Study of the WW $\to$ H $\to$ $t\bar{t}$ Process at TESLA

J. Alcaraz* and E. Ruiz Morales†

*CIEMAT, Avda. Complutense 22, E-28040, Madrid, Spain [1]
†Dep. de Física Teórica, Univ. Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain[1]

Abstract. We present a study of the $e^+e^- \to W^*W^*\ \nu\bar{\nu} \to t\bar{t}\ \nu\bar{\nu}$ process at center-of-mass energies of 800 GeV and 1 TeV in the context of the TESLA project. An integrated luminosity of 1000 fb^{-1} is assumed. The analysis includes a full study of signal and backgrounds at generator and detector simulation levels. We find that a Higgs-like resonance H with Standard Model HWW and H$t\bar{t}$ couplings will be observable in this channel (at the 5σ level) if its mass is in the range $2m_{\rm t} < m_{\rm H} < 650$ GeV. This implies a Higgs-top Yukawa coupling measurement in the same interval with a relative precision better than 10%.

INTRODUCTION

At present, one of the most important questions in particle physics is what is the origin of electroweak symmetry breaking and of elementary particle masses. The top quark may play an essential role to probe the fermion mass generation mechanism [1], since it is expected to have large couplings to the symmetry breaking sector, both in the Standard Model (SM) and in other new physics scenarios [2].

The Higgs-top Yukawa coupling could be measured at the next generation of colliders, although this is a challenging measurement that requires future accelerators with the highest center-of-mass energies and luminosities. For a Higgs boson with mass around 120 GeV, studies at the LHC and at future e^+e^- linear colliders (LC) [3] have shown that a determination with an error close to 10% in associated $t\bar{t}$H production is possible, provided that some large backgrounds are kept under control. Associated production is no longer efficient for higher Higgs masses. If the Higgs is heavier than 350 GeV, the WW $\to$ H $\to$ $t\bar{t}$ fusion process becomes the best way to measure the top Yukawa coupling. While this production mechanism will be hardly observable at the LHC, due to the huge QCD background from gluon fusion, several studies [4] have anticipated a promising environment in the case of e^+e^- colliders.

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TABLE 1. Helicity cross sections (in fb) for the $e^+e^- \to t\bar{t}\nu\bar{\nu}$ process and different Higgs masses (in GeV) at $\sqrt{s} = 1$ TeV. $\sigma(\lambda\lambda')$ is the cross section for production of a top with helicity λ and an antitop with helicity λ'.

m_H	σ(LL) = σ(RR)	σ(LR)	σ(RL)	Total
100	0.11	0.22	0.21	0.65
400	1.89	0.34	0.33	4.45
800	0.33	0.22	0.21	1.09

In this paper, we present a realistic study, with a special emphasis on critical issues at the generation and simulation levels. The study assumes collider center-of-mass energies of 800 GeV and 1 TeV, an integrated luminosity of $\mathcal{L} = 1000$ fb^{-1}, and the detector performance expected in the framework of the TESLA project [5].

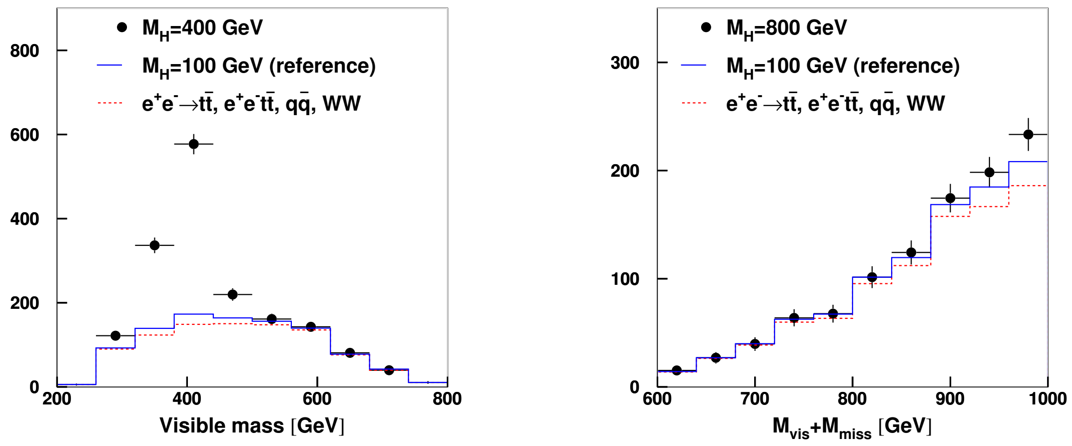
GENERATOR AND SIMULATION ISSUES

For the generation of $e^+e^- \to t\bar{t}\nu\bar{\nu}$ events, an improved version of the EXCALIBUR $e^+e^- \to 4$ fermions generator, called NEXTCALIBUR [6], is used. The improvements relevant for our study are the inclusion of Higgs exchange diagrams and fermion mass effects. A full four-fermion amplitude calculation is necessary since, at center-of-mass energies of 1 TeV or below, there are non-negligible interferences among different diagrams contributing to the same $t\bar{t}\nu\bar{\nu}$ final state. The program has been extended in order to include beamstrahlung effects [7] and to have control on top (and antitop) helicities in the final state. The subsequent decay $t \to bW \to bqq'$ is generated with the PANDORA [8] program, which takes into account the full spin correlation structure and finite width effects for the W boson and the top quark. The helicity cross sections obtained with NEXTCALIBUR for different Higgs mass hypotheses and 1 TeV center-of-mass energy are shown in Table 1.

In addition to the $e^+e^- \to t\bar{t}\nu\bar{\nu}$ process, the backgrounds from $e^+e^- \to q\bar{q}$, $e^+e^- \to WW$, $e^+e^- \to t\bar{t}$, and $e^+e^- \to e^+e^-t\bar{t}$, are generated with PYTHIA [9]. All generated events are passed through SIMDET [10], a fast simulation program which reconstructs energy-flow objects according to the current TESLA detector parameters and the expected reconstruction performance.

The $e^+e^- \to q\bar{q}$ and $e^+e^- \to WW$ backgrounds provide a total cross section of 7 pb at $\sqrt{s} = 1$ TeV, contributing with 7 million events to the final sample. In order to reduce them to a manageable level, strong requirements are applied: six jets in the event, no isolated leptons, cuts on event shape variables and moderate b-tagging requirements. The $e^+e^- \to e^+e^-t\bar{t}$ and $e^+e^- \to t\bar{t}$ backgrounds (with 17 fb and 240 fb, respectively) are largely reduced by applying cuts on missing transverse energy ($E_\perp > 50$ GeV) and reconstructed event missing mass ($M_{\rm miss} > 200$ GeV). The

FIGURE 1. Relevant final distributions in the analysis of the WW $\rightarrow$ H $\rightarrow$ $t\bar{t}$ process at an e^+e^- linear collider with $\sqrt{s}$ = 1 TeV, for m_H = 400 GeV and m_H = 800 GeV. In the plots, dots are the full expectations after cuts and the background is taken as the signal provided by a low-mass higgs particle (m_H = 100 GeV). Also shown is the background component from final states different from $t\bar{t}\nu\bar{\nu}$.



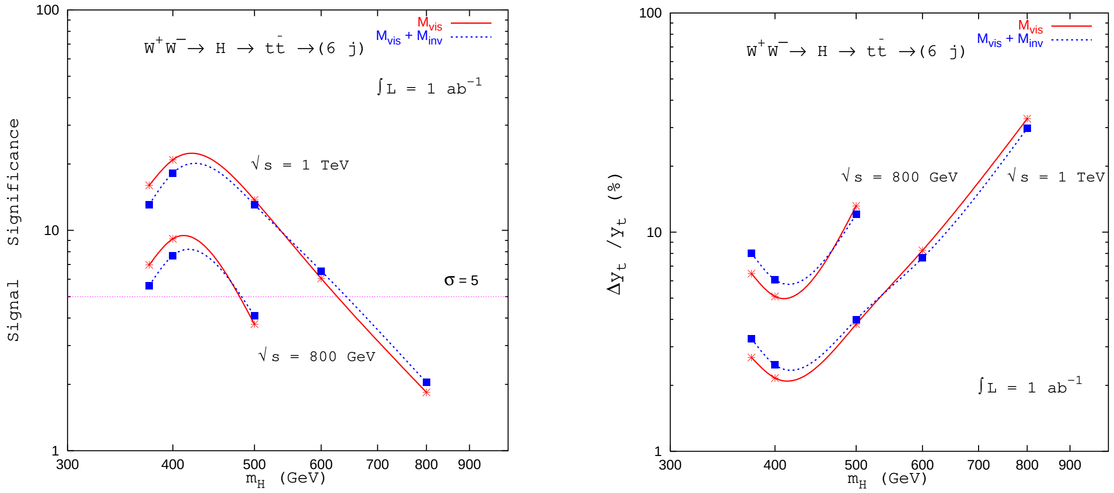
selection is completed by a χ^2 kinematic assignment in which the known values of the W and top masses are used as constraints. Events in which any of the reconstructed masses are more than 5 standard deviations away from the expected value are rejected.

After cuts, signal acceptances are in the range 18% to 12% for $\sqrt{s} = 1$ TeV and Higgs masses from 400 GeV to 800 GeV. The $q\bar{q}$ and WW backgrounds are reduced in a large factor of 200000, becoming a small percentage of the final sample composition. This final sample is dominated by $t\bar{t}$ and $e^+e^-t\bar{t}$ backgrounds. The $e^+e^- \rightarrow t\bar{t}\nu\bar{\nu}$ reference background has been chosen as the data expectations in the case of a low-mass scalar particle ($m_H = 100$ GeV). The signal to background ratio strongly depends on the Higgs mass hypothesis. For $m_H = 400$ GeV, we expect 695 signal events over 993 events of background, and the visible mass distribution is nicely peaked at the expected value (see Figure 1), leading to a significant observation. The situation is different for higher Higgs masses. At $m_H = 800$ GeV, only 52 signal events are expected. One of the most sensitive distributions in this case is the sum of visible and missing masses (Figure 1), which strongly peaks at values close to $\sqrt{s}$ when the Higgs is produced essentially at rest.

RESULTS

The results of the analysis are summarized in Figure 2. The significance of the signal is estimated by a binned fit to the *visible* and *visible plus missing* mass distributions. The measured data in each bin, N, are assumed to follow the dependence

FIGURE 2. Results of the analysis of the $\mathrm{WW} \to \mathrm{H} \to \mathrm{t\bar{t}}$ process in the SM. The plots show the signal significance (left) and the uncertainty on the $\mathrm{Ht\bar{t}}$ Yukawa coupling (right) as a function of the Higgs mass hypothesis. Two center-of-mass energies are considered, $\sqrt{s} = 1$ TeV and $\sqrt{s} = 800$ GeV, and an integrated luminosity of 1000 fb^{-1} is assumed. Two sets lines are obtained, depending on which final distribution (*visible* or *visible plus missing* mass) is fitted.



$N = x\ S + B$, where S and B are the signal and background expectations, respectively. The significance is given by $x/\delta x$, where x is the fitted factor (1 in the SM) and δx is the statistical error from the fit. The results guarantee that a signal at $\sqrt{s} = 1$ TeV can be observed at the 5 standard deviations level if a scalar with properties similar to the SM Higgs is present in the $2m_{\mathrm{t}} < m_{\mathrm{H}} < 650$ GeV range. As expected, the *visible* mass distribution is more sensitive than the *visible plus missing* mass distribution for lower Higgs mass values, and the situation is reversed at masses approaching $\sqrt{s}$. The analysis has been repeated at a lower center-of-mass energy, $\sqrt{s} = 800$ GeV. In this case the 5σ range of observation is reduced to $2m_{\mathrm{t}} < m_{\mathrm{H}} < 500$ GeV, due to a lower signal cross section and a larger cross section for the $\mathrm{e^+e^-} \to \mathrm{t\bar{t}}$ background.

The significance of the signal can be reinterpreted as a direct measurement of the $\mathrm{Ht\bar{t}}$ Yukawa coupling, y_{t}. The results are also presented in Figure 2. The main conclusion is that, for all cases in which there is a 5σ evidence for the signal, the Yukawa coupling can be measured with a relative precision better than 10%. An additional conclusion is that it is feasible to establish a non-vanishing Yukawa coupling at the 95% confidence level for masses as high as $m_{\mathrm{H}} = 800$ GeV (at $\sqrt{s} = 1$ TeV). Finally, we want to point out that tools like kinematic fitting, b,c-tagging detector capabilities or polarization analysis have not been fully employed. This leads us to conclude that: a) the results can be safely extrapolated to other physics cases, like vector resonances (technicolor) and scalar particles with couplings different from the SM ones, and b) the expectations (obtained in the TESLA framework) will not change significantly if other $\mathrm{e^+e^-}$ machines and detector options are used.

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