Determining the *CP* Parity of Higgs Bosons via Their τ Decay Channels at the Large Hadron Collider

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If neutral Higgs bosons are discovered at the CERN Large Hadron Collider (LHC), then an important subsequent issue will be the investigation of their *CP* nature. Higgs boson decays into τ lepton pairs are particularly suited in this respect. By analyzing the three charged pion decay modes of the τ leptons and taking expected measurement uncertainties at the LHC into account, we show that the *CP* properties of a Higgs boson can be pinned down with appropriately chosen observables, provided that sufficiently large event numbers will eventually be available.

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Introduction.—The major physics goal of the upcoming experiments at the CERN Large Hadron Collider (LHC) is the exploration of the hitherto unknown mechanism of electroweak gauge symmetry breaking which, in the context of the standard model (SM) of particle physics and many of its extensions, is tantamount to searching for Higgs bosons, spin-zero and electrically neutral resonances with masses of (a few) hundred GeV (see, e.g., [1] for recent reviews). If (one or several types of) Higgs bosons are found, then the next issue will be the determination of their properties—in particular, their parity (P) and charge conjugation times parity (CP) quantum numbers, respectively, which yield important information about the dynamics of these particles. While the SM Higgs boson is parity-even, SM extensions also predict parity-odd state(s) or, if the Higgs boson dynamics violates CP, states of undefined CP parity with Yukawa couplings to both scalar and pseudoscalar quark and lepton currents. Higgs sector CP violation is a fascinating possibility, especially in view of its potentially enormous impact on an important issue of the physics of the early Universe, namely, baryogenesis [2]. These new interactions can be searched for at the upcoming generation of colliders in several ways [1]. The couplings of W and Z to Higgs bosons can be explored with appropriate observables [3]. The decays of Higgs bosons to $\tau^-\tau^+$ leptons and/or—if the Higgs bosons are heavy enough—to $t\bar{t}$ quarks are particularly suited in this respect [4,5]. In this Letter, we show that, at the LHC, the CP nature of a neutral Higgs boson can be pinned down with appropriately chosen observables in its $\tau^-\tau^+$ decay channel where the τ decay into three charged pions, provided that sufficiently large event numbers will eventually be available.

The analysis of this Letter applies to any neutral Higgs boson h_j with flavor-diagonal couplings to quarks and leptons f (with mass m_f)

$$\mathcal{L}_Y = -(\sqrt{2}G_F)^{1/2}\sum_{j,f} m_f(a_{jf}\bar{f}f + b_{jf}\bar{f}i\gamma_5 f)h_j, \quad (1)$$

where G_F is the Fermi constant and a_{jf} and b_{jf} are the reduced scalar and pseudoscalar Yukawa couplings, respectively, which depend on the parameters of the (effective) Higgs potential of the respective model. In the SM, $a_f = 1$ and $b_f = 0$. As far as SM extensions are concerned, we consider here, for definiteness, models with two Higgs doublets, such as the nonsupersymmetric type II models and the minimal supersymmetric SM extension (MSSM) (see, e.g., [1]). These models contain three physical neutral Higgs fields h_j in the mass basis. If Higgs sector CP violation (CPV) is negligibly small, then the fields h_j describe two scalar states h and $H(b_f = 0)$ and a pseudoscalar A ($a_f = 0$). In the case of Higgs sector CPV, the h_j have nonzero couplings (they can be parametrized in terms of the ratio of the Higgs field vacuum expectation values $\tan\beta = \mathrm{v}_2/\mathrm{v}_1$ and a 3×3 orthogonal matrix that describes the mixing of the neutral spin-zero CP eigenstates) a_{jf} and b_{jf} to quarks and leptons which lead to CP-violating effects in $h_j \to f\bar{f}$ already at the Born level. This is in contrast to the couplings to W^+W^- and to ZZ boson pairs of such a state of undefined CP parity. At the Born level, only the $CP = +1$ component of h_j couples to W^+W^- and to ZZ. The coupling of the pseudoscalar component of h_j—if there is any—to W^+W^- and to ZZ is likely to be very small as it must be induced, in renormalizable theories, by quantum fluctuations. Thus, the observation of Higgs boson production in weak vector boson fusion $W^+W^-, ZZ \to h_j$ or of the decay channels $h_j \to W^+W^-, ZZ$ would tell us that h_j has a significant scalar component. However, even if no pseudoscalar coupling to weak vector bosons were found with appropriate correlations [3], the question would remain of whether or not h_j is really a pure $J^{PC} = 0^{++}$ state or if it has a significant pseudoscalar component, too. This can be answered by investigating the τ decay channel of this particle.

τ spin observables.—In the following, we choose the generic notation ϕ for any of the neutral Higgs bosons h_j

discussed above. The observables discussed here for determining the CP quantum number of ϕ in its decay channel $\phi \to \tau^-\tau^+$ may be applied to any Higgs production process. At the LHC, this includes the gluon and gauge boson fusion processes $gg \to \phi$ and $q_i q_j \to \phi q_i' q_j'$, respectively, and the associated production $t\bar{t}\phi$ or $b\bar{b}\phi$ of a light Higgs boson. We consider the following reactions:

$$pp \to \phi + X \to \tau^-(\mathbf{k}_\tau) + \tau^+(\mathbf{k}_{\bar\tau}) + X \to a(\mathbf{q}_1) + \bar{b}(\mathbf{q}_2) + X, \quad (2)$$

where a and $\bar{b}$ are $\tau^\mp$ decay products to be specified below, $\mathbf{q}_{1,2}$ are their 3-momenta in the respective $\tau^\mp$ rest frames, and $\mathbf{k}_\tau$ and $\mathbf{k}_{\bar\tau} = -\mathbf{k}_\tau$ are the 3-momenta of τ^- and τ^+ in the $\tau\bar\tau$ zero-momentum frame.

Let us assume that experiments at the LHC will discover a neutral boson resonance in a reaction of the type (2) and a sufficiently large sample will eventually be accumulated. The spin of ϕ may be inferred from the polar angle distribution of the tau leptons. Suppose that the outcome of this analysis is that ϕ is a spin-zero (Higgs) particle. One would next like to determine its Yukawa coupling(s) and, specifically, like to know whether ϕ is a scalar, a pseudoscalar, or a state with undefined CP parity. This can be investigated by using the following CP-even and -odd observables involving the spins of τ and $\bar\tau$, and we emphasize that all of them should be used. The $\tau^-\tau^+$ spin-spin correlation $S = \mathbf{s}_\tau \cdot \mathbf{s}_{\bar\tau}$ strongly discriminates between scalar and pseudoscalar Higgs bosons, because $\langle S\rangle_{\tau\tau} = 1/4$ and $-3/4$ for a $J^{PC} = 0^{++}$ and for a $J^{PC} = 0^{-+}$ Higgs boson state, respectively. For general couplings (1), one gets $\langle S\rangle_{\tau\tau} = (a_\tau^2 - 3b_\tau^2)/(4a_\tau^2 + 4b_\tau^2)$, by using the fact that $m_\phi \gg m_\tau$. The case of Higgs sector CP violation $\gamma_{CP}^\tau \equiv -a_\tau b_\tau \neq 0$ can be traced with the CP-odd transverse spin-spin correlation $S_{CP} = \hat{\mathbf{k}}_\tau \cdot (\mathbf{s}_\tau \times \mathbf{s}_{\bar\tau})$, where $\hat{\mathbf{k}}_\tau = \mathbf{k}_\tau/|\mathbf{k}_\tau|$. A nonzero expectation value is generated already at tree level: $\langle S_{CP}\rangle_{\tau\tau} = -a_\tau b_\tau/(a_\tau^2 + b_\tau^2)$, which can be as large as 0.5 in magnitude.

These τ spin correlation effects lead, in turn, through the parity-violating weak decays of the τ leptons, to specific angular distributions and correlations in the final state (2). We recall the τ spin-analyzing power of a particle/jet a in the decay $\tau^- \to a + \nu_\tau$, that is, the coefficient c_a in the distribution $\Gamma_a^{-1} d\Gamma_a/d\cos\theta_a = (1 + c_a \cos\theta_a)/2$, where θ_a is the angle between the τ^- spin vector and the direction of a in the τ^- rest frame (cf., e.g., [6]). CP invariance, which is, as known from experiments, a good symmetry in τ decays at the level of precision required here, implies that the τ spin-analyzing power of $\bar{a}$ in $\tau^+ \to \bar{a} + \bar\nu_\tau$ is $c_{\bar a} = -c_a$.

The spin correlation $\langle S\rangle$ leads to a nonisotropic distribution in $\cos\varphi$, where $\varphi = \angle(\mathbf{q}_1, \mathbf{q}_2)$. If no phase space cuts are applied—modulo cuts on the invariant mass $M_{\tau\bar\tau}$ of the τ pair—this opening angle distribution is of the form:

$$\frac{1}{\sigma_{a\bar b}} \frac{d\sigma_{a\bar b}}{d\cos\varphi} = \frac{1}{2}(1 - D_{a\bar b}\cos\varphi), \qquad D_{a\bar b} = -\frac{4}{3} c_a c_{\bar b} \langle S\rangle_{\tau\tau}. \quad (3)$$

The equivalent of the CP-odd spin observable S_{CP} at the level of the final states (2) is [4]

$$\mathcal{O}_{CP} = (\hat{\mathbf{k}}_\tau - \hat{\mathbf{k}}_{\bar\tau}) \cdot (\hat{\mathbf{q}}_2 \times \hat{\mathbf{q}}_1)/2, \qquad \langle \mathcal{O}_{CP}\rangle_{a\bar b} = -\frac{4}{9} c_a c_{\bar b} \langle S_{CP}\rangle_{\tau\tau}. \quad (4)$$

(The CP-odd observable $\hat{\mathbf{k}}_\tau \cdot \hat{\mathbf{q}}_1 - \hat{\mathbf{k}}_{\bar\tau} \cdot \hat{\mathbf{q}}_2$, which traces an asymmetry in the $\tau^\mp$ polarizations [4], should also be used in future data analyses. For the specific ϕ-production amplitudes taken into account below, its expectation value is, however, small.) An asymmetry corresponding to (4) is $A(\mathcal{O}_{CP}) = [N_{a\bar b}(\mathcal{O}_{CP} > 0) - N_{a\bar b}(\mathcal{O}_{CP} < 0)]/N_{a\bar b} = 9\pi\langle \mathcal{O}_{CP}\rangle_{a\bar b}/16$.

(Multi)pion final states.—In order to obtain sufficient sensitivity to the CP properties of the Higgs boson resonance, one should consider τ decay channels that both have good to maximal τ spin-analyzing power and allow for the reconstruction of the τ decay vertex, i.e., the τ rest frame, which is essential for an efficient helicity analysis. The π^- channel is known to have maximal spin-analyzing power $c_{\pi^-} = 1$. In the case of, e.g., multipion decays of the τ, this optimum analyzing power can also be achieved if all of the pions are observed and the dependence of the hadronic current on the pion momenta is known [7]. The latter is obtained by using empirically tested matrix elements and fits to measured distributions.

In the following section, we consider the decay $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ and the corresponding decay of τ^+. As this decay proceeds to a large extent via the a_1 resonance, we use $\tau^\mp \to a_1^\mp$ for the description of the three-pion final state. The measured pion momenta in the laboratory frame allow, by using known kinematic distributions [6,7], the separation of the longitudinal (a_{1L}) and transverse (a_{1T}) helicity states of the a_1. This leads to an optimal spin-analyzing power $c = \pm 1$ for a_{1L} and a_{1T}, respectively. Moreover, the measured pion momenta yield the τ decay vertex and, in turn, the τ rest frame (see below). The coefficients $D_{a_{1L}^- a_{1L}^+} = D_{a_{1T}^- a_{1T}^+}$ in Eq. (3) are 0.33 and -1 for the channels $\phi(0^{++}) \to \tau\tau \to a_{1i}a_{1j}$ and $\phi(0^{-+}) \to \tau\tau \to a_{1i}a_{1j}$, respectively, if $ij = LL, TT$, while they change sign if $ij = LT, TL$. Thus, for $ij = LL, TT$ the a_1 momenta $\mathbf{q}_1$ and $\mathbf{q}_2$ are predominantly parallel in the case of a pseudoscalar ϕ, while for a scalar ϕ they tend to be antiparallel. If ϕ were an ideal mixture of a CP-even and -odd state $|a_\tau| = |b_\tau|$, the asymmetry corresponding to $\mathcal{O}_{CP}$ would take the value $|A(\mathcal{O}_{CP})| = 0.4$ in the $a_{1i}a_{1j}$ channels $(i, j = L, T)$.

Results.—For nonstandard Higgs bosons ϕ and large $\tan\beta$, the associated production with bottom quarks $gg \to b\bar{b}\phi$ is considered to be the most promising mode in the $\phi \to \tau\bar\tau$ decay channel at the LHC [8]. The results shown below are applicable not only to this production process but also to gluon-gluon fusion $gg \to \phi$ and vector boson fusion. The reason is that our normalized distributions do not depend on the ϕ momentum if no detector cuts are applied. Furthermore, we show for $\phi \to \tau\bar{\tau} \to a_1\bar{a}_1$ that detector cuts have only a very small effect on these distributions for Higgs boson masses larger than 200 GeV. Thus, our results will not change significantly for the different Higgs production modes or if initial-state higher-order QCD corrections are taken into account. We have, therefore, computed in this analysis all distributions for a generic $2 \to 1$ Higgs boson production process at leading order.

As emphasized above, the determination of the distributions of $\cos\varphi$ and of the observable $\mathcal{O}_{CP}$ requires the reconstruction of the $\tau^{\mp}$ rest frames. For the decay channels (2), the $a_1^{\mp}$ momenta in the laboratory frame and the $\tau^{\mp}$ decay vertices can be obtained from the visible tracks of the three charged pions. The $\tau^{\mp}$ production, i.e., the Higgs production vertex, can be reconstructed from the visible tracks of the charged particles/jets produced in association with the ϕ [9]. By using the fact that, for each τ, $\tilde{k}_\tau^\mu = \tilde{q}_{a_1}^\mu + \tilde{q}_\nu^\mu$, $m_\tau^2 = \tilde{E}_\tau^2 - \tilde{\mathbf{k}}_\tau^2$, $\tilde{E}_\nu^2 = \tilde{\mathbf{q}}_\nu^2$ (the tilde refers to the laboratory frame), and $\tilde{\mathbf{k}}_\tau = \kappa\hat{\mathbf{x}}$, where $\hat{\mathbf{x}}$ is the unit vector along the line connecting the τ production and decay vertex, the factor κ is obtained by solving this system of equations. For each τ lepton, we obtain two solutions, and we select the solution for which the sum of the transverse $\tau^{\mp}$ momenta is closest to zero. With this solution for $\tilde{k}_\tau^{\mu\mp}$, the $\tau^{\mp}$ rest frames and the momentum directions $\hat{\mathbf{q}}_{1,2}$ can be reconstructed, which are required for the observables (3) and (4).

Figure 1(a) shows the $\cos\varphi$ distributions for the production of a scalar $\phi = H$ and a pseudoscalar $\phi = A$ in the decay channel (2), assuming a mass $m_{H,A} = 200$ GeV, both for no detector cuts and for applying the cuts $p_T \geq 40$ GeV and $\eta \leq 2.5$ (pseudorapidity) on the pions in the final state. In fact, the cut on η does not change the shape of the normalized distributions shown in Fig. 1. The figure shows that the p_T cuts have only a very minor influence, too. The slopes are given to very good approximation by the numbers for D given above. The influence of the cuts on the shape of the distributions decreases for larger ϕ masses. Only for light Higgs masses $m_\phi \gtrsim 120$ GeV does the chosen minimum p_T cut of 40 GeV have a more significant effect.

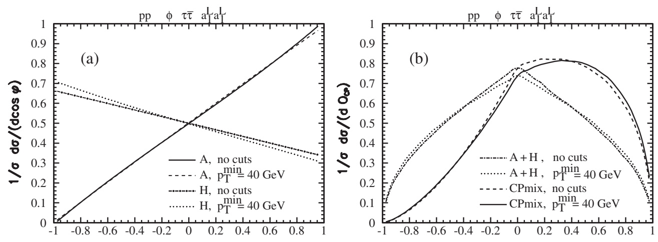

FIG. 1. Distributions of $\cos\varphi$ and $\mathcal{O}_{CP}$ for a_1 polarizations LL or TT.

Let us now discuss the following two situations. (i) Suppose that both a scalar and a pseudoscalar Higgs boson H and A with (nearly) degenerate masses, for instance, $m_{H,A} \sim 200$ GeV, exist and are both produced in the reaction (2). Such degenerate resonances cannot be resolved, e.g., in the $M_{\tau\bar{\tau}}$ spectrum. The resulting $\cos\varphi$ distribution will have a shape somewhere between the scalar and the pseudoscalar extremes shown in Fig. 1(a), depending on the relative reaction rates. (ii) Suppose, on the other hand, that a Higgs boson ϕ with $m_\phi \sim 200$ GeV exists (of course, Higgs bosons of this type might also be degenerate; for simplicity, we do not consider this possibility here) which has both scalar and pseudoscalar couplings to fermions, in particular, to τ leptons. The slope of the resulting $\cos\varphi$ distribution will also differ from the two extremes shown in Fig. 1(a). In other words, the measured distribution does not tell whether degenerate scalar and pseudoscalar resonances or a state of undefined CP parity were produced. This puzzle may be resolved by using the observable $\mathcal{O}_{CP}$. As case (i) corresponds to a CP-invariant Higgs sector, the resulting distribution of $\mathcal{O}_{CP}$ must be symmetric (if the phase space cuts are CP-symmetric) and $\langle\mathcal{O}_{CP}\rangle = 0$, while case (ii) will produce an asymmetric distribution and a nonzero average. This is shown in Fig. 1(b), where case (ii) is illustrated with an "ideal mixture" (label CPmix), i.e., a ϕ boson with scalar and pseudoscalar couplings of equal magnitude—we put $a_\tau = -b_\tau$. Again, the applied cuts have only a minor influence on the distributions. The distributions in Figs. 1(a) and 1(b) do not change if both intermediate a_1 are transversely polarized, while they are reflected with respect to the vertical line passing the abscissa value zero in the case of mixed polarizations.

An important question is how robust the discriminating power of these distributions is with respect to experimental errors. We have studied this issue by "smearing" the relevant quantities with a Gaussian, by using the standard deviations (s.d.): $\sigma_z^P = 15$ μm, $\sigma_T^S = 15$ μm, $\sigma_L^S = 500$ μm, $\sigma_\theta^{a_1} = 0.8$ mrad, and $\delta E/E = 2\%$. Here σ_z^P denotes the s.d. of the position of the τ production vertex along the beam axis, while σ_L^S and σ_T^S are the s.d. of the positions of the respective τ decay vertex along the τ-jet axis (i.e., the direction of a_1) and in the plane transverse to this axis. Furthermore, the uncertainty in determining the direction of a_1 is parametrized by an angle θ with s.d. $\sigma_\theta^{a_1}$, and $\delta E/E$ denotes the relative error of determining the energy of a_1. These values appear to be realistic for the LHC experiments [9,10]. For this simulation we use, in the case of $m_\phi = 200$ GeV, a constant τ flight length of 4.5 mm.

The effect of these uncertainties on the distributions of $\cos\varphi$ and $\mathcal{O}_{CP}$ is shown in Figs. 2(a) and 2(b) by using

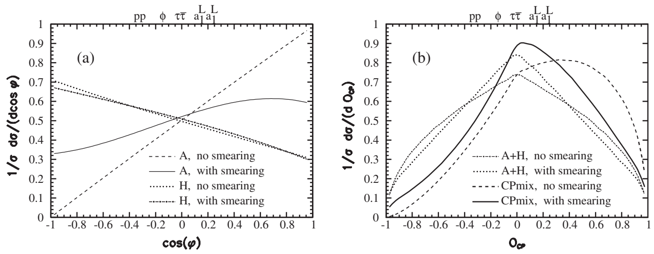

FIG. 2. Distributions of $\cos\varphi$ and $\mathcal{O}_{CP}$ including measurement uncertainties.

again Higgs boson masses $m_\phi = 200$ GeV. For the above set of uncertainties, scalar and pseudoscalar states are still clearly distinguishable [Fig. 2(a)] and, likewise, CP-conserving and CP-violating states [Fig. 2(b)]. We have made a systematic study by varying (i) the masses m_ϕ of the various types of Higgs bosons between 120 and 500 GeV and (ii) the expected measurement errors. By varying m_ϕ, we found that the discriminating power of these distributions does not decrease for heavy Higgs bosons. Concerning measurement errors, we found that it is important to have under control the transverse uncertainty σ_T^S in the reconstruction of the τ decay vertices and also the uncertainties σ_z^P and $\sigma_\theta^{a_1}$ of the position of the τ production vertex and of θ. In order to make use of the discriminating power of the above observables, one should achieve $\sigma_T^S < 18$ μm, $\sigma_z^P < 30$ μm, and $\sigma_\theta^{a_1} < 1$ mrad in future experiments. Least critical are the resolution of the longitudinal τ-jet axes (σ_L^S) and the energy uncertainty of the a_1 meson. Details of our results will be given elsewhere [11].

Finally, we estimate how many events (2) are needed in order to discriminate between (i) a scalar and pseudoscalar Higgs boson and/or (ii) between CP-conserving and CP-violating states, assuming $m_\phi = 200$ GeV. As to (i), we define an asymmetry $A_\varphi = [N(\cos\varphi > 0) - N(\cos\varphi < 0)]/[N_> + N_<]$. From Fig. 2(a), we obtain from the smeared distributions $A_\varphi^H = -0.19$ and $A_\varphi^A = 0.17$. Thus, for distinguishing H from A with 3 s.d. significance requires 69 events (2). Concerning (ii), the result of Fig. 2(b) implies that, for an ideal CP mixture, the CP asymmetry below Eq. (4) takes the value $A(\mathcal{O}_{CP}) = 0.23$ while it is zero for pure H and A and degenerate H and A intermediate states. Thus, 170 events (2) will be needed to establish this CPV effect at the 3 s.d. level. This may be feasible, depending on the masses and couplings of ϕ, after several years of high luminosity runs at the LHC [8]. Considering, in the case of the MSSM with $\tan\beta = 20$, associated $b\bar{b}\phi$ production with an integrated luminosity of 300 fb^{-1}, an overall efficiency of about 0.003 is required to obtain these event numbers. For a SM Higgs boson, one gets, considering only production via vector boson fusion, a decent event rate for a light boson with $m_H \sim 120$ GeV. The above $\cos\varphi$ measurement would require a selection efficiency of about 2% or better. The τ data sample will be significantly increased if the above observables can be applied also to one-prong hadronic τ decays [11].

Conclusions.—The τ decay channel is clearly most suited to explore the CP nature of a light or heavy neutral Higgs boson ϕ. This is an important physics issue if Higgs bosons are discovered. We have discussed a set of observables that serve this purpose, and we have shown, for Higgs boson production at the LHC and its decay via τ leptons into a_1 mesons, that the above correlations and asymmetries provide powerful tools for discriminating between CP-even and -odd Higgs bosons and for searches for CP violation in the Higgs sector. The measurement of these observables is challenging, but our analysis indicates that it should be feasible in the long run, provided enough $\phi \to \tau\tau$ events will be recorded at the LHC.

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