Future $e^+e^-$ Colliders Sensitivity to $Hb\bar{b}$ Coupling and CP Violation

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We perform a complete simulation of the process $e^+e^- \to b\bar{b}\nu\bar{\nu}$, where $\nu$ can be an electron, muon or tau neutrino, in the context of a general Higgs coupling to $b$ quarks. We parametrize the $Hb\bar{b}$ coupling as $\frac{m_b}{\nu}(a + i\gamma_5 b)$. Taking into account interference effects between pure Higgs and Standard Model contributions, we find that sensitivities of the order of 2% and 20% can be obtained at a future $e^+e^-$ collider for deviations of the $a$ and $b$ parameters respectively from their Standard Model values. Combining our analysis with an independent measurement of $\Gamma_{H\to b\bar{b}}$ can provide evidence about the CP nature of the Higgs sector.

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I. INTRODUCTION

The origin of fermion masses and mixings is one of most important issues in particle physics. In the Standard Model (SM), the Higgs field alone is responsible for the electroweak symmetry breaking and mass generation. The SM, however, is incomplete and a thorough study of the coupling of the remnant Higgs boson (or in fact the lightest (pseudo)scalar boson) to fermions can provide hints on the actual mechanism of mass generation.

In a recent paper, we have investigated the possibility of detecting deviations from the SM in the Higgs couplings to $\tau$-leptons [1] at future $e^+e^-$ colliders. In this letter, we expand our analysis to the case of the Higgs couplings to $b$-quarks, which has a better potential in principle due to the larger Yukawa coupling.

For definiteness, we concentrate on the determination of the (pseudo)scalar-$b\bar{b}$ coupling at a Linear Collider with a center-of-mass energy of $\sqrt{s} = 500$ GeV and accumulated luminosity of 1 ab$^{-1}$, based on the TESLA design [2]. We will assume that this particle has already been discovered at the Large Hadron Collider but a detailed study of its couplings is missing.

We take into account all relevant contributions to the process $e^+e^- \to b\bar{b}\nu\bar{\nu}$, where $\nu$ can be an electron, muon or tau neutrino. In particular, weak gauge boson fusion is the dominant contribution to the subset of diagrams containing the Higgs boson for $M_H < 180$ GeV at $\sqrt{s} \geq 500$ GeV.

In extensions of the SM with extra scalars and pseudoscalars, the lightest spin-0 particle can be an admixture of states without a definite parity. Hence, we parametrize the general $Hb\bar{b}$ coupling as:

$$\frac{m_b}{\nu}(a + i\gamma_5 b),$$

where $\nu = 246$ GeV, $m_b$ is the $b$-quark mass and $a = 1$, $b = 0$ in the SM.

We will present results considering $a$ and $b$ as independent parameters and also for the cases of fixed $a = 1$, free $b$ and fixed $b = 0$, free $a$. We will see that there is a region of insensitivity around circles in the $a-b$ plane since we can’t at this level of analysis disentangle the effects of $a$ and $b$.

The cross section for the process $e^+e^- \to b\bar{b}\nu\bar{\nu}$ is sensitive to terms proportional to $a$, which comes from the interference with non-Higgs contributions, and $a^2$ and $b^2$ from pure Higgs contributions. Therefore, we can search for deviations from the SM prediction which could arise, for instance, in supersymmetric models.

The total SM cross section for the process $e^+e^- \to b\bar{b}\nu\bar{\nu}$ is of the order of 180 fb for $M_H = 120$ GeV and at $\sqrt{s} = 500$ GeV, being dominated by the $\nu_e$ final state, because of the many additional diagrams allowed.

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in this case. In particular, only in this channel the weak gauge boson fusion diagram is allowed and it provides an important contribution. For comparison, the process $e^+e^- \rightarrow H\nu_e\bar{\nu}_e$ is of the order of 100 fb at $\sqrt{s} = 500$ GeV.

In Fig. 1 we show the dependence of the total cross section, summed over the three neutrino species, on the parameters $\Delta a \equiv a - 1$ and $b$. The dependence in $b$ is symmetric since only terms proportional to $b^2$ contribute to the cross section. On the other hand, the dependence on $\Delta a$ is asymmetric due to interference with Standard Model processes, which leads to the presence of linear terms in $\Delta a$. We should point out that the $\Delta a$ dependence is more prominent in the previously studied $\tau^+\tau^-$ channel. Our goal is to see how sensitive the experiments performed at the next generation of $e^+e^-$ colliders will be in the determination of these parameters.

II. ANALYSIS AND RESULTS

We performed our Monte Carlo simulation by generating observables represented as series in the $a$ and $b$ couplings multiplied by kinematic factors:

$$\frac{d\sigma}{d\mathcal{O}} = A_0 + a \cdot A_1 + a^2 \cdot A_2 + ab \cdot A_3 + b \cdot A_4 + b^2 \cdot A_5 \ldots$$

where $\mathcal{O}$ is any observable and the $A_i$ terms are purely kinematical structures which do not contain any $a$ and $b$ dependence and results from the amplitude squaring and phase space integration. These $A_i$ structures are the subject of the Monte Carlo simulation and the $a$ and $b$ couplings can be varied without the necessity to re-simulating the data for each $(a,b)$ point. In our particular case, $A_3 = A_4 = 0$.

The event sample reproducing the expected statistics at TESLA was generated using our Monte Carlo package while the detector response was simulated with the code SIMDET version 3.01. We assume an efficiency for $b$-jet pair reconstruction of $\varepsilon_{\text{bb}} = 56 \%$, which is based on the $b$-tag algorithm, as assumed in ref. 3. In our simulations we used $M_H = 120$ GeV.

In Figure 2 we show, for comparison purposes, the differential distribution in $\cos \theta_{bb}$, where $\theta_{bb}$ is the scattering angle between the $b$-jet and initial beam directions, for the total SM contribution and for the Higgs contribution only (including interference with SM). To illustrate the importance of the $\nu_\mu$ final state, we plot both the contribution of only the $\nu_\mu$ final state (which is basically the same as $\nu_\tau$ final state) and the total contribution from the three neutrinos. We can see that in the first case the Higgs contribution is small but in the total contribution it is comparable to the full SM result.

In order to demonstrate the effect of different values of the parameters $a$ and $b$, we show in Figure 3 the $\cos \theta_{bb}$ distribution arising from the Higgs contribution for the SM ($a = 1, b = 0$) compared to the case with $a = b = 0.5$, with only $\nu_\mu$ neutrinos and with the three neutrinos. We see that the shapes are very similar, as expected, but the levels can be noticeable different.

As for the possible contribution from background processes, like $e^+e^- \rightarrow e^+e^- ZZ \rightarrow e^+e^- b\bar{b}\nu\bar{\nu}$ (with e-pair lost), $e^+e^- \rightarrow \nu\bar{\nu}W^+W^- \rightarrow \nu\bar{\nu}b\bar{b}\nu\bar{\nu}$, $e^+e^- \rightarrow ZZZ \rightarrow b\bar{b}h\bar{h}\nu\bar{\nu}$, etc., the cross sections of these processes are either small, or they can be significantly suppressed down to levels of 0.2 fb.

Another important aspect is the assumption about the detector performance and possible sources of the systematic uncertainties. We include the anticipated systematic errors of 0.5% in the luminosity measurement, 1% in the acceptance determination, 1% in the branching ratios, and 1% in the background subtraction, and assume the Gaussian nature of the systematics. To place bounds on the $Hb$ couplings, we use a standard $\chi^2$-criterion to analyze the events. After various kinematical distributions were examined, we found that the most strict bounds are achieved from $\cos \theta_{bb}$ distribution by dividing the distribution event samples into 10 bins. The experimental
error $\Delta \sigma_i^{exp}$ for the $i^{th}$ bin is given by:

$$\Delta \sigma_i^{exp} = \sigma_i^{SM} \sqrt{\delta_{syst}^2 + \delta_{stat}^2}$$

(3)

where

$$\delta_{stat} = \frac{1}{\sqrt{\sigma_i^{SM} \int L dt}}$$

(4)

and $\delta_{syst}$ is the sum in quadrature of the systematic uncertainties mentioned above.

In Fig. 4 we present our final results for a TESLA-like environment with a center-of-mass energy of 500 GeV and for $M_H = 120$ GeV.

We investigated three possible scenarios for the luminosities: 100 fb$^{-1}$, 1 ab$^{-1}$ and 10 ab$^{-1}$. The allowed region for independent $\Delta a$ and $b$ parameters at 95% confidence level is the area between the circles. The horizontal bands are the allowed region for the $\Delta a$ parameter keeping $b = 1$. The vertical bands are the allowed region for the $\Delta a$ parameter keeping $b = 0$.

The bounds that can be obtained at 95% confidence level are:

$$-0.041 \leq \Delta a \leq 0.039 \quad \text{for} \quad L = 100 \text{fb}^{-1};$$

(5)

$$-0.026 \leq \Delta a \leq 0.027 \quad \text{for} \quad L = 1 \text{ab}^{-1};$$

$$-0.024 \leq \Delta a \leq 0.024 \quad \text{for} \quad L = 10 \text{ab}^{-1},$$

for the case of $b = 0$ and free $\Delta a$ and

$$-0.28 \leq b \leq 0.28 \quad \text{for} \quad L = 100 \text{fb}^{-1};$$

(6)

$$-0.23 \leq b \leq 0.23 \quad \text{for} \quad L = 1 \text{ab}^{-1};$$

$$-0.22 \leq b \leq 0.22 \quad \text{for} \quad L = 10 \text{ab}^{-1},$$

for the case of $\Delta a = 0$ and free $b$.

These results are up to an order of magnitude better than the limits obtained in a similar manner for $\tau$-leptons, mainly because of the larger Yukawa coupling in case of $b$-quarks and higher sensitivity of the process.

These results can be roughly scaled for moderate variations in the Higgs boson mass around 120 GeV by multiplying the bounds by a factor ($M_H/120 \text{GeV}$)$^2$.

III. CONCLUSIONS

We have performed a complete analysis of the sensitivity to new $Hb\bar{b}$ couplings from the process $e^+e^- \to b\bar{b}\nu\bar{\nu}$ at the next generation of linear colliders. These new couplings are predicted by many extensions of the Standard Model. We showed that forthcoming experiments will be able to probe deviations of $Hb\bar{b}$ coupling. The weak gauge boson fusion process is instrumental for achieving such a precision. For a TESLA-like environment, we are able to constrain the couplings at the level of a few percent for the $a$ parameter (for fixed $b$) and tens of percent for the $b$ parameter (for fixed $a$). These results are comparable to the study performed in [3], where a global fit analysis for $L = 500 \text{ fb}^{-1}$ and $\sqrt{s} = 500 \text{ GeV}$ has resulted in a relative accuracy of 2.2% in the $g_{Hb\bar{b}}$ Yukawa coupling.

We would like to comment some aspects of the future measurements. Let us assume that the Higgs data anticipated from the new collider experiments will reveal a deviation from the SM predictions. In addition, suppose that one has an independent measurement of the partial width $\Gamma_{H \to b\bar{b}}$ (for instance, from on-mass-shell Higgs production in a muonic collider). It easy to see that, in our parametrization, $\Gamma_{H \to b\bar{b}} \sim (a^2 + b^2)$, while the observables we studied have the following parameter dependence

$$\frac{d\sigma}{d\bar{O}} = A_0 + a \cdot A_1 + a^2 \cdot A_2 + b^2 \cdot A_3.$$

Combining our results and those from $\Gamma_{H \to b\bar{b}}$ one can separate $a$ and $b$ contributions and obtain an explicit indication of CP violation in the Higgs sector.

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[1] A. Chalov, A. Likhoded and R. Rosenfeld, [hep-ph/0205144](http://arxiv.org/abs/hep-ph/0205144), submitted to J. Phys. G.

[2] *Physics at an $e^+e^-$ linear collider*, Tesla Design Report, part 3, [hep-ph/0106319](http://arxiv.org/abs/hep-ph/0106319).

[3] K. Desch and N. Meyer, *LC Notes*, LC-PHSM-2001-025, [http://www.desy.de/~lcnotes/2001/025/ww-fus.ps.gz](http://www.desy.de/~lcnotes/2001/025/ww-fus.ps.gz).

[4] SIMDET - A Parametric Monte Carlo for a TESLA Detector, M. Pohl and H. J. Schreiber, report DESY 99-030.
Hi Rogerio, thank you for the info concerning the forthcoming conference. I will apply.

Now about our paper. Please find below some results for $\sqrt{s} = 500$ GeV and the Higgs mass of 120 GeV.

The cross-sections of the muonic- o tau- neutrino channel is $1.008 \times 10^{-2}$ pb, while total is 0.175 pb.

In figures attached as PS-files one finds:

**Fig. 1.** The $e^+e^- \rightarrow b\bar{b}\nu\bar{\nu}$ cross-section dependence on $\Delta a$ and $b$ parameters.

**Fig. 2a.** Differential distribution of the $e^+e^- \rightarrow b\bar{b}\nu\mu(\tau)\bar{\nu}_\mu(\tau)$ process over $M_{bb}$. Solid points is the total SM contribution, while crossed points is the contribution from Higgs containing diagrams only.

**Fig. 2b.** The same as Fig. 2a, but for case of all three types of neutrinos.

**Fig. 3a.** Differential distribution of the $e^+e^- \rightarrow b\bar{b}\nu\mu(\tau)\bar{\nu}_\mu(\tau)$ process over $M_{bb}$. Solid points is the contribution from Higgs containing diagrams of SM, while crossed points is the case of $a = 0.5$ and $b = 0.5$.

**Fig. 3b.** The same as Fig. 3a, but for case of all three types of neutrinos.

**Fig. 4.** Allowed parameters region (area inside the corresponding contour lines) for 95% C.L. for the case of:

1. independent $a$ and $b$ parameters (curled contours);
2. $b = 0$ (vertical bands);
3. $a = 0$ (horizontal bands).

Long-dashed, solid, and short-dashed lines represent the cases of 100 fb$^{-1}$, 1 ab$^{-1}$, and 10 ab$^{-1}$, correspondingly.

The efficiency for b-jets reconstruction is 0.75. All other systematics is the same as in the tau-tau case. The question is: should we describe the procedure of the background reduction etc.? We can simply refer to paper by K. Deusch and N. Meyer, LC-PHSM-2001-025. In this paper all the details are perfectly described and the case coincide with ours exactly. What do you think?

Andre