מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

SUBTLETIES IN THE BABAR MEASUREMENT OF TIME-REVERSAL VIOLATION

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BaBar makes first direct measurement of time-reversal violation

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OUTLINE

- Introduction
    - to neutral B meson
    - to B factory
- BaBar T-asymmetry
    - construct the BaBar asymmetry
    - is it a true time reversal asymmetry?
- Summary

INTRODUCTION

Three discrete symmetries:

- C - charge conjugation
- P - parity
- T - time reversal

Assuming CPT conservation

- CP and T are related

INTRODUCTION

- time reversal:

  exchange of initial and final states

  T-conjugate state

$$I^T \to F \quad \text{vs.} \quad F^T \to I$$

- T-asymmetry would be:

$$A_T = \frac{\Gamma(I^T \to F) - \Gamma(F^T \to I)}{\Gamma(I^T \to F) + \Gamma(F^T \to I)}$$

- I^T and F^T are experimentally not accessible

INTRODUCTION

CPLEAR - first demonstration of time reversal in Kaon system, **but** also CP-asymmetry:

$$p\bar{p} \to K^+\pi^-\overline{K}^0\,,\;\; K^-\pi^+K^0$$

$$A_{T,K} = \frac{\Gamma(\overline{K}^0 \to K^0) - \Gamma(K^0 \to \overline{K}^0)}{\Gamma(\overline{K}^0 \to K^0) + \Gamma(K^0 \to \overline{K}^0)} \approx 7 \times 10^{-3}$$

time integrated

INTRODUCTION

neutral B-meson:

$B^0 = (\bar{b}d)$

$\overline{B}^0 = (b\bar{d})$

mass eigenstates are linear combination of them (controls the time evolution)

well defined flavor content

INTRODUCTION

neutral B-meson:

$B^0 = (\bar{b}d)$

$\overline{B}^0 = (b\bar{d})$

mixing

mass eigenstates are linear combination of them (controls the time evolution)

well defined flavor content

$B^0 - \overline{B}^0$ oscillations Δm

two level system (like spin 1/2)

INTRODUCTION

B meson decays

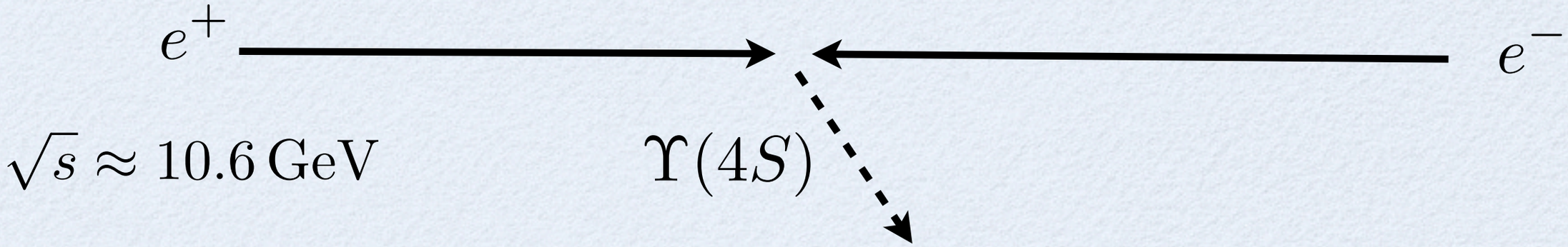
$$A_f = A(B^0 \to f) \qquad \bar{A}_f = A(\overline{B}^0 \to f)$$

B meson inverse decays

$$A_f^{\rm ID} = A(f^T \to B^0) \qquad \bar{A}_f^{\rm ID} = A(f^T \to \overline{B}^0)$$

INTRODUCTION

BaBar is a *B*-factory



INTRODUCTION

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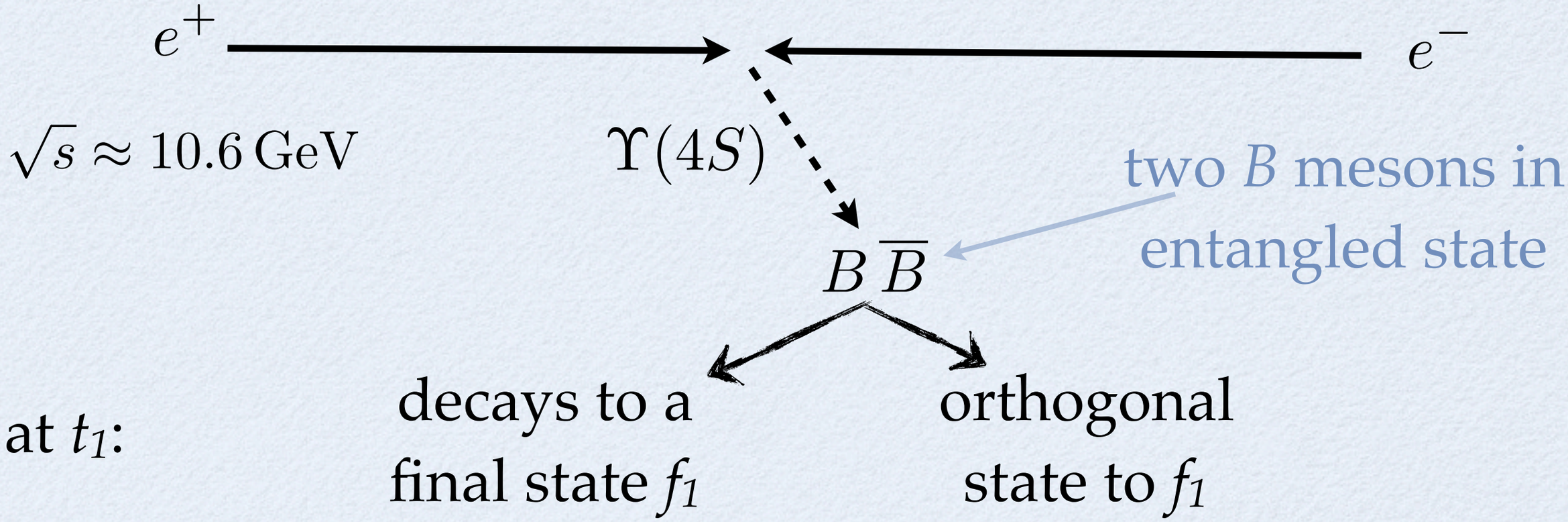
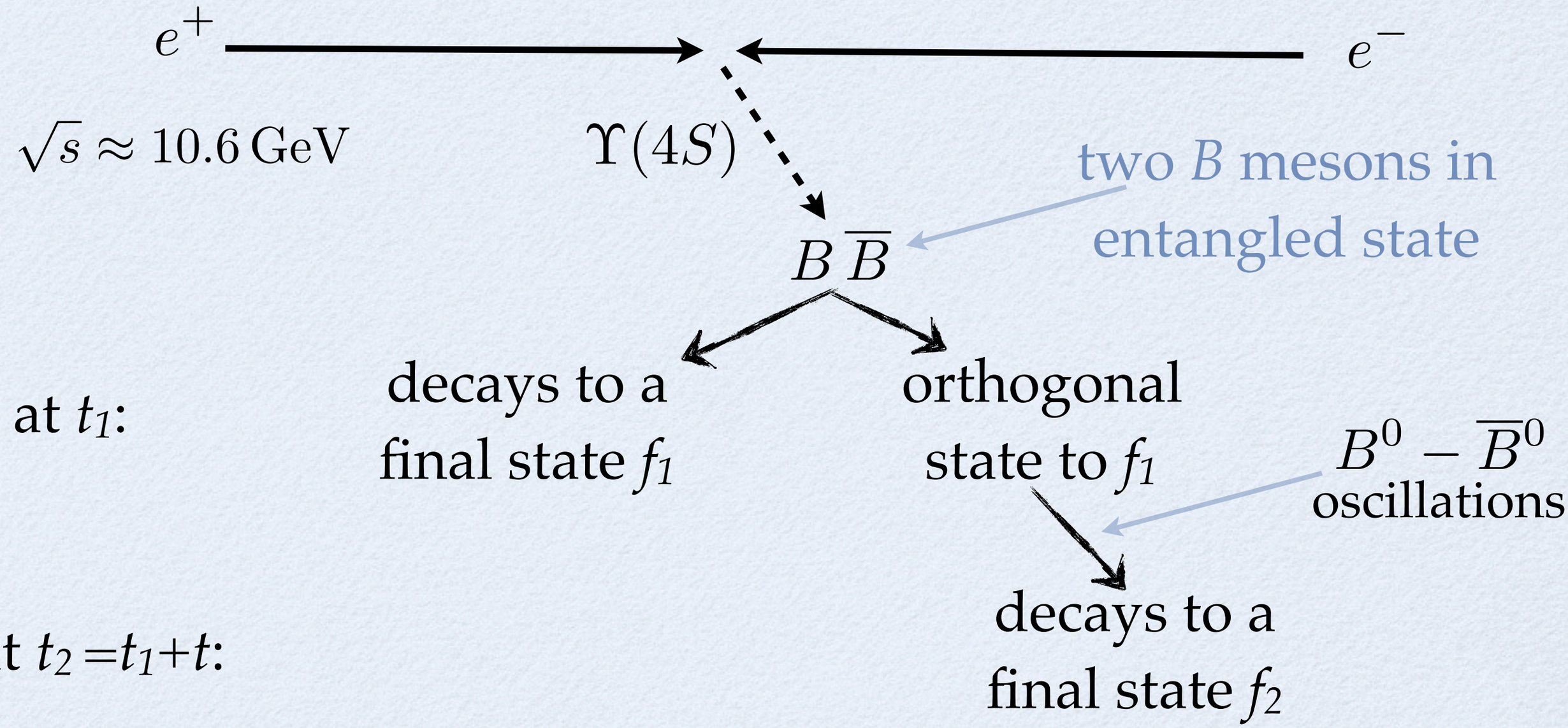


at t_1:

INTRODUCTION

BaBar is a *B*-factory



INTRODUCTION

final states tagging:

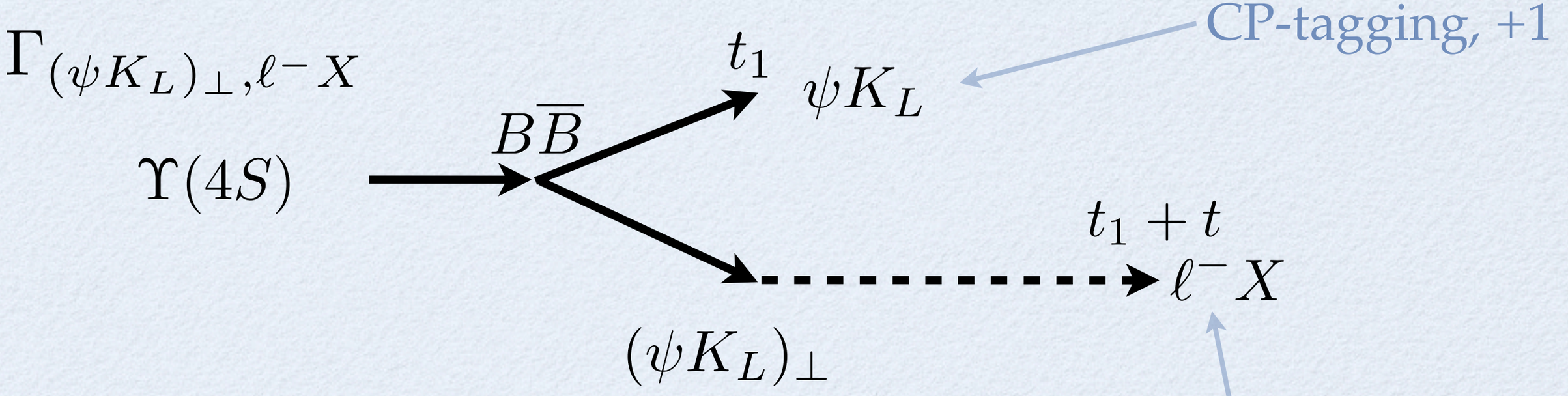
- **flavor tagging** - a final state that probes B states with well defined flavor content (tag B^0 or $\overline{B}^0$)
- **CP tagging** - the final state is a CP eigenstate

$$\psi K_L \, , \psi K_S$$

similar to measure spin $1/2$ in z or x axes

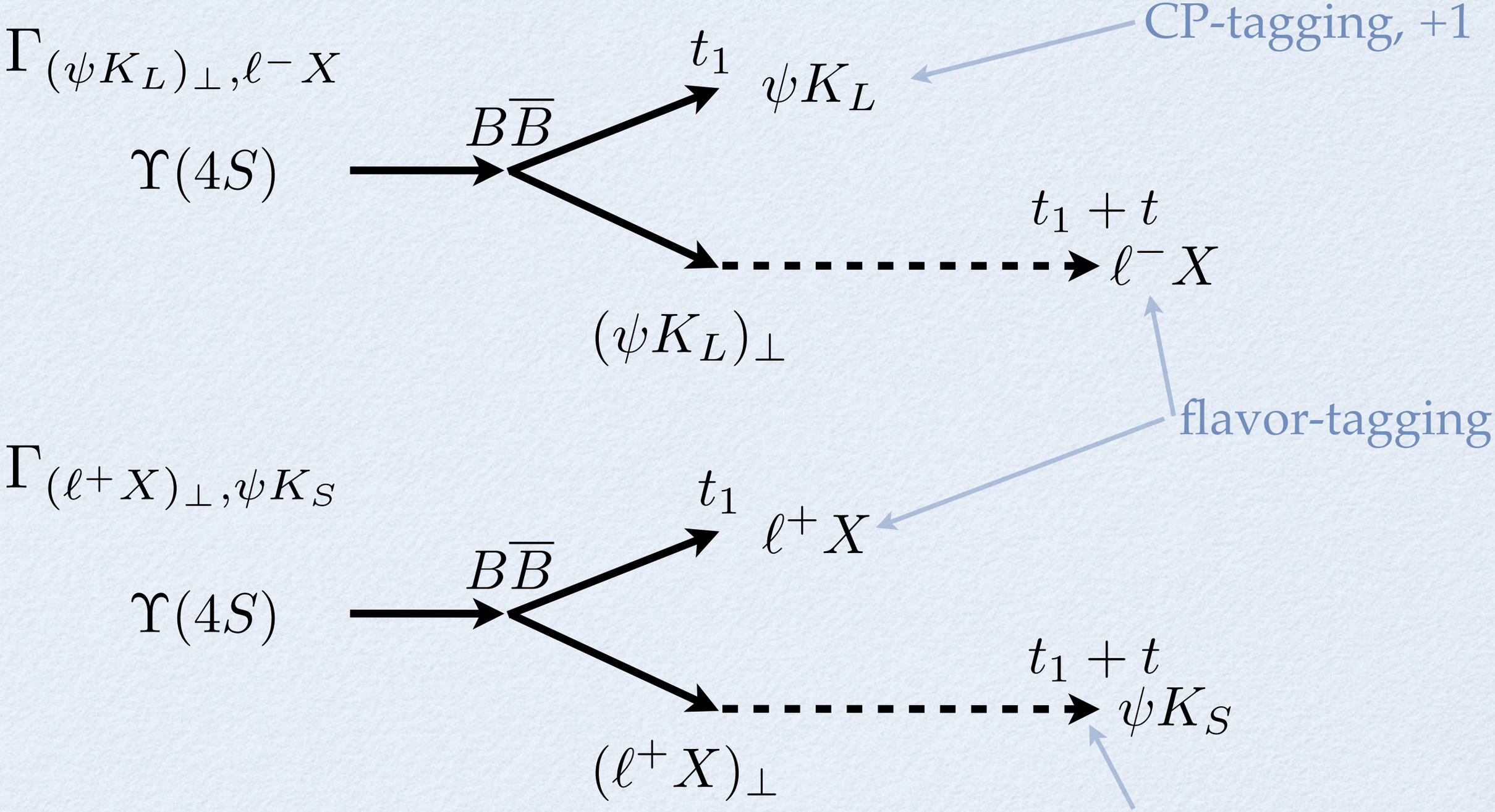
BaBar T-asymmetry

BABAR T-ASYMMETRY



Bernabeu, Martinez-Vidal,
Villanueva-Perez, 1203.0171

BABAR T-ASYMMETRY



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BABAR T-ASYMMETRY

the BaBar T-asymmetry:

$$A_T = \frac{\Gamma_{(\psi K_L)_\perp,\ell^- X} - \Gamma_{(\ell^+ X)_\perp,\psi K_S}}{\Gamma_{(\psi K_L)_\perp,\ell^- X} + \Gamma_{(\ell^+ X)_\perp,\psi K_S}}$$

- Is the initial state in each of the two processes the T-conjugate of the final state in the other? (are these rates related by T conjugation?)
- Would it vanish in the T-symmetry limit?

BABAR T-ASYMMETRY

We analyze the experimental asymmetry with

- CPT violation in mixing and in decay (use effective Hamiltonian)
- wrong sign decays
- wrong strangeness decays

BABAR T-ASYMMETRY

B meson decays

leptonic final state

right sign $\quad B^0 \to \ell^+ X\,, \qquad \overline{B}^0 \to \ell^- X$

wrong sign $\quad B^0 \to \ell^- X\,, \qquad \overline{B}^0 \to \ell^+ X$

BABAR T-ASYMMETRY

B meson decays

leptonic final state

right sign $\quad B^0 \to \ell^+ X\,, \qquad \overline{B}^0 \to \ell^- X$

wrong sign $\quad B^0 \to \ell^- X\,, \qquad \overline{B}^0 \to \ell^+ X$

Kaon final states

right strangeness $\quad B^0 \to K^0\,, \qquad \overline{B}^0 \to \overline{K}^0$

wrong strangeness $\quad \overline{B}^0 \to K^0\,, \qquad B^0 \to \overline{K}^0$

Is the initial state in each of the two processes the T-conjugate of the final state in the other?

BABAR T-ASYMMETRY

the BaBar T-asymmetry compares between

$$\Gamma_{(\psi K_L)_\perp,\ell^- X} \qquad \Gamma_{(\ell^+ X)_\perp,\psi K_S}$$

$$|B_{(\to\psi K_L)_\perp}\rangle \rightsquigarrow |B_{\to\ell^- X}\rangle \qquad |B_{(\to\ell^+ X)_\perp}\rangle \rightsquigarrow |B_{(\to\psi K_S)}\rangle$$

BABAR T-ASYMMETRY

the BaBar T-asymmetry compares between

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$$|B_{(\to\psi K_L)_\perp}\rangle \rightsquigarrow |B_{\to\ell^- X}\rangle \qquad |B_{(\to\ell^+ X)_\perp}\rangle \rightsquigarrow |B_{(\to\psi K_S)}\rangle$$

the **naive** question
(for now, neglecting wrong sign) $|B_{(\to\psi K_L)_\perp}\rangle = |B_{(\to\psi K_S)}\rangle$?

$\Rightarrow$ $\langle B_{(\to\psi K_S)_\perp}|B_{(\to\psi K_L)_\perp}\rangle \propto$ direct CPV in $B \to \psi K$

vanishing overlap $\Rightarrow$ equal states

BABAR T-ASYMMETRY

the BaBar T-asymmetry compares between

$$\Gamma_{(\psi K_L)_\perp,\ell^- X} \qquad \Gamma_{(\ell^+ X)_\perp,\psi K_S}$$

$$|B_{(\to\psi K_L)_\perp}\rangle \rightsquigarrow |B_{\to\ell^- X}\rangle \qquad |B_{(\to\ell^+ X)_\perp}\rangle \rightsquigarrow |B_{(\to\psi K_S)}\rangle$$

but true T-asymmetry should compare between

$$\Gamma_{(\psi K_S)^T,\ell^- X} \qquad \Gamma_{(\ell^- X)^T,\psi K_S}$$

BABAR T-ASYMMETRY

the T-asymmetry compares between

$$\Gamma_{(\psi K_L)_\perp,\ell^- X} \qquad \Gamma_{(\ell^+ X)_\perp,\psi K_S}$$

$$|B_{(\to\psi K_L)_\perp}\rangle \rightsquigarrow |B_{\to\ell^- X}\rangle \qquad |B_{(\to\ell^+ X)_\perp}\rangle \rightsquigarrow |B_{(\to\psi K_S)}\rangle$$

T-conjugate states

the correct question

$$|B_{(\to\psi K_L)_\perp}\rangle = |B_{(\psi K_S\to)}\rangle$$

$$|B_{(\to\ell^+ X)_\perp}\rangle = |B_{(\ell^- X\to)}\rangle$$

?

BABAR T-ASYMMETRY

the correct question

$$|B_{(\to\psi K_L)_\perp}\rangle = |B_{(\psi K_S\to)}\rangle$$

$$|B_{(\to\ell^+ X)_\perp}\rangle = |B_{(\ell^- X\to)}\rangle$$

?

$$\langle B_{(\psi K_S\to)_\perp}|B_{(\to\psi K_L)_\perp}\rangle \to 0$$

no wrong strangeness (or WS without CP or CPT violation)

$$\langle B_{(\ell^- X\to)_\perp}|B_{(\to\ell^+ X)_\perp}\rangle \to 0$$

no wrong sign

vanishing overlap ⇒ equal states

BABAR T-ASYMMETRY

in the limit that

$$|B_{(\to\psi K_L)_\perp}\rangle = |B_{(\psi K_S\to)}\rangle$$

$$|B_{(\to\ell^+ X)_\perp}\rangle = |B_{(\ell^- X\to)}\rangle$$

$$\Gamma_{(\psi K_L)_\perp,\ell^- X} = \Gamma_{(\psi K_S)^T,\ell^- X}$$

$$\Gamma_{(\ell^+ X)_\perp,\psi K_S} = \Gamma_{(\ell^- X)^T,\psi K_S}$$

BABAR T-ASYMMETRY

in the limit that

$$|B_{(\to\psi K_L)_\perp}\rangle = |B_{(\psi K_S\to)}\rangle$$

$$|B_{(\to\ell^+ X)_\perp}\rangle = |B_{(\ell^- X\to)}\rangle$$

$$\Gamma_{(\psi K_L)_\perp,\ell^- X} = \Gamma_{(\psi K_S)^T,\ell^- X}$$

$$\Gamma_{(\ell^+ X)_\perp,\psi K_S} = \Gamma_{(\ell^- X)^T,\psi K_S}$$

$$A_T = \frac{\Gamma_{(\psi K_L)_\perp,\ell^- X} - \Gamma_{(\ell^+ X)_\perp,\psi K_S}}{\Gamma_{(\psi K_L)_\perp,\ell^- X} + \Gamma_{(\ell^+ X)_\perp,\psi K_S}}$$

indeed T-asymmetry

Would the asymmetry vanish in the T-symmetry limit?

BABAR T-ASYMMETRY

- The time dependent rates:

$$\Gamma_{(f_1)_\perp, f_2} \propto e^{-\Gamma t}\left[1 + C_{(1)_\perp,2}\cos(\Delta m\, t) + S_{(1)_\perp,2}\sin(\Delta m\, t)\right]$$

neglecting width difference

mass difference

BaBar collaboration, 1207.5832

BABAR T-ASYMMETRY

- The time dependent rates:

$$\Gamma_{(f_1)_\perp, f_2} \propto e^{-\Gamma t}\left[1 + C_{(1)_\perp,2}\cos(\Delta m\, t) + S_{(1)_\perp,2}\sin(\Delta m\, t)\right]$$

neglecting width difference

mass difference

- the approximate time dependent asymmetry

$$A_T \approx \frac{\Delta C_T^+}{2}\cos(\Delta m\, t) + \frac{\Delta S_T^+}{2}\sin(\Delta m\, t)$$

$$\Delta S_T^+ = S_{(\psi K_L)_\perp,\ell^- X} - S_{(\ell^+ X)_\perp,\psi K_S} = -1.37 \pm 0.15$$

$$\Delta C_T^+ = C_{(\psi K_L)_\perp,\ell^- X} - C_{(\ell^+ X)_\perp,\psi K_S} = +0.10 \pm 0.16$$

BaBar collaboration, 1207.5832

BABAR T-ASYMMETRY

we classified the different contributions to ΔS_T^+ ΔC_T^+

BABAR T-ASYMMETRY

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T odd	T even	quadratic in T odd
establish T-violation	**not** vanish at the T-symm. limit	vanish at the T-symm. limit, **but** T conserving

BABAR T-ASYMMETRY

we classified the different contributions to ΔS_T^+ ΔC_T^+

T odd	T even	quadratic in T odd
establish T-violation	**not** vanish at the T-symm. limit	vanish at the T-symm. limit, **but** T conserving
	CPT violation in decay and wrong strangeness decays	wrong sign decays

BABAR T-ASYMMETRY

We found the conditions that the BaBar measurement demonstrate T violation unambiguously:

- no wrong strangeness decays or inverse decay, (if wrong strangeness decays occur, no CPT violation)
- no wrong sign decays (if wrong sign decays occur, no direct CP violation in semi-leptonic decays)

SUMMARY

- BaBar has measured time-reversal in B decays by using the EPR effect between two B-mesons in $\Upsilon(4S)$ decays and CP and flavor tagging ability.

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- Although a precise exchange of initial and final state is impossible, we showed that only wrong sign decays or wrong strangeness decay with CP or CPT violation can cause differences in the relevant initial and final states.

SUMMARY

- BaBar has measured time-reversal in B decays by using the EPR effect between two B-mesons in $\Upsilon(4S)$ decays and CP and flavor tagging ability.
- Although a precise exchange of initial and final state is impossible, we showed that only wrong sign decays or wrong strangeness decay with CP or CPT violation can cause differences in the relevant initial and final states.
- Cannot exclude the possibility that the measured asymmetry is explained by T-conserving quantities.


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BACKUP SLIDES