FLAVOUR PHYSICS
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THE FIRST DIRECT OBSERVATION OF TIME REVERSAL VIOLATION

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OUTLINE

- Symmetries in the Laws of Physics
- Universe t-Asymmetry, the “Arrow of Time”
- Is it possible to search for TRV in unstable systems?
- EPR-Entanglement: Flavour-Tag, CP-Tag
- Genuine Observables in B-factories: not needing $\Delta\Gamma$
- T-violating parameters
- CPV, TRV, CPTV Asymmetries
- Foundations of the Experimental Analysis
- T raw asymmetries & Significance, from BABAR
- Conclusions

SYMMETRIES IN THE LAWS OF PHYSICS

- ”Microscopic” Symmetry Violations.
- T-Violation exists in the Standard Model or any field theoretic extension.
- All field theories with Lorentz invariance have CPT symmetry

⇨ Automatic connection between CP-violation $\longleftrightarrow$ related T-violation

- T and CPT described by ANTIUNITARY rather than unitary operators, introducing many intriguing subtleties.

⇨ Observed CP-Violation $\Longrightarrow$ T should be violated as well: Is it observed?

T - Violation means Asymmetry under

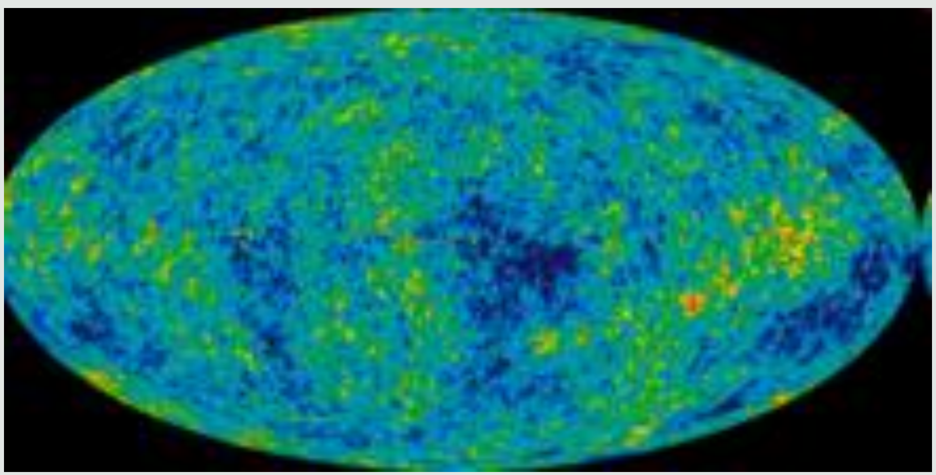
Interchange in $\leftrightarrows$ out states

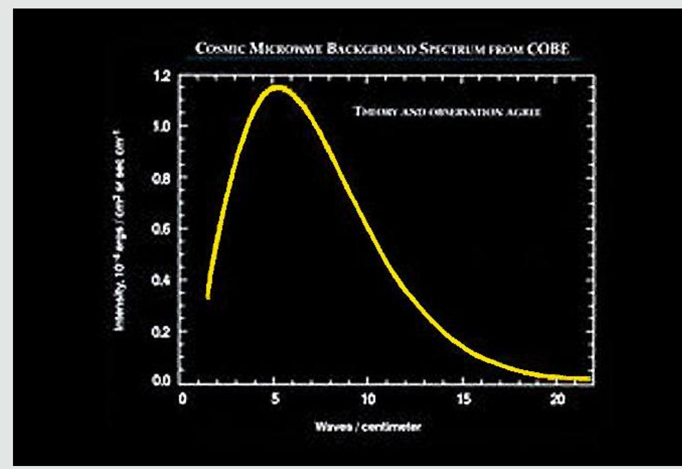
- Effects in particle physics odd under t $\leftrightarrows$ -t are <u>not</u> necessarily T-violating.
- t- asymmetries can occur in theories with exact T- symmetry.

UNIVERSE t - ASYMMETRY

- No doubt Universe is expanding, even accelerating $\rightarrow$ asymmetry t $\leftrightarrows$ -t
- BUT this is perfectly compatible with laws of physics that are TR symmetric
- This t-asymmetry is due to the initial condition of <u>our</u> Universe $\longrightarrow$ Inflation?
- Similar to the fact that in <u>our</u> Universe we have a privileged reference frame

  $\longleftrightarrow$ CMB radiation with same temperature





- BUT this is not a violation of Lorentz invariance of the laws of physics

THE "ARROW OF TIME"

- Macroscopic t-asymmetry
- Nature of Thermodynamics $\Longrightarrow$ (Eddington)

  Time's Arrow is a property of ENTROPY alone

Time is asymmetric with respect to the amount of order in an isolated system.

- Unsolved problem?

Is quantum wave function collapse related to the thermodynamic arrow of time?

- In particle physics,

Particle <u>Decay</u> is an example of a time-asymmetric process:

The mismatch between the <u>preparation</u> of P $\longrightarrow$ 1 +…+ n and 1+…+n $\longrightarrow$ P is <u>not</u> related to T-violation. In fact, it looks like it prevents a true test of T-symmetry in unstable systems [Wolfenstein, Quinn]

- Any connection between the Universe t-asymmetry and the "arrow of time"?

Probably YES, saying that the initial condition was improbable: more ordered.

- But none of these t-asymmetries is a test of TRV

CAN TR BE TESTED IN UNSTABLE SYSTEMS?

- 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

- No existing result up to now had demonstrated TRV in this sense.

Two types of experiments can do it:

1) A non-zero expectation value of a T-odd operator for a non-degenerate stationary state $\longrightarrow$ Electric Dipole Moment: P-odd, C-even, T-odd

It can be generated by either

- Strong T-violation $\longrightarrow$ θ-term $\epsilon_{\mu\nu\varsigma\sigma}\ F^{\mu\nu}\ F^{\varsigma\sigma}$ [Peccei & Quinn], or
- Weak T-violation

2) in $\leftrightarrows$ out: $S_{f,i} \longrightarrow S_{-i,-f}$ transition.

The Kabir asymmetry $K^0 \to \overline{K}^0$ *vs.* $\overline{K}^0 \to K^0$ has been measured in CP-LEAR with non-vanishing value. But $K^0 \to \overline{K}^0$ is a CPT-even transition, so CP≡T here! This is apparent in that the effect is t-independent and proportional to ΔΓ

CP-Violation observed in Mixing x Decay transitions. Is it possible to search for TRV ?

NEUTRAL MESON FACTORIES

EPR-ENTANGLEMENT: FLAVOUR-TAG

- The opportunity arises [M.C. Bañuls, J.B.] from the Quantum Mechanical

Entanglement imposed by the EPR correlation:

one can have SEPARATE tests of CP, T and CPT!

- $B^0 - \overline{B}^0$ 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 Y (4S)-decay: J=1, S=0 $\Rightarrow$

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

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

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

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

$\Rightarrow$ Perfect for Flavour-Tag: The observation of $B^0 \to l^+$, for example, at time t_1, tells us that the complementary (still living) state is $\overline{B}^0$ 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 li> in terms of any other pair of orthogonal states of the individual neutral B-mesons:

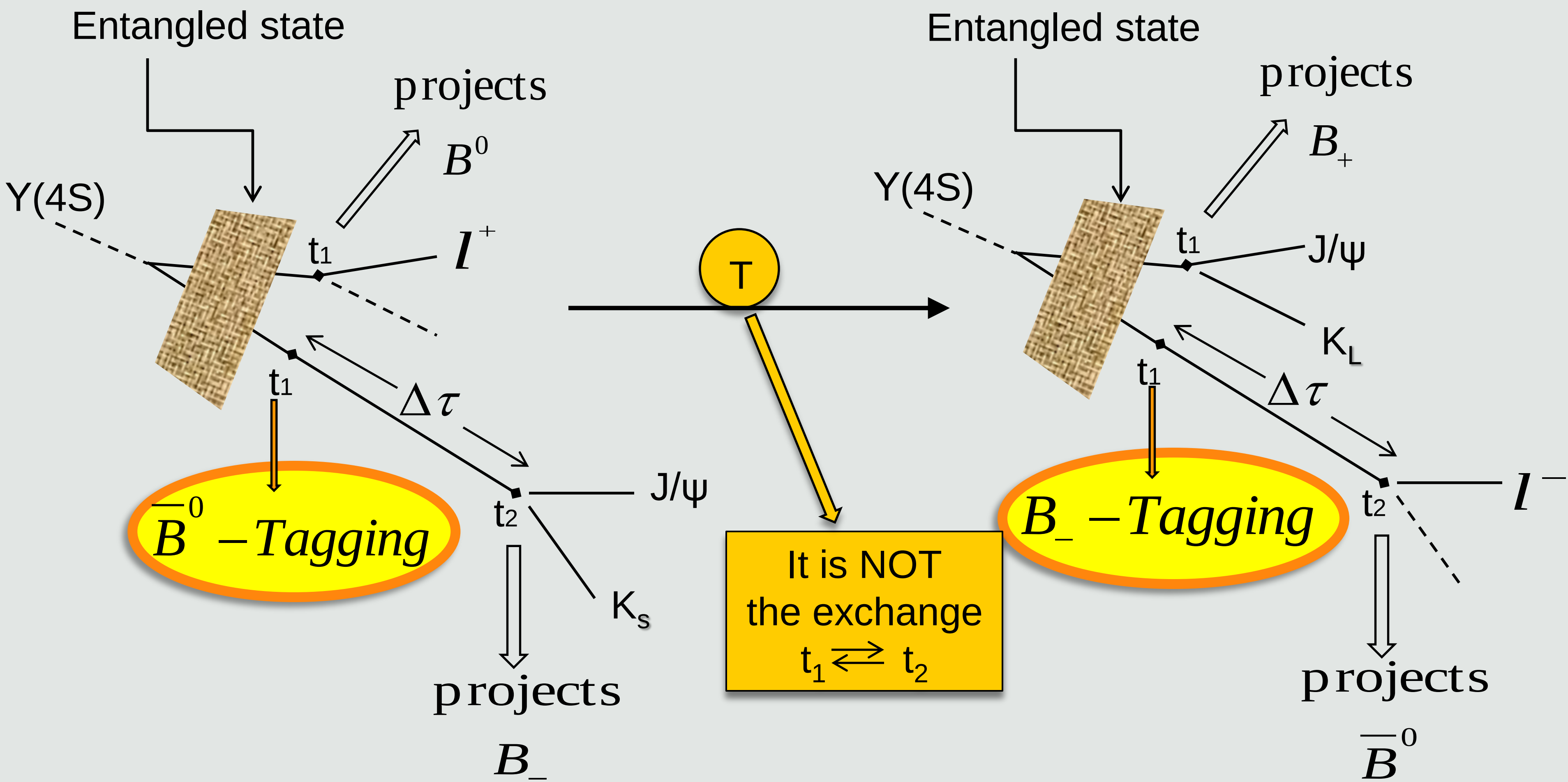
Consider B_+ and B_-, where B_- is filtered by the decay J/Ψ K_+, K_+ being the neutral K-meson decaying $K_+ \rightarrow \pi\pi$, and B_+ is the orthogonal to B_-, not connected to J/Ψ K_+.

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 CP-eigenstates of B’s necessarily.

The same entangled state of the system can be rewritten

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

WHAT IS T-TRANSFORMATION EXPERIMENTALLY?



$$\boxed{\overline{B}^0 \xrightarrow{\Delta\tau} B_-}$$

$$\boxed{B_- \xrightarrow{\Delta\tau} \overline{B}^0}$$

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

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

- For a genuine test of a symmetry, one has to compare the I_i (Δt) of a transition and its transformed.
- Careful: Up to now, for CPV analyses in B-factories, BABAR & BELLE have assumed CPT-invariance and $\Delta\Gamma = 0$:

⇨ Then Δt $\leftrightarrows$ -Δt exchange, which is NOT TR-operation, [M.C.Bañuls, J.B.] becomes equivalent to TR.

⇨ Only 2 independent Intensities to be compared, if CP ~T ~Δt are connected.

⇨ Alternatively, one may establish $S_i \neq 0$ for a single transition.

INTERLUDE: 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 Matrix**.

- The existence of this matrix conveys the fact that the quarks which participate to weak processes are a linear combination of mass eigenstates

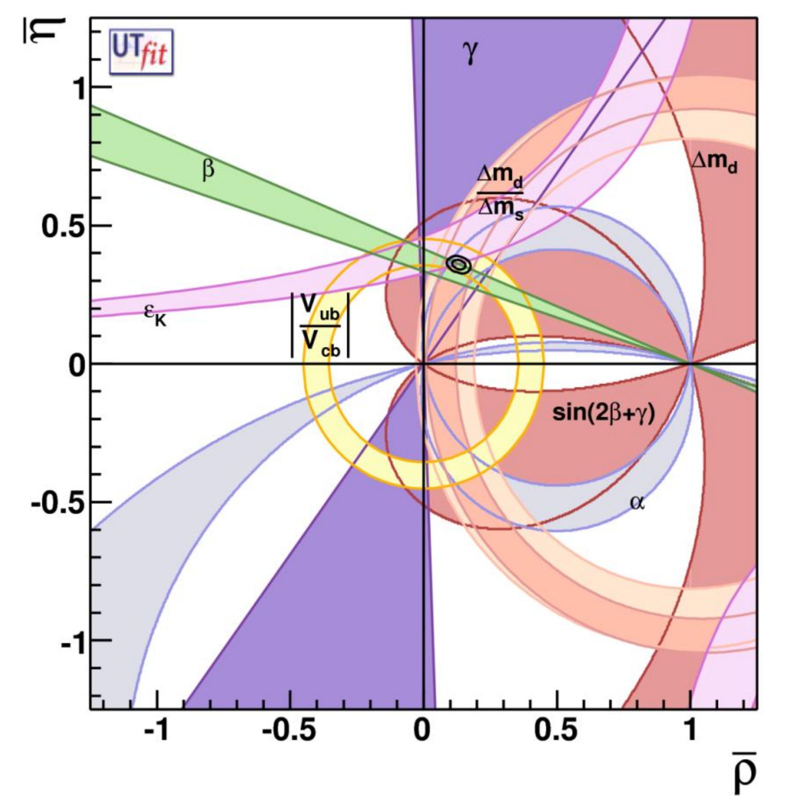
- The unitarity conditions can be represented by triangles in the complex plane.

- 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:

$S_i \sim \sin(2\beta) = 0.67 \pm 0.02$



GENUINE OBSERVABLES NOT NEEDING ΔΓ

- 1) 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

Transition	$B^0 \to B_+$	$\overline{B}^0 \to B_+$	$B_+ \to B^0$	$B_+ \to \overline{B}^0$
(X,Y)	$(l^-, J/\Psi K_L)$	$(l^+, J/\Psi K_L)$	$(J/\Psi K_S, l^+)$	$(J/\Psi K_S, l^-)$
Transformation	Reference	CP	T	CPT

<u>Exercise:</u> Check that the 4 processes are experimentally independent and that Δt-exchange (in the same experimental "sample") X ⇆ Y is NOT in the Table

- 2)Take $B^0 \to B_-$ as the Reference transition. The CP, T and CPT transformed transitions are

Transition	$B^0 \to B_-$	$\overline{B}^0 \to B_-$	$B_- \to B^0$	$B_- \to \overline{B}^0$
(X,Y)	$(l^-, J/\Psi K_S)$	$(l^+, J/\Psi K_S)$	$(J/\Psi K_L, l^+)$	$(J/\Psi K_L, l^-)$
Transformation	Reference	CP	T	CPT

⇒ A second Asymmetry for each of the 3 transformations can be built!

- 3) Select (Y,X) from 1) as Reference.
- 4) Select (Y,X) from 2) as Reference.
- Only QM EPR-Entanglement and time resolution assumed.

⇒ 4 Model-Independent Asymmetries for CP $\oplus$ 4 Model-Independent Asymmetries for T

T-VIOLATING PARAMETERS

- Asymmetries in time dependent decay rates for any pair of T-conjugated transitions would be apparent through differences between $S^{\pm}_{\alpha,\beta}$ or $C^{\pm}_{\alpha,\beta}$
- Example:

  A significant difference between the $S^{+}_{\ell+,K_S}$ and $S^{-}_{\ell-,K_L}$ coefficients implies observation of T violation.
- In the standard model these coeficients are related as a consequence of CPT invariance and $\Delta\Gamma = 0$ [J.B., M.C.Bañuls]

$$S = S^{+}_{l^+,K_S} = -S^{+}_{l^-,K_S} = -S^{-}_{l^+,K_S} = S^{-}_{l^-,K_S} =$$

$$-S^{+}_{l^+,K_L} = S^{+}_{l^-,K_L} = S^{-}_{l^+,K_L} = -S^{-}_{l^-,K_L} \approx 0.7$$

$$C = C^{+}_{l^+,K_S} = -C^{+}_{l^-,K_S} = C^{-}_{l^+,K_S} = -C^{-}_{l^-,K_S} =$$

$$C^{+}_{l^+,K_L} = -C^{+}_{l^-,K_L} = C^{-}_{l^+,K_L} = -C^{-}_{l^-,K_L} \approx 0$$

- Any non-vanishing value of the asymmetry parameters

$$\Delta S^{+}_{\mathrm{T}} = S^{-}_{\ell-,K_L} - S^{+}_{\ell+,K_S}$$

$$\Delta S^{-}_{\mathrm{T}} = S^{+}_{\ell-,K_L} - S^{-}_{\ell+,K_S}$$

$$\Delta C^{+}_{\mathrm{T}} = C^{-}_{\ell-,K_L} - C^{+}_{\ell+,K_S}$$

$$\Delta C^{-}_{\mathrm{T}} = C^{+}_{\ell-,K_L} - C^{-}_{\ell+,K_S}$$

measures T violation in the time evolution between the two decays.

GENUINE CPV-ASYMMETRIES

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

Δt

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

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

Δt

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

GENUINE TRV-ASYMMETRIES

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

Δt

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

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

Δt

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

GENUINE CPTV-ASYMMETRIES

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

Δt

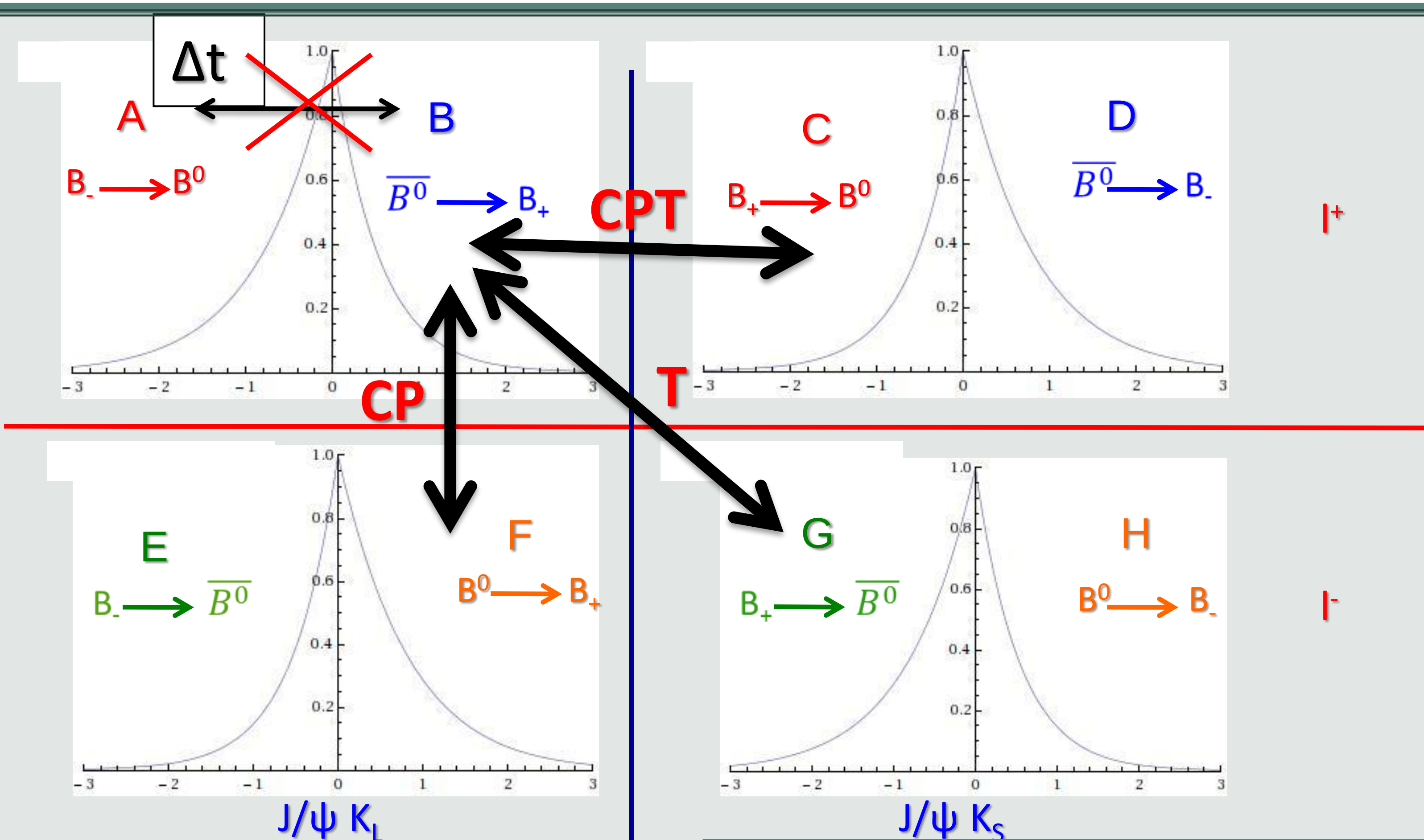
$$A_{CPT,2} = \frac{\Gamma\left(l^-, J/\Psi K_S\right) - \Gamma\left(J/\Psi K_L, l^-\right)}{+}$$

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

Δt

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

FOUNDATIONS OF THE ANALYSIS



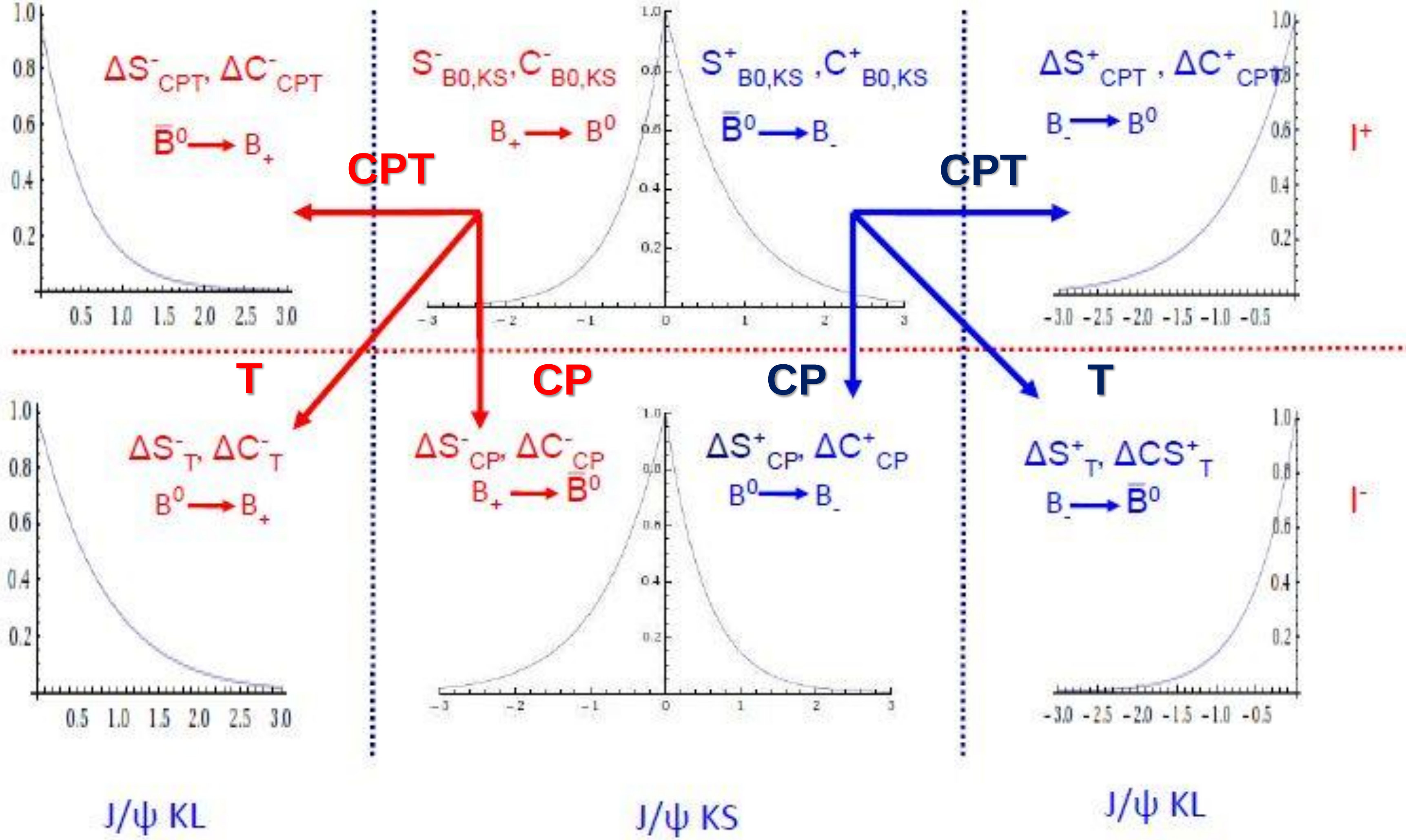
In total we can build:

- 4 Independent T comparisons.
- 4 Independent CP comparisons.
- 4 Independent CPT comparisons.

T implies comparison of:

1) "Opposite Δt sign", i.e. , in ↔ out
2) Different CP states (J/ΨK_S vs. J/ΨK_L)
3) Opposite flavour states $\left(B^0 \; vs. \; \overline{B}^0 \right)$

ΔS± , ΔC± parameters

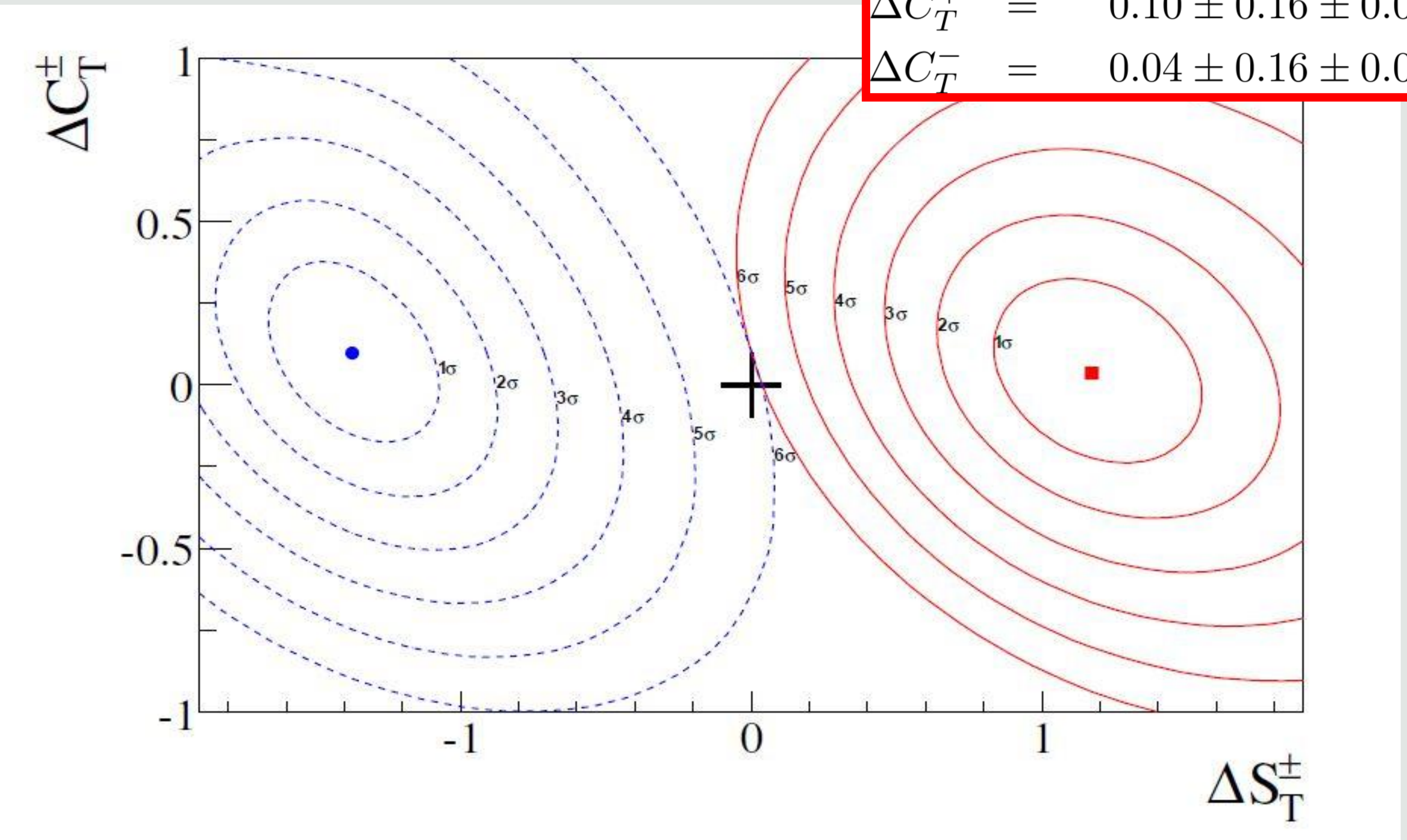


EXPERIMENTAL RESULTS

	PARAMETER	FINAL RESULT	
T	ΔS_T^+	$-1.37 \pm 0.14 \pm 0.06$	
	ΔS_T^-	$1.17 \pm 0.18 \pm 0.11$	
	ΔC_T^+	$0.10 \pm 0.16 \pm 0.08$	
	ΔC_T^-	$1.04 \pm 0.16 \pm 0.08$	
	ΔS_{CP}^+	$-1.30 \pm 0.10 \pm 0.07$	CP
	ΔS_{CP}^-	$1.33 \pm 0.12 \pm 0.06$	
	ΔC_{CP}^+	$0.07 \pm 0.09 \pm 0.03$	
	ΔC_{CP}^-	$0.08 \pm 0.10 \pm 0.04$	
CPT	ΔS_{CPT}^+	$0.16 \pm 0.20 \pm 0.09$	
	ΔS_{CPT}^-	$-0.03 \pm 0.13 \pm 0.06$	
	ΔC_{CPT}^+	$0.15 \pm 0.17 \pm 0.07$	
	ΔC_{CPT}^-	$0.03 \pm 0.14 \pm 0.08$	
	$S_{B^0,K_S^0}^+$	$0.545 \pm 0.084 \pm 0.06$	REF.
	$S_{B^0,K_S^0}^-$	$-0.660 \pm 0.059 \pm 0.04$	
	$C_{B^0,K_S^0}^+$	$0.011 \pm 0.064 \pm 0.05$	
	$C_{B^0,K_S^0}^-$	$0.049 \pm 0.056 \pm 0.03$	

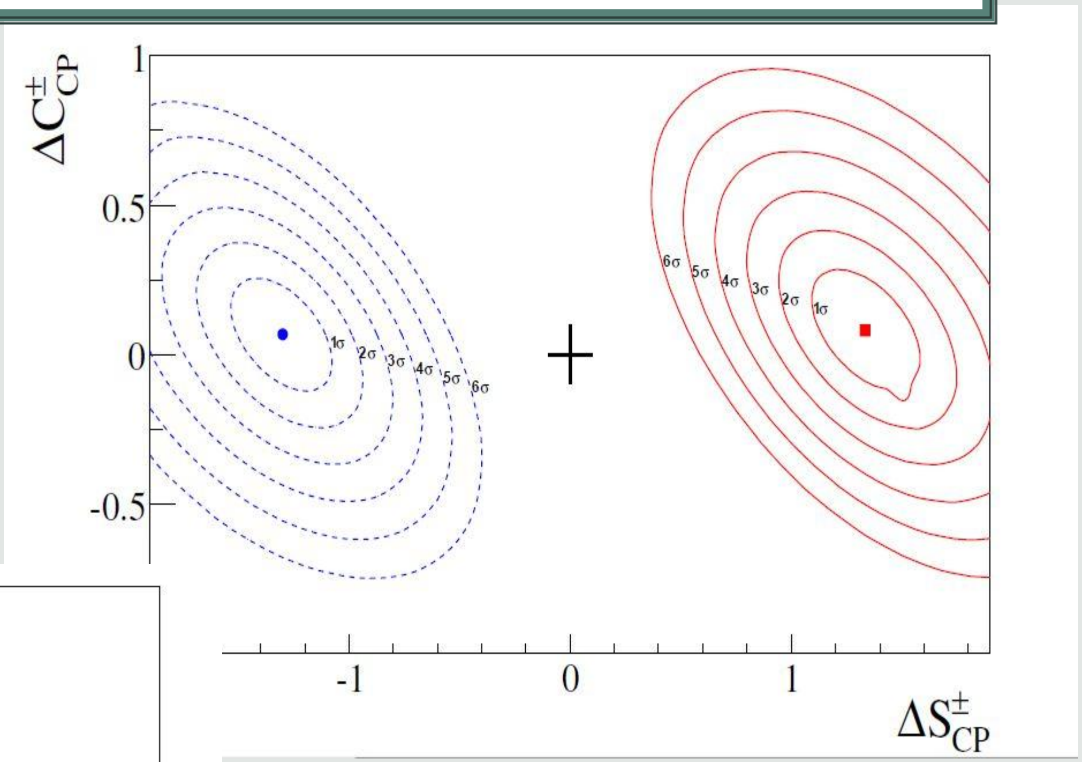
INTERPRETATION OF THE RESULTS

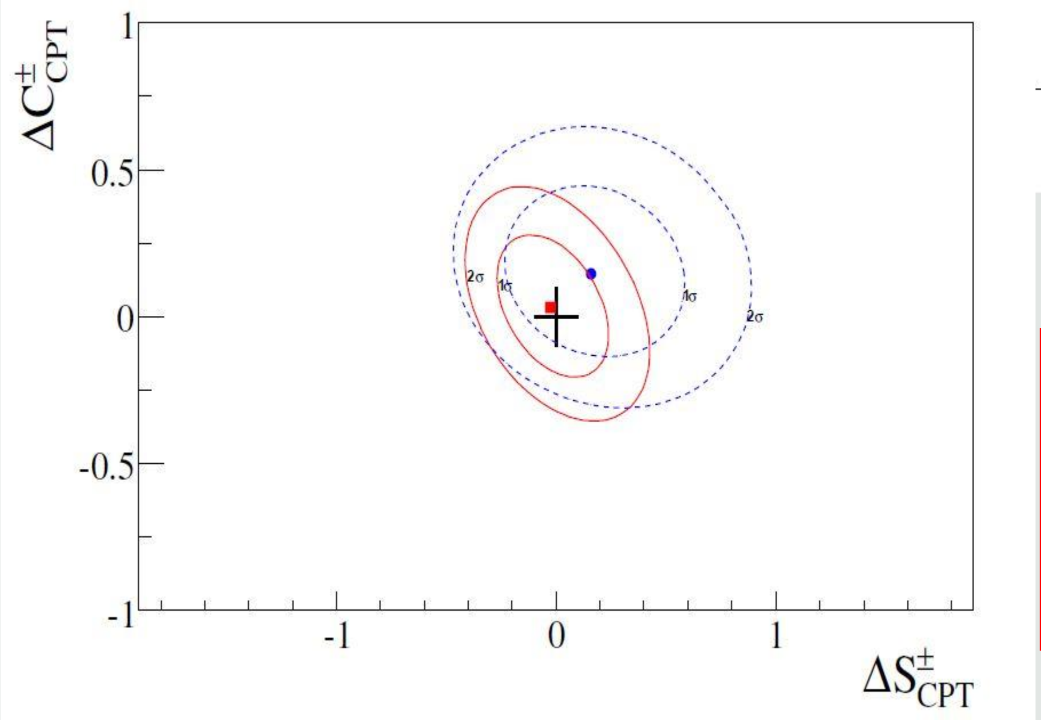
$$\begin{aligned}
\Delta S_T^+ &= -1.37 \pm 0.14 \pm 0.06 \\
\Delta S_T^- &= 1.17 \pm 0.18 \pm 0.11 \\
\Delta C_T^+ &= 0.10 \pm 0.16 \pm 0.08 \\
\Delta C_T^- &= 0.04 \pm 0.16 \pm 0.08
\end{aligned}$$



INTERPRETATION OF THE RESULTS

$$
\begin{aligned}
\Delta S^{+}_{CP} &= -1.30 \pm 0.10 \pm 0.07 \\
\Delta S^{-}_{CP} &= 1.33 \pm 0.12 \pm 0.06 \\
\Delta C^{+}_{CP} &= 0.07 \pm 0.10 \pm 0.03 \\
\Delta C^{-}_{CP} &= 0.08 \pm 0.09 \pm 0.04
\end{aligned}
$$



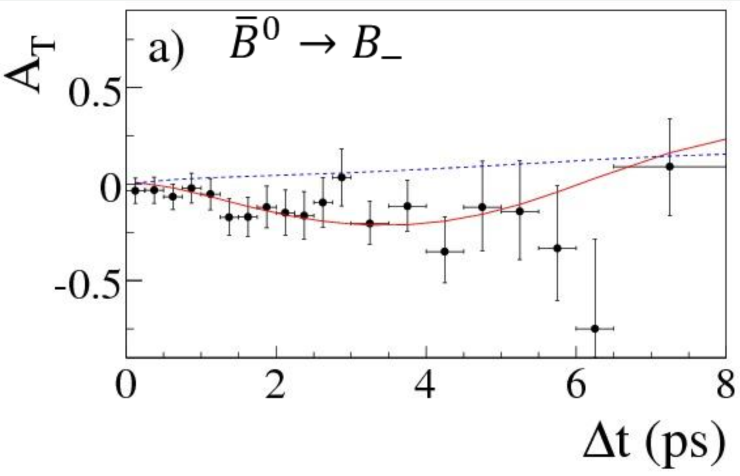


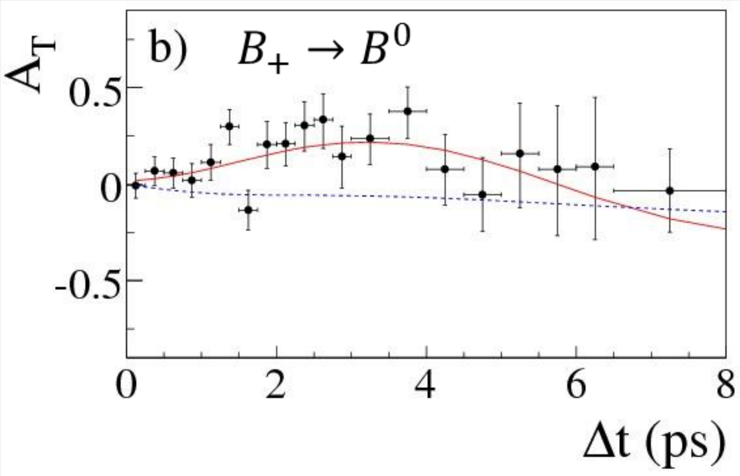
$$
\begin{aligned}
\Delta S^{+}_{CPT} &= 0.16 \pm 0.20 \pm 0.09 \\
\Delta S^{-}_{CPT} &= -0.03 \pm 0.13 \pm 0.06 \\
\Delta C^{+}_{CPT} &= 0.15 \pm 0.17 \pm 0.07 \\
\Delta C^{-}_{CPT} &= 0.03 \pm 0.14 \pm 0.08
\end{aligned}
$$

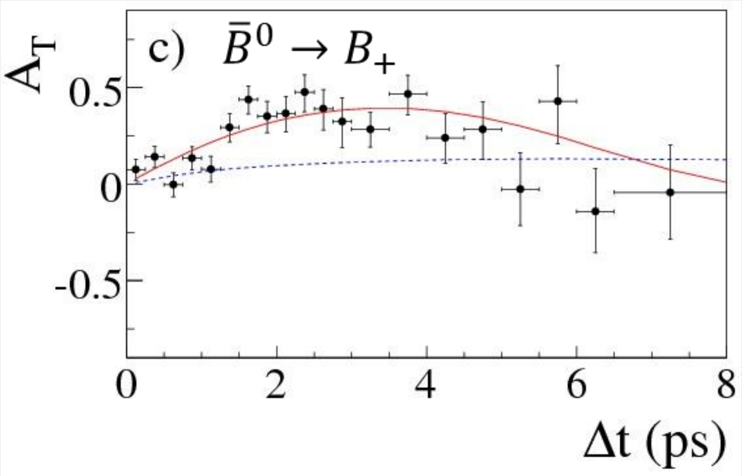
T RAW ASYMMETRIES & SIGNIFICANCE

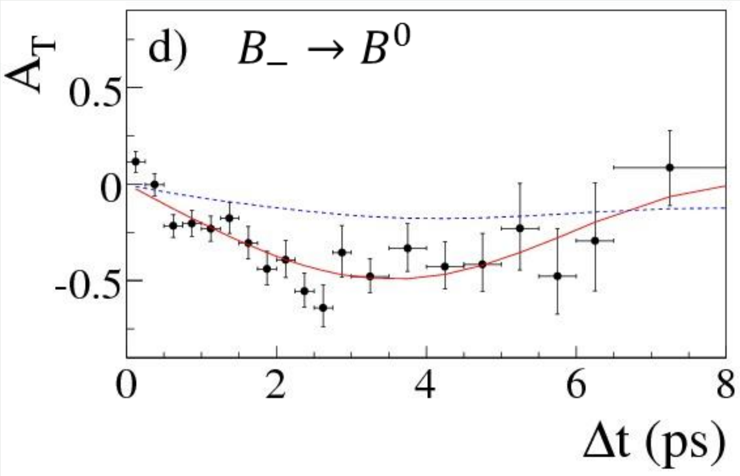
$$s^2_{NoT} = 226 \quad 14\sigma$$
$$s^2_{NoCP} = 307 \quad 16.6\sigma$$
$$s^2_{NoCPT} = 5 \quad 0.33\sigma$$

Stat. only $\Delta\nu$=8









CONCLUSION

- Observed t-Asymmetries are not T-violating:

  Genuine TRV means Asymmetry under in $\rightleftarrows$ out

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

- Mixing x Decay 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

- BABAR observes a large deviation of T invariance at 14 σ level

- 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 any system.

THANK YOU VERY MUCH

FOR YOUR ATTENTION

IS EPR-ENTANGLEMENT APPLICABLE?

- Proposed tests of separate CP, T, CPT symmetries based on EPR-Entanglement imposed by Particle Identity:

  $K^0, \overline{K}^0$ are two states of identical particles.

- Time evolution (including the Mixing $K^0 - \overline{K}^0$) preserves $K^0 \overline{K}^0$, or $K_+ \, K_-$, terms only.

⇨ 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=-,

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

⇨ For the symmetric component, time evolution: ω $K^0 K^0$ terms $\longleftrightarrow$ Demise of tagging

⇨ Look for Correlated Decay Observables.

THE ω-EFFECT

- In some Quantum Gravity models, matter propagation in topologically non-trivial space-time vacua suffers a possible <u>loss of quantum coherence</u> 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. $\Longrightarrow$ 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 $[H_{eff}, CPT] \neq 0$.

- The CPT "Violation" discussed here 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 $K^0 \to \overline{K}^0$ evolution: α,β,γ parameterization [Lindblad].

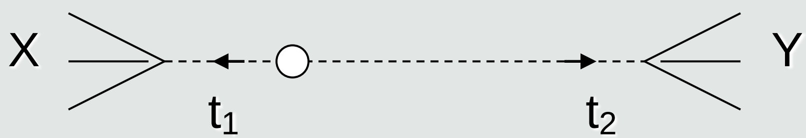
2) for entangled Kaon states in a Φ-factory, **the ω-effect**

ω-EFFECT OBSERVABLES

[J.B., Mavromatos, Papavassiliou]

- Consider the Φ-decay amplitude

$$A(X,Y) = \langle X|K_S\rangle\langle Y|K_S\rangle N(A_1 + A_2)$$
$$A_1 = e^{-i(\lambda_L+\lambda_S)t/2}\left[\eta_X e^{-i\Delta\lambda\Delta t/2} - \eta_Y e^{i\Delta\lambda\Delta t/2}\right]$$
$$A_2 = \omega\left[e^{-i\lambda_S t} - \eta_X\eta_Y e^{-i\lambda_L t}\right]$$

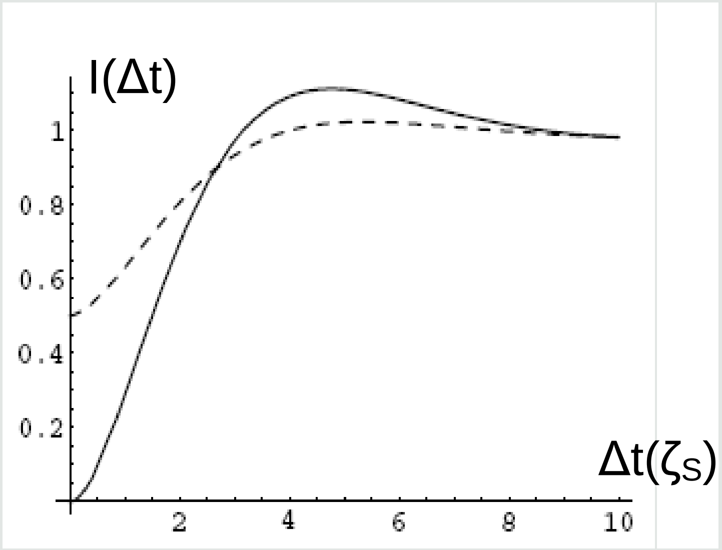


- Strategy: Choose a channel suppressed by η's: $X = Y = \bar{u}^+\bar{u}^-$, CP "forbidden"

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

- Intensity

$$I(\Delta t) \equiv \frac{1}{2}\int_{\Delta t}^{\infty} dt\, |A(X,Y)|^2$$
$$for\ \ |\omega| = |\eta_{+-}|$$
$$\Omega = \phi_{+-} - 0.16\pi$$



MEASUREMENT OF ω-EFFECT

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

$$\left.\begin{aligned} \mathrm{Re}(\omega) &= (-1.6\ {}^{+3.0}_{-2.1}{}_{stat} \pm 0.4_{syst})x10^{-4} \\ \mathrm{Im}(\omega) &= (-1.7\ {}^{+3.3}_{-3.0}{}_{stat} \pm 1.2_{syst})x10^{-4} \end{aligned}\right\}$$

$|\omega| < 1.0 \times 10^{-3}$ 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

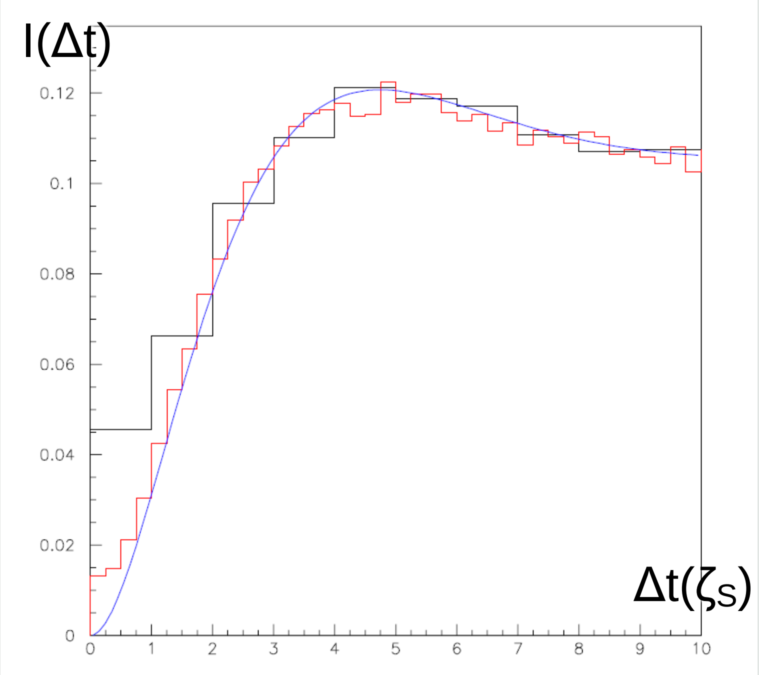
$I\ (\pi^+\pi^-, \pi^+\pi^-; \Delta t=0)=0.$

Hence the reconstruction of events in the region near Δt≈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 $I(l^\pm\ l^\pm; \Delta t)$, gives the bounds [Alvarez,J.B.,Nebot]

$-0.0084 \leq \mathrm{Re}(\omega) \leq 0.0100$ at 95%CL



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

ω-EFFECT FROM SPACE-TIME FOAM MODEL

- ω-effect: as the result of local distortions of space-time in the neighborhood of defects, interacting with matter [J.B., Mavromatos, Sarkar].
- Recoil of Planck-mass defect $\Longrightarrow$ metric deformation $g_{0i} \sim \Delta k^i / M_P = \zeta k^i / M_P$
- Lorentz invariance still holds macroscopically $< \zeta k^i > = 0$, but
- One has non-trivial quantum fluctuations $< \zeta^2 k_i k_j > \alpha\, \delta_{ij} \zeta^2 |\vec{k}|^2$
- Stochastic effects of the space-time foam $\rightsquigarrow$ $|\omega|^2 \sim \dfrac{\varsigma^2 |\vec{k}|^4}{M_P^2 \Delta m^2}$ enhanced by quasi-degeneracy of mass eigenstates.
- At the DAΦNE energy, $|\omega| \sim 10^{-4}\ \zeta$, which lies within the sensitivity of KLOE-2 for not much small values of the momentum transfer fraction ζ.
- In some concrete string-theory-inspired models examined by [Mavromatos, Sarkar], $\varsigma \sim \sum m^2 / |\vec{k}|^2$.