Measuring Higgs Branching Ratios
and telling the SM from a MSSM Higgs Boson
at the $e^+e^-$ Linear Collider

Marco Battaglia

Department of Physics, High Energy Physics Division
University of Helsinki
P.O. Box 9, FIN-00014 University of Helsinki, Finland

To appear in the Proceedings of the
International Workshop on Linear Colliders LCWS99,
Sitges (Spain), April 28 - May 5, 1999
MEASURING HIGGS BRANCHING RATIOS 
AND TELLING THE SM FROM A MSSM HIGGS BOSON 
AT THE $e^+e^-$ LINEAR COLLIDER

M. Battaglia

Department of Physics, High Energy Physics Division
University of Helsinki (Finland)

An accurate determination of the Higgs decay branching ratios to $b\bar{b}$, $c\bar{c}$, $gg$, $WW^*$ 
and $\tau^+\tau^-$ pairs is important for the study of the Higgs couplings and for determining 
its SM or MSSM nature in the mass range $100 \text{ GeV}/c^2 < M_H < 140 \text{ GeV}/c^2$. 
This measurement also represents an important benchmark for the optimisation 
of the detector design. The accuracy on the determination of the Higgs decay 
branching ratio to fermions and $WW^*$ pairs has been studied using the simulation 
of the detector designed for the TESLA $e^+e^-$ linear collider at $\sqrt{s}$ of 350 GeV 
and 500 GeV. The results are discussed in terms of the ability of discriminating 
between the SM and a MSSM neutral Higgs boson and of the predictivity on the 
$A^0$ mass in the MSSM scenario.

1 Introduction

The investigation of the production and decay properties of the Higgs boson 
and the determination of its nature are an important part of the physics pro-
gramme at the $e^+e^-$ linear collider. Furthermore this study sets stringent 
requirements on the response of the experimental apparatus and thus repre-
sents an ideal benchmark for the optimisation of its design.

At the linear collider, detection of the SM or MSSM-like neutral Higgs 
boson will be straightforward and the anticipated large statistics and accu-
rate detector response will enable detailed tests of its production and decay 
characteristics.

This study is based on the simulated response of the detector designed for 
the TESLA CDR. The track impact parameter resolution has been varied 
to reflect the updates in the Vertex Tracker design. Signal $e^+e^- \rightarrow Z^0H^0$, 
$H^0\nu\bar{\nu}$ and background events have been simulated using the PYTHIA 5.02 and 
JETSET 7.405 generators tuned on LEP data for the electroweak and QCD 
variables and on both LEP and CLEO data for heavy flavour decays. Events 
have been generated at $\sqrt{s}$ of 350 GeV and 500 GeV, corresponding to an 
integrated luminosity of $\int L = 100 \text{ fb}^{-1}$. The centre-of-mass energy included 
the smearing effect due to beamstrahlung. The results have been scaled to 
the integrated luminosities of 500 fb$^{-1}$ corresponding to 1 to 2 years (1 year 
$= 10^7 \text{ s}$) of data taking at the TESLA design luminosity of $3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. 
The detector response to charged particle tracks has been studied using a full
GEANT 3.21 simulation and a track fit based on the Kalman filter algorithm. The resulting momentum and impact parameter resolutions have been used as inputs to a parametric smearing simulation program. This program has been also used to model the calorimeter response. Events have been reconstructed using a dedicated event reconstruction and analysis program. Finally a jet flavour tagging algorithm has been applied in order to identify the hadronic final states. The reconstruction, analysis and tagging algorithms are based on programs developed for the study of the LEP-2 data with the DELPHI detector.

2 Determination of Higgs Branching Ratios

The accuracy on the Higgs decay branching ratio measurements at the linear collider has been already the subject of several studies. With improved designs of the Vertex Tracker, more advanced jet flavour tagging techniques, profiting of the experience gained at LEP and SLC, and the large statistics available at the TESLA collider these studies move in the domain of precision measurements.

2.1 Event Reconstruction

This analysis considered neutral Higgs bosons, produced by either the $e^+e^- \rightarrow H^0Z^0$ or the $e^+e^- \rightarrow H^0\bar{\nu}\nu$ processes, in the $(JJ)_H(jj)_Z$, $(JJ)_H(\ell\ell)_Z$ and $(JJ)_H\nu\bar{\nu}$ final states, where $(JJ)_H$ stands both for the two jet hadronic final states and for $\tau^+\tau^-$ and $WW^*$ as discussed below.

After the event selection, hadronic jets have been reconstructed using the LUCLUS algorithm. Events have been forced to either two or four jets and the jet energies have been rescaled using a 4-C fit by imposing energy and momentum conservation at the nominal $\sqrt{s}$. Further selections have been applied on the event topology for the three final states under study. Finally the compatibility of each reconstructed event with the $H^0Z^0$, $H^0\nu\bar{\nu}$ hypotheses has been tested by constructing a $\chi^2_M$ variable based on the reconstructed masses. The di-jet Higgs mass resolution has been found to be $\sigma_{JJ} \approx 2.7$ GeV/$c^2$ at 120 GeV/$c^2$. Candidate Higgs decays have been selected by a cut on this $\chi^2_M$ variable. The efficiency of this selection has been estimated to be 25% with 76% purity, corresponding to a signal to background ratio $S/\sqrt{B} \approx 100$, at both $\sqrt{s} = 350$ GeV and 500 GeV.

The Higgstrahlung cross-section $\sigma_{ZH}$ can be obtained by the study of the di-lepton recoil mass, $M_H$, from $Z^0 \rightarrow \ell^+\ell^-$. This is necessary for the extraction of the absolute Higgs decay branching ratios by flavour tagging of the Higgs decay final states. In addition, a determination of the Higgs production cross-section independent on its decay modes is important in the
study of possible invisible or exotic Higgs decay channels such as decays to SUSY. A dedicated study has shown that an accuracy of about 2\% on $\sigma_{ZH}$ can be obtained for both $M_H = 120 \text{ GeV}/c^2$ and $M_H = 140 \text{ GeV}/c^2$ with an integrated luminosity of 500 fb$^{-1}$.

2.2 $H^0 \rightarrow b\bar{b}, c\bar{c}, gg$

Higgs hadronic final states have been selected by imposing hadronic jet quality cuts. The separation of the $b\bar{b}$, $c\bar{c}$, $gg$ hadronic final states is based on the jet flavour tagging response. Due to their relatively long lifetime, cascade $b \rightarrow c \rightarrow s$ decay chain and large invariant mass of beauty hadrons, the decay topology with two secondary vertices and the secondary particle invariant mass are very distinctive features of $b$ jets. At the linear collider, due to the large boost, the $b$ hadrons decay on average about 0.8 cm away from the beam collision, compared to 0.3 cm at LEP and at the SLc. Furthermore the performances of the new generation of Vertex Trackers presently under study for the linear collider will allow an efficient reconstruction of secondary charged particle and the determination of their point of production. Jet flavour tagging techniques, similar to those already successfully applied at LEP$^{11}$ and at the SLc$^{12}$, will ensure effective performances due to the favourable kinematics and detector response. The tagging algorithm adopted in this analysis combines kinematical and topological variables in order to identify $b\bar{b}$, $c\bar{c}$ and light quark di-jets.

![Image](image.png)

Figure 1: The distribution of the $gg$, $cc$ and $bb$ di-jet flavour tag response for Higgs decay candidates. The points with error bars show the expected data distribution assuming SM couplings for 100 fb$^{-1}$ and the shaded histograms the response for light quark (medium grey), $c\bar{c}$ (light grey) and $b\bar{b}$ (dark grey) di-jets normalised to the fitted fractions.
For each hadronic jet an inclusive secondary vertex search has been performed using charged particles tracks reconstructed in the Vertex Tracker. Neutral particles with large probability of originating from a heavy hadron decay have been also associated to this secondary vertex. The identification of the jet flavour has been based on the following variables: i) probability that all the reconstructed charged particles of the jet originated at the event primary vertex, ii) number of charged particles with an impact parameter larger than twice the measurement accuracy, iii) invariant mass and energy of the secondary particles, iv) transverse momentum of identified leptons in the jets and v) probability that all the secondary particles originated at a common, displaced vertex. The likelihood function has been defined as follows: for each of the N discriminating variables, the fractions $F_{i}^{bb}(x_{i})$, $F_{i}^{cc}(x_{i})$ and $F_{i}^{gg}(x_{i})$ of $b$, $c$ and $g$ di-jets corresponding to a given value $x_{i}$ of the $i^{th}$ variable, have been extracted from samples of Higgs $b\bar{b}$, $c\bar{c}$ and $gg$ decays with equal populations. The $bb$, $cc$ and $gg$ likelihood variables have been computed as the normalised product of these individual fractions as: $\prod_{i=1,N} F_{i}^{QQ}(x_{i})/\sum_{qq=bb,cc,gg} \prod_{i=1,N} F_{i}^{qq}(x_{i})$. Only decays with at least one jet with jet flavour tagging response have been considered in this analysis. The fractions of $b\bar{b}$, $c\bar{c}$ and $gg$ Higgs final states has been extracted by a binned maximum likelihood fit to these di-jet flavour tagging probabilities for the Higgs decay candidates (see Figure 1). The background has been estimated from simulation over a wide interval around the Higgs mass peak and subtracted. It will be possible to study the flavour composition of this background directly on the real data by using the side-bands of the Higgs mass peak, thus reducing the possible systematics error from the simulation modelling. The fitted fractions agreed well with the input values and the performances at $\sqrt{s} = 350$ GeV and 500 GeV have been found to be equivalent.

Table 1: Accuracy in the determination of the hadronic Higgs decay branching ratios for $M_{H} = 120$ GeV/$c^{2}$ and $\sqrt{s} = 350$ GeV

| Channel               | $\delta(\frac{\sigma_{ZH} \times BR(H \rightarrow X)}{\sigma_{ZH} \times BR(H \rightarrow \text{hadrons})})/BR$ | CDR Vtx. | Improved Vtx. |
|-----------------------|--------------------------------------------------------------------------------------------------|----------|----------------|
| $H^{0}/h^{0} \rightarrow bb$ | $\pm 0.011$ | $\pm 0.008$ | $\pm 0.008$ |
| $H^{0}/h^{0} \rightarrow cc$   | $\pm 0.134$ | $\pm 0.080$ | $\pm 0.080$ |
| $H^{0}/h^{0} \rightarrow gg$   | $\pm 0.050$ | $\pm 0.050$ | $\pm 0.050$ |
2.3 $H^0 \rightarrow \tau^+\tau^-$

The selection of $H^0 \rightarrow \tau^+\tau^-$ decays started from events not fulfilling the Higgs hadronic final state selection. Events have been clusterised in either two or four jets with isolated tracks being considered as single particle jets. Similarly to the case of the jet flavour tagging of hadronic final states, a global $\tau\tau$ likelihood has been defined by using the response of the following discriminating variables: i) number of jets (including isolated particles), ii) number of jets with more than 2 charged particles in the event, iii) event Thrust, iv) $E_{\text{tot}}/\sqrt{s}$, v) jet invariant mass, vi) number of charged particles per jet and vii) jet impact parameter probability. This $\tau\tau$ likelihood peaked at one for $H^0 \rightarrow \tau^+\tau^-$ decays and at zero for background events. $H \rightarrow \tau\tau$ decays have been selected by a cut on this likelihood. The background from other Higgs decay channels has been found to be negligible. Results are summarised in Table 2.

Table 2: Performances of the $H \rightarrow \tau\tau$ analysis for $M_H = 120$ GeV/c$^2$ and $\sqrt{s} = 350$ GeV

| Signal $H \rightarrow \tau\tau$ /$100 \text{ fb}^{-1}$ | Background /$100 \text{ fb}^{-1}$ | Eff. | $\delta BR/BR /500 \text{ fb}^{-1}$ |
|--------------------------------------------------|--------------------------|------|----------------------------------|
| 165                                              | 280                      | 19%  | $\pm 0.057$                     |

2.4 $H^0 \rightarrow WW^*$

The determination of the $WW^*$ decay branching ratio has been performed using the $H^0 \rightarrow WW^* \rightarrow \ell\nu q\bar{q}$ channel. This analysis of the $H^0 \rightarrow WW^*$ is presented in details in [3]. The signal is characterised by the event topology and the two-jet recoil mass distribution peaked at the Higgs mass. The results are summarised in Table 3.

Table 3: Performances of the $H \rightarrow WW^*$ analysis for $M_H = 120$ GeV/c$^2$ and $\sqrt{s} = 350$ GeV

| $H \rightarrow WW^*$ /$100 \text{ fb}^{-1}$ | Background /$100 \text{ fb}^{-1}$ | Eff. | $\delta BR/BR /500 \text{ fb}^{-1}$ |
|--------------------------------|--------------------------|------|----------------------------------|
| 101                           | 30                       | 5.3% | $\pm 0.051$                     |

This measurement, combined with the determination of the Higgstrahlung and $WW$ fusion cross-sections, can be used to extract the Higgs width with good accuracy.
3 Telling a SM from a MSSM Higgs Boson

The accuracies on the determination of the decay branching ratio into $b\bar{b}$, $c\bar{c}$, $gg$, $\tau\tau$ and $WW^*$, obtained in this study for the case of a $M_H = 120$ GeV/c$^2$ Higgs boson, are summarised in Table 4. Their implications on distinguishing the SM or MSSM nature of the Higgs boson are discussed in this section.

The sensitivity of the Higgs decay branching ratios in discriminating between the SM and MSSM Higgs hypotheses has been already studied in some details. In MSSM the Higgs decay width to specific final states has the following dependence: \( \Gamma_{MSSM}^{bb} \propto \Gamma_{SM}^{bb} \sin^2 \alpha \cos^2 \beta \), \( \Gamma_{MSSM}^{c\bar{c}} \propto \Gamma_{SM}^{c\bar{c}} \cos^2 \alpha \sin^2 \beta \) and \( \Gamma_{MSSM}^{WW^*} \approx \Gamma_{SM}^{WW^*} \), with \( \tan \alpha = \left( \frac{M_Z^2 + M_A^2}{M_Z^2 - (M_Z^2 - M_H^2) \cos^2 \beta + M_A^2 \sin^2 \beta} \right) \) and \( \tan \beta = \frac{v_2}{v_1} \) being the ratio of vacuum expectation values. Therefore deviations in the ratio of branching ratios such as \( \frac{BR(h \to W W^*)}{BR(h \to b\bar{b})} \), \( \frac{BR(h \to c\bar{c})}{BR(h \to b\bar{b})} \) and \( \frac{BR(h \to gg)}{BR(h \to b\bar{b})} \) from their SM expectations could reveal the MSSM nature of the Higgs boson and provide indirect information on the mass of the CP odd $A^0$ Higgs boson. The accuracy of the SM predictions has been studied assuming $m_b (M_{\Upsilon(1S)}/2) = (4.20 \pm 0.11)$ GeV/c$^2$ for the running \( \overline{MS} \), $m_t - m_c = (3.40 \pm 0.04)$ GeV/c$^2$, $\alpha_s(m_Z) = 0.1164 \pm 0.0025$ and $m_{top} = (175 \pm 2)$ GeV/c$^2$ where the $b$ quark mass has been obtained using a sum rule for the $\Upsilon$ spectroscopy data, the $m_b - m_c$ mass difference has been derived from Heavy Quark Effective Theory while for the top pole mass, $m_{top}$, the uncertainty reflects a conservative estimate of the expected accuracy from the top threshold scan at the linear collider. Improvements on $m_b$ and $m_t - m_c$, possibly by a factor \( \simeq 2 \), can be envisaged after the study of the data on $B$-decays from the $B$-factories and the LHC. The SM Higgs decay branching ratios, including QCD corrections, have been obtained using the HDECAY program. Results are summarised in Figure 2. The $c$-quark mass and the $\alpha_s$ uncertainties limit the predictivity of the $c\bar{c}$ and $gg$ channels to about $\pm 14\%$ and $\pm 7\%$ respectively. On the contrary, the $b\bar{b}$,
Figure 2: The predicted SM Higgs decay branching ratios shown as the 68% confidence level bands with overlayed the measured points using the results of this study.

$\tau^+\tau^-$ and $WW^*$ predictions can be obtained with accuracies comparable to, or better than, the experimental uncertainties.

For comparing these SM predictions to those in MSSM, a scan of the MSSM parameters phase space has been performed assuming:

$$2 < \tan \beta < 60$$
$$150 \text{ GeV}/c^2 < M_A < 1100 \text{ GeV}/c^2$$
$$500 \text{ GeV}/c^2 < M_{SUSY} < 1500 \text{ GeV}/c^2$$
$$-1000 \text{ GeV} < \mu < 1000 \text{ GeV}$$
$$0 < M_{L_R}/M_\tilde{q} < \sqrt{6}$$
$$0.5 < M_\tilde{g}/M_{SUSY} < 1.$$

For each set of parameters the resulting $h^0$ mass has been computed using the diagrammatic two-loop result\[20\] implemented in the F\textsc{eynHiggs} program\[21\]. Solutions corresponding to $M_{h^0} = (120 \pm 2) \text{ GeV}/c^2$ have been selected and used to compute the $h^0$ decay branching ratios with the H\textsc{decay} program, accounting for squark loops, after forcing $M_{h^0} = 120 \text{ GeV}/c^2$. The pull quantity $\Delta(BR) = \frac{|BR_{MSSM} - BR_{SM}|}{\sqrt{\sigma_{BR, MSSM}^2 + \sigma_{BR, SM}^2}}$ has been computed for i) $BR(h \to b\bar{b})/BR(h \to \text{hadrons})$, ii) $BR(h \to c\bar{c})/BR(h \to \text{hadrons})$, iii) $BR(h \to g\bar{g})/BR(h \to \text{hadrons})$ and iv) $BR(h \to b\bar{b})/BR(h \to WW^*)$. From the total $\chi^2$, the SM/MSSM discrimination has been defined as the portion of the $M_A - \tan \beta$ plane with more than 68%, 90% or 95% of the MSSM solutions outside the SM 95% confidence level region. This study has been repeated for four different
scenarios: i) 500 fb$^{-1}$, theory systematics as above with CDR Vertex Tracker, ii) 500 fb$^{-1}$, theory systematics as above with improved Vertex Tracker, iii) 1000 fb$^{-1}$, theory systematics half of the above with CDR Vertex Tracker and iv) 1000 fb$^{-1}$, theory systematics half of the above with improved Vertex Tracker. SM/MSSM 90% C.L. discrimination can be achieved up to $M_A \simeq 550$ GeV/c$^2$ for the scenario i) improving to $M_A \simeq 730$ GeV/c$^2$ assuming scenario iv). Since, with the experimental performances obtained for this analysis, the dominant source of uncertainties is due to the theory systematics, there is not a significant difference in the excluded region between the two assumed performances for the Vertex Tracker. The results are exemplified in Figure 3.

From this comparison it follows that the sensitivity to the SM/MSSM nature of a neutral Higgs boson is mainly limited by the theory uncertainties rather than by the envisaged detector response and the experimental accuracies obtained in the present study.

![TESLA L = 500 fb$^{-1}$](image)

Figure 3. The SM/MSSM discrimination region in the $M_A - \tan \beta$ plane for $M_H = 120$ GeV/c$^2$ and 500 fb$^{-1}$. The lines define the regions with 68% (light grey), 90% (medium grey) and 95% (dark grey) of the MSSM solutions distinguishable at the 95% confidence level from the SM $H^0$ boson.

It is also possible to use the accurate determination of the Higgs decay branching ratios for an indirect estimate of the mass $M_{A^0}$ in the MSSM case. Sensitivity to the $A^0$ mass arises from the MSSM corrections to the Higgs couplings discussed above and it is of special interests for those masses above the kinematical limit for direct $e^+e^- \rightarrow h^0 A^0$, $H^0 A^0$ production. The analysis has been performed assuming given sets of measured values for the
BR(h \to c\bar{c} + gg)/BR(h \to b\bar{b}) and BR(h \to WW^+)/BR(h \to b\bar{b}) ratios. The $A^0$ mass has been varied together with the other MSSM parameters within the range compatible with the measured branching ratios allowing for their total uncertainty. The range of values of $M_A$ for the accepted MSSM solutions corresponded to an accuracy of 70 GeV/$c^2$ to 90 GeV/$c^2$ for the indirect determination of $M_A$ in the mass range $300$ GeV/$c^2 < M_A < 500$ GeV/$c^2$.

4 Conclusions

The accuracy on the determination of the decay branching ratios for a neutral Higgs boson with $M_{H^0} = 120$ GeV/$c^2$ has been studied at a $\sqrt{s} = 350$ GeV and 500 GeV $e^+e^-$ linear collider. The measured branching ratios allow to determine the Higgs decay width with good accuracy, to distinguish a MSSM $h^0$ boson from the SM $H^0$ boson and to indirectly determine the $A^0$ mass up to 600-700 GeV/$c^2$. Significant improvements in the knowledge of the $b$ and $c$ quark masses and good control of QCD corrections are necessary in order to preserve the predictive potential of the $c\bar{c}$ and $gg$ decays for $M_H < 120$ GeV/$c^2$. For higher Higgs masses, the combination of the $b\bar{b}$ and $WW^*$ decay branching ratios provides the bulk of the information on the neutral Higgs nature and the $A^0$ mass.

Acknowledgements

It is a pleasure to thank G. Borisov, A. Djouadi, E. Gross, S. Moretti, R. Orava, M. Peskin, F. Richard, M. Spira, D. Treille and P. Zerwas for suggestions and fruitful discussion. D. Schulte has kindly provided the simulation of beamstrahlung effect. I am also grateful to the organisers of the LCWS 99 Workshop for their invitation and the inspiring atmosphere during the conference.

References

1. P. Janot, in $e^+e^-$ collisions at 500 GeV: The physics potential, DESY 92-123 A.
2. Conceptual Design of a 500 GeV $e^+e^-$ Linear Collider with Integrated X-ray Laser Facility (ed. R. Brinkmann, G. Materlink, J. Rossbach and A. Wagner), DESY 1997-048.
3. M. Caccia et al.; T. Greenshaw et al., in these Proceedings.
4. T. Sjostrand, Comp. Phys. Comm. 82, 74 (1994).
5. D. Schulte, private communication.
6. SIMDET program by H.J. Schreiber et al.
7. W. Lohmann et al., in these Proceedings.
8. M.D. Hildreth, T.L. Barklow and D.L. Burke, Phys. Rev. Lett. 49, 3441 (1994).
9. I. Nakamura and K. Kawagoe, in Proc. of the Workshop on Physics and Experiments with Linear Colliders, vol. II, World Scientific, Singapore 1996.
10. M. Battaglia and R. Vuopionpera, in $e^+e^-$ Linear Colliders: Physics and Detector Studies, DESY 97-123 E.
11. G. Borisov, Nucl. Instrum. Methods A 417, 384 (1998).
12. D. Jackson, Nucl. Instrum. Methods A 388, 247 (1997).
13. G. Borisov and F. Richard, Precise measurement of Higgs decay rate into WW* at future $e^+e^-$ Linear Colliders, LAL 99-26, hep-ph/9905413.
14. H.E. Haber, in Proc. of the 4th Int. Conf. on Physics beyond the Standard Model, Lake Tahoe, CA, USA; World Scientific, Singapore, 1995;
   J. Kamoshita, Y. Okada and M. Tanaka, in Proc. of the Workshop on Physics and Experiments with Linear Colliders, Morioka, Japan; vol. II, World Scientific, Singapore 1996;
   J.F. Gunion, L. Poggioli and R. Van Kooten, in Proc. of the 1996 DPF/DPB Summer Study on New Directions for High-energy Physics, Snowmass, CO, USA; APS, New York, 1997.
15. A. Hoang, Phys. Rev. D 59 (1998), 014039.
16. I. Bigi, M. Shifman and N. Uraltsev, Aspects Of Heavy Quark Theory, TPI-MINN-97-02-T (hep-ph/9703290).
17. A. Hoang, in these Proceedings.
18. A. Djouadi, M. Spira and P. Zerwas, Z. Phys. C 70, 427 (1996).
19. A. Djouadi, J. Kalinowski and M. Spira, HDECAY: A Program for Higgs Boson Decays in the Standard Model and its Supersymmetric Extension, DESY 97-079.
20. S. Heinemeyer, W. Hollik and G. Weiglein, Phys. Lett. B 440, 296 (1998), and Phys. Rev. D 58, 091701 (1998).
21. S. Heinemeyer, W. Hollik and G. Weiglein, FeynHiggs: a program for the calculation of the masses of the neutral CP-even Higgs bosons in the MSSM, CERN-TH/98-389.
22. A. Andreazza and C. Troncon, in $e^+e^-$ Linear Colliders: Physics and Detector Studies, DESY 97-123 E.