# Determining the *CP* Nature of a Neutral Higgs Boson at the CERN Large Hadron Collider

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We demonstrate that certain weighted moments of $t\bar{t}h$ production can provide a determination of the *CP* nature of a light neutral Higgs boson produced and detected in this mode at the CERN Large Hadron Collider. [S0031-9007(96)00272-4]

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It is well known [1,2] that detection of a Higgs boson $h$ with couplings roughly like those of the standard model (SM) Higgs ($\phi^0$) will be possible at the CERN Large Hadron Collider (LHC), the detection mode depending upon the mass $m_h$. If $m_h \lesssim 130$ GeV, the primary techniques for observing such an $h$ rely on $gg \to h$, $W^* \to Wh$, and $gg \to t\bar{t}h$, with $h \to \gamma\gamma$ and, for the latter two modes, $h \to b\bar{b}$. If the $h$ is part of a larger (non-SM) Higgs sector, deviations of the $Wh$ and $t\bar{t}h$ production rates from SM expectations will be present, but difficult to interpret. A direct determination of whether the $h$ is $CP$ even (as predicted for the SM $\phi^0$ and the minimal supersymmetric model $h^0$) would be especially crucial to unraveling the situation. The only procedure proposed to date for directly determining the $CP$ nature of a light $h$ *at the LHC* employs proton beam polarization asymmetries which are only sufficiently large if proton polarization implies substantial polarization for the colliding gluons in the $gg \to h$ process [3]. (Other techniques are available at $e^+e^-$ and $\mu^+\mu^-$ machines [4].) Here, we demonstrate that certain weighted moments of the cross section for $t\bar{t}h$ production are sensitive to the relative magnitudes of the $CP$-even and $CP$-odd coupling coefficients $c$ and $d$ (respectively) in the $t\bar{t}h$ interaction Lagrangian, $\mathcal{L} \equiv \bar{t}(c + id\gamma_5)th$. The accuracy with which these moments can be measured experimentally at the LHC (assuming an accumulated, detector-summed luminosity of $L = 600$ fb$^{-1}$) is sufficient that $CP$-even SM Higgs boson can be shown to be inconsistent with an equal mixture of $CP$-odd and $CP$-even components at the $\sim 1.5\sigma - 2\sigma$ statistical level, and inconsistent with a purely $CP$-odd state at the $\gtrsim 7\sigma$ statistical level.

Consider a general quark-antiquark-Higgs coupling of the form $\overline{Q}(c + id\gamma_5)Qh$, where $c$ and $d$ are both taken to be real; $c$ and $d$ determine the $CP$-even and $CP$-odd components of the coupling, respectively. The spin-averaged cross sections for $gg \to Q\overline{Q}h$ and $q\bar{q} \to Q\overline{Q}h$ production contain no terms proportional to $cd$. However, they do contain terms proportional to both $c^2 + d^2$ and $c^2 - d^2$. Since the $c^2 - d^2$ terms are multiplied by $m_Q^2$, sensitivity to $c^2 - d^2$ terms is only significant if $m_Q^2$ is of the same order as the other invariant masses squared for the subprocess. The latter are fairly large, being set by the scale $m_h^2$, implying that only $t\bar{t}h$ production will have substantial sensitivity to $c^2 - d^2$.

In order to isolate the $c^2 - d^2$ terms in the production amplitude squared in a manner that is free of systematic uncertainties associated with the overall production rate, we compute the ratio

$$\alpha[\mathcal{O}_{CP}] \equiv \frac{\int [\mathcal{O}_{CP}]\{d\sigma(pp \to t\bar{t}X)/dPS\}\, dPS}{\int \{d\sigma(pp \to t\bar{t}X)/dPS\}\, dPS}, \quad (1)$$

where $\mathcal{O}_{CP}$ is an operator designed to maximize sensitivity of $\alpha$ to the $c^2 - d^2$ term. (We use the notation $PS$ for phase space.) Some simple operators that offer substantial sensitivity to $c^2 - d^2$ are

$$\begin{aligned}
a_1 &= \frac{(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})}{|(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})|}, \qquad a_2 = \frac{p_t^x p_{\bar{t}}^x}{|p_t^x p_{\bar{t}}^x|}, \\
b_1 &= \frac{(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})}{p_t^T p_{\bar{t}}^T}, \\
b_2 &= \frac{(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})}{|\vec{p}_t||\vec{p}_{\bar{t}}|}, \\
b_3 &= \frac{p_t^x p_{\bar{t}}^x}{p_t^T p_{\bar{t}}^T}, \qquad b_4 = \frac{p_t^z p_{\bar{t}}^z}{|\vec{p}_t||\vec{p}_{\bar{t}}|},
\end{aligned} \quad (2)$$

where $p_{t,\bar{t}}^T$ denote the magnitudes of the $t$ and $\bar{t}$ transverse momenta. In Eq. (2), $\hat{n}$ is a unit vector in the direction of the beam line and defines the $z$ axis; for the $x$ axis we choose any *fixed* direction perpendicular to the beam. Since all these operators will have somewhat different systematic uncertainties, it will be useful to analyze the $CP$ properties using all of them (and, perhaps, others as well).

The critical question with regard to the usefulness of a given $\alpha$ is the accuracy with which it can be measured relative to the predicted changes in $\alpha$ as a function of the $CP$ nature of the $h$. There will be background as well as $t\bar{t}h$ signal contributions in any $t\bar{t}X$ channel ($X = \gamma\gamma$ or $b\bar{b}$). We define $\alpha_S$ and $\alpha_B$ to be the value of $\alpha$ as defined in Eq. (1) for the signal and background cross sections on their own. We also define

$$\beta[\mathcal{O}_{CP}] \equiv \frac{\int [\mathcal{O}_{CP}]^2\{d\sigma(pp \to t\bar{t}X)/dPS\}\, dPS}{\int \{d\sigma(pp \to t\bar{t}X)/dPS\}\, dPS}, \quad (3)$$

 

and the $\beta_S$ and $\beta_B$ values of $\beta$ for the signal and background individually. Then, one finds that the experimental error for $\alpha_s$ is given by

$$\delta\alpha_S = S^{-1/2}\left[\beta_S - \alpha_S^2 + \frac{B}{S}(\beta_B - 2\alpha_B\alpha_S + \alpha_S^2)\right]^{1/2}, \quad (4)$$

where $S$ and $B$ are the total number of signal and background events, respectively, in the $t\bar{t}X$ channel being considered. Note that $\beta = 1$ for the $a_i$ operators. Since deviations from the SM predictions for the $t\bar{t}X$ background could be present, it will be important to experimentally measure (using data with $M_X$ not in the vicinity of $m_h$) $B$, $\alpha_B$, and $\beta_B$ with high precision. In what follows, we use in Eq. (4) values calculated in the SM as a guide.

Let us now focus on the $X = \gamma\gamma$ channel. Detection of a Higgs boson in the $t\bar{t}\gamma\gamma$ final state was originally proposed in Ref. [5] and has been thoroughly studied by both the ATLAS and CMS Collaborations in their technical proposals [6,7]. The final state employed is that in which one $t$ decays semileptonically, while the other decays hadronically. This allows identification of $t$ vs $\bar{t}$, and reconstruction of the transverse momenta of both $t$ and $\bar{t}$. This is already sufficient for defining $a_{1,2}$ and $b_{1,3}$ in Eq. (2). The $b_{2,4}$ operators of Eq. (2) require knowledge of the full $t$ and $\bar{t}$ three-momenta. For the hadronically decaying $t$, the three jets can be used for this determination. Determination of the $z$ component of momentum of the leptonically decaying $t$ is subject to the usual twofold ambiguity in determining the $z$ component of the momentum of the unobserved neutrino using the missing transverse energy, $m_\nu = 0$, and the known value of $m_t$. The algorithm in which $p_\nu^z$ is chosen so as to minimize the overall rapidity of the $t\bar{t}h$ system yields the correct solution a large fraction of the time.

We first present the values of $\alpha$ and $\beta$ for signal and background, for the various different $\mathcal{O}_{CP}$ operators listed in Eq. (2), assuming a Higgs boson mass of $m_h =$ 100 GeV. These values include mild cuts on the outgoing $t, \bar{t}$ and photons of $|y_{t,\bar{t},\gamma}|\langle 4, p_\gamma^T\rangle m_h/4$. In actual practice, the detector collaborations must compute the expected numbers using their full cuts and resolutions. Results for $\alpha_B$ and $\beta_B$ are given in Table I, and results for $\alpha_S$ and $\beta_S$ are given in Table II for several choices of $c, d$. Also given are the values of $S^{1/2}\delta\alpha_S$ in the limit of zero background. These latter values, in comparison to the changes in $\alpha_S$ as a function of $(c, d)$, give a first indication of the relative sensitivity of the various $\mathcal{O}_{CP}$ operators to different values of $c, d$. We see that the operators $a_1$, $b_1$, $b_2$, and $b_4$ will be most useful, $b_1$ probably being the best, both in that it exhibits the largest relative changes and also in that it can be constructed without the use of $z$-component momenta.

TABLE I. $t\bar{t}\gamma\gamma$ channel $\alpha_B$ and $\beta_B$ values, assuming $m_h = 100$ GeV.

| $\mathcal{O}_{CP}$ | $a_1$ | $b_1$ | $b_2$ | $a_2$ | $b_3$ | $b_4$ |
|---|---|---|---|---|---|---|
| $\alpha_b$ | $-0.863$ | $-0.796$ | $-0.249$ | $-0.698$ | $-0.404$ | 0.130 |
| $\beta_B$ | 1 | 0.806 | 0.127 | 1 | 0.332 | 0.411 |

Of course, we must include the background in order to obtain the true value of $\delta\alpha_S$, see Eq. (4). Let us focus on the case where the $h$ has SM-like couplings and ask how well we can measure $\alpha_S$ in this case. For this purpose, we employ the results from the CMS experimental technical proposal, Fig. 12.8 (in which $L = 162.5$ fb$^{-1}$ is assumed), scaled to the current standard benchmark in which it is assumed that the ATLAS and CMS detectors will (in combination) accumulate an integrated luminosity of $L = 600$ fb$^{-1}$. For our estimates we will sum events in a 5 GeV interval centered at $M_{\gamma\gamma} = m_h = 100$ GeV. From the above-referenced Fig. 12.8, one obtains, after rescaling, $S = 259$ and $B = 42$ for the sum of the $W\gamma\gamma$ and $t\bar{t}\gamma\gamma$ modes. At the LHC, these two modes contribute almost equally, implying $S \sim 130$ and $B \sim 21$ for the $t\bar{t}\gamma\gamma$ mode. To quantify our ability to discriminate the SM case of $c = 1, d = 0$ from the $c = d = 1/\sqrt{2}$ and $c = 0, d = 1$ cases, we define the two discrimination powers

$$D_1 \equiv \frac{|\alpha_S(c = 1, d = 0) - \alpha_S(c = d = 1/\sqrt{2}|}{\delta\alpha_S(c = 1, d = 0)},$$

$$D_2 \equiv \frac{|\alpha_S(c = 1, d = 0) - \alpha_S(c = 0, d = 1)|}{\delta\alpha_S(c = 1, d = 0)}. \quad (5)$$

These definitions of $D_{1,2}$ are those appropriate if the observed Higgs boson is $CP$ even [so that it is appropriate to use $\delta\alpha_S(c = 1, d = 0)$ in computing the experimental error]. [If the $h$ is pure $CP$ odd, $D_2$ should be defined using $\delta\alpha_S(c = 0, d - 1)$; if it is an equal $CP$-even and $CP$-odd mixture, $D_1$ should be defined using $\delta\alpha_S(c = d = 1/\sqrt{2})$.] The numerical values for $D_{1,2}$ are given in Table III and indicate the level of statistical significance at which an observed $CP$-even $h$ could be said to *not* be (1) an equal mixture of $CP$-odd and $CP$-even or (2) a purely $CP$-odd state. These values may be somewhat optimistic in that the above rates are those obtained before reconstructing the $t$ and $\bar{t}$. However, because of the cleanliness of the $t\bar{t}\gamma\gamma$ final state, we do not anticipate a large event rate loss for such reconstruction.

As anticipated, the operators $a_1$, $b_1$, $b_2$, and $b_4$ provide the best discrimination. For the best single operator, $b_1$, discrimination from the $c = d = 1/\sqrt{2}$ case is only achieved at the $\sim 1.5\sigma$ level. To reach the more satisfactory $3\sigma$ level would require about 4 times as much integrated luminosity. Discrimination between the purely $CP$-even case and the purely $CP$-odd case would be possible using $b_1$ at a high level of statistical significance, $\sim 7\sigma$. Better statistical significance in both cases can be achieved to the extent that the different operators are sensitive to different aspects of the $t$ and $\bar{t}$ distributions in the final state. In particular, $b_4$ is primarily sensitive to the $t, \bar{t}$ longitudinal

TABLE II. Values of $\alpha_S$ and $\beta_S$ for the $t\bar{t}h$ production, assuming $m_h = 100$ GeV for the following cases: $c = 1, d = 0$; $c = d = 1/\sqrt{2}$; $c = 0, d = 1$. Also given is $S^{1/2}\delta\alpha_S$ in the limit $B = 0$.

| $\mathcal{O}_{CP}$ | $a_1$ | $b_1$ | $b_2$ | $a_2$ | $b_3$ | $b_4$ |
|---|---|---|---|---|---|---|
| $c = 1, d = 0$ | | | | | | |
| $\alpha_S$ | −0.810 | −0.718 | −0.269 | −0.619 | −0.359 | 0.292 |
| $\beta_S$ | 1 | 0.736 | 0.151 | 1 | 0.308 | 0.376 |
| $S^{1/2}\delta\alpha_S$ | 0.586 | 0.469 | 0.280 | 0.785 | 0.424 | 0.539 |
| $c = d = 1/\sqrt{2}$ | | | | | | |
| $\alpha_S$ | −0.742 | −0.654 | −0.243 | −0.562 | −0.327 | 0.228 |
| $\beta_S$ | 1 | 0.707 | 0.139 | 1 | 0.302 | 0.372 |
| $S^{1/2}\delta\alpha_S$ | 0.671 | 0.528 | 0.283 | 0.827 | 0.442 | 0.566 |
| $c = 0, d = 1$ | | | | | | |
| $\alpha_S$ | −0.486 | −0.407 | −0.147 | −0.335 | −0.200 | −0.005 |
| $\beta_S$ | 1 | 0.593 | 0.096 | 1 | 0.272 | 0.371 |
| $S^{1/2}\delta\alpha_S$ | 0.874 | 0.654 | 0.272 | 0.942 | 0.482 | 0.609 |

momenta distributions, as distinct from the transverse momenta distributions that determine $b_1$. Simply combining the statistics for these two different moments would imply that $c = 1, d = 0$ could be distinguished from $c = d = 1/\sqrt{2}$ at nearly the $2\sigma$ level, assuming the $L = 600$ fb$^{-1}$ SM-like event rate. In reality, the experimental groups would undoubtedly obtain the best level of discrimination by studying the likelihood that a particular $c, d$ mixture fits their data in an overall sense (without assuming knowledge of normalization).

A second possible channel for this type of analysis is the $X = b\bar{b}$ channel (i.e., $t\bar{t}b\bar{b}$ final state). The signal event rate is much larger than in the $t\bar{t}\gamma\gamma$ final state, but there are large backgrounds. This channel for Higgs discovery was first explored in Refs. [8,9], and has been studied by the ATLAS and CMS Collaborations with generally encouraging results [6,7,10]. These analyses isolate a signal by demanding that one of the $t$'s decay semileptonically, and that three or four $b$ quarks be tagged. The expected $b$-tagging efficiency and purity at high luminosity are sufficiently large that statistically significant signals for a SM-like $h$ can be achieved. In Ref. [6], with $L = 100$ fb$^{-1}$ and using 3-$b$ tagging, a roughly $5\sigma$ signal is seen for $m_h \sim 100$ GeV, despite a small $S/B \sim 1/40$ signal to background ratio. In the parton-level study of Ref. [8], it was found that 4-$b$ tagging yields a cleaner $S/B \sim 1/2$, but $S$ is also reduced so that $S/\sqrt{B}$ for $L = 100$ fb$^{-1}$ is at most increased to $S/\sqrt{B} \sim 8-10$. Neither of these analyses demands that the $t$ quarks be reconstructed, as would be required in order to construct the $\mathcal{O}_{CP}$ operators considered here. Such reconstruction could well improve the $S/B$ ratios (in particular, by largely eliminating the combinatoric backgrounds), but undoubtedly at further sacrifice of signal event rate. Nonetheless, it seems probable that, for the combined ATLAS + CMS benchmark luminosity of $L = 600$ fb$^{-1}$, $S/\sqrt{B} \geq 5$ can be achieved after full $t$-quark reconstruction. We assume that after such reconstruction the only significant background will be from the irreducible $t\bar{t}b\bar{b}$ background process. (This is clearly the case if 4-$b$ tagging is employed.) In analyzing the experimental error on the determination of $\alpha_S$ for the different $\mathcal{O}_{CP}$ operators, we then need only compute the $\alpha_B$ and $\beta_B$ values for the irreducible $t\bar{t}b\bar{b}$ background.

The values of $\alpha_B$ and $\beta_B$ for the cuts $|y_{t,\bar{t},b,\bar{b}}| < 4$ and $p^T_{b,\bar{b}} > m_h/4$ are given in Table IV. The corresponding signal reaction $\alpha_S$ and $\beta_S$ values for the various $\mathcal{O}_{CP}$ operators are unchanged from the results appearing in Table II. Although the cuts that will be required in the eventual analysis will be far more complex, the changes in $\alpha_s$, $\beta_S$, $\alpha_B$, and $\beta_B$ are unlikely to be so large as to invalidate the estimates obtained below.

Given $\alpha_s$, $\beta_S$, $\alpha_B$, and $\beta_B$, it is straightforward to compute the signal rate $S$ for a SM-like Higgs that would be required to achieve $D_1 = 2$ (that is, to discriminate a pure $CP$-even coupling from an equal $CP$-even and $CP$-odd mixture at the $2\sigma$ statistical level) as a function of $B/S$. The results are easily summarized. For $B/S \sim 1$, $D_1 = 2$ requires $S \sim 700$ ($\sim$600), equivalent to $S/\sqrt{B} \sim 26$ ($\sim$24), using $\mathcal{O}_{CP} = b_1$ ($b_4$). For $B/S \sim 50$, $D_1 = 2$ requires $S \sim 20\,000$ ($\sim$15 000), equivalent to

TABLE III. $t\bar{t}\gamma\gamma$ channel, $m_h = 100$ GeV: the discrimination powers $D_{1,2}$ for $S = 130$ and $B = 21$.

| $\mathcal{O}_{CP}$ | $a_1$ | $b_1$ | $b_2$ | $a_2$ | $b_3$ | $b_4$ |
|---|---|---|---|---|---|---|
| $D_1$ | 1.26 | 1.47 | 0.97 | 0.78 | 0.81 | 1.21 |
| $D_2$ | 5.97 | 7.10 | 4.67 | 3.87 | 3.97 | 5.65 |

TABLE IV. $t\bar{t}b\bar{b}$ channel $\alpha_B$ and $\beta_B$ values, assuming $m_h = 100$ GeV.

| $\mathcal{O}_{CP}$ | $a_1$ | $b_1$ | $b_2$ | $a_2$ | $b_3$ | $b_4$ |
|---|---|---|---|---|---|---|
| $\alpha_B$ | −0.552 | −0.478 | −0.177 | −0.395 | −0.239 | 0.241 |
| $\beta_B$ | 1 | 0.642 | 0.122 | 1 | 0.284 | 0.375 |

$S/\sqrt{B} \sim 20$ ($\sim$17), for $\mathcal{O}_{CP} = b_1$ ($b_4$). Although the $S$ values for $b_4$ are a bit smaller than for $b_1$, these are not inaccuracies associated with using longitudinal momenta to construct the former. Note that, for large $B/S$, $S/\sqrt{B} \sim 20$ is inevitably required to achieve $D_1 \sim 2$ (using $b_1$). The signal event rate required for $D_2 = 2$, i.e., to distinguish a purely $CP$-even Higgs from a purely $CP$-odd Higgs at the $2\sigma$ level, is only about 1/20 that needed to achieve $D_1 = 2$ (for a given $B/S$); $D_2 \sim 2$ is achieved whenever $S/\sqrt{B} \sim 4-5$.

The above rules arise because $D_{1,2}$ scale as $S/\sqrt{B}$ for large $B/S$, see Eq. (4). At large $B/S$, we find in the $b\overline{b}$ channel

$$D_1 = 2(S/\sqrt{B})/22, \qquad D_2 = 2(S/\sqrt{B})/4.4 \qquad (6)$$

when employing the operator $b_1$ (alone). In fact, the $S/\sqrt{B}$ values required for a given $D_{1,2}$ value are remarkably independent of $B/S$ once $B/S \gtrsim 2$.

Overall, the $t\bar{t}b\overline{b}$ channel will probably not be as useful as the $t\bar{t}\gamma\gamma$ channel in the case of a SM-like $CP$-even Higgs boson. However, for a non-SM-like Higgs boson, $B(h \rightarrow \gamma\gamma)$ might be too small to yield an observable signal in the $t\bar{t}\gamma\gamma$ final state, whereas $B(h \rightarrow b\overline{b})$ will generally be large, and an observable signal in the $t\bar{t}b\overline{b}$ channel will be possible so long as the $t\bar{t}h$ coupling is not significantly suppressed compared to SM strength. The most difficult example is the case of a purely $CP$-odd $A^0$. The absence of the $W^+W^-A^0$ coupling implies very small $B(A^0 \rightarrow \gamma\gamma)$. In a two-Higgs-doublet model of type II, the $t\bar{t}A^0(b\overline{b}A^0)$ coupling is $\propto\cot\beta(\propto\tan\beta)$, where $\tan\beta$ is the ratio of the vacuum expectation values of the two neutral Higgs doublet fields [1,2]. In the preferred $\tan\beta > 1$ region of parameter space, the $t\bar{t}A^0$ production cross section, proportional to $\cot^2\beta$, is suppressed, but $B(A^0 \rightarrow b\overline{b})$ is large (for $m_{A^0}$ below $2m_t$). With $L = 600$ fb$^{-1}$, it might prove possible to achieve $S/\sqrt{B} \sim 5$ for $\tan\beta \lesssim 2$, which [assuming large $B/S$ and employing $\delta\alpha_S(c = 0, d = 1)$ for $b_1$ from Table II in defining $D_2$] would imply $D_2 \sim 1.6$. This would at least add support to the indirect evidence for a large $CP$-odd component deriving simply from the absence of observable $W$ + Higgs and $t\bar{t}\gamma\gamma$ channel signals.

In this Letter, we have shown that weighted moments of the $t\bar{t}h$ production cross section can provide a rough but direct (cross section normalization independent) determination of the $CP$ nature of a light Higgs boson at the LHC. In the $t\bar{t}\gamma\gamma$ final state, if we employ the best single weighting operator that does not depend upon the longitudinal momenta of the $t$ quarks, a SM-like Higgs boson (pure $CP$ even) can be distinguished from a Higgs boson that is an equal mixture of $CP$ odd and $CP$ even at the $\sim 1.5\sigma$ statistical level with about 130 signal events (assuming $B/S \ll 1$). This is roughly the number obtained for a combined ATLAS + CMS luminosity of $L = 600$ fb$^{-1}$ (assuming that the required $t$-quark reconstruction does not cause large losses in this final state). About 240 signal events are needed to achieve $2\sigma$ discrimination. These same numbers of events would distinguish the purely $CP$-even Higgs from a purely $CP$-odd Higgs at the $\sim 7\sigma$ and $\sim 10\sigma$ level, respectively. If the best operator depending upon $t$-quark longitudinal momenta can also be employed, the above statistical significances would increase by about 40%.

In the $t\bar{t}b\overline{b}$ channel, typically characterized by $B/S \gtrsim 1$ (possibly $\gg$1), $2\sigma$ discrimination between a pure $CP$-even Higgs and one with an equal mixture of $CP$-odd and $CP$-even components requires $S/\sqrt{B} \sim 20$, which would, in general, be very difficult to achieve (except for a Higgs with enhanced $t\bar{t}A^0$ coupling—requiring $\tan\beta < 1$ in the $CP$-violating type-II two-Higgs-doublet model). However, distinguishing between purely $CP$-even and purely $CP$-odd coupling at the $\gtrsim 2\sigma$ level is possible whenever $S/\sqrt{B} \gtrsim 4$, that is, whenever the Higgs boson can be detected.

Our analysis has made use of rather simplified cuts; the experimental groups should compute the weightings defined in Eqs. (1) and (3) using their full simulation, including the necessary $t$-quark reconstruction.

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