Determining the CP Properties of the Higgs Boson

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The search and the probe of the fundamental properties of Higgs boson(s) and, in particular, the determination of their charge conjugation and parity (CP) quantum numbers, are the main tasks of future high-energy colliders. We demonstrate that the CP properties of a standard model-like Higgs particle can be unambiguously assessed by measuring just the total cross section and the top polarization in associated Higgs boson production with top quark pairs in $e^+e^-$ collisions.

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We are at last entering the long awaited era, with the Large Hadron Collider (LHC) starting operation, of probing the mechanism by which the electroweak symmetry of the standard model (SM) of strong, weak, and electromagnetic interactions is broken to provide masses for elementary particles. The SM makes use of one isodoublet complex scalar field which, after the spontaneous breaking of the SU(2)$_L \times U(1)$_Y symmetry, generates the weak gauge boson and the fermion masses and leads to the existence of one single spin-zero particle, the Higgs boson $H$, that is even under charge conjugation and parity (CP).

In extensions of the SM, the Higgs sector can be non-minimal and, for instance, the minimal supersymmetric extension is a constrained two-Higgs doublet model (2HDM), leading to a spectrum of five Higgs particles: two CP-even $h$ and $H$, a CP-odd $A$, and two charged $H^\pm$ bosons.

Once a convincing signal for a Higgs boson has been established at the LHC, the next important step would be to determine its properties in all possible detail and to establish that it has the features that are predicted in the SM; that is, it is a spin-zero particle with the $J^{PC} = 0^{++}$ assignment for parity and charge conjugation and that its couplings to fermions and gauge bosons are proportional to their masses. Ultimately, the scalar potential responsible for symmetry breaking should be reconstructed by measuring Higgs self-couplings. To achieve this goal, besides LHC preliminary analyses [1], the complementary high-precision measurements of the International Linear $e^+e^-$ Collider (ILC) would be required [2,3].

While the measurements of the spin, mass, and decay width and couplings to fermions and gauge bosons of a SM-like Higgs boson are relatively straightforward [1,2], the determination of its CP quantum numbers in an unambiguous way turns out to be somewhat problematic [4]. A plethora of observables that can be measured at the LHC and/or ILC, such as angular correlations in Higgs decays into $V = W, Z$ boson pairs [5,6] or in Higgs production with or through these states [5,7], are, in principle, sensitive to the Higgs spin parity. However, if a Higgs boson is observed with substantial rates in these channels, it is very likely that it is CP even since, even in the presence of CP violation, only the CP-even component of the HVV coupling is projected out. The $VV$ couplings of a pure CP-odd $A$ state are zero at tree level and are generated only through tiny loop corrections.

The Higgs boson couplings to fermions provide a more democratic probe of its CP nature since, in this case, the CP-even and CP-odd components can have the same magnitude. One therefore needs to look at channels where the Higgs boson is produced and/or decays through these couplings. At the LHC, discarding the possibility of Higgs production in the main channel $gg \to H$ which proceeds through heavy quark loops followed by $H \to b\bar{b}$, $\tau^+\tau^-$ decays, that are subject to a rather large QCD background, one can only rely on Higgs production in association with top quarks, $pp \to tH$, followed by $H \to \gamma\gamma$ and $H \to b\bar{b}$. Techniques to discriminate between the CP-even or CP-odd state or a mixture, by exploiting the differences in the final state particle distributions in the production of the two states, have been suggested in Ref. [8]. However, these channels are extremely difficult at the LHC: the CMS Collaboration [1] has shown that the $H \to b\bar{b}$ signal cannot be extracted from the huge jet background while the decay channel $H \to \gamma\gamma$ is too rare and the two-photon decays from all production channels need to be combined to have a reasonably high signal significance.

In the clean environment of the ILC, the decay $H \to \tau^+\tau^-$ can be exploited [but only for $M_H \leq 140$ GeV when the branching ratio is significant] and the CP nature of the Higgs boson could be tested by studying the spin correlations between the $\tau$ leptons [9,10]. However, the Higgs has to be produced in the strahlung process $e^+e^- \to HZ$ and again, only the CP-even component of the HZZ coupling is projected out. The same argument holds for a heavy Higgs when the decay $H \to t\bar{t}$ is kinematically accessible.