STUDYING POSSIBLE ANOMALOUS TOP-QUARK COUPLINGS AT PHOTON COLLIDERS*

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Search for new-physics through possible anomalous $t\bar{t}\gamma$, tbW and $\gamma\gamma H$ couplings which are generated by SU(2)× U(1) gauge-invariant dimension-6 effective operators is discussed, using energy and angular distributions of final charged-lepton/b-quark in $\gamma\gamma \to t\bar{t} \to \ell X/bX$ for various beam polarizations. Optimal beam polarizations that minimize uncertainty in determination of those non-standard couplings are found performing an optimal-observable analysis.

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1. Introduction

Although more than ten years have passed since the discovery of the top-quark at Fermilab Tevatron [1], this collider is still the only facility which can produce the top-quark and top properties have not been well determined yet.

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In the near future, however, a more powerful top-quark factory will be realized at Large Hadron Collider (LHC) [2] and/or International Linear Collider (ILC) [3]. It is, therefore, definitely meaningful to get prepared for performing analyses assuming substantial top-quark data.

Since the top-quark mass, m_t, is of the order of the electroweak scale, it is quite reasonable to hope that measurements of top couplings and width could reveal some features of physics beyond the Standard Model (SM). The huge m_t also provides us with some practical advantages, *e.g.*, the top-quark decays before it hadronizes and, therefore, experimental data are going to be free from any substantial contamination by unknown bound state effects [4]. Consequently, one can easily get information concerning top-quark couplings via distributions of its decay products [5]. Furthermore, since the Yukawa coupling of the top-quark is much larger than that of other particles observed to date, the top-quark must be very sensitive to Higgs-boson. Thus, the top-quark could also be useful while testing extensions of the scalar sector of the SM.

Motivated by the above comments, we have carried out an analysis [6, 7] of top-quark production and decay at photon colliders [8, 9]. We have considered the charged-lepton/b-quark momentum distributions in the process $\gamma\gamma \to t\bar{t} \to \ell X/bX$, focusing on possible signals of new physics. Here we are going to present main findings that we obtained up to date: after describing our basic framework in Sec. 2, we show results of our optimal analysis [10] in Sec. 3. A brief summary and discussion are contained in Sec. 4.

2. Framework

In order to describe possible new-physics effects, we have used an effective low-energy Lagrangian [11], *i.e.*, the SM Lagrangian is modified by the addition of a series of SU(3)× SU(2)× U(1) gauge-invariant operators, which are suppressed by inverse powers of a new-physics scale Λ. Among those operators, the largest contribution comes from dimension-6 operators[1], denoted as $\mathcal{O}_i$, and we have the effective Lagrangian as

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i \left(\alpha_i \mathcal{O}_i + {\rm H.c.}\right) + O\left(\Lambda^{-3}\right) . \tag{1}$$

The operators relevant here (for more details see [6, 7]) lead to the following non-standard top-quark- and Higgs-boson-couplings: *(i)* CP-conserving $t\bar{t}\gamma$ vertex, *(ii)* CP-violating $t\bar{t}\gamma$ vertex, *(iii)* CP-conserving $\gamma\gamma H$ vertex, *(iv)* CP-violating $\gamma\gamma H$ vertex, and *(v)* anomalous tbW vertex. We expressed the size of their strength in terms of five independent parameters $\alpha_{\gamma 1}$, $\alpha_{\gamma 2}$, α_{h1},

[1] Dimension-5 operators are not included since they violate lepton number [11] and are irrelevant for the processes considered here.

α_{h2} and α_d. The explicit forms of these anomalous couplings in terms of the coefficients of dimension-6 operators are to be found in [6, 7].

The initial-state polarizations are characterized by the initial electron and positron longitudinal polarizations P_e and $P_{\bar{e}}$, the maximum average linear polarizations P_t and $P_{\tilde{t}}$ of the initial-laser photons with the azimuthal angles φ and $\tilde{\varphi}$ (defined in the same way as in [8]) and their average helicities P_γ and $P_{\tilde{\gamma}}$. The photonic polarizations $P_{t,\gamma}$ and $P_{\tilde{t},\tilde{\gamma}}$ have to satisfy

$$0 \le P_t^2 + P_\gamma^2 \le 1\,, \qquad 0 \le P_{\tilde{t}}^2 + P_{\tilde{\gamma}}^2 \le 1\,. \tag{2}$$

For the linear polarization, we denote the relative azimuthal angle by $\chi \equiv \varphi - \tilde{\varphi}$. In order to find its optimal value, we studied the χ-dependence of $\sigma(\gamma\gamma \to t\bar{t})$ including $\alpha_{\gamma1,\gamma2,h1,h2}$ terms. As a result, we found that the $\alpha_{\gamma2}$ and α_{h2} terms are sensitive to χ with the maximal sensitivity at $\chi = \pi/4$ as long as we are not too close to the Higgs pole, while the others did not lead to any relevant dependence. This has also been noticed in [12] concerning the $\alpha_{\gamma2}$ term. Therefore, we fix χ to be $\pi/4$.

In deriving distributions of secondary fermions ($= \ell/b$) we have treated the decaying t and W as on-shell particles. We have also neglected contributions that are quadratic in α_i ($i = \gamma1, \gamma2, h1, h2, d$). Therefore, the energy-angular distributions of ℓ/b in the $e\bar{e}$ CM frame[2] can be expressed as

$$\frac{d\sigma}{dE_{\ell/b}\,d\cos\theta_{\ell/b}} = f_{\rm SM}(E_{\ell/b}, \cos\theta_{\ell/b}) + \sum_i \alpha_i f_i(E_{\ell/b}, \cos\theta_{\ell/b})\,, \tag{3}$$

where $f_{\rm SM}$ and f_i are calculable functions: $f_{\rm SM}$ denotes the SM contribution, $f_{\gamma1,\gamma2}$ describe the anomalous CP-conserving and CP-violating $t\bar{t}\gamma$-vertices contributions, respectively, $f_{h1,h2}$ those generated by the anomalous CP-conserving and CP-violating $\gamma\gamma H$-vertices, and f_d that by the anomalous tbW-vertex.

In order to apply the Optimal-Observable (OO) method (see [10] for details) to Eq. (3), we first have to calculate the following matrix elements using $f_{\rm SM}$ and f_i

$$\mathcal{M}_{ij} \;=\; \int dE_{\ell/b}\,d\cos\theta_{\ell/b}\; \frac{f_i(E_{\ell/b}, \cos\theta_{\ell/b})\; f_j(E_{\ell/b}, \cos\theta_{\ell/b})}{f_{\rm SM}(E_{\ell/b}, \cos\theta_{\ell/b})}\,, \tag{4}$$

and its inverse matrix X_{ij}, where $i, j = 1, \ldots, 6$ correspond to SM, $\gamma1, \gamma2, h1, h2$ and d, respectively. Then, according to [10], the expected statistical uncertainty for the measurements of α_i is given by

[2] Following the standard approach [8], each photonic beam originates as a laser beam back-scattered on electron (e) or positron ($\bar{e}$) beam. Therefore, the $e\bar{e}$ CM frame refers to those initial electron-positron beams.

$$\Delta\alpha_i = \sqrt{I_0 X_{ii}/N_{\ell/b}}\,, \tag{5}$$

where

$$I_0 \equiv \int dE_{\ell/b} d\cos\theta_{\ell/b}\; f_{\rm SM}(E_{\ell/b},\cos\theta_{\ell/b})$$

and $N_{\ell/b}$ is the total number of collected events. Since we are not stepping into the Higgs-resonance region, we simply compute $N_{\ell/b}$ from the SM total cross section multiplied by the lepton/b-quark detection efficiency $\varepsilon_{\ell/b}$ and the integrated $e\bar{e}$ luminosity $L_{e\bar{e}}$, which leads to $N_{\ell/b}$ independent of m_H.

Concerning the effective Lagrangian approach, readers might wonder why we did not follow the same strategy as in $e\bar{e} \to t\bar{t} \to \ell X/bX$ analysis, where we started from the most general invariant amplitude with non-local (*i.e.*, in general momentum-dependent) form factors [13, 14]. As a matter of fact, such an approach is not possible for $\gamma\gamma \to t\bar{t}$ because of the virtual top-quark line appearing in the t-channel amplitudes. In case of $e\bar{e} \to t\bar{t}$, all the kinematical variables on which the form factors may depend are fixed for a given $\sqrt{s}$ and consequently we can treat all those form factors as constants, while this is not the case for $\gamma\gamma \to t\bar{t}$ [3].

3. Numerical analysis and results

In Ref. [6], where our main concern was to construct a fundamental framework for practical analysis, we used (1) $P_e = P_{\bar{e}} = 1$ and $P_t = P_{\tilde{t}} = P_\gamma = P_{\tilde{\gamma}} = 1/\sqrt{2}$, and (2) $P_e = P_{\bar{e}} = P_\gamma = P_{\tilde{\gamma}} = 1$ as typical polarization examples and performed an OO-analysis. Inverting the matrix $\mathcal{M}_{ij}$, we have noticed that the numerical results for X_{ij} are often unstable [6]: even a tiny variation of $\mathcal{M}_{ij}$ changes X_{ij} significantly. This indicates that some of f_i have similar shapes and, therefore, their coefficients cannot be disentangled easily. The presence of such instability has forced us to refrain from determining all the couplings at once through this process alone. That is, we have assumed that some of α_i's had been measured in other processes (*e.g.*, in $e\bar{e} \to t\bar{t} \to \ell^\pm X$), and we performed an analysis with smaller number of independent parameters.

When estimating the statistical uncertainty in simultaneous measurements, *e.g.*, of $\alpha_{\gamma 1}$ and α_{h1} (assuming all other coefficients are known), we need only the components with indices 1, 2 and 4. In such a "reduced analysis", we still encountered the instability problem, and we selected "stable solutions" according to the following criterion: Let us express the resultant uncertainties as $\Delta\alpha_{\gamma 1}^{[3]}$ and $\Delta\alpha_{h1}^{[3]}$, where "3" shows that we use the input

[3] For more details see the discussion in Sec. 4 of [7]

$\mathcal{M}_{ij}$, keeping three decimal places. In addition, we also compute $\Delta\alpha_{\gamma 1}^{[2]}$ and $\Delta\alpha_{h1}^{[2]}$ by rounding $\mathcal{M}_{ij}$ off to two decimal places. Then, we accept the result as a stable solution if both of the deviations $|\Delta\alpha_{\gamma 1,h1}^{[3]} - \Delta\alpha_{\gamma 1,h1}^{[2]}|/\Delta\alpha_{\gamma 1,h1}^{[3]}$ are less than 10 %.

In [7], varying polarization parameters as $P_{e,\bar{e}} = 0, \pm 1$, $P_{t,\tilde{t}} = 0, 1/\sqrt{2}, 1$, and $P_{\gamma,\tilde{\gamma}} = 0, \pm 1/\sqrt{2}, \pm 1$, we searched for the combinations that could make the statistical uncertainties $\Delta\alpha_i$ minimum for $\sqrt{s_{e\bar{e}}} = 500$ GeV and $\Lambda = 1\,\text{TeV}$. We also changed the Higgs mass as m_H =100, 300 and 500 GeV, which lead to the width $\Gamma_H = 1.08 \times 10^{-2}$, 8.38 and 73.4 GeV, respectively, according to the standard-model formula.

Although we did not find again any stable solution in the four- and five-parameter analysis, we did find some solutions not only in the two- but also in the three-parameter analysis. This is quite in contrast to the results in [6], where we had no stable solution for the three-parameter analysis. However, since not all the stable solutions gave us good statistical precision, we adopted only those which satisfy the following conditions:

- *Three-parameter analysis*
  At least two unknown couplings of three could be determined with accuracy better than 0.1 for an integrated luminosity of $L_{e\bar{e}} = 500\ \text{fb}^{-1}$ without detection-efficiency suppression (*i.e.*, $\varepsilon_{\ell/b} = 1$).

- *Two-parameter analysis*
  We found many stable solutions, therefore, for illustration we adopt the following strategy:

  - we choose a final state (charged-lepton or bottom-quark),
  - we fix the Higgs-boson mass m_H,
  - for each pair of $\Delta\alpha_i$ and $\Delta\alpha_j$ that satisfy $\Delta\alpha_{i,j} \leq 0.1$ for the luminosity of $L_{e\bar{e}} = 500\ \text{fb}^{-1}$ we show only those that make $(\Delta\alpha_i)^2 + (\Delta\alpha_j)^2$ minimum.

The results are presented below. We did not fix the detection efficiencies $\varepsilon_{\ell/b}$ since they depend on detector parameters and will get better with development of detection technology.

(1) Three parameter analysis

$\oplus$ Final charged-lepton detection

$m_H = 500\,\text{GeV}$

- $P_e = P_{\bar{e}} = 0,\ P_t = P_{\tilde{t}} = 1/\sqrt{2},\ P_\gamma = -P_{\tilde{\gamma}} = 1/\sqrt{2},\ N_\ell \simeq 6.1\times 10^3\varepsilon_\ell$
  $\Delta\alpha_{\gamma 2} = 0.94/\sqrt{\varepsilon_\ell},\ \Delta\alpha_{h2} = 0.11/\sqrt{\varepsilon_\ell},\ \Delta\alpha_d = 0.042/\sqrt{\varepsilon_\ell}.$ (6)
  Strictly speaking, this result does not satisfy our condition for the three-parameter analysis, but we show it since $\Delta\alpha_{h2}$ exceeds the limit by only 0.01.

⊕ Final bottom-quark detection

$m_H = 100\,\text{GeV}$

- $P_e = P_{\bar{e}} = 1,\ P_t = P_{\tilde{t}} = 1/\sqrt{2},\ P_\gamma = -P_{\tilde{\gamma}} = 1/\sqrt{2},\ N_b \simeq 4.2\times 10^4\varepsilon_b$
  $\Delta\alpha_{h1} = 0.086/\sqrt{\varepsilon_b},\ \ \Delta\alpha_{h2} = 0.21/\sqrt{\varepsilon_b},\ \ \Delta\alpha_d = 0.037/\sqrt{\varepsilon_b}.$ (7)

$m_H = 500\,\text{GeV}$

- $P_e = P_{\bar{e}} = 0,\ P_t = P_{\tilde{t}} = 1/\sqrt{2},\ P_\gamma = -P_{\tilde{\gamma}} = 1/\sqrt{2},\ N_b \simeq 2.8\times 10^4\varepsilon_b$
  $\Delta\alpha_{\gamma 2} = 0.61/\sqrt{\varepsilon_b},\ \ \Delta\alpha_{h2} = 0.054/\sqrt{\varepsilon_b},\ \ \Delta\alpha_d = 0.052/\sqrt{\varepsilon_b}.$ (8)

(2) Two parameter analysis

⊕ Final charged-lepton detection

Independent of m_H

- $P_e = P_{\bar{e}} = -1,\ P_t = P_{\tilde{t}} = 1,\ P_\gamma = P_{\tilde{\gamma}} = 0,\ N_\ell \simeq 1.0\times 10^4\varepsilon_\ell$
  $\Delta\alpha_{\gamma 1} = 0.051/\sqrt{\varepsilon_\ell},\ \ \Delta\alpha_d = 0.022/\sqrt{\varepsilon_\ell}.$ (9)
  This result is free from m_H dependence since the Higgs-exchange diagrams do not contribute to $\alpha_{\gamma 1}$ and α_d determination within our approximation.

$m_H = 100\,\text{GeV}$

- $P_e = P_{\bar{e}} = -1,\ P_t = P_{\tilde{t}} = 1/\sqrt{2},\ P_\gamma = P_{\tilde{\gamma}} = 1/\sqrt{2},\ N_\ell \simeq 1.9\times 10^4\varepsilon_\ell$
  $\Delta\alpha_{h1} = 0.034/\sqrt{\varepsilon_\ell},\ \ \Delta\alpha_d = 0.017/\sqrt{\varepsilon_\ell}.$ (10)

$m_H = 300$ GeV

- $P_e = P_{\bar{e}} = -1,\ P_t = P_{\tilde{t}} = 0,\ P_\gamma = P_{\tilde{\gamma}} = 1,\ N_\ell \simeq 2.4\times 10^4\varepsilon_\ell$
  $\Delta\alpha_{h1} = 0.013/\sqrt{\varepsilon_\ell},\ \ \Delta\alpha_d = 0.015/\sqrt{\varepsilon_\ell}.$ (11)

$m_H = 500\,\text{GeV}$

- $P_e = P_{\bar{e}} = -1,\ P_t = P_{\tilde{t}} = 0,\ P_\gamma = P_{\tilde{\gamma}} = 1,\ N_\ell \simeq 2.4\times 10^4\varepsilon_\ell$
  $\Delta\alpha_{h1} = 0.023/\sqrt{\varepsilon_\ell},\ \ \Delta\alpha_d = 0.015/\sqrt{\varepsilon_\ell}.$ (12)
- $P_e = P_{\bar{e}} = -1,\ P_t = P_{\tilde{t}} = 0,\ P_\gamma = P_{\tilde{\gamma}} = 1,\ N_\ell \simeq 2.4\times 10^4\varepsilon_\ell$
  $\Delta\alpha_{h2} = 0.030/\sqrt{\varepsilon_\ell},\ \ \Delta\alpha_d = 0.015/\sqrt{\varepsilon_\ell}.$ (13)

⊕ Final bottom-quark detection

$m_H = 100\,\text{GeV}$

- $P_e = P_{\bar{e}} = -1,\ P_t = P_{\tilde{t}} = 1/\sqrt{2},\ P_\gamma = -P_{\tilde{\gamma}} = -1/\sqrt{2},$
  $N_b \simeq 4.2 \times 10^4 \varepsilon_b$
  $$\Delta\alpha_{h1} = 0.058/\sqrt{\varepsilon_b},\ \ \Delta\alpha_d = 0.026/\sqrt{\varepsilon_b}. \qquad (14)$$

$m_H = 300\,\mathrm{GeV}$

- $P_e = P_{\bar{e}} = -1,\ P_t = P_{\tilde{t}} = 1/\sqrt{2},\ P_\gamma = -P_{\tilde{\gamma}} = -1/\sqrt{2},$
  $N_b \simeq 4.2 \times 10^4 \varepsilon_b$
  $$\Delta\alpha_{h1} = 0.009/\sqrt{\varepsilon_b},\ \ \Delta\alpha_{h2} = 0.074/\sqrt{\varepsilon_b}. \qquad (15)$$
- $P_e = P_{\bar{e}} = 1,\ P_t = P_{\tilde{t}} = 1/\sqrt{2},\ P_\gamma = -P_{\tilde{\gamma}} = -1/\sqrt{2},$
  $N_b \simeq 4.2 \times 10^4 \varepsilon_b$
  $$\Delta\alpha_{h1} = 0.025/\sqrt{\varepsilon_b},\ \ \Delta\alpha_d = 0.019/\sqrt{\varepsilon_b}. \qquad (16)$$
- $P_e = P_{\bar{e}} = 1,\ P_t = P_{\tilde{t}} = 1/\sqrt{2},\ P_\gamma = -P_{\tilde{\gamma}} = 1/\sqrt{2},\ N_b \simeq 4.2 \times 10^4 \varepsilon_b$
  $$\Delta\alpha_{h2} = 0.065/\sqrt{\varepsilon_b},\ \ \Delta\alpha_d = 0.010/\sqrt{\varepsilon_b}. \qquad (17)$$

$m_H = 500\,\mathrm{GeV}$

- $P_e = P_{\bar{e}} = -1,\ P_t = P_{\tilde{t}} = 1,\ P_\gamma = P_{\tilde{\gamma}} = 0,\ N_b \simeq 4.6 \times 10^4 \varepsilon_b$
  $$\Delta\alpha_{h1} = 0.030/\sqrt{\varepsilon_b},\ \ \Delta\alpha_d = 0.018/\sqrt{\varepsilon_b}. \qquad (18)$$
- $P_e = P_{\bar{e}} = -1,\ P_t = P_{\tilde{t}} = 1,\ P_\gamma = P_{\tilde{\gamma}} = 0,\ N_b \simeq 4.6 \times 10^4 \varepsilon_b$
  $$\Delta\alpha_{h2} = 0.028/\sqrt{\varepsilon_b},\ \ \Delta\alpha_d = 0.014/\sqrt{\varepsilon_b}. \qquad (19)$$

Using these results one can find (for known m_H) the most suitable polarization for a determination of a given pair of coefficients.

Note that it is difficult to determine $\alpha_{\gamma 1}$ and $\alpha_{\gamma 2}$ together for two- and three-parameter analysis. Although we have found some stable solutions that would allow for a determination of $\alpha_{\gamma 1}$ in the lepton analysis, which we did not find in [6], the expected precision is rather low. Nevertheless, this is telling us that the use of purely linear polarization for the laser is crucial for measuring $\alpha_{\gamma 1}$. Unfortunately, the statistical uncertainty of $\alpha_{\gamma 2}$ is still large even in this analysis, so we did not list it as solutions which gave us good statistical precisions. Therefore, we have to look for other suitable processes to determine this parameter, for a review see [15].

It was found that there are many combinations of polarization parameters that make uncertainties of $\alpha_{h1,h2}$ and α_d relatively small. For instance, analyzing the b-quark final state with the polarization $P_e = P_{\bar{e}} = -1$, $P_t = P_{\tilde{t}} = 1/\sqrt{2}$, $P_\gamma = -P_{\tilde{\gamma}} = -1/\sqrt{2}$ enables us to probe the properties of Higgs-bosons whose mass is around 300 GeV through the determination of α_{h1} and α_{h2}.

As mentioned, the results are obtained for $\Lambda = 1\,\mathrm{TeV}$. If one assumes the new-physics scale to be $\Lambda = \lambda\,\mathrm{TeV}$, then all the above results ($\Delta\alpha_i$) are replaced with $\Delta\alpha_i/\lambda^2$, which means that the right-hand sides of Eqs. (6)–(19) giving $\Delta\alpha_i$ are all multiplied by λ^2.

Some additional comments are here in order.

- If we were going to measure just the decay coefficient α_d, then the optimal polarization would be simply such that makes the top production rate largest with no Higgs-exchange (this is because we keep only linear terms in the anomalous couplings). However, if α_d and α_{h1} or α_{h2} are to be determined then certain compromise of the SM $t\bar{t}$ production rate is necessary as one needs the Higgs-boson exchange diagram as well.

- If, on the other hand, only Higgs couplings are to be measured, then the optimal polarization would make the Higgs-exchange diagram as large as possible. It is obvious that for the most precise determination of the $\gamma\gamma H$ couplings, one should go to the resonance region in order to increase the Higgs-production rate. A detailed study of CP-violating effects in $\gamma\gamma \to H$ has been performed, *e.g.*, in [16]. There, for the luminosity $L_{e\bar{e}} = 20$ fb^{-1}, the authors estimate 3-σ limits for α_{h2} ($d_{\gamma\gamma} = (v/\Lambda)^2\alpha_{h2} + \cdots$ in the notation of [16]) at the level of 10^{-3}–10^{-4} depending on the Higgs-boson mass. Correcting for the luminosity adopted here ($L_{e\bar{e}} = 500$ fb^{-1}) it corresponds to our 1-σ uncertainty for α_{h2} also of the order of 10^{-3}–10^{-4}, so smaller by about two orders of magnitude than the precision obtained here for the off-resonance region. If, however, the Higgs-boson mass is unknown, then the analysis presented here is applicable.

4. Discussions and summary

We discussed possible new-physics search through a detailed analysis of the process $\gamma\gamma \to t\bar{t} \to \ell X/bX$ performed in [6, 7] in order to find optimal beam polarizations that minimize uncertainties in the determination of $t\bar{t}\gamma$, tbW and $\gamma\gamma H$ coupling parameters. To estimate the uncertainties we have applied the optimal-observable method to the final lepton/b-quark energy-angular distribution in $\gamma\gamma \to t\bar{t} \to \ell X/bX$.

Applying the optimal-observable technique, we have encountered the problem of "unstable-solutions" and have concluded that there is no stable solution in the analysis trying to determine more than three anomalous couplings altogether. However, in contrast to [6], adopting more polarization choices we have obtained in [7] some stable solutions with three couplings. We also found a number of two-parameter solutions, most of which allow for the $\gamma\gamma H$- and tbW-couplings determination. The expected precision of the measurement of the Higgs-coupling is of the order of 10^{-2} (for the scale of new physics $\Lambda = 1$ TeV). This shows that the $\gamma\gamma$ collider is going to be useful for testing the Higgs sector of the SM.

Let us consider the top-quark-coupling determination in an ideal case such that the beam polarizations could be easily tuned and that the energy is sufficient for the on-shell Higgs-boson production. Then the best strategy would be to adjust polarizations to construct semi-monochromatic $\gamma\gamma$ beams such that $\sqrt{s_{\gamma\gamma}} \simeq m_H$ and on-shell Higgs-bosons are produced. This would allow for precise $\alpha_{h1,h2}$ measurement, so the virtual Higgs effects in $\gamma\gamma \to t\bar{t}$ would be calculable. Unfortunately, as we have shown earlier, it is difficult to measure $\alpha_{\gamma 2}$ by looking just at $\ell X/bX$ final states from $\gamma\gamma \to t\bar{t}$. Therefore, to fix $\alpha_{\gamma 2}$, one should, *e.g.*, measure the asymmetries adopted in [12] to determine the top-quark electric-dipole moment which is proportional to $\alpha_{\gamma 2}$. Then, following the analysis presented here, one can determine $\alpha_{\gamma 1}$ and α_d.

Finally, one must not forget that it is necessary to take into account carefully the Standard Model contribution with radiative corrections when trying to determine the anomalous couplings in a fully realistic analysis. In particular this is significant when we are interested in CP-conserving couplings since the SM contributions there are not suppressed unlike the CP-violating terms. On this subject, see for instance [17].

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