Testing quantum mechanics at colliders

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Roma Tre Università

ROMA TRE UNIVERSITÀ DEGLI STUDI

TIME vs. REALITY:
Back from the Future in Flavour Entaglement

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EXCELENCIA SEVERO OCHOA

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

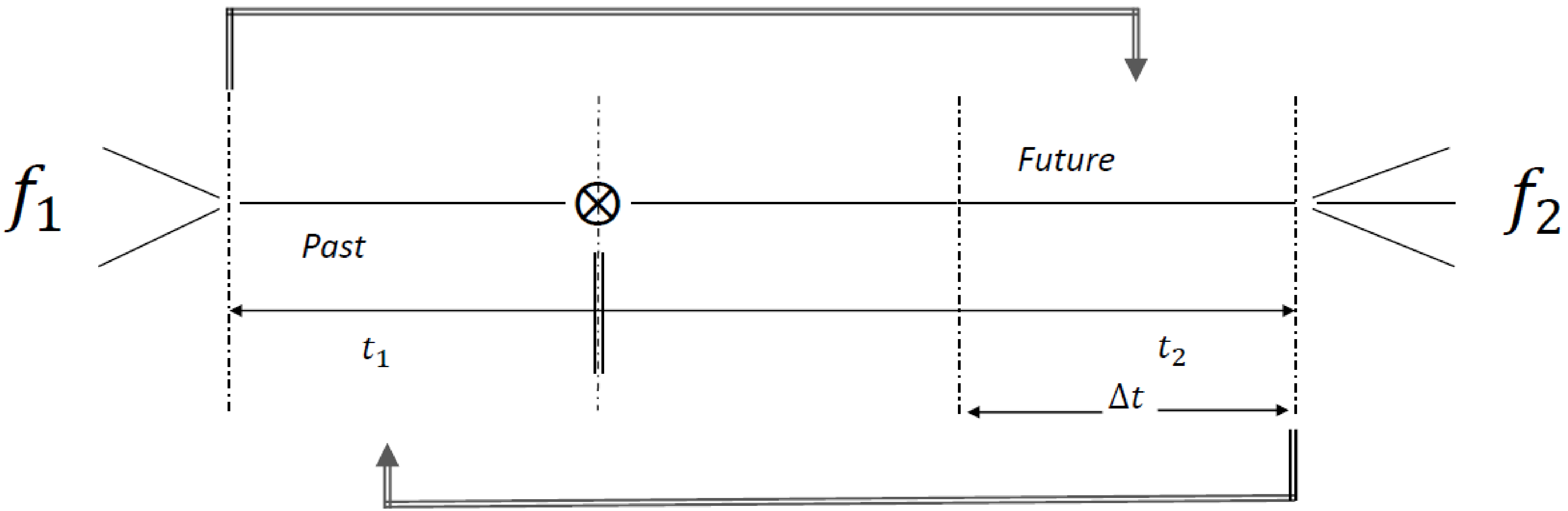
  with rich **distinct** information from one or double decay on the three regimes

- States with definite Mass and Lifetime $\lambda = M - i\Gamma/2$, $\Delta M \neq 0$, $\Delta\Gamma \neq 0$ 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**

- 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 $\Phi \rightarrow K^0\,\overline{K}^0$,

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

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

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

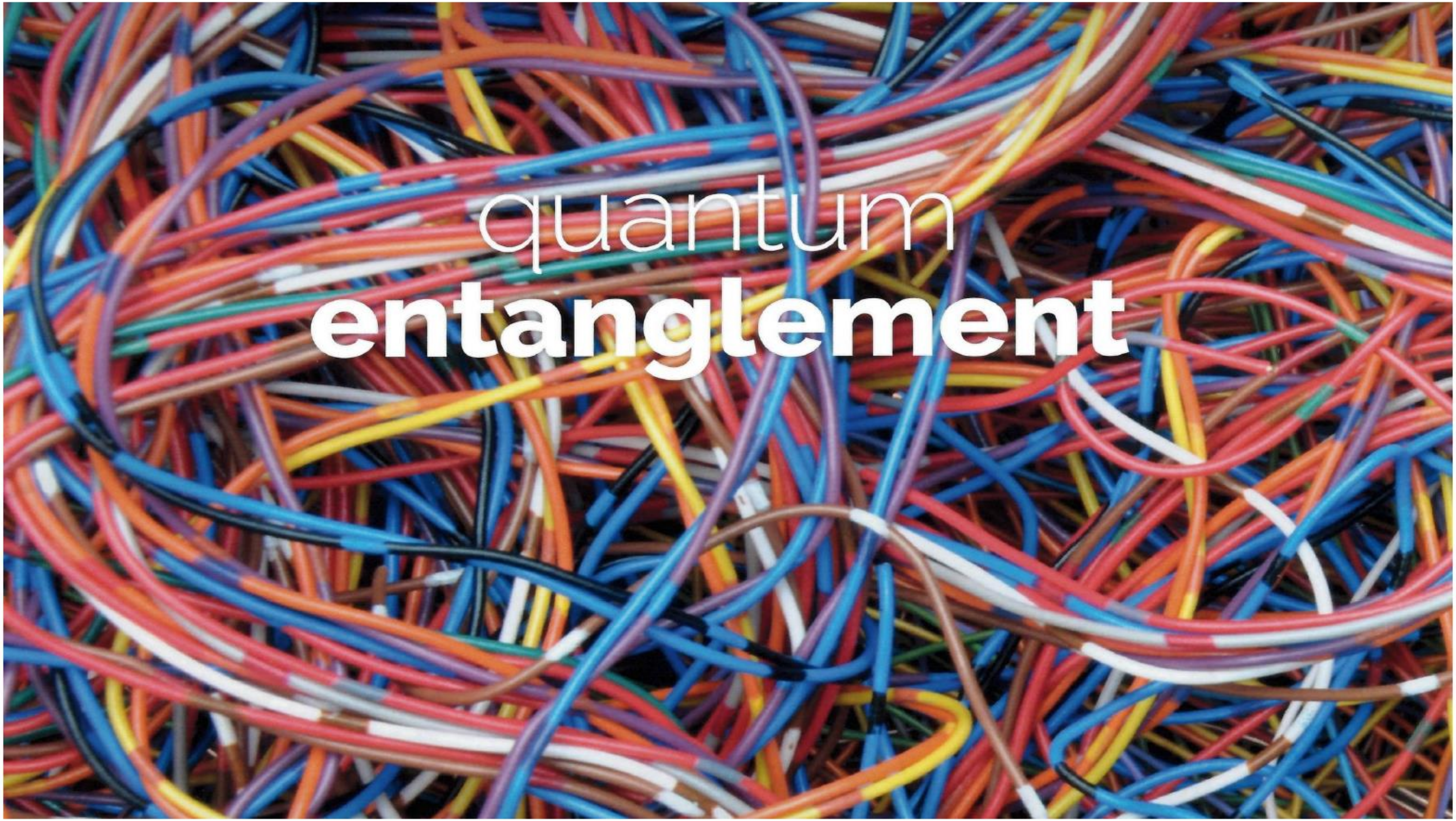
- Even With Mixing, $|\boldsymbol{i}\,(\boldsymbol{t})\rangle$ **does not generate any $K^0\,K^0$, nor $\overline{\boldsymbol{K}}^0\,\overline{\boldsymbol{K}}^0$** ,due to antisymetry (not valid for symmetric C=+ !)

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

$$|K_{S,L}\rangle\,\alpha\left[(1+\epsilon_{S,L})\,|K^0\rangle\,\pm(1-\epsilon_{S,L})|\overline{K}^0\rangle\right],$$

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

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


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

$|i(t)\rangle$ is unaltered, it reamains the same: NO INTEREST BEFORE THE FIRST DECAY.
The considered observable has been the **Double Decay Rate Intensity** I $(f_1, f_2; \Delta t)$!

- **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

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

- 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

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

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 $|K_{\nrightarrow f}\rangle$ and its orthogonal $|K^{\perp}_{\nrightarrow f}\rangle$

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

Decay Rate given by the **decay probability** to f_1 of $|\boldsymbol{K}^{\perp}_{\nrightarrow \boldsymbol{f1}}\rangle$ ≡ **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** $\boldsymbol{K_L tag \Leftrightarrow |\eta_1| e^{-\Delta\Gamma\Delta t/2} \ll 1}$ **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).

TR-ASYMMETRY: 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.**

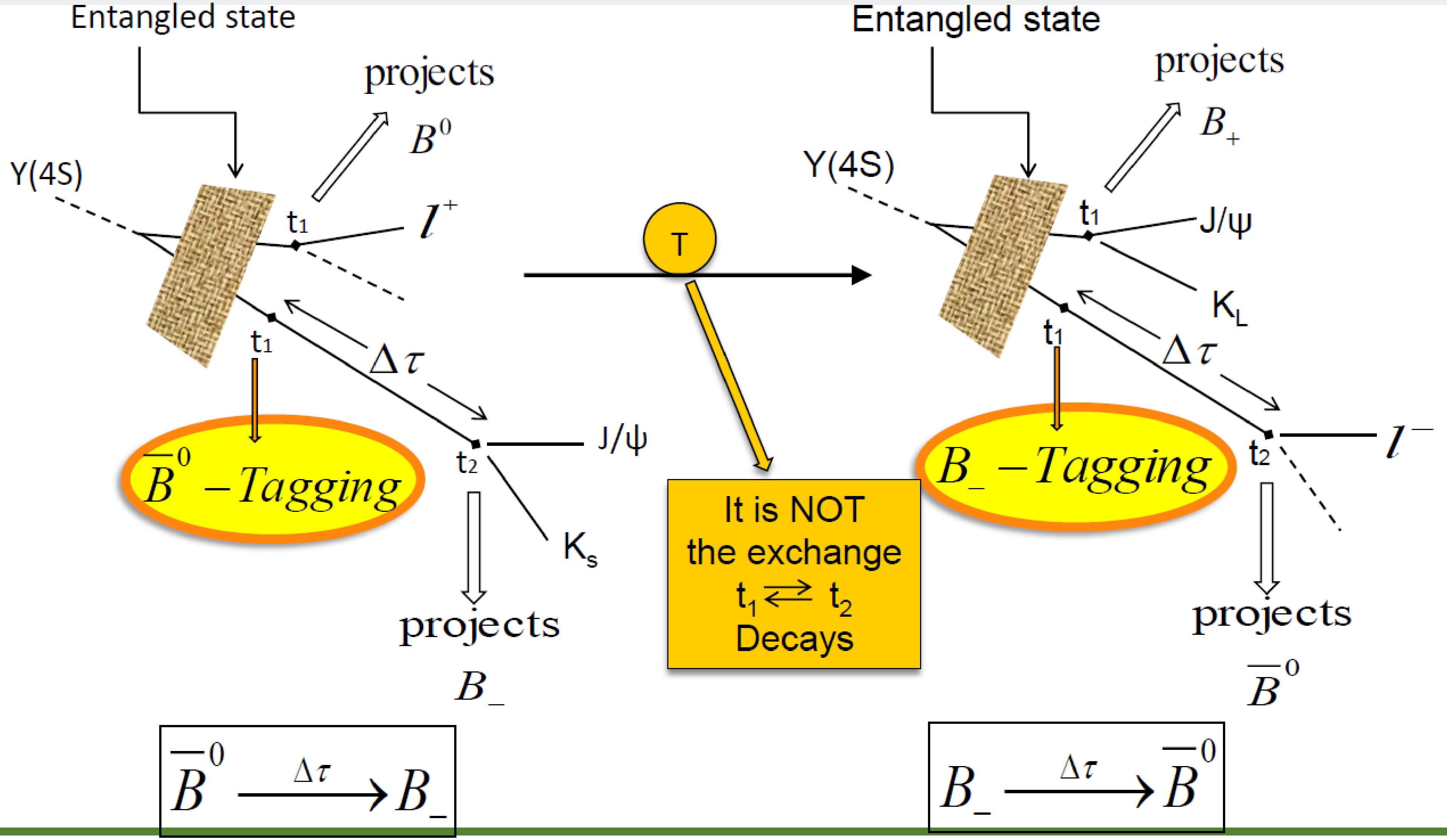
3) The test of Symmetries is made in the Time Evolution of the Partner **from the first to the second decay**.

   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)



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

OBSERVABILITY OF "BACK FROM THE FUTURE" EFFECT

- Entaglement times $t_1 < t_2$
- Decay t_1-time distriburion to $f_1 = f_2 = f$, at different fixed t_2

$$\left|\langle f|T|K^{(1)}(t_1)\rangle\right|^2_{t_2} = \mathcal{N}\{e^{-\Gamma_S t_1} + |\rho|^2 e^{-\Gamma_L t_1} -2(\mathcal{R}\rho)e^{-\Gamma t_1/2}\cos(\Delta m)t_1 -2(\mathcal{I}\rho)e^{-\Gamma t_1/2}\sin(\Delta m)t_1\};$$

$$\Gamma = \Gamma_S + \Gamma_L;$$

- QM post-diction $\quad \rho(t_2) = e^{-i(\lambda_S - \lambda_L)t_2}.$

- Extract the relative PROBABILITY AMPLITUDE

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

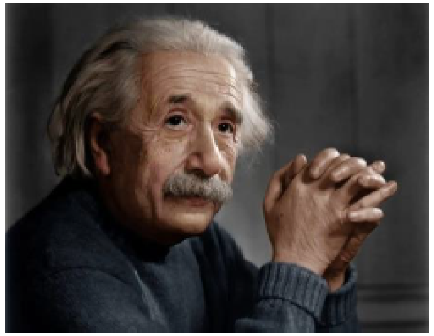
- After 58 years of CPV: **this POST-TAG condition in times is the only way to study rare K_S-decays.** Compare with 60 year history of K_L decays!

- 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**

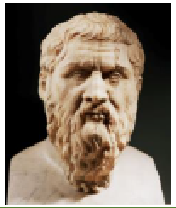
⟷ Scientific Methodology

Philosophy → What QM says about nature's reality?

NEW

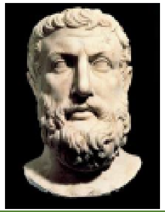
- Spooky Action at a Distance	- Spooky Action to the Past
- EPR Correlation-Bell Theorem	- Surviving Correlation-in-time
- Lack of Local Realism	- Lack of Instant Realism

(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