Top quark effective couplings from top-pair tagged photoproduction in $pe^-$ collisions

Antonio O. Bouzas and F. Larios
Departamento de Física Aplicada, CINVESTAV-IPN
Carretera Antigua a Progreso Km. 6, Apdo. Postal 73 “Cordemex”
Mérida 97310, Yucatán, México

Received 15 March 2023; accepted 16 April 2023

We summarize the quantitative results of our analysis [1] of top-pair photoproduction in semileptonic mode in $pe^-$ collisions at the LHeC and FCC-he. We define three photoproduction regions, based on the rapidity acceptance range of the electron tagger, that provide different degrees of sensitivity to top-quark effective couplings. We focus on the $t\bar{t}\gamma$ dipole couplings and the left-handed vector $tbW$ coupling, for which we determine limits at both energies in the different photoproduction regions. We find that the LHeC and FCC-he will yield tight degrees of sensitivity to top-quark effective couplings. We focus on the $tbW$ coupling, which we determine limits at both energies in the different photoproduction regions. We find that the LHeC and FCC-he will yield tight degrees of sensitivity to top-quark effective couplings. We focus on the $tbW$ coupling, which we determine limits at both energies in the different photoproduction regions. We find that the LHeC and FCC-he will yield tight degrees of sensitivity to top-quark effective couplings. We focus on the $tbW$ coupling, which we determine limits at both energies in the different photoproduction regions. We find that the LHeC and FCC-he will yield tight degrees of sensitivity to top-quark effective couplings. We focus on the $tbW$ coupling, which we determine limits at both energies in the different photoproduction regions. We find that the LHeC and FCC-he will yield tight degrees of sensitivity to top-quark effective couplings. We focus on the $tbW$ coupling, which we determine limits at both energies in the different photoproduction regions. We find that the LHeC and FCC-he will yield tight degrees of sensitivity to top-quark effective couplings. We focus on the $tbW$ coupling, which we determine limits at both energies in the different photoproduction regions. We find that the LHeC and FCC-he will yield tight degrees of sensitivity to top-quark effective couplings. We focus on the $tbW$ coupling, which we determine limits at both energies in the different photoproduction regions. We find that the LHeC and FCC-he will yield tight degrees of sensitivity to top-quark effective couplings. We focus on the $tbW$ coupling, which we determine limits at both energies in the different photoproduction regions. We find that the LHeC and FCC-he will yield tight degrees of sensitivity to top-quark effective couplings. We focus on the $tbW$ coupling, which we determine limits at both energies in the different photoproduction regions. We find that the LHeC and FCC-he will yield tight degrees of sensitivity to top-quark effective couplings. We focus on the $tbW$ coupling, which we determine limits at both energies in the different photoproduction regions. We find that the LHeC and FCC-he will yield tight degrees of sensitivity to top-quark effective couplings. We focus on the $tbW$ coupling, which we determine limits at both energies in the different photoproduction regions. We find that the LHeC and FCC-he will yield tight degrees of sensitivity to top-quark effective couplings. We focus on the $tbW$ coupling, which we determine limits at both energies in the different photoproduction regions.

We consider indirect limits from $b\to s\gamma$ branching ratio and $CP$ asymmetry, that are well known to be very sensitive probes of top electromagnetic dipole moments.

Keywords: top-quark photoproduction electron-proton-collider

1 Introduction

Future $pe^-$ colliders, such as the Large Hadron-electron Collider (LHeC) and the Future Circular Collider (FCC-he), will have among their most important areas of research the study of the top quark effective couplings to the Higgs and the electroweak bosons [2]. Indeed, the top quark effective couplings constitute a phenomenological research area of great interest [3,4]. Top-pair and single-top production at the LHeC are very good probes for charged-current (CC) $tbW$ and neutral-current (NC) $ttZ$ effective couplings [5,6]. Also, anomalous magnetic and electric dipole moments of the top quark can be very well probed through top-pair photoproduction in electron-proton collisions [7–9].

In our recent paper [1] we obtain limits on the top-quark anomalous electromagnetic dipole moments and its left-handed vector $tbW$ coupling, in the context of the Standard Model Effective Field Theory (SMEFT), by means of Monte Carlo simulations including parton showering and hadronization, and fast detector simulation, for both the LHeC and the FCC-he. We compute the photoproduction cross section in tree-level QED, taking the complete kinematics into account, including the scattered-electron transverse momentum. This allows us to determine the phase-space region where the photoproduction process is sensitive to the top anomalous dipole moments, and that in which it is sensitive to the anomalous $tbW$ coupling.

Also studied in [1] are the indirect limits on top dipole moments from the decays $B\to X_s\gamma$. We update our previous results [10] for those limits, and discuss in detail the fact that there are currently two different sets of such limits, based on two incompatible theoretical computations [11,12] of the new physics contributions to the branching ratio for $B\to X_s\gamma$ and its associated $CP$ asymmetry.

In this note we discuss the quantitative results from [1] on direct limits on the anomalous top dipole moments and left-handed vector $tbW$ coupling, and comment also on the indirect limits obtained there. We discuss experimental limits by the CMS collaboration on $tbW$ couplings [13], as well as the very recent limits on top dipole moments [14] which were not included in [1]. We consider also the ATLAS collaboration projections on limits on top dipole moments for the HL-LHC [15].

A number of important issues discussed in [1] are not covered here for reasons of space. We point out among them, an extensive (and hopefully exhaustive) analysis of background processes, a summary of all global SMEFT top-quark analyses to date, and an in-depth discussion of the computation of indirect limits on anomalous couplings based on $B\to X_s\gamma$. We refer the reader to [1] for a comprehensive treatment of those topics.

This note is organized as follows. In section 2 we discuss the dimension-six SMEFT basis operators relevant to this work. In section 3 we discuss the top-pair photoproduction process in $pe^-$ collisions in the SM, and its Monte Carlo simulation and computation. In section 4 we present our limits on top anomalous effective couplings, and compare them to those obtained and projected by experimental collaborations. Finally, in section 5, we give our final remarks.

2 Effective SM Lagrangian

The effective Lagrangian for the SM extended by dimension-six gauge-invariant operators is of the form,

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_{\mathcal{O}} (\bar{\mathcal{C}}_\mathcal{O} \mathcal{O} + \text{h.c.}) + \cdots,$$

where $\mathcal{O}$ denotes the dimension-six effective operators, $\Lambda$ is the new-physics scale, and the ellipsis refers to higher-dimensional operators. It is understood in (1) that the addition of the Hermitian conjugate, denoted $+\text{h.c.}$ in the equa-
tion, is applicable only to non-Hermitian operators. Throughout this paper we use the dimension-six effective operators from the Warsaw operator basis [16]. In particular, we use the same sign convention for covariant derivatives as in [7, 16], namely, \( D_{\mu} = \partial_{\mu} + i e A_{\mu} \) for the electromagnetic coupling. However, we adopt the operator normalization defined in [17] (see also [18]), where a factor \( y_t \) is attached to an operator for each Higgs field it contains, and a factor \( g (g') \) for each \( W_{\mu\nu} (B_{\mu\nu}) \) field-strength tensor. The Wilson coefficients in (1) are denoted \( \tilde{C} \), since we will denote \( C \) the coefficients associated with the original operator basis [16]. In fact, it will be convenient in what follows to express our results in terms of the modified dimensionless couplings

\[
\tilde{C}_O = \frac{v^2}{\Lambda^2} C_O , \tag{2}
\]

where \( Q_{uB}^{33}, Q_{\varphi q}^{(−)33} \) are the basis operators defined in [16]. Notice that both operators \( O_{uB}^{33} \) and \( O_{\varphi q}^{(−)33} \) are \( O(1) \) with respect to the weak coupling constant, which makes the definitions (3) consistent from the point of view of perturbation theory. We stress here the definition

\[
O_{\varphi q}^{(−)33} = C_{O_{\varphi q}}^{(33)} - \lambda_y \theta_2 Q_{\varphi q}^{(−)33} = -y_t^2 Q_{\varphi q}^{(−)33}
\]

(3) is convenient to express our results in terms of the modified dimensionless couplings [20].

The numerical values in this equation arise from the parameters \( \Lambda = 1 \text{ TeV}, \nonumber \nu = 246 \text{ GeV}, \nonumber g' = 0.358, g = 0.648, y_t = 1 \).

It is common practice in the literature to write the anomalous interactions in terms of form factors. We adopt here the definition of top electromagnetic dipole moments given in eq. (2) of [7], and the CC vertex form factors from eq. (7.1) of [13]. Comparing those equations (which are summarized in eq. (5) of [11]), with (1), (2), (3), yields the tree-level relations,

\[
\kappa = 2g_t^2 \tilde{C}_{uB}^{33} , \quad \bar{\kappa} = 2g_t^2 C_{uB}^{(−)33} , \quad \delta f_V^L = y_t^2 \tilde{C}_{\varphi q}^{(−)33} . \tag{5}
\]

These particularly simple relations are a consequence of eq. (2) and the operator normalization discussed in the text immediately above that equation. We see from (5), in particular, that for all practical purposes \( \delta f_V^L = \tilde{C}_{\varphi q}^{(−)33} \).

3 Top-pair photoproduction in the SM

We are interested in top-pair photoproduction in \( p e^- \) collisions in the semileptonic decay channel which, at parton level, leads to the seven-fermion final states:

\[
g \ e^- \rightarrow e^- t\bar{t} \rightarrow e^- b^+tq_d + e^- bq_u\bar{q}_d b^{-}\ell \, , \tag{6}
\]

with \( q_d = u, c, q_u = d, s, \ell = e, \mu \). The set of Feynman diagrams for this process in the photoproduction region in the SM has been presented in figure 1. We consider the top-pair photoproduction process defined by the diagrams in that figure our signal process.

We can divide the set of diagrams in figure 1 into two subsets: the first subset includes diagrams (a), (b), containing three internal top lines, and the second one comprises the remaining diagrams, (c)–(i), containing two internal top lines. The second subset is necessary to preserve electromagnetic gauge invariance in the phase-space regions where \( t \) or
We compute the tree-level cross section for top-pair photoproduction and its backgrounds with MadGraph5_aMC@NLO version 2.6.3 [20], together with Pythia version 6.428 [21] and Delphes version 3.4.2 [22]. The parameters of the simulation are described in section 4 of [1], as are the details of the top-reconstruction method, and the event-selection cuts. We are led to define three photoproduction regions, characterized by the rapidity of the scattered electron,

\[
\begin{align*}
PhP_I : & \quad 4.741 < y(e^-) < -3.0, \\
PhP_{II} : & \quad 5.435 < y(e^-) < -3.0, \\
PhP_{III} : & \quad 6.215 < y(e^-) < -3.0.
\end{align*}
\]

As discussed in detail in [1], the sensitivity to \( \tilde{C}_{ab}^{33} \) is highest in \( PhP_I \) and lowest in \( PhP_{III} \), and the sensitivity to \( \tilde{C}_{eq}^{\tau 33} \) is highest in \( PhP_{II} \) and lowest in \( PhP_I \). Both sensitivities are intermediate in \( PhP_{III} \).

With the phase-space cuts specified in section 4 of [1], the cross sections for the \( t\bar{t} \) photoproduction signal process (6), figure 1, and the \( tbW \) irreducible background, are found to be as follows,

\[
\begin{array}{l|llll}
\text{LHeC} & PhP_I & PhP_{II} & PhP_{III} \\
\text{FCC-he} & PhP_I & PhP_{II} & PhP_{III} \\
\hline
LHeC & 0.40 & 0.73 & 1.32 \\
FCC-he & 4.28 & 6.19 & 10.51 \\
tbW & 0.041 & 0.083 & 0.16 \\
\hline
\end{array}
\]

expressed in femtobarns. We notice here that the \( tbW \) background has cross section at the parton level that is roughly 20% of the signal cross section at the LHeC, and roughly 35% at the FCC-he, the precise number depending on the photoproduction region. We designed the phase-space cuts to reduce this background to levels below 15%. As seen in (8), the \( tbW \) background is 10% of the signal in region \( PhP_I \).
and 11.3% in PhP\textsubscript{I} at both the LHeC and FCC-he. In region PhP\textsubscript{III} we have 12.2% at the LHeC and 13.5% at the FCC-he. This tbW background proves to be the most difficult one to control.

## 4 Results for effective couplings

In this section we summarize the main results for the effective-coupling limits from [1].

### 4.1 Bounds on $\tilde{C}_{\phi q}^{(-)33}$

The largest sensitivity to $\tilde{C}_{\phi q}^{(-)33}$ is obtained in region PhP\textsubscript{I}. Indeed, the anomalous coupling $\tilde{C}_{\phi q}^{(-)33}$ constitutes a perturbation $\delta f_{V}$ to the SM charged-current coupling $f_{V}^{\text{SM}} = 1 + \delta f_{V}^{\text{SM}}$ and, therefore, it also perturbs the cancellation among diagrams discussed above in section 3. Thus, the sensitivity is largest in region PhP\textsubscript{I} where the cancellation is strongest. We obtain limits for $\tilde{C}_{\phi q}^{(-)33}$ at the LHeC and FCC-he energies, in photoproduction region III, at one- and two-sigma levels, assuming a measurement uncertainty of 12%,

\begin{align}
68\% \text{ C.L.} & : -0.039 < \delta f_{V}^\ell < 0.035, \\
95\% \text{ C.L.} & : -0.083 < \delta f_{V}^\ell < 0.067.
\end{align}

These limits are obtained from a single total cross section value, with no other observable involved. We express them in terms of $\delta f_{V}^\ell$ to compare them to the limits reported by CMS; from fig. 6 of [13] we get,

\begin{align}
68\% \text{ C.L.} & : -0.024 < \delta f_{V}^\ell < 0.094, \\
95\% \text{ C.L.} & : -0.062 < \delta f_{V}^\ell < 0.132.
\end{align}

By taking interval length as a measure of sensitivity, we see that both limits in (9) are significantly stronger than those in (10).

### 4.2 Bounds on $\tilde{C}_{uB}^{33}$: single-coupling bounds

The largest sensitivity to $\tilde{C}_{uB}^{33}$ is obtained in region PhP\textsubscript{I}. This is due to the fact that the SM is close to an infrared divergence at $Q^2 = 0$ and, therefore, as $Q^2$ decreases the SM cross section grows much faster than the dipolar cross section, which is infrared finite. This causes the sensitivity to both $\tilde{C}_{uB}^{33}$, $\tilde{C}_{uB}^{33}$ to decrease as we go from PhP\textsubscript{I} to PhP\textsubscript{III}. We obtain limits on $\tilde{C}_{uB}^{33}$ at the LHeC and FCC-he energies, in photoproduction region I, at one- and two-sigma levels, assuming a measurement uncertainty of 12%,

\begin{align}
68\% \text{ C.L.} & : \begin{cases} -0.24 < C_{uB}^{33} < 0.29, \\
-0.89 < C_{uB}^{33} < 0.89, \\
-0.45 < C_{uB}^{33} < 0.65, \\
-1.24 < C_{uB}^{33} < 1.24. \end{cases}
95\% \text{ C.L.} & : \end{align}

The limits on $\tilde{C}_{uB}^{33}$, which is proportional to the magnetic dipole moment, are asymmetric because of the interference with the SM. Also for that reason, they are stronger than those on the imaginary part. Since the electric dipole moment operator is $CP$ odd, the interference with the SM is very small, and the limits on $\tilde{C}_{uB}^{33}$ are symmetric.

We compare the limits (11) with those projected for the HL-LHC by the ATLAS collaboration [15], from the radiative top-pair production and decay process $pp \rightarrow t\bar{t}\gamma$,

\begin{align}
95\% \text{ C.L.} & : -0.5 < C_{uB}^{33} < 0.3.
\end{align}

These are somewhat stricter than those we obtain, (11), based on interval length. We remark, however, that the ATLAS projections are based on two channels ($\ell\ell$ and $\ell j$), and involve the total cross section and two differential cross sections each one spanning about six bins. There are, in total, about a dozen measurements involved in the limits (12), whereas (11) are based on a single observable, the total cross section.

The limits set on $C_{uB}^{33}$ by the ATLAS and CMS collaborations from measurements of $t\bar{t}\gamma$ production are nowadays incorporated into global analyses; we refer to [1] for a detailed review of those. Very recently, the CMS collaboration [14] has measured the total cross section for $pp \rightarrow t\bar{t}\gamma$, as well as two differential cross sections ($d\sigma/d\eta_{\gamma}$, $d\sigma/d\eta_{t}$), in two reaction channels ($\ell\ell$ and $\ell j$). The limits obtained from the dilepton channel,

\begin{align}
95\% \text{ C.L.} : \begin{cases} -1.08 < C_{uB}^{33} & < 1.10, \\
-1.08 < C_{uB}^{33} & < 1.21, \end{cases}
\end{align}

are significantly weaker than ours, (11), by interval length. The limits obtained from a combination of both channels are reported to be,

\begin{align}
95\% \text{ C.L.} : \begin{cases} -0.64 < C_{uB}^{33} & < 0.75, \\
-0.75 < C_{uB}^{33} & < 0.79, \end{cases}
\end{align}

and are substantially stronger than for each separate channel. The limits (14) are only slightly weaker than (11) for $C_{uB}^{33}$, but definitely stronger for $\tilde{C}_{uB}^{33}$. As is the case for the limits (12), the strong limits (14) are the result of combining more than a dozen observables: the total cross section and two differential cross sections, for two reaction channels.

### 4.3 Bounds on $\tilde{C}_{uB}^{33}$: allowed two-coupling regions

In figure 2 we show the allowed regions in the $\kappa-\bar{\kappa}$ plane, determined by the top-pair photoproduction cross section at both the LHeC and FCC-he energies, in region PhP\textsubscript{I} at 68% C.L. These can be related to $C_{uB}^{33}$ through (5), and to $C_{uB}^{33}$ through (4). The allowed regions, given by the circular coronas, correspond to the assumed measurement uncertainties $\varepsilon_{\exp} = 12, 15, 18\%$ in different colors as indicated in the figure caption. Also seen in figure 2 is that the annular allowed regions obtained at the FCC-he are somewhat smaller than those at the LHeC energy. We notice, however, that both sets
of allowed regions are identical in the neighborhood of the origin (i.e., the SM), which is consistent with the individual-coupling bounds we obtain being the same at both energies.

Also shown in the figure are the regions in the \( \kappa - \bar{\kappa} \) plane allowed by the branching ratio and \( CP \) asymmetry for the process \( B \to X_s \gamma \), in both the form obtained from [11], and the form from [12]. The difference in area between these two regions hardly needs to be emphasized. We remark, however, that even the smaller region resulting from [12] is not completely contained in the annular regions determined by top-pair photoproduction, which results in a significant reduction of the allowed parameter space.

5 Final remarks

In this note we summarize the results of our analysis [1] of top-pair photoproduction in semileptonic mode in \( pe \) collisions at the LHeC and FCC-he. Our main results are the limits (9) on \( \tilde{C}_\phi^{(-)33} \) \( \delta f_\nu^L \), and those on \( \tilde{C}_{uB_\gamma}^{33} \tilde{C}_{uB_i}^{33} (\kappa, \bar{\kappa}) \), (11), and the two-dimensional allowed regions for \( \kappa, \bar{\kappa} \) in figure 2. We also made a detailed comparison of our results to those from ATLAS and CMS from [13–15].

Based on our results, we expect the LHeC to provide limits on \( \tilde{C}_\phi^{(-)33} (\delta f_\nu^L) \) similar to those from the HL-LHC. We also expect the LHeC to obtain limits on \( \tilde{C}_{uB_\gamma}^{33} \tilde{C}_{uB_i}^{33} \) stronger than those from the HL-LHC. These will then be the strongest until the operation of \( ee^+ \) colliders begins. Both sets of limits will constitute an important contribution to future global analyses. The FCC-he can yield improved sensitivity to \( \tilde{C}_\phi^{(-)33} \) and \( \tilde{C}_{uB_\gamma}^{33} \tilde{C}_{uB_i}^{33} \), relative to that of the LHeC, from substantially larger statistics and improved systematics.

The recent strong results on limits on top electromagnetic dipole moments by the LHC collaborations [14, 15] suggest, however, that we should upgrade our analysis of top photoproduction in \( pe \) colliders by including appropriate differential cross sections. An enhanced background rejection from a more robust multivariate analysis would also help strengthen the bounds on top couplings. These extensions to our analysis...
are currently in progress; we will report the results elsewhere.

1. A. Bouzas, F. Larios, “Top quark effective couplings from top-pair tagged photoproduction in p e collisions,” Phys. Rev. D 105, 115002 (2022), https://doi.org/10.1103/PhysRevD.105.115002 [arXiv:2111.04723 [hep-ph]].

2. P. Agostini et al. [LHeC and FCC-he Study Group], “The Large Hadron-Electron Collider at the HL-LHC,” J. Phys. G 48 (2021) 110501, https://doi.org/10.1088/1361-6471/abf3ba [arXiv:2007.14491 [hep-ex]].

3. Q. H. Cao, B. Yan, C. P. Yuan and Y. Zhang, polarization in ZZ production at hadron colliders,” Phys. Rev. D 102 (2020) 055010, https://doi.org/10.1103/PhysRevD.102.055010 [arXiv:2004.02031 [hep-ph]].

4. A. Kozachuk and D. Melikhov, “Constraints on the anomalous Wtb couplings from B-physics experiments,” Symmetry 12 (2020) 1506, https://doi.org/10.3390/sym12091506 [arXiv:2004.13127 [hep-ph]].

5. J. de Favereau, C. Delaere, P. Demin, A. Giammanco, T. Sjostrand, S. Mrenna, P. Skands, “Pythia 6.4 Physics and T. Fael and C. Greub, “Matching to parton shower simulations,” J. High Energy Phys. 88 (2013) 094007, https://doi.org/10.1088/1126-6708/2006/05/026 [arXiv:1308.5634 [hep-ph]].

6. A. A. Billur, M. Köksal and A. Gutiérrez-Rodríguez, “Improved sensitivity on the electromagnetic dipole moments of the top quark in γ γ and γ γ γ collisions at the CLIC,” Phys. Rev. D 96 (2017) 056007, https://doi.org/10.1103/PhysRevD.96.056007 [arXiv:1702.07237 [hep-ph]].

7. M. Köksal, A. A. Billur, A. Gutiérrez-Rodríguez and M. A. Hernández-Ruíz, “Sensitivity measuring expected on the electromagnetic anomalous couplings in the tγγ vertex at the FCC-he,” Int. J. Mod. Phys. A 35 (2020) 2050178, doi: 10.1142/S0217751X2050178X [arXiv:1905.02564 [hep-ph]].

8. A. Bouzas, F. Larios, “Electromagnetic dipole moments of the top quark,” Phys. Rev. D 87 (2013) 074015, https://doi.org/10.1103/PhysRevD.87.074015 [arXiv:1212.6575 [hep-ph]].

9. J. L. Hewett and T. G. Rizzo, “Using b → sγ to probe top quark couplings,” Phys. Rev. D 49 (1994) 319, doi:10.1103/PhysRevD.49.319 [arXiv:hep-ph/9305223 [hep-ph]].