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Branching Fraction Measurements of the SM Higgs with a Mass of 160 GeV at Future Linear e^+e^- Colliders

E. Boos[1], V. Ilyin[1], A. Pukhov[1], M. Sachwitz[2] and H.J. Schreiber[2]

[1] Institute of Nuclear Physics, Moscow State University,
119 899 Moscow, Russia

[2] DESY Zeuthen, 15735 Zeuthen, FRG

Abstract

Assuming an integrated luminosity of 500 fb^{-1} and a center-of-mass energy of 350 GeV, we examine the prospects for measuring branching fractions of a Standard Model-like Higgs boson with a mass of 160 GeV at the future linear e^+e^- collider TESLA when the Higgs boson is produced via the Higgsstrahlung mechanism, $e^+e^- \rightarrow$ HZ. The Higgs boson mass chosen close to the W pair threshold covers a mass regime with complicated background structures. We study in detail including some detector responds the precisions achievable for the branching fractions of the Higgs boson into $\mathrm{WW}^{(*)}$, ZZ^* and $b\,\bar{b}$, whereas the measurement of BF($\mathrm{H} \rightarrow \gamma\gamma$) remains a great challenge. Expectations for the total Higgs width are discussed using either the BF($\mathrm{Z} \rightarrow \mathrm{ZZ}^*$) measurement of this study and the expected error for the inclusive Higgsstrahlung cross section or in addition the precise cross section expected for the weak boson fusion process, $e^+e^- \rightarrow \nu\bar{\nu}$ H, or W,Z-universality.

1 Introduction

Discovery and study of Higgs boson(s) will be of primary importance at a next linear e^+e^- collider. Once a Higgs boson has been found, the task will be to determine as precisely as possible and in a model-independent manner its fundamental couplings and total width. In the Standard Model (SM) [1], the mass range from $\sim$100 GeV to about 220 GeV is favored by comparing precision electroweak data with SM predictions [3]. The four LEP experiments set, after combination of their data, a preliminary 95 % confidence level lower bound of 107.7 GeV for the SM Higgs boson mass [2]. For Higgs masses at 120 and 140 GeV branching fraction measurement investigations can be found in e.g. refs. [4], [5], [6]. In this paper we assume a Higgs mass of M_H = 160 GeV which covers a mass domain for the SM Higgs, while $\sim$120 GeV probes a mass region where SM and Higgs bosons within the minimal supersymmetric extension of the Standard Model (MSSM) are ambiguous. For M_H close to the W pair threshold, the Higgs boson decays mostly into WW* whereas the $b\,\bar{b}$ decay rate is stronly suppressed to few percent, opposite to the situation at smaller masses. Additionally, the background expected to contribute is more complicated since a mixture of WW (where both W's are on-mass-shell) and WW* (with one of the W's being off-mass-shell) exists under the Higgs, and due to detector resolution effects the observed width of the Higgs boson is expected to be much larger than its natural width. Also due to the M_H value chosen very close to two times the W mass, finite W width effects have to be accounted for to enable accurate results, and strategies developed for Higgs signal selections below $\mathrm{M}_H \sim$ 140 GeV cannot be applied directly to our case. In ref.[7], H $\rightarrow$ WW* reconstruction in the process $e^+e^- \rightarrow$ HZ, with WW* $\rightarrow l\nu\ q\,\bar{q}$ and Z $\rightarrow q\,\bar{q}$ decays, has been successfully achieved for M_H = 120 GeV, with the advantage of being far away from the W pair threshold. For Higgs masses close to and above 180 GeV, signal and background separation is expected to be clearly simpler: H $\rightarrow$ ZZ and H $\rightarrow$ WW are the almost exclusively decay modes, and selection of Z $\rightarrow l\,\bar{l}$ and W $\rightarrow l\nu$ or $q\,\bar{q}$ decays should result to convincing signals over well-controlled backgrounds.

Future linear e^+e^- colliders operating in the 300 to 500 GeV center-of-mass energy region are ideal machines to investigate the Higgs sector in the mass regime favored by the SM: besides easily Higgs discovery, all major decay modes can be explored.

In order to access the actual capability of an e^+e^- collider to an analysis of the SM Higgs boson it is extremely appealing to apply recently developed tools, thanks to the effort of several groups. In particular, we include in this study

- the full matrix elements for 4-particle final states beyond the usual approximation of computing Higgsstrahlung production cross sections times branching fractions, using the program package CompHEP [8]. In this way, irreducible background and possible interferences between signal and background diagrams are accounted for. Total and partial widths of the Higgs boson corrected for QCD and QED loop contributions were implemented in CompHEP and cross-checked with the HDECAY program [9]. For parton shower and hadronization procedures as well as particle decays the PYTHIA/JETSET package [10] has been interfaced;

- initial state QED [11] and beamstrahlung for the TESLA linear collider option [12];

- a detector response [13], with detector parameters as designed in a series of workshops for the linear e^+e^- collider Conceptual Design Report [14];

- all important reducible background reactions expected to contribute.

The cm energy $\sqrt{s}$ chosen for our study is 350 GeV avoiding thus $t\,\bar{t}$ pair production as background. Although $\sqrt{s}$ is not optimized for the best Higgs production rate with M_H= 160 GeV, it is a compromise between largest machine luminosity and sufficient event rates for the process

$$e^+e^- \to HZ. \qquad (1)$$

All the results presented are based on the high-luminosity option of the TESLA machine [15] with an instantaneous luminosity of $3{\cdot}10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ resulting to an accumulated luminosity of 500 fb^{-1} within about two years of running.

2 Standard Model Signals, Backgrounds and Branching Fractions

Within the SM, the Higgs boson with M_H = 160 GeV decays mostly to $\mathrm{WW}^{(*)}$, in few percent of the time to ZZ^* and $b\,\bar{b}$ and with a very small rate of about $0.5\cdot10^{-3}$ to two photons. We consider only these decay modes as all others are expected to be more difficult to measure. The aim of this study is to provide the statistical uncertainties of the branching fractions for the decay modes mentioned by measuring $\sigma(e^+e^- \to \mathrm{HZ}) \cdot \mathrm{BF}(\mathrm{H} \to \mathrm{X}) \cdot \mathrm{BF}(\mathrm{Z} \to \mathrm{Y})$, $\sqrt{S+B}/S$, where S (B) is the number of Higgs (background) events observed in a small interval of the invariant mass X, centered around M_H . For a narrow resonance one could do self-calibration of the background by estimating its amount under the signal peak via straight line interpolation of the observed mass spectrum between regions just below and above the assumed resonance mass, outside three times the experimental mass resolution Γ_{exp}. Systematic background uncertainties are in general small so that the error on B is dominated by the background statistics.

In order to estimate the optimized number of signal to background events for a narrow Gaussian resonance whose observed width is dominated by instrumental effects, the mass window chosen should be 1.2 Γ_{exp}, centered on the actual Higgs mass.

Event reconstruction has been simulated by means of the program package SIMDETv3 [13], using the program default values for e.g. the magnetic field of 3 Tesla, the lepton identification probabilities and their energy thresholds. The Charged Couple Devices (CCD) option for the superior vertex detector with its first layer positioned 12 mm radial from the interaction point has been adapted. Further details of the detector layout and the performances can be found in [14]. An energy flow algorithm defines the output of the program which consists of particles classified as electrons, photons, muons, charged and neutral hadrons as well as unresolved clusters. For physics studies, however, isolated leptons, photons and clusters of particles close in phase space resulting from quark and gluon fragmentation (= jets) are of primary interest. For multi-hadronic events we used the jet finding algorithm PUCLUS of the PYTHIA package [10] which reconstructs an arbitrary number of jets by means of a cluster analysis method on particle momenta. Also, the JADE algorithm [16] has been applied to 4-jet events to study the reliability of the jet finder adapted. Only small differences were found indicating robustness and non-important ambiguities in the jet-particle association procedure.

Out of all possible SM Higgs and weak boson decay modes expected, we restrict ourself only to H $\rightarrow$ WW$^{(*)}$, ZZ*, $b\,\bar{b}$ and $\gamma\gamma$ decays, with W $\rightarrow q\,\bar{q}$ and Z $\rightarrow q\,\bar{q}$ or $l\,\bar{l}$ (l=e,μ). In other words, we do not consider W $\rightarrow l\nu$, Z $\rightarrow$ $\tau\bar{\tau}$ and $\nu\bar{\nu}$ decays since they require rather sophisticated selection procedures which would go beyond the scope of this paper. Also 6-jet events are not taken into account due to large backgrounds expected and unknown reliabilities of existing jet finders in very large multiplicity events. This restricts our discussion to only the following event topologies: 4-jet plus two isolated leptons, 2-jet plus four isolated leptons, 4-jet and 2-jet plus 2 isolated leptons or photons. In order to avoid or suppress to a large extent backgrounds and contaminations of signal events with different topologies than the one under study, a series of requirements on event, lepton and jet properties are applied. Thus, in the determination of a given Higgs branching fraction all other Higgs decay modes and the irreducible background are accounted for. Reducible background having the same topology as the signal under discussion is also required to satisfy the criteria, and the events passing all cuts are included in the final mass spectra.

Branching fraction errors of the Higgs boson are then computed after convolution with the precision of the inclusive Higgs production cross section σ(HZ) of 2.8 % [5], [17]. Any W and Z branching fraction errors are neglected.

2.1 The Branching Fraction BF ($\mathbf{H} \to \mathbf{WW}^{(*)}$)

For $M_H = 160$ GeV, the Higgs boson decays mostly to WW*, i.e. to a final state where one of the W's is on-mass-shell and the other is off-mass-shell. Most of the background comes from $e^+e^- \to$ WW*Z and WWZ events and requires an accurate treatment of finite W width effects. Therefore exact matrix elements are used to calculate by means of CompHEP the processes

$$e^+e^- \to \bar{u}dWZ \tag{2}$$

$$e^+e^- \to u\bar{d}WZ \tag{3}$$

and

$$e^+e^- \to WWZ\ , \tag{4}$$

with appropriate matching below and above the W pair threshold, and to generate unweigthed events. The final states $\bar{c}$sWZ and c$\bar{s}$WZ were taken into account by doubling the number of events for reactions (2) and (3), respectively. In order to avoid large not useful event samples the following preselection cuts were applied to each final state particle during the generation stage which employ the following kinematical quantities:

- energy > 10 GeV ;
- polar angle $\Theta > 5°$;
- the invariant mass of any particle pairing $M_{ik} > 10$ GeV.

Due to the large H $\to$ WW$^{(*)}$ branching fraction and the luminosity assumed, we expect ~47.000 events for $e^+e^- \to$HZ $\to$WW$^{(*)}$Z which justifies the restriction to only Z $\to e^+e^-$, $\mu^+\mu^-$ and W $\to q\,\bar{q}$ decays, without much loss for branching fraction precision and, at the same time, enables relatively simple signal selection and background suppression procedures. Hence, the signature we have to search for consists of four jets accompanied by two opposite-charged leptons.

For each event of interest we apply the following cuts to select $e^+e^- \to$ HZ $\to$ WW$^{(*)}$Z $\to q\,\bar{q}\ q\,\bar{q}\ l\,\bar{l}$ events and to remove much of the irreducible and reducible backgrounds as well as reflections from other Higgs production channels:

- the visible energy of the event, E_{vis}, exceeds 250 GeV;

- the total transverse energy of the event is larger than 60 GeV;
- the total momentum along the beam direction is within $\pm$ 80 GeV;
- the number of tracks per event is larger than 20;
- out of all leptons with $|\cos\theta_l| < 0.95$, at least one e^+e^- or $\mu^+\mu^-$ pair has an invariant mass within $M_Z \pm 5$ GeV;
- four and only four jets in the final state [1];
- for each jet we require
  - $E_{jet} > 10$ GeV ;
  - $|\cos\theta_{jet}| < 0.85$;
  - number of particles /jet ≥ 4 ;
  - angle (jet_i, jet_k) $> 10°$ for any jet pairing;
- select from all two-jet pairings with 72 GeV $< M(q\,\bar{q}\,) <$ 84 GeV the one best compatible with M_W.

According to these criteria events were selected in which the Higgs recoils against the $Z \to l\,\bar{l}$ boson, with $H \to WW^{(*)}$ and $W \to q\,\bar{q}$ decays.

From all events with different Higgs and Z boson decays, only the process $e^+e^- \to HZ \to (ZZ^*)\ (l\,\bar{l}\,) \to 4$ jets $+\ e^+e^-\ /\mu^+\mu^-$ has the same signature and could contribute to the $H \to WW^{(*)}$ signal. However, after all cuts only 4 events survive and enter the final $WW^{(*)}$ mass spectrum. Contaminations from other signal channels with e.g. $Z \to q\,\bar{q}$ or $\nu\bar{\nu}$ decays have different event topologies and/or large missing energy. They are expected to be discarded by our stringent cuts, especially by the large visible event energy demanded, the restricted total momentum along the beam axis, the selection of only 4-jet events and $M(l\,\bar{l}\,)$ being close to M_Z.

Irreducible background from reactions (2) - (4) are found to be small. Reducible background events from e.g. the large cross section channels

$$e^+e^- \to W^+W^- \to 4jets \tag{5}$$

$$e^+e^- \to ZZ \to 4jets\ , \tag{6}$$

which mimic the signal topology and might fulfil the selection criteria are also expected to be non-important. As an example, 150.000 events of reaction (6) for 500 fb^{-1} of accumulated luminosity were processed and no entry was found in the final $WW^{(*)}$ mass distribution.

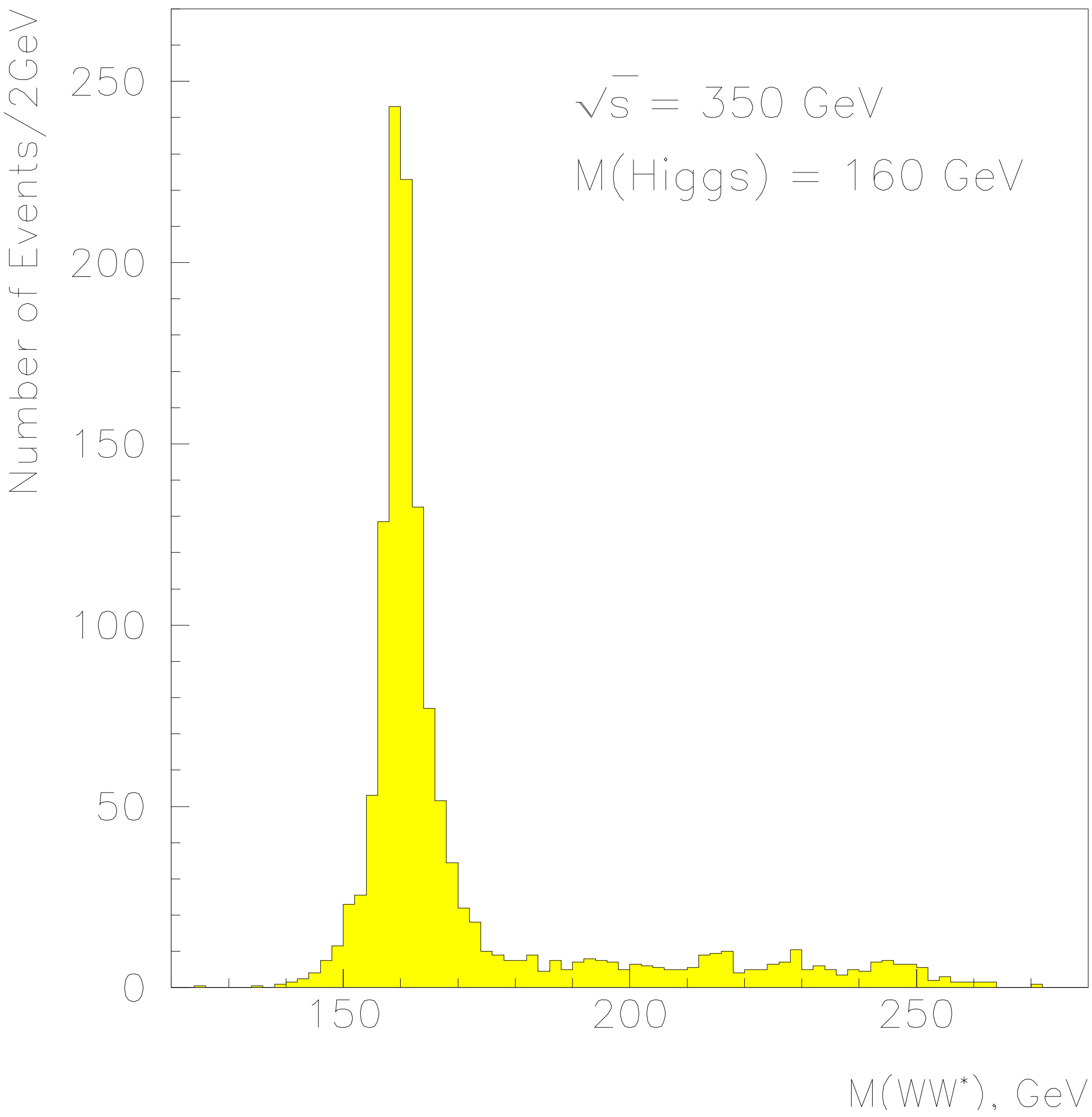

Figure 1: *The WW$^{(*)}$ mass distribution of all events passing the cuts.*

Fig.1 shows the WW$^{(*)}$ mass spectrum for all surviving events. A clear Higgs signal is visible over a very small background which is mainly due to non-signal diagrams contributing in reactions (2) and (3). Within the WW$^{(*)}$ mass range from 152 to 168 GeV we estimate 899 signal events (with the 4 surviving H $\rightarrow$ZZ* events subtracted) and 54 background events which results to a statistical error of 3.4 % for σ(HZ) $\cdot$ BF(H $\rightarrow$ WW$^{(*)}$) $\cdot$ BF(Z $\rightarrow l\,\bar{l}$). After convolution with the error of σ(HZ), the precision for BF(H $\rightarrow$ WW$^{(*)}$) is found to be 4.4 %.

At the LHC, the H $\rightarrow$ WW$^{(*)}$ detection mode is W $\rightarrow l\nu$ which implies two missing neutrinos in the H $\rightarrow$ WW$^{(*)}$ events [18]. Hence, reconstruction of a

[1] The two leptons selected in the previous step were excluded from the jet finder.

narrow Higgs mass peak is excluded and the Higgs signal detection is based on event excess over expected background rates, with QCD dependent normalization. With optimistic assumptions, the combined branching fraction error for both LHC experiments is expected to be ∼8 % [18].

2.2 The Branching Fraction BF ($\mathbf{H \to ZZ^*}$)

Information of the $\mathrm{H} \to \mathrm{ZZ}^*$ partial width respectively branching fraction can be obtained either from the inclusive Higgs production cross section $\sigma(\mathrm{HZ})$ which is proportional to the ZZH coupling-squared or from studies of ZZ^* mass distributions. The latter spectra, obtained from the reaction

$$e^+e^- \to ZZ^*Z \ , \tag{7}$$

contribute to four event topologies depending on the Z decay modes selected:

- 6-jet events;
- 4-jet plus two opposite-charged lepton events;
- 2-jet plus two pairs of opposite-charged lepton events;
- three pairs of opposite-charged lepton events.

Since large event rates are expected from the background reaction $e^+e^- \to$ WWZ $\to$ 6 jets and the signal process $e^+e^- \to \mathrm{HZ} \to \mathrm{WW}^{(*)}\mathrm{Z} \to$ 6 jets, 6-jet like events have been excluded from our study. Also the three lepton pair topology had been omitted due to its very small event rate.

We first consider the 2-jet 4-lepton topology which is very easily recognizable and distinct with respect to other candidates. Efficient rejection of backgrounds and Higgs reflections from other channels is expected due to the presence of four leptons with outstanding properties in the final state. By means of CompHEP the following reactions

$$e^+e^- \to d\bar{d}ZZ \tag{8}$$

$$e^+e^- \to u\bar{u}ZZ \tag{9}$$

$$e^+e^- \to ZZZ \tag{10}$$

were generated and appropriately weighted to account for $s\,\bar{s}$, $c\,\bar{c}$ and $b\,\bar{b}$ contributions in reactions (8) and (9). The two Z bosons (and for reaction (10), two Z's out of the three) are allowed to decay to electron respectively muon pairs. After event reconstruction we apply besides few preselection cuts on general event properties, see sect.2.1, the following criteria:

- only $e^+e^-/\mu^+\mu^-$, e^+e^-/e^+e^- or $\mu^+\mu^-/\mu^+\mu^-$ lepton combinations are allowed in the final state;
- $|\cos\theta_l| < 0.95$ for each lepton;
- there exists at least one lepton pair
  - with $M_{ll} = M_Z \pm 5$ GeV;
  - $E_l + E_{\bar{l}} > 125$ GeV;
  - which recoils against the $(q\,\bar{q}\;\, l\,\bar{l}\,)$ system with an invariant mass of less than 220 GeV;
- two and only two jets in the final state, after excluding the four leptons from the jet finder;
- each jet is required to satisfy criteria as discussed above.

The resulting $M(q\,\bar{q}\;\, l\,\bar{l}\,)$ mass distribution of all events which pass the cuts is shown in Fig.2. Higgs boson production is clearly observed on very small background. We estimate 19 signal and at most 2 background events within $M_H \pm 10$ GeV.

The 4-jet 2-lepton topology, our second candidate to search for $H \to ZZ^*$ decays, is expected to involve about 10 times more signal events due to the large $Z \to q\,\bar{q}$ decay rate. This advantage is however to a great extent compensated by demanding stronger criteria to reduce the background expected. In particular, contaminations from the large cross section signal process $e^+e^- \to HZ \to (WW^{(*)})l\,\bar{l}$, studied in the previous section, have to be avoided. Instead of requiring an optimal W and Z differentation by means of mass cuts in their $q\,\bar{q}$ decays which is due to combinatorics and detector resolution effects difficult, we try to select signal events from the decay chain $H \to ZZ^* \to l\,\bar{l}\;\, q\,\bar{q}$. In this way we rely on non-possible $W \to l\,\bar{l}$ decays and the superior $l\,\bar{l}$ mass resolution. The Z recoiling against the Higgs boson is demanded to decay hadronically. The procedure applied to accumulate events of interest employes

- $E_{vis} > 290$ GeV;
- the total transverse energy is larger than 70 GeV;
- the total momentum along the beam line is within ± 60 GeV;
- the number of total charged particles exceeds 22;

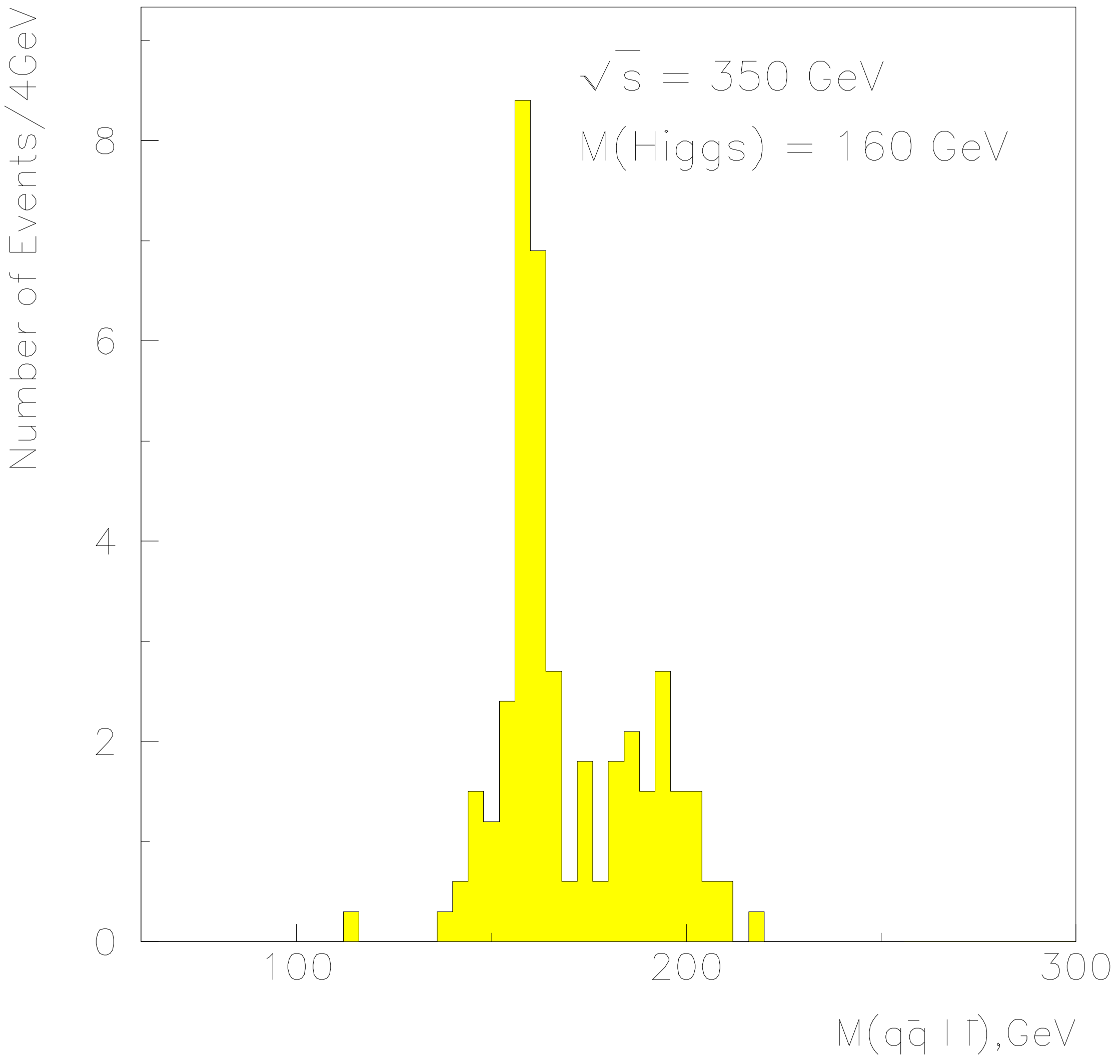

Figure 2: *The $ZZ^* \to q\,\bar{q}\;\; l\,\bar{l}$ mass distribution from the selected events of the 2-jet 4-lepton topology.*

- only e^+e^- or $\mu^+\mu^-$ pairs are accepted if $|\cos\,\theta_l| < 0.95$ and their invariant mass is within $\mathrm{M}_Z \pm 5$ GeV;
- 4 and only 4 jets are allowed in the final state, excluding the two leptons from the jet finder;
- for each jet we require properties as for the 2-jet 4-lepton like events;
- the two-jet invariant mass is within $\mathrm{M}_Z \pm 10$ GeV;
- $\mathrm{E}_l + \mathrm{E}_{\bar{l}} > 125$ GeV;
- the mass recoiling against the Z (with Z $\to q\,\bar{q}$) does not exceed 200 GeV.

The last two criteria on the sum of the lepton energies and on the mass recoiling against the Z $\rightarrow q\,\bar{q}$ are important. They ensure that i) only 32 HZ $\rightarrow$ WW$^{(*)}$Z($\rightarrow l\,\bar{l}$) events survive and contribute mainly above 170 GeV in the ($q\,\bar{q}\;\;l\,\bar{l}$) mass distribution and ii) only 5 ZZZ events pass all cuts.

Fig.3 shows the ($q\,\bar{q}\;\;l\,\bar{l}$) mass spectrum for all surviving candidate events. A convincing Higgs signal is seen on some remaining background which peaks near 190 GeV. We count 23 signal over 5 background events within the mass range M$_H \pm$ 10 GeV.

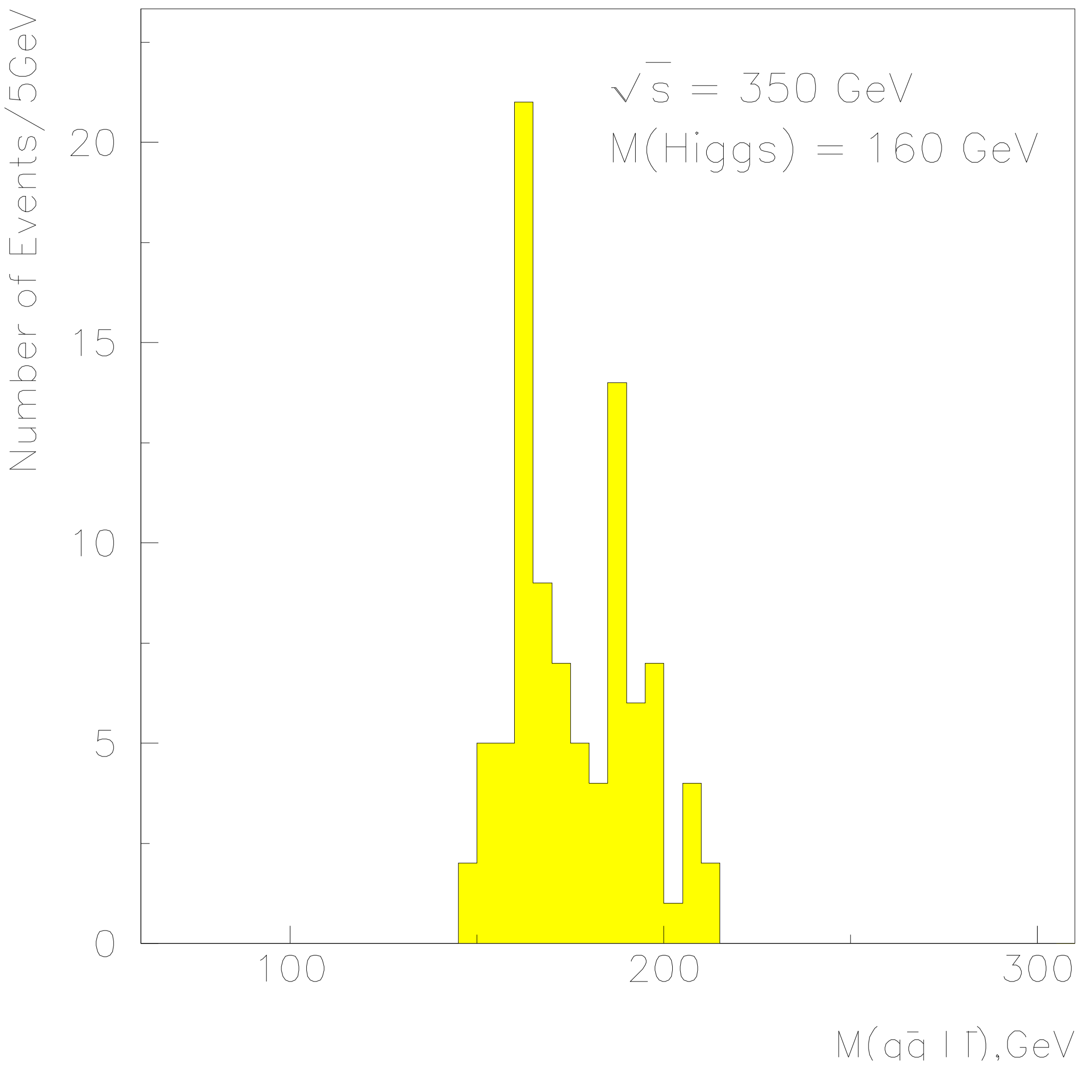

Figure 3: *The ZZ* $\rightarrow q\,\bar{q}\;\;l\,\bar{l}$ mass distribution from the selected events of the 4-jet 2-lepton topology.*

The combined spectrum of Figs.2 and 3 yields for $\sqrt{S+B}/S = 16.7\,\%$, which results to a statistical error of 16.9 % for BF (H $\rightarrow$ ZZ*), after convolution with the uncertainty of σ(HZ).

It is worth to point out that adding further topologies to our analysis would not noticeably improve the H $\to$ ZZ* branching fraction uncertainty due to intense background rates expected to contribute, and the precision obtained is comparable to the combined LHC measurement of $\sim$14 % [18].

2.3 The Branching Fraction BF (H $\to b\,\bar{b}$)

In contrast to the Higgs mass region below $\sim$130 GeV with the dominant H $\to b\,\bar{b}$ decay mode, heavier Higgs bosons are predicted to have a small or negligible decay rate to $b\,\bar{b}$. For M$_H$ = 160 GeV, the SM predicts a 3.8 % branching fraction which requires high luminosity and excellent b-tagging performance for a precise measurement.

The topologies expected for $e^+e^- \to$ HZ $\to (b\,\bar{b}$) Z production consist either of 4-jet events involving at least two b-jets

$$e^+e^- \to b\bar{b}\ q\bar{q} \tag{11}$$

or two b-jet events accompanied by a pair of opposite-charged leptons

$$e^+e^- \to b\bar{b}\ e^+e^-/\mu^+\mu^-. \tag{12}$$

Other Z decay modes are not considered in this paper..

Most of the background comes from the following channels:

$$e^+e^- \to q\bar{q}\ q\bar{q}\ , \tag{13}$$

mainly due to W and Z (Z $\to \neq b\,\bar{b}$) pair production,

$$e^+e^- \to q\bar{q}\ e^+e^-/\mu^+\mu^-, \tag{14}$$

with q = u, d, s and c, dominated by ZZ production and

$$e^+e^- \to q\bar{q}\ g\ g\ . \tag{15}$$

The criteria to select events of reaction (11) are the following

- the visible event energy, E$_{vis}$, exceeds 240 GeV;
- the total transverse energy of the event is larger than 50 GeV;
- the total momentum along the beam direction is within $\pm$ 80 GeV;
- the number of tracks per event is larger than 20;
- four and only four jets occur in the final state;

- for each jet we require
  - $E_{jet} > 12$ GeV;
  - $|\cos\theta_{jet}| < 0.85$;
  - angle (jet_i, jet_k) $> 10°$ for any jet pairing;
  - number of particles/jet ≥ 8;
- out of the four jets demanded at least two jets are tagged as b-jets. This requirement is essential in order to suppress the overwhelming amount of $e^+e^- \to$ 4-jet background events. In linear collider studies sophisticated vertex detectors are planned, and here the CCD option as proposed in [14] has been adopted. From detailed detector studies b-tagging respectively misinterpretation efficiencies were obtained, parametrized [19] and applied to the events of interest. In particular, we demand a b-tagging efficiency of 80 % to accumulate many H $\to b\,\bar{b}$ events, on the cost of a small but non-negligible light quark contamination dominated by $c\,\bar{c}$. The 80 % single b-tag efficiency allows for ~7 % of the c-quarks and ~1 % of the (u,d,s)-quarks to be assigned to a b-jet;
- the two non-b-jets have an invariant mass within $M_Z \pm 8$ GeV, or in cases of ≥ 3 b-jets, all combinations with $M(b\,\bar{b}) = M_Z \pm 8$ GeV are retained.

After this selection procedure, contaminations from Higgs signal events of other topologies are not expected. More important for a meaningful signal-to-background analysis are however events from reactions (13) - (15). Despite of the stringent cuts required some $e^+e^- \to$ ZZ $\to$ 4 light-jet events remain due to imperfect b-jet assignments. In addition, WW $\to$4-jet events, weighted according to their double c-, single c- and no c-quark content, are also processed and found to pass all cuts. Contaminations from $e^+e^- \to q\,\bar{q}$ g g have been estimated after accounting for the $b\,\bar{b}$, $c\,\bar{c}$ and light quark contents, with the result that 22 exclusively $b\,\bar{b}$ g g events would exist within $M_H \pm 8$ GeV for 500 fb^{-1} of integrated luminosity.

For all surviving events, the $b\,\bar{b}$ invariant mass spectrum is shown in Fig.4. Besides the dominating Z, the Higgs boson in its $b\,\bar{b}$ decay mode is clearly visible. From straight line background estimations in regions below and above the Higgs signal we found 168 signal and 214 background events (including the expected $b\,\bar{b}$ 2 gluon contamination), within a window of 8 GeV centered at M_H, which results to a statistical error for $\sigma(\mathrm{HZ}) \cdot \mathrm{BF}(\mathrm{H} \to b\,\bar{b}) \cdot \mathrm{BF}(\mathrm{Z} \to q\,\bar{q}) = 11.6$ %.

Events of the 2-jet dilepton signal topology, produced about ten times less

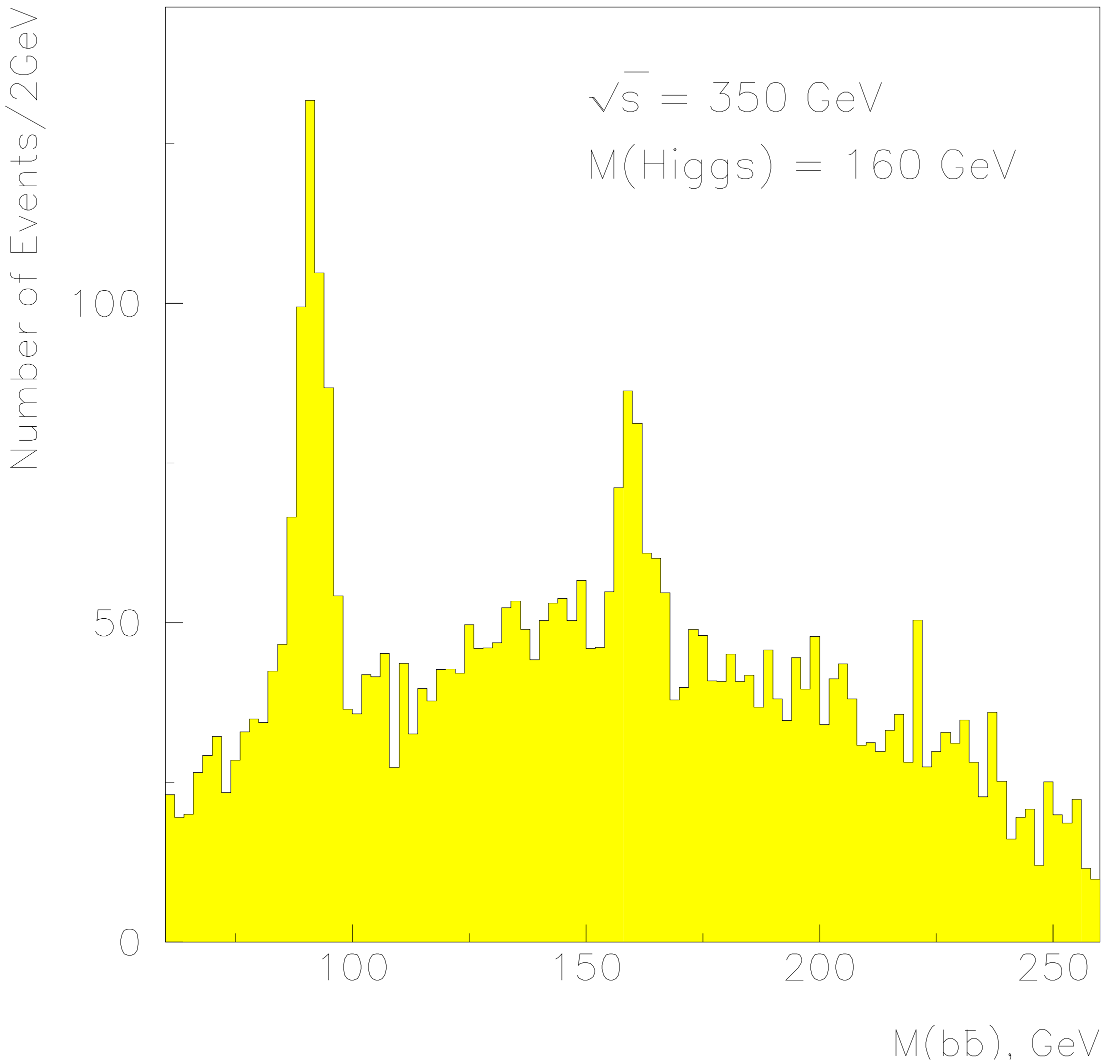

Figure 4: *The $b\,\bar{b}$ mass distribution from the selected events of the 4-jet topology.*

frequently, are selected besides the general event selection criteria mention above by

- identifying an e^+e^- or $\mu^+\mu^-$ pair with $|\cos\theta_l| < 0.95$ and an invariant mass $M_Z \pm 5$ GeV;
- two and only two jets, excluding the lepton pair from the jet finder, are tagged as b-jets, with efficiencies as described for the 4-jet topology.

The simple and outstanding signal signature prevents any contributions from other Higgs decay modes. Background events from reaction (14), assigned to $b\,\bar{b}\ \ l\,\bar{l}$ events, are found to contribute above $M(b\,\bar{b}) = 120$ GeV with a long low-level constant tail. Furthermore, fluctuations from the large WW and $q\,\bar{q}$ event samples are also negligible due to the cuts applied and the convincing non-b-quark rejection efficiency.

The $b\bar{b}$ mass distribution of the events passing all cuts is shown in Fig.5. Prominent signals for the Z and Higgs bosons are evident. The background under the Higgs, however, falls off rather steeply which complicates its realistic estimation. With some conservative assumptions, we deduce 38 H $\rightarrow b\bar{b}$ over 33 background events, within the range $M_H \pm 4$ GeV. Hence, a ~22 % uncertainty for $\sigma(\mathrm{HZ}) \cdot \mathrm{BF}(\mathrm{H} \rightarrow b\bar{b}) \cdot \mathrm{BF}(\mathrm{Z} \rightarrow l\bar{l})$ is obtained from this topology. If this result is combined with that from the 4-jet topology, the statistical error for $\mathrm{BF}(\mathrm{H} \rightarrow b\bar{b})$ results to 11 %, after convolution with the uncertainty of $\sigma(\mathrm{HZ})$.

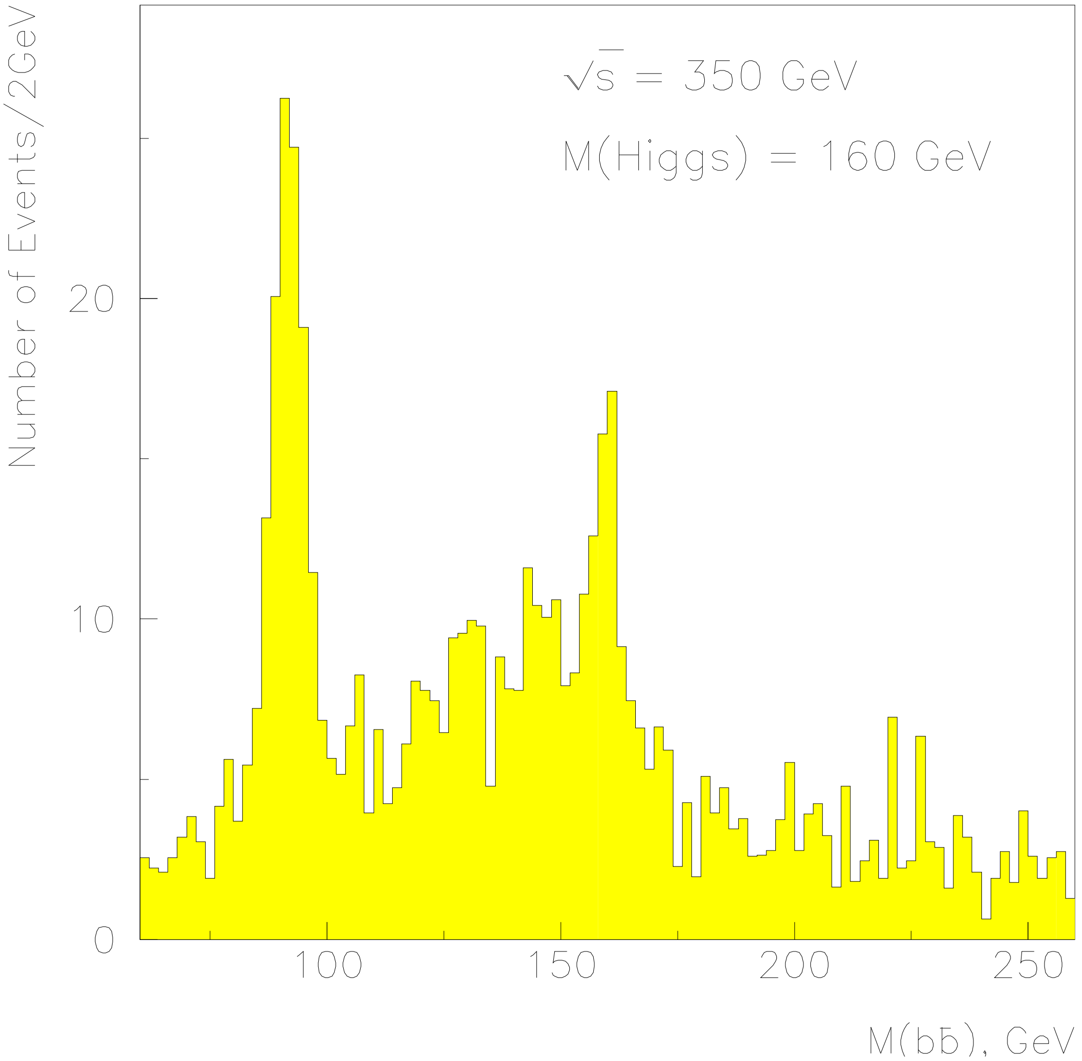

Figure 5: *The $b\bar{b}$ mass distribution from the selected events of the 2-jet dilepton topology.*

Further improvements of the signal to background signature and hence for the H $\rightarrow b\bar{b}$ branching fraction error might be expected from events with Z $\rightarrow \tau\bar{\tau}$ decays. However, additional work is needed for a reliable signal to background determination. It is worth to remark that information on the H $\rightarrow b\bar{b}$ branching fraction is not possible to infer from LHC experiments.

2.4 The Branching Fraction BF (H $\rightarrow \gamma\gamma$)

The Standard Model predicts for BF(H $\rightarrow\gamma\gamma$) with $M_H = 160$ GeV a rate of 0.54 $\cdot 10^{-3}$, so that only very large statistics experiments combined with an excellent electromagnetic calorimeter might have access to this quantity. Deviations of BF(H $\rightarrow\gamma\gamma$) measurements from the SM expectations would be of great importance. In particular, by virtue of the fact that the coupling H $\rightarrow\gamma\gamma$ arises from charged loops, large deviations from the SM value due to new particles (e.g. a fourth generation, supersymmetry) are possible. Measuring BF(H $\rightarrow\gamma\gamma$) at the next linear collider will be, regardless of the size of the deviation from the SM prediction, important to understand the nature of the Higgs and provides hints of new physics that may be beyond the Standard Model.

In principle, similar arguments are also valid for Higgs decays like H $\rightarrow$2 gluons or H $\rightarrow\gamma$Z. However, their measurability is expected to be difficult and requires dedicated studies. Here we consider the easily recognizable H $\rightarrow\gamma\gamma$ decay mode with the hope to observe the 2-photon Higgs decay despite the presence of large background.

For an accumulated luminosity of 500 fb^{-1} we only expect 39 events from the Higgsstrahlung process

$$e^+e^- \rightarrow HZ \rightarrow \gamma\gamma\ q\bar{q}\ , \tag{16}$$

which have to be confronted with orders of magnitude larger irreducible background from the channel

$$e^+e^- \rightarrow \gamma\gamma Z \rightarrow \gamma\gamma\ q\bar{q}\ . \tag{17}$$

The signal and background diagrams contributing to these reactions are presented in Fig.6.

Additional background comes from the reaction

$$e^+e^- \rightarrow \gamma Z \rightarrow \gamma\, q\bar{q}\,(\gamma)\ , \tag{18}$$

where the photon in parentheses comes from initial state radiation and/or quark fragmentation tail and fluctuation effects. Since initial state photon radiation is already covered to a great extent by reaction (17) we have not combined both background rates in the following. Hence, reaction (17) represents some lower background limit, but close to the realistic one after application of the cuts mentioned below.

In order to remove most of this background while retaining significant signal events in the $\gamma\gamma$ mass close to M_H dedicated selection procedures are absolutely

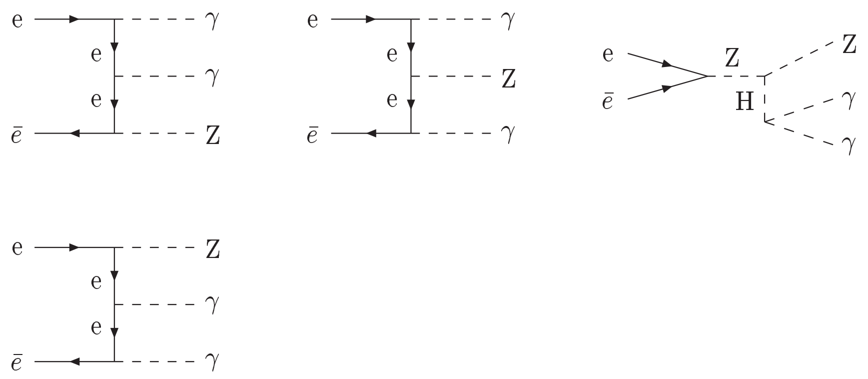

Figure 6: *SM diagrams contributing to reactions (16) and (17).*

mandatory. After exploring a variety of requirements on the photon polar angles, on their individual and summed transverse energies, on the visible event energy and demanding two and only two jets with an invariant mass within $M_Z \pm 10$ GeV, after removal of the two selected photons from the jet finder, we deduce 5 signal and 52 backgrond events from the resulting $\gamma\gamma$ invariant mass distribution (not shown), with the significance of $S/\sqrt{B} = 0.69$ for the optimal window width of 2.5 GeV. A multidimensional analysis based on a likelihood estimator which includes 16 variables had not improved the results obtained [2]. Thus, the surviving Higgs and background event rates do not allow a reasonable BF (H $\rightarrow \gamma\gamma$) measurement, which remains challenging for future investigations. Whether the addition of H $\rightarrow \gamma\gamma$ fusion events, with an about four times less production cross section, would significantly alter our results remains to be studied in detail.

However, to observe a signal significance of 5 in the $\gamma\gamma$ invariant mass having the SM Higgs boson and background production rates, the H$\rightarrow \gamma\gamma$ branching fraction has to be enhanced by a factor of 7.7. In frameworks beyond the SM, where different sectors of the theory are responsible for the physics of flavor and electroweak symmetry breaking, one expects BF(H $\rightarrow \gamma\gamma$) deviations from the SM, see e.g. [20]. In some of these models, the Higgs boson decay to photon pairs is enlarged so that H $\rightarrow \gamma\gamma$ becomes a clean signature, even in the presence of large backgrounds. Under such circumstances, a 26 % precision measurement for BF(H $\rightarrow \gamma\gamma$) is attainable.

From LHC inclusive SM H $\rightarrow \gamma\gamma$ signal and background simulations and for

[2] In particular, variables like production and decay angles, transverse energies, thrust and acoplanarity different for signal and background events were taken into account, and the resulting estimator (probability of being a signal event) was required to be > 0.92.

an integrated luminosity of 100 fb^{-1} for each experiment and high luminosity performance, $S/\sqrt{B} \simeq 3$ and $\Delta[\sigma(\mathrm{pp} \to \mathrm{H} + \mathrm{X})\cdot$ BF(H $\to \gamma\gamma$)] $\simeq$ 40 % [3]. These figures should be, however, considered with some caution since not all systematical errors, e.g. from the luminosity uncertainty or from higher order QCD corrections, were accounted for.

3 The total Higgs width Γ_{tot}(H)

Besides the measurements of the Higgs branching fractions to fermions and bosons - precisely as possible and independent of any model or assumptions - the measurement of its total width is an important concern. As a first step, the procedure for ascertaining this quantity is based on the precisions for BF(H $\to$ ZZ*) of 17 % and the inclusive Higgsstrahlung cross section of 2.8 %. From that the error of the total Higgs width is calculated to 17.2 % which is dominated by the H $\to$ ZZ* uncertainty.

Within the same experiment it is possible to measure the cross section of the weak boson fusion process

$$e^+e^- \to \nu\bar{\nu}H \to \nu\bar{\nu}WW^{(*)} \ , \tag{19}$$

which is proportional to the partial width Γ(H $\to$ WW$^{(*)}$) multiplied by the branching fraction BF(H $\to$ WW$^{(*)}$). This implies that the cross section error for reaction (19) convoluted with the error of the H $\to$WW$^{(*)}$ branching fraction (sect.2.1) provides the precision for Γ(H $\to$ WW$^{(*)}$). Since a realistic detector effects including cross section measurement of process (19) with M_H = 160 GeV at $\sqrt{s}$ = 350 GeV is missing we deduce its possible error close to 2 %, by assuming i) a 20 fb H$\nu\bar{\nu}$ production rate multiplied by 0.9 for BF(H $\to$WW$^{(*)}$), ii) a signal detection efficiency of 30 % in the 4-jet large missing energy topology and iii) a 500 fb^{-1} event sample [4]. Background contributions were assumed to be negligible, as guided by the results shown in Fig.1. The 2 % $\nu\bar{\nu}$ WW$^{(*)}$ cross section error can be translated to a 4.1 % uncertainty for the H $\to$WW$^{(*)}$ partial width, which in turn yields a 6.1 % precision for the total Higgs width, which looks highly promising.

Furthermore, if we rely on the W,Z-universality assumption that the H $\to$ZZ* and H $\to$ WW* partial width are related by SU(2), predicted in the SM as well as in a large class of models like the MSSM, by the ratio z, Γ(H $\to$ ZZ*) =

[3] Both LHC experiments [18] discussed the observability of H $\to \gamma\gamma$ in the mass range $M_H \leq$ 150 GeV. The signal and background event rates expected at M_H = 160 GeV were deduced by linear extrapolation of the backround and assigning the $0.54 \cdot 10^{-3}$ SM H $\to \gamma\gamma$ branching fraction to the Higgs signal.

[4] So far only an error estimate for the cross section of the process $e^+e^- \to \nu\bar{\nu}\,$H(160) $\to \nu\bar{\nu}\, b\bar{b}$ of ~40 % exists [21].

z $\Gamma(\mathrm{H} \to \mathrm{WW}^*)$, we can deduce the total Higgs width from the precise inclusive Higgs production cross section $\sigma(\mathrm{HZ})$ and the well-measured $\mathrm{H} \to \mathrm{WW}^{(*)}$ branching fraction. Adding the errors of both quantities in quadrature, we obtain $\Delta\Gamma_{tot}(\mathrm{H}) = 5.3$ %.

Note that the universality assumption can also be tested at the 15 to 20 % level by combining the $\mathrm{H} \to \mathrm{WW}^{(*)}$ and $\mathrm{H} \to \mathrm{ZZ}^*$ branching fraction errors with $\Delta\Gamma_{tot}(\mathrm{H})$.

At the LHC, the extraction of the total Higgs width requires a measurement of the $\mathrm{qq} \to \mathrm{qqH}$, $\mathrm{H} \to \mathrm{WW}^{(*)}$ cross section, which is expected to be measurable for $\mathrm{M}_H \geq 120$ GeV [22], and for Higgs masses close to the W pair threshold, the precision for $\Gamma_{tot}(\mathrm{H})$ is estimated to about 10 % [23].

It is worth remarking that for M_H of about 120 GeV the suggestion is [24] to measure the $\mathrm{H} \to \gamma\gamma$ partial width by means of a $\gamma\gamma$ collider [5], and if combined with $\mathrm{BF}(\mathrm{H} \to \gamma\gamma)$ and $\mathrm{BF}(\mathrm{H} \to b\bar{b})$ measurements from e^+e^- collisions, $\Gamma_{tot}(\mathrm{H})$ can be calculated. An analogous procedure for a 160 GeV Higgs seems to be prevented as long as an acceptable measurement fails for $\mathrm{BF}(\mathrm{H} \to \gamma\gamma)$, see sect.2.4.

In summary, $\mathrm{BF}(\mathrm{H} \to \mathrm{ZZ}^*)$ and $\sigma(\mathrm{HZ})$ measurements set a rather moderate value for $\Delta\Gamma_{tot}(\mathrm{H})$, while the combination of the accurate values for $\mathrm{BF}(\mathrm{H} \to \mathrm{WW}^{(*)})$ and the WWH coupling from the fusion reaction $e^+e^- \to \nu\bar{\nu}\,\mathrm{H} \to \nu\bar{\nu}\,\mathrm{WW}^{(*)}$ allows for a superior total Higgs width feasibility. The W,Z-universality assumption can be tested at a level of 15 to 20 %, mainly limited by the error for the $\mathrm{H} \to \mathrm{ZZ}^*$ branching fraction.

4 Conclusions

We have studied the prospects for measuring branching fractions for a SM-like Higgs boson with $\mathrm{M}_H = 160$ GeV at the TESLA linear e^+e^- collider, assuming $\sqrt{s} = 350$ GeV and an integrated luminosity of 500 fb^{-1}. In particular, $\mathrm{WW}^{(*)}$, ZZ^*, $b\bar{b}$ and $\gamma\gamma$ decay modes of the Higgs were considered.

For M_H values close to the W pair threshold the background expected to contribute to $\mathrm{H} \to \mathrm{WW}^{(*)}$ is complicated due to a mixture of final states with both W's being on-mass-shell and one of the W's being off-mass-shell. In addition, detector resolution effects determine the relative large Higgs width observed and due to the M_H value chosen very close to two times the W mass, finite W boson width effects must be carefully controlled to enable accurate results.

Since the analysis aims to demonstrate the ability of a linear collider (LC)

[5] The $\mathrm{H} \to \gamma\gamma$ partial width itself stands out as an observable of considerably physical importance. Recent studies [25] indicate that $\gamma\gamma$ collisions allow for a $\sim$5 % error determination of $\Gamma(\mathrm{H} \to \gamma\gamma)$, for $\mathrm{M}_H = 160$ GeV.

with high luminosity to measure the branching fractions discussed only $W \rightarrow q\,\bar{q}$, $Z \rightarrow q\,\bar{q}$ and $Z \rightarrow l\,\bar{l}$ (l=e,μ) decay modes were taken into account avoiding thus rather sophisticated $W \rightarrow l\nu$, $Z \rightarrow \tau\bar{\tau}$ or $Z \rightarrow \nu\bar{\nu}$ selection procedures. Therefore, only the following event topologies were taken into account: 4-jet plus 2 isolated leptons, 2-jet plus 4 isolated leptons, 4-jet and 2-jet plus 2 isolated leptons or photons. Events with 6 jets in the final state were also discarded from the study due to large backgrounds expected and possible significant ambiguities in jet-particle association.

Since we are interested to make a signal-to-background analysis as meaningful as possible we consistently evaluate background rates as well as contaminations from signal events with topologies different to the one under study. In order to achieve this goal, candidate events were required to satisfy sets of requirements on event, lepton and jet properties.

For the $H \rightarrow WW^{(*)}$ branching fraction a very precise value of 4.4 % has been obtained, typically a factor two better than what is expected from LHC measurements. The Higgs boson branching fraction to ZZ^* can be measured at the LC with an accuracy of ~17 %, which is close to LHC estimates. The ability to measure BF($H \rightarrow b\,\bar{b}$) in 4-jet and 2-jet plus two-lepton events has been demonstrated, and an error of 11 % seems possible to achieve. This result benefits to a great extent from the outstanding vertex detector performance planned e.g. for the TESLA linear collider [14]. The large amount of 4-jet background events can be reasonably controlled enabling a clear Higgs signal to be observed in the $b\,\bar{b}$ mass spectrum. Information on the $H \rightarrow b\,\bar{b}$ branching fraction is, however, not possible to infer from LHC experiments.

The resulting errors of our branching fraction measurements are, after convolution with an uncertainty of 2.8 % for the total Higgsstrahlung cross section, summarized in Table 1.

Branching fraction	Expected error
BF ($H \rightarrow WW^*$)	$\pm$ 4.4 %
BF ($H \rightarrow ZZ^*$)	$\pm$ 17 %
BF ($H \rightarrow b\,\bar{b}$)	$\pm$ 11 %

Table 1: *Branching fraction errors expected for the SM Higgs boson with M_H = 160 GeV, at $\sqrt{s}$ = 350 GeV and an integrated luminosity of 500 fb^{-1}.*

The measurement of BF($H \rightarrow \gamma\gamma$) remains a great challence since besides its very small SM value itself the background expected to contribute is orders of magnitude larger which renders a meaningful signal over background selection. We conclude that for $M_H = 160$ GeV the SM Higgs BF(H $\rightarrow \gamma\gamma$) will likely not be measurable. For theoretical models which can accomodate larger H $\rightarrow \gamma\gamma$ branching fractions [20], reasonable measurements seem however feasible having the SM Higgs boson and background production rates.

Procedures for ascertaining the total Higgs width and its accuracy have been discussed, with the results of i) $\Delta\Gamma_{tot}(\mathrm{H}) = 17.2$ %, obtained from the error of BF(H $\rightarrow$ ZZ*) and the total Higgsstrahlung cross section error, ii) $\Delta\Gamma_{tot}(\mathrm{H}) = 6.1$ %, inferred from precise measurements of the cross section for reaction (19) as sketched in the paper and convoluted with the error for BF(H $\rightarrow$WW$^{(*)}$) and iii) $\Delta\Gamma_{tot}(\mathrm{H}) = 5.3$ %, assuming W,Z-universality. These precisions seem to be slightly better than what is feasible from LHC experiments.

Once $\Gamma_{tot}(\mathrm{H})$ has been determined, the ZZ and $b\,\bar{b}$ Higgs boson partial widths (or couplings) can be extracted with precisions dominated by the H $\rightarrow$ ZZ* and H $\rightarrow b\,\bar{b}$ branching fraction errors, whereas that for the H $\rightarrow$WW$^{(*)}$ partial width gets about equal contributions from the BF(H $\rightarrow$ WW$^{(*)}$) and the total Higgs width errors.

Finally, we would like to emphasize that the selection criteria proposed are aimed to be simple and by far not optimized. It is also unclear if machine induced backgrounds and two-photon overlapped events have a significant impact on the results obtained. For the future, we can also expect some improvements if the precise detector behaviour is known, further topologies not yet involved in the analysis are taken into account and, if the Higgs mass is known, $\sqrt{s}$ should be optimized for running in the HZ measurement mode. While much additional work is needed, our study clearly shows that the LC has outstanding potentials to provide detailed and accurate information on the Higgs boson also in a mass region not yet explored and with more complicated background contributions.

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