

# Heavy charged Higgs boson production at next generation $\gamma\gamma$ colliders

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**Abstract.** We investigate the scope of all relevant production modes of charged Higgs bosons in the MSSM, with mass larger than the one of the top quark, at future Linear Colliders operating in  $\gamma\gamma$  mode at the TeV energy scale. Final states with one or two  $H^\pm$  bosons are considered, as produced by both tree- and loop-level interactions.

In the minimal supersymmetric standard model (MSSM) it is not unnatural to assume that the typical mass of the supersymmetric (SUSY) partners of ordinary matter is at the TeV scale or above – well in line with current experimental bounds – this rendering the Higgs sector a privileged probe to access physics beyond the SM. In this respect, it would be intriguing to detect charged Higgs states (henceforth denoted by  $H^\pm$ ), as in this case one would unquestionably be in the presence of some non-standard phenomena. In fact, even the discovery of a (light) neutral Higgs boson would leave open questions as to whether it belongs to the SM or else the MSSM, since in the so-called “decoupling regime” of the latter (i.e., when a hierarchy exists among the masses of the five Higgs states:  $M_{H^0} \sim M_{A^0} \sim M_{H^\pm} \gg M_{h^0}$ ) the fundamental properties of such a particle (quantum numbers, couplings, branching ratios (BRs), etc.) would be the same in both models<sup>1</sup>.

Rumours of possible evidence of light charged Higgs bosons being produced at LEP2 [1] have faded away. One is now left with a model independent limit on  $M_{H^\pm}$ , of order  $M_{W^\pm}$ . In the mass interval  $M_{W^\pm} \lesssim M_{H^\pm} \lesssim m_t$ , charged Higgs bosons could well be found at Tevatron (Run 2) [2], which has already begun data taking at  $\sqrt{s_{pp}} = 2$  TeV [3] at FNAL. In contrast, if  $M_{H^\pm} \gtrsim m_t$  (our definition of a “heavy” charged Higgs boson), one will necessarily have to wait for the advent of the Large Hadron Collider (LHC,  $\sqrt{s_{pp}} = 14$  TeV) at CERN. Even there though, because of the dependence of the production cross section of charged Higgs bosons upon  $\tan\beta^2$ , there is no certainty that these particles will be accessi-

ble to the experiments. This happens if  $\tan\beta$  is in the so-called “intermediate” regime, starting at around 6 or 7 for  $M_{H^\pm} \sim m_t$  and encompassing more and more parameter space as  $M_{H^\pm}$  grows larger, no matter the channels in which the charged Higgs boson decays to, as long as the latter only include ordinary SM objects and neutral Higgs states [4]. Not coincidentally, over the same area of the  $(M_{H^\pm}, \tan\beta)$  parameter plane, the coverage through the neutral Higgs sector of the MSSM is limited to the lightest Higgs boson, which is SM-like (the mentioned decoupling limit).

Lowering the SUSY mass scale may induce new interactions among neutral/charged Higgs boson states and sparticles, so that the former may abundantly be produced in the decay of the latter (gluinos and squarks for example [5]) or, alternatively, new Higgs decay channels into light SUSY particles may well open at a profitable rate (e.g., into chargino–neutralino pairs [6]). This unfortunately implies a proliferation of MSSM parameters rendering the phenomenological analysis very cumbersome.

With the option of an  $e^+e^-$  Linear Collider (LC) [7] being possibly available within the first few years of the LHC, also operating in  $e^\pm\gamma$  and  $\gamma\gamma$  modes (both at an energy scale similar to the one of the primary electron–positron design, i.e.,  $\sqrt{s_{e^+e^-}} = 500$  GeV to 1.5 TeV), with the photons being generated via Compton back-scattering of laser light [8], it is very instructive to assess the potential of this kind of machine in complementing the LHC in the quest for such elusive, yet crucial particles for understanding the Higgs mechanism. Besides, the ability to polarize the incoming particles, both electron<sup>3</sup> and photon beams<sup>4</sup>, is a definite advantage of future LCs with respect to the LHC.

<sup>3</sup> Some proposals also exist for polarizing positrons [9]

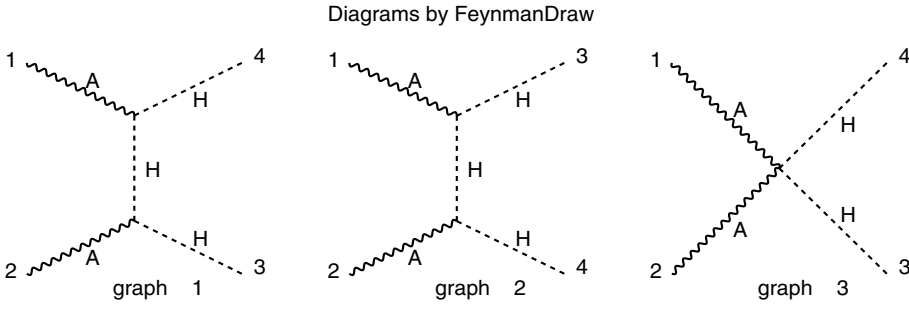
<sup>4</sup> See, e.g., [10] for an example of new physics effects which can be probed by using polarized  $\gamma$ -beams to produce  $H^\pm$  Higgs states

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<sup>1</sup> In practice, decoupling occurs for  $M_{H^0}$ ,  $M_{A^0}$  and/or  $M_{H^\pm}$  around and above 200 GeV

<sup>2</sup> Which, together with  $M_{H^\pm}$ , or  $M_{A^0}$  (the mass of the pseudoscalar Higgs boson), uniquely defines the MSSM Higgs sector at tree level



**Fig. 1.** Feynman diagrams for process (1). The labels  $A$  and  $H$  refer to a photon and a charged Higgs boson, respectively

Historically, with some exceptions, it was mainly the pair production modes of charged Higgs boson states, i.e.,  $e^+e^- \rightarrow H^-H^+$ ,  $e^\pm\gamma \rightarrow e^\pm H^-H^+$  and  $\gamma\gamma \rightarrow H^-H^+$ , that were considered in some detail [11–13]. However, the exploitation of these channels alone may clearly be insufficient to clarify the real potential of future LCs in investigating the Higgs sector, especially considering that in the MSSM framework twice the heavy  $H^\pm$  mass values may mean that the rest mass of  $H^-H^+$  pairs is already comparable to the minimal energy foreseen for these machines. Needless to say, whenever  $2M_{H^\pm}$  exceeds  $\sqrt{s_{e^+e^-}}$ , the double Higgs modes just mentioned are altogether useless and one has to revert to the case of singly produced  $H^\pm$  bosons.

The potential of LCs operating via  $e^+e^-$  and  $e^\pm\gamma$  scatterings in detecting MSSM charged Higgs bosons with mass  $M_{H^\pm} \gtrsim m_t$  produced in single modes (as well as their interplay with the pair production channels) has already been assessed in [14, 15]. Here, we perform a similar study in the context of  $\gamma\gamma$  interactions<sup>5</sup>.

Alongside

$$\gamma\gamma \rightarrow H^-H^+ \quad (\text{pair production}), \quad (1)$$

we have considered several channels where only one charged Higgs boson is produced, namely

$$\gamma\gamma \rightarrow \tau^- \bar{\nu}_\tau H^+ \quad (\tau\nu \text{ associated production}), \quad (2)$$

$$\gamma\gamma \rightarrow b\bar{t}H^+ \quad (bt \text{ associated production}), \quad (3)$$

$$\gamma\gamma \rightarrow h^0 W^- H^+ \quad (h^0 \text{ associated production}), \quad (4)$$

$$\gamma\gamma \rightarrow H^0 W^- H^+ \quad (H^0 \text{ associated production}), \quad (5)$$

$$\gamma\gamma \rightarrow A^0 W^- H^+ \quad (A^0 \text{ associated production}), \quad (6)$$

$$\gamma\gamma \rightarrow W^- H^+ \quad (W^\pm \text{ associated production}). \quad (7)$$

The Feynman graphs associated to process (1) are found in Fig. 1, those for reactions (2) and (3) in Fig. 2, for (4)–(6) see Fig. 3, whereas for (7) refer to Fig. 4. All processes were calculated at leading order only. The first six are tree-level processes whereas the last one originates

<sup>5</sup> In the case of photon–photon collisions, charged Higgs bosons can also be produced as virtual states, e.g., in the loop entering  $\gamma\gamma \rightarrow$  Higgs processes. Such channels can be used as a means to distinguish between various possible Higgs scenarios, e.g.: SM, MSSM and/or a general two-Higgs doublet model (2HDM) [16]

at one-loop level. All the corresponding matrix elements (MEs) have been computed by means of the HELAS libraries [17], with the exception of the one-loop channel (for which we have adapted the calculations of [18]). Apart from the trivial cases of the  $2 \rightarrow 2$  processes (1) and (7), the (numerical) integrations over the final state phase space (PS) (and photon momentum fractions, see below) have been performed by a variety of methods, for cross-checking purposes: by using VEGAS [19], RAMBO [20] and Metropolis [21]. In the case of process (1), we have found agreement with the previous literature.

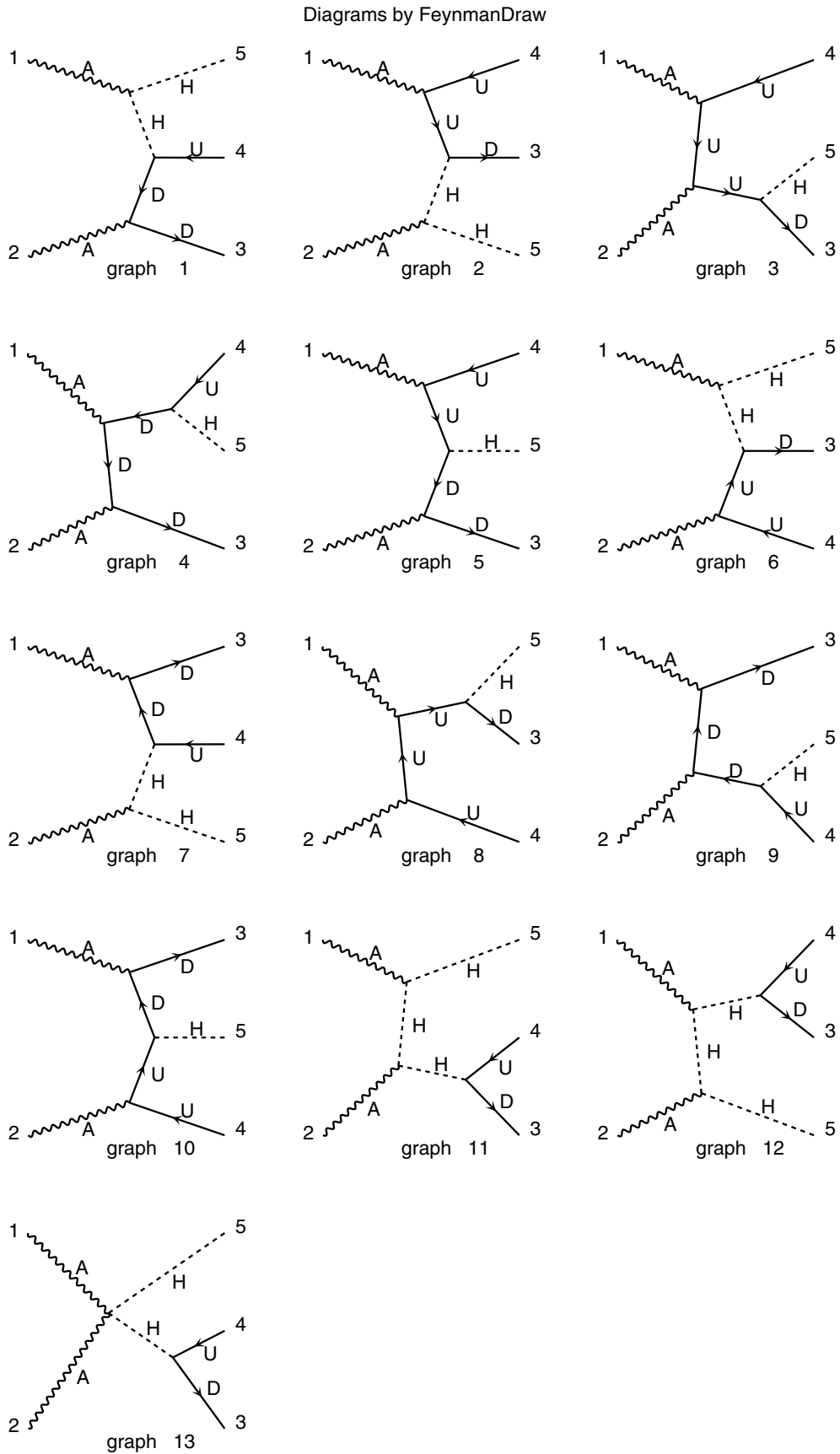
For the 2HDM parameters, we assumed the MSSM throughout. For the SM ones, we adopted the following:  $m_b = 4.25$  GeV (for the  $\overline{\text{MS}}$  bottom quark mass entering the running Yukawa couplings to match the procedure used in computing the Higgs width [22]: see below)<sup>6</sup>,  $m_t = 175$  GeV,  $m_e = 0.511$  MeV,  $m_\tau = 1.78$  GeV,  $m_\nu = 0$ ,  $M_{Z^0} = 91.19$  GeV,  $\Gamma_{Z^0} = 2.50$  GeV,  $M_{W^\pm} = M_{Z^0} \cos \theta_W$  and  $\Gamma_{W^\pm} = 2.08$  GeV, with  $\sin^2 \theta_W = 0.232$ . The top quark width  $\Gamma_t$  was evaluated at leading order for each value of  $M_{H^\pm}$  and  $\tan \beta$ . Neutral and charged Higgs masses and widths were calculated for given values of  $M_{A^0}$  and  $\tan \beta$  using the HDECAY package [22], with the SUSY masses and the Higgsino parameter  $\mu$  being set to 1 TeV, while the (universal) trilinear couplings have been set to zero. (Hence, we only exploit here the MSSM mass relations among the Higgs states; rather than investigating the effects of new SUSY states.)

The back-scattered photon flux has been worked out in [8], where all details of the derivation can be found. For brevity, we do not reproduce here those formulae, rather we simply recall to the reader unfamiliar with this matter the basic features of  $\gamma\gamma$  scatterings initiated by laser light at  $e^+e^-$  LCs. The reflected photon beam carries off only a fraction  $x$  of the electron/positron energy, with  $x_{\text{max}} = z/(1+z) \simeq 0.8$ , while  $x_{\text{min}} = M_X/\sqrt{s_{e^+e^-}}$ , where  $M_X$  is the rest mass in the final state of (1)–(7). Finally, one can cast the production cross sections in the form

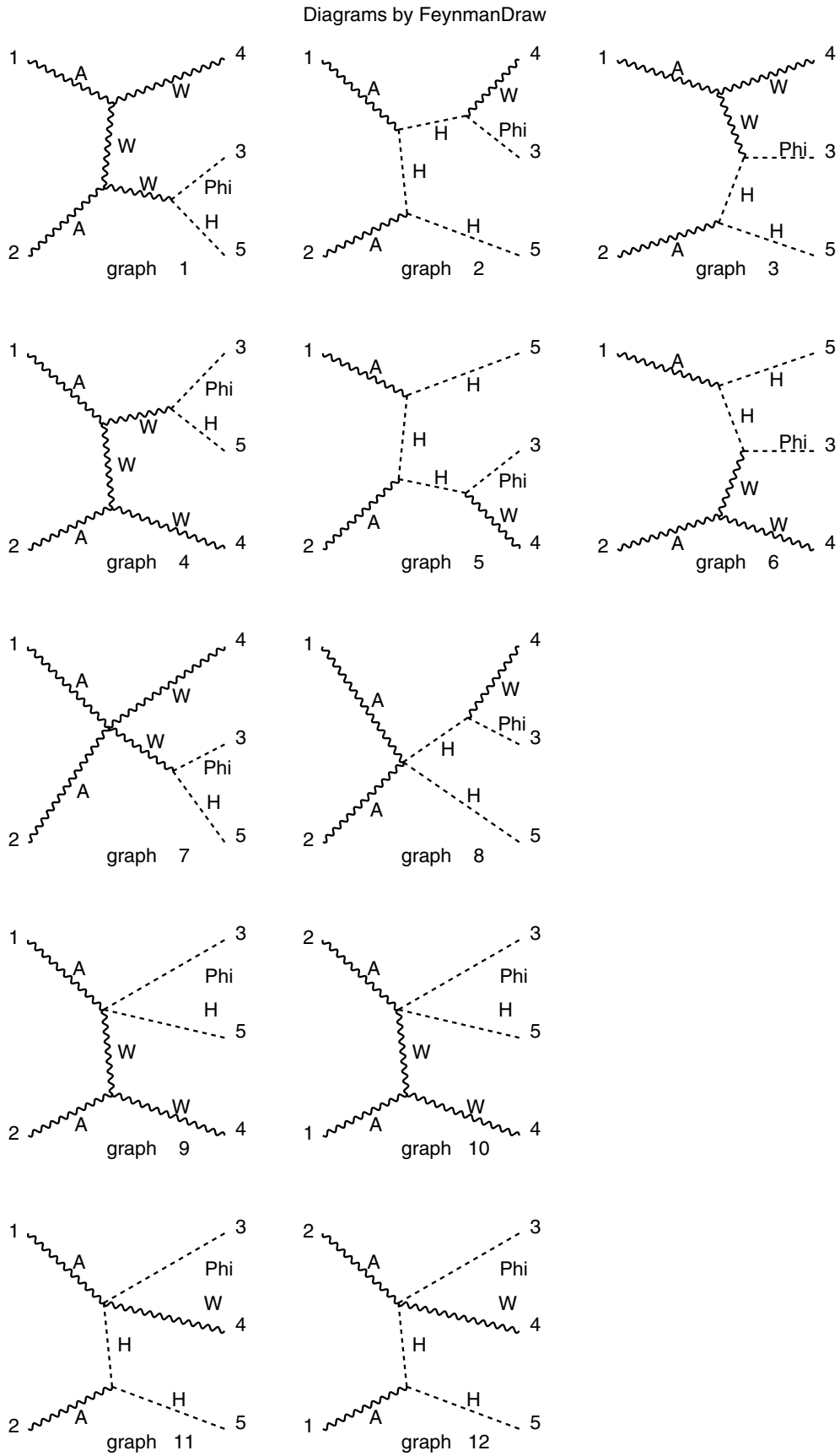
$$\sigma_{e^+e^- \rightarrow \gamma\gamma \rightarrow X}(s) = \int dx_+ dx_- F_+^\gamma(x_+) F_-^\gamma(x_-) \hat{\sigma}_{\gamma\gamma \rightarrow X}(\hat{s}), \quad (8)$$

where  $x_{+(-)}$  is the electron (positron) momentum fraction carried by the emerging photon,  $x_+ x_- = \hat{s}_{\gamma\gamma}/s_{e^+e^-}$ , with  $s_{e^+e^-}$  ( $\hat{s}_{\gamma\gamma}$ ) being the center-of-mass (CM) energy squared

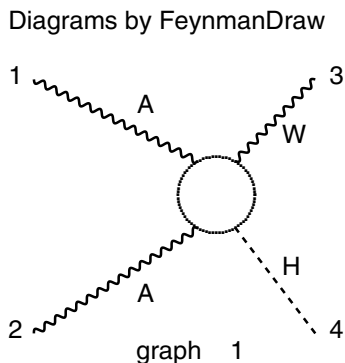
<sup>6</sup> The kinematic effect of  $m_b$  in the MEs of channels (3) and (7) and in the PS of the former is negligible



**Fig. 2.** Feynman diagrams for processes of the type (2) and (3). The labels  $D/U$ ,  $A$  and  $H$  refer to a  $d/u$ -type (anti-) quark, a photon and a charged Higgs boson, respectively



**Fig. 3.** Feynman diagrams for processes of the type (4)–(6). The labels  $A$ ,  $W$  and  $H(\text{Phi})$  refer to a photon, a  $W^\pm$  gauge boson and a charged (neutral) Higgs boson, respectively



**Fig. 4.** Feynman diagrams for process (7). The labels  $A$ ,  $W$  and  $H$  refer to a photon, a  $W^\pm$  gauge boson and a charged Higgs boson, respectively. The “blob” signifies all possible one-loop contributions, as seen in Figs. 1 and 2 of [18]

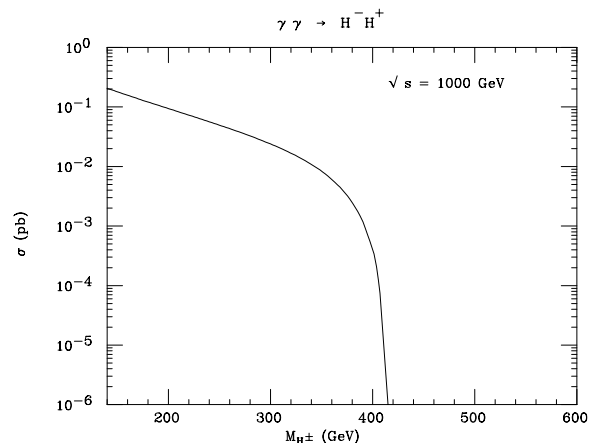
of the  $e^+e^-$  ( $\gamma\gamma$ ) system, and  $F_\pm^\gamma(x_\pm)$  the photon distribution functions, defined in terms of  $x_\pm$ . (As  $\gamma$ -structure functions we have used the analytical ones of [8]. For more recent distributions, see [23].)

The cross sections of processes (1)–(7) can be found in Figs. 5 and 6, respectively, for four reference choices of  $\tan\beta$ . In all our plots and in the discussion, charge conjugated (c.c.) contributions are always included. For brevity, we limit ourselves to the representative case of  $\sqrt{s_{e^+e^-}} = 1$  TeV, noting that the maximal energy achievable in the  $\gamma\gamma$  mode is  $\sqrt{s_{\gamma\gamma}} \approx 0.8 \sqrt{s_{e^+e^-}}$ .

If one recalls the typical pattern of the charged Higgs bosons decays rates into SM particles (see, e.g., [24]), it is clear that some of the final states considered in processes (2)–(7) can proceed via reaction (1) as an intermediate state. Hence, one should take care of avoiding double-counting the  $H^\pm$  production rates. For example, in Fig. 6 the  $H^- \rightarrow \tau^- \bar{\nu}_\tau$  decay is always open (top-left), the  $H^- \rightarrow b\bar{t}$  one shows up at  $M_{H^\pm} \approx m_t$  (top-middle) and the  $H^- \rightarrow h^0 W^-$  channel appears at small  $\tan\beta$  when  $M_{H^\pm} \lesssim m_t$  (top-right). Specifically we point out that

- (i) the dips followed by the peaks around  $M_{H^\pm} \approx m_t$  in case of process (3) are due to the interplay between the cross section in Fig. 5 and the  $\text{BR}(H^- \rightarrow b\bar{t})$ , as seen, e.g., in [24];
- (ii) the peak in the final state of (4) at  $\tan\beta = 1.5$  is due to a large  $\text{BR}(H^- \rightarrow h^0 W^-)$  [24] while the thresholds at larger values of this parameter are a kinematic effect due to the increase of  $M_{h^0}$  with  $\tan\beta$ ;
- (iii) the bumps for  $M_{H^\pm}$  in the vicinity of  $m_t$  for the cross section of channel (7) are due to the onset of the  $t\bar{b}$  threshold in the fermionic loop.

Bearing these considerations in mind, one immediately realises the dominance of  $H^+H^-$  production whenever  $\sqrt{s_{\gamma\gamma}} > 2M_{H^\pm}$ , independently of  $\tan\beta$ , as expected. At and above the threshold point  $\sqrt{s_{\gamma\gamma}} \approx 2M_{H^\pm}$  (where pair production has become extinguished), there are three competing channels that can give sizable signals:  $\tau^- \bar{\nu}_\tau H^+$ ,  $b\bar{t}H^+$  and  $W^- H^+$ , the first two being largest at large  $\tan\beta$



**Fig. 5.** Total cross sections for process (1) at  $\sqrt{s_{e^+e^-}} = 1$  TeV

and the third at small values of the latter<sup>7</sup>. Final states of the type  $h^0 W^- H^+$  (for small to intermediate  $\tan\beta$ ),  $H^0 W^- H^+$  and  $A^0 W^- H^+$  (both also for large  $\tan\beta$ ) are only relevant for  $M_{H^\pm} \lesssim m_t$ , where they may well be useful in testing triple and quartic vertices involving gauge and Higgs bosons.

The total production rates in the region  $\sqrt{s_{\gamma\gamma}} \lesssim 2M_{H^\pm}$  are not very large, as they never exceed the fraction of femtobarns.

After  $500 \text{ fb}^{-1}$  of accumulated luminosity<sup>8</sup>, one should expect at best 50 events or so, both at small and large  $\tan\beta$ . Moreover, given the dependence upon this parameter of the three leading modes, the intermediate  $\tan\beta$  region (i.e., around 7 or so) would have little coverage, only through charged Higgs production in association with a  $W^-$  boson, yielding typical production rates that are one order of magnitude smaller than those seen for extreme values of this parameter (1.5 and 40).

Such small cross sections inevitably require one to select the dominant decay channel of a heavy charged Higgs boson, i.e.,  $H^+ \rightarrow t\bar{b}$  [24]. Therefore, the leading signal signatures would be

$$b\bar{b}W^+ \tau^- \bar{\nu}_\tau, \quad (9)$$

$$b\bar{b}b\bar{b}W^+W^-, \quad (10)$$

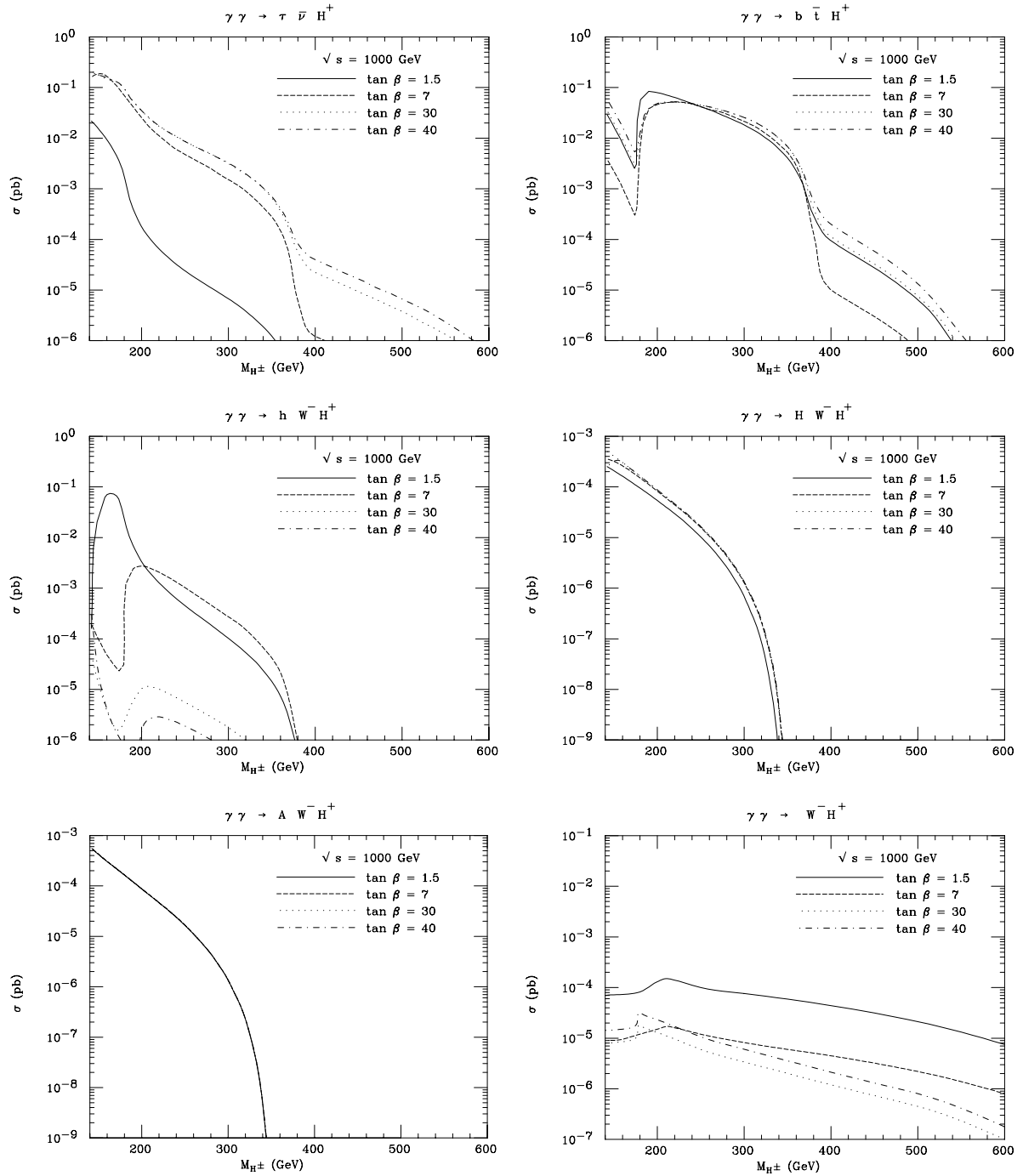
$$b\bar{b}W^+W^-, \quad (11)$$

for processes (2), (3) and (7), respectively. In each case, one should expect the (irreducible) background to be dominated by top quark pair production and decay, i.e.,

$$\gamma\gamma \rightarrow t\bar{t} \rightarrow b\bar{b}W^+W^-, \quad (12)$$

<sup>7</sup> Some limited coverage at intermediate values of  $\tan\beta$  also exists via the one-loop mode (7), though with production cross sections that are one order of magnitude smaller than at the lower end of the  $\tan\beta$  interval

<sup>8</sup> We use this somewhat optimistic value of photon-photon luminosity in order to enable us to perform a straightforward comparison with the results of [25], where the same final states considered here were treated in the context of  $e^+e^-$  and  $e^\pm\gamma$  annihilations. As a golden rule, at a fixed energy in the sub-TeV range, one may typically use  $\mathcal{L}_{\gamma\gamma} \approx \frac{1}{3} \mathcal{L}_{e^+e^-}$



**Fig. 6.** Total cross sections for (clockwise) processes (2), (3), (4), (5), (6) [here, the four curves in the plot coincide within graphical resolution] and (7) plus c.c. at  $\sqrt{s}_{e^+e^-} = 1$  TeV

possibly followed by

$$W^- \rightarrow \tau^- \bar{\nu}_\tau \quad (13)$$

and by gluon radiation as well, eventually yielding two additional  $b$ -quarks:

$$t\bar{t} \rightarrow g^* b\bar{b} W^+ W^- \rightarrow b\bar{b} b\bar{b} W^+ W^-. \quad (14)$$

Given the large hadronic activity associated with multiple production of  $b$ -quarks, one would presumably require semi-leptonic decays of the  $W^+W^-$  and  $W^+\tau^-\bar{\nu}_\tau$

systems, into electrons and/or muons. In the case of the first signature, (9), it has been shown in [26] that, for the case of  $e^+e^-$  collisions, the signal extraction above the  $t\bar{t}$  noise should be feasible in a region of 40 to 80 GeV (depending on  $\tan\beta$ , for values between 30 and 40) above the threshold at  $\sqrt{s}_{e^+e^-} \approx 2M_{H^\pm}$ , with statistical significances between  $3\sigma$  and  $5\sigma$ , in correspondence of  $500\text{fb}^{-1}$  and  $2.5\text{ab}^{-1}$  of accumulated luminosity. Given that the starting signal-to-background ratio ( $S/B$ ) is here not

much different from the case of the corresponding  $e^+e^-$  initiated process (the signal here also being burdened by top–antitop production and decay as dominant background), one should expect the same thing happening in the context of photon–photon collisions, albeit with a reduced charged Higgs mass scope, since the CM energy is smaller in this case (assuming a contemporaneous running in  $e^+e^-$  and  $\gamma\gamma$  modes).

No explicit signal-to-background analysis exists yet for the other two signatures in the context of electron–positron annihilations, although there is some work in progress [27]. While one may reasonably suppose that a selection strategy similar to the one adopted in [26] would also work for the  $\gamma\gamma \rightarrow W^-H^+$  process<sup>9</sup>, the same conclusion is not immediately evident for the  $\gamma\gamma \rightarrow b\bar{t}H^+$  channel. However, here one could even improve on the results achievable in the case of the signatures in (9) and (11), since the probability of a gluon splitting into  $b\bar{b}$  pairs in (10) is rather small [28], even at the energies at which the QCD gauge boson could be emitted in top pair production and/or decay at future LCs. Indeed,  $bbbbW^+W^-$  final states with semi-leptonic gauge boson decays have already been considered in the context of charged Higgs boson searches at the LHC and proven to be accessible over the “pure” QCD background  $q\bar{q}, gg \rightarrow b\bar{b}t\bar{t}$  [29].

Finally, we comment on the energy dependence of the three leading signal processes discussed above. In general, it is the  $\gamma\gamma \rightarrow b\bar{t}H^+$  channel that is the most sensitive to the value of the CM energy, rather than the  $\gamma\gamma \rightarrow \tau^-\bar{\nu}_\tau H^+$  and  $\gamma\gamma \rightarrow W^-H^+$  modes, because of the large mass of the top quark (in comparison to  $m_\tau$  and  $M_{W^\pm}$ ): the larger (smaller)  $\sqrt{s_{e^+e^-}}$  the more (less) relevant process (3) becomes with respect to reactions (2) and (7).

In summary, total cross sections of heavy charged Higgs bosons with mass similar to or larger than approximately half the collider CM energy and produced via  $\gamma\gamma$  modes compare well to the corresponding  $e^+e^-$  ones in most cases (these two beam options offering better chances of  $H^\pm$  detection than the mixed beam setup in  $e^\pm\gamma$  collisions [25]). In absolute terms, the latter are larger at smaller energies whereas the former grows relatively with  $\sqrt{s_{e^+e^-}}$ , due to the respective  $s$ -, and  $t$ - and  $u$ -channel dependence. When compared, the two modes display a similar potential in accessing  $H^\pm$  states with  $2M_{H^\pm} \gtrsim \sqrt{s_{e^+e^-}/\gamma\gamma}$ , the latter being singly produced at a rate of  $\mathcal{O}(10^{-1} \text{ fb})$  at best. It will presumably be the interplay between the typical mass scale of the charged Higgs bosons (that one could, e.g., either have a direct hint of from data or else estimate indirectly within the MSSM from the measured value of  $M_{h^0}$  at Tevatron and/or the LHC) and the machine performance in producing mono-chromatic Compton back-scattered photons that will eventually dictate whether to put more effort in  $\gamma\gamma$  or  $e^+e^-$  analyses in the quest for such particles at next generation LCs.

<sup>9</sup> If anything, notice that the additional source of missing energy due to the decays  $\tau^- \rightarrow \pi^- X$  or  $\tau^- \rightarrow \ell^- X$  ( $\ell = e, \mu$ ) affecting the  $\gamma\gamma \rightarrow \tau^-\bar{\nu}_\tau H^+$  process is here largely absent

However, the running time to be spent on each mode will most likely depend on the measured value of  $M_{h^0}$ . On the one hand, it should be recalled that in electron–positron annihilations the CM energy is typically higher but the lightest Higgs boson is always produced in association with some other particles (hence, with a PS suppression): a  $Z^0$  (Higgs-strahlung), a  $\nu_e\bar{\nu}_e/e^+e^-$  pair ( $W^+W^-/Z^0Z^0$  fusion) or the pseudoscalar Higgs state (pair production). On the other hand, in photon–photon scatterings,  $h^0$  states are produced singly, via a loop of charged (s)particles, but with a reduced energy and possibly, if the Higgs width is rather large, also off-resonance. Whichever the case, should the close investigation of  $h^0$  (and, possibly,  $H^0$  and  $A^0$ ) signatures need to be supported by the detection of charged Higgs states in order to clarify the nature of the EW symmetry breaking, a LC with the option of photon beams will be well placed in pursuing this task, over a considerable  $M_{H^\pm}$  range, provided the value of  $\tan\beta$  is either large or small.

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