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Probing CP properties of the Higgs Boson via $e^+e^- \to t\bar{t}\phi$

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One of the main endeavors at future high-energy colliders is the search for the Higgs boson(s) and, once found, the probe of the fundamental properties. In particular, the charge conjugation and parity (CP) quantum numbers have to be determined. We show that these are unambiguously accessible at future e^+e^- colliders through the measurement of the total cross section and the top polarization in associated Higgs production with top quark pairs.

1 Introduction

After the discovery of the Higgs boson - or several Higgs bosons in extensions beyond the Standard Model (SM) - we have to probe its properties in order to establish the Higgs mechanism [2] as responsible for the creation of particle masses without violating gauge symmetry. In the SM the Higgs mechanism is implemented by adding one isodoublet complex scalar field which leads after electroweak symmetry breaking to one single spin zero CP-even Higgs particle [2, 3]. In extensions beyond the SM the Higgs sector can be non-minimal, as *e.g.* in the Minimal Supersymmetric Standard Model (MSSM), which contains five physical Higgs states, *i.e.* two CP-even h and H, one CP-odd A and two charged $H^\pm$ Higgs bosons [3, 4]. To establish the Higgs mechanism experimentally we have to determine the Higgs spin, its behavior under charge and parity transformations, the couplings to gauge bosons and fermions, and finally the trilinear and quartic Higgs self-interactions must be measured to reconstruct the Higgs potential itself. To fulfill this program the Large Hadron Collider (LHC) analyses [5] must be complemented by the high-precision measurements at a future International Linear e^+e^- Collider (ILC) [6, 7, 8].

We address in this contribution the determination of the Higgs CP quantum numbers. To do so in an unambiguous way is somewhat problematic [9]. Observables sensitive to the Higgs spin-parity such as angular correlations in Higgs decays into $V = W, Z$ pairs [10, 11] or in Higgs production with or through these states [10, 12] only project out the CP-even component of the HVV coupling, even in the presence of CP violation. In addition, the purely pseudoscalar AVV coupling is zero at tree-level and is generated only through tiny loop corrections. In the Higgs couplings to fermions, however, the CP-even and CP-odd components can have the same magnitude. Here, the heaviest fermion discovered so far, the top quark, plays a special role. The Htt coupling is largest being proportional to the top quark mass due to the Higgs mechanism. At a future ILC the Higgs boson can therefore be produced with sufficient rate in associated production with a $t\bar{t}$ pair, $e^+e^- \to t\bar{t}H$ [13, 14]. We propose a simple and straightforward way to determine the CP nature of a SM-like Higgs boson in this process, in an unambigious way, where we exploit that the cross section as well as the top quark polarization behave in a radically different way for CP-even and CP-odd Higgs production.

2 The total production cross section

The diagrams which contribute in the SM to the process $e^+e^- \to t\bar{t}H$ are shown in Fig.1. The bulk of the cross section is generated when the Higgs is radiated off the heavy top quarks [14], whereas the Higgs produced in association with a Z boson which then splits into a $t\bar{t}$ pair provides only a very small contribution, amounting to a few percent for $\sqrt{s} \leq 1$ TeV Detailed simulations have shown the cross section to be measurable with an accuracy of order 10% [15]. We will discuss the case of a SM-like mixed CP Higgs state Φ and use the general form of the $t\bar{t}\Phi$ coupling

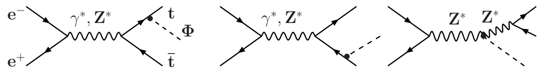

Figure 1: Feynman diagrams for the associated production of Higgs bosons with a top quark pair.

$$g_{\Phi tt} = -i\frac{e}{s_W}\frac{m_t}{2M_W}(a + ib\gamma_5) \; , \tag{1}$$

where the coefficients a and b are assumed to be real and $s_W \equiv \sin\theta_W = \sqrt{1 - c_W^2}$. In the SM we have $a = 1, b = 0$ and for a purely pseudoscalar Higgs boson $a = 0, b \neq 0$. In the pseudoscalar case we take $b = 1$, consistent with a convenient normalization $a^2 + b^2 = 1$ chosen for the general case of a Higgs boson with an indefinite CP quantum number. A non–zero value for the product ab will hence signal CP violation in the Higgs sector. For the $ZZ\Phi$ coupling, we will use the form,

$$g^{\mu\nu}_{ZZ\Phi} = -ic(eM_Z/s_W c_W)g^{\mu\nu} \; . \tag{2}$$

And for the numerical analysis we chose $c = a$ [16] as $c = 1(0)$ in the case of a CP-even (odd) Higgs boson. We will thus have only one free parameter b. However, this simple parametrization for a SM–like Higgs need not be true in *e.g.* a general 2HDM, where a, b and c are three independent parameters. We have calculated the cross section for the production of a mixed CP Higgs state including the polarization dependence of the final state top quarks. The lengthy result has been checked to agree with Ref. [14] for the unpolarized total cross section. In Fig. 2 left panel we show the production cross section for a purely scalar (H with $b = 0$) and a pseudoscalar (A with $b = 1$) Higgs as a function of the c.m. energy and for two mass values $M_\Phi = 120$ and 150 GeV. As can be inferred from the figure, the threshold rise of the cross section in the scalar and the pseudoscalar case is very different. Furthermore, for the same strength of the Φtt couplings, there is an order of magnitude difference between the H and A cross sections at moderate energies. Only at very high energies, $\sqrt{s} \gg 1$ TeV, the chiral limit is reached and the two cross sections become equal, up to the small contribution due to the diagram including the $ZZ\Phi$ coupling. These two features hence provide an extremely powerful tool to discriminate the CP properties of the spin zero particle produced together with the top quark pair. The difference in the threshold behavior of the A and H case is strong enough so that the cross section measurement at only two different c.m. energies allows a clear determination of the CP properties of the Φ state. *e.g.* for $M_\Phi = 120$ GeV, the ratio of the cross sections at $\sqrt{s} = 800$ and 500 GeV is ~ 63 and ~ 7.5 for the scalar and pseudoscalar case, respectively. Finally, taking the ratio makes the conclusion robust with respect to the effect of the top Yukawa coupling, the higher order radiative corrections [17] or systematic errors in the measurement.

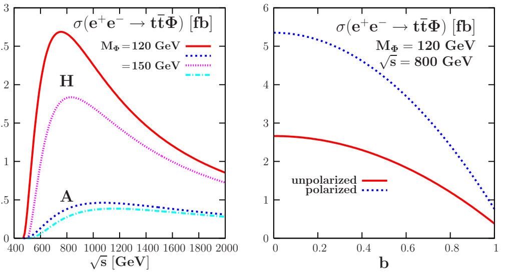

Figure 2: The production cross sections $\sigma(e^+e^- \to t\bar{t}\Phi)$ for a scalar and a pseudoscalar Higgs boson as a function of $\sqrt{s}$ for two masses $M_\Phi = 120$ and 150 GeV (left) and for unpolarized and polarized $e^\pm$ beams as a function of the parameter b at $\sqrt{s} = 800$ GeV with $M_\Phi = 120$ GeV (right).

We also studied the b dependence of the total $t\bar{t}\Phi$ production process at a given energy and for fixed M_Φ. Being a CP even quantity it only depends on b^2. Fig. 2 (right) shows the result for unpolarized and polarized $e^\pm$ beams. For the latter, we used the standard ILC values $P_{e^-} = -0.8$ and $P_{e^+} = 0.6$, which double the total rate.

3 Top quark polarization as a probe of the CP nature of Φ

Since the top quark, due to its large decay width $\Gamma_t \sim 1.5$ GeV, decays much before hadronization, its spin information is translated to the decay distribution before contamination through strong interaction effects. Furthermore, the lepton angular distribution of the decay $t \to bW \to b\bar{l}\nu$ is independent of any non-standard effects in the decay vertex, so that it is a pure probe of the physics of the top quark production process [18]. The net polarization of the top quark therefore provides an interesting tool for the probe of b, see also Ref.[19]. In Fig. 3 (left) we show as a function of $\sqrt{s}$ for $M_\Phi = 120$ and 150 GeV in the $H(b = 0)$ and $A(b = 1)$ case the expected degree of t-quark polarization P_t, given by

$$P_t = \frac{\sigma(t_L) - \sigma(t_R)}{\sigma(t_L) + \sigma(t_R)}\,. \tag{3}$$

As can be inferred from the figure, the degree of top polarization is again strikingly different for the CP even and CP odd case and shows a very different threshold dependence.

In addition, since P_t is constructed as a ratio of cross sections, the insights gained from this variable are not affected by a possibly model dependent normalization of the overall $tt\Phi$ coupling strength, higher order corrections etc. P_t is a parity odd quantity and receives contributions from the interferences between the γ and all Z exchange diagrams, with the one stemming from the diagram involving the $ZZ\Phi$ vertex being small. The parity violation effect for the emission of a (pseudo)scalar is controlled by the (vector) axial-vector $Zt\bar{t}$ coupling $(v_t = (2I_t^{3L} - 4Q_t s_W^2)/(4s_w c_W))$ $a_t = 2I_t^{3L}/(4s_W c_W)$, where I_t^{3L} denotes the top isospin and

Q_t the electric charge. Hence the ratios of the P_t values away from threshold are expected to be given by the $a_t/v_t \sim 3$, which indeed is confirmed by both Figs. 3 at $\sqrt{s} = 800$ GeV.

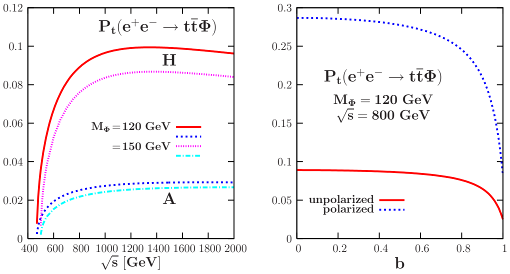

Figure 3: The top polarization in $e^+e^- \to t\bar{t}\Phi$ for a scalar and a pseudoscalar Higgs as a function of $\sqrt{s}$ for $M_\Phi = 120$, 150 GeV (left) and with unpolarized and polarized $e^\pm$ beams as a function of b at $\sqrt{s} = 800$ GeV for $M_\Phi = 120$ GeV (right).

4 The sensitivity to CP mixing

We investigate how the behavior of the cross section and the measurement of the top polarization, which both are clear discriminators between a scalar and pseudoscalar Higgs state, can be used to get information on the CP mixing, *i.e.* the value of b. Ignoring systematical errors, the sensitivity of an observable $O(b)$ to the parameter b at $b = b_0$ is Δb, if $|O(b) - O(b_0)| = \Delta O(b_0)$ for $|b - b_0| < \Delta b$, where $\Delta O(b_0)$ is the statistical fluctuation in O at an integrated luminosity $\mathcal{L}$. For the cross section σ and the polarization P_t, the statistical fluctuation at a level of confidence f are given by $\Delta\sigma = f\sqrt{\sigma/\mathcal{L}}$ and $\Delta P_t = f/\sqrt{\sigma\mathcal{L}} \times \sqrt{1 - P_t^2}$. Fig. 4 (left) shows the sensitivity Δb from the cross section measurement for $M_\phi = 120$ GeV at $\sqrt{s} = 800$ GeV with $\mathcal{L} = 500$ fb^{-1}. For polarized $e^\pm$ beams it varies from 0.25 for $H(b = 0)$ to 0.01 for $A(b = 1)$, a rather precise determination obtained from a simple measurement. The top polarization is less sensitive to b, see Fig. 4 (right).

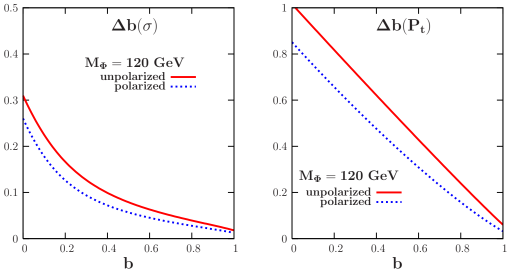

Figure 4: The sensitivity of the cross section (left) and the top polarization (right) to b for $M_\Phi = 120$ at $\sqrt{s} = 800$ with $\mathcal{L} = 500$ fb^{-1}.

Both σ and P_t are CP even quantities, they cannot depend linearly on b and hence not probe CP violation directly. Observables depending directly on the sine of the azimuthal angle (Φ) are linear in b. The up-down asymmetry A_Φ of the antitop quark production with respect to the top-electron plane ($\Phi = 0$) is an example of such an observable:

$$A_\Phi = \frac{\sigma_{\text{partial}}(0 \leq \Phi < \pi) - \sigma_{\text{partial}}(\pi \leq \Phi < 2\pi)}{\sigma_{\text{partial}}(0 \leq \Phi < \pi) + \sigma_{\text{partial}}(\pi \leq \Phi < 2\pi)} \tag{4}$$

with $\sin\Phi = \frac{(\mathbf{p}_{e^-} - \mathbf{p}_{e^+})\cdot(\mathbf{p}_t \times \mathbf{p}'_{\bar{t}})}{|\mathbf{p}_{e^-} - \mathbf{p}_{e^+}|\cdot|\mathbf{p}_t \times \mathbf{p}'_{\bar{t}}|}$, where $\mathbf{p}'_{\bar{t}}$ is the $\bar{t}$ momentum in the $\bar{t}$-Higgs rest frame. Fig. 5 shows the asymmetry A_Φ for a Higgs boson of 120 GeV and a c.m. energy of $\sqrt{s} = 800$ GeV as a function of b. It can reach values of order 5%. The non-zero value of the asymmetry arises from the channel which involves the $ZZ\Phi$ coupling.

5 Summary

We have shown that the total cross section and the top polarization asymmetry for associated Higgs production with top quark pairs in e^+e^- collisions provide a very simple and unambiguous determination of the CP quantum numbers of a SM-like Higgs particle. Exploiting the up-down asymmetry of the anti-top with respect to the top-electron plane we further have a direct probe of CP violation at hand.

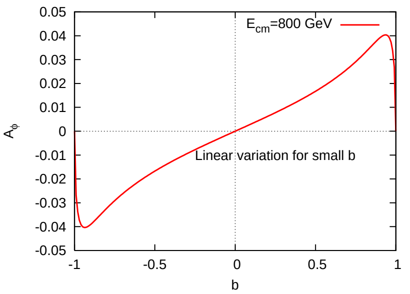

Figure 5: The up-down asymmetry of $\bar{t}$ in associated $t\bar{t}\Phi$ production for $M_\Phi = 120$ at $\sqrt{s} = 800$.

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