Models (& some searches) for CPT Violation

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OUTLINE

I. Theory Background on fundamental symmetries violation:

Quantum OR Classical Gravity (Geometrical Backgrounds in Early Universe) may violate fundamental space-time symmetries:
continuous (Lorentz (LV)) &/or discrete (T & CPT (CPTV))

Quantum Gravity (QG) Microscopic fluctuations *may* induce ***decoherence*** of propagating quantum matter (inaccesibility by local observers to all QG d.o.f.) →
CPT quantum-mechanical **operator *NOT WELL DEFINED***

II. Decoherene-induced CPTV Experimental searches: Entangled Neutral Mesons- ω effect

III. Decoherence CPTV and spin-statistics theorem Possible Pauli Exclusion Principle violation.

IV. Conclusions-Outlook

(CPT Violation in early universe (torsionful) geometries – Standard Model extension type Lagrangian from geometry & matter-antimatter asymmetry in the Universe... - as with decoherence CPTV model, this CPTV is also due to gravitational background but here background is classical, and CPT op. is well-defined)

Part I

CPT Violation

THEORY

CPT Theorem

Schwinger 1951

Lüders 1954

J S Bell 1954

Pauli 1955

Res Jost 1958

CPT Theorem

Conditions for the Validity of CPT Theorem

$$P: \vec{x} \to -\vec{x}, \quad T: t \to -t(T), \quad C\psi(q_i) = \psi(-q_i)$$

CPT Invariance Theorem :
A quantum field theory lagrangian is invariant under CPT if it satisfies
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Schwinger, Pauli, Luders, Jost, Bell

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Schwinger, Pauli, Luders, Jost, Bell
revisited by:
Greenberg, Chaichian, Dolgov, Novikov, Fujikawa, Tureanu ...

(ii)-(iv) Independent reasons for violation

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Kostelecky, Bluhm, Colladay, Potting, Russell, Lehnert, Mewes, Diaz , Tasson….
Standard Model Extension (SME)

(ii)-(iv) Independent reasons for violation

$$\mathcal{L} \ni \cdots + \overline{\psi}^f \Big(i\gamma^\mu \nabla_\mu - m_f \Big) \psi^f + a_\mu \overline{\psi}^f \gamma^\mu \psi^f + b_\mu \overline{\psi}^f \gamma^\mu \gamma^5 \psi^f + \dots$$

Lorentz & CPT Violation

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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)-(iii) CPT V well-defined as Operator Θ does not commute with Hamiltonian

$$[\,\Theta, H\,] \neq 0$$

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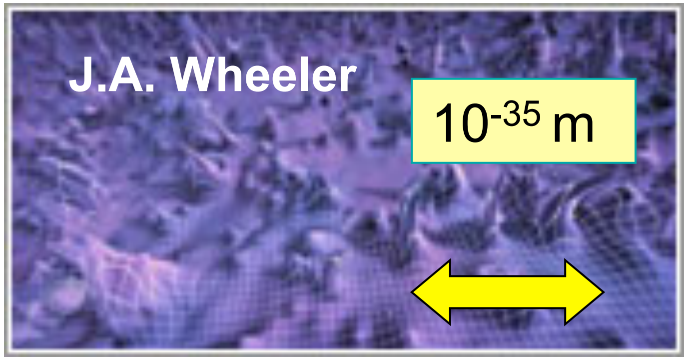
e.g. ***QUANTUM SPACE-TIME FOAM AT PLANCK SCALES***



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

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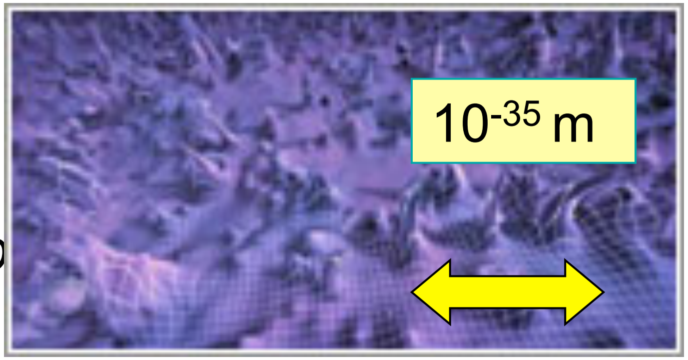
QUANTUM GRAVITY INDUCED DECOHERENCE
EVOLUTION OF PURE QM STATES TO MIXED
AT LOW ENERGIES

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



cf. ω-effect in EPR entanglement

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NB: Decoherence & CPTV

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

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

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

$$\$ \neq S\, S^{\dagger}$$

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

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**

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

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

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

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

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

Bernabeu, NEM, Papavassiliou (04),…

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ω-Effect order of magnitude estimates

(Bernabéu, Sarben Sarkar, NM, hep-th/0606137)

Theoretical models using interactions of particle-probes with specific space-time defects (e.g. D-particles, inspired by string/brane theory); Use stationary perturbation theory to describe gravitationally dressed 2-meson state - medium effects like MSW $\Rightarrow$ initial state:

$$|\psi\rangle = |k,\uparrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)} - |k,\downarrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)} + \xi\,|k,\uparrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)} + \xi'\,|k,\downarrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)}$$

NB: $\xi = -\xi'$: strangeness conserving ω-effect ($|K_L\rangle = |\uparrow\rangle$, $|K_S\rangle = |\downarrow\rangle$.).

In recoil D-particle stochastic model: (momentum transfer: $\Delta p_i \sim \zeta p_i$, $\langle \Delta p_i \rangle = 0$, $\langle \Delta p_i \Delta p_j \rangle \neq 0$)

$$|\omega|^2 \sim \frac{\zeta^2 k^4}{M_P^2 (m_1 - m_2)^2}$$

NB: For neutral kaons, with momenta of the order of the rest energies $|\omega| \sim 10^{-4}|\zeta|$. For $1 > \zeta \geq 10^{-2}$ not far below the sensitivity of current facilities, such as DAΦNE (c.f. Experimental Talk (M. Testa)). Constrain ζ significantly in upgraded facilities.

Perspectives for KLOE-2 at DAΦNE-2 (A. Di Domenico home page) :
$\mathrm{Re}(\omega)$, $\mathrm{Im}(\omega) \longrightarrow 2 \times 10^{-5}$.

NB: ω-Effect also generated by propagation through the medium, but with time-dependent (sinusoidal) $\omega(t)$-terms, can be (in principle) disentangled from initial-state ones...

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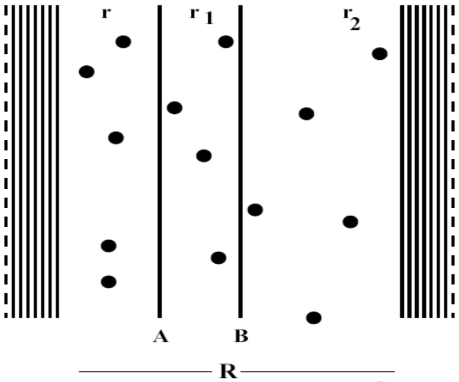

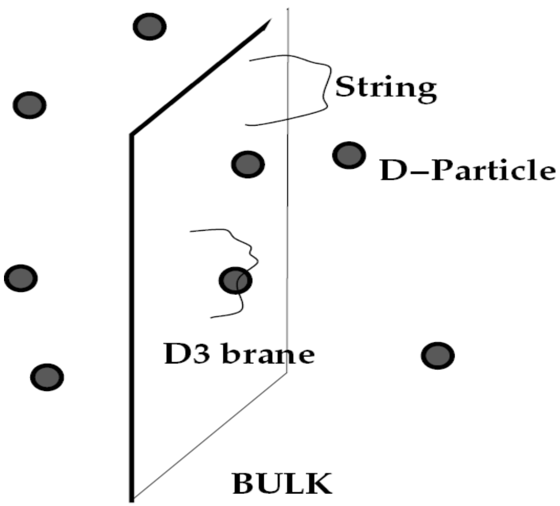

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- Neutral mesons **no** longer **indistinguishable** particles, initial entangled state:

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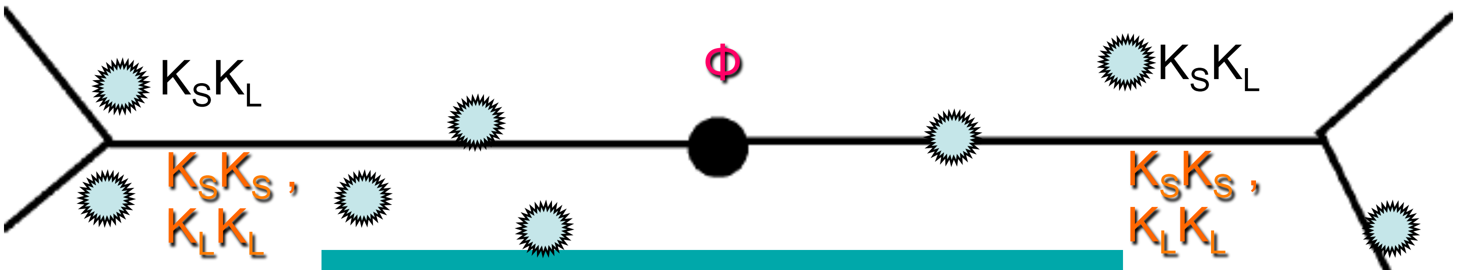

IF CPT ILL-DEFINED (e.g. flavour violating (FV) D-particle Foam)

$$|\omega|^2 \sim \frac{\zeta^2 k^2}{M_{QG}^2 (m_1 - m_2)^2}, \; \Delta p \sim \zeta p \; \text{(kaon momentum transfer)}$$

If QCD effects, sub-structure in neutral mesons ignored, and D-foam acts as if they were structureless particles, then for **$M_{QG} \sim 10^{18}$ GeV** the estimate for ω: **$|\omega| \sim 10^{-4}$ $|\zeta|$,** for $1 > |\zeta| > 10^{-2}$ (natural)
Not far from sensitivity of upgraded meson factories (e.g. **KLOE2**)

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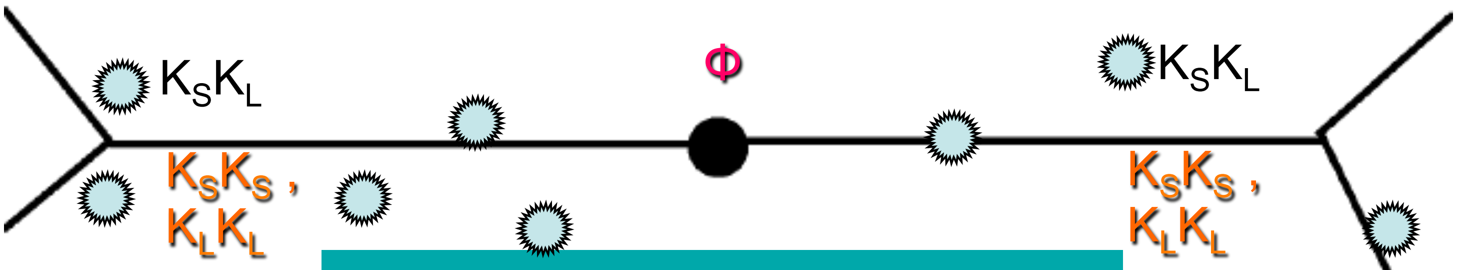

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D-particle recoil and entangled Meson States

- Apply non-degenerate perturbation theory to construct "gravitationally dressed'' states from $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

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$$\boxed{\widehat{H_I} = -\left(r_1\sigma_1 + r_2\sigma_2\right)\widehat{k}}$$

FLAVOUR FLIP

Perturbation due to recoil distortion of space-time

$$g_{0i} \propto \Delta k_i/M_P \otimes (\text{flavour} - \text{flip})$$

$$\Delta k_i = r_i k, << r_i >>= 0, << r_i r_j >>= \Delta\delta_{ij}$$

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ω-effect

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ω-effect

spin-statistics for the gravitationally dressed (**composite**) states**?**

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Part II

Decoherence –induced CPT Violation

&

Entangled meson states

(ω-effect searches)

CPTV & EPR-correlations modification

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

If CPT is broken via Quantum Gravity (QG) decoherence effects on $\$ \ne SS^\dagger$, 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):

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

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)) **Bernabeu, Botella, NEM, Nebot (2016).**

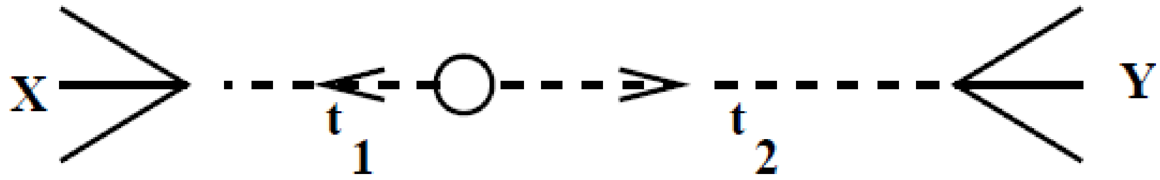
NB1: Disentangle ω C-even background effects ($e^+e^- \Rightarrow 2\gamma \Rightarrow K^0\overline{K}^0$): terms of the type $K_S K_S$ (which dominate over $K_L K_L$) coming from the ϕ-resonance as a result of ω-CPTV can be distinguished from those coming from the $C = +$ background because they interfere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

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 (04),…

ω-effect observables/current bounds

ϕ Decays and the ω Effect

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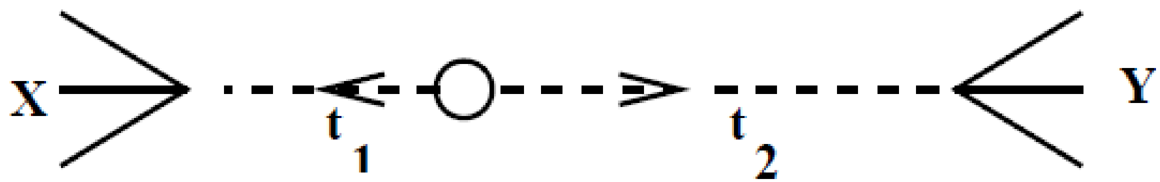

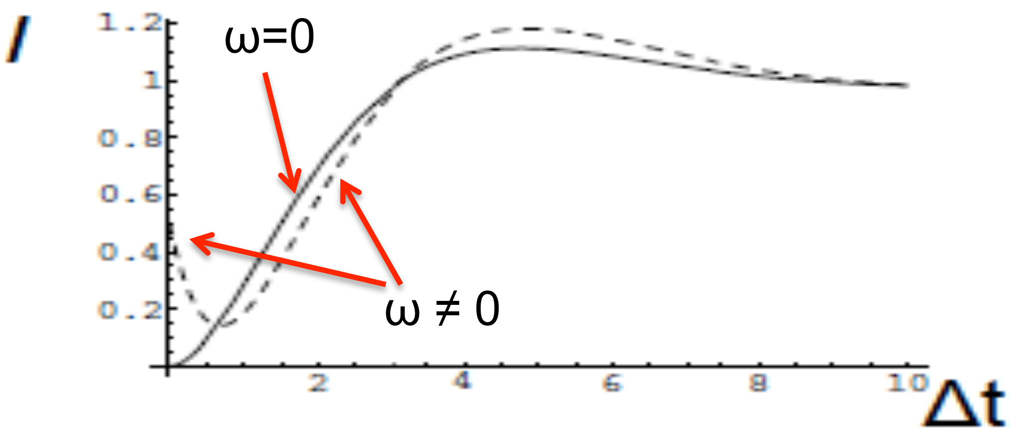

I(Δt=0) ≠ 0
if ω-effect present

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

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

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 (04),...

ω-Effect & Intensities

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

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

enhancement factor due to CP violation compared with, eg, B-mesons

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

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

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

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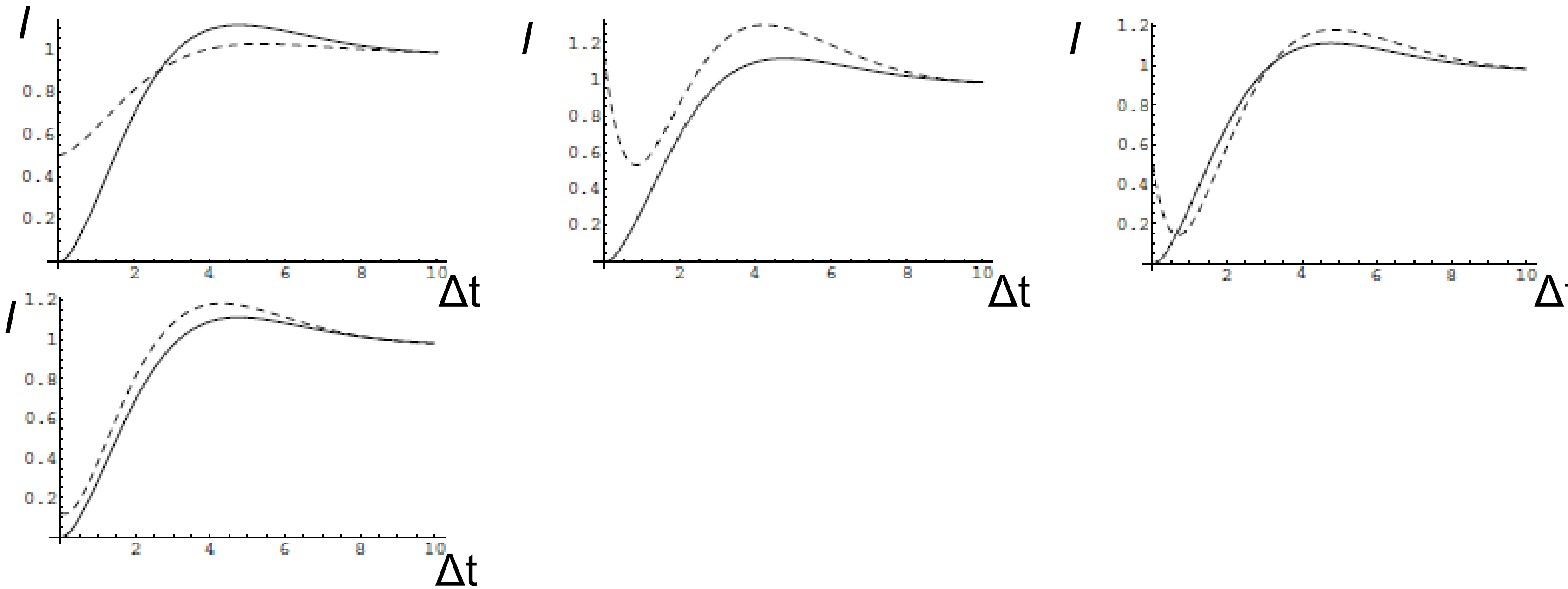
Bernabeu, NEM, Papavassiliou (04),…

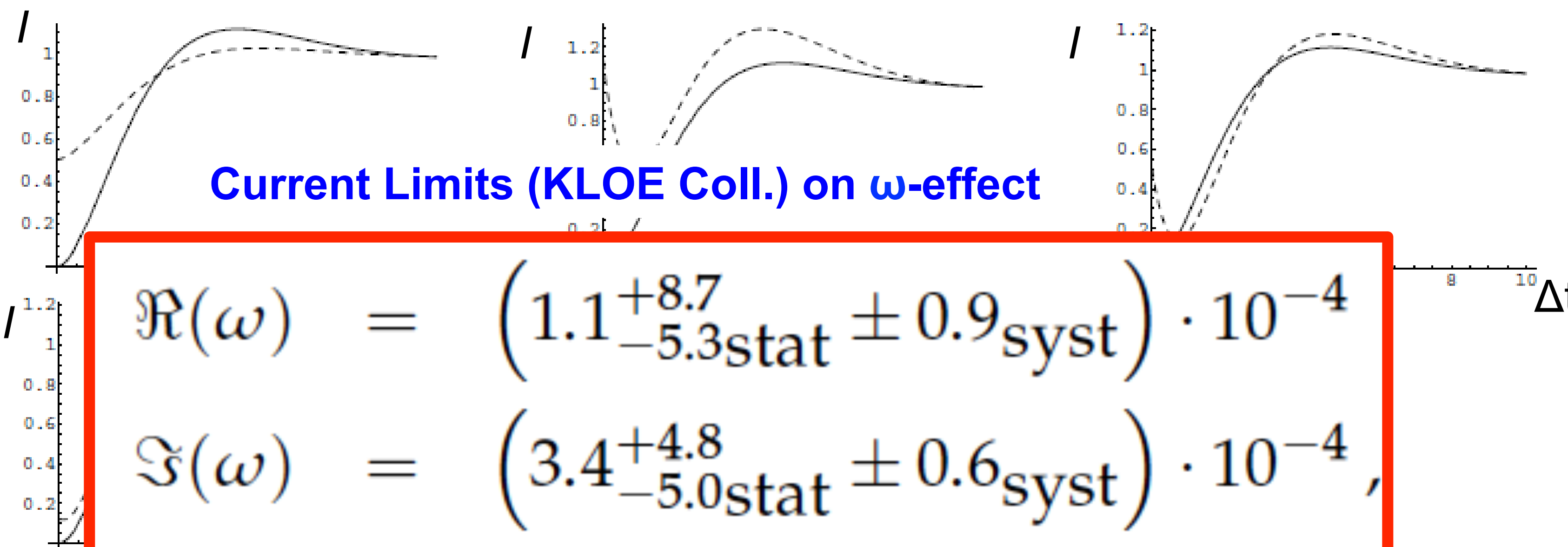
ω-Effect & Intensities



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 (04),…

ω-Effect & Intensities



Current Limits (KLOE Coll.) on ω-effect

$$\Re(\omega) = \left(1.1^{+8.7}_{-5.3}\mathrm{stat} \pm 0.9_{\mathrm{syst}}\right) \cdot 10^{-4}$$
$$\Im(\omega) = \left(3.4^{+4.8}_{-5.0}\mathrm{stat} \pm 0.6_{\mathrm{syst}}\right) \cdot 10^{-4},$$

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

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):

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

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)) **Bernabeu, Botella, NEM, Nebot (2016).**

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)

EquaL-Sign di-lepton charge asymmetry Δt dependence

ALVAREZ, BERNABEU, NEBOT

- Interesting tests of the ω-effect can be performed by looking at the equal-sign di-lepton decay channels

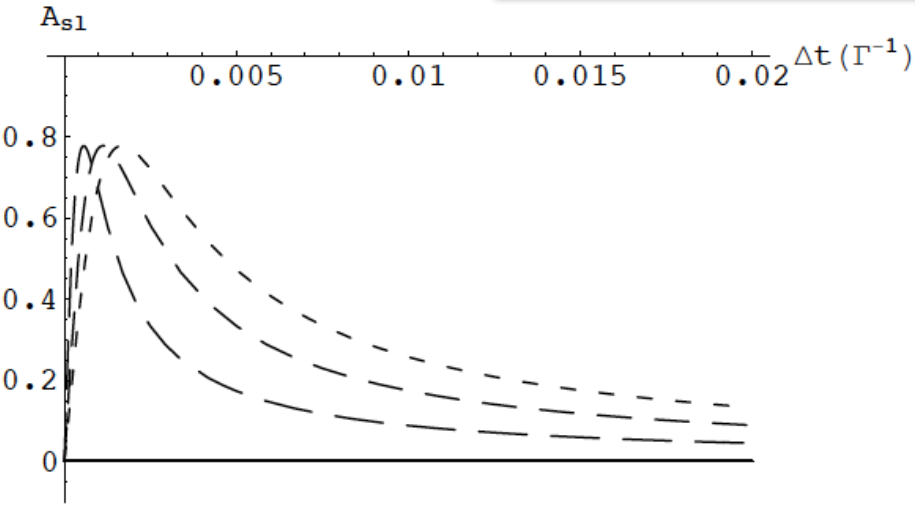
a first decay $B \to X\ell^\pm$ and a second decay, Δt later, $B \to X'\ell^\pm$

$$A_{sl} = \left.\frac{I(\ell^+,\ell^+,\Delta t) - I(\ell^-,\ell^-,\Delta t)}{I(\ell^+,\ell^+,\Delta t) + I(\ell^-,\ell^-,\Delta t)}\right|_{\omega=0} = 4\frac{Re(\varepsilon)}{1+|\varepsilon|^2} + \mathscr{O}((Re\ \varepsilon)^2)$$

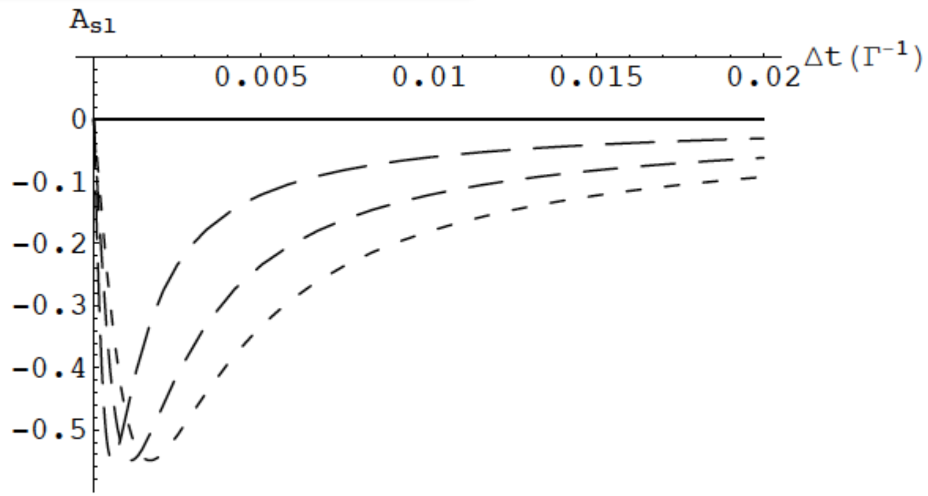
$$\omega = |\omega| e^{i\Omega} \Rightarrow I(\ell^\pm,\ell^\pm,\Delta t = 0) \sim |\omega|^2$$

$$
\begin{aligned}
I(X\ell^{\pm}, X'\ell^{\pm}, \Delta t) = \frac{1}{8} e^{-\Gamma \Delta t} \, |A_X|^2 |A_{X'}|^2 \left| \frac{(1 + s_\epsilon \, \epsilon)^2 - \delta^2/4}{1 - \epsilon^2 + \delta^2/4} \right|^2 \\
\left\{ \left[\tfrac{1}{\Gamma} + a_\omega \tfrac{8\Gamma}{4\Gamma^2 + \Delta m^2} Re(\omega) + \tfrac{1}{\Gamma} |\omega|^2 \right] \cosh\left(\tfrac{\Delta\Gamma \Delta t}{2} \right) + \right. \\
\left[- \tfrac{1}{\Gamma} + b_\omega \tfrac{8\Gamma}{4\Gamma^2 + \Delta m^2} Re(\omega) - \tfrac{\Gamma}{\Gamma^2 + \Delta m^2} |\omega|^2 \right] \cos(\Delta m \Delta t) + \\
\left. \left[d_\omega \tfrac{4\Delta m}{4\Gamma^2 + \Delta m^2} Re(\omega) + \tfrac{\Delta m}{\Gamma^2 + \Delta m^2} |\omega|^2 \right] \sin(\Delta m \Delta t) \right\},
\end{aligned}
$$

A_{sl} (Δt) asymmetry for short $\Delta t \ll 1/\Gamma$



(a) $\Omega = 0$



(b) $\Omega = \frac{3}{2}\pi$

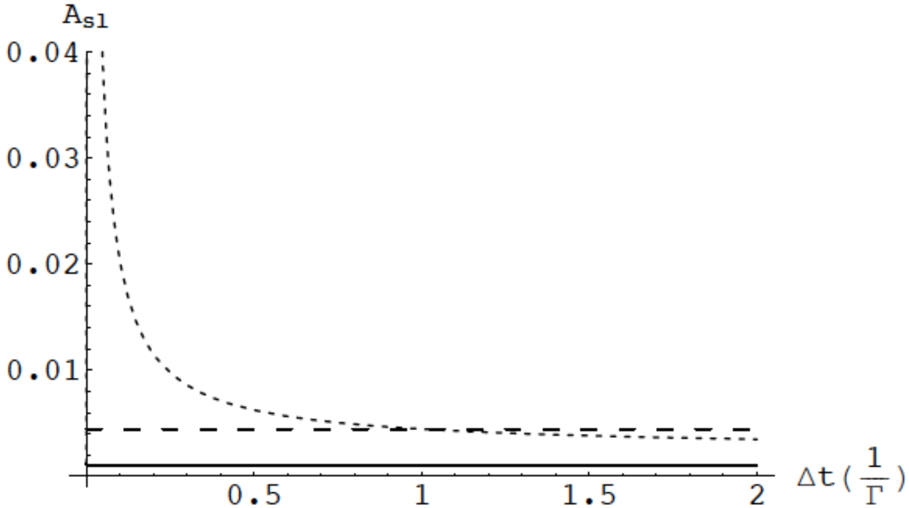
$$\Delta t_{peak} = \frac{1}{\Gamma}\sqrt{\frac{2}{1+x_d^2}}\,|\omega| + \mathcal{O}(\omega^2) \approx \frac{1}{\Gamma}\,1.12\,|\omega|$$

EXPERIMENTAL LIMITS circa 2005

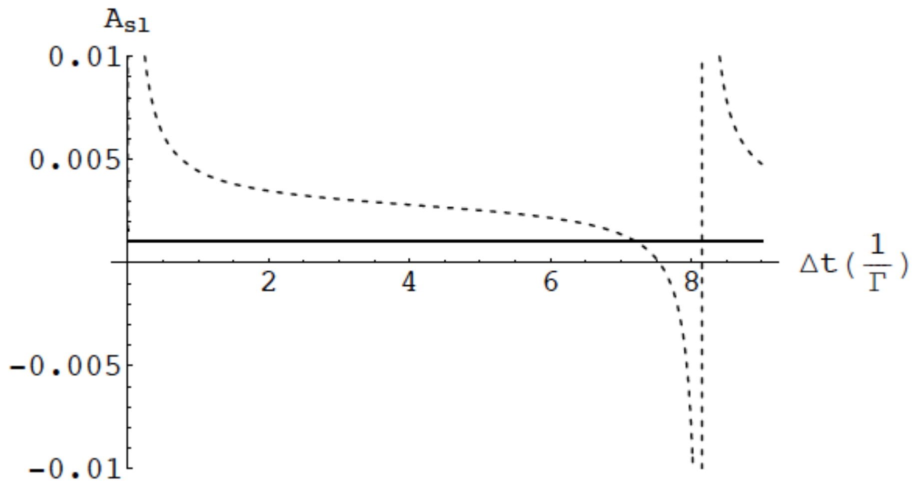
$$A_{sl}^{exp} = 0.0019 \pm 0.0105$$

$$-\,0.0084 \le Re(\omega) \le 0.0100 \qquad 95\%\mathrm{C.L}$$

A_{sl} (Δt) asymmetry for long $\Delta t > 1/\Gamma$



(a)



(b)

Region where asymmetry is quasi-independent but ω-effect shifted

Asymmetry plotted in the range including $\Delta m \ \Delta t \sim 2\pi \rightarrow$ **second peak** due to **quasi periodicity**

$$I(X\ell^{\pm}, X'\ell^{\pm}, \Delta t) = \frac{1}{8} e^{-\Gamma \Delta t} \, |A_X|^2 |A_{X'}|^2 \left| \frac{(1+s_\epsilon\, \epsilon)^2 - \delta^2/4}{1-\epsilon^2+\delta^2/4} \right|^2$$

$$\left\{ \left[\tfrac{1}{\Gamma} + a_\omega \tfrac{8\Gamma}{4\Gamma^2+\Delta m^2} Re(\omega) + \tfrac{1}{\Gamma} |\omega|^2 \right] \cosh\left(\tfrac{\Delta\Gamma \Delta t}{2}\right) + \right.$$

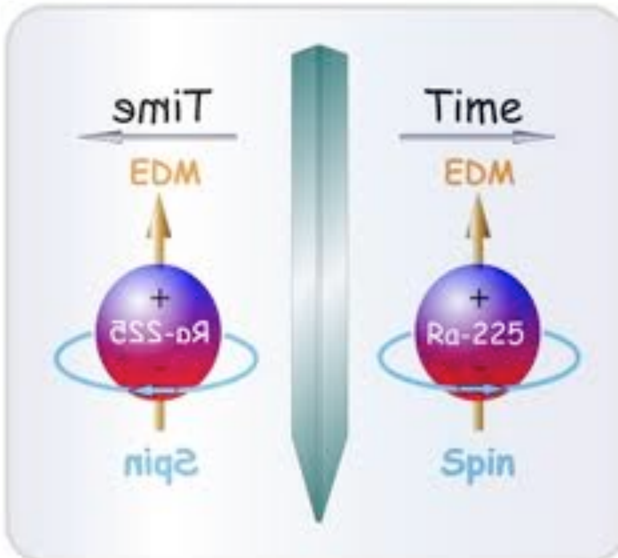
$$\left[-\tfrac{1}{\Gamma} + b_\omega \tfrac{8\Gamma}{4\Gamma^2+\Delta m^2} Re(\omega) - \tfrac{\Gamma}{\Gamma^2+\Delta m^2} |\omega|^2 \right] \cos(\Delta m \Delta t) +$$

$$\left. \left[d_\omega \tfrac{4\Delta m}{4\Gamma^2+\Delta m^2} Re(\omega) + \tfrac{\Delta m}{\Gamma^2+\Delta m^2} |\omega|^2 \right] \sin(\Delta m \Delta t) \right\},$$

Dominant terms for long $\Delta t > 1/\Gamma$

cf. **Bernabeu** talk

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

Early results from **CPLEAR, NA48**

Bernabeu,
+ Banuls (99)
+ di Domenico, Villanueva-Perez (13)
+ Botella, Nebot (16)

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

Hence, in view of recent **T Reversal Violation** measurements exploiting the EPR nature of entangled Kaons we may measure directly **T violation**, independently of **CPT, and CP → novel tests of CPT invariance**

But there are subtleties associated with ω-effect & EPR:
limitations in flavour tagging
New bounds on ω-effect from B-Bar systems

Bernabeu, Botella, NEM, Nebot to appear

$$\mathbf{H}|B_H\rangle = \mu_H|B_H\rangle, \quad |B_H\rangle = p_H|B_d^0\rangle + q_H|\bar{B}_d^0\rangle,$$
$$\mathbf{H}|B_L\rangle = \mu_L|B_L\rangle, \quad |B_L\rangle = p_L|B_d^0\rangle - q_L|\bar{B}_d^0\rangle.$$

$$|\Psi_0\rangle \propto |B_L\rangle|B_H\rangle - |B_H\rangle|B_L\rangle + \omega\left\{\theta\left[|B_H\rangle|B_L\rangle + |B_L\rangle|B_H\rangle\right] + (1-\theta)\frac{p_L}{p_H}|B_H\rangle|B_H\rangle - (1+\theta)\frac{p_H}{p_L}|B_L\rangle|B_L\rangle\right\}$$

ω-effect

CPTV in Hamiltonian

$$\theta = \frac{\mathbf{H}_{22} - \mathbf{H}_{11}}{\mu_H - \mu_L}$$

Part III

Decoherence –induced CPT Violation

&

Spin Statistics Theorem

Spin-Statistics Theorem: **The pioneers**

Fierz 1939:
First formulation

Pauli 1940:
More Systematic formulation

His **Exclusion Principle** (1925) is a **consequence** of spin-statistics theorem

Schwinger 1950:
More conceptual argument
making clear the underlying assumptions
(discussed in and of relevance to the talk)

Spin-Statistics Theorem: Basic concepts

Spin-Statistics Theorem: *The wave function of a system of* ***identical integer-spin*** *particles has the same value when the positions of any two particles are swapped. Particles with* ***wave functions symmetric*** *under exchange are called* **bosons.**
The wave function of a system of ***identical half-integer spin*** particles changes sign when two particles are swapped. Particles with wave functions ***antisymmetric*** under exchange are called ***fermions.***

Consequence: **Wavefunction of two identical fermions is zero**, hence two identical fermions (i.e. with all quantum numbers the same) cannot occupy the same state- **PAULI EXCLUSION PRINCIPLE (PEP).**

In quantum field theory, **Bosons** obey **commutation relations**, whilst **fermions** obey **anticommutation** ones.

Spin-Statistics Theorem: Basic assumptions

The ***proof*** requires the following ***assumptions***:

(1) The theory has a **Lorentz & CPT invariant Lagrangian & relativistic causality**.

(2) The vacuum is Lorentz-invariant (can be weakened).

(3) The **particle** is a **localized excitation**. Microscopically, it is **not attached** to a **string** or **domain wall.**

(4) The particle is **propagating** (has a **not-infinite** mass).

(5) The particle is a real excitation, meaning that **states** containing this particle have a **positive-definite norm** & has **positive energy**.

NB: spinless anticommuting fields for instance are not relativistic invariant
ghost fields in gauge theories are spinless fermions but they have negative norm.
In **2+1 dimensional Chern-Simons** theory has **anyons** (fractional spin)
Despite being attached to a confining string, QCD **quarks** can have a **spin-statistics relation** proven at **short distances** (ultraviolet limit) due to asymptotic freedom.

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The ***proof*** requires the following ***assumptions***:

(1) The theory has a **Lorentz & CPT invariant La**[…]
causality.

(2) The vacuum is Lorentz-invariant (can be weake[…]

Not valid in QG decoherence models where **CPT** operator is **not well defined** (ω-effect) → **spin-statistics violation**? **PEP violation?**

(3) The **particle** is a **localized excitation**. Microscopically, it is **not attached** to a **string** or **domain wall.**

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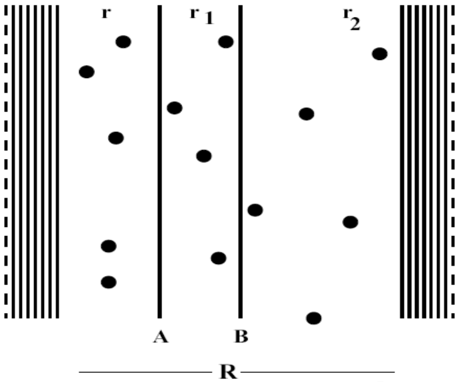
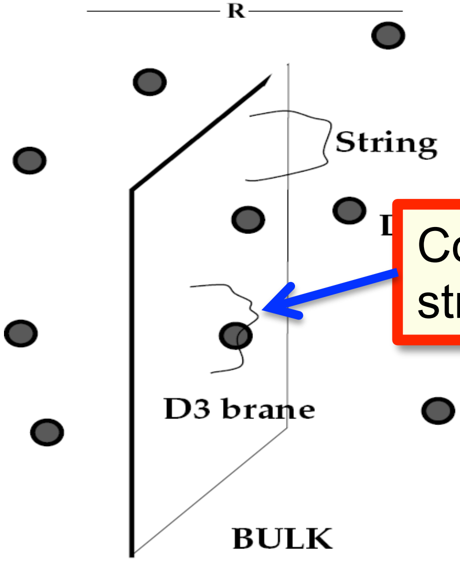


order of magnitude estimates

hep-th/0606137)

tions of particle-probes with specific space-time defects (e.g. ane theory); Use stationary perturbation theory to describe state - medium effects like MSW $\Rightarrow$ initial state:

$$, \downarrow\rangle^{(1)} \, |-k, \uparrow\rangle^{(2)} + \xi \, |k, \uparrow\rangle^{(1)} \, |-k, \uparrow\rangle^{(2)} + \xi' \, |k, \downarrow\rangle^{(1)} \, |-k, \downarrow\rangle^{(2)}$$



Composite particle+ space-time stringy defect strings attached, spin-statistics may be affected?

$\Delta p_i \Delta p_j\rangle \neq 0)$

$$|\omega|^2 \sim \frac{\zeta^2 k^4}{M_P^2 (m_1 - m_2)^2}$$

nenta of the order of the rest energies $|\omega| \sim 10^{-4} |\zeta|$. For $1 > \zeta \geq 10^{-2}$ not far below the sensitivity of current facilities, such as DAΦNE (c.f. Experimental Talk (M. Testa)). Constrain ζ significantly in upgraded facilities.

Perspectives for KLOE-2 at DAΦNE-2 (A. Di Domenico home page) :
$\mathrm{Re}(\omega), \ \mathrm{Im}(\omega) \longrightarrow 2 \times 10^{-5}$.

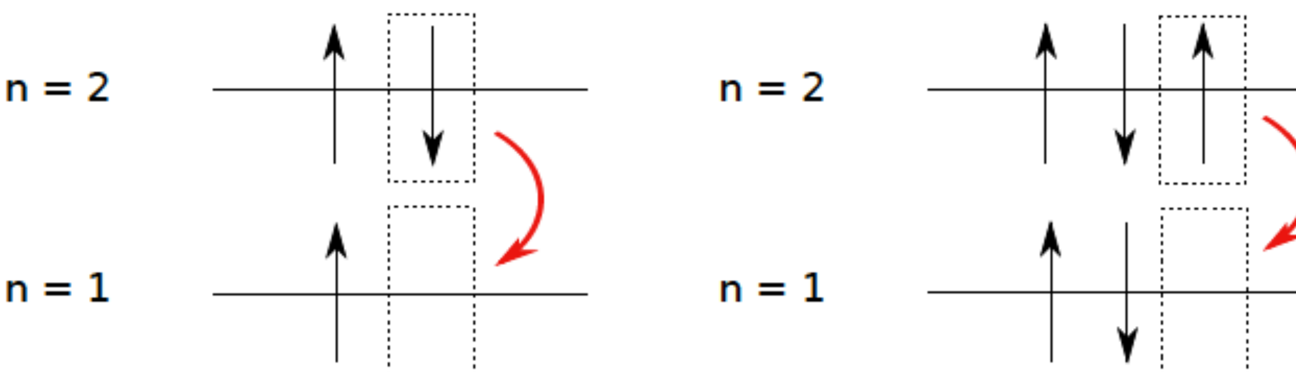
NB: ω-Effect also generated by propagation through the medium, but with time-dependent (sinusoidal) $\omega(t)$-terms, can be (in principle) disentangled from initial-state ones...

The VIolation of Pauli principle Experiment (VIP(2))

C. Curceanu *et al.* arXiv:1602.00867
Found.Phys. 46 (2016) 263

Pichler *et al.* arXiv:1602.00867
PoS EPS-HEP2015 (2015) 570

Look for forbidden 2p → 1s spontaneous transition in Copper (for electrons)



Normal (allowed) 2p - 1s transition with an energy of 8.05 keV for copper (left) and non-Paulian (forbidden) transition with an energy of around 7.7 keV for copper (right).

The **VI**olation of **P**auli principle Experiment (**VIP(2)**)

C. Curceanu *et al.* arXiv:1602.00867
Found.Phys. 46 (2016) 263

Pichler *et al.* arXiv:1602.00867
PoS EPS-HEP2015 (2015) 570

Look for forbidden 2p → 1s spontaneous transition in Copper (for electrons)

VIP result (2010 data) for probability of PEP violation in an atom $\frac{\beta^2}{2}$ $\quad \frac{\beta^2}{2} \leq 4.7 \times 10^{-29}$

Curceanu, C. et al.: J. Phys. 306, 012036 (2011)

Curceanu, C. et al.: J. Phys. Conf Ser. 361, 012006 (2012)

ÖAW AUSTRIAN ACADEMY OF SCIENCES

The parameter “β”

Ignatiev & Kuzmin model — creation and destruction operators connect 3 states

- the vacuum state $|0>$
- the single occupancy state $|1>$
- the non-standard double-occupancy state $|2>$

through the following relations:

$$
\begin{array}{ll}
a|0\rangle = 0 & a^{+}|0\rangle = |1\rangle \\
a|1\rangle = |0\rangle & a^{+}|1\rangle = \beta|2\rangle \\
a|2\rangle = \beta|1\rangle & a^{+}|2\rangle = 0
\end{array}
$$

The parameter β quantifies the degree of violation in the transition $|1> \rightarrow |2>$. It is very small and for β→0 we can have the Fermi - Dirac statistic again.

The **VI**olation of **P**auli principle Experiment (**VIP(2)**)

C. Curceanu *et al.* arXiv:1602.00867
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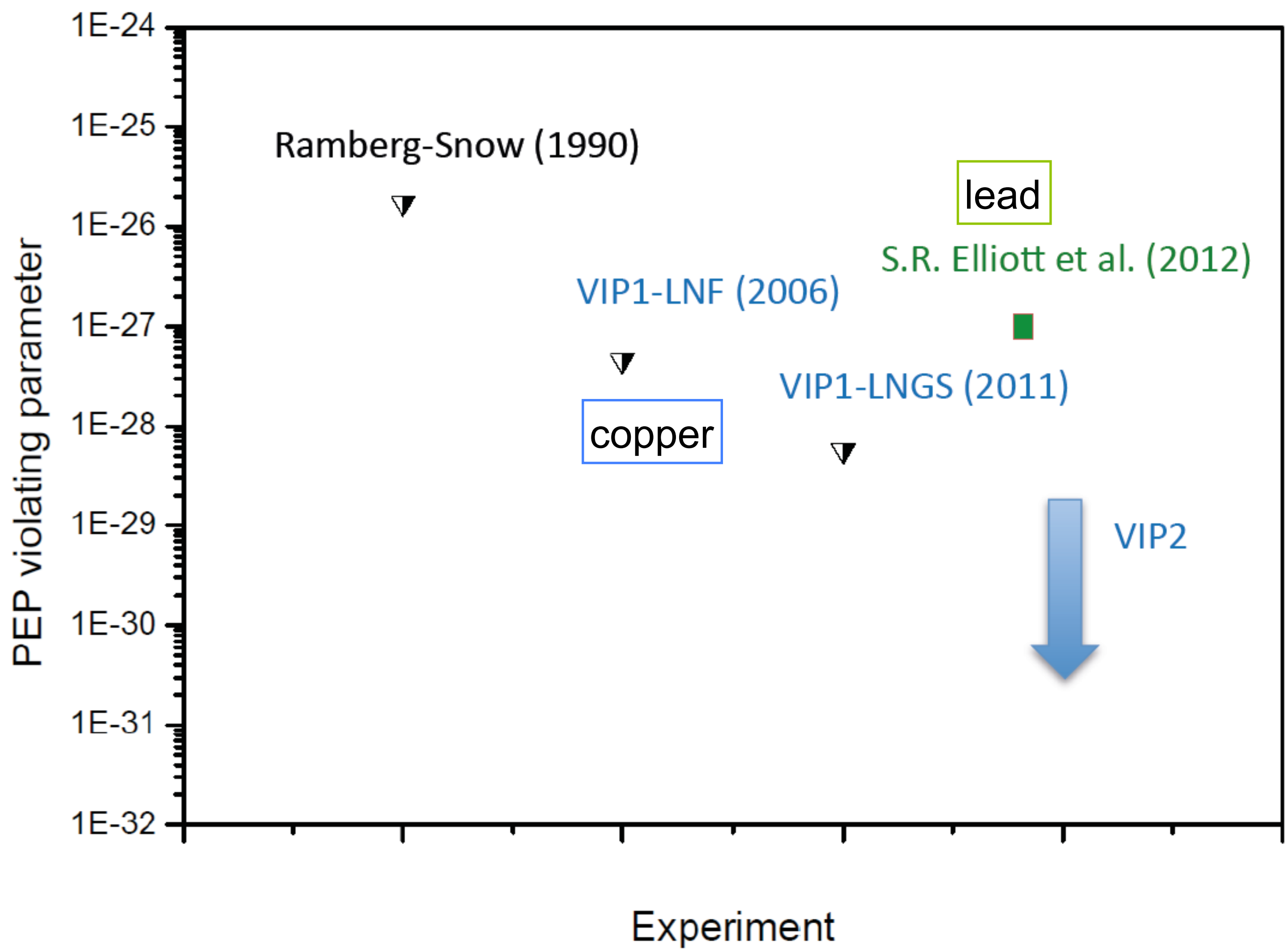
$$\frac{\beta^2}{2} \leq 4.7 \times 10^{-29}$$

VIP2 : forsee improvement by at least 2 orders of magnitude on this bound : **$< 10^{-31}$**


1E-24
1E-25
1E-26
1E-27
1E-28
1E-29
1E-30
1E-31
1E-32
PEP violating parameter
Experiment
Ramberg-Snow (1990)
lead
S.R. Elliott et al. (2012)
VIP1-LNF (2006)
VIP1-LNGS (2011)
copper
VIP2

CONCLUSIONS-OUTLOOK

- Quantum Gravity may imply effects beyond SME such as ω-effect on EPR or decoherence-

  ill-defined CPT generator –ω-effect

- Precision Tests in Entangled States of neutral mesons (ongoing)

- Concrete examples of ω-like-effects in

  string/brane theory → order of magnitude estimates

  ``Quantum Gravity Dressed'' composite particles

- ω-effect & spin-statistics violations, PEP violations?

  ...**to explore**

Outlook

CPT Violation in the Lagrangian

&

Microscopic origin of (some of) SME coefficients

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

Microscopic Origin of SME coefficients?

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LV & CPTV

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STANDARD MODEL EXTENSION

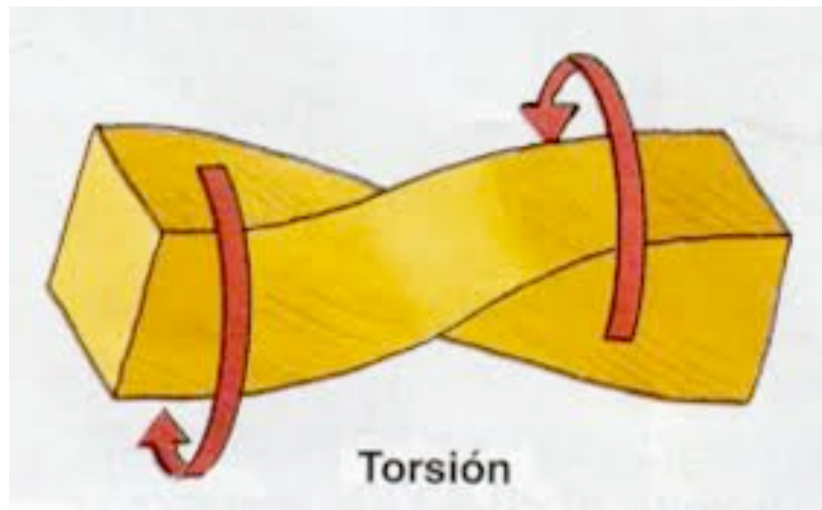
Kostelecky *et al.*

$$\mathcal{L} = \frac{1}{2} i \bar{\psi} \Gamma^\nu \bar{\partial}_\nu \psi - \bar{\psi} M \psi, \qquad M \equiv m + a_\mu \gamma^\mu + b_\mu \gamma_5 \gamma^\mu + \frac{1}{2} H^{\mu\nu} \sigma_{\mu\nu}$$

LV & CPTV

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

In particular,
Space-times with



CPTV Effects of different Space-Time-Curvature/ Spin couplings between fermions/antifermions

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

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

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

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

$$g_{\mu\nu} = e^a_\mu\,\eta_{ab}\,e^b_\nu$$

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

Gravitational covariant derivative including spin connection

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

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

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

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

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

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

NEM & Sarben Sarkar, arXiv:1211.0968
John Ellis, NEM & Sarkar, arXiv:1304.5433
De Cesare, NEM & Sarkar arXiv:1412.7077

Dirac Lagrangian (for concreteness, it ca

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If **torsion** then $\Gamma_{\mu\nu} \neq \Gamma_{\nu\mu}$
antisymmetric part is the contorsion tensor, contributes

Dirac Lagrangian (for concreteness, it ca

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in string theory models antisymmetric tensor field-strength (H-torsion) cosmological backgrounds lead to constant B^0 in FRW frame

PART IIIb

COSMOLOGICAL CONSEQUENCES of SME-type CPTV

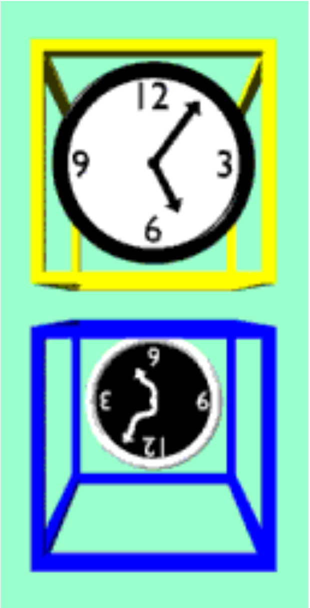
Matter-antimatter asymmetry in Universe

-Lepto(Baryo)genesis

CPT VIOLATION IN THE EARLY UNIVERSE

De Cesare, NEM & Sarkar arXiv:1412.7077
(Eur.Phys.J. C75 (2015) 10, 514)

Right-Handed Majorana Neutrinos



physics.indiana.edu

Mechanism
For Torsion-Background-Induced tree-level
Leptogenesis → Baryogenesis

Through B-L conserving
Sphaleron processes
In the standard model

CPTV Thermal Leptogenesis

Early Universe
T > 10^5 GeV

CPT Violation

Lepton number & CP Violations @ tree-level
due to Lorentz/CPTV Background

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

CPTV Thermal

$$\mathcal{L} = i\overline{N}\not{\partial}N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

CPT Violation

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Early Universe
T > 10^5 GeV

CPT Violation

One generation* of *massive neutrinos N suffices* for generating *CPTV Leptogenesis;

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CPT Violation

Early Universe
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Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

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

One generation* of massive neutrinos N *suffices* for generating CPTV Leptogenesis; mass m *free to be fixed

CPTV Thermal

$$\mathcal{L} = i\overline{N}\partial\!\!\!/ N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}B\!\!\!/\gamma^5 N - Y_k \overline{L}_k \tilde{\phi} N + h.c.$$

Constant H-torsion (antisymmetric tensor field strength in string models)

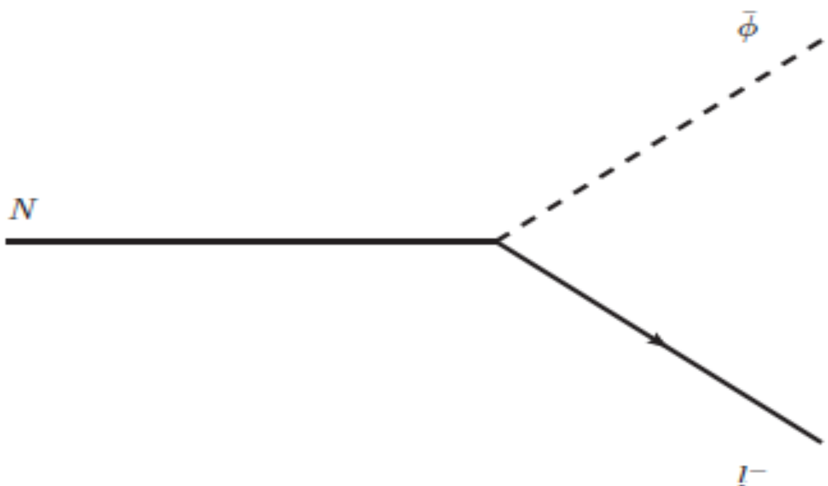
Early Universe
T > 10^5 GeV

CPT Violation

Lepton number & CP Violations @ tree-level
due to Lorentz/CPTV Background

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

Produce Lepton asymmetry



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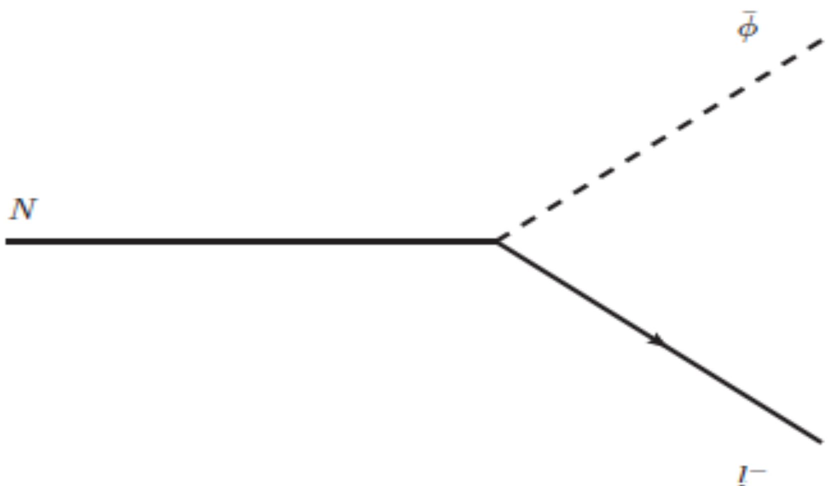
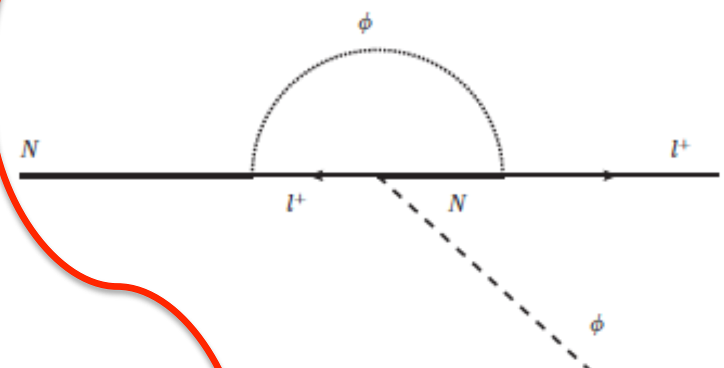


Contrast with one-loop conventional Leptogenesis in absence of H-torsion



Fukugita, Yanagida,

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Constant H-torsion

Early Universe
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CPT Violation

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

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Early Universe
T > 10^5 GeV

CPT Violation

Constant H-torsion
$B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level
due to Lorentz/CPTV Background

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

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

$$\frac{B_0}{m} \simeq 10^{-8}$$

Produce Lepton asymmetry

$$Y_k \sim 10^{-5}$$

$$m \geq 100\mathrm{TeV} \to$$

$$B^0 \sim 1\mathrm{MeV}$$

$$T_D \simeq m \sim 100\ \mathrm{TeV}$$

CPTV Thermal

$$\mathcal{L} = i\overline{N}\not{\partial}N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k \overline{L}_k \tilde{\phi} N + h.c.$$

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Produce Lepton asymmetry

Equilibrated electroweak
B+L violating sphaleron interactions

B-L conserved

Environmental
Conditions Dependent

Observed Baryon Asymmetry
In the Universe (BAU)

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

where

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

Fukugita, Yanagida,

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Observed Baryon Asymmetry
In the Universe (BAU)

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

CPTV Thermal L

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Early Universe
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CPT Violation

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B+L violating sphaleron interactions

B-L conserved

Environmental
Conditions Dependent

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In the Universe (BAU)

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

e.g. May Require
Fine tuning of
Vacuum energy

B^0 : (string) theory underwent a **phase transition** @ $T \approx T_d = 10^5$ GeV, from B^0 = const = 1 MeV **to** :

(i) **either $B^0 = 0$**

(ii) **or B^0 small today but non zero**

$$B^0 \sim \dot{\bar{b}} \sim 1/a^3(t) \sim T^3$$

$$B_0 = c_0 T^3 \qquad c_0 = 10^{-42}\,\mathrm{meV}^{-2}$$

$$\boxed{B_{0\,\mathrm{today}} = \mathcal{O}\left(10^{-44}\right)\,\mathrm{meV}}$$

Quite safe from stringent Experimental Bounds

$$|B^0| < 10^{-2}\,\mathrm{eV}$$
$$B_i \equiv b_i < 10^{-31}\,\mathrm{GeV}$$

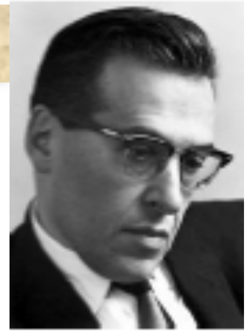
IS THIS CPTV ROUTE WORTH FOLLOWING? ….

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.

SPARES

Spin-Statistics Theorem: (Schwinger's) Proof



Object of interest for generic fields:

$$G(x) = \langle 0|\phi(-x)\phi(x)|0\rangle.$$

Rotation matrix of spin polarization of the field by π : $R(\pi)$

STEP I : Formulate a quantum field theory in **Euclidean space time** where **path integral makes rigorous sense**, in this case: spatial Lorentz transformations are ordinary rotations, but Boosts become also rotations in imaginary time, and hence **a rotation by** π in (**x (space)** -t (time)) plane in **Euclidean** space-time is a **CPT transformation** in the language of Minkowski spacetime. CPT transformation, **if well defined**, takes states in a path integral into their conjugates so

$$\langle 0|R\phi(x)\phi(-x)|0\rangle$$

must be positive-definite at x=0 according to positive-norm-state assumption (5) of the spin-statistics theorem. Propagating states, i.e. finite mass, implies that this correlator is non-zero at **space-like separations. You need relativity to define space-like intervals of course, hence the Lorentz invariance (LI) assumptions (1) + (2).**

STEP II: . LI allows fields to be transformed according to their **spin,** and such that:

$$\langle 0|R R\phi(x) R\phi(-x)|0\rangle = \pm\langle 0|\phi(-x) R\phi(x)|0\rangle$$

where + is for Bosons (integer spin) and – for fermions (half-integer spin).

STEP III : USE CPT INVARIANCE (which is **equivalent to also assuming well-defined CPT operator** and which in Euclidean space-time is equivalent to rotational invariance) to equate the rotated correlation function to G(x), hence

$$\langle 0|(R\phi(x)\phi(y) - \phi(y) R\phi(x))|0\rangle = 0$$

for integer spins, and

$$\langle 0|R\phi(x)\phi(y) + \phi(y) R\phi(x)|0\rangle = 0$$

for half-integer spins.

NB: The theorem essentially implies that: since the operators are spacelike separated, a different order can only create states that differ by a phase. The argument fixes the phase to be −1 or 1 according to the spin. Since it is possible to rotate the space-like separated polarizations independently by local perturbations, the phase should not depend on the polarization in appropriately chosen field coordinates.

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STEP III : USE CPT INVARIANCE (wh … ming **well-defined CPT operator** and which in … lent to rotational invariance) to equate the rotated … hence

> Not valid in QG decoherence models where **CPT** operator is **not well defined** (ω-effect) → **spin-statistics violation**? **PEP violation?**

$$\langle 0|(R\phi(x)\phi(y) - \phi(y)R\phi(x))|0\rangle = 0$$

for integer spins, and

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

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

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

$i = 1, 2, 3$ Light ν species

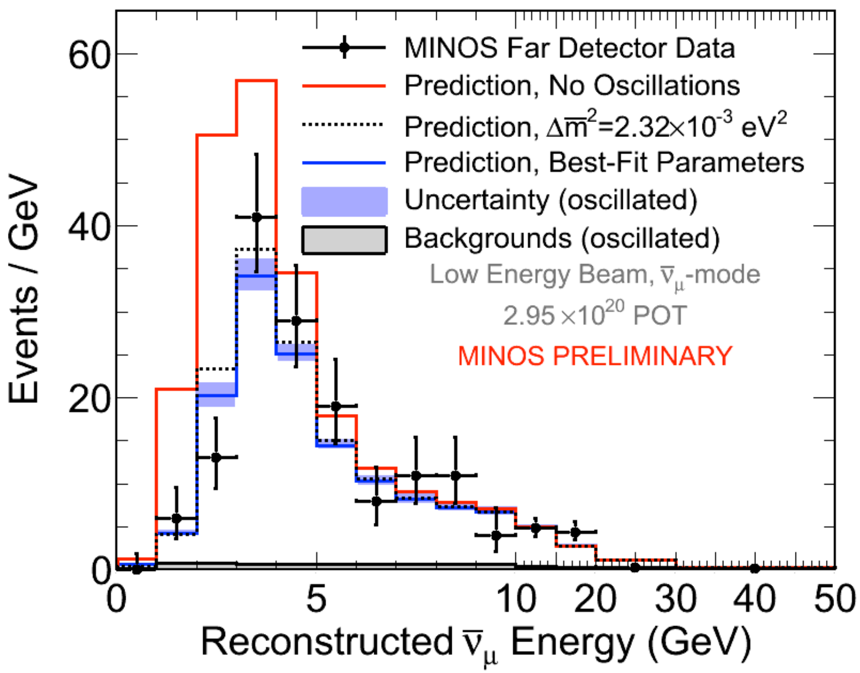
$$\boxed{n_B = n_\nu - n_{\bar{\nu}} \simeq \frac{\mu_\nu T^2}{6}}$$

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

@ 100 GeV ✔

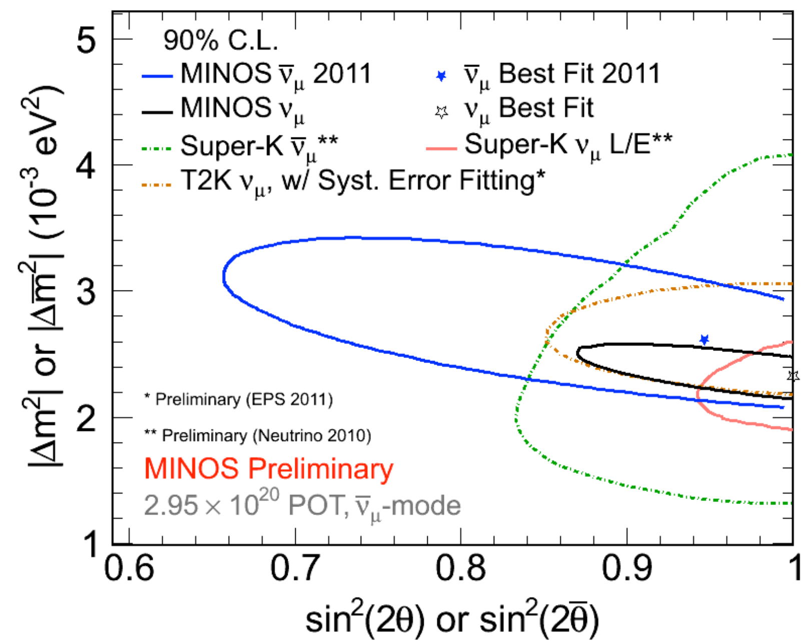
MINOS Exp. RESULTS ON Potential Neutrino-Antineutrino OSCILLATION PARAMETER DIFFERENCES

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 $\Delta\bar{m}^2=(2.62+0.31-0.28\text{ (stat.)} \pm0.09\text{ (syst.)})\times10^{-3}$ eV^2, $\sin^2(2\Theta)=0.95 +0.10-0.11\text{ (stat.)} \pm0.01\text{ (syst.)}$.

ν_μ disappearance: $\Delta m^2=(2.32+0.12-0.08)\times10^{-3}$ 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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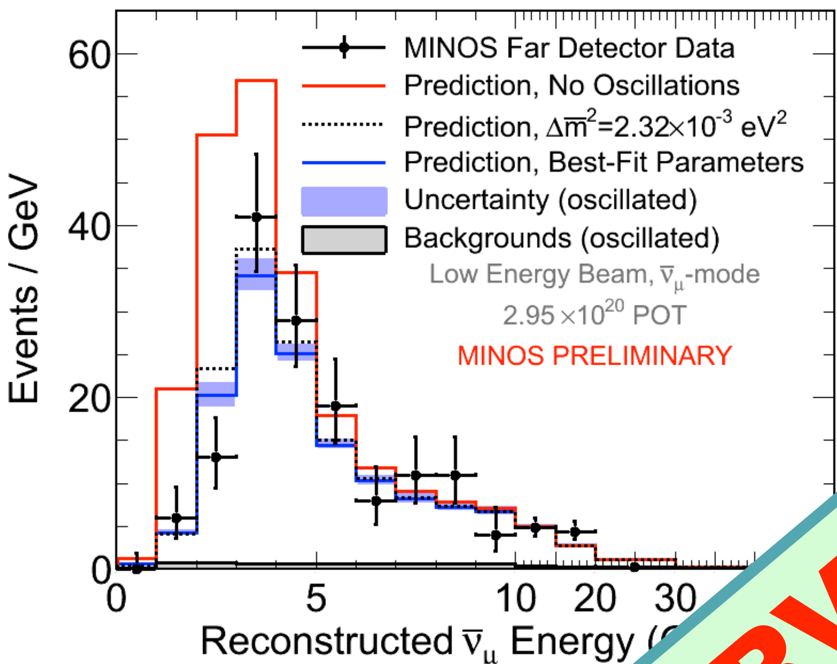
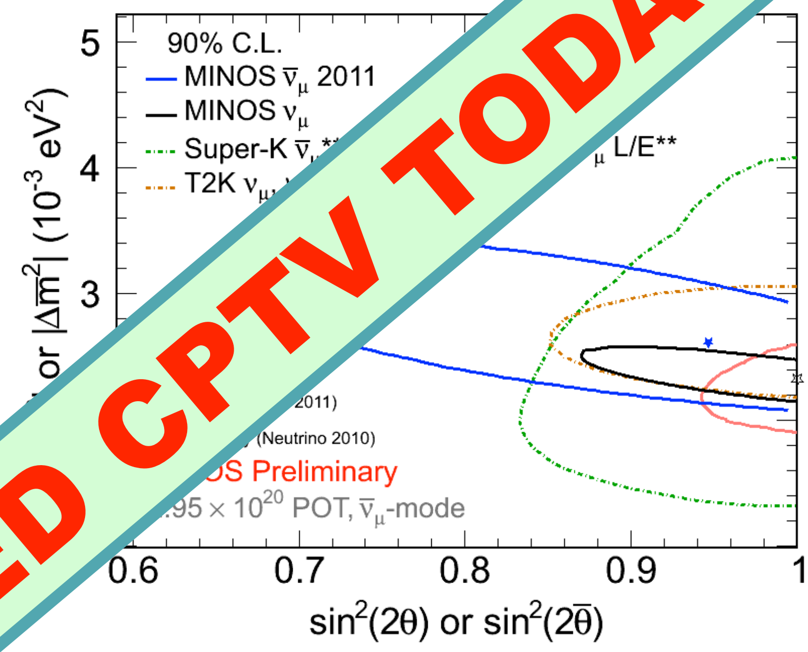


$\bar{\nu}_\mu$ disapearance-Energ

...9]



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

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Consisten... with equality of mass differences between particle/antiparticles

NO OBSERVED CPTV TODAY

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)