PHYSICAL LAWS ARE ASYMMETRIC UNDER TIME REVERSAL

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TIME REVERSAL VIOLATION

Why 48 years after CP Violation?

- G. Drexlin, Karlsruhe

- V. Rubakov, Moscow

The Economist, September 2012

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Physics Today / Volume 65 / Issue 11 / Search and Discove

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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, ...
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.

“it would appear to be a true TRV effect”

THE CONCEPTUAL BASIS - THE EXPERIMENT

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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

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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

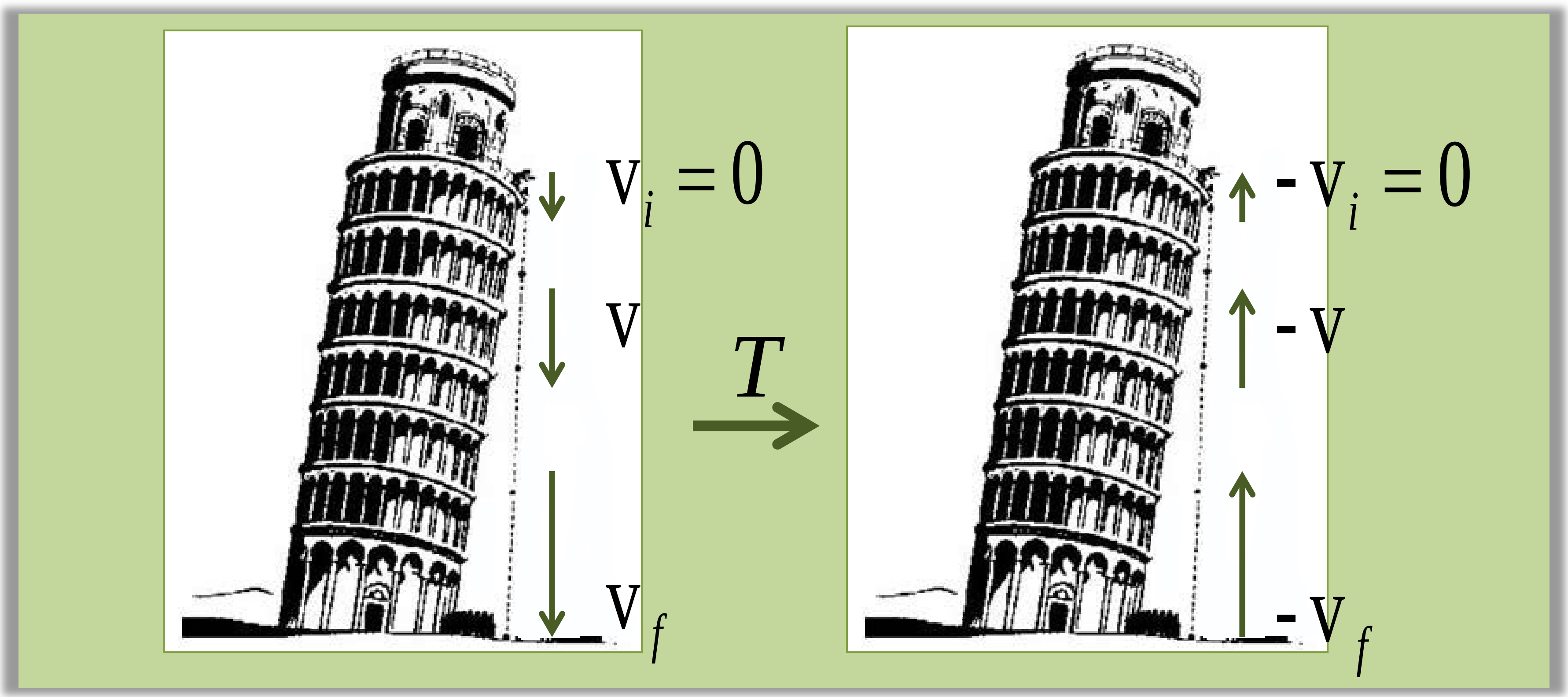
(Received 24 July 2012; published 19 November 2012)

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 $\Delta S_T^+ = -1.37 \pm 0.14(\text{stat}) \pm 0.06(\text{syst})$ and $\Delta S_T = 1.17 \pm 0.18(\text{stat}) \pm 0.11(\text{syst})$. 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

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

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:

$$S_{i\rightarrow f}\xrightarrow{\;T\;}S_{U_T f\rightarrow U_T i}$$

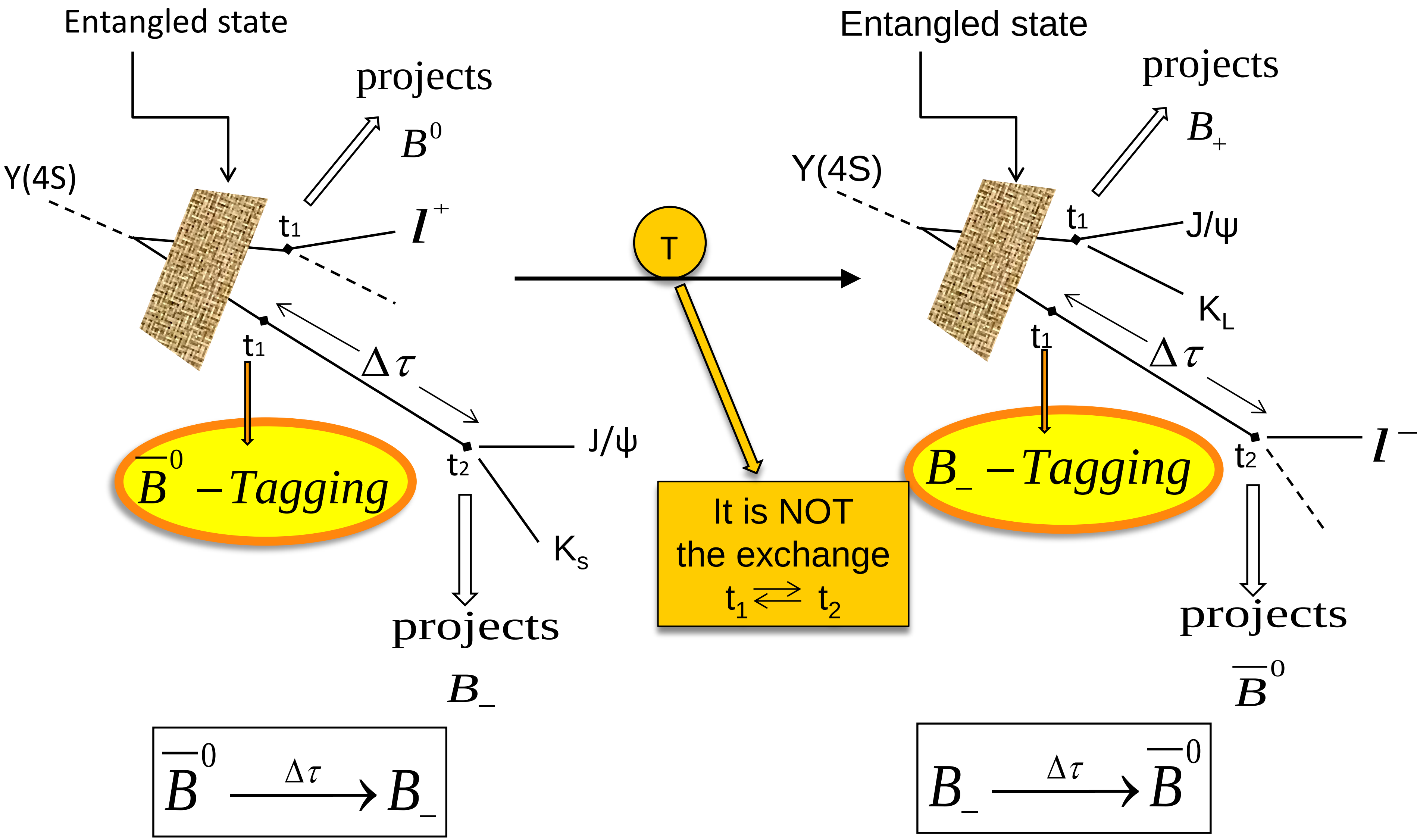
T - Violation means Asymmetry under

Interchange in $\leftrightarrows$ out states

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

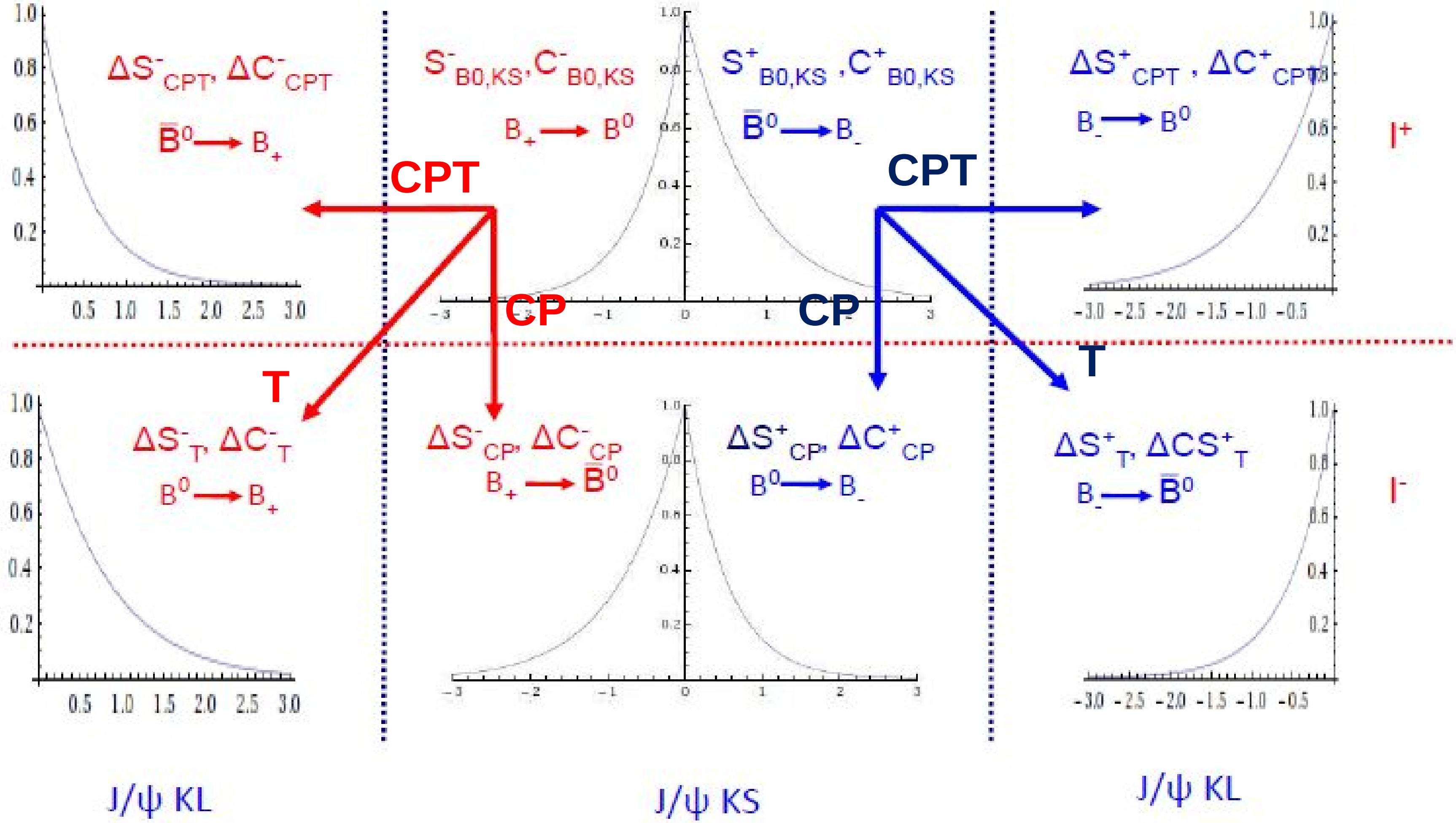
WHAT IS T-TRANSFORMATION EXPERIMENTALLY ?

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



ΔS± , ΔC± ASYMMETRY PARAMETERS

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



- Wigner-Weisskpof framework with

$$H = \begin{pmatrix} \mu - \frac{\Delta\mu}{2}\theta & \frac{p}{q}\frac{\Delta\mu}{2}\sqrt{1-\theta^2} \\ \frac{q}{p}\frac{\Delta\mu}{2}\sqrt{1-\theta^2} & \mu + \frac{\Delta\mu}{2}\theta \end{pmatrix}$$

with

$$\mu \equiv M - \frac{i}{2}\Gamma, \quad \Delta\mu = \Delta M - \frac{i}{2}\Delta\Gamma,$$

- Experimentally motivated: $\Delta\Gamma = 0$, $|q/p| = 1$
- With θ CPT violating parameter
- Probability of decay to states f_1 at t and then f_2 at $t + \Delta t$

$$\text{Prob.} \propto e^{-\Gamma t}\left\{1 + C[f_1, f_2]\,\cos(\Delta M\,\Delta t) + S[f_1, f_2]\,\sin(\Delta M\,\Delta t)\right\}$$

- For decays into f, $\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$,

$$C_f \equiv \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \quad S_f \equiv \frac{2\mathrm{Im}(\lambda_f)}{1 + |\lambda_f|^2}, \quad R_f \equiv \frac{2\mathrm{Re}(\lambda_f)}{1 + |\lambda_f|^2}$$

- Asymmetries

$$\Delta S_T = S[K_L, \ell^-] - S[\ell^+, K_S]\,, \qquad \Delta C_T = C[K_L, \ell^-] - C[\ell^+, K_S]$$
$$\Delta S_{CP} = S[\ell^-, K_S] - S[\ell^+, K_S]\,, \qquad \Delta C_{CP} = C[\ell^-, K_S] - C[\ell^+, K_S]$$
$$\Delta S_{CPT} = S[K_L, \ell^+] - S[\ell^+, K_S]\,, \qquad \Delta C_{CPT} = C[K_L, \ell^+] - C[\ell^+, K_S]$$

- At lowest order in small parameters, using the very good approximation: $C_{K_L} = C_{K_S}$, $S_{K_L} = -S_{K_S}$, $R_{K_L} = -R_{K_S}$

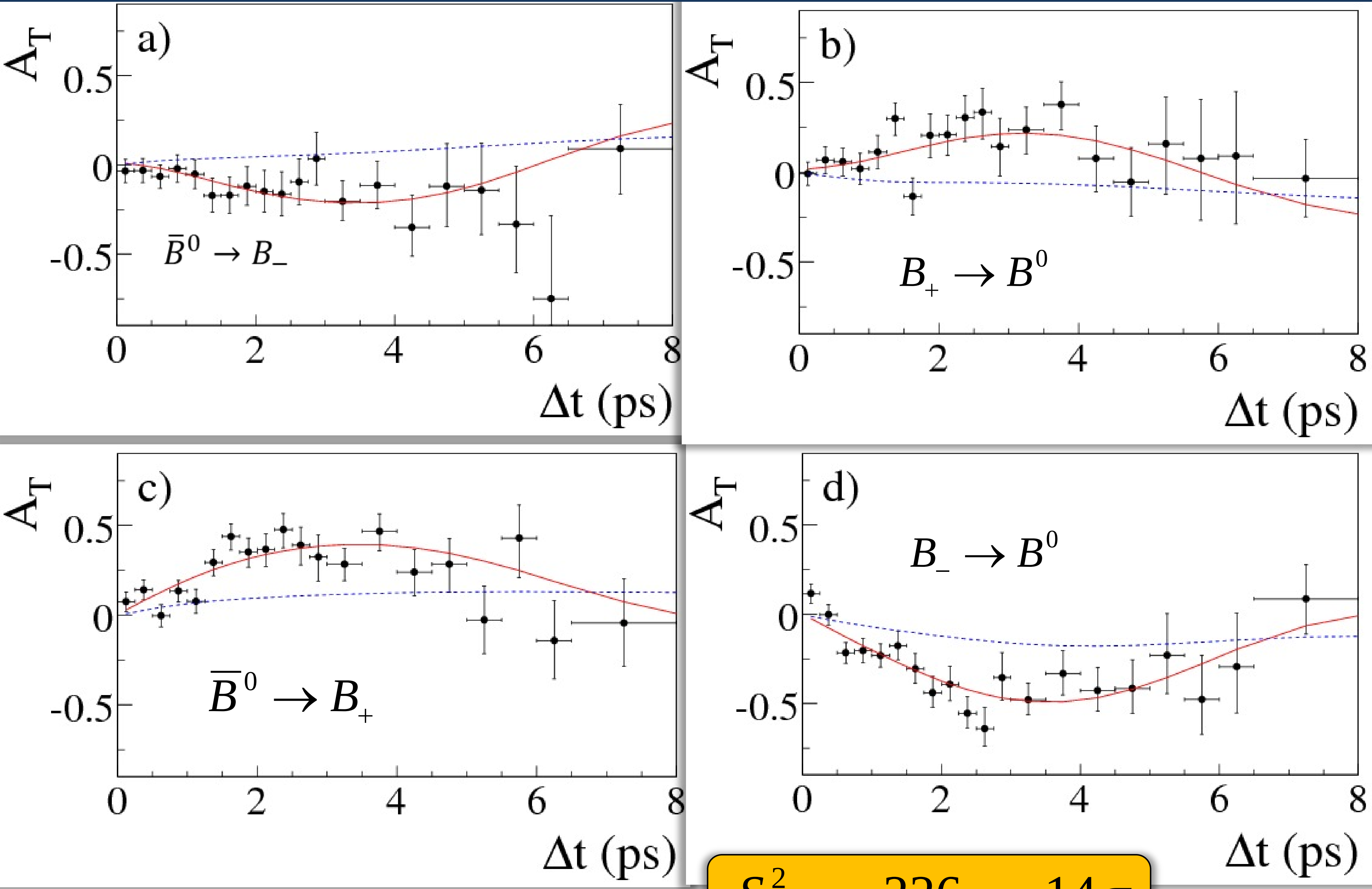
$$\Delta S_T = 2S_{K_S} - 2S_{K_S} R_{K_S} \mathrm{Re}\,\theta$$
$$\Delta C_T = 2C_{K_S} - 2S_{K_S} \mathrm{Im}\,\theta$$
$$\Delta S_{CP} = 2S_{K_S} - (1 - S^2_{K_S}) \mathrm{Im}\,\theta$$
$$\Delta C_{CP} = 2C_{K_S} + 2R_{K_S} \mathrm{Re}\,\theta$$
$$\Delta S_{CPT} = -2R_{K_S} S_{K_S} \mathrm{Re}\,\theta - 2(1 - S^2_{K_S}) \mathrm{Im}\,\theta$$
$$\Delta C_{CPT} = -2R_{K_S} \mathrm{Re}\,\theta - 2S_{K_S} \mathrm{Im}\,\theta$$

$$\Delta S_T \neq \Delta S_{CP}, \quad \Delta C_T \neq \Delta C_{CP}$$

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 $(f_1, f_2) \Leftrightarrow$ 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 $\Leftrightarrow$ New Reference in 3: $(B_{\to f_1}, B_{\to f_2})$

CONCLUSION

- T-tests for unstable systems?
  Bypass → Entanglement $\oplus$ 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.

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

TWO VISIONS OF NEAR FUTURE

BACK-UP

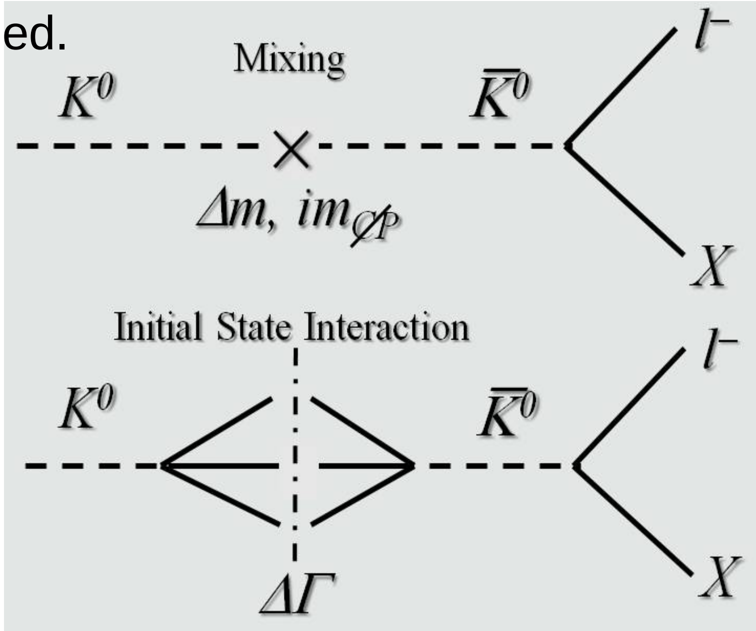
CAN TR BE TESTED IN UNSTABLE SYSTEMS?

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".