QMP

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TIME vs. REALITY: ENTANGLEMENT IN PARTICLE PHYSICS

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What is THE NOVELTY beyond Entanglement in Quantum Optics ?

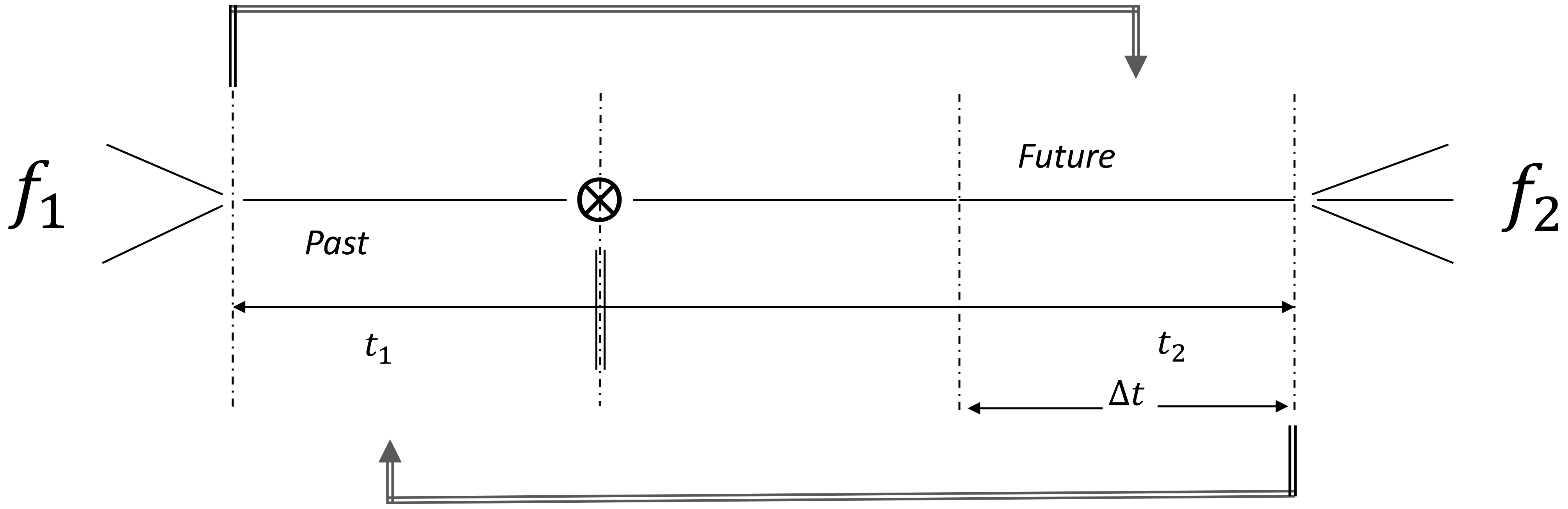
- ***Δ* F = 2 Mixing** ($K^0 - \overline{K^0}, B^0 - \overline{B^0}$, ...)
- **CP Violation**
  - Mixing
  - Mixing - Decay Interference
  - Decay
- **Non-Trivial Time Evolution**: Anton Zeilinger

  Production ➡ Entangled ➡ Interference ➡ Decoherence

  with rich **distinct** information from one or double decay on the three regimes
- States with definite Mass and Lifetime $\lambda = M - i\Gamma/2$, Δ M ≠ 0, ΔΓ≠ 0
  are those with **definite Time Evolution**.
- Existence of B-Factory and Φ-Factory Facilities

I. TIME HISTORY of Entangled System: from Production to its fate

- **TIME REVERSAL** in Δt for unstable particles



II. **POST-TAG** of Past-decayed state: **Entanglement times t_1**

- **K_S - TAG**

NOVEL EFFECTS

(1) As a **Tool** for the BYPASS of (otherwise) NO-GO THEOREMS

1.1 The Conundrum of **Time Reversal - and CPT** - for Unstable Particles

1.2 What is a K_S experimentally ?

(2) The discovery of new quantum phenomena:

SURVIVING CORRELATION - IN - TIME FROM FUTURE TO PAST

It comes definite **from measurement in the future t_2**, when the system is no-longer entangled, **to the state –depending on t_2 (!?) - of the partner in the past t_1**, before its decay when it was entangled and "unspeakable".
It is asymmetric compared to the correlation from past to future.

If EPR → Spooky Action at a Distance → Bell Theorem → end of Hidden Variables and proof of "Lack of Local Realism" → Quantum Information,

then → What about the novel correlation - in - time ? → **Spooky Action to the Past** →???

OUTLINE

- **Entangled** two-body C=- neutral meson system
- Time Evolution and **“Survival”** probalility: the Total Width
- The state $\left|K_{\nrightarrow f}\right\rangle$ not decaying to f. **The K_L tag**
- The Conundrum of **Time Reversal** –and CPT- **for Unstable Particles**: NO-GO and its Bypass (in 1999): **The Conceptual Basis**
- **Experimental TR Asymmetries** for B (in 2012) and K (in 2022) systems
- From the observation of second decay f_2 at t_2 to the partner state before its decay at t_1. **SURPRISE of the “initial” state depending on t_2**.
- **The K_s tag**
- **Conclusion: An epistemological open question**

ENTANGLED C = - neutral meson system

- Actually existing at DAϕNE with $\Phi \rightarrow K^0\,\bar{K}^0$,

  at BABAR and BELLE with $\Upsilon(4S) \longrightarrow B^0\,\bar{B}^0$

  $$C\mathscr{P} = + \;\Rightarrow |i(t=0)\rangle = \frac{1}{\sqrt{2}}\{|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\}$$

  with particle 1 decaying at t_1, particle 2 decaying at $t_2 > t_1$

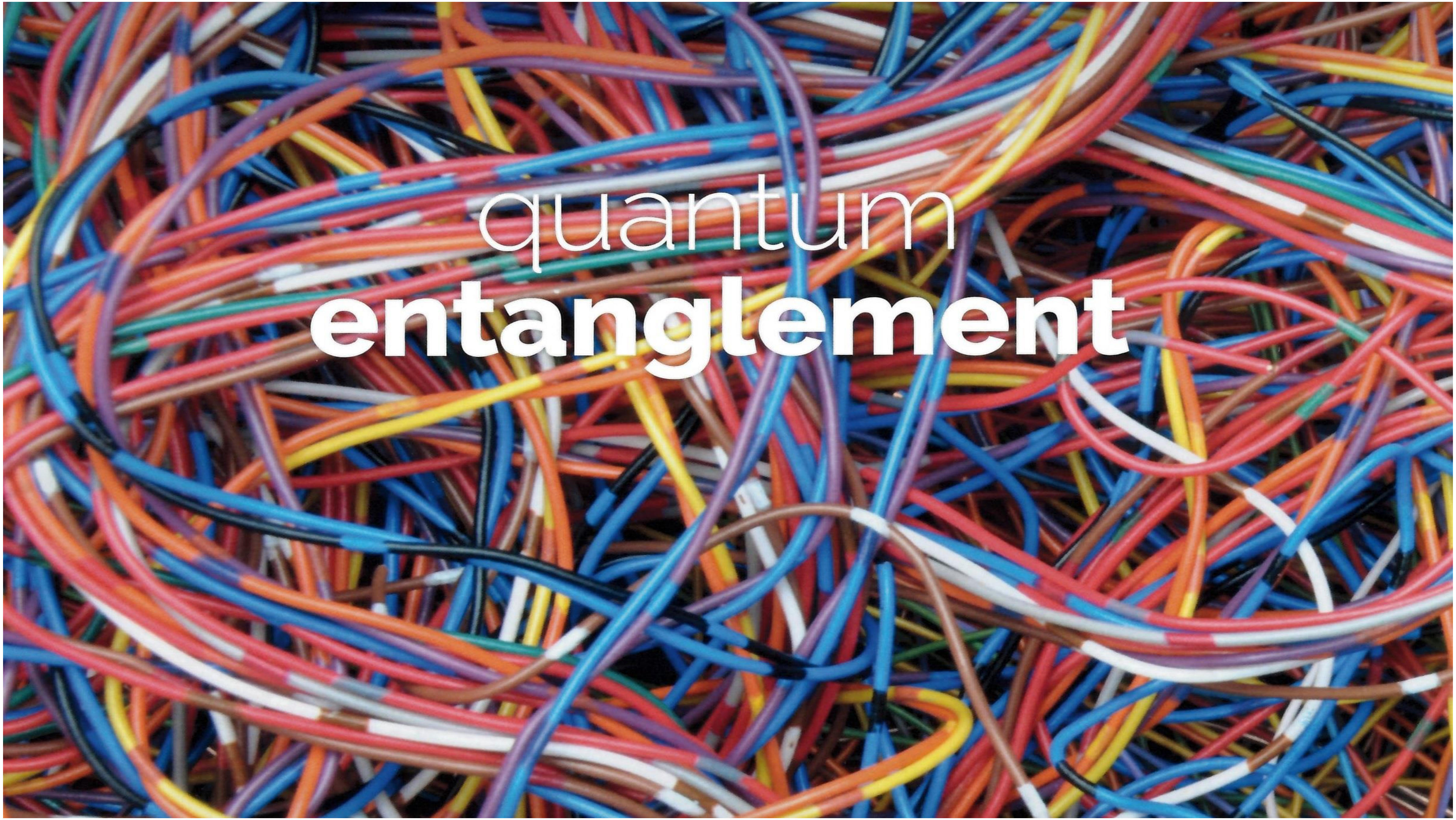
- Even With Mixing, $|\boldsymbol{i}\,(\boldsymbol{t})\rangle$ **does not generate any $K^0\,K^0$, nor $\bar{\boldsymbol{K}}^{\mathbf{0}}\;\bar{\boldsymbol{K}}^{\mathbf{0}}$** ,due to antisymetry (not valid for symmetric C=+ !)

- Time Evolution → definite in terms of **non-orthogonal eigenstates of the non-normal Hamiltonian**

$$|K_{S,L}\rangle\,\alpha\big[(1+\epsilon_{S,L})\,|K^0\rangle\; \pm (1-\epsilon_{S,L})|\bar{K}^0\rangle\big]\,,$$

$$\not{C}\not{P} \longrightarrow \langle K_S|K_L\rangle\; \simeq \epsilon_L + \epsilon_S^*,$$

$$\epsilon = (\epsilon_S + \epsilon_L)/2 \longrightarrow \not{T}, \qquad \delta = (\epsilon_S - \epsilon_L)/2 \longrightarrow \not{C}\not{P}\not{T}$$


quantum
entanglement

TIME EVOLUTION $|i(t)\rangle$

- The entangled state is **non-separable** in parts:

(i) "which is which" is not defined;

(ii) the two parts are not definite: any two lineraly independent combinations.

Only the state $|i>$ is definite: **the state of each part is "unspeakable".**

- The time evolution, written as

$$|i(t=0)\rangle = N/\sqrt{2}\ \{|K_S\rangle\ |K_L\rangle - |K_L\rangle|K_S\rangle\}\ ,\ |N|^2 = (1 - |\langle K_S|K_L\rangle|^2)^{-1} \Rightarrow |i(t)\rangle = e^{-i(\lambda_s+\lambda_L)t}\,|i(t=0)\rangle$$

The Survival Probability $\mathbf{P}(\boldsymbol{t_1}) = \|\boldsymbol{i}(\boldsymbol{t}=\boldsymbol{t_1})\|^2 = \boldsymbol{e}^{\ -\Gamma t_1}$ **, Total Width** $\Gamma = \Gamma_S + \Gamma_L$

$|\boldsymbol{i}(\boldsymbol{t})\rangle$ is unaltered, it reamains the same: NO INTEREST BEFORE THE FIRST DECAY.

The considered observable has been the **Double Decay Rate Intensity** I (f_1, f_2; Δt) !

- **Careful! P(t_1) iff nothing else is observed in the future**
- **How to inquire in the "unspeakable" regime ?**

FIRST DECAY f_1 → TAGGING AND FILTERING

- Any state can decay to f, **but** that with zero probability

$$\left|K_{\nrightarrow f}\right\rangle = N_{\nrightarrow f}\left[K_L\rangle - \eta_f |K_S\rangle\right] ; \qquad \eta_f = \frac{\langle f|\ T\ |K_L\rangle}{\langle f|\ T\ |K_S\rangle}$$

- If you observe the first decay to f_1 at t_1, proyecting $|i(t = t_1)\rangle$ to f_1, the **living partner** (2) corresponds to the pure state

$$\left|K^{(2)}(t = t_1)\right\rangle = \left|K_{\nrightarrow f_1}\right\rangle \quad \Leftarrow \quad \boldsymbol{TAG\ of\ (2)}$$

This fact was always recognized for **"flavour tag":** First decay to $l^+(l^-)$ → Partner tagged to $\bar{K}^0(K^0)$**. It is, however, valid in general as stated**!

- **What for the decayed state (1)?** The state before decay was undefined. Written as a superposition of $\left|K_{\nrightarrow f}\right\rangle$ and its orthogonal $\left|K^{\perp}_{\nrightarrow f}\right\rangle$

$$\boldsymbol{Decay\ to\ f_1 \ \Longrightarrow\ \left|K^{\perp}_{\nrightarrow f1}\right\rangle \quad FILTERED\ for\ (1)}$$

Decay Rate given by the **decay probability** to f_1 of $\left|\boldsymbol{K^{\perp}_{\nrightarrow f1}}\right\rangle$ ≡ **FILTERING IDENTITY**

Δt HISTORY OF THE LIVING PARTNER

- **The subsequent Δt- evolution of particle (2) and its decay to f_2 are definite** from the **pre**pared tagged state.
- For $\Delta t \leq few\ \tau_S$, one has an **interference patern**, because **no decay channel** - due to CP Violation – **projects either K_S or K_L** !
- For long enough Δt, one has **Decoherence** $\boldsymbol{K_L tag} \Leftrightarrow |\boldsymbol{\eta_1}|\boldsymbol{e^{-\Delta\Gamma\Delta t/2}} \ll \mathbf{1}$ **with a quantitative purity** of the K_L –state
- The observable is the **Double Decay Rate, the Intensity** I(f_1, f_2; Δt). Tagging of the living partner at t_1 and Filtering of its state in its Decay to f_2 at t_2

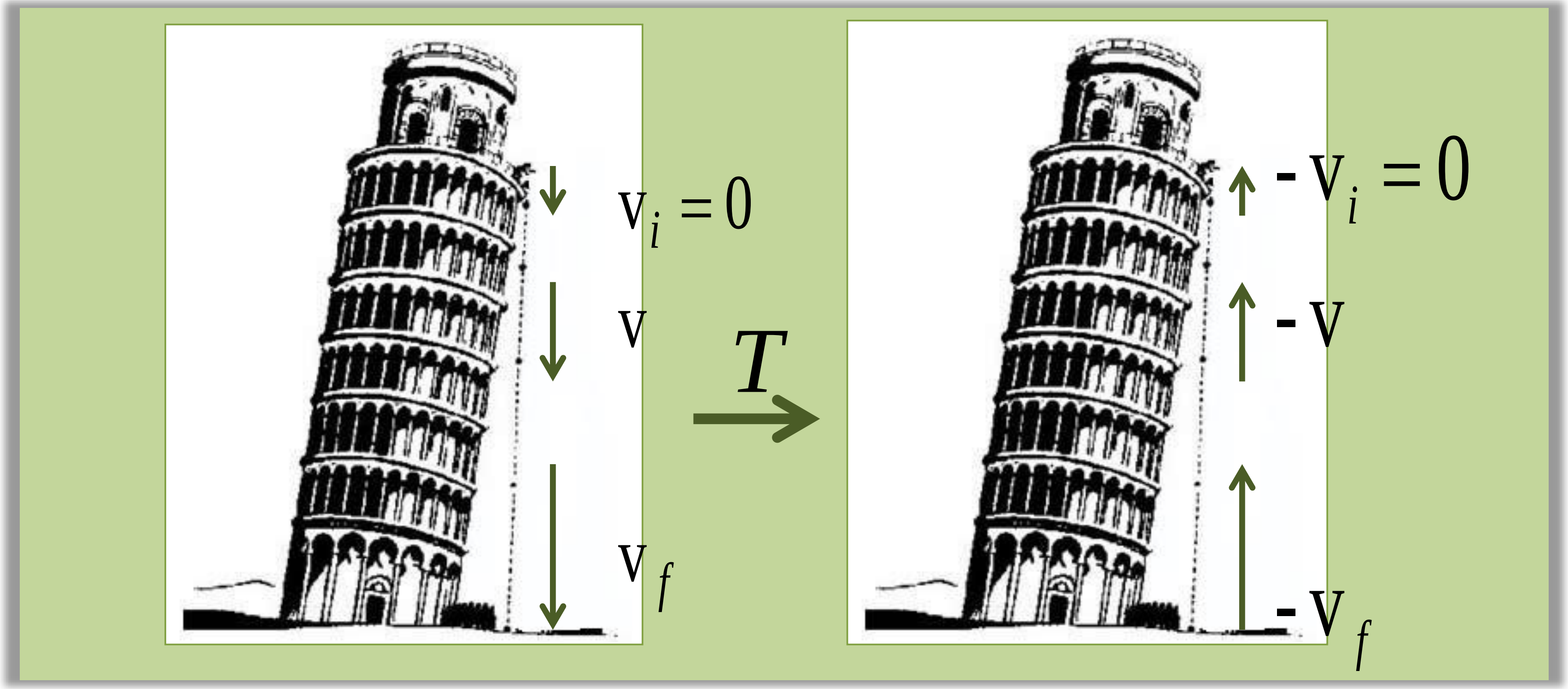
allows to talk of **Δt Transition Probability** $P\left(K_{\nrightarrow f1} \xrightarrow{\Delta t} K^{\perp}_{\nrightarrow f2}\right)$

"independent of the decay" and connected to I(f_1, f_2; Δt).

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: **Reversal-in-Time.**

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



TIME REVERSAL IN QUANTUM MECHANICS

- In Quantum Mechanics, there is an operator U_{CP} implementing the CP-symmetry acting on the states of the physical system, such that

$$U_C\, Q\, U_C^+ = -Q,\; U_P\, \vec{r}\, U_P^+ = -\vec{r},\; U_P\, \vec{p}\, U_P^+ = -\vec{p},\; U_P\, \vec{s}\, U_P^+ = \vec{s}$$

The operator U_{CP} is an observable with Conservation Laws: $K_L \rightarrow \pi\pi$

- The operator U_T implementing T-symmetry is such that in transitions $U_T\, \vec{r}\, U_T^+ = \vec{r},\; U_T\, \vec{p}\, U_T^+ = -\vec{p},\; U_T \vec{s} U_T^+ = -\vec{s}$
- **A DIRECT ASYMMETRY**: Comparison of Transition Probabilities between a Reference process and its T-transformed in a single experiment; NOT a Fit of a parameter describing TR in a given Theoretical Framework.

Q M 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 $i, f \rightarrow \bar{f}, \bar{i}$, in transitions.**

THE CONCEPTUAL BASIS FOR A DIRECT TRV EFFECT

- Guido Drexlin, Valery Rubakov, Lincoln Wolfenstein

- independently -

“ The main difficulty was not
in the experiment itself, but in knowing
WHAT YOU HAD TO MEASURE”

CONCEPTUAL BASIS FOR BYPASSING NO-GO

- Neutral Mesons $K^0 - \overline{K}^0$, $B^0 - \bar{B}^0$ are UNSTABLE and the Decay is irreversible.
- **T and CPT, ANTIUNITARITY! , need however the exchange of initial and final states →NO-GO.**
  L. Wolfenstein, PRL 1999 : "The T-reverse of a decaying state is not a physical state".

- **BYPASS** M. C. Banuls, J. B., PLB 1999, NPB 2000 → Do not include the Decay Products in your Asymmetry, write it in terms of Meson States and the Decay should not be an essential ingredient for getting a non-vanishing value:

1) Use the Decay as a **Quantum Filtering Measurement** of the Meson State ONLY:
   Orthogonal to Non-Decay State.

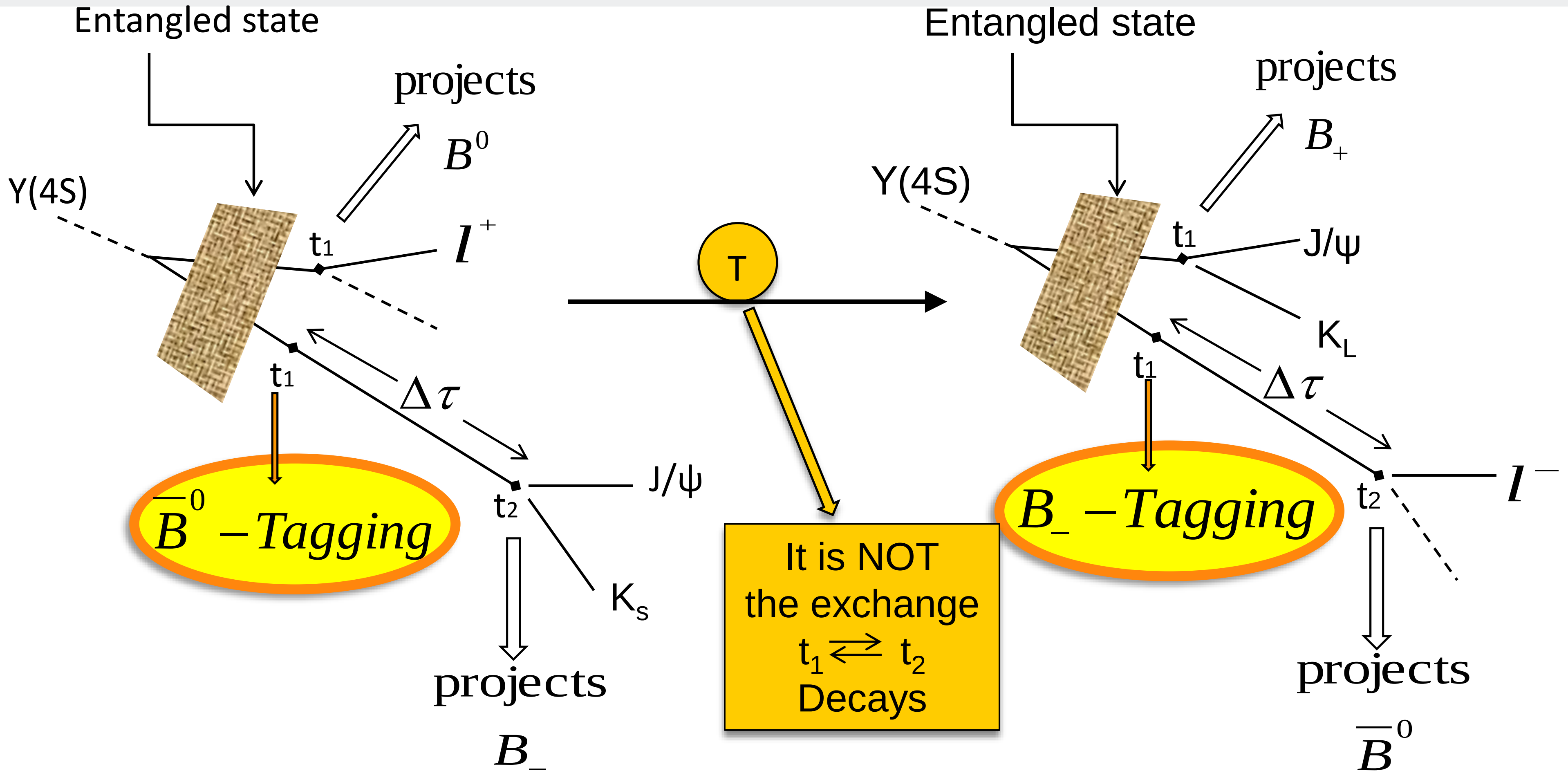
2) **Quantum ENTANGLEMENT: Quantum Information** from the First Decay to the (still alive) Partner for the Preparation of the initial Meson State: Non-Decay State **if Antisymmetric entangled system.**

3) The test of Symmetries is made in the Time Evolution of the Partner
   from the first to the second decay.

L. Wolfenstein, IJMP E 1999: "It appears to be a true TRV Effect"

WHAT IS T-TRANSFORMATION EXPERIMENTALLY ?

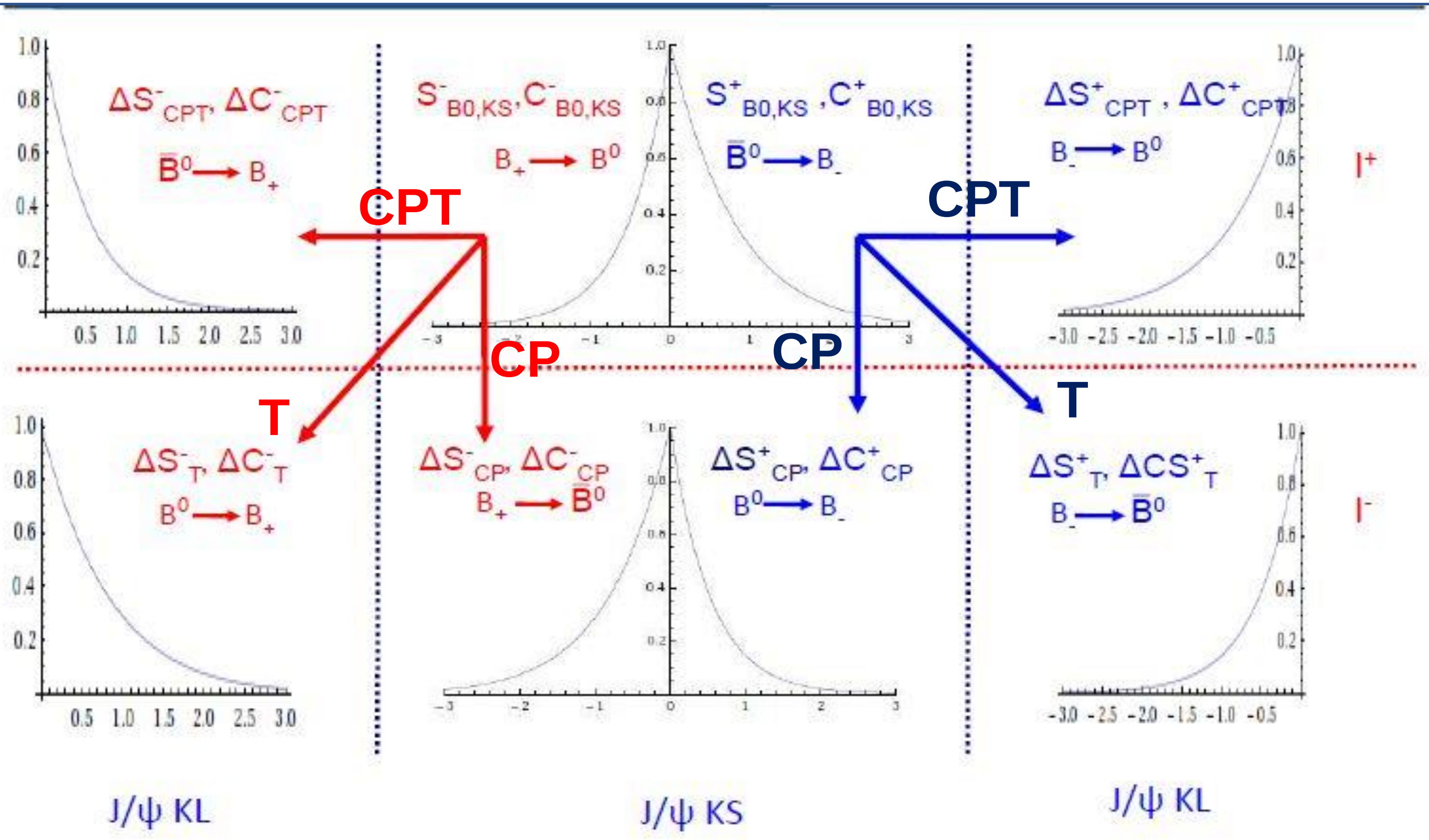
The problem is in the preparation and filtering of the appropriate initial and final meson states for a T-test in transitions J.B., Martinez Vidal, Villanueva, JHEP 2012, COVER PAGE RMP vol. 87 (2015)



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

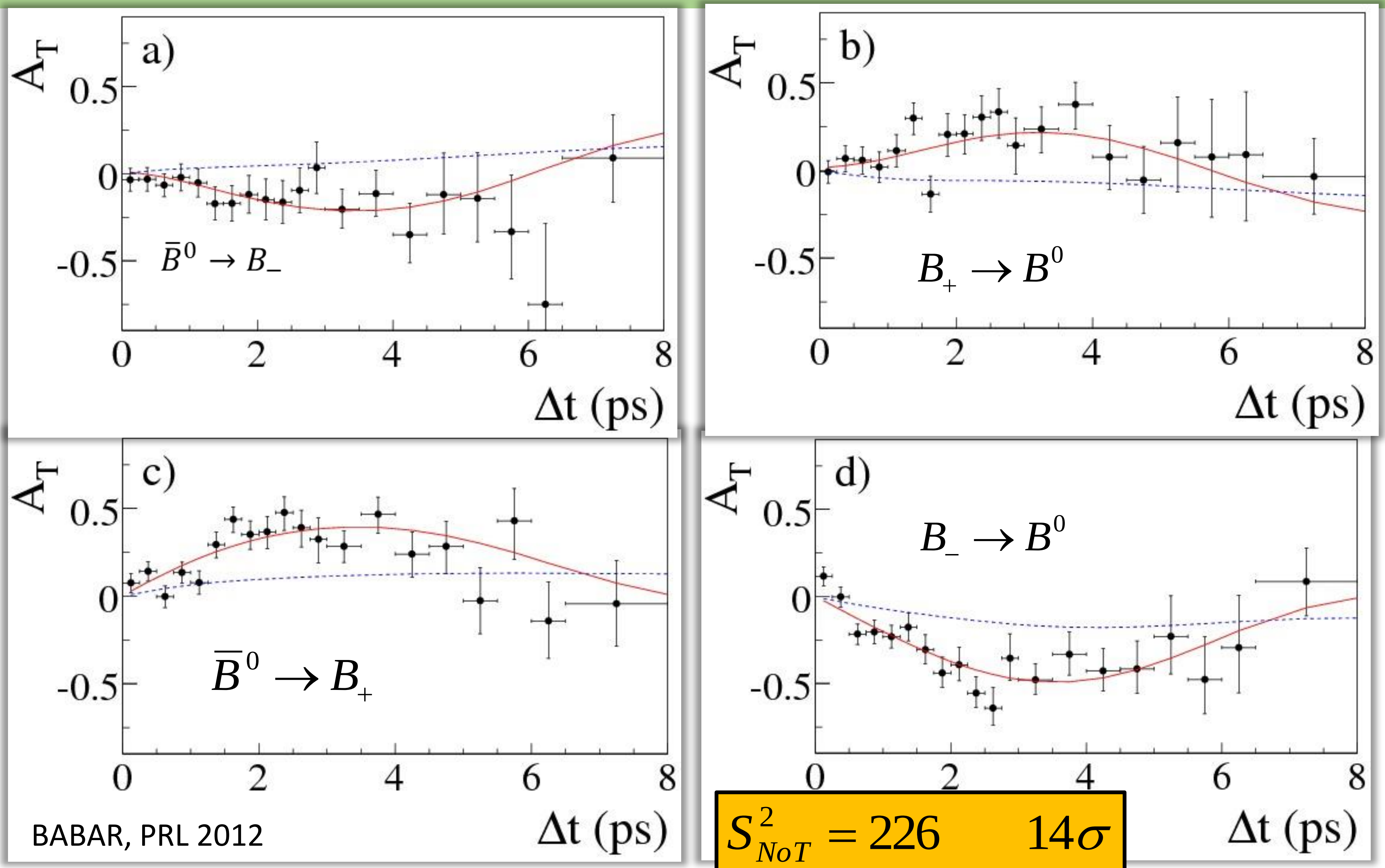
ΔS$^{\pm}$, ΔC$^{\pm}$ ASYMMETRY PARAMETERS

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



→ The Processes (f_1,f_2) and (f_2,f_1) exchanging the Time Ordering of the Decays (red↔blue) are NOT CONNECTED BY A SYMMETRY OPERATION!

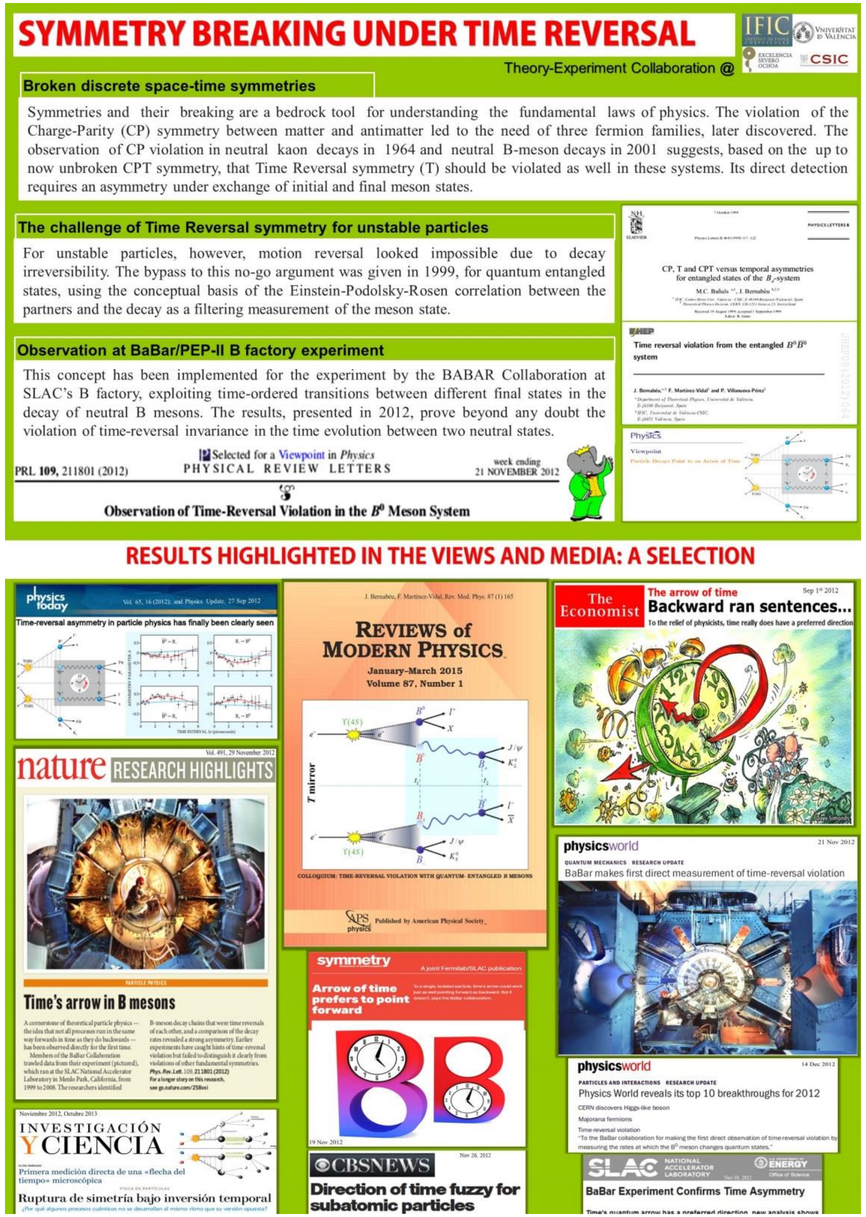
T-RAW ASYMMETRIES & SIGNFICANCE



BABAR, PRL 2012

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

SEPARATE T AND CP VIOLATION EFFECTS



Using BABAR data PRL 2012

Independent direct T and CP Asymmetries:
JB, Botella, Nebot, JHEP 2016

$$\Delta S_C^T = -0.687 \ \pm 0.020,$$

$$\Delta S_C^{CP} = -0.687 \ \pm 0.021$$

Impressive separate evidence of TRV, CPV

"Intriguing" 2σ - effect for CPTV

$$\Delta C_c^{CPT} = -\Delta C_h^{CPT} = (2.7 \ \pm 1.5) \cdot \ 10^{-2}$$

POST-TAG TO THE PAST DECAYED STATE

- In the entangled $|\boldsymbol{i(t)}\rangle$ state, there is no privilege of one of the decay times → **Study the implications of observing the second decay to f_2 at time t_2**
- The partner $K^{(1)}(t = t_2)$ is tagged

$$\left|K^{(1)}(t = t_2)\right\rangle = N_1\{\eta_2|K_s\rangle - |K_L\rangle\}$$

which has not been observed! But it decayed at time $t_1<t_2$

Fixing the observation (η_2, t_2) and evolving t_1 from $t_1=0$ to $t_1=t_2$, **its past state had to be**

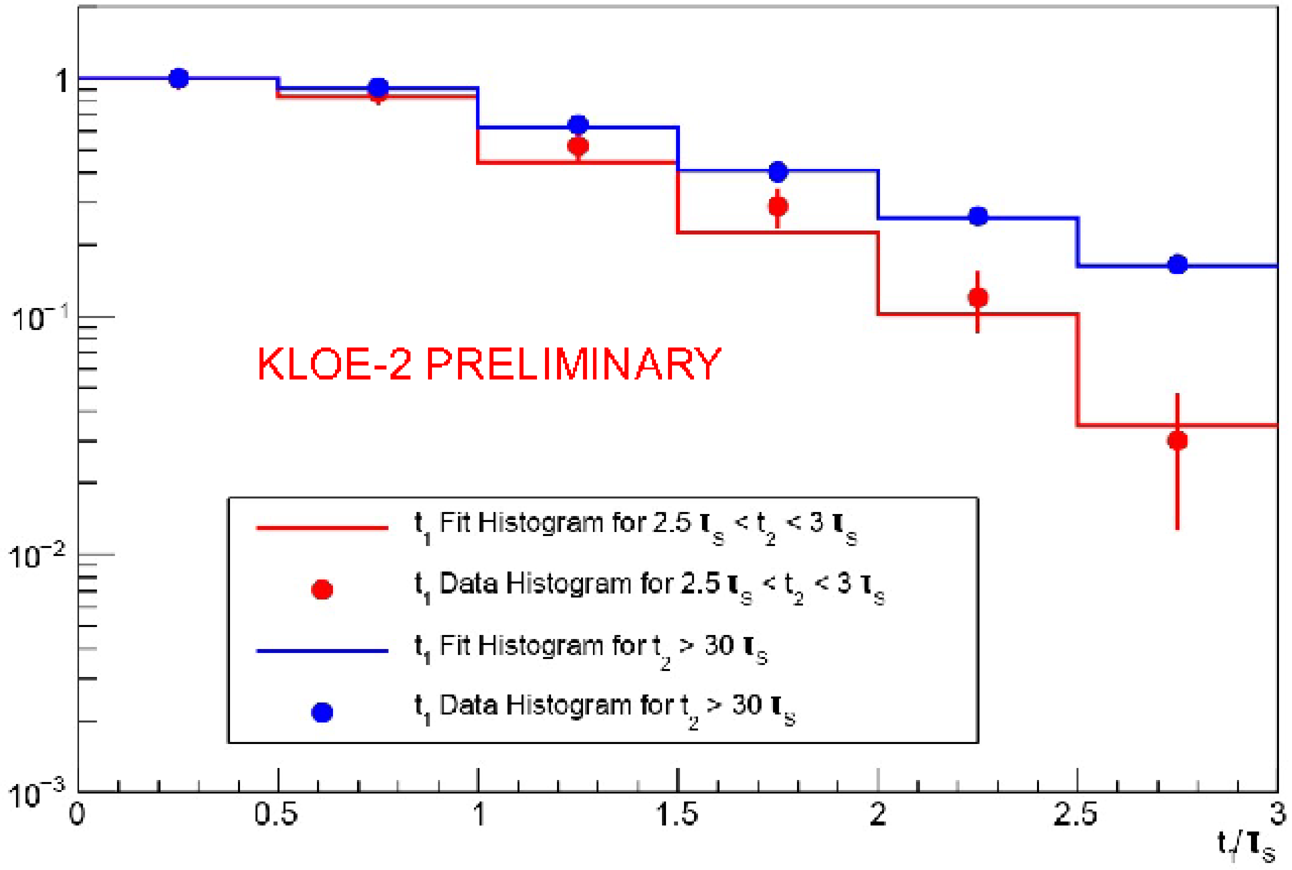
$$\left|K^{(1)}(t = 0)\right\rangle = N\left[\eta_2\, e^{-i\lambda_L t_2}\left|K_S\right\rangle - e^{-i\lambda_s t_2}\left|K_L\right\rangle\right]$$

- DOUBLE SURPRISE! Not only there is a **post-tag of the initial state, it depends on when the second decay will be observed.**

JB, Di Domenico, PRD 2022

OBSERVATION OF THE POST-TAGGED PAST-DECAYED STATE DEPENDING ON t_2

- **Measure** the first-decay time t_1 - **distribution** for $\phi \longrightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ **for two identical observations of the future decay at distinct fixed t_2**



A. Di Domenico on behalf of KLOE-2 Collaboration 2023/Phys. Conf. Serv2446, 012027

THE K_S-TAG

- Decoherence is reached for **large Δt before the observation of the second decay**

$$e^{-\Delta\Gamma\Delta t/2}/|\eta_2| \ll 1$$

leading to a pure Ks-beam

- Most rewarding: - $\not{C}\not{P}$ and $\langle K_L|K_s\rangle \neq 0$ → No decay channel able to tag either K_L or K_s

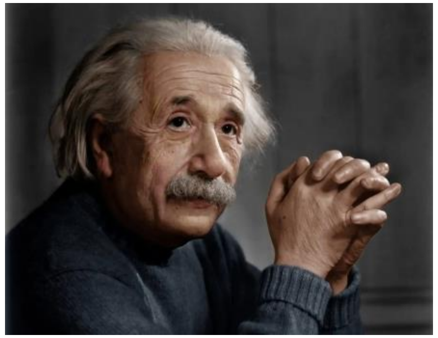
- After 58 years of CPV: **this POST-TAG condition in times is the only way to study rare K_S-decays.** Compare with 60 year history of K_L decays!

- Example: Difference of charge Asymmetries A_L-A_S → Direct test of CPT!

CONCLUSION

- Entanglement in particle anti-particle system $M^0 - \bar{M}^0$
- NOVEL EFFECTS
  - **Tools for Particle Physics**
  - **Quantum Phenomena**
- Solution for NO - GO's
  - **TR for Unstable Particles**
  - **K_S - tag**
- **POST-TAG of the past-decayed state depending on what and when measurement on the partner in the future**.
- In Classical and Quantum Physics, Time is a parameter to describe the **evolving definite reality, not an observable.**
- With the **surviving correlation-in-time,** Einstein would claim **:**

"A Spooky Action to the Past"



NO (UNKNOWN) CAUSAL EFFECT

- CAUSAL INFLUENCE says that the cause must precede the effect according to ALL inertial observers, so that for the Post-Tag effect in the entangled K-mesons system –in which there are both time-like and space- like intervals,

- **If the Interval is time-like**, future is future for all observers → the future to past "influence" is NOT CAUSAL.
- **If the Interval is space-like**, there could be observers exhanging future and past, BUT the two events could only connect with a signal velocity higher than the speed of light → this "influence" is NOT CAUSAL.

- Then, independent of the space-time interval between the future observation in CM of the second decay and the past state of the partner, **"the Post-Tag correlation in time" effect CANNOT BE A CAUSAL INFLUENCE.**
- Whereas the EPR correlation between observables NEEDS a space-like interval to ensure no causal influence, the Post-Tag effect cannot be a causal influence for ALL cases → no loop-holes. This is an additional argument, besides the fact that TIME IS NOT AN OBSERVABLE, to skate that **the Post-Tag effect goes beyond the EPR correlation**.

FOR PHILOSOPHERS ….. EPISTEMOLOGY

Physics → QM correctly describes the **behaviour of nature when it is observed**

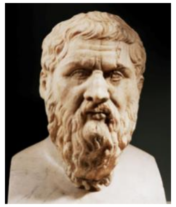
⟷ Scientific Methodology

Philosophy → What QM says about nature's reality?

NEW

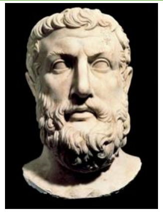
- Spooky Action at a Distance	- Spooky Action to the Past
- EPR Correlation-Bell Theorem	- Surviving Correlation-in-time
- Lack of Local Realism	- Lack of Instant Realism

(x,t) is not a definite, separate event ⟷ Role of time in QM ?

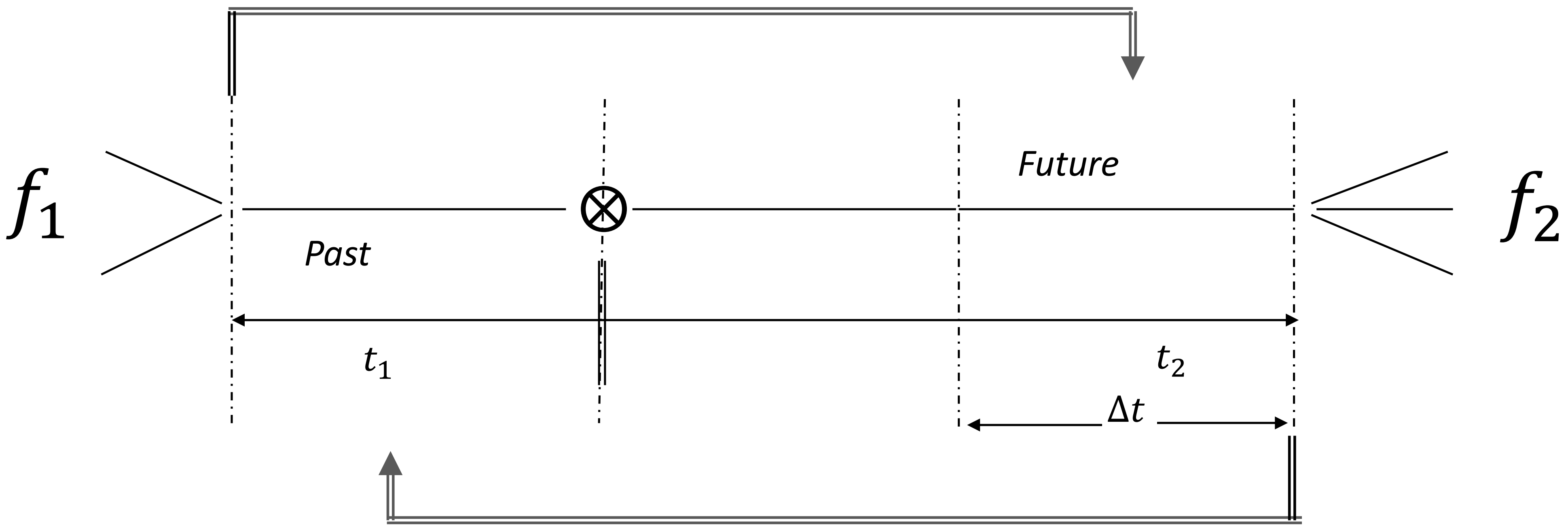


TIME versus REALITY

Heraclitus vs. Parmenides



THANK YOU VERY MUCH FOR YOUR ATTENTION



BACK-UP

CAN TR BE TESTED IN UNSTABLE SYSTEMS?

THE FACTS FOR 4σ Kabir Asymmetry at CPLEAR (1998)

- 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

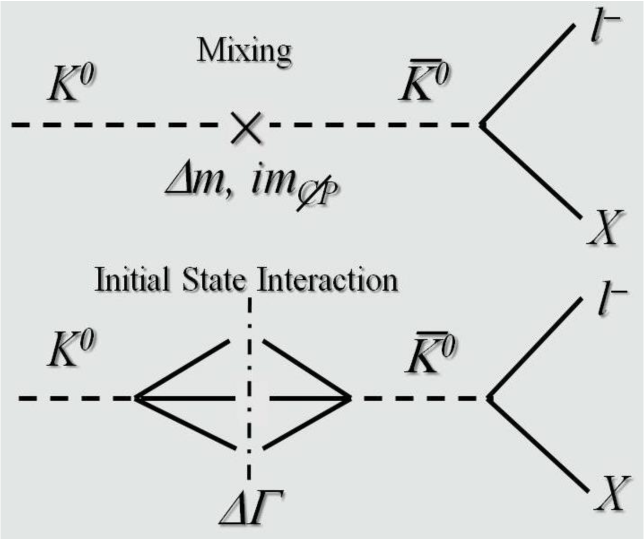
Transition	$K^0 \to \overline{K}^0$	$\overline{K}^0 \to K^0$	$\overline{K}^0 \to K^0$	$K^0 \to \overline{K}^0$	$K^0 \to \overline{K}^0$
(X,Y)	(l^-, l^-)	(l^+, l^+)	(l^+, l^+)	(l^-, l^-)	(l^-, l^-)
Transformation	Reference	CP	T	CPT	Δt

➡ No way to separate T and CP if T were defined. CPT and Δt are the identity!

- 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".