Lorentz and CPT violation in the Standard-Model Extension

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SSP 2012, 18 June 2012, Groningen

Why test Spacetime Symmetries?

Motivation (i): philosophical necessity

physics is an experimental science

→ solid experimental confirmation of foundations of physics is crucial

Motivation (ii): discovery potential

various approaches to physics beyond the Standard Model („quantum gravity") can accomodate tiny violations of Relativity

Outline:

A. It can be modeled in EFT
→ SME test framework

B. It can happen in underlying physics
→ Possible origins of LV

C. It can be tested with Planck reach
→ Phenomenology

A. Effective field theory test framework

Why test model?

- prediction of experimental effects
- analysis and comparison of tests
- theoretical insight

How to obtain test model?

Purpose: broad experimental searches independent of details of underlying physics

→ construct gen. model compatible with key phys. principles

Ingredients for test model?

- established physics → all feasible tests can be described
- effective field theory (well established & versatile tool)
- implementation of Lorentz violation (preferred directions)

Actual construction of the effective field theory (SME)

$$\mathcal{L}_{\text{SME}} = \underbrace{\mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{EH}}}_{\text{present physics}} + e k_\mu A_\nu \tilde{F}^{\mu\nu} + \frac{e}{2\kappa} s^{\mu\nu} R_{\mu\nu} + \ldots$$

- k^μ, $s^{\mu\nu}$, ... coefficients for Lorentz violation
- minimal SME → fermion 44, photon 23, ...
- amenable to ultrahigh-precision tests (Sec C)
- generated by underlying physics (Sec B)

Colladay, Kostelecký '97;'98; Kostelecký '04; Coleman, Glashow '99

Remarks:

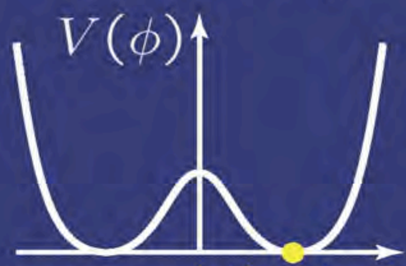
- can consider higher-dim. operators
  (eg, Myers, Pospelov '03; Reyes, Urrutia, Vergara '07; '08)
- can consider spacetime dependence, e.g., $s^{\mu\nu} \sim R^{\mu\nu}$, etc.
  (eg, Shore '02; '03; '04; '07; '08; Sudarsky *et al.* '05; '08)

B. Possible origins for Lorentz/CPT violation

(1) Spontaneous Lorentz breaking in string theory

conventional case: gauge symmet.

$\mathcal{L} \supset \lambda\phi\overline{\psi}\psi$

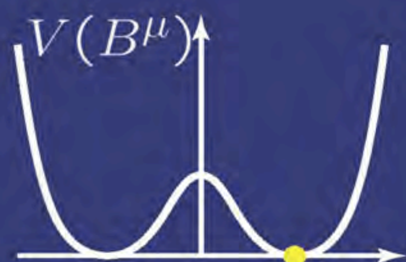


$\langle\phi\rangle \neq 0 \quad \phi$

$\mathcal{L} \supset \underbrace{\lambda\langle\phi\rangle}_{m\,=\,\text{const.}}\overline{\psi}\psi$

string theory: Lorentz symmetry

$\mathcal{L} \supset \lambda B^\mu\overline{\psi}\gamma_5\gamma_\mu\psi$



$\langle B^\mu\rangle \neq 0$

$\mathcal{L} \supset \underbrace{\lambda\langle B^\mu\rangle}_{b^\mu\,=\,\text{const.}}\overline{\psi}\gamma_5\gamma_\mu\psi$

Kostelecký, Perry, Potting, Samuel '89; '90; '91; '95; '00

(2) Cosmol. varying scalars (e.g., fine-structure parameter)

intuitive argument:

☐ small scalar

■ large scalar

gradient of the scalar <u>selects pref. direction</u>

mathematical argument:

$\xi = \xi(x)$ ... varying coupling

ϕ, Φ ... dynamical fields

$$\mathcal{L} \supset \xi\, \partial^\mu \phi\, \partial_\mu \Phi$$

↓

Integration by parts:

$$\mathcal{L}' \supset -(\partial^\mu \xi)\, \phi\, \partial_\mu \Phi$$

↓

slow variation of ξ:

$K^\mu \equiv (\partial^\mu \xi) \simeq \text{const.}$

$$\mathcal{L}' \supset -K^\mu\, \phi\, \partial_\mu \Phi$$

Kostelecký, R.L., Perry '03; Arkani-Hamed et al. '03

Other mechanisms for Lorentz violation

Noncommutative geometry (QM of spacetime points)

$$[\hat{x}^\mu, \hat{x}^\nu] = i\theta^{\mu\nu}$$

Seiberg-Witten: $\hat{x}^\mu \rightarrow$ usual Minkowski coordinates x^μ

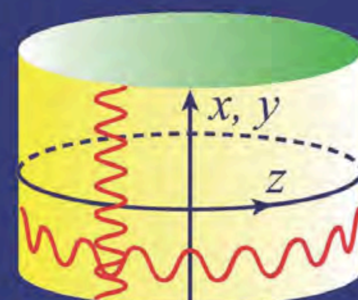
$\rightarrow$ SME terms emerge: $\mathcal{L}_{\text{photon}} \supset \frac{1}{8} q\, \theta^{\alpha\beta} F_{\alpha\beta} F^{\mu\nu} F_{\mu\nu}$

e.g. Mocioiu *et al.* '00; Carroll *et al.* '01

Topology (1 spatial dim. is compact: large radius R)

Vacuum fluctuations along this dim.
have periodic boundary conditions
$\rightarrow$ preferred direction in vacuum

$\rightarrow$ calculation: $k^\mu A^\nu \tilde{F}_{\mu\nu} \subset \mathcal{L}_{\text{SME}}$



Klinkhamer '00

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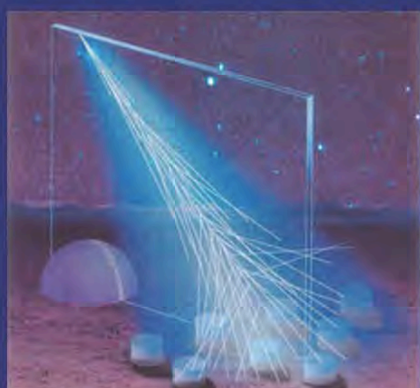
C. Phenomenology and Tests

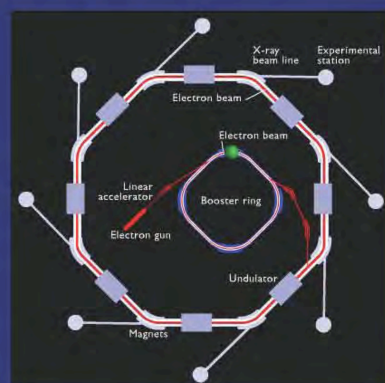
experimental investigations of such effects require ultra-high energies, or ultra-high precision, or both

low precision, ultra-high energies:



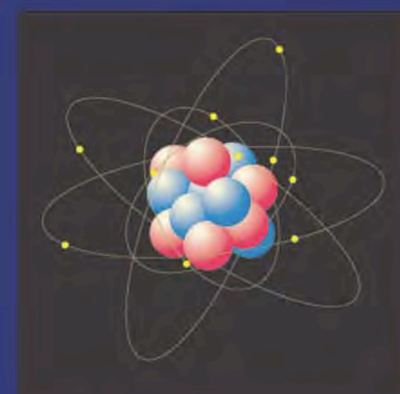
e.g., cosmic rays

high precision, high energies:



e.g., colliders

ultra-high precision, low energies



e.g., spectroscopy

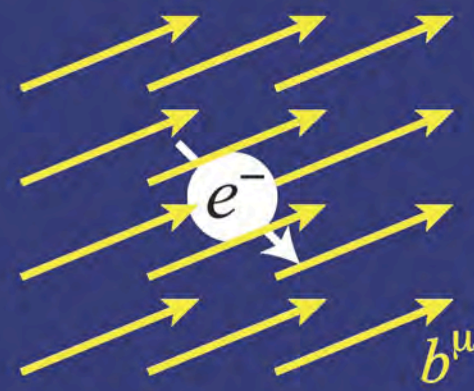
Low-energy tests: bound states

Reminder:

- direction in vacuum
- assumed to be caused by underlying physics
- on observational grounds: extremely small
- want to bound it or measure its size and direction

$$\delta\mathcal{L}_{\mathrm{fermion}} \supset \overline{\psi} b^{\mu} \gamma_5 \gamma_{\mu} \psi$$

wave function of a fermion (e.g., electron) and usual Dirac gamma matrices (details of coupling)



Conventional electrodynamics:

in QED Lagrangian, coupling of *E, B* fields to electrons is:

$$\overline{\psi} A^\mu \gamma_\mu \psi$$

nontrivial potential *A* affects, e.g., atomic spectra:

- Stark effect
- Zeeman effect
- . . .

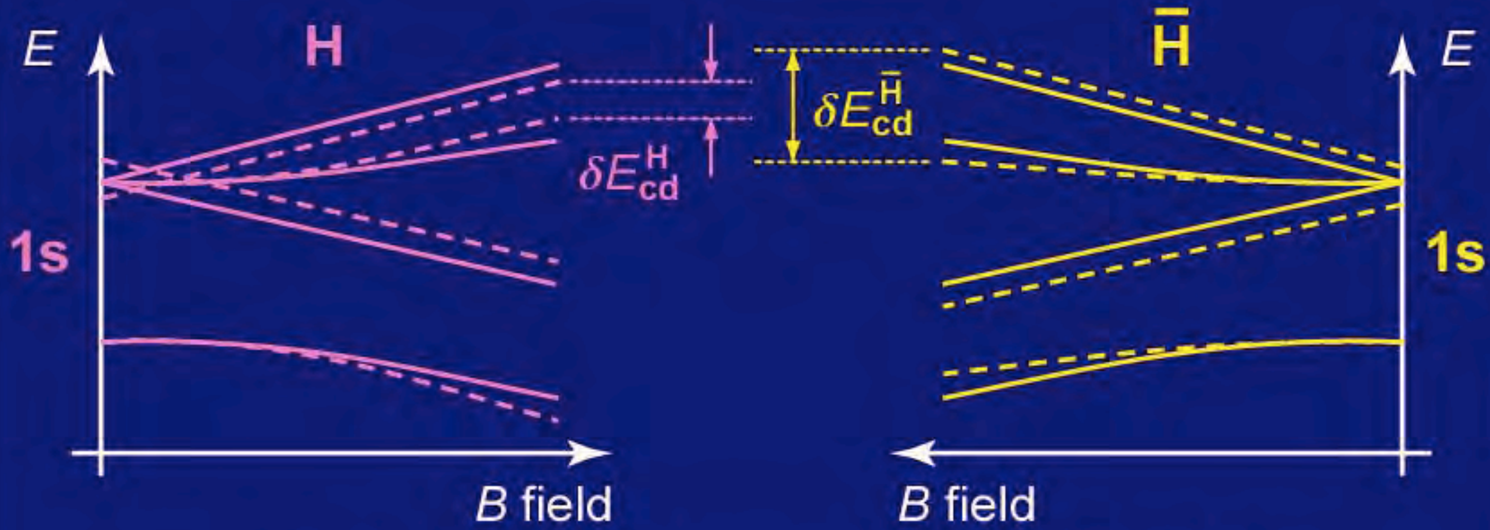
How does Lorentz and CPT breakdown affect matter?

the SME Lagrangian contains $\overline{\psi} b^\mu \gamma_5 \gamma_\mu \psi$

Expect: Lorentz/CPT violation shifts energy levels

(1) matter-antimatter comparisons: e.g., Antihydrogen spectroscopy

H / $\bar{\text{H}}$ spectroscopy: hyperfine Zeeman transitions
(Bluhm, Kostelecký, Russell, PRL '99):



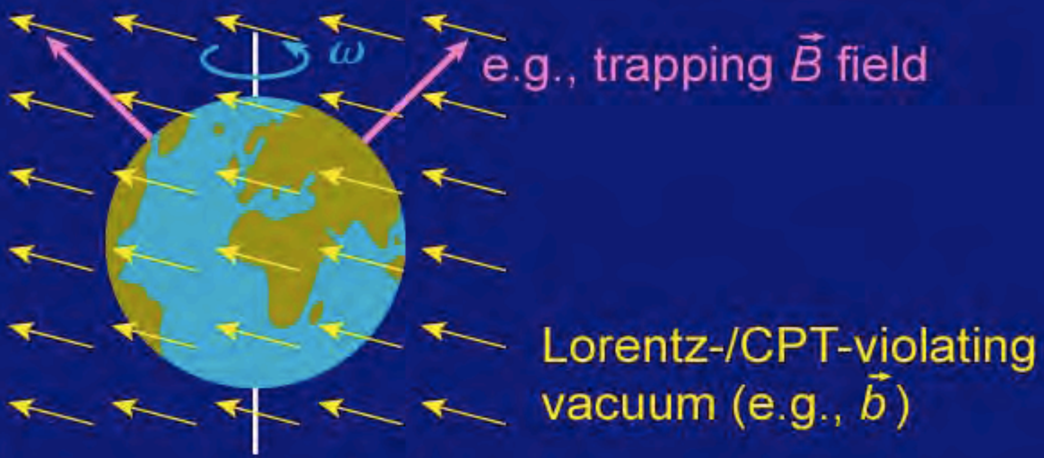
at field-independent transition point ($B \simeq 0.65$T):

$\delta E_{cd}^{\text{H}} - \delta E_{cd}^{\bar{\text{H}}} \simeq$ (CPT-/Lorentz-violating SME coefficient for p)

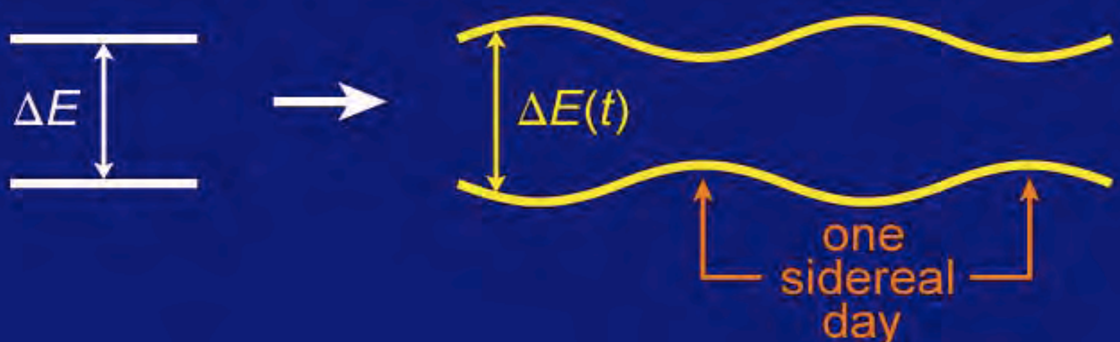
instantaneous comparison assuming 1m Hz resolution:
10^{-17} eV sensitivity to | CPT-/Lorentz-violating SME coefficient for p |

Earlier (G. Gabrielse) + Thur morning (D.P. van der Werf, R. Hayano, E. Widmann)

(2) searches for sidereal variations

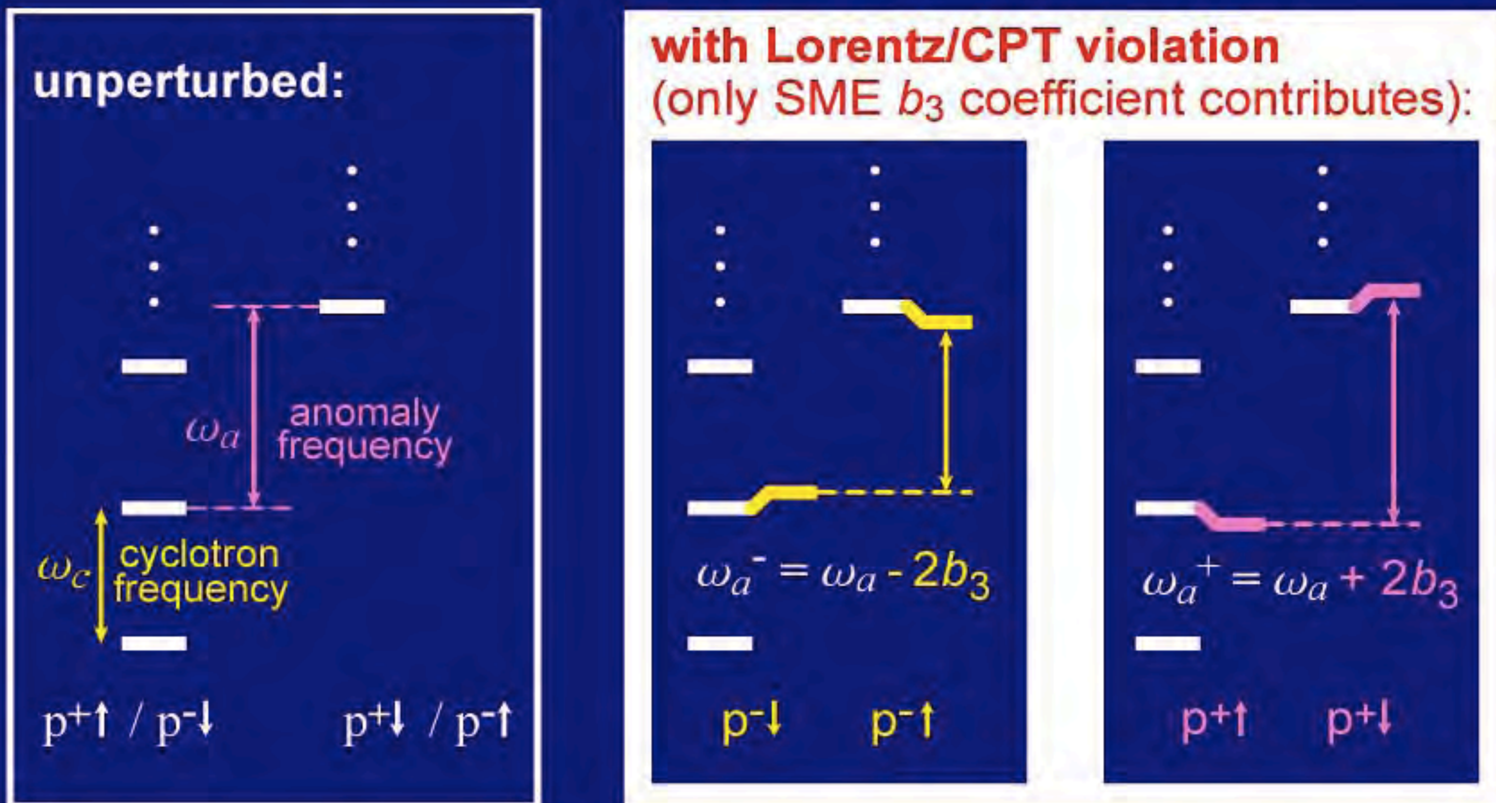


observables ~ $\vec{b} \cdot \vec{B}$ (e.g., transition frequencies) are time dependent:



See, e.g., previous talk by W. Heil

Sample test: antiprotons in Penning traps



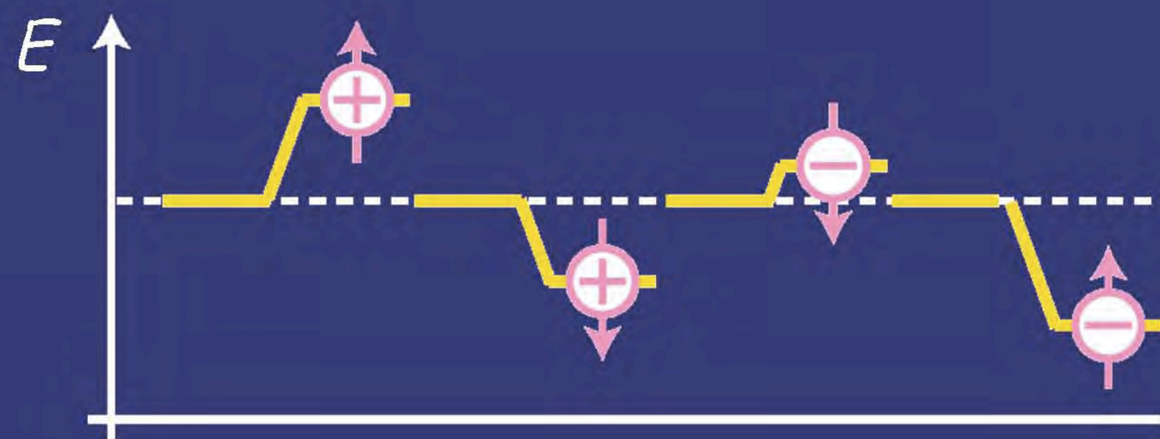
instantaneous comparison assuming 2 Hz resolution:
10^{-24} GeV sensitivity to $|2b_3|$

antiproton mag. moment, earlier today (G. Gabrielse)

3rd Class of Tests: free particles

dispersion relation now contains Lorentz-violating terms:

$$(p^2 - m^2)^2 + \text{SME correction} = 0$$

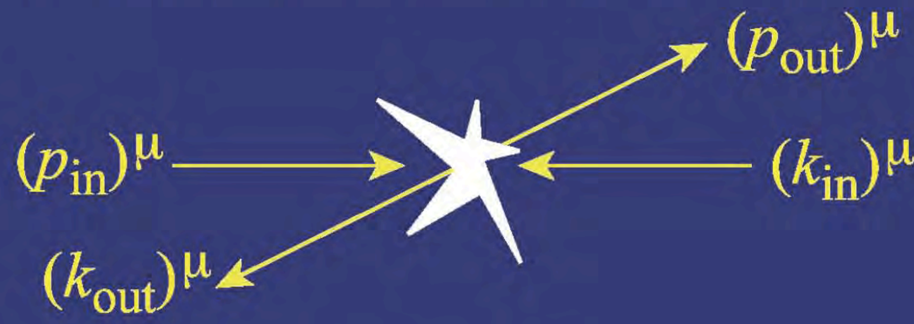


→ usual 4-fold degeneracy for $E(\vec{p} = \text{const.})$ is lifted

Sample effect: threshold modification in particle reactions

kinematical changes in particle collisions:

p dependence of *E* is modified: $E(\vec{p}) = \sqrt{m^2 + \vec{p}^2} + \delta E_{\mathsf{LV}}(\vec{p})$



Energy-momentum conservation:

$$\begin{pmatrix} E^{\vec{p}}_{\mathsf{in}} + \delta E^{\vec{p}}_{\mathsf{in}} \\ \vec{p}_{\mathsf{in}} \end{pmatrix} + \begin{pmatrix} E^{\vec{k}}_{\mathsf{in}} + \delta E^{\vec{k}}_{\mathsf{in}} \\ \vec{k}_{\mathsf{in}} \end{pmatrix} = \begin{pmatrix} E^{\vec{p}}_{\mathsf{out}} + \delta E^{\vec{p}}_{\mathsf{out}} \\ \vec{p}_{\mathsf{out}} \end{pmatrix} + \begin{pmatrix} E^{\vec{k}}_{\mathsf{out}} + \delta E^{\vec{k}}_{\mathsf{out}} \\ \vec{k}_{\mathsf{out}} \end{pmatrix}$$

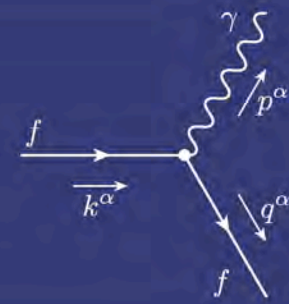
→ thresholds may be shifted
→ decays/reactions normally allowed may now be forbidden
→ decays/reactions normally forbidden may now be allowed
→ kinematical modifications in existing effects

Vacuum Cherenkov radiation: $e \rightarrow e + \gamma$

- not seen for 104.5 GeV electrons at LEP

$\rightarrow$ can extract bound: certain LV < 10^{-11}

(Hohensee, R.L., Phillips, Walsworth, PRL '09)

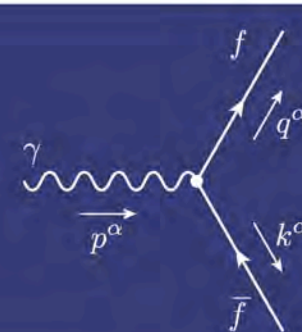


Photon decay: $\gamma \rightarrow e^{+} + e^{-}$

- not seen for 300 GeV photons at Tevatron

$\rightarrow$ can extract bound: certain LV < 10^{-12}

(Hohensee, R.L., Phillips, Walsworth, PRL '09)

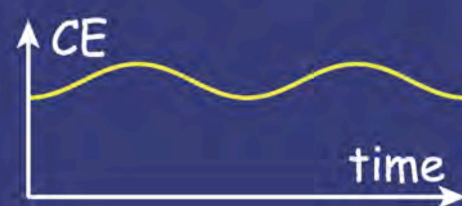


Sidereal variations of the Compton edge: $\gamma + e^{-} \rightarrow \gamma + e^{-}$

- not seen at ESRF's GRAAL facility

$\rightarrow$ can extract bound: certain LV < 10^{-13}

(Bocquet *et al.*, PRL '10)



Other sample tests with free particles:

Muon (g – 2) collaboration:

| certain LV for muon | < 10^{-23} ... 10^{-24} GeV

"Search for Lorentz and CPT Violation Effects in Muon Spin Precession," PRL 100, 091602 (2008)

Weak decay of ^{80}Rb and ^{20}Na (AGOR cyclotron at the KVI):

See talk by Stefan Mueller (this afternoon)

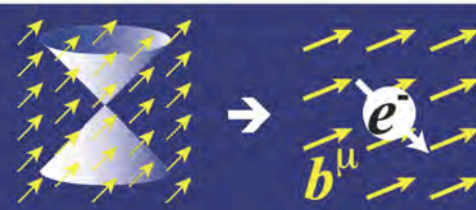
...

Summary

presently no credible exp. evidence for Relativity violations, but:

(1) various theoretical approaches to quantum gravity can cause such violations

(2) at low E, such violations are described by SME test framework (eff. field theory + background fields)



(3) high-precision tests in various atomic and subatomic systems possible