Theory overview of testing fundamental symmetries

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OUTLINE

I. Motivation: Quantum **OR** Classical Gravity (Geometrical Backgrounds in Early Universe) **may violate fundamental** space-time **symmetries**: either continuous (**Lorentz**) or discrete (**T & CPT**) and/or induced **decoherence** of quantum matter

II. Parametrization: from (I) → to Standard Model Extension **and beyond…**

III. Overview of Tests in particle physics: From Cosmic photons and ultra-high energy neutrinos to low-energy antiprotons & antimatter factories – **observables & sensitivities**

IV. Outlook

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emphasis in: spectroscopy, dipole moments, tests of time reversal (independent of CP, CPT)

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scenarios for a possible microscopic origin of some of SME coefficients

...tz) or discrete (T & CPT)

...coherence of quantum matter

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and beyond...

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CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Schwinger, Pauli, Luders, Jost, Bell **revisited by:** Greenberg, Chaichian, Dolgov, Novikov…

(ii)-(iv) Independent reasons for violation

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CPT Invariance Theorem :

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(ii) Lorentz invariance
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Kostelecky , Potting, Russell, Lehnert, Mewes, Diaz ….
Standard Model Extension (SME)
PHENOMENOLOGICAL
3-LV parameter (texture) model for neutrino oscillations fitting also LSND, MINOS

(ii)-(iv) Independent reasons for violation

CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

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(iv) Unitarity

Barenboim, Borissov, Lykken
PHENOMENOLOGICAL
models with non-local
mass parameters

(ii)-(iv) Independent reasons for violation

$$\mathrm{S} = \int d^4x \, \bar{\psi}(x) i\partial\!\!\!/ \psi(x) + \frac{im}{\pi} \int d^3x \int dt dt' \, \bar{\psi}(t, \mathrm{x}) \frac{1}{t - t'} \psi(t', \mathrm{x}).$$

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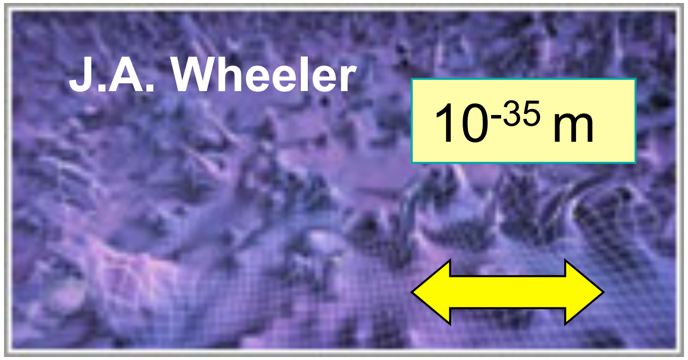
(ii)-(iv) Independent reasons for violation

e.g. ***QUANTUM SPACE-TIME FOAM AT PLANCK SCALES***



CPT VIOLATION

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(i) Flat space-times
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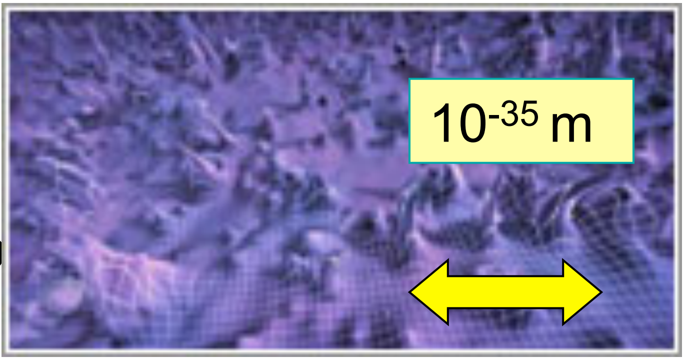
Hawking,
Ellis, Hagelin, Nanopoulos
Srednicki,
Banks, Peskin, Strominger,
Lopez, NEM, Barenboim…

(ii)-(iv) Independent reasons for violation

QUANTUM GRAVITY INDUCED DECOHERENCE
EVOLUTION OF PURE QM STATES TO MIXED
AT LOW ENERGIES

LOW ENERGY ***CPT*** *OPERATOR* ***NOT*** *WELL DEFINED*



cf. ω-effect in EPR entanglement

IF DECOHERENCE IS IGNORED → POSSIBLE TO PARAMETRISE LORENTZ &/OR CPT VIOLATING EFFECTS WITHIN THE FRAMEWORK OF EFFECTIVE FIELD THEORY → STANDARD MODEL EXTENSION (SME)

IN THE PRESENCE OF DECOHERENCE, ILL-DEFINED NATURE OF CPT OPERATOR FOR THE LOW ENERGY THEORY
→ BEYOND LOCAL EFFECTIVE FIELD THEORIES
→ (cf. ω-effects ON MODIFICATIONS OF EPR CORRELATIONS OF ENTANGLED PARTICLE STATES)

PART IA

PARTICLE PHYSICS TESTS OF THE SME

STANDARD MODEL EXTENSION

Kostelecky *et al.*

$$\mathcal{L} = \frac{1}{2}\mathrm{i}\bar{\psi}\Gamma^{\nu}\bar{\partial}_{\nu}\psi - \bar{\psi}M\psi,$$

$$M \equiv m + a_{\mu}\gamma^{\mu} + b_{\mu}\gamma_5\gamma^{\mu} + \frac{1}{2}H^{\mu\nu}\sigma_{\mu\nu}$$

$$\Gamma^{\nu} \equiv \gamma^{\nu} + c^{\mu\nu}\gamma_{\mu} + d^{\mu\nu}\gamma_5\gamma_{\mu} + \mathrm{e}^{\nu} + \mathrm{i}f^{\nu}\gamma_5 + \frac{1}{2}g^{\lambda\mu\nu}\sigma_{\lambda\mu}$$

STANDARD MODEL EXTENSION

V.A. Kostelecký, R. Bluhm, D. Colladay, R. Lehnert, R. Potting, N. Russell

In this case Lorentz symmetry is violated and hence CPT, but no quantum decoherence or unitarity loss. CPT well-defined operator, does not commute with Hamiltonian of the system.

String theory (non supersymmetric) $\rightarrow$ Tachyonic instabilities, coupling with tensorial fields (gauge etc), $\rightarrow < A_\mu > \neq 0$, $< T_{\mu_1 \ldots \mu_n} > \neq 0$,

Spontaneous breaking of Lorentz symmetry by (exotic) string vacua MODIFIED DIRAC EQUATION in SME: for spinor ψ reps. electrons, quarks etc. with charge q

$$(i\gamma^\mu D^\mu - M - a_\mu\gamma^\mu - b_\mu\gamma_5\gamma^\mu - -\frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^\mu D^\nu + id_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0$$

where $D_\mu = \partial_\mu - A^a_\mu T^a - qA_\mu$.

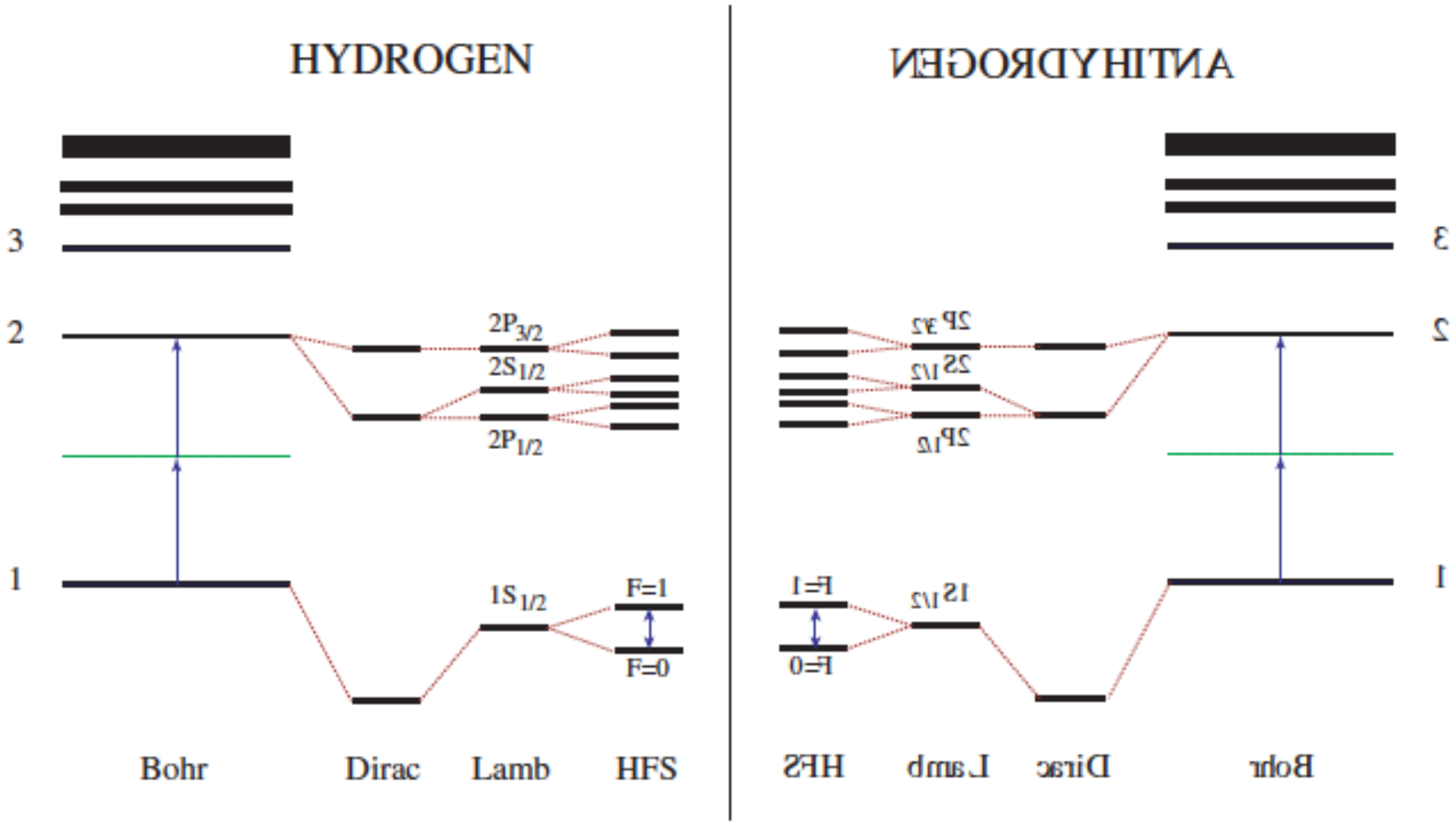
CPT & Lorentz violation: a_μ , b_μ. Lorentz violation only: $c_{\mu\nu}$, $d_{\mu\nu}$, $H_{\mu\nu}$.

NB1: : mass differences between particle/antiparticle not necessarily.

NB2: In general $a_\mu, b_\mu \ldots$ might be energy dependent and NOT constants (c.f. Lorentz-Violation due to quantum space time foam, back reaction effects); ALSO in stochastic models of QG

$\langle a_\mu \, , b_\mu \rangle = 0$, $\langle a_\mu a_\nu \rangle \neq 0$, $\langle b_\mu a_\nu \rangle \neq 0$, $\langle b_\mu b_\nu \rangle \neq 0$, etc ... much more suppressed effects

CPT symmetry requires atomic transitions between H and anti-H to be identical



Rep. Prog. Phys. **70** (2007) 1995–2065

Hayano *et al.*

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Lorentz Violation & (Anti)-Hydrogen

- **Trapped Molecules:**
  Forbidden transitions
  e.g. 1s → 2s

  NB: Sensitivity in b_3 **that rivals astrophysical or atomic-physics bounds can only be attained if spectral resolution of 1 mHz is achieved.**
  Not feasible at present in anti-H factories

EXPER.	SECTOR	PARAMS. (J=X,Y)	BOUND (GeV)
Penning Trap	electron	$\overline{b}_J^e$	5×10^{-25}
Hg–Cs clock comparison	electron	$\overline{b}_J^e$	10^{-27}
	proton	$\overline{b}_J^p$	10^{-27}
	neutron	$\overline{b}_J^n$	10^{-30}
H Maser	electron	$\overline{b}_J^e$	10^{-27}
	proton	$\overline{b}_J^p$	10^{-27}
spin polarized matter	electron	$\overline{b}_J^e / \overline{b}_Z^e$	10^{-29} / 10^{-28}
He–Xe Maser	neutron	$\overline{b}_J^n$	10^{-31}
Muonium	muon	$\overline{b}_J^\mu$	2×10^{-23}
Muon g–2	muon	$\overline{b}_J^\mu$	5×10^{-25} (estimated)

X,Y.Z celestial equatorial coordinates $\overline{b}_J = b_3 - m d_{30} - H_{12}$

(Bluhm, hep–ph/0111323)

NB $|B^0| < 10^{-2}\,\mathrm{eV}$

LORENTZ-VIOLATING QUANTUM ELECTRODYNAMICS (LV QED)

EFT Approach for dimension 5 operators (relevant for dipole moments)

Bolokhov, Pospelov 0703291.

$$O^{\rm SM}_{\mu\nu\ldots} C^{\mu\nu\ldots} \to O^{\rm SM}_{\mu\nu\ldots} \langle C^{\mu\nu\ldots} \rangle$$

Contributions to Matter & Gauge sectors → Complete classification
Operators must be:

- gauge invariant
- Lorentz invariant, after contraction with a background tensor
- not reducible to lower dimension operators by the equations of motion
- not reducible to a total derivative
- coupled to an irreducible background tensor.

Bolokhov, Pospelov 0703291.

Gauge Sector of QED

Only term

$$C^{\mu\nu\rho}\, F_{\mu\lambda}\partial_\nu \widetilde{F}_\rho{}^\lambda \,, \qquad C^\mu{}_\mu{}^\rho = 0 \,.$$

Because:

$$\begin{aligned} F_{\mu\nu}\partial_\lambda F_{\rho\sigma} = \\ & - \frac{1}{5}\epsilon_{\mu\nu\rho\chi}\, \widetilde{F}^{\zeta\chi}\partial_\lambda F_{\zeta\sigma} + \frac{1}{5}\epsilon_{\mu\nu\sigma\chi}\, \widetilde{F}^{\zeta\chi}\partial_\lambda F_{\zeta\rho} + \frac{1}{5}\epsilon_{\rho\sigma\mu\chi}\, \widetilde{F}^{\zeta\chi}\partial_\lambda F_{\zeta\nu} - \frac{1}{5}\epsilon_{\rho\sigma\nu\chi}\, \widetilde{F}^{\zeta\chi}\partial_\lambda F_{\zeta\mu} \\ & - \frac{1}{10}\epsilon_{\mu\lambda\rho\chi}\widetilde{F}^{\zeta\chi}\partial_\nu F_{\zeta\sigma} + \frac{1}{10}\epsilon_{\nu\lambda\rho\chi}\widetilde{F}^{\zeta\chi}\partial_\mu F_{\zeta\sigma} + \\ & + \frac{1}{10}\epsilon_{\mu\lambda\sigma\chi}\widetilde{F}^{\zeta\chi}\partial_\nu F_{\zeta\rho} - \frac{1}{10}\epsilon_{\nu\lambda\sigma\chi}\widetilde{F}^{\zeta\chi}\partial_\mu F_{\zeta\rho} \,. \end{aligned}$$

Matter Sector of QED

$$\begin{aligned} \mathcal{L}_{\rm QED}^{\rm matter} = \\ & [c_1^\mu \cdot \overline{\psi}\,\gamma^\lambda F_{\mu\lambda}\psi^+] + [c_2^\mu \cdot \overline{\psi}\,\gamma^\lambda\gamma^5 F_{\mu\lambda}\psi^-] + \tilde{c}_1^\mu \cdot \overline{\psi}\,\gamma^\lambda \widetilde{F}_{\mu\lambda}\psi^+ + \tilde{c}_2^\mu \cdot \overline{\psi}\,\gamma^\lambda\gamma^5 \widetilde{F}_{\mu\lambda}\psi^- \\ & + f_1^{\mu\nu} \cdot \overline{\psi}\, F_{\mu\nu}\psi^- + f_2^{\mu\nu} \cdot \overline{\psi}\, F_{\mu\nu}\gamma^5\psi^- + h_1^{\mu\nu} \cdot \overline{\psi}\, \mathcal{D}_{(\mu}\mathcal{D}_{\nu)}\psi^+ + h_2^{\mu\nu} \cdot \overline{\psi}\, \mathcal{D}_{(\mu}\mathcal{D}_{\nu)}\gamma^5\psi^+ \\ & + C_1^{\mu\nu\rho} \cdot \overline{\psi}\, \gamma_{(\mu}\mathcal{D}_\nu\mathcal{D}_{\rho)}\psi^- + C_2^{\mu\nu\rho} \cdot \overline{\psi}\, \gamma_{(\mu}\gamma^5\mathcal{D}_\nu\mathcal{D}_{\rho)}\psi^+ \qquad (4) \\ & + D_1^{\mu\nu\rho} \cdot \overline{\psi}\, \gamma_{(\mu}F_{\rho)\nu}\psi^+ + D_2^{\mu\nu\rho} \cdot \overline{\psi}\, \gamma_{(\mu}F_{\rho)\nu}\gamma^5\psi^- \\ & + E_1^{\mu\nu\rho\lambda} \cdot \overline{\psi}\, \sigma_{\mu)\nu}\mathcal{D}_{(\rho}\mathcal{D}_\lambda\psi^- + E_2^{\mu\nu\rho\lambda} \cdot \overline{\psi}\, \sigma_{\mu)(\lambda}F_{\rho)(\nu}\psi^+ + E_3^{\mu\nu\rho\lambda} \cdot \overline{\psi}\, \sigma_{\mu)[\nu}F_{\rho](\lambda}\psi^+ \\ & + E_4^{\mu\nu\rho\lambda} \cdot \overline{\psi}\, \left(\sigma_{\mu)[\nu}\mathcal{D}_{\rho]}\mathcal{D}_{(\lambda} - \sigma_{\nu](\mu}\mathcal{D}_{\lambda)}\mathcal{D}_{[\rho} + 2\,\sigma_{\nu\rho}\mathcal{D}_{(\mu}\mathcal{D}_{\lambda)}\right)\psi^- \,. \end{aligned}$$

Bolokhov, Pospelov 0703291.

Standard Model

Gauge Sector

$$\mathcal{L}_{\rm SM}^{\rm gauge} = C^{\mu\nu\rho}_{\rm U(1)} \cdot F_{\mu\lambda}\,\partial_\nu\,\widetilde{F}_\rho{}^\lambda \;+\; C^{\mu\nu\rho}_{\rm SU_L(2)} \cdot {\rm tr}\, W_{\mu\lambda}\,\mathcal{D}_\nu\,\widetilde{W}_\rho{}^\lambda \;+\; C^{\mu\nu\rho}_{\rm SU_C(3)} \cdot {\rm tr}\, G_{\mu\lambda}\,\mathcal{D}_\nu\,\widetilde{G}_\rho{}^\lambda \;.$$

Quark Sector

$$\begin{aligned}
\mathcal{L}_{\rm SM}^{\rm quark} = {} & \\
& c^\mu_{Q,1} \cdot \overline{Q}\,\gamma^\lambda F_{\mu\lambda}\, Q \;+\; c^\mu_{Q,3} \cdot \overline{Q}\,\gamma^\lambda W_{\mu\lambda}\, Q \;+\; c^\mu_u \cdot \overline{u}\,\gamma^\lambda F_{\mu\lambda}\, u \;+\; c^\mu_d \cdot \overline{d}\,\gamma^\lambda F_{\mu\lambda}\, d \;+ \\
+ \; & \tilde{c}^\mu_{Q,1} \cdot \overline{Q}\,\gamma^\lambda \widetilde{F}_{\mu\lambda}\, Q \;+\; \tilde{c}^\mu_{Q,2} \cdot \overline{Q}\,\gamma^\lambda \widetilde{W}_{\mu\lambda}\, Q \;+\; \tilde{c}^\mu_{Q,3} \cdot \overline{Q}\,\gamma^\lambda \widetilde{G}_{\mu\lambda}\, Q \;+ \\
+ \; & \tilde{c}^\mu_{u,1} \cdot \overline{u}\,\gamma^\lambda \widetilde{F}_{\mu\lambda}\, u \;+\; \tilde{c}^\mu_{u,3} \cdot \overline{u}\,\gamma^\lambda \widetilde{G}_{\mu\lambda}\, u \;+\; \tilde{c}^\mu_{d,1} \cdot \overline{d}\,\gamma^\lambda \widetilde{F}_{\mu\lambda}\, d \;+\; \tilde{c}^\mu_{d,3} \cdot \overline{d}\,\gamma^\lambda \widetilde{G}_{\mu\lambda}\, d \;+ \\
+ \; & C^{\mu\nu\rho}_Q \cdot \overline{Q}\,\gamma_{(\mu}\mathcal{D}_\nu\mathcal{D}_{\rho)}\, Q \;+\; C^{\mu\nu\rho}_u \cdot \overline{u}\,\gamma_{(\mu}\mathcal{D}_\nu\mathcal{D}_{\rho)}\, u \;+\; C^{\mu\nu\rho}_d \cdot \overline{d}\,\gamma_{(\mu}\mathcal{D}_\nu\mathcal{D}_{\rho)}\, d \;+ \\
+ \; & D^{\mu\nu\rho}_{Q,1} \cdot \overline{Q}\,\gamma_{(\mu}F_{\rho)\nu}\, Q \;+\; D^{\mu\nu\rho}_{Q,2} \cdot \overline{Q}\,\gamma_{(\mu}W_{\rho)\nu}\, Q \;+\; D^{\mu\nu\rho}_{Q,3} \cdot \overline{Q}\,\gamma_{(\mu}G_{\rho)\nu}\, Q \;+ \\
+ \; & D^{\mu\nu\rho}_{u,1} \cdot \overline{u}\,\gamma_{(\mu}F_{\rho)\nu}\, u \;+\; D^{\mu\nu\rho}_{u,3} \cdot \overline{u}\,\gamma_{(\mu}G_{\rho)\nu}\, u \;+ \\
+ \; & D^{\mu\nu\rho}_{d,1} \cdot \overline{d}\,\gamma_{(\mu}F_{\rho)\nu}\, d \;+\; D^{\mu\nu\rho}_{d,3} \cdot \overline{d}\,\gamma_{(\mu}G_{\rho)\nu}\, d \;.
\end{aligned}$$

Lepton Sector

$$
\begin{aligned}
\mathcal{L}_{\rm SM}^{\rm lepton} = \\
& c_L^{\mu} \cdot \overline{L}\, \gamma^{\lambda} F_{\mu\lambda}\, L \;+\; \tilde{c}_{L,1}^{\mu} \cdot \overline{L}\, \gamma^{\lambda} \widetilde{F}_{\mu\lambda}\, L \;+\; \tilde{c}_{L,2}^{\mu} \cdot \overline{L}\, \gamma^{\lambda} \widetilde{W}_{\mu\lambda}\, L \,+ \\
& + \; \tilde{c}_{\nu}^{\mu} \cdot \overline{\psi}_{\nu}\, \gamma^{\lambda} \widetilde{F}_{\mu\lambda}\, \psi_{\nu} \;+\; \tilde{c}_{e}^{\mu} \cdot \overline{\psi}_{e}\, \gamma^{\lambda} \widetilde{F}_{\mu\lambda}\, \psi_{e} \;+ \\
& + \; C_L^{\mu\nu\rho} \cdot \overline{L}\, \gamma_{(\mu} \mathcal{D}_{\nu} \mathcal{D}_{\rho)}\, L \;+\; C_{\nu}^{\mu\nu\rho} \cdot \overline{\psi}_{\nu}\, \gamma_{(\mu} \mathcal{D}_{\nu} \mathcal{D}_{\rho)}\, \psi_{\nu} \;+\; C_{e}^{\mu\nu\rho} \cdot \overline{\psi}_{e}\, \gamma_{(\mu} \mathcal{D}_{\nu} \mathcal{D}_{\rho)}\, \psi_{e} \;+ \\
& + \; D_{L,1}^{\mu\nu\rho} \cdot \overline{L}\, \gamma_{(\mu} F_{\rho)\nu}\, L \;+\; D_{L,2}^{\mu\nu\rho} \cdot \overline{L}\, \gamma_{(\mu} W_{\rho)\nu}\, L \;+ \\
& + \; D_{\nu}^{\mu\nu\rho} \cdot \overline{\psi}_{\nu}\, \gamma_{(\mu} F_{\rho)\nu}\, \psi_{\nu} \;+\; D_{e}^{\mu\nu\rho} \cdot \overline{\psi}_{e}\, \gamma_{(\mu} F_{\rho)\nu}\, \psi_{e} \;.
\end{aligned}
$$

Higgs Sector

Higgs-gauge

$$\mathcal{L}_{\rm SM}^{\rm Higgs-gauge} =$$

$$l^{\mu} \cdot i\, H^{\dagger} H \cdot H^{\dagger} \mathcal{D}_{\mu} H \; + \; \kappa^{\mu\nu\rho} \cdot i\, H^{\dagger} \mathcal{D}_{(\mu} \mathcal{D}_{\nu} \mathcal{D}_{\rho)} H \; +$$

$$+ \; m_1^{\mu} \cdot i\, H^{\dagger} F_{\mu\lambda} \mathcal{D}^{\lambda} H \; + \; m_2^{\mu} \cdot i\, H^{\dagger} W_{\mu\lambda} \mathcal{D}^{\lambda} H \; + \; \text{h.c.} \; +$$

$$+ \; \widetilde{m}_1^{\mu} \cdot i\, H^{\dagger} \widetilde{F}_{\mu\lambda} \mathcal{D}^{\lambda} H \; + \; \widetilde{m}_2^{\mu} \cdot i\, H^{\dagger} \widetilde{W}_{\mu\lambda} \mathcal{D}^{\lambda} H \; +$$

$$+ \; n_1^{\mu\nu\rho} \cdot i\, H^{\dagger} F_{\nu(\mu} \mathcal{D}_{\rho)} H \; + \; n_2^{\mu\nu\rho} \cdot i\, H^{\dagger} W_{\nu(\mu} \mathcal{D}_{\rho)} H \; + \; \text{h.c.}$$

Higgs-quark

$$\mathcal{L}_{\rm SM}^{\rm Higgs-quark} = h_{QQ}^{\mu} \cdot \overline{Q} H \gamma_{\mu} H^{\dagger} Q \; +$$

$$+ \; p_{QQ}^{\mu} \cdot \overline{Q} \gamma_{\mu} Q \cdot H^{\dagger} H \; + \; p_{uu}^{\mu} \cdot \overline{u} \gamma_{\mu} u \cdot H^{\dagger} H \; + \; p_{dd}^{\mu} \cdot \overline{d} \gamma_{\mu} d \cdot H^{\dagger} H$$

$$+ \; q_{Qd}^{(1)\mu} \cdot \overline{Q}\, d\, \mathcal{D}_{\mu} H \; + \; q_{Qu}^{(1)\mu} \cdot \overline{Q}\, u\, \mathcal{D}_{\mu} \epsilon H^{*} \; + \; \text{h.c.}$$

$$+ \; q_{Qd}^{(2)\nu} \cdot \overline{Q}\, \sigma^{\mu\nu} d\, \mathcal{D}_{\nu} H \; + \; q_{Qu}^{(2)\nu} \cdot \overline{Q}\, \sigma^{\mu\nu} u\, \mathcal{D}_{\nu} \epsilon H^{*} \; + \; \text{h.c.}$$

$$+ \; r_{Qd}^{(1)\mu\nu\rho} \cdot \overline{Q}\, \mathcal{D}_{(\mu} \sigma_{\nu)\rho} d \cdot H \; + \; r_{Qd}^{(2)\mu\nu\rho} \cdot \overline{Q}\, \sigma_{\nu)\rho} d\, \mathcal{D}_{(\mu} H \; + \; \text{h.c.}$$

$$+ \; r_{Qu}^{(1)\mu\nu\rho} \cdot \overline{Q}\, \mathcal{D}_{(\mu} \sigma_{\nu)\rho} u \cdot \epsilon H^{*} \; + \; r_{Qu}^{(2)\mu\nu\rho} \cdot \overline{Q}\, \sigma_{\nu)\rho} u\, \mathcal{D}_{(\mu} \epsilon H^{*} \; + \; \text{h.c.}$$

Higgs-Lepton

$$\mathcal{L}_{\rm SM}^{\rm Higgs-lepton} = h_{LL}^{\mu} \cdot \overline{L} H \gamma_{\mu} H^{\dagger} L \; + \; p_{LL}^{\mu} \cdot \overline{L} \gamma_{\mu} L \cdot H^{\dagger} H \; + \; p_{ee}^{\mu} \cdot \overline{e} \gamma_{\mu} e \cdot H^{\dagger} H$$

$$+ \; q_{Le}^{(1)\mu} \cdot \overline{L}\, e\, \mathcal{D}_{\mu} H \; + \; q_{Le}^{(2)\nu} \cdot \overline{L}\, \sigma^{\mu\nu} e\, \mathcal{D}_{\nu} H \; + \; \text{h.c.}$$

$$+ \; r_{Le}^{(1)\mu\nu\rho} \cdot \overline{L}\, \mathcal{D}_{(\mu} \sigma_{\nu)\rho} e \cdot H \; + \; r_{Le}^{(2)\mu\nu\rho} \cdot \overline{L}\, \sigma_{\nu)\rho} e\, \mathcal{D}_{(\mu} H \; + \; \text{h.c.}$$

$$+ \; \varsigma^{\mu\nu} \cdot \left(H^{\dagger} L\right)^{T} \sigma_{\mu\nu} \left(H^{\dagger} L\right) \; + \; \text{h.c.}$$

Phenomenology of LV & CPTV dim 5 operators

Operators	Typical constraints	Source of constraints
Unprotected operators		
$\tilde{c}^{\mu}_{Q,1}$ $\tilde{c}^{\mu}_{Q,3}$ $\tilde{c}^{\mu}_{q,1}$ $\tilde{c}^{\mu}_{q,3}$ $\tilde{c}^{\mu}_{L,1}$ $\tilde{c}^{\mu}_{\psi}$	$\ll 10^{-31}$ GeV^{-1}	constraints on dim 3 operators
Operators growing with energy (UV-enhanced operators)		
$C^{\mu\nu\rho}_{q}$ $C^{\mu\nu\rho}_{q,5}$ $C^{\mu\nu\rho}_{l}$ $C^{\mu\nu\rho}_{l,5}$ $C^{\mu\nu\rho}_{\rm EM}$	$\lesssim 10^{-33-34}$ GeV^{-1}	high energy cosmic rays
Soft LV interactions		
$c^{\mu}_{q,5}$ $D^{\mu\nu\rho}_{q,5}$ $D^{\mu\nu\rho}_{qg}$ $D^{\mu\nu\rho}_{q}$ $r^{\mu\nu\rho}_{q}$	$\lesssim 10^{-28-30}$ GeV^{-1}	nuclear spin precession
$c^{\mu}_{q,5}$ $D^{\mu\nu\rho}_{q,5}$ $D^{\mu\nu\rho}_{qg,5}$ $c^{\mu}_{e,5}$ $D^{\mu\nu\rho}_{e,5}$	$\lesssim 10^{-25}$ $e$cm	atomic and nuclear EDMs
$\Delta L = 2$ interaction		
$\varsigma^{\mu\nu}_{\nu}$	$\lesssim 10^{-23-24}$ GeV^{-1}	data on neutrino oscillations

Bolokhov, Pospelov 0703291.

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$$(i\gamma^\mu D^\mu - M - a_\mu \gamma^\mu - b_\mu \gamma_5 \gamma^\mu - -\frac{1}{2} H_{\mu\nu} \sigma^{\mu\nu} + i c_{\mu\nu} \gamma^\mu D^\nu + i d_{\mu\nu} \gamma_5 \gamma^\mu D^\nu)\psi = 0$$

where $D_\mu = \partial_\mu - A_\mu^a T^a - q A_\mu$.

CPT & Lorentz violation: a_μ , b_μ. Lorentz violation only: $c_{\mu\nu}$, $d_{\mu\nu}$, $H_{\mu\nu}$.

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$\langle a_\mu , b_\mu \rangle = 0$, $\langle a_\mu a_\nu \rangle \neq 0$, $\langle b_\mu a_\nu \rangle \neq 0$, $\langle b_\mu b_\nu \rangle \neq 0$, etc ... much more suppressed effects

Tests of Lorentz Violation in Neutral Kaons

(A. Kostelecky, hep-ph/9809572 (PRL))

Wave-function of neutral Kaon: Ψ (two-component $K^0, \overline{K}^0$)

Evolution within quantum mechanics but Lorentz & CPT Violation: $i\partial_t \Psi = \mathcal{H}\Psi$

$\mathcal{H}$ $\ni$ CP-violation: $\epsilon_K \sim 10^{-3}$ & CPT-violation δ_K, $\delta_K \sim (\mathcal{H}_{11} - \mathcal{H}_{22})/2\Delta\lambda$, $\Delta\lambda$ eigenvalue difference.

NB: $\mathcal{H}_{11} - \mathcal{H}_{22}$ is flavour diagonal. Parameter δ_K must be C violating but P,T preserving (c.f. strong interaction properties in neutral meson evolution):

Hence look for terms in SME that are flavour diagonal, violate C but preserve T, P. δ_K sensitive ONLY to $-a^q_\mu \overline{q}\gamma_\mu q$ terms in SME (q quark fields, meson composition: $M = q_1\overline{q}_2$):

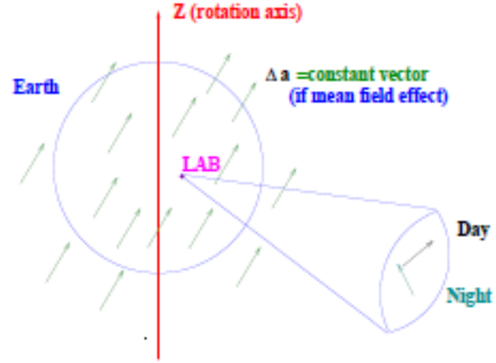
$$\delta_K \simeq i\sin\widehat{\phi}\exp(i\widehat{\phi})\gamma\left(\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a}\right)/\Delta m,$$

S=short-lived, L=long-lived, I=interference term, $\Delta m = m_L - m_S$, $\Delta\Gamma = \Gamma_S - \Gamma_L$,

$\widehat{\phi} = \arctan(2\Delta m/\Delta\Gamma)$, $\Delta a_\mu \equiv a^{q_2}_\mu - a^{q_1}_\mu$, and $\beta^\mu_K = \gamma(1, \vec{\beta}_K)$ is the 4-velocity of boosted kaon.

EXPERIMENTAL BOUNDS

Experimental bounds on a_μ: Look for sidereal variations of δ_K (day-night effects):



From KTeV: $\Delta a_X, \Delta a_Y < 9.2 \times 10^{-22}$ GeV.

From ϕ factories: (NB: additional polar (θ) and azimuthal (ϕ) angle dependence of δ_K):

$$\delta_K^{\phi}(|\vec{p}|, \theta, t) = \frac{1}{\pi}\int_0^{2\pi} d\phi \delta_K(\vec{p}, t) \simeq i\sin\widehat{\phi}\exp(i\widehat{\phi})(\gamma/\Delta m)\left(\Delta a_0 + \beta_K \Delta a_Z \cos\chi\cos\theta + \beta_K \Delta a_X \sin\chi\cos\theta\cos(\Omega t) + \beta_K \Delta a_Y \sin\chi\cos\theta\sin(\Omega t)\right)$$

(Ω: Earth's sidereal frequency, χ: angle between Z-lab axis and Earth's axis.)

KLOE (at DAΦNE) is sensitive to a_Z (actually limits on $\delta(\Delta a_Z)$ from forward-backward asymmetry $A_L = 2\mathrm{Re}\epsilon_K - 2\mathrm{Re}\delta_K$). For KLOE-2 at DaΦNE-2): expected sensitivity $\Delta a_\mu = \mathcal{O}(10^{-18})$ GeV, not competitive with KTeV for $a_{X,Y}$ limits . Similar tests for other mesons (B-mesons, *etc.*...). Are QG LV effects Universal?

EXPERIMENTAL BOUNDS

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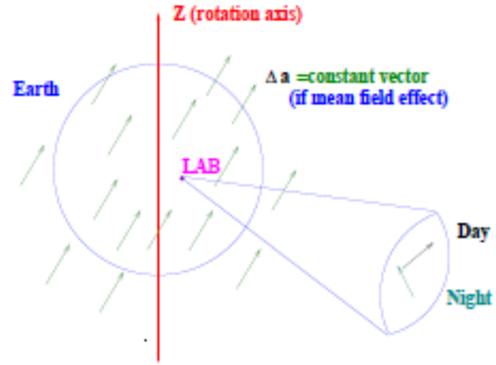

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(Ω: Earth's sidereal frequency, χ: angle between Z-lab axis and Earth's axis.)

KLOE (at DAΦ ...

$A_L = 2\mathrm{Re}\epsilon_K$ ...

$\Delta a_\mu = \mathcal{O}(10$ ...

. Simila ...

$$\Delta a_0 = (0.4 \pm 1.8) \cdot 10^{-17}\,\mathrm{GeV}.$$

KLOE result

Probing CPT Violation via Atomic Dipole moments

Bolokhov, Pospelov, Romalis 0609.153

Non-relativistic Hamiltonian

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S} .$$

In the presence of Lorentz-violating background vector

$$\mathcal{L}_{\rm EDM} = \frac{-i}{2} d_{\rm CP} \overline{\psi} \sigma^{\mu\nu} F_{\mu\nu} \psi + d_{\rm CPT} \overline{\psi} \gamma_\mu \gamma_5 \psi F_{\mu\nu} n^\nu$$

$$d_{\rm CP} + d_{\rm CPT} = d.$$ Total atomic dipole moment

nil result of neutron EDM → constraint on combination

SME & Atomic Dipole moments

Bolokhov, Pospelov, Romalis 0609.153

$$\mathcal{L}_3 = -\sum \bar{\psi}(a^\mu \gamma_\mu + b^\mu \gamma_\mu \gamma_5)\psi,$$

a_μ , b_μ LV background

+

$$\mathcal{L}_5 = -\sum [c^\mu \overline{\psi} \gamma^\lambda F_{\lambda\mu} \psi \ + \ d^\mu \overline{\psi} \gamma^\lambda \gamma^5 F_{\lambda\mu} \psi \\ + \ f^\mu \overline{\psi} \gamma^\lambda \gamma^5 \widetilde{F}_{\lambda\mu} \psi \ + \ g^\mu \overline{\psi} \gamma^\lambda \widetilde{F}_{\lambda\mu} \psi].$$

properties

Coefficient	Operator	C	P	T
a^0	$\overline{\psi}\gamma_0\psi$	$-$	$+$	$+$
b^0	$\overline{\psi}\gamma_0\gamma_5\psi$	$+$	$-$	$+$
c^0	$F_{\lambda 0}\overline{\psi}\gamma^\lambda\psi$	$+$	$+$	$-$
d^0	$F_{\lambda 0}\overline{\psi}\gamma^\lambda\gamma^5\psi$	$-$	$-$	$-$
f^0	$\widetilde{F}_{\lambda 0}\overline{\psi}\gamma^\lambda\gamma^5\psi$	$-$	$+$	$+$
g^0	$\widetilde{F}_{\lambda 0}\overline{\psi}\gamma^\lambda\psi$	$+$	$-$	$+$

CPT V @ low energies (1 GeV) in SU(2) x U(1)

Bolokhov, Pospelov, Romalis 0609.153

manipulating field identities

$$\mathcal{L}_{\rm CPT} = \sum_{i=u,d,s} d_i^{\mu} \bar{q}_i \gamma^{\lambda}\gamma^5 F_{\lambda\mu} q_i .$$

light quarks (u, d, s)
+ photons, gluons

Disentangle CP- from CPT-odd operators

CP-odd terms require helicity flip → dim 6 operators . suppressed by $1/\Lambda_{\rm CP}^2$
→ spin precession with magnetic field $[\mathbf{B} \times \mathbf{v}]$

CPT-odd terms do not require helicity flip → dim 5 operators in SU(2) X U(1)
→ no spin precession

$$\bar{q}_{R(L)}\gamma^{\lambda}\gamma^5 F_{\lambda\mu} q_{R(L)} \quad ; \quad \bar{q}_L \gamma^{\lambda}\gamma^5 \tau^a F^a_{\lambda\mu} q_L$$

Current bounds → $\Lambda_{\rm CPT} \sim (10^{11} - 10^{12})$ GeV

EDM neutrons
diamagnetic atoms (Hg, Xe,…)
paramagnetic atoms (Tl, Cs,…)

EDM-induced CPT bounds

Bolokhov, Pospelov, Romalis 0609.153

Neutron

$$d_n \simeq 0.8 d_d^0 - 0.4 d_u^0 - 0.1 d_s^0.$$

$|d_n| < 3 \times 10^{-26} e\text{cm}$ (2002)

CPT-odd EDMs
limited @ $\mathcal{O}(10^{-25} e\text{cm})$.

Diamagnetic atoms

$$d_{\text{Hg}} \simeq -5 \times 10^{-4}(d_n + 0.1 d_p)$$
$$\simeq -5 \times 10^{-4}(0.74 d_d^0 - 0.32 d_u^0 - 0.11 d_s^0),$$

$d_{\text{Hg}}/d_n \sim -5 \times 10^{-4}$ → if $d_n \neq 0$ → *CPTV*

paramagnetic atoms

EDMs predicted to be extremely suppressed

higher-loop CPV corrections yields imprecise estimates

$$a^\mu, b^\mu \sim d^\mu (10^{-20} - 10^{-18}) \times \text{GeV}^2.$$

$$d_\mu \leq \mathcal{O}(10^{-12})\text{GeV}^{-1}$$

Tensor-LV-background induced EDMs

Bolokhov, Pospelov, Romalis 0609.153

$D_{\mu\nu\rho} \neq 0$ **tensor background → EFT terms** $\ni \bar{e} F_{\mu\nu} \gamma_\rho \gamma_5 e D^{\mu\nu\rho}$

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - \mathcal{D}^{ij} E_i \cdot \frac{S_j}{S}. \qquad \mathcal{D}^{ik} = \mathcal{D}^{i[0k]} + \mathcal{D}^{k[0i]}.$$

→ corection to spin precession frequency $\propto \mathcal{D}^{ij} E_i B_j$ → signature in EDM expt for **paramagnetic atoms** ≈ O(1/10) CP-odd

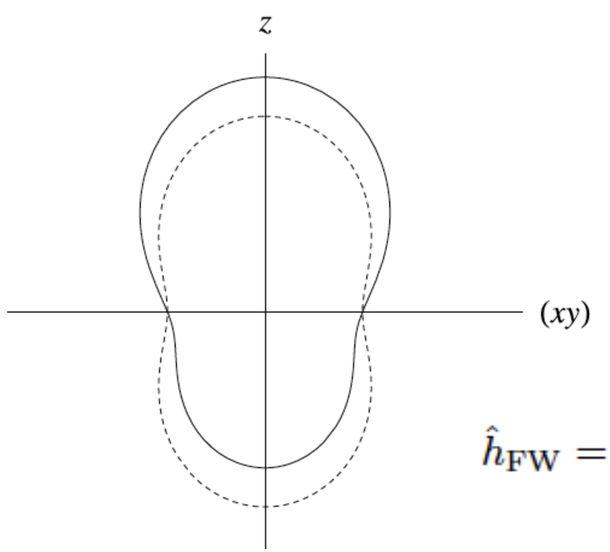
↑

Change orientation rel. Lab during the day

Effects of B_μ on dipole moments in Hydrogen-like atoms

Angular distribution for spontaneous radiation for the transition

$$2p_{1/2,1/2} \to 1s_{1/2,-1/2}$$



Corrections to electromagnetic dipole moments of bound electrons calculated in 1/c expansion (Foldy-Wouthysen (FW) method) to second order in B^0 → contributions to **anapole moment** of the atomic orbital → **asymmetry of angular distribution of radiation** of, e.g. hydrogen atom

Kharlanov, Zhukovsky 0705.3306

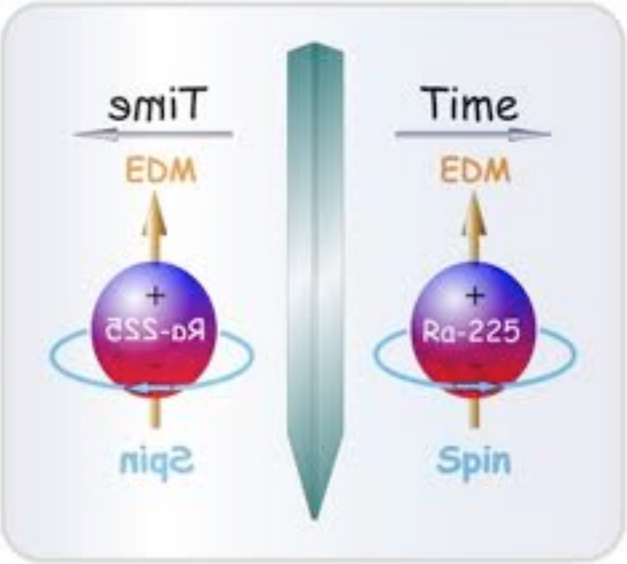
$$\hat{h}_{\rm FW} = \frac{\hat{\boldsymbol{p}}^2}{2m_e} + \boldsymbol{\sigma}\boldsymbol{b} - \frac{b_0}{m_e c}\boldsymbol{\sigma}\hat{\boldsymbol{p}} + \frac{\hat{p}_j\sigma_l}{2m_e^2c^2}(b_j\hat{p}_l - b_l\hat{p}_j) + \frac{b_0}{2m_e^3c^3}\hat{\boldsymbol{p}}^2(\boldsymbol{\sigma}\hat{\boldsymbol{p}}).$$

electric & magnetic dipole corrections

$$\hat{\boldsymbol{\mu}}_A = \frac{eb_0}{m_e}\gamma^0[\boldsymbol{\Sigma}\boldsymbol{r}],$$

$$\hat{\boldsymbol{d}}_A = -i\gamma_5\hat{\boldsymbol{\mu}}_A = -\frac{ieb_0}{m_e}[\boldsymbol{\gamma}\boldsymbol{r}].$$

TIME REVERSAL TESTS



INDEPENDENTLY OF CP VIOLATION

IN EPR ENTANGLED STATES

Testing Time Reversal (T) Symmetry independently of CP & CPT in entangled particle states : some ideas for antiprotonic Atoms

Bernabeu, Banuls (99)
+ di Domenico, Villanueva-Perez (13)

Direct evidence for T violation: experiment must show it **independently** of violations of **CP** & potentially **CPT**

opportunity in **entangled states** of mesons, such as neutral Kaons, B-mesons; **EPR entanglement crucial**
Observed in B-mesons (Ba-Bar Coll) Phys.Rev.Lett. 109 (2012) 21180

Experimental Strategy:

Use initial (|i>) EPR correlated state for flavour tagging

$$|i\rangle = \frac{1}{\sqrt{2}}\{|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\}$$
$$= \frac{1}{\sqrt{2}}\{|K_+\rangle|K_-\rangle - |K_-\rangle|K_+\rangle\} .$$

infer flavour $(K^0 \text{ or } \bar{K}^0)$ by observation of flavour specific decay $(\pi^+\ell^-\bar{\nu} \text{ or } \pi^-\ell^+\nu)$ of the other meson

construct observables by looking at appropriate T violating transitions interchanging in & out states, not simply being T-odd

Reference		$\mathcal{T}$-conjugate	
Transition	Decay products	Transition	Decay products
$K^0 \to K_+$	$(\ell^-, \pi\pi)$	$K_+ \to K^0$	$(3\pi^0, \ell^+)$
$K^0 \to K_-$	$(\ell^-, 3\pi^0)$	$K_- \to K^0$	$(\pi\pi, \ell^+)$
$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$	$K_+ \to \bar{K}^0$	$(3\pi^0, \ell^-)$
$\bar{K}^0 \to K_-$	$(\ell^+, 3\pi^0)$	$K_- \to \bar{K}^0$	$(\pi\pi, \ell^-)$

Reference		$\mathcal{CP}$-conjugate	
Transition	Decay products	Transition	Decay products
$K^0 \to K_+$	$(\ell^-, \pi\pi)$	$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$
$K^0 \to K_-$	$(\ell^-, 3\pi^0)$	$\bar{K}^0 \to K_-$	$(\ell^+, 3\pi^0)$
$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$	$K^0 \to K_+$	$(\ell^-, \pi\pi)$
$\bar{K}^0 \to K_-$	$(\ell^+, 3\pi^0)$	$K^0 \to K_-$	$(\ell^-, 3\pi^0)$

Reference		$\mathcal{CPT}$-conjugate	
Transition	Decay products	Transition	Decay products
$K^0 \to K_+$	$(\ell^-, \pi\pi)$	$K_+ \to \bar{K}^0$	$(3\pi^0, \ell^-)$
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T-violation Observables in entangled Kaons

Banuls, Bernabeu (1999)

Bernabeu, di Domenico, Villanueva-Perez 2012

$$R_1^{\exp}(\Delta t) \equiv \frac{I(\ell^-, \pi\pi; \Delta t)}{I(3\pi^0, \ell+; \Delta t)} = R_1(\Delta t) \times \frac{C(\ell^-, \pi\pi)}{C(3\pi^0, \ell+)}$$

$$R_2^{\exp}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell+; \Delta t)} = R_2(\Delta t) \times \frac{C(\ell^-, 3\pi^0)}{C(\pi\pi, \ell+)}$$

$$R_3^{\exp}(\Delta t) \equiv \frac{I(\ell^+, \pi\pi; \Delta t)}{I(3\pi^0, \ell-; \Delta t)} = R_3(\Delta t) \times \frac{C(\ell^+, \pi\pi)}{C(3\pi^0, \ell-)}$$

$$R_4^{\exp}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)} = R_4(\Delta t) \times \frac{C(\ell^+, 3\pi^0)}{C(\pi\pi, \ell-)} \ ,$$

$$\begin{aligned}
R_1(\Delta t) &= P\left[\mathrm{K}^0(0) \to \mathrm{K}_+(\Delta t)\right] / P\left[\mathrm{K}_+(0) \to \mathrm{K}^0(\Delta t)\right] \\
R_2(\Delta t) &= P\left[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)\right] / P\left[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)\right] \\
R_3(\Delta t) &= P\left[\bar{\mathrm{K}}^0(0) \to \mathrm{K}_+(\Delta t)\right] / P\left[\mathrm{K}_+(0) \to \bar{\mathrm{K}}^0(\Delta t)\right] \\
R_4(\Delta t) &= P\left[\bar{\mathrm{K}}^0(0) \to \mathrm{K}_-(\Delta t)\right] / P\left[\mathrm{K}_-(0) \to \bar{\mathrm{K}}^0(\Delta t)\right]
\end{aligned}$$

$$\begin{aligned}
I(f_{\bar{X}}, f_Y; \Delta t) &= \int_0^\infty I(f_{\bar{X}}, t_1; f_Y; t_2) dt_1 \\
&= \frac{1}{\Gamma_S + \Gamma_L} \left| \langle \mathrm{K_X} \bar{\mathrm{K}}_\mathrm{X} | i \rangle \langle f_{\bar{X}} | T | \bar{\mathrm{K}}_\mathrm{X} \rangle \langle \mathrm{K_Y} | \mathrm{K_X}(\Delta t) \rangle \langle f_Y | T | \mathrm{K_Y} \rangle \right|^2 \\
&= C(f_{\bar{X}}, f_Y) \times P\left[\mathrm{K_X}(0) \to \mathrm{K_Y}(\Delta t)\right] \ , \qquad (31)
\end{aligned}$$

Relevance to antiprotonic atoms? preliminary ideas…

entangled (EPR correlated) Kaons can produced by **s-wave annihilation** in antiprotonic atom

$$(\bar{p}p)_S \to K^0 \bar{K}^0.$$

coherent decays of neutral kaons have been considered in the past as a way of measurement of CP ε'/ε

Bernabeu, Botella, Roldan (89)

In view of recent **T Reversal Violation** measurements exploiting the EPR nature of entangled Kaons we may **use antiprotonic atoms** to measure directly **T violation**, independently of **CPT,** **via coherent decays of Kaons from the annihilation?**

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But there are subtleties associated with Quantum Gravity & EPR

PART IB
BEYOND LOCAL FIELD THEORY

CPT VIOLATION IN QUANTUM GRAVITY
Beyond Local Field Theory

Conditions for the Validity of the CPT Theorem

CPT Invariance Theorem :

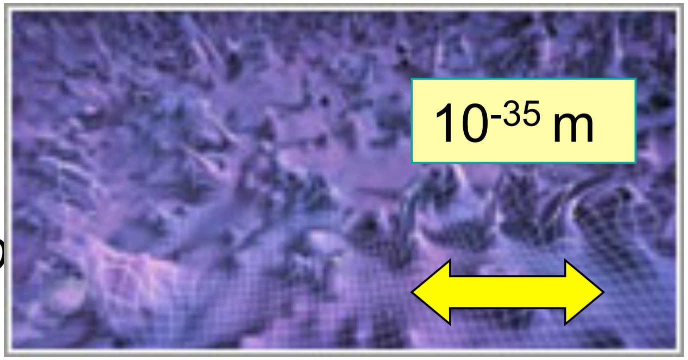
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Hawking,
Ellis, Hagelin, Nanopoulos
Srednicki,
Banks, Peskin, Strominger,
Lopez, NEM, Barenboim…

(ii)-(iv) Independent reasons for violation

QUANTUM GRAVITY INDUCED DECOHERENCE
EVOLUTION OF PURE QM STATES TO MIXED
AT LOW ENERGIES

LOW ENERGY ***CPT*** *OPERATOR* ***NOT*** *WELL DEFINED*



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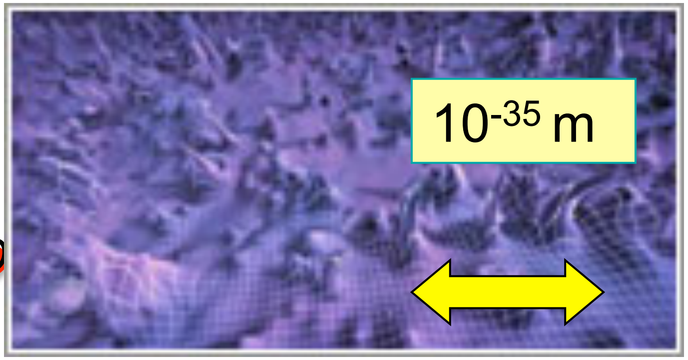

NB: Decoherence & CPTV

Decoherence implies that asymptotic density matrix of low-energy matter :

$$\rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$

$$\rho_{\rm out} = \$\rho_{\rm in}$$

$$\$ \neq S\,S^\dagger$$

$$S = e^{i\int H dt}$$

May induce **quantum decoherence** of propagating matter and **intrinsic CPT Violation** in the sense that the CPT operator **Θ** is **not well-defined → beyond Local Effective Field theory**

$$\Theta \rho_{\rm in} = \overline{\rho}_{\rm out}$$

If Θ well-defined can show that $\$^{-1} = \Theta^{-1}\$\Theta^{-1}$

exists !

INCOMPATIBLE WITH DECOHERENCE !

Hence Θ ill-defined at low-energies in QG foam models

Wald (79)

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$$\rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$

$$|i\rangle = \mathcal{N}\Big[|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle - |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle + \omega\Big(|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle + |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle\Big)\Big]$$

$$\omega = |\omega| e^{i\vartheta}$$

May contaminate initially antisymmetric neutral meson *M* state by symmetric parts (ω-effect)

Hence Θ ill-defined at low-energies in QG foam models → may affect EPR

Wald (79)

Bernabeu, NEM, Papavassiliou,…

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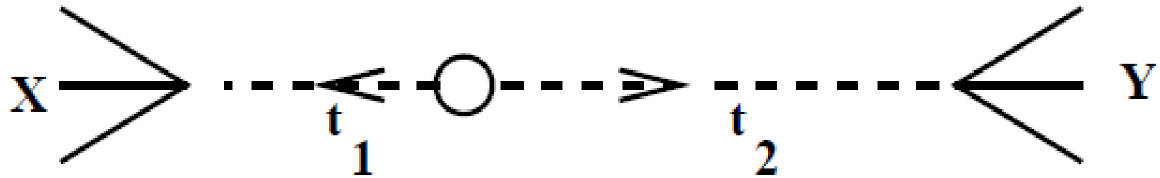
Bernabeu, NEM, Papavassiliou,…

ω-effect observables/current bounds

ϕ Decays and the ω Effect

Consider the ϕ decay amplitude: final state X at t_1 and Y at time t_2 ($t = 0$ at the moment of ϕ decay)



Amplitudes:

$$A(X,Y) = \langle X|K_S\rangle\langle Y|K_S\rangle \mathcal{N}\ (A_1 + A_2)$$

with

$$\begin{aligned} A_1 &= e^{-i(\lambda_L+\lambda_S)t/2}[\eta_X e^{-i\Delta\lambda\Delta t/2} - \eta_Y e^{i\Delta\lambda\Delta t/2}] \\ A_2 &= \omega[e^{-i\lambda_S t} - \eta_X \eta_Y e^{-i\lambda_L t}] \end{aligned}$$

the CPT-allowed and CPT-violating parameters respectively, and $\eta_X = \langle X|K_L\rangle/\langle X|K_S\rangle$ and $\eta_Y = \langle Y|K_L\rangle/\langle Y|K_S\rangle$.

The "intensity" $I(\Delta t)$: $(\Delta t = t_1 - t_2)$ is an observable

$$I(\Delta t) \equiv \frac{1}{2}\int_{|\Delta t|}^{\infty} dt\, |A(X,Y)|^2$$

Bernabeu, NEM, Papavassiliou,…

ω-Effect & Intensities

$$I(\Delta t) \equiv \frac{1}{2}\int_{|\Delta t|}^{\infty} dt\, |A(\pi^+\pi^-,\pi^+\pi^-)|^2 = |\langle\pi^+\pi^-|K_S\rangle|^4 |\mathcal{N}|^2 |\eta_{+-}|^2 \Big[I_1 + I_2 + I_{12}\Big]$$

$$I_1(\Delta t) = \frac{e^{-\Gamma_S \Delta t} + e^{-\Gamma_L \Delta t} - 2e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\cos(\Delta M \Delta t)}{\Gamma_L + \Gamma_S}$$

$$I_2(\Delta t) = \frac{|\omega|^2}{|\eta_{+-}|^2}\,\frac{e^{-\Gamma_S \Delta t}}{2\Gamma_S}$$

$$I_{12}(\Delta t) = -\frac{4}{4(\Delta M)^2 + (3\Gamma_S + \Gamma_L)^2}\,\frac{|\omega|}{|\eta_{+-}|} \times$$

$$\Big[2\Delta M \Big(e^{-\Gamma_S \Delta t}\sin(\phi_{+-} - \Omega) - e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\sin(\phi_{+-} - \Omega + \Delta M \Delta t)\Big)$$

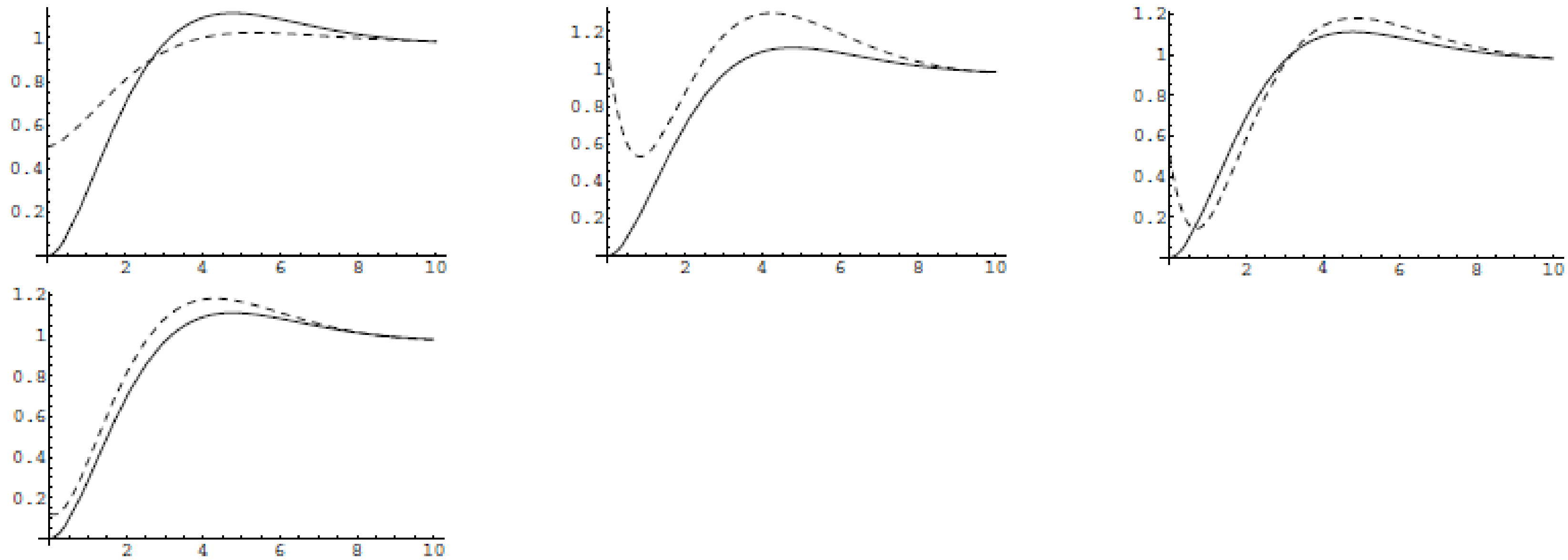
$$-(3\Gamma_S + \Gamma_L)\Big(e^{-\Gamma_S \Delta t}\cos(\phi_{+-} - \Omega) - e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\cos(\phi_{+-} - \Omega + \Delta M \Delta t)\Big)\Big]$$

$\Delta M = M_S - M_L$ and $\eta_{+-} = |\eta_{+-}| e^{i\phi_{+-}}$.

NB: sensitivities up to $|\omega| \sim 10^{-6}$ in ϕ factories, due to enhancement by $|\eta_{+-}| \sim 10^{-3}$ factor.

Bernabeu, NEM, Papavassiliou,…

ω-Effect & Intensities



Characteristic cases of the intensity $I(\Delta t)$, with $|\omega| = 0$ (solid line) vs $I(\Delta t)$ (dashed line) with (from top left to right): (i) $|\omega| = |\eta_{+-}|$, $\Omega = \phi_{+-} - 0.16\pi$, (ii) $|\omega| = |\eta_{+-}|$, $\Omega = \phi_{+-} + 0.95\pi$, (iii) $|\omega| = 0.5|\eta_{+-}|$, $\Omega = \phi_{+-} + 0.16\pi$, (iv) $|\omega| = 1.5|\eta_{+-}|$, $\Omega = \phi_{+-}$. Δt is measured in units of τ_S (the mean life-time of K_S) and $I(\Delta t)$ in units of $|C|^2 |\eta_{+-}|^2 |\langle \pi^+ \pi^- | K_S \rangle|^4 \tau_S$.

Bernabeu, NEM, Papavassiliou,…

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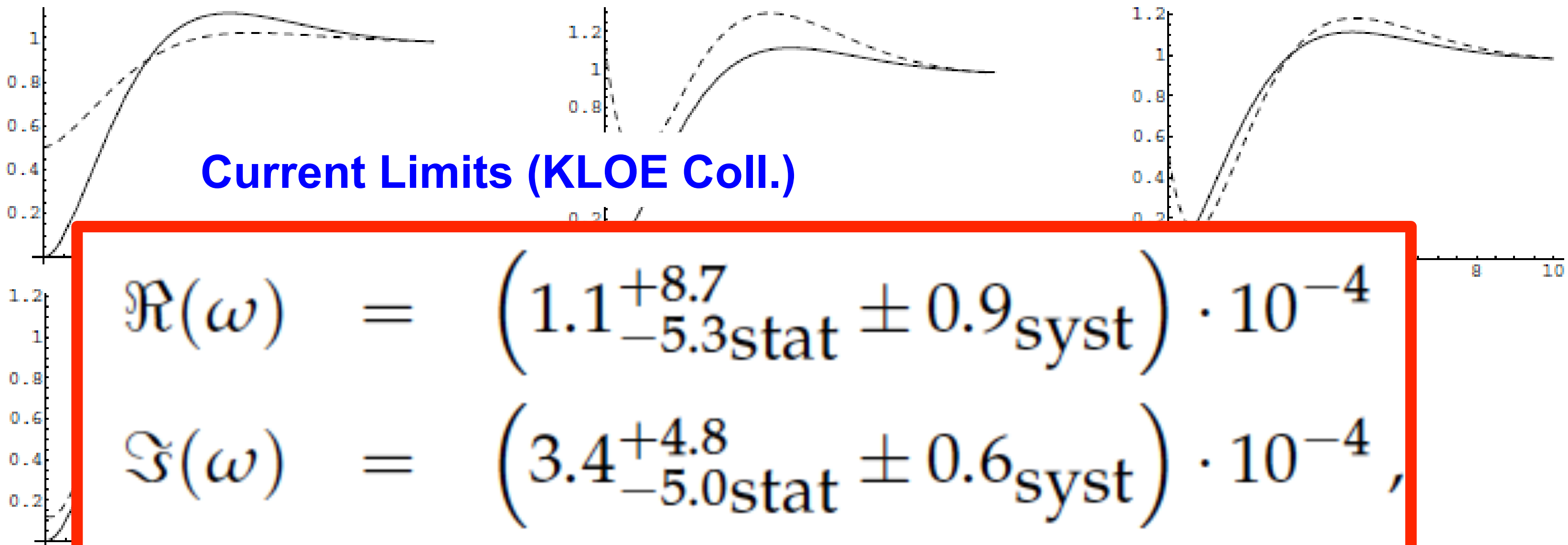

Current Limits (KLOE Coll.)

$$\Re(\omega) = \left(1.1^{+8.7}_{-5.3}{}_{\text{stat}} \pm 0.9_{\text{syst}}\right) \cdot 10^{-4}$$

$$\Im(\omega) = \left(3.4^{+4.8}_{-5.0}{}_{\text{stat}} \pm 0.6_{\text{syst}}\right) \cdot 10^{-4},$$

Characteristic cases of the intensity $I(\Delta t)$, with $|\omega| = 0$ (solid line) vs $I(\Delta t)$ (dashed line) with (from top left to right): (i) $|\omega| = |\eta_{+-}|$, $\Omega = \phi_{+-} - 0.16\pi$, (ii) $|\omega| = |\eta_{+-}|$, $\Omega = \phi_{+-} + 0.95\pi$, (iii) $|\omega| = 0.5|\eta_{+-}|$, $\Omega = \phi_{+-} + 0.16\pi$, (iv) $|\omega| = 1.5|\eta_{+-}|$, $\Omega = \phi_{+-}$. Δt is measured in units of τ_S (the mean life-time of K_S) and $I(\Delta t)$ in units of $|C|^2|\eta_{+-}|^2|\langle\pi^+\pi^-|K_S\rangle|^4\tau_S$.

Perspectives for KLOE-2 : Re(ω), Im(ω) → 2 x 10^{-5}

A di Domenico

Bernabeu, NEM, Papavassiliou,…

CPTV & EPR-correlations modification

(Bernabeu, NM and Papavassiliou, hep-ph/0310180 (PRL 92))

If CPT is broken via Quantum Gravity (QG) decoherence effects on $\$ \neq SS^\dagger$, then: CPT operator Θ is ILL defined $\Rightarrow$ Antiparticle Hilbert Space INDEPENDENT OF particle Hilbert space.

Neutral mesons K^0 and $\overline{K}^0$ SHOULD NO LONGER be treated as IDENTICAL PARTICLES. $\Rightarrow$ initial Entangled State in ϕ (B) factories $|i>$ (in terms of mass eigenstates):

$$\begin{aligned} |i> &= \mathcal{N}\Big[\big(|K_S(\vec{k}), K_L(-\vec{k})> - |K_L(\vec{k}), K_S(-\vec{k})>\big) \\ &+ \omega\big(|K_S(\vec{k}), K_S(-\vec{k})> - |K_L(\vec{k}), K_L(-\vec{k})>\big)\Big] \end{aligned}$$

$$\omega = |\omega| e^{i\Omega}$$

NB! $K_S K_S$ or $K_L - K_L$ combinations, due to CPTV ω, important in decay channels. There is contamination of C(odd) state with C(even). Complex ω controls the amount of contamination by the "wrong" (C(even)) symmetry state.

Experimental Tests of ω-Effect in ϕ, B factories... in B-factories: ω-effect $\rightarrow$ demise of flavour tagging (Alvarez et al. (PLB607))

NB1: Disentangle ω C-even background effects ($e^+e^- \Rightarrow 2\gamma \Rightarrow K^0\overline{K}^0$): terms of the type $K_S K_S$ (which dominate over $K_L K_L$) coming from the ϕ-resonance as a result of ω-CPTV can be distinguished from those coming from the $C = +$ background because they interfere differently with the regular $C = -$ resonant contribution with $\omega = 0$.

NB2: Also disentangle ω from non-unitary evolution ($\alpha = \gamma$ ...) effects (different structures) (Bernabéu, NM, Papavassiliou, Waldron NP B744:180-206,2006)

NB: Decoherence & CPTV

Decoherence implies that asymptotic density matrix of low-energy matter :

May induce **quantum decoherence** of propagating matter and **intrinsic CPT Violation** in the sense that the CPT operator **Θ** is **not well-defined → beyond Local Effective Field theory**

$$\rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$

$$|i\rangle = \mathcal{N}\Big[|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle - |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle + \omega\Big(|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle + |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle\Big)\Big]$$

$$\omega = |\omega| e^{i\vartheta}$$

May contaminate initially antisymmetric neutral meson *M* state by symmetric parts (ω-effect)

Wald (79)

Hence Θ ill-defined at low-energies in QG foam models → may affect EPR

Bernabeu, NEM, Papavassiliou,…

Other beyond Local EFT Effects- QG-induced ecoherence

Quantum Gravity (QG) may induce decoherence and oscillations $K^0 \to \overline{K}^0$ $\Rightarrow$ **could use Lindblad-type approach (one example)** (Ellis, Hagelin, Nanopoulos, Srednicki, Lopez, NM):

$$\partial_t \rho = i[\rho, H] + \delta\!\!/H\rho$$

where

$$H_{\alpha\beta} = \begin{pmatrix} -\Gamma & -\frac{1}{2}\delta\Gamma & -\mathrm{Im}\Gamma_{12} & -\mathrm{Re}\Gamma_{12} \\ -\frac{1}{2}\delta\Gamma & -\Gamma & -2\mathrm{Re}M_{12} & -2\mathrm{Im}M_{12} \\ -\mathrm{Im}\Gamma_{12} & 2\mathrm{Re}M_{12} & -\Gamma & -\delta M \\ -\mathrm{Re}\Gamma_{12} & -2\mathrm{Im}M_{12} & \delta M & -\Gamma \end{pmatrix}$$

and

$$\delta\!\!/H_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -2\alpha & -2\beta \\ 0 & 0 & -2\beta & -2\gamma \end{pmatrix}$$

positivity of ρ requires: $\alpha, \gamma > 0, \qquad \alpha\gamma > \beta^2.$

α, β, γ violate CPT (Wald : decoherence) & CP: $CP = \sigma_3 \cos\theta + \sigma_2 \sin\theta, \qquad [\delta\!\!/H_{\alpha\beta}, CP] \neq 0$

Neutral Kaon Entangled States

- Complete Positivity of Decoherence matrix → Different parametrization **(Benatti-Floreanini)**

(in α, β, γ framework: $\alpha = \gamma,\ \beta = 0$)

FROM DAΦNE :

KLOE preliminary (A. Di Domenico Home Page, (c.f. Experimental Talk (M. Testa)).)
http://www.roma1.infn.it/people/didomenico/roadmap/kaoninterferometry.html

$$\alpha = \left(-10^{+41}_{-31\,\mathrm{stat}} \pm 9_{\mathrm{syst}}\right) \times 10^{-17}\ \mathrm{GeV}\ ,$$

$$\beta = \left(3.7^{+6.9}_{-9.2\,\mathrm{stat}} \pm 1.8_{\mathrm{syst}}\right) \times 10^{-19}\ \mathrm{GeV}\ ,$$

$$\gamma = \left(-0.4^{+5.8}_{-5.1\,\mathrm{stat}} \pm 1.2_{\mathrm{syst}}\right) \times 10^{-21}\ \mathrm{GeV}\ ,$$

NB: For entangled states, **Complete Positivity** requires (Benatti, FLoreanini) $\alpha = \gamma, \beta = 0$, **one independent parameter** (which has the greatest experimental sensitivity by the way) γ !

with $L = 2.5\ fb^{-1}$: $\gamma \to \pm 2.2_{stat} \times 10^{-21}$ GeV ,

Perspectives with KLOE-2 at DAΦNE-2 :

$\gamma \to \pm 0.2. \times 10^{-21}$ GeV

(present best measurement $\gamma \;=\; \left(1.3^{+2.8}_{-2.4\mathrm{stat}} \pm 0.4_{\mathrm{syst}}\right) \cdot 10^{-21}\,\mathrm{GeV}$
(KLOE)

Part II
Microscopic Origin of SME coefficients?

Several ``Geometry-induced" examples:

Non-Commutative Geometries
Axisymmetric Background
Geometries of the Early Universe
Torsionful Geometries (including strings…)

Early Universe T-dependent effects:
large @ high T, low values today
for coefficients of SME

STANDARD MODEL EXTENSION

V.A. Kostelecký, R. Bluhm, D. Colladay, R. Lehnert, R. Potting, N. Russell

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Non-commutative effective field theories

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

Moyal $\star$ products

$$f \star g(x) \equiv \exp(\tfrac{1}{2} i\theta^{\mu\nu}\partial_{x^\mu}\partial_{y^\nu}) f(x) g(y)\big|_{x=y}$$

$$\mathcal{L} = \tfrac{1}{2} i\overline{\widehat{\psi}} \star \gamma^\mu \overleftrightarrow{\widehat{D}_\mu} \widehat{\psi} - m\overline{\widehat{\psi}} \star \widehat{\psi} - \frac{1}{4q^2}\widehat{F}_{\mu\nu} \star \widehat{F}^{\mu\nu}$$

$$\widehat{D}_\mu \widehat{\psi} = \partial_\mu \widehat{\psi} - i\widehat{A}_\mu \star \widehat{\psi}$$

$$\widehat{f} \star \overleftrightarrow{\widehat{D}_\mu} \widehat{g} \equiv \widehat{f} \star \widehat{D}_\mu \widehat{g} - \widehat{D}_\mu \widehat{f} \star \widehat{g}$$

$$\theta_{\mu\nu}\theta^{\mu\nu} > 0$$

$$\widehat{A}_\mu = A_\mu - \tfrac{1}{2}\theta^{\alpha\beta} A_\alpha(\partial_\beta A_\mu + F_{\beta\mu}),$$
$$\widehat{\psi} = \psi - \tfrac{1}{2}\theta^{\alpha\beta} A_\alpha \partial_\beta \psi.$$

$$D_\mu \psi = \partial_\mu \psi - iqA_\mu \psi$$

$$\begin{aligned}\mathcal{L} = {} & \tfrac{1}{2} i\overline{\psi}\gamma^\mu \overleftrightarrow{D_\mu} \psi - m\overline{\psi}\psi - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & -\tfrac{1}{8} iq\theta^{\alpha\beta} F_{\alpha\beta}\overline{\psi}\gamma^\mu \overleftrightarrow{D_\mu} \psi + \tfrac{1}{4} iq\theta^{\alpha\beta} F_{\alpha\mu}\overline{\psi}\gamma^\mu \overleftrightarrow{D_\beta} \psi \\ & +\tfrac{1}{4} mq\theta^{\alpha\beta} F_{\alpha\beta}\overline{\psi}\psi \\ & -\tfrac{1}{2} q\theta^{\alpha\beta} F_{\alpha\mu}F_{\beta\nu}F^{\mu\nu} + \tfrac{1}{8} q\theta^{\alpha\beta} F_{\alpha\beta}F_{\mu\nu}F^{\mu\nu}.\end{aligned}$$

CPT invariant SME type field theory (Q.E.D.) - only even number of indices appear in effective non-renormalisable terms. (**Carroll et al. hep-th/0105082**)

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& + \tfrac{1}{4} m q \theta^{\alpha\beta} F_{\alpha\beta} \overline{\psi}\psi \\
& - \tfrac{1}{2} q \theta^{\alpha\beta} F_{\alpha\mu} F_{\beta\nu} F^{\mu\nu} + \tfrac{1}{8} q \theta^{\alpha\beta} F_{\alpha\beta} F_{\mu\nu} F^{\mu\nu}.
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Gravitational Baryogenesis

Davoudiasl, Kitano, Kribs, Murayama, Steinhardt

Quantum Gravity (or something else (e.g. SUGRA)) may lead at low-energies (below Plnack scale or a scale M_*) to a term in the effective Lagrangian (in curved back space-time backgrounds):

$$J^\mu = \overline{\psi}_i \, \gamma^\mu \, \psi_i$$

$$\frac{1}{M_*^2} \int d^4x \sqrt{-g} (\partial_\mu \mathcal{R}) J^\mu$$

Standard Model extension type

Term Violates CP but is CPT conserving *in vacuo*
It ***Violates* CPT** in the background space-time of an ***expanding FRW Universe***

$$\dot{\mathcal{R}} = -(1-3w)\frac{\dot{\rho}}{M_P^2} = \sqrt{3}\,(1-3w)(1+w)\frac{\rho^{3/2}}{M_P^3}$$

Energy differences between particle vs antipartic $\pm\dot{\mathcal{R}}/M_*^2$; ***Dynamical CPTV***

Baryon Asymmetry $\frac{n_B}{s} \approx \frac{\dot{\mathcal{R}}}{M_*^2 T}\Big|_{T_D}$

Calculate for various w in some scenarios

@ $T < T_D$, T_D = Decoupling T

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CPTV Effects of different Space-Time-Curvature/Spin couplings between neutrinos/antineutrinos

B. Mukhopadhyay, U. Debnath, N. Dadhich, M. Sinha
Lambiase, Mohanty, NEM, Ellis, Sarkar

Curvature Coupling to **fermion spin** may lead to different dispersion relations between neutrinos and antineutrinos (assumed ***dominant*** in the Early eras) in **non-spherically symmetric** geometries, or geometries with **torsion** in the Early Universe.

Dirac Lagrangian (for concreteness, it can be extended to Majorana neutrinos)

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar{\psi}\,\gamma^a D_a \psi - m\,\bar{\psi}\psi\right)$$

$$D_a = \left(\partial_a - \frac{i}{4}\omega_{bca}\sigma^{bc}\right),$$

Gravitational covariant derivative including spin connection

$$\sigma^{ab} = \tfrac{i}{2}\left[\gamma^a, \gamma^b\right]$$

$$\omega_{bca} = e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\gamma\mu} e^\gamma_c e^\mu_a\right).$$

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\bar{\psi}\left[(i\gamma^a\partial_a - m) + \gamma^a\gamma^5 B_a\right]\psi,$$

$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu} e^\alpha_c e^\mu_a\right)$$

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$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\bar{\psi}\left[(i\gamma^a\partial_a - m) + \gamma^a\gamma^5 B_a\right]\psi,$$

$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e^{\lambda}_{c} + \Gamma^{\lambda}_{\alpha\mu} e^{\alpha}_{c} e^{\mu}_{a}\right)$$

Standard Model Extension type Lorentz-violating coupling (Kostelecky *et al.*)

Dirac Lagrangian (for concreteness, it can be extended to Majorana neutrinos)

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar{\psi}\,\gamma^a D_a \psi - m\,\bar{\psi}\psi\right)$$

$$D_a = \left(\partial_a - \frac{i}{4}\omega_{bca}\sigma^{bc}\right),$$

Gravitational covariant derivative including spin connection

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For homogeneous and isotropic **Friedman-Robertson-Walker** geometries the resulting B^μ ***vanish***

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Can be constant in a given local frame in Early Universe **axisymmetric (Bianchi) cosmologies** or **near rotating Black holes**, or **in stringy antisymmetric tensor backgrounds**

COSMOLOGICAL CONSEQUENCES

DISPERSION RELATIONS OF NEUTRINOS ARE *DIFFERENT* FROM THOSE OF ANTINEUTRINOS IN *SUCH* GEOMETRIES

$(p_a \pm B_a)^2 = m^2,$ ± refers to chiral fields (here neutrino/antineutrino)

CPTV Dispersion relations

$$E = \sqrt{(\vec{p} - \vec{B})^2 + m^2} + B_0 \ , \quad \bar{E} = \sqrt{(\vec{p} + \vec{B})^2 + m^2} - B_0$$

but (bare) masses are equal between particle/anti-particle sectors

Abundances of neutrinos in Early Universe, then, ***different*** from those of antineutrinos if $\mathbf{B_0}$ is ***non-trivial***, **ALREADY IN THERMAL EQUILIBRIUM**

Equilibrium Distributions different between particle-antiparticles

Can these create the observed matter-antimatter asymmetry?

$$f(E,\mu) = \frac{1}{\exp[(E-\mu)/T] \pm 1}$$

$$\delta n \equiv n - \bar{n} = g_{df} \int \frac{d^3p}{(2\pi)^3} \left[f(E,\mu) - f(\bar{E},\bar{\mu})\right]$$

Abundances of neutrinos in Early Universe *different* from those of antineutrinos if $B_0 \neq 0$

$$\Delta n = \frac{g}{(2\pi)^3} \int d^3\mathrm{p} \left[\frac{1}{1 + \exp(E_\nu / T)} - \frac{1}{1 + \exp(E_{\bar{\nu}} / T)} \right]$$

$$\Delta n = \frac{g}{(2\pi)^2} T^3 \int_0^\infty \int_0^\pi \left[\frac{1}{1 + e^u \, e^{B_0/T}} - \frac{1}{1 + e^u \, e^{-B_0/T}} \right] u^2 \, d\theta \, du$$

$$u = |\vec{p}|/T$$

$$\Delta n_\nu \equiv n_\nu - n_{\overline{\nu}} \sim g^\star \, T^3 \left(\frac{B_0}{T} \right)$$

with $g^\star$ the number of degrees of freedom for the (relativistic) neutrino.

DISPERSION RELATIONS OF NEUTRINOS ARE *DIFFERENT* FROM THOSE OF ANTINEUTRINOS IN *SUCH* GEOMETRIES

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Abundances of neutrinos in Early Universe, then, ***different*** from those of antineutrinos if B_0 is ***non-trivial***, **ALREADY IN THERMAL EQUILIBRIUM**

Lepton Asymmetry, *e.g*. for neutrinos

$$\Delta L(T < T_d) = \frac{\Delta n_\nu}{s} \sim \frac{B_0}{T_d}$$

CPTV BARYOGENESIS through B-L conserving sphalerons? NO NEED FOR ENHANCED CP VIOLATION IN EARLY UNIVERSE?

Microscopic Origin of SME coefficients?

Several ``Geometry-induced" examples:

Non-Commutative Geometries

Axisymmetric Background

Geometries of the Early Universe

Torsionful Geometries (including strings…)

MOTIVATION?

Early Universe T-dependent effects:
large @ high T, low values today
for coefficients of SME

Early Universe Matter Dominance

- ***Ultimate question: why is the Universe made only of matter?***

- ***Leptogenesis***: physical ***out of thermal equilibrium*** processes in the (***expanding)*** Early Universe that produce an asymmetry between leptons & antileptons

- ***Baryogenesis***: The corresponding processes that produce an asymmetry between baryons and antibaryons

Early Universe Matter Dominance

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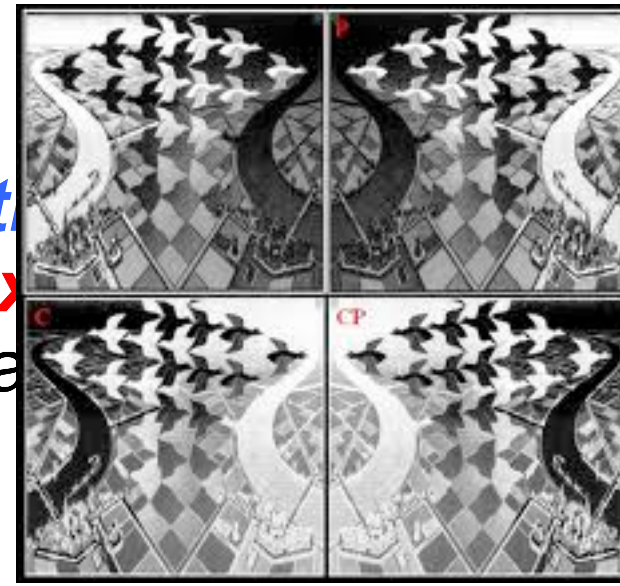

escher

- ***Baryogenesis***: The corresponding processes that produce an asymmetry between baryons and antibaryons

STANDARD MODEL INCOMPATIBLE WITH BARYOGENESIS

- Matter-Antimatter asymmetry in the Universe ⇒ Violation of Baryon # (B), C & CP

- Tiny CP violation (O(10^{-3})) in Labs: e.g. $K^0 \overline{K}^0$

- But Universe consists only of matter

$$\frac{n_B - \overline{n}_B}{n_B + \overline{n}_B} \sim \frac{n_B - \overline{n}_B}{s} = (8.4 - 8.9) \times 10^{-11}$$ T > 1 GeV

Sakharov : Non-equilibrium physics of early Universe, **B, C, CP violation**

⇒ $n_B - \bar{n}_B$ but **not quantitatively in SM**, still a mystery

Within the Standard Model, lowest CP Violating structures

Assume CPT

$$d_{CP} = \sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin\delta_{CP}$$
$$\cdot(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

Cabbibo-Kobayashi-Maskawa CP Violating phase

Shaposhnikov

$$D = \mathrm{Im}\ \mathrm{Tr}\left[\mathcal{M}_u^2 \mathcal{M}_d^2 \mathcal{M}_u \mathcal{M}_d\right]$$

$$\delta_{KM}^{CP} \sim \frac{D}{T^{12}} \sim 10^{-20} \quad << \frac{n_B - \overline{n}_B}{n_B + \overline{n}_B} \sim \frac{n_B - \overline{n}_B}{s} = (8.4 - 8.9) \times 10^{-11}$$

$$T \simeq T_{\mathrm{sph}}$$ sphaleron freeze-out temperature

$$T_{\mathsf{sph}}(m_H) \in [130, 190]\,\mathrm{GeV}$$

This CP Violation Cannot be the Source of Baryon Asymmetry in The Universe

Role of Neutrinos?

- Several Ideas to go beyond the SM (e.g. GUT models, Supersymmetry, extra dimensional models etc.)
- Massive ν are **simplest** extension of SM

Shaposhnikov et al. νMSM

- Right-handed massive ν may provide extensions of SM with:

  extra CP Violation and thus Origin of Universe's matter-antimatter asymmetry due to neutrino masses, **Dark Matter**

Thermal Leptogenesis

Independent of Initial Conditions @ T >>T_{eq}

Heavy Right-handed Majorana neutrinos enter ***equilibrium at $T = T_{eq} > T_{decay}$***

enhanced CP V. **Lepton number Violation**

$$N_I \to H\nu,\ \bar{H}\bar{\nu}$$

RIGHT-HANDED NEUTRINOS

Out of Equilibrium Decays

$$T \simeq T_{\rm decay} > T_{\rm sph}$$

Produce Lepton asymmetry

Equilibrated electroweak B, L violating sphaleron interactions (B-L conserv)

Independent of Initial Conditions

Observed Baryon Asymmetry In the Universe (BAU)

Fukugita, Yanagida,

Kuzmin, Rubakov, Shaposhinkov

Estimate BAU by solving Boltzmann equations for Heavy Neutrino Abundances

Pilafsis, Riotto… Buchmuller, di Bari *et al.*

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Extra CP Violation: a delicate issue?

- No observed CP Violation as yet in Lepton sector of the Standard Model

- ν MSM & in general: Models good for Baryogenesis if sufficient amount of extra CP Violation → (ii) delicate arrangements to obtain necessary CP violation in ν sector

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Extra CP Violation: a delicate issue?

- No observed CP Violation as yet in Lepton sector of the Standard Model
- ν MSM & in general: Models good for Baryogenesis if sufficient amount of extra CP Violation → (ii) delicate arrangements to obtain necessary CP violation in ν sector
- NO RIGHT-HANDED NEUTRINOS observed as yet

CPT Violation in non-standard (axisymmetric, torsionful) Geometries of the Early Universe → particle/antiparticle asymmetries in thermal equilibrium.

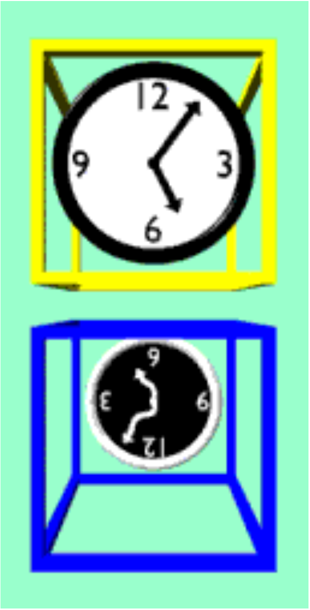
No need for extra CP Violation (or even sterile ν) for explanation of matter over anti-matter dominance?

Geometry-Induced CPTV can do the job of reproducing the observed Baryon Asymmetry unlike simple case of assumed CPTV mass difference between particle and antiparticle

CPT VIOLATION IN THE EARLY UNIVERSE

GENERATE Baryon and/or Lepton ASYMMETRY without Heavy Sterile Neutrinos?

Assume CPT Violation.
e.g. due to ***Quantum Gravity*** fluctuations,
strong in the Early Universe



physics.indiana.edu

ONE POSSIBILITY:

particle-antiparticle mass differences

$$m \neq \overline{m}$$

Equilibrium Distributions different between particle-antiparticles

Can these create the observed matter-antimatter asymmetry?

$$f(E,\mu) = \frac{1}{\exp[(E-\mu)/T] \pm 1}$$

$$m \neq \overline{m}$$

$$\delta m = m - \overline{m}$$

$$\delta n \equiv n - \bar{n} = g_{df} \int \frac{d^3p}{(2\pi)^3} \left[f(E,\mu) - f(\bar{E},\bar{\mu}) \right]$$

$$E = \sqrt{p^2 + m^2},\ \bar{E} = \sqrt{p^2 + \bar{m}^2}$$

Dolgov, Zeldovich
Dolgov (2009)

Assume dominant contributions to Baryon asymmetry from quarks-antiquarks

$$m(T) \sim gT$$

High-T quark mass >> Lepton mass

Equilibrium Distributions different between particle-antiparticles

Can these create the observed matter-antimatter asymmetry?

$$f(E,\mu) = \frac{1}{\exp[(E-\mu)/T] \pm 1}$$

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Assuming dominant contributions to Baryon asymmetry from quarks-antiquarks

$$\beta_T = \frac{n_B}{n_\gamma} = -8.4 \cdot 10^{-3} \left(18 m_u \delta m_u + 15 m_d \delta m_d\right)/T^2$$

Dolgov, Zeldovich
Dolgov (2009)

$n_\gamma = 0.24 T^3$ photon equilibrium density at temperature T

$$\beta_T = \frac{n_B}{n_\gamma} = -8.4 \cdot 10^{-3} \left(18 m_u \delta m_u + 15 m_d \delta m_d\right) / T^2$$

$$n_\gamma = 0.24 T^3$$

Dolgov (2009)

Current bound for proton-anti proton mass diff.

$$\delta m_p < 7 \cdot 10^{-10}\ \mathrm{GeV}$$

ASACUSA Coll. (2011)

Reasonable to take: $\delta m_q \sim \delta m_p$ → ***Too small*** $\boldsymbol{\beta^{T=0}}$

NB: To reproduce the observed $\beta^{(T=0)} = 6 \cdot 10^{-10}$ need

$$\delta m_q (T = 100\ \mathrm{GeV}) \sim 10^{-5} - 10^{-6}\ \mathrm{GeV} >> \delta m_p$$

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CPT Violating quark-antiquark Mass difference alone CANNOT REPRODUCE observed BAU

CPT Violating Thermal Leptogenesis: a scenario involving antisymmetric Kalb-Ramond tensor

Ellis, NEM, Sarkar (2013)

Neutrino/Antineutrino oscillations, due to **$B^0 \neq 0$**, originating from string antisymmetric tensor backgrounds; these oscillations are the local processes in the early Universe responsible for the **CPT Violation**
They occur provided the oscillation length is smaller than the Hubble horizon

For **$T_d = O(10^9$ GeV$)$** the Hubble horizon size is 10^{-12} cm & for **$B_0 = O(0.1)$ GeV** the oscillation length is 10^{-13} cm, i.e. smaller than Hubble Horizon, so oscilaltions can occue → provide chemical equilibrium for $T > T_d$

Can reproduce BAU → fermion action of SME type with b_μ background

CPT Violating Thermal Leptogenesis

Early Universe
$T > T_d = 10^9$ GeV

CPT Violation

already in thermal equilibrium

No need for **enhanced CPV.**
Heavy Right-handed Majorana **neutrino/ antineutrino oscillations**

Produce Lepton asymmetry

T = O(100) GeV

$$L = \frac{2}{M} l_L l_L \phi\phi + \text{H.c.}$$

where

$$l_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

Equilibrated electroweak B+L violating sphaleron interactions

Independent of Initial Conditions

Observed Baryon Asymmetry In the Universe (BAU)

Estimate BAU by fixing CPTV background parameters
In some models this may imply fine tuning ….

Neutrino/natineutrino oscillation processes are ***UNIQUE*** to Majorana neutrinos

Charged leptons and quarks of the Standard Model, which also couple to H-torsion, cannot exhibit such oscillation due to electric charge conservation

Hence: above scenario for Leptogenesis @ T = 10^9 GeV and then Baryogenesis at T = O(100 GeV) through standard-model B-L conserving sphaleron processes appears **unique to Majorana Neutrinos**

Consistent with absence of observed CPTV today in neutrino sector

Torsion $B^0 = 0$ (or very small) today

If a small B^a is present today

Standard Model Extension type coupling b_μ

Kostelecky, Mewes, Russell, Lehnert …

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\bar{\psi}\left[(i\gamma^a\partial_a - m) + \gamma^a\gamma^5 B_a\right]\psi,$$

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If due to GRAVITY, it should couple universally to all particle species of the standard model (electrons etc)

Very Stringent constraints from astrophysics (e.g. for electrons (Masers))

$$|\vec{B}| < 10^{-19}\,\mathrm{eV} \qquad |B^0| < 10^{-2}\,\mathrm{eV}$$

Connect smoothly with a linear in T dependence to the B^0 of O(0.1 GeV) in our case, required for Leptogenesis at T> 10^9 GeV in the model?

IS THIS CPTV ROUTE WORTH FOLLOWING? ….

CPT Violation

Construct Microscopic Quantum Gravity models with strong CPT Violation in Early Universe, but maybe weak today… Fit with all available data… Estimate in this way matter-antimatter asymmetry in Universe.

CONCLUSIONS-OUTLOOK

- Interesting Physics in the Early Universe may imply microscopic origin of SME & allow for smooth connection (T-dependent) with **current** era

- Plethora of Tests of SME
- At best it may determine today's values of coefficients and connect with early unvierse
- Quantum Gravity though may imply effects beyond SME such as ω-effect on EPR or decoherence
- Independent tests of T & CPT possible in entangled states of particles → use in antipotonic atoms ?

SPARES

Can neutrinos provide
an explanation of observed
matter-antimatter asymmetry
via CPT VIOLATION (CPTV)?

NB …CPT Violating neutrino-antineutrino Mass difference alone MAY REPRODUCE observed BAU

$$m_i = \tan\beta_i \overline{m}_i$$

$i = 1, 2, 3$ Light ν species

Barenboim, Borissov, Lykken, Smirnov (01) PHENOMENOLOGICAL MODELS

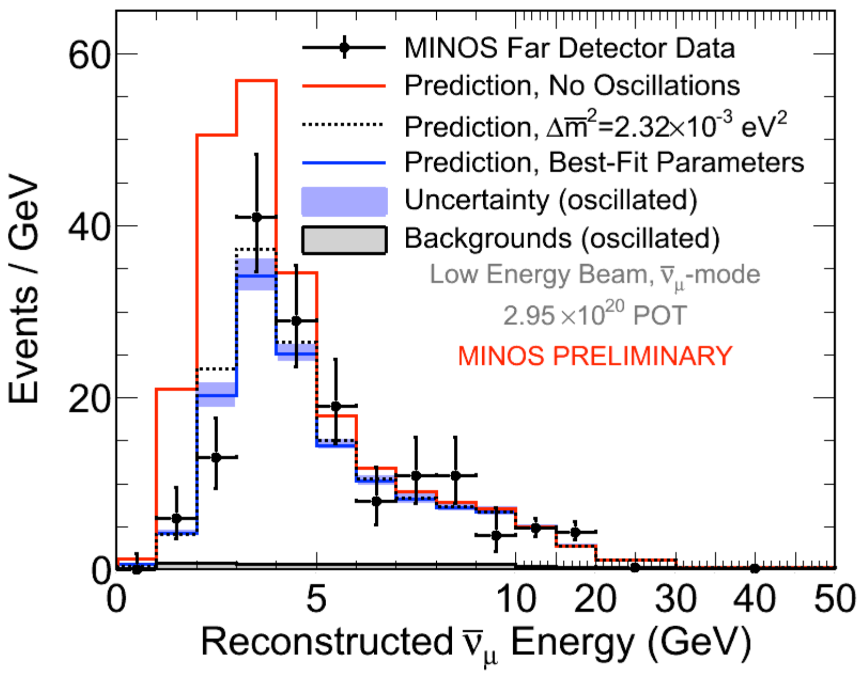
$$n_B = n_\nu - n_{\bar{\nu}} \simeq \frac{\mu_\nu T^2}{6}$$

$$\frac{n_B}{s} \sim \frac{\mu_\nu}{T} \sim 10^{-11}$$

@ 100 GeV ✔

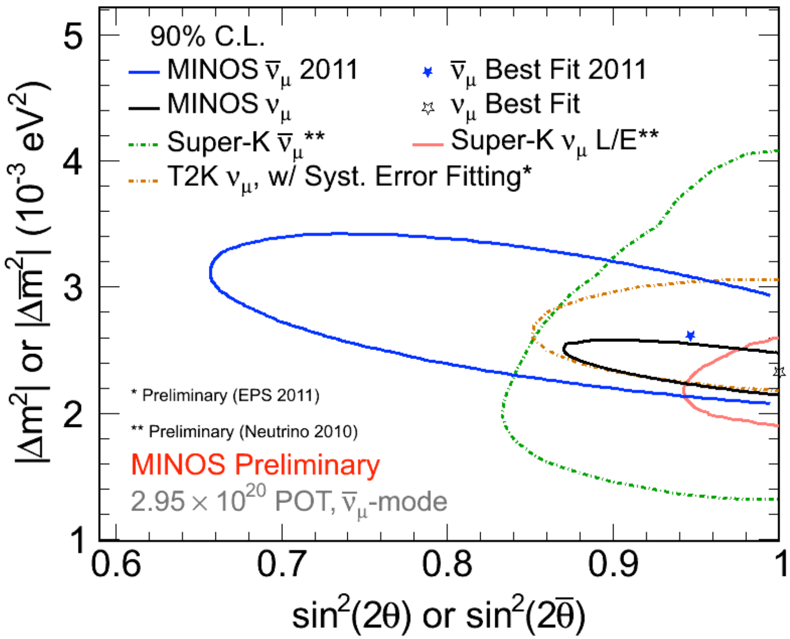
MINOS Exp. RESULTS ON Potential Neutrino-Antineutrino OSCILLATION PARAMETER DIFFERENCES

http://www-numi.fnal.gov



$\bar{\nu}_\mu$ disapearance-Energy spectrum

[arXiv:1108.1509]



$\bar{\nu}_\mu$ vs ν_μ Oscillation parameters

[arXiv:1104.0344] [arXiv1103.0340]

$\bar{\nu}_\mu$ disappearance $\Delta\bar{m}^2$=(2.62+0.31-0.28 (stat.) ±0.09 (syst.))x10^{-3} eV^2, $\sin^2(2\Theta)$=0.95 +0.10-0.11 (stat.) ±0.01 (syst.).

ν_μ disappearance: Δm^2=(2.32+0.12-0.08)x10^{-3} eV^2 , $\sin^2(2\Theta)$ =1.00 ($\sin^2(2\Theta)$ > 0.90 @ 90% CL

Consistent with equality of mass differences between particle/antiparticles

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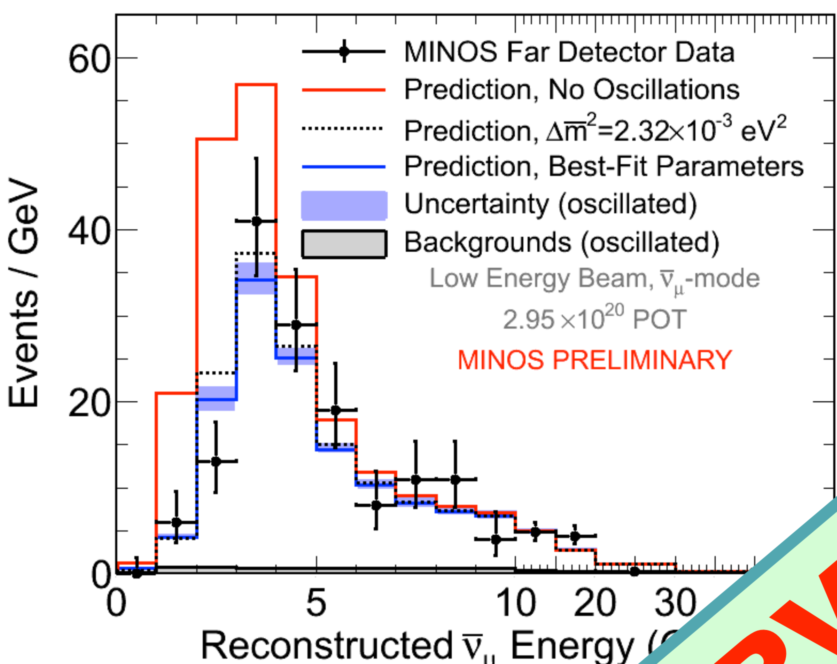
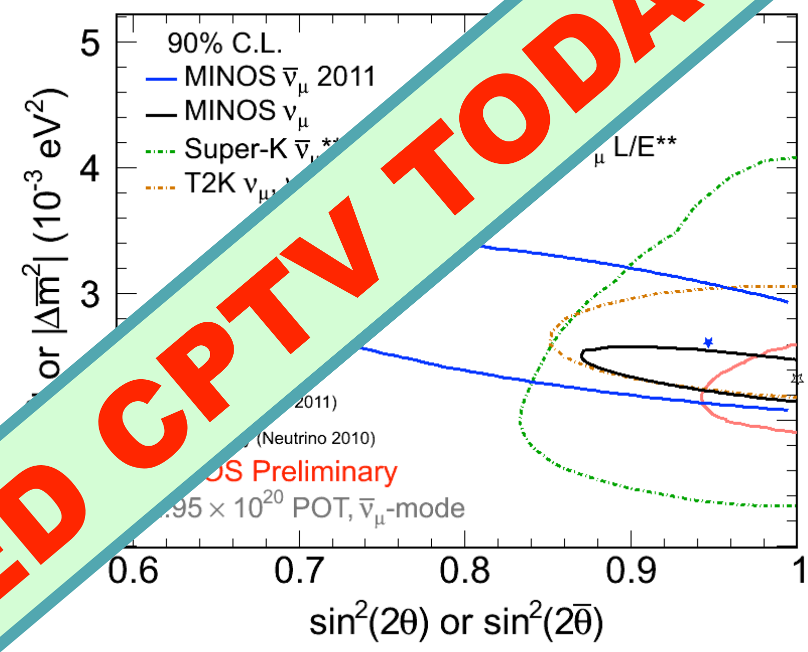
http://ww… l.gov



$\bar{\nu}_\mu$ disapearance-Energ…

…09]



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NO OBSERVED CPTV TODAY

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Consisten… with equality of mass differences between particle/antiparticles