# CPT & Quantum Mechanics Tests with Kaons: Theory


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# QUESTIONS on CPT SYMMETRY

- **WHAT IS CPT SYMMETRY.**
- **WHY CPT VIOLATION ?** Theoretical models and ideas, and generic order of magnitude estimates of expected effects: **Quantum Gravity Models violating Lorentz symmetry and/or quantum coherence**:

  (i) space-time foam,

  (ii) Standard Model Extension

  (iii) Loop Quantum Gravity/background independent formalism. Non-linear deformations of Lorentz symmetry (DSR) (?)
- **HOW CAN WE DETECT CPT VIOLATION?**

  Complex Phenomenology: no single figure of merit

  (i) neutral mesons: KAONS, B-MESONS, entangled states in $\phi$ and $B$ factories **(this talk)**

  (ii) antihydrogen (precision spectroscopic tests on free and trapped molecules look for forbidden transitions )

  (iii) Low energy atomic physics experiments.

  (iv) Ultra cold neutrons

  (v) Neutrino Physics

  (vi) Terrestrial & Extraterrestrial tests of Lorentz Invariance (modified dispersion relations of matter probes: GRB, AGN photons, Crab Nebula synchrotron-radiation constraint on electrons ...)

# ORDER OF MAGNITUDE

**Naively, Quantum Gravity (QG) has a dimensionful constant: $G_N \sim 1/M_P^2$, $M_P = 10^{19}$ GeV. Hence, CPT violating and decoherening effects may be expected to be suppressed at least by $\frac{E^3}{M_P^2}$ , where $E$ is a typical energy scale of the low-energy probe.**

**HOWEVER: RESUMMATION & OTHER EFFECTS in theoretical models may result in much larger effects of order: $\frac{E^2}{M_P}$.**
**(This happens, e.g., loop gravity, some stringy models of QG involving open string excitations)**

**SUCH LARGE $1/M_P$ EFFECTS ARE ACCESSIBLE BY CURRENT OR NEAR FUTURE EXPERIMENTS.**

**$1/M_P^2$ EFFECTS MAY BE ACCESSIBLE IN FUTURE ASTROPHYSICS EXPTS (ultra-high-energy cosmic neutrinos, synchrotron radiation from astro sources etc.).**

# SOME THEORY

# CPT THEOREM

**C(harge) -P(arity=reflection) -T(ime reversal) INVARIANCE is a property of any quantum field theory in Flat space times which respects: (i) Locality, (ii) Unitarity and (iii) Lorentz Symmetry.**

$$\Theta \mathcal{L}(x) \Theta^\dagger = \mathcal{L}(-x) \ ,$$
$$\Theta = CPT \ , \ \mathcal{L} = \mathcal{L}^\dagger \ \text{(Lagrangian)}$$

Theorem due to: Jost, Pauli (and John Bell).

Jost proof uses covariance trnsf. properties of Wightman's functions (i.e. quantum-field-theoretic (off-shell) correlators of fields $< 0|\phi(x_1) \dots \phi(x_n)|0 >$ ) under Lorentz group. (O. Greenberg, hep-ph/0309309)

**Theories with HIGHLY CURVED SPACE TIMES , with space time boundaries of black-hole horizon type, may violate (ii) & (iii) and hence CPT.**

**E.g.: LORENTZ-VIOLATING NON-TRIVIAL VACUA OF STRINGS, SPACE-TIME FOAMY SITUATIONS IN SOME QUANTUM GRAVITY MODELS.**

# COMPLEX PHENOMENOLOGY OF CPT VIOLATION

## (I) CPT Operator well defined, does not commute with Hamiltonian

## LORENTZ & CPT VIOLATION IN THE HAMILTONIAN

- **Standard Model Extension: Neutral Mesons & factories, atomic physics, neutrinos...**
- **Modified Dispersion Relations (GRB, neutrino oscillations, synchrotron radiation )**

## (II) CPT Operator ill defined (Wald), intrinsic violation, modified concept of antiparticle

## Decoherence-CPTV TESTS

- **Neutral Mesons: Neutral Kaons, B-mesons, and neutral-meson Factories (entangled states: novel effects: modified (perturbatively) EPR correlations).**

  Ultracold Neutrons

  Neutrinos (highest sensitivity)
- **Light-Cone fluctuations (GRB, Gravity Wave Interferometers, neutrino oscillations)**

## INDIRECT TESTS: astrophysical evidence for dark Energy

- Relaxation off-equilibrium models of dark Energy and fundamental time irreversibility. If cosmological constant (de Sitter) then due to cosmic horizon CPT may be not well defined (NM, Wald).

# STANDARD MODEL EXTENSION (SME)

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) → Tachyonic instabilities, coupling with tensorial fields (gauge etc), $\rightarrow < A_\mu > \neq 0$ , $< T_{\mu_1 \dots \mu_n} > \neq 0$ ,

Spontaneous breaking of Lorentz symmetry by (exotic) string vacua MODIFIED DIRAC EQUATION in SME: for spinor $\psi$ 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: $a_\mu$ , $b_\mu$. Lorentz violation only: $c_{\mu\nu}$ , $d_{\mu\nu}$ , $H_{\mu\nu}$.

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

**NB2: In general $a_\mu, b_\mu \dots$ 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 (c.f. below) $\langle a_\mu \, , b_\mu \rangle = 0$, $\langle a_\mu a_\nu \rangle \neq 0$, $\langle b_\mu a_\nu \rangle \neq 0$, $\langle b_\mu b_\nu \rangle \neq 0$, etc ... much more suppressed effects**

# Tests of Lorentz violation in neutral Kaons

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

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

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

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

**NB: $\mathcal{H}_{11} - \mathcal{H}_{22}$ is flavour diagonal. Parameter $\delta_K$ 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 $T, P$. $\delta_K$ sensitive ONLY to $-a^q_\mu \overline{q}\gamma_\mu q$ terms in SME ($q$ quark fields, meson composition: $M = q_1\overline{q}_2$):

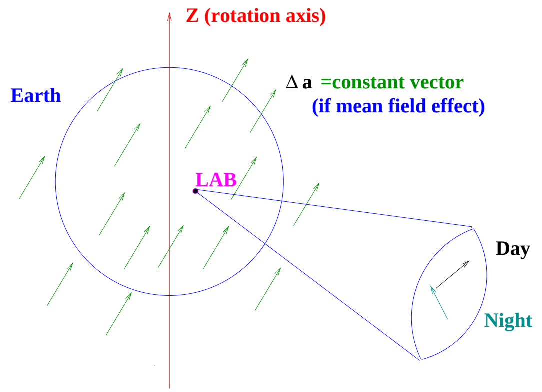
$$\delta_K \simeq i\sin\widehat{\phi}\exp(i\widehat{\phi})\gamma\left(\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a}\right)/\Delta m,$$

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

$\widehat{\phi} = \arctan(2\Delta m/\Delta\Gamma), \quad \Delta a_\mu \equiv a^{q2}_\mu - a^{q1}_\mu$, and $\beta^\mu_K = \gamma(1, \vec{\beta}_K)$ is the 4-velocity of boosted kaon.

# EXPERIMENTAL BOUNDS

**Experimental bounds on $a_\mu$: Look for sidereal variations of $\delta_K$ (day-night effects):**




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

From $\phi$ factories: **(NB: additional polar ($\theta$) and azimuthal ($\phi$) angle dependence of $\delta_K$)**:

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

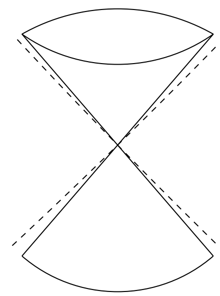
($\Omega$: Earth's sidereal frequency, $\chi$: angle between Z-lab axis and Earth's axis.)

KLOE (at DA$\Phi$NE) is sensitive to $a_Z$ (actually limits on $\delta(\Delta a_Z)$ from forward-backward asymmetry $A_L = 2\text{Re}\epsilon_K - 2\text{Re}\delta_K$). For KLOE-2 at Da$\Phi$NE-2 (if approved): expected sensitivity $\Delta a_\mu = \mathcal{O}(10^{-18})$ GeV, not competitive with KTeV for $a_{X,Y}$ limits **(c.f. Experimental Talk (M. Testa)).** **Similar tests for other mesons (B-mesons, *etc.*... ). Are QG LV effects Universal?**

# LIGHT CONE FLUCTUATIONS (LCF)

Light Cone fluctuations may be another effect of Quantum Gravity **( Ford, Yu, ..., Ellis, NM, Nanopoulos)**

Stochastic fluctuations in arrival times of photons with the same energy but also decoherence of matter




"Fuzzy" Space times may induce (Ford, Yu 1994, 2000): $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, $\langle g_{\mu\nu} \rangle = \eta_{\mu\nu}$ BUT $\langle h_{\mu\nu}(x) h_{\lambda\sigma}(x') \rangle \neq 0$, , i.e. Quantum light cone fluctuations BUT NOT mean-field effects on dispersion relations, that is, Lorentz symmetry is respected on average BUT not on individual measurements. Path of light: null geodesics $0 = ds^2 = g_{\mu\nu} dx^\mu dx^\nu$. Fluctuations: Geodesic deviations $\frac{D^2 n^\mu}{d\tau^2} = -R^\mu_{\alpha\nu\beta} u^\alpha n^\nu u^\beta$ , quantum fluctuate.

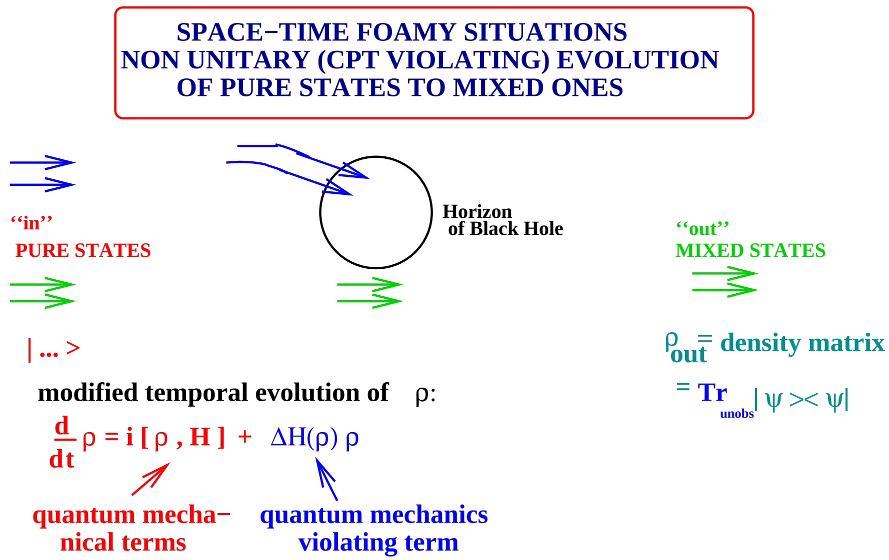
Fluctuations in arrival time of photons at detector: ($|\phi\rangle$=state of gravitons, $|0\rangle$= vacuum state)

$$\Delta t^2_{obs} = |\Delta t^2_\phi - \Delta t^2_0| = \frac{|\langle \phi | \sigma_1^2 | \phi \rangle - \langle 0 | \sigma_1^2 | 0 \rangle|}{r^2} \equiv \frac{|\langle \sigma_1^2 \rangle_R|}{r} .$$

$$\langle \sigma_1^2 \rangle_R = \frac{1}{8} (\Delta r)^2 \int_{r_0}^{r_1} dr \int_{r_0}^{r_1} dr' \; n^\mu n^\nu n^\rho n^\sigma \; \langle \phi | h_{\mu\nu}(x) h_{\rho\sigma}(x') + h_{\mu\nu}(x') h_{\rho\sigma}(x) | \phi \rangle$$

# SPACE-TIME FOAM AND UNITARITY VIOLATION

SPACE-TIME FOAM: Quantum Gravity SINGULAR Fluctuations (microscopic (Planck size) black holes etc) **MAY** imply: pure states $\longrightarrow$ mixed




$\rho_{out} = \mathrm{Tr}_{\mathrm{unobs}}|out><out| = \$ \; \rho_{in}$, $\$ \neq SS^{\dagger}$ , $S = e^{iHt}$ =scattering matrix, \$=**non invertible**, unitarity lost in effective theory. **BUT...HOLOGRAPHY can change the picture**: Strings in anti-de-Sitter space times (Maldacena, Witten), Hawking 2003- **BUT NO PROOF AS YET... OPEN ISSUE...**

# SPACE-TIME FOAM and Intrinsic CPT Violation

A THEOREM BY R. WALD (1979): **If $\$ \neq S\ S^\dagger$, then CPT is violated, at least in its strong form.**

PROOF: Suppose CPT is conserved, then there exists unitary, invertible operator $\Theta$ : $\Theta\overline{\rho}_{in} = \rho_{out}$

$\rho_{out} = \$\ \rho_{in} \rightarrow \Theta\overline{\rho}_{in} = \$\ \Theta^{-1}\overline{\rho}_{out} \rightarrow \overline{\rho}_{in} = \Theta^{-1}\$\ \Theta^{-1}\overline{\rho}_{out}$.

But $\overline{\rho}_{out} = \$\overline{\rho}_{in}$, hence : $\overline{\rho}_{in} = \Theta^{-1}\$\Theta^{-1}\ \$\ \overline{\rho}_{in}$

BUT THIS IMPLIES THAT \$ HAS AN INVERSE- $\Theta^{-1}\$\Theta^{-1}$, IMPOSSIBLE (information loss), hence CPT MUST BE VIOLATED (at least in its strong form).

**NB1**: IT ALSO IMPLIES: $\Theta = \$\ \Theta^{-1}\ \$$ (fundamental relation for a full CPT invariance).

**NB2: My preferred way of CPTV by Quantum Gravity Introduces fundamental arrow of time/microscopic time irreversibility...**

**NB3: Effective theories decoherence, i.e. (low-energy ) experimenters do not have access to all d.o.f. of quantum gravity (e.g. back-reaction effects...)**

# QG-FOAM DECOHERENCE: FORMALISM

(I)*Lindblad (linear) model-independent formalism* (not specific to foam): **Requirements: (i) Energy conservation on average, (ii)(complete) positivity of $\rho$, (iii) monotonic entropy increase**, Generic Decoherening Lindblad Evolution for N-level systems, $h_i$ Hamiltonian terms:

$$\frac{\partial \rho_\mu}{\partial t} = \sum_{ij} h_i \rho_j f_{ij\mu} + \sum_\nu L_{\mu\nu}\rho_\nu \ , \quad \mu,\nu = 0,\dots N^2-1, \quad i,j = 1,\dots N^2-1$$

$L_{0\mu} = L_{\mu 0} = 0$ , $L_{ij} = \frac{1}{4}\sum_{k,\ell,m} c_{l\ell}\left(-f_{i\ell m}f_{kmj} + f_{kim}f_{\ell mj}\right)$ , $c_{ij}$ a positive definite matrix.

**NB: $e^{-(\dots)t}$ damping in interference terms**

(II)*Stochastically (random) fluctuating space times* (c.f. light-cone flcts. ) **(Sarben Sarkar, NM 2006)**

$$g^{\mu\nu} = \begin{pmatrix} -(a_1+1)^2 + a_2^2 & -a_3(a_1+1) + a_2(a_4+1) \\ -a_3(a_1+1) + a_2(a_4+1) & -a_3^2 + (a_4+1)^2 \end{pmatrix} .$$

with random variables $\langle a_i \rangle = 0$ and $\langle a_i a_j \rangle = \delta_{ij}\sigma_i$ . EXAMPLE: Oscillation prob., 2-generation Dirac neutrinos with MSW-medium interaction $V$ :

$$\langle e^{i(\omega_1-\omega_2)t}\rangle = e^{i\frac{\left(z_0^+ - z_0^-\right)t}{k}} e^{-\frac{1}{2}\left(-i\sigma_1 t\left(\frac{(m_1^2-m_2^2)}{k} + V\cos 2\theta\right)\right)} \times$$
$$e^{-\frac{1}{2}\left(\frac{i\sigma_2 t}{2}\left(\frac{(m_1^2-m_2^2)}{k} + V\cos 2\theta\right) - \frac{i\sigma_3 t}{2} V\cos 2\theta\right)} \times$$
$$e^{-\left(\frac{(m_1^2-m_2^2)^2}{2k^2}(9\sigma_1+\sigma_2+\sigma_3+\sigma_4) + \frac{2V\cos 2\theta(m_1^2-m_2^2)}{k}(12\sigma_1+2\sigma_2-2\sigma_3)\right)t^2} \quad \text{where } \Upsilon = \frac{Vk}{m_1^2-m_2^2},$$

$|\Upsilon| \ll 1$, and $k^2 \gg m_1^2, m_2^2$, and $2z_0^\pm = m_{1(2)}^2 + \Upsilon(1 \pm \cos 2\theta)(m_1^2 - m_2^2) \pm \Upsilon^2(m_1^2 - m_2^2)\sin^2 2\theta$,

**NB: $\sigma$-modifications of oscillation period, $e^{-(\dots)t^2}$ suppression.**

# QG-DECOHERENCE & CPT:

# NEUTRAL MESONS PHENOMENOLOGY

# QG Decoherence in neutral Kaons: Single States

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):

$$\partial_t \rho = i[\rho, H] + \delta\not{H}\rho$$

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

$$\delta\not{H}_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -2\alpha & -2\beta \\ 0 & 0 & -2\beta & -2\gamma \end{pmatrix}$$

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

$\alpha, \beta, \gamma$ violate CPT (Wald : decoherence) & CP: $CP = \sigma_3 \cos\theta + \sigma_2 \sin\theta, \qquad [\delta\not{H}_{\alpha\beta}, CP] \neq 0$

# DECOHERENCE vs. CPTV IN QM

**Should distinguish two types of CPT Violation (CPTV)**:

(i) CPTV within Quantum Mechanics: $\delta M = m_{K^0} - m_{\overline{K}^0}$, $\delta\Gamma = \ldots$. This could be due to (spontaneous) Lorentz violation.

(ii) CPTV through decoherence $\alpha, \beta, \gamma$ (entanglement with QG 'environment').

**Experimentally two types can be disentangled !**

RELEVANT OBSERVABLES: $\langle O_i \rangle = \mathrm{Tr}\,[O_i \rho]$

LOOK AT DECAY ASYMMETRIES for $K^0, \overline{K}^0$:

$$A(t) = \frac{R(\bar{K}^0_{t=0} \to \bar{f}) - R(K^0_{t=0} \to f)}{R(\bar{K}^0_{t=0} \to \bar{f}) + R(K^0_{t=0} \to f)} \ , \qquad (1)$$

$R(K^0 \to f) \equiv \mathrm{Tr}\,[O_f \rho(t)]$ =decay rate into the final state $f$ (pure $K^0$ at $t = 0$).

NEUTRAL KAON ASYMMETRIES: identical final states $f = \bar{f} = 2\pi$: $A_{2\pi}$ , $A_{3\pi}$,

semileptonic: $A_T$ (final states $f = \pi^+ l^- \bar{\nu} \ \neq \ \bar{f} = \pi^- l^+ \nu$), $A_{CPT}$ ($\overline{f} = \pi^+ l^- \bar{\nu}, \ f = \pi^- l^+ \nu$), $A_{\Delta m}$.

# NEUTRAL KAON ASYMMETRIES

Typically

$$R_{2\pi}(t) = c_S\, e^{-\Gamma_S t} + c_L\, e^{-\Gamma_L t} + 2c_I\, e^{-\Gamma t} \cos(\Delta m t - \phi)\ ,$$

$S$=short-lived, $L$=long-lived, $I$=interference term, $\Delta m = m_L - m_S$, $\Gamma = \frac{1}{2}(\Gamma_S + \Gamma_L)$.

**Decoherence Parameter**

$$\zeta = 1 - \frac{c_I}{\sqrt{c_S c_L}}\ .$$

Can Look at this parameter also in the presence of a regenerator.

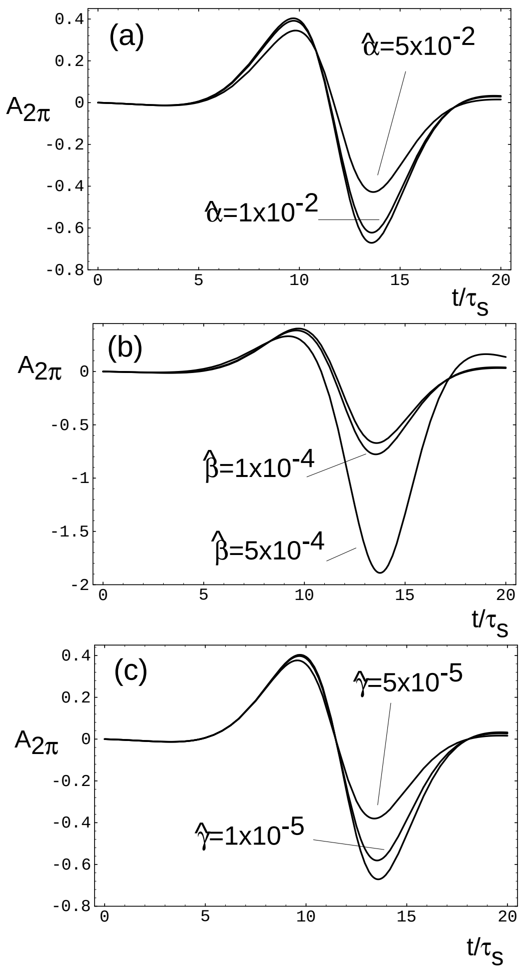
In our QG-induced Lindblad decoherence scenario (QG plays rôle of "medium"):

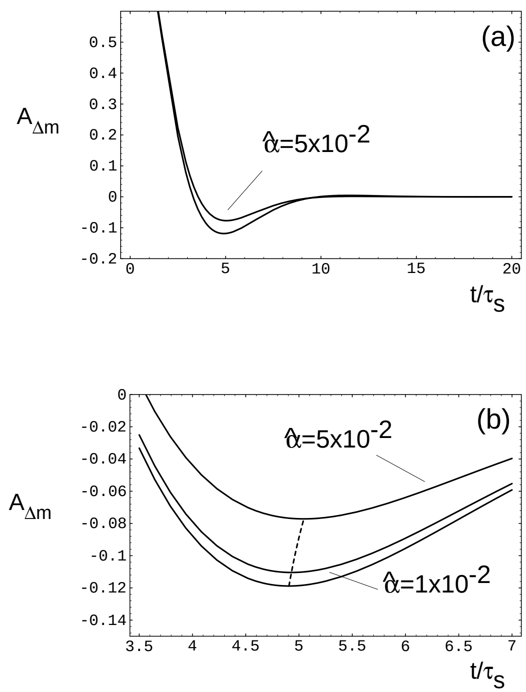
$$\zeta \to \frac{\widehat{\gamma}}{2|\epsilon^2|} - 2\frac{\widehat{\beta}}{|\epsilon|}\sin\phi$$

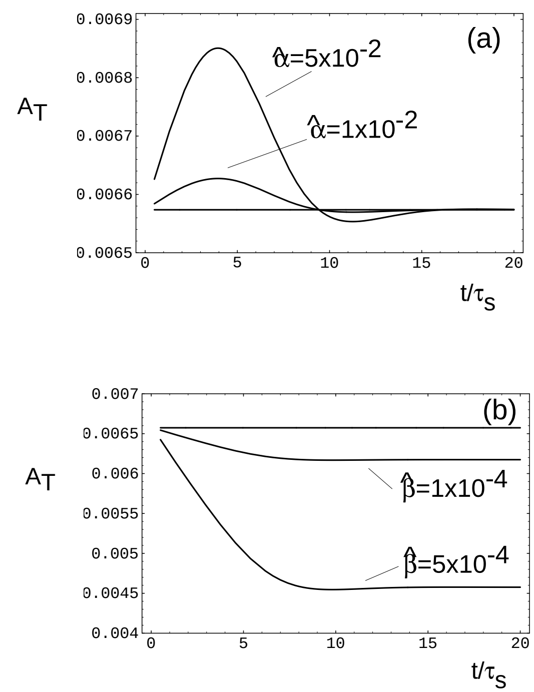
(for meson-factories, complete positivity $\widehat{\beta} = 0$).

[Convenient parametrization: $\widehat{a}$, $\widehat{\beta}$, $\widehat{\gamma} \equiv \frac{\alpha,\ \beta,\ \gamma}{\Delta\Gamma}$, $\Delta\Gamma = \Gamma_S - \Gamma_L$. For Kaons: $\Delta\Gamma \sim 10^{-15}$ GeV.]

# NEUTRAL KAON ASYMMETRIES



# QMV vs. QM effects

(Ellis, Lopez, NM and Nanopoulos, hep-ph/9505340 (PRD))

Table 1: Qualitative comparison of predictions for various observables in CPT-violating theories beyond (QMV) and within (QM) quantum mechanics. Predictions either differ ($\neq$) or agree ($=$) with the results obtained in conventional quantum-mechanical CP violation. Note that these frameworks can be qualitatively distinguished via their predictions for $A_{\rm T}$, $A_{\rm CPT}$, $A_{\Delta m}$, and $\zeta$.

| Process | QMV | QM |
|---|---|---|
| $A_{2\pi}$ | $\neq$ | $\neq$ |
| $A_{3\pi}$ | $\neq$ | $\neq$ |
| $A_{\rm T}$ | $\neq$ | $=$ |
| $A_{\rm CPT}$ | $=$ | $\neq$ |
| $A_{\Delta m}$ | $\neq$ | $=$ |
| $\zeta$ | $\neq$ | $=$ |

# INDICATIVE BOUNDS

Table 2: Compilation of indicative bounds on CPT-violating parameters and their source.

| Source | Indicative bound |
|---|---|
| $R_{2\pi}\, , A_{2\pi}$ | $\widehat{\alpha} < 5.0 \times 10^{-3}$ |
| $R_{2\pi}\, , A_{2\pi}$ | $\widehat{\beta} = (2.0 \pm 2.2) \times 10^{-5}$ |
| $\vert m_{K^0} - m_{\bar{K}^0}\vert$ | $\widehat{\beta} < 2.6 \times 10^{-5}$ |
| $R_{2\pi}$ | $\widehat{\gamma} \lesssim 5 \times 10^{-7}$ |
| $\zeta$ | $\frac{\widehat{\gamma}}{2\vert\epsilon\vert^2} - \frac{2\widehat{\beta}}{\vert\epsilon\vert} \sin\phi = 0.03 \pm 0.02$ |
| Positivity | $\widehat{\alpha} > \widehat{\beta}^2/\widehat{\gamma}_{\rm max} \sim (10^3\widehat{\beta})^2$ |

**FROM CPLEAR MEASUREMENTS (PLB364 (1995) 239)**:
$\alpha < 4.0 \times 10^{-17}$ GeV , $|\beta| < 2.3. \times 10^{-19}$ GeV , $\gamma < 3.7 \times 10^{-21}$ GeV

NB(1): Theoretically expected values (some models) $\alpha\ , \beta\ , \gamma = \mathcal{O}(\xi \frac{E^2}{M_P})$.

NB(2): $m_{K^0} - m_{\overline{K}^0} \sim 2|\beta|$

(at present $(m_{K^0} - m_{\overline{K}^0})/m_{K^0} < 7.5 \times 10^{-19}$)

# INDICATIVE BOUNDS

**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) $\gamma$ !**

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

**Perspectives with KLOE-2 at DAΦNE-2 :**

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

**(present best measurement:$\gamma = (1.1 \pm 2.5) \times 10^{-21}\ \mathrm{GeV}$)**

# ENTANGLED STATES (Neutral Mesons)

- Complete Positivity

  Different parametrization of Decoherence matrix for (entangled) mesons (Benatti, Floreanini) (in $\alpha, \beta, \gamma$ framework: $\alpha = \gamma$, $\beta = 0$)

- Novel (genuine) two-body effects: EPR correlation modification ($\omega$) (Bernabéu, Papavassiliou, NM, Alvarez, Nebot, Sarkar, Waldron ).

# EPR correlated states and particle physics

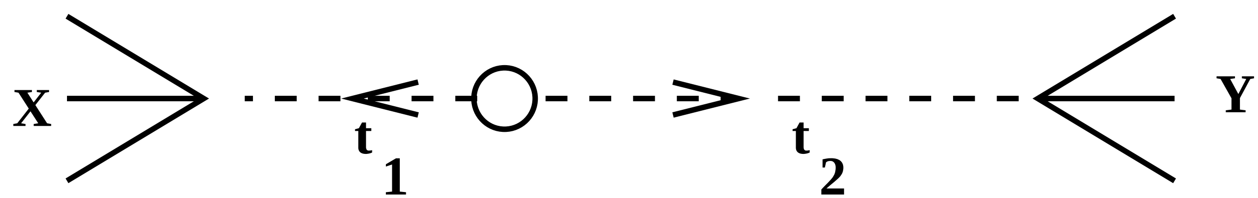
What are EPR correlations?

Einstein-Podolsky-Rosen (EPR) effect proposed originally as a **PARADOX** testing foundations of Quantum Theory.

Correlations between spatially separated events, instant transport of information? contradicts relativity?

**NO, NO PARADOX**

EPR has been confirmed EXPERIMENTALLY:
(i) pair of particles can be created in a definite quantum state,
(ii) move apart,
(iii) decay when they are widely separated (spatially).




EPR CORRELATIONS between different decay modes should be taken into account, when interpreting any experiment. (Lipkin (1968))

# EPR and $\phi$ Factories

(Dunietz, Hauser, Rosner (1987), Bernabeu, Botella, Roldan (1988), Lipkin (1989))

Was **claimed** that due to EPR correlations, irrespective of CP, CPT violation, FINAL STATE in $\phi$ decays: $e^+e^- \Rightarrow \phi \Rightarrow K_S K_L$ WHY? *Entangled* meson states: *Bose statistics* for the state $K^0\overline{K}^0$, to which $\phi$ decays, implies that the physical neutral meson-antimeson state must be *symmetric* under $C\mathcal{P}$, with $C$ the charge conjugation and $\mathcal{P}$ the operator that permutes the spatial coordinates.

Assuming *conservation* of angular momentum, and a proper existence of the *antiparticle state* (denoted by a bar), one observes that: for $K^0\overline{K}^0$ states which are $C$-conjugates with $C = (-1)^\ell$ (with $\ell$ the angular momentum quantum number), the system has to be an eigenstate of $\mathcal{P}$ with eigenvalue $(-1)^\ell$. Hence, for $\ell = 1$: $C = - \longrightarrow \mathcal{P} = -$. Bose statistics ensures that for $\ell = 1$ the state of two identical bosons is forbidden. Hence initial entangled state:

$$|i> = \frac{1}{\sqrt{2}}\left(|K^0(\vec{k}), \overline{K}^0(-\vec{k}) > - |\overline{K}^0(\vec{k}), K^0(-\vec{k}) >\right) =$$
$$\mathcal{N}\left(|K_S(\vec{k}), K_L(-\vec{k}) > - |K_L(\vec{k}), K_S(-\vec{k}) >\right)$$

with $\mathcal{N} = \frac{\sqrt{(1+|\epsilon_1|^2)(1+|\epsilon_2|^2)}}{\sqrt{2}(1-\epsilon_1\epsilon_2)} \simeq \frac{1+|\epsilon^2|}{\sqrt{2}(1-\epsilon^2)}$, and $K_S = \frac{1}{\sqrt{1+|\epsilon_1^2|}}(|K_+ > +\epsilon_1|K_- >)$, $K_L = \frac{1}{\sqrt{1+|\epsilon_2^2|}}(|K_- > +\epsilon_2|K_+ >)$, where $\epsilon_1, \epsilon_2$ are complex parameters, such that, $\delta \equiv \epsilon_1 - \epsilon_2$ parametrizes the CPT violation within quantum mechanics.

BUT, if CPT is intrinsically violated...The concept of antiparticle may be MODIFIED (perturbatively)!

# CPTV and 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 $\Theta$ 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 $\phi$ (B) factories $|i>$ (in terms of mass eigenstates):

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

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

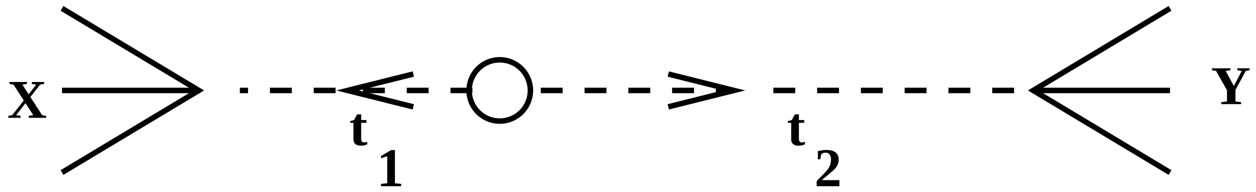
Experimental Tests of $\omega$-Effect in $\phi$, B factories... in B-factories: $\omega$-effect $\rightarrow$ demise of flavour tagging (Alvarez et al. (PLB607))

**NB1: Disentangle $\omega$ $C$-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 $\phi$-resonance as a result of $\omega$-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 $\omega$ from non-unitary evolution ($\alpha = \gamma$ ...) effects (different structures) (Bernabéu, NM, Papavassiliou, Waldron NP B744:180-206,2006)**

# $\phi$ Decays and the $\omega$ Effect

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

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

# $\omega$-Effect & Intensities

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

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

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

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

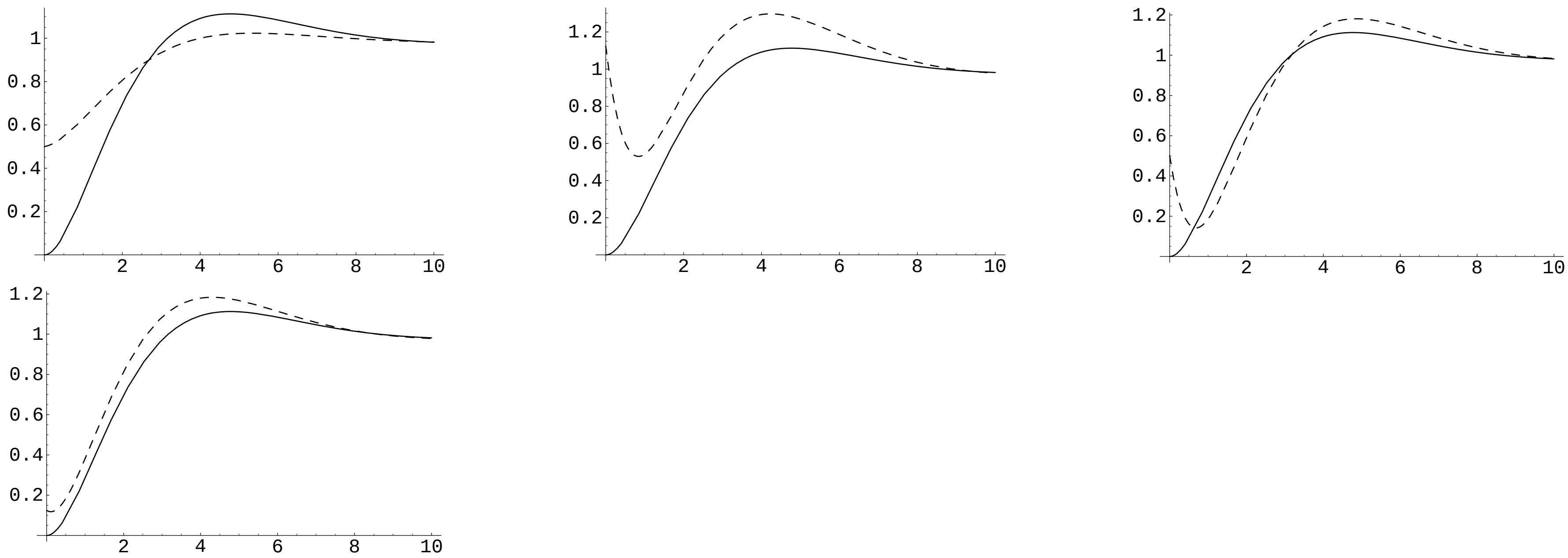
$$\Big[ 2\Delta M \Big( e^{-\Gamma_S \Delta t}\sin(\phi_{+-} - \Omega) - e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\sin(\phi_{+-} - \Omega + \Delta M \Delta t) \Big)$$

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

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

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

# $\omega$-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) $|\omega| = 1.5|\eta_{+-}|$, $\Omega = \phi_{+-}$. $\Delta t$ is measured in units of $\tau_S$ (the mean life-time of $K_S$) and $I(\Delta t)$ in units of $|C|^2|\eta_{+-}|^2|\langle\pi^+\pi^-|K_S\rangle|^4\tau_S$.

# $\omega$-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 $\omega$-effect $(|K_L\rangle = |\uparrow\rangle \ , \quad |K_S\rangle = |\downarrow\rangle\,.)$.

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 DA$\Phi$NE **(c.f. Experimental Talk (M. Testa))**. Constrain $\zeta$ significantly in upgraded facilities.

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

**NB: $\omega$-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...**

# CONCLUDING QUESTIONS

- Experimentally Testing Quantum Gravity (QG) may not be an oxymoron scheme....
  CPT Violation may not be an academic issue, but a real feature of QG.
- Various ways for CPT breaking, in principle independent, e.g. decoherence and Lorentz Violation (LV) are independent effects. One may have Lorentz invariant decoherence in Quantum Gravity (Millburn), frame dependence of LV effects (e.g. day-night measurement differences etc disentangle LV from LI CPTV, e.g. meson factories).
- Precision experiments in meson factories, will provide sensitive probes of QG-induced decoherence & CPT Violation, including NOVEL effects ($\omega$-effect) exclusive to ENTANGLED states: modified EPR correlations, Theoretical (intrinsic) limitations on flavour tagging...Lorentz invariance would imply effects similar in $\phi$ and $B$-meson factories-: $\phi$-meson produced at rest, $\Upsilon$- state boosted...in contrast LV would lead to differences/frame dependence...
- Are there any effects of intrinsic (QG decoherence) CPT Violation on viewing entangled (neutral) mesons as Quantum Erasers & Markers ?
- What about Equivalence principle and QG?: are QG effects universal among particle species?
- Are QG-decoherence effects of the same strength between particles & antiparticles ? tests in antimatter factories ? neutrinos ?

More work (Theory & Expt) to be done before conclusions are reached...

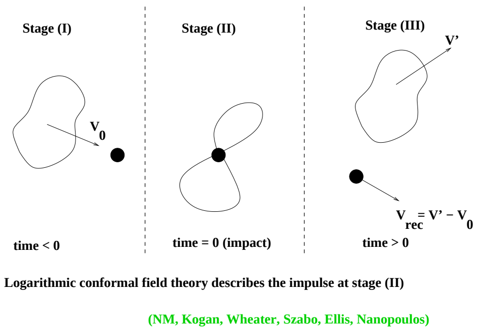
Excitement persists for years to come... More precision experiments necessary...

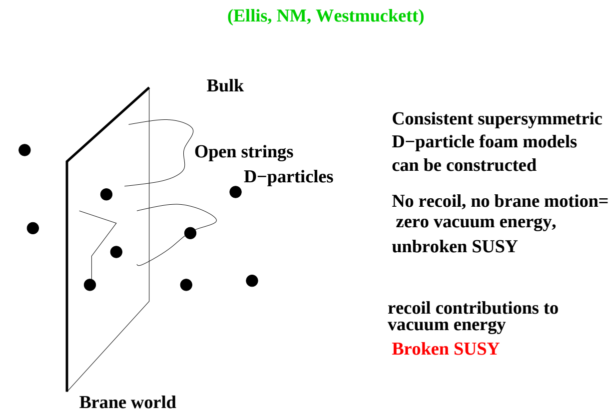
Worthy of investing effort...

# BACK-UP SLIDES

# Microscopic Models for the $\omega$-effect

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




Left: Recoil of closed string states with D-particles (space-time defects). Right: A supersymmetric brane world model of D-particle foam. In both cases recoil of (massive) D-particle defect causes distortion of space time , metric fluctuations, emergent post-recoil string state may differ by flavour and CP phases. Induced metric distortions (including flavour changes, $\sigma_i$=Pauli matrices):
$g^{00} = (-1 + r_4)\,\mathbf{1}\,, \quad g^{01} = g^{10} = r_0\mathbf{1} + r_1\sigma_1 + r_2\sigma_2 + r_3\sigma_3, \qquad g^{11} = (1 + r_5)\,\mathbf{1}$

The target space metric state is a density matrix $\rho_{\rm grav} = \int d^5 r\ f(r_\mu)\,|g(r_\mu)\rangle\,\langle g(r_\mu)|\,.$

The parameters $r_\mu$ $(\mu = 0, \dots, 5)$ are stochastic with a gaussian $f(r_\mu)$

$$\langle r_\mu \rangle = 0,\ \langle r_\mu r_\nu \rangle = \Delta_\mu \delta_{\mu\nu}\,.$$

$\mathcal{O}(r)$: $g_{0i} \simeq \overline{v}_{i,rec} \propto g_s \frac{\Delta p_i}{M_s}$ ($\Delta p_i \sim \zeta p_i$ momentum transfer, $g_s < 1$ string coupling, $M_s$ string scale).

# Order of magnitude estimates

Gravitationally-dressed initial entangled state - stationary perturbation theory and order of magnitude estimates of the $\omega$-effect. Propagation of matter on above stochastic metric

$$\widehat{H} = g^{01}\left(g^{00}\right)^{-1}\widehat{k} - \left(g^{00}\right)^{-1}\sqrt{(g^{01})^2 k^2 - g^{00}\left(g^{11}k^2 + m^2\right)}$$

Leading-order-in-$r$'s interaction hamiltonian: $(|M_L\rangle = |\uparrow\rangle \ , \quad |M_S\rangle = |\downarrow\rangle \ .)$

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

$$\left|k^{(i)},\downarrow\right\rangle_{QG}^{(i)} = \left|k^{(i)},\downarrow\right\rangle^{(i)} + \left|k^{(i)},\uparrow\right\rangle^{(i)}\alpha^{(i)}$$

where $\alpha^{(i)} = \frac{{}^{(i)}\left\langle\uparrow,k^{(i)}\left|\widehat{H_I}\right|k^{(i)},\downarrow\right\rangle^{(i)}}{E_2-E_1}$. For $\left|k^{(i)},\uparrow\right\rangle^{(i)}$ the dressed state obtained by $|\downarrow\rangle \leftrightarrow |\uparrow\rangle$ and $\alpha \rightarrow \beta$ where $\beta^{(i)} = \frac{{}^{(i)}\left\langle\downarrow,k^{(i)}\left|\widehat{H_I}\right|k^{(i)},\uparrow\right\rangle^{(i)}}{E_1-E_2}$.

Totally antisymmetric "gravitationally-dressed" state of two mesons (Kaons):

$$\begin{aligned}
&|k,\uparrow\rangle_{QG}^{(1)}\,|-k,\downarrow\rangle_{QG}^{(2)} - |k,\downarrow\rangle_{QG}^{(1)}\,|-k,\uparrow\rangle_{QG}^{(2)} = |k,\uparrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)} - |k,\downarrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)}\\
&+|k,\downarrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)}\left(\beta^{(1)}-\beta^{(2)}\right) + |k,\uparrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)}\left(\alpha^{(2)}-\alpha^{(1)}\right)\\
&+\beta^{(1)}\alpha^{(2)}\,|k,\downarrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)} - \alpha^{(1)}\beta^{(2)}\,|k,\uparrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)}
\end{aligned}$$

# Order of magnitude estimates

I.e. 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: for $r_i \propto \delta_{i1}$ we have $\xi = \xi'$, strangeness violation, whilst for $r_i \propto \delta_{i2} \longrightarrow \xi = -\xi'$) (since $\alpha^{(i)} = \beta^{(i)}$) : strangeness conserving $\omega$-effect.

Averaging density matrix over $r_i$, only terms $|\omega|^2$ survive:

$$|\omega|^2 = \mathcal{O}\left(\frac{1}{(E_1 - E_2)^2}(\langle\downarrow, k|H_I|k,\uparrow\rangle)^2\right) \sim \frac{\Delta_2 k^2}{(m_1 - m_2)^2}$$

for momenta of order of the rest energies.

In recoil D-particle model: $\Delta_2 = \zeta^2 k^2/M_P^2$ (recall momentum transfer: $\Delta p_i \sim \zeta p_i$), hence

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

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 DA$\Phi$NE. Constrain $\zeta$ significantly in upgraded facilities.

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

# Time-Evolution Generated $\omega$-effects

Hamiltonian evolution in stochastically fluctuating D-particle-recoil-distorted space times:
$|\psi(t)\rangle = \exp\left[-i\left(\widehat{H}^{(1)} + \widehat{H}^{(2)}\right)\frac{t}{\hbar}\right]|\psi\rangle$. Assume $\xi = \xi' = 0$.

Time evolved state of two Kaons $\ni$ strangeness-conserving $\omega$-terms:

$$|\psi(t)\rangle \sim e^{-i\left(\lambda_0^{(1)}+\lambda_0^{(2)}\right)t}\varpi(t)\left\{|k,\uparrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)} - |k,\downarrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)}\right\}$$

(with $|M_L\rangle = |\uparrow\rangle$ , $|M_S\rangle = |\downarrow\rangle$, $M = \text{Kaon}$); $\varpi(t)$=**Purely Imaginary in the model**

$$O(\varpi) \simeq i\frac{2\Delta_1^{\frac{1}{2}}k}{(k^2+m_1^2)^{\frac{1}{2}} - (k^2+m_2^2)^{\frac{1}{2}}}\cos\left(\left|\lambda^{(1)}\right|t\right)\sin\left(\left|\lambda^{(1)}\right|t\right) = \varpi_0\sin\left(2\left|\lambda^{(1)}\right|t\right).$$

with $\Delta_1^{1/2} \sim |\zeta|\frac{|k|}{M_P}$, $\varpi_0 \equiv \frac{\Delta_1^{\frac{1}{2}}k}{(k^2+m_1^2)^{\frac{1}{2}}-(k^2+m_2^2)^{\frac{1}{2}}}$,
$\left|\lambda^{(1)}\right| \sim \left(1+\Delta_4^{\frac{1}{2}}\right)\sqrt{\chi_1^2+\chi_3^2}$, $\chi_3 \sim (k^2+m_1^2)^{\frac{1}{2}} - (k^2+m_2^2)^{\frac{1}{2}}$.

**NB1:** Time dependence of the medium-generated effect. If in initial state $\xi = -\xi'$ ($\xi = \xi'$) strangeness-conserving (-violating) combination, then, time evolution generates time-dependent strangeness-violating (-conserving $\omega$-) imaginary effects.

**NB2: No $\omega$-like effects generated by Thermal Bath-like (rotationally invariant, isotropic) space-time foam situations (Garay)** ! Can distinguish various types of space time foam...

## Disentangling the $\omega$-Effect....

- (i) From C(even) Background,

- (ii) from QG-Decoherence evolution $\alpha = \gamma$ effects

# (i) $\omega$-Effect & C(even) Background

The C(even) background: $e^+e^- \Rightarrow 2\gamma \Rightarrow K^0\overline{K}^0$

$$|b >= |K^0\overline{K}^0(C(\text{even}) >= \frac{1}{\sqrt{2}}\left(K^0(\vec{k})\overline{K}^0(-\vec{k}) + \overline{K}^0(\vec{k})K^0(-\vec{k})\right)$$

mimic $\omega$-Effect. Can we disentangle ? YES...

(i) Order of Magnitude of C(even) Background mass smaller than C(odd) resonant contribution expected theoretically (c.f. above); Unitarity bounds (Dunietz *et al.* (1987), 2nd DA$\Phi$NE Handbook) estimate:

$$\frac{\sigma(e^+e^- \to K^0\overline{K}^0, J^P = 0^+)}{\sigma(e^+e^- \to \phi \to K_S K_L)} \geq 3.6 \times 10^{-10}$$

Expect inequality to be saturated ...

This is an important difference from the $\omega$-Effect order of magnitude (in the optimistic case).

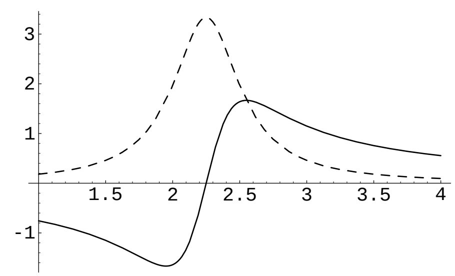
(ii) More important: Different interference with C(odd) background ...

# (i) $\omega$-Effect vs. C(even) Background: Interference

Terms of the type $K_S K_S$ (which dominate over $K_L K_L$) coming from the $\phi$-resonance as a result of $\omega$-CPTV can be distinguished from those coming from the $C = +$ background because they interfere differently with the regular $C = -$ resonant contribution with $\omega = 0$.

Indeed, in the CPTV case, the $K_L K_S$ and $\omega K_S K_S$ terms have the same dependence on the centre-of-mass energy $s$ of the colliding particles producing the resonance, because both terms originate from the $\phi$-particle. Their interference, therefore, being proportional to the real part of the product of the corresponding amplitudes, still displays a peak at the resonance.

On the other hand, the amplitude of the $K_S K_S$ coming from the $C = +$ background has no appreciable dependence on $s$ and has practically vanishing imaginary part.




Therefore, given that the real part of a Breit-Wigner amplitude vanishes at the top of the resonance , this implies that the interference of the $C = +$ background with the regular $C = -$ resonant contribution vanishes at the top of the resonance, with opposite signs on both sides of the latter. **This clearly distinguishes experimentally the two cases.**

# (ii) $\omega$-Effect & QG-Decoherence

Initial entangled state density matrix $\tilde{\rho}_\phi = \mathrm{Tr}|\phi><\phi|$:

For $\omega = 0$ (Huet & Peskin) **NB: Complete Positivity :** $\alpha = \gamma, \beta = 0$ **(Benatti, Floreanini)**

$$\tilde{\rho}_\phi = \rho_S \otimes \rho_L + \rho_L \otimes \rho_S - \rho_I \otimes \rho_{\overline{I}} - \rho_{\overline{I}} \otimes \rho_I$$
$$-\frac{i\alpha}{\Delta M}(\rho_I \otimes \rho_I - \rho_{\overline{I}} \otimes \rho_{\overline{I}}) - \frac{2\gamma}{\Delta\Gamma}(\rho_S \otimes \rho_S - \rho_L \otimes \rho_L)$$

where $\rho_S = |S><S|$, $\rho_L = |L><L|$, $\rho_I = |S><L|$, $\rho_{\overline{I}} = |L><S|$, and an overall multiplicative factor of $\frac{1}{2}\frac{(1+2|\epsilon|^2)}{1-2|\epsilon|^2\cos(2\phi_\epsilon)}$ has been suppressed.

For $\omega \neq 0$ but $\alpha, \beta, \gamma = 0$:

$$\begin{aligned}
\rho_\phi &= \rho_S \otimes \rho_L + \rho_L \otimes \rho_S - \rho_I \otimes \rho_{\overline{I}} - \rho_{\overline{I}} \otimes \rho_I \\
&- \omega(\rho_I \otimes \rho_S - \rho_S \otimes \rho_I) - \omega^*(\rho_{\overline{I}} \otimes \rho_S - \rho_S \otimes \rho_{\overline{I}}) \\
&- \omega(\rho_{\overline{I}} \otimes \rho_L - \rho_L \otimes \rho_{\overline{I}}) - \omega^*(\rho_I \otimes \rho_L - \rho_L \otimes \rho_I) \\
&- |\omega|^2(\rho_I \otimes \rho_I + \rho_{\overline{I}} \otimes \rho_{\overline{I}}) + |\omega|^2(\rho_S \otimes \rho_S + \rho_L \otimes \rho_L)
\end{aligned}$$

with the same multiplicative factor suppressed.

**Disentanglement of $\omega$ from $\alpha, \gamma$ due to different symmetry properties and time evolution**.

Detailed phenomenology in various channels: Bernabéu, NM, Papavassiliou, Waldron NP B744:180-206,2006

# $B$-factories and $\omega$ Effect

(Alvarez, Bernabéu, Nebot, NM, Papavassiliou, 2005, 2006)

Although, formally, the situation is identical to the $\phi$ factories, however the sensitivity of the CPTV $\omega$ effect for the $B$ system is much smaller.

This is due to the fact that in $B$ factories there is no particularly "good" channel $X$ (with $X = Y$) for which the corresponding $\eta_X$ is small .

The analysis in that case may therefore be performed in the equal sign dilepton channel, where the branching fraction is more important, and a high statistics is expected.

**If $\omega$-effect exists: Theoretical limitations (due to Quantum gravity) on flavour tagging...**