Constraining the top quark effective field theory using the $t\bar{t}g$ production at future lepton colliders

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Our main aim in this paper is to constrain the effective field theory describing the top quark couplings through the $e^-e^+\rightarrow t\bar{t}g$ process. The analysis is carried out considering four different center-of-mass energies of 500, 1000, 1500, and 3000 GeV including a realistic simulation of the detector response and the main sources of background processes. The study is performed on the benchmark scenarios proposed by the future electron-positron colliders such as CLIC and ILC. The expected limits at 95% CL are derived on the new physics couplings such as $t\bar{t}g$, $t\bar{t}Z$, $ht\bar{t}$, and $t\bar{t}g$ for each benchmark scenario using the dileptonic $t\bar{t}$ final state. We show that the 95% CL limits on dimensionless Wilson coefficients $\bar{c}_i$ determined in this analysis could be probed down to $10^{-4}$. Our findings indicate that a future lepton collider operating at a center-of-mass energy above the $t\bar{t}$ threshold would improve the constraints by orders of magnitude with respected to the LHC expectations.

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I. INTRODUCTION

Since the Higgs boson observation $[1, 2]$ at the Large Hadron Collider (LHC) by the ATLAS and CMS Collaborations, the primary focus of high energy particle physics is to probe its properties in details $[3,4]$. In addition to the Higgs boson, the heaviest discovered particle to date, i.e. the top quark which was discovered by D0 and CDF Collaborations at Fermilab $[6, 7]$, is expected to play an important role in the electroweak symmetry breaking (EWSB) mechanism due to its large mass.

Looking further into the future, in addition to the LHC, precision measurements of the top quark and Higgs boson properties motivate the construction of future lepton colliders which provide cleaner environments due to the absence of hadronic initial state and their relatively smaller experimental uncertainties with respect to hadron colliders. Hence, there is currently a growing interest in studying the physics accessible by possible future high-energy and high-luminosity electron-positron colliders that would continue the investigations made with the large electron-positron (LEP) collider to much higher energy and luminosity $[8,10]$. So far, there have been several proposals over the past years for the future electron-positron colliders, such as the Compact Linear Collider (CLIC) $[11,13]$, the International Linear Collider (ILC) $[14,16]$, Circular Electron Positron Collider (CPEC) $[17,18]$, and the highest-luminosity energy frontier Future Circular Collider with electron-positron collisions (FCC-ee) at CERN $[19]$, previously known as TLEP $[20]$ (see, for example, the most recent Conceptual Design Report by FCC Collaboration $[21, 22]$ for recent review).

Phenomenological and experimental studies over the past decades have provided important information on the validity of the Standard Model (SM) as well as the physics beyond the SM (BSM) $[23,25]$. The focus of many studies has been on the top quark and Higgs boson phenomenology and search for the new physics (NP) through them. These include, for example, the precise measurements of the top quark and Higgs boson masses, their couplings to the other fundamental particles in the framework of the SM and BSM, and searches for NP effects beyond the SM in both model dependent and independent ways. In the case that the possible new degrees of freedom are not light enough to be directly produced at a collider, they could affect the SM observables indirectly through virtual effects. In such conditions, a powerful tool to parametrize any potential deviations from
the SM predictions in a model independent way is the standard model effective field theory (SMEFT). SMEFT provides a general framework where non-redundant bases of independent operators can be built and would be able to match them to explicit ultraviolet complete (UV-complete) models in a systematic way. From the phenomenological point of view, there is a large volume of published works to study the SMEFT in particular in the top quark and Higgs boson sectors from the LHC, from electron-positron colliders, and from future proposed high-energy lepton-hadron and hadron-hadron colliders [26][65].

At future lepton colliders, the process $e^-e^+ \rightarrow t\bar{t}g$ is sensitive to both top quark electroweak and strong couplings. The overall cross section is smaller than the top quark pair production because of the presence of an additional $\alpha_s$ however the process has low background and would be able to provide reasonable precision to probe the top quark interactions, and is considered as a complementary process to $e^-e^+ \rightarrow t\bar{t}$. The aim of present study is to examine the sensitivity of the top quark pair production in association with a gluon at future electron-positron colliders to the SMEFT. All dimension-six operators in the SILH basis which involve top quark and/or Higgs and gauge bosons assuming CP-conservation are included [60][67]. We perform a detailed sensitivity study and present the expected 95% CL limits on the operator coefficients for several benchmark values of center-of-mass energies $\sqrt{s}$ and integrated luminosity $L$ related to the proposed electron-positron colliders such as ILC and CLIC. It is shown that the $e^-e^+ \rightarrow t\bar{t}g$ process has the ability to probe several effective couplings such as $hgt$, $t\bar{t}g$, $t\bar{t}\gamma$, and $t\bar{t}Z$

This paper is organized as follows: In section [II] the SMEFT framework is briefly introduced. In section [III] the details of the simulation for probing SMEFT operators through the production processes of $t\bar{t}$ in association with a gluon at the electron-positron collision are described. In section [IV] the methodology applied in this analysis to constrain the Wilson coefficients as well as the results are presented. Finally, section [V] concludes the paper.

II. THEORETICAL FRAMEWORK

As no clear evidence of new physics beyond the standard model has been observed, an efficient approach for examining the SM and possible deviations from SM could be provided by the SMEFT. In this approach, beyond the SM effects are probed via series of higher dimensional SM operators. The coefficients of the operators, so-called Wilson coefficients, can be connected to the parameters of explicit models. The effective Lagrangian is provided considering the operators which are invariant under the SU(3) × SU(2) × U(1) gauge symmetries and Lorentz transformations. We restrict ourself to the operators with lepton and baryon number conservation. In such a case, the leading contributions come from dimension-six operators. The general Lagrangian of the SM effective theory with dimension-six operators is given by [68][70],

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i O_i}{\Lambda^2},$$

(1)

In the above relation, $\Lambda$ is the energy scale of new physics, $c_i$‘s are dimensionless Wilson coefficients and the gauge invariant dimension-six operators denoted by $O_i$ are constructed out of the SM fields. There are various bases where the operators $O_i$ are classified in an independent way. In this work, the dimension-six operators sensitive to the $e^-e^+ \rightarrow t\bar{t}g$ process are discussed in the SILH basis [68][71][73]. This basis is not a unique basis and can be connected to the other bases. The SMEFT Lagrangian $\mathcal{L}_{\text{SMEFT}}$ in the SILH basis can be expressed as follows:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i c_i O_i = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{SILH}} + \mathcal{L}_{F_1} + \mathcal{L}_{F_2} + \mathcal{L}_G + \mathcal{L}_{CP}.$$

The first term in the above effective Lagrangian, $\mathcal{L}_{\text{SM}}$, is the well-known SM Lagrangian. The second term, $\mathcal{L}_{\text{SILH}}$, consists of a set of operators which involve the Higgs doublet $\Phi$ and could arise from UV-models where Higgs boson contributes to the strongly interacting sector. The interactions between two Higgs boson fields and a pair of quarks or a pair of leptons are described by $\mathcal{L}_{F_1}$ while the interactions of a quark pair or a lepton pair with one single Higgs field and a gauge boson are addressed by $\mathcal{L}_{F_2}$. All the modifications related to the gauge sector, from the gauge bosons self energies to the gauge bosons self-interactions are parameterized in $\mathcal{L}_G$. The CP-violating interactions are described by $\mathcal{L}_{CP}$. In this work, the concentration is on the CP-conserving operators. Within the SMEFT framework, in addition to the new Feynman diagrams contributing to the $e^-e^+ \rightarrow t\bar{t}g$, the SM Feynman diagrams are modified. The representative Feynman diagrams for $t\bar{t}g$ production at electron-positron colliders are depicted in Fig. [I]. The filled circles are the vertices which receive modification from the SM effective field theory. It is notable that in addition to the diagrams for the $t\bar{t}g$ production where the SM couplings are modified, a new diagram arising from $hgt$ contribute to the $e^-e^+ \rightarrow t\bar{t}g$ process. In the current study, we restrict ourselves to effective operators contributing to $e^-e^+ \rightarrow t\bar{t}g$ process involving at least one top quark. Although other effective operators can affect the $e^-e^+ \rightarrow t\bar{t}g$ process via for example $hee$, $hgg$, $Zee$ or $\gamma ee$ vertices, they have only small impacts on the cross section and could be constrained by other processes. The CP-conserving operators in the SILH basis that affect the top quark interac-
tions at leading order in the $e^- e^+ \rightarrow t \bar{t} g$ are listed below:

\[
O_{uG} = \frac{g_s}{m_W^2} y_u \bar{Q} L H^c \sigma^{\mu \nu} \chi^a u_R G^a_{\mu \nu}, \\
O_{uW} = \frac{g}{m_W^2} y_u \bar{Q} L \sigma^i H^c \sigma^{\mu \nu} u_R W^i_{\mu \nu}, \\
O_{uB} = \frac{g}{m_W^2} y_u \bar{Q} L H^c \sigma^{\mu \nu} u_R B_{\mu \nu}, \\
O_u = \frac{y_u}{v^2} \Phi^+ \Phi \bar{Q} L u_R, \\
O_{HQ} = \frac{i}{v^2} (\bar{Q} L \gamma^\mu Q_L) (H^\dagger D^-_\mu H), \\
O_{H\sigma} = \frac{i}{v^2} (\bar{Q} L \gamma^\mu \sigma^i Q_L) (H^\dagger \sigma^i D^-_\mu H), \\
O_{Hu} = \frac{i}{v^2} (\bar{u}_R \gamma^\mu u_R) (H^\dagger D^-_\mu H),
\]

(3)

where the left-handed and right-handed quarks are denoted by $Q_L$ and $u_R$, respectively. $y_u$ is the $3 \times 3$ Yukawa coupling matrix in flavor space, $v$ is the vacuum expectation value, and $H^\dagger D^-_\mu H \equiv H^\dagger D^-_\mu H - D^-_H H^\dagger$.

Among the mentioned operators, $O_{uG}$ modifies the interaction of the top quark and gluons, i.e. $g t \bar{t}$. In addition, $O_{uG}$ generates the new four-leg interaction of $h g t \bar{t}$ which also contributes to the $t \bar{t} g$ production. The $O_{uW}$ and $O_{uB}$ operators modify the interactions between the top quark, photon and the $Z$ boson. The $O_u$, $O_{HQ}$, $O'_{HQ}$, and $O_{Hu}$ operators contribute to the $h t \bar{t}$ Yukawa coupling however, they do not affect the $e^- e^+ \rightarrow t \bar{t} g$ production rate significantly due to the presence of $hee$ Yukawa coupling. As a result, in the analysis we neglect $O_u$, $O_{HQ}$, $O'_{HQ}$, and $O_{Hu}$ operators and focus on $O_{uG}$, $O_{uW}$, and $O_{uB}$. The $O_{uW}$ and $O_{uB}$ operators modify the oblique parameters $S, T$, and $U$ at one loop level. In particular, the $\tilde{c}_{uW}$ and $\tilde{c}_{uB}$ Wilson coefficients have been constrained at percent level using the oblique parameters [74]. The imaginary parts of the coefficients of these operators can be constrained using the upper limit on the neutron electric dipole moment. The derived upper bound on $\text{Im}(\tilde{c}_{uG})$ at 95% CL is of the order of $10^{-4}$ [73].

In order to calculate the impacts of the operators on the $t \bar{t} g$ production, MadGraph5_aMC@NLO [79][77] package is used. The effective SM Lagrangian introduced in Eq. (2) is implemented in the FeynRule program [78] and then the Universal FeynRules Output (UFO) model [79] is fed to the MadGraph5_aMC@NLO program. Figure 2 shows the $e^- e^+ \rightarrow t \bar{t} g$ production cross section as a function of the centre-of-mass energy at leading order for three signal scenarios as well as the SM background. In this figure the Wilson coefficients are normalised to the $b\bar{b}$ notation, $\tilde{c}_X = c_X v^2/\Lambda^2$, and the $O_{uG}$, $O_{uW}$, and $O_{uB}$ operators are individually switched on. As it can be seen, there is a significant enhancement which occurs at top quark pair threshold. For the SM, the production rate approximately falls down as $1/s$. For the cases that the effective operators are switched on the enhancement of the cross section is even more pronounced at the top pair mass threshold. At $\sqrt{s} = 3$ TeV, the cross section due to the operator $O_{uG}$ increase by one order of magnitude with respect to the SM while the enhancement arising from $O_{uW}$ is at the order of $10^3$. Such raises of the cross section occur because of the momentum dependence of the $O_{uG}$, $O_{uW}$, and $O_{uB}$ operators. The $O_{uW}$ and $O_{uB}$ operators lead to much larger increase in the cross section of $e^- e^+ \rightarrow t \bar{t} g$ with respect to $O_{uG}$ because the involved virtual photon and $Z$ boson momenta could grow up to the total electron-positron center-of-mass energy while less momentum is running to the $O_{uG}$ vertex. As mentioned previously, in this analysis the aim is to examine the potential of the future lepton colliders to probe the SMEFT via the $e^- e^+ \rightarrow t \bar{t} g$ process. We neglect the insensitive operators and those with no top quark and only focus on $\tilde{c}_{uB}$, $\tilde{c}_{uG}$ and $\tilde{c}_{uW}$. 

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**Figure 1:** Representative Feynman diagrams for the $t \bar{t} g$ production in association with a gluon in electron-positron collisions at the leading-order within the SMEFT.
where events are generated using the SM input parameters are considered as [80]. In the event generation process, the ground processes to the signal considered in the analysis and missing transverse momentum. The dominant back-ing from the gluon, two opposite sign charged leptons, originating from the top quarks decay, one light jet com-
ting from the gluon, two opposite sign charged leptons, and missing transverse momentum. The dominant back-ground processes to the signal considered in the analysis are as follows:

- SM production of $t\bar{t}g$.
- Top quark pair production $t\bar{t}$.
- $e^-e^+ \rightarrow Z^* Z^* V^* \rightarrow 2\ell + \text{jets} + \text{missing momentum}$, where $V = \gamma, Z$.
- $e^-e^+ \rightarrow W^* W^* V^* \rightarrow 2\ell + \text{jets} + \text{missing momentum}$, where $V = \gamma, Z$.
- $e^-e^+ \rightarrow V^* V^* V^* V' \rightarrow 2\ell + \text{jets} + \text{missing momentum}$, where $V, V' = W^\pm, Z, \gamma$.

where $\ell = e, \mu$. The SM background processes and signal events are generated using the MadGraph5_aMC@NLO [75] event generator. In the event generation process, the SM input parameters are considered as [80]:

\[
\begin{align*}
    m_t &= 173.34 \text{ GeV} \quad \text{for the top quark mass}, \\
    m_W &= 80.385 \text{ GeV} \quad \text{for the W boson mass}, \\
    m_Z &= 91.187 \text{ GeV} \quad \text{for the Z boson}.
\end{align*}
\]

The generated samples are passed through the PYTHIA 6 [81, 82] for parton shower, hadronization, and decay of unstable particles. In order to take into account detector effects, we use the Delphes 3.4.1 [83] by which an ILD-like detector [84] is simulated. For jet reconstruction, the anti-$k_t$ algorithm [85] based on the FastJet package [86] with the cone size parameter $R = 0.5$ is employed. The $b$-tagging efficiency and misidentification rates are applied depending on the jet transverse momentum [83]. The efficiency of $b$-tagging for a jet with $p_T = 40 \text{ GeV}$ is 60%, and the charm-jet and light flavor jets misidentification rates are 14% and 1.1%, respectively. To select signal events, it is required to have exactly two same flavor opposite sign isolated charged leptons (either electron or muon) with the transverse momentum $p_T \geq 20 \text{ GeV}$ and the pseudorapidity $|\eta| \leq 2.5$. Each event is required to have at least three jets ($n_{\text{jets}} \geq 3$) with $p_T \geq 20 \text{ GeV}$ and $|\eta| \leq 2.5$ from which exactly two have to be $b$-tagged jets. In order to make sure all selected objects are well isolated, we require that the angular separation $\Delta R_{i,j} = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} \geq 0.4$, where $i, j = \ell$ and jets. The magnitude of missing transverse momentum is required to be larger than 20 GeV. Cross sections in the unit of fb for signal and sum of the major SM background processes after imposing the cuts are presented in the Table I for the center-of-mass energies of $\sqrt{s} = 500, 1000, 1500$, and 3000 GeV. The cross sections of the signal are given for three scenarios of $\epsilon_{uB} = 0.1$, $\epsilon_{uG} = 0.1$, and $\epsilon_{uW} = 0.1$. The main contributions to the background come from $t\bar{t}$ and SM $t\bar{t}g$ production, respectively.

\[\text{Figure 2:}\] The leading order cross section for the production of $e^- e^+ \rightarrow t\bar{t}g$ versus the the center-of-mass energy. The results are shown for the SM and for the signal scenarios in bar notation $\epsilon_X = c_X v^2 / \Lambda^2$ with the assumptions of $\epsilon_{uG} = 0.2$, $\epsilon_{uW} = 0.2$, and $\epsilon_{uB} = 0.2$. The cross sections have been calculated with a minimum cut of $p_T \geq 10 \text{ GeV}$ on the gluon.

III. SIMULATION AND DETAILS OF THE ANALYSIS

In this section, the details of the simulation and the analysis strategy to examine the $O_{uW}, O_{uB}$, and $O_{uG}$ operators using the $e^- e^+ \rightarrow t\bar{t}g$ process are discussed. We focus on the dileptonic decay channel of the $t\bar{t}$ system therefore the final state consists of two energetic $b$-jets originating from the top quarks decay, one light jet coming from the gluon, two opposite sign charged leptons, and missing transverse momentum. The dominant background processes to the signal considered in the analysis are as follows:

- SM production of $t\bar{t}g$.
- Top quark pair production $t\bar{t}$.
- $e^-e^+ \rightarrow Z^* Z^* V^* \rightarrow 2\ell + \text{jets} + \text{missing momentum}$, where $V = \gamma, Z$.
- $e^-e^+ \rightarrow W^* W^* V^* \rightarrow 2\ell + \text{jets} + \text{missing momentum}$, where $V = \gamma, Z$.
- $e^-e^+ \rightarrow V^* V^* V^* V'^* \rightarrow 2\ell + \text{jets} + \text{missing momentum}$, where $V, V' = W^\pm, Z, \gamma$.

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The generated samples are passed through the PYTHIA 6 [81, 82] for parton shower, hadronization, and decay of unstable particles. In order to take into account detector effects, we use the Delphes 3.4.1 [83] by which an ILD-like detector [84] is simulated. For jet reconstruction, the anti-$k_t$ algorithm [85] based on the FastJet package [86] with the cone size parameter $R = 0.5$ is employed. The $b$-tagging efficiency and misidentification rates are applied depending on the jet transverse momentum [83]. The efficiency of $b$-tagging for a jet with $p_T = 40 \text{ GeV}$ is 60%, and the charm-jet and light flavor jets misidentification rates are 14% and 1.1%, respectively. To select signal events, it is required to have exactly two same flavor opposite sign isolated charged leptons (either electron or muon) with the transverse momentum $p_T \geq 20 \text{ GeV}$ and the pseudorapidity $|\eta| \leq 2.5$. Each event is required to have at least three jets ($n_{\text{jets}} \geq 3$) with $p_T \geq 20 \text{ GeV}$ and $|\eta| \leq 2.5$ from which exactly two have to be $b$-tagged jets. In order to make sure all selected objects are well isolated, we require that the angular separation $\Delta R_{i,j} = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} \geq 0.4$, where $i, j = \ell$ and jets. The magnitude of missing transverse momentum is required to be larger than 20 GeV. Cross sections in the unit of fb for signal and sum of the major SM background processes after imposing the cuts are presented in the Table I for the center-of-mass energies of $\sqrt{s} = 500, 1000, 1500$, and 3000 GeV. The cross sections of the signal are given for three scenarios of $\epsilon_{uB} = 0.1$, $\epsilon_{uG} = 0.1$, and $\epsilon_{uW} = 0.1$. The main contributions to the background come from $t\bar{t}$ and SM $t\bar{t}g$ production, respectively.

\[\text{Figure 2:}\] The leading order cross section for the production of $e^- e^+ \rightarrow t\bar{t}g$ versus the the center-of-mass energy. The results are shown for the SM and for the signal scenarios in bar notation $\epsilon_X = c_X v^2 / \Lambda^2$ with the assumptions of $\epsilon_{uG} = 0.2$, $\epsilon_{uW} = 0.2$, and $\epsilon_{uB} = 0.2$. The cross sections have been calculated with a minimum cut of $p_T \geq 10 \text{ GeV}$ on the gluon.
This analysis are larger than the energy scale of the interaction, i.e. \( \Lambda > \sqrt{s} \), which is consistent with the EFT description. The \( \mathcal{O}_{uW} \) and \( \mathcal{O}_{uB} \) operators have been probed using the \( \bar{t}t \) production in Ref. [74] for various scenarios at the CLIC and ILC. It has been shown that using observables such as total cross section, forward-backward asymmetries, and utilising different sets of beam polarisation would lead to constraints on \( \bar{c}_{6W} \) and \( \bar{c}_{6B} \) at the order of \( \lesssim 10^{-4} \). The results from this analysis derive a comparable bound on \( \mathcal{O}_{uW} \) with respect to the \( \bar{t}t \) channel while the bound on the coefficient of \( \mathcal{O}_{uB} \) operator is looser by a factor around two. We note that combining the semi-leptonic topology of \( \bar{t}t \bar{g} \) process with the dileptonic one, considered in this analysis, would improve the bounds. The \( \bar{t}t \bar{g} \) process is a complementary channel to \( \bar{t}t \) production at lepton colliders and the combination of both channels will lead to more stringent constraints.

The derived limits in this analysis could be used to probe the parameters of explicit models which their low energy limits tend to the SMEFT. For instance, in beyond the SM scenarios with strongly interacting Higgs boson, a naive estimation leads to the following for the Wilson coefficients [73, 87]:

\[
\bar{c}_{6W}, \bar{c}_{6B}, \bar{c}_{6G} \sim \mathcal{O}(\frac{g^* m_t^2}{16\pi^2 M^2}). \tag{5}
\]

where \( M \) is the mass scale of the new physical state and \( g^* (\leq 4\pi) \) denotes the coupling strength of the Higgs boson to the new physics state. The obtained limit on \( \bar{c}_{6W} \) at \( \sqrt{s} = 3 \) TeV with 3 ab\(^{-1}\) integrated luminosity of data lead to a lower bound of 3.2 TeV on \( M \), in the strongly interacting regime \( g^* = 4\pi \).

### V. Summary and Conclusions

We have performed a full simulation study to probe the sensitivity of future lepton colliders to the top quark couplings at the center-of-mass energies of 500, 1000, 1500, and 3000 GeV. In particular, we concentrated on the top pair production in association with a gluon within the SMEFT framework. The SMEFT is an attractive and an efficient way to describe the possible effects of new physics until new particles from beyond the SM are observed. The \( e^- e^+ \rightarrow \bar{t}t \bar{g} \) process is found to be mostly sensitive to \( \mathcal{O}_{uW} \), \( \mathcal{O}_{uB} \), and \( \mathcal{O}_{uG} \) operators, respectively. The clean environment at lepton colliders and the expected high resolution for measurements of leptons and

| \( \sqrt{s} \) [GeV] | \( \bar{c}_{6W} \) | \( \bar{c}_{6B} \) | \( \bar{c}_{6G} \) | Background rate in fb |
|---|---|---|---|---|
| 500 | 1.7 | 0.2 | 3.3 | 0.43 |
| 1000 | 7.8 | 0.8 | 16.4 | 0.56 |
| 1500 | 11.5 | 0.8 | 25.0 | 0.35 |
| 3000 | 16.2 | 0.7 | 35.8 | 0.12 |

Table I: Expected cross sections after all cuts for signal and the main SM background processes. The signal cross sections are presented for \( \bar{c}_{6B} = 0.1 \), \( \bar{c}_{6G} = 0.1 \), and \( \bar{c}_{6W} = 0.1 \) in the unit of fb.
jets properties allow us to characterize the \( t\bar{t}g \) events through the dileptonic channel, where the final state consists of two charged lepton, three jets from which two are originating from hadronization of \( b \)-quarks, and missing transverse momentum. The results are based on a comprehensive analysis where the major sources of background processes and a realistic simulation of the detector response, flavor tagging, and jet clustering have been considered. It has been found that using 3 ab\(^{-1}\) of data at \( \sqrt{s} = 3 \) TeV would allow us to constrain the \( c_{uW} \) and \( c_{uB} \) of the level of \( 10^{-4} \) and \( 10^{-3} \), respectively. It is also found that moving up from the center-of-mass energy of 500 GeV to 3000 GeV at a future electron-positron collider with same amount of data would improve the limits on the \( c_{uW} \) and \( c_{uB} \) Wilson coefficients by a factor of around five. Using the \( t\bar{t}g \) process, possible future lepton colliders at the center-of-mass energy above 1 TeV, with the proposed benchmarks of the integrated luminosity, provides the possibility to examine the energy scale of new physics up to the order of \( \Lambda \sim 10 \) TeV. It is expected that the \( t\bar{t}g \) production provides a complementary avenue to the \( t\bar{t}t \) channel in probing the top quark electroweak couplings and the combination of both channels at various center-of-mass energies would remarkably improve the sensitivity.
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