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

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Lorentz Invariance Violation (LIV) ?

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

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

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

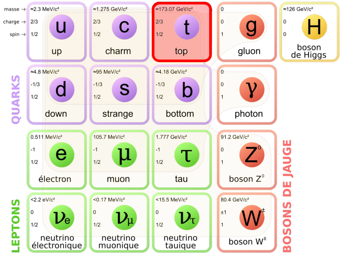
It is convenient to use a mathematical object named Lagrangian to represent laws of physics.

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

The previous definition of Lorentz symmetry can be summarized as :

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

Standard Model : A Lorentz symmetric quantum field theory



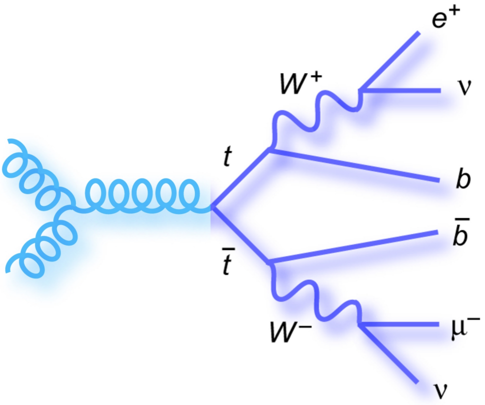
For the top quark, the kinematic part of Standard Model Lagrangian $\mathcal{L}^{\text{SM}}$ is :

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

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 covariant derivative

The $t\bar{t}$ production



- Top mean lifetime of 5×10^{-25} s.
- 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 : $\sigma_{t\bar{t}} = 831$ pb at 13TeV.

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.

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) [4].

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

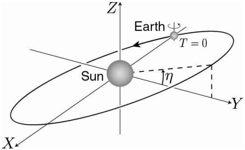
Lorentz Invariance Violation (LIV) for Top Quark

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

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

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 : $\mathcal{L}^{\text{SME}\prime} \neq \mathcal{L}^{\text{SME}}$ thus $t\bar{t}$ cross-section is function of sidereal time.

Sidereal time defined one day (24 sidereal hours) as duration between two crossing of a given distant star and Greenwich meridian.

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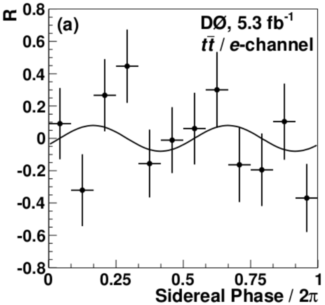
Previous exploration : D∅ experiment [6]

- 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 [1]

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

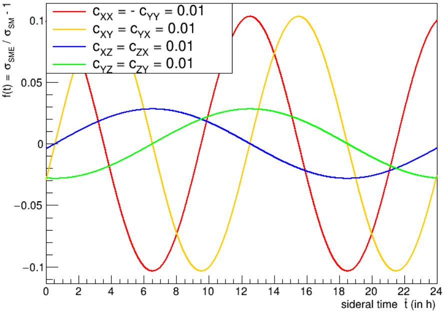
From the LO cross-section in the SME (known [7]), we compute the modulation of the cross section.

Benchmarks:

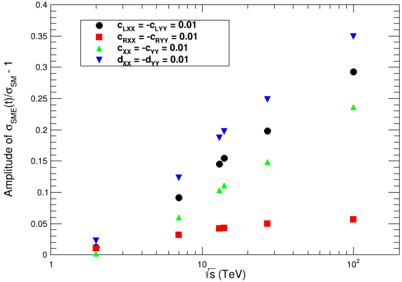
- $c_{XX} = -c_{YY}$

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

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



Amplitude evolution with energy [1]



Scenarii for colliders :

- ▷ Tevatron ($\mathcal{L} = 5.3$ fb^{-1}, $\sqrt{s} = 1.96$ TeV)
- ▷ LHC Run II ($\mathcal{L} = 150$ fb^{-1}, $\sqrt{s} = 13$ TeV)
- ▷ HL-LHC ($\mathcal{L} = 3$ ab^{-1}, $\sqrt{s} = 14$ TeV)
- ▷ HE-LHC ($\mathcal{L} = 15$ ab^{-1}, $\sqrt{s} = 27$ TeV)
- ▷ FCC-hh ($\mathcal{L} = 15$ ab^{-1}, $\sqrt{s} = 100$ TeV)

Expected precisions for different colliders [1]

	D∅ [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 D∅ :

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

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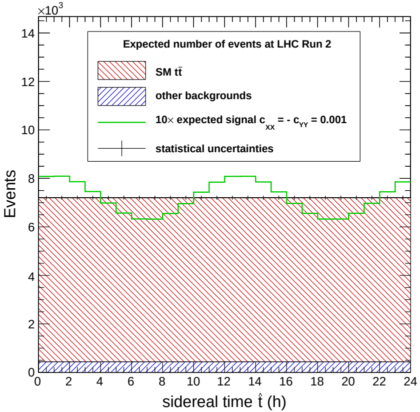
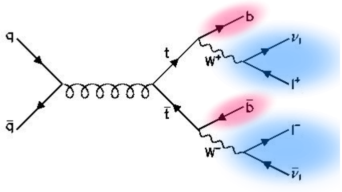
Principle of the Analysis [1]



- ▷ Binning data in sidereal time bins with study of associated systematic uncertainties.
- ▷ Extraction of the signal by statistical analysis.
- ▷ Eventually, measure $c_{\mu\nu}$ coefficients.

Relevant Observable



- Dilepton mass.

$$m_{\ell\bar{\ell}} = m_{\ell}^2 + m_{\bar{\ell}}^2 + 2(E_{\ell}E_{\bar{\ell}} - \boldsymbol{p_{\ell}} \cdot \boldsymbol{p_{\bar{\ell}}}) \tag{4}$$

- b-jets multiplicity.

For each sidereal time bin, we want to get a signal quantity by fit of these observables.

Analysis in dilepton final state

- We select events with 1 electron, 1 muon, 1 jet identified as b-jet and apply sequential selection criteria.
- We correct for data/MC discrepancies in electron and muon reconstruction and identification, b-jet identification.

Data/Monte-Carlo validation

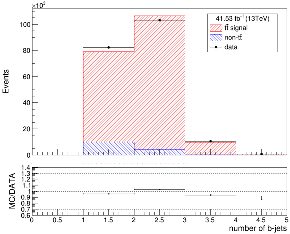


Figure: b-jets multiplicity

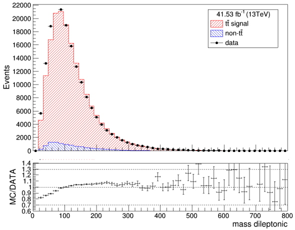


Figure: Dilepton mass

Measuring $c_{\mu\nu}$ coefficient.

$c_{\mu\nu}$ coefficients will be measured with a likelihood ratio method using CMS software.

Systematics list

- luminosity
- electron identification
- electron reconstruction
- electron-muon trigger
- muon identification
- muon isolation

Missing Systematics

- b-tagging
- pileup
- jet energy scale
- theory uncertainties

Asimov test: estimate precision on signal measurement from simulation, in the hypothesis of absence of time-dependent signal.

Signal strengh r per time bins

- ▷ 24 signal strength $r = \frac{\sigma_{\text{obs}}}{\sigma_{\text{SM}}}$ fit independantly for each bin of time.
- ▷ Signal strengths fully uncorrelated over bins.
- ▷ Systematic uncertainties fully correlated over bins.

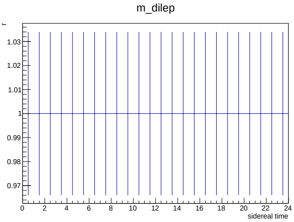


Figure: Dilepton mass

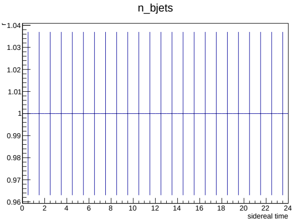


Figure: b-jets multiplicity

- ▷ Dilepton mass : $r = 1 + 0.035 - 0.033$ (stat + syst)
- ▷ b-jets multiplicity : $r = 1 + 0.038 - 0.037$ (stat + syst)

Conclusion

- ▷ Phenomenology studies were performed [1]. We expect a factor 10^2, 10^3 improvement relative to DØ on the precision on the Wilson coefficients.
- ▷ Working on adding remaining systematics
- ▷ Working on estimating time-dependent systematics (luminosity).
- ▷ Working on signal extraction of $c_{\mu\nu}$ Lorentz-violating coefficient.

Thanks ! :)

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

[9] `https://cms-analysis.github.io/HiggsAnalysis-CombinedLimit/`

BackUp

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

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

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

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

Cross section

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

Warning !!!

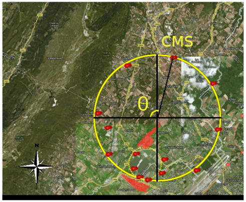
The matrix rotation is from CMS to SCF

$$\oplus \to \odot$$

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].

Amplitude with detector's orientation [8]

Proceeding of CPT'19, Bloomington, IN, United States (C19-05-12.1)

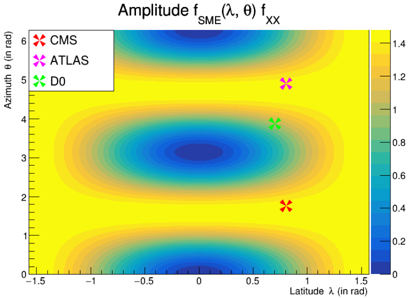


Figure: For $c_{XX} = -c_{YY} = 0.01$ benchmark

- ▷ At a given energy (here 13 TeV).
- ▷ Azimuth : angle between CMS location on LHC ring and a meridian.

Unix/Sidereal time transformation

$$\boxed{\Omega_{\text{GMST}} t_{\text{sideral}} = \Omega_{\text{UTC}}(t_{\text{CMS}} - t_0) + \phi_{\text{Unix}} + \phi_{\text{longitude}}} \tag{5}$$

- Ω_{UTC} is Earth angular velocity : ($\Omega_{\text{UTC}} \simeq 7.2936 \times 10^{-5}$rad.s^{-1} (UTC))
- t_{CMS} is time in CMS in second (UTC).
- t_0 reference time, 1 January 2017, 12:00am ($t_0 = 1483228800$ s (UTC))
- ϕ_{Unix} is the delay between J2000 and Unix epoch [?] :

$$\phi_{\text{Unix}} = 1.7493 \text{ rad} = 100.23^\circ$$

Unix epoch : 1 January 1970, 00:00:00 UTC

- $\phi_{\text{longitude}}$ is the phase due to longitude angle, for CMS :

$$\phi_{\text{longitude}} = 1.5336 \text{ rad} = 87.8705^\circ \tag{6}$$