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Detection of heavy charged Higgs bosons at future Linear Colliders via $\tau^- \bar{\nu}_\tau H^+$ production[1]

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Abstract

We show how a statistically significant signal of heavy charged Higgs bosons of a Type II Two-Higgs Doublet (2HDM) Model produced in association with tau-neutrino pairs can be established at future e^+e^- Linear Colliders (LCs) in the $H^+ \to t\bar{b} \to 4$ jet decay channel for large $\tan\beta$ in the $M_{H^\pm} \gtrsim \sqrt{s}/2$ mass region.

[1]Based on talks given at the Second Workshop of the Extended Joint ECFA/DESY Study on Physics and Detectors for a Linear Electron-Positron Collider, St. Malo, France, 12-15 April 2002 and at the International Workshop on Linear Colliders (LCWS2002), Jeju Island, Korea, 26-30 August 2002.

1 Introduction

Charged Higgs bosons, $H^\pm$, appear in the particle spectrum of a general Type II 2HDM, including the minimal Supersymmetric version of it: the Minimal Supersymmetric Standard Model (MSSM). In this context, the importance of singly produced charged Higgs bosons at future LCs [1] has been emphasised lately in several instances [2, 3, 4]. In fact, while the detection of $H^\pm$ states would represent an unequivocal evidence of physics beyond the Standard Model (SM), their mass could well be very large. For example, within the MSSM in the so-called 'decoupling-limit', one expects the following configuration of masses among the five Higgs states of the model: $M_h \lesssim 130$ GeV $\ll M_H \sim M_A \sim M_{H^\pm}$, for any $\tan\beta$. Moreover, if only a light Higgs state is found at the Large Hadron Collider (LHC), the initial task of a LC would be to start running at a rather low energy (say, $\sqrt{s} = 350$ to 500 GeV), where the corresponding Higgs production cross section (via $e^+e^- \to Z^* \to Zh$) is largest. At such energies, the heavier Higgs states may not be produced in the leading channels $e^+e^- \to ZH, AH, H^-H^+$ [5, 6], either because below threshold (i.e., $M_A + M_H, M_{H^+} + M_{H^-} > \sqrt{s}$) or since the intervening MSSM coupling in the decoupling limit becomes zero (e.g., in the ZZH vertex). Whereas in the neutral Higgs sector the heavy H and A resonances can always be accessed via $\gamma\gamma \to$ 'triangle loop' $\to H/A$, this is not possible for the charged Higgs boson states. Besides, in the large $\tan\beta$ region, for neutral Higgs states, one could alternatively resort to the associate production mode $e^+e^- \to b\bar{b}H/A$. The corresponding channel for a charged Higgs boson would be $e^+e^- \to b\bar{t}H^+$, which has an additional large mass in the final state (i.e., $m_t = 175$ GeV).

2 Single $H^\pm$ production

Hence, it becomes clear the importance of studying production modes of charged Higgs bosons with only one such particles in the final state. An analysis of various single production modes was performed in Ref. [2], limitedly to their inclusive rates. There, it was shown that only two channels offer some chances of detection for $M_{H^\pm} \gtrsim \sqrt{s}/2$, when $\sqrt{s} = 500$ GeV [2]:

$$e^+e^- \;\to\; \tau^-\bar{\nu}_\tau H^+, \tau^+\nu_\tau H^- \quad \text{(tree level)}, \tag{1}$$
$$e^+e^- \;\to\; W^\mp H^\pm \quad \text{(one loop)}. \tag{2}$$

The former is relevant in the large $\tan\beta$ region, whereas the latter is important for the low one. As LEP2 data seem to prefer large values of $\tan\beta$, at least in the MSSM [8], the first of these two processes has been analysed already against the background in Ref. [9]. We summarise the finding of that paper, where a successful selection procedure of channel (1) was devised. A similar study for the case of process (2) is also in progress [10].

The poor production rates of process (1) reported in Ref. [2] require one to resort to the main decay channel of heavy charged Higgs bosons, i.e., $H^+ \to t\bar{b}$ [11], so that the signal (S)

[2] When $\sqrt{s} \gg M_{H^\pm} + m_t$, the channel $e^+e^- \to b\bar{t}H^+$ becomes important too [3]. Furthermore, see Ref. [7] for an illustration of the scope of the $\tau^-\bar{\nu}_\tau H^+$ final state in $\gamma\gamma$ collisions.

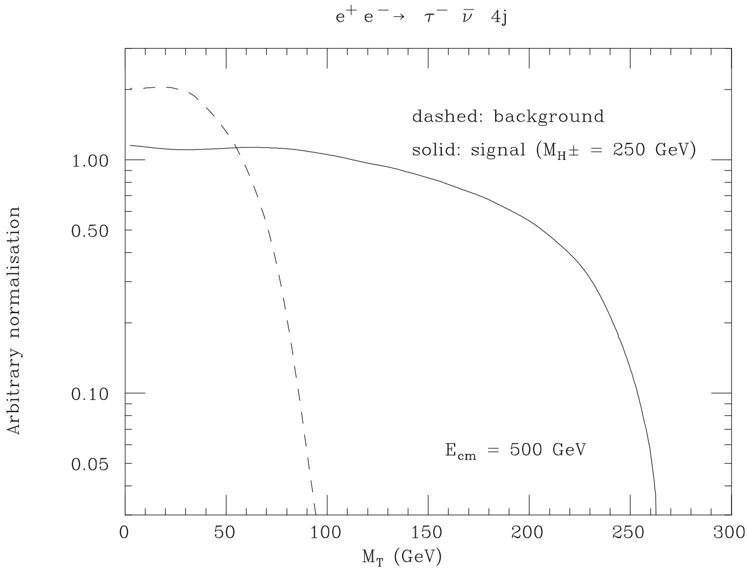

Figure 1: Distribution in the transverse mass (9) for processes (3)–(4) before cuts.

and (main) irreducible background (B) are:

$$e^+e^- \rightarrow \tau^-\bar{\nu}_\tau H^+ \rightarrow \tau^-\bar{\nu}_\tau t\bar{b}, \quad (3)$$

$$e^+e^- \rightarrow \bar{t}t \rightarrow \tau^-\bar{\nu}_\tau t\bar{b}. \quad (4)$$

One then requires the emerging top to decay hadronically, i.e., $t \rightarrow bW^+ \rightarrow 3$ jets, whereas one assumes the τ's to be tagged as narrow jets in their 'one-prong' hadronic decays:

$$\begin{array}{lll} \tau^\pm & \rightarrow & \pi^\pm\nu_\tau \quad (12\%), \\ \tau^\pm & \rightarrow & \rho^\pm(\rightarrow \pi^\pm\pi^0)\nu_\tau \quad (26\%), \\ \tau^\pm & \rightarrow & a_1^\pm(\pi^\pm\pi^0\pi^0)\nu_\tau \quad (8\%). \end{array}$$

Altogether, the complete signature is:

$$\tau - \text{jet} \;+\; p_T^{\text{miss}} \;+\; 4 \text{ jets}. \quad (5)$$

3 Numerical results

The simulation of Ref. [9] was carried out at parton level, for a Type II 2HDM, with $\tan\beta = 40$ as reference value. Therein the programs of Refs. [2, 12] were used, supplemented by a finite calorimeter resolution emulated through a Gaussian smearing of the jet transverse momenta. A double tagging of b-jets in the final state was assumed throughout.

The cuts used were as follows. Like in Ref. [13], the Cambridge jet clustering algorithm [14] was enforced to isolate a five jet sample, by using $y_{\text{cut}} = 0.001$, wherein the τ-jet was treated on the same footing as the quark-jets. Besides, both τ- and quark-jets were required to pass the following cuts in energy and polar angle (hereafter, j represents a generic jet):

$$E_j > 5 \text{ GeV}, \qquad |\cos\theta_j| < 0.995. \tag{6}$$

Further assuming that the former can be distinguished from the latter thanks to very different sub-jet distributions, one can apply a sequential $W^\pm$ and t mass reconstruction only to quark-jets:

$$|M_{jj} - M_{W^\pm}| < 10 \text{ GeV}, \qquad |M_{jjj} - m_t| < 15 \text{ GeV}. \tag{7}$$

The cut in missing transverse momentum was:

$$p_T^{\text{miss}} > 40 \text{ GeV}. \tag{8}$$

A minimum transverse mass constructed from the visible τ-jet and the missing transverse momentum was also required:

$$M_T \equiv \sqrt{2p_T^\tau p_T^{\text{miss}}(1 - \cos\Delta\phi)} > M_{W^\pm}, \tag{9}$$

where $\Delta\phi$ is the relative azimuthal angle. Finally, following the findings of Refs. [15, 16] in case of $H^\pm$ hadroproduction, it was imposed the requirement

$$R_\tau = p^{\pi^\pm}/p_T^\tau > 0.8, \tag{10}$$

where $p^{\pi^\pm}$ is the momentum of the leading pion coming from the τ-lepton, and p_T^τ is the visible momentum of the latter.

Fig. 1 illustrates the strong impact of the constraint in transverse mass, by comparing the shape of the signal and background before the kinematic selection. The signal distributions are obtained at the points $M_{H^\pm} \approx \sqrt{s}/2$.

The upper plots in Fig. 2 present the signal rates after the full kinematic selection has been enforced. (The background cross section is constant with $M_{H^\pm}$ as the above cuts do not depend on this parameter.) In the lower plots we display from Ref. [9] the significances (in black) of the signal rates, after 1 and 5 ab^{-1} of accumulated luminosity, $\mathcal{L}$. It is clear that at this point neither evidence ($\gtrsim 3\sigma$) nor discovery ($\gtrsim 5\sigma$) of charged Higgs bosons is possible in the region $M_{H^\pm} \gtrsim \sqrt{s}/2$, whereas for $M_{H^\pm} \lesssim \sqrt{s}/2$ the signal should be comfortably observed. The dominant contributions to the latter in this mass regimes come from pair production $e^+e^- \to H^-H^+$, followed by $H^- \to \tau^-\bar{\nu}_\tau$ decays.

One can however exploit the invariant mass of the four-quark jet system. Fig. 3 shows this quantity. For the signal, it represents the reconstructed resonance of the charged Higgs boson (which was originally generated at the point $M_{H^\pm} \approx \sqrt{s}/2$). For the background, it correspond to a non-resonant kinematic distribution. The width of the signal spectra is dominated by detector smearing effects and suggests that a further selection criterium can be enforced to enhance the S/B rates, e.g.:

$$|M_{4j} - M_{H^\pm}| < 35 \text{ GeV}, \tag{11}$$

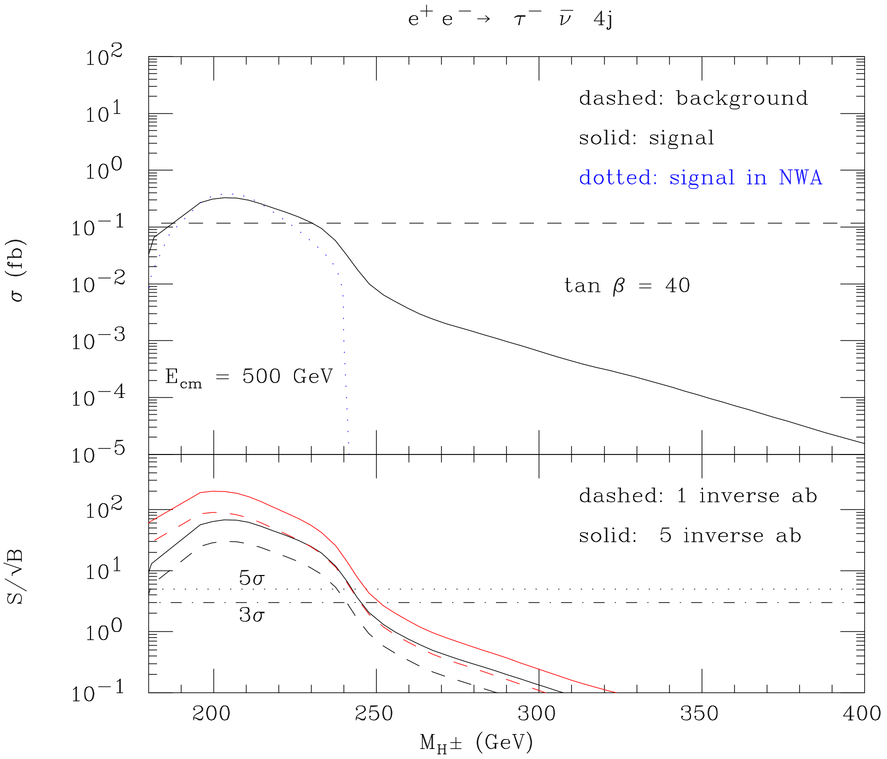

Figure 2: (Top) Total cross sections for processes (3)–(4) yielding the signature (5), after the kinematic cuts in (6)–(10), including all decay BRs. For comparison, we also include the result for the signal in Narrow Width Approximation (NWA) (blue). (Bottom) Statistical significances of the signal for two values of integrated luminosity (the 3σ and 5σ 'evidence' and 'discovery' threshold are also given) after the kinematic cuts in (6)–(10) (in black) and the additional one in (11) (in red).

where the value used for $M_{H^\pm}$ would be the central or fitted mass resonance of the region in M_{4j} were an excess of the form seen in Fig. 3 will be established.

The two red lines in Fig. 2 show the significances of the charged Higgs boson signals in presence of the constraint in (11), alongside those in (6)–(10). These prove that one can expect to extend the reach in $M_{H^\pm}$ obtained from pair production of charged Higgs bosons and decays by about 50 GeV or so around and above the $M_{H^\pm} \approx \sqrt{s}/2$ point (see the dotted blue line in the top plot of Fig. 2). Finally, recalling that $H^\pm$ rates have been given at $\tan\beta = 40$ and that process (1) is proportional to the square of $\tan\beta$ for large values of the latter, the number of events in the threshold region would scale like $6(30)(\tan\beta/40)^2$, in correspondence of $\mathcal{L} = 1(5)$ ab^{-1}. (According to Ref. [13], the single b-tag efficiency is expected to be close to the value $\epsilon_b = 90\%$, so that our main conclusions should remain unchanged even in presence of a finite double-b-tagging efficiency.) An analysis of the considered signature (5) within the full event generator environment provided by

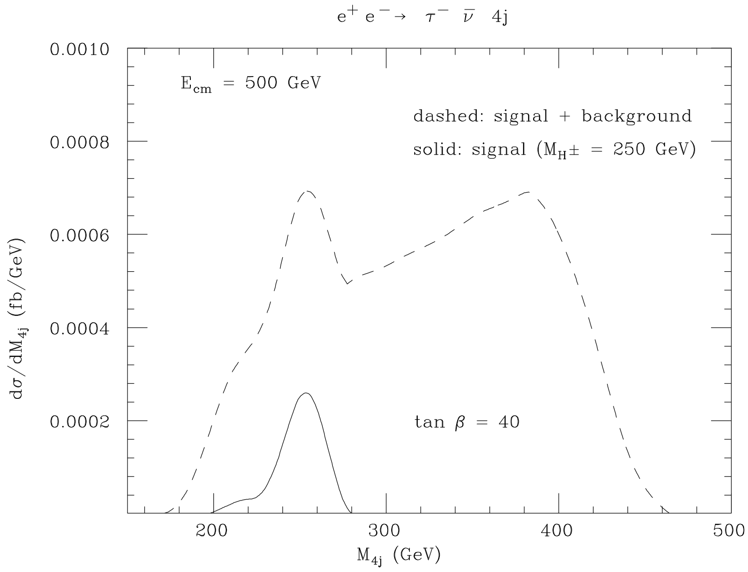

Figure 3: Distribution in the invariant mass of the four quark-jets recoiling against the τ-jet for the sum of processes (3)–(4) and for the former separately yielding the signature (5), after the kinematic cuts in (6)–(10), including all decay BRs.

HERWIG [17] is also in progress [18].

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