Torsion limits from $t\bar{t}$ production at the LHC

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Torsion models constitute a well-known class of extended quantum gravity models. In this work, one investigates the phenomenological consequences of a torsion field interacting with top quarks at the LHC. A torsion field could appear as a new heavy state characterized by its mass and couplings to fermions. This new state would form a resonance decaying into a top antitop pair. The latest ATLAS $t\bar{t}$ production results from LHC 13 TeV data are used to set limits on torsion parameters. The integrated luminosity needed to observe torsion resonance at the next LHC upgrades are also evaluated, considering different values for the torsion mass and its couplings to Standard Model fermions. Finally, prospects for torsion exclusion at the future LHC phases II and III are obtained using fast detector simulations.

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I. INTRODUCTION

Since the start of the LHC era, its experiments have performed an impressive set of measurements in different energy regimes that has strengthened our confidence in the Standard Model (SM). The most significant result was the discovery of the Higgs boson by the ATLAS and CMS experiments [1,2]. On the other hand, new physics has not yet appeared, and so far we have no indications from the data on what kind of physics beyond SM lies in the high energy scales. Drastic experimental constraints have been put in many extensions of the SM, making some of them less appealing. As a result, the famous SM puzzles that motivated the pre-LHC model building era are still unsolved.

The various SM extensions deal with one or more problems of the theory, but few of them try to incorporate quantum gravity. In fact, it is generally accepted that a consistent quantum gravity theory does not exist. In this scenario, the most realistic candidate to a universal theory would be the string theory, which induces gravitational interactions in the low energy limit. However, there is no

perspective in the near future that this theory could be verified experimentally. The alternative has been to apply effective approaches to the problem by considering natural extension of general relativity (GR), assuming they might come from a still unknown fundamental theory. One of the most natural extensions of GR is the torsion gravity theory [3]. Torsion could be induced in string theory [4], and its possible manifestation could be a way to understand low-energy effects of that theory. Torsion has also been studied as a source of local Lorentz invariance violation [5] and in extra dimension scenarios [6].

There are different approaches to treat the torsion field, but for the purpose of this paper, we consider the one where torsion is a fundamental propagating field, with a well-defined action and characterized by a mass and couplings between torsion and fermions [4]. As the torsion is taken as a dynamical field, it is incorporated into the SM along with the other vector fields. The coupling between torsion and fermions can be, in principle, nonuniversal. This possibility is explored in this paper.

At the LHC, torsion signals could be observed through its decay into fermions. The LHC theoretical reach to probe torsion was investigated in [7,8]. Limits on torsion parameters have been derived using LEP and TEVATRON results [9,10]. The ATLAS experiment has put limits on torsion mass and couplings using 7 TeV data in the dilepton channel [11]. The impact of a heavy torsion on top pair asymmetries was studied in [12]. In most of these studies, the torsion-fermion couplings were considered universal. Limits on torsion coupling to a scalar field, when it is identified as a dark matter candidate, were derived in [13].

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In this paper, we use the latest ATLAS $t\bar{t}$ production results to constrain torsion parameters assuming representative values for the torsion-top coupling. Limits on torsion from this channel, using LHC published data, are derived here for the first time. The torsion discovery potential and exclusion at LHC runs II and III are also evaluated. Torsion decaying into $t\bar{t}$ at the LHC was first investigated in [8], but the subsequent top decay and the final state reconstruction were not taken into account. In the present study, we go a step further in understanding the actual collider signature by considering measurable final states.

This article is organized as follows. In Sec. II a very brief review of the torsion model is given, highlighting the features that are most relevant to the current analysis. Section III describes the Monte Carlo and detector simulation procedures. In Sec. IV, experimental bounds on torsion mass and couplings are derived from ATLAS published 13 TeV LHC collision data. Section V presents a fast detector simulation performed to obtain the LHC potential to observe torsion resonances decaying into $t\bar{t}$. Prospects for torsion exclusion at the next LHC upgrades are also presented. Conclusions are drawn in Sec. VI.

II. THE TORSION INTERACTIONS

The interaction between a Dirac field and torsion, assuming that the metric is flat, is described by the following action [10]:

$$\mathcal{S}_{\text{non-min}}^{\text{TS-matter}} = i \int d^4x \bar{\psi}_{(i)} (\gamma^\mu \partial_\mu + i\eta_i \gamma^\mu \gamma^5 S_\mu - im_i) \psi_{(i)}, \quad (1)$$

where $\psi_{(i)}$ stands for each of the SM fermions, S_μ is an axial vector field and η_i is the nonminimal interaction parameter for the corresponding spinor. The spinor-torsion interaction enters the SM as interactions of fermions with the new axial vector S_μ , characterized by new dimensionless parameter, the coupling constants η_i .

Unitarity and renormalization conditions in the effective low-energy quantum theory lead to the torsion action of the form

$$\mathcal{S}^{\text{TS-Free}} = \int d^4x \left(-\frac{1}{4} S_{\mu\nu} S^{\mu\nu} + \frac{1}{4} M_{\text{TS}}^2 S_\mu S^\mu \right), \quad (2)$$

where M_{TS} is the torsion mass and $S_{\mu\nu} = \partial_\mu S_\nu - \partial_\nu S_\mu$. To preserve unitarity, it has been shown that the following relation must be satisfied for each fermion of mass m_i [14]:

$$\frac{M_{\text{TS}}^2}{\eta_i} \gg m_i^2. \quad (3)$$

The torsion-fermion interactions are not necessarily universal since the values of the couplings η_i may not be the same for all fermions. The difference comes from the renormalization group equations for each η_i that depend on

the Yukawa coupling for the corresponding fermion. From simplified assumptions [8] it is possible to conclude that, at TeV scale, the values of all η_i must be the same, except for the top quark. The torsion-top coupling, denoted hereafter by η_t , may be different because of the potentially stronger running between the Planck and TeV scales. Hence, the free parameters of the theory include M_{TS} , the torsion-top coupling η_t and the coupling between torsion and all other SM fermions, denoted by η_f . In order to be as general as possible, using these assumptions, we explore in our analyses the parameter space regions where $\eta_t < \eta_f$, $\eta_t = \eta_f$ and $\eta_t > \eta_f$.

III. MONTE CARLO AND DETECTOR SIMULATION

The torsion effective model was implemented in the CALCHEP event generator [15] according to Eq. (1). The implementation was validated and tested for consistency and unitarity. CALCHEP is used to calculate cross sections and to generate events in which a torsion resonance is produced in proton-proton collisions and decays into a pair of top quarks. The simulation is done using the MSTW2008nlo parton distribution function [16] and center-of-mass energy of 13 TeV. The generated events are processed by PYTHIA 8 [17] for hadronization and decays. PYTHIA 8 is also used to generate SM $t\bar{t}$ background events. For this study, the semileptonic decay of the top quark is selected. A fast detector simulation is performed using DELPHES [18] with ATLAS detector configuration, but pileup is not taken into account (the DELPHES simulation is only used in the analysis described in Sec. V). The torsion masses were taken in the range 500 to 4500 GeV. The coupling η_f varied from 0.1 to 0.5 in steps of 0.1. Three representative values η_t were chosen: 0.1, 0.5 and 1.0. These coupling values were selected to produce significant variation on $\sigma(pp \rightarrow \text{TS} \rightarrow t\bar{t})$ without violating the constraint imposed by Eq. (3).

A torsion signal can be observed at the LHC as an increase in the number of $t\bar{t}$ events produced via s-channel torsion exchange. The Feynman diagram of the process is shown in Fig. 1. The leading order (LO) cross sections at 13 TeV, as a function of torsion mass and η_f , are shown in Figs. 2(a) and 2(b) for $\eta_t = 0.1$ and $\eta_t = 1$, respectively.

FIG. 1. Torsion contribution to $t\bar{t}$ production at LHC.

FIG. 2. LO cross section for process $pp \rightarrow TS \rightarrow t\bar{t}$ as a function of M_{TS} and η_f for $\eta_t = 0.1$ $\eta_t = 1.0$.

In the analysis that will follow, a K-factor of 1.3 is applied to the LO cross sections to account for next-to-leading-order effects.

As we can see in Fig. 2(a), for $\eta_t = 0.1$, $\sigma(pp \rightarrow TS \rightarrow t\bar{t})$ does not change significantly with η_f . In this case, the torsion production increases with η_f , but it is compensated by decrease of $\text{Br}(TS \rightarrow t\bar{t})$. Changes in the cross section as a function of η_f are only important when $\eta_t > \eta_f$, as illustrated in Fig. 2(b). For this reason, different values of η_f are considered in the next sections only when $\eta_t = 0.5$ and $\eta_t = 1.0$.

IV. OBSERVED EXCLUSION LIMITS

The ATLAS experiment has searched for heavy particles decaying into $t\bar{t}$ at center-of-mass energy of 13 TeV with a data sample corresponding to an integrated luminosity of 3.2 fb^{-1} [19]. The analysis selected events where the top and the antitop quarks decay to W boson and bottom quarks ($t \rightarrow W^+ b, \bar{t} \rightarrow W^- \bar{b}$), one of the W 's decays to leptons and the other decays to quarks, forming the lepton-plus-jets topology. The number of selected events from data and from different SM processes estimated by the experiment, in the electron-plus jet channel ($e + \text{jets}$), is listed in Table I. As we can see, there is a deficit of events in data

TABLE I. Number of events from data and expected background after the $e + \text{jets}$ selection obtained by the ATLAS experiment [19].

	Number of events
$t\bar{t}$	3000 ± 700
$W + \text{jets}$	200 ± 140
$Z + \text{jets}$	33 ± 12
Multijet	130 ± 70
Diboson	46 ± 11
Total	3700 ± 800
Data	3352

compared to total expected background, but it is still compatible with the prediction within the uncertainty.

The results from Table I and the theoretical cross sections calculated in Sec. III are used to set limits on torsion mass and couplings. The ATLAS acceptance times efficiency in the $e + \text{jets}$ channel is also used to calculate the number of torsion signal events. Upper limits on the signal cross section are obtained by applying a Bayesian technique implemented in the MCLIMIT program [20,21]. This approach assumes that the signal adds incoherently to the background. The inputs for the calculations are the number of events observed in data, the expected number of torsion events and the expected number of background events. The limit on the cross section is translated in the lower limit on the torsion mass for each combination of η_f and η_t . Figures 3(a) and 3(b) show the 95% C.L. exclusion regions on the $M_{TS} \times \eta_f$ plane for $\eta_t = 0.5$ and $\eta_t = 1.0$, respectively. The large difference between the observed and expected limits is due to the deficit of data events mentioned above.

In a scenario where torsion is strongly coupled to the top quark but the interaction with other fermions is weak ($\eta_f = 0.1$), the current data excludes torsion with a mass between 1700 and 1800 GeV. For the highest coupling values considered in this paper, the lower limit on torsion mass is pushed to ~ 2700 GeV. For $\eta_t = 0.1$, the observed limit is $M_{TS} > 1200$ GeV. The observed limits for $\eta_t = 0.5$ and $\eta_t = 1.0$ are summarized in Table II.

V. DISCOVERY POTENTIAL AND LIMITS AT RUNS II AND III

The aim of this section is to perform high mass $t\bar{t}$ resonance reconstruction and investigate the LHC potential to discover torsion at 13 TeV. A fast detector simulation using DELPHES is performed to determine the efficiency for reconstructing the decaying tops from torsion and from SM processes. Jets are reconstructed using the anti- k_t

FIG. 3. Exclusion region on the $M_{TS} \times \eta_f$ plane for $\eta_t = 0.5$ (a) and for $\eta_t = 1.0$ (b), based on the ATLAS 13 TeV resonance search. The red, long dashed black and dashed blue curves are the observed limits, expected limits and 1σ error bands, respectively. The green areas are excluded at 95% C.L.

algorithm. The missing transverse momentum E_T^{miss} is calculated from calorimeter cell energies.

The $t\bar{t}$ system is reconstructed from the hadronic top ($t \rightarrow Wb \rightarrow bq\bar{q}$) and from the semileptonic top ($t \rightarrow Wb \rightarrow be\nu_e$). The events are required to have exactly one electron with $p_T > 30$ GeV and pseudorapidity $|\eta| < 2.5$.¹ Their missing transverse momenta are required to be greater than 30 GeV. The three jets from the hadronic top quark decay can be so collimated in the detector that they cannot be distinguished from each other and therefore are reconstructed as a single jet or two jets. To select the high boosted top candidates, the following criteria are applied for events with at least two jets:

- (i) The leptonic-top jet is selected by requiring $\Delta R(\text{jet}_\ell, e) < 1.5$, where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ and jet_ℓ is the jet identified with the expected b-jet from the leptonic top quark. If more than one jet satisfies this condition, the one with highest p_T is chosen.
- (ii) The hadronic-top jet candidate jet_h must be well separated from the lepton by an azimuthal angle distance of $\Delta\phi(\text{jet}_h, e) > 2.3$ rad. Additionally, the monojet jet_h must have $p_T > 400$ GeV and $\Delta\phi(\text{jet}_h, \text{jet}_\ell) > 1.5$ rad.

For the events that do not pass the above selection, three jets are required with one of them having a mass above 70 GeV. It is assumed that the highest mass jet contains the two merged jets from the W decay or one of the W jets merged with the b-jet. The signal efficiency after these selections depends on M_{TS} and η_f , and it reaches the maximum value of $\sim 2\%$. This efficiency already includes the top and W decay branching ratios.

The invariant mass $m_{t\bar{t}}$ is reconstructed by adding the four-momentum of the selected semileptonic and hadronic top quarks. For the semileptonic top quark, the longitudinal component of the neutrino momentum is calculated from E_T^{miss} and imposing an on-shell W mass constraint. When two jets are selected, the monojet jet_h is assumed to be the reconstructed hadronic top quark. For the events where three jets are selected, the following χ^2 is used to determine which jet must be assigned to the semileptonic or hadronic tops [22,23]:

$$\chi^2 = \left[\frac{m_{jj} - m_{t_h}}{\sigma_{t_h}} \right]^2 + \left[\frac{m_{j\ell\nu} - m_{t_\ell}}{\sigma_{t_\ell}} \right]^2, \quad (4)$$

where m_{t_h} , m_{t_ℓ} are the expected mean masses of hadronic and leptonic top quarks, and σ_{t_h} and σ_{t_ℓ} are their respective standard deviations. These four parameters are determined from Monte Carlo simulation studies from [24]. All jet combinations are tested, and the one with the lowest χ^2 value is chosen to calculate $m_{t\bar{t}}$. Figure 4 shows the reconstructed $m_{t\bar{t}}$ from the selected events for three torsion mass hypotheses and particular values of torsion-fermions couplings. The broad distribution observed for $M_{TS} = 3.0$ TeV is due to the large resonance width.

The main background in this analysis is the SM $t\bar{t}$ production. The expected number of background events is estimated using the measured $t\bar{t}$ cross section at 13 TeV

TABLE II. Observed 95% C.L. lower limits on torsion mass with varying η_f .

η_f	0.1	0.2	0.3	0.4	0.5
Observed limit [TeV] ($\eta_t = 0.5$)	1.72	1.96	2.05	2.15	2.22
Observed limit [TeV] ($\eta_t = 1.0$)	1.80	2.16	2.40	2.51	2.69

¹ η , without subscription, stands for pseudorapidity.

FIG. 4. Reconstructed top pair invariant mass distribution for three torsion mass hypotheses.

[25] and the background event selection efficiency determined from simulation. Other backgrounds include production of W and Z bosons associated with jets, single top production, multijet and diboson productions. We have estimated the number of reconstructed events from these various backgrounds as 20% of the SM $t\bar{t}$ reconstructed events. Hence, the total number of background events N_b is

$$N_b = 1.2 \times \sigma_{t\bar{t}}^{\text{SM}} \times \epsilon_b \times \mathcal{L}, \quad (5)$$

where $\sigma_{t\bar{t}}^{\text{SM}}$ is the SM $t\bar{t}$ cross section, ϵ_b is the background selection efficiency and $\mathcal{L}$ is the integrated luminosity.

In order to determine the LHC experimental sensitivity to probe torsion, the invariant mass $m_{t\bar{t}}$ is used as the signal/background discriminant variable. The background is considerably suppressed by applying the cut $m_{t\bar{t}} > 900$ GeV. This selection criteria keeps more than 90% of the signal events for $M_{\text{TS}} \geq 1500$ GeV. The background invariant mass distribution, above 900 GeV, is modeled as an

exponential using a large simulated MC sample, and a numerical probability density function is used to model the signal shape. For a given integrated luminosity $\mathcal{L}$, a likelihood fit is performed to the signal-plus-background invariant mass distribution in the $m_{t\bar{t}}$ range of [900,5000] GeV. The number of signal and background events are the fitted parameters. Asymptotic formulas for likelihood-based tests [26] is used to calculate the P -value, the probability of a background fluctuation being greater than or equal to the excess observed in the simulated data. The value of $\mathcal{L}$ is increased and the fitting procedure is repeated until $P\text{-value} < 3 \times 10^{-7}$, the probability required to claim a discovery. This test is performed for various torsion mass and coupling hypotheses, and for each one of them the minimal integrated luminosity needed to discover torsion is obtained. The results are shown in Fig. 5 for $\eta_t = 0.5$ and $\eta_t = 1.0$.

From Fig. 5 we can estimate that by the end of run II, torsion with mass ~ 1500 GeV can be observed at LHC if $\eta_t = 0.5$ and $\eta_f = 0.1$. The discovery reach of run II (run III) is ~ 2500 GeV (~ 3000 GeV) if torsion is strongly coupled to quarks ($\eta_t = 1.0$, $\eta_f = 0.5$). In the high-luminosity LHC scenario ($\mathcal{L} = 3000 \text{ fb}^{-1}$), torsion mass up to ~ 4000 GeV can be probed. For $\eta_t = 0.1$, the maximum discovery reach at LHC is $M_{\text{TS}} \sim 1700$ GeV.

The invariant mass distribution is also used to calculate torsion expected limits at runs II and III. Expected upper limits on $\sigma \times \text{Br}(\text{TS} \rightarrow t\bar{t})$ are calculated using simulated pseudoexperiments assuming that only SM processes are present. A Bayesian approach is used [27], with a flat prior probability distribution for σBr . The most probable number of signal events, and the corresponding confidence intervals, are determined from a likelihood function defined as the product of the Poisson probabilities over all $m_{t\bar{t}}$ mass bins in the search region, using the appropriate signal invariant mass distribution. The limit on the number of

FIG. 5. Experimental sensitivity to observe a torsion signal at LHC 13 TeV. The plots (a) and (b) show the minimal discovering integrated luminosity as a function of M_{TS} for $\eta_t = 0.5$ and $\eta_t = 1.0$, respectively.

FIG. 6. Upper limit on $\sigma \times \text{Br}(\text{TS} \rightarrow t\bar{t})$ for $\eta_t = 0.1$ assuming an integrated luminosity of 300 fb^{-1} for different torsion masses. The lower limit on torsion mass is obtained from the crossing between the expected limit and the torsion theoretical cross section.

events is converted into a limit on σBr . A 95% C.L. upper limit on σBr for each pseudoexperiment is obtained, and the median value is chosen to represent the expected limit. This calculation is performed for each combination of the parameters ($M_{\text{TS}}, \eta_f, \eta_t$). The 68% and 95% error bands are also calculated. By comparing the limits on σBr with the torsion theoretical cross sections, the lower limits on torsion mass are determined. The procedure result is illustrated in Fig. 6 for $\eta_t = 0.1$ and $\mathcal{L} = 300 \text{ fb}^{-1}$. In this case, the lower bound $M_{\text{TS}} > 1.52 \text{ TeV}$ can be achieved.

Figures 7 and 8 show the expected exclusion region on the $M_{\text{TS}} \times \eta_f$ plane for $\eta_t = 0.5$ and $\eta_t = 1.0$ considering $\mathcal{L} = 100 \text{ fb}^{-1}$ and $\mathcal{L} = 300 \text{ fb}^{-1}$, respectively. With 100 fb^{-1} of data, the torsion mass limits range from 1.96 to 3.10 TeV. With $\mathcal{L} = 300 \text{ fb}^{-1}$, the limits can be extended to $\sim 3.5 \text{ TeV}$.

In Table III we summarize the results obtained for $\eta_t = 1.0$ for the different integrated luminosities considered. The second table column shows the limits obtained in

FIG. 7. Expected limits on torsion parameters for $\eta_t = 0.5$ (a) and $\eta_t = 1.0$ (b) assuming $\mathcal{L} = 100 \text{ fb}^{-1}$. The long dashed black lines are the expected limits, and the dashed red lines are the 1σ variations. The shaded areas would be excluded at 95% C.L.

FIG. 8. Same as Fig. 7, but assuming $\mathcal{L} = 300 \text{ fb}^{-1}$.

TABLE III. Comparison between the lower limits on M_{TS} obtained by the ATLAS experiment at 7 TeV in the dilepton channel and the results from $t\bar{t}$ derived in this paper, for $\eta_t = 1.0$.

η_f	Lower limits on M_{TS} at 95% C.L. [TeV]			
	ATLAS dilepton 7 TeV $\mathcal{L} = 5.0 \text{ fb}^{-1}$	$t\bar{t}$ 13 TeV $\mathcal{L} = 3.2 \text{ fb}^{-1}$	$t\bar{t}$ 13 TeV $\mathcal{L} = 100 \text{ fb}^{-1}$	$t\bar{t}$ 13 TeV $\mathcal{L} = 300 \text{ fb}^{-1}$
0.1	1.94	1.80	2.02	2.24
0.2	2.29	2.16	2.57	2.86
0.3	2.50	2.40	2.89	3.16
0.4	2.69	2.51	2.95	3.27
0.5	2.91	2.69	3.11	3.45

the dilepton channel by the ATLAS experiment at 7 TeV [11]. Since dilepton is a cleaner signature with better efficiencies, the torsion limits obtained from $t\bar{t}$ with the current data are still less restrictive. The $t\bar{t}$ channel, however, provides a unique way to test the torsion-top coupling and the torsion nonuniversality interactions.

VI. CONCLUSIONS

Exclusion limits on torsion mass and couplings based on ATLAS $t\bar{t}$ results from LHC 13 TeV data are derived. Considering nonuniversal torsion-quarks couplings, torsion with masses between 1.2 to 2.7 TeV are excluded at 95% C.L. The LHC potential to observe torsion decaying into $t\bar{t}$ is also investigated. Taking into account the reconstruction and selection efficiencies of the decaying top quarks, it is found that torsion with mass up to

~ 3.0 TeV can be observed by the end of run III. The results also show that a torsion mass of 4.0 TeV set the maximum M_{TS} value that can be probed at LHC from $t\bar{t}$ production in the electron-plus-jets selection. New data from runs II and III can extend the current torsion mass limits to ~ 3.5 TeV. The results presented in this paper are complementary to torsion searches in the dilepton channel and provide information on torsion-top coupling.

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