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Production of MSSM Higgs Bosons in Photon-Photon Collisions*

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Abstract

The heavy neutral Higgs bosons H, A in the minimal supersymmetric extension of the Standard Model can be produced as single resonances at high-energy $\gamma\gamma$ colliders. We have studied the prospects of the search for these particles in $b\bar{b}$ and neutralino-pair final states. The Higgs bosons can be found with masses up to 70–80% of the initial $e^{\pm}e^{-}$ collider energy for medium values of $\mathrm{tg}\beta$, i.e. in areas of the supersymmetric parameter space not accessible at other colliders.

1 Introduction

The search for Higgs bosons [1] is one of the most important endeavours of present and future experiments [2]. The minimal supersymmetric extension of the Standard Model [MSSM] includes two isodoublet Higgs fields which materialize, after electroweak symmetry breaking, in five elementary Higgs bosons [3]: two neutral CP-even (h, H), one neutral CP-odd (A) and two charged $(H^{\pm})$ particles. To leading order, the MSSM Higgs

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sector can be described by two parameters which are in general chosen as the pseudoscalar mass M_A and $\mathrm{tg}\beta = v_2/v_1$, the ratio of the two vacuum expectation values of the scalar Higgs fields. While the mass of the light Higgs boson h is bounded to $M_h \lesssim 130$ GeV [4], the masses of the heavy Higgs bosons $H, A, H^\pm$ are expected to be of the order of the electroweak scale up to about 1 TeV. The heavy Higgs bosons are nearly mass degenerate, $M_H - M_A \approx (M_Z^2 \sin^2 2\beta + \epsilon \cos^2\beta)/2M_A \lesssim 2$ GeV for $M_A \gtrsim 250$ GeV with $\epsilon = 3G_F m_t^4 \log(1 + M_{susy}^2/m_t^2)/\sqrt{2}\pi^2 \sin^2\beta$. An important property of the SUSY Higgs bosons is the enhancement of the bottom Yukawa couplings with increasing $\mathrm{tg}\beta$. Moreover, the couplings to supersymmetric particles, charginos and neutralinos can be significant [5].

The light Higgs boson h of the MSSM can be discovered at existing or future $p\bar{p}/pp$ and e^+e^- colliders. However, the heavy Higgs bosons H, A may escape detection in a wedge centered around medium values of $\mathrm{tg}\beta \sim 7$, and masses above 200 GeV even at the LHC [6]. At $e^\pm e^-$ linear colliders, heavy MSSM Higgs bosons can only be discovered in associated production $e^+e^- \to HA$ [7] according to the decoupling theorem. In first-phase e^+e^- colliders with a total energy of 500 GeV, the heavy Higgs bosons can thus be discovered with masses up to about 250 GeV. To extend the mass reach, the $\gamma\gamma$ option of linear colliders can be used in which high-energy photon beams are generated by Compton back-scattering of laser light [8]. Neutral Higgs particles can be formed as resonances in $\gamma\gamma$ collisions [9]:

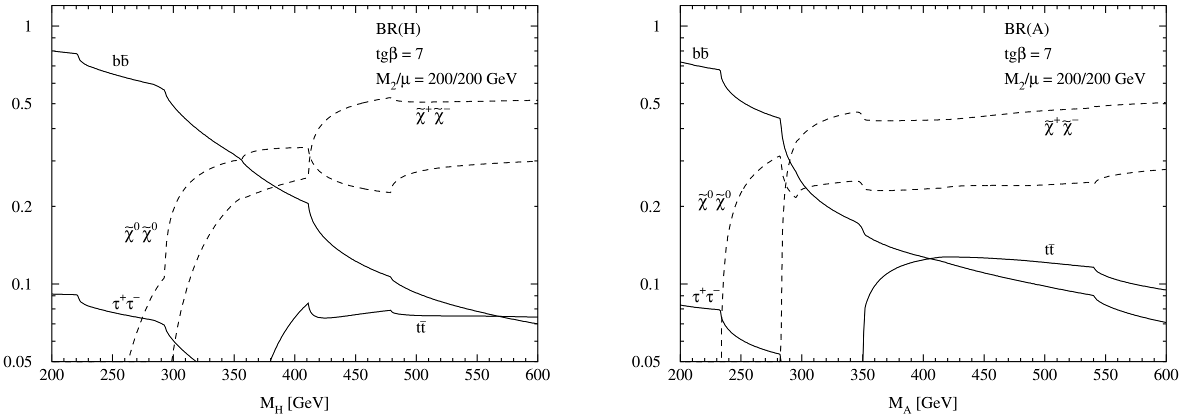
$$\gamma\gamma \to h, H \text{ and } A \tag{1}$$

Center-of-mass energies of about 80% of the primary $e^\pm e^-$ collider energies and high degrees of longitudinal photon polarization can be reached at $\gamma\gamma$ colliders. Sufficient event rates are guaranteed for the expected high-energy luminosities $\int \mathcal{L} = 300$ fb^{-1} *per annum* [10]. Photon colliders therefore provide a useful instrument for the search for heavy Higgs bosons not accessible elsewhere [11].

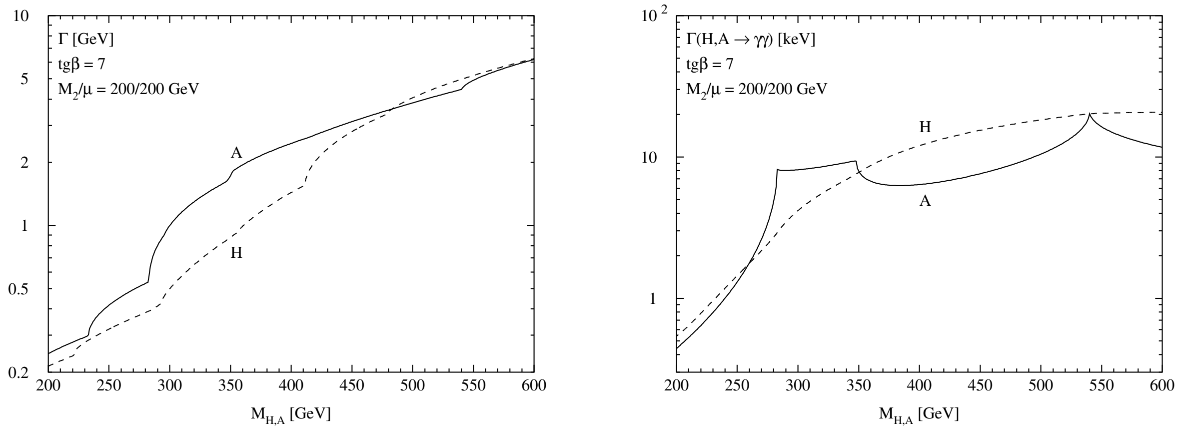
2 Analysis

Branching Ratios. As promising examples for the discovery of heavy MSSM Higgs bosons in $\gamma\gamma$ collisions the two decay modes $H, A \to b\bar{b}$ and $\tilde{\chi}^0\tilde{\chi}^0$ have been investigated in detail for $\mathrm{tg}\beta = 7$ and Higgs masses $M_{H,A} > 200$ GeV. In this region the LHC is blind, if SUSY parameters are not realized in a small favourable region, and linear colliders cannot reach masses beyond 250 GeV in the first phase of the e^+e^- mode. For illustration, the additional MSSM parameters of the gaugino sector have been chosen as $M_2 = \pm\mu = 200$ GeV, assuming a universal gaugino mass at the GUT scale. These parameters correspond for positive μ to neutralino masses $m_{\tilde{\chi}^0_{1,2,3,4}} = 85, 148, 208, 271$ GeV and to chargino masses $m_{\tilde{\chi}^\pm_{1,2}} = 141, 270$ GeV. For the sake of simplicity, sleptons and squarks are assumed to be so heavy that they do not affect the analysis in a significant way.

The decay branching ratios [5, 12, 13, 14] are presented in Fig. 1a, the kinks corresponding to thresholds of new channels. For moderate masses, the $b\bar{b}$ decay modes turn out to be dominant, while for large Higgs masses the dominant modes are the decays into charginos and neutralinos. The decays to $\tau^+\tau^-$ and $t\bar{t}$ pairs are suppressed with respect to $b\bar{b}$ decays by about an order of magnitude.



(a)



(b)

Figure 1: *(a) Branching ratios, and (b) total widths and partial $\gamma\gamma$ widths of the heavy Higgs bosons H, A as a function of the Higgs masses. The MSSM parameters have been chosen as* $\mathrm{tg}\beta = 7, M_2 = \mu = 200$ *GeV. The branching ratios are given for the sum of all charged and neutral $\tilde{\chi}\tilde{\chi}$ pairs except the LSP pair.*

The partial decay widths $H, A \to \gamma\gamma$ determine the production cross sections. The $\gamma\gamma$ couplings of the Higgs bosons are mediated by charged-particle loops [15]. The loops of top quarks and charginos are dominant for the MSSM parameters chosen above. Congruent with the uncertainty principle, the charginos decouple asymptotically with increasing chargino masses. The partial $\gamma\gamma$ widths are shown in Fig. 1b.

Signals and Backgrounds. To leading order and in the narrow-width approximation, the production of Higgs bosons in $\gamma\gamma$ collisions is described by the cross section

$$\langle\sigma(\gamma\gamma \to H, A)\rangle = \frac{8\pi^2}{s}\frac{\Gamma(H, A \to \gamma\gamma)}{M_{H,A}}\frac{d\mathcal{L}^{\gamma\gamma}}{d\tau_{H,A}} \tag{2}$$

where $d\mathcal{L}^{\gamma\gamma}/d\tau_{H,A}$ denotes the differential $\gamma\gamma$ luminosity, normalized to unity, for $\tau_{H,A} = M_{H,A}^2/s$. The next-to-leading order QCD corrections consist of gluon insertions in the quark triangle loops of the photonic Higgs couplings and gluon radiation in the Higgs decays to quark-antiquark ($b\bar{b}$) pairs. The two-loop contributions to the Higgs-$\gamma\gamma$ couplings are of moderate size, if the quark mass inside the triangle loop is chosen as the running quark mass at a typical scale determined by the c.m. energy of the process [16]. The QCD corrections to the Higgs decays into bottom quarks generate large logarithms, which however can be absorbed in the running Yukawa coupling at the scale of the c.m. energy [13, 17]. After inserting the running quark masses, the total QCD corrections increase the signal cross section by about 20–40%.

The main background processes $\gamma\gamma \to b\bar{b}$ and $\tilde{\chi}^+\tilde{\chi}^-$ are pure QED reactions in lowest order. Since the signals are generated for equal photon helicities, this configuration can be enhanced by choosing the same helicities for the incoming laser photons and helicities for the electrons/positrons that are opposite to the laser photons in the initial state [8, 18]; at the same time the background processes are suppressed. The NLO corrections to $\gamma\gamma \to b\bar{b}$ for polarized photon beams have been calculated in Ref. [19]. They are moderate for photons of opposite helicities but large for photons of equal helicity. The differential cross section for photons of equal helicity is suppressed by a factor m_b^2/s at lowest order due to the helicity flip in the bottom-quark line. This suppression is removed by gluon radiation and the size of the cross section increases to order α_s. Large Sudakov and non-Sudakov logarithms due to soft gluon radiation and soft gluon and bottom-quark exchange in the virtual corrections must be resummed [20]. In order to suppress the gluon radiation we have selected slim two-jet configurations in the final state as defined within the Sterman–Weinberg criterion. If the radiated gluon energy is larger than $\epsilon_g = 10\%$ of the total $\gamma\gamma$ invariant energy and if, at the same time, the opening angle between all three partons in the final state is larger than $\theta_c = 20^o$, the event is classified as three-jet event and rejected. The contamination of $b\bar{b}$ final states by the process $\gamma\gamma \to c\bar{c}$ can be kept under experimental control by b tagging.

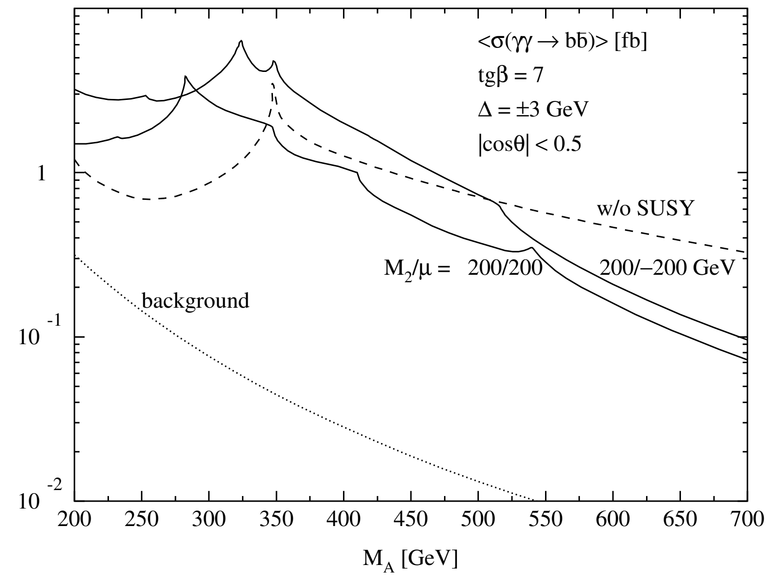
Moreover, the interference between the signal and background mechanisms has been taken into account properly. This part affects only configurations with equal photon helicities in the initial state. We have calculated the next-to-leading order QCD corrections of the interference terms to quark final states including the resummation of the large (non-) Sudakov logarithms [for details see Ref. [11]]. The QCD corrections to the interference terms are large.

3 Results

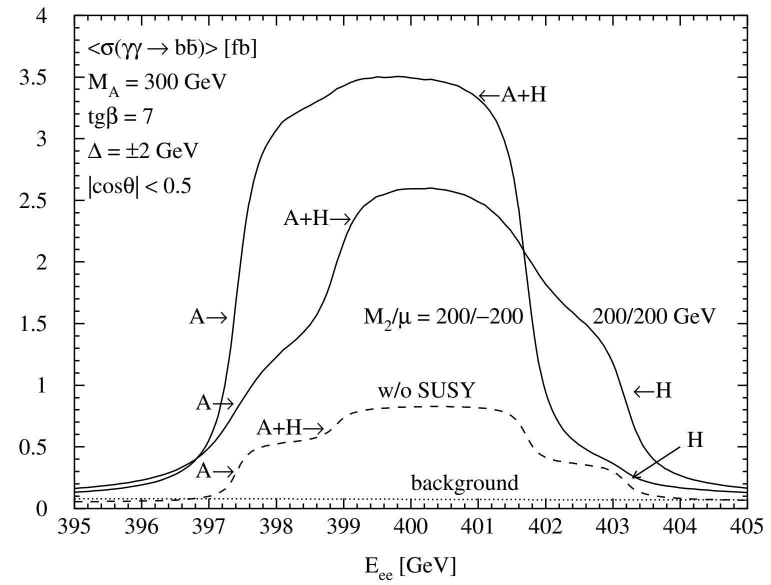
$b\bar{b}$ Channel. We assume that a rough scan in the $\gamma\gamma$ energy will first be performed, from which preliminary evidence for the observation of a Higgs boson can be derived. Since the luminosity spectrum of equal-helicity photons is strongly peaked at about 80% of the $e^{\pm}e^{-}$ c.m. energy [8, 18], the maximum can be tuned in the second step to the value of the pseudoscalar Higgs mass M_A at which the signal peak in the energy scan appeared. The scalar resonance H at a small distance $M_H - M_A \sim 1$ GeV nearby is included by the non-zero experimental resolution at the same time. The analysis can be optimized by final-state cuts. The background is strongly reduced by a cut in the production angle of the bottom quarks, $|\cos\theta| < 0.5$, while the signal is affected only moderately. By collecting $b\bar{b}$ final states with a resolution in the invariant mass $M_A \pm 3$ GeV, that can be expected at photon colliders [21], the sensitivity to the combined A and H resonance peaks above the background is strongly increased. The result for the peak cross section is shown in Fig. 2a as a function of the pseudoscalar mass M_A for tg$\beta = 7$. It can be inferred from the figure that the background is strongly suppressed. The significance of the heavy Higgs boson signals is sufficient for the discovery of the Higgs particles up to about 70–80% of the e^+e^- c.m. energy. Thus, at a 500 GeV e^+e^- linear collider the H, A bosons with masses up to about 400 GeV can be discovered in the $b\bar{b}$ channel in the photon-collider mode, while for c.m. energies above 800 GeV the range can be extended to about 600 GeV. For heavier Higgs masses the signal rate becomes too small for detection.

In a fine scan of the resonance region within a minimal bracket of ± 2 GeV of the invariant-mass resolution, the two Higgs bosons A and H can be disentangled at least in part of the supersymmetry parameter space. Increasing the energy stepwise from below, the Higgs boson A is produced first, followed by the combination of A and H, while finally H is left before the scan leaves the resonance region. This procedure is analyzed quantitatively in Fig. 2b. If the supersymmetry parameters are favourable, the steps in the resonance formation curve are clearly visible. However, this theoretical analysis must be backed by future experimental simulations.

$\tilde{\chi}^0\tilde{\chi}^0$ Channels. For the MSSM parameters introduced above, the heavy Higgs bosons have significant decay branching ratios to pairs of charginos and neutralinos, cf. Figs. 1. However, due to the integer chargino charge, the chargino background from continuum production is in general more than an order of magnitude larger than the signal. Pairs of neutralinos cannot be produced in $\gamma\gamma$ collisions at leading order so that neutralino decays open a potential discovery channel for the heavy Higgs bosons H, A [see also Ref. [22]]. This is apparent for moderate Higgs masses below the chargino decay threshold. Detailed analyses of the topologies in the final state are needed however to separate the neutralinos from the background charginos above the chargino threshold. For example, the signal channel $\gamma\gamma \to H, A \to \tilde{\chi}^0_2\tilde{\chi}^0_1$ leads in the $\tilde{\chi}^0_2$ cascade decay predominantly to the hadronic final states $jj+ \not{E}$ with the jet-pair invariant mass M_{jj} clustering near the $\tilde{\chi}^0_2 - \tilde{\chi}^0_1$ mass difference if the sfermions are heavy. By contrast, the continuum process $\gamma\gamma \to \tilde{\chi}^+_1\tilde{\chi}^-_1$ generates the final state $W^*W^*+ \not{E}$ with distinct $jjjj+ \not{E}$ jet topologies. Thus, the neutralino decays are expected to provide novel discovery channels of the heavy Higgs bosons at photon-photon colliders.



(a)



(b)

Figure 2: *(a) Cross sections for resonant heavy Higgs boson H, A production in $\gamma\gamma$ collisions as a function of the pseudoscalar Higgs mass M_A with final decays into $b\bar{b}$ pairs, and the corresponding background cross section. The maximum of the photon luminosity has been tuned to M_A. Cuts as indicated. The MSSM parameters have been chosen as* tg$\beta = 7, M_2 = \pm\mu = 200$ *GeV; the limit of vanishing SUSY-particle contributions is shown for comparison. (b) Threshold scans for H, A production as a function of the $e^{\pm}e^{-}$ collider energy with final decay into $b\bar{b}$ pairs. The cross sections are defined in $b\bar{b}$ mass bins of $\pm$ 2 GeV around the maximum of the $\gamma\gamma$ luminosity.*

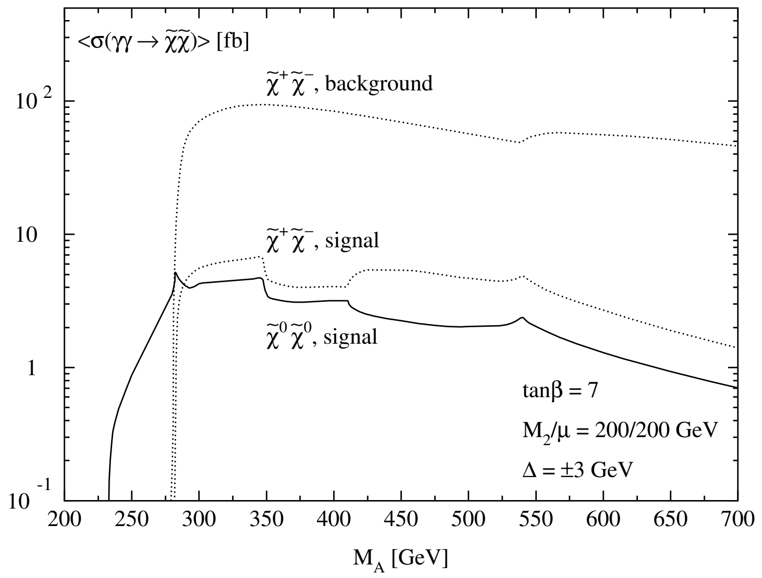


Figure 3: *Same as Fig. 2a for chargino and neutralino final states;* $M_2 = \mu = 200$ *GeV.*

4 Summary

It has been shown in this letter that the heavy scalar and pseudoscalar Higgs bosons H and A of the minimal supersymmetric extension of the Standard Model MSSM can be discovered for medium values of tgβ up to masses of about 400 GeV in the photon-photon collider mode of a linear collider project in the first phase; the mass reach can be extended to values above 600 GeV at a TeV collider. The discovery potential for the heavy Higgs bosons is unique since this region is not accessible neither in the respective e^+e^- phase of a linear collider, nor at the LHC in general.

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References

[1] P.W. Higgs, Phys. Lett. **12** (1964) 132; F. Englert and R. Brout, Phys. Rev. Lett. **13** (1964) 321; G.S. Guralnik, C.R. Hagen and T.W. Kibble, Phys. Rev. Lett. **13** (1964) 585.

[2] P. Igo-Kemenes, Proceedings of The XXX Int. Conference on High Energy Physics, Osaka, 2000.

[3] J.F. Gunion and H.E. Haber, Nucl. Phys. **B272** (1986) 1 and **B278** (1986) 449.

[4] M. Carena, H.E. Haber, S. Heinemeyer, W. Hollik, C.E.M. Wagner and G. Weiglein, Nucl. Phys. **B580** (2000) 29, and references therein.

[5] A. Djouadi, J. Kalinowski and P.M. Zerwas, Z. Phys. **C57** (1993) 569.

[6] ATLAS Coll., Technical Design Report, CERN–LHCC 99–14 (May 1999); CMS Coll., Technical Proposal, CERN–LHCC 94–38 (Dec. 1994).

[7] A. Djouadi, J. Kalinowski, P. Ohmann and P.M. Zerwas, Z. Phys. **C74** (1997) 93; E. Accomando et al., Phys. Rep. **299** (1998) 1; P.M. Zerwas, Proceedings, 1999 Cargèse Lectures, hep-ph/0003221.

[8] I.F. Ginzburg, G.L. Kotkin, S.L. Panfil, V.G. Serbo and V.I. Telnov, Nucl. Inst. Meth. **219** (1984) 5.

[9] D.L. Borden, D.A. Bauer and D.O. Caldwell, Phys. Rev. **D48** (1993) 4018; J.F. Gunion and H.E. Haber, Phys. Rev. **D48** (1993) 5109; M. Krämer, J. Kühn, M.L. Stong and P.M. Zerwas, Z. Phys. **C64** (1994) 21; G. Jikia and S. Söldner-Rembold, Nucl. Phys. Proc. Suppl. **82** (2000) 373; E. Asakawa, J. Kamoshita, A. Sugamoto and I. Watanabe, Eur. Phys. J. **C14** (2000) 335; J. Illana, Report DESY-99-167, hep-ph/9912467; K. Hagiwara, Proceedings "Workshop on $\gamma\gamma$ Colliders", DESY Hamburg (2000), hep-ph/0011360.

[10] V. Telnov, Proceedings "Workshop on $\gamma\gamma$ Colliders", DESY Hamburg (2000), hep-ex/0010033.

[11] M.M. Mühlleitner, PhD thesis, DESY-THESIS-2000-033, hep-ph/0008127.

[12] A. Djouadi, P. Janot, J. Kalinowski and P.M. Zerwas, Phys. Lett. **B376** (1996) 220.

[13] A. Djouadi, M. Spira and P.M. Zerwas, Z. Phys. **C70** (1996) 427.

[14] A. Djouadi, J. Kalinowski and M. Spira, Comput. Phys. Comm. **108** (1998) 56.

[15] J. Ellis, M.K. Gaillard, D.V. Nanopoulos, Nucl. Phys. **B106** (1976) 292; J.F. Gunion, H.E. Haber, Phys. Rev. **D48** (1993) 5109.

[16] A. Djouadi, M. Spira, J.J. van der Bij and P.M. Zerwas, Phys. Lett. **B257** (1991) 187; A. Djouadi, M. Spira and P.M. Zerwas, Phys. Lett. **B311** (1993) 255; K. Melnikov and O. Yakovlev, Phys. Lett. **B312** (1993) 179; M. Inoue, R. Najima, T. Oka and J. Saito, Mod. Phys. Lett. **A9** (1994) 1189; M. Spira, A. Djouadi, D. Graudenz and P.M. Zerwas, Nucl. Phys. **B453** (1995) 17.

[17] E. Braaten and J.P. Leveille, Phys. Rev. **D22** (1980) 715; N. Sakai, Phys. Rev. **D22** (1980) 2220; T. Inami and T. Kubota, Nucl. Phys. **B179** (1981) 171; S.G. Gorishny, A.L. Kataev and S.A. Larin, Sov. J. Nucl. Phys **40** (1984) 329; M. Drees and K. Hikasa, Phys. Rev. **D41** (1990) 1547, Phys. Lett. **B240** (1990) 455 and (E) *ibid.* **B262** (1991) 497.

[18] J.H. Kühn, E. Mirkes and J. Steegborn, Z. Phys. **C57** (1993) 615.

[19] B. Kamal, Z. Merebashvili and A.P. Contogouris, Phys. Rev. **D51** (1995) 4808 and (E) *ibid.* **D55** (1997) 3229; G. Jikia and A. Tkabladze, Phys. Rev. **D54** (1996) 2030 and hep-ph/0004068.

[20] V.S. Fadin, V.A. Khoze and A.D. Martin, Phys. Rev. **D56** (1997) 484; M. Melles and W.J. Stirling, Phys. Rev. **D59** (1999) 094009, Eur. Phys. J. **C9** (1999) 101 and Nucl. Phys. **B564** (2000) 325.

[21] H.J. Schreiber (TESLA Coll.), private communication.

[22] G. Bélanger, Talk at the ECFA/DESY Workshop Oxford 1999.