Single top quark production through unparticles at photon colliders

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We investigate the single top quark production with the exchange of unparticles through high energy photon-photon collision \( \gamma\gamma \rightarrow t\bar{c} \). The effects of unparticles on the scattering cross section for different polarization configurations, and for various values of the scaling dimension \( d, 1 < d < 2 \), is analysed. It is shown that the \((+-)\) polarisation configuration is more preferable searching for unparticle physics signatures.

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After launching the Large Hadron Collider(LHC) at CERN new horizons in particle physics will be sought in exploring new physics beyond the Standard Model(SM). One of the research directions of the LHC is examining the predictions of the SM at the electroweak scale, as well as, to discover possible new physics effects in details. For these goals, the properties of the top quark which is the heaviest particle in the framework of the SM will be studied comprehensively. Being complementary to the LHC and other high energy hadron colliders, multi-TeV \( e^+e^- \) linear colliders, such as the ILC(International Linear Collider) and CLIC(Compact Linear Collider), which are free of difficulties of the hadron contaminations effects, will be very powerful tools to examine conceivable new physics outcomes. Comparing with the hadron colliders, the \( e^+e^- \) linear colliders are very powerful for precise determination of the masses and spin properties of the potential new particles. \[1\]. Another very important property of a linear \( e^+e^- \) linear collider is that it can be converted into \( e^-e^-, e^-\gamma, \) or \( \gamma\gamma \) collider mode, where high energy photon beams are generated by using the Compton backscattering of the initial electron and laser photon beams. The energy and the luminosity of the photon beams are practically same as of the initial electron and positron beams. A detailed description of the photon collider is presented in \[2\]. Physics programme of the photon colliders is described in \[3\], and in \[4\], a detailed analysis on \( \gamma\gamma \) option of an \( e^+e^- \) collider has been given. It should be noted that the cross sections for the considered processes in \( \gamma\gamma \) collisions are larger than in the \( e^+e^- \) case. Therefore, the photon colliders also can open new windows and new possibilities searching for new physics beyond the SM.

One of the new physics models beyond the SM is the unparticle physics proposed by Georgi, \[5, 6\]. According to the Georgi’s scenario, if there is a conformal symmetry in nature it should be broken at a very high energy scale which must be above the current energy scale of the colliders. Based on the idea of Banks and Zaks, \[7\], Georgi presents the scale invariant sector as a set of the Banks-Zaks operators \( O_{BZ} \), and defines it at the very high energy scale, \[5\]. Interactions of the SM operators \( O_{SM} \) with the BZ operators \( O_{BZ} \) are expressed by the exchange of particles with a very high energy mass scale \( \mathcal{M}_U \) as the following form

\[
\frac{1}{\mathcal{M}_U} O_{BZ} O_{SM}
\]

where BZ, and SM operators are defined as \( O_{BZ} \in \mathcal{O}_{BZ} \) with mass dimension \( d_{BZ} \), and \( O_{SM} \in \mathcal{O}_{SM} \) with mass dimension \( d_{SM} \). Low energy effects of the scale invariant \( O_{BZ} \) fields lead a dimensional transmutation. Hence, after the dimensional transmutation Eq.(1) is given as

\[
\frac{C_\Lambda \mathcal{M}_U^{d_{BZ}-d}}{\mathcal{M}_U} O_{BZ} O_{SM}
\]

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where $d$ is the scaling mass dimension (or anomalous dimension) of the unparticle operator $O_U$, and the constant $C_U$ is a coefficient function. Interactions between the unparticles and the SM fields have been listed by Ref [8]. Possible manifestations of the unparticles via their direct and indirect effects have been investigated in many works (see for example, [2], and references there in).

In present work, we study the single top quark production in the process $\gamma\gamma \rightarrow t\bar{c}$ in the $\gamma\gamma$ collider option of a multi-TeV linear collider, eg. the CLIC, in unparticle physics. Our results can easily be extended for other possible future multi TeV-scale linear electron-positron colliders.

For the calculation of the matrix element of $\gamma\gamma \rightarrow t\bar{c}$ process in the unparticle model, the interaction vertices of unparticles with photon and quarks are needed. In this work, we consider only scalar unparticle contribution, vector and tensor unparticle contributions are neglected. The reason for neglecting the contributions of the vector and tensor unparticle contributions is as follows. In [10], it was shown that for the vector and tensor unparticles $d > 3$ and $d > 4$ respectively. Numerical calculations show that for these values of $d$ contributions of unparticles are negligible.

The effective interactions between the scalar unparticle and the SM fermions, and the photons are given in the following form, respectively,

$$\frac{1}{\Lambda_d} \bar{f}(\lambda_S f' + i\gamma_5\lambda_P f') f' O_U \quad (3)$$

$$\frac{1}{\Lambda_d} \{\lambda_0 F_{\mu
u} F^{\mu\nu} + \lambda_0' \tilde{F}_{\mu
u} F^{\mu\nu}\} O_U \quad (4)$$

where $f$ and $f'$ denote different flavor of quarks, with the same electric charge, $F_{\mu\nu}$ is the electromagnetic field tensor, and $\tilde{F}_{\mu
u} = \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} F^{\alpha\beta}$, and $O_U$ stands for the scalar unparticle (Refs. [8], [11]). Here we would like to make the following remark. In Ref. [12] it is obtained that interaction of the unparticle sector with the SM fields can be proceeded via interaction $c_2 H^2 O_U$, where $H$ is the Higgs field. Hence this operator leads to the conformal symmetry breaking at low energy scales when the Higgs field gets the vacuum expectation value, and this symmetry breaking imposes some strong constraints on the unparticle sector. Following the arguments present in [12], we assume $c_2 << 1$. Under this condition at TeV energy scale, the effects of unparticle sector on future high energy collider energies can be probed. One can see from the above vertices one of the very promising properties of the unparticle physics is that it permits the existence of the flavor changing neutral current interactions in the interactions of the unparticles with the SM particles at the tree level.

The scalar unparticle propagator is given as

$$\Delta_F(P^2) = \frac{A_d}{2 \sin d\pi} (-P^2 - i\epsilon)^{d-2} \quad (5)$$

where

$$A_d = \frac{16 \pi^{5/2}}{(2\pi)^d} \frac{\Gamma(d + 1/2)}{\Gamma(d - 1)\Gamma(2d)} \quad (6)$$

Since there is no tree level SM background effects, the $\gamma\gamma \rightarrow t\bar{c}$ process is one of the unique processes to probe flavor changing unparticle effects, Fig 1. The scattering amplitude for $\gamma\gamma \rightarrow t\bar{c}$ process can be written in the following

FIG. 1: Feynman diagram for the $\gamma\gamma \rightarrow t\bar{c}$ processes through scalar unparticle exchange.
The unpolarized total cross section with $\lambda_0/\Lambda_U = 5.10^{-1}$ TeV$^{-1}$.

\[ M = \left[ \epsilon^\mu(p_1) \left[ 4i|\lambda_0(-p_1 \cdot p_2 g_{\mu\nu} + p_1 \cdot p_2 \rho_\mu) + i\lambda_0'(|\epsilon_\rho\omega_\mu p_1^\rho p_2^\mu)| \right] \epsilon^\nu(p_2) \right] \times \left[ i(p_4)|\lambda_s - i\gamma_s \lambda_\rho|v(p_4) \right] \left[ \frac{iA_d}{2\sin \pi \left[ -(p_1 + p_2)^2 \right]^{d-2}} \right] \left[ \frac{1}{\Lambda_U^{d-1}} \right] \]  

(7)

Using this matrix element the cross section can be calculated straightforwardly. For the calculations of the unpolarized and polarized cross sections, we use the expressions given in the Appendix 1. The unpolarized total cross section with respect to the center of mass energy of the mono-energetic photon beams is plotted in the Figure 2. For illustration of unparticle effects, we assume $\lambda_0 \equiv \lambda_s \equiv \lambda_\rho$ and, $\lambda_0/\Lambda_U = 0.5$ TeV$^{-1}$.

Depending on the initial electron(positron) polarization $P_e$ and the laser beam polarization $h_l$, the differential scattering cross section in terms of the average helicity $h_\gamma$ can be written as

\[ \frac{d\sigma}{d\cos \theta} = \frac{1}{(64\pi)} \int_{x_{1_{\text{min}}}}^{0.83} dx_1 \int_{x_{2_{\text{min}}}}^{0.83} dx_2 \frac{f(x_1)f(x_2)}{\tilde{s}} \left[ \frac{1}{2} \left( 1 + h_\gamma(x_1)h_\gamma(x_2) \right) \right] \left[ M(\pp) \right]^2 + \left( \frac{1}{2} - h_\gamma(x_1)h_\gamma(x_2) \right) \left[ M(-+) \right]^2 \]  

(8)

where $f(x) = f(x, P_e, P_l)$ is the photon number density, and $h_\gamma = h_\gamma(x, P_e, P_l)$ is the average helicity function presented in the Appendix 2 and as $\sqrt{s_{ee}} \equiv \sqrt{\tilde{s}}$ being the center of mass energy of the $e^+ e^-$ collider, $\tilde{s} = \sqrt{x_1 x_2 s_{ee}}$ is the reduced center of mass energy of the back-scattered photon beams, and $x = E_\gamma/E_e$ is the fraction of energy taken by the back-scattered photon beam.

In our analysis, we follow the usual collider assumptions, and we take $|h_l| = 1$, and $|P_e| = 0.9$. Also, we use the angular cuts $\pi/6 < \cos \theta < 5\pi/6$, and $\sqrt{0.4} < x_i < x_{\text{max}}$ which have been used in the literature, where $x_{\text{max}}$ is the maximum energy fraction of the back-scattered photon, and its optimum value is 0.83.

In Figure 3 and Figure 4 we plot the cross section for two different polarization configurations of initial electron and laser beams to present the behavior of the polarized cross section with unparticle contributions with respect to $\sqrt{s_{ee}}$. For the figures, we use the following definitions for the polarization configurations: $\pp \equiv (\pp) = (P_e = 0.9, h_{l1} = 1; P_{l2} = 0.9, h_{l2} = 1)$, and $\pp \equiv (+-+-) = (P_e = 0.9, h_{l1} = -1; P_{l2} = 0.9, h_{l2} = -1)$, and we take $\lambda_0/\Lambda_U = 0.5$ TeV$^{-1}$. 

FIG. 2: The unpolarized total cross section with $\lambda_0/\Lambda_U = 5.10^{-1}$ TeV$^{-1}$. 

- $d=1.1$
- $d=1.3$
- $d=1.5$
- $d=1.7$
- $d=1.9$
FIG. 3: The polarized cross sections with the polarization configuration (++), we assume $\lambda_0/\Lambda_U = 0.5 \text{ TeV}^{-1}$.

FIG. 4: The polarized cross sections with the polarization configuration (+−), we assume $\lambda_0/\Lambda_U = 0.5 \text{ TeV}^{-1}$.

In the Figures 3 and 4 we plot the polarized cross sections with respect to the scaling dimension $d$ for the polarization configurations (++) and (+−), respectively. From those figures one can see that for any values of anomalous dimension $d$, the cross section $\sigma_{+−}$ is about one order larger than the $\sigma_{++}$, i.e. to search for unparticle physics effects the polarisation configuration (+−) is more preferable than (++).
The dependence of the cross section on the ratio of $\sqrt{s}/\Lambda$, and $d$ can be understood in the following sense. From the expression of the total cross section for the the $\gamma\gamma \to t\bar{t}$ process, it follows that

$$\sigma \sim \Lambda^{-2}(\sqrt{s}/\Lambda)^{4d-4}.$$  

(9)
Therefore, since $1 < d < 2$ the cross section grows as $\sqrt{s}$ increases. From Eq. 7 one can easily obtain that the unitarity condition leads to the following (in derivation this result, for simplicity, we assume that $\lambda_s = \lambda_p$, and $\lambda_0^0 = 0$)

$$\frac{\lambda_0 \lambda_s}{16\pi \sin(d\pi)} A_d \frac{m_t}{\Lambda} \frac{(\sqrt{s})^{2d-2}}{\Lambda} < 1.$$  \hfill (10)

Hence for the above given analysis unitarity condition is preserved up to $\sim 100$ TeV collider energies, when $\lambda_0 = \lambda_s \sim 1$ and at $\Lambda = 1$ TeV.

Finally, let us discuss the possibility for experimental detectability of the considered process. For this purpose we estimate the number of events. As we already noted that there is no background effects for the $\gamma\gamma \rightarrow tc$ process and we assume the number of events as the poisson variable. In the Figure 7 we present the dependence of the predicted number of events. As we already noted that there is no background effects for the $\gamma\gamma \rightarrow tc$ process. In the Table I, and Table II we present the limits on the number of events on the scaling dimension $d$, for the energy options of the collider. In the analysis, for simplicity, we take $\lambda \equiv \lambda_0 = \lambda_s = \lambda_p$. Therefore, we extract upper limits on the unparticle coupling $\lambda$ regarding 5$\sigma$ analysis for the number of events $\nu = \sigma \times \mathcal{L}$. For 95% C.L. we take $\tilde{\nu} \geq 9.15$. In the Table II and Table III we present the limits on the unparticle coupling $\lambda$ for the photon polarization $(++)$, and $(+-)$, respectively, for various $d$ values, and for $\Lambda = 1000$ GeV. As expected, from the Tables II and III one can see that with increasing $\sqrt{s}$ at given values of $d$ the upper limits on $\lambda$ becomes more stringent. Our limits are consistent with the limits calculated from other low and high energy physics implications (see, for example, [9, 13], and references there in.).

In conclusion, we have studied the single top quark production in a prospected multi-TeV $\gamma\gamma$ collider via unparticle exchange, namely the process $\gamma\gamma \rightarrow tc$. For different polarization considerations we obtain upper limits on the flavor violating unparticle coupling constant. We show that different polarizations give different upper limits, and as the collider energy increases the limits gets more stringent.

APPENDIX

1.

In the calculations, we assume the following center of mass reference frame kinematical relations

$$p_1^\mu = E(1, 0, 0, 1), \quad p_2^\mu = E(1, 0, 0, -1)$$

$$\epsilon_1^\mu = -\frac{1}{\sqrt{2}}(0, h_1, i, 0) \quad \epsilon_2^\mu = -\frac{1}{\sqrt{2}}(0, -h_2, i, 0)$$

$$(p_1 + p_2)^2 = s = (p_3 + p_4)^2, \quad 2p_3.p_4 = s - m_t^2$$

where $\epsilon_1 \equiv \epsilon_1(h_1)$, $\epsilon_2 \equiv \epsilon_1(h_2)$, etc., $h_1, h_2 = \{+, -\}$ stand for the polarizations, $m_t$ is the mass of the top quark.
FIG. 7: The number of events with respect to $d$ for the polarization configuration $(+-)$. We assume $\lambda_0/\Lambda_U = 0.1 \text{ TeV}^{-1}$.

Using these definitions we obtain

$$|M(++)|^2 = |M(--)|^2 = 8|f(d)|^2[-s^{2d-2}((s-m_t^2)(\lambda_1^2 + \lambda_2^2)
-2m_c * m_t(\lambda_1^2 - \lambda_2^2))]$$

(14)

$$|M(+-)|^2 = |M(-+)|^2 = 0$$

(15)

where

$$f(d) = \frac{\lambda_0^2 A_d}{2\Lambda^{2d-1}\sin(d\pi)}.$$ 

(16)

2.

Here, we present the definitions of the functions appearing in the expression of the differential cross section. Let $h_e$ and $h_l$ be the polarizations of the electron beam and the laser photon beam, respectively. Following to [4],

$$C(x) = \frac{1}{1-x} + 1 - x - 4r(1-r) - h_e h_l r z (2r-1)(2-x)$$

(17)

where $r = \frac{z}{z(1-x)}$. Thus, the photon number density is given by

$$f(x,h_e,h_l,z) = \left(\frac{2\pi\alpha^2}{m_e^2 z \sigma_c}\right) C(x)$$

(18)

where

$$\sigma_c = \left(\frac{2\pi\alpha^2}{m_e^2 z \sigma_c}\right) \left[\left(1 - \frac{4}{z} - \frac{8}{z^2}\right) \ln(z+1) + \frac{1}{2} + \frac{8}{z} - \frac{1}{2(z+1)^2}\right] + h_e h_l \left(\frac{2\pi\alpha^2}{m_e^2 z \sigma_c}\right) \left[\left(1 + \frac{2}{z}\right) \ln(z+1) - \frac{5}{2} + \frac{1}{z+1} - \frac{1}{2(z+1)^2}\right]$$

(19)
The average helicity in terms of the function $C(x)$ can be given by

$$h_\gamma(x, h_e, h_l, z) = \frac{1}{C(x)} \left\{ h_e \left[ \frac{x}{1 - x} + x(2r - 1)^2 \right] - h_l(2r - 1)(1 - x + \frac{1}{1 - x}) \right\}$$  \hspace{1cm} (20)