Exploring the Anomalous Higgs-top Couplings

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Abstract

Top quark with its large Yukawa coupling is crucially important to explore TeV scale physics. Therefore, the study of Higgs-top sector is highly motivated to look for any deviations from the standard model predictions. The most general lowest order Lagrangian for the Higgs-top Yukawa coupling has scalar ($\kappa$) and pseudoscalar ($\tilde{\kappa}$) components. Currently, these couplings are constrained indirectly using the present experimental limits on the Higgs-$\gamma$-$\gamma$ and Higgs-gluon-gluon couplings. Furthermore, stronger bounds on $\kappa$ and $\tilde{\kappa}$ are obtained using the limits on the electric dipole moments (EDM). In this work, we propose an asymmetry-like observable $O_\phi$ in $t\bar{t}H$ production at the LHC to probe the Higgs-top coupling and to distinguish between the scalar and pseudoscalar components. We also show that the presence of the pseudoscalar component in the Higgs-top Yukawa coupling leads to a sizeable value for the top quark EDM. It is shown that a limit of $10^{-19}$ e.cm, which is achievable by the future $e^-e^+$ collider, allows us to exclude a significant region in the $(\kappa, \tilde{\kappa})$ plane.

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1 Introduction

In the framework of the Standard Model (SM) the Higgs boson gives masses to fermions (charged leptons and quarks) through Yukawa couplings. The couplings of the Higgs boson to the gauge bosons and fermions have measured in different decay modes. The Higgs couplings to \( W \) and \( Z \) bosons are measured with the uncertainties of around 20% – 30% and the Higgs couplings to the top and bottom quarks are known with the uncertainties of 30% and 40%, respectively \[1\]. The couplings are in agreement with the SM predictions within these relatively large uncertainties. Top quark which is the heaviest particle among the SM particles has the largest coupling with the Higgs boson. The precise measurement of the Higgs-top Yukawa interaction enables us to check the spontaneous symmetry breaking mechanism closely and in case of observing any deviation it is a window to new physics beyond the SM. So far, there are many attempts in the way of probing top Yukawa couplings at the colliders using \( t\bar{t}H \) production, single top plus Higgs boson production and via the Higgs pair production \[2\], \[3\], \[4\], \[5\], \[6\], \[7\], \[8\], \[9\]. There are also many studies to explore the standard and exotic Higgs couplings by using the available data and by proposing new sensitive observables to achieve precise measurements and to look for deviations from the SM \[10\], \[11\], \[12\], \[13\], \[14\], \[15\], \[16\], \[17\], \[18\], \[19\], \[20\].

Within the SM, the Higgs-top coupling is described by only purely scalar type of coupling. However, in models beyond the SM the Higgs-top coupling can consists of both scalar and pseudoscalar components. In these models the Higgs boson can be a CP-mixed state \[21\], \[22\]. It also should be noted that based on the present data the admixture of the scalar and pseudoscalar couplings is still possible \[2\], \[8\]. The generic form of the Higgs-top Yukawa coupling can be parametrized as \[23\]:

\[
L = -\frac{m_t}{v} (\kappa + i\tilde{\kappa}\gamma_5)tH + h.c.
\]

where \( m_t \) is the top quark mass and \( v \) denotes the vacuum expectation value. The parameters \( \kappa \) and \( \tilde{\kappa} \) are dimensionless real parameters. In the SM at the leading order (LO), the value of \( \kappa = 1 \) and \( \tilde{\kappa} = 0 \). It is notable that the CP-violating component, \( \tilde{\kappa} \), can arise from loops at higher orders in the SM which is expected to be small. At present, there are indirect limits on \( \kappa \) and \( \tilde{\kappa} \) from the experimental measurements of \( H - \gamma - \gamma \) and Higgs-gluon-gluon couplings and from the upper bounds on the electron, neutron, etc. electric dipole moments (EDM) \[24\], \[25\]. Among the electron, neutron and mercury electric dipole moments, the upper limit on the electron EDM gives the most stringent limit on \( \tilde{\kappa} \). The contribution of the CP-violating component of the top-Higgs Yukawa coupling to the electron EDM is given
by:

\[ d_e = 9 \times 10^{-27} \kappa \text{ e.cm} \]  

(2)

where the electron Yukawa coupling is taken to be equal to the SM value. This leads to an upper bound of 0.01 on \( \kappa \). The production of the Higgs boson through gluon fusion and the Higgs decay into di-photon are affected by the CP-violating component of the Higgs-top coupling \( \tilde{\kappa} \). The ratio of the cross section of the Higgs production in gluon fusion considering CP-violating component to the SM cross section has been found to be:

\[ \mu_{gg}(\kappa, \tilde{\kappa}) \simeq 1.11\kappa^2 + 2.6\tilde{\kappa}^2 - 0.11\kappa \]  

(3)

As it can be seen, the cross section of Higgs production via gluon fusion is more affected by the CP-violating term than the SM component. Also, the CP-violating term has positive contribution and always lead to enhance the Higgs production rate (or to the decay of Higgs to gluon-gluon). In the Higgs boson decay into di-photon the ratio of the \( H \rightarrow \gamma\gamma \) in the presence of \( \tilde{\kappa} \) to the SM width has the following form:

\[ \mu_{\gamma\gamma}(\kappa, \tilde{\kappa}) \simeq 0.078\kappa^2 - 0.71\kappa + 0.18\tilde{\kappa}^2 + 1.6 \]  

(4)

Similar to the Higgs production in gluon fusion the CP-violating coupling has a constructive effect on the rate of Higgs decay into di-photon and leads to an enhancement. However, the power of enhancement is weaker than the Higgs-gluon-gluon coupling. A global analysis including several observables provides the following best-fit values for the anomalous parameters \( \kappa \) and \( \tilde{\kappa} \) [8]:

\[ \kappa, \tilde{\kappa} \rightarrow 0.8, \pm 0.3 \]

This means that non-zero values for the CP-violating coupling \( \tilde{\kappa} \) are allowed. It is remarkable that \( \tilde{\kappa} \) is allowed to vary in the range of -0.4 to 0.4 when \( \kappa \) is fixed to unity [8]. In this paper, the main idea is to develop a sensitive kinematic observable to the Higgs-top Yukawa coupling.

As mentioned previously, there are several studies at colliders to examine the Higgs-top Yukawa couplings. For example, in [26] the authors have proposed an asymmetry in the charged lepton energy in top pair events at hadron colliders. It has been shown that such an asymmetry is sensitive to the CP violating term \( \tilde{\kappa} \) and is large enough above the backgrounds. In [2], the sensitivity of the total cross sections of the \( t\bar{t}H, tH, \) and \( \bar{t}H \) processes have been examined to the Higgs-top Yukawa couplings. It has been found that the total cross section
of $t\bar{t}H$ process decreases significantly with increasing the ratio of $\tilde{\kappa}/\kappa$. In addition, it has been shown that the distribution of $\Delta \phi_{t\bar{t}l}$ (the difference between the azimuthal angle of the charged leptons in top quarks decay) is sensitive to both the sign and the magnitude of $\tilde{\kappa}/\kappa$.

In the next section, based on the angular distributions of the final state particles in $pp \to t\bar{t}H$ process an asymmetry-like observable $O_\phi$ is defined. We show that this observable considerably sensitive to the CP violating term of the Higgs-top coupling. We examine the effect of the main background and kinematic cuts on this observable. Then, the sensitivity of $O_\phi$ at the LHC with the center-of-mass energy of 14 TeV as a function of the integrated luminosity is presented. In section 3, we show that the general Higgs-top couplings generates a sizeable EDM for the top quark. Then, using a possible future bound of $10^{-19}$ e.cm [27] on the top EDM, which is achievable by the future electron-positron collider, an allowed region in $\kappa, \tilde{\kappa}$ is obtained. Finally, section 4 concludes the paper.

2 Azimuthal angular observable

We construct an asymmetry-like observable from the azimuthal angular distributions of the final state objects in $pp \to t\bar{t}H$ process. This observable, $O_\phi$, is a sensitive discriminant to distinguish between the CP-conserving ($\kappa$) and CP-violating ($\tilde{\kappa}$) parts of the $t\bar{t}H$ couplings.

We define an angular asymmetry-like $O_\phi$ with respect to the azimuthal angle differences $\Delta \phi_{t\bar{t}} = \phi_{t} - \phi_{\bar{t}}$ and $\Delta \phi_{tH} = \phi_{t} - \phi_{H}$ as:

$$O_\phi = \frac{N(|\Delta \phi(t\bar{t})| > |\Delta \phi(tH)|)}{N(|\Delta \phi(t\bar{t})| > |\Delta \phi(tH)|) + N(|\Delta \phi(t\bar{t})| < |\Delta \phi(tH)|)}$$

(5)

Here the first (second) term in the nominator denotes the number of $t\bar{t}H$ events with $|\Delta \phi(t\bar{t})| > |\Delta \phi(tH)|$ ($|\Delta \phi(t\bar{t})| < |\Delta \phi(tH)|$). The denominator is the total number of events.

Now we would like to examine our proposed observable $O_\phi$. To generate the hard scattering matrix elements the MadGraph 5 package [28] is used with the CTEQ6L [29] as the proton parton distribution function (PDF). In our analysis, we concentrate on the LHC run with the center-of-mass energy of $\sqrt{s} = 14$ TeV. In order to simulate the signal events, i.e. $pp \to t\bar{t}H$ with the general form of the $t\bar{t}H$, the effective Lagrangian of Eq.1 is implemented within the FeynRules package [30], [31]. Then the model is imported to a UFO module [32] and then inserted to the MadGraph 5.

We show the values of $O_\phi$ for the SM case ($\kappa = 1$ and $\tilde{\kappa} = 0$) for different cuts on the Higgs boson transverse momentum in Table 1. As it can be seen the value of $O_\phi$ decreases when the cut on the Higgs-$p_T$ grows. To understand the reason for such a behavior, in Fig.1 we
cut on Higgs-$p_T$ (GeV) & 0.0 & 50.0 & 100.0 & 200.0 & 300.0 \\
\hline
$O_\phi(\kappa = 1, \tilde{\kappa} = 0)$ & 0.356 & 0.229 & 0.021 & -0.265 & -0.411 \\
$O_\phi(\kappa = 1, \tilde{\kappa} = 0.4)$ & 0.317 & 0.191 & -0.006 & -0.299 & -0.441 \\
\hline
\end{tabular}

Table 1: The values of the asymmetry-like observable $O_\phi$ for the SM and the case of $\tilde{\kappa} = 0.4$ for several cuts on the Higgs boson transverse momentum.

plot parton level distributions of $\Delta \phi_{t\bar{t}}$ and $\Delta \phi_{tH}$ for example for the SM case ($\kappa = 1, \tilde{\kappa} = 0$) with different cuts on the Higgs boson transverse momentum. When no cut is applied on the Higgs-$p_T$, the top and anti-top quarks prefer to fly in opposite directions in the transverse plane. However, with increasing the Higgs-$p_T$ cut the $\Delta \phi_{t\bar{t}}$ distribution tends to become flat and instead the top quark and the Higgs boson move to a back-to-back position in the transverse plane. As shown in Fig.1, the number of the events with $|\Delta \phi(t\bar{t})| > |\Delta \phi(tH)|$ decreases when we impose a larger cut on the Higgs boson transverse momentum.

There are sources of theoretical uncertainties to the observable $O_\phi$. The uncertainty originating from the variation of the factorization and renormalization scales is obtained by varying the two scales together in the range of $\mu = \mu_0/2$ to $\mu = 2\mu_0$ with the central scale $\mu_0$ is set to $\sqrt{p_T^2 + m_t^2}$. The uncertainty coming from the limited knowledge of the parton distribution functions PDF is calculated using the 44 members of the CTEQ6.6 PDFs [33]. There is an uncertainty from the top quark mass which is obtained by variation of the top quark mass $\pm 1$ GeV. The relative uncertainties from variation of the factorization/renormalization scales, PDF, and top quark mass are found to be 1%, 0.3%, and 0.09%, respectively. The dominant source of the theoretical uncertainty is from the variation of the factorization/renormalization scales. These uncertainties are small with respect to the relative deviation from the CP violating term, $\tilde{\kappa}$. From Table 1 the relative deviation due to the presence of CP violating term with $\kappa = 1, \tilde{\kappa} = 0.4$ leads to around 10.95% change with respect to the SM value.

Now, we switch to our general effective Lagrangian, Eq.(1) with arbitrary values of $\kappa$ and $\tilde{\kappa}$. In the left panel of Fig.2 we depict the shape of $O_\phi$ observable for $\kappa = 1$ and various values of $\tilde{\kappa}$ as a function of the Higgs boson $p_T$. The presence of a CP-violating coupling in $t\bar{t}H$ interaction reduces the amount of $O_\phi$ at any value of the cut on Higgs boson $p_T$.

Notably the variation of $\kappa$ in the range of for example 0.0 to 1.0 at a given value of $\tilde{\kappa}$ leads to no significant deviation in $O_\phi$. The deviation is of the order of 1%. This indicates that our azimuthal angular based observable is only sensitive to the CP-violating part of the $tH$ coupling and can be used to probe $\tilde{\kappa}$ coupling. Therefore, such an observable allows us
Figure 1: The distributions of the angular separations of $t \bar{t}$ and $tH$ for $t \bar{t}H$ final state in proton-proton collisions at $\sqrt{s} = 14$ TeV for different values of cut on the transverse Higgs momentum.

to distinguish between scalar and pseudoscalar couplings in $t - \bar{t} - H$ interaction.

The amount of observable $O_\phi$ drops for the case that the Higgs bosons have larger transverse momentum. It tends to zero at the cut value of around 105 GeV on the Higgs boson $p_T$ for the SM ($\kappa = 1, \tilde{\kappa} = 0$). The Higgs transverse momentum at which $O_\phi = 0$ varies for different values of $\tilde{\kappa}$. The larger value of $\tilde{\kappa}$ is corresponding to lower Higgs $p_T$ at which $O_\phi$ becomes zero. This phenomena happens when there is a balance between the number of events with $|\Delta \phi_{t\bar{t}}| > |\Delta \phi_{tH}|$ and $|\Delta \phi_{t\bar{t}}| < |\Delta \phi_{tH}|$. The value of cut on Higgs transverse momentum that leads zero for $O_\phi$ could be a criteria to probe the $t \bar{t}H$ coupling. It is noticeable that including the backgrounds, cuts and detector effects change the situation.

In this study, we only concentrate on the lepton+jets decay mode of the $t \bar{t}$ ($t \bar{t} \rightarrow l\nu q\bar{q}'b\bar{b}$) and consider the Higgs boson decay into a bottom-quark pair (other Higgs decays can be included). Background estimations by the CMS experiment for the analysis of search for $t \bar{t}H$ at 7 and 8 TeV center-of-mass energies show that the main background contributions are originating from $t \bar{t}$+light flavor quarks, $t \bar{t} + c\bar{c}$ and $t \bar{t} + b\bar{b}$. In the right side of Fig.2 we show that including these backgrounds change the values and shape of $O_\phi$ for different cuts and on Higgs $p_T$. The trend of $O_\phi$ versus the Higgs $p_T$ cut does not take significant effect after including the main background. Including this background even leads to larger slope for $O_\phi$.

At this stage, we turn to impose kinematic cuts on the final state objects. The cuts are chosen similar to the ones used by the CMS experiment in search for the $t \bar{t}H$ channel. Charged lepton is required to have $p_T > 25$ GeV and $|\eta| < 2.5$. All jets must have $p_T > 40$...
Figure 2: Left: the shape of $O_\phi$ for the SM and several values of $\tilde{\kappa}$ versus cuts on the transverse Higgs momentum. Right: the shape of $O_\phi$ of $t\bar{t}H$ for the SM case and for the $t\bar{t}H$ plus the main background $t\bar{t}+\text{jets}$.

GeV and $|\eta| < 2.5$. In order to have well-separated objects, it is required that the angular separation between objects should be greater than 0.4, i.e. $\Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} > 0.4$. Finally, the magnitude of missing transverse energy has to be larger than 30 GeV. In Fig. 3 the effect of these cuts are presented on our observable $O_\phi$. We show the shape of $O_\phi$ versus the cut on Higgs transverse momentum before applying any cut, after applying only $p_T$ cuts and after applying all cuts. One can see that imposing cuts on the final state object in particular the cuts on transverse momenta of the final particles enhance the amount of $O_\phi$ with respect to the case of applying no cuts. Applying these kinematic cuts increase the contribution of events in which the Higgs boson recoils against the $t\bar{t}$ pair. Obviously, this effect is more visible for the events that Higgs boson has larger boost.

The statistical significance for the observable $O_\phi$ is determined as the ratio of $O_\phi$ to its standard deviation $\Delta O_\phi$: $S = O_\phi / \Delta O_\phi$. After some algebra, one can show:

$$\Delta O_\phi = \sqrt{\frac{1 - O_\phi^2}{\sigma_{pp\rightarrow t\bar{t}H} \times \mathcal{L}}}$$

(6)

where $\sigma_{pp\rightarrow t\bar{t}H}$ is the cross section of the $pp \rightarrow t\bar{t}H$ in the SM and $\mathcal{L}$ denotes the total integrated luminosity. The signal significance $S$ in the presence of the anomalous couplings can be defined as:

$$S(\kappa, \tilde{\kappa}) = \frac{O_\phi(\kappa, \tilde{\kappa}) - O_\phi^{SM}}{\sqrt{1 - (O_\phi^{SM})^2}} \sqrt{\frac{\sigma_{pp\rightarrow t\bar{t}H}}{\sigma_{pp\rightarrow t\bar{t}H} \times \mathcal{L}}}$$

(7)

The statistical significance $S$ is a function of $\kappa$ and $\tilde{\kappa}$. Since $O_\phi$ is not sensitive to $\kappa$, we set $\kappa = 1$ (its SM value) and concentrate on $\tilde{\kappa}$. In our analysis, we determine the value of cut on
the Higgs boson $p_T$ that maximizes the statistical significance. We choose several values of $\tilde{\kappa}$ and calculate the statistical significance in terms of Higgs boson transverse momentum. We find that for all values of $\tilde{\kappa}$ parameter, the maximum takes place at $p_{T,H} > 0$ i.e. no cut on the Higgs boson transverse momentum. This is the value at which our proposed observable takes its largest value. It is reasonable since when no cut is applied on the Higgs $p_T$ there is more statistics that leads to smaller statistical uncertainty and larger signal significance.

The left plot in Fig.4 shows the statistical significance versus $\tilde{\kappa}$ for the integrated luminosities of 10,50,100 fb$^{-1}$ at the LHC for the center-of-mass energy of 14 TeV. In the right side of Fig.4 the 1$\sigma$,3$\sigma$ and 5$\sigma$ regions of $\tilde{\kappa}$ are shown. In obtaining these results we have set $\kappa = 1$. As it can be seen, the 1$\sigma$ region of $\tilde{\kappa}$ is achieved using $\approx 60$ fb$^{-1}$ of the integrated luminosity of data.

We should mention that our estimation is almost raw due to the lack of including the effects of parton shower, hadronization, detector simulation and final state reconstruction. Including such components with a more detailed analysis is beyond the scope of the current analysis and must be performed by the experimental collaborations. However, we emphasize that the above issues may affect the results at a considerable level.

3 Electric dipole moment analysis

Beside the high energy studies in the search for the top quark Yukawa couplings, the low energy probes like electric dipole moments also provide the possibility to constrain the scalar
$(\kappa)$ and pseudoscalar ($\bar{\kappa}$) components of Higgs-top couplings. There are already several studies to probe $\kappa$ and $\bar{\kappa}$ using the electron and neutron etc. electric dipole moments [25], [36]. In [37], [38], it has been shown that the neutral Higgs boson exchange with CP-violating couplings at the order of one-loop generates sizeable electric and chromo-electric dipole moments for the top quark. Our main aim in this section is to derive bounds on the $\kappa$ and $\bar{\kappa}$ parameters using the future achievable bound on the top quark EDM. It has been shown that the future electron-positron collider would be able to set an upper limit of $10^{-19}$ e.cm directly on the EDM of the top quark. In the following, we extract bounds on $\kappa$ and $\bar{\kappa}$ using this upper limit on the top EDM.

The EDM of a spin-1/2 fermion can be defined using the form factor decomposition of the electromagnetic current $j_\mu$:

$$<p',s'|j_\mu(x)|p,s> \propto \bar{u}(p',s')[f_1(q^2)\gamma_\mu + f_2(q^2)\gamma_5q^\nu + ...]u(p,s)$$

where $q = p' - p$, $f_1(q^2 = 0)$ points out the electric charge of the fermion and $f_2(q^2 = 0)$ is the fermion electric dipole moment. More precisely: $d_f = -f_2(q^2 = 0)$. In the non-relativistic limit the EDM of a fermion with spin $\vec{s}$ appears in the interaction of the fermion with an external electric field $\vec{E}$ according to the Hamiltonian of $H = -d_f\vec{E}.\vec{s}$. Therefore, in the language of Lagrangian, the EDM of a spin 1/2 particle is defined by the effective Lagrangian

$$\mathcal{L} = -\frac{i}{2}d_f\bar{\psi}\sigma_{\mu\nu}\gamma_5\psi F^{\mu\nu}$$

In general for a theory of fermion $\psi_f$ interacting with other heavy fermions $\psi_i$ and heavy scalars $\phi_k$'s with masses $m_i, m_k$ and charges $Q_i, Q_k$ the interaction which consists of CP
violation is given by

\[ \mathcal{L} = - \sum_{i,k} \bar{\psi}_f [G_{L,ik}P_L + G_{R,ik}P_R] \psi_i \phi_k + h.c. \]  

(10)

where \( P_{L,R} \) are left-handed and right-handed projection operators. It is noted that \( \mathcal{L} \) violates CP invariance if \( \text{Im}(G_{L,ik}G^*_{R,ik}) \neq 0 \). The one loop EDM of the fermion \( f \) in this case is given by \[37\], \[38\], \[39\], \[40\]:

\[ |d_t| = \sum_{i,k} \frac{m_i}{16\pi^2m_k^2} \text{Im}(G_{L,ik}G^*_{R,ik}) \times (Q_i I_1(\frac{m_i^2}{m_k^2}) + Q_k I_2(\frac{m_i^2}{m_k^2})) \] (11)

where because of the charge is conserved at the vertices, \( Q_k = Q_f - Q_i \). In Eq. (11) \( I_{1,2}(r) \) have the following form:

\[ I_1(r) = \int_0^1 dx \frac{x^2}{1 - x + rx^2}, \quad I_2(r) = \int_0^1 dx \frac{x(1-x)}{1 - x + rx^2} \] (12)

In our case, \( \psi_i \) and \( \psi_f \) are the same (top quark) and \( \phi \) is the Higgs field so \( Q_k = 0 \). As we mentioned previously the EDM of the top quark can be explored in the future electron-positron collider in the \( e^-e^+ \rightarrow t\bar{t} \) process. It has been shown that the top quark EDM can be explored down to \( 10^{-19} - 10^{20} \) e.cm. After replacing the parameters and the limit of \( |d_t| < 10^{-19} \) e.cm the excluded region of \( \kappa \) and \( \tilde{\kappa} \) is shown in Fig. 5. Stronger bound on the pseudoscalar component is achieved when we are close to the SM i.e. \( \kappa = 1 \). In other word, the top EDM analysis gives stronger exclusion limit for larger values of pure scalar type Yukawa coupling. At the value of \( \kappa = 1 \), the upper limit of \( 10^{-19} \) e.cm leads to exclude any value of \( \tilde{\kappa} \) above 0.2. Stringent bound of the order of \( 10^{-21} \) e.cm on top quark EDM excludes \( \tilde{\kappa} \) above 0.01 at \( \kappa = 1 \). The top quark EDM allows an admixture of scalar and pseudoscalar Higgs-top coupling. We find that the limit on \( \tilde{\kappa} \) is negligibly sensitive to the Higgs boson mass. The change of limit on \( \tilde{\kappa} \) due to shifting the Higgs mass with \( \pm 5 \) GeV is less than 0.1%

For comparison, the allowed region on the plane of \( (\kappa, \tilde{\kappa}) \) that has been extracted from a global fit on 42 observables such as \( H \rightarrow WW^* \rightarrow 2l2\nu, H \rightarrow ZZ^* \rightarrow 4l, H \rightarrow 2\gamma, \) etc. The details of the analysis and list of all observables can be found in \[8\] and references therein. In addition, we depict the 1\( \sigma \) and 3\( \sigma \) regions that can be obtained by 30 fb\(^{-1}\) of LHC data using the proposed asymmetry-like observable \( O_\phi \) in the previous section in Fig. 5. The \( O_\phi \) observable is not sensitive to \( \kappa \) but is able to provide strong limits on \( \tilde{\kappa} \). The reachable 1\( \sigma \) region using this observable is \( \tilde{\kappa} < 0.06 \) for almost any value of \( \kappa \).

Finally, we point out that the pseudoscalar coupling \( \tilde{\kappa} \) contributes to the electron EDM electric dipole through a two-loop diagram \[41\]. The experimental upper bound on the
Figure 5: 68% CL allowed region from the global analysis taken from [8] (violet dashed-curve), the 1σ and 3σ allowed region obtained using the $O_\phi$ observable with 30 fb$^{-1}$ of the LHC data at 14 TeV. The red solid curve shows the allowed region that could be obtained by the future upper limit on the top quark EDM ($d_t < 10^{-19}$ e.cm).
electron EDM provides also stringent limit on the $\tilde{\kappa}$ coupling. The recent upper limit of $8.7 \times 10^{-29}$ e.cm \cite{42} leads to an upper limit of $\tilde{\kappa} < 0.01$. However, as discussed in \cite{2} direct probes for $\tilde{\kappa}$ are necessary since experimentally there is no measurement on the electron Yukawa coupling and there might be other contributions (from BSM such as supersymmetry) to the electron EDM that could lead to a cancellation of the two-loop top contribution.

4 Conclusions

The associated production of the Higgs boson with a pair of top quarks at the LHC enables us to explore the Higgs-top Yukawa coupling directly. In general, the Higgs-top interaction may consist of pseudoscalar component ($\tilde{\kappa}$) in addition to only the scalar part ($\kappa$). In this paper, based on the angular distributions of the final state particles in the $pp \rightarrow t\bar{t}H$ process we have suggested a new asymmetry-like observable $O_\phi$ to explore the Higgs-top coupling. We show that value of $O_\phi$ is sensitive to the pseudoscalar component of Higgs-top couplings and receives negligible contribution from the scalar coupling. Therefore, it can be a good observable to distinguish between the scalar and pseudoscalar terms. We find that the value of $O_\phi$ drops for the events with boosted Higgs boson and it takes its largest value when there is no cut on the Higgs transverse momentum. The value of cut on Higgs transverse momentum at which $O_\phi = 0$ is also a sensitive observable to $\tilde{\kappa}$. It is shown that applying the common kinematic cuts similar to what used by the CMS experiment on the final state particles does not disturb the trend of $O_\phi$ versus the cut on the Higgs boson $p_T$. Applying the kinematic cuts leads to significant increment in the amount of $O_\phi$. Finally, we find that the $1\sigma$ region of $\tilde{\kappa}$ is accessible using $O_\phi$ with less than 100 fb$^{-1}$ of LHC data at the center-of-mass energy of 14 TeV. In the second part of this work we concentrate on the fact that the presence of the CP violating component of the Higgs-top coupling ($\tilde{\kappa}$) leads to a sizeable EDM for the top quark that is achievable by the future $e^-e^+$ collider. We show that a bound of $10^{-19}$ e.cm on the top quark EDM excludes a significant range of $\kappa$ and $\tilde{\kappa}$. In particular, for the values of $\kappa$ close to the SM ( $\kappa = 1$) reasonable bounds can be obtained on $\tilde{\kappa}$. Using an upper bound of $10^{-19}$ e.cm on the top EDM excludes any value of the pseudoscalar component $\tilde{\kappa}$ above 0.2.

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