Constraints on a scalar-pseudoscalar Higgs mixing at future e^+e^- colliders: An update

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We perform an update of our previous analysis of the constraints on possible deviations of $Hb\bar{b}$ coupling parametrized as $(m_b/v)(a+i\gamma_5 b)$, arising from a scalar-pseudoscalar mixing, where the process $e^+e^- \to b\bar{b}\nu\bar{\nu}$ was used. In this paper we include a complete simulation of the process $e^+e^- \to b\bar{b}e^+e^-$ and combine these results to obtain tighter bounds on the deviations of the parameters a and b from their standard model values that could be measured at the Next Linear Collider.

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I. INTRODUCTION

The origin of fermion masses and mixings is an outstanding open problem in particle physics. In the standard model (SM), the Higgs mechanism is responsible for the electroweak symmetry breaking and mass generation via *ad hoc* Yukawa couplings. There are reasons to believe that the SM is not the final model and a complete study of the coupling of the lightest boson, which we will call the Higgs boson, to fermions can provide hints on new physics beyond the SM.

In a recent Letter [1], we performed a realistic simulation of the process $e^+e^- \to b\bar{b}\nu\bar{\nu}$, where ν can be an electron, muon or tau neutrino, in the environment of a future linear collider with a center-of-mass energy of $\sqrt{s}=500$ GeV with an accumulated luminosity of 1 ab^{-1}, based on the TESLA design [2]. In particular, we noticed that weak gauge boson fusion is the dominant contribution to the subset of diagrams containing the Higgs boson for $M_H<180$ GeV at $\sqrt{s} \geqslant 500$ GeV and hence this process is sensitive to the Higgs boson couplings to b quarks. We have used a similar technique to investigated the possibility of detecting deviations from the SM in the Higgs couplings to τ leptons at future e^+e^- colliders [3], which can be improved by using τ spin correlations [4].

In this Brief Report, we update the result [1] by combining it with the results of a detailed analysis of the process $e^+e^- \to b\bar{b}e^+e^-$. This process has a very clean final state, with no missing energy and easy reconstruction, which can compensate for its smaller rate. It certainly must be included in a global analysis of the $Hb\bar{b}$ vertex.

In order to perform our analysis, we will assume that the Higgs boson has already been discovered at the Large Hadron Collider (LHC) and concentrate on the determination of its coupling to b quarks. 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

$$\frac{m_b}{v}(a+i\gamma_5 b), \tag{1}$$

where $v=246$ GeV, m_b is the b-quark mass and $a=1$, $b=0$ in the SM. In CP-violating extensions of the SM, deviations of these parameters may be generated at tree level [5].

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. There is a region of insensivity around circles in the a-b plane since we cannot at this level of analysis disentangle the effects of a and b.

In the SM the $e^+e^- \to b\bar{b}e^+e^-$ process is determined by 50 Feynman diagrams. Only 2 of these [Higgs radiative production, $Z^* \to H(\to b\bar{b})Z$, and vector boson fusion, $Z^*Z^* \to H(\to b\bar{b})$] can be considered as signal, where deviations from SM Higgs couplings to b quarks show up. The remaining diagrams are not changed by new physics in the Higgs sector.

The total SM cross section for the process $e^+e^- \to b\bar{b}e^+e^-$ is approximately 43 fb for $M_H=120$ GeV at $\sqrt{s}=500$ GeV, with cuts in the scattering angle between initial and final electrons, $|\cos\theta_{ee}| \leqslant 0.9962$, and in the final electron-positron invariant mass, $M_{e^+e^-}>2$ GeV. The angular cut avoids the region of $\pm 5°$ around the pipeline, used by the beam pipe itself and by the small angle monitor (SAM) for luminosity measurements. The invariant mass cut ensures that the electrons and positrons will be detected in the lead glass calorimeter [2]. Backgrounds from $e^+e^- \to e^+e^-ZZ \to e^+e^-b\bar{b}\nu\bar{\nu}$, $e^+e^- \to ZZZ \to e^+e^-b\bar{b}\nu\bar{\nu}$, etc., can be reduced to the 0.1 fb level by appropriate cuts [6].

In our analysis we will assume SM couplings of the Higgs bosons to the electroweak gauge bosons. A full analysis taking into account non-SM HWW and HZZ couplings would introduce many more parameters and is beyond the scope of this paper.

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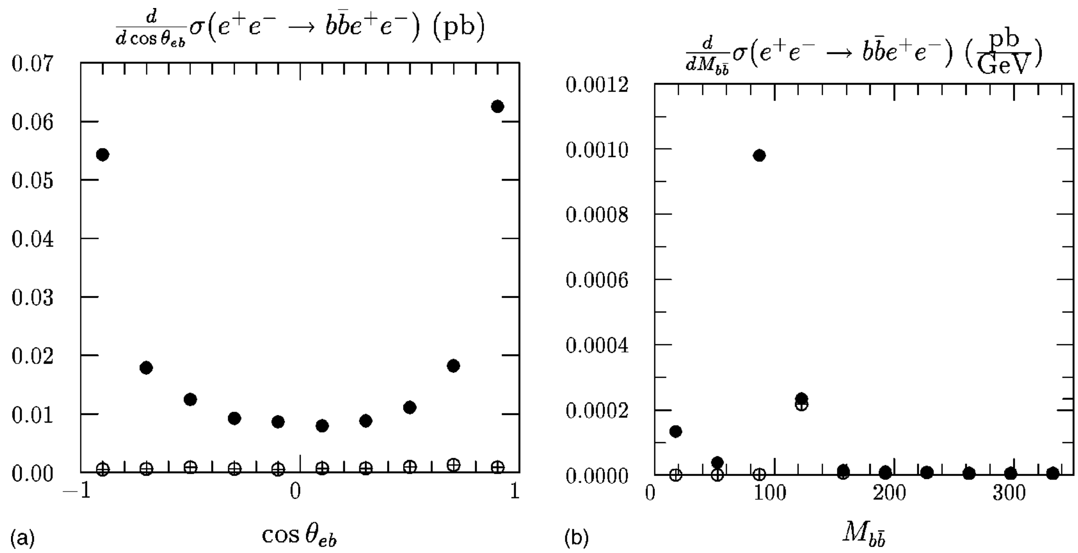

FIG. 1. The differential cross sections for $\cos\theta_{eb}$ and $M_{b\bar{b}}$ for the process $e^+e^- \to b\bar{b}e^+e^-$. Solid circles are the full SM result while crossed circles are the contribution from Higgs boson only (including interference effects).

II. ANALYSIS AND RESULTS

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

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

where $\mathcal{O}$ is any observable and the A_i terms are purely kinematical structures that do not contain any a and b dependence and results from the amplitude squaring and phase space integration. In this way we only simulate the process once for each observable. In our case, terms linear in b parameter vanish and hence $A_3 = A_4 = 0$. We have studies the following observables: transverse b-quark momentum p_{Tb}, $b\bar{b}$ invariant mass $M_{b\bar{b}}$, $\cos\theta_{eb}$, where θ_{eb} is the scattering angle between the b jet and initial beam directions, and the T correlation, defined by $T = [1/(\sqrt{s})^3]\vec{p}_{el}\cdot(\vec{p}_b\times\vec{p}_{\bar{b}})$.

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 [7]. We assume an efficiency for b-jet pair reconstruction of $\varepsilon_{bb} = 56\%$, which is based on the b-tag algorithm, as assumed in Ref. [6]. In our simulations we used $M_H = 120$ GeV.

In Fig. 1 we show, for comparison purposes, the differential distributions in the invariant $b\bar{b}$ mass and $\cos\theta_{eb}$, for the total SM contribution, and for the Higgs contribution only (including interference with SM). Notice the Z-boson peak and the smaller Higgs peak in the $M_{b\bar{b}}$ distribution, and how the Higgs contribution dominates around its peak.

In order to demonstrate the effect of different values of the parameters a and b, we show in Fig. 2 the $\cos\theta_{eb}$ distribution arising from the Higgs contribution for the SM ($a = 1$, $b = 0$) compared to the case with $a = 1$, $b = 0.5$. We see that the shapes are very similar, as expected, but the levels can be noticeably different.

Another important aspect is the assumption about the detector performance and possible sources of the systematic uncertaintes. 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 [2]. To place bounds on the $Hb\bar{b}$ couplings,

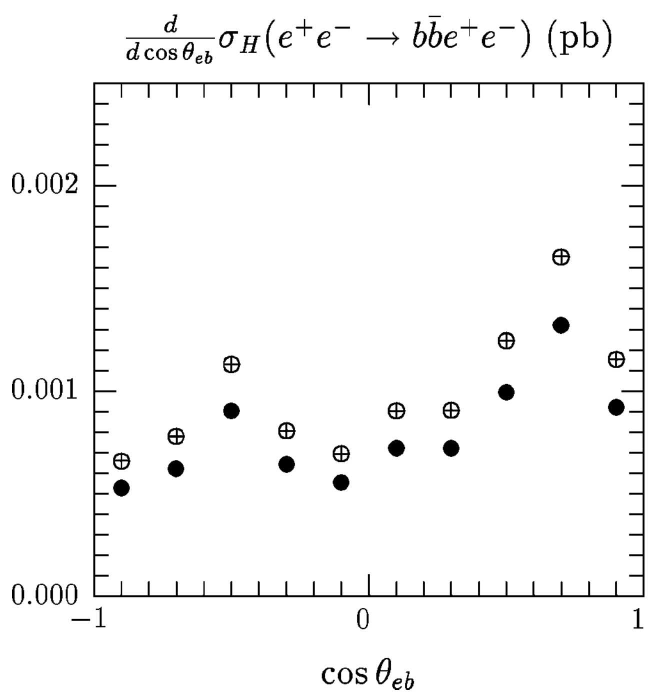

FIG. 2. Contribution of Higgs diagrams to the differential $\cos\theta_{eb}$ distribution in the $e^+e^- \to b\bar{b}e^+e^-$ process for the standard model ($a = 1, b = 0$, black dots) and $a = 1.0, b = 0.5$ (crossed dots).

we use a standard χ^2 criterion to analyze the events. After various kinematical distributions were examined, we found that the strictest bounds are achieved from $\cos\theta_{eb}$ distribution by dividing the distribution event samples into 10 bins. The experimental error $\Delta\sigma_i^{expt}$ for the ith bin is given by

$$\Delta\sigma_i^{expt} = \sigma_i^{SM}\sqrt{\delta_{syst}^2 + \delta_{stat}^2}, \tag{3}$$

where

$$\delta_{stat} = \frac{1}{\sqrt{\sigma_i^{SM}\varepsilon_{bb}\int \mathcal{L}dt}} \tag{4}$$

and δ_{syst}^2 is the sum in quadrature of the systematic uncertainties mentioned above.

Below we present our final results for a TESLA-like environment [2] 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 bounds that can be obtained at 95% confidence level from $e^+e^- \to b\bar{b}e^+e^-$ process on the $\Delta a = a - 1$ and b parameters are

$$\begin{aligned} -0.09 &\leq \Delta a \leq 0.08 \quad \text{for } \mathcal{L}=100 \ \text{fb}^{-1}, \\ -0.056 &\leq \Delta a \leq 0.055 \quad \text{for } \mathcal{L}=1 \ \text{ab}^{-1}, \\ -0.05 &\leq \Delta a \leq 0.05 \quad \text{for } \mathcal{L}=10 \ \text{ab}^{-1}, \end{aligned} \tag{5}$$

for the case of $b=0$ and free Δa and

$$\begin{aligned} -0.42 &\leq b \leq 0.42 \quad \text{for } \mathcal{L}=100 \ \text{fb}^{-1}, \\ -0.32 &\leq b \leq 0.32 \quad \text{for } \mathcal{L}=1 \ \text{ab}^{-1}, \\ -0.3 &\leq b \leq 0.3 \quad \text{for } \mathcal{L}=10 \ \text{ab}^{-1}, \end{aligned} \tag{6}$$

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

We will combine these limits with our previous bounds from the $e^+e^- \to b\bar{b}\bar{\nu}\nu$ process according to the following procedure. Given two bounds on the same quantity X, say $|X| \leq c_1$ and $|X| \leq c_2$, the combined bound will be

$$|X| \leq c_3 \quad \text{where } c_3 = \sqrt{(c_1\omega_1)^2 + (c_2\omega_2)^2}, \tag{7}$$

and the statistical weights ω_1 and ω_2 are given by

$$\omega_1 = \frac{N_1}{N_1+N_2} \quad \text{and} \quad \omega_2 = \frac{N_2}{N_1+N_2}, \tag{8}$$

where N_1 and N_2 are the number of events for each process.

With these prescription we obtain the improved bounds:

$$\begin{aligned} -0.037 &\leq \Delta a \leq 0.035 \quad \text{for } \mathcal{L}=100 \ \text{fb}^{-1}, \\ -0.024 &\leq \Delta a \leq 0.024 \quad \text{for } \mathcal{L}=1 \ \text{ab}^{-1}, \\ -0.022 &\leq \Delta a \leq 0.022 \quad \text{for } \mathcal{L}=10 \ \text{ab}^{-1}, \end{aligned} \tag{9}$$

for the case of $b=0$ and free Δa and

$$\begin{aligned} -0.24 &\leq b \leq 0.24 \quad \text{for } \mathcal{L}=100 \ \text{fb}^{-1}, \\ -0.20 &\leq b \leq 0.20 \quad \text{for } \mathcal{L}=1 \ \text{ab}^{-1}, \\ -0.19 &\leq b \leq 0.19 \quad \text{for } \mathcal{L}=10 \ \text{ab}^{-1}, \end{aligned} \tag{10}$$

for the case of $\Delta a = 0$ and free b. 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 an update in our previous constraints on deviations of the $Hb\bar{b}$ coupling from its SM value by including a complete analysis of the sensitivity due to the process $e^+e^- \to b\bar{b}e^+e^-$ at the next generation of linear colliders. These deviations are predicted by many extensions of the standard model. We improved our previous bounds by roughly 10%.

We showed that future e^+e^- linear collider 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 Ref. [2], where a global fit analysis for $\mathcal{L}=500$ fb^{-1} and $\sqrt{s}=500$ GeV has resulted in a relative accuracy of 2.2% in the g_{Hbb} Yukawa coupling. For comparison, the top quark Yukawa coupling can be determined with a statistical accuracy of 16% at the LHC for $M_H = 130$ GeV [8].

In our analysis we cannot disentangle the contributions from deviations in the a and b parameters. However, notice that the partial width $\Gamma_{H\to b\bar{b}}$ is proportional to (a^2+b^2). Our distributions have a different dependence:

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

Therefore, if an independent measurement of $\Gamma_{H\to b\bar{b}}$ is obtained (for instance, from on-mass-shell Higgs production in Higgs-strahlung or in a muonic collider), one would be able to separate the a and b contributions and obtain an explicit indication of CP violation in the Higgs sector.

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