We explore $CP$-violation effects of Higgs-top interactions in the associated production of a Higgs boson with top-pair in the dileptonic decay modes of top-quark originating from proton proton collisions $pp \rightarrow t\bar{t}H \rightarrow (l^+\nu_l b)(l^-\bar{\nu}_l \bar{b})H$ at NLO in QCD matched to parton shower via T-odd observables using momenta of various particles involved in the process. In particular, we predict the constraints on the $CP$-violating $t\bar{t}H$ coupling obtained through the production asymmetries associated with the T-odd observables in the dileptonic decay channel of the $t\bar{t}$ pair for the LHC with centre-of-mass energy of 13 TeV and an integrated luminosity of 139 fb$^{-1}$. We also present the corresponding limits for future hadron colliders, namely the High Luminosity LHC (HL-LHC) and the Future Circular Collider (FCC-HH). Our estimates of the $t\bar{t}H$ interaction strength reveal that the upper bound on pseudoscalar coupling $c_p$ corresponding to the largest asymmetry would be of about $1.96 \times 10^{-2}$ at 2.5$\sigma$ C.L. for $c_s = 1$ at the LHC with $\sqrt{S} = 13$ TeV for an integrated luminosity of 139 fb$^{-1}$. The respective limits for HL-LHC and FCC-hh with the projected Luminosities of 3 ab$^{-1}$ and 30 ab$^{-1}$ are found to be to $3.4 \times 10^{-3}$ and $1.6 \times 10^{-4}$ respectively at 2.5$\sigma$ C.L.
1 Introduction

The Standard Model (SM) [1–4] was considered an enormously successful and affluent model prior to experimental evidence in the discovery of the Higgs boson [5–8] which is an essential component of SM. The discovery of the Higgs boson marked the beginning of a new era in particle physics when the ATLAS [9] and CMS [10] in Run-1 of the Large Hadron Collider (LHC) strongly confirmed the existence of the Higgs boson with a mass of about 125 GeV, which is analogous to the SM Higgs boson with spin-zero and parity even. After the discovery of the Higgs boson, it has become paramount to determine its physical properties. Some of its properties like spin and mass have been measured with data sets collected during Run-1 and Run-2 of the LHC that are identical to those predicted by SM within the limits of theoretical and experimental uncertainties. Deviations are still allowed since the Higgs boson in the SM has a very unnatural mass and the current data show large uncertainties in the measurement of many Higgs couplings, such as Higgs-top couplings, indicating that these need to be explored precisely. The fact that there are large uncertainties in the measurement of the Higgs boson coupling with the fermion and vector bosons indicates that there is ample room for the existence of new physics, therefore the Higgs boson sector is of high relevance for studying new physics effects in BSM investigations. Consequently, one of the main objectives of the future LHC run is to investigate the true nature of the Higgs boson and precisely measure the Higgs boson properties such as its coupling with SM particles, its \( CP \) nature, etc. To absolutely establish the true nature of the Higgs boson requires precisely measuring the Higgs coupling to fermion and gauge bosons and the Higgs self-coupling, so the important task of upcoming experiments at the LHC is to measure these couplings to the greatest possible accuracy. The LHC is currently undergoing significant upgrades for its upcoming Run which is Run-3 which will be a High Luminosity Phase [11] where the Luminosity will be significantly enhanced. It is anticipated that much larger data sets will be collected during Run-3 which will lead to better understanding of systematic uncertainties and increase experimental accuracy by substantially reducing experimental errors. Considering such promising experimental possibilities in future High Luminosity and high energy experiments, it is beneficial to conduct a comprehensive study to explore the properties of the Higgs boson in different BSM scenarios.

Exploring the \( CP \) nature of the Higgs boson interactions is crucial in order to find an explanation for the existing imbalance between matter and antimatter. Since the SM does not provide a sufficient amount of \( CP \)-violation to explain the current matter-antimatter asymmetry of the Universe [12–15], exploring Higgs boson interactions may provide new sources for the investigation of such phenomena in many beyond the Standard Model (BSM) theories. Interestingly, new sources of \( CP \)-violation may play a major role in understanding the present asymmetry, hence exploring new \( CP \)-violation sources beyond SM theories is of utmost importance for the future Hadron Colliders. In addition to unravelling the matter-antimatter asymmetry, studies concerning the hierarchy problem or the naturalness problem [16–18], dark matter (DM) abundance [19,20], non-vanishing neutrino masses [21], inflation [22], etc. specifically demand exploring the Higgs boson extensions.

The interaction of the Higgs boson with the heaviest fermion, that is, the top-quark, is phenomenologically and theoretically important as it has the strongest coupling with the Higgs boson since the associated Yukawa coupling is the largest. Thus, the accurate measurement of the Higgs-top interaction plays a crucial role in establishing the true nature
of the Higgs boson and also contributes to understanding the vital problem of vacuum stability [23, 24] and several cosmological phenomena, such as baryogogenesis [25, 26] and electroweak phase transition [27] etc. The possible production modes of the Higgs boson at the LHC are: gluon-gluon fusion (ggf), vector-boson fusion (VBF), associated production with a $W^\pm$ or Z boson (VH, V=W or Z) and production in association with a single top-quark ($tH$) or with a top-pair ($ttH$). Although Higgs-top coupling can be accessed through loop-induced processes [28–30] however the leading contribution comes primarily through two possible processes: a) the production of the Higgs Boson in association with top pair [31–47] and b) associated production of the Higgs Boson with single top [48–64] at the LHC. The production rate of the Higgs boson in association with the top pair is relatively high and is dominant, therefore, crucial to potentially disentangle the new physics effects [43, 65–68]. Furthermore, the importance of the process $pp \rightarrow t\bar{t}H$ [38, 69] lies in the fact that the actual presence of the top-quark can be observed in the final state particles [32, 70]. In the case of Yukawa coupling, the $CP$ -odd contribution in the interaction of Higgs to fermion is unsuppressed and therefore the study of the Higgs-fermion-fermion interaction is much more useful in this respect and will allow us to have a clear understanding of the $CP$ structure of the Higgs Boson. The $t\bar{t}H$ channel was detected by ATLAS with a significance of about 6.3 and by CMS with a significance of approximately 5.2 [71, 72].

In the present manuscript, we perform a systematic and detailed investigation of the $CP$-violating effects of the Higgs-top coupling using T-odd observables considering the dominating Higgs production process, $pp \rightarrow t\bar{t}H$ in the dileptonic decay mode of the top-quark. We conduct the analysis at Next-to-leading order (NLO) accuracy in QCD matched to parton-showers (NLO+PS). The present study aims to explore the potential of the T-odd triple product correlations constructed via the momenta of the final decay products in the corresponding Higgs top-pair production at the LHC and Future Hadron Colliders for improving $CP$-violation sensitivity to anomalous Higgs-top interactions. We work in an effective field theory framework to make our study model-independent and analytical enough for studying CP-violating Higgs-top interactions in the BSM models. In this approach, an effective Lagrangian is constructed by introducing higher dimensional operators to incorporate new physics contributions to the Standard Model and where the $t\bar{t}H$ vertex is parameterized in terms of two unknown factors, a $CP$-even component $c_\alpha$ and a $CP$-odd component $c_\beta$. Particularly in this work, the main idea is to find the constraints on the $CP$-violating anomalous Higgs-top coupling at NLO accuracy including parton-shower effects (NLO+PS) from cross-section measurements as well as from production asymmetries for the LHC with $\sqrt{S} = 13$ TeV and an integrated luminosity of $\int Ldt = 139$ fb$^{-1}$. In addition, we derive projections for Future Hadron Colliders, namely, HL-LHC and FCC-hh for $\sqrt{S} = 14$ TeV and 100 TeV with luminosities of 3 ab$^{-1}$ and 30 ab$^{-1}$, respectively.

So far $CP$-violation in Higgs-top interactions via Higgs production and decay has received considerable attention and has been extensively probed in the literature [31–41, 48–51, 56–58, 64, 65, 70, 72–87]. However Refs. [45, 88–90] discuss the Higgs interactions at NLO accuracy in QCD including the parton shower effects. The first phenomenological study of the Higgs production in association with top-antitop pair to NLO accuracy in QCD matched to parton showers for both $CP$-even and -odd cases was performed in Ref. [38]. Ref. [90] first provided a complete analysis of the Higgs-top interaction in the $ttH$ channel at NLO in QCD, interfaced with parton showers for BSM studies by including the
necessary Ultraviolet (UV) and $R_2$ terms in the UFO model. The model is also publicly available. Also, they showed that angular pseudorapidity separation between the leptons or between b-jets in the context of the Higgs production with top pair is a promising observable to probe $CP$ nature of Higgs interactions at high $p_T$ region. In addition, studies related to Higgs coupling to gluons [91], tau leptons [92–95], and muons [96,97] have also been explored independently. Besides, $CP$-violation in the processes of top-production and decay has also been searched immensely in the existing literature [98–105]. Upper limits on neutron, mercury and electric dipole moments (EDMs) have placed indirect constraints on the anomalous Higgs-top interactions. The contribution of the $CP$-violation component of the anomalous Higgs-top interactions determines the strongest constraint for electron EDM [28]. Furthermore, other studies such as low-energy physics probes set relatively lower bounds [29, 85, 106–111].

The structure of the paper is as follows: In Section 2, we discuss the parameterization for the Higgs-top Yukawa coupling and present the effective Lagrangian that we have considered as a benchmark model for our study. Furthermore, we discuss the key observables relevant for our study to probe the $CP$-violation sensitivity of the Higgs top interaction. In Section 3, we present a detailed analysis and investigate the sensitivity of the anomalous Higgs-top interactions through cross-section measurements at NLO+PS. Also in the same section, we construct the production asymmetries corresponding to the various $CP$-violating observables, defined in section 2 in the context of the di-leptonic decay modes of both top-quarks and derive constraints on the anomalous $t\bar{t}H$ coupling corresponding to the most promising asymmetries encountered here at the LHC and the Future Hadron Colliders such as HL-LHC and FCC-hh. Finally, Section 4 concludes the paper.

2 $pp \rightarrow t\bar{t}H$ Process and T-odd Observables

The present study includes the Higgs production in association with a top and anti-top-quark where the top (anti-top)-quark further decays leptonically into $bl^+\nu_l$ ($\bar{b}\bar{l}^-\bar{\nu}_l$). However, there can be possibilities for many other potential signatures, although we are mainly interested only in those signatures in which most of the leptons are in the final state as this would lead to a smaller background. Representative parton level diagrams showing the production mechanism of the Higgs boson with the top-pair are displayed in Fig. 1. It includes the production of Higgs with top-pair via gluon-gluon annihilation and $q\bar{q}$ annihilation, where the first five diagrams in the two rows represent production via gluon-gluon annihilation and the last row shows the $q\bar{q}$ annihilation process. The process $pp \rightarrow t\bar{t}H$ occurs primarily through the gluon-gluon annihilation process $gg \rightarrow t\bar{t}H$ while the leading contribution comes from one-loop diagrams. Gluon-initiated processes are anticipated to play a vital role in the search for new physics at the Hadron Colliders as gluon luminosity increases with an increase in center-of-mass energy. On the other hand, the $q\bar{q}$ annihilation processes, due to Higgs boson coupling and very light quarks, make a negligible contribution. The current study aims to investigate the $CP$-violating effects of Higgs-top coupling arising due to the presence of the $t\bar{t}H$ vertex in the $pp \rightarrow t\bar{t}H$ process. In SM, Higgs-top coupling is a purely scalar interaction and consists only scalar-type of components, whereas models beyond SM include both scalar and pseudoscalar couplings as the non-linear perception of electroweak gauge symmetry comes into the scenario. The Higgs boson can also be a $CP$-mixed state in these models [112,113] and the possibility
of a mixture of scalar and pseudoscalar couplings has also been confirmed by the present
data [56,79]. Typically, constructing a model that can specifically induce \( CP \)-violating
operators is difficult. Furthermore, the idea of a completely \( CP \)-odd Higgs boson has not
been favored experimentally and the LHC experiment has already rejected speculation
of a pure \( CP \)-odd Higgs. However, the constraint imposed by the experiments on the
\( CP \)-mix state, that is, mixing of \( CP \)-odd and \( CP \)-even states of the Higgs boson, is very
low [114,115]. Consequently, a model that contains a Lagrangian with both \( CP \)-even and
\( CP \)-odd components, will be more realistic.

![Feynman diagrams](image)

Figure 1: Representative parton-level Feynman diagrams of the process \( pp \to t\bar{t}H \) in leading
order at the LHC. The diagrams were obtained through JaxoDraw [116,117].

We consider the following most general parameterization of the Higgs-top Yukawa cou-
pling by employing an effective Lagrangian [74],

\[
L_{t\bar{t}H} = -\frac{y_t}{\sqrt{2}} t(c_s + ic_p \gamma_5)H,
\]

(1)

where \( H \) is the Higgs field, \( y_t = \sqrt{2} \frac{m_t}{v} \) in which \( m_t \) is the mass of the top-quark and \( v \)
is the electroweak symmetry breaking scale known as the Higgs vacuum expectation value
\((v = 246 \text{ GeV})\). \( c_s \) and \( c_p \) are dimensionless parameters known as scalar and pseudo-scalar
component that represent \( CP \)-even and \( CP \)-odd anomalous Higgs-top interaction, respec-
tively. In SM at the tree level, \( c_s \) and \( c_p \) take the values \( c_s = 1 \) and \( c_p = 0 \), while a non zero
value of the coupling \( c_p \) would indicate a deviation towards the non SM and show beyond
the SM contribution. It is to be noted here that the \( CP \)-violating component \( c_p \) receives a
contribution from the loop at higher order in the SM but is very small. However, in models beyond SM, it is anticipated that $CP$-violating component may receive a relatively large contribution from higher order effects such as higher dimensional operators in an effective field theory scenario. It is worth mentioning here the importance of considering the production of Higgs boson with top-pair which lies in the fact that the top-quark is unique among all quarks owing the largest mass $m_t = 172.5 \pm 0.7$ GeV [118]. It is because of its large mass, the top-quark has a very short life-time ($\sim 10^{-25}$ sec), which is shorter than the characteristic hadronization time scale. Therefore it decays rapidly before it can form any bound state by getting affected with the non-perturbative QCD effects and hence the properties of the top-quark are passed on entirely to its decay products. Consequently, the top-quark properties can be traced back from its decay products as decay products preserve information of its properties and are therefore useful for investigating direct $CP$-violation effects in these events.

Several kinematic observables sensitive to the Higgs-top $CP$ structure have been discussed in the literature so far, e.g., cross-section, invariant mass distribution, transverse Higgs momentum distribution and azimuthal angular separation between $t\bar{t}$ and $tH$ [90, 119–121]. But these are $CP$-even observables and require the full reconstruction of the top and the anti-top momenta. Such observables only give an indirect measure of $CP$-violation and are therefore not helpful in investigating direct $CP$-violation. To probe direct $CP$-violation, $CP$-odd observables must be considered. Typical $CP$-odd observables can be constructed using the angular distribution but these are often experimentally challenging. Alternatively, an indirect approach is considered which can provide important complementary information. Although an indirect approach can impose stringent constraints on the $CP$-violating coupling, it is not necessary that the contribution is solely from $CP$-violating interactions and may also be due to $CP$-even interactions. The genuine $CP$-odd observable, as we considered in our study can be constructed from the anti-symmetric tensor product defined as $\epsilon(a, b, c, d) = \epsilon_{\mu\nu\alpha\beta} a^\mu b^\nu c^\alpha d^\beta$ [99,122]. Another prominent example of $CP$-odd observables are EDMs that place strong constraints on $CP$-violating Higgs-top anomalous coupling as we discussed before. As we mentioned earlier, the goal of the present study is to investigate the $CP$-violation effects of the anomalous Higgs-top interactions in the target process $pp \rightarrow t\bar{t}H$. For this, several observables can be proposed to investigate $CP$-violation effects, particularly in this study we consider the T-odd triple product correlations [99,100,105,123] constructed through the momenta of the end state products. The T-odd correlations represent the naive T-odd [124] which can also be $CP$-even and not necessarily $CP$-odd. In Ref. [100] many T-odd correlations were identified in view of the anomalous top-quark interactions in the process $pp \rightarrow t\bar{t} \rightarrow (b\ell^+\nu_l)(\bar{b}\ell^-\bar{\nu}_l)$. Of these, we have projected out some observables that are best suited for our study and can exploit the final decay channel of the target process i.e. $pp \rightarrow t\bar{t}H \rightarrow (b\ell^+\nu_l)(\bar{b}\ell^-\bar{\nu}_l)H$. Along with them, we propose other possibilities that can explore the final decay state in greater detail and may increase the sensitivity to the anomalous Higgs-top coupling. We devote special attention to the inclusion of the observables that contain momenta of Higgs boson to investigate the $CP$-violation effects that arise due to the presence of the Higgs boson.
The analysis considers the following observables:

\[ O_1 \equiv \epsilon(P, p_b - p_b, p_{l+}, p_{l-}), \]
\[ O_2 \equiv \epsilon(p_b, p_b - p_b, p_{l+}, p_{l-}), \]
\[ O_3 \equiv \epsilon(p_b, p_b, p_{l+}, p_{l-}), \]
\[ O_4 \equiv q \cdot (p_{l+} - p_{l-}) \epsilon(p_b, p_b, p_{l+} + p_{l-}, q), \]
\[ O_5 \equiv \epsilon(p_b + p_{l+}, p_{l+}, p_{l-}, p_b + p_b, p_{l+} + p_{l-}), \]
\[ O_6 \equiv \epsilon(P, p_{l+}, p_b - p_b, p_{l+} - p_{l-}), \]
\[ O_7 \equiv \epsilon(q, p_h, p_b - p_b, p_{l+} - p_{l-}), \]

(2)

where \( \epsilon \) represents the Levi Civita symbol of rank 4 which is completely anti-symmetric with \( \epsilon_{0123} = 1 \), which is contracted with the four vectors \( a, b, c, \) and \( d \) as \( \epsilon(a, b, c, d) = \epsilon_{\mu \nu \alpha \beta} a^\mu b^\nu c^\alpha d^\beta \); \( p_{l+} (p_{l-}) \) denotes the momenta of the lepton (anti-lepton) which is identified as arising from the \( W^+ (W^-) \) boson and \( p_b (p_h) \) refer the momenta of the \( b \) (\( \bar{b} \))-quark, Higgs boson respectively. \( P \) is defined as the sum of four momenta of b-quark, \( b \)-quark, lepton, anti-lepton and Higgs and \( q \) is the difference of two beam four momenta, i.e.,

\[ P \equiv p_b + p_b + p_{l+} + p_{l-} + p_h, \]
\[ q \equiv P_1 - P_2. \]

(3)

The observables defined in Eq. 2 are proportional to the triple product and take the form \( \vec{p}_i (\vec{p}_2 \times \vec{p}_3) \), where \( \vec{p}_i \) \( (i = 1, 2, 3) \) are momentum vectors. All these observables listed above are odd under \( CP \)-transformation and hence these constructions are \( CP \)-odd. Furthermore, there are many other possibilities that we have not listed above as the sensitivity corresponding to them is not significant to account for. Before moving on to further analysis, let us first discuss some important points related to the observables listed above and discuss how much information is required to conduct an efficient analysis. The importance of the above observables lies in the fact that they do not demand spin-related information of the produced particles nor do they require the reconstruction of the top-quark, rather they are constructed with momentum of the reconstructable final state particles which can be well measured in the LHC experiment. Some of these observables do not need to distinguish between \( b \) and \( \bar{b} \)-quark while others require it. However, for the cases where \( b \) and \( \bar{b} \) distinction is required, direction of leptons for the corresponding \( b \)-quarks could be used i.e. \( b \)-jet that will be near \( l^+ \) will be identified as originated from \( b \)-quarks and another \( b \)-jet closer to \( l^- \) would have originated from \( \bar{b} \)-quarks.

Obtaining non-zero value for a \( CP \)-odd observable would be a clear sign of \( CP \)-violation and therefore ensures the existence of new physics. Our search strategy relies on the measurement of asymmetry. Therefore, we conduct the analysis by constructing asymmetries corresponding to each observable given in Eq. 2 through the following expression:

\[ A_{CP} = \frac{N(O_1 > 0) - N(O_1 < 0)}{N(O_1 > 0) + N(O_1 < 0)}, \]

(4)

The above expression for the calculation of \( CP \)-violating asymmetry gives the difference between the number of events for which an observable is positive to the number of events for which it is negative, normalised to the total number of events. The presence of \( CP \)-violation in the Higgs–top interactions would be manifested by a non-zero value of the
asymmetry $A_{\mathcal{CP}}$. In SM, the asymmetry $A_{\mathcal{CP}}$ will be negligible for all the observables listed in Eq. 2. However, in case of beyond SM where anomalous $t\bar{t}H$ coupling comes into the scenario, sizable asymmetries can be produced. Since The prime focus of our study is to search for $\mathcal{CP}$-violating effects of anomalous Higgs-top interactions and since a non-zero value of asymmetry $A_{\mathcal{CP}}$ would indicate the presence of $\mathcal{CP}$-violation, we will present the values of the asymmetries measured as one of the primary results of our analysis that would indeed be the explicit verification of the statement given earlier in our analysis that all the observables are $\mathcal{CP}$-odd.

3 Numerical Analysis

We begin the analysis considering the Higgs characterisation model proposed in Ref. [89, 90, 125] to study the $\mathcal{CP}$ properties of the Higgs-top interactions in the associated Higgs production with top pair at NLO accuracy. We perform the analysis in a fully automatic manner by incorporating the relevant interaction Lagrangian given in Eq. 1 in FeynRules [126, 127]. The resulting UFO model was used to generate $t\bar{t}H$ events at NLO accuracy with the aid of the MadGraph5_aMC@NLO [128–131] framework and then the produced events were passed to Madspin [132] for the top (anti-top)-quark to decay into $b\ell^+\nu_\ell$ ($b\ell^-\bar{\nu}_\ell$). The decayed events were then interfaced to Pyhtia8 [133, 134] for parton showering and Hadronization. Experimental values of the SM input parameters considered in our study are presented in Table 1, the central values for renormalization and factorization scale has been set to $M_Z$, the parton density function (PDF) has been considered to be NN23NLO [135, 136] and the strong coupling constant has been set to a value of $\alpha_s = 0.118$. We conduct the analysis at LHC with $\sqrt{S} = 13$ TeV and an integrated luminosity of $\int Ldt = 139$ fb$^{-1}$. Moreover, we explore the Future Hadron Colliders, viz, HL-LHC and FCC-hh with $\sqrt{S} = 14$ TeV and 100 TeV, respectively.

The effects of the new physics contribution in Eq. 1 will be reflected in Higgs production as well as Higgs decay. Although our study aims to investigate new physics effects in Higgs production, exploring final state objects, as the total signal rate changes more relevantly with Higgs decays. This would uplift new physics sensitivity from the $\mathcal{CP}$ violating effects of the Higgs-top Yukawa interactions.

| SM parameter | Experimental value |
|--------------|-------------------|
| $m_b(m_b)$ | $4.18^{+0.03}_{-0.02}$ GeV |
| $m_t(m_t)$ | $172.5 \pm 0.7$ GeV |
| $M_W$ | $80.377 \pm 0.012$ GeV |
| $M_Z$ | $91.188 \pm 0.0021$ GeV |
| $M_H$ | $125.25 \pm 0.17$ GeV |

Table 1: Experimental values of Standard Model input parameters [118].

We impose the kinematic cuts on the final state objects by closely following the experimental analysis, which corresponds to a simplified version of the standard pre-selection cuts used by the CMS experiment for the measurement of the $t\bar{t}H$ channel [137]. Our
choice of the event selection criteria resembles the basic cuts used in Ref. [73]. All events require objects with pseudorapidity $|\eta| < 2.5$ and the transverse momentum $P_T > 25$ GeV. Besides the angular separation between the objects is assumed to be $R > 0.4$.

Using the setup defined above, we generate 10 million events for 10 different benchmark points. We allow to vary both $c_s$ and $c_p$ to different values. Specifically, we examine the cases $c_p = 0.0, 0.2, 0.4, 0.6, 0.8$ and 1.0 and $c_s = 0.8, 0.9$ and 1.0. Among these benchmark points, the point corresponding to $c_s = 1$ and $c_p = 0$ represents the SM. After event generation and imposing the cuts, we calculate the asymmetry for the set of observables listed in Eq. ~2 for LHC with $\sqrt{S} = 13$ TeV, HL-LHC with $\sqrt{S} = 14$ TeV and FCC-hh with $\sqrt{S} = 100$ TeV. The results obtained are then used for further simulation.

The results obtained for the asymmetries at Next-to-leading order interfaced to parton showers (NLO+PS) for the set of observables defined in Eq. ~2 for LHC with $\sqrt{S} = 13$ TeV, HL-LHC with $\sqrt{S} = 14$ TeV and FCC-hh with $\sqrt{S} = 100$ TeV are shown in Tables 2, 3 and 4, respectively. It is to be noted that the signal should be larger than 3$\sigma$ C.L. i.e. $A_i \sim 1 \times 10^{-3}$ (0.1%). According to Tables 2, 3 and 4, almost all observables except $\mathcal{O}_7$ are found to be non-zero at 3$\sigma$ C.L., although some observables are only weakly sensitive to the $\mathcal{CP}$-violating coupling $c_p$ of the Higgs-top interaction. The observables $\mathcal{O}_1$, $\mathcal{O}_2$, $\mathcal{O}_3$, $\mathcal{O}_4$, $\mathcal{O}_5$ and $\mathcal{O}_6$ give promising results as the asymmetries corresponding to them are non zero within the statistical uncertainty at 3$\sigma$ C.L. and significantly large. Additionally, the observable $\mathcal{O}_2$ is quite interesting to explore the $\mathcal{CP}$ effects as it involves Higgs momentum as well. We will therefore find constraints on the pseudo-scalar coupling $c_p$ corresponding to the observables $\mathcal{O}_1$, $\mathcal{O}_2$, $\mathcal{O}_3$, $\mathcal{O}_4$, $\mathcal{O}_5$ and $\mathcal{O}_6$ that are strongly sensitive to the $\mathcal{CP}$-odd nature of the Higgs-top interaction and will not pursue for the observable $\mathcal{O}_7$. Consequently, we expect promising results as the asymmetries corresponding to these observables are large.

From Tables 2, 3 and 4 two comments are in order. First, we see that asymmetries become large as we increase the value of pseudo-scalar coupling $c_p$. Second, all the observables $\mathcal{O}_{1-7}$ do not get contributions from the SM ($c_s = 1, c_p = 0$), confirming our a-priori statement that the asymmetries in the SM are zero. Our results are based only on phenomenological simulations and we have not used any experimental data to obtain our final results.

In order to arrive at the functional form of various asymmetries for different LHC energies, we fit the data obtained for various values of $c_s$ and $c_p$ for a given $\mathcal{CP}$ asymmetry at a time with the assumption that the cross-section is consistent with the Standard Model cross-section for a given LHC energy. Based on the numerical results given in Table 2, we expect the following functional form of cross-section and asymmetries $A_1$, $A_2$, $A_3$, $A_4$, $A_5$ and $A_6$ at LHC for $\sqrt{S} = 13$ TeV at NLO+PS accuracy:

$$
\begin{align*}
\sigma^{13\text{TeV}}_{\text{NLO+PS}} &= 6.38 c_s^2 + 2.51 c_p^2, \\
A^{13\text{TeV}}_{1,\text{NLO+PS}} &= \frac{3.87 - 0.26 c_p^2 + 24.82 c_p c_s - 3.69 c_s^2}{\sigma^{13\text{TeV}}_{\text{NLO+PS}}}, \\
A^{13\text{TeV}}_{2,\text{NLO+PS}} &= \frac{5.06 - 2.95 c_p^2 + 24.45 c_p c_s - 5.61 c_s^2}{\sigma^{13\text{TeV}}_{\text{NLO+PS}}}, \\
A^{13\text{TeV}}_{3,\text{NLO+PS}} &= \frac{-2.80 + 1.02 c_p^2 - 23.74 c_p c_s + 2.91 c_s^2}{\sigma^{13\text{TeV}}_{\text{NLO+PS}}}, 
\end{align*}
$$
Table 2: The measured integrated asymmetries $A_{1-7}$ (in %) at NLO+PS for the set of observables $O_{1-7}$ at LHC with $\sqrt{S} = 13$ TeV for the process $pp \rightarrow t\bar{t}H$ with dileptonic tops for various values of coupling $c_s$ and $c_p$ for $10^7$ events.

| $c_s$ | $c_p$ | $\sigma$ (fb) | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ | $A_7$ | error (1$\sigma$) |
|------|------|-------------|------|------|------|------|------|------|------|---------------|
| 0.8  | 0.8  | 3.11        | 2.98 | 2.65 | -2.72| -0.98| -1.91| -0.53| -0.03| 0.05          |
| 0.8  | 1.0  | 3.58        | 3.21 | 2.68 | -2.86| -1.01| -1.98| -0.45| -0.01| 0.05          |
| 0.9  | 0.8  | 3.71        | 2.84 | 2.57 | -2.51| -0.90| -1.77| -0.46| 0.00 | 0.05          |
| 0.9  | 1.0  | 4.19        | 2.98 | 2.57 | -2.71| -0.95| -1.87| -0.46| 0.04 | 0.05          |
| 1.0  | 0.0  | 6.38        | 0.04 | -0.06| 0.02 | -0.10| 0.05 | 0.13 | 0.02 | 0.06          |
| 1.0  | 0.2  | 6.48        | 0.75 | 0.65 | -0.73| -0.21| -0.53| -0.07| 0.02 | 0.06          |
| 1.0  | 0.4  | 6.78        | 1.54 | 1.26 | -1.33| -0.36| -0.86| -0.21| 0.02 | 0.06          |
| 1.0  | 0.6  | 7.28        | 2.02 | 1.71 | -1.89| -0.63| -1.20| -0.31| 0.04 | 0.06          |
| 1.0  | 0.8  | 7.98        | 2.45 | 2.16 | -2.29| -0.78| -1.43| -0.41| 0.01 | 0.06          |
| 1.0  | 1.0  | 8.89        | 2.78 | 2.34 | -2.54| -0.90| -1.73| -0.39| 0.08 | 0.06          |

Table 3: The measured integrated asymmetries $A_{1-7}$ (in %) at NLO+PS for the set of observables $O_{1-7}$ at HL-LHC with $\sqrt{S} = 14$ TeV for the process $pp \rightarrow t\bar{t}H$ with dileptonic tops for various values of coupling $c_s$ and $c_p$ for $10^7$ events.

| $c_s$ | $c_p$ | $\sigma$ (fb) | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ | $A_7$ | error (1$\sigma$) |
|------|------|-------------|------|------|------|------|------|------|------|---------------|
| 0.8  | 0.8  | 9.70        | 2.93 | 2.54 | -2.66| -0.93| -1.88| -0.49| -0.03| 0.05          |
| 0.8  | 1.0  | 11.26       | 3.17 | 2.74 | -2.91| -1.00| -2.01| -0.52| -0.02| 0.05          |
| 0.9  | 0.8  | 11.54       | 2.78 | 2.43 | -2.53| -0.86| -1.78| -0.46| -0.06| 0.05          |
| 0.9  | 1.0  | 13.10       | 3.04 | 2.64 | -2.76| -1.00| -1.92| -0.55| 0.00 | 0.05          |
| 1.0  | 0.0  | 10.80       | -0.09| -0.07| 0.06 | 0.01 | -0.04| -0.06| -0.04| 0.05          |
| 1.0  | 0.2  | 10.98       | 0.82 | 0.76 | -0.79| -0.38| -0.65| -0.16| 0.00 | 0.05          |
| 1.0  | 0.4  | 11.52       | 1.51 | 1.33 | -1.41| -0.51| -0.97| -0.23| -0.02| 0.05          |
| 1.0  | 0.6  | 12.39       | 2.22 | 1.89 | -1.94| -0.68| -1.30| -0.31| 0.04 | 0.05          |
| 1.0  | 0.8  | 13.60       | 2.67 | 2.37 | -2.43| -0.80| -1.63| -0.48| 0.02 | 0.05          |
| 1.0  | 1.0  | 15.16       | 2.90 | 2.50 | -2.63| -0.90| -1.80| -0.53| 0.01 | 0.05          |

\begin{align}
A^{13TeV}_{1,NLO+PS} &= \frac{-1.04 - 1.82 c_p^2 - 5.70 c_p c_s + 0.68 c_s^2}{\sigma^{13TeV}_{NLO+PS}}, \\
A^{13TeV}_{5,NLO+PS} &= \frac{-3.66 + 0.22 c_p^2 - 15.34 c_p c_s + 3.77 c_s^2}{\sigma^{13TeV}_{NLO+PS}}, \\
A^{13TeV}_{6,NLO+PS} &= \frac{-1.87 + 2.59 c_p^2 - 7.02 c_p c_s + 2.74 c_s^2}{\sigma^{13TeV}_{NLO+PS}}.
\end{align}
Table 4: The measured integrated asymmetries $A_{1-7}$ (in %) at NLO+PS for the set of observables $O_{1-7}$ at FCC-hh with $\sqrt{S} = 100$ TeV for the process $pp \rightarrow t\bar{t}H$ with dileptonic tops for various values of $c_s$ and $c_p$ for $10^7$ events.

| $c_s$ | $c_p$ | $\sigma$ (fb) | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ | $A_7$ | error (1$\sigma$) |
|-------|-------|---------------|-------|-------|-------|-------|-------|-------|-------|------------------|
| 0.8   | 0.8   | 343.25        | 2.74  | 2.42  | -2.85 | -0.88 | -1.76 | -0.37 | -0.04 | 0.07             |
| 0.8   | 1.0   | 501.84        | 2.91  | 2.77  | -2.87 | -0.86 | -1.89 | -0.61 | 0.03  | 0.06             |
| 0.9   | 0.8   | 495.49        | 2.60  | 2.56  | -2.68 | -0.78 | -1.74 | -0.48 | 0.01  | 0.06             |
| 0.9   | 1.0   | 576.18        | 2.85  | 2.64  | -2.87 | -0.83 | -1.88 | -0.42 | -0.09 | 0.06             |
| 1.0   | 0.0   | 358.09        | -0.01 | 0.07  | 0.05  | 0.00  | 0.04  | -0.03 | -0.06 | 0.07             |
| 1.0   | 0.2   | 365.24        | 0.98  | 0.77  | -0.95 | -0.29 | -0.67 | -0.10 | 0.11  | 0.07             |
| 1.0   | 0.4   | 386.94        | 1.64  | 1.47  | -1.59 | -0.36 | -0.89 | -0.28 | 0.02  | 0.07             |
| 1.0   | 0.6   | 422.13        | 2.09  | 1.87  | -2.19 | -0.69 | -1.51 | -0.33 | 0.01  | 0.07             |
| 1.0   | 0.8   | 472.52        | 2.45  | 2.36  | -2.64 | -0.73 | -1.61 | -0.50 | 0.09  | 0.07             |
| 1.0   | 1.0   | 535.98        | 2.87  | 2.48  | -2.96 | -0.91 | -1.72 | -0.41 | 0.03  | 0.07             |

Similarly, the functional form obtained for HL-LHC with $\sqrt{S} = 14$ TeV and FCC-hh with $\sqrt{S} = 100$ TeV at NLO+PS from the numerical results given in Tables 3 and 4 will be:

$$
\sigma_{14\text{TeV}}^{\mathrm{NLO+PS}} = 10.81 \ c_s^2 + 4.34 \ c_p^2,
$$

$$
A_{1,\mathrm{NLO+PS}}^{14\text{TeV}} = \frac{0.34 - 2.63 \ c_p^2 + 47.95 \ c_p \ c_s - 1.18 \ c_s^2}{\sigma_{14\text{TeV}}^{\mathrm{NLO+PS}}},
$$

$$
A_{2,\mathrm{NLO+PS}}^{14\text{TeV}} = \frac{0.33 - 2.69 \ c_p^2 + 41.82 \ c_p \ c_s - 0.85 \ c_s^2}{\sigma_{14\text{TeV}}^{\mathrm{NLO+PS}}},
$$

$$
A_{3,\mathrm{NLO+PS}}^{14\text{TeV}} = \frac{-0.78 + 1.35 \ c_p^2 - 41.94 \ c_p \ c_s + 1.06 \ c_s^2}{\sigma_{14\text{TeV}}^{\mathrm{NLO+PS}}},
$$

$$
A_{4,\mathrm{NLO+PS}}^{14\text{TeV}} = \frac{-0.91 + 0.54 \ c_p^2 - 13.87 \ c_p \ c_s + 0.46 \ c_s^2}{\sigma_{14\text{TeV}}^{\mathrm{NLO+PS}}},
$$

$$
A_{5,\mathrm{NLO+PS}}^{14\text{TeV}} = \frac{-2.51 - 0.07 \ c_p^2 - 26.37 \ c_p \ c_s + 1.63 \ c_s^2}{\sigma_{14\text{TeV}}^{\mathrm{NLO+PS}}},
$$

$$
A_{6,\mathrm{NLO+PS}}^{14\text{TeV}} = \frac{1.63 - 2.82 \ c_p^2 - 4.54 \ c_p \ c_s - 2.23 \ c_s^2}{\sigma_{14\text{TeV}}^{\mathrm{NLO+PS}}}. 
$$
Particularly, the variation of $\sqrt{S}$ for an integrated luminosity of 139 fb$^{-1}$ from the Figs. 3, 4 and 5, as the value of coupling $c_p$.

Three illustrative values of scalar coupling, $c_S$, are considered. We notice that the asymmetry is highly sensitive to the pseudoscalar coupling $c_p$ which can be seen from the Figs. 3, 4 and 5, as the value of coupling $c_p$ changes for a given value of coupling $c_S$, the asymmetry changes significantly. Furthermore, we notice that the asymmetry is symmetric around $c_p = 0$ and is equally sensitive to both positive and negative values of coupling $c_p$. Interestingly, the asymmetry increases by changing the coupling $c_p$.

From the expressions 5, 6 and 7, we notice that the asymmetry arises mostly from the interfering term i.e. the term proportional to $c_s$ $c_p$ while the constant term and the term proportional to $c_c^2$ and $c_s^2$ contribute less.

In Fig. 2, we show the cross-section calculated at NLO+PS as a function of pseudoscalar coupling $c_p$ for three different parameter points: $c_s = 1, \frac{1}{\sqrt{2}}$ and $\frac{1}{2}$ at LHC with $\sqrt{S} = 13$ TeV for an integrated luminosity of 139 fb$^{-1}$, HL-LHC with $\sqrt{S} = 14$ TeV for the projected luminosity of 3 ab$^{-1}$ and FCC-hh with $\sqrt{S} = 100$ TeV for the projected luminosity of 30 ab$^{-1}$. We see that the cross-section is symmetric around $c_p = 0$ and is equally sensitive to both positive and negative values of the pseudoscalar coupling $c_p$. Furthermore, we observe that the presence of CP-violating coupling $c_p$ in $t\bar{t}H$ interaction increases the cross-section. Particularly, the variation of $c_p$ at a given value of $c_s$ leads to a significant increase in the value of cross-section. For all the parameter points, the cross-section can increase as much as two times or more by varying the pseudo-scalar coupling $c_p$. However, the cross-section gets strongest contribution corresponding to the point $c_s = 1$. This indicates that the cross-section is sensitive to the CP-violating part of the $t\bar{t}H$ interaction and can be used to probe pseudoscalar coupling $c_p$. Individual bounds on pseudoscalar coupling $c_p$ at NLO+PS at three different values of $c_s$, viz, $c_s = 1, \frac{1}{\sqrt{2}}$ and $\frac{1}{2}$ obtained from the cross-section measurements at LHC with $\sqrt{S} = 13$ TeV, HL-LHC with $\sqrt{S} = 14$ TeV and FCC-hh with $\sqrt{S} = 100$ TeV are shown in Table 5.

In Figs. 3, 4 and 5, we show the production asymmetry calculated at NLO+PS corresponding to the observables $O_1$, $O_2$, $O_3$, $O_4$, $O_5$ and $O_6$ as a function of pseudoscalar coupling $c_p$ at different values of scalar coupling $c_s$ at LHC with $\sqrt{S} = 13$ TeV for an integrated luminosity of 139 fb$^{-1}$, HL-LHC with $\sqrt{S} = 14$ TeV for the projected luminosity of 3 ab$^{-1}$ and FCC-hh with $\sqrt{S} = 100$ TeV for the projected luminosity of 30 ab$^{-1}$, respectively. Three illustrative values of scalar coupling, $c_s = 1, \frac{1}{\sqrt{2}}$, and $\frac{1}{2}$ are considered. We notice that the asymmetry is highly sensitive to the pseudoscalar coupling $c_p$ which can be seen from the Figs. 3, 4 and 5, as the value of coupling $c_p$ changes for a given value of coupling $c_s$, the asymmetry changes significantly. Furthermore, we notice that the asymmetry is symmetric around $c_p = 0$ and is equally sensitive to both positive and negative values of coupling $c_p$. Interestingly, the asymmetry increases by changing the coupling $c_p$.

\[
\begin{align*}
\sigma_{100\text{ TeV}}^{100\text{ NLO} + \text{PS}} &= 253.26 \, c_p^2 + 343.16 \, c_s^2, \\
A_{100\text{ TeV}}^{100\text{ NLO} + \text{PS}} &= -44.98 + 287.24 \, c_p^2 + 1348.11 \, c_p \, c_s + 68.75 \, c_s^2, \\
A_{20\text{ TeV}}^{100\text{ NLO} + \text{PS}} &= -36.14 + 355.57 \, c_p^2 + 1147.06 \, c_p \, c_s + 64.27 \, c_s^2, \\
A_{30\text{ TeV}}^{100\text{ NLO} + \text{PS}} &= 89.60 - 209.46 \, c_p^2 - 1506.58 \, c_p \, c_s - 83.36 \, c_s^2, \\
A_{40\text{ TeV}}^{100\text{ NLO} + \text{PS}} &= 10.76 - 112.51 \, c_p^2 - 388.40 \, c_p \, c_s - 12.76 \, c_s^2, \\
A_{50\text{ TeV}}^{100\text{ NLO} + \text{PS}} &= -28.57 - 120.45 \, c_p^2 - 938.67 \, c_p \, c_s + 27.26 \, c_s^2, \\
A_{60\text{ TeV}}^{100\text{ NLO} + \text{PS}} &= 33.16 - 107.71 \, c_p^2 - 170.47 \, c_p \, c_s - 41.57 \, c_s^2. 
\end{align*}
\]
Figure 2: Cross-section as a function of anomalous coupling $c_p$ at three different values of coupling $c_s$, viz, $c_s = 1$, $\frac{1}{\sqrt{2}}$, and $\frac{1}{2}$ at LHC with $\sqrt{S} = 13$ TeV (upper left), HL-LHC with $\sqrt{S} = 14$ TeV (upper right) and FCC-hh with $\sqrt{S} = 100$ TeV (lower) at NLO+PS accuracy.
Figure 3: Asymmetry as a function of anomalous coupling $c_p$ at three different values of coupling $c_s$, viz, $c_s = 1$, $\frac{1}{\sqrt{2}}$, and $\frac{1}{2}$ at LHC with $\sqrt{S} = 13$ TeV corresponding to the observables $\mathcal{O}_1$, $\mathcal{O}_2$, $\mathcal{O}_3$, $\mathcal{O}_4$, $\mathcal{O}_5$, and $\mathcal{O}_6$ at NLO+PS.
Figure 4: Asymmetry as a function of anomalous coupling $c_p$ at three different values of coupling $c_s$, viz, $c_s = 1$, $\frac{1}{\sqrt{2}}$ and $\frac{1}{2}$ at HL-LHC with $\sqrt{S} = 14$ TeV corresponding to the observables $O_1$, $O_2$, $O_3$, $O_4$, $O_5$, and $O_6$ at NLO+PS.
Figure 5: Asymmetry as a function of anomalous coupling $c_p$ at three different values of coupling $c_s$, viz, $c_s = 1$, $\frac{1}{\sqrt{2}}$, and $\frac{1}{2}$ at FCC-hh with $\sqrt{S} = 100$ TeV corresponding to the observables $O_1$, $O_2$, $O_3$, $O_4$, $O_5$, and $O_6$ at NLO+PS.
with a bound of observables asymmetry. However, we conduct a more detailed analysis regarding the sensitivity of the allowed at 2.5 σ region present in the limit from production asymmetry. The complementarity of both measurements is beautifully depicted here: the intersection of the circle shaped region from cross-section and the lines from production asymmetry gives much more stringent bounds than the separate measurements. The combination of both measurements is very powerful and almost removes the large $c_p$ region present in the limit from production asymmetry. The resulting combined regions are shown in red and yellow which corresponds to the region allowed at 2.5 σ and 5 σ C.L. respectively. From here we can give a rough estimate of the constraint on the coupling $c_p$ from the combined measurement of $\sigma$ and production asymmetry. However, we conduct a more detailed analysis regarding the sensitivity of the observables $O_1$, $O_2$, $O_3$, $O_4$, $O_5$ and $O_6$ to the CP-violating Higgs-top coupling $c_p$ for three different parameter points: $c_s = 1$, $\frac{1}{\sqrt{2}}$ and $\frac{1}{2}$ at LHC with $\sqrt{S} = 13$ TeV and an integrated luminosity of 139 fb$^{-1}$ and for the Future Hadron Colliders, namely HL-LHC and FCC-hh with $\sqrt{S} = 100$ TeV respectively.

Table 5: Individual constraints on anomalous coupling $c_p$ at three different values of $c_s$, viz, $c_s = 1$, $\frac{1}{\sqrt{2}}$ and $\frac{1}{2}$ at 2.5 σ C.L. obtained from $t\bar{t}H$ production cross-section at the LHC with $\sqrt{S} = 13$ TeV, HL-LHC with $\sqrt{S} = 14$ TeV and FCC-hh with $\sqrt{S} = 100$ TeV respectively at NLO+PS accuracy.

In Figs. 6, we show 2.5σ and 5σ regions in $c_p - c_s$ plane allowed by the combined measurements of cross-section and production asymmetry measured at NLO+PS for the observables $O_1$, $O_2$, $O_3$, $O_4$, $O_5$ and $O_6$ for the process $pp \rightarrow t\bar{t}H$ in the dileptonic decay channel of top-quark at the LHC with $\sqrt{S} = 13$ TeV for an integrated luminosity of 139 fb$^{-1}$ and 2.5σ regions for HL-LHC with $\sqrt{S} = 14$ TeV and FCC-hh with $\sqrt{S} = 100$ TeV for the projected luminosities of 3 ab$^{-1}$ and 30 ab$^{-1}$ in Figs. 7 and 8 respectively. The solid lines represent the region allowed by the cross-section and the dotted lines represent the region allowed by the production asymmetry. The complementarity of both measurements is beautifully depicted here: the intersection of the circle shaped region from cross-section and the lines from production asymmetry gives much more stringent bounds than the separate measurements. The combination of both measurements is very powerful and almost removes the large $c_p$ region present in the limit from production asymmetry. The resulting combined regions are shown in red and yellow which corresponds to the region allowed at 2.5σ and 5σ C.L. respectively. From here we can give a rough estimate of the constraint on the coupling $c_p$ from the combined measurement of $\sigma$ and production asymmetry. However, we conduct a more detailed analysis regarding the sensitivity of the observables $O_1$, $O_2$, $O_3$, $O_4$, $O_5$ and $O_6$ to the CP-violating Higgs-top coupling $c_p$ for three different parameter points: $c_s = 1$, $\frac{1}{\sqrt{2}}$ and $\frac{1}{2}$ at LHC with $\sqrt{S} = 13$ TeV and an integrated luminosity of 139 fb$^{-1}$ and for the Future Hadron Colliders, namely HL-LHC and FCC-hh with $\sqrt{S}$, $\int L dt = (14$ TeV, 3 ab$^{-1}$) and (100 TeV, 30 ab$^{-1}$) respectively. The results corresponding to these measurements at 2.5σ C.L. are presented in Table 6.

Let us now compare our findings with the existing limits on pseudoscalar coupling $c_p$ derived from previous literature. In Ref. [74], the authors applied machine-learning based interference to derive the expected constraints on CP-violating top-Yukawa coupling in the context of top-associated Higgs production with the Higgs boson decaying to two photons and found that a CP-odd top Yukawa coupling at the LHC can be constrained to $-0.8 < c_p < 0.8$ and $-0.5 < c_p < 0.5$ at 68.3 % C.L. level for the luminosities of 139 fb$^{-1}$ and 300 fb$^{-1}$ respectively and for HL-LHC with a projected luminosity of 3000 fb$^{-1}$, a bound of $-0.25 < c_p < 0.25$ can be found. These results were obtained at LO with a Higgs decay to two photons, whereas our findings are at NLO+PS with a stable Higgs.
Figure 6: Contour plots of cross-section and production asymmetry measured at NLO+PS accuracy in $c_p - c_s$ plane at LHC with $\sqrt{S} = 13$ TeV for the observables $O_1, O_2$ (top row), $O_3, O_4$ (middle row), $O_5$ and $O_6$ (lower row). The red and yellow area represent the parameter space allowed at 2.5$\sigma$ and 5$\sigma$ C.L. respectively from combined measurements of cross-section and production asymmetry.
Figure 7: Contour plots of cross-section and production asymmetry measured at NLO+PS accuracy in $c_p - c_s$ plane at HL-LHC with $\sqrt{S} = 14$ TeV for the observables $O_1$, $O_2$ (top row), $O_3, O_4$ (middle row), $O_5$ and $O_6$ (lower row). The red and yellow area represent the parameter space allowed at 2.5\(\sigma\) and 5\(\sigma\) C.L. respectively from combined measurements of cross-section and production asymmetry.
Figure 8: Contour plots of cross-section and production asymmetry measured at NLO+PS accuracy in $c_p - c_s$ plane at FCC-hh with $\sqrt{S} = 100$ TeV for the observables $O_1$, $O_2$ (top row), $O_3, O_4$ (middle row), $O_5$ and $O_6$ (lower row). The red and yellow area represent the parameter space allowed at 2.5$\sigma$ and 5$\sigma$ C.L. respectively from combined measurements of cross-section and production asymmetry.
| Collider | $\sqrt{S}$, $\int L dt$     | Asymmetry | $c_p \times (10^{-2})$ |
|----------|-----------------|------------|----------------|
|          | $c_s$ | $1$ | $\frac{1}{\sqrt{2}}$ | $\frac{1}{2}$ |
| LHC      | LHC 13 TeV, 39 fb⁻¹ | $\mathcal{A}_1$ | $c_p \leq 1.96$ | $c_p \leq 1.38$ | $c_p \leq 0.98$, |
|          | $\mathcal{A}_2$ | $c_p \leq 1.99$ | $c_p \leq 1.41$ | $c_p \leq 0.99$, |
|          | $\mathcal{A}_3$ | $-2.05 \leq c_p$ | $-1.45 \leq c_p$ | $-1.02 \leq c_p$, |
|          | $\mathcal{A}_4$ | $-8.55 \leq c_p$ | $-6.04 \leq c_p$ | $-4.27 \leq c_p$, |
|          | $\mathcal{A}_5$ | $-3.17 \leq c_p$ | $-2.24 \leq c_p$ | $-1.58 \leq c_p$, |
|          | $\mathcal{A}_6$ | $-6.93 \leq c_p$ | $-4.90 \leq c_p$ | $-3.47 \leq c_p$, |
| HL-LHC   | HL-LHC 14 TeV, 3 ab⁻¹ | $\mathcal{A}_1$ | $c_p \leq 0.34$ | $c_p \leq 0.24$ | $c_p \leq 0.17$, |
|          | $\mathcal{A}_2$ | $c_p \leq 0.38$ | $c_p \leq 0.27$ | $c_p \leq 0.19$, |
|          | $\mathcal{A}_3$ | $-0.38 \leq c_p$ | $-0.27 \leq c_p$ | $-0.19 \leq c_p$, |
|          | $\mathcal{A}_4$ | $-1.16 \leq c_p$ | $-0.82 \leq c_p$ | $-0.58 \leq c_p$, |
|          | $\mathcal{A}_5$ | $-0.61 \leq c_p$ | $-0.43 \leq c_p$ | $-0.30 \leq c_p$, |
|          | $\mathcal{A}_6$ | $-3.54 \leq c_p$ | $-2.51 \leq c_p$ | $-1.77 \leq c_p$, |
| FCC-hh   | FCC-hh 100 TeV, 30 ab⁻¹ | $\mathcal{A}_1$ | $c_p \leq 0.016$ | $c_p \leq 0.011$ | $c_p \leq 0.008$, |
|          | $\mathcal{A}_2$ | $c_p \leq 0.019$ | $c_p \leq 0.013$ | $c_p \leq 0.009$, |
|          | $\mathcal{A}_3$ | $-0.014 \leq c_p$ | $-0.010 \leq c_p$ | $-0.007 \leq c_p$, |
|          | $\mathcal{A}_4$ | $-0.055 \leq c_p$ | $-0.039 \leq c_p$ | $-0.028 \leq c_p$, |
|          | $\mathcal{A}_5$ | $-0.023 \leq c_p$ | $-0.016 \leq c_p$ | $-0.011 \leq c_p$, |
|          | $\mathcal{A}_6$ | $-0.125 \leq c_p$ | $-0.089 \leq c_p$ | $-0.063 \leq c_p$, |

Table 6: Individual constraints on anomalous coupling $c_p$ at NLO+PS accuracy at three different values of $c_s$, viz., $c_s = 1, \frac{1}{\sqrt{2}}, \frac{1}{2}$ at 2.5σ C.L. allowed by the production asymmetries $\mathcal{A}_1, \mathcal{A}_2, \mathcal{A}_3, \mathcal{A}_4, \mathcal{A}_5$, and $\mathcal{A}_6$ corresponding to the observables $\mathcal{O}_1, \mathcal{O}_2, \mathcal{O}_3, \mathcal{O}_4, \mathcal{O}_5$ and $\mathcal{O}_6$ at LHC, HL-LHC and FCC-hh with $\sqrt{S} = 13$ TeV, 14 TeV and 100 TeV respectively and the luminosities of 139 fb⁻¹ to 30 ab⁻¹ have been explored.

Ref. [108], the CP-odd component $c_p$ is constrained at 2σ level to $c_p < 0.37$ by combining the LHC Run-1 and -2 Higgs data sets. However, EDM measurements placed the strongest
constraints on the $CP$-violating Higgs-top couplings and found an upper limit of 0.01 on the $c_p$ [29].

4 Results and Discussion

The discovery of the Higgs boson at the LHC furnishes new opportunities for exploring physics beyond the SM. Since its discovery at the Large Hadron Collider, it has always been crucial to investigate its $CP$-properties as it is expected that it can provide an explanation of the fundamental question of matter–antimatter asymmetry. Probing the top-Yukawa coupling is important for measuring the $CP$ nature of Higgs boson. In this study, we have explored the anomalous Higgs-top coupling and discussed the $CP$-violation effects of Higgs-top interaction in the associated production of top-pair with Higgs boson, followed by the dileptonic decay of top-quark by means of T-odd observables constructed via the momenta of final state particles. Our results are obtained in a fully automatic way following the Higgs characterization model at next-to-leading order accuracy in QCD, including the parton shower effects. In particular, we derive constraints on the $CP$-violating component of the $Ht\bar{t}$ interaction.

We measured the cross-section for the associated production of Higgs boson with top-pair at NLO+PS accuracy and show that the cross-section can be a crucial ingredient for finding the $CP$-violation sensitivity to anomalous Higgs-top interaction. The measured cross-section was used to set constraints on the $CP$-violating coupling $c_p$. The constraints were obtained at 2.5σ C.L. for LHC with $\sqrt{S} = 13$ TeV for the integrated luminosity of 139 fb$^{-1}$ and for future hadron colliders, viz, HL-LHC and FCC-hh with $\sqrt{S} = 14$ TeV and 100 TeV with projected luminosities of 3 ab$^{-1}$ and 30 ab$^{-1}$. The bounds on the pseudoscalar coupling $c_p$ obtained from cross-section measurements are presented in Table 5 for three parameter points: $c_s = 1$, $\frac{1}{\sqrt{2}}$ and $\frac{1}{2}$ at 2.5σ C.L. Ref. [85] obtained constraints on the $CP$-violating coupling $c_p$ in the interval $[-0.3,0.3]$ at 1σ level in the 2D parameterization, where the significant contribution originates from the production of Higgs boson through gluon-gluon annihilation and decay of Higgs boson to two photons. It has also been shown that allowing additional freedom to Higgs coupling weakens the constraints.

The production asymmetries were measured corresponding to the observables defined in Eq. 2 at NLO+PS and showed that the observables provide a sensitive probe for $CP$-violation in the Higgs-top interaction. We find that the $CP$-violating component $c_p$ has been constrained corresponding to the largest asymmetry $A_1$ to its maximum value to $1.96\times10^{-2}$ at 2.5σ CL for $c_s = 1$ for the LHC with $\sqrt{S} = 13$ TeV and an integrated luminosity of 139 fb$^{-1}$. The corresponding limits for its luminosity intense variant HL-LHC and Future Circular Collider FCC-hh are estimated to be to $0.34\times10^{-2}$ and $0.016\times10^{-2}$ for the projected luminosities of 3.0 ab$^{-1}$ and 30 ab$^{-1}$ respectively at 2.5σ CL. The limits obtained corresponding to all the asymmetries $A_1$–6 are presented in Table 6. In Ref. [138], the bounds on the $CP$-violating anomalous $ttH$ interaction were obtained using the angular separation of leptons in the $tt$ center-of-mass frame and set an exclusion limit on $c_p$: $c_p = [-0.698, 0.698]$ at 95% CL for HL-LHC. This study was performed with the production of Higgs boson with a top pair where Higgs decays into a $b\bar{b}$ pair. Our study is however based on sensitivity measurement to $CP$-violating anomalous coupling using $CP$-odd observables in the $ttH$ system. In addition, studies related to finding the Higgs-top $CP$ phase were performed in Refs. [87, 139]. To the best of our knowledge, this is the first study to
measure the bounds on $CP$-violating anomalous $ttH$ coupling at NLO+PS order using $CP$-odd observables constructed through momenta of the produced particles.

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