



Forward–backward asymmetry of top quark in unparticle physics

Chuan-Hung Chen^{a,b}, G. Cvetič^c, C.S. Kim^{d,*}

^a Department of Physics, National Cheng-Kung University, Tainan 701, Taiwan

^b National Center for Theoretical Sciences, Hsinchu 300, Taiwan

^c Department of Physics and Valparaíso Center for Science and Technology, Universidad Técnica Federico Santa María, Valparaíso, Chile

^d Department of Physics & IPAP, Yonsei University, Seoul 120-479, Republic of Korea

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ABSTRACT

The updated CDF measurement of the forward–backward asymmetry A_{FB} in the top quark production $p\bar{p} \rightarrow t\bar{t}$ at Tevatron (with $\sqrt{s} = 1.96$ TeV) shows a deviation of 2σ from the value predicted by the Standard QCD Model. We present calculation of this quantity in the scenario, where colored unparticle physics contributes to the s-channel of the process, and obtain the regions in the plane of the unparticle parameters λ and d_U , which give the values of the A_{FB} and of the total $t\bar{t}$ production cross section compatible with the present measurements.

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Due to C-parity invariance, it is known that the forward–backward asymmetry (FBA) of top quark pair production at Tevatron vanishes at leading order (LO) [1] in the standard QCD model (SM). The inclusive nonzero charge asymmetry can be induced by (i) radiative corrections to quark–antiquark annihilation and (ii) interference between different amplitudes contributing to gluon–quark scattering $qg \rightarrow t\bar{t}q$ and $\bar{q}g \rightarrow t\bar{t}\bar{q}$ [1,2]. Within the SM, this leads, at the Tevatron with $\sqrt{s} = 1.96$ TeV, to the nonzero but relatively low prediction [3],

$$A_{FB}^{p\bar{p}}(\text{SM}) = 0.050 \pm 0.015. \quad (1)$$

Measurement of any significant deviation from this SM prediction could be attributed to the new physics effects.

When D0 Collaboration published the first measurement on the FBA in top–quark pair production in the $p\bar{p}$ laboratory frame with 0.9 fb^{-1} of data, an unexpectedly larger FBA value was indicated [4]. By using 1.9 fb^{-1} [5], the CDF Collaboration observed the asymmetry (at $\sqrt{s} = 1.96$ TeV) to be

$$A_{FB}^{p\bar{p}} = 0.17 \pm 0.08, \quad A_{FB}^{t\bar{t}} = 0.24 \pm 0.14, \quad (2)$$

in the $p\bar{p}$ frame and $t\bar{t}$ frame, respectively. The updated CDF result with luminosity of 3.2 fb^{-1} , in the $p\bar{p}$ (lab) frame, is [6]

$$A_{FB}^{p\bar{p}}(\text{exp}) = 0.193 \pm 0.065(\text{stat}) \pm 0.024(\text{syst}). \quad (3)$$

* Corresponding author.

E-mail addresses: physchen@mail.ncku.edu.tw (C.-H. Chen), gorazd.cvetic@usm.cl (G. Cvetič), cskim@yonsei.ac.kr (C.S. Kim).

As seen in Eq. (3), the large value of the FBA of top–quark is not smeared by the statistics. Inspired by the 2σ deviation of the observed value of the top quark FBA from the SM–predicted value, several possible solutions have been proposed and studied by authors in Refs. [7–23].

In general, the top–pair production by the new physics could be through s-, t- and u-channel and the situation depends on the property of the new particle. No matter to which channel they contribute, the extensions of the SM in the framework of particle physics, such as axigluon [8,11], Z' [9], W' [10], diquarks [13], etc., have some drawbacks. For instance, in order to explain the observed top–quark FBA value, one has to introduce unimaginably large flavor–changing couplings in the t- and u-channels. The couplings in the s-channel could be as large as the strong gauge coupling of the SM. However, beside the serious constraint from the invisible production of a new resonance, the sign of the top–quark couplings has to be chosen opposite to that of the light quarks in order to get the correct sign of the FBA value. In order to avoid the aforementioned problems, we study in this work the top quark FBA in the framework of unparticle physics which is dictated by the scale of conformal invariance.

An exact scale-invariant “stuff” cannot have a definite mass unless it is zero. Therefore, in order to distinguish it from the conventional particles, Georgi named the “stuff” unparticle [24,25]. It was found that the unparticle has a noninteger scaling dimension d_U and behaves as an invisible particle [24] (see also [26]). Further implications of the unparticle to collider and low energy physics are discussed in Refs. [27–29]. We will adopt three aspects of unparticle physics in order to present a possible explanation of the aforementioned large value of the FBA. Firstly, if we take the pro-

tecting symmetry to be exact, then, due to the unique character of indefinite mass, no visible resonant unparticle will be produced in the $p\bar{p}$ collisions. Secondly, by utilizing the noninteger scale dimension, the differential cross section for $t\bar{t}$ production could be enhanced without fine-tuning the large couplings of unparticle and quarks. Finally, to match the interaction structure of the SM, the considered scale invariant stuff (unparticle) is a vector boson and carries color charges [30]; it has chiral couplings to quarks and its representation in $SU(3)_c$ belongs to color-octet.

Since there is no well established approach to give a full theory for unparticle interactions, we study instead the topic from the phenomenological viewpoint. In order to escape the large couplings from flavor changing neutral currents (FCNCs), the couplings of unparticle to quarks are chosen to be flavor conserving. Hence, we write the interactions of colored unparticle with quarks as

$$\mathcal{L} = \bar{q}(g_V^q \gamma_\mu + g_A^q \gamma_\mu \gamma_5) T^a q \mathcal{O}_U^{a\mu}, \quad (4)$$

where $g_\chi = \lambda_\chi^q / \Lambda_U^{d_U-1}$ and $\chi = V$ and A . Here, λ_χ^q is the dimensionless coupling and the index q denotes the quark flavor, Λ_U is the scale above which the unparticle is formed, and $\{T^a\} = \lambda^a/2$ are the $SU(3)_c$ generators (where λ^a are the Gell-Mann matrices) normalized by $\text{tr}(T^a T^b) = \delta^{ab}/2$. The power $d_U - 1$ is determined from the effective Lagrangian of Eq. (4) in four-dimensional space-time when the dimension of the colored unparticle $\mathcal{O}_U^{a\mu}$ is taken as d_U . By following the scheme shown in Ref. [31], the propagator of the colored vector unparticle is written as

$$\int d^4x e^{-ik \cdot x} \langle 0 | T \mathcal{O}_U^a(x) \mathcal{O}_U^b(0) | 0 \rangle = -iC_V \frac{\delta^{ab}}{(-p^2 - i\epsilon)^{3-d_U}} \left[p^2 g_{\mu\nu} - \frac{2(d_U - 2)}{d_U - 1} p_\mu p_\nu \right] \quad (5)$$

with

$$C_V = \frac{A_{d_U}}{2 \sin d_U \pi},$$

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

After introducing the interactions of unparticle with quarks and the virtual unparticle propagator, we can now calculate the $t\bar{t}$ pair production at the quark level. Using Eqs. (4) and (5), the scattering amplitude for $q\bar{q} \rightarrow t\bar{t}$ by unparticle exchange in the s -channel is

$$A_U = \bar{q}(g_V^q \gamma_\mu + g_A^q \gamma_\mu \gamma_5) T^a q \frac{C_V}{(-p^2 - i\epsilon)^{3-d_U}} \times \left[p^2 g_{\mu\nu} - \frac{2(d_U - 2)}{d_U - 1} p_\mu p_\nu \right] \times \bar{t}(g_V^t \gamma_\nu + g_A^t \gamma_\nu \gamma_5) T^a t \quad (7)$$

where flavor q denotes the light u and d quark, and $p = p_q + p_{\bar{q}} = p_t + p_{\bar{t}}$. The t -channel does not contribute, due to flavor-conserving vertices Eq. (4). With the equations of motion, $\bar{q}\not{p}q = 0$ and $\bar{q}\not{p}\gamma_5 q = -2m_q \bar{q}\gamma_5 q$. Thus, the factor $2(d_U - 2)/(d_U - 1)$ in the propagator is associated with the light quark mass and is negligible. Consequently, the scattering amplitude combined with the SM contributions is given by

$$A = A_{SM} + A_U$$

$$= \frac{g_s^2}{\hat{s}} \bar{q} \gamma_\mu T^a q \bar{t} \gamma^\mu T^a t + \frac{\hat{s} C_V}{\hat{s}^{3-d_U}} e^{-i\pi(3-d_U)} \bar{q}(g_V^q \gamma_\mu + g_A^q \gamma_\mu \gamma_5) T^a q \bar{t}(g_V^t \gamma^\mu + g_A^t \gamma^\mu \gamma_5) T^a t, \quad (8)$$

with g_s being the strong coupling of the QCD SM and $\hat{s} = (p_q + p_{\bar{q}})^2 = (p_t + p_{\bar{t}})^2$. For explicitly showing the differential cross section in $t\bar{t}$ invariant mass frame, we choose the relevant coordinates of particle momenta as

$$p_{q,\bar{q}} = \frac{\sqrt{\hat{s}}}{2} (1, 0, 0, \pm 1),$$

$$p_{t,\bar{t}} = \frac{\sqrt{\hat{s}}}{2} (1, \pm \beta_t \sin \hat{\theta}, 0, \pm \beta_t \cos \hat{\theta}), \quad (9)$$

with $\beta_t^2 = 1 - 4m_t^2/\hat{s}$. The polar angle $\hat{\theta}$ is the relative angle between outgoing top-quark and the incoming q -quark. The spin and color averaged amplitude-square is straightforwardly obtained as

$$|\bar{A}|^2 = \frac{1}{2^2} \frac{1}{N_C^2} |A|^2$$

$$= \frac{N_C^2 - 1}{16N_C^2} \left\{ 4(4\pi\alpha_s)^2 \left(1 + \beta_t^2 \cos^2 \hat{\theta} + 4 \frac{m_t^2}{\hat{s}} \right) + 8(C_V 4\pi\alpha_s) \cos \pi (3 - d_U) \frac{\hat{s}^2}{\hat{s}^{3-d_U}} \times \left[g_V^q g_V^t \left(1 + \beta_t^2 \cos^2 \hat{\theta} + 4 \frac{m_t^2}{\hat{s}} \right) + 2g_A^q g_A^t \beta_t \cos \hat{\theta} \right] + 4\hat{s}^2 \left(\frac{\hat{s} C_V}{\hat{s}^{3-d_U}} \right)^2 \left[(g_V^t)^2 ((g_V^q)^2 + (g_A^q)^2) \times \left(1 + \beta_t^2 \cos^2 \hat{\theta} + \frac{4m_t^2}{\hat{s}} \right) + (g_A^t)^2 ((g_V^q)^2 + (g_A^q)^2) \left(1 + \beta_t^2 \cos^2 \hat{\theta} - \frac{4m_t^2}{\hat{s}} \right) + 8g_V^q g_V^t g_A^q g_A^t \beta_t \cos \hat{\theta} \right] \right\}. \quad (10)$$

As a consequence, the differential cross section for $q\bar{q} \rightarrow t\bar{t}$ process as a function of $\hat{\theta}$ in $t\bar{t}$ frame is found to be

$$\frac{d\hat{\sigma}^{q\bar{q} \rightarrow t\bar{t}}}{d \cos \hat{\theta}} = \frac{N_C^2 - 1}{128N_C^2 \pi \hat{s}} \beta_t \left\{ (4\pi\alpha_s)^2 \left(1 + \beta_t^2 \cos^2 \hat{\theta} + 4 \frac{m_t^2}{\hat{s}} \right) + 2C_V (4\pi\alpha_s) \cos \pi (3 - d_U) \frac{\hat{s}^2}{\hat{s}^{3-d_U}} \times \left[g_V^q g_V^t \left(1 + \beta_t^2 \cos^2 \hat{\theta} + 4 \frac{m_t^2}{\hat{s}} \right) + 2g_A^q g_A^t \beta_t \cos \hat{\theta} \right] + \left(\frac{\hat{s}^2 C_V}{\hat{s}^{3-d_U}} \right)^2 \left[(g_V^t)^2 ((g_V^q)^2 + (g_A^q)^2) \times \left(1 + \beta_t^2 \cos^2 \hat{\theta} + \frac{4m_t^2}{\hat{s}} \right) + (g_A^t)^2 ((g_V^q)^2 + (g_A^q)^2) \left(1 + \beta_t^2 \cos^2 \hat{\theta} - \frac{4m_t^2}{\hat{s}} \right) + 8g_V^q g_V^t g_A^q g_A^t \beta_t \cos \hat{\theta} \right] \right\}. \quad (11)$$

Since the FBA is to measure the difference in cross section between $\hat{\theta}$ and $\pi - \hat{\theta}$ with $\hat{\theta} \leq \pi/2$, it is clear that in the s -channel, only $\cos \hat{\theta}$ terms are related to the asymmetry. From Eq. (11), the relevant effects are associated with $g_A^q g_A^t$ and $g_V^q g_V^t g_A^q g_A^t$, in which the former is from the interference between unparticle and SM while the latter is from the contribution of unparticle itself. In both terms, we see clearly the axial-vector couplings are the essential to generate the FBA.

To obtain the hadronic cross section from the parton level, we have to consider the convolution with the parton distribution functions. Thus, the differential cross section at the hadronic level is

$$\frac{d\sigma(p\bar{p} \rightarrow t\bar{t})}{d\cos\theta} = \sum_{ij} \int_{x_2=0}^1 \int_{x_1=0}^1 dx_1 dx_2 f_i(x_1) f_j(x_2) \frac{\partial \hat{\sigma}^{q_i \bar{q}_j \rightarrow t\bar{t}}(\theta, x_1, x_2)}{\partial \cos\theta}, \quad (12)$$

where f_i (f_j) is the parton distribution function of the parton q_i (\bar{q}_j) in the proton (antiproton), the angle θ represents the angle between the three-momentum of the produced t quark and the three-momentum of the proton p (\Leftrightarrow of the quark q) in the lab system (center of mass system of $p\bar{p}$). The sum over (i, j) in Eq. (12) is over all parton pair combinations $q\bar{q} = q_i \bar{q}_j$ for the scattering process $q_i \bar{q}_j \rightarrow t\bar{t}$ ($q_i, q_j = u, d, s$).

In the following, all the unprimed kinematic quantities are in the lab system, and all the “hatted” kinematic quantities are in the center of mass system (CMS) of $q\bar{q}$ (\Leftrightarrow CMS of $t\bar{t}$). Taking into account the relations $p_q = x_1 p_p$ and $p_{\bar{q}} = x_2 p_{\bar{p}}$ in the lab system, considering the four-momentum conservation in the scattering $q\bar{q} \rightarrow t\bar{t}$ in the $q\bar{q}$ CMS, and relating the lab and $q\bar{q}$ CMS quantities via the corresponding boost relations, the following relation can be obtained between the angle θ and its $q\bar{q}$ CMS analog $\hat{\theta} = \hat{\theta}(\theta, x_1, x_2)$:

$$\cos(\hat{\theta}(\theta, x_1, x_2)) = \frac{1}{\beta_t [(x_1 + x_2)^2 - \cos^2\theta (x_1 - x_2)^2]} \left\{ -(x_1^2 - x_2^2) \sin^2\theta + 4 \cos\theta \left[x_1^2 x_2^2 \beta_t^2 - \frac{m_t^2}{s} (x_1 - x_2)^2 \sin^2\theta \right]^{1/2} \right\}, \quad (13)$$

where β_t is the aforementioned quantity involving $\hat{s} = (p_q + p_{\bar{q}})^2 = x_1 x_2 s$

$$\beta_t = \beta_t(x_1 x_2) = \sqrt{1 - \frac{m_t^2}{x_1 x_2 s}}. \quad (14)$$

The relevant independent kinematic quantities in the integration (12) are all lab-related: x_1 , x_2 , and θ . On the other hand, Eq. (13) shows that the $q\bar{q}$ CMS-related angle $\hat{\theta}$ is a function of the aforementioned three independent quantities x_1 , x_2 , and θ . The quantity $\partial \hat{\sigma}^{q\bar{q} \rightarrow t\bar{t}} / \partial \cos\hat{\theta}$ appearing as integrand in Eq. (12) is obtained directly from Eqs. (11) and (13) by applying the derivatives at fixed x_1 and x_2

$$\frac{\partial \hat{\sigma}^{q\bar{q} \rightarrow t\bar{t}}(\theta, x_1, x_2)}{\partial \cos\theta} = \frac{d\hat{\sigma}^{q\bar{q} \rightarrow t\bar{t}}}{d\cos\hat{\theta}} \frac{\partial \cos(\hat{\theta}(\theta, x_1, x_2))}{\partial \cos\theta}, \quad (15)$$

where the partial derivatives $\partial / \partial \cos\theta$ are at fixed x_1 and x_2 .

The total hadronic cross section $\sigma(p\bar{p} \rightarrow t\bar{t})$ and the corresponding forward-backward asymmetry are then obtained by the corresponding integrations of the expression (12) in the lab frame

$$\sigma(p\bar{p} \rightarrow t\bar{t}) = \int_{-1}^1 d\cos\theta \frac{d\sigma(p\bar{p} \rightarrow t\bar{t})}{d\cos\theta}, \quad (16)$$

$$A_{\text{FB}}^{p\bar{p}} = \left(\int_0^1 d\cos\theta \frac{d\sigma(p\bar{p} \rightarrow t\bar{t})}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\sigma(p\bar{p} \rightarrow t\bar{t})}{d\cos\theta} \right) / \sigma(p\bar{p} \rightarrow t\bar{t}). \quad (17)$$

Another physical observable of experimental interest is the invariant mass distribution $d\sigma/dM_{t\bar{t}}$ [32] where $M_{t\bar{t}}^2 = (p_t + p_{\bar{t}})^2 = x_1 x_2 s$

$$\frac{d\sigma(p\bar{p} \rightarrow t\bar{t})}{dM_{t\bar{t}}} = 2 \frac{M_{t\bar{t}}}{s} \int_{M_{t\bar{t}}^2/s}^1 \frac{dx_1}{x_1} \sum_{i,j} f_i(x_1) f_j(x_2) \times \int_{-1}^1 d\cos\theta \frac{\partial \hat{\sigma}^{q_i \bar{q}_j \rightarrow t\bar{t}}(\theta, x_1, x_2)}{\partial \cos\theta} \Big|_{x_2=M_{t\bar{t}}^2/(sx_1)}. \quad (18)$$

The integrations in Eqs. (16)–(18) are performed across the kinematically allowed regions, i.e., such that β_t and $\cos\hat{\theta}$ are real.

After having presented formulas for the three physical observables, we can now numerically investigate the unparticle contributions to top-quark pair production. At first, in order to reduce the number of free parameters, we assume that the colored vector unparticle is flavor blind, i.e. $g_V^t = g_A^t = g_V^q = g_A^q = g$. Then, the remaining unknown parameters appearing in the physical quantities are: $g = \lambda / \Lambda_U^{d_U-1}$, and the scale dimension d_U . This means that in such a case we have only two independent parameters λ and d_U , both dimensionless quantities, and we can fix the scale Λ_U formally to an arbitrary value. We will set it equal to $\Lambda_U = 1$ TeV. We note that, unlike the situation in the axigluon model [8,11] in which $g_A^t = -g_A^q$ is necessary to get the positive sign in FBA, in unparticle physics the flavor-blind and chirality-independent couplings are enough to fit the data.

Further, it is necessary to consider the measurements of at least two of the aforementioned three observables, namely $\sigma(p\bar{p} \rightarrow t\bar{t})$ and $A_{\text{FB}}^{p\bar{p}}$, Eqs. (16)–(17), in order to restrict the area of the parameters λ and d_U . The value of the $t\bar{t}$ production cross section $\sigma(p\bar{p} \rightarrow t\bar{t})$ was measured by the CDF Collaboration [33]

$$\sigma(p\bar{p} \rightarrow t\bar{t})^{\text{exp}} = 7.50 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{th}) \text{ pb} = 7.50 \pm 0.48 \text{ pb}. \quad (19)$$

On the other hand, the SM prediction is $\sigma(p\bar{p} \rightarrow t\bar{t})^{\text{SM}} = 6.73_{-0.79}^{+0.71}$ pb [34], which includes the contributions from the tree-level, the next-to-leading order in α_s , and the next-to-leading in threshold logarithms (LO + NLO + NLL). In the specific case of using the CTEQ6.6 parton distribution functions [35] (which we use), the central value for the SM prediction goes slightly down to $\sigma(p\bar{p} \rightarrow t\bar{t})^{\text{SM}} = 6.61$ pb, Ref. [34] (Cacciari et al., 2008) when the top quark (pole) mass is taken to be $m_t = 175$ GeV.

The other measurement is the aforementioned FBA value Eq. (3). The NLO effects in the QCD SM give nonzero FBA value 0.050 ± 0.015 , Eq. (1). However, in our calculations, the SM amplitude is the tree-level amplitude [rescaled accordingly in order to obtain $\sigma(p\bar{p} \rightarrow t\bar{t})^{\text{SM}} = 6.6$ pb, see below], which gives $A_{\text{FB}}^{p\bar{p}} = 0$. Therefore, we will regard the $A_{\text{FB}}^{p\bar{p}}$ as calculated according to Eq. (17) [using Eqs. (15), (12) and (11)] to be responsible for the deviation of the experimental from the SM FBA value

$$A_{\text{FB}}^t \equiv A_{\text{FB}}^{p\bar{p}}(\text{exp}) - A_{\text{FB}}^{p\bar{p}}(\text{SM}) = 0.143 \pm 0.071, \quad (20)$$

where the uncertainties (± 0.065 , ± 0.024 , ± 0.015) were added in quadrature.

In our calculations we use the CTEQ6.6 parton distribution functions, the value $m_t = 175$ GeV for the t quark (pole) mass, and for the QCD coupling the value $\alpha_s \approx \alpha_s(m_t) \approx 0.11$. With such values, we obtain the tree-level $\sigma(\text{SM}; \text{tree}) \approx 4.85$ pb. We use for the SM amplitude the rescaling factor $\sqrt{1.36}$ in order to obtain $\sigma(\text{SM}) = 6.6$ pb, which is according to Ref. [34] (the second entry: Cacciari et al., 2008) the central value of $\sigma(\text{SM})$ when

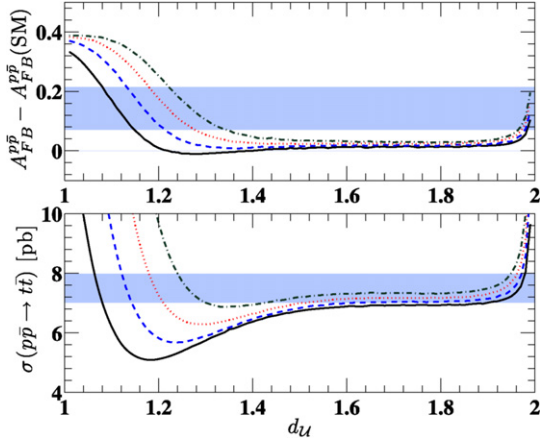


Fig. 1. $t\bar{t}$ production cross section (the lower) and top-quark FBA (the upper figure) as a function of the scale dimension d_U , where the solid, dashed, dotted and dash-dotted lines represents $\lambda = 1.4, 1.6, 1.8, 2.0$, respectively. The band in the plot represents the measured values with 1σ uncertainties.

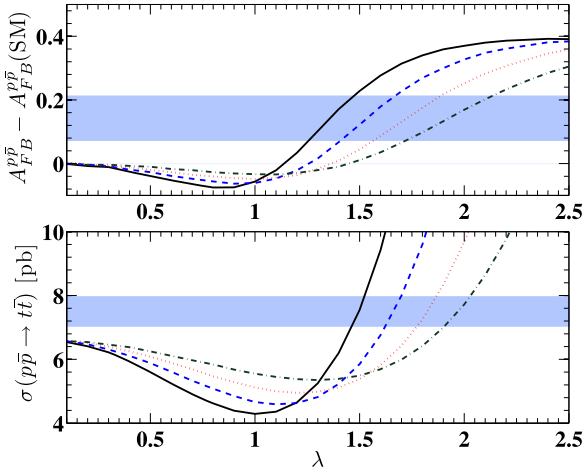


Fig. 2. As Fig. 1, but as a function of the parameter λ . The solid, dashed, dotted and dash-dotted lines represents $d_U = 1.1, 1.15, 1.2, 1.25$, respectively.

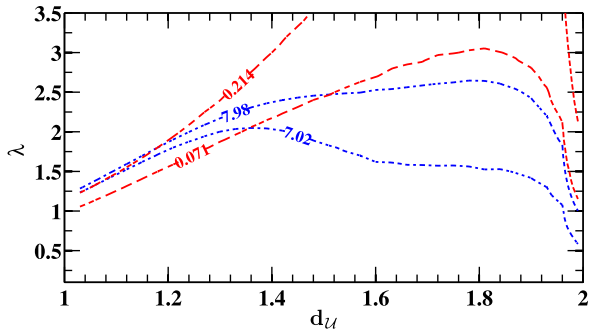


Fig. 3. Contours for $\sigma(p\bar{p} \rightarrow t\bar{t})$ (dotted) and $A_{FB}^{pp} - A_{FB}^{pp}(SM)$ (dashed) as a function of d_U and λ . The numbers in the plot denote the lower and upper bounds of each observable with 1σ uncertainties of the data: $\sigma = 7.50 \pm 0.48$ pb; A_{FB}^{pp} as in Eq. (20).

$m_t = 175$ GeV and CTEQ v6.6 is used for the parton distribution functions.

The physically interesting regime for unparticle physics is $1 < d_U < 2$, and $\lambda \lesssim 10^0$. We calculated A_{FB} , σ and $d\sigma/dM_{t\bar{t}}$, scanning over the parameter regions $0 < \lambda < 3.5$ and $1 < d_U < 2$. The numerical results are presented in Figs. 1–5. We show the

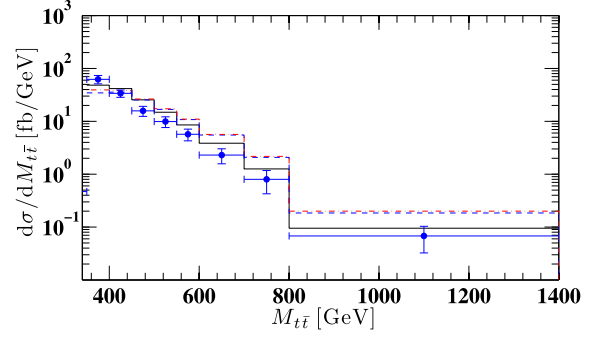


Fig. 4. $d\sigma/dM_{t\bar{t}}$ as a function of invariant mass of top-pair $M_{t\bar{t}}$, where the solid, dash-dotted and dashed lines represent the SM result and colored unparticle with $(\lambda, d_U) = (2.05, 1.28)$ and $(1.70, 1.175)$, respectively. The vertical bars are the data from CDF measurement with an integrated luminosity of 2.5 fb^{-1} , Ref. [32].

$t\bar{t}$ production cross section and $[A_{FB}^{pp} - A_{FB}^{pp}(SM)]$ as a function of d_U (λ) in Figs. 1, 2, where the solid, dashed, dotted and dash-dotted lines represents $\lambda = 1.4, 1.6, 1.8, 2.0$ ($d_U = 1.1, 1.15, 1.2, 1.25$), respectively. Fig. 3 is the central result of our calculations. It shows the region in the d_U - λ parameter plane which simultaneously fulfills the experimental constraints (19) and (20). This region lies between the two dotted and simultaneously between the two dashed lines. The central measured values $\sigma \approx 7.5$ pb and $A_{FB}^{pp}(\text{exp}) - A_{FB}^{pp}(SM) \approx 0.14$ are achieved at $\lambda = 2.05$ and $d_U = 1.28$. In Fig. 3, we scanned over the free parameter space in finite steps $\Delta\lambda = 0.1$ and $\Delta d_U = 0.01$.

In Fig. 4 we present the average values of $d\sigma/dM_{t\bar{t}}$ in eight different $M_{t\bar{t}}$ -intervals (“bins”) as used by the CDF measurement [32]. The presented results are for: (a) the QCD SM case (solid line: $\lambda = 0$; $\sigma(t\bar{t}) = 7.5$ pb); (b) the “central” case (dash-dotted line; $\lambda = 2.05$ and $d_U = 1.28$, giving $\sigma(t\bar{t}) = 7.5$ pb and FBA of Eq. (20) equal 0.14); (c) another, more “marginal” case (dashed line; $\lambda = 1.70$ and $d_U = 1.175$, giving $\sigma(t\bar{t}) = 7.01$ pb and FBA of Eq. (20) equal 0.178). The CDF measurements are the points with vertical lines. All our results (including the QCD SM) are above the CDF measurements, with the exception of the first two bins $M_{t\bar{t}} \leq 450$ GeV. The deviations could plausibly be ascribed to two main uncertainties [36]:

- (i) The chosen scales of renormalization (μ_R) and factorization (μ_F) for which the usual possible values could be taken between $m_t/2$ and $2m_t$. Here we adopted $\mu_R = \mu_F = m_t$.
- (ii) The $M_{t\bar{t}}$ -dependent NLO effects which include the NLO parton distribution function (PDF). Here for simplicity we just use an $M_{t\bar{t}}$ -independent scale factor value of $K = 1.36$ (i.e., the factor $\sqrt{K} = \sqrt{1.36}$ for the tree-level SM amplitude A_{SM}) to fit the $t\bar{t}$ production cross section with LO calculations.

For a detailed analysis of the various uncertainties see Ref. [36]. Nonetheless, most of our results for $d\sigma/dM_{t\bar{t}}$ are at least marginally compatible with the CDF results, within 2σ .

In order to make a more detailed inspection, in Fig. 5 we present the $M_{t\bar{t}}$ -restricted forward–backward asymmetries, i.e., those calculated by the expression (17) where the phase space in the numerator and the denominator is restricted by $M_{t\bar{t}} < M_{t\bar{t}}^{\text{edge}}$ (the quantity $A_{FB}^{t, \text{low}}$) or by $M_{t\bar{t}} > M_{t\bar{t}}^{\text{edge}}$ (the quantity $A_{FB}^{t, \text{high}}$). These asymmetries were calculated for the two aforementioned choices of parameter values (λ, d_U) , and are compared in Fig. 5 with the CDF measured values [37] subtracted by the (LO + NLO + NLL) SM values [38]. This subtraction is needed for comparison

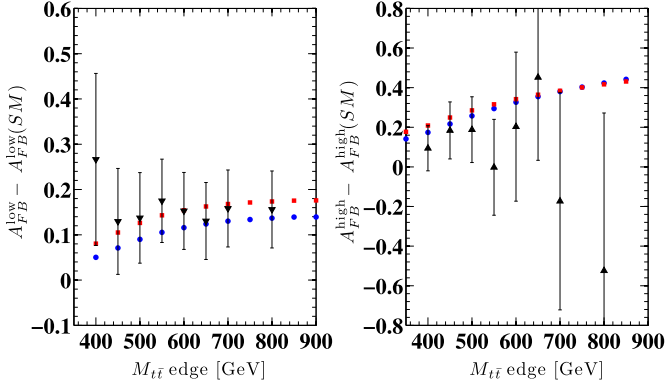


Fig. 5. Restricted forward-backward asymmetries $A_{FB}^{t,low}$ and $A_{FB}^{t,high}$ as functions of the threshold (“edge”) $M_{t\bar{t}}$ values, for $(\lambda, d_{\mathcal{L}}) = (2.05, 1.28)$ (circles) and $(1.70, 1.175)$ (squares). Included are also the corresponding CDF measured values [37] (their 8th and 9th figures) subtracted by the SM values [38], as bars with triangles.

with our results, for the same reason as in the (unrestricted) A_{FB}^t of Eq. (20),

$$A_{FB}^{t,X} = A_{FB}^X(\text{exp}) - A_{FB}^X(\text{SM}) \quad (X = \text{low, high}). \quad (21)$$

We see that the experimental uncertainties are very large, especially for $A_{FB}^{t,high}$ at $M_{t\bar{t}}^{\text{edge}} = 600$ GeV or higher. Nonetheless, the central experimental values appear to suggest the fall of $A_{FB}^{t,high}$ as a function of $M_{t\bar{t}}^{\text{edge}}$ at $M_{t\bar{t}}^{\text{edge}} > 600$ GeV. It is interesting that a model involving axigluon exchange does give such a fall for at least one (benchmark) choice of parameters (with: $g_A^q = -g_A^t$) [11]. On the other hand, our model does not show such a behavior. This issue remains inconclusive because of: (i) the aforementioned very large experimental uncertainties of $A_{FB}^{t,high}$ at high $M_{t\bar{t}}^{\text{edge}}$; (ii) the severely restricted phase space at high $M_{t\bar{t}}^{\text{edge}}$. Namely, our simplified approach of rescaling the tree-level SM (QCD) amplitude by a fixed factor ($\sqrt{K} = \sqrt{1.36}$) for all $M_{t\bar{t}}$ values becomes increasingly unreliable when $M_{t\bar{t}}^{\text{edge}}$ increases in $A_{FB}^{t,high}$, because the phase space becomes so severely restricted.

In conclusion, we investigated whether colored flavor-conserving unparticle physics can explain the measured forward-backward asymmetry value for the $t\bar{t}$ production at the Tevatron; the latter measured value shows 2σ deviation from the QCD SM value. *With a natural assumption of quark flavor-blind and chirality-independent interactions to unparticle*, our calculations indicate that the aforementioned unparticle contributions can explain this deviation. We found an area of the (two-)parameter space of the unparticle physics which gives the results compatible with the measurements of the forward-backward asymmetry and of the total cross section for the $t\bar{t}$ production at the Tevatron. The resulting values of the differential $d\sigma/dM_{t\bar{t}}$ cross section and the $M_{t\bar{t}}$ -restricted forward-backward asymmetries are only marginally compatible with the measured values.

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