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A Direct Determination of $\tan\beta$: $e^+e^- \to b\bar{b}A$ at a Future e^+e^- Linear Collider

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The experimental sensitivity of the reaction $e^+e^- \to b\bar{b}A$ has been studied in the general Two-Higgs Doublet Model (2HDM) with a full-statistics background simulation for $\sqrt{s} = 500$ GeV and $\mathcal{L} = 500$ fb^{-1}. The simulation is based on a fast and realistic simulation of a TESLA detector. For the first time this reaction has been analyzed for a future linear collider and we show that a signal could be observed. A significant signal over background is achieved by the application of an Iterative Discriminant Analysis (IDA). For a signal production cross section of only 2 fb, which is expected for a Higgs boson mass of 100 GeV and $\tan\beta = 50$, we achieve 100 signal over 100 background events, and obtain for a $\tan\beta$ measurement: $\Delta\tan\beta/\tan\beta = 0.07$. This measurement requires a high-luminosity future collider as proposed in the TESLA project.

1 Introduction

A future linear collider has a great potential for discovering new particles and measuring their properties. While many parameters of theories beyond the Standard Model can be measured with high precision, the determination of the important $\tan\beta$ parameter, the ratio of the vacuum expectation values of two Higgs boson doublets, is difficult, in particular when $\tan\beta$ is large. This study uses the fact that the Yukawa coupling $b\bar{b}A$ is proportional to $\tan\beta$. Therefore, the value of $\tan\beta$ can be directly derived from the measurement of the $e^+e^- \to b\bar{b}A \to b\bar{b}b\bar{b}$ production cross section. The challenge of this study is the low expected production rate and the large irreducible background for a four-jet final state. The signal production process and the expected event rate [1] are shown in Fig. 1 for the 2HDM, where the decay branching ratio into a $b\bar{b}$ pair is 91%. Searches for this four-jet channel were performed at LEP with data taken at the Z resonance [2,3,4].

2 Event Simulation

The simulated production process is $e^+e^- \to b\bar{b}A \to b\bar{b}b\bar{b}$, leading to four b-quark jets in the final state. The signal [5] and background [6] event generators include

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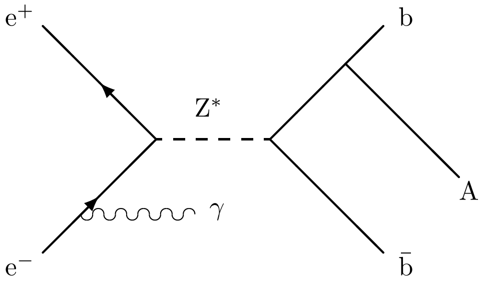
initial state radiation and beamstrahlung. We simulated a 100 GeV pseudoscalar Higgs boson. The generated events are passed through the fast detector simulation SGV [7]. This program follows the helical paths of charged particles through the detector in order to estimate their track-parameter covariance matrices. The track-parameters are then smeared according to these matrices. Calorimeters are simulated by parametrization of the detector response function. A probability-based b-tagging method is implemented using the simulated track-parameters (measured mainly with the micro-vertex detector). Particle identification and track-finding efficiencies are also simulated. The detector properties closely follow the TESLA detector CDR [8]. The simulation of the b-tagging performance is very important for this analysis. Therefore, the efficiency versus purity distribution is shown in Fig. 2 for the hadronic event sample $e^+e^- \rightarrow q\bar{q}$. The efficiency is defined as the ratio of simulated $b\bar{b}$ events after the selection and all simulated $b\bar{b}$ events, and the purity is defined as the ratio of simulated $b\bar{b}$ events after the selection and all selected events.

Figure 1: Signal production process and expected event rate.



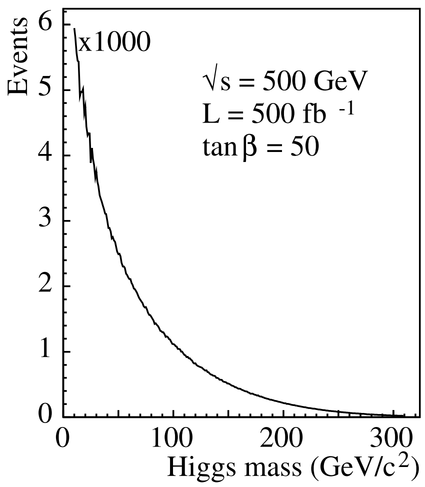
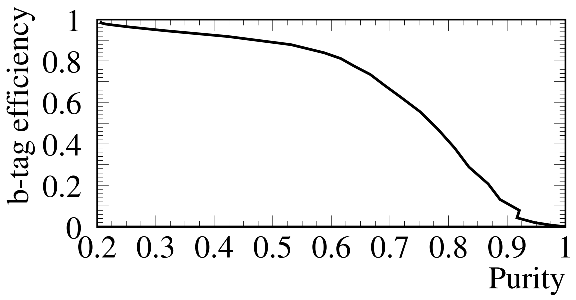


Figure 2: b-tagging performance.



3 Event Preselection

First, an event preselection is applied using the hadronic character and expected b-quark characteristics of the simulated signal. The following preselection cuts are applied: $N_{3\mathrm{b}} > 2$, $N_{\mathrm{cluster}} > 17$, $E_{\mathrm{vis}}/\sqrt{s} > 0.6$, $E_{\mathrm{neutral}}/\sqrt{s} < 0.5$, $E_\gamma < 30$ GeV, thrust < 0.92, where $N_{3\mathrm{b}}$ is the b-tagging variable of the third most b-like jet[b], N_{cluster} the number of energy deposits, E_{vis} the total visible energy, E_{neutral} the total energy deposits of neutral particles, E_γ the maximum energy of a detected photon and the event thrust. The number of simulated events for the signal and for each background channel, as well as the remaining events after the preselection are given in Table 1. The number of SM background events corresponds to 500 fb^{-1} and for the reaction $\mathrm{e^+e^-} \rightarrow \mathrm{hA} \rightarrow \mathrm{b\bar{b}b\bar{b}}$ about twice the maximum expected rate for $m_\mathrm{h} = m_\mathrm{A} = 100$ GeV has been simulated.

Table 1: Number of simulated signal and background events before and after the preselection.

Channel	bbA	qq	WW	eWν	tt	ZZ	eeZ	hA
(in 1000)	50	6250	3500	2500	350	300	3000	50
After presel.	73%	20991	7481	0	89983	10278	145	12665

4 Iterative Discriminant Analysis

In order to separate the signal from the background, the following selection variables are defined: highest and third significant jet b-tagging, thrust value, second Fox-Wolfram moment, d_{join} value where the event changes from five to four jets, minimum and maximum jet energy, isolation angle of the most energetic jet, minimum angle and invariant mass between any jet pair, minimum jet and event charge multiplicity, charged and neutral event energy. Figure 3 shows the simulated b-tagging variable for the third significant jet and the second Fox-Wolfram moment after the preselection for 141544 remaining background events. The thrust value and the IDA output variable are shown in Fig. 4. Half of these events and half of the signal events are used to train the IDA [10]. In a first step, a cut on the IDA output variable is applied such that the efficiency is reduced by 30% relative to the preselection efficiency. The remaining signal and 6745 background events are again passed through the IDA. Figure 5 shows the second IDA output variable and the resulting number of background events as a function of the signal efficiency.

[b] Jets are formed with the LUCLUS algorithm [9].

Figure 3: b-tagging variable and Fox-Wolfram moment after the preselection.

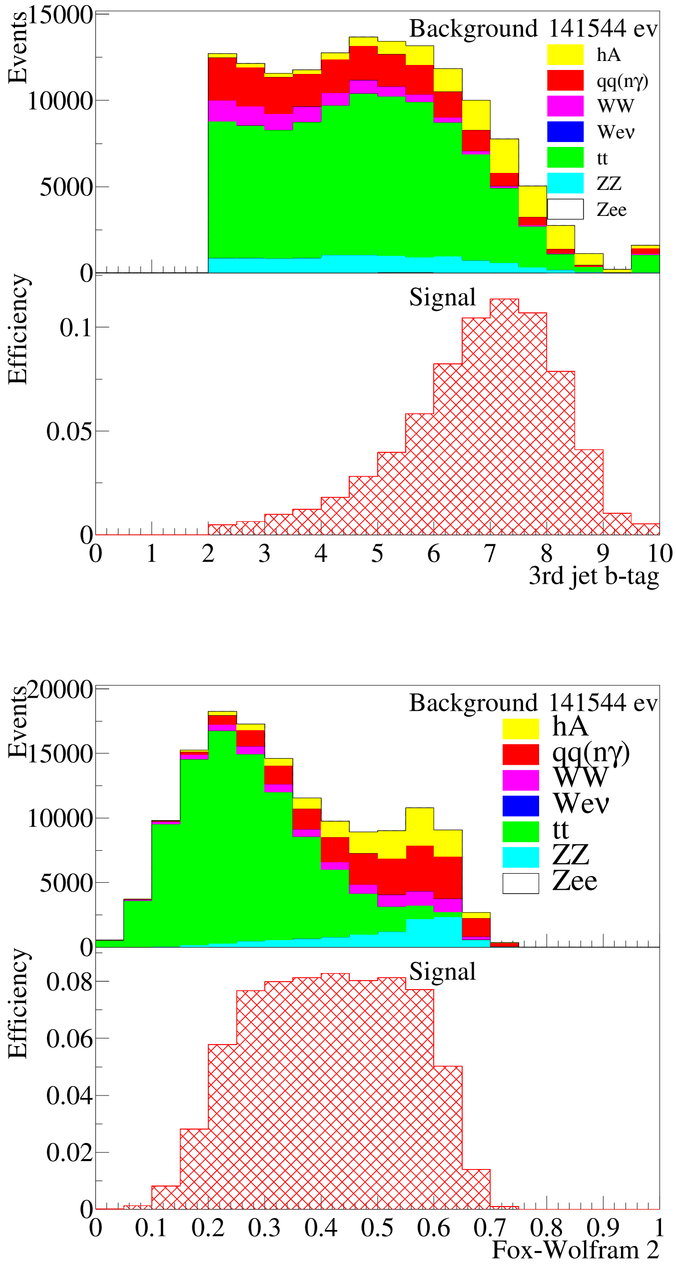
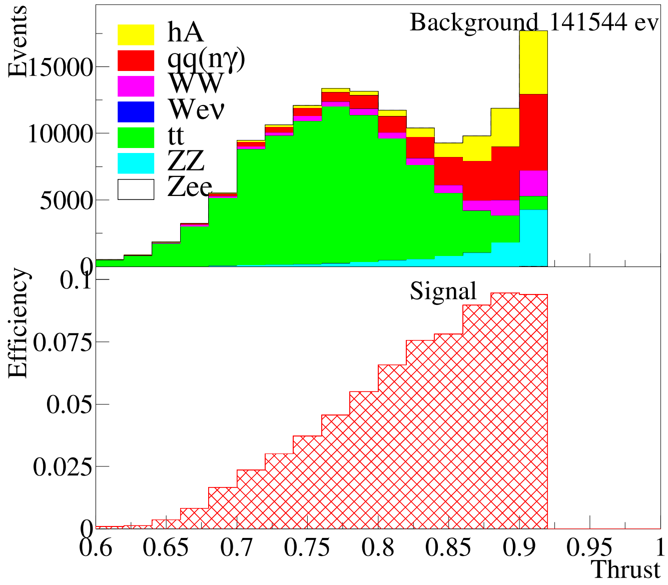


Figure 4: Thrust value and first step IDA output.



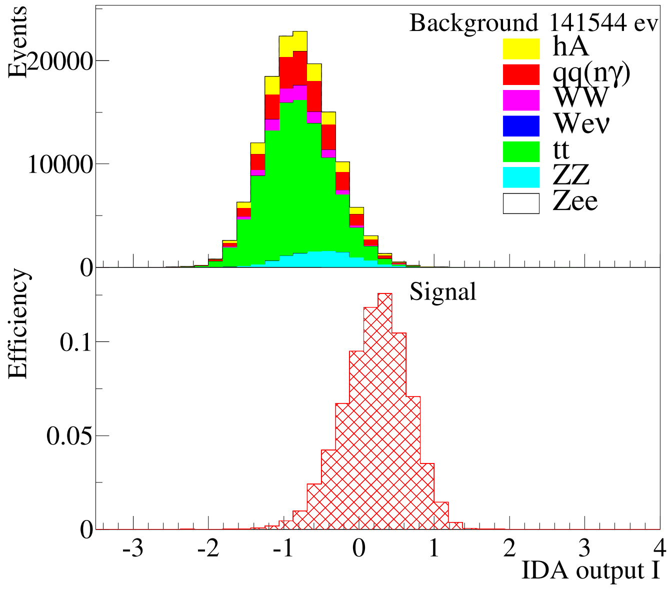
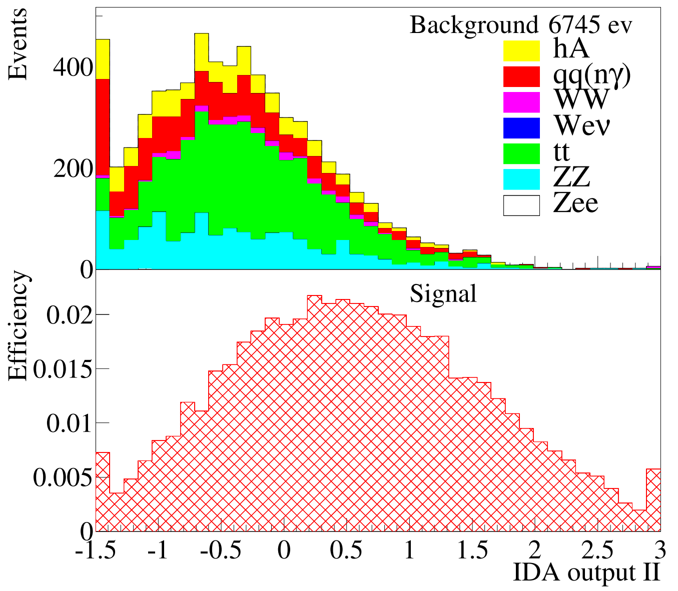
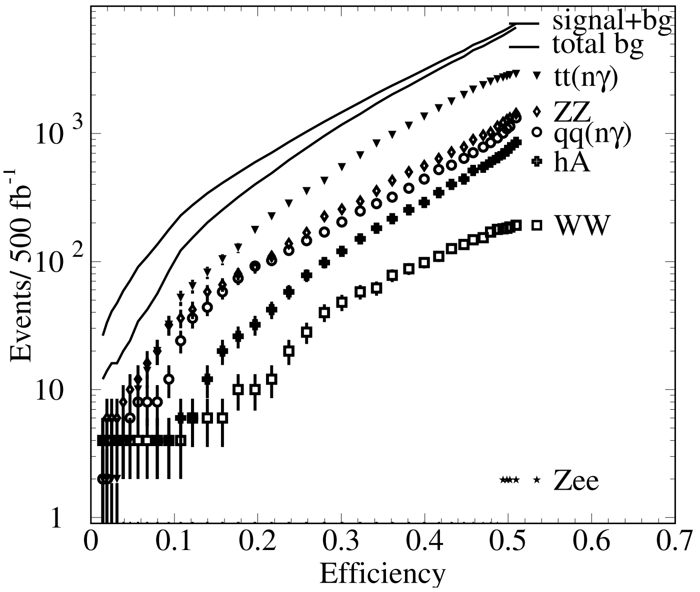


Figure 5: Final IDA output and background vs. signal efficiency.





5 Results

We have determined the expected background rate for a given signal efficiency and evaluated that the sensitivity for a 100 GeV pseudoscalar Higgs boson in the process $e^+e^- \rightarrow b\bar{b}A$ suffices to determine the value of $\tan\beta$. The sensitivity $N_{\text{signal}}/\sqrt{N_{\text{background}}}$ is almost independent of the working point signal efficiency in the range 5% to 50%. For a working point of 10% efficiency, the total simulated background of about 16 million events is reduced to 100 background events. The resulting error on $\tan\beta = 50$ is 7%:

$$\Delta \tan^2\beta/\tan^2\beta = \Delta N_{\text{signal}}/N_{\text{signal}} = \sqrt{N_{\text{signal}} + N_{\text{background}}}/N_{\text{signal}} = 0.14.$$

Although the number of hA background is very small compared to the other background reactions, interference between the signal bbA $\rightarrow b\bar{b}b\bar{b}$ and the background hA $\rightarrow b\bar{b}b\bar{b}$ reaction could be important. At the working point four hA events are selected, thus the expected rate is 2 ± 1 events. We calculate the cross sections $\sigma_{\text{bbA}}(e^+e^- \rightarrow \text{bbA} \rightarrow b\bar{b}b\bar{b})$, $\sigma_{\text{hA}}(e^+e^- \rightarrow \text{hA} \rightarrow b\bar{b}b\bar{b})$, and $\sigma_{\text{bbA+hA}}(e^+e^- \rightarrow \text{bbA}, \text{hA} \rightarrow b\bar{b}b\bar{b})$ with CompHEP [11] and define the interference as $\sigma_{\text{interf}} = \sigma_{\text{bbA+hA}} - \sigma_{\text{bbA}} - \sigma_{\text{hA}}$. For the default value $m_{\text{b}} = 4.62$ GeV, we obtain $\sigma_{\text{bbA}} = 1.83 \pm 0.01$ fb, $\sigma_{\text{hA}} = 36.85 \pm 0.10$ fb, $\sigma_{\text{bbA+hA}} = 39.23 \pm 0.12$ fb, $\sigma_{\text{interf}} = 2.38 \pm 0.16$ fb. We observe a constructive interference of the same size as the signal, thus more signal events are expected than simulated and the statistical error estimate is conservative. The systematic error is largely effected by the interference term, since we cannot determine how many of the additional events were signal or background events. If the events from the interference were background-like, the resulting systematic error would be small, since the hA background is only a small part of the total background. The maximum systematic error would be obtained if all interference events were signal-like. This systematic error could be controlled by simultaneously simulating signal and hA background events for various $\tan\beta$ values and chosing the distribution which fits best the data.

For smaller values of $\tan\beta$ the sensitivity reduces quickly. A 5σ signal detection is still possible for $\tan\beta = 35$.

In addition to the hA Higgs boson background two other Higgs boson processes could lead to a $b\bar{b}b\bar{b}$ topology. First, the process $e^+e^- \rightarrow$ hZ can give a $b\bar{b}b\bar{b}$ final state. The maximal hZ production cross section is similar to the hA production cross section, but the hZ $\rightarrow b\bar{b}b\bar{b}$ branching is below 10% compared to about 80% for hA $\rightarrow b\bar{b}b\bar{b}$. The hA process contributed only 2% of the total background, therefore, the contribution to the background from the hZ process is negligible. The second Higgs boson process leading to a $b\bar{b}b\bar{b}$ topology is $e^+e^- \rightarrow b\bar{b}h$. This process leads to the same signature as the signal $e^+e^- \rightarrow b\bar{b}A$ process, except a small difference in the angular distribution due to the different production matrix elements. Thus, the selection efficiency is almost identical. The production rate of the $b\bar{b}A$ process is proportional to $\tan^2\beta$ while the $b\bar{b}h$ production rate is proportional to $\sin^2\alpha/\cos^2\beta$. For the large $\tan\beta$ value discussed, $\tan\beta \approx 1/\cos\beta$, therefore, the expected rate depends mostly on $\sin\alpha$ and the h mass. In the particular case $m_{\text{h}} \approx m_{\text{A}}$, the $b\bar{b}h$ process would enhance the signal and the relation between $\tan\beta$ and $\sin\alpha$ could be measured. From independent measurements of the hZ and hA production rates the value of $\beta - \alpha$ could be determined and thus α and β be measured separately.

In conclusion, an IDA analysis based on experience at LEP2 was applied and gave sufficient sensitivity to detect the signal process. A high-luminosity linear collider is essential and unique for this channel and allows the value of $\tan\beta$ to be measured with precision. Theoretical uncertainties related to the production cross section remain to be studied in the future.

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