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Probing Lorentz Invariance With Top Pair Production at the LHC and Future Colliders

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This article presents prospects for Lorentz-violation searches with $t\bar{t}$ at the LHC and future colliders. After a short presentation of the Standard-Model Extension as a Lorentz-symmetry-breaking effective field theory, we will focus on $t\bar{t}$ production. We study the impact of Lorentz violation as a function of center-of-mass energy and evaluate the sensitivity of collider experiments to this signal.

1. Introduction

The top-quark sector of Standard-Model Extension (SME) is weakly constrained. Since the LHC is a top factory, it provides a unique opportunity to search for Lorentz violation (LV). The SME is an effective field theory including all LV operators. Here, we consider the LV CPT-even part of the lagrangian modifying the top-quark kinematics: [1]

$$\mathcal{L}^{\rm SME} \supset \frac{i}{2}(c_L)_{\mu\nu}\bar{Q}_t\gamma^\mu \overset{\leftrightarrow}{D^\nu} Q_t + \frac{i}{2}(c_R)_{\mu\nu}\bar{U}_t\gamma^\mu \overset{\leftrightarrow}{D^\nu} U_t, \tag{1}$$

where Q_t and U_t denote the left- and right-handed top-quark spinors, respectively. The $c_{\mu\nu}$ coefficients are constant in an inertial frame, taken to be the Sun-centered frame. We aim at measuring the constant coefficients: [2]

$$c_{\mu\nu} = \frac{1}{2}\left[(c_L)_{\mu\nu} + (c_R)_{\mu\nu}\right], \qquad d_{\mu\nu} = \frac{1}{2}\left[(c_L)_{\mu\nu} - (c_R)_{\mu\nu}\right]. \tag{2}$$

Expressions for these coefficients in a laboratory frame on Earth will introduce a time dependence of the cross section for $t\bar{t}$ production owing to the Earth's rotation around its axis. This time dependence can be exploited to search for LV at hadron colliders.

To express the $c_{\mu\nu}$ coefficients in the reference frame of a hadron circular collider, we need:

- the latitude λ, i.e., the angle between the equator and the poles,
- the azimuth θ,[3] i.e., the angle between the Greenwich tangent vector and the clockwise ring collider tangent vector,
- the longitude impacts only the phase of the signal because of the Earth's rotation around its axis, and
- the Earth's angular velocity Ω.

2. Modulation of the $t\bar{t}$ cross section

The analysis aims at measuring the time dependence of the $t\bar{t}$ cross section

$$\sigma_{\mathrm{SME}} = [1 + f(t)]\, \sigma_{\mathrm{SM}}. \tag{3}$$

A first analysis of this kind was performed with the D0 detector at the Tevatron.[4] We use here the same benchmarks. We analyze Wilson's coefficients for a couple of non-null $c_{\mu\nu}$: $c_{XX} = -c_{YY}$, $c_{XY} = c_{YX}$, $c_{XZ} = c_{ZX}$ or $c_{YZ} = c_{ZY}$. Each of these scenarios generates an oscillating behavior of the amplitude. The latitude λ and the azimuth θ affect the amplitude while the Earth's angular velocity Ω affects the frequency. In the case of $c_{XX} = -c_{YY}$ and $c_{XY} = c_{YX}$, $f(t)$ has a period of one sidereal day. On the other hand, in the $c_{XZ} = c_{ZX}$ and $c_{YZ} = c_{ZY}$ case, the amplitude has a period of one half of a sideral day. More detailed expressions are given in Refs. 2, 4.

3. Expected sensitivity

In this work, samples of $t\bar{t}$ with dilepton decay were generated with MadGraph-aMC@NLO 2.6. It was found that the amplitude of the LV $t\bar{t}$ signal is increasing with the center-of-mass energy. The signal amplitude as a function of the center-of-mass energy in p–p collisions (with CMS or ATLAS as the laboratory frame) increases from 0.001 at D0 (in the $c_{XY} = c_{YX} = 0.01$ scenario) to 0.045 at the LHC Run II (13 TeV) and to 0.055 at the Future Circular Collider (FCC, 100 TeV).

We evaluate the expected sensitivity to the signal for each benchmark.[5] As a consequence of the increase in luminosity, the increase in cross section, and the increase in the amplitude of the LV signal, we find the following expected sensitivities to the SME coefficient $c_{\mu\nu}$ in the $c_{XX} = -c_{YY}$ case:

- $\Delta c = 7 \times 10^{-1}$: D0 ($\sqrt{s} = 1.96\,\mathrm{TeV}$, $\mathcal{L} = 5.3\,\mathrm{fb}^{-1}$),
- $\Delta c = 1 \times 10^{-3}$: LHC Run II ($\sqrt{s} = 13\,\mathrm{TeV}$, $\mathcal{L} = 150\,\mathrm{fb}^{-1}$),
- $\Delta c = 2 \times 10^{-4}$: HL-LHC ($\sqrt{s} = 14\,\mathrm{TeV}$, $\mathcal{L} = 3000\,\mathrm{fb}^{-1}$),

- $\Delta c = 3 \times 10^{-5}$: HE-LHC ($\sqrt{s} = 27\,\mathrm{TeV}$, $\mathcal{L} = 15\,\mathrm{ab}^{-1}$),
- $\Delta c = 9 \times 10^{-6}$: FCC ($\sqrt{s} = 100\,\mathrm{TeV}$, $\mathcal{L} = 15\,\mathrm{ab}^{-1}$).

4. Signal amplitude at hadron colliders

A noticeable fact is the dependence of the signal amplitude on the latitude and azimuth of the collider experiment on Earth. This dependence is presented in Fig. 1. We find that performing such an experiment at the

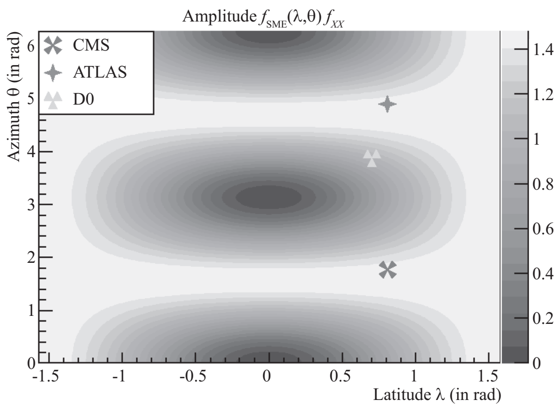

Fig. 1. Amplitude of $f(\lambda, \theta)$ as a function of latitude and azimuth for the XX, YY, and XY benchmarks.

LHC would increase the sensitivity to SME coefficients in the top sector by two orders of magnitude. Further improvements are expected at future colliders.

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