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מכון ויצמן למדע
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Time reversal violation

From theory to experiment & back

Applebaum, AE, Grossman, Nir and Soreq, Phys. Rev. D **89**, 076011 (2014)

Banuls and Bernabeu, Phys. Lett. B **464**, 117 (1999)

Bernabeu, Martinez-Vidal and Villanueva-Perez, JHEP **1208**, 064 (2012)

Discrete 2014, London

Introduction

CP&*CPT*

T asymmetries

CP

CP transformation

$$CP(\psi) = \bar{\psi}$$
$$CP\left(\Gamma_{a,b,\ldots\to x,y,\ldots}\right) = \Gamma_{\bar{a},\bar{b},\ldots\to\bar{x},\bar{y},\ldots}$$

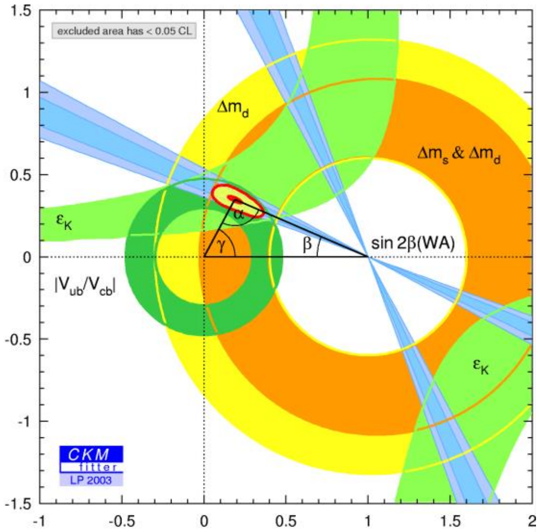
CP is violated in nature

We know it because

- We see it in the lab (since 1964)
- We live

CP is violated in the Standard Model

- Precisely enough to explain the experimental observations
- Not enough to live



CPT

CPT symmetry is inherent in any local QFT respecting Lorentz invariance

It results, for instance, in $m_\psi = m_{\bar{\psi}}$ & $\Gamma_\psi = \Gamma_{\bar{\psi}}$

CPT conservation implies that

CP violation = *T* violation

Measurement of *T* asymmetry is an important test for *CPT*

T asymmetries

Distinguish between two types of *T* asymmetries

Macroscopic (the ``arrow of time”)

- The 2nd law of thermodynamic
- Ordered systems become disordered with time
- The opposite process is extremely unlikely
- *T* asymmetry which is unrelated to the microscopic laws

Microscopic

- *T* violation in the laws of particle physics
- But what exactly is *T* transformation?

$$T\left(\Gamma_{a,b,\ldots\to x,y,\ldots}\right)=\Gamma_{x,y,\ldots\to a,b,\ldots}\qquad ??$$

T transformation

T transformation:

- Not only reversing the time, but also interchanging between incoming and outgoing states
- ψ^T is *T*-conjugate to ψ

$$T\left(\Gamma_{a,b,\ldots\rightarrow x,y,\ldots}\right) \neq \Gamma_{x,y,\ldots\rightarrow a,b,\ldots}$$

$$T\left(\Gamma_{a,b,\ldots\rightarrow x,y,\ldots}\right) = \Gamma_{x^T,y^T,\ldots\rightarrow a^T,b^T,\ldots}$$

So, to measure *T* violation one needs to compare a microscopic process with its inverse process

Not an easy task!

T asymmetries

H. Quinn, Discrete 2008

Direct

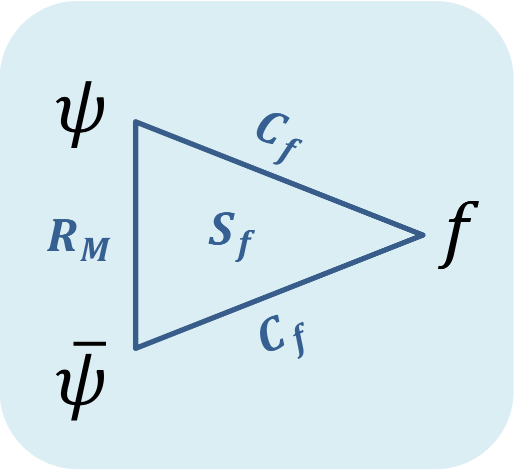
- Decay vs. inverse decay
- Impractical to realize in an experiment
- Problematic preparation of the initial state
- Weak process swamped by the strong processes

Mixing

- CPLEAR 1998

Interference

- BABAR 2012



Measuring *T* asymmetries

CPLEAR measurement

BABAR measurement

CPLEAR measurement

In 1998 the CPLEAR collaboration measured the Kabir asymmetry

CPLEAR Collaboration, Phys. Lett. B 444, 43 (1998)

Kabir, Phys. Rev. D 2, 540 (1970)

$$\Gamma_1: \quad p\bar{p} \to K^-\pi^+K^0 \rightsquigarrow \overline{K}^0$$

$$\qquad\qquad\qquad\qquad \hookrightarrow e^-\pi^+\bar{\nu}$$

$$\Gamma_2: \quad p\bar{p} \to K^+\pi^-\overline{K}^0 \rightsquigarrow K^0$$

$$\qquad\qquad\qquad\qquad \hookrightarrow e^+\pi^-\nu$$

$K^\pm$ is used to tag K^0 or $\overline{K}^0$ at t_1

$e^\pm$ is used to tag K^0 or $\overline{K}^0$ at t_2

CPLEAR measurement

Constructing

$$A_{T,K} = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2} \approx \frac{\Gamma_{K^0 \to \overline{K}^0} - \Gamma_{\overline{K}^0 \to K^0}}{\Gamma_{K^0 \to \overline{K}^0} + \Gamma_{\overline{K}^0 \to K^0}}$$

CPLEAR measured

$$\langle A_{T,K} \rangle_{(1-20)\tau_S} = (6.6 \pm 1.6) \times 10^{-3}$$

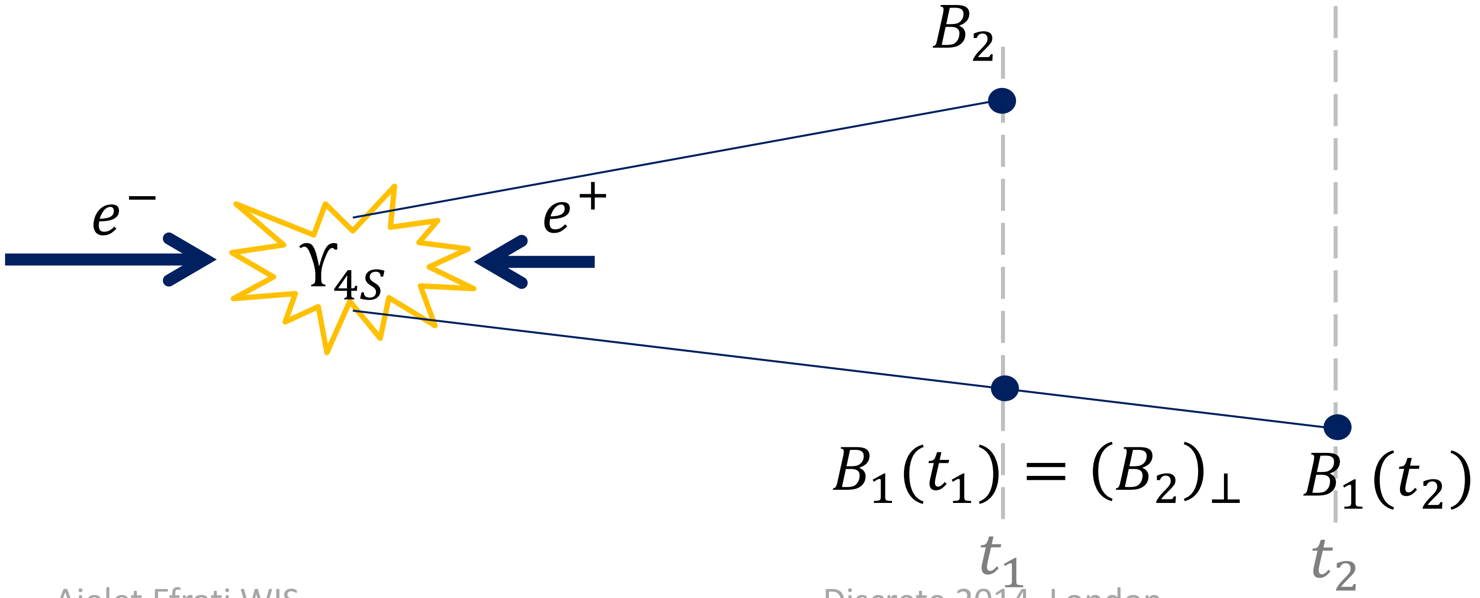
A measurement of *T* asymmetry which is also a *CP* asymmetry

Can we measure *T* asymmetry which is not a *CP* asymmetry?

Banuls and Bernabeu, Phys. Lett. B 464, 117 (1999)

BABAR measurement

1. e^+e^- collision at the Υ_{4S} threshold
2. Υ_{4S} decays to an anti-symmetric coherent state of two B mesons
3. Using the EPR effect in entangled systems, measuring B_2 at t_1 determine B_1 at t_1
4. Then measure B_1 at t_2 to get information on its time evolution



BABAR measurement

The entangled B system offers two sets of tagging

Banuls and Bernabeu, Phys. Lett. B **464**, 117 (1999)

Flavor tagging

- B^0 decay to ℓ^+
- $\bar{B}^0$ decay to ℓ^-

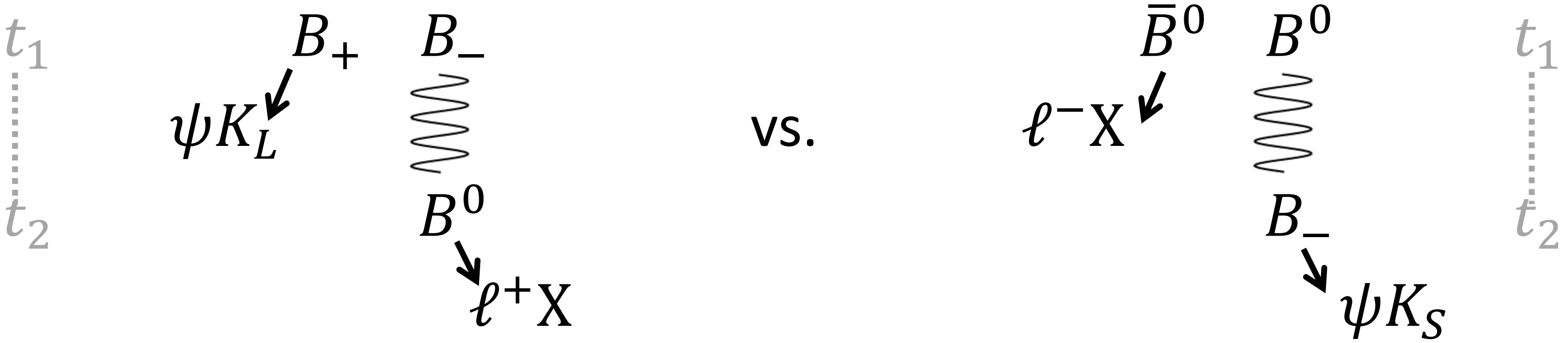
CP tagging

- B_+ decay to ψK_L
- B_- decay to ψK_S

$$\begin{aligned} |i(t_1)\rangle &= \frac{1}{\sqrt{2}}\left(|B^0\rangle_1|\bar{B}^0\rangle_2 - |\bar{B}^0\rangle_1|B^0\rangle_2\right) \\ &= \frac{1}{\sqrt{2}}\left(|B_-\rangle_1|B_+\rangle_2 - |B_+\rangle_1|B_-\rangle_2\right) \end{aligned}$$

BABAR measurement

Using different tagging at t_1 and t_2 BABAR can construct a *T* asymmetry (*) which is not a *CP* asymmetry:



t_1 $\quad B_+ \quad B_-$ $\qquad\qquad$ $\bar{B}^0 \quad B^0$ $\quad t_1$

ψK_L $\qquad\qquad$ vs. $\qquad\qquad$ $\ell^- X$

t_2 $\quad B^0$ $\qquad\qquad$ B_- $\quad t_2$

$\ell^+ X$ $\qquad\qquad$ ψK_S

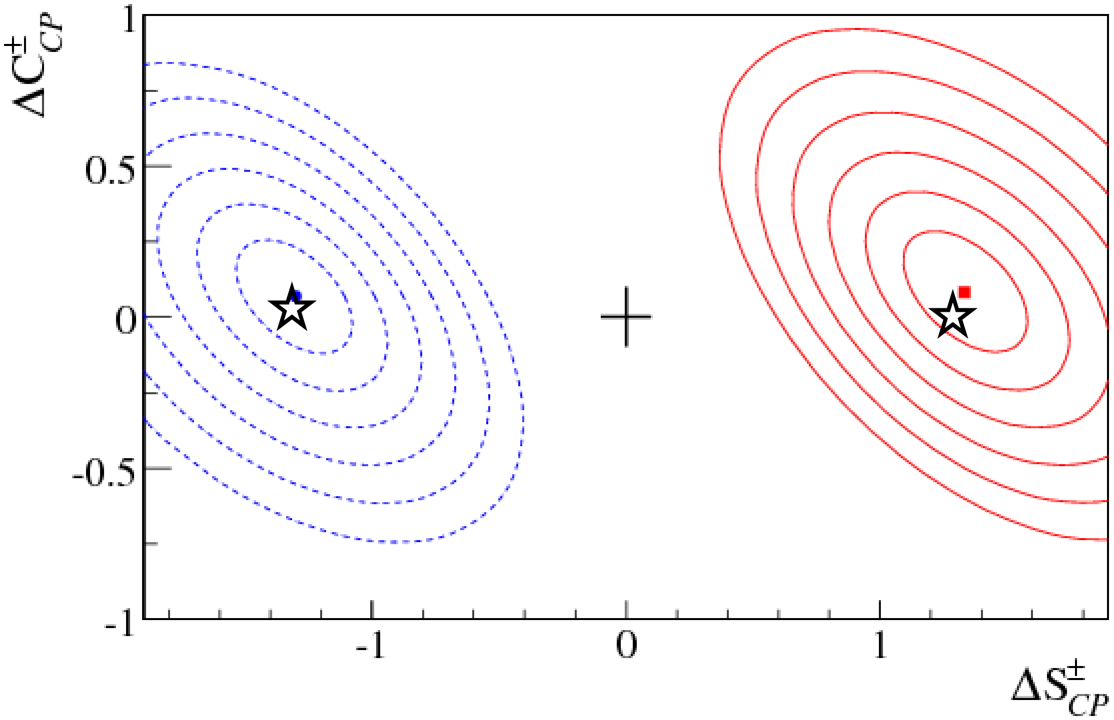
$B_- \to B^0$ vs. $B^0 \to B_-$

Construct 6 asymmetries: 2 *T*, 2 *CP and* 2 *CPT*

(*) Under some assumptions

BABAR measurement - *CP*

Measure *CP* asymmetry at 17σ

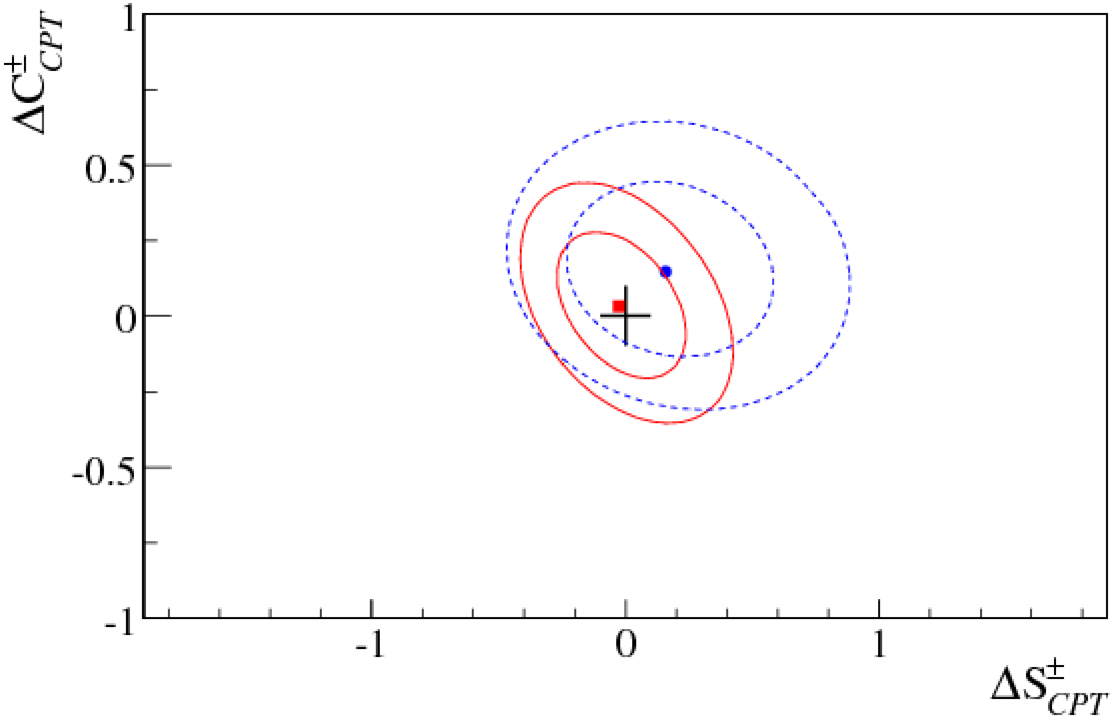


Naive world average:

$|\Delta C| \simeq 0.00 \pm 0.04$ $|\Delta S| \simeq 1.32 \pm 0.04$

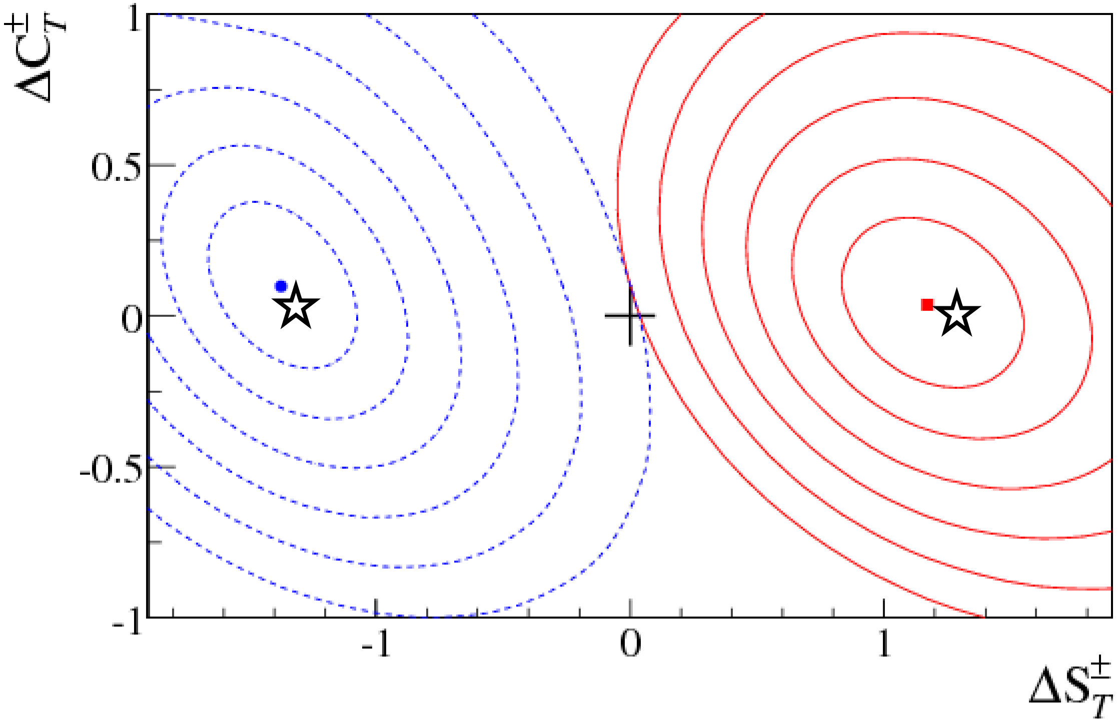
BABAR measurement - *CPT*

CPT symmetry is consistent at 0.3σ



BABAR measurement - *T*

Measure *T* asymmetry at 14σ



From *CP* measurements, assuming *CPT*,

$|\Delta C| \simeq 0.00 \pm 0.04$ $|\Delta S| \simeq 1.32 \pm 0.04$

IOP Physics World - the member magazine of the Institute of Physics

physicsworld.com

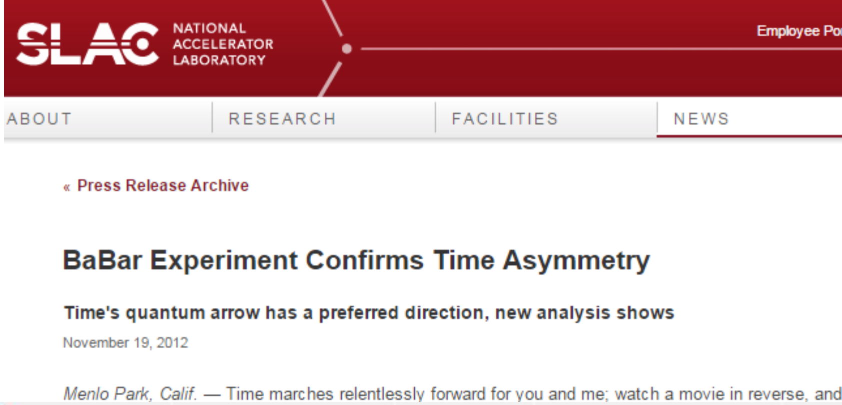
BaBar makes first direct measurement of time-reversal violation

Nov 21, 2012 15 comments

Forwards and backwards at BaBar

The BaBar collaboration has made the first direct obs
time-reversal (T) violation. The results are in agreem
basic tenets of quantum field theory and reveal differ
rates at which the quantum states of the B^0 meson t
one another. The researchers say that this measured
symmetry is statistically significant and consistent w
observations.

The BaBar detector at the PEP-II facility at SLAC in
designed to study the collisions of electrons and pos
determine the differences between matter and antima
particular, physicists working on the experiment are i



SLAC NATIONAL ACCELERATOR LABORATORY

BaBar Experiment Confirms Time Asymmetry

Time's quantum arrow has a preferred direction, new analysis shows

November 19, 2012

Menlo Park, Calif. — Time marches relentlessly forward for you and me; watch a movie in reverse, and

The Economist

The arrow of time

Backward ran sentences...

To the relief of physicists, time really does have a preferred direction

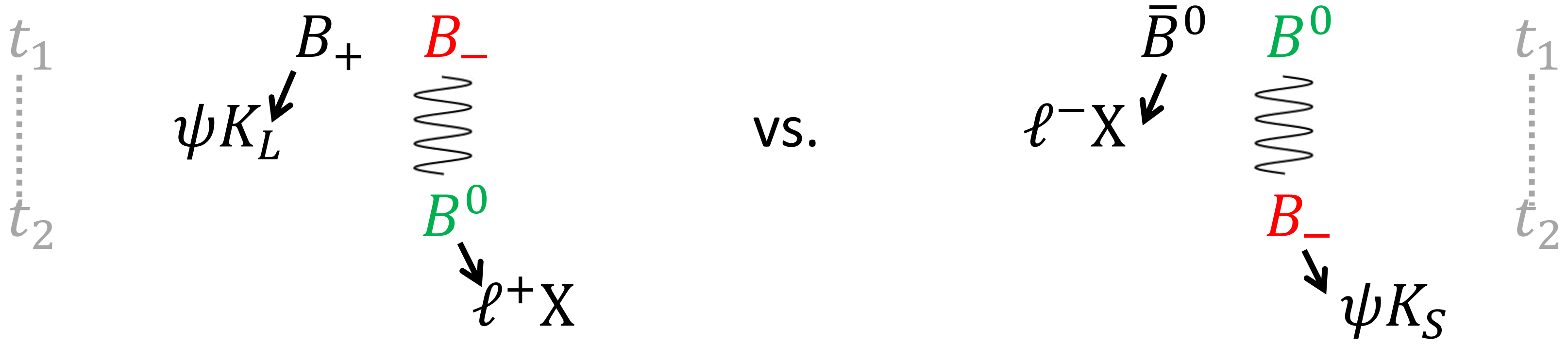
Sep 1st 2012 | From the print edition

TIME seems to flow inexorably in one direction. Superficially, that is because things

Subtleties in the BABAR measurement

Subtleties in BABAR measurement

1. Time conjugation



t_1 B_+ B_-

ψK_L

t_2 B^0

$\ell^+ \mathrm{X}$

vs.

$\bar{B}^0$ B^0 t_1

$\ell^- \mathrm{X}$

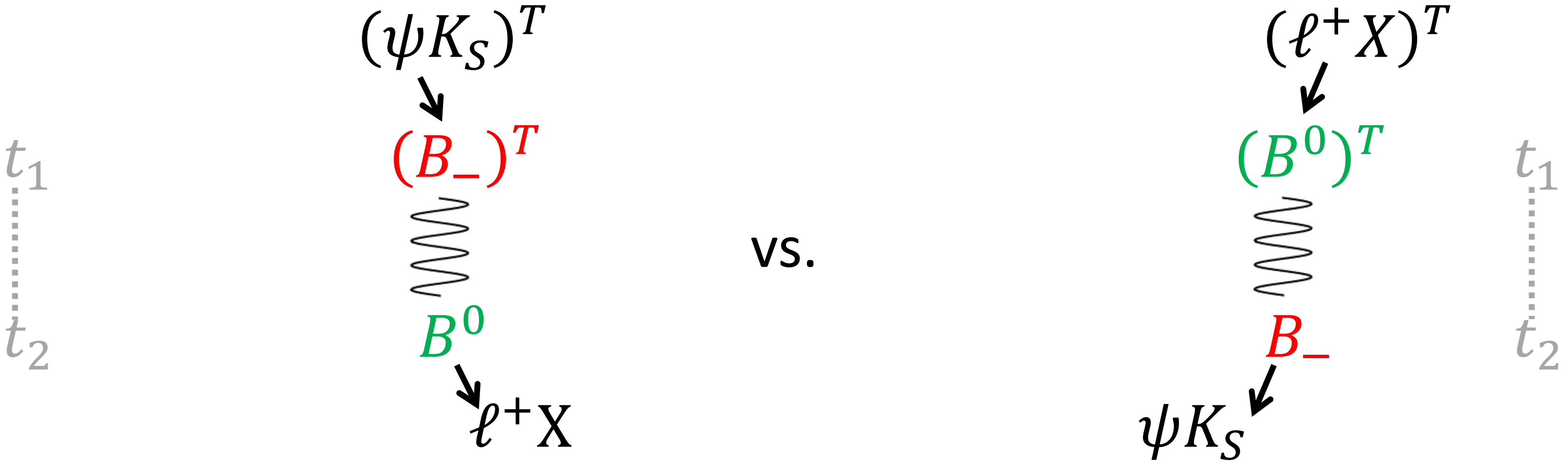
B_- t_2

ψK_S

Not precisely time conjugated processes

Subtleties in BABAR measurement

1. Time conjugation



t_1

t_2

$(\psi K_S)^T \searrow (B_-)^T$ ⌇ $B^0 \searrow \ell^+ X$

vs.

$(\ell^+ X)^T \swarrow (B^0)^T$ ⌇ $B_- \swarrow \psi K_S$

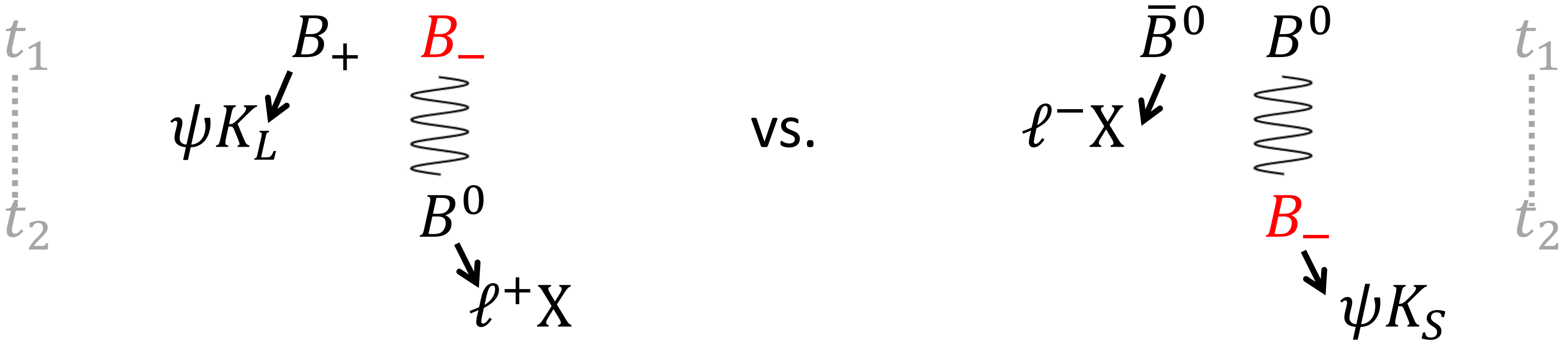
t_1

t_2

- Inverse decays are not accessible to the experiment
- Need to include the effect of CPT violation in decays
- *T*-even *CPT*-odd contribution to BABAR’s *T* asymmetries
- Unconstrained (forever?) and impossible to calculate

Subtleties in BABAR measurement

2. *CP* tagging



t_1 B_+ B_-

ψK_L

t_2 B^0

$\ell^+\text{X}$

vs.

$\bar{B}^0$ B^0 t_1

$\ell^-\text{X}$

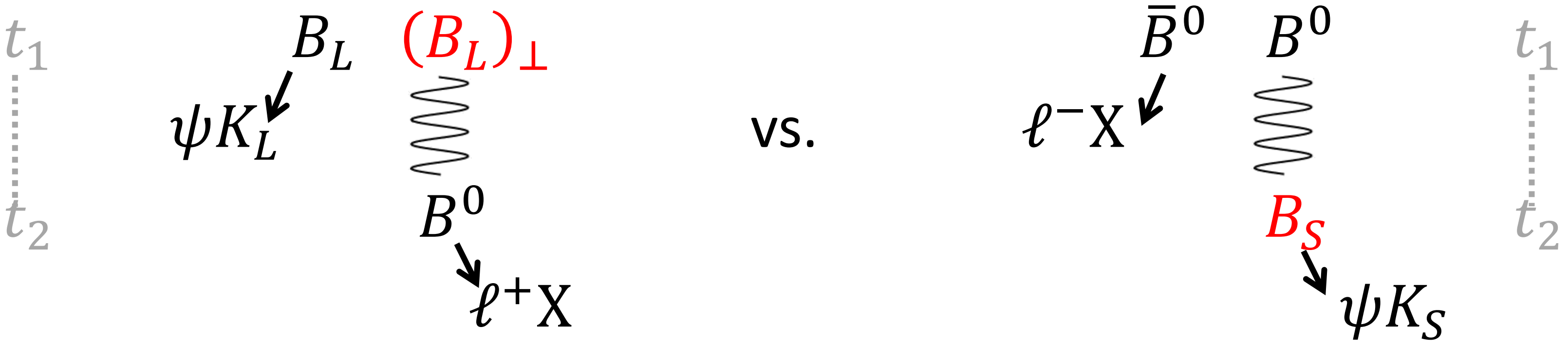
B_- t_2

ψK_S

Not precisely the same states

Subtleties in BABAR measurement

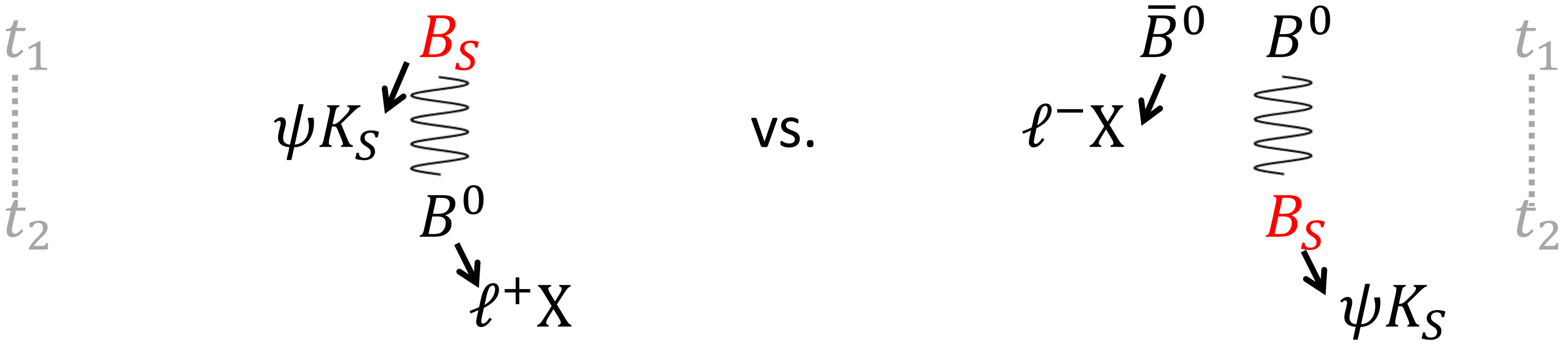
2. *CP* tagging



$(B_L)_\perp \neq B_S$ due to wrong strangeness decays

Subtleties in BABAR measurement

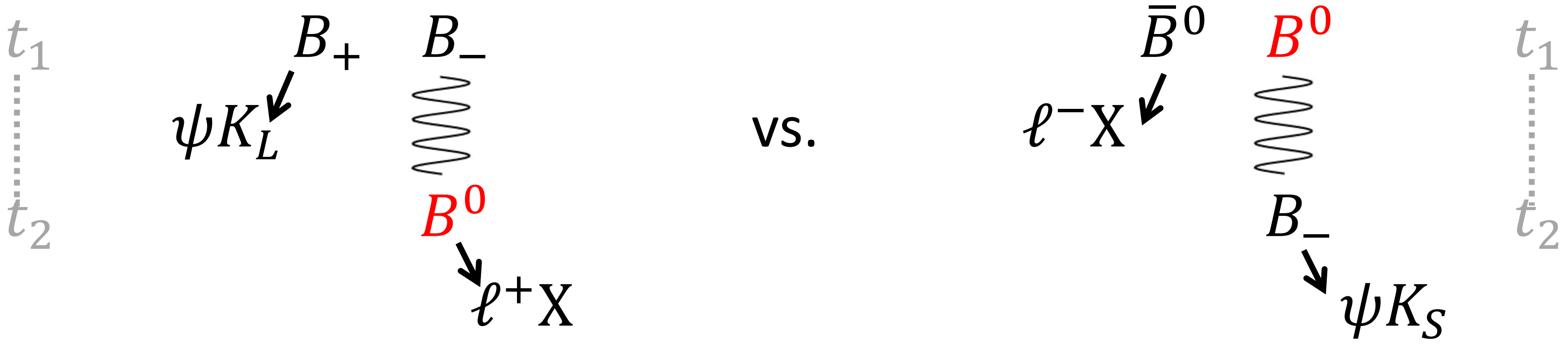
2. *CP* tagging



- Impossible in quantum measurements
- Need to include the effect of wrong strangeness decays
- Do not contribute to BABAR’s *T* asymmetries
- *CPT*-even *T*-odd contribution to BABAR’s *CPT* asymmetries
- Surprisingly, only weakly constrained by experiments

Subtleties in BABAR measurement

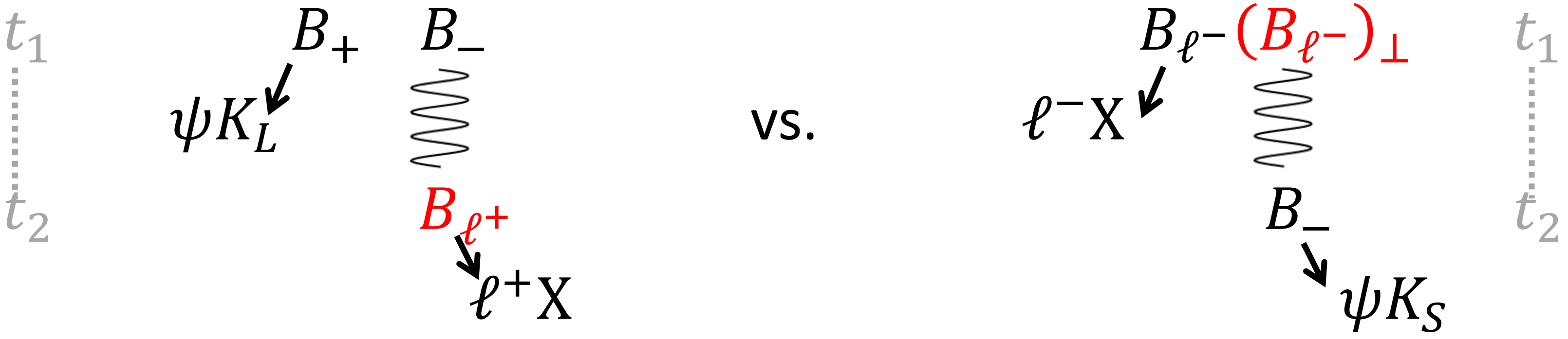
3. Flavor tagging



Not precisely the same states

Subtleties in BABAR measurement

3. Flavor tagging



t_1 $\quad B_+ \quad B_-$

ψK_L

t_2 $\quad B_{\ell^+}$

$\ell^+ \mathrm{X}$

vs.

B_{ℓ^-} $(B_{\ell^-})_\perp$ $\quad t_1$

$\ell^- \mathrm{X}$

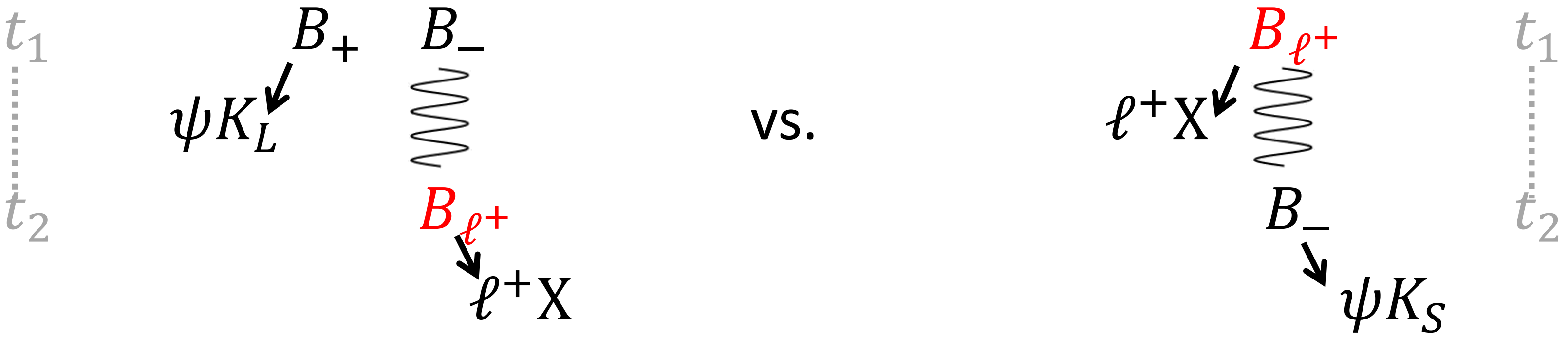
B_- $\quad t_2$

ψK_S

$(B_{\ell^-})_\perp \neq B_{\ell^+}$ due to wrong sign decays

Subtleties in BABAR measurement

3. Flavor tagging



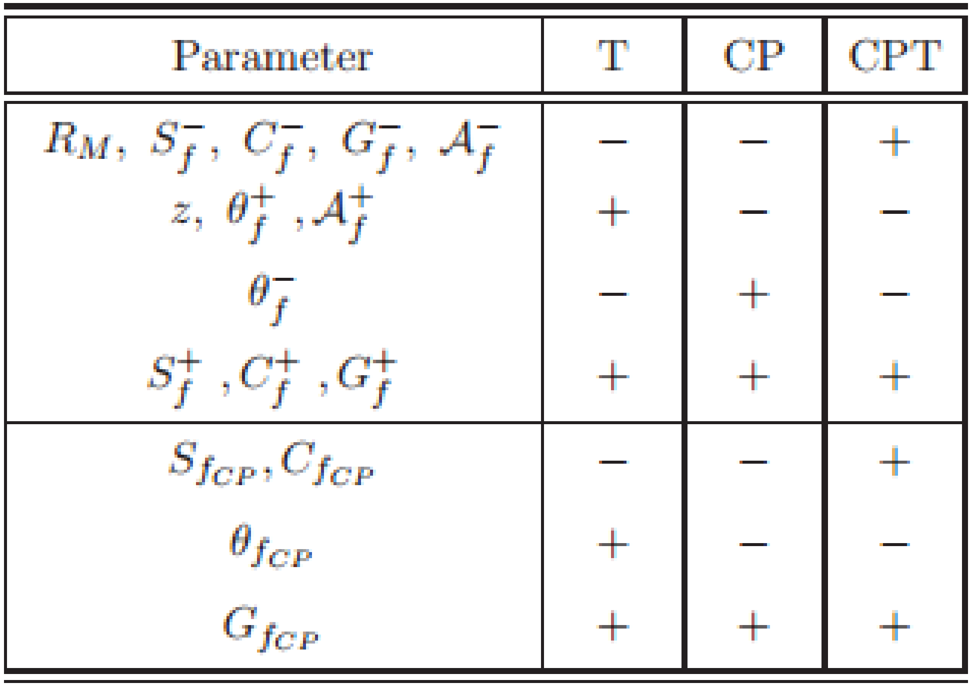
- Impossible in quantum measurement
- Need to include the effect of wrong sign decays
- Contribute to BABAR’s *T* asymmetries
- Numerically, cannot explain alone BABAR’s *T* asymmetry
- Surprisingly, only weakly constrained by experiments

BABAR measurement

Including the effects of

- CPT violation in mixing
- CPT violation in decays
- Wrong sign decays
- Wrong strangeness decays

we identify `theoretical' parameters that have well defined transformation properties



Parameter	T	CP	CPT
R_M, S_f^-, C_f^-, G_f^-, A_f^-	$-$	$-$	$+$
z, θ_f^+, A_f^+	$+$	$-$	$-$
θ_f^-	$-$	$+$	$-$
S_f^+, C_f^+, G_f^+	$+$	$+$	$+$
S_{fCP}, C_{fCP}	$-$	$-$	$+$
θ_{fCP}	$+$	$-$	$-$
G_{fCP}	$+$	$+$	$+$

BABAR measurement

Find relations between the experimental observables and the theoretical parameters

Wrong sign decays

CPT violation in mixing

CPT violation in decay

$$\Delta S_T^+ = -\Delta S_T^- = -2\left[\hat{S}_{\psi K}\left(1+\hat{G}_{\psi K}\left(G_\ell^- - z^R\right)\right) - \hat{G}_{\psi K}\hat{\theta}^I_{\psi K}\right] ,$$

$$\Delta C_T^+ = \Delta C_T^- = 2\left[\hat{C}_{\psi K} + \hat{S}_{\psi K}\left(S_\ell^- - z^I\right) + \hat{\theta}^R_{\psi K}\right] ,$$

$$\Delta S_{CP}^+ = -\Delta S_{CP}^- = -2\left[S_{\psi K_S} - G_{\psi K_S}\theta^I_{\psi K_S} + S_{\psi K_S}G_{\psi K_S}G_\ell^+ - z^I\left(1-\hat{S}^2_{\psi K}\right)\right] ,$$

$$\Delta C_{CP}^+ = \Delta C_{CP}^- = 2\left[C_{\psi K_S} + S_{\psi K_S}S_\ell^+ + \theta^R_{\psi K_S} + G_{\psi K_S}z^R\right] ,$$

$$\Delta S_{CPT}^+ = -\Delta S_{CPT}^- = -2\left[\Delta S_{\psi K} - z^I\left(1-\hat{S}^2_{\psi K}\right) + \hat{G}_{\psi K}\left(\hat{S}_{\psi K}G_{\ell+} - \Delta\theta^I_{\psi K} - \hat{S}_{\psi K}z^R\right)\right] ,$$

$$\Delta C_{CPT}^+ = \Delta C_{CPT}^- = 2\left[\Delta C_{\psi K} + \Delta\theta^R_{\psi K} + \hat{S}_{\psi K}\left(S_{\ell+} - z^I\right) + \hat{G}_{\psi K}z^R\right] .$$

Wrong strangeness decays

Wrong sign decays

BABAR measurement

Use BABAR measurements to constrain these effects

$$
\begin{aligned}
&\hat{S}_{\psi K} - \hat{G}_{\psi K}\hat{\theta}^{I}_{\psi K} = 0.69 \pm 0.04\,.\\
&|\hat{C}_{\psi K} + \hat{\theta}^{R}_{\psi K}| < 0.07\,,\\
&|G_{\psi K_{S,L}} S_{\psi K_{S,L}} \left(G_\ell^- - z^R\right)| < 0.10\,,\\
&|S_{\psi K_{S,L}} \left(S_\ell^- - z^I\right)| < 0.06\,,\\
&|S_\ell^-| < 0.10\,, \qquad |G_\ell^-| < 0.21\,,
\end{aligned}
$$

Experimental constraints are still weak

Summary

Summary

1. A quantum two level system can keep on surprising
2. The BABAR measurement demonstrates a genuine *T* reversal violation if
   - No *CPT* violation in strangeness changing decays;
   - No wrong sign decays
3. New methods to constrain wrong sign decays and wrong strangeness decays are called for
4. Future measurements of *T* violation in
   - entangled K mesons (KLEO2 experiment at DAΦNE)

     Bernabeu, Domenico and Villanueva-Perez, Nucl. Phys. B **868**, 102
   - neutrino oscillations Bernabeu, Cape Town 1999, Weak interactions and neutrinos

   exhibit similar subtleties

Thank you

Subtleties in the BaBar measurement of time-reversal violation
Phys. Rev. D **89**, 076011 (2014) 1312.4164 [hep-ph]

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