ON MEASURING THE $\gamma \gamma$ WIDTH OF THE INTERMEDIATE-MASS HIGGS AT A PHOTON LINEAR COLLIDER

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Abstract

The identification of the intermediate-mass Higgs process $\gamma \gamma \rightarrow H \rightarrow b\bar{b}$ will be one of the most important goals of a future photon linear collider. Backgrounds from the continuum $\gamma \gamma \rightarrow c\bar{c}, b\bar{b}$ leading-order processes can be suppressed by using polarized photon beams in the $J_z = 0$ initial-state. The radiative processes $\gamma \gamma \rightarrow c\bar{c}g, b\bar{b}g$ can mimic the two-jet topology of the Higgs signal and provide the dominant background in the $J_z = 0$ channel. Particularly problematic is the $\gamma \gamma \rightarrow c\bar{c}g \rightarrow 2$ jets process. The effects of imposing additional cuts are investigated and it is shown that the radiative background could be reduced to a manageable level.

1. Introduction

The rapid advance of laser technology makes possible the collision of high-brightness, high-energy photon beams at future linear colliders [2-3] through Compton backscattering. One particularly intriguing use of such a photon linear collider is to measure the two-photon decay with a Higgs boson, $\Gamma(H \rightarrow \gamma\gamma)$ [4-6]. In a photon linear collider $\Gamma(H \rightarrow \gamma\gamma)$ is deduced by measuring the Higgs production cross section in the reaction $\gamma\gamma \rightarrow H \rightarrow X$ where $X$ is the detected final state. The number of events is proportional to the product $\Gamma(H \rightarrow \gamma\gamma) B(H \rightarrow X)$ where $B(H \rightarrow X)$ is the branching ratio of the Higgs boson into the final state $X$.

For a Higgs boson in the intermediate-mass region, 50 GeV $\lesssim 150$ GeV, the dominant decay mode is to $b\bar{b}$. Measurement of the two-photon width in this mass region requires suppressing the continuum $\gamma\gamma \rightarrow b\bar{b}, c\bar{c}$ background beneath the resonant $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$ signal, assuming light quarks can be distinguished from heavy quarks. 

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by vertexing. The background can be greatly suppressed by using polarized photon beams. The Higgs signal is produced by photons in a $J_z = 0$ initial state, whereas the backgrounds are primarily produced by photons in the $J_z = \pm 2$ initial state, the $J_z = 0$ Born cross section being suppressed for large angles by a factor of $m_q^2/s [6, 7]$.

The radiative processes can have an important impact ("radiation damage") since the presence of the additional gluon(s) in principle removes the suppression of the $J_z = 0$ background channel [1, 8]. The radiative process $\gamma\gamma \rightarrow q\bar{q}g$ with $q = b, c$ can mimic the dominant two-jet topology of the Higgs signal in two important cases: (i) if two of the three partons are collinear, for example a fast quark recoiling against a collinear quark and gluon, or (ii) if one of the partons is either quite soft or is directed down the beampipe and is therefore not tagged as a distinct jet. A particularly interesting example of the latter is when one of the incoming photons splits into a quark and an antiquark, one of which carries most of the photon’s momentum and Compton scatters off the other photon, $q(\bar{q})\gamma \rightarrow q(\bar{q})g$. Two jets are then identified in the detector, with the third jet remaining undetected. Here we discuss the impact of the radiative $q\bar{q}g$ process on the study of an intermediate-mass Higgs boson at a photon linear collider.

2. Non-radiative processes

For Higgs boson in the intermediate-mass region, the beam energy spread is much greater than the total width, and so the number of $H \rightarrow b\bar{b}$ events expected is

$$N_{H \rightarrow b\bar{b}} = \frac{dL_{H \rightarrow b\bar{b}}}{dW_{\gamma\gamma}} \bigg|_{M_H} \frac{8\pi^2 \Gamma(H \rightarrow \gamma\gamma) B(H \rightarrow b\bar{b})}{M_H^2}$$

(1)

where $W_{\gamma\gamma} = \sqrt{s}$ is the two-photon invariant mass.

In the Born approximation the background $(\gamma\gamma \rightarrow b\bar{b}, c\bar{c})$ cross section is given by

$$\frac{d\sigma(\gamma\gamma \rightarrow q\bar{q})}{d \cos \theta} = \frac{12\pi\alpha^2 Q_q^4}{s} \frac{\beta}{(1 - \beta^2 \cos^2 \theta)^2}$$

$$\times \begin{cases} 1 - \beta^4 & \text{for } J_z = 0 \\ \beta^2(1 - \cos^2 \theta)(2 - \beta^2 + \beta^2 \cos^2 \theta) & \text{for } J_z = \pm 2 \end{cases}$$

(2)

where $\beta \equiv \sqrt{1 - 4m_q^2/s}$ and $m_q$ and $Q_q$ are the mass and electric charge of the quark respectively.

Note the strong $\cos \theta$ dependence of the cross section and that the $J_z = 0$ cross section vanishes, for $|\cos \theta| < 1$, in the high-energy limit. This cross section can therefore be significantly reduced by using polarized beams and cutting on $\cos \theta$.

Note that in comparing signal ($S$) to background ($B$) cross sections it is convenient to normalize the signal cross sections as if $(dL/dW)_S = (L)_B/(10 \text{ GeV})$. This is equivalent to assuming that the experimental resolution on reconstructing the Higgs mass is 10 GeV, see [5].
Fig. 1 shows the Born cross sections for $b\bar{b}$ and $c\bar{c}$ production and illustrates the very large suppression that is possible with polarized photons in the $J_z = 0$ state.

Before discussing the radiative background we comment on the origin of the large-angle suppression of $q\bar{q}$ production in the $J_z = 0$ channel as $m_q^2/s \to 0$. Consider the symmetry properties of the Born amplitude in the $\beta \to 1$ limit. Because of helicity conservation at the photon vertices, only amplitudes with opposite helicities for the quark and antiquark survive. However, the combined impact of $C-$, $P-$ and $T-$ invariance, photon Bose statistics, and unitarity, can be shown to lead to a vanishing amplitude in this limit at lowest order in perturbation theory.

There are some instructive lessons from studying these symmetry properties:

1. For the $J_z = 0$ case the interferences between the Born and higher-order non-radiative diagrams are additionally suppressed by a factor of $m_q/\sqrt{s}$.

2. For $b\bar{b}$ production at $W_{\gamma\gamma} \sim 100$ GeV the suppression factor $m_b/\sqrt{s} \sim \alpha_S$ and the virtual gluon $O(\alpha_S^2)$ corrections should be taken into account in computation of the two-jet background in the $J_z = 0$ channel.

3. For the special case of scattering at $90^\circ$, the $m_q/\sqrt{s}$-suppression of all $J_z = 0$ non-radiative amplitudes (i.e. not just at leading order) follows simply from rotational invariance about the fermion direction and photon Bose statistics. For this particular angular configuration the $T$-invariance argument is redundant.

### 3. Radiative background

While at sufficiently high energies the lowest order $q\bar{q}$ large-angle cross sections are $O(\alpha^2/s)$ and $O(\alpha^2m_q^2/s^2)$ for $J_z = \pm 2$ and 0, respectively, the $q\bar{q}g$ cross sections are $O(\alpha^2\alpha_S/s)$ in both cases, i.e. the $\gamma\gamma \to q\bar{q}g$ cross section is in principle not suppressed in the $J_z = 0$ channel. Furthermore, there are regions of phase space where the three-parton final state may be tagged as a two-jet event. In the case of $b\bar{b}g$ and $c\bar{c}g$, the event may have a vertex structure similar to the non-radiative case, in which case this process could easily be misidentified as a $b\bar{b}$ final state. In contrast, the $J_z = \pm 2$ cross section for $\gamma\gamma \to q\bar{q}g$ is simply an $O(\alpha_S)$ correction to the much larger $J_z = \pm 2, \gamma\gamma \to q\bar{q}$ cross section and will not be considered further here.

In Ref. [1] we discussed the various radiative contributions which could be tagged as two-jet events. The analytic formulae were presented in the limit of vanishing quark masses and the results for the realistic case of massive quarks were calculated numerically. Recall that in the total cross section the infrared singularity is cancelled by one-loop virtual gluon correction to the Born cross section.

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2In the $b\bar{b}$ case the lowest-order results of Refs. [1, 5] could be considered only as the qualitative guide allowing one to estimate the scale of the background effects (see also [6]). In the $c\bar{c}$ case which is our main concern the tree-level calculations are quite appropriate.
The largest background is from the $\gamma\gamma \rightarrow c\bar{c}$ process which results in an order of magnitude increase of the $J_z = 0$ two-jet production cross section at $\sqrt{s} \sim 100$ GeV. This cross section is, in principle, in excess of the Higgs signal. An important contribution corresponds to one of the photons splitting into a quark and an antiquark, one of which undergoes a Compton scattering with the other photon to produce an energetic quark and gluon. The extent to which these two jets are back-to-back in the $\gamma\gamma$ center-of-mass frame (and therefore constitute a background to $H \rightarrow q\bar{q}$) depends on how the momentum is apportioned between the active and spectator quark in the $\gamma \rightarrow q\bar{q}$ splitting. It is worth noting that there is no $J_z = 0$ suppression in this case.

To estimate the size of the virtual Compton scattering contribution, one can use the leading pole approximation $[9]$, i.e.

$$d\sigma(\gamma\gamma \rightarrow q\bar{q}g) \simeq dW(\gamma \rightarrow q\bar{q}) \, d\sigma(q\gamma \rightarrow qg)|_{p^\prime = k_1 - \vec{p}_1},$$

(3)

$$dW(\gamma \rightarrow q\bar{q}) = \frac{\alpha Q_q^2}{4\pi^2} \left[ \frac{x^2 + (1 - x)^2}{k_1 \vec{p}_1} + \frac{(1 - x)m_q^2}{(k_1 \vec{p}_1)^2} \right] \frac{d^3p}{p_0},$$

(4)

where $x = 2p_0/\sqrt{s}$ is the energy fraction of the quark which does not participate in the hard scattering. For this process to give a two-jet background, most of the $\gamma\gamma$ scattering energy $\sqrt{s}$ should be deposited in the detector, thus $0 < x < \epsilon$ where $\epsilon$ is a small parameter that will be directly related to the allowed acollinearity of the two jets in the detector. Recall that discriminating two-jet topology on an event-by-event basis requires specifying a jet-finding algorithm.

It is convenient to use a clustering formalism exemplified by the JADE algorithm $[10]$. If we use this algorithm $\epsilon \sim y_{cut}$ and the pure $q\bar{q}$ events could be efficiently tagged with a $y_{cut}$ of 0.02–0.03.

The transverse momentum integration of the spectator quark gives rise to a large logarithm, $\ln(\Delta s/m_q^2)$, where $\Delta s$ is some fraction of $s$, and so the overall size of this contribution is roughly

$$\sigma(\gamma\gamma \rightarrow q\bar{q}g \rightarrow 2 \text{ jets})_{\text{comp}} \simeq \frac{\alpha Q_q^2}{2\pi} O(\epsilon) \ln \left( \frac{\Delta s}{m_q^2} \right) \sigma(q\gamma \rightarrow qg) \simeq$$

$$\simeq \frac{\alpha^2}{s} \alpha_S O(y_{cut}) \ln \left( \frac{\Delta s}{m_q^2} \right).$$

(5)

Note that the requirement that most of the collision energy should be deposited at large angles in the detector in the case of monochromatic photon beams provides a very strong suppression of other ‘resolved photon’ contributions, such as $\gamma \rightarrow gX$ followed by $g\gamma \rightarrow q\bar{q}$. $[3]$.

Recall that for $\sqrt{s} \approx 100$ GeV, $m_h/\sqrt{s} \sim \alpha S \sim y_{cut}$ and the Born contribution and the virtual and gluon radiative corrections to the two-jet cross section are all of the same order.
4. Experimental considerations

The $J_z = 0, \gamma\gamma \rightarrow q\bar{q}g$ cross section, even for small values of $y_{cut}$, is a few percent of the $J_z = \pm 2, \gamma\gamma \rightarrow q\bar{q}$ cross section. This cross section for bottom and charm quarks, in the massless approximation is illustrated in Fig. 2 along with the non-radiative backgrounds. In a photon linear collider, it is possible to achieve a $\frac{J_z = 0}{J_z = \pm 2}$ ratio of 20(50), so in order to bring the rates for the radiative processes down it is necessary to find cuts which further reduce the radiative backgrounds by a factor of about 5-10, without seriously degrading the $H \rightarrow b\bar{b}$ signal. To explore this in Ref. [1] a Monte-Carlo integration was employed (via JETSET 6.3 [11]) with a simple detector simulation.

Assuming $W_{\gamma\gamma} \simeq 100$ GeV and imposing a $y_{cut}$ of 0.02 with $|\cos \theta| < 0.7$ we found

\begin{align}
\sigma_{J_z=0}(\gamma\gamma \rightarrow H \rightarrow b\bar{b} \rightarrow 2\text{jets}) &= 0.86 \text{ pb}, \\
\sigma_{J_z=\pm 2}(\gamma\gamma \rightarrow b\bar{b} \rightarrow 2\text{jets}) &= 2.21 \text{ pb}, \\
\sigma_{J_z=\pm 2}(\gamma\gamma \rightarrow c\bar{c} \rightarrow 2\text{jets}) &= 35.6 \text{ pb}, \\
\sigma_{J_z=0}(\gamma\gamma \rightarrow b\bar{b}g \rightarrow 2\text{jets}) &= 0.035 \text{ pb}, \\
\sigma_{J_z=0}(\gamma\gamma \rightarrow c\bar{c}g \rightarrow 2\text{jets}) &= 0.87 \text{ pb}.
\end{align}

Although a $y_{cut}$ tends to select very two-jet events the $q\bar{q}g$ backgrounds (especially in the case of the Compton-regime configuration) still correspond to a somewhat different profile of jets. In addition vertexing proves to be a very useful tool in separating $b$’s from $c$’s. In order to reduce the radiative backgrounds to a manageable level it was proposed in [1] to impose additional event shape, jet width and vertex cuts.

Applying a sphericity cut of 0.02, a jet width cut of $20^{\circ}$, and requiring 5 tracks with high 3-D impact parameter results in the following cross sections:

\begin{align}
\sigma_{J_z=0}(\gamma\gamma \rightarrow H \rightarrow b\bar{b} \rightarrow 2\text{jets}) &= 0.48 \text{ pb}, \\
\sigma_{J_z=\pm 2}(\gamma\gamma \rightarrow b\bar{b} \rightarrow 2\text{jets}) &= 1.2 \text{ pb}, \\
\sigma_{J_z=\pm 2}(\gamma\gamma \rightarrow c\bar{c} \rightarrow 2\text{jets}) &= 0.54 \text{ pb}, \\
\sigma_{J_z=0}(\gamma\gamma \rightarrow b\bar{b}g \rightarrow 2\text{jets}) &= 0.0031 \text{ pb}, \\
\sigma_{J_z=0}(\gamma\gamma \rightarrow c\bar{c}g \rightarrow 2\text{jets}) &= 0.0059 \text{ pb}.
\end{align}

Thus, we anticipate that a modern vertex detector should be capable of achieving the necessary rejection of background events while remaining reasonably efficient for the signal $b$-quark events.

This discussion should not be closed without underlying that the results presented in Refs. [1], [8] can be considered only as the starting points for more refined and detailed investigations.
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Figure Captions

Fig. 1 Born cross sections for $\gamma\gamma \rightarrow b\bar{b}$ and $\gamma\gamma \rightarrow c\bar{c}$ in polarized collisions. A cut of $|\cos \theta| < 0.7$ has been applied. For comparison the Higgs boson signal has been superimposed with the normalization as described in the text ($\frac{dL}{dW} = 0.2 \text{fb}^{-1}/\text{GeV}$).

Fig. 2 Born cross sections for $\gamma\gamma \rightarrow b\bar{b}$ and $\gamma\gamma \rightarrow c\bar{c}$ and the radiative background computed in the massless approximation.
This figure "fig1-1.png" is available in "png" format from:

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