Spin-Statistics, Quantum Decoherence & CPT Violation:

models, consequences & searches

KING'S College LONDON

Nick E. Mavromatos

King’s College London,
Physics Dept., London UK

John Templeton Foundation

INFN
Istituto Nazionale
di Fisica Nucleare
Laboratori Nazionali di Frascati

Seminar organized within the project:
"Hunt for the "impossible atoms":
the quest for a tiny violation of the Pauli Exclusion Principle. Implications for physics, cosmology and philosophy,"
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OUTLINE

I. Spin-Statistics Theorem: assumptions, connection to CPT invariance

II. Spin-Statistics theorem violation if CPT Violation?

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***

Possible Pauli Exclusion Principle violation – the VIP(2) experiment

III. Decoherene-induced CPTV Experimental searches in Entangled Neutral Mesons- ω effect, searches in Kaon, B-meson factories, theoretical models and estimates – links with spin statistics violation?

IV. Conclusions-Outlook

Part I

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

In quantum theory: two **indistinguishable** particles, occupying two separate points, have only **one state**, not two.

A physical state is described by **a wavefunction.** Two different wavefunctions are physically equivalent if their absolute value is equal. Hence, *under **exchange** of identical particles **positions**, two particle wavefunction may **pick up a phase.***

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-invariant Lagrangian & relativistic causality**.

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

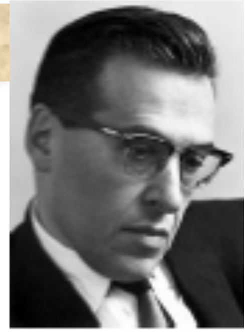
(3) The **particle** is a **localized excitation**. Microscopically, it is **not attached** to a **string** or **domain wall.**

(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.

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:

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

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.

Part II

Spin-Statistics Theorem Violation

if

CPT Violation?

CPT Theorem

Schwinger 1951

Lüders 1954

J S Bell 1954

Pauli 1955

Res Jost 1958

CPT Theorem

In **Quantum Field Theory**
not in quantum mechanics

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

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

(ii)-(iv) Independent reasons for violation

CPT VIOLATION

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Kostelecky, Bluhm, Colladay, Potting, Russell, Lehnert, Mewes, Diaz , Tasson….

Standard Model Extension (SME)

(ii)-(iv) Independent reasons for violation

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

Lorentz & CPT Violation

Lorentz & CPT Violation

STANDARD MODEL EXTENSION

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

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), $\to < A_\mu > \neq 0$, $< T_{\mu_1 \dots \mu_n} > \neq 0$,

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

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

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 $a_\mu, b_\mu \dots$ 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

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

CPT VIOLATION

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

(ii)-(iv) Independent reasons for violation

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

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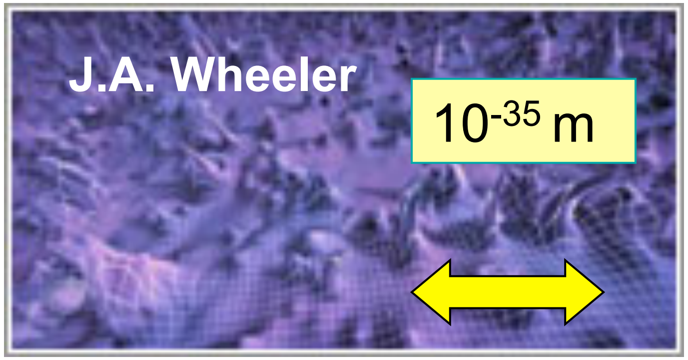
e.g. ***QUANTUM SPACE-TIME FOAM AT PLANCK SCALES***



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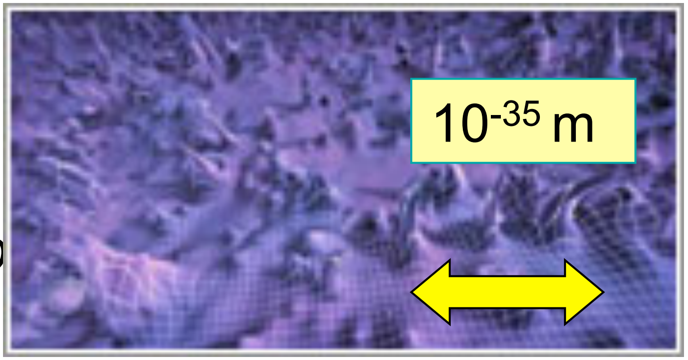
Hawking,
Ellis, Hagelin, Nanopoulos
Srednicki,
Banks, Peskin, Strominger,
Lopez, NEM, Barenboim…

(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



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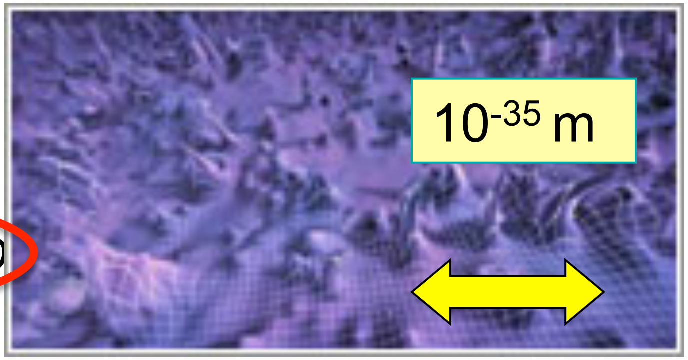

NB: Decoherence & CPTV

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

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

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

$$\$ \ne S\,S^\dagger$$

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

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)

Proof

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 Θ : $\Theta\overline{\rho}_{in} = \rho_{out}$ acting on density matrices ρ = Tr |ψ><ψ|

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

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...)

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CPT is **antiunitary**
(due to T)
when acting on |ψ>

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CPT symmetry without CPT invariance ?

But....nature may be tricky: WEAK FORM OF CPT INVARIANCE might exist, such that the fundamental “arrow of time” does not show up in any experimental measurements (scattering experiments).

Probabilities for transition from ψ =initial pure state to ϕ =final state

$$P(\psi \to \phi) = P(\theta^{-1}\phi \to \theta\psi)$$

where θ: $\mathcal{H}_{\rm in} \to \mathcal{H}_{\rm out}$, $\mathcal{H}$= Hilbert state space,
$\Theta\rho = \theta\rho\theta^\dagger, \quad \theta^\dagger = -\theta^{-1} \ ({\rm anti-unitary})$.

In terms of superscattering matrix $\$$:

$$\$^\dagger = \Theta^{-1}\$\Theta^{-1}$$

Here, Θ is well defined on pure states, but $\$$ has no inverse, hence $\$^{\,\dagger} \ne \$^{-1}$ (full CPT invariance: $\$ = SS^\dagger$, $\$^\dagger = \$^{-1}$).

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Supporting evidence for Weak CPT from Black-hole thermodynamics: *Although white holes do not exist (strong CPT violation), nevertheless the CPT reverse of the most probable way of forming a black hole is the most probable way a black hole will evaporate:* **the states resulting from black hole evaporation are precisely the CPT reverse of the initial states which collapse to form a black hole.**

In principle this question can be settled experimentally

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(i) If CPT ill-defined → tiny effect (if due to Quantum Gravity decoherence) → concept of antiparticle still well-defined, but…

↓

spin-stastistics theorem violation?

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

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

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

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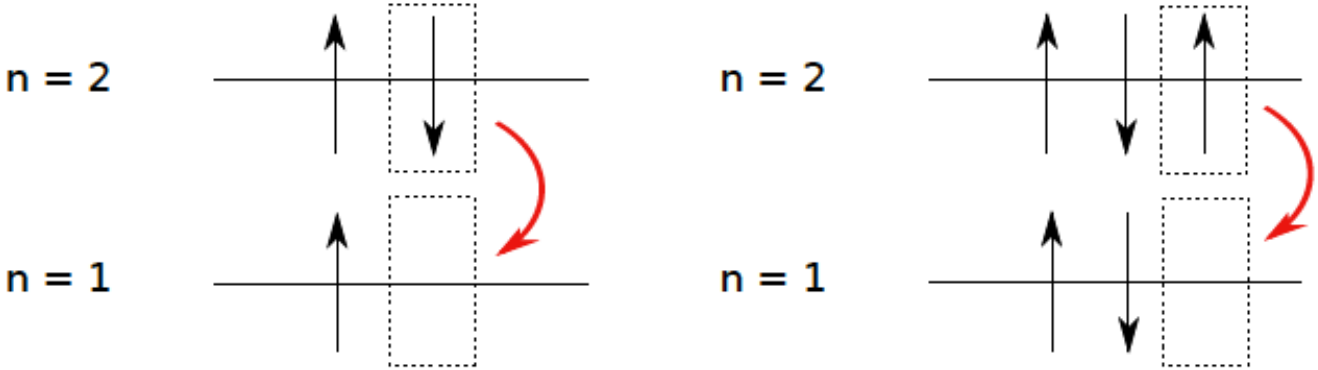
Pauli-Principle Violation?

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)



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).

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VIP result (2010 data) for probability of PEP violation in an atom $\frac{\beta^2}{2}$

$$\frac{\beta^2}{2} \leq 4.7 \times 10^{-29}$$

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

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

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:

$$a|0\rangle = 0 \qquad a^{+}|0\rangle = |1\rangle$$

$$a|1\rangle = |0\rangle \qquad a^{+}|1\rangle = \beta|2\rangle$$

$$a|2\rangle = \beta|1\rangle \qquad a^{+}|2\rangle = 0$$

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.

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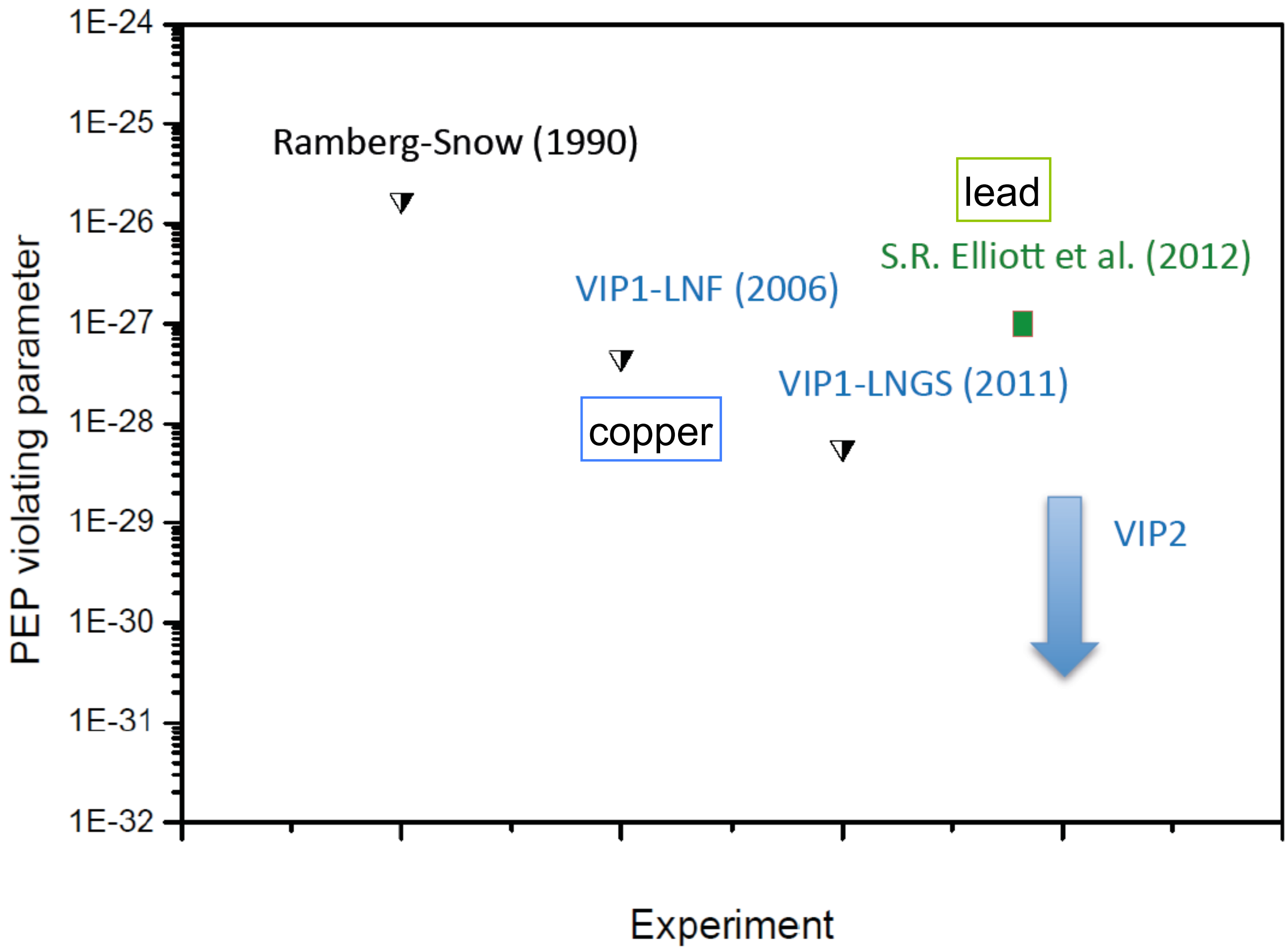
VIP2 : forsee improvement by at least 2 orders of magnitude on this bound : **$< 10^{-31}$**


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)
VIP1-LNF (2006)
copper
VIP1-LNGS (2011)
lead
S.R. Elliott et al. (2012)
VIP2

(ii) Decoherence CPTV- entangled mesons

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, PRL(04)

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Part III

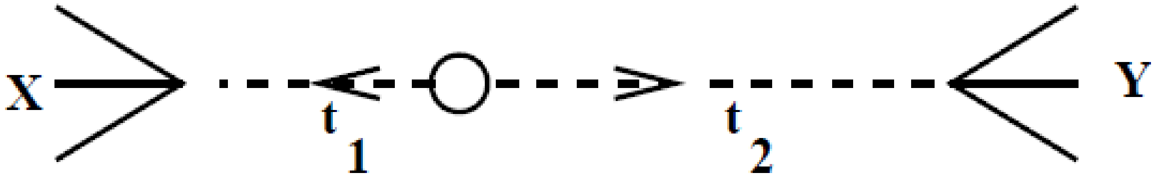
Decoherence-Induced CPT Violation & Entangled Neutral Mesons

ω-effect

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.

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ω-Effect & Intensities

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

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

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

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

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

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Bernabeu, NEM, Papavassiliou,…

ω-effect observables/current bounds

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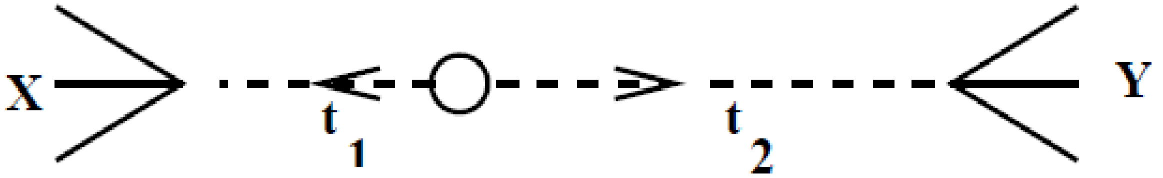
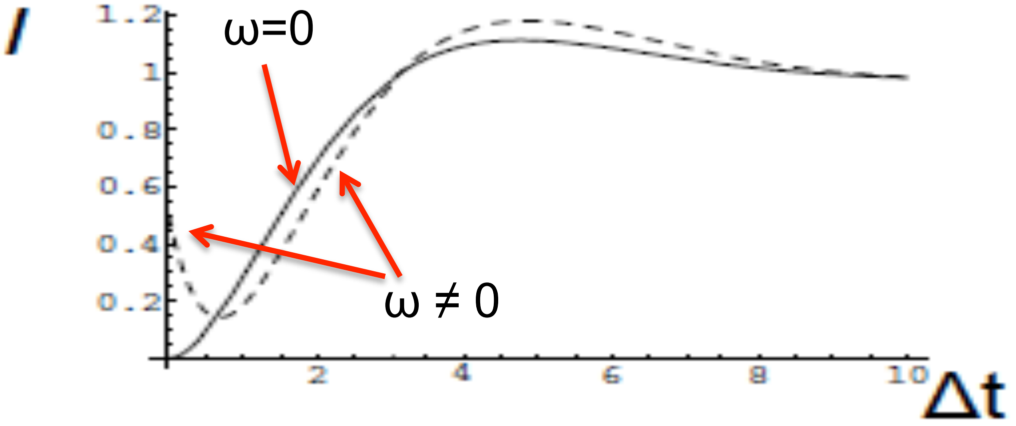
Consider the ϕ decay amplitude: final state X at t_1 and Y at time t_2 ($t = 0$ at the moment of ϕ decay)





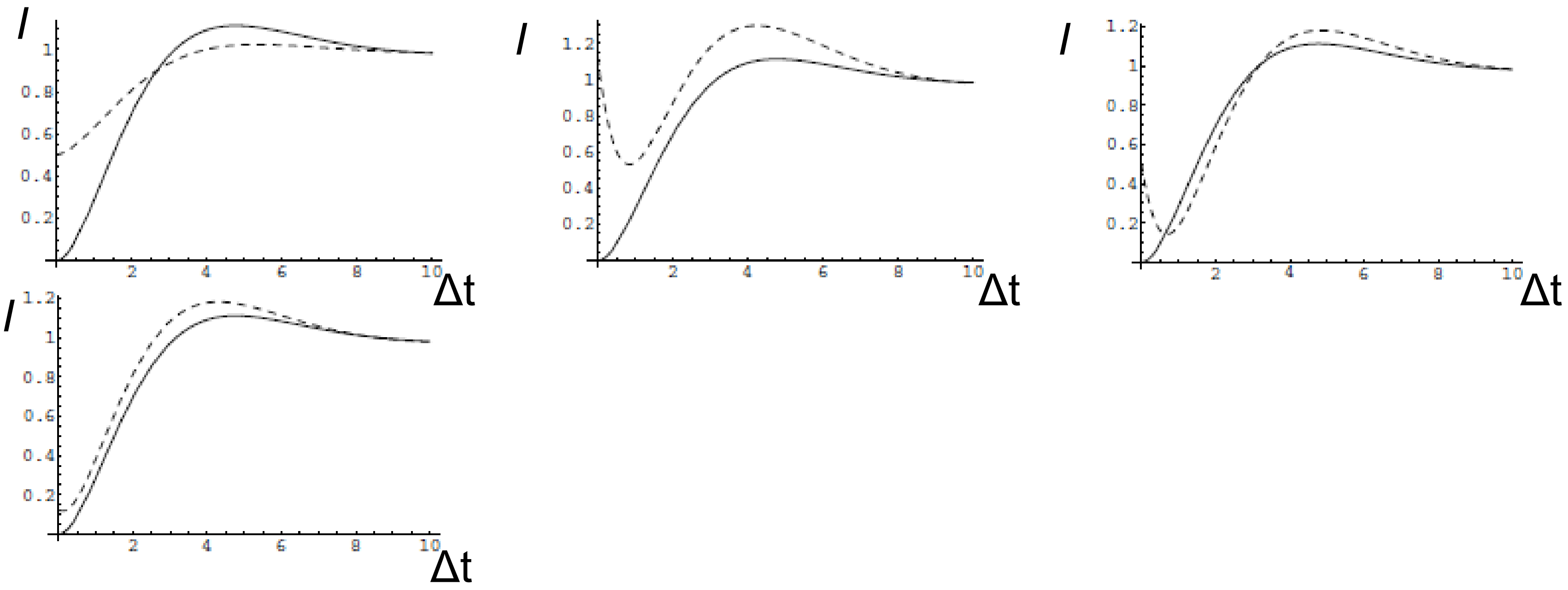
I(Δt=0) ≠ 0
if ω-effect present

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

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

Bernabeu, NEM, Papavassiliou,…

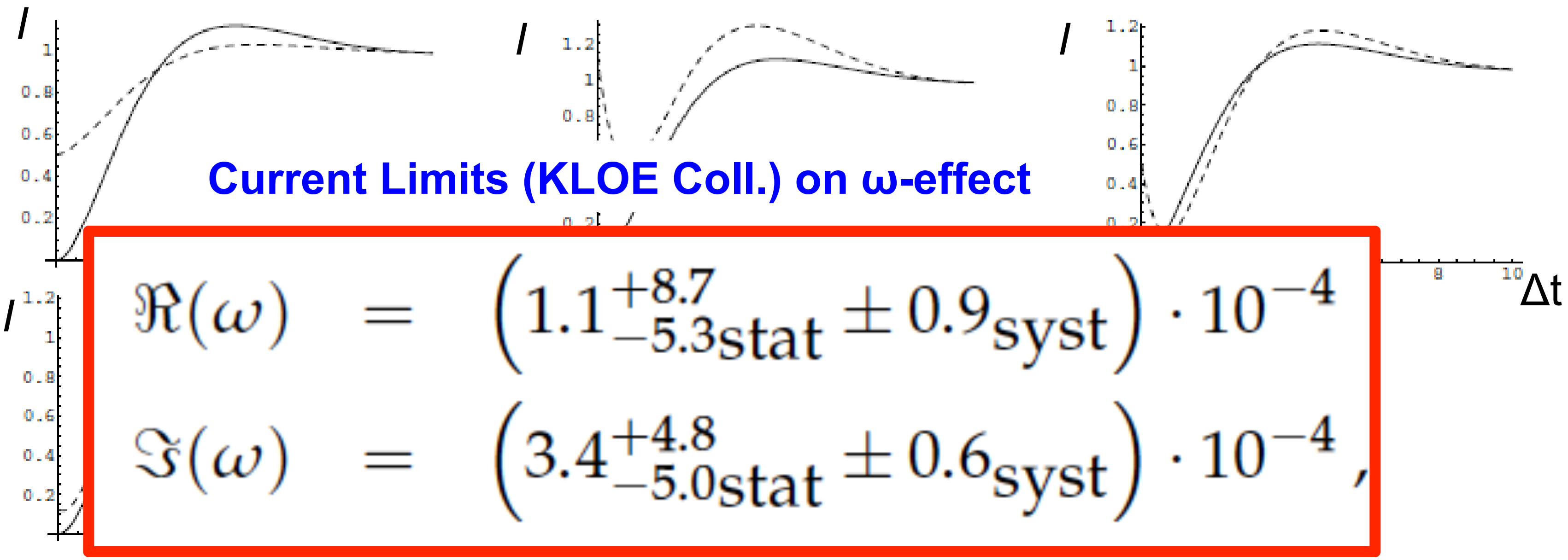
ω-Effect & Intensities



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,…

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

Disentangling ω-effect from background

(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):

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

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.

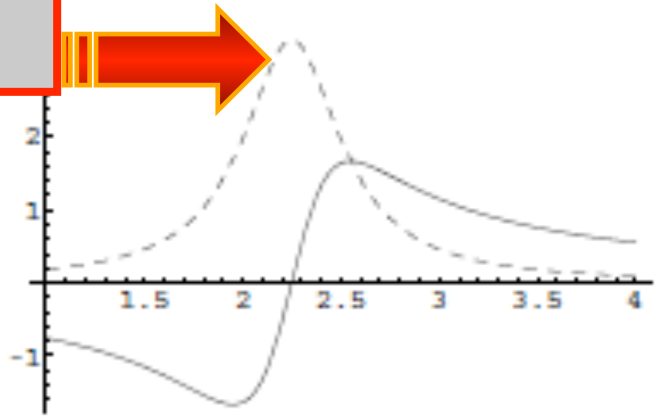
Experimental Tests of ω-Effect in ϕ, B factories... in B-factories: ω-effect $\rightarrow$ demise of flavour tagging (Alvarez et al. (PLB607))

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)

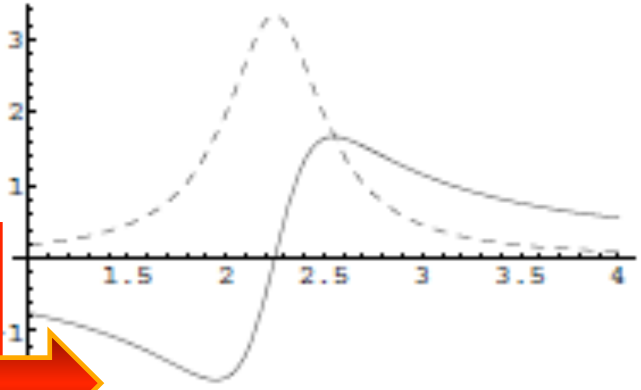
Disentangling ω-effect from background

CPTV K_LK_L, ωK_SK_S terms originate from Φ-particle , hence same dependence on centre-of-mass energy s. Interference proportional to real part of amplitude, exhibits peak at the resonance….



Bernabeu, NEM, Papavassiliou, PRL(04)

Disentangling ω-effect from background

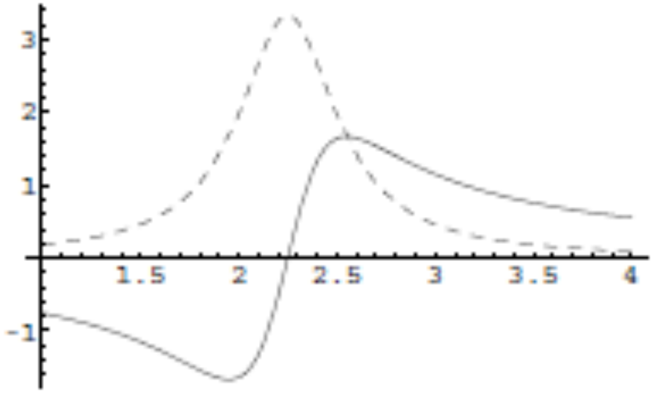


$K_S K_S$ terms from C=+ background
no dependence on centre-of-mass energy s.
Real part of Breit-Wigner amplitude
Vanishes at top of resonance, Interference
of C=+ with C=-- background, vanishes
at top of the resonance, opposite signature
on either side…..

Bernabeu, NEM, Papavassiliou, PRL(04)

Disentangling ω-effect from background

CLEAR EXPERIMENTAL DISTINCTION BETWEEN THE TWO CASES



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

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B-systems, ω-effect & demise of flavour-tagging

$$|\psi(0)\rangle = \frac{1}{\sqrt{2\left(1+|\omega|^2\right)}}\left\{|B^0\overline{B}^0\rangle - |\overline{B}^0 B^0\rangle + \omega\left[|B^0\overline{B}^0\rangle + |\overline{B}^0 B^0\rangle\right]\right\}$$

$$|B_1\rangle = \frac{1}{\sqrt{2\left(1+|\epsilon_1|^2\right)}}\left((1+\epsilon_1)|B^0\rangle + (1-\epsilon_1)|\overline{B}^0\rangle\right)$$

$$|B_2\rangle = \frac{1}{\sqrt{2\left(1+|\epsilon_2|^2\right)}}\left((1+\epsilon_2)|B^0\rangle - (1-\epsilon_2)|\overline{B}^0\rangle\right)$$

$$\Delta M = M_1 - M_2$$

$$\Delta\Gamma = \Gamma_1 - \Gamma_2$$

$$\Gamma = (\Gamma_1 + \Gamma_2)/2$$

$$|B_1(0)\rangle \mapsto e^{-iMt-\frac{\Gamma}{2}t} e^{-i\frac{\Delta M}{2}t-\frac{\Delta\Gamma}{4}t}|B_1(0)\rangle\,, \quad |B_2(0)\rangle \mapsto e^{-iMt-\frac{\Gamma}{2}t} e^{+i\frac{\Delta M}{2}t+\frac{\Delta\Gamma}{4}t}|B_2(0)\rangle$$

$$I_{ab}(t) = |\langle X_{ab}|\psi(t)\rangle|^2$$

$$I_{ab}(t) = |\langle Y_a|B^a\rangle|^2\,|\langle Z_b|B^b\rangle|^2\,\frac{e^{-\Gamma t}}{2(1+|\omega|^2)}\,|C_{ab}(t)|^2$$

In terms of intensities, $\omega \neq 0$ allows

$$I_{00}(t) \neq 0 \quad ; \quad I_{\bar{0}\bar{0}}(t) \neq 0\ .$$

B-systems, ω-effect & demise of flavour-tagging

CP-type asymmetry of the form

$$A_{CP}(t) = \frac{I_{00}(t) - I_{\bar{0}\bar{0}}(t)}{I_{00}(t) + I_{\bar{0}\bar{0}}(t)} \quad ; \quad \mathcal{A}_{CP} = \frac{\mathcal{I}_{00} - \mathcal{I}_{\bar{0}\bar{0}}}{\mathcal{I}_{00} + \mathcal{I}_{\bar{0}\bar{0}}} \quad .$$

$$\mathcal{I}_{ab} = \int_0^\infty dt\ I_{ab}(t)$$

$$\boxed{A(t) = \frac{2\Re e\left(\omega f(t)\right)}{1 + |\omega f(t)|^2}}$$

$$f(t) = \frac{1}{(1 - \epsilon^2 + \frac{\delta^2}{4})^2}\left[\delta^2 + \frac{1}{2}\left((1+\epsilon)^2 - \frac{\delta^2}{4}\right)\left((1-\epsilon)^2 - \frac{\delta^2}{4}\right)\left(e^{\alpha t} + e^{-\alpha t}\right)\right]$$

CP parameter

CPTV parameter (QM)

$\alpha \equiv i\Delta M/2 + \Delta\Gamma/4$

$\epsilon = (\epsilon_1 + \epsilon_2)/2,$ $\quad \delta = \epsilon_1 - \epsilon_2$

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, $B \to X'\ell^{\pm}$

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

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

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

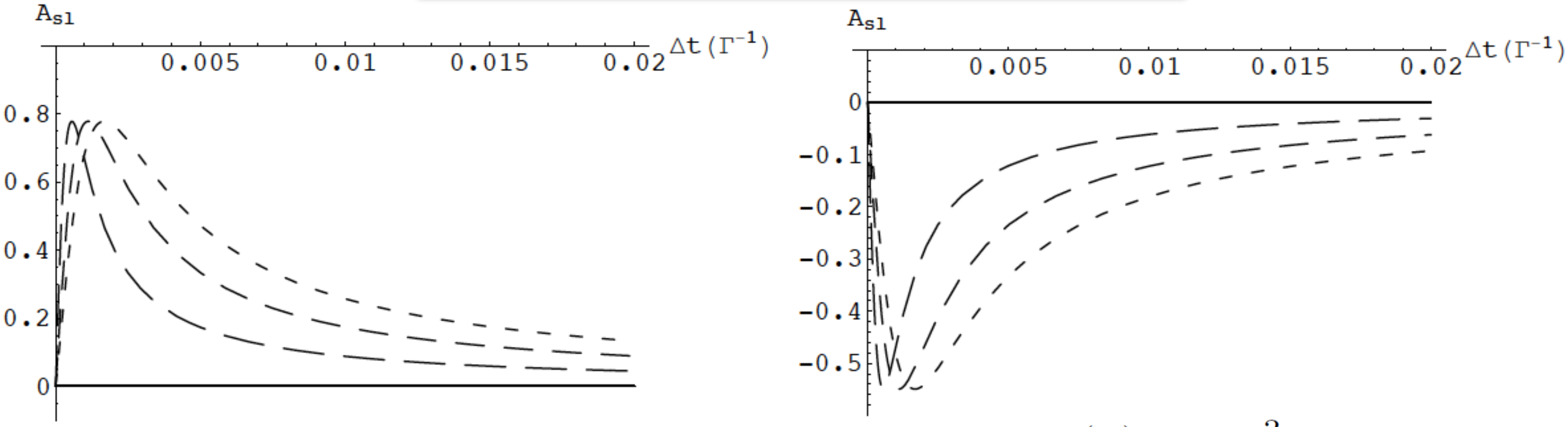
$$I(X\ell^{\pm}, X'\ell^{\pm}, \Delta t) = \frac{1}{8} e^{-\Gamma \Delta t} \, |A_X|^2 |A_{X'}|^2 \left| \frac{(1 + s_{\epsilon}\, \epsilon)^2 - \delta^2/4}{1 - \epsilon^2 + \delta^2/4} \right|^2$$

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

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

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

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

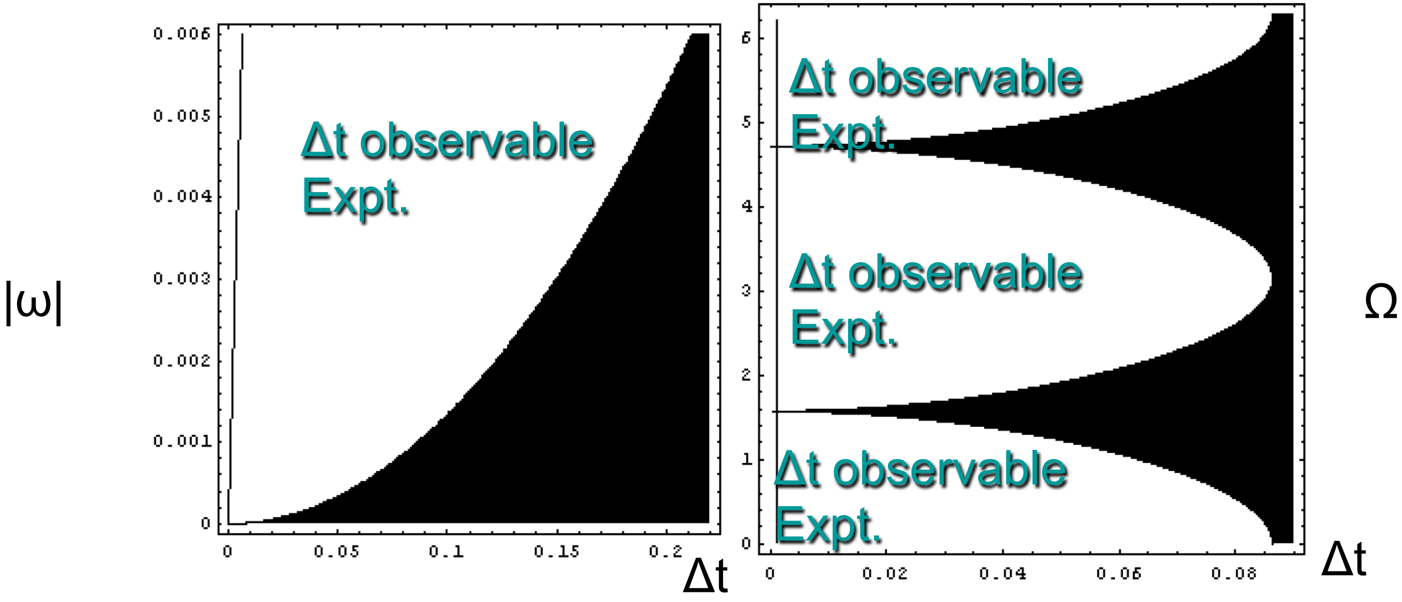


(a) $\Omega = 0$

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

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

Figure 2: Equal-sign dilepton charge asymmetry for different values of ω; $|\omega| = 0$ (solid line), $|\omega| = 0.0005$ (long-dashed), $|\omega| = 0.001$ (medium-dashed), $|\omega| = 0.0015$ (short-dashed). When $\omega \neq 0$ a peak of height $A_{sl}(peak) = 0.77\cos(\Omega)$ appears at $\Delta t(peak) = 1.12\,|\omega|\,\frac{1}{\Gamma}$, producing a drastic difference with the $\omega = 0$ case, in particular in its time dependence. Observe that the peak, independently of the value of $|\omega|$, can reach enhancements up to 10^3 times the value of the asymmetry when $\omega = 0$.



(a) $|\omega|$ *vs.* $\Delta t(\Gamma^{-1})$; for $\Omega = 0$ (b) Ω *vs.* $\Delta t(\Gamma^{-1})$; for $|\omega| = 0.001$

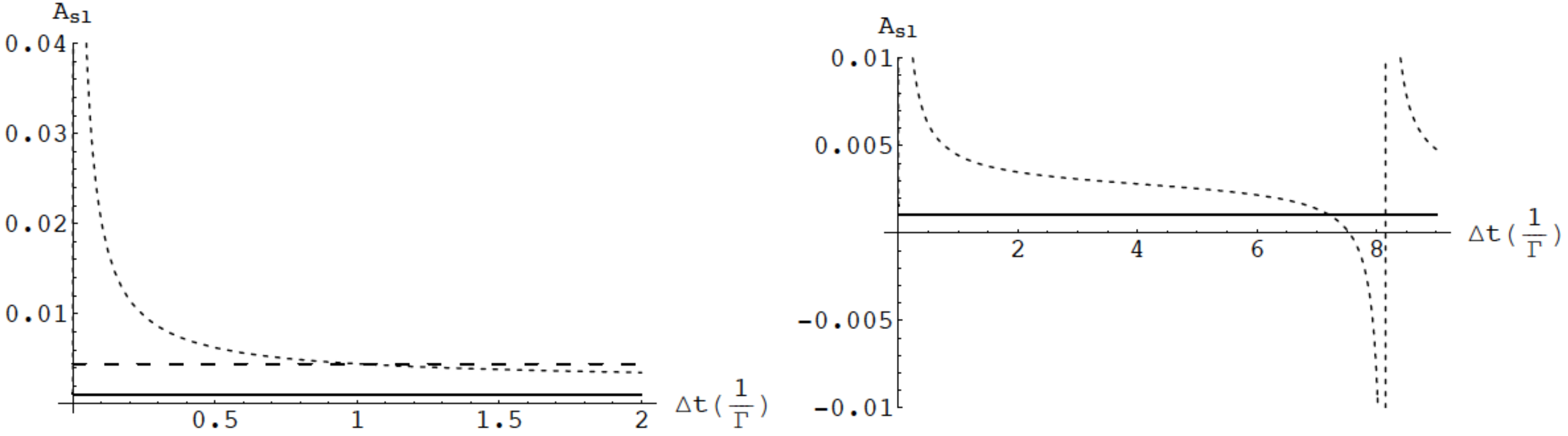
Figure 4: Contour curves for $\frac{1}{\Gamma}|dA_{sl}/d\Delta t| = 0.1$, the white area represents the points where $\frac{1}{\Gamma}|dA_{sl}/d\Delta t| > 0.1$, and hence the time variation would be (expected to be) experimentally detectable. Notice the tiny dark line on the left of each graph which represents the first peak of the asymmetry, where of course the derivative also goes to zero. Fig. (a) plots $|\omega|$ *vs.* Δt for a fixed $\Omega = 0$, observe that although to see the peak in A_{sl} a very high Δt-resolution is required, the region where the time variation is detectable might be more accessible experimentally. Fig. (b) plots the phase Ω *vs.* Δt for a fixed value of $|\omega| = 0.001$, note that disregarding the values of the phase around $\pi/2$ and $3\pi/2$, the measurable region (white) is quite favoured in Δt.

EXPERIMENTAL LIMITS circa 2005

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

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

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



(a)

(b)

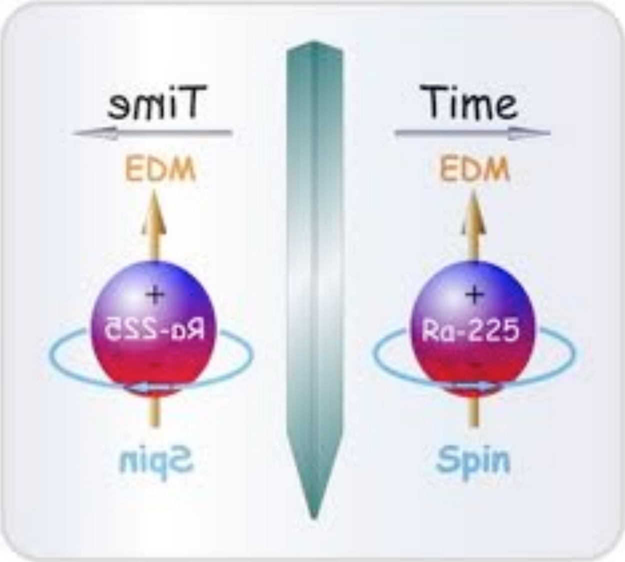
Region where asymmetry is quasi-independent but ω-effect shifted

Asymmetry plotted in the range including Δm Δt ~ 2π → **second peak** due to **quasi periodicity**

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

Dominant terms for long Δt > 1/Γ

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

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

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

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

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

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

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

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

Banuls, Bernabeu (1999)

Bernabeu, di Domenico,
Villanueva-Perez 2012

Bernabéu, Botella, Nebot
JHEP 1606, 100 (2016)

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

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

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

Relevance to antiprotonic atoms? preliminary ideas…

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

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

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?

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 ⇒ initial state:

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

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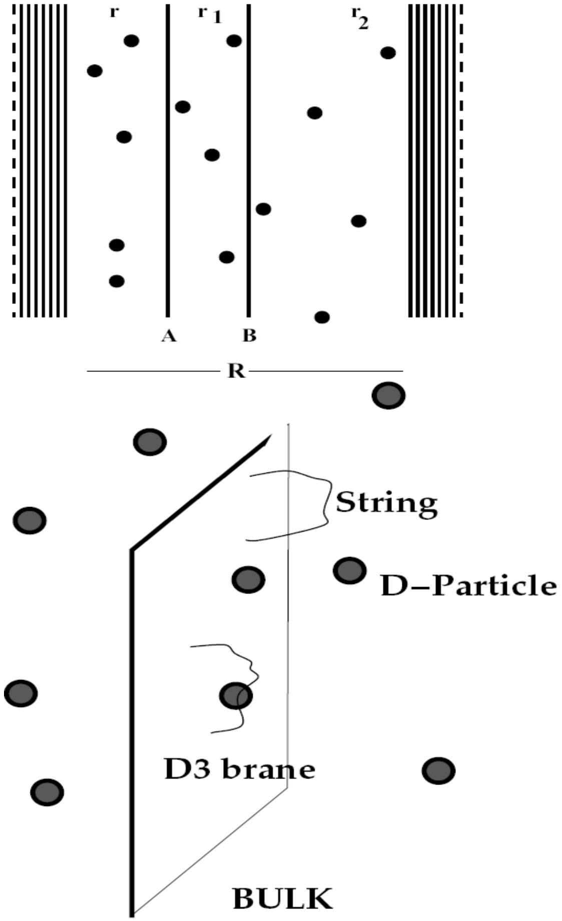

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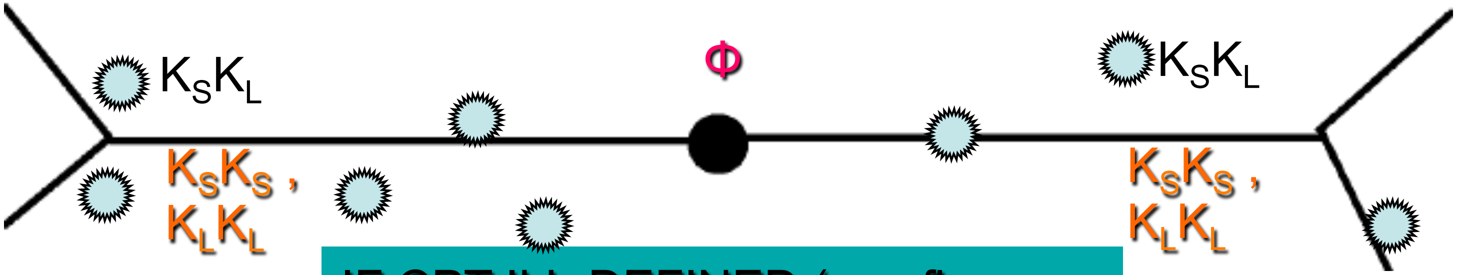
- Neutral mesons **no** longer **indistinguishable** particles, initial entangled state:

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

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



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

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

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: **| ω | ~ 10^{-4} |ζ|,** for 1 > |ζ| > 10^{-2} (natural)
Not far from sensitivity of upgraded meson factories (e.g. **KLOE2**)

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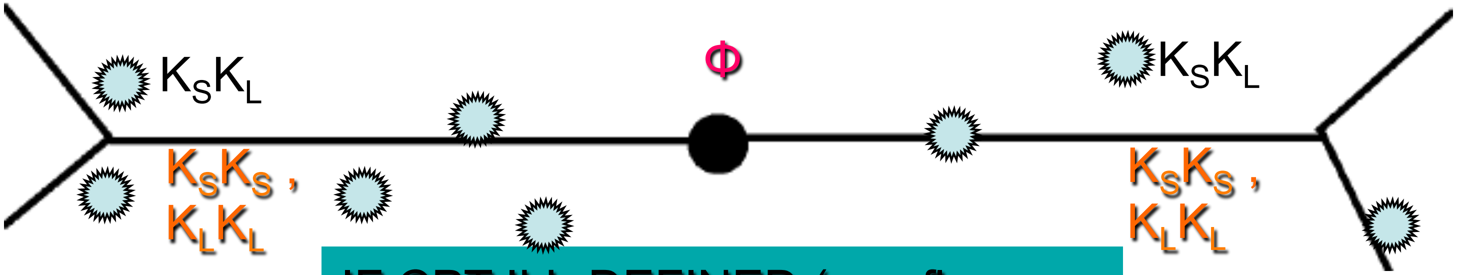

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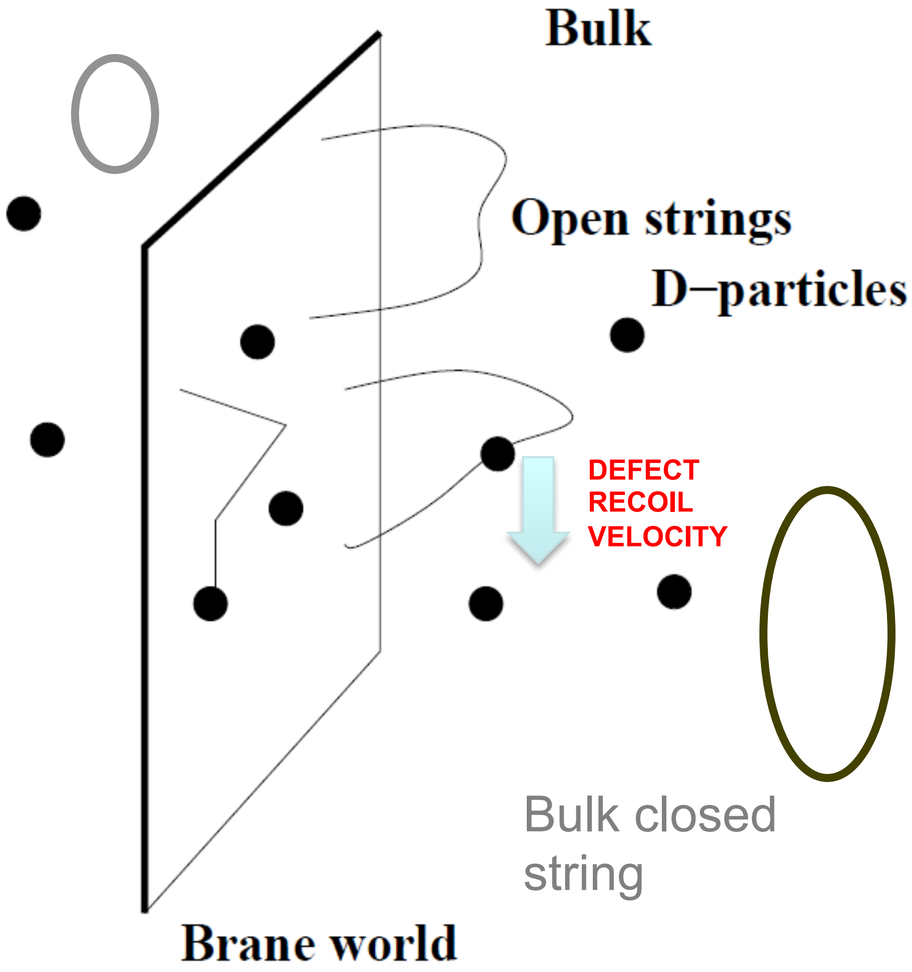
(

- A THEORETICAL MODEL OF SPACE-TIME FOAM INSPIRED FROM NON-CRITICAL STRING THEORY

D-PARTICLE (D0-BRANE) FOAM

(Ellis, NM, Westmuckett, Nanopoulos, Sarkar)

D-particle Foam Models



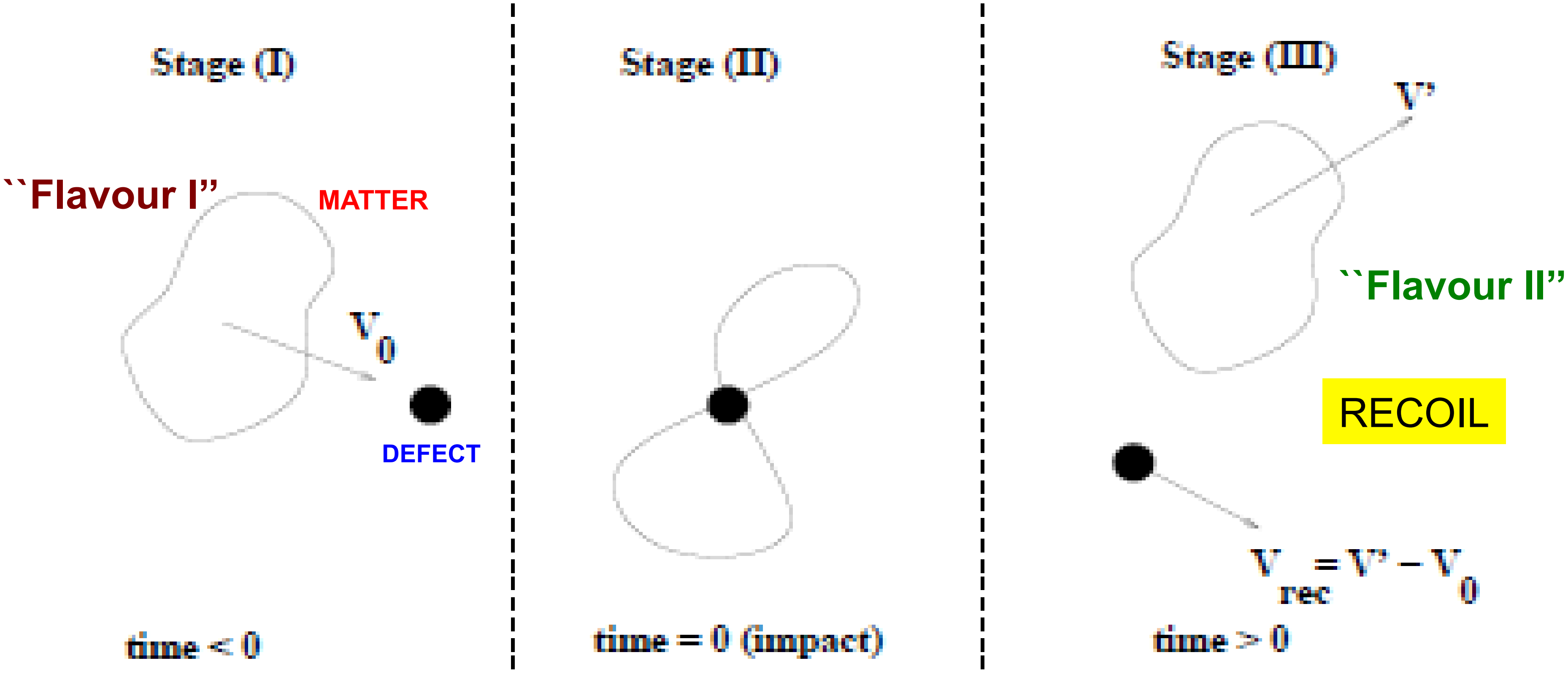
Consistent supersymmetric D–particle foam models can be constructed

No recoil, no brane motion= zero vacuum energy, unbroken SUSY

recoil contributions to vacuum energy

Broken SUSY

D-particle Recoil & LIV models



``Flavour I”

MATTER

DEFECT

``Flavour II”

RECOIL

Logarithmic conformal field theory describes the impulse at stage (II)

D-particle Recoil & the ω-effect

Not all particle **species** interact the **same way with D-particles** e.g. electric charge symmetries should be preserved, hence **electrically-charged excitations cannot split and attach to neutral D-particles….**

Neutrinos (or neutral mesons) are good candidates…

But there may be flavour oscillations during the capture/recoil process, i.e. wave-function of recoiling string might differ by a phase from incident one….

In statistical populations of D-particles, one might have isotropic situations, with recoil velocity $<< u_i >> = 0$, but stochastically fluctuating $<< u_i u^i >> \neq 0$.

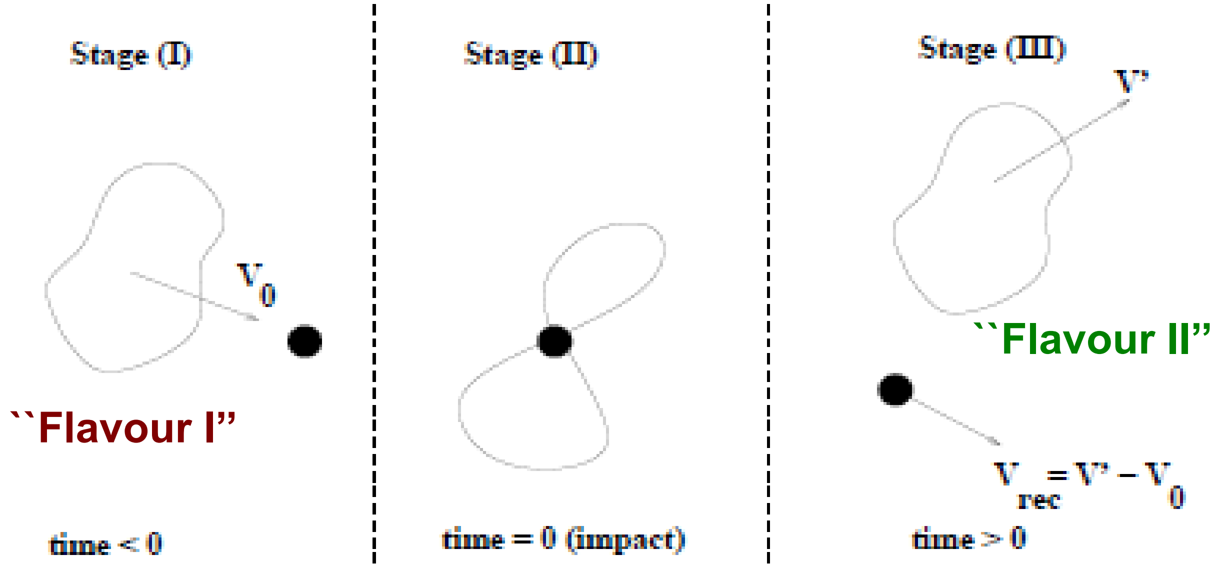
Metric distortion due to recoil/capture – Propagation in curved (fluctuating) space-time

$$\boxed{g_{0i} \propto u_i = \Delta k_i / M_P \otimes (\mathrm{flavour-flip})}$$

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

momentum transfer

D-particle Recoil & the ω-effect



Logarithmic conformal field theory describes the impulse at stage (II)

For neutral mesons: Consider Klein-Gordon in curved background due to recoil-induced metric distortions with two “flavours’ ’ corresponding to mass eigenstates, e.g. for Kaons K_L , K_S .

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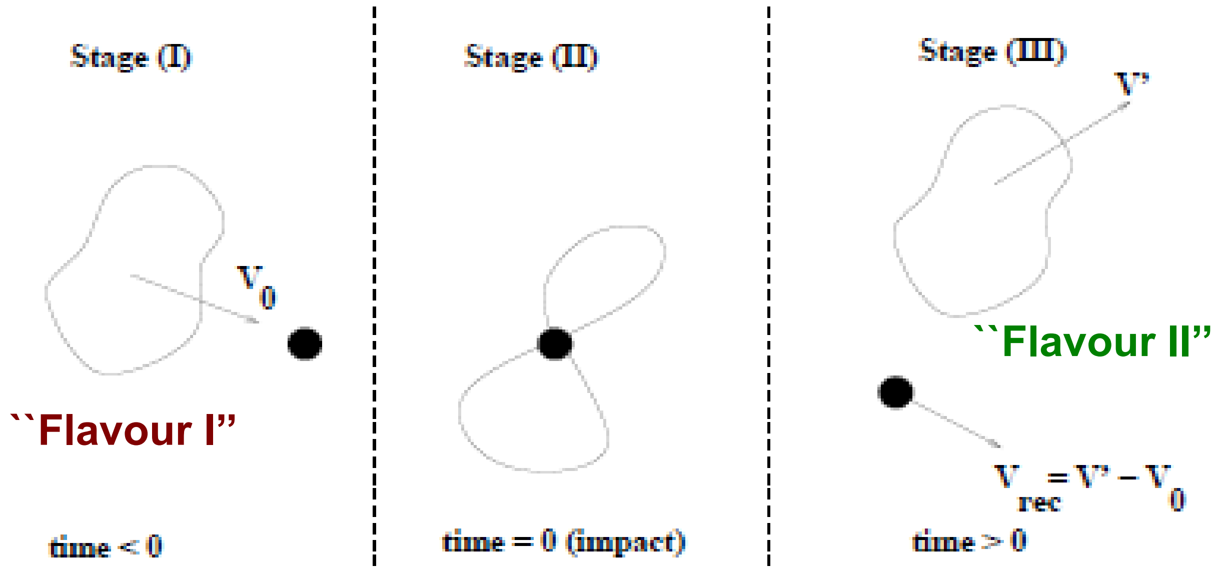

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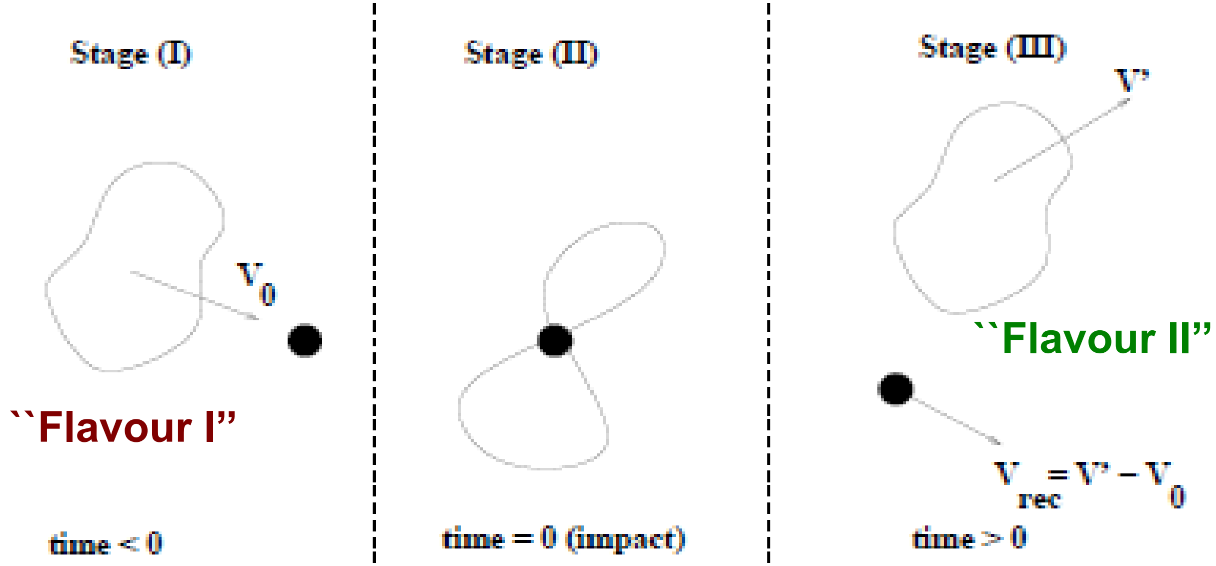

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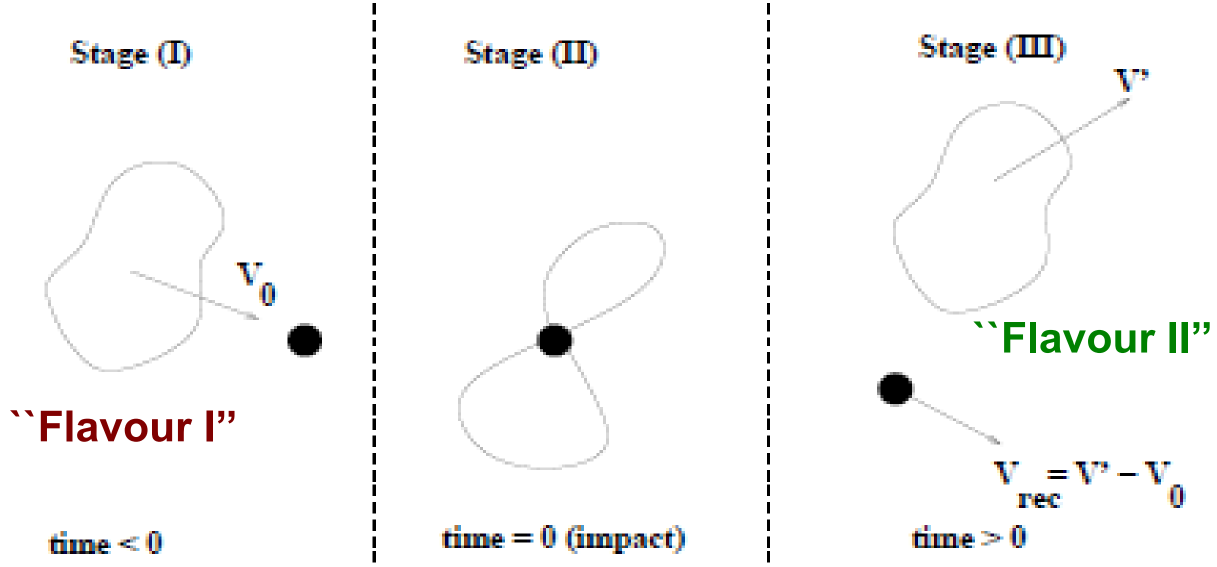
$$g^{01} = g^{10} = r_0 1 + r_1 \sigma_1 + r_2 \sigma_2 \qquad u_i \Longrightarrow \frac{r}{M_P}\widehat{p}$$

$$\text{mass matrix } m = \tfrac{1}{2}(m_1 + m_2)\,1 + \tfrac{1}{2}(m_1 - m_2)\,\sigma_3$$

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

D-particle Recoil & the ω-effect



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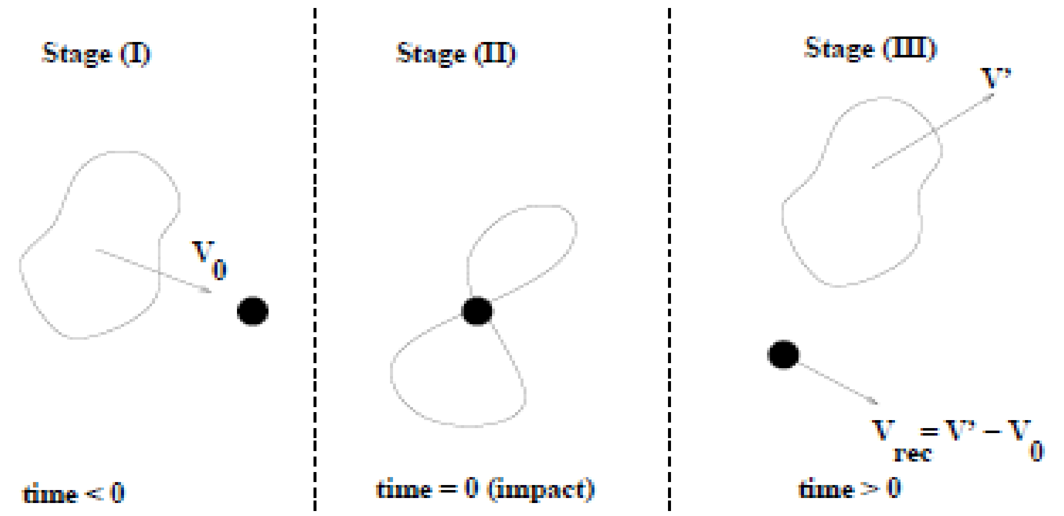
For slow recoiling heavy D-particles the resulting Hamiltonian, expressing interactions of neutrinos (or "flavoured" particles, including oscillating neutral mesons), reads:

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

$$g^{01} = g^{10} = r_0 1 + r_1\sigma_1 + r_2\sigma_2 \quad \Longrightarrow \quad \widehat{H_I} = -\left(r_1\sigma_1 + r_2\sigma_2\right)\widehat{k}$$

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

$$\Delta_\mu \sim O\left(\frac{E^2}{M_P^2}\right)$$



Logarithmic conformal field theory describes the impulse at stage (II)

NB: direction of recoil dependence LIV ….+ Stochastically flct. Environment **Decoherence, CPTV ill defined…**

In statistical populations of D-particles, one might have isotropic situations, with $\langle\langle u_i \rangle\rangle = 0$, but stochastically fluctuating $\langle\langle u_i u^i \rangle\rangle \neq 0$.
For slow recoiling heavy D-particles the resulting Hamiltonian, expressing interactions of neutrinos (or "flavoured" particles, including oscillating neutral mesons), reads:

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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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FLAVOUR FLIP

Perturbation due to recoil distortion of space-time

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

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

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$$\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)}
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ω-effect

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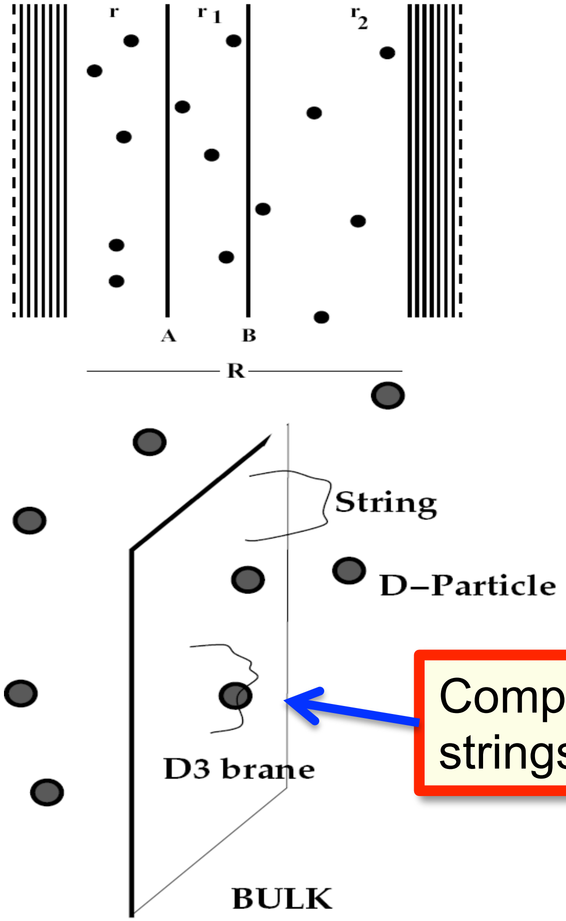
ω-effect

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



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

ω-effect as discriminant of space-time foam models

Bernabeu, NM, Sarben Sarkar

- ω-effect *not generic*, depends on *details* of *foam*

Initially dressed states → depend on form of interaction Hamiltonian H_I → (non-degenerate) perturbation theory → determine existence of ω-effects

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

features: ***direction of k violates Lorentz symmetry,*** *flavour non conservation* → **non-trivial ω-effect**

(II) Quantum Gravity Foam as "thermal Bath'' (Garay)

$$\mathcal{H} = \nu a^\dagger a + \frac{1}{2}\Omega\sigma_3^{(1)} + \frac{1}{2}\Omega\sigma_3^{(2)} + \gamma\sum_{i=1}^{2}\left(a\sigma_+^{(i)} + a^\dagger\sigma_-^{(i)}\right)$$

→ **no ω-effect**

"atom''

(matter) frequency

Bath frequency

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(III) **ω-effect in early Universe & matter-antimatter asymmetry?** ... to explore

)

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

- QUANTUM GRAVITY DECOHERENCE MAY LEAD TO ILL-DEFINED CPT OPERATOR →
- NON-TRIVIAL EFFECTS ON SPIN-STATISTICS THEOREM→ VIOLATION OF PAULI EXCLUSION PRINCIPLE
- ω-effect in entangled neutral meson states – "smoking gun evidence of this type of CPTV

- Concrete examples from string/brane theory early universe ω-effect & baryon-asymmetry

  …**to explore**

….LOOKING FORWARD TO EXCITING NEW RESULTS FROM EXPERIMENTS LIKE KLOE2, VIP2

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  SPIN-S
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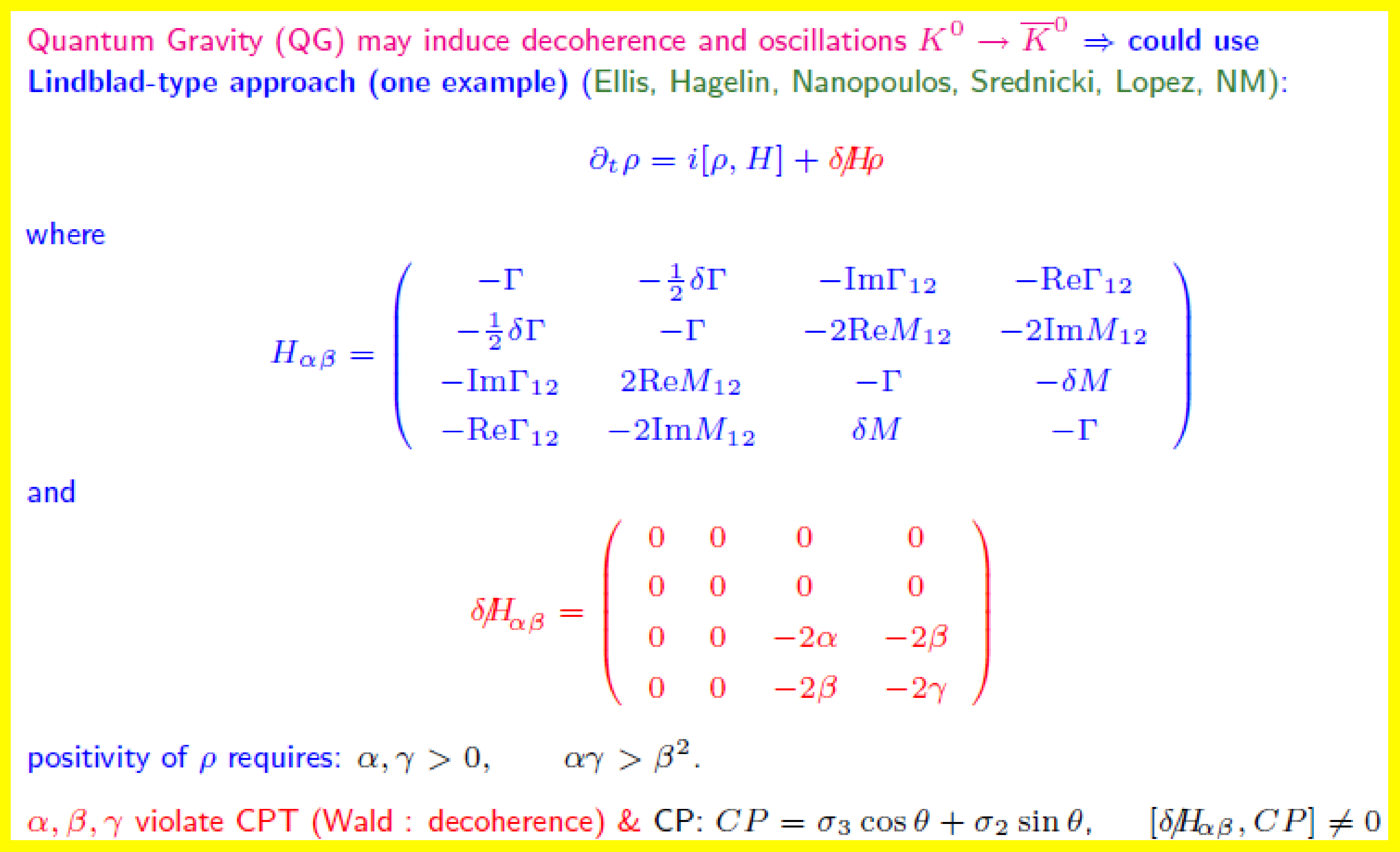
THANK YOU !

THANK YOU !

SPARES

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):

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

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

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

Neutral Kaon Entangled States

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