Top Quark Asymmetries and Unparticle Physics at the Tevatron and LHC

Sara Khatibi and Mojtaba Mohammadi Najafabadi

School of Particles and Accelerators,
Institute for Research in Fundamental Sciences (IPM)
P.O. Box 19395-5531, Tehran, Iran

Abstract

Among different measured observables of top-antitop quark pairs at hadron colliders, the forward-backward asymmetry ($A_{FB}$) 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 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 $A_{FB}$ observed by the Tevatron. We show that in spite of the intrinsic tension between the LHC charge asymmetry and $A_{FB}$, there exists a region in the unparticle parameters space where the top $A_{FB}$ 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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1 Introduction

Top quark, with its mass near to the scale of electroweak symmetry breaking can be more sensitive to new physics at 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 ($A_{FB}$) which has about 2$\sigma$ deviation from the SM expectation. The forward-backward asymmetry ($A_{FB}$) is defined as the difference between the number of top quark in the forward ($\cos \theta > 0$) and backward ($\cos \theta < 0$) region of the detector:

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

Where $\theta$ is the top quark production angle in the $t\bar{t}$ rest frame. The SM prediction for $A_{FB}$ at loop level is 0.089 \[3\], \[4\], \[5\], \[6\]. While the recent measurements reported by CDF and D0 are $A_{FB} = 0.158 \pm 0.075$ \[7\], \[8\], $A_{FB} = 0.196 \pm 0.065$ \[9\]. 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 $A_{FB}$, the total $t\bar{t}$ cross section which has been measured in 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 NLO+NNLL QCD predictions \[11\]. The measured top pair cross section at the LHC confirms the SM expectation at the 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 $A_{FB}$ vanishes at the LHC because of the symmetric initial state. However, another asymmetry at the LHC ($A_{C}$) can be defined as the relative difference between top pair events with $|y_t| > |y_{\bar{t}}|$ and the events with $|y_t| < |y_{\bar{t}}|$:  

$$A_{C} = \frac{N_t(|y_t| > |y_{\bar{t}}|) - N_t(|y_t| < |y_{\bar{t}}|)}{N_t(|y_t| > |y_{\bar{t}}|) + N_t(|y_t| < |y_{\bar{t}}|)} \tag{2}$$

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: $A_C = -0.018 \pm 0.036$ [14], $A_C = 0.004 \pm 0.015$ [15], and the SM prediction is $A_C = 0.0115$ [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 $A_{FB}$ also predict sizeable charge asymmetry at the LHC [16], [17], [18], [19]. Therefore, in those models there exists a tension between the top forward-backward asymmetry at Tevatron and the 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], [21], [22]. In [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 large $t\bar{t}$ invariant mass region. It has been shown in [20] that there is an apparent tension between the forward-backward asymmetry and the charge asymmetry in 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 Tevatron measurement but $A_C$ is consistent with the SM value. There are studies on this issue which for example can be found in [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 Tevatron and LHC, respectively. We investigate the tension between $A_C$ and $A_{FB}$ and perform a full scan on the main unparticle parameters space. In constraining the unparticle parameters we combine $A_{FB}$ ($m_{t\bar{t}}$ dependent), $\sigma_{LHC}$, and $\sigma_{Tev}$ into a global $\chi^2$ fit to obtain 68% C.L. region. We also require that the resulting region to be consistent with the constraints coming from the dijet resonance searches. The organization of this letter is as follows. Next section is devoted to unparticle physics and its effect on top production rate. In section 3, we show our numerical calculations and discuss the results. Finally,
conclusions are presented in section 4.

2 Influence of unparticle on top pair production

The effects of unparticle on top properties at hadron colliders have been intensively studied in the literatures [26], [27], [28], [29], [30], [31], [32], [33]. Also, there are some papers in which the top $A_{FB}$ at the Tevatron has been studied. In [34], the authors have found the regions of parameters where colored vector unparticle can produce the values of top $A_{FB}$ and the top pair cross sections compatible with the Tevatron measurements. In [35], the influence of 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 unparticle on the LHC charge asymmetry and any possible tension with $A_{FB}$ have not been investigated.

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

$$
\lambda_1 \frac{1}{\Lambda d_{U}} c_v \bar{f} \gamma_{\mu} f O_{U}^{\mu}, \quad \lambda_1 \frac{1}{\Lambda d_{A}} c_a \bar{f} \gamma_{\mu} \gamma_{5} f O_{A}^{\mu}
$$

(3)

Where $\lambda_1$ is dimensionless effective couplings labeling vector unparticle operator. The coefficients $c_v, c_a$ represent vector and axial vector couplings of vector unparticle, respectively. The parameter $d_{U}$ is the scaling dimension of the unparticle operators and $\Lambda$ denotes the effective mass scale above which 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 vector unparticle with SM fields, only the partonic cross section for $t\bar{t}$ production via quark-antiquark annihilation is modified, because vector unparticle only interacts with fermionic fields and it does not couple to gluons. The parton level differential cross section for the process of $q\bar{q} \rightarrow t\bar{t}$ at leading order in the presence of color singlet vector unparticle is as follows [26]:

$$
\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q} \rightarrow t\bar{t}) = \frac{A_{V}^2}{8\pi\hat{s}_{U}^{2}(\hat{s})^{4-2d_{U}}} \left[ c_{v}^{4}(2m^{4} - 4(\hat{s} + \hat{t})m^{2} + (\hat{s} + \hat{t})^{2} + \hat{t}^{2}) \right. \\
+ c_{v}^{4}(2m^{4} - 4\hat{t}m^{2} + (\hat{s} + \hat{t})^{2} + \hat{t}^{2}) \\
+ 2c_{v}^{2}c_{a}^{2}(2m^{4} - 2(3\hat{s} + 2\hat{t})m^{2} + 3\hat{s}^{2} + 2\hat{t}^{2} + 6\hat{s}\hat{t}) \\
\left. + \frac{d\sigma^{0}_{q\bar{q}}}{d\hat{t}} \right],
$$

(4)
where

\[ A_V = \frac{\lambda_1^2 A_{d\ell}}{2 \sin(d\ell \pi) \Lambda^{2(d\ell - 1)}} \quad A_{d\ell} = \frac{16 \pi^2 \sqrt{\pi}}{(2\pi)^{2d\ell}} \frac{\Gamma(d\ell + \frac{1}{2})}{\Gamma(d\ell - 1) \Gamma(2d\ell)}. \quad (5) \]

In the cross sections relation, \( \frac{d\sigma}{dt} \) is the SM contribution.

In Eq.4 for the case that \( c_v = 1 \) is corresponding to vector unparticle, \( c_v = c_a = 1 \) is corresponding to 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.

**3 Numerical Results and Discussion**

In the numerical calculations, the top quark mass has been set \( m_t = 173 \text{ GeV} \). All cross sections at the partonic level is calculated by employing CTEQ6 parton distribution functions \([37]\). The calculation is performed at fixed renormalization and factorization scale \( \mu_R = \mu_F = m_t \).

We present our numerical result at Tevatron with \( \sqrt{s} = 1.96 \text{ TeV} \) and at LHC with \( \sqrt{s} = 7 \text{ TeV} \). 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 results for the case of \( m_t = 173 \text{ GeV/c}^2 \). This \( k \)-factor is introduced so that the tree level SM result after applying \( k \)-factor gives the SM higher order results. The NNLO cross section of top pair production at Tevatron is 7.08 pb 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 pure vector unparticle i.e. \( c_v = 1 \) and \( c_a = 0 \), we saw that negligible forward-backward asymmetry is produced which can not compensate the observed value by Tevatron experiments.

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

The forward-backward asymmetry ($A_{FB}$) at 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 $d_U$ the forward-backward asymmetry grows when $\Lambda$ decreases, i.e. unparticle can produce larger asymmetry by assuming small values of $\Lambda$. Note that for larger values of $\Lambda$, the allowed interval of $d_U$ parameter that can produce desirable forward-backward asymmetry becomes smaller. According to Fig. 1 at $\Lambda = 1$ TeV, unparticle with any value of $d_U$ in the range of 1.2 to 1.32 can generate the desired $A_{FB}$.

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

In Fig. 2 we present the allowed regions in the plane of $(d_U, \Lambda)$ which satisfy the measured forward-backward asymmetry by Tevatron and the LHC charge asymmetry. The combination of limits from $A_C$ and the allowed band for $A_{FB}$ leads to a very small allowed interval of 1.27 to 1.3 for $d_U$ at the value of $\Lambda = 1$ TeV. As it can be seen from Fig. 2 charge asymmetry excludes a large
Figure 2: Region of $\Lambda$ (in GeV) in terms of $d_U$ 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.

part of the parameter spaces which could explain the Tevatron forward-backward asymmetry. For any value of $\Lambda$ above 3400 GeV, the LHC charge asymmetry excludes the points in $(d_U, \Lambda)$ 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 $\Lambda$.

It has been shown that there is an intrinsic tension between the observed large positive forward-backward asymmetry by Tevatron and the LHC measurement of charge asymmetry [20]. The relation between the Tevatron $A_{FB}$ and the LHC charge asymmetry $A_C$ is model dependent. Models like $W', Z'$ can generate the desired forward-backward asymmetry but the LHC charge asymmetry disfavors the regions where $A_{FB}$ is generated according to the Tevatron measurements. In contrary, there can be found models such as axigluon which can produce all related observables according to the Tevatron and LHC measurements.

Now we combine the observables $A_{FB}$ (considering the available measured values in all bins of $m_{t\bar{t}}$), $\sigma_{LHC}$, and $\sigma_{TeV}$ into a global $\chi^2$ fit to obtain 68% C.L region. The results of the global $\chi^2$ fit together with the constraints arising from dijet resonance searches are presented in Fig.3.
Unparticles can contribute to the production of dijet at the Tevatron and LHC. We studied the dijet production at parton level in unparticle model and compared the results with the dijet invariant mass spectra measured by the CDF experiment at the Tevatron. 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 $A_{FB}$ could be generated according to the Tevatron measurements. We note that when we move toward the large values of $\Lambda$, the allowed area in the parameter space which can produce the desired forward-backward asymmetry gets smaller. For any valid value of $d_U$, the dijet analysis excludes the region of $\Lambda$ above 10 TeV.

The CDF experiment has measured the forward-backward asymmetry $A_{FB}$ in different $t\bar{t}$ invariant mass bins. In Fig. 3 (right), $A_{FB}$ is presented including data, the NLO SM prediction, and the unparticle expectation with $d_U = 1.3, \Lambda = 1$ TeV. We note that $d_U = 1.3$ is the best fitted point for $\Lambda = 1$ TeV. Except for the first invariant mass bin ($m_{t\bar{t}} \in (350, 400)$) that 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 $1\sigma$.

4 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 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 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 which can reproduce the $A_{FB}$ without being in tight conflict with other $t\bar{t}$ measurements. It has been shown that the data from dijet resonance searches reduces the parameter space where the $A_{FB}$ can be generated according to the Tevatron observation. In particular, for any value of $d_U$, 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 [35].

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