Impact of Torsion Space-Time on $t\bar{t}$ observables at Hadron Colliders

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Abstract

Starting from the effective torsion space-time model, we study its effects on the top pair production cross section at hadron colliders. We also study the effect of this model on top pair asymmetries at the Tevatron and the LHC. We find that torsion space-time can explain forward-backward asymmetry according to measured anomaly at Tevatron. We find an allowed region in the parameters space which can satisfy simultaneously all $t\bar{t}$ observables measured at Tevatron and LHC.

1 Introduction

Top quark physics is one of the most promising probe of beyond Standard model (SM) since top quark is the heaviest known particle and is copiously produced at hadron colliders. A very large number of top quarks are produced at the LHC eventually more than $10^7$ $t\bar{t}$ pairs per year [1]. Moreover, due to the large mass of the top quark which is at the order of the electroweak symmetry breaking, its lifetime is very short. This feature causes that it decays before hadronization and provide an opportunity to explore precision test of the SM and its various properties like charge, mass and spin.

Experimental results for the cross section of top pair at Tevatron and LHC are well consistent with the SM prediction. Another important measurement for top quark production is top Forward-Backward Asymmetry
(FBA) at Tevatron. The CDF and D0 collaborations reported sizable measurement difference with SM prediction [2,3] for FBA. Actually, this observation at Fermilab Tevatron may already be a hint of new physics. In the SM, top pair production can be produced via the $q\bar{q}$ annihilation and $gg$-fusion. The interference between radiative corrections involving gluon emission and also the interference of leading order diagram with box diagrams lead to FBA in the top pair production [4].

Since the initial state of proton-proton collisions at the LHC is symmetric, FBA is not observed but another asymmetry can be observed (Charge Asymmetry) [4]. Charge Asymmetry (CA) at the LHC is defined as the difference between events with positive and negative absolute values of rapidities of top and antitop quarks. The CMS collaboration has recently presented CA measurement in $t\bar{t}$ production at the LHC for the center-of-mass energy of 7 TeV and 1.09 fb$^{-1}$ of data. This measurement is well consistent with the SM prediction. Nevertheless, the measurement of CA at LHC can provide an independent criterion to search for NP models which explain FBA at Tevatron. It seems difficult to explain the size and nature of FBA by any new extension of SM. Because experimental constraint from Tevatron and LHC on parameters space of these theories, must be simultaneously satisfied and there seems to be a correlation between Tevatron FBA and LHC CA.

Despite the impressive success of SM, common point of view is that SM can not play the role of fundamental theory because at least it does not include quantum gravity. Therefore, desired fundamental theory is expected to provide the solution to the quantum gravity and maybe even explain the low energy observables. Traces of such fundamental theories could be identified by some additional characteristics of the space-time, different from the SM fields. Space-time torsion is one of the candidates which can play this role. So far, the effect of torsion space-time on low-energy experiment
have been studied in the literature [5].

In order to explain the measured FBA, many extensions of SM have been proposed. Some of these models propose unknown heavy particles which can be exchanged in top pair production process [6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. In this paper, taking into account the possibility of torsion field effect on top pair production at hadron colliders and the consistency of this theory with all observables specially with FBA is studied.

The rest of this paper is organized as follows: In the next section, we introduce effective approach to torsion and study effect of torsion field on top pair production at hadron colliders. In section 3, we summarize observables which we study at the LHC and Tevatron and study the effects of torsion field exchange in production of $t\bar{t}$ at Tevatron and LHC. We also calculate torsion effect on forward-backward top pair asymmetry at Tevatron and charge asymmetry at the LHC. This enables us to put the constraint on parameters space of torsion extension the SM by using the present experimental measurements. The conclusions are given in section 4.

2 The space-time Torion and its phenomenological aspects

In this section, we briefly review notation of the gravity with torsion and quantum theory of matter fields in the external torsion field. In the following, we study the effects of torsion space-time on our observable specially top pair production at Tevatron and LHC.

In the theory with torsion field, $T^\alpha_{\beta\gamma}$ is defined as follows [16]:

$$T^\alpha_{\beta\gamma} = \Gamma^\alpha_{\beta\gamma} - \Gamma^\alpha_{\gamma\beta},$$  \hspace{1cm} (1)

where $\Gamma^\alpha_{\beta\gamma}$ are the christopher symbols. In general case the torsion field can be presented in the irreducible components [17]

$$T_{\alpha\beta\gamma} = \frac{1}{3} T_{\beta} g_{\alpha\gamma} - T_{\gamma} g_{\alpha\beta} - \frac{1}{6} \epsilon_{\alpha\beta\gamma\delta} S^\delta + q_{\alpha\beta\gamma},$$  \hspace{1cm} (2)
where the axial vector \( S^\delta = \varepsilon^{\alpha\beta\gamma\delta} T_{\alpha\beta\gamma} \), \( T_\alpha \) is a vector trace of torsion and \( q_{\alpha\beta\gamma} \) is a tensor which satisfies the constraints \( q^\alpha_{\beta\alpha} = 0 \) and \( q_{\alpha\beta\gamma} \varepsilon^{\alpha\beta\gamma\delta} = 0 \).

In this paper, we calculate the contribution of exchange of torsion field to top pair production at hadron colliders. Let us now consider the interaction of Dirac spinor \( \psi \) as external gravitational field with torsion which has the following form:

\[
S_f = \int d^4x \sqrt{g} \{ \bar{\psi}^\gamma \mu (\nabla_\mu - i\eta_1 \gamma^5 S_\mu + i\eta_2 T_\mu) \psi - m\bar{\psi}\psi \},
\]

where \( \eta_1 \) and \( \eta_2 \) are non-minimal parameters and \( \nabla_\mu \) is Riemannian covariant derivative without torsion. For special case of minimal coupling this expression corresponds to the values \( \eta_1 = -1/8 \) and \( \eta_2 = 0 \). It is shown in [18] that for a fixed non-zero value of \( \eta_1 \), this action is not renormalizable while the zero value for \( \eta_2 \) does not imply any difficulties. In this paper, we consider \( \eta_1 \) as an arbitrary parameter and take \( \eta_2 = 0 \). Therefore, the interaction between a Dirac field, with torsion is described by following action:

\[
S_{TS-matter} = i \int d^4x \sqrt{g} \{ \bar{\psi}^\gamma \mu (\gamma_\alpha \nabla_\alpha + i\eta_1 \gamma^5 S_\mu - im) \psi \},
\]

where \( \eta_1 \) is the non-minimal interaction parameter for corresponding spinor. Notice that this action corresponds to the complementary antisymmetric torsion \( T_{\alpha\beta\gamma} = -\frac{1}{6}\varepsilon_{\alpha\beta\gamma\delta} S^\delta \). In our case, we suppose that the metric is flat \( g_{\mu\nu} = \eta_{\mu\nu} \). Unitarity and renormalizability conditions in effective low energy quantum field theory lead to free torsion action with this form:

\[
S_{TS-free} = \int d^4x (\frac{1}{4} S_{\mu\nu} S^{\mu\nu} + \frac{1}{2} M_{TS}^2 S_\mu S^\mu),
\]

where \( M_{TS} \) is the mass of torsion and \( S_{\mu\nu} = \partial_\mu S_\nu - \partial_\nu S_\mu \). As it has been seen in [11], we can enter spinor-torsion interaction to SM as interactions between fermions with a new vector field \( S_\mu \). Therefore, the total action include \( \mathcal{L}_{SM}, \mathcal{L}_{TS-matter} \) and \( \mathcal{L}_{TS-free} \). In low energy limit, the total action leads to four fermions interaction term with the following form:

\[
\mathcal{L}_{int} = -\frac{\eta_a \eta_b}{M_{TS}^2} (\bar{\psi}_a \gamma_5 \gamma_\mu \psi_a) (\bar{\psi}_b \gamma_5 \gamma_\mu \psi_b),
\]
where $\eta_a$ and $\eta_b$ are dimensionless coupling constants. Therefore, the new four fermions interaction is characterized by dimensionless parameters $\eta_a$, $\eta_b$ and mass of the torsion field $M_{TS}$. In the following, we consider $\eta_a$, $\eta_b$ and $M_{TS}$ as arbitrary parameters and study the effect of exchange of torsion field on top pair production at the Tevatron and the LHC. The leading order (LO) processes for the production of top pair at hadron colliders include these two processes $q\bar{q} \rightarrow t\bar{t}$ and $gg \rightarrow t\bar{t}$. We neglect interaction between non-abelian gauge fields (gluons) with torsion since interaction of purely antisymmetric torsion with gauge field does not save gauge invariant[16].

We have calculated the $q\bar{q} \rightarrow t\bar{t}$ including the above four fermion effects. When $q\bar{q}$ is the initial state, the amplitude for top pair production is given by:

$$|\mathcal{M}|^2_{TS} = \frac{\eta_t^2 \eta_q^2 s^2}{M_{TS}^2} \left[1 + \left(1 - \frac{4m_q^2}{s}\right)\beta^2 \cos^2 \theta - \frac{4m_t^2}{s} \beta^2\right], \quad (7)$$

where $s$ is partonic center-of-mass energy, $\beta = \sqrt{1 - 4m_t^2/s}$, $m_t$ and $m_q$ are the top quark and $q$ quark masses. In Eq. 7, $\theta$ is the production angle of the outgoing top in the center-of-mass system. Another contribution to this process arises from the interference between SM contribution and torsion effects. Amplitude for this interference given by:

$$\frac{16\eta_t \eta_q s g_s^2}{3M_{TS}^2} \left[1 + \left(1 - \frac{4m_q^2}{s}\right)\beta \cos \theta\right]^2, \quad (8)$$

where $g_s$ is the strong coupling constant. As we can see in the above amplitudes, the only quantity which appear in this approach is the ratio $\frac{\eta \eta}{M_{TS}^2}$ and therefore for heavy torsion field the phenomenological consequences depend only on this single parameter.

3 Observables and Numerical results

In this section, we study the total cross section of top pair production at the Tevatron and LHC and consider top pair forward backward asymmetry
and charge asymmetry as observables and study the effect of torsion field on them.

Top pair production cross section at the Tevatron (by D0 collaboration [19]) and LHC7 (by CMS experiment [20]) have been measured to be:

\[
\sigma_{\text{Tevatron}}(pp \to t\bar{t}) = 7.56 \pm 0.83 \text{ [pb]} \text{ (stat } \oplus \text{ sys),} \tag{9}
\]

\[
\sigma_{\text{LHC}}(pp \to t\bar{t}) = 165.8 \pm 13.3 \text{ [pb]} \text{ (stat } \oplus \text{ sys).} \tag{10}
\]

These measurements are in good agreement with the SM predictions [21, 22].

The total cross section of top pair production at hadron colliders can be obtained by convoluting the partonic cross section with the parton distribution functions (PDF) for the initial hadrons. To calculate \(\sigma(pp \to t\bar{t})\), we have used the MSTW parton structure functions [23] and set the center-of-mass energy to 7 TeV for the LHC and 1.96 TeV for the Tevatron. The total cross section for production of \(t\bar{t}\) is given by:

\[
\sigma(pp \to t\bar{t}) = \sum_{ab} \int dx_1dx_2f_a(x_1,Q^2)f_b(x_2,Q^2)\hat{\sigma}(ab \to t\bar{t}), \tag{11}
\]

where \(f_{a,b}(x_i,Q^2)\) are the parton structure functions of proton. \(x_1\) and \(x_2\) are the parton momentum fractions and \(Q\) is the factorization scale.

Here, we emphasis that for proton-antiproton collision FBA is measured by using invariant difference of \(t\) and \(\bar{t}\) rapidities. The rapidity \(y\) of the top quark is given by:

\[
\frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right) \tag{12}
\]

with \(E\) being the total top quark energy and \(p_z\) is the top quark momentum along beam axis. The definition of FBA is identical to asymmetry in the top production angle in the \(t\bar{t}\) rest frame:

\[
A_{FB} = \frac{N_t(\cos \theta > 0) - N_t(\cos \theta < 0)}{N_t(\cos \theta > 0) + N_t(\cos \theta < 0)}. \tag{13}
\]
Prediction of SM for FBA is as small as a few percent which arises from the interference between the Born amplitude for $q\bar{q} \rightarrow Q\bar{Q}$ and box diagrams and the interference term between initial state radiation and final state radiation [4]. At the Tevatron, since the initial state is asymmetric (proton-antiproton collisions), the top quark forward-backward asymmetry can be measured. Recent measurements of FBA have been reported by CDF [2] ($A_{FB} = 0.158 \pm 0.075$) and D0 [3] ($A_{FB} = 0.196 \pm 0.065$) collaborations which show $2\sigma$ deviation from the SM prediction.

At the LHC, since initial state is symmetric (proton-proton collisions), FBA vanishes. However, charge asymmetry in $t\bar{t}$ production at LHC can be measured which reflects the top quark rapidity distribution. The top quark charge asymmetry in top pair production is defined by [25]

$$A_C = \frac{N_t(\Delta(y^2) > 0) - N_t(\Delta(y^2) < 0)}{N_t(\Delta(y^2)) > 0 + N_t(\Delta(y^2) < 0)}$$

(14)

where $\Delta(y^2)$ is,

$$\Delta(y^2) = (y_t - y_{\bar{t}})(y_t + y_{\bar{t}}).$$

(15)

In proton-proton collisions at the LHC, $t\bar{t}$ has a boost along the direction of the incoming quark, and therefore this leads to a larger average rapidity for top quarks than anti-top quarks. As a result, CA in $t\bar{t}$ production is not zero. The ATLAS and CMS collaboration have reported the charge asymmetry measurements: $A_C = -0.019 \pm 0.036$ [24], $A_C = -0.013 \pm 0.041$ ($A_C = 0.004 \pm 0.014$) [25], and the SM prediction is $A_C = 0.0115$ [26]. Note that measurement of charge asymmetry at the LHC is in agreement with SM prediction while measurements of the FBA show a deviation from the SM expectations. It means that any new physics which explains the $t\bar{t}$ forward-backward asymmetry must satisfy $A_C$ measurements consistent with the SM predictions. We are also interested in the differential cross section as a function of invariant mass $M_{tt} = \sqrt{(p_t + p_{\bar{t}})^2}$, where $p_t$ and
\( p_T \) are the four-momenta of top and anti-top, respectively. This quantity is defined by

\[
\frac{d\sigma(pp \to t\bar{t})}{dM_{t\bar{t}}} = \sum_{ab} \int_{M_{t\bar{t}}^2}^{1} dx_1 \left[f_a(x_1, Q^2)f_b\left(\frac{M_{t\bar{t}}^2}{x_1 E_{CMS}^2}, Q^2\right)\right] \times \frac{2M_{t\bar{t}}^2}{x_1 E_{CMS}^2} \tilde{\sigma}(ab \to t\bar{t}), \tag{16}
\]

As it is mentioned, physical observables related to torsion field depend on the mass of torsion \( M_{TS} \) and coupling constant between torsion and fermion field \( \eta_\psi \). In [27], a search for narrow resonances has been performed by CMS experiment at LHC and any resonance below 1 TeV has been excluded. In this paper, we consider mass of torsion field in energy scale more than 1 TeV. For the sake of simplicity, we choose identical couplings for interaction between torsion field and fermions. This assumption enables us to put the limit in two dimensional parameters space \((M_{TS} - \eta)\) using the present experimental measurements.

To perform our analysis, we have set \( m_t = 172.5 \text{ GeV} \) and fixed renormalization and factorization scale \( \mu_R = \mu_F = m_t \). For including higher order QCD effects, we have normalized the cross section to the ratio of measured experimental cross section and the leading order SM cross section.

In Fig. 1 we have displayed the total cross section of top-antitop production at the Tevatron and LHC as a function of torsion field mass. The curves with different colors and lines show various values of constant coupling \( \eta \).

As it is shown in Eq. 7 amplitude for torsion exchange depend on \( \cos^2 \theta \) which is symmetric after integrating over \( \cos \theta \). However Eq. 8 shows that interference term depend on \( \cos \theta \). As a result, torsion exchange can contribute to FBA via the interference term with the SM contribution.

Fig. 2-a(b) depicts \( A_{FB}(A_C) \) at Tevatron (LHC). Different values for couplings have been considered. As it can be seen, for instance the allowed values for \( \eta = 0.2 \) in \( A_{FB}(A_C) \) curves are satisfied for \( M_{TS} > 1100 \text{ GeV} \).
(\(M_{TS} > 1300 \text{ GeV}\)). This means that for a given value \(\eta = 0.2\), there are allowed regions in parameters space which are consistent with top asymmetries measurements.

The dependence of \(A_{FB}\) on invariant mass of \(t\bar{t}\) are studied in Fig. 3. In this figure, we display a histogram which depicts forward-backward asymmetry as a function of invariant mass \(t\bar{t}\) with seven bins. The green distribution shows SM expectation at to next leading order and red distribution shows measured data at Tevatron \([28]\). The uncertainties on the data contain statistical and systematics. The blue graph shows torsion model prediction in each bin. To draw this histogram, we set \(\eta = 0.2\) and \(M_{TS} = 3 \text{ TeV}\). This histogram compare the experimental measurement at Tevatron and SM (NLO) with torsion model prediction. It is remarkable that the SM predictions in each bin are far from measured data at Tevatron and torsion prediction is approximately correspond with data.

We perform a \(\chi^2\)-fit for forward-backward asymmetry as a function of
Figure 2: The Top pair asymmetries as a function of torsion mass. a) Forward-Backward asymmetry at Tevatron. b) Charge asymmetry at LHC. The horizontal red lines show the allowed ranges of experimental measurements for asymmetries.

Figure 3: Forward-backward asymmetry as function of invariant mass $M_{t\bar{t}}$ for torsion model compared to the experimental measurement at Tevatron and SM (NLO) expectation.
Figure 4: Shaded areas depict ranges of parameters space in torsion mass $M_{TS}$ and coupling constant plane for which are consistent with 68% C.L and 90% C.L.

Invariant mass $t\bar{t}$ system ($M_{t\bar{t}}$). This quantity has been defined as:

$$\chi^2 = \sum_i \left( \frac{A_{FB}^i - (A_{FB}^{exp})^i}{(\sigma_{exp})^i} \right)^2,$$

where summation is over all bins of invariant mass. The size of bins have been chosen according to bins in Fig. 3. In Fig. 4 we show range of parameters space in torsion mass of $M_{TS}$ and coupling constant $\eta$ plane which are consistent with 68% C.L and 90% C.L. The blue area shows regions with 1 $\sigma$ (68% C.L) and green area depicts regions with 1.7 $\sigma$ (90% C.L) deviation from measured data in global analyze.

Another observable which can help us to study torsion space-time effects on top pair production is differential cross section. Fig. 5 depicts differential cross section of $t\bar{t}$ production at Tevatron as a function of invariant mass $t\bar{t}$ system. The green distribution shows SM expectation at to next leading order and red distribution shows measured data at Tevatron [29]. The uncertainties on the data contain statistical and systematics and luminosity.
Figure 5: Differential cross section of top-antitop production at the Tevatron as a function of invariant mass $M_{\tau\tau}$ for torsion model compared to the experimental measurement at Tevatron and SM (NLO) expectation.

The blue graph shows torsion model prediction in each bin. To draw this histogram, we set $\eta = 0.2$ and $M_{TS} = 3$ TeV. This histogram compares the experimental measurement at Tevatron and SM (NLO) with torsion model prediction. As it is shown, the consistency between torsion model prediction with measurement is reasonable.

As it was mentioned in explanation of Fig. 2, there are allowed regions in parameters space which are consistent with top asymmetries measurements. However, this result may conflict with allowed regions for cross section measurement at Tevatron and LHC. To better study of all parameters space which can simultaneously satisfy experimental constraints on $\sigma_{\text{Tevatron}}$, $\sigma_{\text{LHC}}$, $A_{FB}$ and $A_{C}$, we display Figs. 6. In Fig. 6 the shaded areas depict ranges of parameters space in torsion mass $M_{TS}$ and coupling constant plane for which prediction of effect of torsion space-time on observables $\sigma_{\text{LHC}}$, $\sigma_{\text{Tev}}$, $A_{FB}$ and $A_{C}$ are consistent with experimental measurements. It is notable that the allowed regions of top pair production cross section at the LHC and Tevatron, overlap with allowed regions of $A_{C}$ and $A_{FB}$. Also there is
an overlapping region between the measured $A_C$ at LHC and measured $A_{FB}$ at Tevatron which increases at high torsion mass $M_{TS}$. It is remarkable that we find regions in torsion parameters space which all experimental measurement are simultaneously satisfied. This means torsion model can explain measured forward-backward anomaly at Tevatron and top pair cross section measurement and charge asymmetry measurement at LHC can not exclude this model within the present uncertainty.

4 Concluding remarks

In this paper, we have studied the effects of torsion space-time on top pair asymmetries and the cross section productions at the Tevatron and the LHC. We studied the dependence of $A_{FB}$ on invariant mass of $t\bar{t}$. It is shown that prediction of torsion model is more consistent with measured data at Tevatron than SM prediction for $A_{FB}$ in each bins of $M_{t\bar{t}}$. We performed
global $\chi^2$-fit on forward-backward asymmetry as a function of invariant mass $M_{t\bar{t}}$ and showed regions with 1 $\sigma$ and 1.7 $\sigma$ deviation from measured data in effective torsion model. We also investigate the differential cross section of $t\bar{t}$ production as independent observable and showed the consistency of this observable for torsion model with data.

Lastly, We have found overlapping regions in parameters space of torsion space-time which all experimental measurement ($\sigma_{\text{LHC}}$, $\sigma_{\text{Tev}}$, $A_{\text{FB}}$ and $A_{\text{C}}$) are simultaneously satisfied. This means torsion model can explain measured forward-backward anomaly at Tevatron and top pair cross section measurement and charge asymmetry measurement at LHC can not exclude this model.

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