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Top quark asymmetries and unparticle physics at the Tevatron and LHC

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Among different measured observables of top-antitop quark pairs at hadron colliders, the forward-backward asymmetry ($A_{\rm FB}$) measured by the CDF and D0 collaborations has inconsistency with the Standard Model prediction. The measured forward-backward asymmetry grows with $t\bar{t}$ invariant mass. Several new physics models have been proposed to explain this deviation. We consider the consistency of the parameter space of vector unparticle (in the flavor-conserving scenario) with the existing $t\bar{t}$ production measurements. In particular, we look at the total cross sections at the LHC and Tevatron, differential cross section with $t\bar{t}$ invariant mass, and the LHC charge asymmetry to identify the regions in parameter space that can give the desired top $A_{\rm FB}$ observed by the Tevatron. We show that, in spite of the intrinsic tension between the LHC charge asymmetry and $A_{\rm FB}$, there exists a small region in the unparticle parameters space where the top $A_{\rm FB}$ and the LHC charge asymmetry are satisfied simultaneously. Finally, we show that the consistent region with $t\bar{t}$ observables is consistent with the constraints coming from the dijet resonance searches.

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I. INTRODUCTION

The top quark, with its mass near the scale of electroweak symmetry breaking, can be more sensitive to new physics at the TeV scale than the other Standard Model (SM) particles. Most of its properties have been examined at the Tevatron and LHC and found to be in agreement with the SM predictions [1,2], except the observed forward-backward asymmetry in top quark pair production ($A_{\rm FB}$) which has about a 2σ deviation from the SM expectation. The forward-backward asymmetry is defined as the difference between the number of top quarks in the froward ($\cos\theta > 0$) and backward ($\cos\theta < 0$) region of the detector:

$$A_{\rm FB} = \frac{N_t(\cos\theta > 0) - N_t(\cos\theta < 0)}{N_t(\cos\theta > 0) + N_t(\cos\theta < 0)}, \qquad (1)$$

where θ is the top quark production angle in the $t\bar{t}$ rest frame. The SM prediction for $A_{\rm FB}$ at loop level is 0.089 [3–6]. While the recent measurements reported by CDF and D0 are $A_{\rm FB} = 0.158 \pm 0.075$ [7,8], $A_{\rm FB} = 0.196 \pm 0.065$ [9]. We note that the observed forward-backward asymmetry increases with the $t\bar{t}$ invariant mass such that it approaches 0.3 for $m_{t\bar{t}} \geq 700$ GeV.

Unlike the top $A_{\rm FB}$, the total $t\bar{t}$ cross section, which has been measured at the Tevatron, is in agreement with the SM prediction [10]. The $t\bar{t}$ differential cross section with the $t\bar{t}$ invariant mass ($d\sigma/dm_{t\bar{t}}$) has been also measured by the CDF Collaboration. The $t\bar{t}$ spectrum has been found to be consistent with the SM expectation including next-to-leading-order (NLO) plus next-to-next-to-leading logarithmic QCD predictions [11]. The measured top pair cross section at the LHC confirms the SM expectation at the next-to-next-to-leading-order (NNLO) QCD prediction [12]. The present measured differential cross section ($d\sigma/dm_{t\bar{t}}$) by the LHC experiments are limited by statistical and systematic uncertainties [13].

It is interesting to note that the $A_{\rm FB}$ vanishes at the LHC because of the symmetric initial state. However, another asymmetry at the LHC ($A_{\rm C}$) can be defined as the relative difference between top pair events with $|y_t| > |y_{\bar{t}}|$ and the events with $|y_t| < |y_{\bar{t}}|$:

$$A_C = \frac{N_t(|y_t| > |y_{\bar{t}}|) - N_t(|y_t| < |y_{\bar{t}}|)}{N_t(|y_t| > |y_{\bar{t}}|) + N_t(|y_t| < |y_{\bar{t}}|)}. \qquad (2)$$

At the LHC, the top quarks produced in the quark-antiquark annihilation process are statistically more boosted to the beam direction in comparison with the antitop quark. This is because of the fact that the top quark prefers to fly in the direction of the incident quark which carries a larger longitudinal momentum. As a consequence, a charge asymmetry as described above is generated. The ATLAS and CMS measurements for the charge asymmetry are $A_{\rm C} = -0.018 \pm 0.036$ [14], $A_{\rm C} = 0.004 \pm 0.015$ [15], and the SM prediction is $A_{\rm C} = 0.0115$ [6]. Within the uncertainties, the Standard Model prediction is in agreement with the measured values by the LHC experiments. The charge asymmetry has been measured in various $m_{t\bar{t}}$ bins by ATLAS and CMS experiments but with large uncertainties; therefore, we use the inclusive measured charge asymmetry in our analysis.

It is notable that some of the SM extensions proposed to explain the Tevatron $A_{\rm FB}$ also predict sizeable charge asymmetry at the LHC [16–19]. Therefore, in those models, there exists a tension between the top forward-backward asymmetry at the Tevatron and LHC charge asymmetry. From another side, the LHC charge asymmetry measurement is consistent with the SM expectation;

consequently, the models which predict also enhancement in A_C are disfavored. For example, it has been shown that in the W' and Z' models, there is a tight correlation between A_{FB} and A_C. Therefore, these models are not able to explain the charge asymmetry and A_{FB} at the same time [18,20–22]. In Ref. [23], the effective Lagrangian approach has been utilized to explain the A_{FB}. In this approach, an enhancement in A_C is also expected, in particular, at the large $t\bar{t}$ invariant mass region. It has been shown in Ref. [20] that there is an apparent tension between the forward-backward asymmetry and the charge asymmetry in the axigluon model, but there exists an allowed region compatible with both A_{FB} and A_C.

It seems difficult to develop a model that can produce large A_{FB} deviated from the SM prediction according to the Tevatron measurement, but A_C is consistent with the SM value. There are studies on this issue, which, for example, can be found in Refs. [18,19].

In this work, we study the effects of color singlet vector unparticles [24,25] on the forward-backward asymmetry and charge asymmetry at the Tevatron and LHC, respectively. We investigate the tension between A_C and A_{FB} and perform a full scan on the main unparticle parameter space. In constraining the unparticle parameters, we combine A_{FB} ($m_{t\bar{t}}$ dependent), σ_{LHC}, and σ_{TeV} into a global χ^2 fit to obtain a 68% C.L. region. We also require that the resulting region is consistent with the constraints coming from the dijet resonance searches. The organization of this letter is as follows. The next section is devoted to unparticle physics and its effect on the top prodution rate. In Sec. III, we show our numerical calculations and discuss the results. Finally, conclusions are presented in Sec. IV.

II. INFLUENCE OF THE UNPARTICLE ON TOP PAIR PRODUCTION

The effects of the unparticle on top properties at hadron colliders have been intensively studied in the literature [26–33]. Also, there are some papers in which the top A_{FB} at the Tevatron has been studied. In Ref. [34], the authors have found the regions of parameters where a colored vector unparticle can produce the values of top A_{FB} and the top pair cross sections compatible with the Tevatron measurements. In Ref. [35], the influence of a vector and tensor unparticle, including color, on top pair cross section and the forward-backward asymmetry has been investigated. However, in these studies, the impact of the unparticle on the LHC charge asymmetry and any possible tension with A_{FB} has not been studied.

Effective interaction of a vector unparticle with SM fields is given as follows [36]:

$$\lambda_1 \frac{1}{\Lambda^{d_{\mathcal{U}}-1}} c_v \bar{f}\gamma_\mu f O^\mu_{\mathcal{U}}, \quad \lambda_1 \frac{1}{\Lambda^{d_{\mathcal{U}}-1}} c_a \bar{f}\gamma_\mu \gamma_5 f O^\mu_{\mathcal{U}}, \qquad (3)$$

where λ_1 is dimensionless effective couplings labeling a vector unparticle operator. The coefficients c_v, c_a represent vector and axial vector couplings of a vector unparticle, respectively. The parameter $d_{\mathcal{U}}$ is the scaling dimension of the unparticle operators, and Λ denotes the effective mass scale above which the unparticle is formed.

Within the SM at hadron colliders, $t\bar{t}$ pairs are produced either via quark-antiquark annihilation or through gluon-gluon fusion. With considering new interactions of a vector unparticle with SM fields, only the partonic cross section for $t\bar{t}$ production via quark-antiquark annihilation is modified because a vector unparticle only interacts with fermionic fields, and it does not couple to gluons. The parton level differential cross section for the process of $q\bar{q} \to t\bar{t}$ at leading order in the presence of a color singlet vector unparticle is as follows [26]:

$$\begin{aligned} \frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}\to t\bar{t}) &= \frac{A_V^2}{8\pi\hat{s}^2(\hat{s})^{4-2d_{\mathcal{U}}}}[c_a^4(2m^4 - 4(\hat{s}+\hat{t})m^2 + (\hat{s}+\hat{t})^2 + \hat{t}^2) \\ &\quad + c_v^4(2m^4 - 4\hat{t}m^2 + (\hat{s}+\hat{t})^2 + \hat{t}^2) \\ &\quad + 2c_v^2c_a^2(2m^4 - 2(3\hat{s}+2\hat{t})m^2 + 3\hat{s}^2 + 2\hat{t}^2 + 6\hat{s}\hat{t})] \\ &\quad + \frac{d\sigma^0_{q\bar{q}}}{d\hat{t}}, \end{aligned} \qquad (4)$$

where

$$\begin{aligned} A_V &= \frac{\lambda_1^2 A_{d_{\mathcal{U}}}}{2\sin(d_{\mathcal{U}}\pi)\Lambda^{2(d_{\mathcal{U}}-1)}}, \\ A_{d_{\mathcal{U}}} &= \frac{16\pi^2\sqrt{\pi}}{(2\pi)^{2d_U}} \frac{\Gamma(d_{\mathcal{U}}+\frac{1}{2})}{\Gamma(d_{\mathcal{U}}-1)\Gamma(2d_{\mathcal{U}})}. \end{aligned} \qquad (5)$$

In the cross sections relation, $\frac{d\sigma^0_{q\bar{q}}}{d\hat{t}}$ is the SM contribution.

In Eq. (4), for the case that $c_v = 1$ is corresponding to a vector unparticle, $c_v = c_a = 1$ is corresponding to a vector unparticle with right-handed coupling to the SM fields, and $c_v = -c_a = 1$ presents the vector unparticle with left-handed coupling. According to Eq. (4), the cross section is similar in both cases with $c_v = c_a = 1$ and $c_v = -c_a = 1$. Therefore, the $t\bar{t}$ cross section and forward-backward asymmetry in this scenario are chirality independent or blind to left-hand or right-handed couplings.

III. NUMERICAL RESULTS AND DISCUSSION

In the numerical calculations, the top quark mass has been set to $m_t = 173$ GeV. All cross sections at the partonic level are calculated by employing CTEQ6 parton distribution functions [37]. The calculation is performed at the fixed renormalization and factorization scale $\mu_R = \mu_F = m_t$. We present our numerical result at the Tevatron with $\sqrt{s} = 1.96$ TeV and at the LHC with $\sqrt{s} = 7$ TeV. Indeed, the cross sections that we get from the calculations are the leading-order values. Therefore, we scale the tree-level calculation by a k factor of 1.3 so that the leading-order calculations match with the higher-order

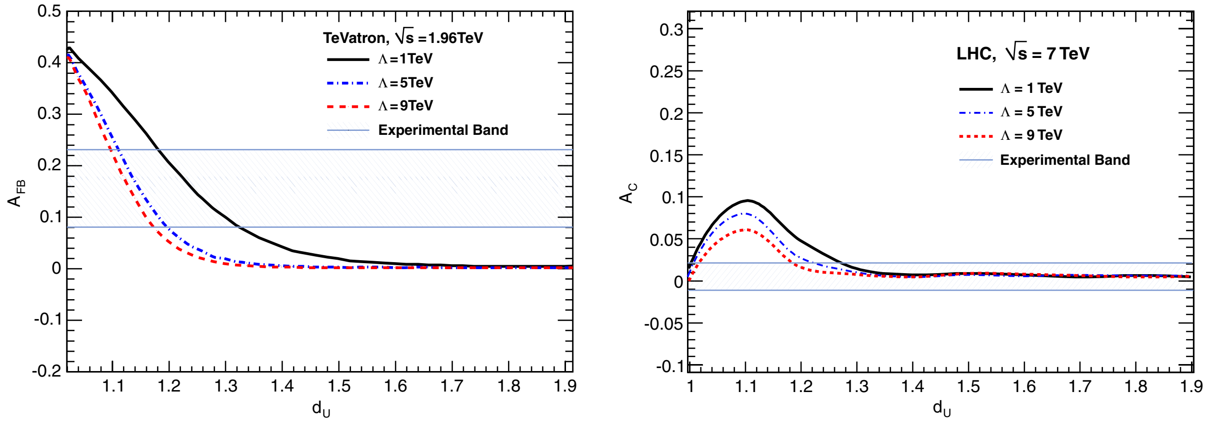

FIG. 1 (color online). Left: The forward-backward asymmetry ($A_{\rm FB}$) in top pair production generated by a vector unparticle for $\lambda_1 = 1$ and $c_a = c_v = 1$ and various values of Λ. The shaded region is the band measured by the CDF experiment. Right: The charge asymmetry at the LHC with the same parameters as the $A_{\rm FB}$ plot and different values of Λ.

results for the case of $m_t = 173\ {\rm GeV}/c^2$. This k factor is introduced so that the tree-level SM result after applying the k factor gives the SM higher-order results. The NNLO cross section of top pair production at the Tevatron is 7.08 and 163 pb at the LHC with the center-of-mass energy of 7 TeV [38].

As we mentioned before, the results are chirality independent, and the right-handed and left-handed unparticle couplings to the SM fields give similar cross sections and asymmetries in top pair events. In the case of having a pure vector unparticle, i.e., $c_v = 1$ and $c_a = 0$, we saw that negligible forward-backward asymmetry is produced, which cannot compensate the observed value by Tevatron experiments.

First, we present asymmetries in terms of $d_{\mathcal{U}}$ for three various values of Λ and consider $\lambda_1 = 1$ and $c_a = c_v = 1$. Then, we identify an allowed region in the $d_{\mathcal{U}}$, Λ plane by combining $A_{\rm FB}$ (taking into account data in various $t\bar{t}$ invariant mass bins), charge asymmetry ($A_{\rm C}$), $\sigma_{\rm LHC}$, and $\sigma_{\rm TeV}$ into a global χ^2 fit. We concentrate on the values of unparticle parameters which are physically interesting, i.e., $1 < d_{\mathcal{U}} < 2$ and Λ at the order of few TeV [39].

The forward-backward asymmetry at the Tevatron and the charge asymmetry at the LHC are shown in Fig. 1. The shaded area is according to the present experimental measurement. As it can be seen, for a specific value of $d_{\mathcal{U}}$, the forward-backward asymmetry grows when Λ decreases, i.e., the unparticle can produce larger asymmetry by assuming small values of Λ. Note that for larger values of Λ, the allowed interval of the $d_{\mathcal{U}}$ parameter that can produce desirable forward-backward asymmetry becomes smaller. According to Fig. 1, at $\Lambda = 1$ TeV, the unparticle with any value of $d_{\mathcal{U}}$ in the range of 1.2 to 1.32 can generate the desired $A_{\rm FB}$. It is interesting to note that behavior of $A_{\rm FB}$ in terms of $d_{\mathcal{U}}$ in the color-singlet scenario is similar to the color-octet case [34], while in the color-octet case, there is an additional term contributing to $A_{\rm FB}$ coming from the interference between the unparticle and SM. In addition to the shape, for the set of parameters taken in Ref. [34], even the size of $A_{\rm FB}$ is comparable with the color-singlet scenario.

The charge asymmetry $A_{\rm C}$ increases with increasing $d_{\mathcal{U}}$, reaches a maximum value at $d_{\mathcal{U}} = 1.1$, and then it decreases and tends to the SM expectation at the tail of $d_{\mathcal{U}}$. The peak position does not move for various values of Λ. The shaded region is according to the CMS measurement. For example, when $\Lambda = 1$ TeV, the unparticle with $d_{\mathcal{U}} \leq 1.28$ is excluded. For larger values of Λ, the exclusions interval is smaller.

In Fig. 2, we present the allowed regions in the plane of $(d_{\mathcal{U}}, \Lambda)$ which satisfy the measured forward-backward asymmetry by the Tevatron and LHC charge asymmetry. The combination of limits from $A_{\rm C}$ and the allowed band for $A_{\rm FB}$ lead to a very small allowed interval of 1.27 to 1.3

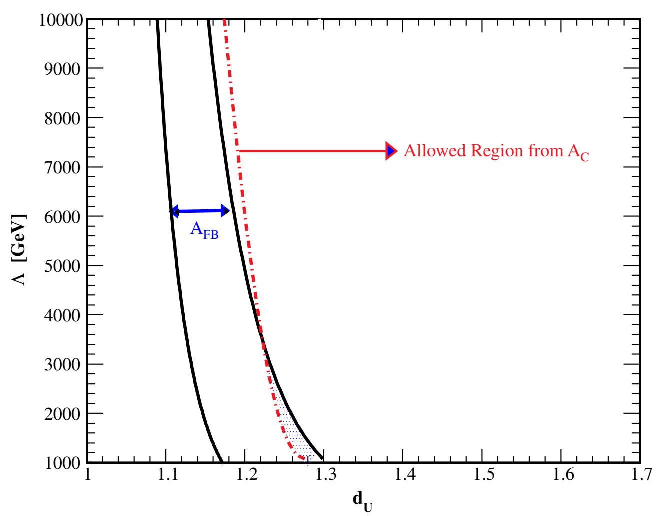

FIG. 2 (color online). Region of Λ (in GeV) in terms of $d_{\mathcal{U}}$ consistent with Tevatron measurements of the $t\bar{t}$ forward-backward asymmetry (region between two solid black curves). The consistent region with the LHC charge asymmetry is the area in the right side of the dotted-dashed red curve.

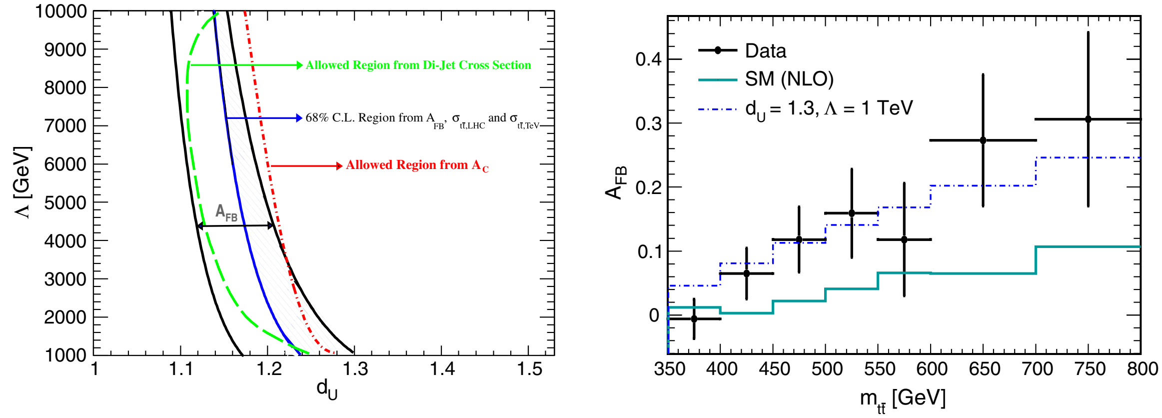

FIG. 3 (color online). Left: The 68% C.L. region of Λ (in GeV) in terms of $d_{\mathcal{U}}$ consistent with the Tevatron measurement of $A_{\rm FB}$, $\sigma_{\rm TeV}$, $\sigma_{\rm LHC}$. The right side of the dashed green curve is consistent with the dijet cross section measured by CDF. Right: The Tevatron $A_{\rm FB}$ versus top pair invariant mass.

for $d_{\mathcal{U}}$ at the value of $\Lambda = 1$ TeV. As it can be seen from Fig. 2, charge asymmetry excludes a large part of the parameter space which could explain the Tevatron forward-backward asymmetry. For any value of Λ above 3400 GeV, the LHC charge asymmetry excludes the points in $(d_{\mathcal{U}}, \Lambda)$, which are consistent with the measured forward-backward asymmetry. According to Fig. 2, there is an apparent tension between the forward-backward asymmetry and charge asymmetry for this model. We note that this tension gets tighter for large values of Λ.

Now, we combine the observables $A_{\rm FB}$ (considering the available measured values in all bins of $m_{t\bar{t}}$), $\sigma_{\rm LHC}$, and $\sigma_{\rm TeV}$ into a global χ^2 fit to obtain the 68% C.L region. The results of the global χ^2 fit together with the constraints arising from dijet resonance searches are presented in Fig. 3 (left). As it can be seen, the inclusion of $t\bar{t}$ cross sections reduces the consistent region with $A_{\rm FB}$, and the charge asymmetry reduces the allowed region significantly. Unparticles can contribute to the production of dijet at the Tevatron and LHC [40]. We studied the dijet production at the parton level in the unparticle model and compared the results with the dijet invariant mass spectra measured by the CDF experiment at the Tevatron [41]. The allowed region is depicted in Fig. 3 (left) in the right side of the green dashed curve. We observe that the dijet constraints reduce the region where $A_{\rm FB}$ could be generated according to the Tevatron measurements. We note that when we move toward the large values of Λ, the allowed area in the parameter space that can produce the desired forward-backward asymmetry gets smaller. For any valid value of $d_{\mathcal{U}}$, the dijet analysis excludes the region of Λ above 10 TeV. However, the LHC charge asymmetry provides stronger constraints than the top pair cross section and the limits from the dijet spectrum.

The CDF experiment has measured the forward-backward asymmetry $A_{\rm FB}$ in different $t\bar{t}$ invariant mass bins. In Fig. 3 (right), $A_{\rm FB}$ is presented including data, the NLO SM prediction, and the unparticle expectation with $d_{\mathcal{U}} = 1.3$, $\Lambda = 1$ TeV. We note that $d_{\mathcal{U}} = 1.3$ is the best-fit point for $\Lambda = 1$ TeV. Except for the first invariant mass bin ($m_{t\bar{t}} \in (350, 400)$), for which the unparticle has predicted larger forward backward asymmetry than the experimental measurement, other bins show consistency with the measurements. However, our results are compatible with the measurements within 1σ.

IV. CONCLUSIONS

New physics models that have been proposed to explain the observed Tevatron forward-backward asymmetry are expected to affect the $t\bar{t}$ observables at the Tevatron and LHC. Therefore, the new measurements are able to constrain the parameter space of the new models or discard the models. In this paper, we have performed an analysis to address the observed forward-backward asymmetry of the top at the Tevatron considering the color singlet vector unparticles. We have examined the essential observables of the model at the Tevatron and LHC including the total cross sections, the LHC charge asymmetry, the $t\bar{t}$ invariant mass distribution, and dijet invariant mass spectra. In spite of the significant tension between the reported forward-backward asymmetry of the top at the Tevatron with other experimental measurements, we have found a small region in the space of parameters of the color singlet vector unparticle that can reproduce the $A_{\rm FB}$. We have also found that there is a strong tension between the LHC charge asymmetry and the Tevatron forward-backward asymmetry. It has been shown that the data from dijet resonance searches reduces the parameter space where the $A_{\rm FB}$ can be generated according to the Tevatron observation. In particular, for any value of $d_{\mathcal{U}}$, dijet data excludes unparticles with $\Lambda >$ 10 TeV, which have been compatible with $t\bar{t}$ observables.

Note added.—While this analysis was being completed, a related work appeared in Ref. [35].

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