Tests of Lorentz symmetry and CPT invariance

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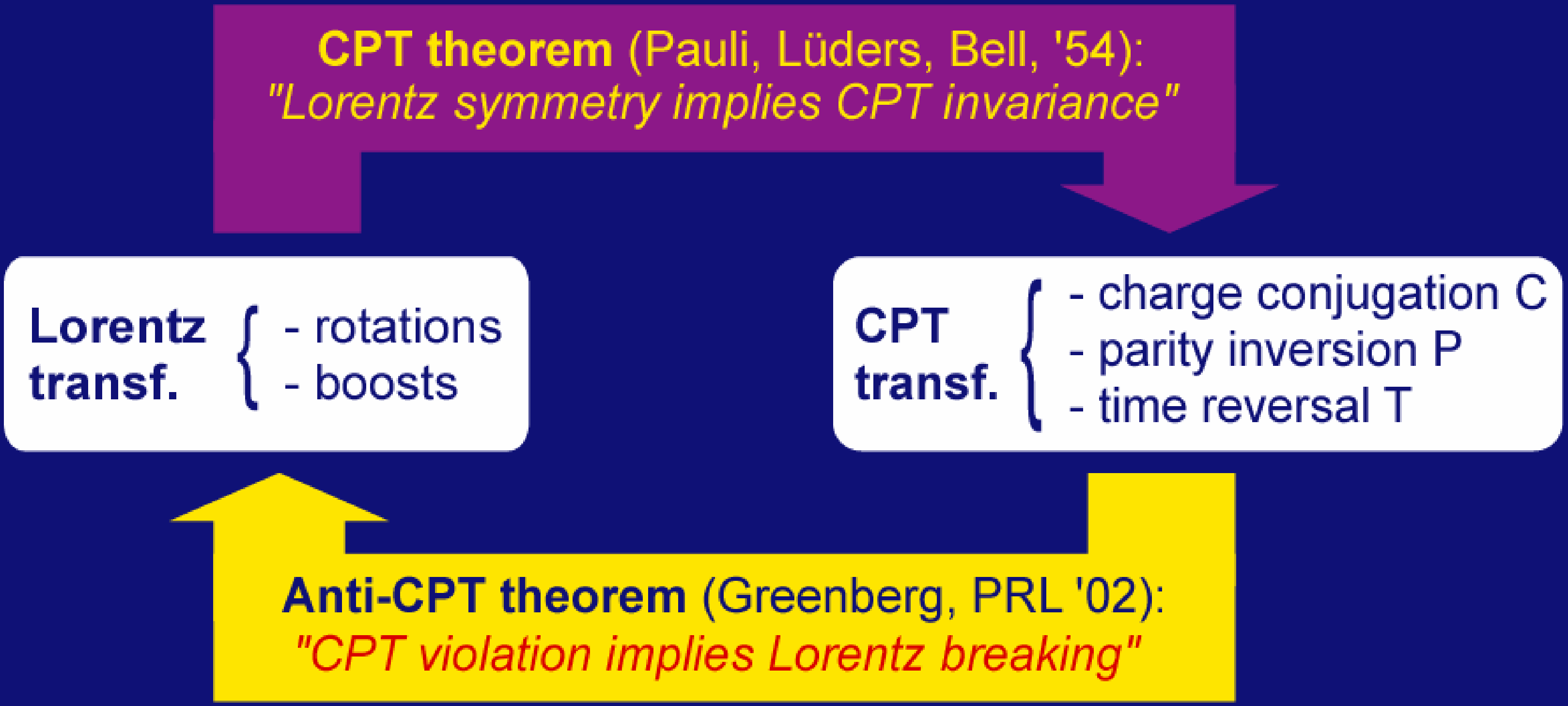
Prologue: Connection between Lorentz and CPT symmetry

Local, point-particle quantum field theories:



CPT theorem (Pauli, Lüders, Bell, '54):
"Lorentz symmetry implies CPT invariance"

Lorentz transf.
- rotations
- boosts

CPT transf.
- charge conjugation C
- parity inversion P
- time reversal T

Anti-CPT theorem (Greenberg, PRL '02):
"CPT violation implies Lorentz breaking"

→ **CPT tests are also Lorentz tests**
→ **will discuss CPT and Lorentz violation together**

Outline:

A. Motivation

B. SME test framework

C. Phenomenology and tests

A. Motivations for spacetime-symmetry tests

(i) philosophical necessity

spacetime symmetries are cornerstone of:

- present-day physics
- many candidate fundamental theories

→ spacetime symmetries must be tested

(ii) possibility of testing Planck-scale physics

Nongravitational physics is well described by Standard Model (SM),

but:
- phenomenological (many parameters)
- several distinct interactions
- excludes gravity

Solution: look for more fundamental theory

Candidates: string (M) theory, loop gravity, supergravity, …

Problem: Planck-scale measurements
(attainable energies ≪ Planck scale)

common approach: scan predictions of a given theory for sub-Planck effects accessible with near-future technology, e.g.,
- novel particles (SuSy)
- large extra dimensions & microscopic black holes
- gravitational-wave background …

Alternative approach: What *can* be measured with Planck precision? *Is* there a corresponding quantum-gravity effect?

Symmetries:

- allow exact theoretical prediction
- are typically amenable to ultrahigh-precision (null) tests

Tests of spacetime symmetries could probe Planck-scale physics

Quantum gravity: likely to affect spacetime structure

- More than 4 dimensions?
- Non-commuting coordinates?
- Discreteness?
- “Foamy” structure? …

B. The SME test framework

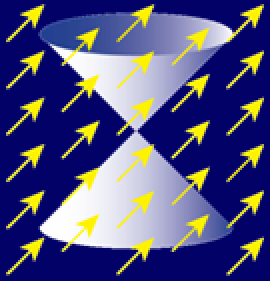
(1) new transformations

- vacuum remains "empty"
- no Minkowski structure
- deformed lightcone

- relativ. simple, kinematical, and phenomenological

(2) "background" fields

- ext. "fields" in vacuum
- conv. Minkowski structure
- conv. lightcone



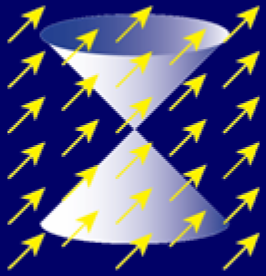
- microscopic, dynamical, can be motivated (later)

E.g.: Robertson's framework, its Mansouri-Sexl extension, DSR, ...

SME; contains some of the kinematical approaches; will focus on this description

Construction of the SME

$$\mathcal{L}_{\text{SME}} = \underbrace{\mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{EH}}}_{\text{present physics}}$$



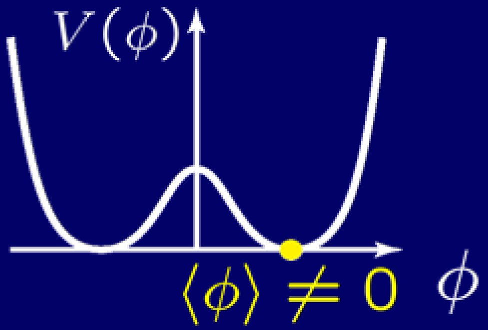
- k^{μ}, $s^{\mu\nu}$, ... coefficients for Lorentz violation
- minimal SME → fermion 44, photon 23, ...
- generated by underlying physics (Sec A & next)
- amenable to ultrahigh-precision tests (Sec C)

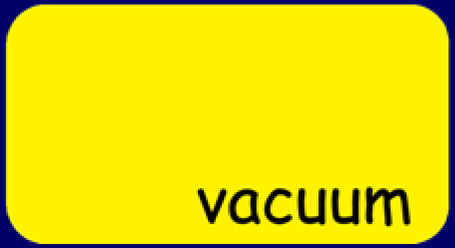
Q: Can these effects actually be generated in underlying physics?
A: **Yes!** (see next slides)

(1) Spontaneous Symmetry Breaking

conventional
case:
gauge symmet.

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

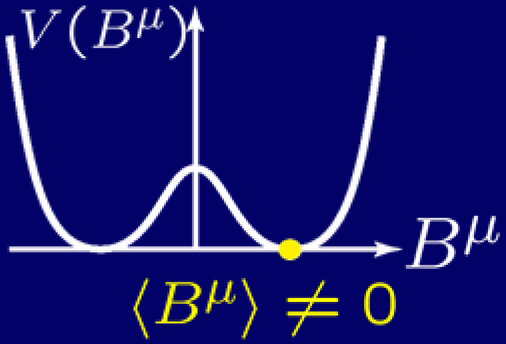


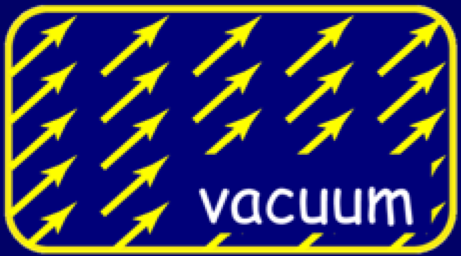


$$\mathcal{L} \supset \underbrace{\lambda \langle\phi\rangle}_{m = \text{const.}} \overline{\psi} \psi$$

string theory:
Lorentz
symmetry

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



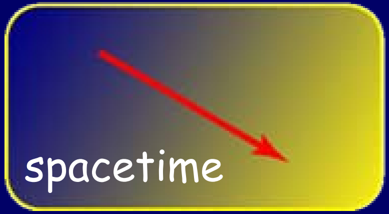


$$\mathcal{L} \supset \underbrace{\lambda \langle B^{\mu}\rangle}_{b^{\mu} = \text{const.}} \overline{\psi} \gamma_5 \gamma_\mu \psi$$

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 selects pref. direction

mathematical argument:

$a = a(x)$ ... cosm. varying coupling (axion?)
F ... vector-field strength (photon?)

$$\mathcal{L} \supset a(x)\, F\tilde{F}$$

Integration by parts:

$$\mathcal{L}' \supset -2(\partial^\mu a)\, A^\nu \tilde{F}_{\mu\nu}$$

slow variation of ξ:
$k^\mu \equiv 2(\partial^\mu a) \simeq \text{const.}$

$$\mathcal{L}' \supset -k^\mu A^\nu \tilde{F}_{\mu\nu}$$

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

Other mechanisms for Lorentz violation

Noncommutative geometry (QM of spacetime points)

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

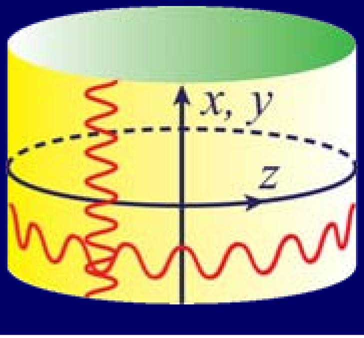
Seiberg-Witten: $\widehat{x}^\mu \to$ usual Minkowski coordinates x^μ

→ 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., Carroll *et al.* '01

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

Vacuum fluctuations along this dim.
have periodic boundary conditions
→ preferred direction in vacuum



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

Klinkhamer '00

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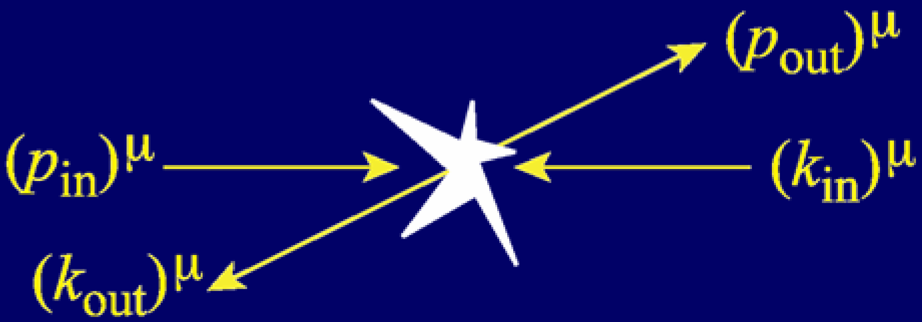
C. Phenomenology

(1) Free particles: modified dispersion relations

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



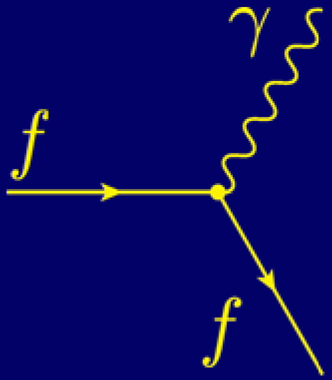
Energy-momentum conservation:

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

→ thresholds may be shifted
→ decays/reactions normally allowed may now be forbidden
→ decays/reactions normally forbidden may now be allowed

Sample tests at colliders

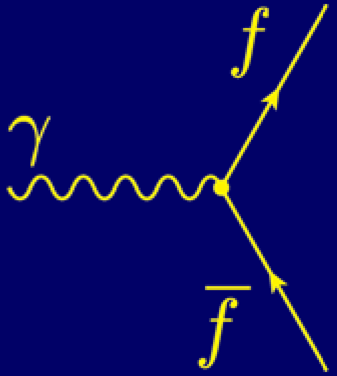
Vacuum Cherenkov radiation (charges become unstable):



-threshold effect: higher $E \rightarrow$ better bound
-look at LEP electrons: not observed

$\rightarrow$ exp. limit: (certain LV in QED) < 10^{-11}

Photon decay (photons become unstable):



-threshold effect: higher $E \rightarrow$ better bound
-look at Tevatron photons: not observed

$\rightarrow$ exp. limit: (certain LV in QED) > -10^{-12}

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

Sample astrophysical test

Spectropolarimetry of cosmological sources

Lorentz-violating vacuum can lead to birefringence ($v_R \neq v_L$)

→ cosm. sources at large distances with known polarization permit searching for predicted energy-independent polarization changes

polarization at emission ≠ observed polarization

(see also W.-T. Ni's talk later today)

Result: $|(k_{AF})^{\mu}| \lesssim 10^{-42}$ GeV (Carrol, Field, Jackiw '90)

Result: $|(k_F)^{\alpha\beta\gamma\delta}| \lesssim 2 \cdot 10^{-32}$ (Kostelecký, Mewes '01)

(2) Energy-level shifts in bound states

Analogy to 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
- . . .

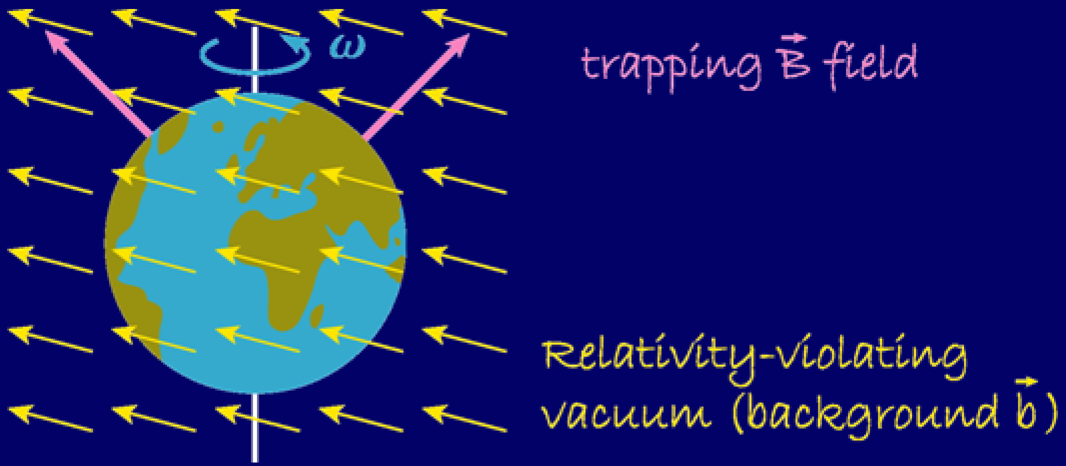
How does Lorentz and CPT breakdown affect matter?

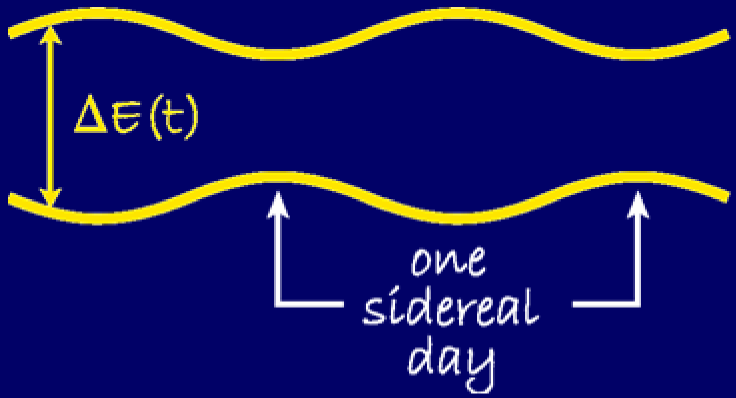
the SME Lagrangian contains $\overline{\psi} b^\mu \gamma_5 \gamma_\mu \psi$

Expect: Lorentz/CPT violation shifts energy levels

Sample test: clock comparisons – sidereal variations

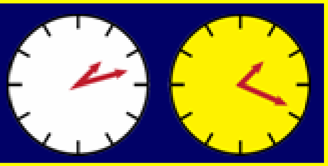
clock: nuclear or atomic transition in trapped particle





transition frequencies ~ $\vec{b}\cdot\vec{B}$
→ time dependent

no effect in various clock-comparison tests
→ Relativity holds to ~10^{-30} GeV



Sample phenomenological studies performed within the SME

(Anti)Hydrogen spectroscopy

Bluhm, Kostelecký, Russell '99	(Indiana)
Phillips *et al.* '01	(Harvard-Smithsonian)

Experiments in Penning traps

Bluhm, Kostelecký, Russell '97; '98	(Indiana)
Gabrielse *et al.* '99	(Harvard)
Mittelman *et al.* '99	(Seattle)
Dehmelt *et al.* '99	(Seattle)

Studies with muons

Bluhm, Kostelecký, Lane '99	(Indiana)
Hughes, Jungmann *et al.* '00	(Yale, Heidelberg, ...)
(g-2) collaboration '08	(Brookhaven)

Clock comparisons

Kostelecký, Lane '99	(Indiana)
Hunter *et al.* '99	(Amherst)
Stoner '99	(Harvard-Smithsonian)
Bear *et al.* '00	(Harvard-Smithsonian)
Canè *et al.* '04	(Harvard-Smithsonian)

Space-based tests

Kostelecký *et al.* '02; '03	(Indiana)
ACES	(CNES, SYRTE, PTB, LUH, ...)
PARCS?	(JPL, NIST, ...)
RACE?	(Penn State, JPL, CalTech)
SUMO?	(Stanford, ...)
OPTIS?	(ZARM, Humboldt, ...)

Tests with Photons and radiative corrections

Carroll, Field, Jackiw '90	(M.I.T.)
Colladay, Kostelecký '98	(Indiana)
Jackiw, Kostelecký '99	(M.I.T. & Indiana)
Kostelecký, Mewes '01; '02; ‘06; ‘07	(Indiana)
Lämmerzahl *et al.* '03	(ZARM, Humboldt)
Lipa *et al.* '03	(Stanford)
Stanwix *et al.* '05	(Western Australia)

Gravity

Lämmerzahl ‘97	(ZARM)
Bailey, Kostelecký '06	(Indiana)
Battat *et al.* ‘07	(Harvard-Smithsonian)
Müller *et al.* ‘08	(Stanford, ...)

Neutrinos

Barger, Pakvasa, Weiler, Whisnant '00	(Wisconsin, ...)
Kostelecký *et al.* '03; '04; '06	(Indiana)
LSND ‘05	(Los Alamos)

Cosmic radiation

Coleman, Glashow '99	(Harvard)
R.L. '03	(München)
Altschul ‘06; ‘07	(South Carolina)

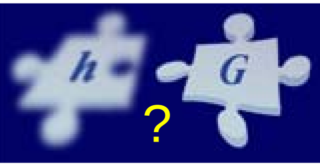
Meson oscillations

Kostelecký *et al.* '95; '96; '98; '00	(Indiana)
KTeV collaboration, Hsiung *et al.* '99	(Fermilab)
FOCUS collaboration, Link *et al.* '03	(Fermilab)
OPAL collaboration, Ackerstaff *et al.* '97	(CERN)
DELPHI collaboration, Feindt *et al.* '97	(CERN)
BELLE collaboration	(KEK)
BaBar collaboration ‘08	(SLAC)

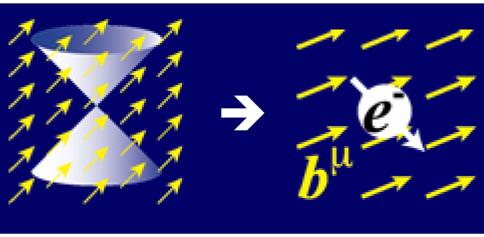
Summary

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

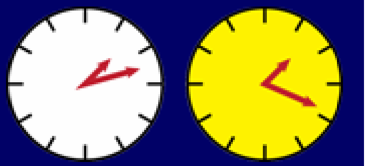
(1) various theoretical approaches to quantum gravity can cause such violations



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



(3) high-precision tests (spectroscopy, astrophysical studies, satellite missions, atomic clocks, interferometry, ...) possible



"Data Tables for Lorentz and CPT Violation"
arXiv: 0801.0287

Bounds on SME coeff. for matter

Coefficient	Proton	Neutron	Electron
$\tilde{b}_X$	10^{-27} GeV	10^{-31} GeV	10^{-31} GeV
$\tilde{b}_Y$	10^{-27} GeV	10^{-31} GeV	10^{-30} GeV
$\tilde{b}_Z$	–	–	10^{-29} GeV
$\tilde{b}_T$	–	10^{-27} GeV	–
$\tilde{b}^*_J$ $(J = X, Y, Z)$	–	–	–
$\tilde{c}_-$	10^{-25} GeV	10^{-27} GeV	10^{-19} GeV
$\tilde{c}_Q$	10^{-22} GeV	–	10^{-19} GeV
$\tilde{c}_X$	10^{-25} GeV	10^{-25} GeV	10^{-19} GeV
$\tilde{c}_Y$	10^{-25} GeV	10^{-25} GeV	10^{-19} GeV
$\tilde{c}_Z$	10^{-24} GeV	10^{-27} GeV	10^{-19} GeV
$\tilde{c}_{TX}$	10^{-20} GeV	–	10^{-18} GeV
$\tilde{c}_{TY}$	10^{-20} GeV	–	10^{-18} GeV
$\tilde{c}_{TZ}$	10^{-21} GeV	–	10^{-20} GeV
$\tilde{c}_{TT}$	–	–	10^{-18} GeV
$\tilde{d}_+$	–	10^{-27} GeV	10^{-17} GeV
$\tilde{d}_-$	–	10^{-27} GeV	10^{-17} GeV
$\tilde{d}_Q$	–	10^{-27} GeV	10^{-17} GeV
$\tilde{d}_{XY}$	–	10^{-27} GeV	10^{-18} GeV
$\tilde{d}_{YZ}$	–	10^{-26} GeV	10^{-18} GeV
$\tilde{d}_{ZX}$	–	–	10^{-17} GeV

Coefficient	Proton	Neutron	Electron
$\tilde{d}_X$	10^{-25} GeV	10^{-29} GeV	10^{-22} GeV
$\tilde{d}_Y$	10^{-25} GeV	10^{-28} GeV	10^{-22} GeV
$\tilde{d}_Z$	–	–	10^{-19} GeV
$\tilde{H}_{XT}$	–	10^{-26} GeV	–
$\tilde{H}_{YT}$	–	10^{-27} GeV	–
$\tilde{H}_{ZT}$	–	10^{-27} GeV	–
$\tilde{g}_T$	–	10^{-27} GeV	–
$\tilde{g}_c$	–	10^{-27} GeV	–
$\tilde{g}_Q$	–	–	–
$\tilde{g}_-$	–	–	–
$\tilde{g}_{TJ}$ $(J = X, Y, Z)$	–	–	–
$\tilde{g}_{XY}$	–	–	–
$\tilde{g}_{YX}$	–	–	–
$\tilde{g}_{ZX}$	–	–	–
$\tilde{g}_{XZ}$	–	–	–
$\tilde{g}_{YZ}$	–	–	–
$\tilde{g}_{ZY}$	–	–	–
$\tilde{g}_{DX}$	10^{-25} GeV	10^{-29} GeV	10^{-22} GeV
$\tilde{g}_{DY}$	10^{-25} GeV	10^{-28} GeV	10^{-22} GeV
$\tilde{g}_{DZ}$	–	–	–

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Bounds on photon SME coeff.

Coefficient	Sensitivity	Coefficient	Sensitivity
$(\tilde{\kappa}_{e+})^{XY}$	10^{-32}	$(\tilde{\kappa}_{e-})^{YZ}$	10^{-16}
$(\tilde{\kappa}_{e+})^{XZ}$	10^{-32}	$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	10^{-15}
$(\tilde{\kappa}_{e+})^{YZ}$	10^{-32}	$(\tilde{\kappa}_{e-})^{ZZ}$	10^{-14}
$(\tilde{\kappa}_{e+})^{XX} - (\tilde{\kappa}_{e+})^{YY}$	10^{-32}	$(\tilde{\kappa}_{o+})^{XY}$	10^{-12}
$(\tilde{\kappa}_{e+})^{ZZ}$	10^{-32}	$(\tilde{\kappa}_{o+})^{XZ}$	10^{-12}
$(\tilde{\kappa}_{o-})^{XY}$	10^{-32}	$(\tilde{\kappa}_{o+})^{YZ}$	10^{-12}
$(\tilde{\kappa}_{o-})^{XZ}$	10^{-32}	$\tilde{\kappa}_{tr}$	10^{-7}
$(\tilde{\kappa}_{o-})^{YZ}$	10^{-32}	$k^{(3)}_{(V)00}$	10^{-42} GeV
$(\tilde{\kappa}_{o-})^{XX} - (\tilde{\kappa}_{e+})^{YY}$	10^{-32}	$k^{(3)}_{(V)10}$	10^{-42} GeV
$(\tilde{\kappa}_{o-})^{ZZ}$	10^{-32}	$\mathrm{Re}\ k^{(3)}_{(V)11}$	10^{-42} GeV
$(\tilde{\kappa}_{e-})^{XY}$	10^{-16}	$\mathrm{Im}\ k^{(3)}_{(V)11}$	–
$(\tilde{\kappa}_{e-})^{XZ}$	10^{-16}		