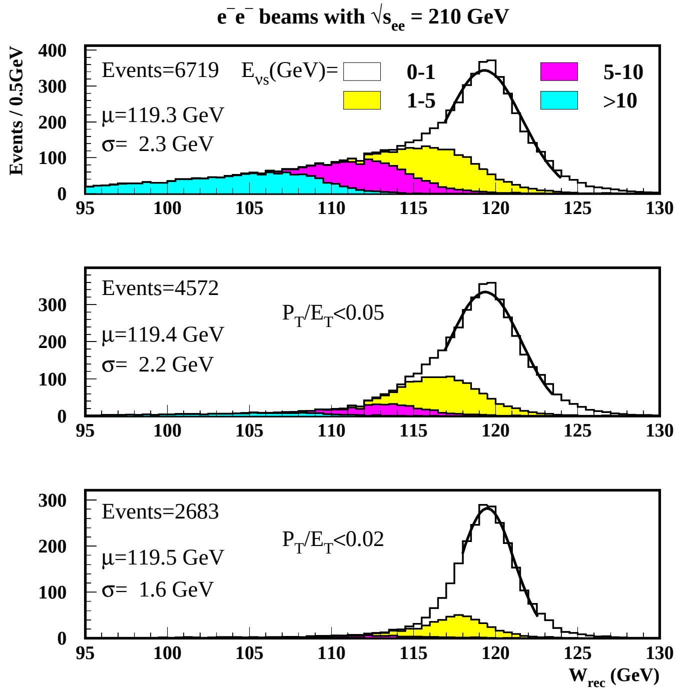

Fig. 4. Reconstructed invariant mass W_{rec} distributions for $\gamma\gamma \to h \to b\bar{b}$ events, for various $P_{\mathrm{T}}/E_{\mathrm{T}}$ cuts. Contributions of events with a different total energy of neutrinos in the event $E_{\nu s}$ are indicated by different colors. The parameters μ and σ are obtained from the Gaussian fit in the region $(\mu - \sigma,\ \mu + 2\sigma)$.

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

We have found a method, which allows an increase of 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[4]. Then, we introduce the corrected, reconstructed invariant mass as

$$W_{\mathrm{corr}} \equiv \sqrt{W_{\mathrm{rec}}^2 + 2P_{\mathrm{T}}(E_{\mathrm{vis}} + P_{\mathrm{T}})}\,.$$

[4] Due to a large spread of the photon beam energy, no constraints can be imposed on the longitudinal momentum.

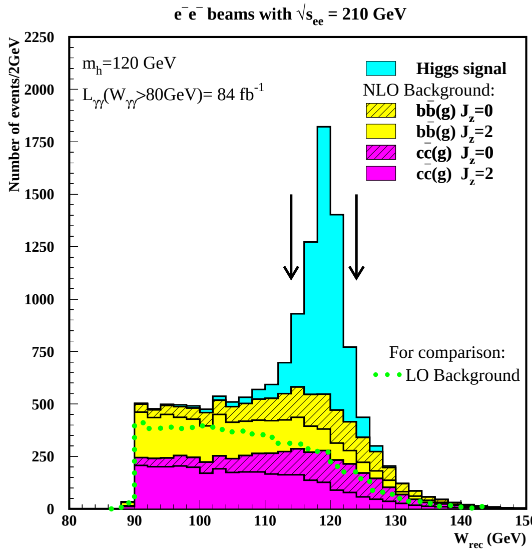

Fig. 5. As in Fig. 3, for the reconstructed invariant mass $W_{\rm rec}$ distributions for the selected $b\bar{b}$ events, obtained by applying an additional cut on the ratio of the total transverse momentum and total transverse energy, $P_{\rm T}/E_{\rm T} < 0.04$.

The distributions of the $W_{\rm corr}$, 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 $W_{\rm corr}$ be-

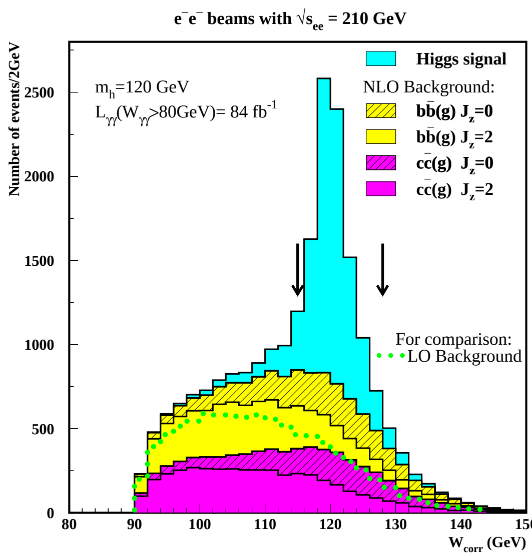

Fig. 6. As in Fig. 3, for the corrected invariant mass $W_{\rm corr}$ distributions.

tween 115 and 128 GeV, as indicated by arrows. In the selected $W_{\rm corr}$ 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

$$\frac{\Delta\left[\Gamma(h \to \gamma\gamma){\rm BR}(h \to b\bar{b})\right]}{\left[\Gamma(h \to \gamma\gamma){\rm BR}(h \to b\bar{b})\right]} = 1.7\%\,.$$

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 a precision of the measurement of the $\Gamma(h \to \gamma\gamma){\rm BR}(h \to b\bar{b})$ equal to 1.7%. The obtained accuracy is in an agreement with the result of a previous analysis, based on the idealistic Compton spectrum [6]. Note, however, that the realistic photon–photon luminosity spectrum that we use is more challenging.

The measurement discussed in this paper can be used to derive the partial width $\Gamma(h \to \gamma\gamma)$, taking ${\rm BR}(h \to b\bar{b})$ value from precise measurement at the e^+e^- Linear Collider. With 1.7% accuracy on $\Gamma(h \to \gamma\gamma){\rm BR}(h \to b\bar{b})$, obtained in this analysis, assuming ${\rm BR}(h \to b\bar{b})$ will be measured to 1.5% [14], Higgs boson partial width $\Gamma(h \to \gamma\gamma)$ can be extracted with accuracy of 2.3%. Using in addition the result from the e^+e^- Linear Collider for ${\rm BR}(h \to \gamma\gamma)$ [15], one can also extract $\Gamma_{\rm tot}$ with precision of 10%.

The SM Higgs boson production $\gamma\gamma \to h \to b\bar{b}$ can be considered for masses up to about 160 GeV [6]. For higher masses of the SM Higgs boson one should consider other decay channels, see *e.g.* [16].

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Appendix A

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 $\gamma\gamma \to b\bar{b}$ are large. Whereas the LO background is strongly suppressed for a $J_z = 0$ 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 $W_{\rm rec}$ distribution, for the process $\gamma\gamma \to b\bar{b}(g)$, for different values of $N_{\rm jets}$ 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 of the LO estimates cannot be recommended as a substitute of the full NLO background analysis.

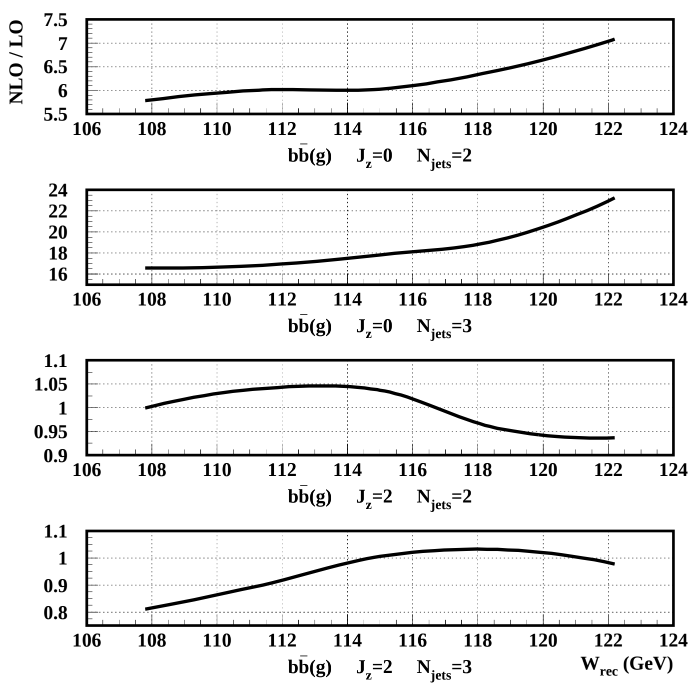

Fig. 7. Ratio of the NLO to LO results for the reconstructed invariant mass $W_{\rm rec}$ distribution for the background process $\gamma\gamma \to b\bar{b}(g)$.

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