Testing Lorentz and CPT symmetries in High Energy Collisions

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V. A. Kostelecký [a], E. Lunghi [a], N. Sherrill [b] and A. R. Vieira [c]

[a]Department of Physics, Indiana University, Bloomington, IN 47405, U. S. A.
[b]Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK
[c]Universidade Federal do Triângulo Mineiro, Campus Iturama, 38280-000, Iturama MG, Brasil

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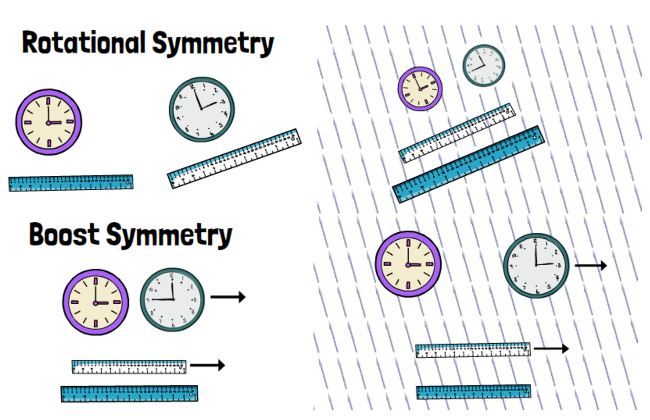
Abstract

In this work, we consider the strong sector of the minimal and the non-minimal Standard Model Extension (SME) [1] in order to compute the cross section for Drell Yan and deep inelastic scattering processes. We use this framework to test Lorentz and CPT symmetries with real data, collected at colliders such as LHC and HERA, and simulated data for the future US-based electron-ion collider.

Basics

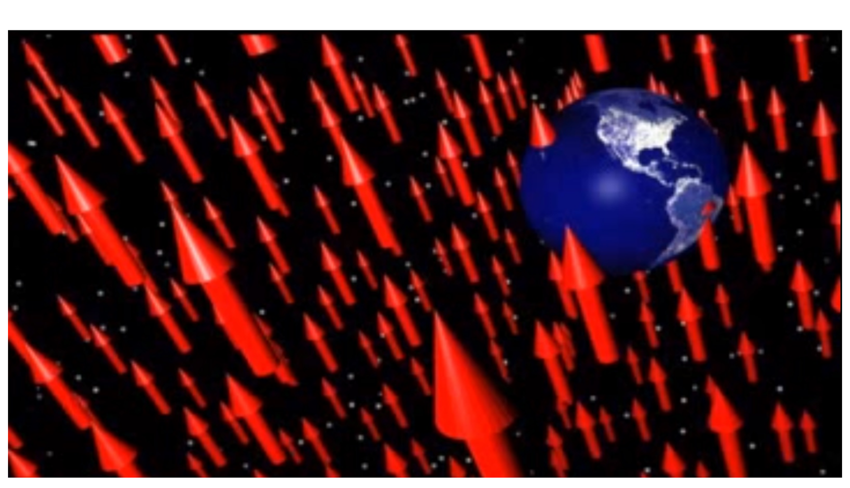
- The SME describes anisotropic space-time and this affects clocks and rulers.



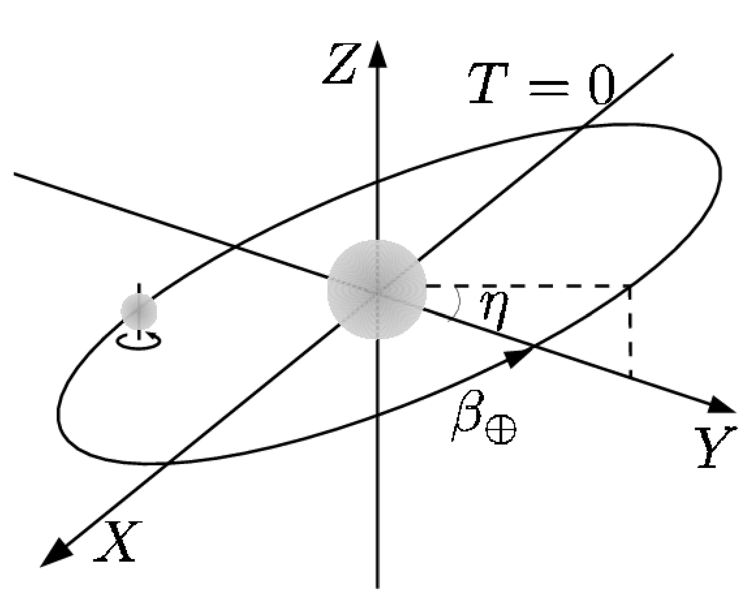
- Unlike the QED extension coefficients, the QCD extension ones are not yet stringent constrained by experiments [2].
- For a single massless Dirac fermion, the gauge invariant, Lorentz and CPT-violating Lagrange density is given by

$$\mathcal{L}_{quark} = \frac{1}{2}\bar{\psi}(i\not{D} + \hat{Q})\psi + h.c. \qquad (1)$$

where $\hat{Q}$ describes the Lorentz-violating effects.



- $\hat{Q}$ is a fixed tensorial background. The cross section varies with time as the Earth rotates
- To find out how observables oscillates with time, we change from the Sun-centered frame to the detector frame.



- The modified dispersion relation for quarks is given by $\tilde{k}^2 \simeq 0$.
- The parton carries a fraction of the parent hadron: $\tilde{k}^\mu = \xi p^\mu$, where $\tilde{k}^\mu_f = (\eta^{\mu\nu} + c_f^{\mu\nu})k_\nu$.

Deep inelastic scattering

- For massless fermions, the lagrangians for the minimal CPT-even and non-minimal CPT-odd Lorentz violation are:

$$\mathcal{L}_{CPT-even} = \sum_{f=u,d} \frac{1}{2}\bar{\psi}_f(\eta^{\mu\nu} + c_f^{\mu\nu})\gamma_\mu i \overleftrightarrow{D}_\nu \psi_f \qquad (2)$$

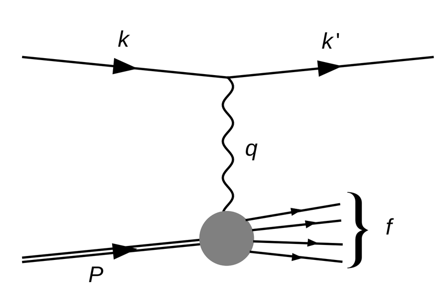
and

$$\mathcal{L}_{CPT-odd} = -(a^{(5)})^{\mu\alpha\beta}\bar{\psi}\gamma_\mu i D_{(\alpha} i D_{\beta)}\psi + h.c \qquad (3)$$

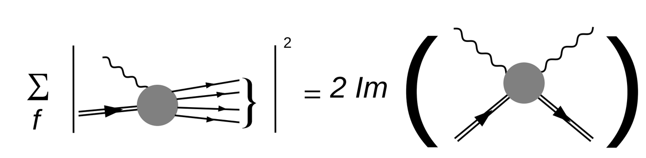
- The differential cross-section for DIS is given by:

$$\frac{d\sigma}{dx dy d\phi} = \frac{\alpha^2 y}{2\pi Q^4}\sum_i R_i (L_i)_{\mu\nu}(Im\, T_i)^{\mu\nu}, \qquad (4)$$

where $i = \gamma, Z, W^\pm$ and R_i denotes the ratio of the exchanged boson propagator.



(a)

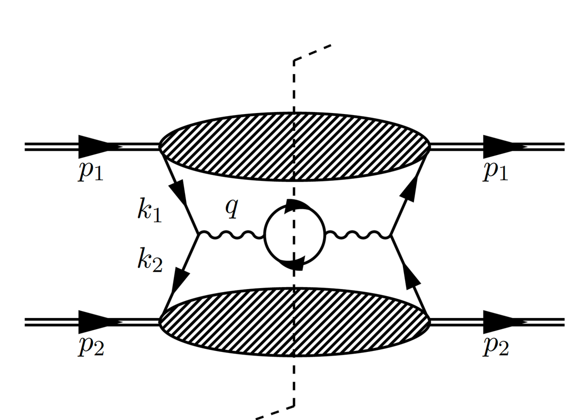


(b)

(a) DIS of an electron off a proton. (b) Optical theorem for the proton-proton interaction.

Drell-Yan process

$$\frac{d\sigma}{d^4 q d\Omega_l} = \frac{\alpha^2}{(2\pi)^4 s q^4}\sum_i R_i (L_i)_{\mu\nu}(W_i)^{\mu\nu} \qquad (5)$$



The dominant contribution for the DY hadronic tensor.

- For instance, the hadronic tensor is modified by the coefficient $c^{\mu\nu}$:

$$W_f^{\mu\nu} = \int d\xi_1 d\xi_2 H_f^{\mu\nu}(\xi_1,\xi_2)[f_f(\xi_1, c_f^{p_1p_1})f_{\bar{f}}(\xi_2, c_f^{p_2p_2}) + \\ + f_{\bar{f}}(\xi_1, c_f^{p_1p_1})f_f(\xi_2, c_f^{p_2p_2})] \qquad (6)$$

where

$$H_f^{\mu\nu}(\xi_1,\xi_2) = \frac{2e_f^2}{3\tilde{s}} Tr\left[(\eta^{\mu\alpha} + c_f^{\alpha\mu})\gamma_\alpha \frac{\xi_1 \not{p}_1}{2}(\eta^{\nu\beta} + c_f^{\beta\nu})\gamma_\beta \frac{\xi_2 \not{p}_2}{2}\right] \\ \times (2\pi)^4 \delta^4(q^\mu + \xi_1 c_f^{\mu p_1} + \xi_2 c_f^{\mu p_2} - \xi_1 p_1^\mu - \xi_2 p_2^\mu).$$

Estimated sensitivities

- Using data collected at colliders [4] for each process and simulated data of future colliders [5], it is possible to extract constraints for coefficients:

	HERA	JLEIC (one year)	eRHIC (one year)	JLEIC (ten years)	eRHIC (ten years)
$\lvert c_u^{TX}\rvert$	6.4 [6.7]	1.1 [11.]	0.26 [11.]	0.072 [9.3]	0.084 [11.]
	6.4 [6.7]	1.0 [10.]	0.19 [7.7]	0.062 [8.5]	0.058 [7.9]
$\lvert c_u^{TY}\rvert$	6.4 [6.7]	1.1 [11.]	0.27 [11.]	0.069 [9.4]	0.085 [11.]
	6.4 [6.7]	1.0 [10.]	0.18 [7.8]	0.065 [8.5]	0.058 [7.8]
$\lvert c_u^{XZ}\rvert$	32. [33.]	1.9 [16.]	0.36 [15.]	0.12 [16.]	0.11 [15.]
	32. [33.]	2.2 [19.]	0.85 [35.]	0.14 [19.]	0.26 [36.]
$\lvert c_u^{YZ}\rvert$	32. [33.]	1.8 [16.]	0.37 [15.]	0.12 [16.]	0.12 [15.]
	32. [33.]	2.2 [19.]	0.84 [35.]	0.14 [19.]	0.26 [36.]
$\lvert c_u^{XY}\rvert$	16. [16.]	7.0 [60.]	0.96 [40.]	0.44 [58.]	0.31 [40.]
	16. [16.]	3.3 [28.]	0.40 [17.]	0.20 [27.]	0.13 [17.]
$\lvert c_u^{XX} - c_u^{YY}\rvert$	50. [50.]	6.0 [51.]	2.8 [120.]	0.37 [50.]	0.89 [120.]
	50. [50.]	6.4 [54.]	2.0 [82.]	0.40 [53.]	0.63 [82.]

(a)

	LHC
$\lvert c_u^{XZ}\rvert$	7.3 [19]
$\lvert c_u^{YZ}\rvert$	7.1 [19]
$\lvert c_u^{XY}\rvert$	2.7 [7.0]
$\lvert c_u^{XX} - c_u^{YY}\rvert$	15 [39]
$\lvert c_d^{XZ}\rvert$	72 [180]
$\lvert c_d^{YZ}\rvert$	70 [180]
$\lvert c_d^{XY}\rvert$	26 [69]
$\lvert c_d^{XX} - c_d^{YY}\rvert$	150 [400]
$\lvert a_{\mathrm{S}u}^{(5)TXX} - a_{\mathrm{S}u}^{(5)TYY}\rvert$	0.015 [0.039]
$\lvert a_{\mathrm{S}u}^{(5)TXY}\rvert$	0.0027[0.0070]
$\lvert a_{\mathrm{S}u}^{(5)TXZ}\rvert$	0.0072[0.019]
$\lvert a_{\mathrm{S}u}^{(5)TYZ}\rvert$	0.0070 [0.018]
$\lvert a_{\mathrm{S}d}^{(5)TXX} - a_{\mathrm{S}d}^{(5)TYY}\rvert$	0.19[0.49]
$\lvert a_{\mathrm{S}d}^{(5)TXY}\rvert$	0.034[0.088]
$\lvert a_{\mathrm{S}d}^{(5)TXZ}\rvert$	0.090[0.23]
$\lvert a_{\mathrm{S}d}^{(5)TYZ}\rvert$	0.089[0.23]

(b)

	EIC	LHC
$\lvert c_u^{XX} - c_u^{YY}\rvert$	0.37	15
$\lvert c_u^{XY}\rvert$	0.13	2.7
$\lvert c_u^{XZ}\rvert$	0.11	7.3
$\lvert c_u^{YZ}\rvert$	0.12	7.1
$\lvert a_{\mathrm{S}u}^{(5)TXX} - a_{\mathrm{S}u}^{(5)TYY}\rvert$	2.3	0.015
$\lvert a_{\mathrm{S}u}^{(5)TXY}\rvert$	0.34	0.0027
$\lvert a_{\mathrm{S}u}^{(5)TXZ}\rvert$	0.13	0.0072
$\lvert a_{\mathrm{S}u}^{(5)TYZ}\rvert$	0.12	0.0070

(c)

(a) Expected best sensitivities on individual coefficients c_f^{JK} estimated for HERA, JLEIC and eRHIC. Values are in units of 10^{-5}. (b) Expected best sensitivities on individual coefficients c_f^{JK} and $a_f^{(5)TJK}$ from studies of the DY process at the LHC. (c) Comparison of estimated attainable sensitivities to equivalent u-quark coefficients at the EIC and thte LHC. Values are in units of 10^{-5} and $10^{-6}\ GeV^{-1}$, for minimal and non-minimal coefficients, respectively.

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