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 $d_{\mathcal{U}}$. 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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I. 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 un-particles, and thus play a role in low energy physics [1, 2]. This scheme has, since then, been further developed and studied very extensively, exploiting it from all phenomenological perspectives [3].

In this letter we exploit implications of unparticle physics for the single top production processes. We consider these processes 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 I [4, 5, 6, 7]. For the ILC we consider two options with $\sqrt{s} = 0.5$ and $\sqrt{s} = 1$ TeV.

In an our earlier paper [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 were some kind of competition between these two types of contributions. However, the single production processes, on the other hand, always manifest themselves via FV vertices. Because in these processes the top quarks are always accompanied by an antiquark with a different flavor, the actual type of which depending on the relevant production channel. As these FV vertices do not exist in the SM, none of these reactions considered here have SM counterparts, and all are purely unparticle processes.

The propagators and effective interactions of scalar, vector and tensor unparticles were already given in several references [1, 2, 8, 9, 10], therefore we are not going to present them here once more and refer the reader to those references.

II. 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 $e^+e^- \to t\bar{q}$, $ep \to et + X$ and $pp \to t(\bar{q}, g, \mathcal{U}) + X$.

A. $e^+e^- \to t\bar{q}$

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

$$\frac{d\hat{\sigma}_V}{d\hat{t}} = \frac{3|\tilde{A}_V|^2}{8\pi\hat{s}^2(\hat{s})^{4-2d_\mathcal{U}}}\Big[(c_v^4 + c_a^4)(\hat{t}^2 + (\hat{s}+\hat{t})^2 - (2\hat{t}+\hat{s})m^2) + 2c_v^2c_a^2(2\hat{t}^2 + 3\hat{s}(\hat{s}+2\hat{t}) - (3\hat{s}+2\hat{t})m^2)\Big] \tag{1}$$

where

$$\tilde{A}_V = \frac{\lambda_1^2 A_{d_\mathcal{U}} e^{-i\pi d_\mathcal{U}}}{2\sin(d_\mathcal{U}\pi)\Lambda^{2(d_\mathcal{U}-1)}}, \tag{2}$$

$$\frac{d\hat{\sigma}_T}{d\hat{t}} = \frac{3|\tilde{A}_T|^2}{2\pi\hat{s}^2(\hat{s})^{4-2d_\mathcal{U}}}\Big[-(8\hat{t}+\hat{s})m^6 + (3\hat{s}^2 + 26\hat{t}\hat{s} + 40\hat{t}^2)m^4 - (3\hat{s}^3 + 28\hat{t}\hat{s}^2 + 82\hat{t}^2\hat{s} + 64\hat{t}^3)m^2 + \hat{s}^4 + 32\hat{t}^4 + 64\hat{s}\hat{t}^3 + 42\hat{s}^2\hat{t}^2 + 10s^3\hat{t})\Big] \tag{3}$$

where

$$\tilde{A}_T = \frac{\lambda_2^2 A_{d_\mathcal{U}} e^{-i\pi d_\mathcal{U}}}{32\sin(d_\mathcal{U}\pi)\Lambda^{2d_\mathcal{U}}}, \tag{4}$$

$$\frac{d\hat{\sigma}_S}{d\hat{t}} = \frac{3|\tilde{A}_S|^2}{4\pi\hat{s}^2(\hat{s})^{4-2d_\mathcal{U}}}\Big[\hat{s}(\hat{s}-m^2)\Big] \tag{5}$$

where

$$\tilde{A}_S = \frac{\lambda_0^2}{\lambda_1^2}\tilde{A}_V \tag{6}$$

B. $ep \to et + X$

Production of single top quarks in ep collisions through the sub-processes $eq \to et$ proceeds via t-channel unparticle exchange only. The differential cross sections in this case are

$$\frac{d\hat{\sigma}_V}{d\hat{t}} = \frac{|\tilde{A}_V|^2}{8\pi\hat{s}^2(-\hat{t})^{4-2d_{\mathcal{U}}}}\Big[(c_v^4+c_a^4)(\hat{s}^2+(\hat{s}+\hat{t})^2-(2\hat{s}+\hat{t})m^2) -2c_v^2c_a^2(\hat{t}^2+2\hat{s}(\hat{t}-\hat{s})+(2\hat{s}-\hat{t})m^2)\Big] \quad (7)$$

$$\frac{d\hat{\sigma}_T}{d\hat{t}} = \frac{|\tilde{A}_T|^2}{2\pi\hat{s}^2(-\hat{t})^{4-2d_{\mathcal{U}}}}\Big[(-8\hat{s}-\hat{t})m^6+(40\hat{s}^2+26\hat{t}\hat{s}+3\hat{t}^2)m^4 - (64\hat{s}^3+82\hat{t}\hat{s}^2+28\hat{t}^2\hat{s}+3\hat{t}^3)m^2+32\hat{s}^4+\hat{t}^4+10\hat{s}\hat{t}^3+42\hat{s}^2\hat{t}^2+64\hat{s}^3\hat{t}\Big] \quad (8)$$

$$\frac{d\hat{\sigma}_S}{d\hat{t}} = \frac{|\tilde{A}_S|^2}{4\pi\hat{s}^2(-\hat{t})^{4-2d_{\mathcal{U}}}}\Big[-\hat{t}(\hat{s}+\hat{t})\Big] \quad (9)$$

C. $pp \to t(\bar{q}, g, \mathcal{U}) + X$

In pp collisions at the LHC there are 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) $q\bar{q} \to t\bar{q}$

ii) $gg \to t\bar{q}$

iii) $qg \to tg, t\mathcal{U}$

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

$$\frac{d\hat{\sigma}_V}{d\hat{t}} = \frac{|\tilde{A}_V|^2}{8\pi\hat{s}^2}\Bigg\{\frac{1}{(\hat{s})^{4-2d_{\mathcal{U}}}}\Big[(c_v^4+c_a^4)((\hat{s}+\hat{t})^2+\hat{t}^2-m^2(\hat{s}+2\hat{t}) + 2c_v^2c_a^2(3\hat{s}^2+6\hat{s}\hat{t}+2\hat{t}^2-m^2(3\hat{s}+2\hat{t})))\Big] + \frac{1}{(-\hat{t})^{4-2d_{\mathcal{U}}}}\Big[(c_v^4+c_a^4)((\hat{s}+\hat{t})^2+\hat{s}^2-m^2(2\hat{s}+\hat{t}) + 2c_v^2c_a^2(2\hat{s}^2+6\hat{s}\hat{t}+3\hat{t}^2-m^2(2\hat{s}+3\hat{t})))\Big] + \frac{2\cos d_{\mathcal{U}}\pi}{3(\hat{s})^{2-d_{\mathcal{U}}}(-\hat{t})^{2-d_{\mathcal{U}}}}\Big[(c_v^4+6c_a^2c_v^2+c_a^4)(m^2-\hat{s}-\hat{t})(\hat{s}+\hat{t})\Big]\Bigg\} \quad (10)$$

$$
\begin{aligned}
\frac{d\hat{\sigma}_T}{d\hat{t}} &= \frac{|\tilde{A}_T|^2}{2\pi\hat{s}^2}\Bigg\{\frac{1}{(\hat{s})^{4-2d_{\mathcal{U}}}}\Big[\hat{s}^4+10\hat{s}^3\hat{t}+42\hat{s}^2\hat{t}^2+64\hat{s}\hat{t}^3+32\hat{t}^4-m^6(\hat{s}+8\hat{t}) \\
&+ m^4(3\hat{s}^2+26\hat{s}\hat{t}+40\hat{t}^2)-m^2(3\hat{s}^3+28\hat{s}^2\hat{t}+82\hat{s}\hat{t}^2+64\hat{t}^3)\Big] \\
&+ \frac{1}{(-\hat{t})^{4-2d_{\mathcal{U}}}}\Big[32\hat{s}^4+64\hat{s}^3\hat{t}+42\hat{s}^2\hat{t}^2+10\hat{s}\hat{t}^3+\hat{t}^4-m^6(8\hat{s}+\hat{t}) \\
&+ m^4(40\hat{s}^2+26\hat{s}\hat{t}+3\hat{t}^2)-m^2(64\hat{s}^3+82\hat{s}^2\hat{t}+28\hat{s}\hat{t}^2+3\hat{t}^3)\Big] \\
&+ \frac{\cos d_{\mathcal{U}}\pi}{3(\hat{s})^{2-d_{\mathcal{U}}}(-\hat{t})^{2-d_{\mathcal{U}}}}\Big[2m^6(\hat{s}+\hat{t})-(\hat{s}+\hat{t})^2(4\hat{s}^2+17\hat{s}\hat{t}+4\hat{t}^2) \\
&- m^4(8\hat{s}^2+21\hat{s}\hat{t}+8\hat{t}^2)+2m^2(5\hat{s}^3+22\hat{s}^2\hat{t}+22\hat{s}\hat{t}^2+5\hat{t}^3)\Big]\Bigg\} \qquad (11)
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\hat{\sigma}_S}{d\hat{t}} &= \frac{|\tilde{A}_S|^2}{4\pi\hat{s}^2}\Bigg\{\frac{1}{(\hat{s})^{4-2d_{\mathcal{U}}}}\Big[(m^2-\hat{t})(\hat{s}+\hat{t}-m^2)\Big]+\frac{1}{(-\hat{t})^{4-2d_{\mathcal{U}}}}\Big[\hat{t}(\hat{t}-m^2)\Big] \\
&- \frac{\cos d_{\mathcal{U}}\pi}{3(\hat{s})^{2-d_{\mathcal{U}}}(-\hat{t})^{2-d_{\mathcal{U}}}}(\hat{s}\hat{t})\Bigg\} \qquad (12)
\end{aligned}
$$

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:

$$
\begin{aligned}
\frac{d\hat{\sigma}_T}{d\hat{t}} &= \frac{3|\tilde{A}_T|^2}{\pi\hat{s}^2(\hat{s})^{4-2d_{\mathcal{U}}}}\Big[-\hat{t}((\hat{s}+2\hat{t})m^4-(2\hat{s}^2+5\hat{t}\hat{s}+4\hat{t}^2)m^2 \\
&+ \hat{s}^2(\hat{s}+3\hat{t})+2\hat{t}^2(\hat{t}+2\hat{s}))\Big] \qquad (13)
\end{aligned}
$$

$$
\frac{d\hat{\sigma}_S}{d\hat{t}} = \frac{3|\tilde{A}_S^g|^2}{256\pi\hat{s}^2(\hat{s})^{4-2d_{\mathcal{U}}}}\Big[\hat{s}^2(\hat{s}-m^2)\Big] \qquad (14)
$$

where

$$
\tilde{A}_S^g = \frac{2\lambda_0^2 A_{d_{\mathcal{U}}} e^{-i\pi d_{\mathcal{U}}}}{\sin(d_{\mathcal{U}}\pi)\Lambda^{2d_{\mathcal{U}}-1}} \qquad (15)
$$

The last group of processes involve 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 $qg \to tg$ are

$$\frac{d\hat{\sigma}_T}{d\hat{t}} = \frac{8|\tilde{A}_T|^2}{\pi \hat{s}^2(-\hat{t})^{4-2d_{\mathcal{U}}}}\Big[\hat{s}((2\hat{s}+\hat{t})m^4 - (4\hat{s}^2+5\hat{t}\hat{s}+2\hat{t}^2)m^2 + 2\hat{s}^2(\hat{s}+2\hat{t}) + \hat{t}^2(\hat{t}+3\hat{s}))\Big] \quad (16)$$

$$\frac{d\hat{\sigma}_S}{d\hat{t}} = \frac{|\tilde{A}_S^g|^2}{32\pi \hat{s}^2(-\hat{t})^{4-2d_{\mathcal{U}}}}\Big[\hat{t}^2(m^2-\hat{t})\Big] \quad (17)$$

and finally the differential cross sections for the subprocesses $qg \to t\mathcal{U}$

$$\frac{d\hat{\sigma}_T}{d\hat{t}} = \frac{\lambda_2^2\alpha_s}{192\hat{s}^2\Lambda^{2d_{\mathcal{U}}}}\Big[-\frac{3\hat{t}m^2+4\hat{s}^2+5\hat{s}\hat{t}}{\hat{s}} + \frac{2}{(\hat{u}-m^2)^2}(4m^6-4(2\hat{s}+\hat{t})m^4 + (2\hat{t}^2+\hat{t}\hat{s}-\hat{s}^2)m^2 + 2(\hat{s}-\hat{t})(\hat{s}+\hat{t})^2) + \frac{2}{\hat{s}(\hat{u}-m^2)}(4m^6-(7\hat{s}+5\hat{t})m^4 + (\hat{s}^2+6\hat{t}\hat{s}+\hat{t}^2)m^2 - 2\hat{s}\hat{t}(\hat{s}+\hat{t}))\Big] \quad (18)$$

$$\frac{d\hat{\sigma}_S}{d\hat{t}} = \frac{\lambda_0^2\alpha_s}{12\hat{s}^2\Lambda^{2d_{\mathcal{U}}-2}}\Big[\frac{\hat{s}+\hat{t}}{\hat{s}} - \frac{2m^4-(\hat{s}+\hat{t})(2m^2+\hat{s})}{(\hat{u}-m^2)^2} - \frac{2m^4-2(\hat{s}+\hat{t})(m^2+\hat{s})}{\hat{s}(\hat{u}-m^2)}\Big] \quad (19)$$

TABLE I: The main parameters of future colliders

e^+e^- (ILC)	E_{e^+} (TeV)	E_{e^-} (TeV)	$\sqrt{s}$ (TeV)	$L_{int}(pb^{-1})$
	0.25 (0.5)	0.25 (0.5)	0.5 (1)	10^4
ep (THERA)	E_e (TeV)	E_p (TeV)	$\sqrt{s}$ (TeV)	$L_{int}(pb^{-1})$
	0.25	1	1	40
pp (LHC)	E_p (TeV)	E_p (TeV)	$\sqrt{s}$ (TeV)	$L_{int}(pb^{-1})$
	7	7	14	10^5

III. NUMERICAL ANALYSIS

In Fig. 1, we plot the $d_{\mathcal{U}}$ dependencies of cross sections for both vector and scalar unparticle contributions in the interval $2 < d_{\mathcal{U}} < 3$ for the sake of practical advantage of depicting both contributions in the same figure. Namely there is a constraint on $d_{\mathcal{U}}$,$d_{\mathcal{U}} > 2$, for vector unparticle, in the case of FV reactions [11], but non for the scalar mediator. In the figure both options of ILC were considered for the Λ=1 TeV value of the mass scale. We see that for a very narrow interval of $2 < d_{\mathcal{U}} < 2.12$, effects of vector and scalar unparticles can be observed at ILC with $\sqrt{s} = 500$ 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 larger number of events for scalar unparticles by considering the region $1 < d_{\mathcal{U}} < 2$, as can easily be seen by extrapolating the dashed lines in Fig.1. For tensor unparticles the relevant interval is $3 < d_{\mathcal{U}} < 4$. In this range the cross sections are too small. To give an example $\sigma = 1.5 \times 10^{-8}$ pb for $d_{\mathcal{U}}$=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 $eq_i \to et$ ($q_i = u, c$) for Λ=1 TeV, at THERA with $\sqrt{s} = 1$ TeV. Furthermore, tensor contributions are 8 order smaller than that of scalar case. Taking into account the fact that integrated luminosity $L = 40$ pb^{-1}, then its clear that THERA will not be a suitable platform to probe unparticle physics. In numerical calculations we used CTEQ5 parton distributions [12].

The LHC precesses are plotted in Figs. 3- 10. In Figs. 3 and 4, we have plotted, the cross sections originating from the reactions $pp \to t\bar{q}_i + X$ for Λ=1 TeV and $\sqrt{s}$=14 TeV, for vector and scalar, and tensor cases, respectively. With the large luminosity value of LHC, $L = 10^5$ pb^{-1}, we see that about 100 events are possible for both vector and scalar mediated processes with upper bounds $d_{\mathcal{U}} = 2.48$ and $d_{\mathcal{U}} = 2.34$, respectively. For the tensor case the cross sections are rather small for a wide region of $d_{\mathcal{U}}$, except at $d_{\mathcal{U}} = 3.1$. Here we expect about 30 events per year.

In Figs. 5 and 6 we have plotted the total cross sections originating from the t-channel reactions $q_i\bar{q}_j \to t\bar{q}_j$ ($q_j = d, s, b$) for vector and scalar, and tensor uparticle contributions, respectively. We expect about 110 events for vector and scalar cases at $d_{\mathcal{U}} = 2.38$, and $d_{\mathcal{U}} = 2.34$, respectively. The tensor case is however significant at $d_{\mathcal{U}}$=3.1, and the expected number of events is about 40.

Figs. 7 and 8 show total cross sections originating from gluon fusion $gg \to t\bar{q}_i$, for the scalar and tensor cases, respectively. The upper bound on $d_{\mathcal{U}}$ corresponding to hundred events is $d_{\mathcal{U}} = 2.75$ for the scalar. The tensor case, however is rather small with 5 events per year at only $d_{\mathcal{U}} = 3.1$.

Cross sections originating from the reaction $q_ig \to tg$ are plotted in Figs. 9 and 10 for t-channel scalar and tensor unparticle mediators, respectively. In the scalar case the number of signals will be very significant in the interval $2 < d_{\mathcal{U}} < 3$ with about 1000 corresponding to $d_{\mathcal{U}} = 2.9$. In the tensor case we get observable number of events, in the interval $3 < d_{\mathcal{U}} < 3.14$, with about 100 events per year at $d_{\mathcal{U}} = 3.14$.

The cross sections for the associated production of top quarks with unparticles, $qg \to t\mathcal{U}$, through s- and u-channels, turn out to be very small. Namely, we have found that the expected number of events will be only 7 at $d_{\mathcal{U}} = 2.1$ 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 corresponding to these processes.

Finally, our analysis clearly shows that LHC will be the most suitable platform to probe unparticle physics, the most striking process being the one originating from $q_i g \to tg$.

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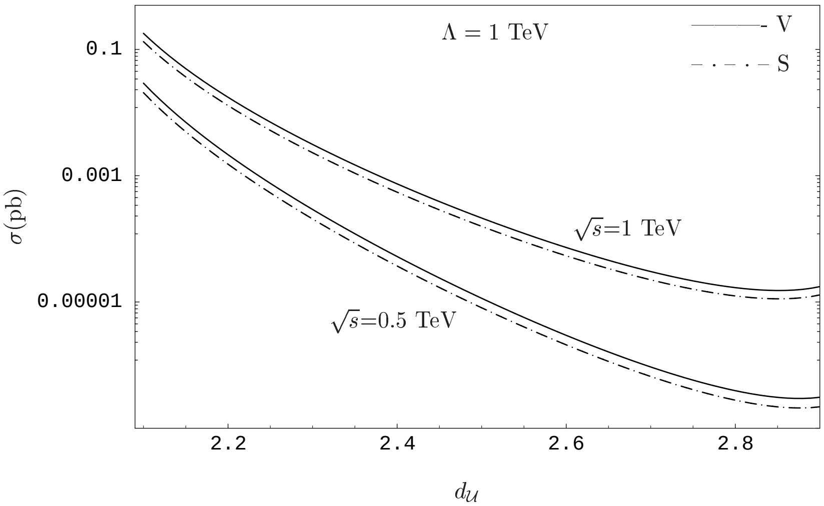

FIG. 1: Total cross section in pb originating from the reaction $e^+e^- \to \bar{q}t$ for Λ= 1 TeV, $\lambda_0 = \lambda_1 = 1$, and $c_v = c_a = 1$ at ILC($\sqrt{s}$=0.5 TeV and $\sqrt{s}$=1 TeV)

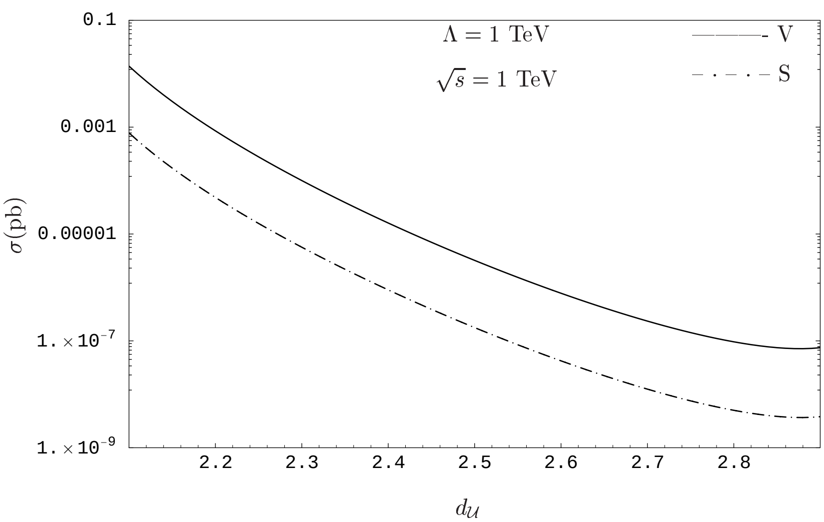

FIG. 2: Total cross section in pb originating from the reaction $eq_i \to et$ for Λ= 1 TeV, $\lambda_0 = \lambda_1 = 1$, and $c_v = c_a = 1$ at THERA

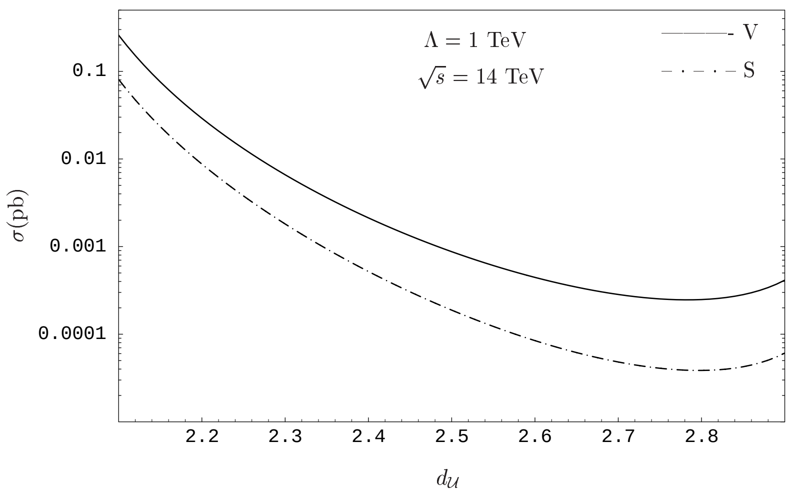

FIG. 3: Total cross section in pb for the reaction $pp \to t\bar{q}_i + X$ ($q_i = u, c$) for Λ= 1 TeV, $\lambda_0 = \lambda_1 = 1$, and $c_v = c_a = 1$ at LHC

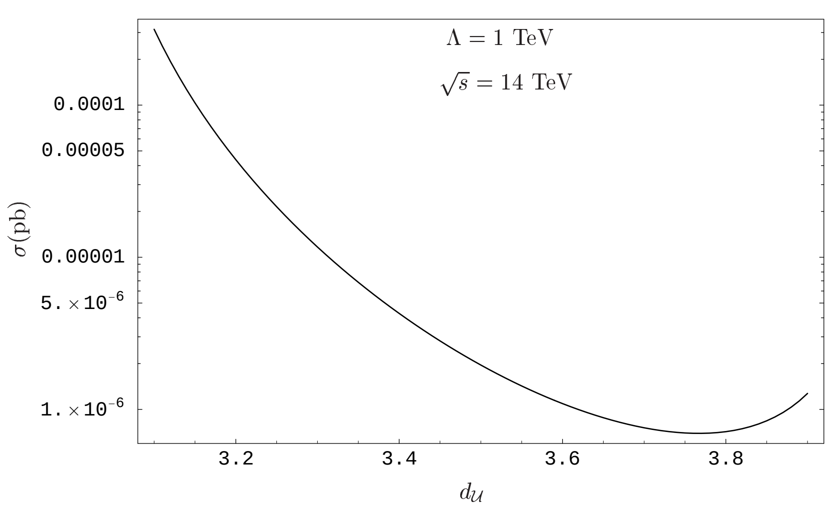

FIG. 4: Total cross section in pb for the reaction $pp \to t\bar{q}_i + X$ ($q_i = u, c$) for Λ= 1 TeV, $\lambda_2 = 1$, at LHC through tensor unparticle

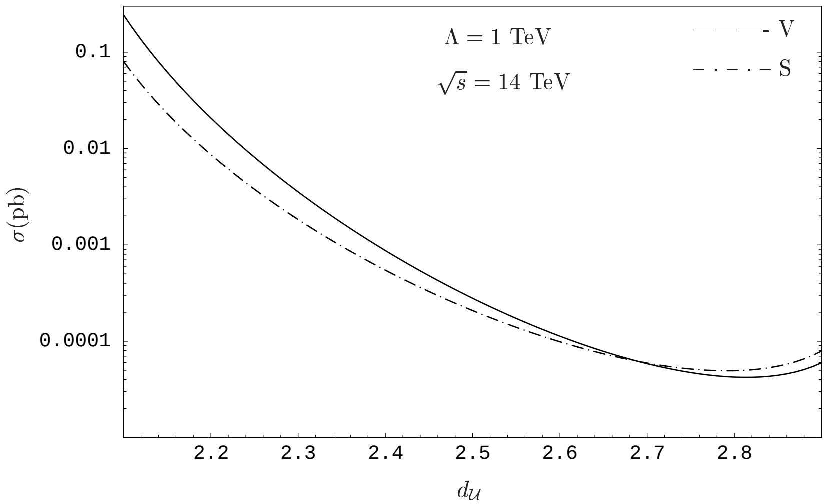

FIG. 5: Total cross section in pb originating from the reaction $q_i\bar{q}_j \to t\bar{q}_j$ ($q_j = d, b, s$) for Λ= 1 TeV, $\lambda_0 = \lambda_1 = 1$, and $c_v = c_a = 1$ at LHC

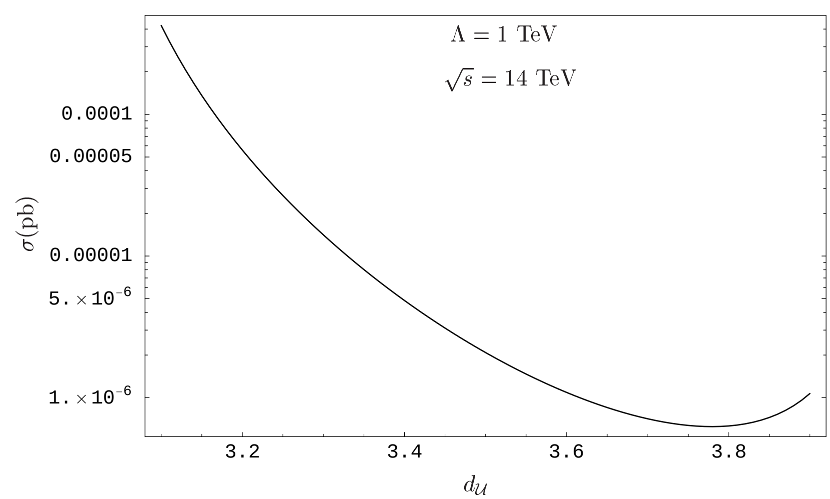

FIG. 6: Total cross section in pb originating from the reaction $q_i\bar{q}_j \to t\bar{q}_j$ ($q_j = d, b, s$) for Λ= 1 TeV, $\lambda_2 = 1$, at LHC through tensor unparticle

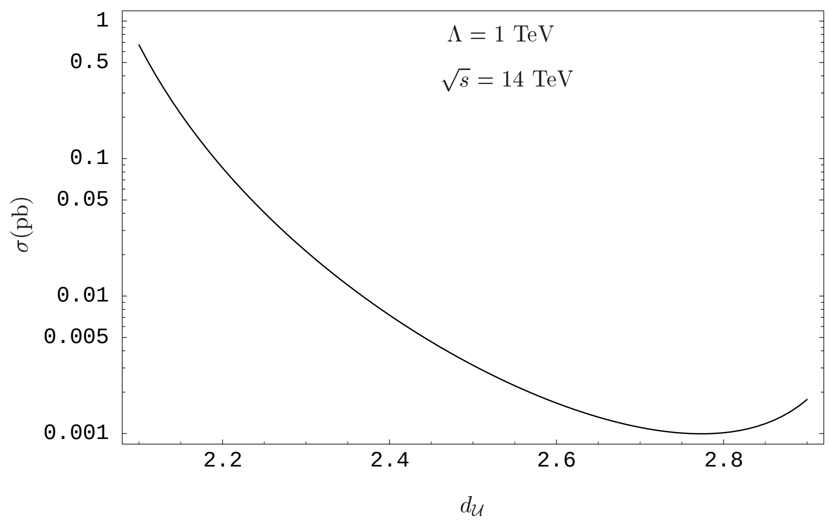

FIG. 7: Total cross section in pb originating from the reaction $gg \to t\bar{q}_i$ for Λ= 1 TeV, $\lambda_0 = 1$ at LHC through scalar unparticle

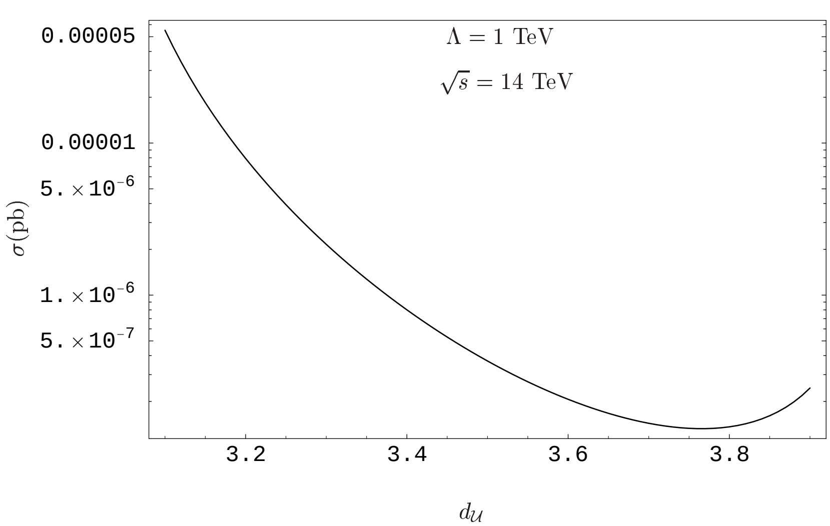

FIG. 8: Total cross section in pb originating from the reaction $gg \to t\bar{q}_i$ for Λ= 1 TeV, $\lambda_2 = 1$ at LHC through tensor unparticle

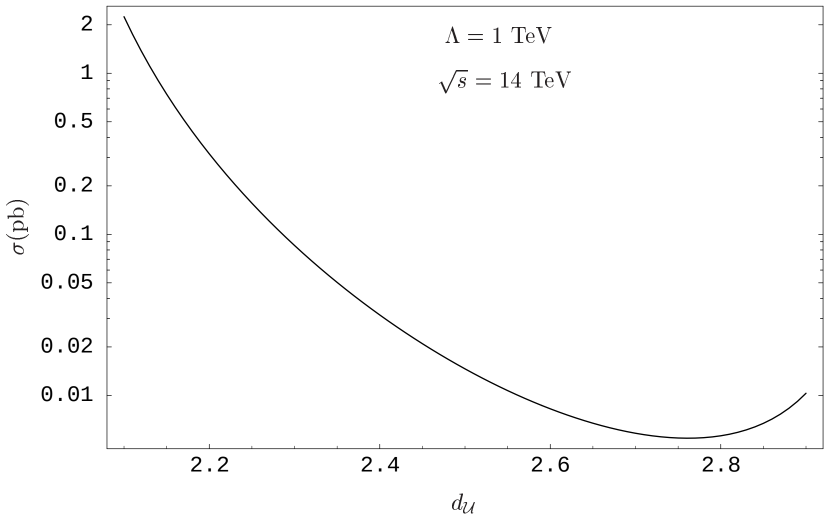

FIG. 9: Total cross section in pb originating from the reaction $q_i g \to tg$ for Λ= 1 TeV, $\lambda_0 = 1$ at LHC through scalar unparticle

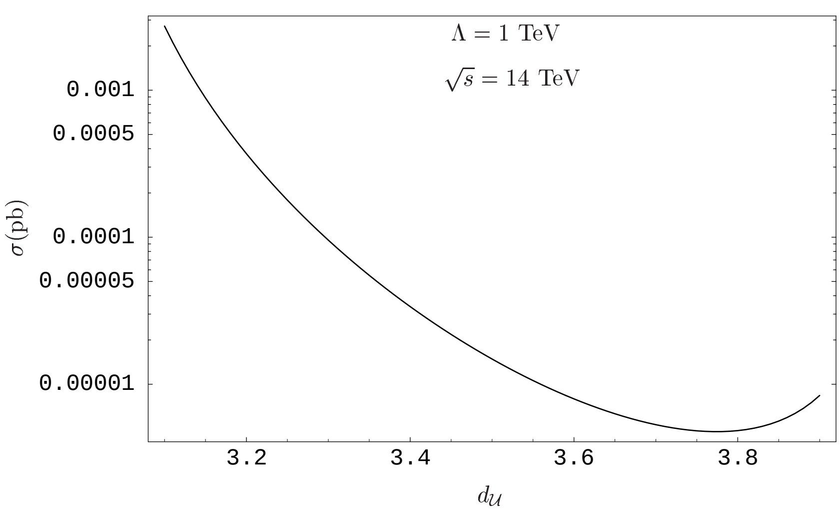

FIG. 10: Total cross section in pb originating from the reaction $q_i g \to tg$ for Λ= 1 TeV, $\lambda_2 = 1$ at LHC through tensor unparticle