Probing the $\mathcal{CP}$ violation of the top-Yukawa coupling at future colliders

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To explain baryogenesis, $\mathcal{CP}$-violating effects beyond those predicted by the Standard Model are essential. With the discovery of the Higgs boson, attention has turned to exploring the $\mathcal{CP}$ structure within the Higgs sector. While $\mathcal{CP}$-violating Higgs couplings to vector bosons are loop-suppressed in most BSM models, such models often predict the largest amount of $\mathcal{CP}$ violation in Higgs-fermion couplings. The top-Yukawa coupling is particularly important, as it is the largest and most accessible one.

In this study, we use the Higgs Characterization Model and parameterize the Higgs-top coupling via

$$\mathcal{L}_{\text{top-Yuk}} = -\frac{y_t^{SM}}{\sqrt{2}}\bar{t}\left(c_t + i\gamma_5\tilde{c}_t\right)tH, \tag{1}$$

where y_t^{SM} is the SM top-Yukawa interaction and $c_t = 1$ as well as $\tilde{c}_t = 0$ for the SM. Events are generated using `MadGraph5_aMC@NLO` and are passed to `Pythia8` and `Delphes3` for parton showering, hadronisation, and detector simulation.

The goal of this study is to evaluate the constraints that future colliders could impose on the parameters c_t and $\tilde{c}_t$, and therefore on their potential sensitivity to deviations from the SM in the Higgs-top coupling. While an e^+e^- collider like the FCC-ee benefits from a very clean background, which allows precise measurements of final states with many quarks, a proton-proton collider like the FCC-hh offers the advantage of a massive amount of events and data.

In order to examine the CP structure of the top-Yukawa coupling, we generate data for the scenarios $c_t = 1$, $\tilde{c}_t = 0$ and $c_t = 0$, $\tilde{c}_t = 1$. This process results in separate data sets corresponding to purely $\mathcal{CP}$-even and purely $\mathcal{CP}$-odd contributions, respectively. The distribution of events across various kinematic variables is analyzed to construct likelihood functions. For example, Figure 1 shows the kinematic distribution for E_H, the energy of the produced Higgs boson, which is notably sensitive to the $\mathcal{CP}$ structure. These likelihoods are combined to explore the parameter space of c_t and $\tilde{c}_t$, enabling us to set limits on the couplings. By combining different kinematic distributions in a machine learning algorithm, we can enhance the distinction between $\mathcal{CP}$-even and $\mathcal{CP}$-odd scenarios, which allows us to set tighter constraints on c_t and $\tilde{c}_t$ and increase the sensitivity to $\mathcal{CP}$-violating effects. An example of the resulting constraints on c_t and $\tilde{c}_t$ is illustrated in Figure 2.

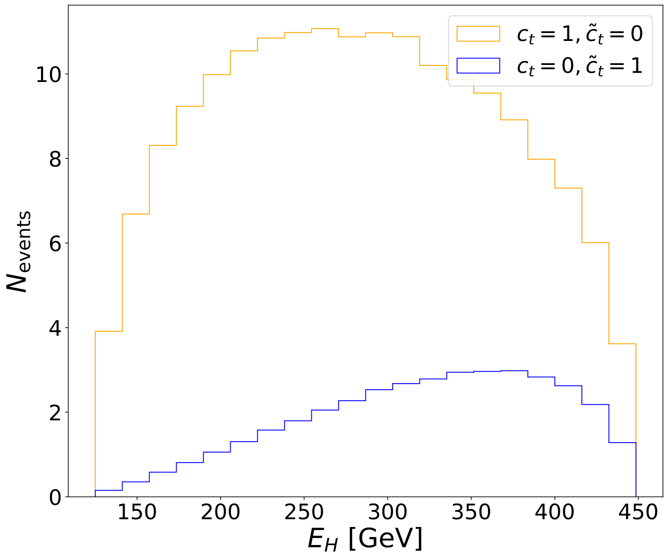

Figure 1: Distributions of the kinematic variable E_H for the two scenarios $c_t = 1$, $\tilde{c}_t = 0$ and $c_t = 0$, $\tilde{c}_t = 1$. The distributions illustrate the differences between the $\mathcal{CP}$-even and $\mathcal{CP}$-odd cases.

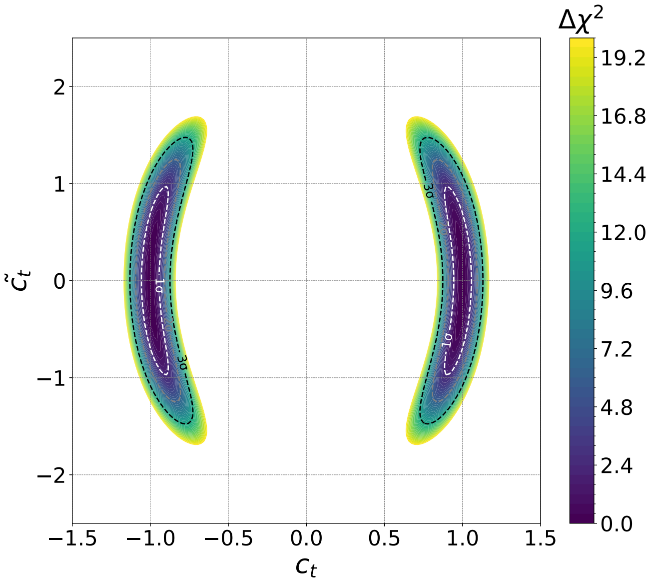

Figure 2: Limits derived from the classifier trained to distinguish between the scenarios $c_t = 1$, $\tilde{c}_t = 0$ and $c_t = 0$, $\tilde{c}_t = 1$. The 1-, 2-, and 3-σ confidence level contours are marked by white, grey, and black dashed lines, respectively.