DISCRETE2010
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T and CPT SYMMMETRIES in ENTANGLED NEUTRAL MESON SYSTEMS

VNIVERSITAT DE VALÈNCIA

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

José Bernabéu, IFIC-Valencia

OUTLINE

- Symmetries in the Laws of Physics
- Universe t-Asymmetry, the “Arrow of Time”
- Can TRV be searched in unstable system?
- EPR-Entanglement: CP-Tag
- Genuine Observables in B-factories: not needing ΔΓ
- CPV, TRV, CPTV Asymmetries
- Monte Carlo Study for TRV: Significance of Asymmetries
- Genuine Asymmetries in Φ-factory
- The ω-effect: $K^0 \to \overline{K}^0$ Identity?
- Observables and Measurements of ω-effect
- Conclusions, Outlook

SYMMETRIES IN THE LAWS OF PHYSICS

- "Microscopic" Symmetry Violations.
- T-Violation exists in the Standard Model or any field theoretic extension.
- All field theories with Lorentz invariance have CPT symmetry

⇨ Automatic connection between CP-violation ⟷ related T-violation

- T and CPT described by ANTIUNITARY rather than unitary operators, introducing many intriguing subtleties.

⇨ Observed CP-Violation ⟹ T should be violated as well: Is it observed?

T - Violation means Asymmetry under

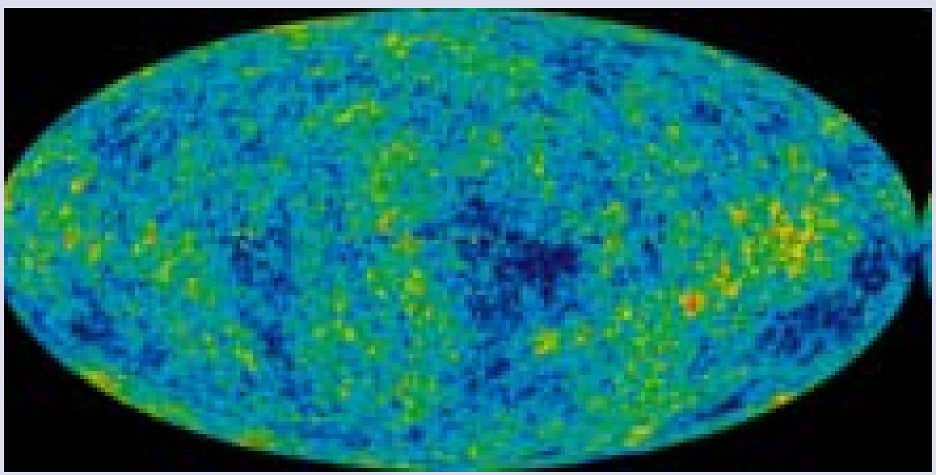
Interchange in ⇆ out states

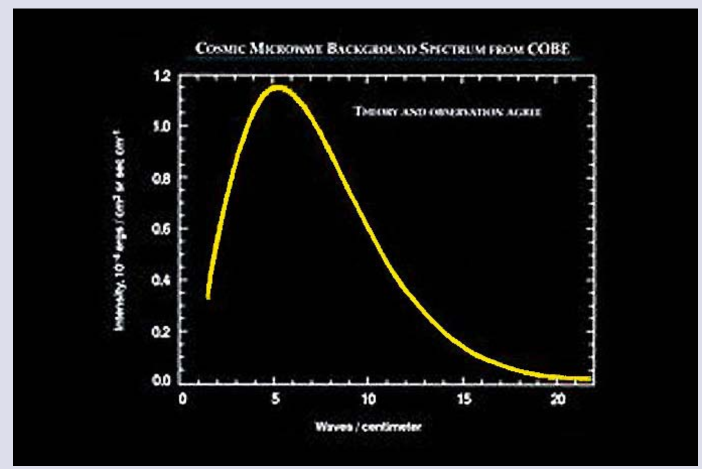
- Effects in particle physics odd under t ⇆ -t are <u>not</u> necessarily T-violating.
- t- asymmetries can occur in theories with exact T- symmetry.

UNIVERSE t - ASYMMETRY

- No doubt Universe is expanding, even accelerating → asymmetry t ⇆ -t
- BUT this is perfectly compatible with laws of physics that are TR symmetric
- This t-asymmetry is due to the initial condition of <u>our</u> Universe → Inflation?
- Similar to the fact that in <u>our</u> Universe we have a privileged reference frame

  ↔ CMB radiation with same temperature





- BUT this is not a violation of Lorentz invariance of the laws of physics

THE "ARROW OF TIME"

- Macroscopic t-asymmetry

- Nature of Thermodynamics ⟶ (Eddington)

Time's Arrow is a property of ENTROPY alone

Time is asymmetric with respect to the amount of order in an isolated system.

- Unsolved problem?

Is quantum wave function collapse related to the thermodynamic arrow of time?

- In particle physics,

Particle <u>Decay</u> is an example of a time-asymmetric process:

The mismatch between the <u>preparation</u> of P ⟶ 1 +…+ n and 1+…+n ⟶ P is <u>not</u> related to T-violation. In fact, it looks like it prevents a true test of T-symmetry in unstable systems [Wolfenstein]

- Any connection between the Universe t-asymmetry and the "arrow of time"? Probably YES, saying that the initial condition was improbable: more ordered.

- But none of these t-asymmetries is a test of TRV

CAN TR BE TESTED IN UNSTABLE SYSTEMS?

➢ A direct evidence for TRV would mean an experiment that, considered by itself, clearly shows TRV INDEPENDENT and unconnected to the results for CPV

➢ No existing result up to now clearly demonstrates TRV in this sense.

Two types of experiments:

1) A non-zero expectation value of a T-odd operator for a non-degenerate stationary state $\longrightarrow$ Electric Dipole Moment: P-odd, C-even, T-odd [Semertzidis]

It can be generated by either

- Strong T-violation $\longrightarrow$ θ-term $\epsilon_{\mu\nu\varsigma\sigma}$ $F^{\mu\nu} F^{\varsigma\sigma}$ [Peccei & Quinn], or
- Weak T-violation

2) in $\leftrightarrows$ out: $S_{f,i} \longrightarrow S_{-i,-f}$ transition.

[Sozzi] The Kabir asymmetry $K^0 \to \overline{K}^0$ vs. $\overline{K}^0 \to K^0$ has been measured in CP-LEAR with non-vanishing value. But $K^0 \to \overline{K}^0$ is a CPT-even transition, so CP≡T here! This is apparent in that the effect is t-independent and proportional to ΔΓ

Is it possible to search for TRV in Mixing x Decay transitions?

NEUTRAL MESON FACTORIES

CAN TR BE TESTED IN UNSTABLE SYSTEMS? CP-TAG

- The opportunity arises [M.C. Bañuls, J.B.] from the quantum mechanical entanglement imposed by the EPR correlation: one can have SEPARATE tests of CP, T and CPT!

- This coherence between the orthogonal $B^0, \overline{B}^0$ states has been used for flavour tag:

$$|i\rangle = \frac{1}{\sqrt{2}}\left[B^0(t_1)\overline{B}^0(t_2) - \overline{B}^0(t_1)B^0(t_2)\right]$$

where the states 1 and 2 are defined by the time of their decay with $t_1 < t_2$ .The observation of $B^0 \rightarrow l^+$, for example, at time t_1, tells us that the complementary (still living) state is $\overline{B}^0$ at t_1 and, since t_1, single state evolution.

- BUT the INDIVIDUAL STATE of each neutral meson is NOT DEFINED BEFORE its collapse as a filter imposed by the observation of the decay of its companion!

- One can rewrite |i> in terms of any other pair of orthogonal states of the individual neutral B-mesons:

Consider B_+ and B_-, where B_- is filtered by the decay $J/\Psi\ K_+$, K_+ being the neutral K-meson decaying $K_+ \rightarrow \pi\pi$, and B_+ is the orthogonal to B_-, not connected to $J/\Psi\ K_+$.

We may call the filter imposed by a first observation of one of these decays a "CP-tag", although $B_\pm$ are not CP-eigenstates of B's necessarily.

GENUINE OBSERVABLES NOT NEEDING ΔΓ

- The same entangled state of the system can be rewritten

$$|i\rangle = \frac{1}{\sqrt{2}}\left[B_+(t_1)B_-(t_2) - B_-(t_1)B_+(t_2)\right]$$

- We may proceed to a partition of the complete set of events into four categories, defined by the tag in the first decay at t_1: $B_+ , B_- , B^0 \; or \; \overline{B}^0$ so we have 8 different Decay-Intensities at our disposal as functions of $\Delta t = t_2 - t_1 \rangle 0$

- Each of these 8 processes

$$\mathrm{I}_i(\Delta t) \sim e^{-\Gamma \Delta t}\{ C_i \cos(\Delta m \Delta t) + S_i \sin(\Delta m \Delta t) + \mathrm{C'}_\mathrm{i} \cosh(\Delta\Gamma \Delta t) + S'_i \sinh(\Delta\Gamma \Delta t) \}$$

- Careful: Up to now, for CPV analyses in B-factories, BABAR & BELLE have assumed CPT-invariance and $\Delta\Gamma = 0$:

⇒ A "theorem": Then Δt ⇆ -Δt exchange, which is NOT TR-operation, becomes equivalent to TR -> CP-odd ~ T-odd ~ Δt-odd.

⇒ Only 2 independent Intensities to be compared, if CP ~T ~Δt are connected.

GENUINE OBSERVABLES NOT NEEDING ΔΓ

- 1) Take $B_0 \rightarrow B_+$ as the Reference transition and call (X,Y) the observed decays at times t_1 and t_2. The CP, T and CPT transformed transitions are

Transition	$B^0 \rightarrow B_+$	$\overline{B}^0 \rightarrow B_+$	$B_+ \rightarrow B^0$	$B_+ \rightarrow \overline{B}^0$
(X,Y)	(l^-,$J/\Psi K_L$)	(l^+,$J/\Psi K_L$)	($J/\Psi K_S$, l^+)	($J/\Psi K_S$, l^-)
Transformation	Reference	CP	T	CPT

Exercise: Check that the 4 processes are experimentally independent and that Δt-exchange (in the same experimental "sample") X ⇆ Y is NOT in the Table

- 2)Take $B^0 \rightarrow B_-$ as the Reference transition. The CP, T and CPT transformed transitions are

Transition	$B^0 \rightarrow B_-$	$\overline{B}^0 \rightarrow B_-$	$B_- \rightarrow B^0$	$B_- \rightarrow \overline{B}^0$
(X,Y)	(l^-,$J/\Psi K_S$)	(l^+,$J/\Psi K_S$)	($J/\Psi K_L$, l^+)	($J/\Psi K_L$, l^-)
Transformation	Reference	CP	T	CPT

⇨ A second Asymmetry for each of the 3 transformations can be built!

- 3) Select (Y,X) from 1) as Reference.
- 4) Select (Y,X) from 2) as Reference.
- Only QM EPR-Entanglement assumed.

⇨ 4 Model-Independent Asymmetries for CP

$\oplus$

4 Model-Independent Asymmetries for T

GENUINE CPV-ASYMMETRIES

$$A_{CP,1} = \frac{\Gamma\left(l^-, J/\Psi K_L\right) - \Gamma\left(l^+, J/\Psi K_L\right)}{+}$$

$$A_{CP,2} = \frac{\Gamma\left(l^-, J/\Psi K_S\right) - \Gamma\left(l^+, J/\Psi K_S\right)}{+}$$

$$A_{CP,3} = \frac{\Gamma\left(J/\Psi K_L, l^-\right) - \Gamma\left(J/\Psi K_L, l^+\right)}{+}$$

$$A_{CP,4} = \frac{\Gamma\left(J/\Psi K_S, l^-\right) - \Gamma\left(J/\Psi K_S, l^+\right)}{+}$$

Δt ($A_{CP,1} \leftrightarrow A_{CP,3}$)

Δt ($A_{CP,2} \leftrightarrow A_{CP,4}$)

GENUINE TRV-ASYMMETRIES

$$A_{T,1} = \frac{\Gamma\left(l^{-}, J/\Psi K_{L}\right) - \Gamma\left(J/\Psi K_{S}, l^{+}\right)}{+}$$

Δt

$$A_{T,2} = \frac{\Gamma\left(l^{-}, J/\Psi K_{S}\right) - \Gamma\left(J/\Psi K_{L}, l^{+}\right)}{+}$$

$$A_{T,3} = \frac{\Gamma\left(J/\Psi K_{L}, l^{-}\right) - \Gamma\left(l^{+}, J/\Psi K_{S}\right)}{+}$$

Δt

$$A_{T,4} = \frac{\Gamma\left(J/\Psi K_{S}, l^{-}\right) - \Gamma\left(l^{+}, J/\Psi K_{L}\right)}{+}$$

GENUINE CPTV-ASYMMETRIES

$$A_{CPT,1} = \frac{\Gamma\left(l^-, J/\Psi K_L\right) - \Gamma\left(J/\Psi K_S, l^-\right)}{+}$$

Δt

$$A_{CPT,2} = \frac{\Gamma\left(l^-, J/\Psi K_S\right) - \Gamma\left(J/\Psi K_L, l^-\right)}{+}$$

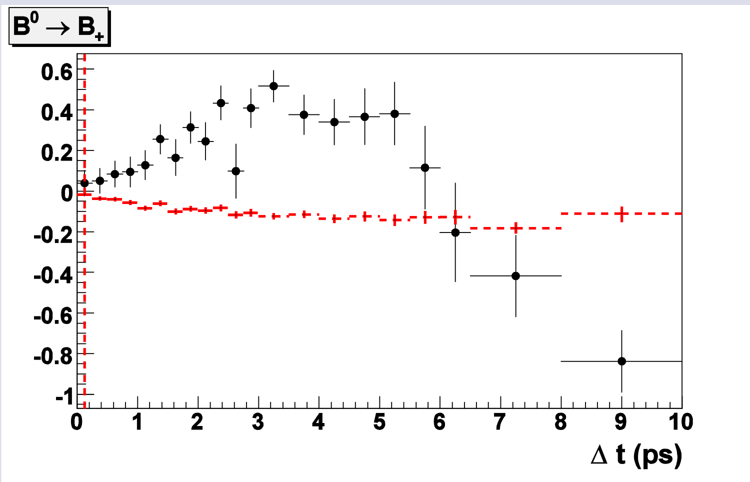
$$A_{CPT,3} = \frac{\Gamma\left(l^+, J/\Psi K_L\right) - \Gamma\left(J/\Psi K_S, l^+\right)}{+}$$

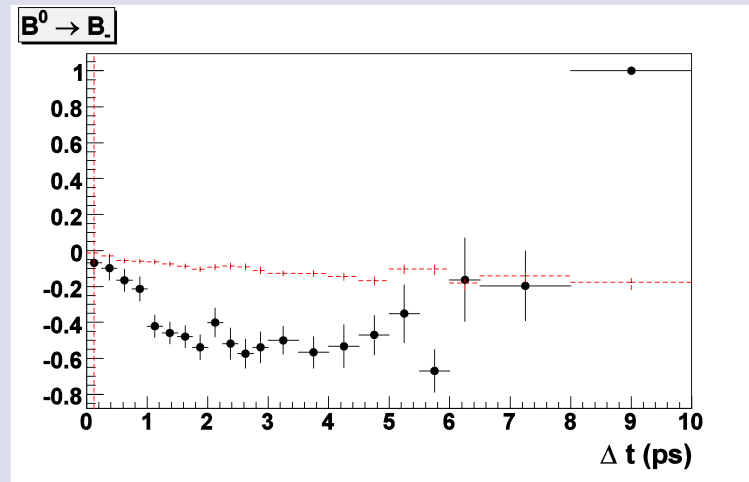
Δt

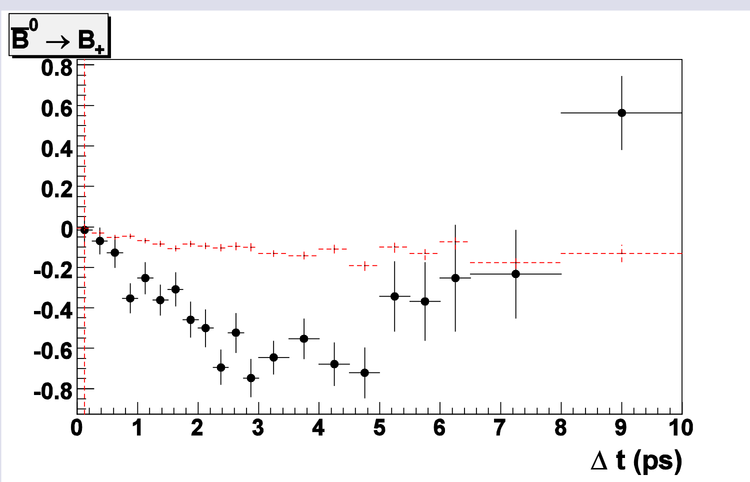
$$A_{CPT,4} = \frac{\Gamma\left(l^+, J/\Psi K_S\right) - \Gamma\left(J/\Psi K_L, l^+\right)}{+}$$

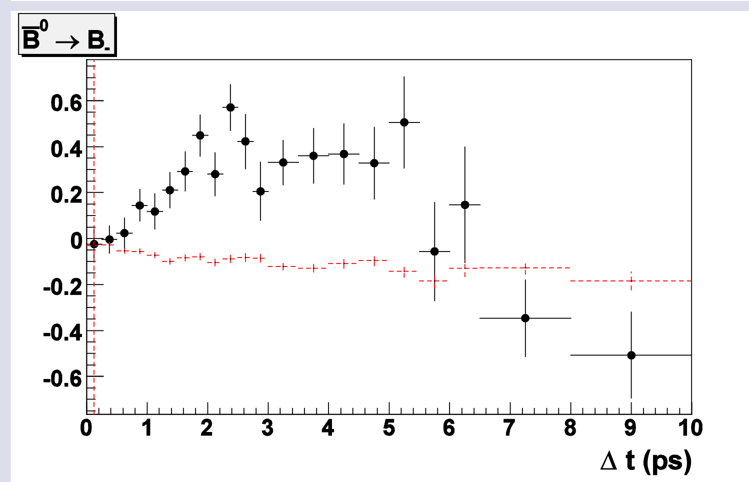
MONTE CARLO STUDY FOR TRV

➢Pablo Villanueva [see parallel session talk] has generated events with a PDF allowing CP, T & CPT violation parameters. The true value taken from Standard Model: CPT-symmetry, $\Delta\Gamma = 0$, $C_i = 0$, $S_i = \pm 0.672$ ($\sin 2\beta$). For A_T asymmetries, including proper-time resolution, mistags and efficiency effects (from BABAR published papers),









SIGNIFICANCE OF TRV ASYMMETRIES

➢ Each one of the 4 TRV-Asymmetries has an experimental significance obtained from a χ^2 test. One gets much more than 5 σ- effect !

TRV test	$B^0 \to B_+$	$B^0 \to B_-$	$\overline{B}^0 \to B_+$	$\overline{B}^0 \to B_-$
Standard Deviations	6.70	9.84	9.42	7.34

➢ The global significance could be obtained in the χ^2-test because, to first order, the four results are statistically independent.

Expected "guarantee" of a significant discovery for TRV ⟷ a fundamental result:

A first observation of true, direct evidence for genuine TRV by many σ's from zero, without any reference to, and independent of, CPV.

➢ Similar significances are expected for the Asymmetries testing genuine CPV independently

GENUINE ASYMMETRIES IN DAPHNE

- For $K^0 \to \overline{K}^0$, contrary to $B^0 \to \overline{B}^0$, the “physical” states of definite mass have $\Delta\Gamma \neq 0$, essentially $\Delta\Gamma$ -□Γ_S -□$2\Delta m$, so that the “theorem” is not valid: CP-odd is NOT Δt-odd.

- If K_+ is the neutral K-state filtered by the decay to 2π and K_- is its orthogonal state, the Master Table for the Φ-factory becomes

Reference	***CP***	***T***	***CPT***
$K^0 \to K_+$ $(l^-, 2\pi)$	$\overline{K}^0 \to K_+$ $(l^+, 2\pi)$	$K_+ \to K_0$ $(3\pi, l^+)$	$K_+ \to \overline{K}^0$ $(3\pi, l^-)$
$K^0 \to K_-$ $(l^-, 3\pi)$	$\overline{K}^0 \to K_-$ $(l^+, 3\pi)$	$K_- \to K_0$ $(2\pi, l^+)$	$K_- \to \overline{K}^0$ $(2\pi, l^-)$
$K_- \to \overline{K}^0$ $(2\pi, l^-)$	$K_- \to K^0$ $(2\pi, l^+)$	$\overline{K}^0 \to K_-$ $(l^+, 3\pi)$	$K^0 \to K_-$ $(l^-, 3\pi)$
$K_+ \to \overline{K}^0$ $(3\pi, l^-)$	$K_+ \to K^0$ $(3\pi, l^+)$	$\overline{K}^0 \to K_+$ $(l^+, 2\pi)$	$K^0 \to K_+$ $(l^-, 2\pi)$

Δt

Δt

- Experimental analyses of CP, T, CPT Asymmetries with DAΦNE data are going on [A.Di Domenico, P.Villanueva]

IS EPR-ENTANGLEMENT APPLICABLE?

- Proposed tests of separate CP, T, CPT symmetries based on EPR-Entanglement imposed by Particle Identity: $K^0, \overline{K}^0$ are two states of identical particles.
- The two states connected by C, so that C$\mathscr{P}$= + [$\mathscr{P}$: permutation operation].
- In neutral meson factories, $K^0 \to \overline{K}^0$ produced by Φ-decay: J=1, S=0 ➡

L=1➡C= - ➡ **$\mathscr{P}$= -, antisymmetric wave function** ⟷

Time evolution (including the Mixing $K^0 \to \overline{K}^0$) preserves $K^0\overline{K}^0$ terms only.

⇨ Perfect for tagging: Flavour-Tag, CP-Tag,…

- **What if the $K^0, \overline{K}^0$ Identity is lost ?** [J.B. , Mavromatos, Papavassiliou]

The two particle system would not satisfy the requirement C$\mathscr{P}$= +.

In perturbation theory, if still J=1, C=-,

$$|i\rangle = |antisymmetric\rangle + \omega\,|symmetric\rangle \longrightarrow$$ **the ω-effect**

⇨ Time evolution: ω K^0K^0 terms ⟷ Demise of tagging

THE ω-EFFECT

➢ Loosing the $K^0, \overline{K}^0$ Identity…

➢ In some Quantum Gravity models, matter propagation in topologically non-trivial space-time vacua suffers a possible <u>loss of quantum coherence</u> or “decoherence”.

➢ Originated by space-time foam backgrounds? [Wheeler, Ellis et al.]

The matter quantum system is an open system, interacting with the “environment” of quantum gravitational d. o. f. ⟹ Apparent loss of unitarity for low-energy observers

⇨ Not a well-defined S-matrix between asymptotic states ⟹ The CPT-operator is NOT well-defined [Wald]

➢ It should be disentangled from the case of effective theories for Lorentz violation [Altschul], in which CPT breaking means $[H_{eff}, CPT] \neq 0$.

➢ The CPT “Violation” discussed here would be an “intrinsic” microscopic time irreversibility, so that $\overline{K}^0$ is not “well-defined” from K^0. It implies:

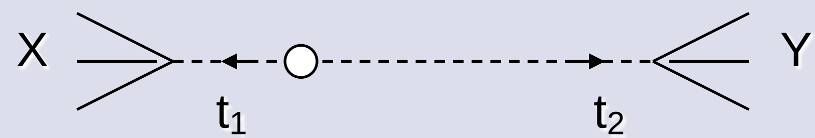
1) a modified single $K^0 \rightarrow \overline{K}^0$ evolution: α,β,γ parameterization [Lindblad].

2) for entangled Kaon states in a Φ-factory, **the ω-effect**

ω-EFFECT OBSERVABLES

[J.B., Mavromatos, Papavassiliou]

- Consider the Φ-decay amplitude



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

$$A_1 = e^{-i(\lambda_L+\lambda_S)t/2}\left[\eta_X e^{-i\Delta\lambda\Delta t/2} - \eta_Y e^{i\Delta\lambda\Delta t/2}\right]$$

$$A_2 = \omega\left[e^{-i\lambda_S t} - \eta_X\eta_Y e^{-i\lambda_L t}\right]$$

- Strategy: Choose a channel suppressed by η's: $X = Y = \bar{u}^+\bar{u}^-$, CP "forbidden"

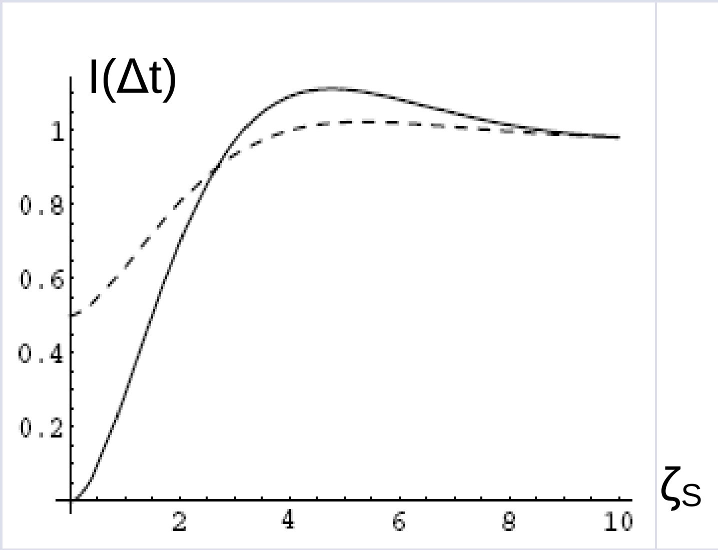
⇨ Enhanced effects ω/|η_{+-}|

- Intensity

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

$$for\ \ |\omega| = |\eta_{+-}|$$

$$\Omega = \phi_{+-} - 0.16\pi$$



MEASUREMENT OF ω-EFFECT

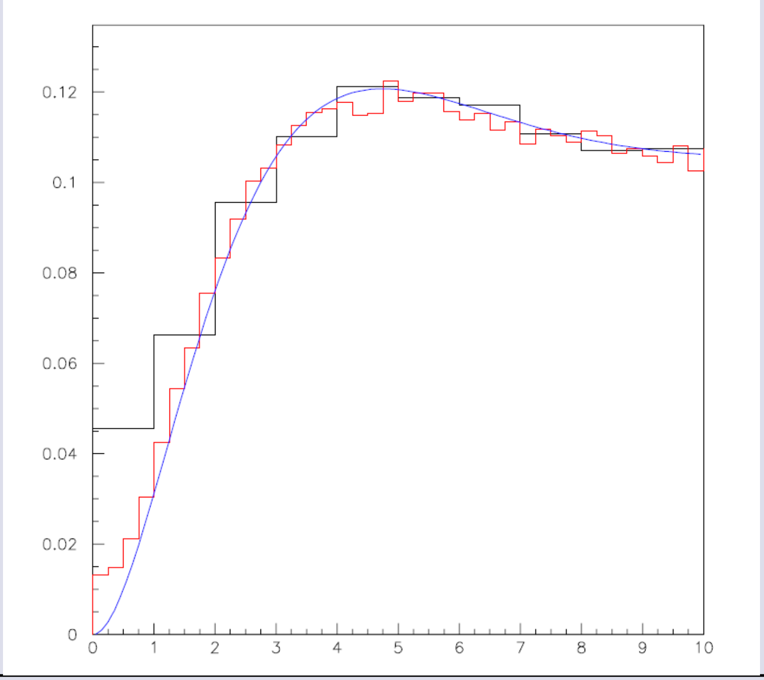
- KLOE [Di Domenico et al.] obtained the first measurement of the ω-parameter

$$\left.\begin{aligned} \mathrm{Re}(\omega) &= (-1.6\ ^{+3.0}_{-2.1\,stat} \pm 0.4_{syst})x10^{-4} \\ \mathrm{Im}(\omega) &= (-1.7\ ^{+3.3}_{-3.0\,stat} \pm 1.2_{syst})x10^{-4} \end{aligned}\right\}$$

$|\omega| < 1.0 \times 10^{-3}$ at 95% CL

- At least one order of magnitude improvement is expected with KLOE-2 at the upgraded DAΦNE.

- All decoherence effects, including the ω-effect, manifest as a DEVIATON from the QM prediction of the correlation I (π+π-,π+π-; Δt=0)=0. Hence the reconstruction of events in the region near Δt≈0 is crucial ⟷ vertex resolution.



[de Santis]Monte Carlo simulation of I(π+π-, π+π-; Δt), with the KLOE resolution $\sigma_{\Delta t} \approx \zeta s$ and with the expected KLOE-2 $\sigma_{\Delta t} \approx 0.3\ \zeta s$

- **In B-factories, there is no such a privileged channel.**

- With currently available data from BABAR and BELLE, the CPV semileptonic charge asymmetry, in equal sign dilepton channel I(l± l±; Δt), gives the bounds [Alvarez,J.B.,Nebot]

$$-0.0084 \le \mathrm{Re}(\omega) \le 0.0100 \text{ at } 95\%\text{CL}$$

ω-EFFECT FROM SPACE-TIME FOAM MODEL

- ω-effect: as the result of local distortions of space-time in the neighborhood of defects, interacting with matter [J.B., Mavromatos, Sarkar].
- Recoil of Planck-mass defect $\Longrightarrow$ metric deformation $g_{0i} \sim \Delta k^i / M_P = \zeta k^i / M_P$
- Lorentz invariance still holds macroscopically $< \zeta k^i > = 0$, but
- One has non-trivial quantum fluctuations $< \zeta^2 k_i k_j > \alpha\, \delta_{ij} \zeta^2 |\vec{k}|^2$
- Stochastic effects of the space-time foam $\rightsquigarrow$ $|\omega|^2 \sim \dfrac{\varsigma^2 |\vec{k}|^4}{M_P^2 \Delta m^2}$

  enhanced by quasi-degeneracy of mass eigenstates.
- At the DAΦNE energy, $|\omega| \sim 10^{-4}\ \zeta$, which lies within the sensitivity of KLOE-2 for not much small values of the momentum transfer fraction ζ.
- In some concrete string-theory-inspired models examined by [Mavromatos, Sarkar], $\varsigma \sim \sum m^2 / |\vec{k}|^2$.

CONCLUSION

- Observed t-Asymmetries are not T-violating:

  TRV means Asymmetry under in $\leftrightarrows$ out

- Unique opportunity for unstable systems: EPR-Entanglement between the two neutral mesons in B-, and Φ-, factories.

- Golden Channels $\longrightarrow$ 8 different Decay-Intensities.

In appropriate combinations,

4 Genuine independent Asymmetries for each: CP, T, CPT

- Monte Carlo study for TRV in B-factories $\longrightarrow$ more than 5 σ's in each of the 4 asymmetries $\Longrightarrow$

Expectation of a first observation of true TRV

- In QG models, S-matrix not well defined, CPT-operator not well defined

The ω-effect: Prefered channel in Φ-factory $\longrightarrow$ $I(\pi^+\pi^-, \pi^+\pi^-; \Delta t)$

- A sensitivity to $|\omega| \sim 10^{-4}$ at KLOE-2 not far from expectations in certain models of space-time foam.