CP violation in $tbW$ couplings at the LHC

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Abstract

We study in a model-independent way anomalous CP-violating $tbW$ effective couplings that might arise from new physics in the processes $pp \rightarrow tW^-X$ and $pp \rightarrow tW^+X$, followed by semileptonic decay of $t$ and $\bar{t}$. These processes have a dependence on effective $tbW$ couplings both in the production process as well as in the decay of the $t$ or $\bar{t}$. We propose several CP-violating asymmetries constructed out of variables in the two processes, including $t$ and $\bar{t}$ polarization, and energy and azimuthal angles of the decay particles. We find that it is feasible to probe a certain CP-violating combination of anomalous couplings at the per cent level at the LHC for centre-of-mass energy 14 TeV and an integrated luminosity of 10 fb$^{-1}$.

1. Introduction: The top quark, with a mass close to the scale of electroweak symmetry breaking (EWSB), is generally believed to hold a key to the understanding of the mechanism of symmetry breaking and responsible for masses of all standard model (SM) particles. While the so-called Higgs mechanism is the dominant scenario for EWSB, it has not yet been established experimentally. The currently operational Large Hadron Collider (LHC), which is proceeding full-steam with the search for the Higgs boson, can produce top quark-antiquark pairs in great profusion. It will shed light on the details of the properties of the top quark, and hopefully, of EWSB. Due to its large mass, the top quark decays before hadronization effects, thus preserving polarization information in the decay products. The study of the top-quark properties through its production and decay at the LHC would thus be of immense significance in arriving at a detailed understanding of the one of the major mysteries of nature.

In addition to EWSB, another important phenomenon which lacks full understanding is CP violation (CPV). Apart from having been seen experimentally in mixing and decay of $K$ and $B$ mesons, CPV is also essential in understanding the observed baryon asymmetry of the universe. In the SM, the only source of CPV is the phase associated with the Cabibbo-Kobayashi-Maskawa (CKM) inter-generational quark mixing matrix. However, the SM cannot adequately explain the baryon asymmetry $[1]$. Extensions of the SM are needed to understand baryogenesis, and examples of extensions which fit the bill are the two Higgs doublet models (THDM) and minimal supersymmetric standard model (MSSM), which have additional particles and newer mechanisms of CPV. In fact, in these models, it is the CP-violating scalar couplings of the top quark which drive baryogenesis $[2]$. Thus the study of CPV, particularly in the top-quark sector, could shed light on primordial processes responsible for baryogenesis.

Apart from $tt$ pair production, which occurs dominantly through strong interaction, single-top production, which necessarily proceeds via weak interaction, also has a large cross

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section at the LHC [3]–[11], and has already been seen [12]. Single-top production will therefore be able to give us information about the size and nature of the weak-interaction coupling of the top quark to the $b$ quark and the weak-interaction gauge boson $W$, i.e., the $tbW$ coupling, as well as the $tb$ (33) element of the CKM matrix. Thus, for example, top polarization, which is negligible in the SM in top pair production because strong interactions conserve parity, would be large in single-top production because of the chiral nature of weak interactions [9].

In this work we investigate the possibility of probing putative CP-violating $tbW$ couplings in a model-independent way using single-top production in association with a $W$ boson. There are a number of proposals for the study of CPV in top-pair production at lepton [15], photon [16] and hadron colliders [17]. However, CPV in single-top production has received little attention [18, 19]. The reason can be seen to be two-fold. For one, unlike in $t\bar{t}$ production, where the final state is self-conjugate, in single-top production, a process involving $t$ has to be related to another involving $\bar{t}$, which is not straightforward. The other reason is the low event rate for single-top production expected at Tevatron. Single-top production at the LHC can be substantial, and it would be worthwhile attempting to extract information on CPV, even though it needs more elaborate analysis than in the case of pair production. Recent earlier work on CPV in single-top production at the LHC has been in $tH^-$ associated production [18] or in the context of flavor-changing top couplings [19], but not so far in $tW^-$ production. This, therefore, is the first time that the possibility of studying CP-violating $tbW$ couplings at the LHC is being explored.

There are three distinct mechanisms for single-top production, viz., a) the $t$-channel process $bq \to tq'$, b) the $s$-channel process $qq' \to t\bar{b}$ and c) the $tW$ associated production process $bg \to tW^-$ [4]. Although the process a) has the largest cross section, the other processes also occur at a significant level. Since each process has a distinctive final state, it would be possible to study each one of them separately.

The process c), in which we are interested, is difficult to isolate due to backgrounds, the dominant one being top-pair production. The backgrounds have been studied in [4, 5], and kinematic cuts which can clearly isolate the $tW$ channel have been suggested there. A similar analysis including NLO effects has been carried out in [6, 7]. Recently, with integrated luminosities of 0.7 fb$^{-1}$ and 2.1 fb$^{-1}$ respectively, ATLAS [13] and CMS [14] have presented results on a search for the $tW$ signal, where both $W$’s decay leptonically. They have been able to put an upper bound on the cross section.

In a recent work [20], we examined in the context of the LHC the capability of the process c) above, viz., single-top production in association with a $W$, for providing information on possible anomalous $tbW$ couplings in a model-independent way. The processes a) and b), while sensitive to $tbW$ couplings, could also get contribution from other processes like scalar exchange, and do not permit a model-independent approach. In [20], anomalous $tbW$ couplings were found to change the production mechanism, giving rise to top polarization different from that predicted by SM. In addition, top decay distributions can also get modified by anomalous couplings. Thus, a study of decay distributions in the laboratory (lab) frame were shown to carry signatures of anomalous $tbW$ couplings firstly through the degree of polarization, and secondly through the contribution to the decay process itself.

Tevatron provides the only existing direct limits on anomalous $tbW$ couplings through $W$ polarization measurements. These results [21] lead to a limit of 0.3 at the 95% confidence level (CL) on the magnitude of the tensor coupling $f_{2R}$, the only coupling relevant in high-energy processes. (The couplings are defined later, in eqs. (4), (5)). Early LHC data [22]
on measurements of $W$ polarization in $t\bar{t}$ production and $t$-channel single-top production allow a limit of $[-0.6, 0.3]$ to be put on $f_{2R}$ \cite{11}. There are stringent indirect constraints coming from low-energy measurements of anomalous $tbW$ couplings. The measured rate of $b \to s\gamma$ puts stringent constraints on the couplings $f_{1R}$ and $f_{2L}$ of about $4 \times 10^{-3}$, since their contributions to $B$-meson decay get an enhancement factor of $m_t/m_b$ \cite{23, 24}. The bound on the anomalous coupling $f_{2R}$, however, is weak, viz., $[-0.15, 0.57]$ at the 95\% CL \cite{24}. In \cite{25} a slightly more stringent bound has been found utilizing $B_{d,s} - B_{d,s}$ mixing. It is thus clear that better direct limits on $f_{2R}$ are needed.

We propose making use of the same lab-frame variables which we employed in \cite{20} for $tW^-$ production, but for a study of CPV, we would also need analogous variables for $t\bar{W}^+$ production. The difference (in certain cases the sum) of these variables for the cases of $tW^-$ and $t\bar{W}^+$ production would be a measure of CPV. For convenience, we will adopt a linear approximation for the couplings. This enables determination of limits on the CP-violating parameter which are independent of the parameter itself. Moreover, we find that for maximal CPV, which we define in terms of equality in magnitude of $\tilde{t}$ and $\tilde{\bar{t}}$ couplings, there is no quadratic contribution to the asymmetry, making the linear approximation an excellent one.

At the LHC, the initial state being $pp$ is not self-conjugate and it is not evident that a study of CP-conjugate final-state particles can reveal the extent of CPV, if present. Nevertheless, associated $tW^-$ production is initiated by partons $b$ and $g$, whose respective densities in $p$ are equal to those of the conjugates $\bar{b}$ and $\bar{g}$, from simple charge conjugation invariance of strong interactions governing parton distributions in hadrons.

To see the consequences of CP invariance, consider a partial cross section for $tW^-$ inclusive production at the LHC which may be written as

$$d\sigma(p(p_1)p(p_2)\to t(p_t, h_t)W^-(p_W)X)=\int dx_1 dx_2 f_b(x_1) f_g(x_2) d\sigma_{bg\to tW^-(x_1 p_1, x_2 p_2, p_t, h_t, p_W)}$$

(1)

where $d\sigma_{bg\to tW^-}$ is the corresponding parton-level partial cross section, and $f_b$, $f_g$ are the densities of $b$, $g$ partons in the proton. $p_1$, $p_2$, $p_t$ and $p_W$ are respectively the momenta of the two protons, $t$ and $W^-$, and $h_t$ is the helicity of $t$. One can write an analogous expression for the partial cross section $d\sigma(p(p_1)p(p_2)\to \bar{t}(p_t, h_t)W^+(p_W)\bar{X})$ for $t\bar{W}^+$ production. CP invariance at the parton level, which implies

$$d\sigma_{bg\to tW^-}(x_1 p_1, x_2 p_2, p_t, h_t, p_W) = d\sigma_{bg\to \bar{t}\bar{W}^+}(x_1 p_1, x_2 p_2, p_t, -h_t, p_W),$$

(2)

gives, for the hadron-level cross sections,

$$d\sigma(pp \to t(p_t, h_t)W^-(p_W)X) = d\sigma(pp \to \bar{t}(p_t, -h_t)W^+(p_W)\bar{X}).$$

(3)

A violation of this relation would signal CPV. Thus, CP invariance implies equal and opposite longitudinal polarizations for $t$ and $\bar{t}$ in the two processes.

2. Effective vertices: We can write the most general effective vertices up to mass dimension 5 for the four distinct processes of $\hat{t}$ decay, $\tilde{t}$ decay, production and $\tilde{t}$ production as

$$V_{t\to tW^+} = -(g/\sqrt{2})V_{tb}[\gamma^\mu(f_{1L} P_L + f_{1R} P_R) - i(\sigma^{\mu\nu} q_\nu / m_W)(f_{2L} P_L + f_{2R} P_R)],$$

(4)

$$V_{t\to \tilde{t}W^-} = -(g/\sqrt{2})V_{tb}^*[\gamma^\mu(f_{1L}^* P_L + f_{1R}^* P_R) - i(\sigma^{\mu\nu} q_\nu / m_W)(f_{2L}^* P_L + f_{2R}^* P_R)],$$

(5)

$$V_{\bar{t}\to tW^-} = -(g/\sqrt{2})V_{tb}^*[\gamma^\mu(f_{1L}^* P_L + f_{1R}^* P_R) - i(\sigma^{\mu\nu} q_\nu / m_W)(f_{2L}^* P_R + f_{2R}^* P_L)],$$

(6)

$$V_{\bar{t}\to \tilde{t}W^+} = -(g/\sqrt{2})V_{tb}[\gamma^\mu(f_{1L}^* P_L + f_{1R}^* P_R) - i(\sigma^{\mu\nu} q_\nu / m_W)(f_{2L}^* P_R + f_{2R}^* P_L)].$$

(7)
where \( f_{1L}, f_{1R}, f_{2L}, f_{2R}, \bar{f}_{1L}, \bar{f}_{1R}, \bar{f}_{2L}, \) and \( \bar{f}_{2R} \) are form factors, \( P_L, P_R \) are left-chiral and right-chiral projection matrices, and \( q \) represents the \( W^+ \) or \( W^- \) momentum, as applicable in each case. In the SM, at tree level, \( f_{1L} = \bar{f}_{1L} = 1 \), and all other form factors vanish. New physics effects would result in deviations of \( f_{1L} \) and \( \bar{f}_{1L} \) from unity, and nonzero values for other form factors.

At tree level, i.e., in the absence of any absorptive parts in the relevant amplitudes giving rise to the form factors, the following relations would be obeyed:

\[
\begin{align*}
    f_{1L}' &= \bar{f}_{1L}; \\
    f_{1R}' &= \bar{f}_{1R}; \\
    f_{2L}' &= \bar{f}_{2L}; \\
    f_{2R}' &= \bar{f}_{2R}.
\end{align*}
\]  

(8)

This can be seen to follow from the fact that in the absence of final-state interactions leading to absorptive parts, the effective Lagrangian is hermitian. Thus, the hermiticity of the Lagrangian

\[
\mathcal{L}_i = -(g/\sqrt{2}) \left[ V_{tb} \left\{ \gamma^\mu (f_{1L} P_L + f_{1R} P_R) - (\sigma^{\mu\nu}/m_W) \partial_\nu W^-_\mu (f_{2L} P_L + f_{2R} P_R) \right\} t \\
+ V_{tb}^* \left\{ \gamma^\mu (\bar{f}_{1L} P_L + \bar{f}_{1R} P_R) - (\sigma^{\mu\nu}/m_W) \partial_\nu W^+_\mu (\bar{f}_{2L} P_L + \bar{f}_{2R} P_R) \right\} \bar{b} \right] + \text{H.c.},
\]  

(9)

from which the \( t \) and \( \bar{t} \) decay and production amplitudes \((1)-(7)\) may be derived, implies the relations \((8)\).

On the other hand, if CP is conserved, the relations obeyed by the form factors are

\[
\begin{align*}
    f_{1L} &= \bar{f}_{1L}; \\
    f_{1R} &= \bar{f}_{1R}; \\
    f_{2L} &= \bar{f}_{2L}; \\
    f_{2R} &= \bar{f}_{2R}.
\end{align*}
\]  

(10)

We can write the phases of the form factors as sums and differences of two phases, one corresponding to a nonzero absorptive part, and another corresponding to CP nonconservation:

\[
\begin{align*}
    f_{1L,R} &= |f_{1L,R}| \exp (i\alpha_{1L,R} + i\delta_{1L,R}); \\
    \bar{f}_{1L,R} &= |f_{1L,R}| \exp (i\alpha_{1L,R} - i\delta_{1L,R}); \\
    f_{2L,R} &= |f_{2L,R}| \exp (i\alpha_{2L,R} + i\delta_{2L,R}); \\
    \bar{f}_{2L,R} &= |f_{2L,R}| \exp (i\alpha_{2L,R} - i\delta_{2L,R}).
\end{align*}
\]  

(11)

where, for convenience, magnitudes of the couplings are assumed to be equal in appropriate pairs. In case there are no absorptive parts (\( \alpha_i = 0 \)), we get the relations \((8)\) as a special case. In case of CP conservation, we get the relations \((10)\) as a special case. In what follows, we will deal with a more general case when both CPV and absorptive parts are present. When calculating differences of variables for \( tW^- \) and \( \bar{t}W^+ \) production, we will encounter only the combination

\[
\Delta_{2R} \equiv (\text{Re} \bar{f}_{2L} - \text{Re} \bar{f}_{2R}) = -2|f_{2R}| \sin \alpha_{2R} \sin \delta_{2R}.
\]  

(12)

(We assume \( f_{1L} = \bar{f}_{1L} = 1 \) and \( V_{tb} = 1 \) throughout). For \( \Delta_{2R} \) to be nonzero, both absorptive parts and CPV have to be present, as can be seen from eq. \((12)\).

The effective vertices \((1)-(7)\) contribute to the production and decay of the top quark and antiquark. The parton-level Feynman diagram for \( tW^- \) is shown in Fig. \(1\) with the effective vertex shown as a filled circle. The effect of anomalous couplings would show up in the production process in the total cross section, \( t \) or \( \bar{t} \) angular distributions and or \( t \) polarizations. This is apart from \( W \) polarization, which we do not consider here. As for the decay process, for a given production angle and polarization of \( t/\bar{t} \), anomalous couplings would change the angular distribution of the decay products.

In what follows, we obtain the contribution of CP-violating \( tbW \) couplings in sums or differences of observables in \( tW^- \) and \( \bar{t}W^+ \) production and decay, and examine how well the
couplings can be constrained by them. We retain only $\text{Re} f_{2R}$ and $\text{Re} \bar{f}_{2L}$, since these are the only ones which contribute in the limit of vanishing bottom mass, which we set to zero. We will assume that the anomalous couplings are small and a linear approximation of the couplings found to be good for $|\text{Re} f_{2R}|$ up to about 0.05 [20].

3. CP-violating asymmetries: We now formulate CP-violating asymmetries in the single-top production subprocess $gb \rightarrow tW^-$ and its CP-conjugated subprocess $\bar{g}b \rightarrow \bar{t}W^+$ through CP-violating anomalous $tbW$ couplings. In [20], we have obtained analytical expressions for the spin density matrix for the top quark produced in the process $gb \rightarrow tW^-$ and for the top decay including the full contribution of anomalous $tbW$ couplings. The corresponding expressions for the CP-conjugated process $\bar{g}b \rightarrow \bar{t}W^+$ and $\bar{t} \rightarrow \bar{b}W^-$ can be obtained from those expressions by replacing $\text{Re} f_{2R}$ by $\text{Re} \bar{f}_{2L}$ taking appropriate helicity of the antitop.

The simplest asymmetry we consider is the rate asymmetry in the production of $tW^-$ and $\bar{t}W^+$. Assuming the equality of $b$ and $\bar{b}$ densities in the proton, we can write, at linear order in the anomalous couplings,

$$
\sigma(pp \rightarrow tW^- X) = \sigma_0 + \text{Re} f_{2R} \sigma_1, \quad \sigma(pp \rightarrow \bar{t}W^+ X) = \sigma_0 + \text{Re} \bar{f}_{2L} \sigma_1,
$$

where $\sigma_0$ is the SM cross section, which is identical for $pp \rightarrow tW^- X$ as well as $pp \rightarrow \bar{t}W^+ X$ and $\sigma_1$ is the cross section arising from interference of the anomalous contribution with the SM amplitude, for unit anomalous coupling. We can then write the fractional rate asymmetry,

$$
A_{\sigma}^{CPV} = 1/(2\sigma_0) (\text{Re} \bar{f}_{2L} - \text{Re} f_{2R}) \sigma_1 = 1/(2\sigma_0) \Delta_{2R} \sigma_1.
$$

In the linear approximation, the $t$ polarization $P_t$ and the $\bar{t}$ polarization $P_{\bar{t}}$ can be written as

$$
P_t = P_t^0 + \text{Re} f_{2R} P_t^1, \quad P_{\bar{t}} = - P\bar{t}^0 - \text{Re} \bar{f}_{2L} P_{\bar{t}}^1,
$$

where $P_t^0$ and $P_t^1$ are contributions from the SM and from the pure anomalous couplings at linear order, respectively. In the linear order in anomalous couplings, a CP-violating asymmetry $A_{P_t}^{CPV}$ in top and antitop polarization defined by $A_{P_t}^{CPV} = P_t + P_{\bar{t}}$ takes the form

$$
A_{P_t}^{CPV} = -(\text{Re} \bar{f}_{2L} - \text{Re} f_{2R}) P_{\bar{t}}^1 = - \Delta_{2R} P_{\bar{t}}^1.
$$

The asymmetries so far did not take into account top decay. A measurement of these asymmetries would need full reconstruction of the top. Thus the corresponding efficiencies
would have to be taken into account. We now look at asymmetries where an explicit decay channel of \( \tilde{t} \) is taken into account.

A rate asymmetry may be found corresponding to the combined production and semileptonic decay of the \( t \) and \( \tilde{t} \), where both the production and decay processes get contributions from the anomalous couplings. Using the narrow-width approximation, we can write the cross section for the process \( pp \to tW^-X \to b\ell^+\nu W^- \) as

\[
\sigma_{tW^-} \equiv \sigma(pp \to b\ell^+\nu W^-X) = (1/\Gamma_t) \times \left[ \rho(pp \to tW^-X) \otimes \Gamma(t \to b\ell^+\nu) \right],
\]

where \( \Gamma_t \) is total decay width of the top, \( \rho(pp \to tW^-X) \), \( \Gamma(t \to b\ell^+\nu) \) are respectively the production and decay density matrices (with appropriate integration of the phase space carried out), and \( \otimes \) denotes a matrix product. The density matrix formalism is used here to ensure proper spin coherence between production and decay. Writing an analogous expression for the cross section \( \sigma_{\tilde{t}W^-} \) for the conjugate process, we define the asymmetry in charged-lepton production rates as

\[
A_{t}^{\text{CPV}} = [\sigma_{tW^-} - \sigma_{\tilde{t}W^-}]/[\sigma_{tW^-} + \sigma_{\tilde{t}W^-}].
\]

where \( A_{t}^{\text{CPV}} \) gets contribution not only from the asymmetry in \( \tilde{t} \) production, but also from the anomalous coupling in the decay into the leptonic channel.

In all the following cases, we write the generic asymmetry in the \( tW^- \) process as \( A^- \), and that in \( \tilde{t}W^+ \) production as \( A^+ \). We can then write, in the linear approximation,

\[
A^- = A^0 + \text{Re} f_{2R} A^1; \quad A^+ = A^0 + \text{Re} f_{2L} A^1,
\]

where \( A^0 \) is the asymmetry in the SM, and \( A^1 \) is the contribution coming from the interference between the term with anomalous couplings and the SM term, for unit value of the coupling. The CP-violating asymmetry is then

\[
A_{\text{CPV}} \equiv A^+ - A^- = \Delta_{2R} A^1.
\]

The azimuthal distributions of the charged lepton and the \( b \) quark arising from the top decay are sensitive to anomalous couplings \cite{20} and we define the corresponding azimuthal asymmetries as

\[
A_{\phi_{\ell,b}} = [\sigma(\cos \phi_{\ell,b} > 0) - \sigma(\cos \phi_{\ell,b} < 0)]/[\sigma(\cos \phi_{\ell,b} > 0) + \sigma(\cos \phi_{\ell,b} < 0)],
\]

where \( \phi_{\ell} \), \( \phi_{b} \) are respectively the azimuthal angles of the charged lepton and the \( b \) quark w.r.t. the top production plane. An analogous asymmetry can be defined for the charged lepton and \( b \) arising in antitop production. The CP-violating asymmetries \( A_{\phi_{\ell}}^{\text{CPV}} \) and \( A_{\phi_{b}}^{\text{CPV}} \) are then defined as the differences between the relevant azimuthal asymmetries from the \( tW^- \) process and the conjugate process.

The charged-lepton energy distribution is also sensitive to anomalous \( tbW \) couplings \cite{20}, and the distributions for SM and different anomalous couplings all intersect at about \( E_{\ell}^C = 62 \) GeV. To quantify the differences in distributions for different couplings, we constructed in \cite{20} an asymmetry around the intersection energy \( E_{\ell}^C \) of the curves, defined by

\[
A_{E_{\ell}} = [\sigma(E_{\ell} < E_{\ell}^C) - \sigma(E_{\ell} > E_{\ell}^C)]/[\sigma(E_{\ell} < E_{\ell}^C) + \sigma(E_{\ell} > E_{\ell}^C)],
\]

Using this, and the corresponding asymmetry for antitop production and decay, we define a CP-violating asymmetry \( A_{E_{\ell}}^{\text{CPV}} \) as their difference.
3. Numerical Results: We now evaluate the various asymmetries defined. For our numerical analysis, we consider for the LHC a cm energy $\sqrt{s} = 7$ TeV for integrated luminosity $L = 5$ fb$^{-1}$, and $\sqrt{s} = 14$ TeV with $L = 10$ fb$^{-1}$. While the present run of the LHC is at $\sqrt{s} = 8$ TeV, we have checked that our results for this energy would be similar to those for $\sqrt{s} = 7$ TeV. We use the leading-order parton distribution function sets of CTEQ6L [26] with a factorization scale of $m_t = 172.6$ GeV. Values of parameters used are: $M_W = 80.403$ GeV, $\alpha_{em}(m_Z) = 1/128$ and $\sin^2 \theta_W = 0.23$.

We have imposed acceptance cuts on the charged-lepton rapidity and transverse momentum, viz., $|\eta| < 2.5$, and $p_T^\ell > 20$ GeV. We have assumed an ideal situation of 100% efficiency for $W$ and $b$-jet identification, since we have used analytical expressions integrated over the full kinematic range for $W$ and $b$. We later discuss the effect of realistic cuts needed for isolating the $Wt$ final state. In order to discriminate the charge of the lepton which comes from top decay, we thus restrict ourselves to leptonic decay of the top and hadronic decay of the $W$.

In the linear approximation, the asymmetry is given by the parameter $\Delta_{2R}$ multiplied by the quantity $A^1$ for each asymmetry which is given in Table 1 against the corresponding asymmetry. As can be seen, the lepton energy asymmetry is the largest among the asymmetries constructed out of decay distributions. Also shown in Table 1, for various asymmetries, are the possible $1\sigma$ limits on the CP-violating parameter $\Delta_{2R}$, using for the statistical uncertainty in $A^{CPV}$ the value $\delta A^{CPV} = \sqrt{2}/\sqrt{L \sigma_{SM}}$, where $\sigma_{SM}$ is the SM cross section for the relevant final state. For this, we have taken only one of the leptonic decay modes for the top, while including all hadronic channels for the decay of the $W$. The results are shown in Table 1. For the estimation of limits using $A^{CPV}_\sigma$ and $A^{CPV}_{P_t}$, we assume 100% efficiency in the detection of the top, as well in the measurement of its polarization. The corresponding idealized limits are for comparison with the remaining more realistic ones obtained from kinematics of decay products.

We see from the Table 1 that $1\sigma$ limits on $|\Delta_{2R}|$ possible for $\sqrt{s} = 7$ TeV with $L = 5$ fb$^{-1}$ are of the order of about 0.1, perhaps at the limit of validity of our linear approximation. The limit from $A^{CPV}_{P_t}$ is nominally better, but cannot be realized since the polarization cannot be measured with 100% accuracy. For $\sqrt{s} = 14$ TeV, on the other hand, the limits are of
Table 1: The value of various CP-violating asymmetries for unit value of the CP-violating combination of couplings, $\Delta_{2R}$, and the corresponding 1σ limits on $|\Delta_{2R}|$ possible at the LHC.

| $\sqrt{s}$ | $A_{\sigma}^{CPV}$ | $A_{E_t}^{CPV}$ | $A_{E_{\phi}}^{CPV}$ | $A_{E_\ell}^{CPV}$ | $A_{E_{\phi\ell}}^{CPV}$ | $A_{E_{\phi}\ell}^{CPV}$ |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 7 TeV      | $A_{\sigma}^{CPV}$ for $\Delta_{2R} = 1$ Limit ($L = 5 \text{ fb}^{-1}$) | 0.508 | 0.526 | 0.362 | 0.198 | 0.464 | 0.093 |
| 14 TeV     | $A_{\sigma}^{CPV}$ for $\Delta_{2R} = 1$ Limit ($L = 10 \text{ fb}^{-1}$) | 0.502 | 0.536 | 0.369 | 0.186 | 0.438 | 0.086 |

We now discuss how the results of Table 1 would be affected on inclusion of realistic cuts needed for the isolation of the $tW$ events and suppression of background. For this we make use of the analysis carried out recently by the ATLAS and CMS collaborations for the LHC data.

We determine the factor by which the theoretical number for the $Wt$ events get reduced by cuts in a single leptonic channel in top as well as $W$ decay, making use of Table 2 of [13] and also Table 2 of [14]. We find this factor to be approximately 0.1. These searches use leptonic decay channels of $W$ whereas a search for CPV should necessarily use the two-jet decays of $W$. For such a final state, ref. [5] indicates a somewhat better efficiency than 0.1 for each channel, so we are being somewhat conservative.

We then assume that the same factor can be used in our CP-asymmetry analysis (also at 14 TeV) to get an idea of the number of events which survive the cuts. Undoing the leptonic cut already used in Table 1, and including all leptonic channels (we assume detection efficiency of 0.6 for $\tau$’s), we arrive at a correction factor of 0.325 for the event rates, and 1.754 for the limits in Table 1.

We thus see that in the best scenario of $\sqrt{s} = 14 \text{ TeV}$ with $L = 10 \text{ fb}^{-1}$, a realistic limit of about 0.04 on $|\Delta_{2R}|$ should be possible using the leptonic energy asymmetry.

4. Conclusions and Discussion: We have investigated the possibility of measuring CP-violating $tbW$ couplings at the LHC through the conjugate processes of $tW^-$ and $\bar{t}W^+$ production. We proposed a number of CP-violating asymmetries which would be sensitive to the CP-odd combination of couplings $\Delta_{2R} \equiv f_{2L} - f_{2R}$, the difference of the couplings associated with the top and the antitop.

We conclude from our analysis that the $tW$ mode of single-top production is a good alternative process to look for CP-violating $tbW$ couplings apart from a comparison of $t$ and $\bar{t}$ decays in top-pair production. We find that the energy asymmetry, $A_{E_t}^{CPV}$, is the most sensitive to the CP-violating parameter and would enable a limit of about 0.04 to be placed on $|\Delta_{2R}|$, for a cm energy of 14 TeV and integrated luminosity of 10 fb$^{-1}$. The limits possible for an operational energy of 7 TeV for integrated luminosity of up to 5 fb$^{-1}$ are not as good, being at the level of 0.1-0.2.

Higher-order QCD and electroweak effects can give rise to a partonic-level forward-backward asymmetry at the per cent level in the background process of $tt$ production. This asymmetry can, because of valence-sea PDF difference, induce in the lab frame observables a charge asymmetry which does not originate in CPV. However, this is present only in the
sub-dominant quark-antiquark process. Moreover, how our leptonic observables would be affected needs detailed investigation, beyond the scope of this work. Table 1 shows that $A_{E_l}^{CPV}$ is fairly close in magnitude to $A_{P_l}^{CPV}$, and seems to be a good measure of the polarization asymmetry. Since polarization can only arise from chiral couplings, higher-order QCD effects cannot generate it. $A_{E_l}^{CPV}$, at least, is therefore unlikely to get significant contribution from higher-order QCD effects. Top polarization due to electroweak effects is tiny [27].

All in all we conclude that it would be possible to obtain limits on the CP-violating anomalous coupling in the region of $10^{-2}$ by employing the energy asymmetry of the charged lepton. Since this is the first investigation in this direction, these numbers corresponding to direct limits should be taken as encouraging. It would be worthwhile carrying out a more detailed and refined analysis.

Various extensions of the SM would have specific predictions for these anomalous couplings. For example, the contributions to these form factors in 2HDM, MSSM and top-color assisted Technicolor model have been evaluated in [28]. The predictions in these models, especially for the imaginary parts of the couplings, seem to be much smaller than the limits we expect from LHC with $L = 10$ fb$^{-1}$.

Acknowledgment: SDR acknowledges financial support from the Department of Science and Technology, India, under the J.C. Bose National Fellowship programme, grant no. SR/SB/JCB-42/2009.

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