



QMP

QMP SEMINAR

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TIME vs. REALITY: ENTANGLEMENT IN PARTICLE PHYSICS

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What is THE NOVELTY beyond Entanglement in Quantum Optics ?

➤ $\Delta F = 2$ Mixing ($K^0 - \overline{K}^0, B^0 - \overline{B}^0, \dots$)

➤ CP Violation $\left\{ \begin{array}{l} \text{Mixing} \\ \text{Mixing - Decay Interference} \\ \text{Decay} \end{array} \right.$

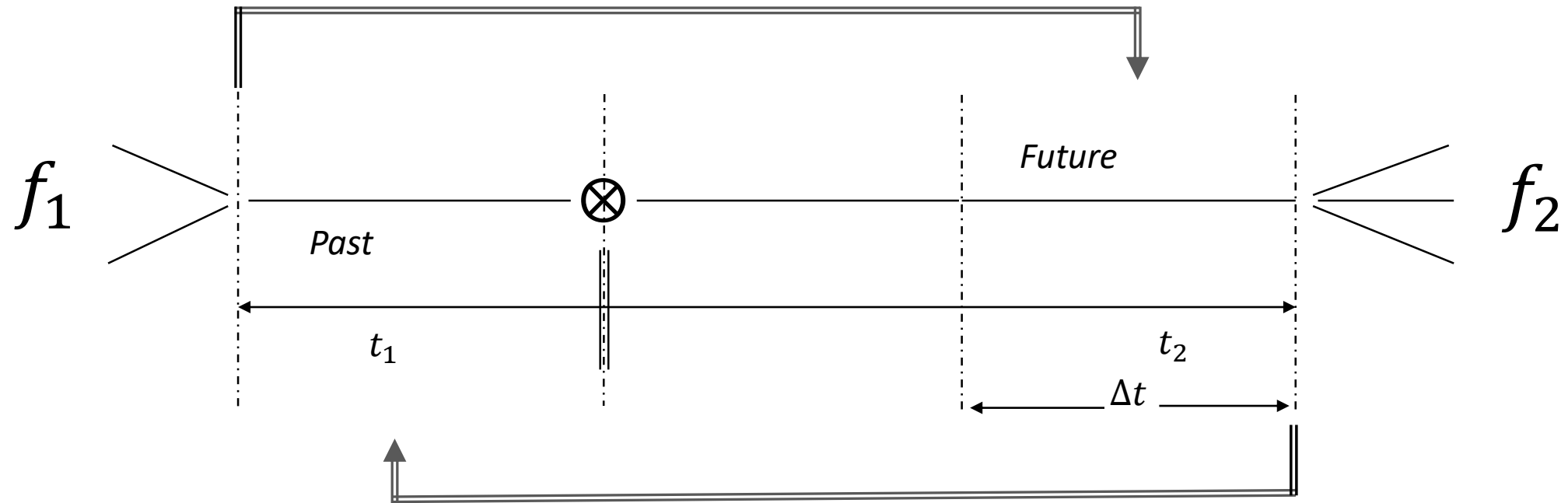
➤ Non-Trivial Time Evolution: Anton Zeilinger
Production \Rightarrow Entangled \Rightarrow Interference \Rightarrow Decoherence

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”** probability: the Total Width
- The state $|K_{\leftrightarrow f}\rangle$ 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 $\Upsilon(4S) \rightarrow B^0 \bar{B}^0$

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

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

- Even With Mixing, $|i(t)\rangle$ **does not generate any $K^0 K^0$, nor $\bar{K}^0 \bar{K}^0$** , due to antisymmetry (not valid for symmetric C=+ !)
- Time Evolution \rightarrow definite in terms of **non-orthogonal eigenstates of the non-normal Hamiltonian**

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

$$\mathcal{CP} \rightarrow \langle K_S | K_L \rangle \simeq \epsilon_L + \epsilon_S^*,$$

$$\epsilon = (\epsilon_S + \epsilon_L)/2 \rightarrow \mathcal{T}, \quad \delta = (\epsilon_S - \epsilon_L)/2 \rightarrow \mathcal{CPT}$$



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 linearly independent combinations.

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

➤ The time evolution, written as

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

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

$|i(t)\rangle$ is unaltered, it remains 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 $f_1 \rightarrow$ TAGGING AND FILTERING

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

$$|K_{\rightarrow f}\rangle = N_{\rightarrow f} [|K_L\rangle - \eta_f |K_S\rangle] ; \quad \eta_f = \frac{\langle f | T | K_L \rangle}{\langle f | T | K_S \rangle}$$

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

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

This fact was always recognized for “**flavour tag**”: First decay to $l^+(l^-) \rightarrow$ 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 $|K_{\rightarrow f}\rangle$ and its orthogonal $|K_{\rightarrow f}^\perp\rangle$

$$\text{Decay to } f_1 \Rightarrow |K_{\rightarrow f_1}^\perp\rangle \quad \text{FILTERED for (1)}$$

Decay Rate given by the **decay probability** to f_1 of $|K_{\rightarrow f_1}^\perp\rangle \equiv$ **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 **prepared** tagged state.
- For $\Delta t \leq \text{few } \tau_s$, one has an **interference pattern**, because **no decay channel** - due to CP Violation – **projects either K_S or K_L !**
- For long enough Δt , one has **Decoherence** $K_L \text{tag} \Leftrightarrow |\eta_1| e^{-\Delta\Gamma\Delta t/2} \ll 1$ **with a quantitative purity** of the K_L –state
- The observable is the **Double Decay Rate, the Intensity** $I(f_1, f_2; \Delta t)$. Tagging of the living partner at t_1 and Filtering of its state in its Decay to f_2 at t_2

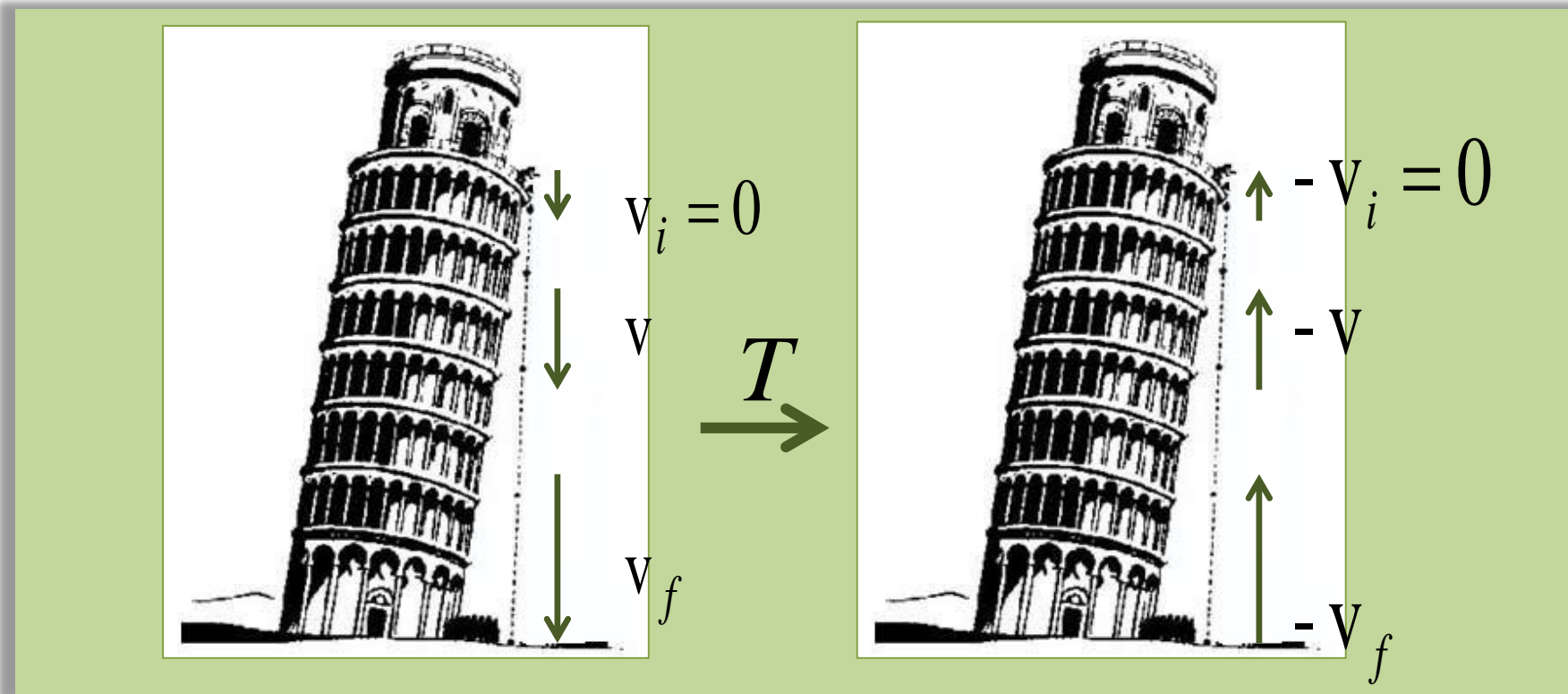
allows to talk of Δt **Transition Probability** $P \left(K_{\rightarrow f_1} \xrightarrow{\Delta t} K_{\rightarrow f_2}^\perp \right)$

“independent of the decay” and connected to $I(f_1, f_2; \Delta t)$.

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

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

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 $U_T \vec{r} U_T^\dagger = \vec{r}, U_T \vec{p} U_T^\dagger = -\vec{p}, U_T \vec{s} U_T^\dagger = -\vec{s}$

➤ **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:

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

T - Violation means Asymmetry under Interchange in \longleftrightarrow out states

➤ Similarly for ANTIUNITARY CPT which needs not only in \leftrightarrow 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

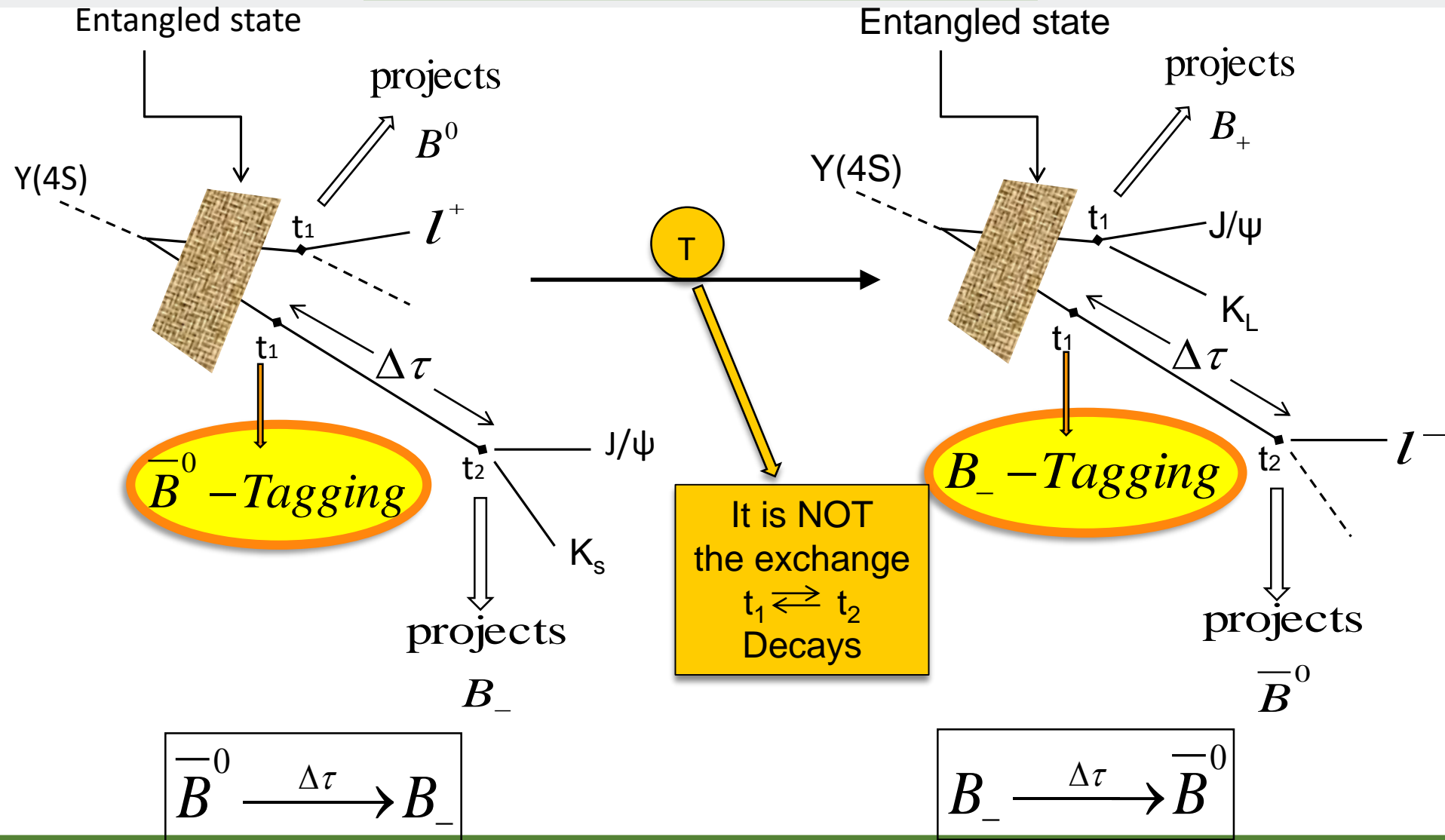
- Neutral Mesons $K^0 - \bar{K}^0$, $B^0 - \bar{B}^0$ are UNSTABLE and the Decay is irreversible.
 - **T and CPT, ANTIUNITARITY!**, need however the exchange of initial and final states → NO-GO.
L. Wolfenstein, PRL 1999 : "The T-reverse of a decaying state is not a physical state".
- **BYPASS** M. C.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

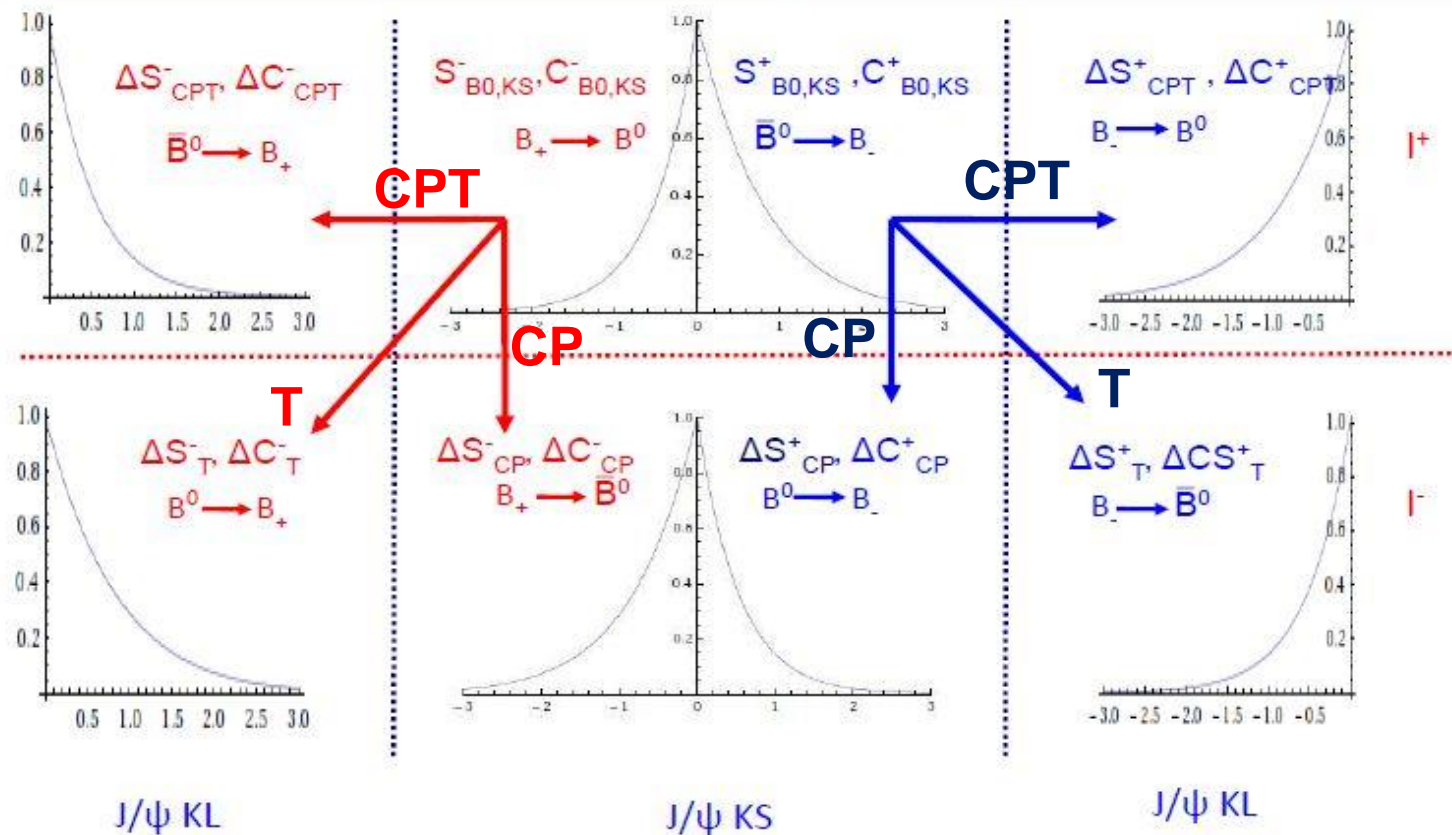
J.B., Martinez Vidal, Villanueva, JHEP 2012,

COVER PAGE RMP vol. 87 (2015)



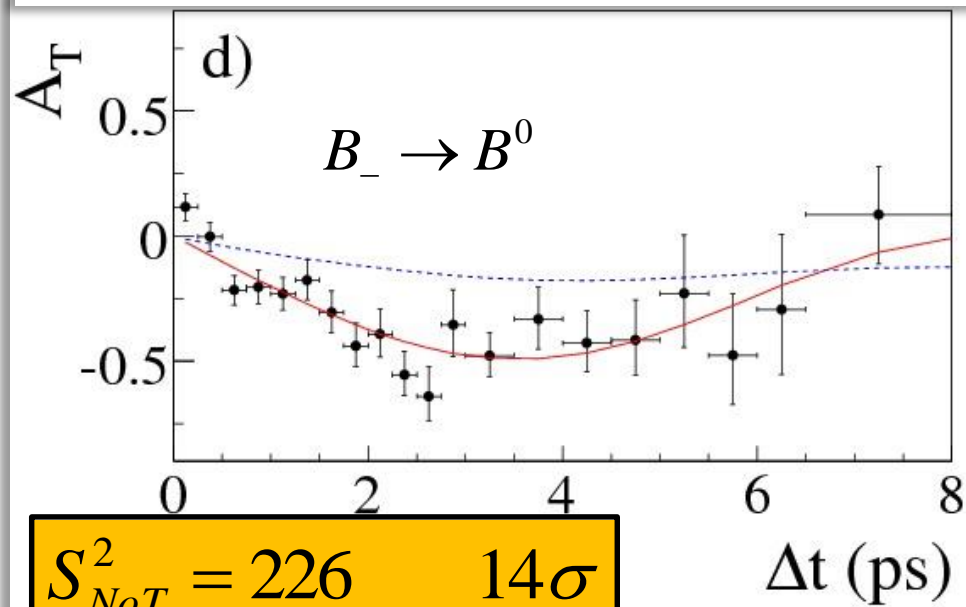
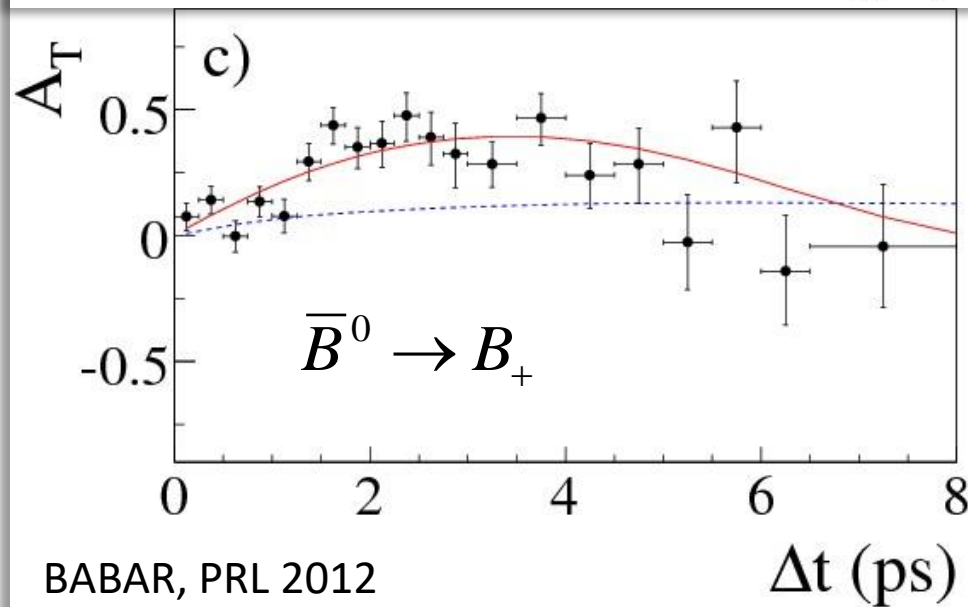
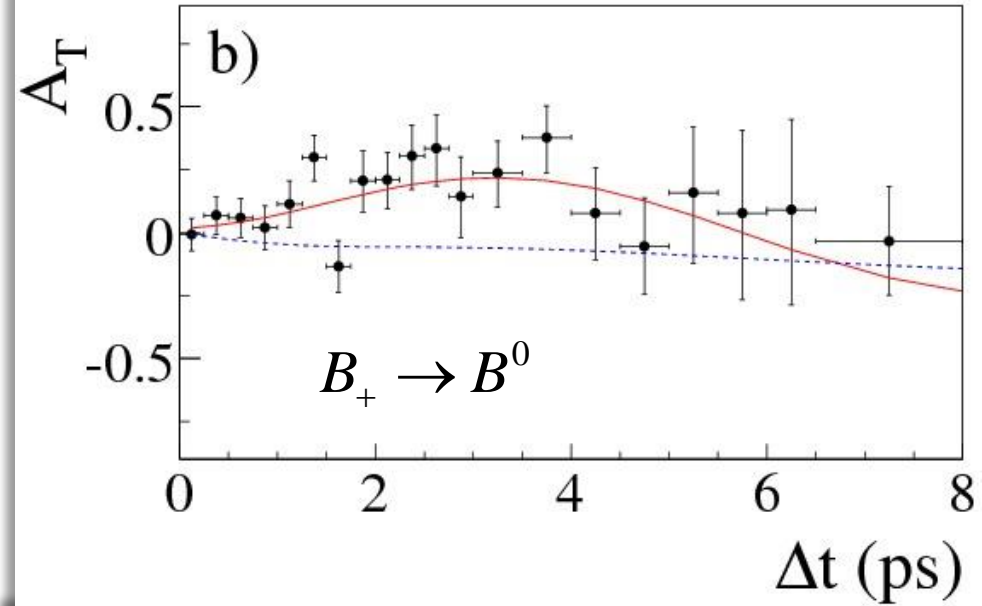
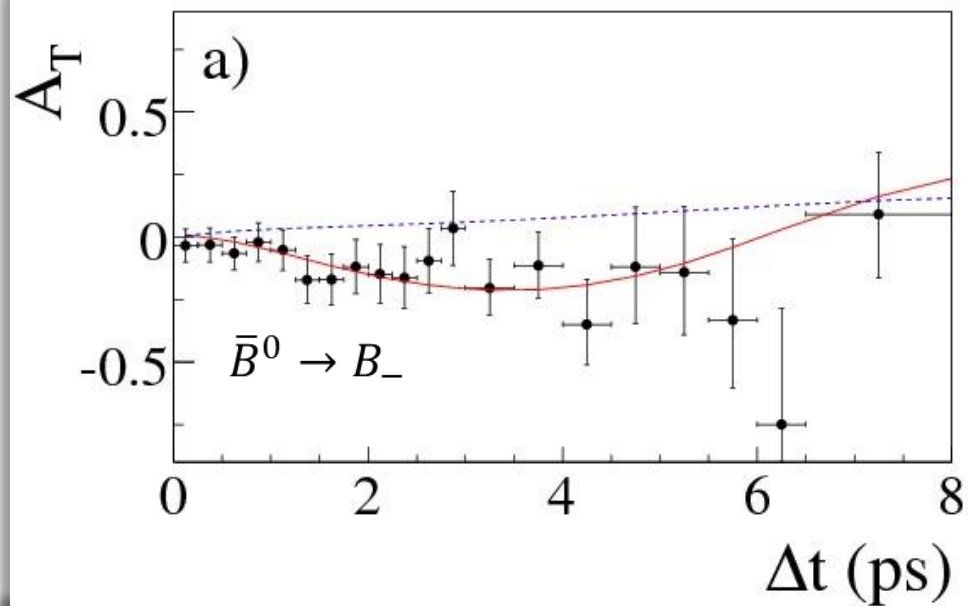
$\Delta S^\pm, \Delta C^\pm$ ASYMMETRY PARAMETERS

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



→ 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 & SIGNIFICANCE



$$S_{NoT}^2 = 226 \quad 14\sigma$$

SEPARATE T AND CP VIOLATION EFFECTS

SYMMETRY BREAKING UNDER TIME REVERSAL

Theory-Experiment Collaboration @ IFIC, CSIC, UNIVERSITY OF VALENCIA

Broken discrete space-time symmetries

Symmetries and their breaking are a bedrock tool for understanding the fundamental laws of physics. The violation of the Charge-Parity (CP) symmetry between matter and antimatter led to the need of three fermion families, later discovered. The observation of CP violation in neutral kaon decays in 1964 and neutral B-meson decays in 2001 suggests, based on the up to now unbroken CPT symmetry, that Time Reversal symmetry (T) should be violated as well in these systems. Its direct detection requires an asymmetry under exchange of initial and final meson states.

The challenge of Time Reversal symmetry for unstable particles

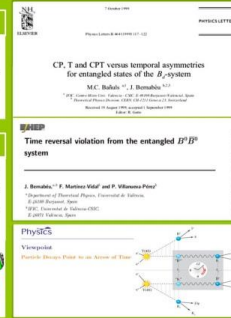
For unstable particles, however, motion reversal looked impossible due to decay irreversibility. The bypass to this no-go argument was given in 1999, for quantum entangled states, using the conceptual basis of the Einstein-Podolsky-Rosen correlation between the partners and the decay as a filtering measurement of the meson state.

Observation at BaBar/PEP-II B factory experiment

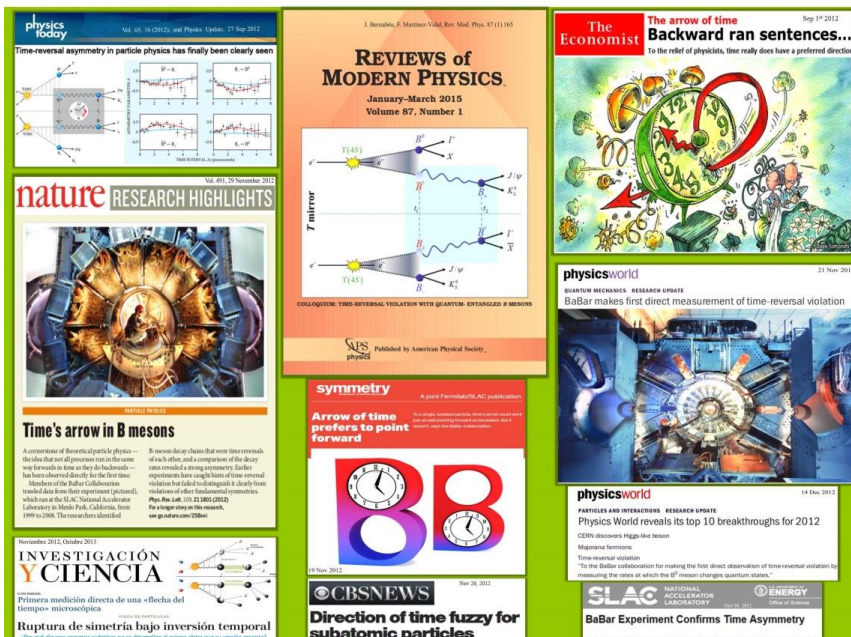
This concept has been implemented for the experiment by the BABAR Collaboration at SLAC's B factory, exploiting time-ordered transitions between different final states in the decay of neutral B mesons. The results, presented in 2012, prove beyond any doubt the violation of time-reversal invariance in the time evolution between two neutral states.

Selected for a Viewpoint in Physics
PHYSICAL REVIEW LETTERS
PRL 109, 211801 (2012) week ending 21 NOVEMBER 2012

Observation of Time-Reversal Violation in the B^0 Meson System



RESULTS HIGHLIGHTED IN THE VIEWS AND MEDIA: A SELECTION



physics today
Vol. 45, 14 (2012), and Physics Update, 27 Sep 2012
Time-reversal asymmetry in particle physics has finally been clearly seen

REVIEWS of MODERN PHYSICS
January-March 2015
Volume 87, Number 1
J. Bernab... F. Martinez Vidal, Rev. Mod. Phys. 87 (1) 145

The Economist
The arrow of time
Backward ran sentences...
To the relief of physicists, time really does have a preferred direction

nature RESEARCH HIGHLIGHTS
Vol. 491, 20 November 2012
Time's arrow in B mesons
A cornerstone of theoretical physics is the idea that not all processes run in the same way forwards in time as they do backwards — has been observed directly for the first time. Members of the BABAR Collaboration in the US, the National Institute of Standards and Technology (NIST) in the US, and the University of California, Berkeley, have used data from their experiment (published in the 14 November 2012 issue of Nature) to show that the time-reversal symmetry of the laws of physics is broken in the decay of B mesons.

symmetry
A joint Fermilab/SLAC publication
Arrow of time prefers to point forward
To us, time is a straight line. But to the particles of the universe, time is a loop. The BABAR Collaboration has shown that the arrow of time is not always pointing forward.

CBSNEWS
Nov 20, 2012
Direction of time fuzzy for subatomic particles

physicsworld
QUANTUM MECHANICS RESEARCH UPDATE
BaBar makes first direct measurement of time-reversal violation
The BABAR collaboration has made the first direct observation of time-reversal violation by measuring the rates at which the B^0 meson changes quantum states.

physicsworld
PARTICLES AND INTERACTIONS RESEARCH UPDATE
Physics World reveals its top 10 breakthroughs for 2012
CERN discovers Higgs-like boson
Majorana fermions
Time-reversal violation
"To the BABAR collaboration for making the first direct observation of time-reversal violation by measuring the rates at which the B^0 meson changes quantum states."

SLAC NATIONAL ACCELERATOR LABORATORY
BaBar Experiment Confirms Time Asymmetry
Time's direction arrow has a preferred direction, says analysis shows

INVESTIGACIÓN Y CIENCIA
Primer medición directa de una «flecha del tiempo» microscópica.
Ruptura de simetría bajo inversión temporal
[Por qué algunas partículas cambian de comportamiento al invertir el tiempo, pero no todas.]

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 $|\mathbf{i}(\mathbf{t})\rangle$ 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

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

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

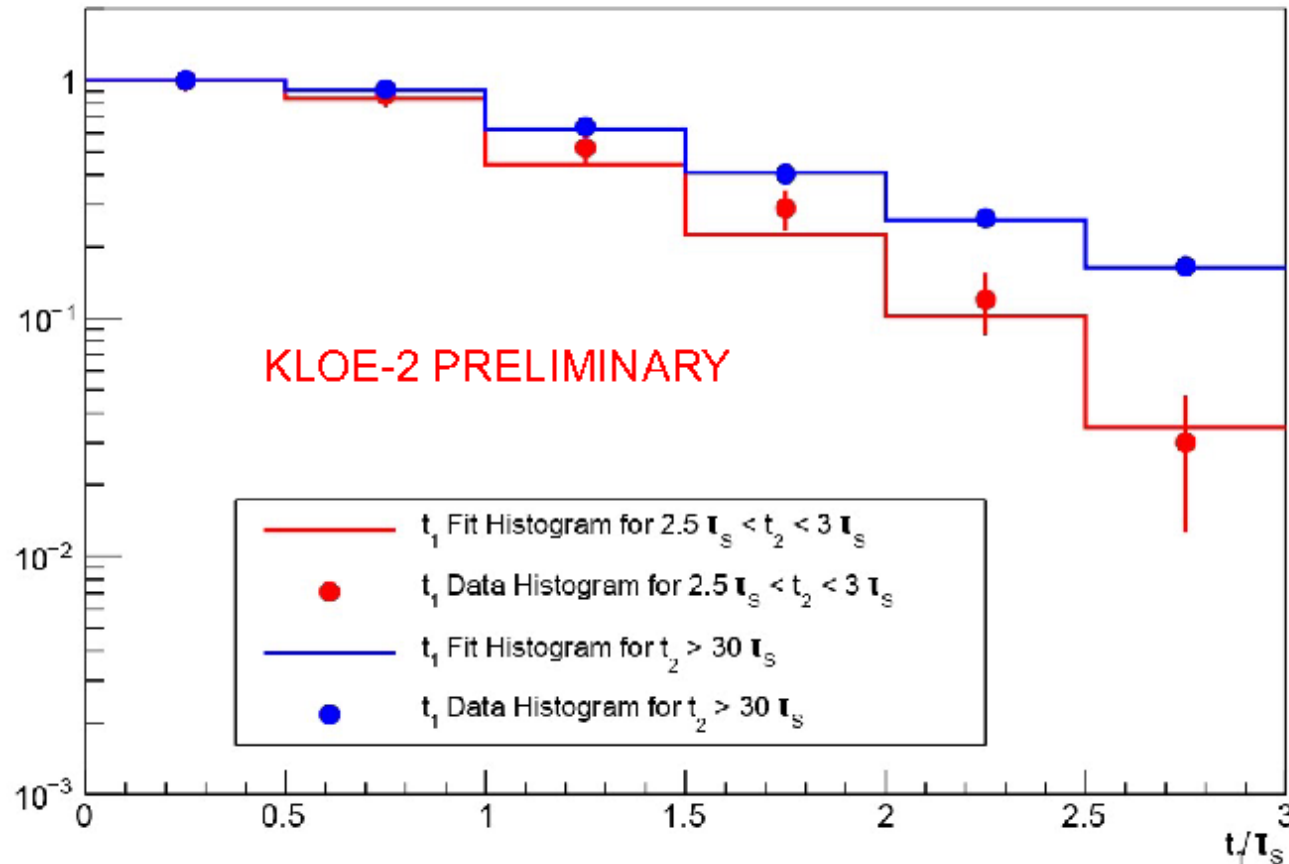
Fixing the observation (η_2, t_2) and evolving t_1 from $t_1=0$ to $t_1=t_2$, **its past state had to be**

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

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

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

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



THE K_S -TAG

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

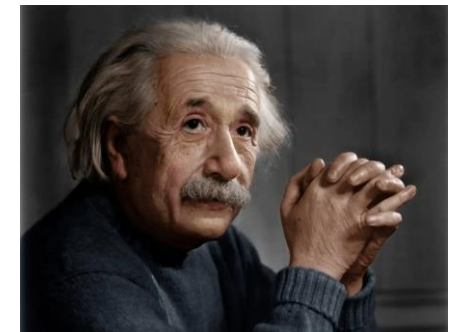
$$e^{-\Delta\Gamma\Delta t/2}/|\eta_2| \ll 1$$

leading to a pure K_S -beam

- Most rewarding: - ~~CP~~ and $\langle K_L | K_S \rangle \neq 0 \rightarrow$ 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 $A_L - A_S \rightarrow$ 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 exchanging 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**

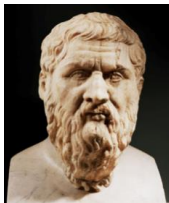
↔ Scientific Methodology

Philosophy → What QM says about nature's reality?

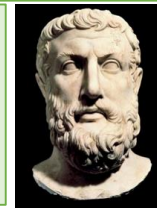
NEW

- | | |
|--------------------------------|---------------------------------|
| - 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 |

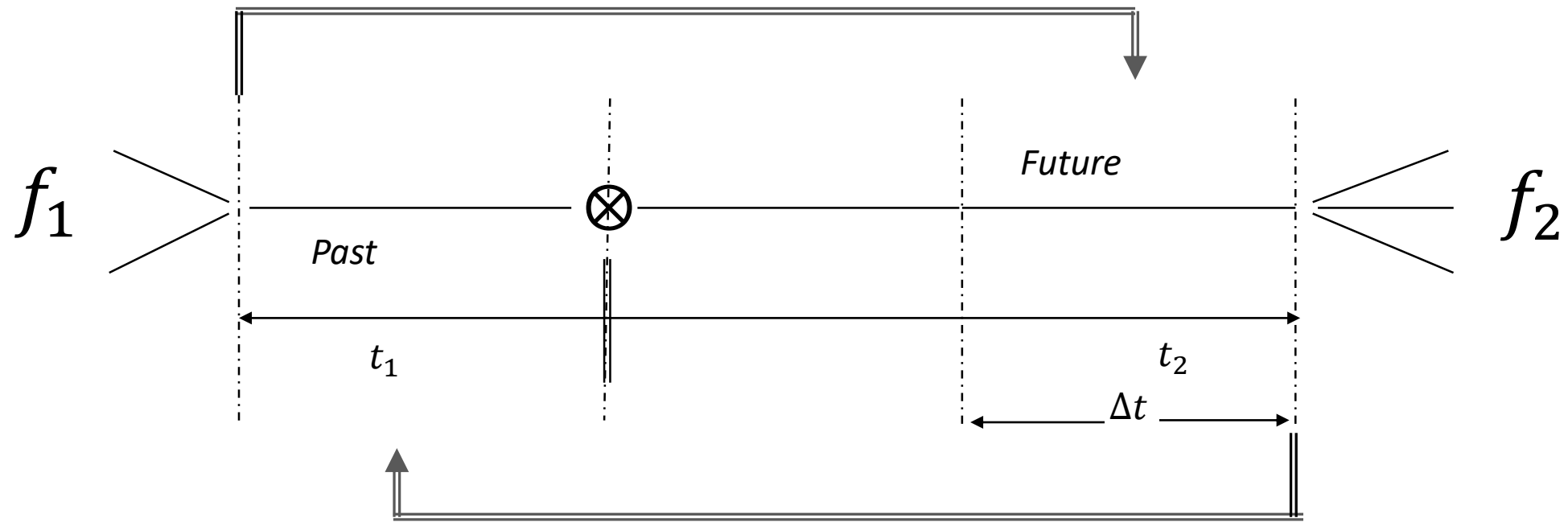
(x,t) is not a definite, separate event ↔ Role of time in QM ?



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

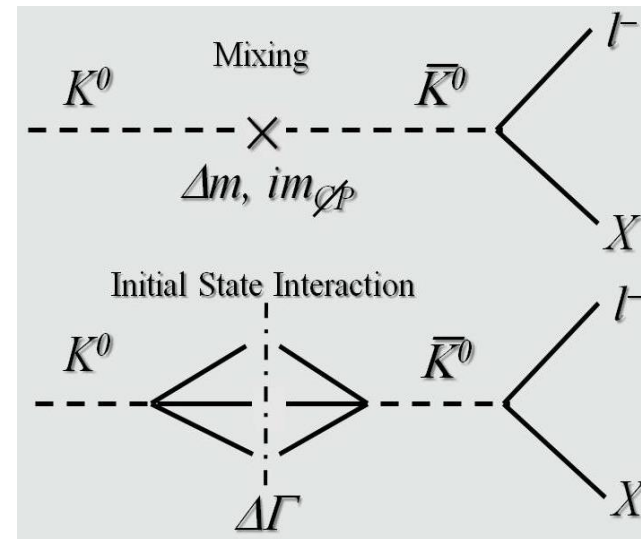
➡ No way to separate T and CP if T were defined. CPT and Δt are the identity!

➤ 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 $\Delta\Gamma$.

The decay plays an essential role

➤ The **time evolutions** of $K^0 \rightarrow \bar{K}^0$ and $\bar{K}^0 \rightarrow K^0$ 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”.