The process $e^+e^- \to b\bar{b}W^+W^-$ at the next linear collider in the Minimal Supersymmetric Standard Model

Stefano Moretti

1 Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge, CB3 0HE, UK
2 Dipartimento di Fisica Teorica, Università di Torino, and INFN, Via Pietro Giuria 1, 10125 Torino, Italy
(e-mail: moretti@hep.phy.cam.ac.uk, moretti@to.infn.it)

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Abstract. The complete matrix element for $e^+e^- \to b\bar{b}W^+W^-$ is computed at tree-level within the Minimal Supersymmetric Standard Model. Rates of interest to phenomenological analyses at the Next Linear Collider are given. In particular, we study:

- $tt$ production and decay $tt \to (bW^+)(bW^-)$;
- $ZH$ production followed by $Z \to bb$ and $H \to W^+W^-$;
- $AH$ production followed by $A \to bb$ and $H \to W^+W^-$;
- $hW^+W^-$ production followed by $h \to bb$.

Top and Higgs finite width effects are included, as well as all those of the irreducible backgrounds.

1 Introduction

By the time that the next linear collider (NLC) [1] will be operating, both the exact value of the top quark mass and the structure of the Higgs sector of the electroweak (EW) interactions will be already known, thanks to the combined action of the Tevatron [2], of LEP II [3] and of the LHC [4, 5]. It is however clear that detailed studies of both top quark and Higgs boson properties will have to wait the advent of an $e^+e^-$ linear machine.

In two previous papers [6, 7] detailed studies of the process $e^+e^- \to b\bar{b}W^+W^-$ at centre-of-mass (CM) energies typical of the NLC were presented. Those analyses were concerning the Standard Model ($SM$). In that framework, the importance of the process $e^+e^- \to b\bar{b}W^+W^-$ is evident if one considers that it represents a signature to top production in $tt$ pairs as well as to that of the $SM$ Higgs boson $\phi$ in the $Z\phi$ channel. In fact, on the one hand, top pairs produced via the process $e^+e^- \to tt$ decay through $tt \to (bW^+)(bW^-)$ whereas, on the other hand, the channel $Z\phi \to (bb)(W^+W^-)$ might well be one of best ways to detect a heavy Higgs, thanks to the expected performances of the vertex detectors in triggering the $Z$ boson [8]. From those studies, the importance of top finite width effects and of those due to the non-resonant background in $b\bar{b}W^+W^-$ events clearly came out, together with positive prospects of Higgs detection.

It is the purpose of this report to extend those analyses to the case of the Minimal Supersymmetric Standard Model ($MSSM$). In this context, the reaction $e^+e^- \to bbW^+W^-$ is important in at least four respects. First and second, like in the $SM$, it allows studies of top pair production and decay $tt \to (bW^+)(bW^-)$ as well as of the Higgs channel $ZH \to (bb)(W^+W^-)$. Third and fourth, it also allows one to analyse Higgs production in the channels $e^+e^- \to AH \to (bb)(W^+W^-)$ and $e^+e^- \to hW^+W^- \to (bb)W^+W^-$. In particular, we notice that the $SM$-like channel $t \to bW^\pm$ is the dominant top decay mechanism over a large part of the $MSSM$ parameter space, especially if the mass of the charged Higgs boson $H^\pm$ is comparable to $m_t$, such that the decay channel $t \to bH^\pm$ is strongly suppressed by the available phase space [10]. Conversely, when this is not the case, finite width effects should be more important in the $MSSM$ [11, 12], as for $M_{1/2} < m_t - m_b$ (i.e., small values of $M_{1/2}$) one gets $\Gamma_{e^+e^- \to AH} > \Gamma_{e^+e^- \to HZ}$.

Furthermore, the process $e^+e^- \to ZH$ is nothing else than counterpart of the $SM$ Higgs bremsstrahlung mechanism, where the heaviest of the neutral scalar Higgses of the $MSSM$, $H$, plays the rôle of $\phi$ [13]. Finally, the decays $h, A \to bb$ (of the light scalar and of the pseudoscalar Higgs bosons, respectively) and $H \to W^+W^-$ can be the dominant ones of these particles over a sizable portion of the plane $(M_h, \tan \beta)$, with the rates of $e^+e^- \to AH$ being comparable to those of $e^+e^- \to ZH$ [14] and the cross sections for $e^+e^- \to hW^+W^-$ being possibly of a few picobarns for $M_h \leq 100$ GeV (the increased $hb\bar{b}$...
c coupling compensating the reduced $hW^+W^-$ one, with respect to the corresponding $\mathcal{F}\mathcal{M}$ values).

We further remind the reader that the four processes $e^+e^- \to \ell\nu, e^+e^- \to Z\ell\nu, e^+e^- \to AH$ and $e^+e^- \to b\bar{b}W^+W^-$ cannot be unambiguously separated, and studied independently one from the others. Therefore any of them constitutes an irreducible background to the other three in the $b\bar{b}W^+W^-$ channel, and such interplay must be carefully taken into account when studying full $e^+e^- \to b\bar{b}W^+W^-$ events. As we are here computing the complete Matrix Element (ME) of such a process, also non-resonant background effects will be present. In this respect, Matrix Element (ME) of such a process, also non-resonant (via splitting carefully taken into account when studying full $e^+e^- \to b\bar{b}W^+W^-$ etc.

Significant digits in REAL

For the technical details of the numerical evaluation of the three different gauges (Unitary, Feynman and Landau).

MSSM techniques described in [16], with the appropriate FORTRAN code produced has been compared against

the MSSM parameter space, we have chosen here, as representative for $\tan\beta$, the two extreme values 1.5 and 30, whereas $M_A$ spans the range 50 to 350 GeV, that is, between the experimental lower limit [18] and the region where the $t\bar{t}$ channels of $\mathcal{M}\mathcal{S}\mathcal{M}$ neutral Higgs bosons start dominating the decay phenomenology over a substantial part of the $(M_A, \tan\beta)$ plane [17].

The top width $\Gamma_t$ has been evaluated according to the formulae given in [19] (see also [20]), corrected by means of the expressions of [21], to account for the $\mathcal{M}\mathcal{S}\mathcal{M}$ decay $t \to bH^\pm$. In order to obtain results in Narrow Width Approximation (NWA) for the top, we have written the heavy quark propagator as

\[ \frac{p + m_t}{p^2 - m_t^2 + i m_t \Gamma} \left( \frac{\Gamma}{\Gamma_t} \right)^{1/2}. \]

In this way, for $\Gamma = \Gamma_t$, the standard expression is recovered, whereas for $\Gamma \to 0$ one is able to correctly reproduce the rates for $e^+e^- \to \ell\nu$ times the (squared) branching ratio $[BR(t \to bH^\pm)]^2$. Numerically, we have used $\Gamma = 10^{-5}$ in NWA.

For the discussion of the results we have assumed the following values for the top mass: $m_t = 170, 172$ and 174 GeV [22] and $m_t = 195, 197$ and 199 GeV [23]. In correspondence, we have taken as CM energy $\sqrt{s} = 350$ and 400 GeV. This has been done in order to perform studies of top-antitop production at threshold, according to the values of $m_t$ measured by CDF and D0, respectively. As top measurements will be certainly performed also far above threshold, we have produced results for the

When this work was almost completed the Fermilab Collaborations have both announced new measurements of $m_t$ [24], which seem to shift the top mass towards the lower part of the $m_t$ spectrum considered here. However, as also the new values suffer from rather large uncertainties (such that by summing statistics and systematics the experimental error band would include the most part of top masses that we have chosen), we decided to maintain in the present paper also the part of studies devoted to the case $m_t \approx 199$ GeV.