Searches for Lorentz Invariance Violation (LIV) with $t\bar{t}$ production

based on arXiv:1908.11256 [1]

Aurélien CARLE

Nicolas Chanon, Stéphane Perries

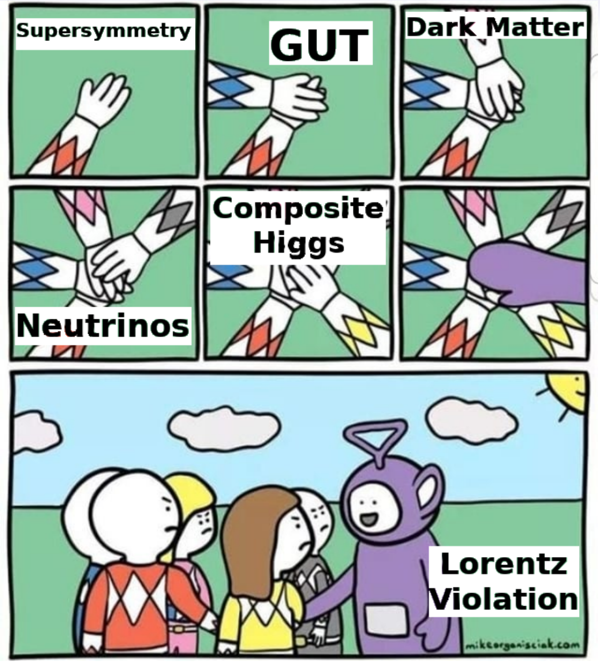
Journées de Rencontres des Jeunes Chercheurs

29 Novembre 2019

Lorentz Invariance Violation (LIV) ? $t\bar{t}$ production ?

Phenomenology of LIV in $t\bar{t}$ production

Searches for LIV in $t\bar{t}$ production at CMS


Supersymmetry
GUT
Dark Matter
Neutrinos
Composite Higgs
Lorentz Violation
mikeorganisciak.com

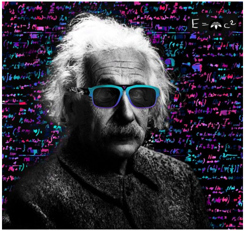
Lorentz Symmetry / Special Relativity

Laws of physics stay unchanged under :

rotations

boosts

of the frame in which they are expressed.



Laws of Physics in Particle Physics

It is convenient to use a mathematical object named Lagrangian to represent laws of physics.

$$\mathcal{L} = \text{(kinetic part)} + \text{(interaction part)} + \text{(mass part)}$$

The previous definition of Lorentz symmetry can be resume as :

$\mathcal{L}(\Lambda x) = \mathcal{L}(x)$	Follow Lorentz Symmetry
$\mathcal{L}(\Lambda x) \neq \mathcal{L}(x)$	Not Follow Lorentz Symmetry

Standard Model

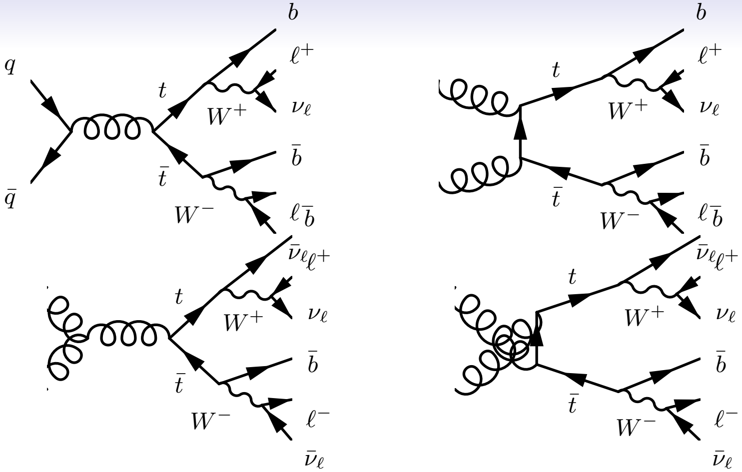
Quantum Field Theory is built on special relativity thus, as a QFT, SM is Lorentz symmetric.

Models of Lorentz Violation

The Lorentz symmetry is not expected to be necessarily conserved at high energy scale (quantum gravity).

- String theory [2].
- Loop quantum gravity [3].

Remnants from the symmetry breaking would manifest themselves at a lower energy, and constitute an appealing signature.



The $t\bar{t}$ production

- ▷ Fully leptonic channel : $t\bar{t} \to b\ell^+\nu + \bar{b}\ell^-\bar{\nu}$
- ▷ $t\bar{t}$ is produced with very high cross-section : $\sigma_{t\bar{t}} = 831$pc at 13TeV.

Lagrangian of the Standard Model

For the top quark, the kinematics part of Standard Model Lagrangian $\mathcal{L}^{\text{SM}}$ is :

$$\mathcal{L}^{\text{SM}} \supset \frac{i}{2}\bar{Q}_t\gamma^\mu \overleftrightarrow{D}_\mu Q_t + \frac{i}{2}\bar{U}_t\gamma^\mu \overleftrightarrow{D}_\mu U_t \quad (1)$$

where :

- Q_t, U_t are respectively Left-handed and Right-handed top spinor
- γ^μ are Dirac matrices (spin $\frac{1}{2}$)
- D_μ is the covariante derivative (kinetics + interactions)

Standard Model Extension (SME)

We start from the SM Lagrangian, add fields breaking the Lorentz symmetry, and write all Lorentz-violating terms in the Lagrangian at the lowest order. This effective field theory (EFT) is called Standard Model Extension (SME) arXiv:9810274 [hep-ph] [4].

$$\mathcal{L}^{\text{SME}} = \mathcal{L}^{\text{SM}} + (\text{violating part}) \quad (2)$$

Lorentz Invariance Violation (LIV) for Top Quark

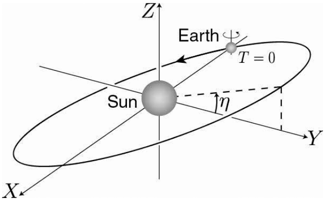
Lorentz violating terms modifying the kinematics of the top quark [1]:

$$\mathcal{L}^{\text{SME}} \supset \frac{i}{2}(c_L)_{\mu\nu}\bar{Q}_t\gamma^\mu \overleftrightarrow{D}^\nu Q_t + \frac{i}{2}(c_R)_{\mu\nu}\bar{U}_t\gamma^\mu \overleftrightarrow{D}^\nu U_t \quad (3)$$

with Q_t is Left-handed top spinor and U_t is Right-handed top spinor.

Wilson's coefficient $c_{\mu\nu}$ (with μ, ν = T,X,Y,Z) need to be :

- ▷ constant ($c'_{\mu\nu} = c_{\mu\nu} \rightarrow$ not Lorentz covariant).
- ▷ define in a given reference frame : Sun-centered frame.



- Z-axis : colinear to the Earth rotation axis.
- X-axis : is pointing at vernal equinox point.
- Y-axis : complete the direct basis.

With these $c_{\mu\nu}$ constraints : $\mathcal{L}^{\text{SME}\prime} \neq \mathcal{L}^{\text{SME}}$

Lorentz Invariance Violation (LIV) for Top Quark

o

U

i

g

n

a

m

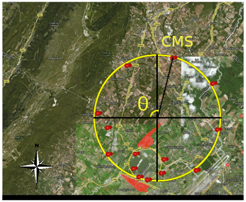
a

n n

From Sun-centered frame to CMS frame

We will express observables in lab frame. The change of frame, taken to be rotation transformation, uses :

- ▷ Latitude ($\lambda = 46.31^\circ$).
- ▷ Azimuth ($\theta = 101.28^\circ$) [5] angle on LHC ring.
- ▷ Earth Angular Velocity ($\Omega = 7.29.10^{-5}$ rad.s^{-1}).



Azimuth θ definition

- In LIV context, rotation of reference frame with top quark gives additional terms to Lagrangian.
- Top quarks have (in average) a direction changing with time. As a result, $\sigma_{t\bar{t}}$ is modulating with time [1].

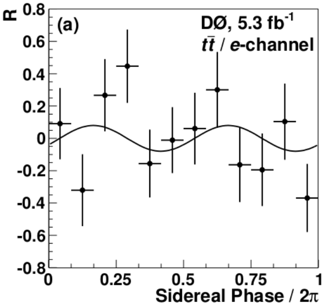
Lorentz Invariance Violation (LIV) ? $t\bar{t}$ production ?

Phenomenology of LIV in $t\bar{t}$ production

Searches for LIV in $t\bar{t}$ production at CMS

Previous exploration : D∅ experiment [6]

- ▷ The first ever results of LIV in $t\bar{t}$ production.
- ▷ Measuring number of $t\bar{t}$ events during time with R ratio.
- ▷ Found no evidence of LIV with ∼10% absolute uncertainty.



Unprecedented study at CMS

- ▷ LIV with top quark.
- ▷ Time dependent analysis.

Modulation of $t\bar{t}$ cross-section at CMS

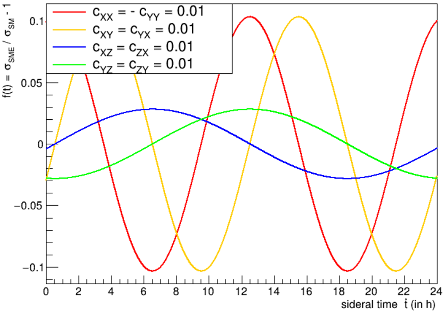
We analyze Wilson's coefficients for a couple of non-null $c_{\mu\nu}$.

From the LO cross-section in the SME (known [7]), we compute the modulation of the cross section.

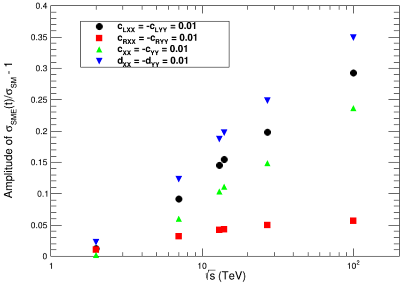
- $c_{XX} = -c_{YY}$

$$c_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & c_{XX} & 0 & 0 \\ 0 & 0 & -c_{XX} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- $c_{XY} = c_{YX}$
- $c_{XZ} = c_{ZX}$
- $c_{YZ} = c_{ZY}$



Amplitude evolution with energy



Scenarii for colliders : Tevatron, LHC, HL-LHC, HE-LHC, FCC-hh.

Amplitude with detector's orientation [8].

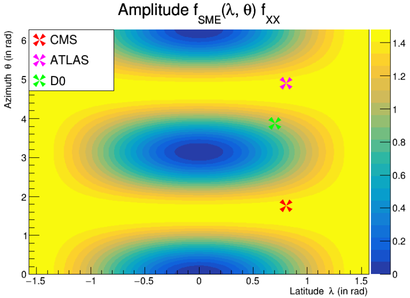


Figure: For $c_{XX} = -c_{YY} = 0.01$ benchmark

At a given energy (here 13 TeV).

Amplitude with detector's orientation [8].

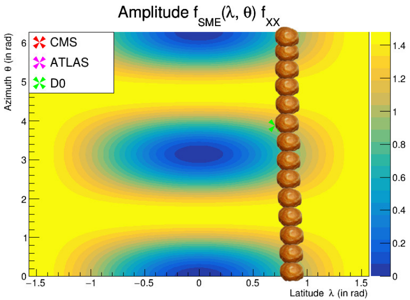


Figure: The Butter Line

Moulin-Mer latitude : 48.390394°.

Expected precisions for different colliders

$$\chi^2 = \frac{1}{N_{\text{bin}}} \sum_{i=1}^{N_{\text{bin}}} \frac{\left(N_{i,\text{tot}} - (cf(t_i)+1)N_{i,\text{signal}} - N_{i,\text{background}}\right)^2}{\sigma_i^2} \quad (5)$$

	DØ [6]	LHC (Run II)	HL-LHC	HE-LHC	FCC
$\Delta c_{LXX}, \Delta c_{LXY}$	1×10^{-1}	2×10^{-4}	2×10^{-5}	4×10^{-6}	1×10^{-6}
$\Delta c_{LXZ}, \Delta c_{LYZ}$	8×10^{-2}	5×10^{-4}	9×10^{-5}	2×10^{-5}	4×10^{-6}
$\Delta c_{RXX}, \Delta c_{RXY}$	9×10^{-2}	4×10^{-4}	9×10^{-5}	2×10^{-5}	5×10^{-6}
$\Delta c_{RXZ}, \Delta c_{RYZ}$	7×10^{-2}	2×10^{-3}	3×10^{-4}	6×10^{-5}	2×10^{-5}
$\Delta c_{XX}, \Delta c_{XY}$	7×10^{-1}	2×10^{-4}	3×10^{-5}	6×10^{-6}	1×10^{-6}
$\Delta c_{XZ}, \Delta c_{YZ}$	6×10^{-1}	6×10^{-4}	1×10^{-4}	2×10^{-5}	4×10^{-6}
$\Delta d_{XX}, \Delta d_{XY}$	1×10^{-1}	1×10^{-4}	2×10^{-5}	3×10^{-6}	8×10^{-7}
$\Delta d_{XZ}, \Delta d_{YZ}$	7×10^{-2}	4×10^{-4}	7×10^{-5}	1×10^{-5}	3×10^{-6}

Sensitivity comparaison with DØ :

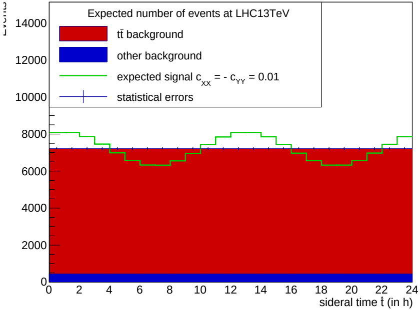
- ▷ Improvement by a 10^2-10^3 factor for Run II.
- ▷ Improvement by a 10^4-10^5 factor for FCC-hh.

Lorentz Invariance Violation (LIV) ? $t\bar{t}$ production ?

Phenomenology of LIV in $t\bar{t}$ production

Searches for LIV in $t\bar{t}$ production at CMS

Principe of the Analysis



- ▷ Time division of data with study of associated systematic uncertainties.
- ▷ Extraction of the signal by statistical analysis.
- ▷ Finally, put limits on $c_{\mu\nu}$ coefficients.

Summary

- LIV can be modeled with EFT.
- Modulation of $t\bar{t}$ cross-section as a signature of LIV.
- Center-of-mass energy and detector orientation affects amplitude.
- Colliders scenarii improve expected precision.

Thanks ! :)

Bibliography

[1] A. Carle, N. Chanon, and S. Perriès, arXiv:1908.11256 [hep-ph]

[2] V.A. Kostelecký, S. Samuel, Phys. Rev. D. **39**, 683 (1989);

[3] R. Gambini, J. Pullin, Phys. Rev. D. **59**, 124021 (1999);

[4] V.A. Kostelecký, Phys. Rev. D. **58**, 116002 (1998);

[5] M. Jones, Activity Report, EDMS, 322747 (2005);

[6] DØ Collaboration, Phys. Rev. Lett. **108**, 261603 (2012);

[7] M.S. Berger, V.A. Kostelecký and Z. Liu, Phys. Rev. D. **93**, 036005 (2016);

[8] A. Carle, N. Chanon, and S. Perriès, arXiv:1909.01990 [hep-ph]

BackUp

backup

Lorentz Symmetry

Laws of physics stay unchanged under rotations or boosts of the frame in which they are expressed.

Such change can be seen as a transformation Λ of the coordinates x :

$$x \to x' = \Lambda x$$

Laws of Physics in Particle Physics

It is convenient to use a mathematical object named Lagrangian to represent laws of physics.

$$\mathcal{L} = (\text{kinetic part}) + (\text{interaction part}) + (\text{mass part})$$

The previous definition of Lorentz symmetry can be resume as :

$$\mathcal{L}(\Lambda x) = \mathcal{L}(x) \qquad \text{Follow Lorentz Symmetry}$$

$$\mathcal{L}(\Lambda x) \neq \mathcal{L}(x) \qquad \text{Not Follow Lorentz Symmetry}$$

SME

$$\mathcal{L} \supset \frac{i}{2}(c_Q)_{\mu\nu AB}\bar{Q}_A\gamma^\mu \overleftrightarrow{D}^\nu Q_B + \frac{i}{2}(c_U)_{\mu\nu AB}\bar{U}_A\gamma^\mu \overleftrightarrow{D}^\nu U_B$$

Q_A : Left-handed spinor $\qquad$ U_A : Right-handed spinor

$$(c_Q)_{\mu\nu 33} = (c_L)_{\mu\nu} \qquad\qquad c_{\mu\nu} = \frac{1}{2}\left((c_L)_{\mu\nu} + (c_R)_{\mu\nu}\right)$$

$$(c_U)_{\mu\nu 33} = (c_R)_{\mu\nu}$$

$$\begin{aligned}\frac{|\mathcal{M}|^2_{\text{SME}}}{|\mathcal{M}|^2_{\text{SM}}} &= 1 + c_{\mu\nu}A_P^{\mu\nu} + (c_L)_{\mu\nu}A_F^{\mu\nu} \\ &= 1 + (c_L)_{\mu\nu}\left(\frac{A_P^{\mu\nu}}{2} + A_F^{\mu\nu}\right) + (c_R)_{\mu\nu}\frac{A_P^{\mu\nu}}{2}\end{aligned}$$

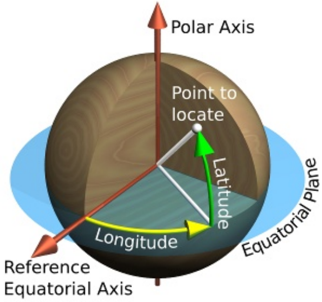
Cross section

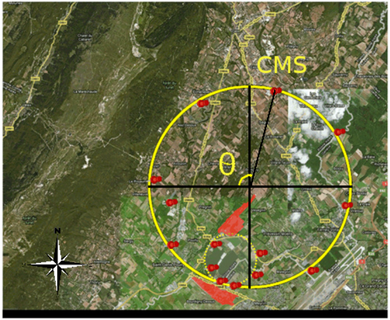
$$\sigma_{\mathsf{SME}} = \left(1 + c_{\mu\nu} A^{\mu\nu}_{\odot}\right) \sigma_{\mathsf{SM}}$$
$$= \left(1 + c_{\mu\nu} R^{\mu}_{\alpha} R^{\nu}_{\beta} A^{\alpha\beta}_{\oplus}\right) \sigma_{\mathsf{SM}}$$

Warning !!!

The matrix rotation is from CMS to SCF

$$\oplus \to \odot$$

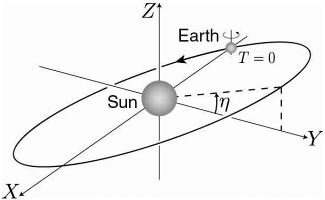




Angles

$$R(t) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -\cos(\Omega t)s_\lambda s_\theta + \sin(\Omega t)c_\theta & \cos(\Omega t)c_\lambda & \cos(\Omega t)s_\lambda c_\theta + \sin(\Omega t)s_\theta \\ 0 & -\sin(\Omega t)s_\lambda s_\theta - \cos(\Omega t)c_\theta & \sin(\Omega t)c_\lambda & \sin(\Omega t)s_\lambda c_\theta - \cos(\Omega t)s_\theta \\ 0 & -c_\lambda s_\theta & -s_\lambda & c_\lambda \; c_\theta \end{pmatrix}$$

Angles pour CMS



- ▷ Azimuth $\theta = 101.28^\circ$
- ▷ Latitude $\lambda = 46.31^\circ$
- ▷ Vitesse angulaire sidérale $\Omega = 7.29211.10^{-5}$ rad.s^{-1}

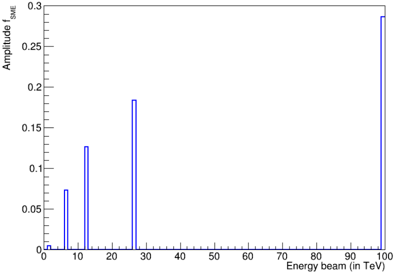
Analytiques functions f

$$\begin{cases} f_{SME}^{(XX)}(t) = 2c_{XX}\left(\left(\frac{a_1-a_2}{2}\right)\cos(2\Omega t) + a_3\sin(2\Omega t)\right) \\ f_{SME}^{(XY)}(t) = 2c_{XY}\left(\left(\frac{a_1-a_2}{2}\right)\sin(2\Omega t) - a_3\cos(2\Omega t)\right) \\ f_{SME}^{(XZ)}(t) = 2c_{XZ}\left(a_4\cos(\Omega t) + a_5\sin(\Omega t)\right) \\ f_{SME}^{(YZ)}(t) = 2c_{YZ}\left(a_4\sin(\Omega t) - a_5\cos(\Omega t)\right) \end{cases}$$

a coefficients

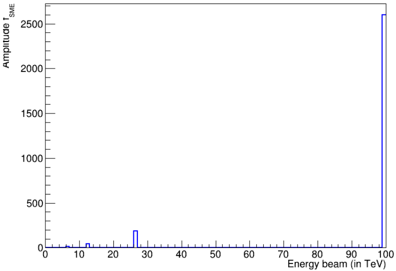
$$\begin{cases} a_1 = \left(s_\lambda^2 s_\theta^2 + c_\lambda^2\right)\langle A^{XX}\rangle + s_\lambda^2 c_\theta^2 \langle A^{ZZ}\rangle \\ a_2 = \left(c_\theta^2\langle A^{XX}\rangle + s_\theta^2\langle A^{ZZ}\rangle\right) \\ a_3 = s_\lambda c_\theta s_\theta\left(\langle A^{ZZ}\rangle - \langle A^{XX}\rangle\right) \\ a_4 = c_\lambda s_\lambda c_\theta^2\left(\langle A^{ZZ}\rangle - \langle A^{XX}\rangle\right) \\ a_5 = s_\theta c_\lambda c_\theta\left(\langle A^{ZZ}\rangle - \langle A^{XX}\rangle\right) \end{cases}$$

Fonction de l'energie



avec pdf pour

$c_{XX} = -c_{YY} = 0.01$



sans pdf pour

$c_{XX} = -c_{YY} = 0.01$