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Higgs CP properties using the τ decay modes at the ILC

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ABSTRACT

We investigate the prospects of determining the *CP* nature of the 126 GeV neutral spin-0 (Higgs) boson h, discovered at the LHC, at a future linear e^+e^- collider (ILC). We consider the production of h by the Higgsstrahlung process $e^+e^- \to Z + h$ and its subsequent decays to τ leptons, $h \to \tau^-\tau^+$. We investigate how precisely a possible pseudoscalar component of h can be detected by the measurement of a suitably defined angular distribution, if all major decay modes of the τ lepton are used. From our numerical simulations, we estimate the expected precision to the scalar–pseudoscalar mixing angle ϕ, including estimates of the background and of measurement uncertainties, to be $\Delta\phi \simeq 2.8°$ for Higgs-boson production at a center-of-mass energy of 250 GeV and for a collider with integrated luminosity of 1 ab^{-1}.

1. Introduction

The recent results [1–4] by CMS and ATLAS on the production, decays, and properties of the neutral boson h of mass $\simeq 126$ GeV that was discovered last year by these experiments [5,6] at the LHC support the hypothesis that h is the long-sought Standard Model (SM) Higgs boson. Nevertheless, much more detailed investigations will be necessary to firmly establish this expectation. In particular, the spin-parity analyses made in $h \to ZZ^* \to 4l$ [1,3] do not yet prove that h is a pure scalar – they imply that h cannot be a pure pseudoscalar, but do not rule out the possibility that it is a mixture of a scalar and a pseudoscalar state. It is expected that the profile of this resonance can be explored to a large extent at the LHC.

A high-energy linear e^+e^- collider would be an ideal machine to investigate the properties of this spin-0 resonance in great detail, i.e., its decay modes, couplings, and *CP* parity (and, of course, also the properties of other, not too heavy resonances of similar type if they exist). For assessing the prospects of exploring this particle at a future linear collider, one may revert to the many existing phenomenological investigations, within the SM and many of its extensions, of Higgs-boson production and decay in e^+e^- collisions. As to the prospects of exploring the spin and *CP* properties of a Higgs boson, there have been a number of proposals and studies, including [7–40], that are relevant for Higgs-boson production and decay at a linear collider.

In this Letter, we apply a method [33,35] for the determination of the *CP* nature of a neutral spin-0 (Higgs) boson in its $\tau^+\tau^-$ decays to the production of h at a future e^+e^- linear collider (ILC). For definiteness, we consider $e^+e^- \to Zh$, but the analysis outlined below is applicable to any other h production mode, where the h production vertex can be determined. In our analysis, all major 1-prong and 3-prong τ decays are taken into account. We demonstrate that the *CP* nature of h can be determined by this approach in a precise and unambiguous way.

2. Higgs-boson production and decay

The CMS and ATLAS results [2,4] on h production and its couplings to the weak gauge bosons are consistent with expectations for the Standard Model Higgs boson. Therefore, the e^+e^- production of h by the Higgsstrahlung process

$$e^+e^- \to Z + h \tag{1}$$

has a cross section $\sim \sigma_{SM}(Zh)$. We are interested here in the decay mode $h \to \tau^-\tau^+$, with subsequent decays

$$h \to \tau^-\tau^+ \to a^- a'^+ + X, \tag{2}$$

where $a^\pm, a'^\pm \in \{e^\pm, \mu^\pm, \pi^\pm, a_1^{L,T,\pm}\}$ and X denotes neutrinos and π^0.

The interaction of a Higgs boson h of arbitrary *CP* nature to τ leptons is described by the Yukawa Lagrangian

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$$\mathcal{L}_Y = -(\sqrt{2}G_F)^{1/2} m_\tau (a_\tau \bar{\tau}\tau + b_\tau \bar{\tau} i\gamma_5 \tau) h, \tag{3}$$

where G_F denotes the Fermi constant and a_τ, b_τ are the reduced dimensionless τ Yukawa coupling constants. In order to be able to compare with other studies in the literature, we use in the following sections, instead of (3), the equivalent parameterization

$$\mathcal{L}_Y = -g_\tau (\cos\phi \bar{\tau}\tau + \sin\phi \bar{\tau} i\gamma_5 \tau) h, \tag{4}$$

where g_τ is the effective strength of the Yukawa interaction and ϕ describes the degree of mixing of the scalar and pseudoscalar component:

$$g_\tau = (\sqrt{2}G_F)^{1/2} m_\tau \sqrt{a_\tau^2 + b_\tau^2}, \qquad \tan\phi = \frac{b_\tau}{a_\tau}. \tag{5}$$

In the following sections, we take into account the main 1- and 3-charged prong τ decay modes:

$$\tau \to l + \nu_l + \nu_\tau, \quad l = e, \mu, \tag{6}$$

$$\tau \to \pi + \nu_\tau, \tag{7}$$

$$\tau \to \rho + \nu_\tau \to \pi + \pi^0 + \nu_\tau, \tag{8}$$

$$\tau \to a_1 + \nu_\tau \to \pi + 2\pi^0 + \nu_\tau, \tag{9}$$

$$\tau \to a_1^{L,T} + \nu_\tau \to 2\pi^\pm + \pi^\mp + \nu_\tau. \tag{10}$$

The decay mode (10), in fact a 3-prong τ decay with three charged pions, will also be called '1-prong' because the track, i.e., the 4-momentum of the $a_1^\pm$ resonance can be obtained from the 4-momenta of the three charged pions. Moreover, by using known kinematic distributions, the longitudinal (L) and transverse (T) helicity states of the a_1 resonance can be separated [41–44]. Thus, the $\tau^-\tau^+$ decays that we analyze are of the form (2) with a, a' as specified below (2).

The observables that we use to determine the *CP* nature of h in its τ decays are based on τ-spin correlations [9,21,32,33,35]. The charged lepton $l = e, \mu$ in (6), the charged pion in (7)–(9), and the $a_1^{L,T}$ in (10) act as τ-spin analyzers. The τ-spin analyzing power is maximal for the direct decays to pions, $\tau^\mp \to \pi^\mp$, and for $\tau^\mp \to a_1^{L,T,\mp}$. For a_1^{L-} and a_1^{T-} it is $+1$ and -1, respectively. For the decays (6), (8), and (9), the τ-spin analyzing power of $l^\mp$ and $\pi^\mp$ depends on the energy of these particles, cf. Appendix A. We will apply cuts on the respective energy to optimize the τ-spin analyzing power.

The differential cross section of the production process (1) and subsequent decay (2) can be derived from Eq. (4) of [35]. For a Higgs boson of arbitrary *CP* nature it is given by

$$\begin{aligned} d\hat{\sigma} = {} & N_\tau \overline{|M_{a^-a'^+}|}^2 d\Omega_Z\, d\Omega_\tau\, dE_{a^-}\, d\Omega_{a^-}\, dE_{a'^+}\, d\Omega_{a'^+}/(2\pi) \\ & \times n(E_{a^-}) n(E_{a'^+}) \{ A - b(E_{a^-}) b(E_{a'^+}) \\ & \times [c_1 \hat{\mathbf{q}}^- \cdot \hat{\mathbf{q}}^+ + c_2 \hat{\mathbf{k}} \cdot \hat{\mathbf{q}}^- \hat{\mathbf{k}} \cdot \hat{\mathbf{q}}^+ + c_3 \hat{\mathbf{k}} \cdot (\hat{\mathbf{q}}^- \times \hat{\mathbf{q}}^+)] \}, \end{aligned} \tag{11}$$

where

$$N_\tau = \frac{\sqrt{2} G_F m_\tau^2 \beta_\tau}{128\pi^3 s},$$

$$\overline{|M_{a^-a'^+}|}^2 = \overline{\sum} |M(e^-e^+ \to Zh)|^2 |D^{-1}(h)|^2 \mathrm{B}_{\tau^- \to a^-} \mathrm{B}_{\tau^+ \to a'^+}.$$

In Eq. (11), $\hat{\mathbf{k}}$ denotes the normalized τ^- momentum in the Higgs-boson rest frame and $\hat{\mathbf{q}}^-$ ($\hat{\mathbf{q}}^+$) is the a^- (a'^+) direction of flight in the τ^- (τ^+) rest frame. The functions n and b are defined in Appendix A, the coefficients A, c_i are given in Table I of [35], β_τ is the τ velocity, $s = E_{cm}^2$, and D^{-1} is the Higgs-boson propagator.

Choosing $\hat{\mathbf{k}}$ to be the z axis of a right-handed coordinate system and integrating Eq. (11) over the polar angles $d\theta_{a'^-}$ and $d\theta_{a^+}$, we obtain:

$$\begin{aligned} d\hat{\sigma} = {} & N_\tau \overline{|M_{a^-a'^+}|}^2 d\Omega_Z\, d\Omega_\tau\, dE_{a^-}\, dE_{a'^+}\, d\varphi \\ & \times [v + u \cdot \cos(\varphi - 2\phi)], \end{aligned} \tag{12}$$

where

$$\varphi = \phi_{a^-} - \phi_{a'^+}, \quad 0 \leqslant \varphi \leqslant 2\pi,$$

is the difference of the azimuthal angles of a^- and a'^+,

$$u = -n(E_{a^-}) b(E_{a^-}) n(E_{a'^+}) b(E_{a'^+}) \frac{\pi^2 p_h^2}{8} \frac{g_\tau^2}{\sqrt{2} G_F m_\tau^2},$$

$$v = 4n(E_{a^-}) n(E_{a'^+}) A,$$

and ϕ is the Higgs mixing angle defined in (5).

The distribution (12) holds also in the $\tau\tau$ zero-momentum frame (ZMF). The angle φ is equal to the angle between the *signed* normal vectors of the $\tau^- \to a^-$ and $\tau^+ \to a'^+$ decay planes spanned by the unit vectors $\hat{\mathbf{k}}$, $\hat{\mathbf{q}}^-$ and $-\hat{\mathbf{k}}$, $\hat{\mathbf{q}}^+$, respectively. Instead of determining φ in the $\tau\tau$ ZMF one can measure this angle also in the zero-momentum frame of the charged prongs a^- and a'^+ (cf. [33] and below). This has the advantage that the $\tau^\mp$ momenta need not be reconstructed.

3. Method and observables

Our method to determine the *CP* nature of h requires, in the case of the 1-prong $\tau^-\tau^+$ decays (2), the measurement of the 4-momenta of the charged prongs a^-, a'^+ and their impact parameter vectors (unit vectors) $\hat{\mathbf{n}}_\mp$ in the laboratory frame. The 4-vectors $n_\mp^\mu = (0, \hat{\mathbf{n}}_\mp)$ are then boosted into the $a^-a'^+$ zero-momentum frame (ZMF). The spatial parts of the resulting 4-vectors $n_\mp^{*\mu}$ are decomposed into their normalized components $\hat{\mathbf{n}}_\parallel^{*\mp}$ and $\hat{\mathbf{n}}_\perp^{*\mp}$ that are parallel and perpendicular to the respective a^- and a'^+ 3-momentum. With this prescription, one determines in the $a^-a'^+$ ZMF the *unsigned* normal vectors $\hat{\mathbf{n}}_\perp^{*-}$ and $\hat{\mathbf{n}}_\perp^{*+}$ of the $\tau^- \to a^-$ and $\tau^+ \to a'^+$ decay planes. The distribution of the angle between these two planes [33],

$$\varphi^* = \arccos(\hat{\mathbf{n}}_\perp^{*+} \cdot \hat{\mathbf{n}}_\perp^{*-}), \tag{13}$$

where $0 \leqslant \varphi^* \leqslant \pi$, discriminates between $CP = \pm 1$ Higgs boson states. The simultaneous measurement of (13) and of the *CP*-odd and *T*-odd triple correlation

$$\mathcal{O}_{CP}^* = \hat{\mathbf{q}}_-^* \cdot (\hat{\mathbf{n}}_\perp^{*+} \times \hat{\mathbf{n}}_\perp^{*-}), \tag{14}$$

where $\hat{\mathbf{q}}_-^*$ is the normalized a^- momentum in the $a^-a'^+$ ZMF, allows for an unambiguous determination of the *CP* nature of h [33]. If h is a mixture of a *CP*-even and -odd state, the distribution of (14) is asymmetric with respect to $\mathcal{O}_{CP}^* = 0$. In order to determine the ratio b_τ/a_τ of the reduced Yukawa couplings (3) or, equivalently, the mixing angle ϕ defined in (5), one would fit theoretical predictions for $\sigma^{-1} d\sigma/d\varphi^*$ and $\sigma^{-1} d\sigma/d\mathcal{O}_{CP}^*$ to the corresponding measured distributions. In addition, associated asymmetries can be measured. Some results of this approach, applied to the reactions (1), (2), were presented in the workshop report [38].

Here we use a slight variation of our approach just outlined. Instead of using both the distribution of the 'unsigned' angle φ^*, Eq. (13), which is defined in the range $0 \leqslant \varphi^* \leqslant \pi$, and of $\mathcal{O}_{CP}^*$, the same information is of course contained in the distribution of the 'signed' angle between the $\tau^- \to a^-$ and $\tau^+ \to a'^+$ decay planes in the $a^-a'^+$ ZMF. This angle which will be called φ_{CP}^* in the following and that varies between 0 and 2π is obtained by the following prescription:

$$\varphi_{CP}^* = \begin{cases} \varphi^* & \text{if } \mathcal{O}_{CP}^* \geqslant 0, \\ 2\pi - \varphi^* & \text{if } \mathcal{O}_{CP}^* < 0. \end{cases} \tag{15}$$