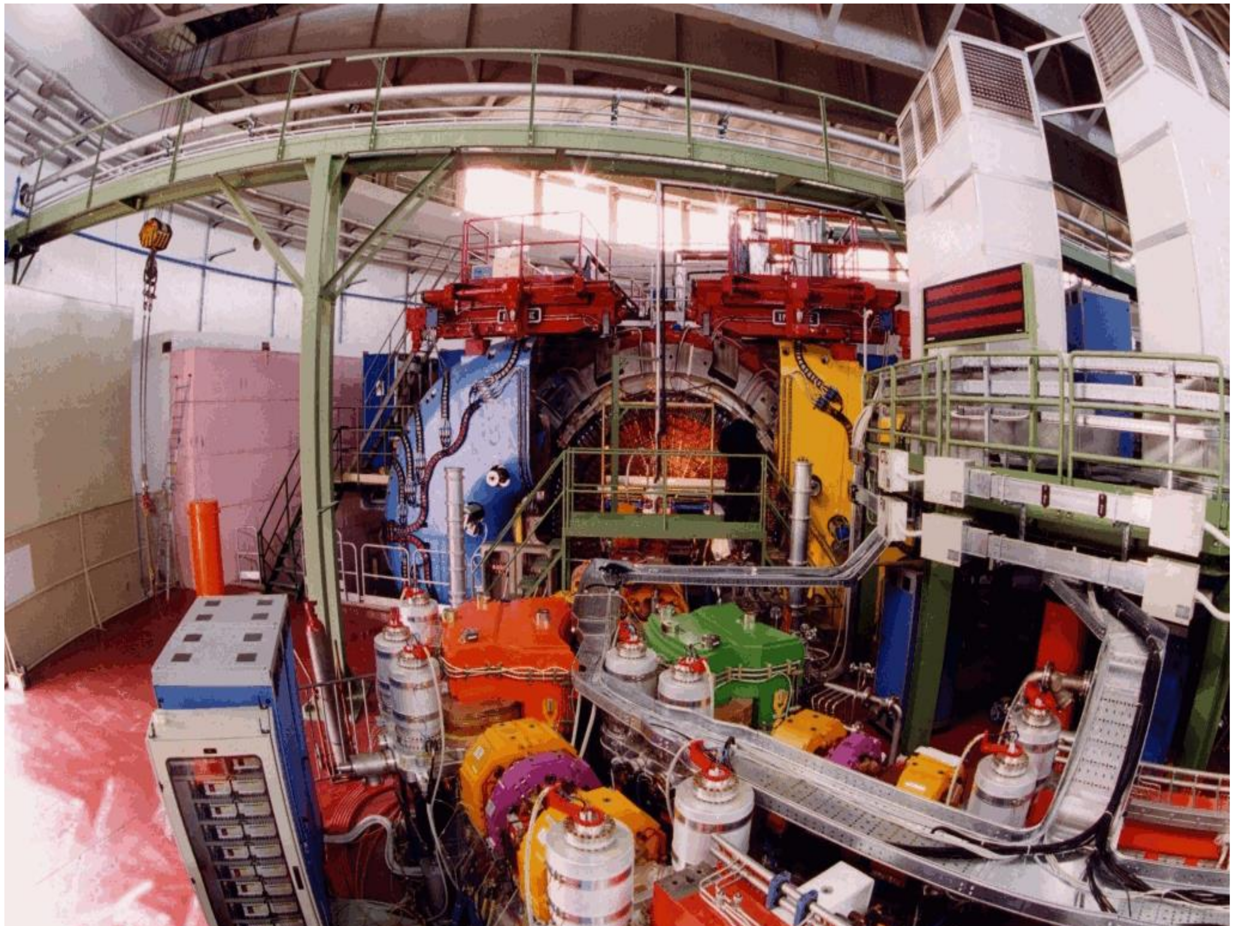
KLOE-2 Workshop on $e^+ e^-$ collision physics at 1 GeV

26-28 October 2016

INFN - Laboratori Nazionali di Frascati, Italy



DISCRETE SYMMETRIES WITH NEUTRAL MESONS

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CSIC

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 → transfer to the orthogonal partner

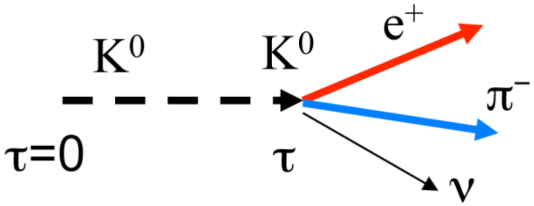
- CPTV ? ⇨ - Beyond QFT paradigm
  - Nothing in QM forbids CPTV

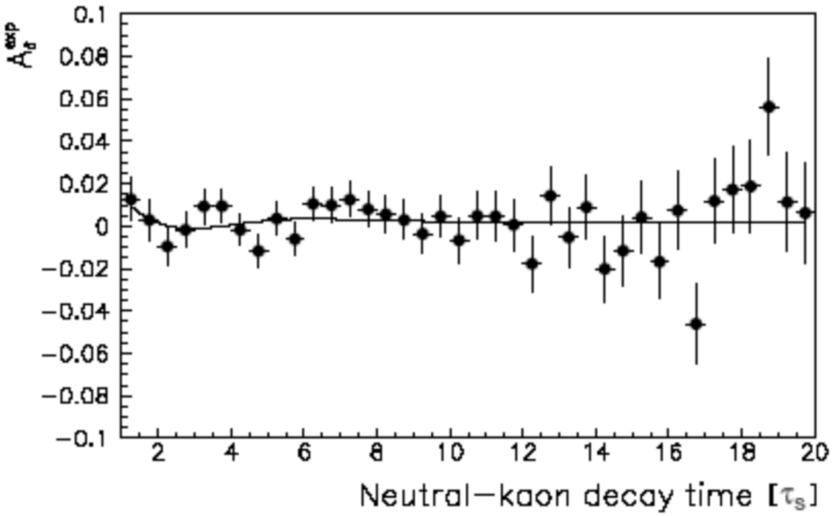
OUTLINE

- CPTV in SemiLeptonic Decays of Neutral Kaons
- Genuine T, CP, CPT Separate Asymmetries in B_d-Transitions
- Direct Measurements of TRV in Neutral Kaon Transitions at KLOE-2
- Direct Tests of CPT in Neutral Kaon Transitions at KLOE-2
- The ω-EFFECT
- Outlook

CPT test at CPLEAR

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





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

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

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

CPLEAR PLB444 (1998) 52

$A_S - A_L$ at KLOE – 2

Semileptonic decays of neutral kaons

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

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

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

parameter describing $\mathcal{CP}$ violation

parameter describing $\mathcal{CPT}$ violation

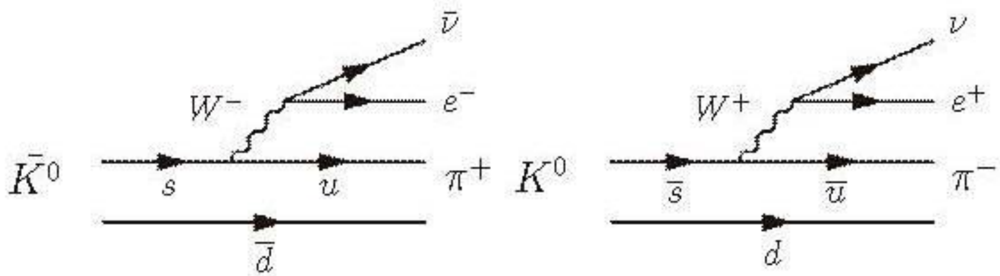
Possible semileptonic decays:

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

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

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

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



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

$A_S - A_L$ at KLOE – 2

We can parametrize semileptonic amplitudes in the following way:

$$a + b = \langle \pi^- e^+ \nu | H_{weak} | K^0 \rangle = (if\ \mathcal{CP}) = a^* + b^*,$$

$$a^* - b^* = \langle \pi^+ e^- \bar{\nu} | H_{weak} | \bar{K}^0 \rangle = (if\ \mathcal{CP}) = a + b$$

and then we obtain following relations between symmetries and semileptonic amplitudes:

	$\mathcal{CP}$	$\mathcal{T}$	$\mathcal{CPT}$
a	$Im = 0$	$Im = 0$	
b	$Re = 0$	$Im = 0$	$= 0$

; CPTV in Decay Amplitude

→ y = - b/a

Charge Asymmetry

$$A_{S,L} = \frac{\Gamma(K_{S,L}\to\pi^- e^+ \nu) - \Gamma(K_{S,L}\to\pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L}\to\pi^- e^+ \nu) + \Gamma(K_{S,L}\to\pi^+ e^- \bar{\nu})} = 2\,[Re\,(\epsilon_K) \pm Re\,(\delta_K) - Re\,(y)]$$

$A_L = (3.332 \pm 0.058_{stat} \pm 0.047_{syst}) \cdot 10^{-3}$ [KTeV Collaboration, PRL 88 (2002)]

$A_S = (1.5 \pm 9.6_{stat} \pm 2.9_{syst}) \cdot 10^{-3}$ [KLOE, PL B 636 (2006) 173-182]

SYMMETRIES IN THE LAWS OF PHYSICS

- In Quantum Mechanics, there is an operator U_T implementing the T-symmetry acting on the states of the physical system, 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:

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

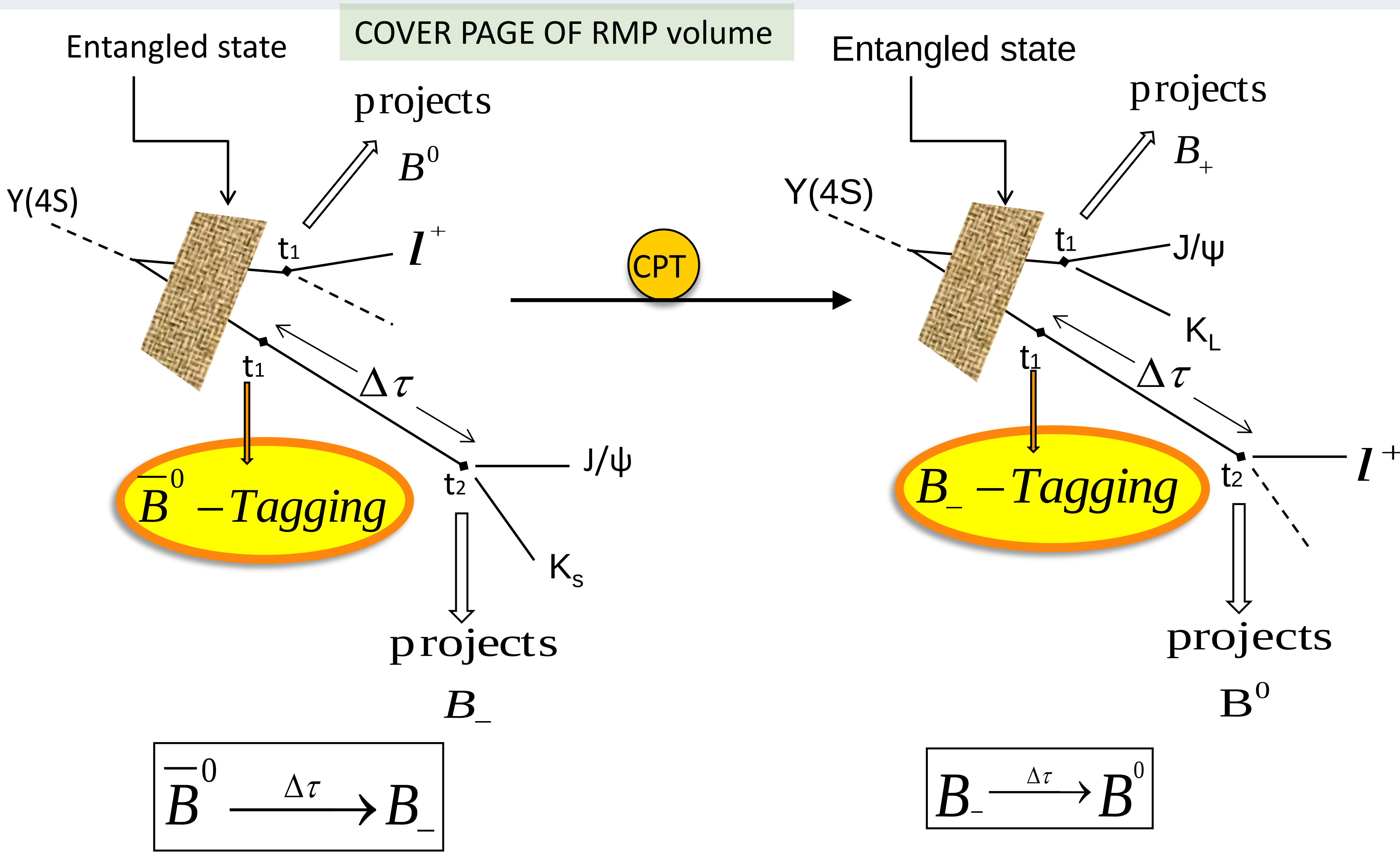
T - Violation means Asymmetry under

Interchange in $\leftrightarrows$ out states

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

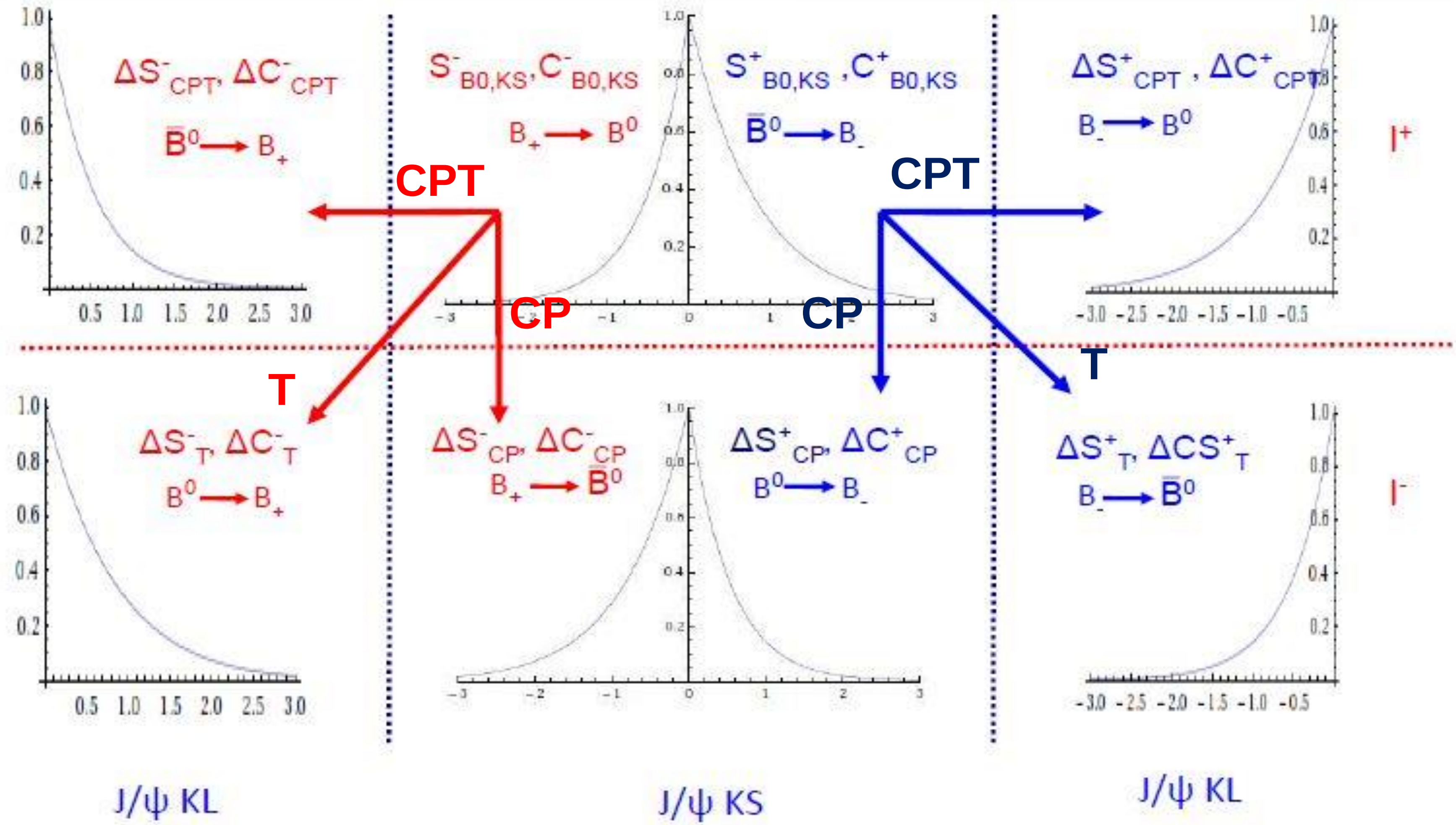
WHAT IS CPT-TRANSFORMATION EXPERIMENTALLY ?

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



ΔS±, ΔC± ASYMMETRY PARAMETERS

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



GENUINE T, CP, CPT ASYMMETRIES

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

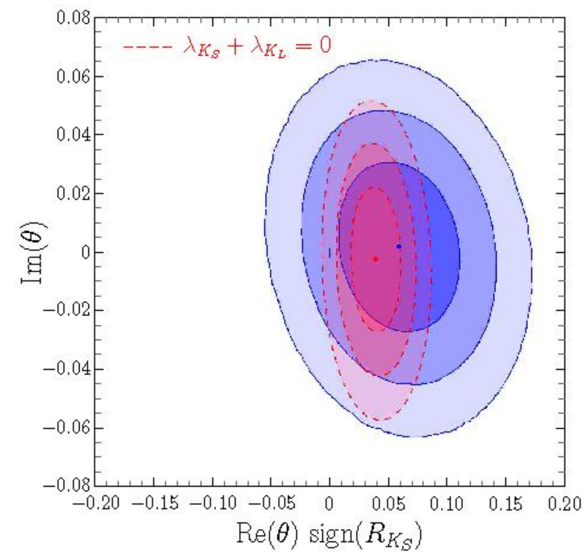
- 3 different Observables ΔC_h, ΔC_c, ΔS_c for each symmetry

9 Asymmetry parameters with different information content

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

Impressive separate evidence of TRV, CPV

"Intriguing" 2σ - effect for CPTV $\Re\delta$



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)

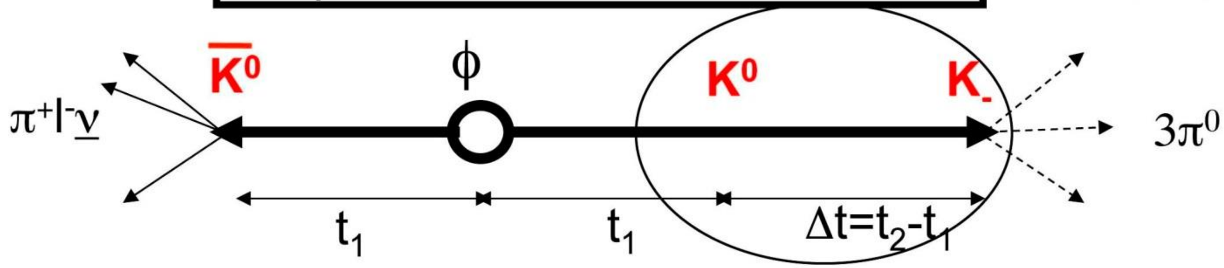
- Weakening Entanglement → CPTV ω-effect violates this relation, in progress

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

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

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

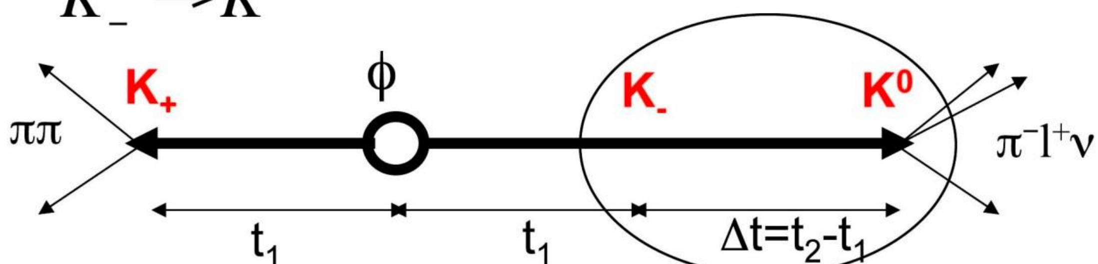


$K^0 \rightarrow K_-$ reference process

Note: CP and CPT conjugated process

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

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



TIME REVERSAL VIOLATION IN NEUTRAL KAON TRANSITIONS

T symmetry test

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

One can define the following ratios of probabilities:

$$
\begin{aligned}
R_1(\Delta t) &= P\left[K^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to K^0(\Delta t)\right] \\
R_2(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right] \\
R_3(\Delta t) &= P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] \\
R_4(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right] .
\end{aligned}
$$

Any deviation from $R_i = 1$ constitutes a violation of T-symmetry

J. B., A. Di Domenico, P. Villanueva, NPB 868(2013)102

TIME REVERSAL VIOLATION IN NEUTRAL KAON TRANSITIONS

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

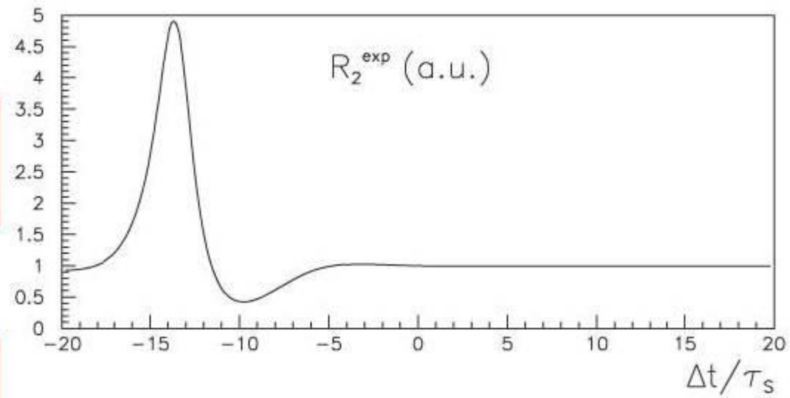
$$\boxed{R_2^{\mathrm{exp}}(\Delta t) \equiv \frac{I(\ell^-,3\pi^0;\Delta t)}{I(\pi\pi,\ell^+;\Delta t)} = R_2(\Delta t) \times \frac{C(\ell^-,3\pi^0)}{C(\pi\pi,\ell^+)}}$$

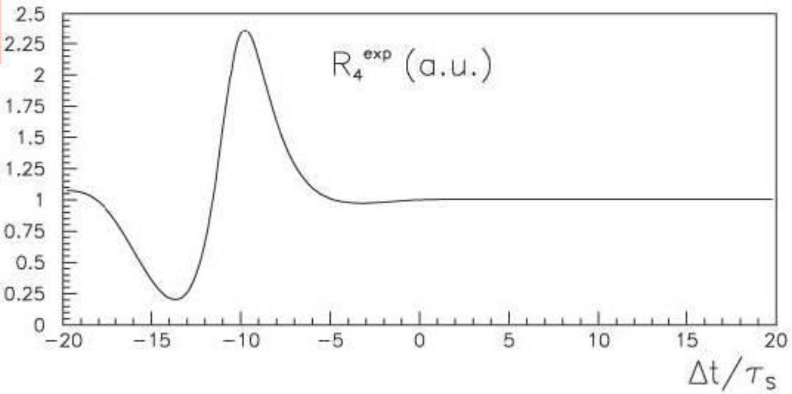
$$R_3^{\mathrm{exp}}(\Delta t) \equiv \frac{I(\ell^+,\pi\pi;\Delta t)}{I(3\pi^0,\ell^-;\Delta t)} = R_3(\Delta t) \times \frac{C(\ell^+,\pi\pi)}{C(3\pi^0,\ell^-)}$$

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

In practice two measurable ratios with $\Delta t < 0$ or > 0

$$\boxed{\begin{aligned} R_2^{\mathrm{exp}}(-\Delta t) &= \frac{1}{R_3^{\mathrm{exp}}(\Delta t)} = \frac{1}{R_3(\Delta t)} \times \frac{C(3\pi^0,\ell^-)}{C(\ell^+,\pi\pi)}, \\ R_4^{\mathrm{exp}}(-\Delta t) &= \frac{1}{R_1^{\mathrm{exp}}(\Delta t)} = \frac{1}{R_1(\Delta t)} \times \frac{C(3\pi^0,\ell^+)}{C(\ell^-,\pi\pi)}. \end{aligned}}$$





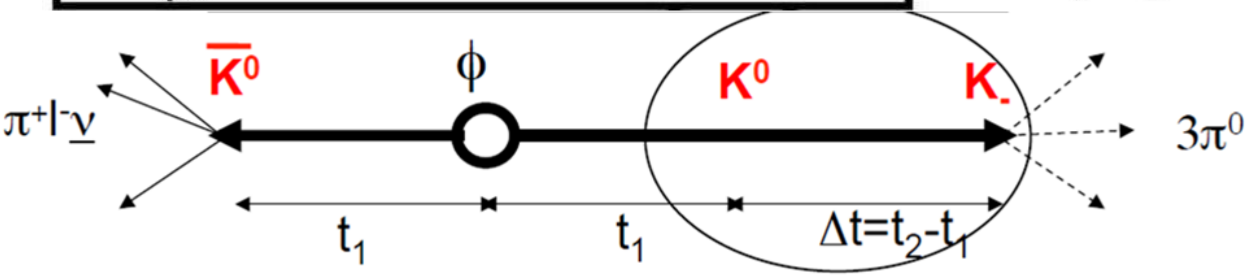
T test could be feasible at KLOE-2 @ DAPHNE with L=O(10 fb^{-1})

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

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

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

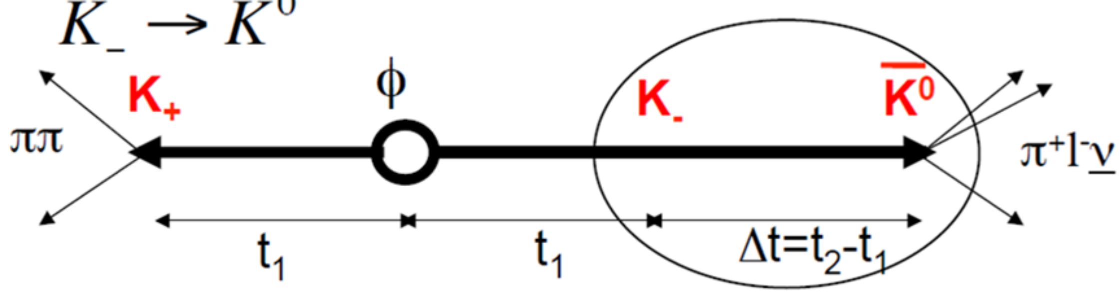


$K^0 \rightarrow K_-$ reference process

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

Note: CP and T conjugated process

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



DIRECT TEST OF CPT IN NEUTRAL KAON TRANSITIONS

CPT symmetry test

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

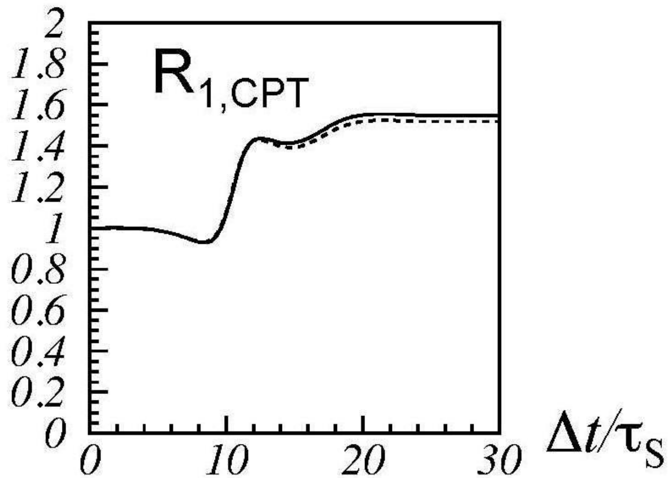
One can define the following ratios of probabilities:

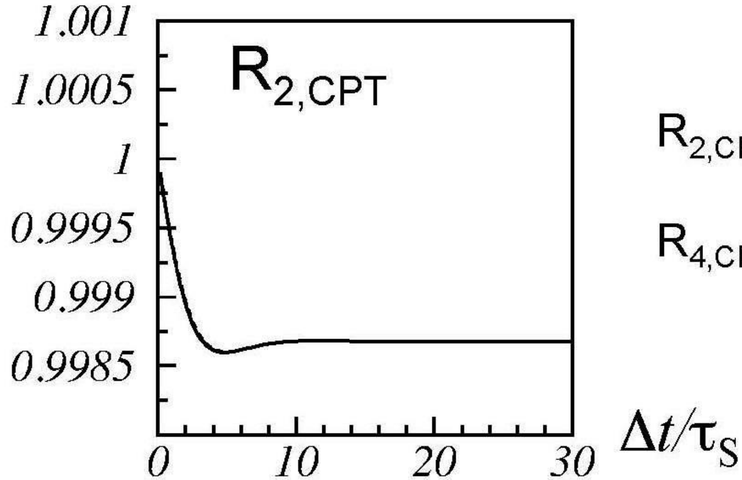
$$R_{1,\mathcal{CPT}}(\Delta t) = P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] / P\left[K^0(0) \to K_+(\Delta t)\right]$$
$$R_{2,\mathcal{CPT}}(\Delta t) = P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right]$$
$$R_{3,\mathcal{CPT}}(\Delta t) = P\left[K_+(0) \to K^0(\Delta t)\right] / P\left[\bar{K}^0(0) \to K_+(\Delta t)\right]$$
$$R_{4,\mathcal{CPT}}(\Delta t) = P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right]$$

Any deviation from $R_{i,CPT}=1$ constitutes a violation of CPT-symmetry

DIRECT TEST OF CPT IN NEUTRAL KAON TRANSITIONS

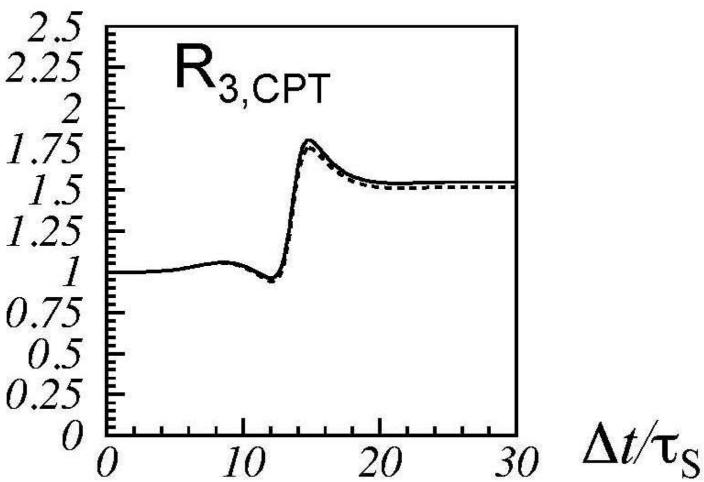
for visualization purposes, plots with $Re(\delta)=3.3\ 10^{-4}$ $Im(\delta)=1.6\ 10^{-5}$ (---- $Im(\delta)=0$)

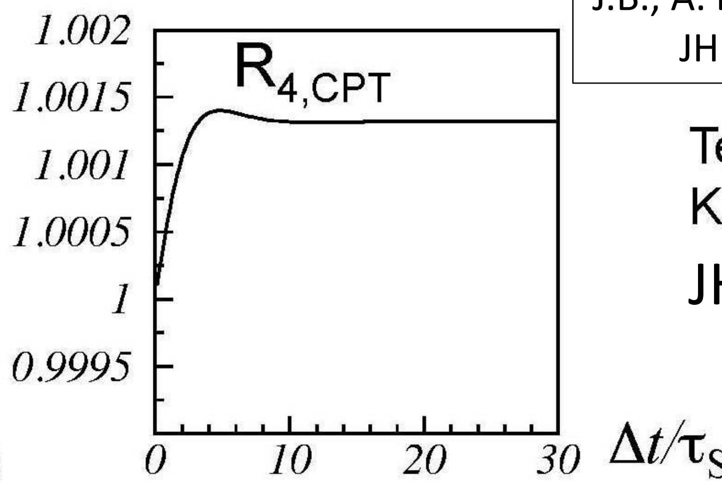




$R_{2,CPT}(\Delta t>>\tau_S)=1-4Re(\delta)$

$R_{4,CPT}(\Delta t>>\tau_S)=1+4Re(\delta)$





J.B., A. Di Domenico, P. Villanueva, JHEP 1510 (2015)139

Test feasible at KLOE/KLOE-2

JHEP 2015

THE ω - EFFECT

In presence of decoherence and CPT violation induced by quantum gravity (CPT operator "ill-defined") the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the kaon state:

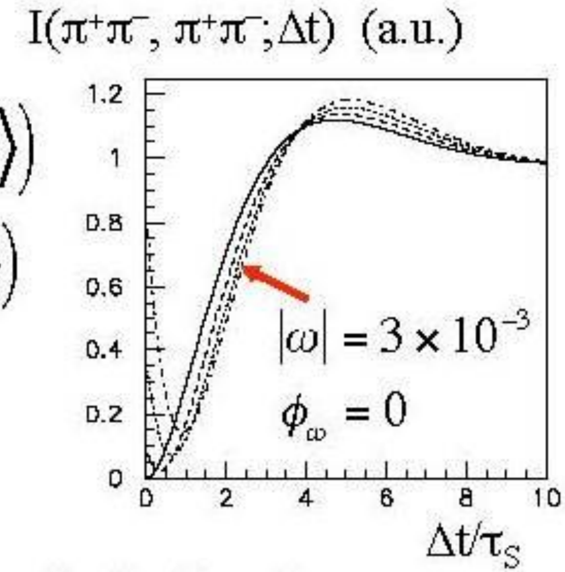
[JB, Mavromatos, Papavassiliou, PRL 92(2004) 131601]

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

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

at most one expects:

$$\boxed{|\omega|^2 = O\left(\frac{E^2/M_{PLANCK}}{\Delta\Gamma}\right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3}}$$



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 $f_1 = f_2 = \pi^+\pi^-$

All CPTV effects induced by QG (α,β,γ,ω) could be simultaneously disentangled.

MEASUREMENT OF ω - EFFECT

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

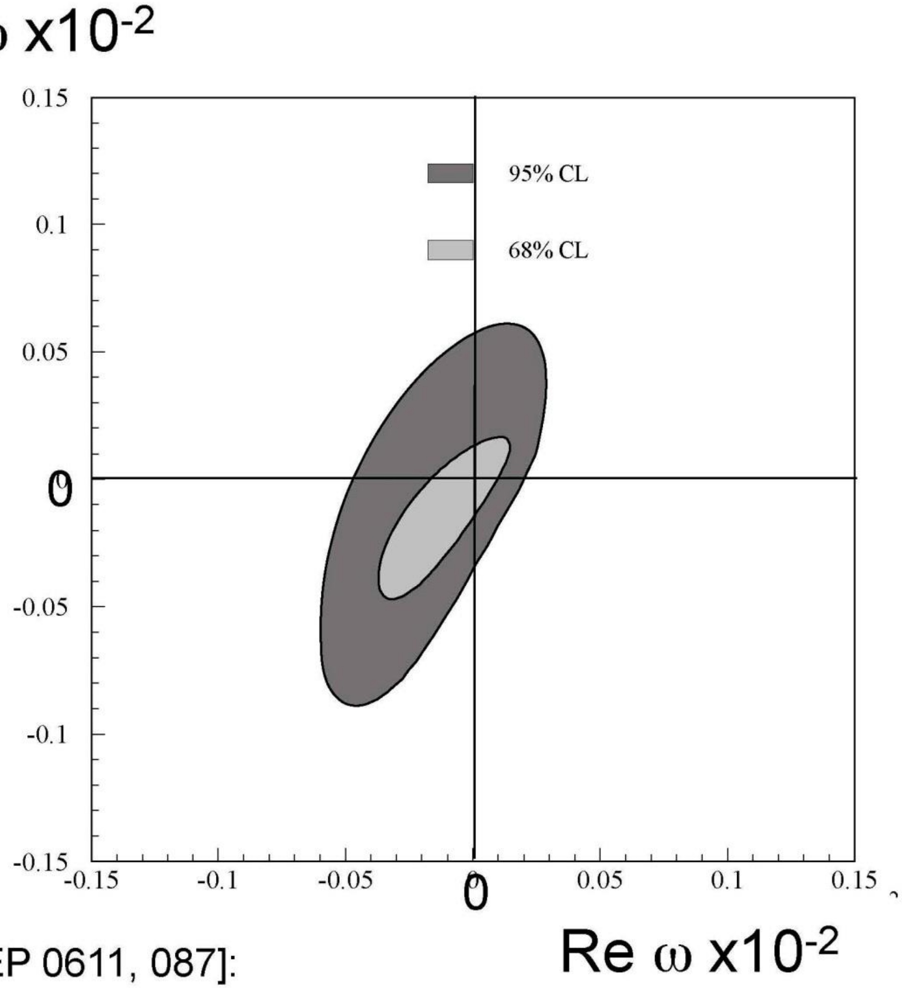
- Analysed data: 1.5 fb^{-1}

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

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

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

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



In the B system [Alvarez, Bernabeu, Nebot JHEP 0611, 087]:

$-0.0084 \le \Re\omega \le 0.0100$ at 95% C.L. ; *$\Re\omega$ and $\Im\omega$ in progress*

OUTLOOK

- Fundamental Role of Discrete Symmetry Breaking → Importance of Direct Asymmetries for Separate T, CP, CPT in Transitions → **Need of Entanglement for Neutral Mesons**

- DAPHNE → K_S decays → Charge Asymmetry in Semileptonic Decays of K_S at KLOE-2 → **Separation of CPTV in the Mass Matrix of $\boldsymbol{K^0 - \bar{K}^0}$**

- Flavour-CP Transitions in Entangled $B^0 - \bar{B}^0$ have demonstrated **Genuine Separate Asymmetries for T and CP with high statistical significance** and compatibility with CPT invariance (with a 2 σ tension)

- **KLOE-2** is able to accomplish a **complete Program of Genuine Separate Asymmetries for T, CP and CPT in Flavour-CP Transitions for $\boldsymbol{K^0 - \bar{K}^0}$** → Possible fake effects controlled in the same experiment

- 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 signature from CPTV in the Effective Hamiltonian for $K^0 - \bar{K}^0$

THANK YOU VERY MUCH FOR YOUR ATTENTION

BACK-UP

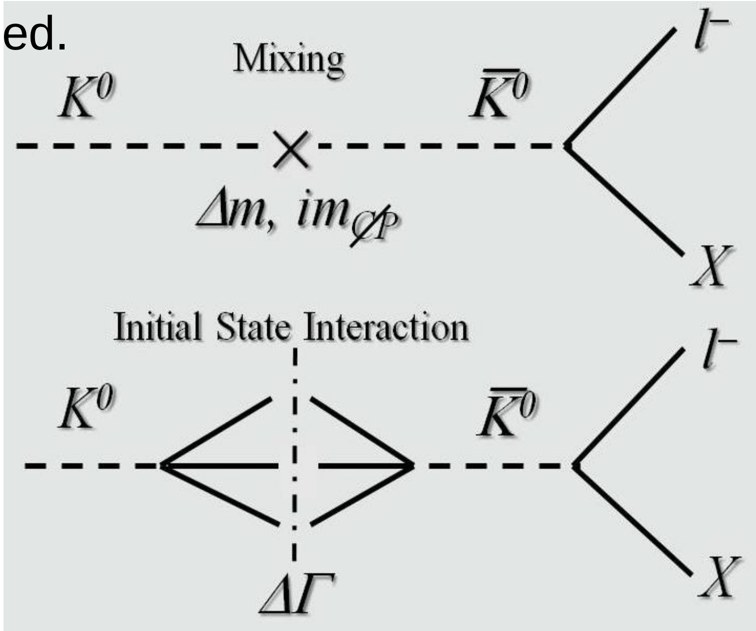
CAN TR BE TESTED IN UNSTABLE SYSTEMS?

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 $\Delta\Gamma$.

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".