SEPARATE T, CP, CPT ASYMMETRIES IN ENTANGLED NEUTRAL MESON TRANSITIONS

Cover page
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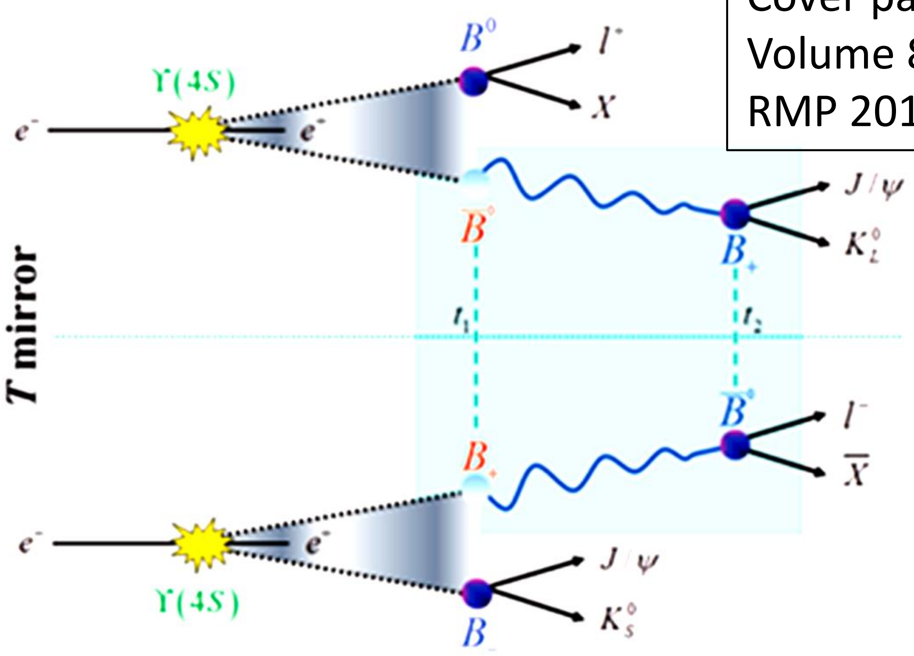

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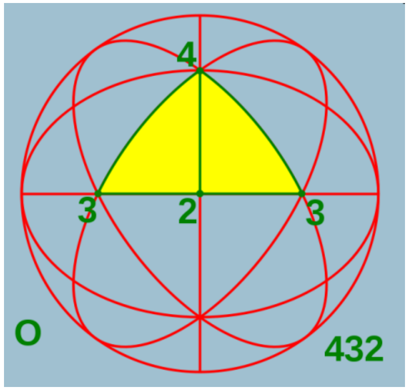
OUTLINE

- CRUCIAL ROLE OF SYMMETRY BREAKING IN FUNDAMENTAL PHYSICS
- CONCEPTUAL BASIS FOR T, CPT ASYMMETRIES IN UNSTABLE PARTICLE TRANSITIONS: **ENTANGLEMENT**
- **FILTERING IDENTITY**: CONNECTION BETWEEN THEORETICAL TRANSITION AND EXPERIMENTAL DOUBLE DECAY OF ENTANGLED MESONS
- GENUINE T, CP, CPT ASYMMETRIES IN B-PHYSICS
- PERSPECTIVES FOR K-PHYSICS
- CPT VIOLATION LIMITS
- THE CPT BREAKING ω – EFFECT WEAKENING ENTANGLEMENT
- MEASUREMENT OF ω FOR K'S AND B'S
- OUTLOOK

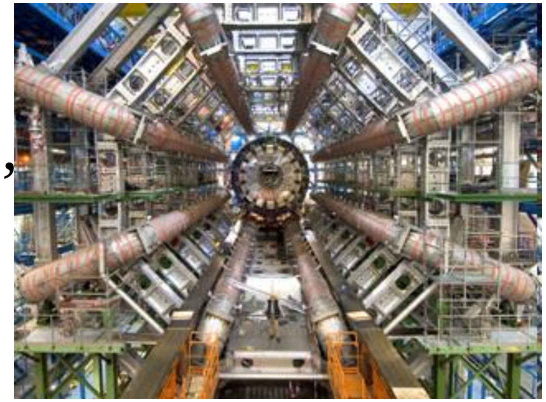
SYMMETRY OF OBJECTS

Characteristic feature of geometric forms,

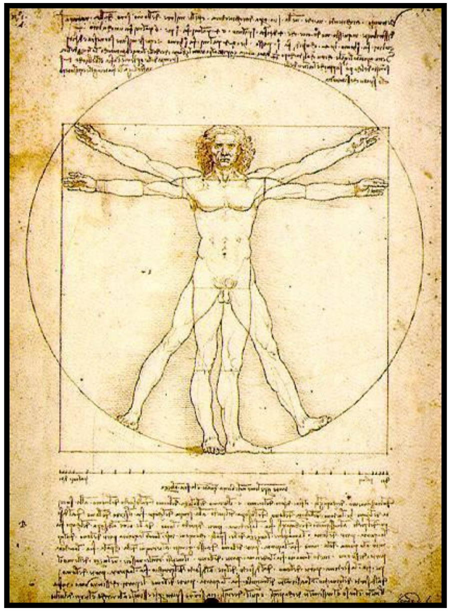


Symmetry Group of sphere

of material objects,



ATLAS experiment of LHC



Vitrubio, Leonardo da Vinci (1487)

of biological bodies,

related to their invariance under

definite transformations.

One object is symmetric if, after a transformation is applied, the result remains the same: it remains "invariant".

SYMMETRY BREAKING

This three-span arch, painted bright blue and orange, appears perfectly symmetric when viewed directly from below, but has a carefully calculated asymmetry from its other views.

The former Fermilab Director R.R. Wilson freely adopted the style of the sculptor A.Calder for giving an example of Symmetry and Symmetry Breaking, which are so important in the field of elementary particle physics.

SYMMETRIES IN THE LAWS OF PHYSICS

FUNDAMENTAL ROLE OF SYMMETRY BREAKING

- Gauge Symmetry Breaking → Origin of Mass (1964-2012)

- Parity PV → Fields of definite transformation properties under Gauge Group: CHIRAL FIELDS
  ⇒ Standard Model (1955 → 1957 →1962→ 1967 → 1973)

- CPV → 3 Families of Elementary Fermions ⇔ Mixing
  ⇒ Flavour Physics (1964-1973-2001)

- TRV → Antiunitary ⇔ $i \rightleftarrows f$ → "impossible" (?) for decaying particles …

BYPASS (1999→2012-?)
- Decay as Filtering of parent state ONLY
- Quantum Entanglement →information transfer to the orthogonal partner

---

- CPTV ? ⇒
  - Beyond QFT paradigm
  - Nothing in QM forbids CPTV

SYMMETRIES IN THE LAWS OF PHYSICS

- In Quantum Mechanics, there is an operator U_{CP} implementing the CP-symmetry acting on the states of the physical system, such that

$$U_C\, Q\, U_C^{+} = -Q,\; U_P\, \vec{r}\, U_P^{+} = -\vec{r},\; U_P\, \vec{p}\, U_P^{+} = -\vec{p},\; U_P\, \vec{s}\, U_P^{+} = \vec{s}$$

The operator U_{CP} is an observable with Conservation Laws: $K_L \to \pi\,\pi$

- The operator U_T implementing T-symmetry is such that

$$U_T\, \vec{r}\, U_T^{+} = \vec{r},\; U_T\, \vec{p}\, U_T^{+} = -\vec{p},\; U_T\, \vec{s}\, U_T^{+} = -\vec{s}$$

By considering the commutator $[r_j, p_k] = i\hbar\delta_{jk} I$ **the operator U_T must be**

ANTI-UNITARY: UNITARY- for conserving probabilities, ANTI- for complex conjugation

ANTIUNITARITY introduces many intriguing subtleties:

$$S_{i\to f} \xrightarrow{T} S_{U_T f \to U_T i}$$

T - Violation means Asymmetry under Interchange in ⟷ out states

- **Similarly for ANTIUNITARY CPT which needs not only in ⇆ out, but also $\mathrm{i,f} \to \bar{\mathrm{f}}, \bar{\mathrm{i}}$, in transitions.**

WORDING ⟷ PHYSICS

1) DIRECT Evidence of Symmetry Breaking (SB) →

- For CP: Violation of the Conservation Law
- For ALL CP, T, CPT: Comparison between a Reference process and its Symmetry Transformed in a single experiment.
- NOT by a Fit of parameters describing SB in a given Theoretical Framework

2) GENUINE Asymmetries →

- A set of Observables, for each Symmetry, in yes-no biunivocal correspondence with Symmetry Violation.
- NO Fake Terms or controlled in the same experiment.

3) SEPARATE T, CP, CPT Asymmetries →

- TRV INDEPENDENT of CPV or CPT invariance.
- DIFFERENT Information Content from DIFFERENT Transformed processes.

4) TRANSITION Processes →

- Interest in going beyond "Expectation Values" of SB.
- In 1st. order perturbation theory diagonal matrix elements vanish if Perturbation is odd under non-perturbed quantum numbers:

$$\langle + / - / + \rangle , \langle - / - / - \rangle = 0 \,!$$

Well known Examples { - Stark Effect in Atomic Physics
- TRV for e.d.m. in Particle Physics.

CONCEPTUAL BASIS FOR BYPASSING NO-GO

M. C. Banuls, J. B., PLB 1999, NPB 2000

- Neutral Mesons $K^0 - \bar{K}^0$, $B^0 - \bar{B}^0$ are UNSTABLE and the Decay is irreversible.
- **T and CPT, ANTIUNITARITY! , need however the exchange of initial and final states →NO-GO.**
  L. Wolfenstein, PRL 1999 : "The T-reverse of a decaying state is not a physical state".

- BYPASS → Do not include the Decay Products in your Asymmetry, write it in terms of Meson States and the Decay should not be an essential ingredient for getting a non-vanishing value:

1) Use the Decay as a **Quantum Filtering Measurement** of the Meson State ONLY: Orthogonal to Non-Decay State.

2) **Quantum ENTANGLEMENT Information Transfer** from the First Decay to the (still alive) orthogonal Partner for the Preparation of the initial Meson State: Non-Decay State.

3) The test of Symmetries is made in the Time Evolution of the Partner **from the first to the second decay**.
   L. Wolfenstein, IJMP E 1999: "It appears to be a true TRV Effect"

WHAT IS T-TRANSFORMATION EXPERIMENTALLY ?

The problem is in the preparation and filtering of the appropriate initial and final meson states for a T-test

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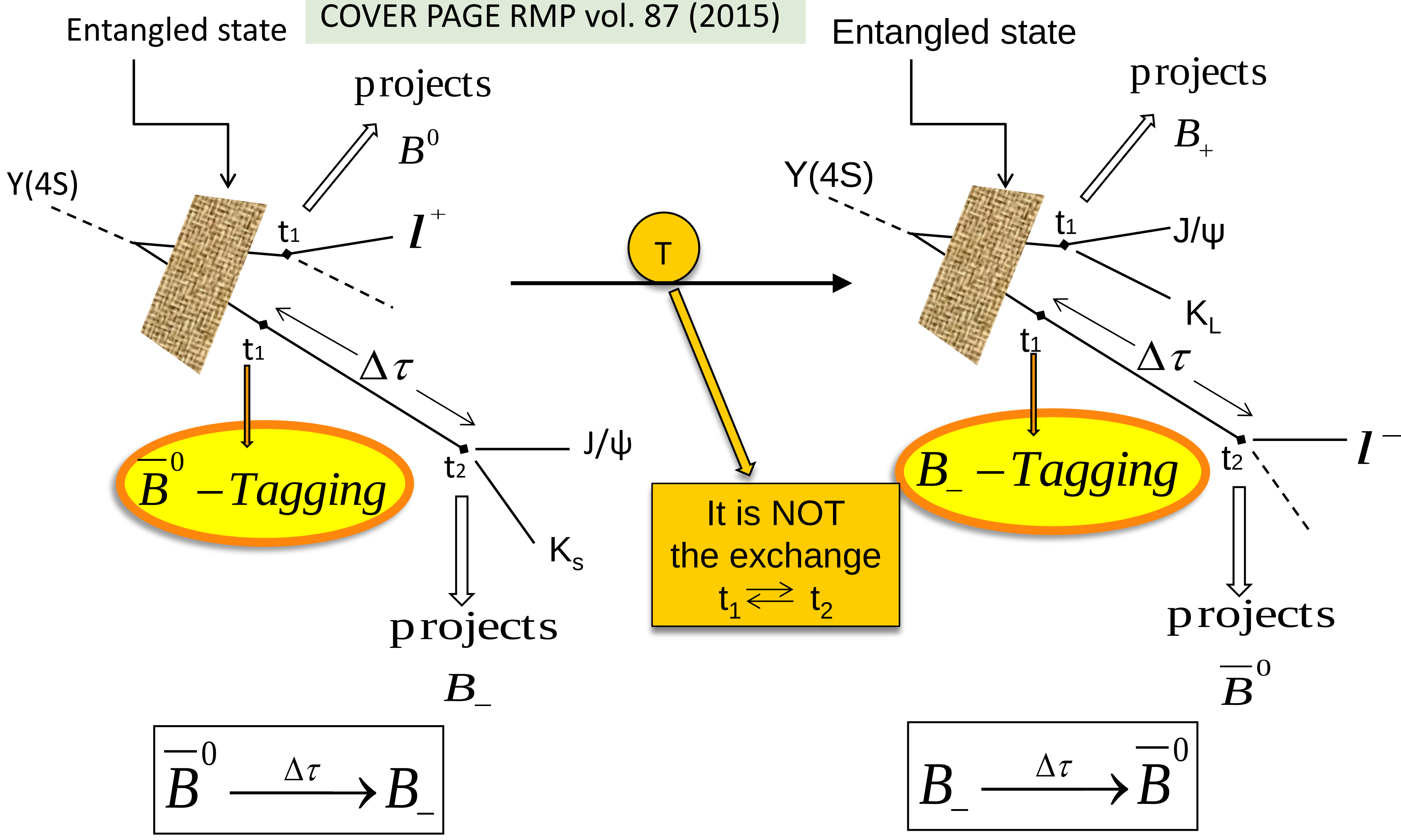


MESON TRANSITION PROBABILITY ⟺ DOUBLE DECAY RATE INTENSITY

- In a B factory operating at the Υ(4S) peak, our initial two-meson state is Einstein-Podolsky-Rosen entangled,

$$|\Psi_0\rangle = \frac{1}{\sqrt{2}}\left(|B_d^0\rangle|\bar{B}_d^0\rangle - |\bar{B}_d^0\rangle|B_d^0\rangle\right) = \frac{1}{\sqrt{2}(p_L q_H + p_H q_L)}\left(|B_L\rangle|B_H\rangle - |B_H\rangle|B_L\rangle\right),$$

which maintains its antisymmetric entangled character in the H eigenstate basis. This implies the **antisymmetric character of the two meson state at all times and for any two independent linear combinations of Entangled $\boldsymbol{B_d^0}$ *and* $\boldsymbol{\bar{B}_d^0}$.** The corresponding evolution before the first decay is therefore trivial for perfect Entanglement.

- Given a decay "f", the **Partner Meson** is tagged by

$$|B_{\nrightarrow f}\rangle = \frac{1}{\sqrt{|A_f|^2 + |\bar{A}_f|^2}}\left(\bar{A}_f|B_d^0\rangle - A_f|\bar{B}_d^0\rangle\right)$$

and the "filtered state" is its orthogonal

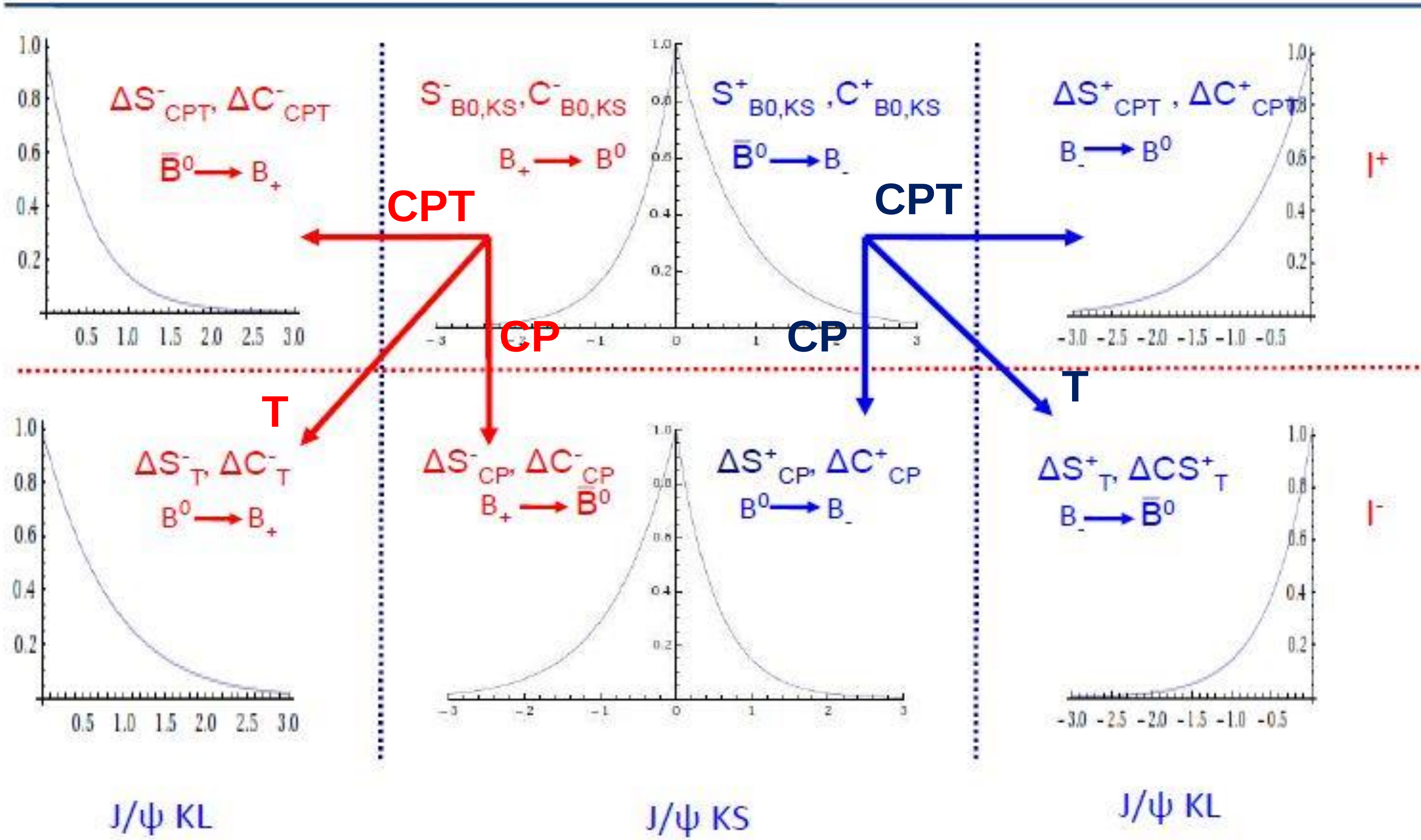
- The FILTERING IDENTITY establishes the **connection between the Meson Transition Probability and the experimental "reduced" Intensity**

$$\hat{I}(f,g;t) = \frac{|\langle g|T|B_{\nrightarrow f}(t)\rangle|^2}{|A_g|^2+|\bar{A}_g|^2} = |\langle B^{\perp}_{\nrightarrow g}|B_{\nrightarrow f}(t)\rangle|^2$$

- There are NO FAKE TERMS for a proof of Symmetry Breaking if the ratio of decay amplitudes $\bar{A}/A$ is a pure phase: $B_- \leftrightarrow J/\psi\ K_S$, $B_+ \leftrightarrow J/\psi\ K_L$. Controlled in the same experiment.

ΔS± , ΔC± ASYMMETRY PARAMETERS

$$I_i(\Delta t) \sim e^{-\Gamma\Delta t}\left\{ C_i \cos(\Delta m \Delta t) + S_i \sin(\Delta m \Delta t) + C'_i \cosh(\Delta\Gamma\Delta t) + S'_i \sinh(\Delta\Gamma\Delta t) \right\}$$



→ The Processes (f, g) and (g,f) exchanging the Time Ordering of the Decays are NOT CONNECTED BY A SYMMETRY OPERATION!

GENUINE T, CP, CPT ASYMMETRIES

J.B., F. Botella, M. Nebot, JHEP 1606 (2016) 100

- 3 different Observables ΔC_h, ΔC_c, ΔS_c for each symmetry

9 Asymmetry parameters with different information content

Using BABAR data PRL 2012, we obtain

$$\Delta S_c^T = -0.687 \pm 0.020\,; \quad \Delta S_c^{CP} = -0.680 \pm 0.021$$

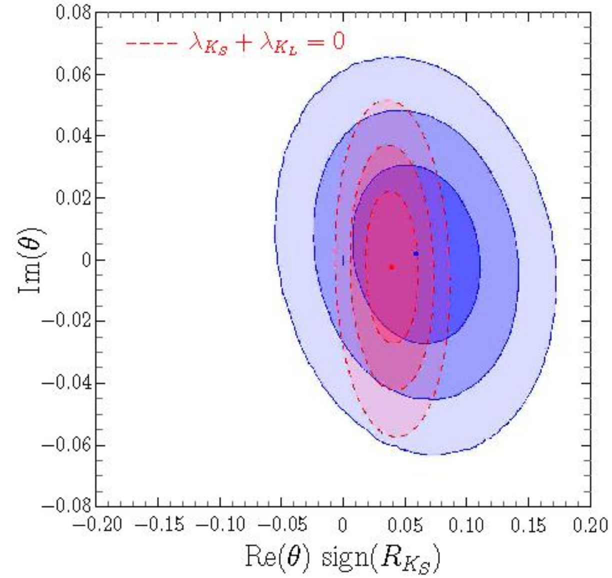
Impressive separate evidence of TRV, CPV

- "Intriguing" 2σ - effect for CPTV

$$\Delta C_c^{CPT} = -\Delta C_h^{CPT} = (2.7 \pm 1.5) \cdot 10^{-2}$$

interpreted in the evolution Hamiltonian

it should be seen in $\Delta C_c^{CP} = (5.0 \pm 1.5) \cdot 10^{-2}$ at LHCb: **Unorthodox CPV term!**



- Analysis assuming perfect ENTANGLEMENT

The two Time-Ordered Decays **f, g** satisfy

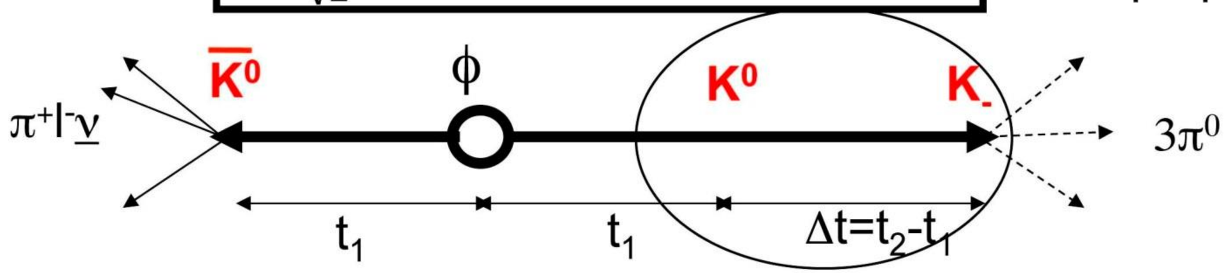
$C_h(f,g) = C_h(g,f)$; $C_c(f,g) = C_c(g,f)$; $S_c(f,g) = -S_c(g,f)$

TIME REVERSAL VIOLATION IN NEUTRAL KAON TRANSITIONS

EPR correlations at a ϕ-Factory can be exploited to study T-conjugated TRANSITIONS between $K^0, \overline{K}^0$ and the orthogonal K_+, K_- states filtered by CP-eigenstate decay products

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\overline{K}^0(-\vec{p})\rangle - |\overline{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]$$
$$= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]$$

- decay as filtering measurement
- entanglement -> preparation of state

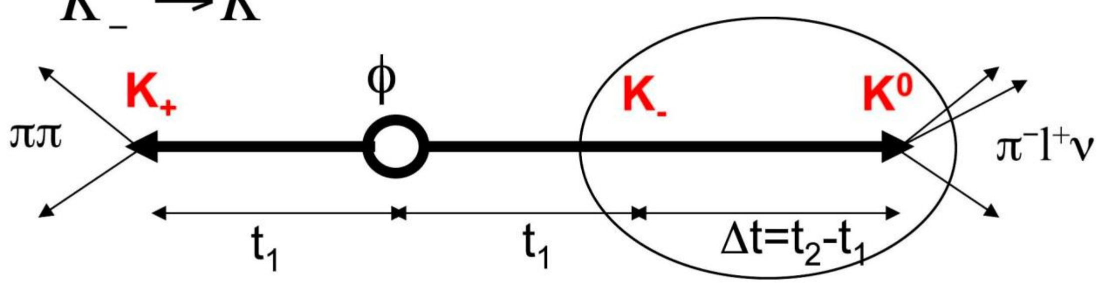


$K^0 \rightarrow K_-$ reference process

$K_- \rightarrow K^0$ T-conjugated process

Note: CP and CPT conjugated process

$\overline{K}^0 \rightarrow K_- \qquad K_- \rightarrow \overline{K}^0$



A. Di Domenico

CPT VIOLATION LIMITS

Extension of CPT theorem to a theory beyond Quantum Field Theory is far from obvious. (e.g. CPT violation appears in several QG models)

Need of predictive theories incorporating CPT violation and phenomenological models to be constrained by experiments.

Conventional Consequences of CPT symmetry: equality of masses, lifetimes, |q| and |μ| of a particle and its anti-particle.

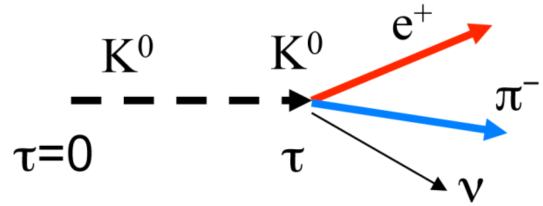
Neutral meson systems offer unique possibilities to test CPT invariance;
e.g. taking as figure of merit the fractional difference between the masses of a particle and its anti-particle:

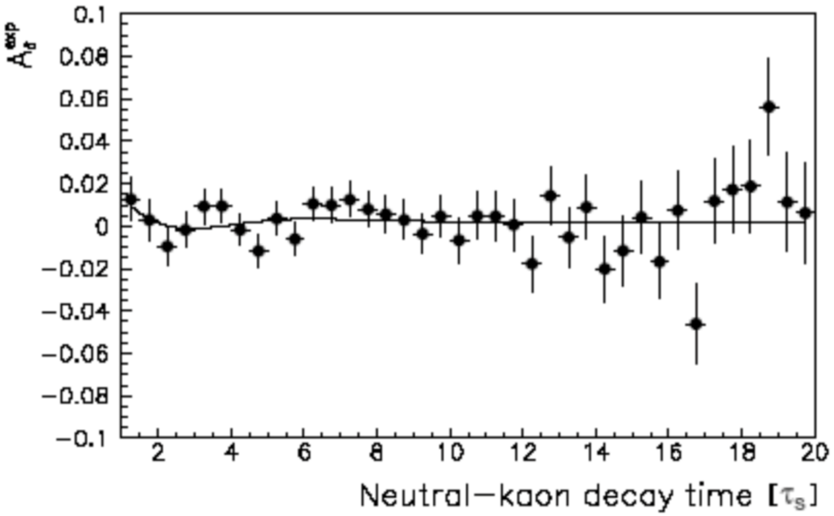
	neutral K system	$\left| m_{K^0} - m_{\overline{k}^0} \right| / m_K < 10^{-18}$	CPLEAR
New! →	neutral B system	$\left| m_{B^0} - m_{\overline{B}^0} \right| / m_B < 10^{-14}$	J.B., F.B., M.N. from BABAR data
New! →	proton- anti-proton	$\left| m_p - m_{\overline{p}} \right| / m_p < 8 \, . \, 10^{-10}$	ASACUSA Antiprotonic Helium

Other interesting CPT tests: GO TO NEUTRAL MESON TRANSITIONS

CPT test at CPLEAR

Test of **CPT** in the time evolution of neutral kaons using the semileptonic asymmetry





$$
\begin{cases}
A_\delta(\tau) = \dfrac{\overline{R}_+(\tau) - \alpha R_-(\tau)}{\overline{R}_+(\tau) + \alpha R_-(\tau)} + \dfrac{\overline{R}_-(\tau) - \alpha R_+(\tau)}{\overline{R}_-(\tau) + \alpha R_+(\tau)} \\
R_{+(-)}(\tau) = R\left(K^0{}_{t=0} \to (e^{+(-)}\pi^{-(+)}\nu)_{t=\tau}\right) \\
\overline{R}_{-(+)}(\tau) = R\left(\overline{K}^0{}_{t=0} \to (e^{-(+)}\pi^{+(-)}\nu)_{t=\tau}\right) \\
\alpha = 1 + 4\Re\varepsilon_L
\end{cases}
$$

$$
A_\delta(\tau >> \tau_S) = 8\Re\delta
$$

$$
\Re\delta = (0.30 \pm 0.33 \pm 0.06) \times 10^{-3}
$$

CPLEAR PLB444 (1998) 52

$A_S - A_L$ at KLOE – 2

Semileptonic decays of K_S, K_L of neutral kaons

A. Di Domenico

$$|K_S\rangle = \frac{1}{\sqrt{2(1+|\epsilon_S|^2)}}\left((1+\epsilon_S)|K^0\rangle + (1-\epsilon_S)|\bar{K^0}\rangle\right)$$

$$|K_L\rangle = \frac{1}{\sqrt{2(1+|\epsilon_L|^2)}}\left((1+\epsilon_L)|K^0\rangle - (1-\epsilon_L)|\bar{K^0}\rangle\right)$$

$$\epsilon_{S\setminus L} = \epsilon_K \pm \delta_K$$

ϵ_K: parameter describing $\mathcal{CP}$ violation

δ_K: parameter describing $\mathcal{CPT}$ violation

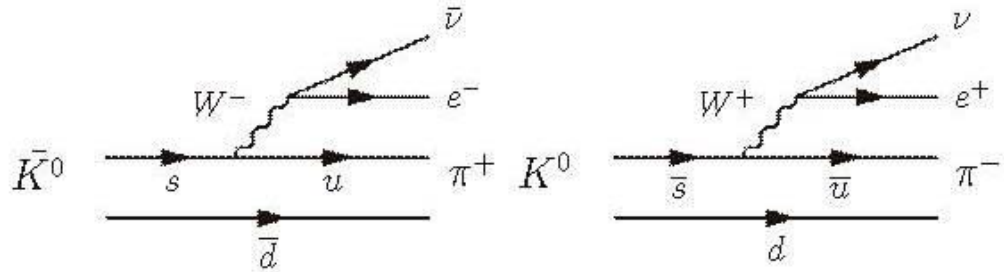
Possible semileptonic decays:

$K^0 \to \pi^- e^+ \bar{\nu}$

$\bar{K^0} \to \pi^+ e^- \nu$

$K^0 \to \pi^+ e^- \nu$

$\bar{K^0} \to \pi^- e^+ \bar{\nu}$



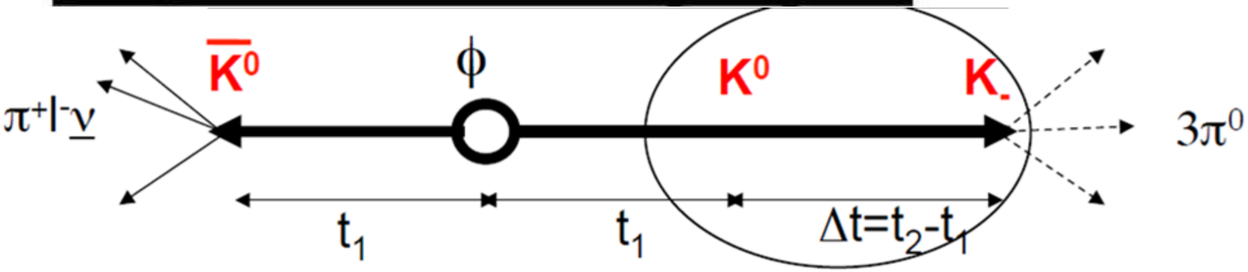
Two decays are allowed according to elementary Quarks ($\Delta S = \Delta Q$ rule)

DIRECT TEST OF CPT IN NEUTRAL KAON TRANSITIONS

EPR correlations at a ϕ-Factory can be exploited to study CPT-conjugated Transitions involving Flavour $\boldsymbol{K^0} - \boldsymbol{\bar{K}^0}$ and the filtered K+ and K- from CP-eigenstate Decay Products

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]$$
$$= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]$$

- decay as filtering measurement
- entanglement -> preparation of state

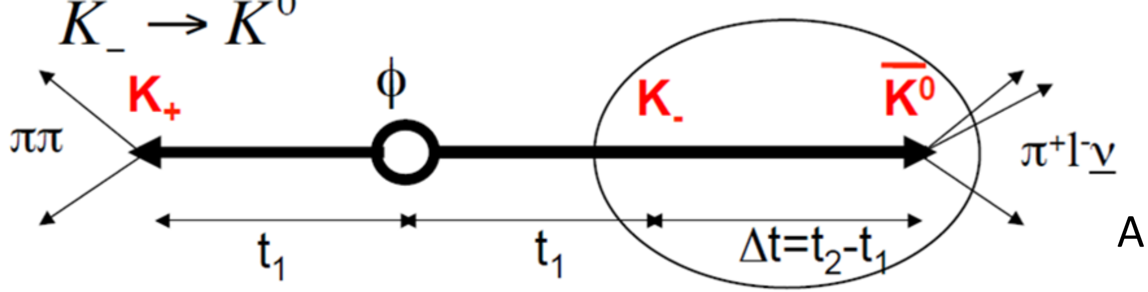


$K^0 \to K_-$ reference process

$K_- \to \bar{K}^0$ CPT-conjugated process

Note: CP and T conjugated process

$\bar{K}^0 \to K_-$ $\quad K_- \to K^0$



A. Di Domenico

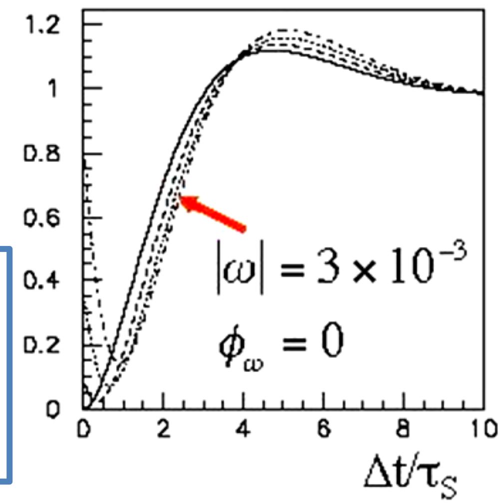
THE ω – EFFECT, beyond [CPT, H] ≠ 0

In presence of decoherence and CPT breaking induced by quantum gravity (CPT operator "ill-defined") the definition of particle-antiparticle states could be modified. This in turn induces **a weakening of the perfect Entanglement** imposed by Bose statistics (EPR correlation) to the two kaon state:

[JB, Mavromatos, Papavassiliou, PRL 92(2004) 131601]

$$|i\rangle \propto \left(|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right) + \omega\left(|K^0\rangle|\overline{K}^0\rangle + |\overline{K}^0\rangle|K^0\rangle\right)$$

$$\propto \left(|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle\right) + \omega\left(|K_S\rangle|K_S\rangle - |K_L\rangle|K_L\rangle\right)$$



Contrary to ω = 0 the presence of terms with ω makes **the time evolution of $|i\rangle$ before the first decay non-trivial → Demise of Flavour or CP Tag**

In some microscopic models of space-time foam arising from non-critical string theory:

[JB, Mavromatos, Sarkar, PRD 74(2006) 045014]

$$|\omega| \sim 10^{-4} \div 10^{-5}$$

The maximum sensitivity to ω is expected for $f_1 = f_2 = \pi^+ \pi^-$, mesauring ω/ε- effects

All CPTV effects induced by [CPT, H] ≠ 0 could be simultaneously disentangled

MEASUREMENT OF ω - EFFECT

Fit of $I(\pi^+\pi^-, \pi^+\pi^-; \Delta t, \omega)$:

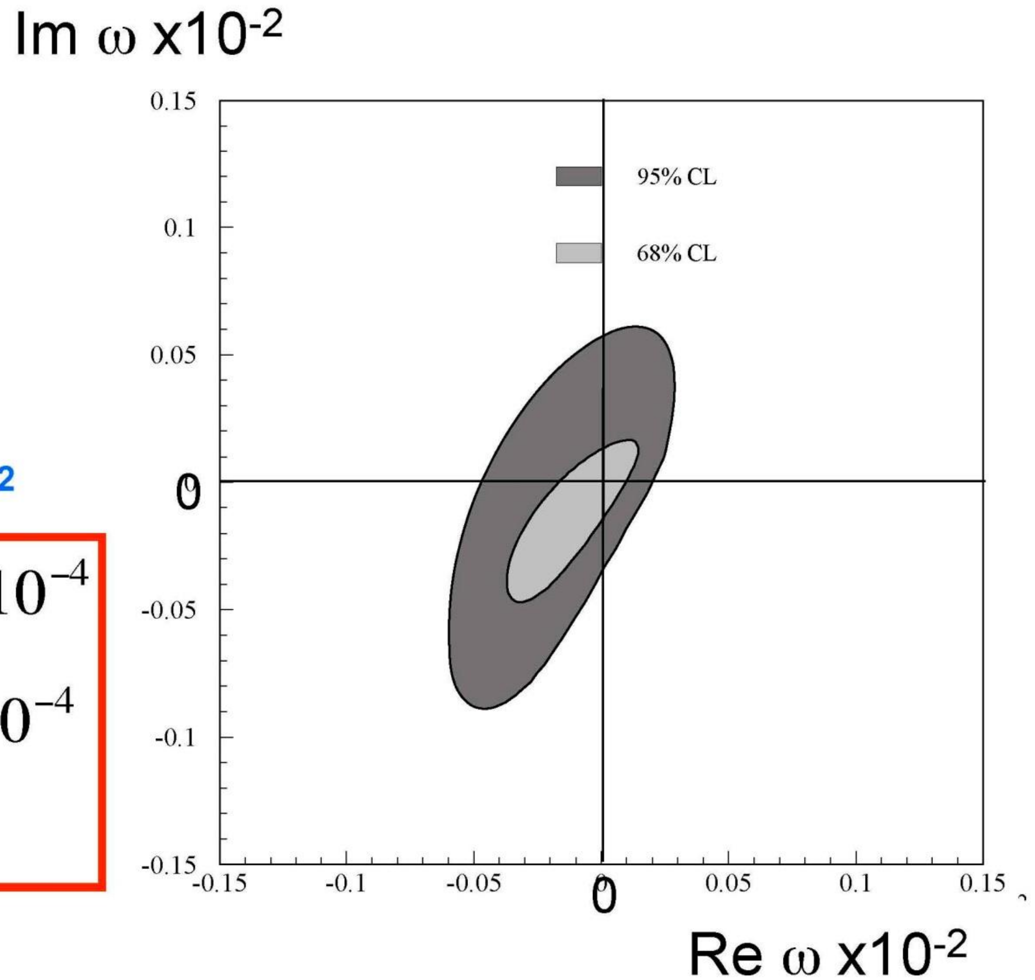
- Analysed data: 1.5 fb^{-1}

KLOE result: PLB 642(2006) 315
Found. Phys. 40 (2010) 852

$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right) \times 10^{-4}$$

$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right) \times 10^{-4}$$

$$|\omega| < 1.0 \times 10^{-3} \quad \text{at } 95\% \text{ C.L.}$$



KLOE – 2 prospects → A. Di Domenico

ω – EFFECT IN THE B-SYSTEM

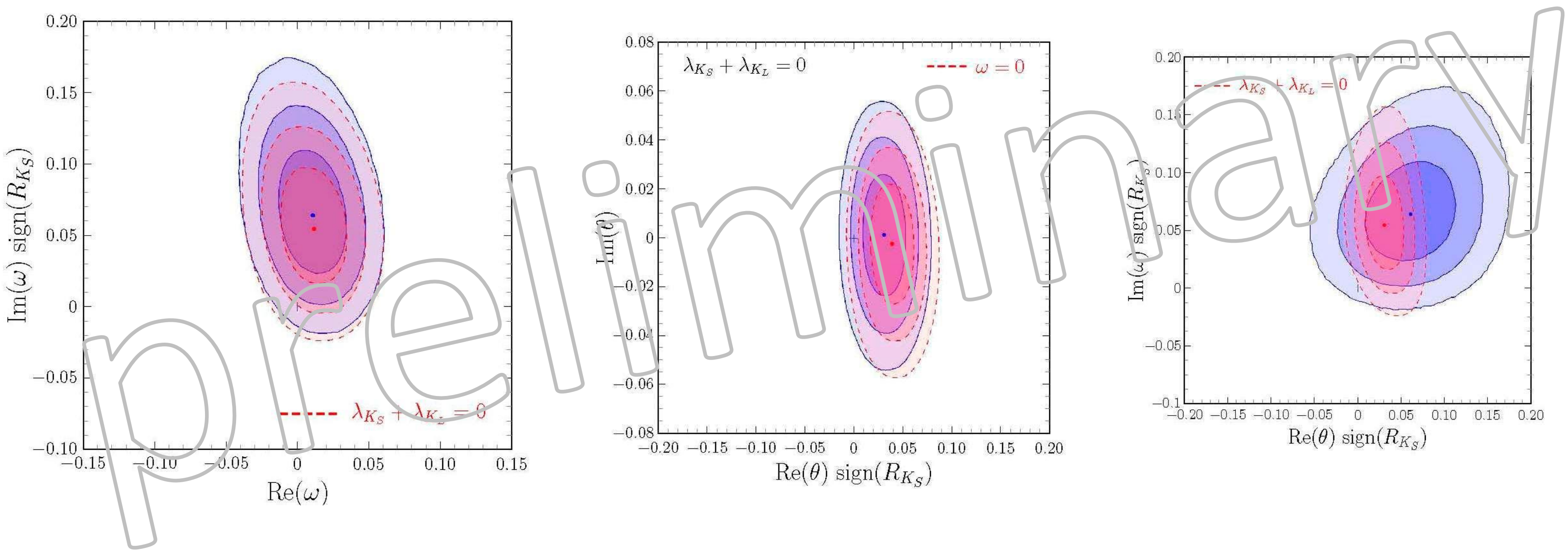
- In the B system [Alvarez, JB, Nebot JHEP 0611(2006)],

Equal-sign Dilepton Asymmetry → $-0.0084 \leq \Re\omega \leq 0.0100$ at 95% CL

- Novel signal from **Violation of (f,g) ↔ (g,f) Connection**

→ Gateway for separating both $\Re\omega$ and $\Im\omega$ when (Flavour, CP)

C(f,g) – C(g,f) ; S(f,g) + S(g,f)



Fascinating Non-Correlated $\Re e\,(\theta)$ and $\Im m\,(\omega)$ 2σ Values

OUTLOOK

- Importance of Direct Asymmetries for Separate T, CP, CPT in Transitions → **Need of Entanglement for Neutral Mesons**

- Flavour-CP transitions in Entangled $\boldsymbol{B^0 - \bar{B}^0}$ have demonstrated **Genuine Separate Asymmetries for T and CP**

$$\Delta S_c^T = 0.687 \pm 0.020 \,, \qquad \Delta S_c^{CP} = -0.680 \pm 0.021$$

  and compatibility with CPT invariance, with a 2σ tension,

$$\Delta C_c^{CPT} = -\Delta C_h^{CPT} = (2.7 \pm 1.5) \cdot 10^{-2}$$

  to be followed at **BELLE II** with ΔC^{CPT}, and at **LHCb** with ΔC^{CP} !

- Good Perspectives with KLOE-2 for a Program of Genuine Separate **Asymmetries for T, CP and CPT in Flavour-CP Transitions in Entangled $\boldsymbol{K^0 - \bar{K}^0}$**

OUTLOOK

- CPT Violation Limits from $M^0 - \overline{M}^0$ for $K^0 - \overline{K}^0$, $B^0 - \overline{B}^0$, $p \quad - \overline{p}$, to be complemented by Direct Asymmetries for Neutral Meson Transitions.

- The best way to study the **ω-effect** weakening Entanglement due to "ill-defined CPT" → **CPV ($\pi^+\pi^-$, $\pi^+\pi^-$) Correlated Decay at KLOE-2** → Distinguished from [CPT, H] ≠ 0.

- **In B-system at BELLE-II**
    - **Equal-sign Dilepton Asymmetry**
    - **Flavour-CP Transitions**, exploiting the exchange properties under Time-Ordering of the Decays (f,g): Present **Indication (2σ) of an effect for Imω= 0.06 ± 0.03**

THANK YOU VERY MUCH FOR YOUR ATTENTION

BACK-UP

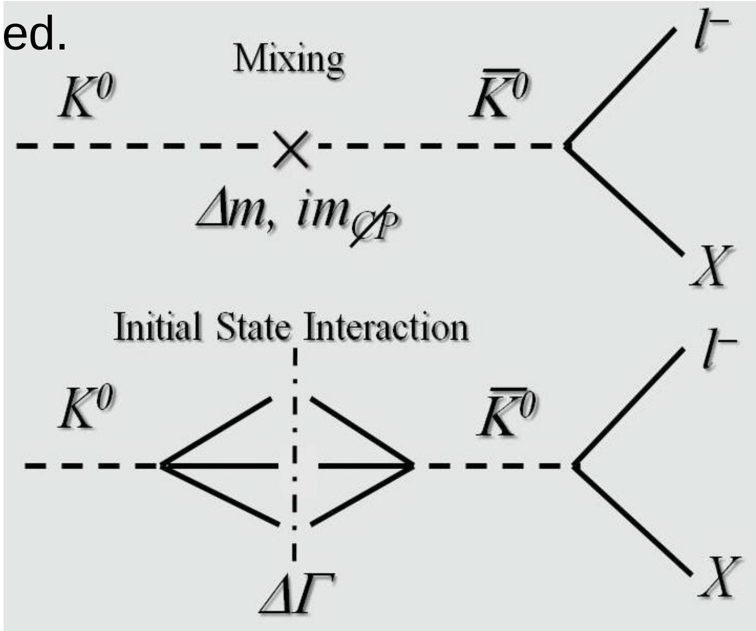
CAN TR BE TESTED IN UNSTABLE SYSTEMS?

THE FACTS

- Taking as Reference $K^0 \to \overline{K}^0$ and calling (X,Y) the observed decays at times t_1 and t_2, with $\Delta t \equiv t_2 - t_1 > 0$, the CP, T and CPT transformed transitions are

Transition	$K^0 \to \overline{K}^0$	$\overline{K}^0 \to K^0$	$\overline{K}^0 \to K^0$	$K^0 \to \overline{K}^0$	$K^0 \to \overline{K}^0$
(X,Y)	(l^-, l^-)	(l^+, l^+)	(l^+, l^+)	(l^-, l^-)	(l^-, l^-)
Transformation	Reference	CP	T	CPT	Δt

➡ No way to separate T and CP if T were defined.



- T-operator is not defined for **decaying** states: its time reverse is not a physical state.
- The Kabir asymmetry NEEDS the interference of CP mixing with the "initial state interaction" to generate the effect, directly proportional to ΔΓ.

The decay plays an essential role

- The time evolutions of $K^0 \to \overline{K}^0$ and $\overline{K}^0 \to K^0$ are equal, the asymmetry is time independent.
- In the WW approach, the entire effect comes from the overlap of non-orthogonal K_L, K_S states. If the **stationary** states were orthogonal ➡ no asymmetry.
- L. Wolfenstein: "it is not as direct a test of TRV as one might like".