Unparticle physics in single top signals

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Abstract – We study the single production of top quarks in $e^+e^−$, $ep$ and $pp$ collisions in the context of unparticle physics through the Flavor Violating (FV) unparticle vertices and compute the total cross-sections for single top production as functions of scale dimension $d_{\ell t}$. We find that among all, LHC is the most promising facility to probe the unparticle physics via single top quark production processes.

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Introduction. – Recently Georgi has proposed a new scheme which is based on the existence of a non-trivial scale-invariant sector at a much higher scale than that of the Standard Model (SM). He conjectured that this sector might couple to SM fields via non-renormalizable effective interactions involving invisible massless objects of fractional scale dimension, dubbed as unparticles, and thus play a role in low-energy physics \cite{1,2}. This scheme has, since then, been further developed and studied very extensively, exploiting it from all phenomenological perspectives \cite{3}.

In this letter we exploit implications of unparticle physics on the single top production as a new Flavor Changing Neutral Current (FCNC) process. Due to GIM mechanism FCNC interactions of top quarks are extremely suppressed in the SM. Nevertheless, their large mass close to electroweak symmetry breaking scale is the main reason to expect the first observation of an evidence for new physics at top quark sector. We consider the single production of top quarks in all types of colliders, namely International Linear Collider (ILC), lepton-hadron collider THERA and CERN Large Hadron Collider (LHC), main parameters, such as center-of-mass energies and integrated luminosities, of which are given in table 1 \cite{4–7}.

For the ILC we consider two options with $\sqrt{s} = 0.5$ and $\sqrt{s} = 1$ TeV.

In an earlier paper \cite{8} we have analyzed the effects of unparticle physics in the pair production of top quarks at LHC energies. In those processes there were both Flavor Conserving (FC) and Flavor Violating (FV) contributions, the FC ones having counterparts in the framework of SM, and there was some kind of competition between these two types of contributions. However, the single production processes, on the other hand, always manifest themselves via FCNC vertices. Because in these processes the top quarks are always accompanied by an antiquark with a different flavor, the actual type of which depends on the relevant production channel. As these FCNC vertices do not exist in the SM at tree level, none of these reactions considered here have SM counterparts, and all are purely unparticle processes at this level.

The propagators were already given in several references \cite{1,2,9}. The SM gauge-invariant effective interactions of scalar, vector and tensor unparticles with the SM fields are given by \cite{9,10}

\begin{equation}
\begin{align*}
\lambda_0 \frac{1}{N_c} f f O_{\ell t}, \quad \lambda_0 \frac{1}{N_c} f i \gamma_5 f O_{\ell t}, \quad \lambda_0 \frac{1}{N_c} G_{\alpha\beta} G^{\alpha\beta} O_{\ell t}, \\
\lambda_1 \frac{1}{N_c} c_\gamma f \gamma_\mu f O_{\ell t}, \quad \lambda_1 \frac{1}{N_c} c_\gamma f \gamma_\mu f O_{\ell t}, \\
- \frac{1}{4} \lambda_2 \frac{1}{N_c} f i \left( \gamma_\mu D_\nu + \gamma_\nu D_\mu \right) f O_{\ell t}^{\nu\nu}, \quad \lambda_2 \frac{1}{N_c} G_{\mu\alpha} G^{\mu\alpha} O_{\ell t}^{\nu\nu},
\end{align*}
\end{equation}

where $\lambda_i$ ($i = 0, 1, 2$) are dimensionless effective couplings labeling scalar, vector and tensor unparticle operators, respectively. $c_\gamma$, $c_\alpha$ represent vector and axial vector couplings of vector unparticle, respectively. $D_\mu$ is the covariant derivative, $f$ are SM fermions. Finally, $G_{\mu\alpha}$ are the gluon field strength.

As unparticle interactions are flavor-blind \cite{2}, the above-mentioned structures are used for also FCNC $t-q-\ell t$ vertices with the constraints imposed on the scale dimension $d_{\ell t}$, namely, $d_{\ell t} > 3$ for tensor unparticle and $d_{\ell t} > 2$.
unparticle contributions are given as proceeds via s-channel unparticle exchange only. The differential
the processes 

\[ e^+ e^- \rightarrow t\bar{q} \] for vector unparticle if the coupling strengths, \( c_v \) and \( c_u \), for the FCNC case are chosen to be of the same magnitude as in the FC case, and without any constraint on \( d_{lt} \) for scalar unparticle [11].

**Differential cross-sections for single top productions in unparticle physics.** – In this section we will present the differential cross-sections by considering the contributions of all three types of unparticles, vector, tensor and scalar, for the single top productions through the processes \( e^+ e^- \rightarrow t\bar{q}, \) \( ep \rightarrow et + X \) and \( pp \rightarrow t(q,g,U) + X \).

\[ e^+ e^- \rightarrow t\bar{q} \] Single top production in \( e^+ e^- \) collisions proceeds via s-channel unparticle exchange only. The differential cross-sections for vector, tensor and scalar unparticle contributions are given as

\[
\frac{d\sigma_V}{dt} = \frac{3A_V^2}{8\pi s^2(s)^{4/2s}} \left[ \left(c_v^4 + c_u^4\right)s + (s + t)^2 + 2c_v^2c_u^2(2t^2 + 3s + 2t) - (3s + 2t)^2 \right],
\] (1)

\[
\frac{d\sigma_T}{dt} = \frac{3A_T^2}{2\pi s^2(s)^{4/2s}} \left[ -8s(t + s)m^6 + (3s^2 + 26ts + 40t^2)m^4 - (3s^3 + 28ts^2 + 82t^2s + 64ts^2)m^2 + s^4 + 64s^2t^2 + 42s^2t^2 + 10s^3t \right],
\] (2)

\[
\frac{d\sigma_S}{dt} = \frac{3A_S^2}{4\pi s^2(s)^{4/2s}} \left[s(s - m^2)\right],
\] (3)

respectively, \( m \) is the top quark mass, \( s \) and \( t \) refer to the usual Mandelstam variables. The coefficients \( A_V, \) \( A_T \) and \( A_S \) in (1), (2) and (3) are given by

\[
A_V = \frac{\lambda_3^2 A_{d_{lt}}}{2\sin(\frac{d_{lt}}{\pi})} \Lambda^{2|d_{lt}| - 1}, \quad A_T = \frac{\lambda_3^2 A_{d_{lt}}}{32\sin(\frac{d_{lt}}{\pi})} \Lambda^{2|d_{lt}|}, \quad A_S = \frac{\lambda_3^2}{\Lambda} A_V,
\] (4)

where \( \Lambda \) is the energy scale, \( \lambda_i \) (\( i = 0, 1, 2 \) for scalar, vector and tensor unparticles, respectively) are dimensionless effective couplings and

\[
A_{d_{lt}} = [16\pi^{5/2} \Gamma(d_{lt} + 1/2)/[(2\pi)^{2d_{lt}} \Gamma(d_{lt} - 1) \Gamma(2d_{lt})]].
\]

**ep \rightarrow et + X.** Production of single top quarks in \( ep \) collisions through the sub-processes \( eq \rightarrow et \) proceeds via \( t \)-channel unparticle exchange only. The differential cross-sections in this case are

\[
\frac{d\sigma_V}{dt} = \frac{A_V^2}{8\pi s^2(-t)^{4-2d_{lt}}} \left[ (c_v^4 + c_u^4)(s^2 + (s + t)^2) - (2s + t)m^2 - 2c_v^2c_u^2(2t^2 + 2s(s - t)) - (2s - t)m^2 \right],
\] (5)

\[
\frac{d\sigma_T}{dt} = \frac{A_T^2}{2\pi s^2(-t)^{4-2d_{lt}}} \left[ (-8s - t)m^6 + (40s^2 + 26ts + 3t^2)m^4 - (64s^3 + 82ts^2 + 28t^2s + 3t^3)m^2 + 32s^4 + 4t^4 + 10s^3t + 42s^2t^2 + 64s^3t \right],
\] (6)

\[
\frac{d\sigma_S}{dt} = \frac{A_S^2}{4\pi s^2(-t)^{4-2d_{lt}}} \left[-t(s + t)\right].
\] (7)

Here \( \bar{s} \) and \( \bar{t} \) refer to parton level Mandelstam variables.

**pp \rightarrow t(q,g,U) + X.** In \( pp \) collisions at the LHC there is a rich variety of mechanisms giving rise to single top productions as compared to the ones discussed above. There are three types of sub-processes:

i) \( q\bar{q} \rightarrow t\bar{q}, \)

ii) \( gg \rightarrow t\bar{q}, \)

iii) \( gg \rightarrow tg, tU. \)

For the first type of processes we have both \( s \)- and \( t \)-channel unparticle contributions. The differential cross-section for each type of unparticles are given as

\[
\frac{d\sigma_V}{dt} = A_V^2 \left\{ \frac{1}{(s)^{4-2d_{lt}}} \left( c_v^4 + c_u^4 \right) \left((s + t)^2 + t^2 \right. \right.
\] 

\[- m^2(s + 2t) + 2c_v^2c_u^2(3s^2 + 6s + 2t^2)
\] 

\[- m^2(3s + 2t)) + \frac{1}{(s)^{4-2d_{lt}}} \left( c_v^4 + c_u^4 \right) \left((s + t)^2 \right. \right.
\] 

\[ + s^2 - m^2(2s + t) + 2c_v^2c_u^2(2s + 6s + 2t^2)
\] 

\[- m^2(2s + 3t)) \right) + \frac{2 \cos d_{lt}}{3(s)^{2-2d_{lt}} \left( -t \right)^{2-2d_{lt}}} \left( c_v^4 + 6c_v^2c_u^2 \right.
\] 

\[ + c_u^4 \left(m^2 - s - t)(s + t) \right) \right),
\] (8)
The differential cross-sections are given as

\[
\frac{d\sigma_T}{dt} = \frac{A_T^2}{2\pi s^2} \left\{ \frac{1}{(s\bar{t})^{2-2\alpha}} \left[ s^4 + 10s^3\bar{t} + 42s^2\bar{t}^2 + 64s\bar{t}^3 + 32\bar{t}^4 - m^6(s + 8\bar{t}) + m^4(3s^2 + 26s\bar{t} + 40\bar{t}^2) - m^2(3s^3 + 28s^2\bar{t} + 82s\bar{t}^2 + 64\bar{t}^3) \right] \\
+ \frac{1}{(-\bar{t})^{2-2\alpha}} \left[ 32s^4 + 64s^3\bar{t} + 42s^2\bar{t}^2 + 10s\bar{t}^3 + \bar{t}^4 - m^6(8s + \bar{t}) + m^4(40s^2 + 26s\bar{t} + 3\bar{t}^2) - m^2(64s^3 + 82s^2\bar{t} + 28s\bar{t}^2 + 3\bar{t}^3) \right] \\
+ \frac{\cos d_{UL}}{3(\bar{t})^2 - d_{UL}} \left[ 2m^6(s + \bar{t}) - (s + \bar{t})^2(4s^2 + 17s\bar{t} + 4\bar{t}^2) - m^6(8s^2 + 21s\bar{t} + 8\bar{t}^2) + 2m^2(5s^3 + 22s^2\bar{t} + 22s\bar{t}^2 + 5\bar{t}^3) \right] \right\},
\]

(9)

The second type is the gluon fusion which proceeds via s-channel scalar and tensor unparticle exchanges only, and the differential cross-sections are given as

\[
\frac{d\sigma_T}{dt} = \frac{3A_T^2}{\pi s^2(\bar{t})^{2-2\alpha}} \left\{ \frac{1}{\bar{t}^2 - d_{UL}} \left[ \bar{t}(s + \bar{t}m^4 - (2s^2 + 5\bar{t}s + 4\bar{t}^2)m^2 + (s + 3\bar{t} + 2\bar{t}^2(\bar{t} + 2s)) \right] \right\},
\]

(11)

\[
\frac{d\sigma_S}{dt} = \frac{3A_S^2}{256\pi s^2(\bar{t})^{4-2\alpha}} \left\{ (s^2 - m^2) \left[ (s^2 - m^2)^2 \right] \right\},
\]

(12)

where

\[
\bar{A}_S = \frac{2\lambda_2^3 A_{ul}}{\sin(d_{UL}/\pi)\Lambda^{2\alpha - 1}}.
\]

(13)

The last group of processes involves associated production of top quarks with gluons which proceed via t-channel scalar and tensor exchanges, as well as the rather peculiar process of associated productions of t quarks with scalar and tensor unparticle through s- and u-channel q (initial quark) and t quark exchanges, respectively. Here only scalar and tensor unparticles are produced in association with the top quark. Differential cross-sections for the subprocess qq → t\bar{t} are

\[
\frac{d\sigma_T}{dt} = \frac{8A_T^2}{\pi s^2(\bar{t})^{4-2\alpha}} \left\{ \bar{t}(s^2 + \bar{t}m^4 - (4s^2 + 5\bar{t}s + 4\bar{t}^2)m^2 + 2\bar{t}^2)m^2 + 2s^2(\bar{t} + 2\bar{t} + \bar{t}^2(\bar{t} + 3s)) \right\},
\]

(14)

\[
\frac{d\sigma_S}{dt} = \frac{\bar{A}_S^2}{32\pi s^2(\bar{t})^{4-2\alpha}} \left\{ \bar{t}^2(m^2 - \bar{t}) \right\}.
\]

(15)

Finally the differential cross-sections for the subprocesses gg → t\bar{t} are given by

\[
\frac{d\sigma_T}{dt} = \frac{\lambda_2^2 A_{ul}}{128\pi \Lambda^{2\alpha - 1}} \left\{ \bar{t}(s + \bar{t}m^4 - (4s^2 + 5\bar{t}s + 4\bar{t}^2)m^2 + 2s^2(\bar{t} + 2\bar{t} + \bar{t}^2(\bar{t} + 3s)) \right\}.
\]

(16)

\[
\frac{d\sigma_S}{dt} = \frac{\lambda_2^2 A_{ul}}{128\pi \Lambda^{2\alpha - 1}} \left\{ \frac{\bar{t}^2(m^2 - \bar{t})}{(u - m^2)^2} \right\}.
\]

(17)

**Numerical analysis.** – In fig. 1, we plot the d\_\bar{t} dependencies of cross-sections for both vector and scalar unparticle contributions in the interval 2 < d\_\bar{t} < 3 for the sake of practical advantage of depicting both contributions in the same figure. Namely there is a constraint on d\_\bar{t}, d\_\bar{t} > 2, for vector unparticle, in the case of FCNC reactions [11], but not for the scalar mediator. In the figure both options of ILC were considered for the Λ = 1 TeV value of the mass scale. In plotting cross-sections we have taken the parameter values of λ_0 = λ_1 = λ_2 = 1 and c_v = c_a = 1 in all figures. We see that for a very narrow interval of 2 < d\_\bar{t} < 2.12, effects of vector and scalar unparticles can be observed at ILC with √s = 500 GeV and with an integrated luminosity, L = 10^4 pb^–1 assuming an observability limit of number of the single top events to be about one hundred. Furthermore, one gets a larger number of events for scalar unparticles by considering the region 1 < d\_\bar{t} < 2, as can be easily seen by extrapolating the dashed lines in fig. 1. For tensor...
unparticles the relevant interval is $3 < d_{d,t} < 4$. In this range the cross-sections are too small. To give an example $\sigma = 1.5 \times 10^{-8}$ pb for $d_{d,t} = 3.1$ at $\sqrt{s} = 500$ GeV. In fig. 2 we have plotted the cross-sections for the vector and scalar cases, originating from the reaction $eq_i \rightarrow et$ ($q_i = u, c$) for $\Lambda = 1$ TeV, at THERA with $\sqrt{s} = 1$ TeV. Furthermore, tensor contributions are 8 orders smaller than that of the scalar case. Taking into account the fact that integrated luminosity $L = 40$ pb$^{-1}$, then it is clear that THERA will not be a suitable platform to probe unparticle physics. In numerical calculations we used CTEQ5 parton distributions [12].

The LHC processes are plotted in fig. 3 for scalar and vector unparticle and in fig. 4 for tensor unparticle. In these figures, we have plotted, $pp \rightarrow t + jet$ cross-sections by collecting the contributions originating from the subprocesses $q\bar{q} \rightarrow t\bar{q}$, $gg \rightarrow t\bar{q}$ and $gg \rightarrow tg$. The parameter values $\Lambda = 1$ TeV, $\lambda_0 = \lambda_1 = \lambda_2 = 1$ and $\sqrt{s} = 14$ TeV were used. With the large luminosity value of LHC, $L = 10^{5}$ pb$^{-1}$, we see that about 1000 events are possible for both scalar and vector unparticle mediated processes with upper bounds $d_{d,t} = 2.6$ and $d_{d,t} = 2.3$, respectively. For the tensor case the cross-sections are rather small for a wide region of $d_{d,t}$, except at $d_{d,t} = 3.15$. Here we expect about 100 events per year.

We should note that, from eq. (4), all the cross-sections scale as $\lambda_i^4$, so taking say $\lambda_1 = 0.5$ would reduce the cross-sections by a factor of 16 at all types of colliders.

The cross-sections for the associated production of top quarks with scalar or tensor unparticles, $qq \rightarrow tU$, through $s$- and $u$-channels, turn out to be very small. Namely, we have found that the expected number of events will be only 28 at $d_{d,t} = 2.1$ for the scalar case. Furthermore, the tensor case is seven orders of magnitude more suppressed than this case. Therefore we are not including any plots for $pp \rightarrow t + missing\ energy$ cross-sections corresponding to these processes.

Finally, in this work we have studied the effects of unparticle physics on FCNC single top production processes. The SM predictions via charged current processes are about 4.9 pb at Tevatron [13] and 160 pb at LHC [14] energies, $\sqrt{s} = 1.96$ and 14 TeV, respectively. As already pointed out in the introduction, the FCNC processes considered here in the framework of SM do not occur at tree level, and get the principle contributions from one loop level which is only $8.46 \times 10^{-5}$ pb for LHC [15]. The FCNC single top production processes in the framework of unparticle physics occur at the tree level and are about 1 pb for scalar and vector unparticles. Furthermore, in practice, it is much easier not to bother measuring final state charges, so top and anti-top signals are normally lumped together. It is to be pointed out, however, that if this “lumping together” is taken into account, the cross-sections we have presented above would be enhanced further. We have analyzed these contributions as well, without depicting them in detail for all values of $d_{d,t}$. For ILC, $t$ and $\bar{t}$ cross-sections, considered together, double the single top result. At LHC the contributions to $t$ production from the vector and scalar unparticles are 0.35 pb and 0.9 pb, respectively, whereas the corresponding contributions for the top were 0.5 pb and 3 pb for $d_{d,t} = 2.1$. Hence, unparticle physics effects can be observed at the ILC and LHC, through the FCNC single top production processes.
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