Top off the unparticle

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The existence of an exactly scale invariant sector possessing a non-trivial infrared fixed point at a higher energy scale and its possible communication with the Standard Model particles through a heavy messenger sector has been shown to lead to curious unparticle effects. We demonstrate that top physics at the Tevatron can already constrain such theories. We also consider possible improvements at the LHC and delineate some striking signatures.

The top quark, with a mass very close to the electroweak symmetry breaking scale, plays a unique role in understanding the Standard Model (SM). For example, the agreement between the directly measured value m_t, and the one indicated by precision measurements [1], has played a crucial role in testing the SM to the loop level. Similarly, a study of the production and the properties of the top quark at the TeV colliders can be used as a 'low' energy probe for any ('high scale') new physics beyond the SM [2]. At the Tevatron, this has already led to very fruitful investigations [3, 4] and one expects a top factory such as the LHC to provide a very productive arena for studying the SM as well as the beyond the SM physics [5]. Recent discussions have addressed the possibility of identifying Kaluza Klein (KK) gluons of the bulk Randall-Sundrum Model through their rôle in $t\bar{t}$ production at the Tevatron or the LHC [6]; and, similarly, of probing models with extended color sectors [7]. The use of spin-spin correlations have also been advocated to increase the sensitivity, whether for Z' searches [8], or for KK excitations of the graviton [9].

While all of the above are but examples of new hypothetical particles playing a detectable rôle in $t\bar{t}$ production, note that the latter could also be affected even in the absence of a relatively light new particle. A striking example is afforded by the recently introduced "unparticle" [10], a consequence of having a scale invariant sector with a non-trivial infrared fixed point. As is well known, an exact scale invariance requires that the mass spectrum be either continuous or that all masses be zero. Thus, the SM, with its discrete mass spectrum manifestly breaks scale invariance. However, this does not preclude the existence of a new sector that is so weakly coupled to the SM that we have been unable to probe it experimentally. If this new physics were to be described by a nontrivial scale invariant theory sector with an infrared fixed point (examples being afforded by a vector-like non-abelian gauge theory with a large number of massless fermions as studied by Banks and Zaks (BZ) [11], or certain nonlinear sigma models [12]), it would manifest itself in the existence of asymptotic states that are not particle-like but are "unparticles" [10] in the sense of having a continuous mass spectrum. (It has been demonstrated [13] that the unparticle can be deconstructed as the limiting case of an infinite tower of particles of different masses with a regular mass spacing.) With the interaction of the two sectors being mediated by an unspecified superheavy messenger sector, at low energies, it can be parametrized in terms of effective Lagrangians. Curiously, the unparticle operators $O_{\mathcal{U}}$ (which can have any possible spin structure) need not have an integral mass dimension. Rather, the final state spectrum corresponding to an operator of dimension $d_{\mathcal{U}}$ (possibly fractional) resembles that of $d_{\mathcal{U}}$ massless particles. This aspect is also reflected in the structure of the unparticle propagator[10, 14, 15]. Not surprisingly, these novel features lead to curious phenomenological consequences [10, 13, 14, 15, 16, 17, 18]

In this note, we examine the possible consequences of such a sector on top physics, in particular the constraints that the current measurements on $t\bar{t}$ production at the Tevatron [3, 4] imply for such theories. The relevant operators in the effective Lagrangian are given by

$$
\begin{aligned}
\mathcal{L} \;=\; & \Lambda^{-d_{\mathcal{U}}} \mathcal{O}_S \left[-c_t \bar{t}\, \overleftrightarrow{\not{\partial}} \gamma_5 t \;+ G_{\mu\nu} \Big(\frac{c_1}{4} G^{\mu\nu} + \frac{c_2}{4} \widetilde{G}^{\mu\nu} \Big) \right] \\
& + \;\Lambda^{1-d_{\mathcal{U}}} \sum_q \bar{q} \gamma_\eta (\tilde{v}^q + \tilde{a}^q \gamma_5) q \; \mathcal{O}_V^\eta \\
& + \;\Lambda^{-d_{\mathcal{U}}} \; \mathcal{O}_T^{\mu\nu} \left[\frac{-1}{4} \sum_q \bar{q} \gamma_{\{\mu} \overleftrightarrow{\partial}_{\nu\}} \; (a_q + b_q \gamma_5) q \right. \\
& \qquad \left. + G^\alpha_\nu \; \Big(a_g \; G_{\mu\alpha} + b_g \; \widetilde{G}_{\mu\alpha} \Big) \right]
\end{aligned}
\tag{1}
$$

where $\mathcal{O}_{S,V,T}$ respectively denote scalar, transverse vector and transverse symmetric tensor operator with mass dimension $d_{\mathcal{U}}$ in each case and Λ denotes the characteristic scale of the interaction. In the spirit of effective theories, we shall consider the coefficients to be either unity or zero. And, unless stated otherwise, we restrict ourselves to right-handed fermion fields alone. Note that the coupling of $\mathcal{O}_S$ to light fermions vanishes with the fermion mass. Armed with the above, and using the propagators as derived in Refs. [14, 15], we may now calculate the parton-level cross sections for $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$. For all our computations we use the CTEQ-6L1 parton distributions [19], with a choice of $Q^2 = m_t^2$ for the factorization scale. The QCD correction, within the SM, has been calculated in Refs. [20]. In the absence of such calculations in generic theories, we use the SM K-factor for the entire process. In view of its relative smallness, any error on this account is expected to be small.

At the Tevatron, the $q\bar{q}$-initiated process dominates the gg-initiated one by a factor of over 15, mainly on account of the relative sizes of the fluxes. Thus, we expect that even for the unparticle-mediated contributions, a similar hierarchy would hold and this is borne out by explicit calculations. While several unparticle operator can contribute to $t\bar{t}$ production, we choose one set of operators (or, equivalently, one new partonic process) at a time and study its effects.

In Fig.1a, we display the $t\bar{t}$ cross section at the Tevatron as a function of scale $\Lambda_\mathcal{U}$, in the presence of a vector unparticle. With the latter being exchanged in the s-channel, there is no interference with the (dominant) QCD amplitude. Thus, unparticle effects can become appreciable only when the amplitude becomes comparable to the QCD one. With the electroweak contribution being very small, the famed phase factor $\exp(-i\pi d_\mathcal{U})$ in the unparticle propagator is of little consequence. As expected, for a given $d_\mathcal{U}$, the dependence on Λ is power-law ($\Lambda^{4-4d_\mathcal{U}}$). For comparison, we also display the current experimental data which gives (CDF Run II results averaged over all channels) [3]

$$\sigma(t\bar{t}) = 7.3 \pm 0.5\,(stat) \pm 0.6\,(syst) \pm 0.4\,(lum) \text{ pb} \,.$$

While the scalar unparticle amplitude is suppressed by the light quark mass, the tensor operator too does not give a substantial enhancement over the SM value. This can be easily understood in view of the stronger suppression in Eq.(1).

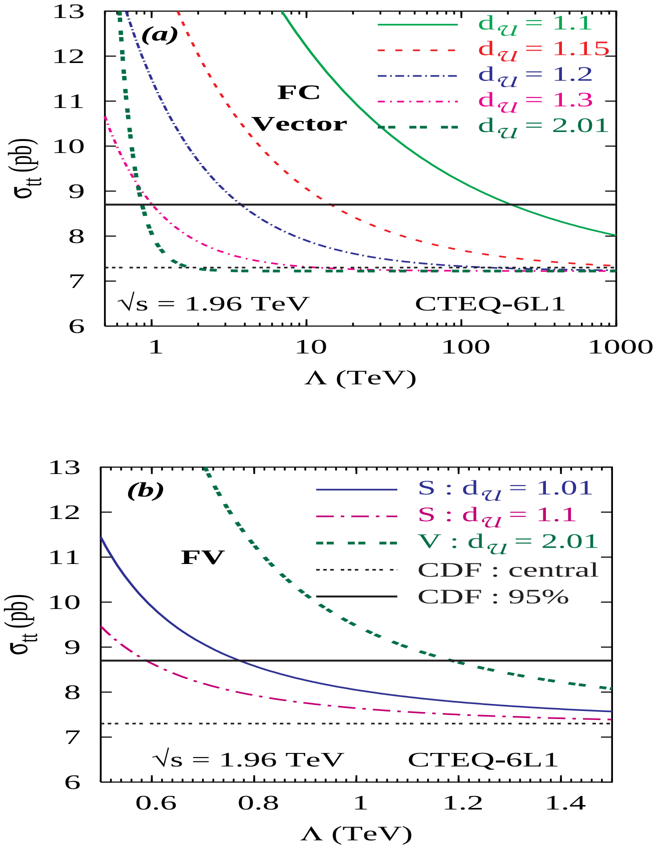

FIG. 1: $\sigma(t\bar{t})$ *at Tevatron.* (a) *flavour-conserving vector unparticle;* (b) *FV unparticle (both scalar and vector) The horizontal lines correspond to the current central value from the CDF experiment [3] and the* 95% *C.L. upper limit.*

This being only an effective theory, flavour-violating (FV) unparticle couplings are also possible [10, 16, 18]. For example, the vector coupling can be generalized to

$$\mathcal{L}_{FV} \supset \Lambda^{1-d_\mathcal{U}}\, \bar{q}\,\gamma_\eta\,(\tilde{v}^{qq'} + \tilde{a}^{qq'}\,\gamma_5)\,q'\,\mathcal{O}_V^\eta \tag{2}$$

and similarly for the scalar and tensor operators. Note that consistency demands that, for such FV couplings to be present, $d_{\mathcal{U}} > 2$ for $\mathcal{O}_V$ [18] and $d_{\mathcal{U}} > 3$ for $\mathcal{O}_T$. These operators result in a t-channel diagram for $u\bar{u} \to t\bar{t}$, which, of course, interferes with the QCD amplitude. In Fig.1(b), we exhibit the corresponding $\sigma_{t\bar{t}}$ in the presence of either a scalar or a vector FV type coupling.

Using the aforementioned experimental determination of $\sigma_{t\bar{t}}$ (with errors added in quadrature), we may impose bounds on the unparticle parameter space, for a given choice of operators. In Fig.2, we display the 95% C.L. bounds assuming that only one of the operators, whether flavour-conserving (FC) or FV, contributes. As expected, the constraint is strongly dependent on the structure of the operator involved as well as on the scale dimension $d_{\mathcal{U}}$. The sharp rise of the limit at $d_{\mathcal{U}} = 2$ is but a manifestation of the presence of physical poles in the unparticle propagator at all integral values of $d_{\mathcal{U}} > 1$. It should be noted that these bounds are what can be achieved from the use of currently published total cross section data alone. Once more data is analysed, the constraints would only be stronger.

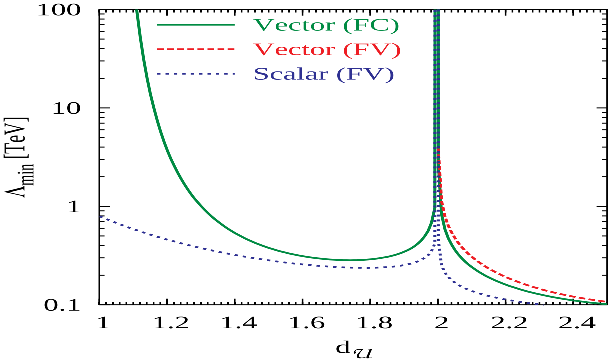

FIG. 2: *The 95% CL lower bound on the scale* Λ *as a function of* $d_{\mathcal{U}}$ *as obtained from* $\sigma(t\bar{t})$ *at Tevatron Run II [3]. FC (FV) denotes flavour conserving(violating) operators.*

With unparticle operators being chiral in nature, they have the interesting consequence of leading to a potentially large forward-backward asymmetry (see Fig.3). With A_{FB} in the standard model being very small, this could potentially lead to added sensitivity. Furthermore, with the extent and the sign of the asymmetry being dependent on the nature of the coupling, this could also serve as a discriminator between scenarios.

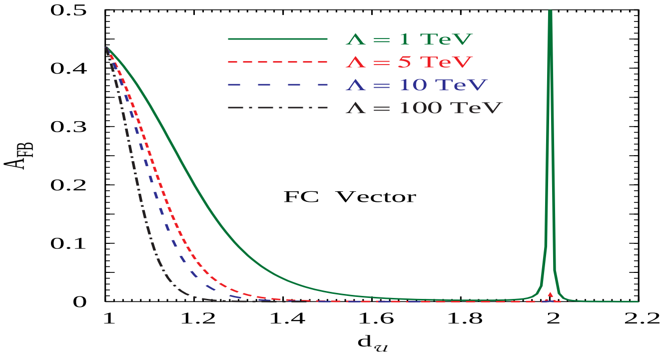

FIG. 3: Forward-backward asymmetry in $t\bar{t}$ production caused by vector unparticle (right-handed FC coupling)

Simultaneous presence of both FV and FC couplings could give rise to single-top production (viz. $u\bar{u}, d\bar{d} \to u\bar{t}$), processes which have no SM counterpart. The rates could be as large as $\sim 100\,\text{fb}$. While single-top production has been measured at the Tevatron [21], the search strategy so far has explicitly assumed an associated b in the hard process and, consequently, the said data cannot be readily used in this context.

We now turn our sights on the forthcoming LHC. The situation here is somewhat different. With the much larger gluon flux, the rôle of unparticle mediation in gluon-initiated $t\bar{t}$ production assumes importance and we begin to be able to probe such couplings. However, since the gluons couple only to $\mathcal{O}_S$ and $\mathcal{O}_T$, the constraints are always weaker than those derivable for the $\mathcal{O}_V$ mediated process initiated from $q\bar{q}$. In anticipating the bounds, we make an assumption that the $t\bar{t}$ cross section ($\sim$ 830 pb in the SM) would be determined to an accuracy of 10 pb (a conservative estimate given the accuracy at Tevatron and the expected luminosity at the LHC). The corresponding 3σ reaches are displayed in Fig.4*a*. Note that, with the relative signs of the unparticles couplings with the top and the gluon being undetermined, the interference with the QCD diagrams may have either sign. The consequent effect has been illustrated for $\mathcal{O}_S$ in Fig.4. At large $d_{\mathcal{U}}$, away from integral values, the reach in Λ tends to have very little dependence on $d_{\mathcal{U}}$. This is easily understood by realizing that the unparticle amplitude typically behaves as $(\hat{s}/\Lambda^2)^\gamma$, where $\gamma = d_{\mathcal{U}},\ 1 - d_{\mathcal{U}}$. With the bounds already in the regime of $\Lambda \sim 2\,m_t$, changing $d_{\mathcal{U}}$ naturally has very little effect. Improvement in the $\sigma_{t\bar{t}}$ measurement does have an effect, though (see Fig.4*b*). The improvement is marginal at larger $d_{\mathcal{U}}$ on account of the power law suppression. It should be noted here that further improvements in the sensitivity may be possible if one were to consider phase-space distributions of the $t\bar{t}$ pair [7] or the spin-spin correlations [8, 9]

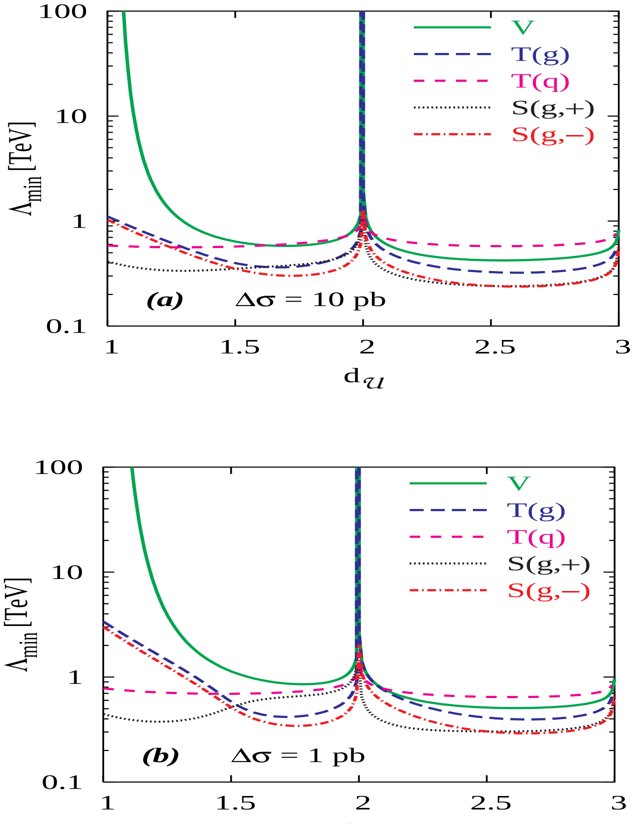

FIG. 4: 3σ reach in Λ as a function of $d_{\mathcal{U}}$ for flavour conserving operators using the $\sigma(t\bar{t})$ at the LHC. $S(g, \pm)$ corresponds to the $gg \to \mathcal{O}_S \to t\bar{t}$ process with opposing signs of the product of gluon and top couplings. Panel *(a)* assumes a measurement error of 10 pb and *(b)* of 1 pb.

While all our discussion so far about the LHC has been confined to FC coupling, FV couplings can be probed similarly, both through $t\bar{t}$ as well as single-top production. It is amusing to consider though the possibility of producing like-sign tops (through $uu \to tt$), particularly because it is precluded at the Tevatron on account of the low uu flux. As Fig.5 testifies, the rates at the LHC could be sizable, leading to spectacular signals.

In summary, we have probed the effect of unparticle-couplings of the SM fields (matter and gauge) in top pair production at the Tevatron and the LHC. The current Tevatron measurements can be used to impose significant constraints on unparticle physics. The bounds are strongly dependent on the Lorentz structure of the relevant unparticle operator as well as its mass dimension $d_{\mathcal{U}}$. For flavour-conserving vector couplings, the bound on the scale Λ could be as large as several hundred TeVs for $d_{\mathcal{U}}$ close to 1. For larger $d_{\mathcal{U}}$, the bounds get progressively weaker by a power-law since the amplitude scales as $\Lambda^{2-2d_{\mathcal{U}}}$. With the theory also allowing flavour-violating interactions, additional contributions to $u\bar{u} \to t\bar{t}$ may accrue. As such amplitudes interfere with the QCD one (unlike the FC ones), the bounds are slightly stronger for identical $d_{\mathcal{U}}$ (it should be remembered though that the FV operators are restricted to have higher $d_{\mathcal{U}}$). As for the scalar and tensor operators, the constraints are understandably weaker. Analysis of further data by CDF/D0 would not only strengthen these bounds, but also allow for the exploitation of forward-backward asymmetry, which, in such models, can be very large indeed.

At the LHC, if one assumes an experimental accuracy in $\sigma_{t\bar{t}}$ of only 10 pb, the bound on FC vector unparticle improves only marginally for smaller $d_{\mathcal{U}}$. For larger $d_{\mathcal{U}}$ the improvement is significant compared to Tevatron bound.

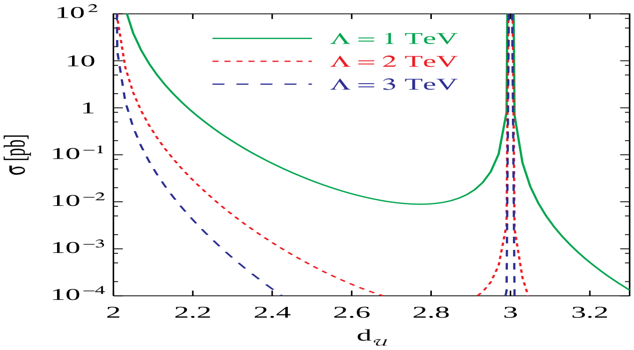

FIG. 5: Cross section for tt (like sign) production at the LHC through FV vector unparticle.

An accuracy at the 1 pb level, changes the situation considerably. In addition, large luminosities would also allow the exploitation of the distortion in the $t\bar{t}$ spectrum, thus increasing sensitivity. More importantly, the LHC allows us to probe the gluonic couplings of the unparticles in the $t\bar{t}$ mode, which the Tevatron is insensitive to. Finally, the presence of FV violating couplings could lead to like sign top pair production. Even with parameters perfectly in agreement with Tevatron data, the production rate can be as high as 100 pb, leading to spectacular signatures. We thus hope that the analysis presented here would encourage our colleagues at both the Tevatron and the LHC to carry out more detailed investigations to probe the curious world of unparticles.

DC thanks the DST, India for support under project SR/S2/RFHEP-05/2006. DKG thanks the Theory Division, CERN and the HECAP Section of the AS-ICTP for hospitality while part of the work was completed.

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