Testing Lorentz Symmetry with an Electron-Ion Collider

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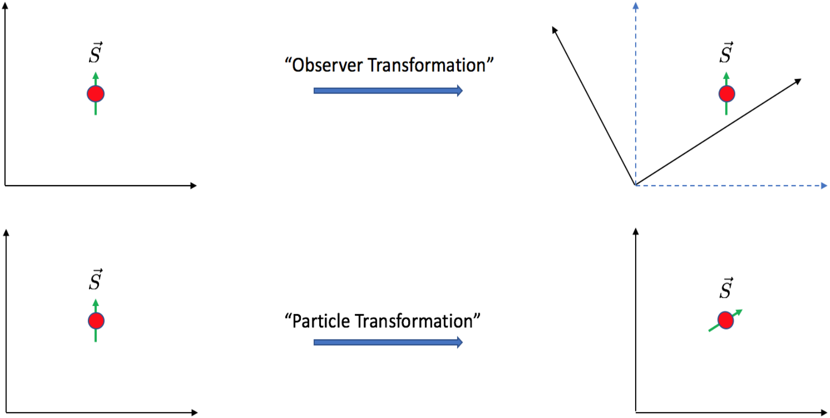
Outline

1. Introduction and motivation
   - Some basic notions of Lorentz violation
   - The Standard-Model Extension (SME)
2. Quark-sector application: Deep-inelastic *e*-*p* scattering (DIS)
   - Setup
   - Cross-section
   - Sun-centered frame and rotations
3. Previous studies and impact of an EIC
   - HERA analysis
   - Prospects at the EIC and (preliminary!) results
   - Wrap-up

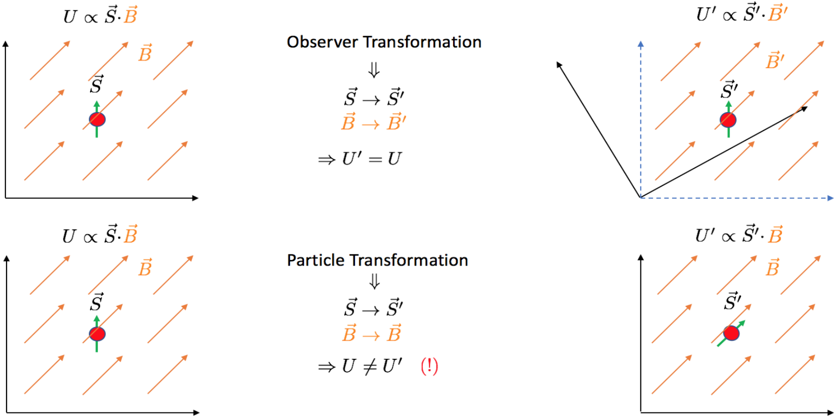
Basic ideas

- Consider the following:



- An observer transformation is simply a change of coordinates
- The system is unchanged under the particle transformation – we say the system possesses *rotation symmetry*

- Let's now add a background $\vec{B}$-field that permeates all of space:



- Performing a particle transformation now produces a physical effect
- This is what we mean by *rotation violation*
- The same ideas apply to *Lorentz violation* (rotations are a type of Lorentz transformation)

The Standard-Model Extension (SME)

- The most general effective field theory characterizing Lorentz and CPT violation is the *framework* known as the SME[1,2]

$$\mathcal{L}_{SME} = \mathcal{L}_{Gravity} + \mathcal{L}_{SM} + \mathcal{L}_{LV}$$

- The terms $\mathcal{L}_{LV}$ contain *all possible terms that break Lorentz symmetry*

  For example: $\mathcal{L}_{LV}^{QED} \supset a_\mu \bar{\psi}\gamma^\mu\psi,\ c_{\mu\nu}\bar{\psi}\gamma^\mu \overleftrightarrow{D}^\nu\psi$

- Important point: coefficients $a_\mu, c_{\mu\nu}$, etc. transform as 4-vectors/tensors under observer transformations but as scalars under particle transformations
- Some terms in the SME also violate CPT symmetry
- Since CPT violation implies Lorentz violation[3] the SME generally characterizes this effect as well

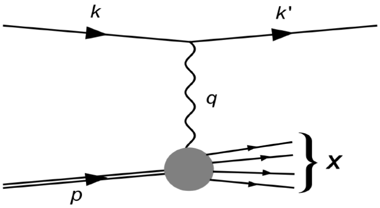
[1] D. Colladay & V. A. Kostelecký, PRD 55, 6760 (1997); PRD 58, 1166002 (1998)

[2] V. A. Kostelecký, PRD 69, 105009 (2004)

[3] O.W. Greenberg, PRL 89, 231602 (2002)

Outline

Setup



- At zeroth order in the strong interaction quarks dominantly interact electromagnetically with the electron
- There are many possible terms to consider but we focus solely on one class of spin-independent CPT-even contributions:[4]

$$\mathcal{L} = \sum_{f=u,d} (g^{\mu\nu} + c_f^{\mu\nu})\bar{\psi}_f \left(\frac{1}{2} i\gamma_\mu \overleftrightarrow{\partial}_\nu - q_f \gamma_\mu A_\nu\right) \psi_f$$

- Equivalent to $\gamma_\mu \to \gamma_\mu + c_{\mu\nu}\gamma^\nu$ for $f = u, d$ only (dominant proton flavor content)

[4] V. A. Kostelecký, E. Lunghi, A. Vieira, PLB 729, 272-280, 2017

- The observable of interest is the differential cross-section $d\sigma$
- Schematically:

$$d\sigma \sim \frac{|\mathcal{M}|^2}{F} dQ$$

- Effects of LV are considered on the amplitude $\mathcal{M}$

$$i\mathcal{M} = (-ie)\bar{u}(k')\gamma_\mu u(k)\frac{-i}{q^2}(ie)\int \mathrm{d}^4x e^{iq\cdot x}\langle X| J^\mu(x)|P\rangle$$

$$J^\mu(x) = q_f\bar{\psi}_f(x)\Gamma^\mu_f\psi_f(x)$$

$$\Gamma^\mu_f = \gamma^\mu + c_f^{\mu\nu}\gamma_\nu$$

- Using the optical theorem the hadronic vertex is related to the forward Compton-amplitude $W^{\mu\nu}$ which we evaluate using the parton model

$$W^{\mu\nu} \simeq i\int \mathrm{d}^4x e^{iq\cdot x}\int_0^1 d\xi \sum_{f=u,d}\frac{f_f(\xi)}{\xi}\langle\xi P| T\{J^\mu(x)J^\nu(0)\}|\xi P\rangle$$

- The spin-averaged differential cross-section is

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}\phi} = \frac{\alpha^2 y}{2\pi q^4} L^{\mu\nu} \mathrm{Im}[W_{\mu\nu}]$$

- In the presence of LV there is a non-trivial dependence on the azimuthal (final state electron) scattering angle ϕ
- Averaging over ϕ enables us to split up the cross-section

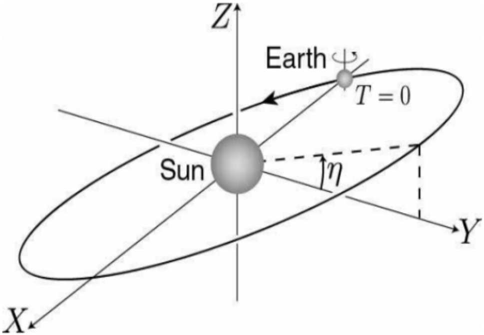
$$\left.\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}y}\right|_{SME} = \left.\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}y}\right|_{SM} + \left.\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}y}\right|_{LV}$$

with

$$\left.\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}y}\right|_{LV} \propto c_f^{\mu\nu} \beta_{\mu\nu}(p, q, x, y)_f$$

Sun-centered frame and rotations

- The standard choice of frame is the Sun-centered celestial-equatorial frame[5,6]
- This frame is approximately inertial over the duration of most experiments

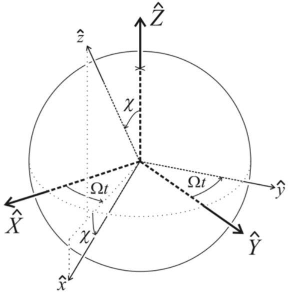


- Coefficients for LV are approximately constant in this frame

[5] V.A. Kostelecký and M. Mewes, Phys. Rev. D 66, 056005 (2002)

[6] Q. Bailey and V.A. Kostelecký, Phys. Rev. D 74, 045001 (2006)

- For laboratory measurements the rotation of the Earth *induces a sidereal time-dependence in $d\sigma$*



$$R = \begin{pmatrix} \pm 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & \mp 1 & 0 \end{pmatrix} \begin{pmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\chi\cos\Omega t & \cos\chi\sin\Omega t & -\sin\chi \\ -\sin\Omega t & \cos\Omega t & 0 \\ \sin\chi\cos\Omega t & \sin\chi\sin\Omega t & \cos\chi \end{pmatrix}$$

- To compare with experimental data, we must therefore perform a frame rotation
- Rotated coefficients from Sun-centered frame to lab frame are

$$c_{f,lab}^{\mu\nu} = \begin{cases} c_{f,sun}^{kl} R_{ik} R_{jl}, & \mu,\nu = i,j \in \{1,2,3\} \\ c_{f,sun}^{0k} R_{ik}, & \mu,\nu = 0, i \end{cases}$$

Outline

HERA analysis

- The first (estimated) constraints on the sidereal time-dependent coefficients of $c_f^{\mu\nu}$ were recently determined[7] from data taken at HERA[8]

Coefficient	Individual	Combined
$\lvert c_u^{TX}\rvert$	$< 4\times10^{-5}$	$< 1\times10^{-5}$
$\lvert c_u^{TY}\rvert$	$< 4\times10^{-5}$	$< 1\times10^{-5}$
$\lvert c_u^{XZ}\rvert$	$< 4\times10^{-5}$	$< 5\times10^{-6}$
$\lvert c_u^{YZ}\rvert$	$< 4\times10^{-5}$	$< 5\times10^{-6}$
$\lvert c_u^{XY}\rvert$	$< 4\times10^{-5}$	$< 3\times10^{-6}$
$\lvert c_u^{XX}-c_u^{YY}\rvert$	$< 1\times10^{-5}$	$< 8\times10^{-6}$
$\lvert c_d^{TX}\rvert$	$< 3\times10^{-4}$	$< 1\times10^{-4}$
$\lvert c_d^{TY}\rvert$	$< 3\times10^{-4}$	$< 1\times10^{-4}$
$\lvert c_d^{XZ}\rvert$	$< 4\times10^{-5}$	$< 2\times10^{-5}$
$\lvert c_d^{YZ}\rvert$	$< 4\times10^{-5}$	$< 2\times10^{-5}$
$\lvert c_d^{XY}\rvert$	$< 2\times10^{-5}$	$< 1\times10^{-5}$
$\lvert c_d^{XX}-c_d^{YY}\rvert$	$< 5\times10^{-5}$	$< 3\times10^{-5}$

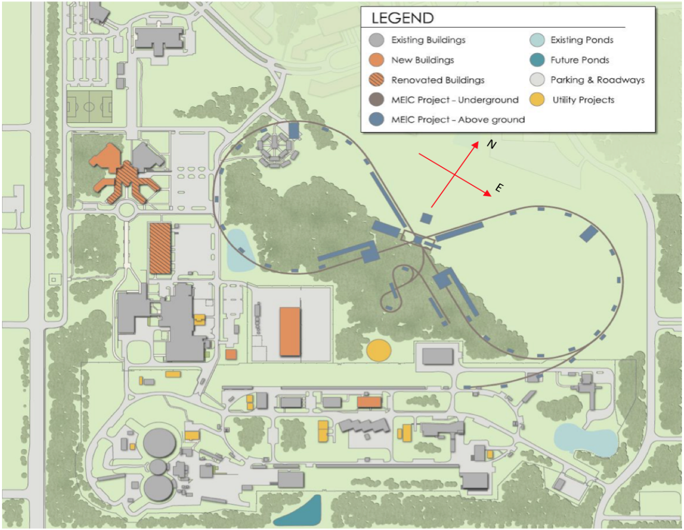
- Time-*independent* contributions to $d\sigma_{LV}$ were not constrained in this analysis

[7] V. A. Kostelecký, E. Lunghi, A. Vieira, PLB 729, 272-280, 2017

[8] H1 and ZEUS Collaboration, Eur. Phys. J. C (2015) 75:580

Prospects at EIC and (preliminary!) results

- JLab EIC (JLEIC) proposed configuration:



- Simulated reduced cross-section σ_r data of inclusive e-p DIS have been provided[9] for with ranges of x and Q^2 characteristic of the JLEIC design parameters
- The data include values of $x \in [0.009, 0.9]$ and $Q^2 \in [2.5, 631]$ GeV^2 along with statistical and systematic uncertainties
- Detector electron beam energy is fixed at $E_e = 10$ GeV whereas we have datasets with the proton beam energy set to $E_p = 20, 60, 80,$ and 100 GeV
- The general outline of the extraction of bounds on the coefficients is as follows:

  -We integrate the LV part of the cross-section into 4 bins of sidereal time

  -1000 randomized, Gaussian-distributed pseudo-experiments are generated that produce $\sigma^{exp.}_{r,ijk}$ at each (x, Q^2, Δ) value i, pseudo-experiment j, and bin k

[9] Data generated by A. Accardi (JLab/Hampton U.) and Y. Furletova (JLab)

- The 95% confidence level constraints on the magnitudes of each sidereal time-dependent coefficient are found by minimizing the χ^2:

$$\chi^2[c_f^{\mu\nu}]_{i,j} = \sum_{k=1}^{nbins} \frac{\left[\sigma_{r,ijk}^{exp.} - \sigma_{r,ik}^{SME}(c_f^{\mu\nu})\right]^2}{\Delta_i^2}$$

- The JEIC colatitude is $\chi \approx 52.9^\circ$ and there are two detectors with the following directions North of East:

  Orientation 1: $\psi \approx 47.6^\circ$
  Orientation 2: $\psi \approx -35.0^\circ$

- Table 1. and Table 2. on the following pages summarize our best estimates

TABLE 1. Orientation I – Un(correlated) Constraints

c_u^{TX}

E_p(GeV)	Constraint$\times 10^5$
20	7.89(3.38)
60	3.72(1.79)
80	1.04(0.97)
100	0.86(0.68)

c_u^{TY}

E_p(GeV)	Constraint$\times 10^5$
20	7.91(3.39)
60	3.73(1.80)
80	1.06(0.96)
100	0.85(0.67)

c_u^{XZ}

E_p(GeV)	Constraint$\times 10^5$
20	13.9(5.95)
60	6.41(3.08)
80	1.78(1.65)
100	1.47(1.16)

c_u^{YZ}

E_p(GeV)	Constraint$\times 10^5$
20	13.9(5.97)
60	6.43(3.10)
80	1.81(1.64)
100	1.45(1.14)

c_u^{XY}

E_p(GeV)	Constraint$\times 10^5$
20	50.1(22.5)
60	23.7(11.5)
80	6.78(6.13)
100	5.46(4.26)

$|c_u^{XX} - c_u^{YY}|$

E_p(GeV)	Constraint$\times 10^5$
20	42.8(19.2)
60	20.2(9.81)
80	5.79(5.23)
100	4.66(3.64)

c_d^{TX}

E_p(GeV)	Constraint$\times 10^4$
20	13.0(5.66)
60	6.35(3.06)
80	1.71(1.53)
100	1.36(1.16)

c_d^{TY}

E_p(GeV)	Constraint$\times 10^4$
20	13.1(5.69)
60	6.45(3.07)
80	1.75(1.53)
100	1.37(1.15)

c_d^{XZ}

E_p(GeV)	Constraint$\times 10^4$
20	22.8(9.96)
60	10.9(5.27)
80	2.92(2.61)
100	2.33(2.00)

c_d^{YZ}

E_p(GeV)	Constraint$\times 10^4$
20	23.0(10.0)
60	11.1(5.28)
80	2.99(2.62)
100	2.35(1.96)

c_d^{XY}

E_p(GeV)	Constraint$\times 10^4$
20	86.1(37.1)
60	41.8(19.4)
80	10.9(9.91)
100	8.67(7.21)

$|c_d^{XX} - c_d^{YY}|$

E_p(GeV)	Constraint$\times 10^4$
20	73.5(31.7)
60	35.7(16.5)
80	9.31(8.39)
100	7.41(6.16)

Table 2. Orientation II – Un(correlated) Constraints

c_u^{TX}

E_p(GeV)	Constraint$\times 10^5$
20	7.18(3.04)
60	3.47(1.66)
80	0.98(0.87)
100	0.78(0.61)

c_u^{TY}

E_p(GeV)	Constraint$\times 10^5$
20	7.02(3.10)
60	3.45(1.62)
80	0.96(0.87)
100	0.76(0.61)

c_u^{XZ}

E_p(GeV)	Constraint$\times 10^5$
20	16.3(6.90)
60	7.69(3.67)
80	2.15(1.92)
100	1.72(1.35)

c_u^{YZ}

E_p(GeV)	Constraint$\times 10^5$
20	15.9(7.03)
60	7.64(3.60)
80	2.10(1.91)
100	1.71(1.35)

c_u^{XY}

E_p(GeV)	Constraint$\times 10^5$
20	23.9(10.3)
60	11.3(5.39)
80	3.16(2.84)
100	2.56(2.02)

$|c_u^{XX} - c_u^{YY}|$

E_p(GeV)	Constraint$\times 10^5$
20	46.5(19.9)
60	22.0(10.49)
80	6.12(5.52)
100	4.98(3.93)

c_d^{TX}

E_p(GeV)	Constraint$\times 10^4$
20	11.8(5.19)
60	5.84(2.79)
80	1.58(1.41)
100	1.23(1.04)

c_d^{TY}

E_p(GeV)	Constraint$\times 10^4$
20	11.9(5.16)
60	5.90(2.78)
80	1.58(1.42)
100	1.23(1.05)

c_d^{XZ}

E_p(GeV)	Constraint$\times 10^4$
20	26.8(11.8)
60	12.94(6.17)
80	3.48(3.10)
100	2.71(2.29)

c_d^{YZ}

E_p(GeV)	Constraint$\times 10^4$
20	26.9(11.7)
60	13.1(6.17)
80	3.47(3.13)
100	2.71(2.31)

c_d^{XY}

E_p(GeV)	Constraint$\times 10^4$
20	39.1(17.2)
60	19.1(8.99)
80	5.01(4.56)
100	3.99(3.40)

$|c_d^{XX} - c_d^{YY}|$

E_p(GeV)	Constraint$\times 10^4$
20	76.0(33.5)
60	37.2(17.5)
80	9.74(8.88)
100	7.41(6.16)

Wrap-up

- We have estimated the constraints obtainable on a particular subset of LV coefficients in the quark-sector of the SME
- This was done by analyzing simulated inclusive DIS data for the proposed JLEIC collider
- Preliminary results suggest similar sensitivities to the estimated bounds obtained by the HERA analysis—but the set of coefficients are unique
- Analysis of RHIC EIC pseudo-data underway
- We look forward to the first real bounds being placed by experiments in the near future!

Backup

- The (γ exchange only) LV cross-section is

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}\phi} = \frac{\alpha^2}{q^4}\sum_f q_f^2 f_f(x_f')x_f' \left[\frac{ys^2}{\pi}(1+(1-y)^2)\delta_f + \frac{y^2 s}{x}x_f \right.$$
$$+4\left(c_f^{k'p} + c_f^{pk'}\right) + \frac{4}{x}(1-y)c_f^{kk} - 4xyc_f^{pp}$$
$$\left. -\frac{4}{x}c_f^{k'k'} + 4(1-y)(c_f^{kp} + c_f^{pk})\right]$$

$$c_f^{kp} \equiv c_f^{\mu\nu} k_\mu p_\nu$$
$$x_f' = x - \frac{2}{ys}\left(c_f^{qq} + x(c_f^{pq} + c_f^{qp}) + x^2 c_f^{pp}\right) \equiv x - x_f$$
$$\delta_f = \frac{\pi}{ys}\left(1 - \frac{2}{ys}(c_f^{pq} + c_f^{qp} + 2xc_f^{pp})\right)$$