SCALARS 2013

12-16 September 2013

Warsaw, Poland

Time Reversal Violation for Entangled Neutral Mesons

José Bernabéu

IFIC-Valencia

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

TIME REVERSAL VIOLATION

Why 48 years after CP Violation?

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

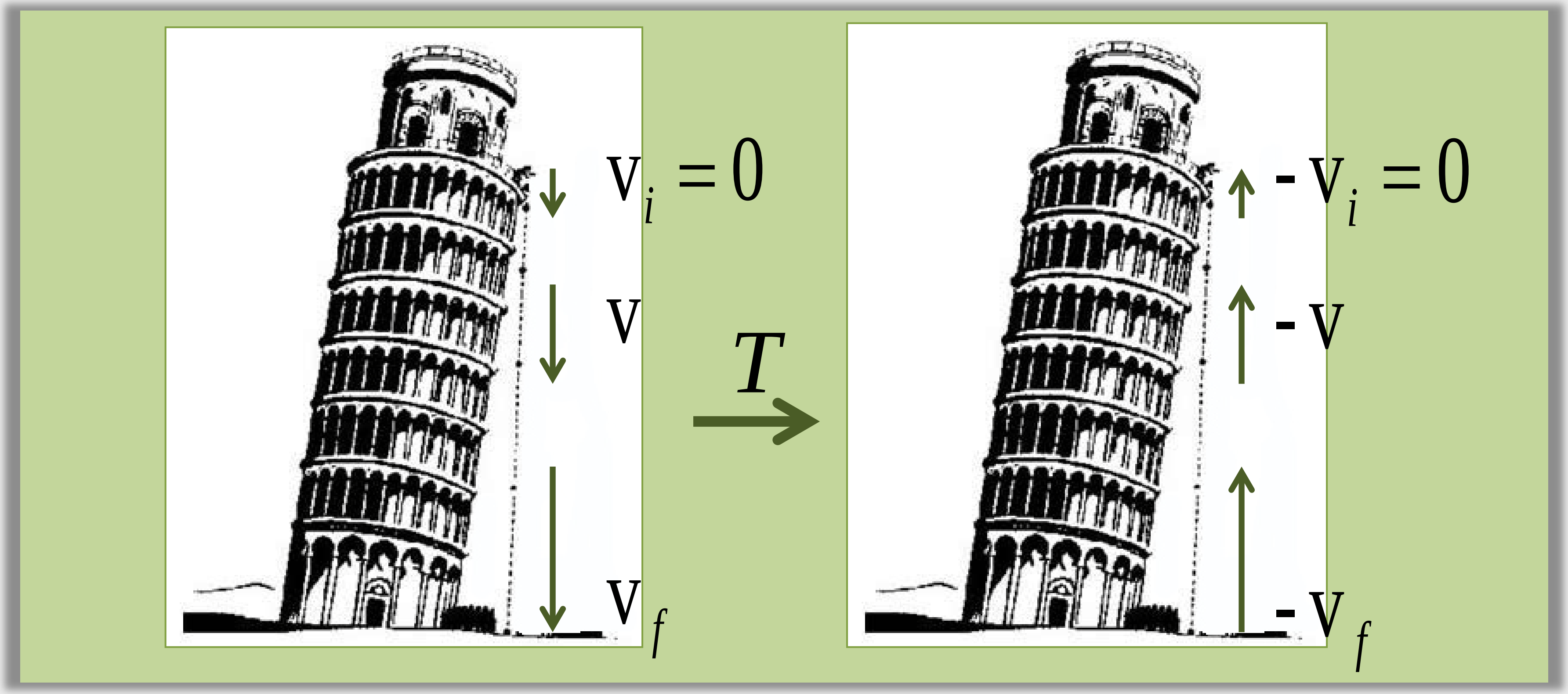
> 1964	CPV observed in the $K^0 - \overline{K}^0$ and (later) $B^0 - \overline{B}^0$ systems: unstable particles.
CPT-"Theorem"	TRV expected in these systems as well.
1998	CPLEAR $K^0 \Leftrightarrow \overline{K}^0$ needs ΔΓ; CP&T experimentally identical
< 1999	L. Wolfenstein, R.G. Sachs, …: "For a decaying state, its T-reverse does not exist“ → "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, …
PROPOSAL & SIMULATION	J.B., F. Martínez-Vidal, P. Villanueva-Pérez, JHEP (2012)
EXPERIMENTAL RESULT	BABAR Collaboration, PRL (2012)

“it would appear to be a true TRV effect”

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:

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

- We are interested in the fundamental laws of Physics, from Newton’s law to the behaviour of elementary constituents of matter and their interactions.

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 ⟷ out states

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

EPR-ENTANGLEMENT: FLAVOUR-TAG

- **For unstable particles, avoid using the decay dynamics in the observable (not needing $\Delta\Gamma$) for MESON TRANSITIONS**

- $B^0 - \overline{B}^0$ EPR-Entanglement imposed by Particle Identity:
  $B^0, \overline{B}^0$ are two states of a unique (complex) field

- The two states connected by C, so that C$\mathscr{P}$= + [$\mathscr{P}$: permutation operation].

- In neutral meson factories, $B^0 - \overline{B}^0$ produced by Υ (4S)-decay: J=1, S=0 $\Rightarrow$

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

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

where the states 1 and 2 are defined by the time of their decay with $t_1 < t_2$.

Time evolution (including the Mixing $B^0 \rightarrow \overline{B}^0$) preserves $B^0\,\overline{B}^0$ terms only.

➡ Perfect for Flavour-Tag: The observation of l^+ decay product at time t_1 tells us that the complementary (still living) state is tagged $\overline{B}^0$ at t_1, and, once the state is prepared at t_1 , we have single state time evolution for $t_1 < t < t_2$.

EPR-ENTANGLEMENT: CP-TAG

- 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 orthogonal partner!

- One can rewrite $|i\rangle$ 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/Ψ K_+, K_+ being the neutral K-meson decaying $K_+ \rightarrow \pi\pi$, and B_+ is the orthogonal to B_-, not connected to J/Ψ K_+

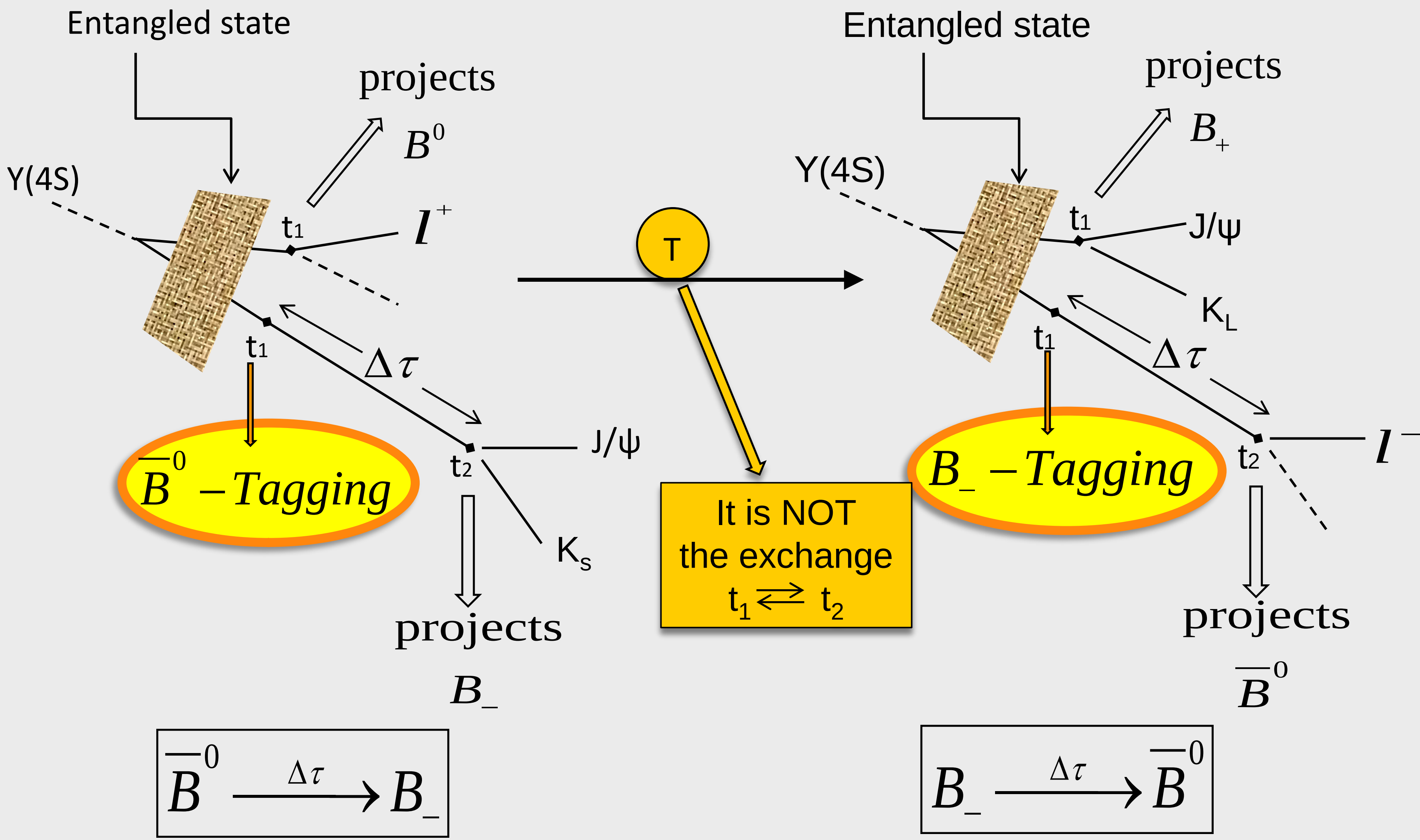
⇨ **automatic transfer of information.**

We may call the preparation of the initial state at t_1, using the filter imposed by a first observation of one of these decays, a "CP-tag", although $B\pm$ are not necessarily CP-eigenstates of B's. The same entangled state of the system can be rewritten

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

- **The decays are only used as FILTERING MEASUREMENTS**

WHAT IS T-TRANSFORMATION EXPERIMENTALLY ?



GENUINE OBSERVABLES NOT NEEDING ΔΓ

- 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 $\Delta\tau = t_2 - t_1 \rangle 0$

- Each of these 8 processes

$$I_i(\Delta\tau) \sim e^{-\Gamma\Delta\tau}\{ C_i \cos(\Delta m \Delta\tau) + S_i \sin(\Delta m \Delta\tau) + C'_i \cosh(\Delta\Gamma\Delta\tau) + S'_i \sinh(\Delta\Gamma\Delta\tau) \}$$

- For a genuine test of a symmetry, one has to compare the I_i (Δt) of a transition and its transformed. For the case of T: in <=> out

- 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 (Dictionary)

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

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

- 4 Model-Independent Asymmetries for CP and 4 for T

GENUINE TRV-ASYMMETRIES

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

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

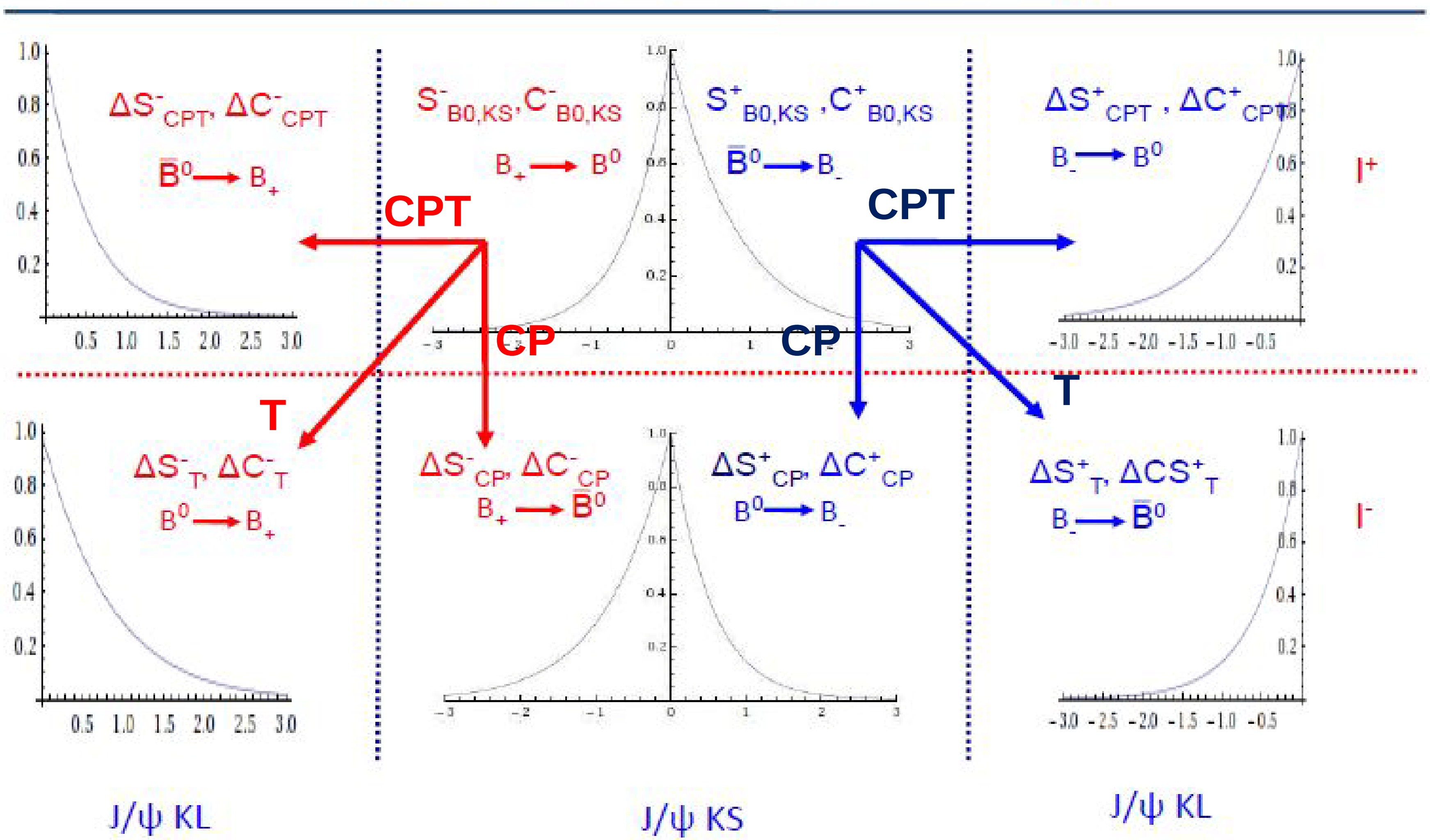
$$A_{T,3} = \frac{\Gamma\left(J/\Psi K_L, l^-\right) - \Gamma\left(l^+, J/\Psi K_S\right)}{+}$$

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

Δt

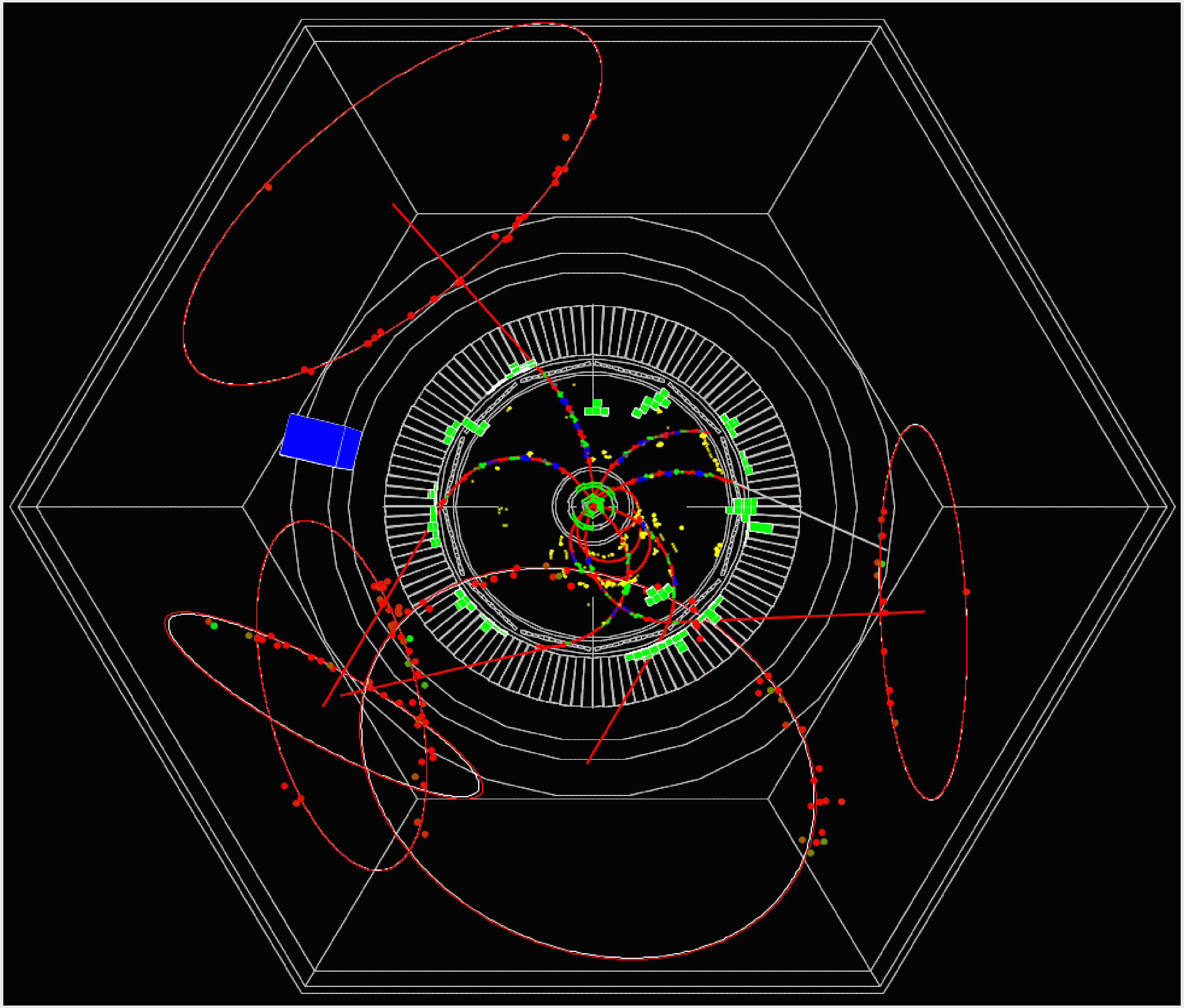
Δt

TRV $\Delta S^{\pm}$, $\Delta C^{\pm}$ parameters



EVENTS IN BABAR

Transverse cut of BABAR Detector with the electronic reconstruction of one of the hundreds of millions of interesting events. They are detected, analyzed and identified by means of a sophisticated computation system for obtaining the signal of symmetry violation under Time Reversal (Source: BABAR Collaboration).

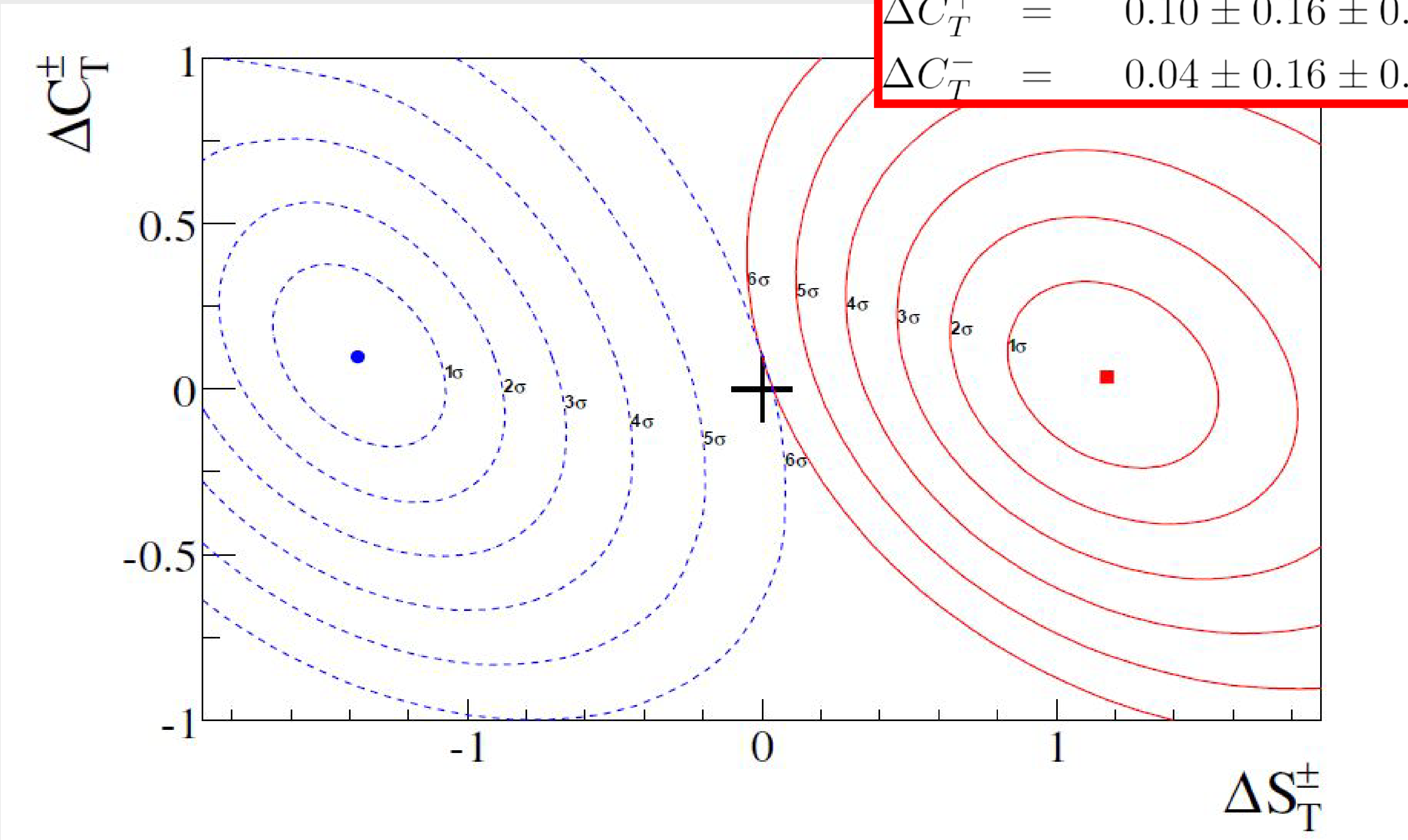


EXPERIMENTAL RESULTS

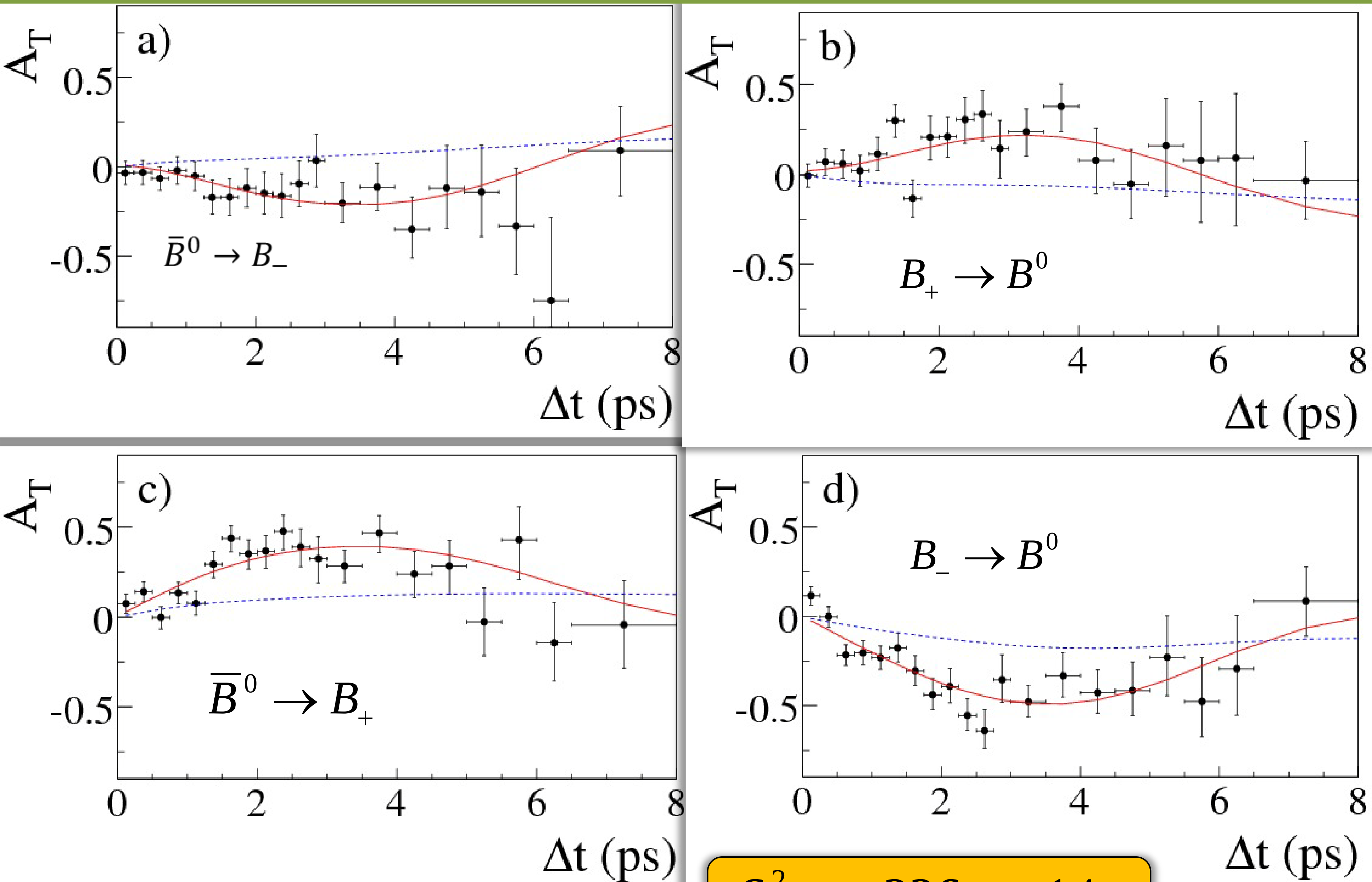
Parameter	Final result	SM expected val.
ΔS_T^+	$-1.37 \pm 0.14 \pm 0.06$	-1.34
ΔS_T^-	$1.17 \pm 0.18 \pm 0.11$	1.34
ΔC_T^+	$0.10 \pm 0.14 \pm 0.08$	0.
ΔC_T^-	$0.04 \pm 0.14 \pm 0.08$	0.
ΔS_{CP}^+	$-1.30 \pm 0.11 \pm 0.07$	-1.34
ΔS_{CP}^-	$1.33 \pm 0.12 \pm 0.06$	1.34
ΔC_{CP}^+	$0.07 \pm 0.09 \pm 0.03$	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.
$S_{\ell+,K_S^0}^+$	$0.55 \pm 0.09 \pm 0.06$	0.67
$S_{\ell+,K_S^0}^-$	$-0.66 \pm 0.06 \pm 0.04$	-0.67
$C_{\ell+,K_S^0}^+$	$0.01 \pm 0.07 \pm 0.05$	0.
$C_{\ell+,K_S^0}^-$	$-0.05 \pm 0.06 \pm 0.03$	0.

INTERPRETATION OF THE RESULTS

$$
\begin{aligned}
\Delta S_T^+ &= -1.37 \pm 0.14 \pm 0.06 \\
\Delta S_T^- &= 1.17 \pm 0.18 \pm 0.11 \\
\Delta C_T^+ &= 0.10 \pm 0.16 \pm 0.08 \\
\Delta C_T^- &= 0.04 \pm 0.16 \pm 0.08
\end{aligned}
$$



T RAW ASYMMETRIES & SIGNFICANCE



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

CONCLUSION

- Observed t-Asymmetries in complex systems, like the Arrow of Time, are not T-violating: Genuine TRV means Asymmetry under in $\leftrightarrows$ out

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

- Flavour-CP Channels $\longrightarrow$ 8 different Decay-Intensities.

In appropriate combinations,

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

2 Independent Asymmetry parameters for each CP, T, CPT

- T-violating parameters in the time evolution of a neutral B meson, between flavour and CP decay times, have been measured by BABAR.

BABAR observes a large deviation of T invariance at 14 σ level, far more than needed to declare a Discovery.

- The results are consistent with CPT invariance in the time-evolution of the $B^0 - \overline{B}^0$ system, connecting CPV and TRV in DIFFERENT transitions.

This is the first direct observation of Time Reversal Violation in the time evolution of any system.

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 for the T-study is based on:

1) Entanglement
2) The decay as a Filtering Measurement

PERSPECTIVE

- For $K^0 \to \overline{K}^0$ system in Φ-Factory, again with Flavour-CP,

  J.B., A. Di Domenico, P. Villanueva-Pérez, NPB (2012)

- Opening of TRV test to any pair of decay channels, beyond Flavour-CP?
  - Confrontation with "orthogonality problem"
  - Alternative Asymmetry

	OLD		NEW
REFERENCE TRANSITION	$P_{\nrightarrow f_1}(t_1) \to P^{\perp}_{\nrightarrow f_2}(t_2)$	$\Longrightarrow$	$P_{\nrightarrow f_1}(t_1) \to P_{\nrightarrow f_2}(t_2)$
T TRANSFORMED TRANSITION	$P^{\perp}_{\nrightarrow f_2}(t_1) \to P_{\nrightarrow f_1}(t_2)$	$\Longrightarrow$	$P_{\nrightarrow f_2}(t_1) \to P_{\nrightarrow f_1}(t_2)$

J.B., F.J. Botella, M. Nebot, arXiv:1309.0439 [hep-ph] 2 Sep 2013

The way is open to a full experimental programme of studies for T violation observables at meson factories

BACK-UP

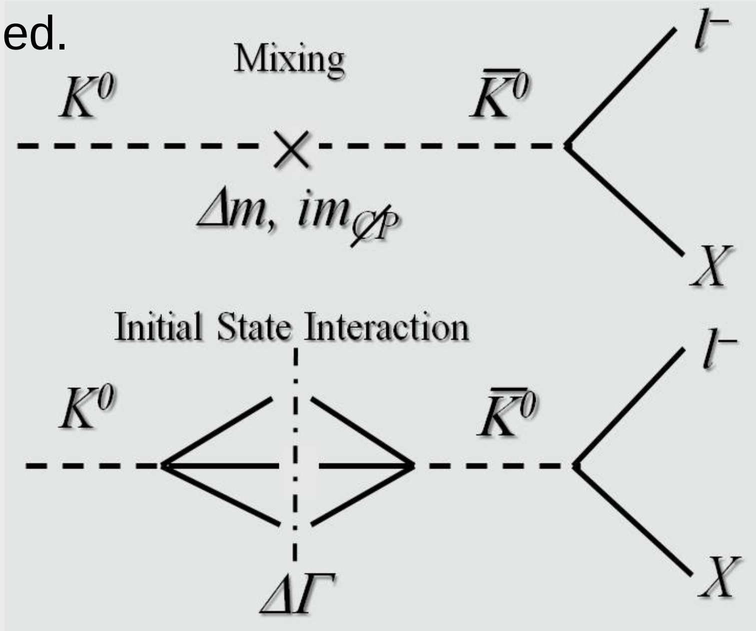
CAN TR BE TESTED IN UNSTABLE SYSTEMS?

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".