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BRIEF REPORTS

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Measuring the $\gamma\gamma$ coupling of the Higgs boson at linear colliders

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Observing the production of the Higgs particle in the $\gamma\gamma$ mode of a linear e^+e^- collider allows for the measurement of the $H\gamma\gamma$ coupling. We point out that for the intermediate Higgs mass range this measurement is considerably more challenging than previously believed. The $b\bar{b}$ signature receives a large background from the production of heavy quark pairs by resolved photons. We quantify the experimental requirements needed to make a meaningful measurement in the presence of this background.

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Experiments at future linear e^+e^- colliders, such as the 500 GeV Next Linear Collider (NLC), will be able to do detailed investigations of the interactions of gauge bosons, fermions, and scalars. One of the prime targets is the detailed study of the interactions of the Higgs boson, assuming that it is light enough to be produced at these machines. In particular it has been suggested [1] to use the $\gamma\gamma$ collision mode of such a machine, with the photons generated by backscattered laser beams [2], in order to investigate the production process

$$\gamma\gamma \to H \tag{1}$$

and thereby achieving a direct measurement of the $H\gamma\gamma$ coupling. Measuring this coupling should be a high priority as it is in principle sensitive to all charged particles which acquire their mass via the Higgs mechanism. The accuracy of this measurement critically depends on the magnitude of the competing backgrounds. In the analysis of Ref. [1] the $\gamma\gamma \to b\bar{b}$ background was evaluated and the possibility of highly polarized photon beams was explored as a way to enhance the signal over background. In addition a measurement of the $b\bar{b}$ invariant mass with an optimistic error of ± 2.5 GeV was assumed.

We here point out that, unfortunately, at a photon collider large additional irreducible backgrounds will be present which can be traced to the hadronic content of the photon. The splitting sequence $\gamma \to$ quark $\to$ gluon will provide for an effective beam of strongly interacting partons with the resultant cross sections for producing $b\bar{b}$ pairs of strong interaction size [3, 4]. As a result additional irreducible backgrounds arise from the processes

$$\begin{aligned} &\gamma g \to b\bar{b}, \\ &gg \to b\bar{b}\ , \quad q\bar{q} \to b\bar{b}\ , \end{aligned} \tag{2}$$

and corresponding backgrounds appear to be due to the even larger production cross sections of charmed quarks. The latter represent, in principle, a reducible background although they have the potential to fake b quarks in a realistic experiment as they exceed the b-pair background by up to one order of magnitude. One additional problem is that the polarization information of the original photon is largely lost in the splitting $\gamma \to$ gluon and therefore the use of polarized photon beams will be ineffective in reducing this resolved photon background.

A defining feature of the $H \to b\bar{b}$ signal is the S-wave nature of the resonance which results in the production of the b quarks at large c.m. scattering angles. In contrast all the backgrounds peak at small scattering angles. Following Ref. [1] we therefore require that the scattering angle of the b's with respect to the beam axis is large enough, $|\cos\theta| < 0.85$ in the $b\bar{b}$ rest frame. Imposing this cut in all of the following, we compare in Fig. 1(a) the total cross section of the Higgs signal $\sigma(H \to b\bar{b})$, measured in fb, with the invariant mass distributions (measured in fb/10 GeV) of the various backgrounds. For the $\gamma\gamma \to b\bar{b}$ background the reduction due to polarized beams with $\langle\lambda\lambda'\rangle = 80\%$ has been included. It amounts to a factor of 5. Convolution with realistic photon distributions [5, 3] is already included in all cross sections, therefore the corresponding number of events will be given by $N_{ev} = \mathcal{L}_{e^+e^-} k\sigma$ where the conversion coefficient k represents the average number of high energy photons per electron. For the 500 GeV NLC a reasonable assumption is $\mathcal{L}_{e^+e^-}k$ = 10–100 fb^{-1} year^{-1} [5, 6].

One finds that for all interesting Higgs masses the resolved photon background is at least a factor 3–8 larger than the $\gamma\gamma \to b\bar{b}$ background and this factor approaches 2 orders of magnitude for Higgs masses around 70 GeV. The dominant resolved photon background is dominated by the process $\gamma g \to b\bar{b}$. Gluon-gluon fusion and $q\bar{q}$ annihilation are, in comparison, negligible. For the results shown in Fig. 1(a) we have summed all resolved contributions. In the γg process the photon typically carries much more energy in the laboratory frame than the gluon which leads to a substantial boost of the event along the beam axis in the incoming photon direction. As a result the larger of the two b rapidities is bigger in the resolved photon background than in the signal as is shown in Fig. 1(b). As illustrated in Table I, requiring a maximum value for the b-quark jet rapidities leads to a substantial improvement in the signal to background ratio. As seen from the table, the improvement is optimal for $|y_b| \lesssim 1.5$, a value which compares favorably with realistic coverage assumptions of the microvertex detectors which will be essential for b identification.

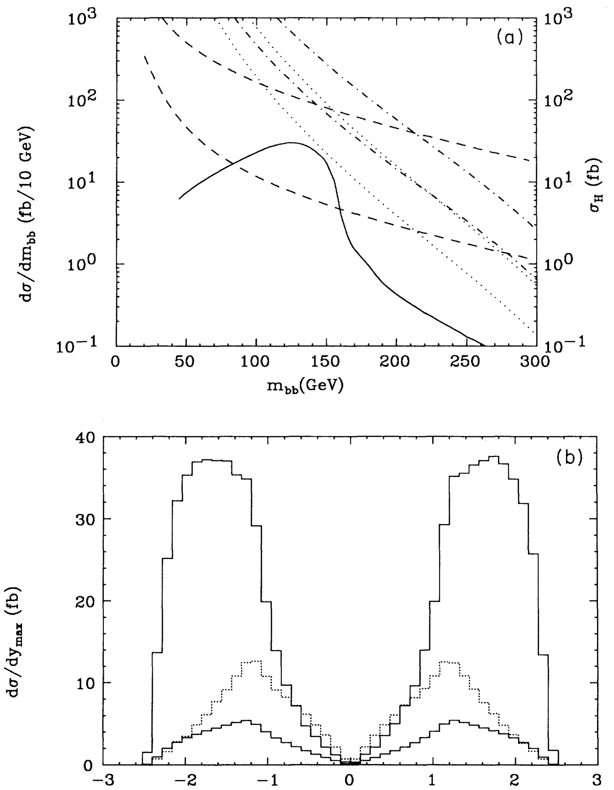

FIG. 1. (a) Total cross section for the Higgs signal $\sigma(H \to b\bar{b})$ measured in fb (solid line) and invariant mass distributions (measured in fb/10 GeV) of the various backgrounds. The dashed lines correspond to the direct photon backgrounds. Dotted (dash-dotted) lines correspond to resolved photon backgrounds for DG (LAC3) photon structure functions. In all cases the lower (upper) line corresponds to $b\bar{b}$ ($c\bar{c}$) background. (b) Maximum rapidity distribution of b quarks with invariant mass $m_{b\bar{b}} = 130 \pm 10$ GeV. The dotted histogram corresponds to b's from the decay of a Higgs boson with $m_H = 130$ GeV. The solid lines correspond to the $\gamma\gamma \to b\bar{b}$ background (lower) and $\gamma g \to b\bar{b}$ (upper) for the DG photon structure functions. In all cases we require $|\cos\theta|_Q < 0.85$ in the $Q\bar{Q}$ rest frame. For the $\gamma\gamma \to Q\bar{Q}$ background the reduction due to polarized beams with $\langle\lambda\lambda'\rangle = 80\%$ has been included.

Because the gluon content of the photon has not been reliably measured to date (experiments at the DESY e-p collider HERA should soon remedy this situation), there is considerable uncertainty regarding the effective $b\bar{b}$ production cross section. We have used two presently popular sets of gluon distribution functions inside the photon to span these uncertainties, the parameterization by Drees and Grassie [7] (DG) which provides for a relatively soft gluon distribution and the Levy-Charchula-Abramowicz set 3 (LAC3) parameterization of Ref. [8] which gives a considerably harder gluon distribution. Use of the LAC3 structure function not only results in significantly larger resolved backgrounds, but the difference in rapidity distribution between signal and background, shown in Fig. 1(b), is further reduced. Because of the presence of harder gluons the photon-gluon c.m. frame receives a smaller boost along the beam axis and the b-rapidity distribution overlaps even more with the one for the Higgs signal.

Because the $\gamma\gamma \to q\bar{q}$, $\gamma g \to q\bar{q}$, and $gg \to q\bar{q}$ cross sections scale like Q_q^4, Q_q^2, and Q_q^0, respectively, where Q_q denotes the quark electric charge, the charm production cross sections are larger by a factor 16 and 4, respectively, for $\gamma\gamma$ and γg fusion. Hence an excellent suppression of charm events is required. At the same time an excellent $b\bar{b}$ invariant mass resolution is required in order to identify the $H \to b\bar{b}$ invariant mass peak. Unfortunately these two requirements are at least partially exclusive: leptonic B decay would provide a powerful tool in suppressing the charm background, however, every leptonic decay in the $b \to c \to$ light-quark decay chain produces missing momentum due to escaping neutrinos and hence intrinsically limits the mass resolution. Excellent mass resolution is only possible when restricting

TABLE I. $\sigma_{\mathrm{signal}}/\sqrt{\sigma_{\mathrm{background}}}$ ($\sqrt{\mathrm{fb}}$) for the main backgrounds. For the backgrounds an invariant mass resolution $m_H \pm 10$ GeV is assumed.For the resolved photon backgrounds the numbers correspond to DG structure functions. The significance of the signal in standard deviations is obtained multiplying these numbers by $\sqrt{\mathcal{L}_{e^+e^-}k} \approx$ 3–10 $\mathrm{fb}^{-1/2}$.

		$\sigma_{\mathrm{signal}}/\sqrt{\sigma_{\mathrm{background}}}$ ($\sqrt{\mathrm{fb}}$)			
M_{Higgs} (GeV)	$y_{\max}$	$\gamma\gamma \to b\bar{b}$	$\gamma\gamma \to c\bar{c}$	$\gamma g \to b\bar{b}$	$\gamma g \to c\bar{c}$
60	∞	1.2	0.35	< 0.14	< 0.007
	2	1.1	0.32	< 0.18	< 0.09
	1.5	0.98	0.29	< 0.21	< 0.11
	1	0.77	0.22	< 0.2	< 0.1
140	∞	7.2	1.86	< 3.1	< 1.55
	2	7.9	1.94	< 3.3	< 1.65
	1.5	7.3	1.88	< 3.5	< 1.76
	1	5.6	1.45	< 3.2	<1.65

to events without leptonic decays, with double displaced vertices as a signature for both a B and a subsequent D decay. While this imposes severe requirements on the performance of the microvertex detectors, it also eliminates about 70% of all signal events. The only practical solution appears to be to accept leptonic decay modes and hence a reduced mass resolution. The problem has been considered before in Ref. [9] in the context of Higgs production at CERN's Large Electron-Positron Collider (LEP) and Large Hadron Collider (LHC). The intrinsic mass resolution of the $H \to b\bar{b}$ peak was found to be around ±10 GeV for a 120 GeV Higgs boson, with substantial tails due to missing particles. Any improvements come at the price of substantial loss in rate. Somewhat optimistically we assume in the following that the Higgs peak will be contained in a 20 GeV bin centered at m_H and we integrate the backgrounds over the same bin when making rate comparisons.

The results are shown in Fig. 2 where we have ignored any charm background. Even for a soft gluon distribution inside the photon the Higgs signal never is larger than half the background cross section. The total background is strongly dependent on the rejection of charm events. A 90% efficiency for rejecting charm, combined with a 90% identification probability of actual $b\bar{b}$ events would lead to a value of $\sigma_{\text{signal}}/\sqrt{\sigma_{\text{background}}} = 2.2\ \text{fb}^{1/2}$ for $m_H = 140$ GeV and using DG structure functions, which for an integrated luminosity of 10 fb^{-1} corresponds to a 7 σ signal. Obviously this result is based on quite optimistic assumptions and the Higgs mass range for which the result applies is only of order 20 GeV. For lighter masses the situation worsens rapidly, as is evident from Table I. It should be pointed out that even a 7σ result does not allow a determination of the top quark loop contribution to the $H\gamma\gamma$ coupling.

Although it might seem by now that this measurement is impossible, this might not be the case. There are two more ways for reducing the resolved background. One can in principle reduce the beam energy and run the accelerator so that the maximum photon-photon energy corresponds to the mass of the Higgs. All the high energy photons which are the origin of the resolved background have thus been eliminated. In practice it is unrealistic to expect that a new collider will run for a sufficient length of time at a reduced energy where WW production is below threshold. A more realistic way to reduce the background is by tagging the resolved photon by its beam jet. The efficiency of this is completely dictated by the architecture of the detector. Obviously good coverage at small angles is required and in order to perform this measurement the detector design will have to emphasize hadron detection very close to the beams.

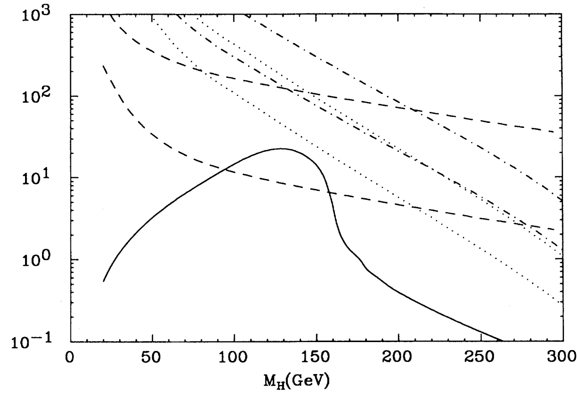

FIG. 2. Cross section for the Higgs signal and backgrounds (same notation as Fig. 1). For the backgrounds an invariant mass resolution $m_H \pm 10$ GeV is assumed. In all cases we require $|\cos\theta|_Q < 0.85$ in the $Q\bar{Q}$ rest frame and a maximum rapidity $|y_{\max}|_Q < 1.5$. For the $\gamma\gamma \to Q\bar{Q}$ background the reduction due to polarized beams with $\langle\lambda\lambda'\rangle = 80\%$ has been included.

We summarize our conclusions by emphasizing once more that in order to measure the $H\gamma\gamma$ coupling over most of the intermediate mass range (60–140 GeV) one requires a detector with (i) good b identification in the central region, (ii) excellent charm rejection, and (iii) identification of narrow angle beam jets associated with resolved photons. We also argued that improving the situation by assuming $b\bar{b}$ mass resolutions as small as ±2.5 GeV [1] is quite unrealistic.

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