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The direct method to measure the Higgs branching ratios at the future e^+e^- linear collider

Jean-Claude Brient
Laboratoire Leprince-Ringuet - Ecole Polytechnique

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Abstract
A direct method to measure the Higgs branching ratios at the future linear collider is presented. The results obtained are mainly uncorrelated with the indirect method, using cross section measurements, which previously was taken as reference for the expected precision on the linear collider. When compare to previous estimation, the combination of the two methods yields an important improvement on the expected precision for such a machine.

I. INTRODUCTION

The study of the Higgs coupling at a linear collider is one of the most important feature of the physics programme on such a machine. Therefore the expected precisions on the different couplings are key points for the physics case of this machine. A large effort has been performed to give an estimation on these precisions using the indirect method [1], based on a set of cross section measurements.

In this note, a direct method is presented, dramatically different from the indirect one, as it is shown below. For this study, it is assumed a luminosity of 500 fb^{-1} and a standard model Higgs boson with a mass of 120 GeV.

A. The indirect method

The indirect method is described in the Tesla TDR [1]. To summarize, it uses cross section measurements, starting with the inclusive one $\sigma_{\mathrm{inc.}} = \sigma(e^+e^- \to ZH) \times BR(Z \to \ell^+\ell^-)$

The measurement is based on a sample of events selected with the di-leptons $\ell^+\ell^-$ mass, centered at the Z peak, and the di-leptons kinematic recoil mass, which exibits a peak at the Higgs mass. Consequently, no informations from the Higgs decays is used in the selection, the results are therefore independent from it. The expected relative precision is about $\pm 2.5\%$ for a luminosity of 500 fb^{-1}.

Then, cross section is measured for each individual final state, corresponding to the different Higgs branching ratio $\sigma\ (\mathrm{X}) = \sigma(\mathrm{e}^+\mathrm{e}^- \to \mathrm{ZH}) \times \mathrm{BR}(\mathrm{H} \to \mathrm{X}) \times \mathrm{BR}(\mathrm{Z} \to \mathrm{Y})$
where Y stands for $\ell^+\ell^-$, hadrons, $\nu\bar{\nu}$. Since the Z branching ratios to $\ell^+\ell^-$, hadrons, $\nu\bar{\nu}$ have been measured with a high precision at LEP, the branching fraction BR($\mathrm{H} \to \mathrm{X}$) can be extracted from the ratio $\sigma\ (\mathrm{X})/\sigma_{\mathrm{inc.}}$

[2]. This method suffers from the irreductible ±2.5% relative error on the inclusive cross section measurement $\sigma_{\mathrm{inc.}}$. This indirect method has been used for the study of the TESLA TDR [2]

B. The direct method

The direct method consists in building a Higgs sample from the process $\mathrm{e^+e^-} \rightarrow \mathrm{ZH}$ with Z boson decaying to lepton pairs. The selected sample is independent of the Higgs decays, as already mentionned. The branching ratios are then measured directly among this sample, using the event kinematics and topology to separate the different Higgs boson decays. A similar method has been used by the ALEPH collaboration to measure the tau lepton branching ratio [3], [4].
For the study, the signal and background samples have been generated with PYTHIA 6.115 [5], but the signal has been normalised to the cross section given by the program HPROD [6], and the Higgs boson total width and branching ratios are taken from the program HDECAY [7].

II. SELECTION

To build the signal sample, the events are selected like in the inclusive cross section measurement [8]. To summarize, it is based on a signal/background likelihood estimator built from kinematical variables like the di-lepton mass, recoil mass,polar angle and acollinearity. Figure 1 compares the estimator distribution for signal and background. Events with signal likelihood estimator smaller than 0.7 are removed.

The recoil mass distribution of the remaining sample is shown on Fig. 2. A clear Higgs(120) signal is visible. To improve the signal/background in the sample, events with di-leptons recoil mass outside of [118,160] GeV/c^2 are rejected.

The final sample consists in 4092 selected events ($\mathrm{N}_{sel.}$) with 1880 from background processes (non-Higgs processes). Now, the branching ratios are measured directly in this final sample. The different Higgs boson decay channels are separated using a very simple estimator based on the number of jet(s), the jet energies, the multiplicity of eflow-object, the event missing mass (after removing the di-letpon), the number of displaced vertices from heavy meson decays [9].

This estimator is probably not optimal, but it is good enough for the demonstration. To illustrate this point, Fig. 3 shows the distribution of the estimator separating Higgs boson decays in $b\bar{b}$ decays from the other Higgs boson decays. In the case of a cut at 0.5 on this estimator, 95% of Higgs into $b\bar{b}$ are kept by the cut, with only 1.1% of residual Higgs background (cross contamination).

In addition, to further reduce the contribution from non-Higgs background, a cut on the mass and the recoil mass of the Higgs decays products is applied. Following the same example of the Higgs into $b\bar{b}$ decay, a cut in the plane $[\mathrm{M_{b\bar{b}}}, \mathrm{M^{recoil}_{b\bar{b}}}]$ reduces very significantly the non-Higgs background contribution as illustrated by the Fig. 4. For this channel, the non-Higgs contamination is reduced by a factor 5 with an efficiency of 94% for the signal.

III. METHOD

The branching ratios of the channel I is calculated using the following formula:

$$\mathrm{BR(H \rightarrow I)} = \frac{\mathrm{N_I(1 - F_I^{non-H} - F^H_{non-I})}}{\mathrm{N_{sel.}(1 - F^{non-H})}} \frac{1.}{\varepsilon^{\mathrm{H \rightarrow I}}} \tag{1}$$

where
- N_{sel} is the number of events in the di-lepton selected sample.
- F^{non-H} is the contamination from non-Higgs background in the di-lepton sample. Since $N_{sel.}$ is a fixed number, the error on F^{non-H} is of binomial type.
- N_I is the number of events after selection of the channel I, in the di-lepton sample. The statistical error on N_I is of binomial type.
- F_I^{non-H} is the contamination in the channel I selected sample, coming from the non-Higgs processes. Here again, the error is of binomial type because N_I is fixed.
- F^H_{non-I} is the Higgs cross contamination from non-I Higgs decays obtained with ZH Monte Carlo simulation. The major branching ratios are supposed to be known at ±20%.

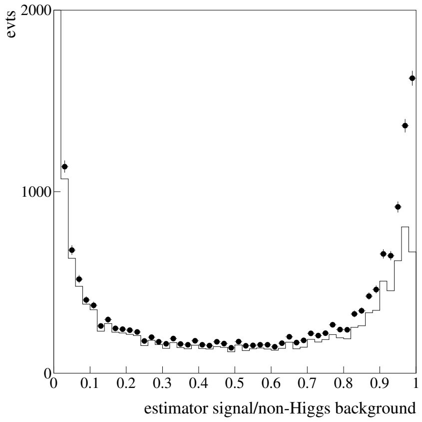

FIG. 1: Likelihood estimator used to discrimate $e^+e^- \to ZH \to \ell^+\ell^- H$ from background processes. Black dots are the sum of signal and background, the histogram is the non-Higgs processes contribution.

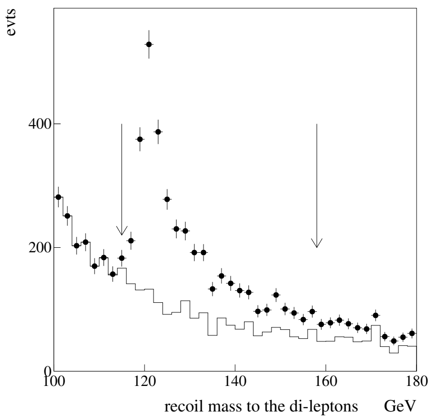

FIG. 2: $\ell^+\ell^-$ recoil mass for the selected sample. The arrows indicate the cut values used to select the final ZH di-lepton sample. Dots is the sum of signal and non-Higgs background, the histogram is the non-Higgs contribution

- $\varepsilon^{H\to I}$ is the efficiency to select the channel I, in the ZH di-lepton sample.

The table below shows the different possible sources of error on the branching ratio, illustrated with the values for the Higgs into $b\bar{b}$, where a total δBR/BR=±1.9% is expected.

source	statistical	δF^{non-H}	$\delta F^{non-H}_{b\bar{b}}$	$\delta F^{H}_{non-b\bar{b}}$	TOTAL
δBR/BR %	1.08	1.42	0.55	0.2	1.88

IV. RESULTS

The selection efficiencies, cross contamination from other Higgs boson decays and contamination of the non-Higgs background processes are listed in table I, while the precision on the branching ratios for all these

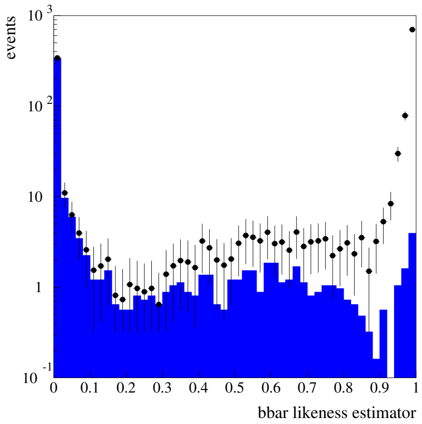

FIG. 3: $b\bar{b}$ likeness estimator distribution. Dots is the sum of signal (Higgs into $b\bar{b}$) and the other Higgs decays, histogram is the non-$b\bar{b}$ Higgs decays

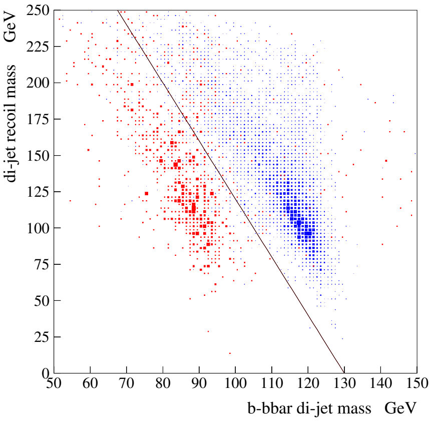

FIG. 4: $b\bar{b}$ dijet mass versus their recoil mass for the selected sample. The two populations, Higgs and non-Higgs, are clear visibles on both side of the line. The final cut for $b\bar{b}$ selection corresponds to this line.

modes are presented in the table II.

As expected the two photons mode suffers from a large non-Higgs background contribution (mainly double ISR) with respect to a small signal level due to a tiny branching ratio of $\sim 2\ 10^{-3}$. Therefore a tight angular cut has been applied leading to a selection efficiency for this mode of only 46%. Even, the signal/background ratio remains very low as indicated on Fig 5, where the $\gamma\gamma$ invariant mass is displayed.

V. CONCLUSION

Testing the physics potential of the futur electron-positron linear collider below the TeV energy center-of-mass, it is shown that the direct method to measure the Higgs branching ratios, inspired from ALEPH measurement of the tau branching ratios [3, 4], gives similar precision when compared to the indirect method based on cross section measurement. The two methods are independant with a small statistical correlation and therefore the combination leads to an important gain on the expected precision at the futur linear collider.

decays	efficiency (%)	$F^{H}_{otherchannels}$	$F^{non-H}_{channel}$
bb	88.	0.01	0.039
$\tau\tau$	98	0.12	0.267
$c\bar{c}$	75	0.59	0.005
gluon-gluon	89	0.06	0.006
$\gamma\gamma$	46	0.00	0.30
WW*	91	0.07	0.005
Invisible	100	0.	0.94

TABLE I: Efficiency of the channel selection in the di-letpon sample, cross contamination from other decay channel, and fraction of non-Higgs background in the final sample for the main decays channels. The SM Higgs branching ratio are assumed. A branching ratio of 1.65% is assumed for the invisible decay of the Higgs boson which corresponds to the minimum value to reach a signal evidence at five standard deviation

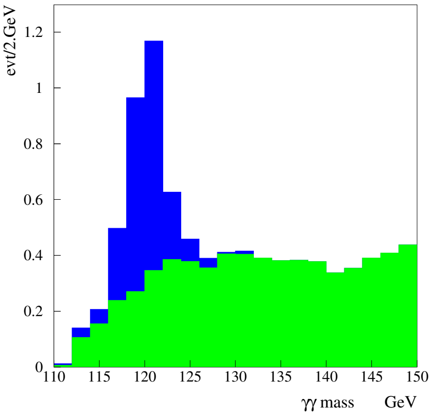

FIG. 5: $\gamma\gamma$ invariant mass after selecting the Higgs decays into 2 photons. The only residual background comes from Z(γ) final state with inital state radiation(s).

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decays	BR (%)	δB/B (%)	δB/B (%)	δB/B (%)
		direct method	indirect method	combined
		(this note)	from ref. [2]	
bb	68.	1.9	2.4	1.5
$\tau\tau$	6.85	7.1	5.0	4.1
$c\bar{c}$	3.1	8.1	8.3	5.8
gluon-gluon	7.0	4.8	5.5	3.6
$\gamma\gamma$	0.22	35.	26	21.
WW*	13.3	3.6	4.2	2.7
Invisible	1.65	20.	50	19.

TABLE II: The expected precisions on the Higgs branching ratios using the direct, the indirect method and their combination. An integrated luminosity of 500 fb^{-1} collected at $\sqrt{s}$=360GeV has been assumed. The error of 4.2% on BR(H$\rightarrow$ WW*) with the indirect method comes from reference [10]