Top quark physics at the LHeC

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Abstract. We study the DIS and photo-production modes of $t\bar{t}$ pairs at the proposed LHeC and its potential to probe the electromagnetic and weak dipole moments (MDM and EDM for $t\bar{t}\gamma$) of the top quark. A framework of eight independent gauge invariant dimension six operators involving the top quark and the electroweak gauge bosons is used. Four of those operators modify the charged $tbW$ coupling which can be probed through the single (anti) top production mode as reported in the literature. One generates $t\bar{t}\gamma(Z)$ as well as $tbW$ couplings, while other two do not generate $tbW$ but only $t\bar{t}\gamma(Z)$. Our focus is on the MDM and EDM of the top quark for which the photo-production mode of $t\bar{t}$ can be an excellent probe. At the proposed electron energies of $E_e = 60$ and $140 \text{ GeV}$ the LHeC could set constraints stronger than the indirect limits from $b\to s\gamma$ and the potential limits of the LHC through $t\bar{t}\gamma$ production[1].

1. Introduction
The Large Hadron Electron Collider (LHeC) is the proposal of a new electron beam with an energy $E_e = 60 \text{ GeV}$, or possibly $E_e = 140 \text{ GeV}$, to collide with one of the 7 TeV LHC proton beams at the high luminosity phase[2]. In this work we focus on top quark production and the potential of this machine to study the anomalous top-gauge boson couplings. In particular, for the case of the charged $tbW$ effective vertex a recent study has shown that the LHeC sensitivity will surpass the one achievable at the LHC[3]. As we shall see below, for the case of $t\bar{t}$ production, even though the rate is about one order of magnitude lower, the potential for measuring the $t\bar{t}\gamma$ magnetic (MDM) and electric dipole (EDM) moments is also better than at the LHC[1]. The reason for this is that in $t\bar{t}$ photoproduction the highly energetic incoming photon couples only to the $t$ quark so that the cross section depends directly on the $t\bar{t}\gamma$ vertex. In contrast, at the LHC the way to probe the $t\bar{t}\gamma$ vertex is through $t\bar{t}\gamma$ production, and in this case the outgoing photon could come from other charged sources, like the top decay products. The DIS regime of $t\bar{t}$ production will also be able to probe the $ttZ$ coupling, albeit with less sensitivity. In the framework of the effective Lagrangian with $SU(2)\times U(1)$ gauge invariant operators, some of the $ttZ$ couplings are generated by the same operators that give rise to $tbW$ and $t\bar{t}\gamma$. This correlation could be used to accomplish a complete and very sensitive analysis of $tbW$, $t\bar{t}\gamma$ and $ttZ$ couplings at the LHeC.

2. Dimension-six $SU(2)\times U(1)$ effective operators
The minimal non-redundant set of dimension-six gauge-invariant operators that give rise to effective top quark vertices with the gauge bosons is [4]:

$$O_{\phi}^{(3,ij)} = i\phi^{\dagger I} D_\mu \phi \bar{q}_{Li} \gamma_\mu \tau^I q_{Lj}, \quad O_{uW}^{ij} = \bar{q}_{Li} \sigma^{\mu\nu} \tau^I u_{Rj} \tilde{\gamma} W_{\mu\nu}^I,$$

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\[ O_{\phi q}^{(1,ij)} = i\phi^1 D_\mu \phi \tilde{q} L_i \gamma^\mu q_{L_j}, \quad O_{dW}^{ij} = \tilde{q} L_i \sigma^{\mu\nu} \tau^I d_{R_j} \phi W_{\mu\nu}^I, \]
\[ O_{\phi u}^{ij} = i\phi^1 D_\mu \phi \tilde{u}_{R_i} \gamma^\mu u_{R_j}, \quad O_{uB\phi}^{ij} = \tilde{q} L_i \sigma^{\mu\nu} u_{R_j} \phi B_{\mu\nu}, \]
\[ O_{\phi \phi}^{ij} = i\phi^1 D_\mu \phi \tilde{u}_{R_i} \gamma^\mu d_{R_j}, \quad O_{uG\phi}^{ij} = \tilde{q} L_i \lambda^a \sigma^{\mu\nu} u_{R_j} \phi C^a_{\mu\nu}. \]

Where, \( W_{\mu\nu}^I = \partial_\mu W_{\mu}^I - \partial_\nu W_{\mu}^I + g \epsilon_{IJK} W_{\mu}^J W_{\nu}^K \) and \( B_{\mu\nu} = \partial_\mu B_{\nu} - \partial_\nu B_{\mu} \) the \( SU(2)_L \) and \( U(1)_Y \) field strength tensors, respectively. In addition, for the operators on the left column \( D_\mu = \partial_\mu - ig/2 \tau^a W_{\mu}^a - ig' B_{\mu} \) is the Higgs covariant derivative.

We make the assumption:
\[ C_{\phi q}^{(3,33)} = C_{\phi \phi}. \]

We can write down the effective \( tt\gamma, ttZ \) and \( tbW \) couplings in terms of form factors:
\[ L_{it\gamma} = \frac{g}{\sqrt{2}} \left( \gamma \mu W_{\mu}^I (F_1^L P_L + F_1^R P_R) - \frac{1}{2m_W} \sigma^{\mu\nu} W_{\mu\nu} (F_2^L P_L + F_2^R P_R) \right) b, \]
\[ + \alpha t \left( Q_i \gamma^\mu A_{\mu} + \frac{1}{4m_t} \sigma^{\mu\nu} F_{\mu\nu}(\kappa + i\kappa \gamma_5) \right) t \]
\[ + \frac{g}{2c_W} \tau^a Z_{\mu} \left( (1 - \frac{4}{3}s_W^2 + F_{1Z}^L) P_L + (\frac{4}{3}s_W^2 + F_{1Z}^R) P_R \right) t \]
\[ + \frac{g}{2c_W} \left( \frac{1}{4m_t} \sigma^{\mu\nu} Z_{\mu\nu}(\kappa Z + i\kappa Z \gamma_5) \right) t \]

The relation between the form factors and the operator coefficients \( C^r_x \) is given by:
\[ F_1^L = V_{tb} + \frac{v^2}{\Lambda^2} C_{\phi q}, \quad F_1^R = \frac{v^2}{2\Lambda^2} C_{\phi \phi}, \]
\[ F_2^L = -\sqrt{2} \frac{v^2}{\Lambda^2} C_{\phi W}, \quad F_2^R = -\sqrt{2} \frac{v^2}{\Lambda^2} C_{\phi W}, \]
\[ F_{1Z}^L = \frac{v^2}{\Lambda^2} C_{\phi q}, \quad F_{1Z}^R = \frac{v^2}{2\Lambda^2} C_{\phi t}, \]
\[ \kappa = \frac{2\sqrt{2} v m_t}{e} \left( s_W C_{\phi W}^L + c_W C_{\phi W}^R \right), \quad \kappa_Z = \frac{4\sqrt{2} v m_t}{e} s_W c_W (c_W C_{\phi W}^L - s_W C_{\phi W}^R). \]

The imaginary parts of the coefficients generate \( CP \)-odd interactions. Comparing with other definitions we obtain:
\[ \kappa = -F_{2V}^\gamma = \frac{2m_t}{e} \mu_t = Q_t a_t, \]
\[ \tilde{\kappa} = F_{2A}^\gamma = \frac{2m_t}{e} d_t. \]

Where \( a_t = (g_t - 2)/2 \) is the anomalous MDM in terms of the gyromagnetic factor \( g_t \). Recent constraints coming from the branching ratio and a \( CP \) asymmetry for \( b \to s\gamma \) can be found in Ref. [5]: \(-2.0 < \kappa < 0.3 \) and \(-0.5 < \tilde{\kappa} < 1.5 \).

### 3. Top quark production at the LHeC

The most important top-production processes at the LHeC are single top, \( tt \), and associated \( tW \) production. In Table 3 we show the values of the associated cross sections for three electron energies. As seen there, the main source of production is single top via the charged current \( t \)-channel (see Figure 1), whereas for the other modes, \( tt \) and \( tW \), there is a lower though still sizeable production cross section. Given the advantage of an experimental environment cleaner than the LHC, we can envisage a good performance of this machine to do top quark physics.
Table 1. Diagonal operators with $CP$-even and $CP$-odd parts written separately. For $O_{\phi q}^{(1,33)}$, $O_{\phi q}^{(3,33)}$ and $O_{dw}^{33}$ only the terms that involve the top quark are shown. We define $\phi_0 = v + h$, $D_{\mu\nu}^+ = \partial_\mu W_\nu^\pm + ig W_\mu^+ W_\nu^3$ and $D_{\mu\nu}^3 = \partial_\mu W^3_\nu - ig W^\pm_\mu W^\mp_\nu$. The real (imaginary) part of each coefficient multiplies the $CP$-even (odd) part of the corresponding operator (the scale factor $\Lambda^{-2}$ is taken as 1 TeV$^{-2}$).

| Operator | Coefficient | $CP$-even ($O_{\phi q}^{33} + O_{\phi q}^{33}$) | $CP$-odd $i(O_{\phi q}^{33} - O_{\phi q}^{33})$ |
|----------|-------------|---------------------------------|---------------------------------|
| $(tb)O_{\phi q}^{33,33}$ | $C_{\phi q}$ | $\frac{g}{2\sqrt{2}}\phi_0^2 (W_\mu^+ t_L \gamma^\mu b_L + h.c.)$ | $-i\frac{g}{2\sqrt{2}}\phi_0^2 (W_\mu^+ t_R \gamma^\mu b_R - h.c.)$ |
| $O_{\phi \phi}^{33}$ | $C_{\phi \phi}$ | $\frac{g}{2\sqrt{2}}\phi_0^2 (W_\mu^+ t_R \gamma^\mu b_R + h.c.)$ | $i\frac{g}{2\sqrt{2}}\phi_0^2 (W_\mu^+ t_R \gamma^\mu b_R - h.c.)$ |
| $(tb)O_{dW}^{33}$ | $C_{dW}$ | $2\phi_0 D_{\mu\nu}^\pm b_L \sigma^{\mu\nu} t_R + D_{\mu\nu}^3 b_R \sigma^{\mu\nu} t_L$ | $2\phi_0 D_{\mu\nu}^\pm b_L \sigma^{\mu\nu} t_R + D_{\mu\nu}^3 b_R \sigma^{\mu\nu} t_L$ |

Table 2. Current bounds on the coefficients (real part). The indirect bounds for the first four coefficients are taken from electroweak data, whereas for the last three: $C_{dW}$, $C_{dB}$ and $C_{dG\phi}$, they are taken from $b \rightarrow s\gamma$ measurements. Direct bounds come from measurements on the $W$ helicity in top decays as well as single top production.

| Operator | LHC (7.8 TeV) |
|----------|---------------|
| $O_{\phi q}^{(1,33)}$ | $-0.35 < C_{\phi q} < 2.35$ | $-2.1 < C_{\phi q} < 6.7$ |
| $O_{\phi \phi}^{(3,33)}$ | $0.004 < C_{\phi \phi} < 0.056$ | $-6.6 < C_{\phi \phi} < 7.6$ |
| $O_{dW}^{33}$ | $-0.1 < C_{dW} < 3.7$ | $-1.6 < C_{dW} < 0.8$ |
| $O_{dW}^{33}$ | $-1.6 < C_{dW} < 0.8$ | $-1.0 < C_{dW} < 0.5$ |
| $O_{dB}^{33}$ | $-6.0 < C_{dB} < 0.9$ | $-6.0 < C_{dB} < 0.9$ |
| $O_{dG\phi}^{33}$ | $-0.1 < C_{dG\phi} < 0.03$ | $-0.3 < C_{dG\phi} < 0.06$ |

Table 3. The SM cross sections (pb) for single anti-top, $t\bar{t}$ and associated $tW^-$ (or $\bar{t}W^+$) production processes at the LHeC. The bottom row shows $t\bar{t}$ production at an LHeC–based $\gamma p$ collider.
4. Limits from $t\bar{t}$ photoproduction.

The branching fractions for $W$ decay are 21.32% for light leptonic decays $\ell\nu$ ($\ell = e, \mu$), 11.25% for $\tau\nu$ decays, and 67.6% for hadronic decays. Thus, for $t\bar{t}$ production followed by $bW$ decays we have the branching fractions given in Table 4. The dominant modes are the hadronic ($jjjj$) and the semileptonic ($\ell jj$).

\begin{center}
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
$\ell\ell$ & $\tau\tau$ & $jjjj$ & $\ell\tau$ & $\ell jj$ & $\tau jj$ \\
4.55% & 1.27% & 45.70% & 4.80% & 28.82% & 15.2% \\
\hline
\end{tabular}
\end{center}

Table 4. Approximate branching fractions for the decay of $t\bar{t}$ through $t \to bW$.

4.1. Semileptonic mode

For the semileptonic mode the signal ($S$) and signal plus total irreducible background ($S + B$) in the SM are defined as

$$S : \gamma g \to t \bar{t} \to b\bar{b}jj\ell\nu, \quad S + B : \gamma g \to b\bar{b}jj\ell\nu,$$  \hspace{1cm} (4)

with $\ell = e^\pm, \mu^\pm$ and $j = u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c}$. In the SM the signal process $S$ involves 16 Feynman diagrams, whereas $S + B$ involves 3704 diagrams in total, 2952 with one QCD vertex and five electroweak vertices like the signal process, and 752 with three QCD vertices and three electroweak vertices.
and quarks. We use for background processes free from infrared instabilities, due to the emission of massless leptons sections, computed in the SM, are summarized. Whereas a experimental measurements. In Table 5 the effects of those cuts on the signal and total cross

Figure 2. Bounds on the top quark dipole moments κ and ˜κ. Light-gray area: region allowed by the measurements of the branching ratio and CP asymmetry of B → X_sγ [5]. Dashed line: region allowed by a hypothetical experimental result for σ(pp → tℓγ) with semileptonic final state at the LHC at √s = 14 TeV with E_T^γ > 10 GeV and 5% experimental uncertainty. Solid line: region allowed by a hypothetical measurement of σ(γp → tℓ) with semileptonic final state, with the cuts C_f, (5), and 18% experimental uncertainty. Dark-gray area: same as previous, with 10% experimental error.

For the computation of the cross section we impose on the final–state momenta a set of appropriate phase-space cuts. We have considered several such sets defined as

C_0 : |η(j)| < 5, |p_T(j)| > 1 GeV, |η(ℓ)| < 5, |p_T(ℓ)| > 1 GeV,
C_1 : \begin{cases} |η(b)| < 3, |p_T(b)| > 15 GeV (E^b_e = 60 GeV) \\ |η(b)| < 3, |p_T(b)| > 20 GeV (E^b_e = 140 GeV) \end{cases},
C_f : C_1, ΔR(x) > 0.4 (x = b\bar{b}, ℓ\ell, ℓb, bj, jj),

where b stands for b or \bar{b}, j refers to the light jets, ℓ to the charged leptons, and ΔR = \sqrt{(Δη)^2 + (Δφ)^2} is the distance in the η-φ plane. The kinematic variables η, φ, correspond to the laboratory frame. The cuts C_0 are a minimal set needed to render the scattering amplitude for background processes free from infrared instabilities, due to the emission of massless leptons and quarks. We use C_0 only for reference. We have tested the cuts in the different kinematic variables one by one to assess their efficiency to reduce the ratio \epsilon_σ = (σ(S+B)−σ(S))/σ(S+B). We have found that only the cuts in b and \bar{b} lead to a significant enhancement of the signal. In the set C_1 we use a standard centrality cut for η(b) and choose the cut in |p_T(b)| so that |\epsilon_σ|15%. The cuts on leptons and light jets do not seem effective at improving the signal-to-background ratio, so in C_1 we keep them as loose as realistically possible. Finally, in the set C_f, which is the one used in our computations, we add standard isolation cuts for the b and light-quark jets, and the charged leptons, as idealized analogues of the ones required in actual experimental measurements. In Table 5 the effects of those cuts on the signal and total cross sections, computed in the SM, are summarized. Whereas a ∼ 15% background is sufficiently small for our purposes, further enhancement of the signal is in principle possible by imposing
additional cuts, for instance, on the invariant mass of the hadronic decay products. Let us assume a cut of the form

$$m_t - \sqrt{(p_b + p_q + p_{q'})^2} < W,$$

(6)

where $p_b$ stands for the four-momentum of either one of the two $b$-tagged jets and $p_q$, $p_{q'}$ for those of the non-$b$ jets. Then, at $E_e = 140$ GeV and $W = 30$ GeV, with the cut (6) in addition to $C_f$, we get $\sigma(S) = 22.06$ fb and $\sigma(S + B) = 24.90$ fb, corresponding to $\epsilon_{\sigma} = 11 \%$, which constitutes a slight improvement on $C_f$. An even larger enhancement of the signal would be obtained in the ideal case in which the missing momentum carried by the neutrino could be fully reconstructed. In that case, imposing the cuts $C_f$ together with (6) and the analogous cut on the leptonic decay products leads to $\sigma(S) = 21.79$ fb and $\sigma(S + B) = 23.30$ fb, yielding $\epsilon_{\sigma} = 6 \%$ which is less than one half of the background level in table 5.

With an integrated luminosity of 100 fb$^{-1}$ and the cross sections from Table 5, at $E_e = 60$ GeV we expect $\sim 385$ photoproduction events. Taking into account a $b$-tagging efficiency of 60% per $b$-jet, we are left with about 140 events corresponding to a statistical error of 8.4%. Similarly, at $E_e = 140$ GeV the expected statistical error is 3.5%.

One important source of systematic errors lies in the SM reducible background to the signal process $S$ in (4), given by processes of the form $e^- (\gamma)p \rightarrow jjjj\ell\nu$ (where $j$ stands for a gluon or a quark or antiquark of the first two generations), or $e^- (\gamma)p \rightarrow bjjj\ell\nu$ (where $b$ refers to $b$ or $\bar{b}$). The former class of processes involves two $b$-mistagging, and their cross-section is smaller than that of the signal by about two orders of magnitude which, multiplied by the probability of two mistagging, results in a negligible contribution. We take the $b$-mistagging probability to be 1/10 for $c$, and 1/100 for lighter partons. The second class of processes, involving a single $b$-mistagging, comprises 7408 Feynman diagrams. The overwhelmingly dominant contribution to the cross section, however, originates in diagrams containing two resonant intermediate propagators.

Thus, the reducible background is essentially given by the processes

$$\gamma b \rightarrow tW \rightarrow bq\ell\bar{\nu}c \ell\nu, \gamma b \rightarrow tW \rightarrow bq\ell\bar{\nu}d\ell\nu,$$

(7)

where the quark symbols stand for either those quarks or their antiquarks, and $\ell$ for $e^\pm$, $\mu^\pm$. All possible quark and lepton flavor combinations in the final state result in 204 diagrams for the charmed process, and as many diagrams for the charmless final state, with a cross section of 10.5 fb each at $E_e = 140$ GeV, and 2.04 fb each at $E_e = 60$ GeV. We have explicitly separated the charmed and charmless final states in (7) due to the different mistagging probabilities for the $c$ and lighter partons. For each of the processes in (7) we have to ascertain the fraction of events in which some or none of the three non-$b$ jets pass the cuts for $b$-jets (so they can therefore potentially be mistagged), and how many of them, and whether those jets passing the cuts are $c$ or lighter. For brevity, we skip the combinatorial analysis and the results for the partial cross sections for each case and just state the results. At $E_e = 140$ GeV the cross section for events with a single $b$-mistagging is 1.15 fb, or 5.16% of $\sigma(S)$ as given in Table 5, and at $E_e = 60$ GeV it is 0.25 fb, or 6.5% of $\sigma(S)$.

| $E_e = 60$ GeV | $E_e = 140$ GeV |
|----------------|-----------------|
| $\sigma(S)[fb]$ | $\sigma(S + B)[fb]$ | $\epsilon_{\sigma}$ | $\sigma(S)[fb]$ | $\sigma(S + B)[fb]$ | $\epsilon_{\sigma}$ |
| $\emptyset$ | 5.91 | | 30.94 | | |
| $C_0$ | 5.84 | 9.21 | 36.6% | 30.92 | 47.99 | 34.3% |
| $C_1$ | 4.50 | 5.26 | 14.4% | 25.59 | 29.87 | 14.3% |
| $C_f$ | 3.85 | 4.50 | 14.4% | 22.25 | 25.90 | 14.1% |

Table 5. The effect of the cuts defined in (5) on the SM signal and total semi–leptonic cross sections. $\emptyset$ refers to no cuts.
measurement of the would yield the bounds systematical error, we consider total experimental errors of 18% and 10% at \( \kappa = 140 \) GeV due to the larger event sample. We assume \( E_t \) the MDM section (which can be much better at 140 GeV due to the larger event sample). We assume \( E_t \) the

to right-handed bottom quarks and there is a negligible interference with the SM amplitude. On the other hand, if we assume that the single top cross section is measured with 2% (essentially systematic) error that is assumed for the asymmetries in Ref. [3] we obtain (based only on the resulting amplitude consists of 5136 Feynman diagrams, excluding those with internal Higgs lines as done for calculation with the signal process. The results obtained considering one coupling at a time are displayed in Table 6.

Table 6. The bounds obtained from \( t\bar{t} \) photoproduction including irreducible background, with the set of cuts \( C_f \) from (5).

| \( \epsilon = 10\% \) | min | max | \( \epsilon = 18\% \) | min | max |
|-------------------|-----|-----|-------------------|-----|-----|
| \( C_{t\bar{t}W}^f \) | \(-0.28\) | \(0.32\) | \( C_{t\bar{t}W}^f \) | \(-0.48\) | \(0.62\) |
| \( C_{t\bar{t}B}^f \) | \(-1.02\) | \(1.02\) | \( C_{t\bar{t}B}^f \) | \(-1.37\) | \(1.37\) |
| \( C_{t\bar{t}B}^f \) | \(-0.15\) | \(0.17\) | \( C_{t\bar{t}B}^f \) | \(-0.26\) | \(0.33\) |
| \( C_{t\bar{t}B}^f \) | \(-0.65\) | \(0.65\) | \( C_{t\bar{t}B}^f \) | \(-0.87\) | \(0.87\) |

Adding the statistical and mistagging errors discussed above in quadrature we obtain an error of 10.6% at \( E_e = 60 \) GeV and 6.2% at \( E_e = 140 \) GeV. Allowing for other unspecified sources of systematical error, we consider total experimental errors of 18% and 10% at \( E_e = 60 \) and 140 GeV, respectively, as plausible estimates.

In order to assess more accurately the effects on our results of the irreducible background processes passing the cuts, we repeated a small part of the analysis of the previous section including background effects. We considered only the semileptonic mode in PHP, \( e^- (\gamma \gamma)p(g) \rightarrow b\bar{b}jj\ell\nu \), including all possible insertions of the anomalous operators \( O^{dW}_{uW\phi} \) and \( O^{dB}_{uB\phi} \). The resulting amplitude consists of 5136 Feynman diagrams, excluding those with internal Higgs boson helicity in the decay of \( t \). On the other hand, the bounds for \( C_{t\bar{t}W}^f \) and \( C_{t\bar{t}B}^f \) are much weaker, this is because those operators are related to right-handed bottom quarks and there is a negligible interference with the SM amplitude. On the other hand, if we assume that the single top cross section is measured with 2% (essentially systematic) error that is assumed for the asymmetries in Ref. [3] we obtain (based only on the cross section) \(-0.34 < C_{\phiq} < 0.33 \), \( |C_{\phi\phi}| \lesssim 2.8 \), \(-0.7 < C_{t\bar{t}W}^f < 0.9 \) and \( |C_{t\bar{t}B}^f| \lesssim 1.1 \). The bounds for \( C_{\phiq} \) and \( C_{t\bar{t}W}^f \) obtained from the variation of \( \sigma(ep \rightarrow \nu t) \) are about one order of magnitude weaker than the bounds obtained by analyzing the \( W \) boson helicity in the decay of \( t \). On the other hand, the bounds for \( C_{t\bar{t}W}^f \) and \( C_{t\bar{t}B}^f \) (that involve \( b_R \)) are about the same order of magnitude.

Our focus is on the potential to probe the MDM and the EDM of the top quark through the \( t\bar{t} \) photoproduction process. The sensitivity changes very little going from \( \kappa = 140 \) GeV, it only depends on the accuracy achieved in measuring the production cross section (which can be much better at 140 GeV due to the larger event sample). We assume two possible values of the experimental error \( \Delta \sigma/\sigma = 10\%, 18\% \) and derive allowed regions for the MDM \( \kappa = 2m_{t\mu}/e \) and the EDM \( \tilde{\kappa} = 2m_{t\nu}/e \) as shown in Figure 2. In both cases, the measurement of the \( t\bar{t} \) photoproduction at the LHeC could greatly improve the limits imposed by the indirect constraints from \( b \rightarrow s\gamma \) and even the limits imposed by a future measurement of \( t\bar{t} \gamma \) production at the LHC (14 TeV). Specifically, measuring \( \sigma(\gamma \gamma \rightarrow t\bar{t}) \) with 10% (18%) error would yield the bounds \( |\kappa| < 0.05(0.09) \) and \( |\tilde{\kappa}| < 0.20(0.28) \).

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