XLIII International Meeting on
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2015, Mar 15 - Mar 21
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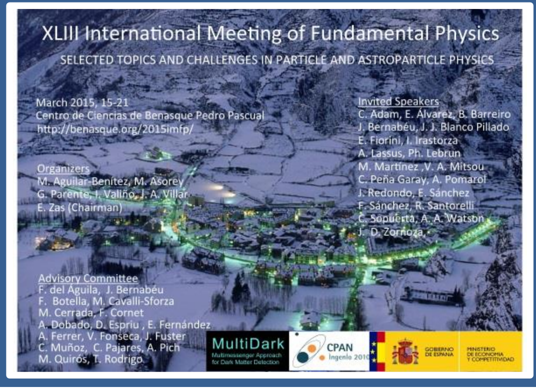

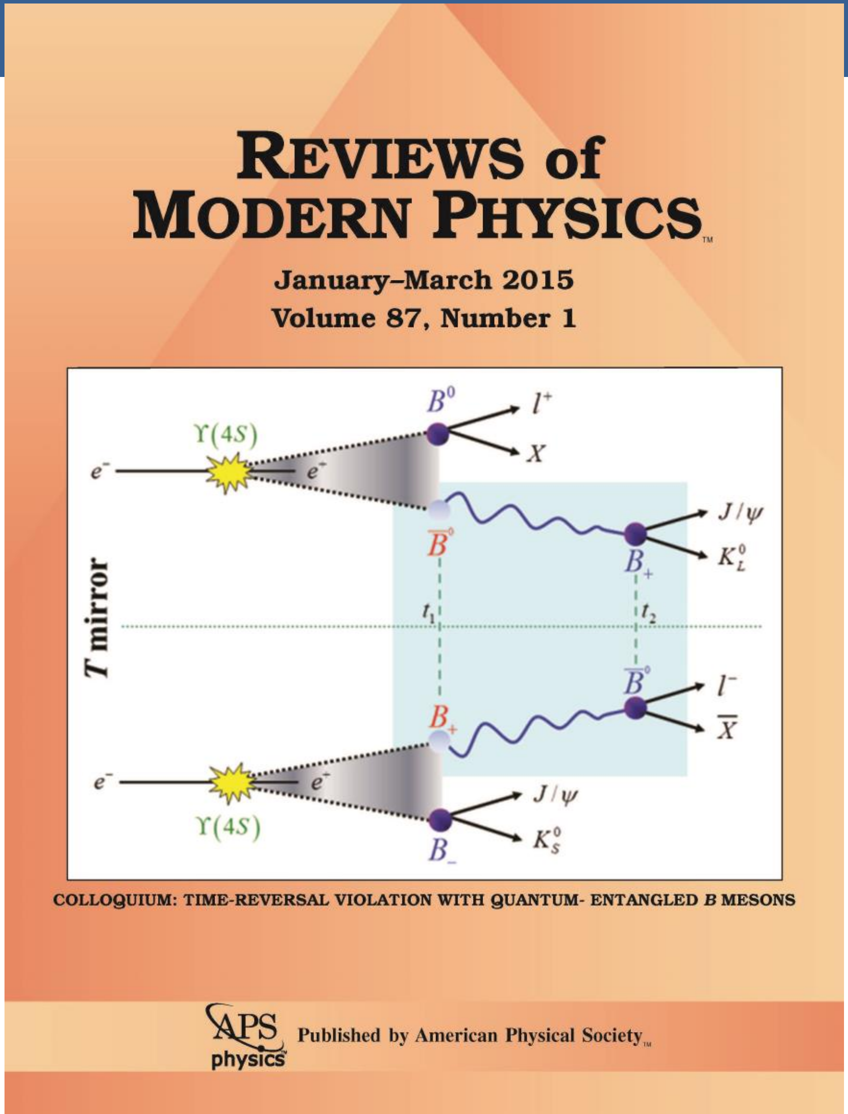

DISCRETE SYMMETRIES
CP, T, CPT

José Bernabéu

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CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
IFIC
INSTITUT DE FÍSICA CORPUSCULAR
VNIVERSITAT DE VALÈNCIA

50 YEARS OF CP-VIOLATION

On july 10th 1964 Cronin, Fitch, Christenson and Turlay submitted a paper to Phys. Rev. Lett. announcing the discovery of CP violation in the weak decays of neutral kaons.

The Nobel Prize in Physics 1980
James Cronin, Val Fitch

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The Nobel Prize in Physics 1980

James Watson Cronin
Prize share: 1/2

Val Logsdon Fitch
Prize share: 1/2

The Nobel Prize in Physics 1980 was awarded jointly to James Watson Cronin and Val Logsdon Fitch *"for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"*

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, K_2^0 mesons were pro-

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion. In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu 3}$, from 280 to ~516; and the $K_{\pi 3}$, from 280 to 363 MeV. We emphasize

CP-SYMMETRY BREAKING BY PARTICLE CONTENT IN SM

Progress of Theoretical Physics

PTP is predecessor journal of Progress of Theoretical and Experimental Physics (PTEP)

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Oxford Journals › Progress of Theoretical Physics › Volume 49, Issue 2 › Pp. 652-657.

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto Kobayashi and **Toshihide Maskawa**

+ Author Affiliations

Received September 1, 1972.

Abstract

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

The Nobel Prize in Physics 2008
Yoichiro Nambu, Makoto Kobayashi, Toshihide Maskawa

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The Nobel Prize in Physics 2008

Photo: University of Chicago

Yoichiro Nambu

Prize share: 1/2

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Photo: U. Montan

Makoto Kobayashi

Prize share: 1/4

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Photo: U. Montan

Toshihide Maskawa

Prize share: 1/4

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

CP-VIOLATION IN STANDARD MODEL

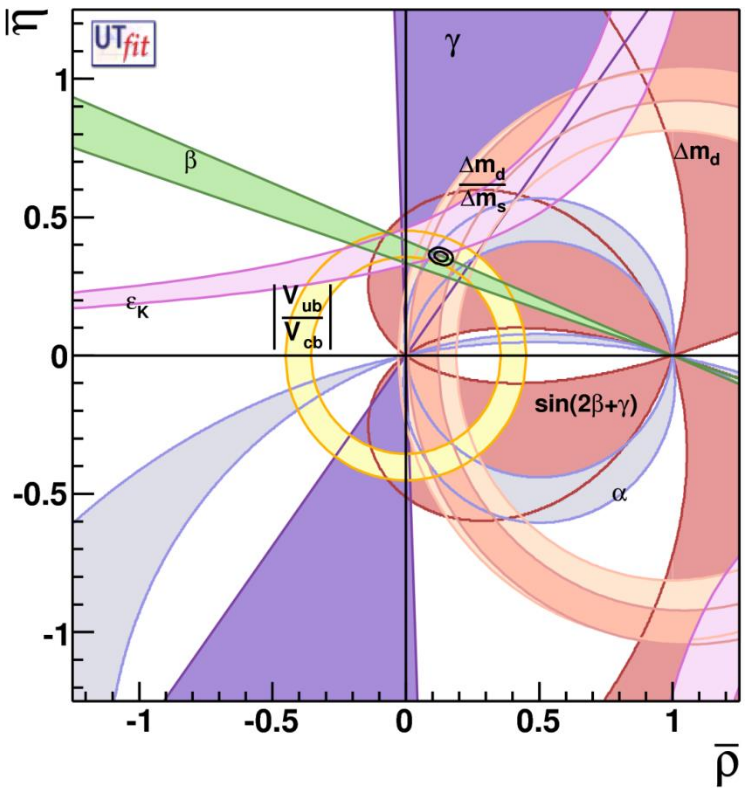
- In the Standard Model, charged weak interactions among quarks are codified in a 3 X 3 unitarity matrix: the **CKM Mixing Matrix**.
- The existence of this matrix conveys the fact that the quarks which participate to weak processes are a linear combination of mass eigenstates
- The unitarity conditions can be represented by triangles in the complex plane.
- For the B-Bbar system, the unitarity triangle is given by

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

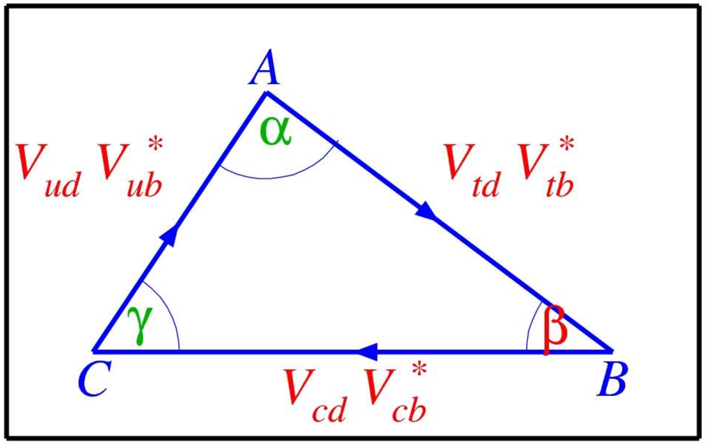
- Flavour Mixing and CP-Violation are described with high precision in the SM.

The best measured CP-phase is

S = sin(2 β) = 0.682 ± 0.019



THE CP ANGLES OF THE UNITARITY TRIANGLE



$$B_d \to "\psi" K_{L,S} \left[b \to c\,\bar{c}\,s \right]$$

$$\beta = \left(21.5^{+0.8}_{-0.7}\right)^0 or\ \beta = \left(68.5^{+0.7}_{-0.8}\right)^0$$

$$\Downarrow$$

$$\cos(2\beta)?$$

$B \to \pi^+\pi^- \Rightarrow \sin(2\alpha) = -0.65 \pm 0.06$ [Interference Mixing-No mixing]

[Direct CPV]: $C_{\pi^+\pi^-} = -0.29 \pm 0.05$

$B^+ \to DK^+$ [Direct CPV] and related transitions:

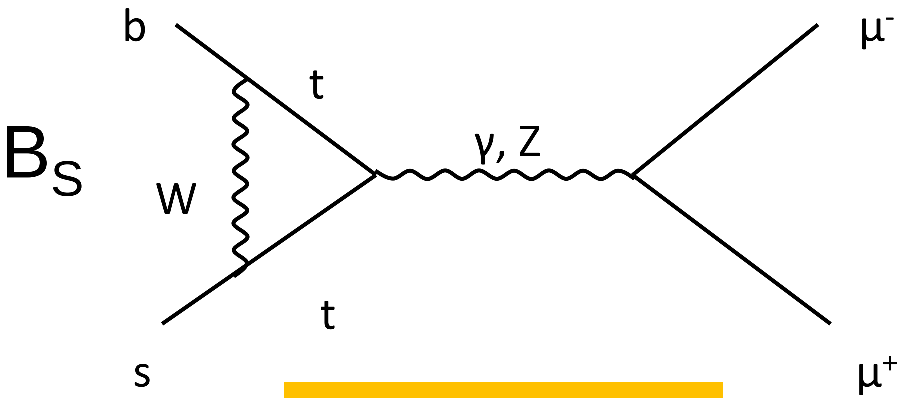
BaBar, Belle, LHCb $\Rightarrow \gamma = (67 \pm 12)^0$

Ideal Experiment: From Entangled states, Equal time Decays $\to J/\psi\ K_s, \pi^+\pi^-$

➢ **Phenomenology of CPV is different in K, D, B and B_s decays**

RARE DECAY $B_s \rightarrow \mu\,\mu$

LHCb Collaboration, PRL (2013)



FCNC, CPV

- ➢ Prospects for new physics, thinking on:
- Origin of Baryogenesis
- Essence of Dark Matter

➢ **Z-penguin can induce NON DECOUPLING effects,** providing information on EWSB:

$\boxed{Z \rightarrow b\ \ s/d}$

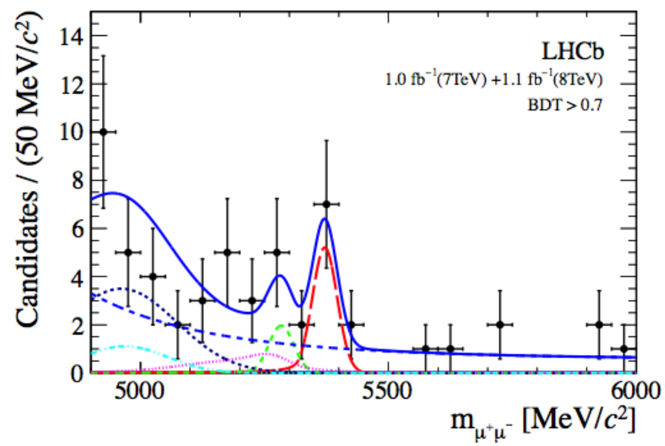
Penguin projected to a pseudoscalar

➡ Helicity suppression

➡ Proportionality with the mass of the lepton

Latest disappointment:

first evidence for very rare decay $B_s \rightarrow \mu^+\mu^-$

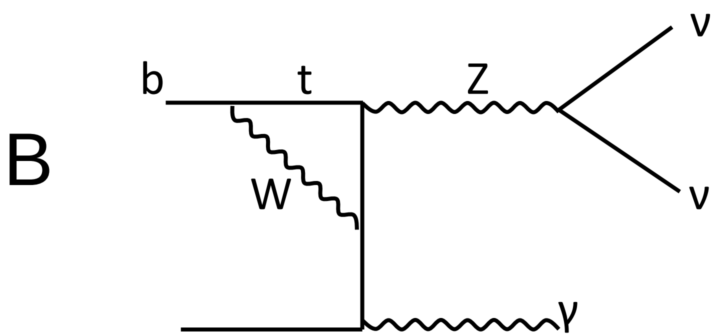


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\mathrm{stat})\,^{+0.5}_{-0.3}(\mathrm{syst})) \times 10^{-9}$$

SM: $(3.23 \pm 0.27) \times 10^{-9}$

$B_d, B_S \rightarrow \nu\, \nu\, \gamma$ / $b \rightarrow s\, \nu\, \nu$

- Box with the Penguin Vertex: Similar arguments for non-decoupling,
- But… no proportionality to ν mass.
- The point is that the penguin is **NOT projected to a pseudo-scalar**

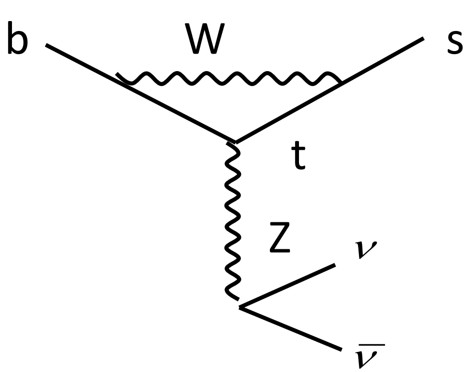


BABAR, PRD (2012) : B_d

$Br < 4.7 \times 10^{-5}$, 90% CL

- **For LHC detectors: Is Displaced Vertex enough ?**

- Move the penguin away from the s-channel
- Non-decoupling again



$B \rightarrow K^{(*)}\, \nu\, \nu$

Not proportional to ν mass

TIME REVERSAL VIOLATION

Why 48 years after CP Violation?

- G. Drexlin, Karlsruhe

- V. Rubakov, Moscow

The Economist, September 2012

physicstoday

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Time-reversal asymmetry in particle physics has finally been clearly seen

> 1964	CPV observed in the $K^0 - \overline{K}^0$ and $B^0 - \overline{B}^0$ systems: unstable particles.
CPT-"Theorem"	TRV expected in these systems as well.
1998	CPLEAR $K^0 \Leftrightarrow \overline{K}^0$ needs ΔΓ; CP&T experimentally identical
< 1999	L. Wolfenstein, R.G. Sachs, ...: "For a decaying state, its T-reverse is not a physical state“ ➡ "Impossible" test of T-symmetry!?
= 1999	Bypass to "No-Go" by means of Quantum Entanglement
CONCEPT	M.C. Bañuls, J.B., PLB (1999), NPB (2000); scrutinized by L. Wolfenstein, IJMP(1999); H. Quinn, JPCS(2009); V. Rubakov; T. Nakada; F. Botella, ... *“it would appear to be a true TRV effect”*
METHOD	J.B., F. Martínez-Vidal, P. Villanueva-Pérez, JHEP (2012)
EXPERIMENT	BABAR Collaboration, PRL (2012): 14 σ
PERSPECTIVE >2012	Extension to any pair of decay channels in B-physics? TRV for K- decays in DAPHNE.

THE CONCEPTUAL BASIS - THE EXPERIMENT

Reprinted from

PHYSICS LETTERS B

Physics Letters B 464 (1999) 117–122

CP, T and CPT versus temporal asymmetries for entangled states of the B_d-system

M.C. Bañuls [a,1], J. Bernabéu [b,2,3]

[a] *IFIC, Centro Mixto Univ. Valencia - CSIC, E-46100 Burjassot (Valencia), Spain*
[b] *Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland*

Received 19 August 1999; accepted 1 September 1999
Editor: R. Gatto

ELSEVIER

Selected for a Viewpoint in *Physics*

PRL **109,** 211801 (2012) PHYSICAL REVIEW LETTERS week ending 21 NOVEMBER 2012

Observation of Time-Reversal Violation in the B^0 Meson System

The BaBar Collaboration

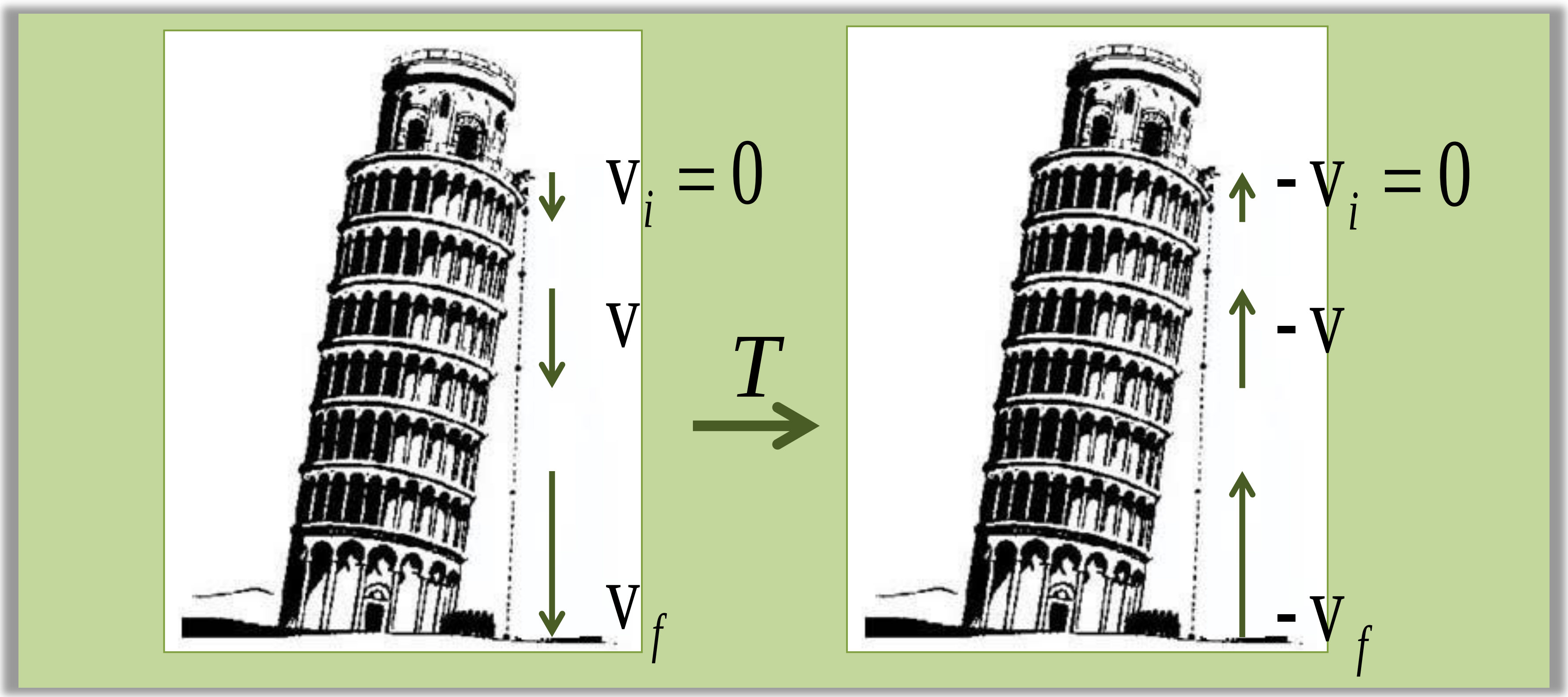
(Received 24 July 2012; published 19 November 2012)

Although CP violation in the B meson system has been well established by the B factories, there has been no direct observation of time-reversal violation. The decays of entangled neutral B mesons into definite flavor states (B^0 or $\bar{B}^0$), and $J/\psi K_L^0$ or $c\bar{c}K_S^0$ final states (referred to as B_+ or B), allow comparisons between the probabilities of four pairs of T-conjugated transitions, for example, $\bar{B}^0 \rightarrow B$ and $B \ \rightarrow \bar{B}^0$, as a function of the time difference between the two B decays. Using 468×10^6 $B\bar{B}$ pairs produced in $\Upsilon(4S)$ decays collected by the *BABAR* detector at SLAC, we measure T-violating parameters in the time evolution of neutral B mesons, yielding $\Delta S_T^+ = -1.37 \pm 0.14(\mathrm{stat}) \pm 0.06(\mathrm{syst})$ and $\Delta S_T \ =$ $1.17 \pm 0.18(\mathrm{stat}) \pm 0.11(\mathrm{syst})$. These nonzero results represent the first direct observation of T violation through the exchange of initial and final states in transitions that can only be connected by a T-symmetry transformation.

WHAT IS "TIME REVERSAL"?

- A symmetry transformation, T, that changes one physical system into another with an inverted sense of time evolution is called Time Reversal.

In classical mechanics, this corresponds to substituting for each trajectory $\vec{r} = \vec{r}\,(t)$ the trajectory $\vec{r} = \vec{r}\,(-t)$, to moving along the given trajectory with the opposite velocity at each point.



TIME REVERSAL INVARIANCE ?

- If the original trajectory is dynamically possible, it is not necessary, in general, that the time reverse trajectory be so for the same dynamics.

- One would need that the equation of motion remains invariant in form under the transformation

$$\boxed{t \to -t, \quad \vec{r} \to \vec{r}, \quad \vec{p} \to -\vec{p}}$$

In our elementary example, one would need to neglect velocity-dependent friction:

$$\frac{d\,\vec{p}}{d\,t} = \vec{F}(\vec{r}) \quad \textbf{INVARIANT;} \qquad \frac{d\,\vec{p}}{d\,t} = \vec{F}(\vec{r}, \vec{\mathrm{v}}) \quad \textbf{VIOLATED}$$

- **A direct evidence of a TRV Effect** means the measurement of **a separate genuine TRV Asymmetry** in a single experiment, independent of CPV or CPT Invariance.

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:

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

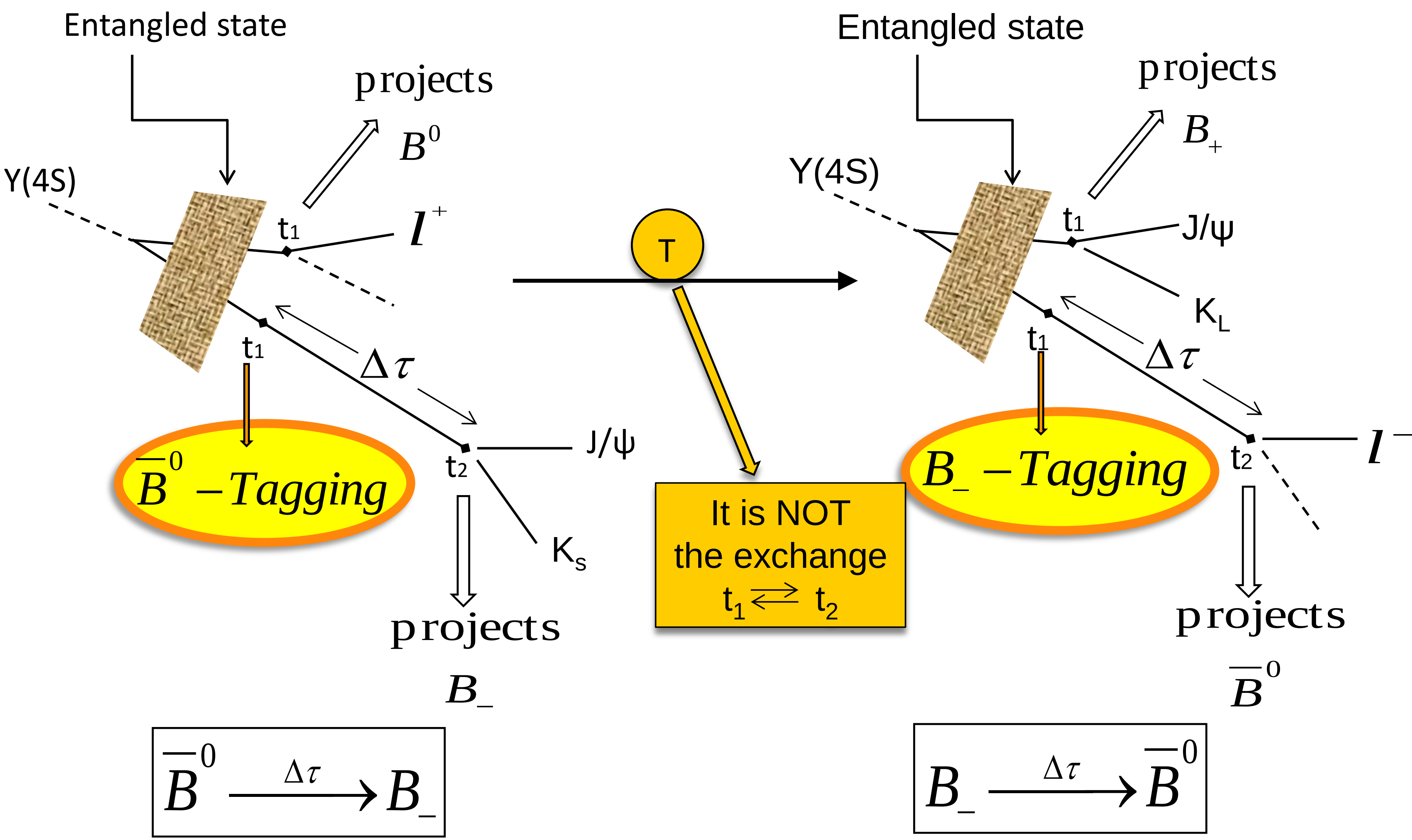
T - Violation means Asymmetry under

Interchange in $\leftrightarrows$ out states

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

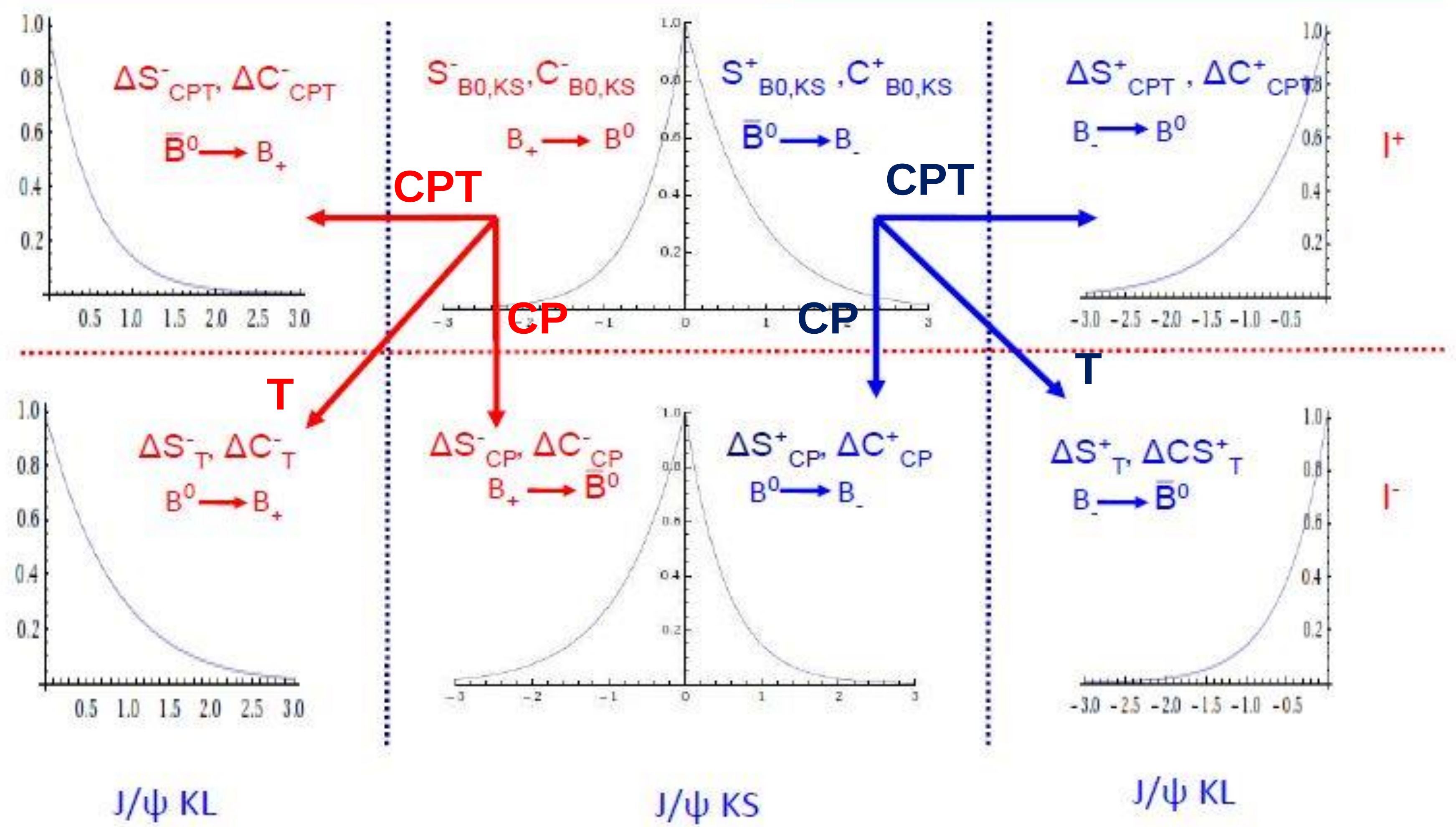
WHAT IS T-TRANSFORMATION EXPERIMENTALLY ?

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



ΔS±, ΔC± ASYMMETRY PARAMETERS

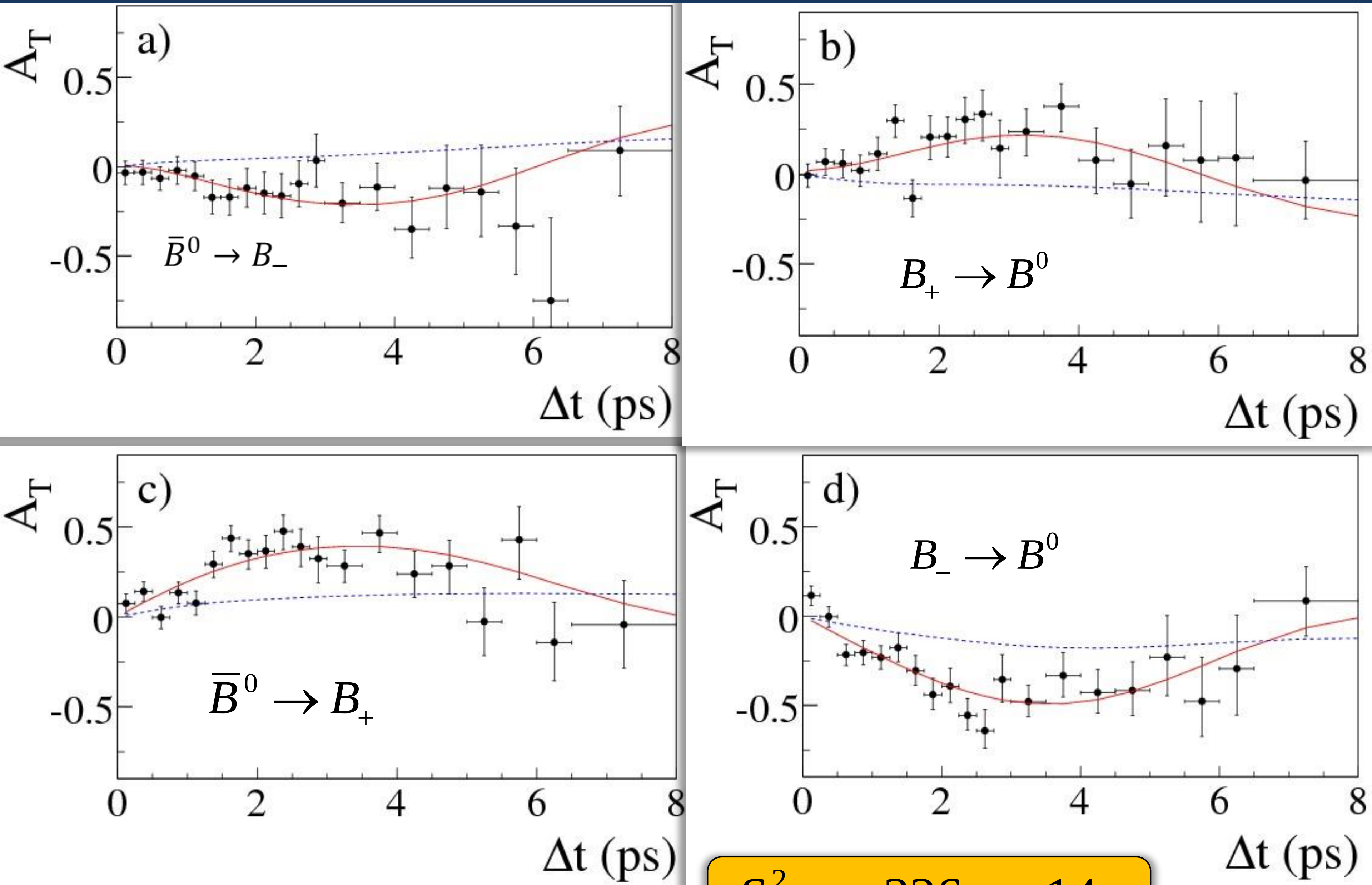
$$\mathrm{I}_i(\Delta t) \sim e^{-\Gamma\Delta t}\left\{ C_i \cos(\Delta m\Delta t) + S_i \sin(\Delta m\Delta t) + \mathrm{C'}_{\mathrm{i}} \cosh(\Delta\Gamma\Delta t) + S'_i \sinh(\Delta\Gamma\Delta t) \right\}$$



EXPERIMENTAL RESULTS

Parameter	Final result	SM expected val.
ΔS_T^+	$-1.37 \pm 0.14 \pm 0.06$	-1.36
ΔS_T^-	$1.17 \pm 0.18 \pm 0.11$	1.36
ΔC_T^+	$0.10 \pm 0.14 \pm 0.08$	0.
ΔC_T^-	$0.04 \pm 0.14 \pm 0.08$	0.
ΔS_{CP}^+	$-1.30 \pm 0.11 \pm 0.07$	-1.36
ΔS_{CP}^-	$1.33 \pm 0.12 \pm 0.06$	1.36
ΔC_{CP}^+	$0.07 \pm 0.09 \pm 0.03$	0.
ΔC_T^-	$0.08 \pm 0.10 \pm 0.04$	0.
ΔS_{CPT}^+	$0.16 \pm 0.21 \pm 0.09$	0.
ΔS_{CPT}^-	$-0.03 \pm 0.13 \pm 0.06$	0.
ΔC_{CPT}^+	$0.14 \pm 0.15 \pm 0.07$	0.
ΔC_{CPT}^-	$0.03 \pm 0.12 \pm 0.08$	0.
$S_{\ell^+,K_S^0}^+$	$0.55 \pm 0.09 \pm 0.06$	0.68
$S_{\ell^+,K_S^0}^-$	$-0.66 \pm 0.06 \pm 0.04$	-0.68
$C_{\ell^+,K_S^0}^+$	$0.01 \pm 0.07 \pm 0.05$	0.
$C_{\ell^+,K_S^0}^-$	$-0.05 \pm 0.06 \pm 0.03$	0.

T-RAW ASYMMETRIES & SIGNFICANCE



$S^2_{NoT} = 226 \qquad 14\sigma$

This Discovery was made possible thanks to the spectacular quantum properties of EPR entangled states:

"The reality of two entangled B's is much more than the sum of two separate B local realities"

The appropriate preparation of initial and final meson states based on:

1) Entanglement
2) The two decays as Filtering Measurements

PROSPECTS

- For the $K^0 - \overline{K}^0$ system in DAPHNE.
- Extension to any pair of decay channels in B-Factories

1. "Theoretical" Asymmetry in terms of initial and final **meson** states:
   S(B$_1$ → B$_2$) vs. S(TB$_2$ → TB$_1$)
2. Tag initial state from first decay to "f" in a Meson Factory:
   $$\left| B_{\not\to f} \right\rangle \alpha \left[\overline{A}_f \left| B^0 \right\rangle - A_f \left| \overline{B}^0 \right\rangle \right]$$
   using Entanglement of orthogonal states $B_{\not\to f} - B^{\perp}_{\not\to f}$
   Tagged-Filtered by the decay to "f"
3. After time-evolution, second decay and Reference $B_{\not\to f_1} \Rightarrow B^{\perp}_{\not\to f_2}$
   i.e., Experiment (f_1, f_2) ⟺ Theory $(B_{\not\to f_1}, B^{\perp}_{\not\to f_2})$
4. T-reverse transition: $B^{\perp}_{\not\to f_2} \Rightarrow B_{\not\to f_1}$
   Which is the decay channel such that: Given "f", $\exists f' : \left| B_{\not\to f'} \right\rangle = \left| B^{\perp}_{\not\to f} \right\rangle$?
   "The ortogonality problem": Flavour and CP-eigenstates privileged.

   Alternative → Bypass to 4 ⟺ New Reference in 3: $(B_{\to f_1}, B_{\to f_2})$

IS EPR-ENTANGLEMENT APPLICABLE?

- Existing and Proposed tests of separate CP, T, CPT symmetries in transitions 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 $\to$ L=1 $\to$ C= $\to$ **$\mathscr{P}$= -, antisymmetric wave function** $\leftrightarrow$

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

$\Rightarrow$ Perfect for tagging: Flavour-Tag, CP-Tag,…

- **What if the $K^0, \overline{K}^0$ Identity is lost ?**

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

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

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

$\Rightarrow$ Time evolution: ω $K^0 K^0$ terms $\longleftrightarrow$ 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 loss of quantum coherence 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. $\Rightarrow$ Apparent loss of unitarity for low-energy observers

$\Rightarrow$ Not a well-defined S-matrix between asymptotic states $\Rightarrow$ The CPT-operator is NOT well-defined [Wald]

- It should be disentangled from the case of effective theories for Lorentz violation, in which CPT breaking means [H_{eff}, CPT] ≠ 0.
- The new CPT "Violation" 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

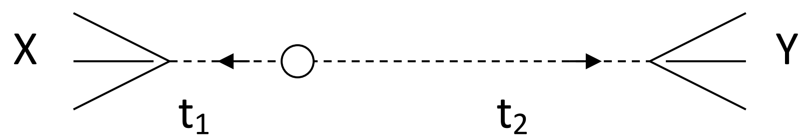
- Consider the Φ-decay amplitude

[J.B., Mavromatos, Papavassiliou]
[A. Di Domenico]

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

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

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



$$\eta_X\equiv\frac{\langle X|K_L\rangle}{\langle X|K_S\rangle}$$

- Strategy:

Choose a channel suppressed by η's: $X=Y=\pi^+\pi^-$,CP "forbidden"

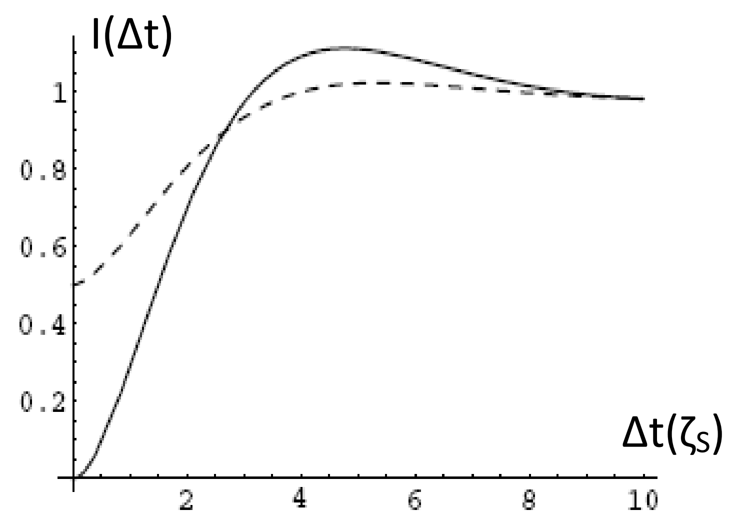
⇒ Enhanced effects $\omega/|\eta_{+-}|$

- Intensity

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

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

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



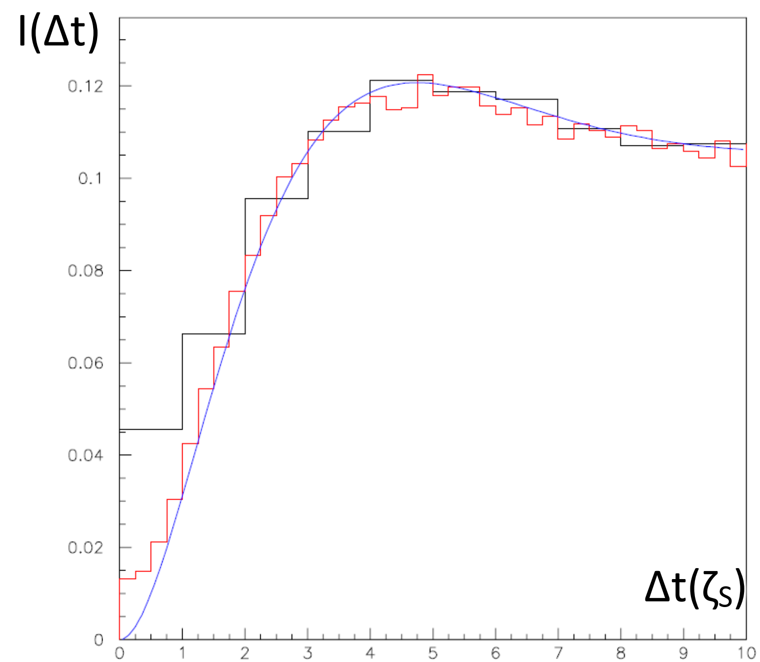
MEASUREMENT OF ω-EFFECT

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

$$\left.\begin{aligned} Re(\omega) &= (-1.6\,^{+3.0}_{-2.1\,stat} \pm 0.4_{syst})x10^{-4} \\ Im(\omega) &= (-1.7\,^{+3.3}_{-3.0\,stat} \pm 1.2_{syst})x10^{-4} \end{aligned}\right\} \quad |\omega| < 1.0 \times 10^{-3} \text{ at 95\% CL}$$

- 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 ($\pi+\pi-,\pi+\pi-$; $\Delta t=0$)=0. Hence the reconstruction of events in the region near $\Delta t \approx 0$ is crucial ⟷ vertex resolution.
- In B-factories, there is no such 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]

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



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

CONCLUSION

- CPV asymmetries well described by CKM-Mixing Matrix Mechanism.
- Current level of experimental accuracy and theoretical uncertainties leave room for additional sources of CPV.
- SM unable to explain the Matter-Antimatter Asymmetry of the Universe → New Physics!

- T-tests for unstable systems?
  Bypass → Entanglement ⊕ Decays as Filtering Measurements
- Flavour-CP channels in B decays →
  Independent Asymmetries for each CP, T, CPT
- TRV observed at 14 σ level, consistent with CPT invariance.

- CPTV search, ill-defined CPT?
  - in single K, B transitions: the α, β, γ parameterization
  - for entangled states: the ω-effect

- Prospects for a full experimental programme on T-violation and CPT-tests → Bypass the "orthogonality problem".

TWO VISIONS OF NEAR FUTURE

BACK-UP

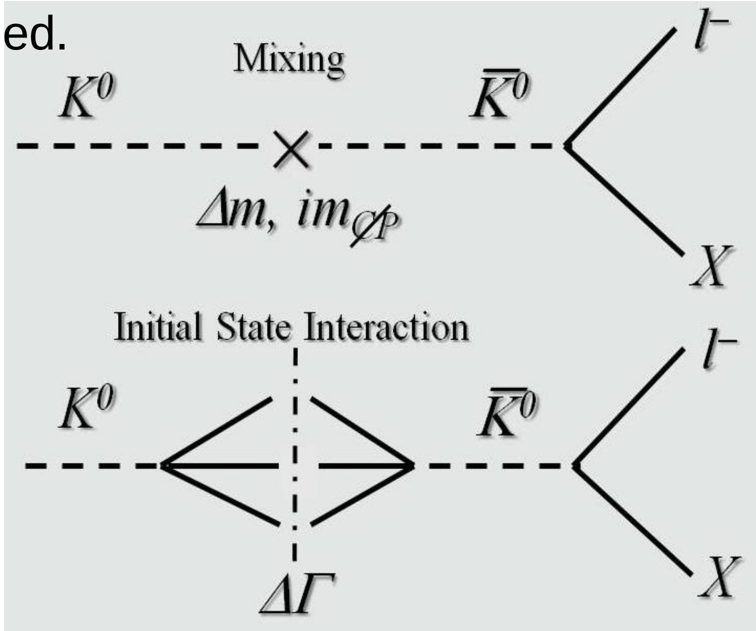
CAN TR BE TESTED IN UNSTABLE SYSTEMS?

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”.