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Experimental studies of $\mathcal{T}$-violation

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Based on work by AB, Gianluca Inguglia, and Michele Zoccali

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AB, Inguglia, Zoccali arXiv:1302.4191

Overview

- Formalism
- Implications for future studies of weak interactions under T symmetry.
- Summary

Formalism

- Need to test a T conjugate process, and compare a state $|i\rangle$ to some other state $|f\rangle$:

$$A_T = \frac{P(|i\rangle \to |f\rangle) - P(|f\rangle \to |i\rangle)}{P(|i\rangle \to |f\rangle) + P(|f\rangle \to |i\rangle)}$$

c.f. CP asymmetries constructed from CP conjugate processes.

- The problem resides in identifying a T conjugate pair of processes that can be experimentally distinguished.
- ... and which could be used to experimentally test T symmetry non-invariance.
  - Given strong and EM conservation we want to identify weak decays that can be transformed under T to a conjugate state that can also be studied.

Formalism

- A number of papers exist outlining how to test T with B decays using flavour tagged charmonium + K^0 decays: e.g.

  Banuls & Bernabeu [PLB **464** 117 (1999); PLB **590** 19 (2000)]
  Alverex & Szynkman [hep-ph/0611370]
  Bernaneu, Martinez-Vidal, Villanueva-Perez [JHEP **1208** 064 (2012)]

- The proposed route involves measuring a time-dependent asymmetry of T conjugate pairs of B decays.
- The key is to use EPR correlated B mesons, where:

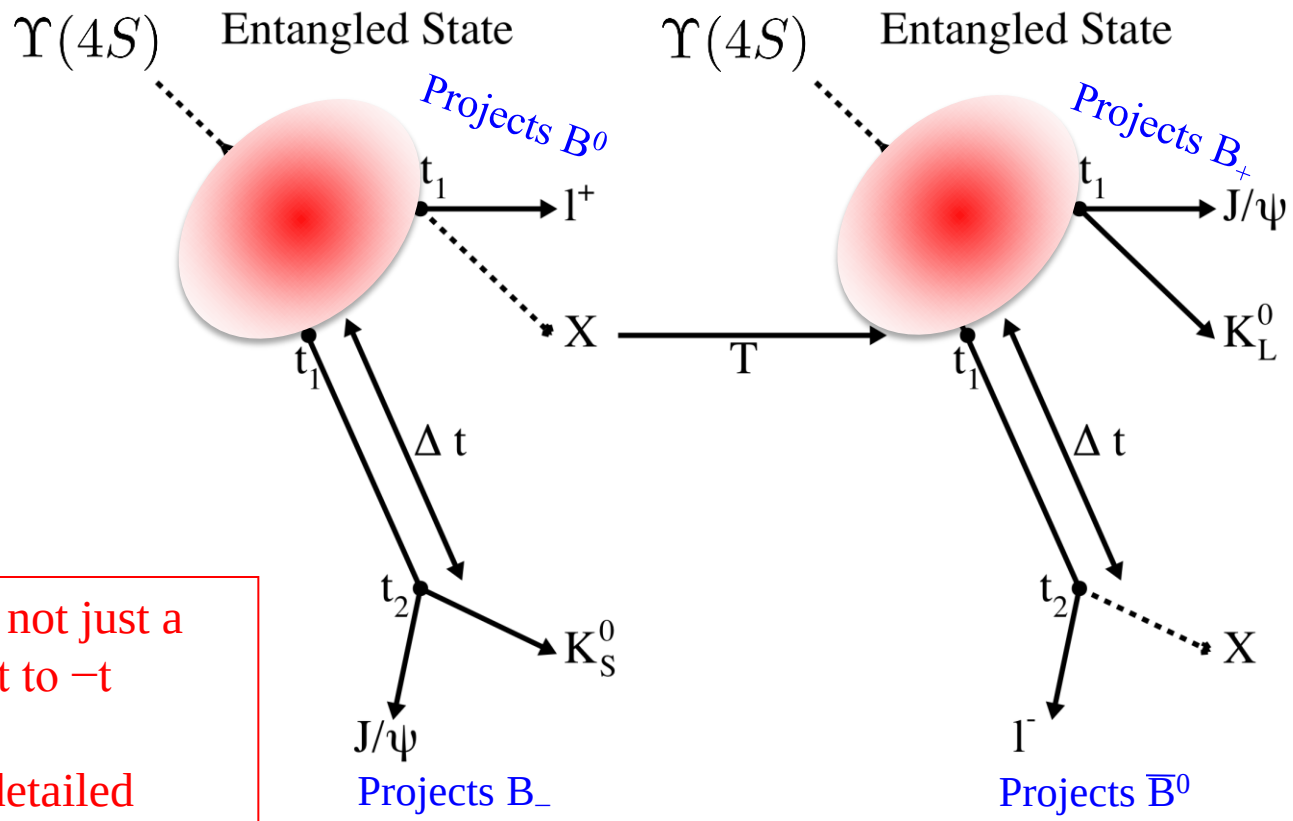
$$\Phi = \frac{1}{\sqrt{2}}\left(P_1^0\overline{P}_2^0 - \overline{P}_1^0 P_2^0\right)$$

- One can compare the results of one time-ordering of meson pairs decaying with those of the second ordering from an ensemble of measurements.
- Use 2 different orthonormal filter bases: Flavor ($B^0, \overline{B}^0$) and CP (B_+, B_-)

Formalism

- What do we compare?
  - T conjugate pairs of B meson decays.

$$\overline{B}^0 \longrightarrow B_- \qquad\qquad B_- \longrightarrow \overline{B}^0$$



This is not just a flip of t to −t

More detailed formalism in backup slides

$$\Delta t = t_2 - t_1$$

- T-conjugate pairings:

Reference		T-conjugate	
Transition	Final state	Transition	Final state
$\overline{B}^0 \to B_-$	$(\ell^+X, J/\psi K_S)$	$B_- \to \overline{B}^0$	$(J/\psi K_L, \ell^-X)$
$B_+ \to B^0$	$(J/\psi K_S, \ell^+X)$	$B^0 \to B_+$	$(\ell^-X, J/\psi K_L)$
$\overline{B}^0 \to B_+$	$(\ell^+X, J/\psi K_L)$	$B_+ \to \overline{B}^0$	$(J/\psi K_S, \ell^-X)$
$B_- \to B^0$	$(J/\psi K_L, \ell^+X)$	$B^0 \to B_-$	$(\ell^-X, J/\psi K_S)$

- Similarly CP and CPT conjugate parings can be defined (see Banuls & Bernabeu).

- Can study the time-evolution in the context of the "usual" *B* Factory time-dependent analysis methodology.

Implications ...

- One can go beyond the current measurements to realise a programme of T invariance study in weak decay.
  - Based on weak interaction study of EPR correlated decays to pairs of T conjugate decays:
    - one decay filtered by quark flavour
    - the other by CP eigen value

Filter states into any two different orthonormal bases to separate CP and T symmetry tests

- $B^0(\overline{B}^0)$ are filtered by flavour.

- The next step is to identify T conjugate B_{CP} filters: the (CP=+1) B_+ and (CP=−1) B_-

AB, Inguglia, Zoccali arXiv:1302.4191

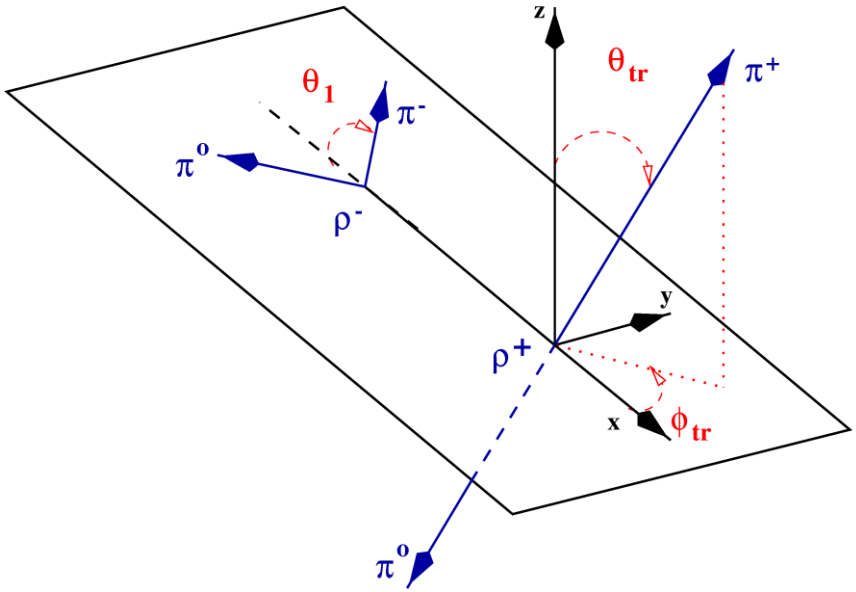
Implications ...

- CP filters:
  - Tree decays: $b \to c\bar{c}s$ i.e. $B \to J/\psi K_{S/L}$ which measure sin2β [BaBar result in backup slides].
  - Loop decays: $b \to s$ penguins e.g. $B \to (\eta', \omega, ...)K_{S/L}$ also measure β.
- NP could be manifest
  - via a difference in tree vs. penguin values of sin2β under CP or T measurements (6 measures to check: S, ΔS^+, ΔS^-, C, ΔC^+, and ΔC^-).
    - No one told the weak interaction how to behave, we need to learn what it can teach us.
  - via CPT violation (over-constain test of CPT using CP and T)

AB, Inguglia, Zoccali arXiv:1302.4191

B_{CP} filters for VV decays

- How does this work...? Look at the transversity basis



In the helicity basis: h=+1, -1 are CP admixtures.

In the transversity basis we combine the +1, -1 amplitudes to form an orthonormal set of orthogonal CP eigenstates: $\{A_\perp, A_{//}\}$

Time-dependent analyses of T-self conjugate states such as J/ψK*, φK* and $\rho^0\rho^0$ can be performed... should focus on states with sizeable $A_\perp$ to maximize sensitivity to A_T.

$$
\begin{aligned}
CP\text{-even longitudinal} &: A_L &= A_0 \\
CP\text{-even transverse} &: A_{||} &= \frac{A_{+1}+A_{-1}}{\sqrt{2}} \\
CP\text{-odd transverse} &: A_\perp &= \frac{A_{+1}-A_{-1}}{\sqrt{2}}
\end{aligned}
$$

AB, Inguglia, Zoccali arXiv:1302.4191

B_{CP} filters for VV decays

- Experimentally one can follow the methodology used by BaBar for time-dependent B decays to $\phi K_S \pi^0$ to extract CP parameters for CP even/odd parts of the decay.
  - Extract CP asymmetry distributions for each transversity amplitude as a function of Δt.
  - Combine CP even and CP odd parts in analogy with VP decays:

$$B \to VP$$

Reference		T-conjugate	
Transition	Final state	Transition	Final state
$\overline{B}^0 \to B_-$	$(\ell^+ X, J/\psi K_S)$	$B_- \to \overline{B}^0$	$(J/\psi K_L, \ell^- X)$
$B_+ \to B^0$	$(J/\psi K_S, \ell^+ X)$	$B^0 \to B_+$	$(\ell^- X, J/\psi K_L)$
$\overline{B}^0 \to B_+$	$(\ell^+ X, J/\psi K_L)$	$B_+ \to \overline{B}^0$	$(J/\psi K_S, \ell^- X)$
$B_- \to B^0$	$(J/\psi K_L, \ell^+ X)$	$B^0 \to B_-$	$(\ell^- X, J/\psi K_S)$

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- Experimentally one can follow the methodology used by BaBar for time-dependent B decays to $\phi K_S \pi^0$ to extract CP parameters for CP even/odd parts of the decay.
  - Extract CP asymmetry distributions for each transversity amplitude as a function of Δt.
  - Combine CP even and CP odd parts in analogy with VP decays:

$$B \to VV$$

Reference		T-conjugate
$\overline{B}^0 \to B_- (\ell^+ X, \mathcal{B}_\perp)$	vs	$B_- \to \overline{B}^0 (\mathcal{B}_{0,//}, \ell^- X)$
$B_+ \to B^0 (\mathcal{B}_\perp, \ell^+ X)$	vs	$B^0 \to B_+ (\ell^- X, \mathcal{B}_{0,//})$
$\overline{B}^0 \to B_+ (\ell^+ X, \mathcal{B}_{0,//})$	vs	$B_+ \to \overline{B}^0 (\mathcal{B}_\perp, \ell^- X)$
$B_- \to B^0 (\mathcal{B}_{0,//}, \ell^+ X)$	vs	$B^0 \to B_- (\ell^- X, \mathcal{B}_\perp)$

AB, Inguglia, Zoccali arXiv:1302.4191

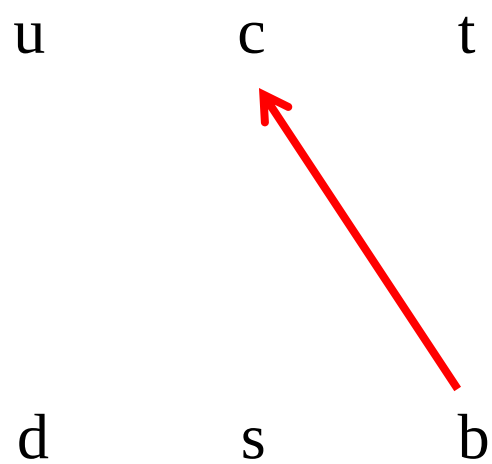
This is not the same thing as interpreting the published results.

B decays at the Υ(4S)

- From the CKM matrix perspective...

Measures sin2β

$$J/\psi K_{S,L}$$
$$\psi(2S)K_{S,L}$$
$$\chi_{c1}K_{S,L}$$
$$\eta_c K_{S,L}$$
$$J/\psi K^*$$
$$\ldots$$

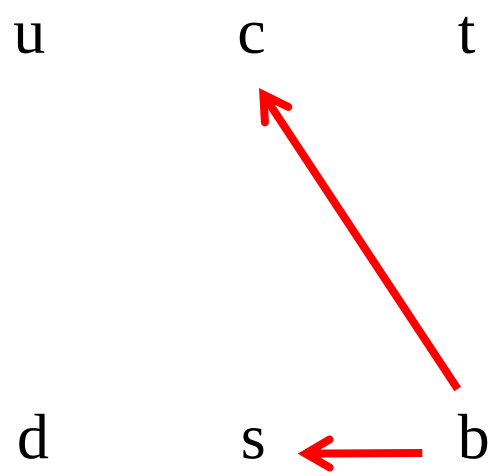


$$V_{CKM} = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) + A\lambda^5(\bar\rho - i\bar\eta)/2 \\ -\lambda + A^2\lambda^5[1-2(\bar\rho+i\bar\eta)]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3[1-\bar\rho-i\bar\eta] & -A\lambda^2 + A\lambda^4[1-2(\bar\rho+i\bar\eta)]/2 & 1-A^2\lambda^4/2 \end{pmatrix} \end{array} + \mathcal{O}(\lambda^6)$$

AB, Inguglia, Zoccali arXiv:1302.4191

B decays at the Υ(4S)

- From the CKM matrix perspective...



Measures sin2β

$J/\psi K_{S,L}$
$\psi(2S)K_{S,L}$
$\chi_{c1}K_{S,L}$
$\eta_c K_{S,L}$
$J/\psi K^*$
...

$\eta^{(\prime)}K_{S,L}$
$\phi K_{S,L}$
$\omega K_{S,L}$
ϕK^*
...

Measures sin2β

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$J/\psi K_{S,L}$
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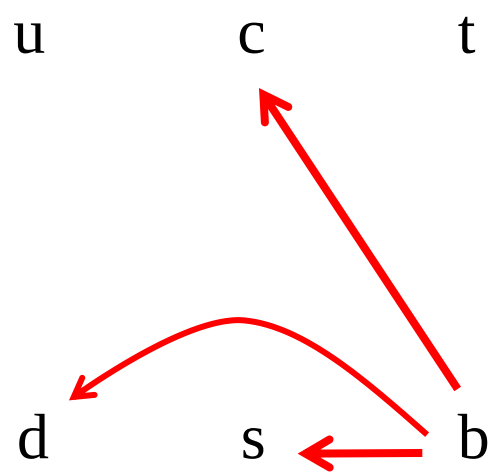


$D^* D^*$
...

Measures sin2β

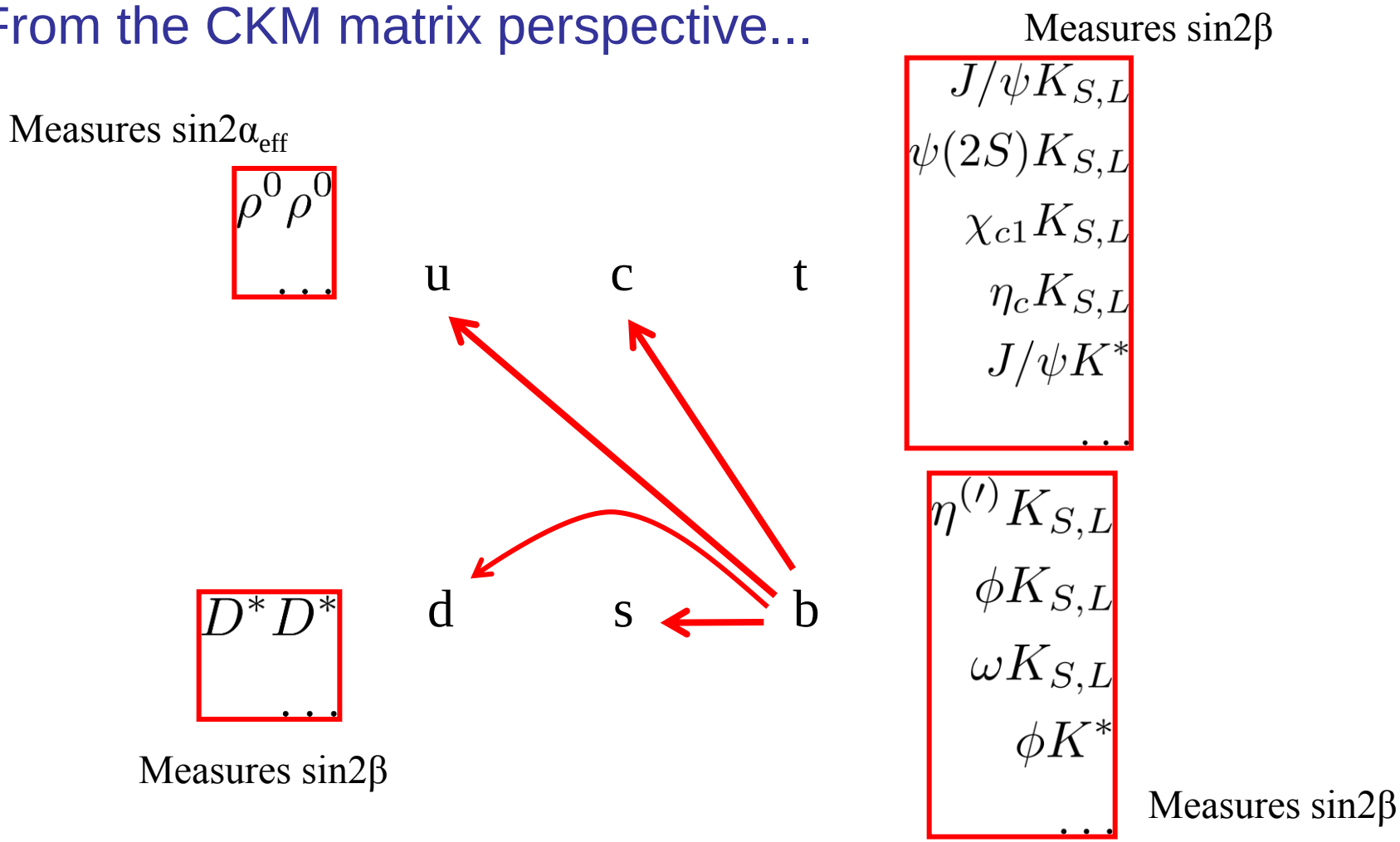
$\eta^{(\prime)} K_{S,L}$
$\phi K_{S,L}$
$\omega K_{S,L}$
ϕK^*
...

Measures sin2β

AB, Inguglia, Zoccali arXiv:1302.4191

B decays at the Υ(4S)

- From the CKM matrix perspective...



- There is at least one route to test each transition type from a *b* quark.

AB, Inguglia, Zoccali arXiv:1302.4191

D decays at the ψ(3770)

- From the CKM matrix perspective...

Measures mixing phase (null tests)

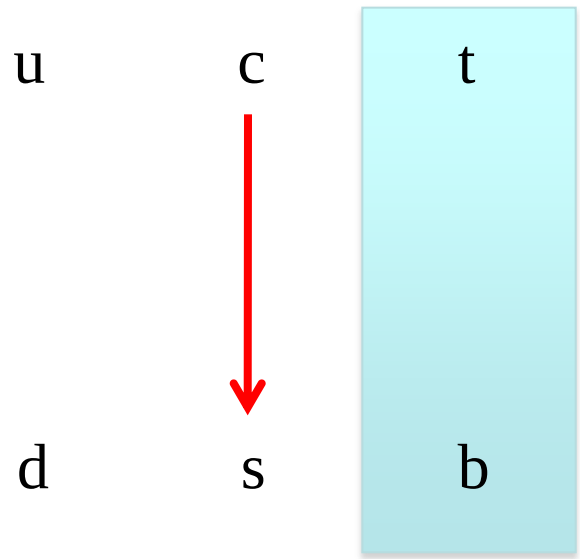
$\pi^+\pi^- K_{S,L}$

$\phi\rho^0$

$3K^0$

$\phi K_{S,L}$

$\ldots$



$$V_{CKM} = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) + A\lambda^5(\bar\rho - i\bar\eta)/2 \\ -\lambda + A^2\lambda^5[1-2(\bar\rho+i\bar\eta)]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3[1-\bar\rho-i\bar\eta] & -A\lambda^2 + A\lambda^4[1-2(\bar\rho+i\bar\eta)]/2 & 1-A^2\lambda^4/2 \end{pmatrix} \end{array} + \mathcal{O}(\lambda^6)$$

AB, Inguglia, Zoccali arXiv:1302.4191
AB, Inguglia, Meadows PRD 84 114009 (2011)

D decays at the ψ(3770)

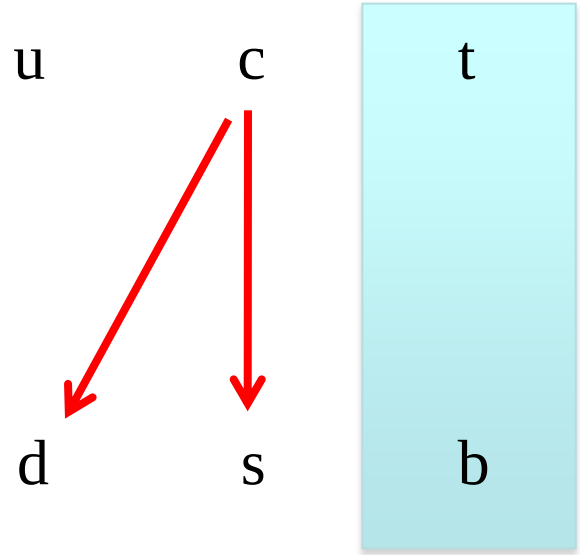
- From the CKM matrix perspective...

Measures mixing phase (null tests)

$\pi^+\pi^- K_{S,L}$
$\phi\rho^0$
$3K^0$
$\phi K_{S,L}$
$\ldots$

Measures β_c

$K^+K^- K_{S,L}$
$\rho^-\rho^+$
$\rho^0\rho^0$
$\eta^{(\prime)} K_{S,L}$
$\ldots$



$$\beta_c = \arg\left[-V_{\rm ud}^* V_{\rm cd} / V_{\rm us}^* V_{\rm cs}\right]$$

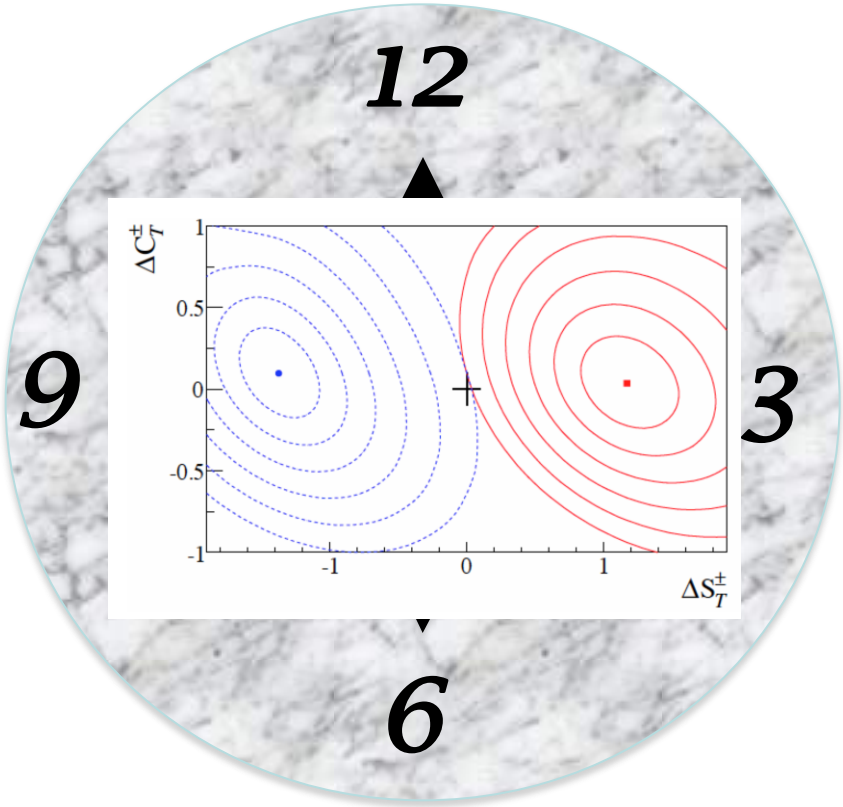
- There is at least one route to test each transition type from a *c* quark (ignoring the *c*→*u* penguin).

AB, Inguglia, Zoccali arXiv:1302.4191
AB, Inguglia, Meadows PRD 84 114009 (2011)

Implications ...

- BaBar, Belle and Belle II can now start to systematically probe the question:
  - Does the Kobayashi-Maskawa mechanism work under the T symmetry as well as the CP one?
- Similar tests could be performed at an asymmetric energy τ-charm factory to probe the up-quark sector.
- Can be compared with more traditional parameterisations of CPT violation in the entangled state.
  - Methodology differs from CP LEAR approach significantly.

Back up slides



Time-evolution

- Assuming $\Delta\Gamma=0$ (good for B_d decays)

$$g^{\pm}_{\alpha,\beta}(\Delta t) \propto e^{-\Gamma\Delta t}\left[1 + C^{\pm}_{\alpha,\beta}\cos(\Delta m\Delta t) + S^{\pm}_{\alpha,\beta}\sin(\Delta m\Delta t)\right]$$

Time-evolution

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$\alpha \in \{\ell^+, \ell^-\}$

$\beta \in \{K_S, K_L\}$ i.e. $CP = \pm 1$

Time-evolution

- Assuming ΔΓ=0 (good for B_d decays)

$$C^{\pm}_{\alpha,\beta} = \frac{1-|\lambda|^2}{1+|\lambda|^2} \qquad S^{\pm}_{\alpha,\beta} = \frac{2Im\lambda}{1+|\lambda|^2}$$

$$g^{\pm}_{\alpha,\beta}(\Delta t) \propto e^{-\Gamma\Delta t}\left[1 + C^{\pm}_{\alpha,\beta}\cos(\Delta m\Delta t) + S^{\pm}_{\alpha,\beta}\sin(\Delta m\Delta t)\right]$$

$$\alpha \in \{\ell^+, \ell^-\} \qquad \beta \in \{K_S, K_L\} \text{ i.e. } CP = \pm 1$$

- So one can relate the time-dependence to the weak structure of the decay (i.e. test the CKM formalism of the SM with an appropriate asymmetry observable).
- Need to account for mis-tag probability ω_α and detector resolution.

Time-evolution

- Assuming ΔΓ=0 (good for B_d decays)

$$C^{\pm}_{\alpha,\beta} = \frac{1-|\lambda|^2}{1+|\lambda|^2}$$

Superscripts:
+ = normal ordering
− = T reversed ordering

$$S^{\pm}_{\alpha,\beta} = \frac{2Im\lambda}{1+|\lambda|^2}$$

$$g^{\pm}_{\alpha,\beta}(\Delta t) \propto e^{-\Gamma\Delta t}\left[1 + C^{\pm}_{\alpha,\beta}\cos(\Delta m\Delta t) + S^{\pm}_{\alpha,\beta}\sin(\Delta m\Delta t)\right]$$

$$\alpha \in \{\ell^+, \ell^-\} \qquad \beta \in \{K_S, K_L\} \text{ i.e. } CP = \pm 1$$

- So one can relate the time-dependence to the weak structure of the decay (i.e. test the CKM formalism of the SM with an appropriate asymmetry observable).
- Need to account for mis-tag probability ω_α and detector resolution.

Time-evolution

- Physical distribution is

$$h^{\pm}_{\alpha,\beta}(\Delta t) \propto (1-\omega_\alpha) g^{\pm}_{\alpha,\beta}(\Delta t) + \omega_\alpha g^{\pm}_{\overline{\alpha},\beta}(\Delta t)$$

Note this is the conjugate flavor filter

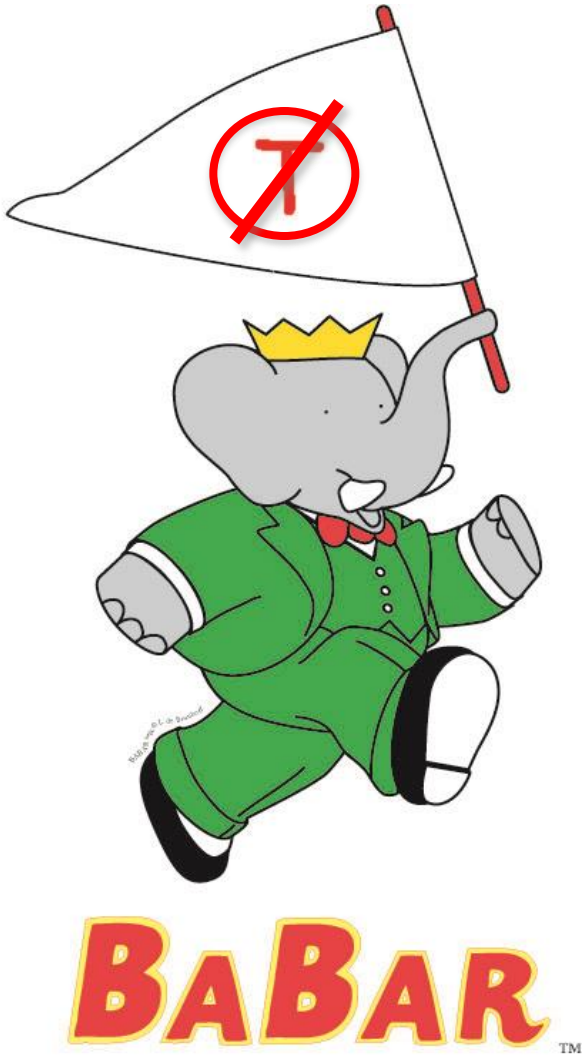
- In reality one has to account for detector resolution to obtain the asymmetry A_T.

$$A_T \simeq \frac{\Delta C_T^{\pm}}{2} \cos \Delta m \Delta t + \frac{\Delta S_T^{\pm}}{2} \sin \Delta m \Delta t$$

- In the SM (for the charmonium modes)

$$\Delta S_T^{\pm} = \mp 2 \sin 2\beta$$

- Hence, expect $|\Delta S^{\pm}| \sim 1.4$, and similarly expect $\Delta C^{\pm} \sim 0$.


BABAR
TM

Event Selection: CP filters

- The same as for the sin2β CPV measurement in *Phys.Rev. D**79**:072009 (2009)*

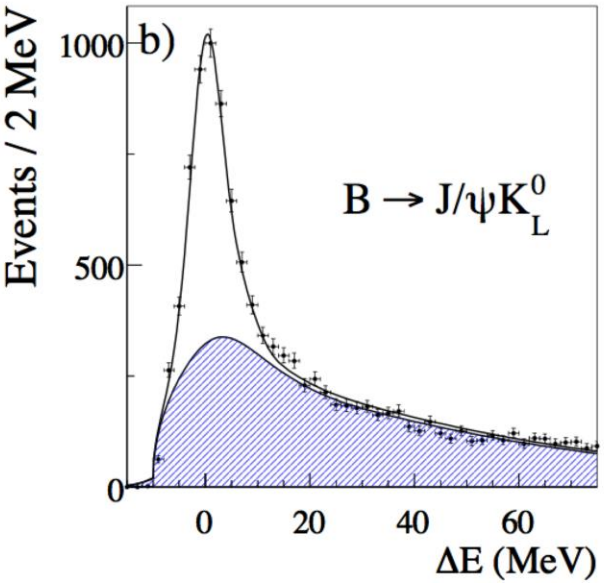
- CP even filter:

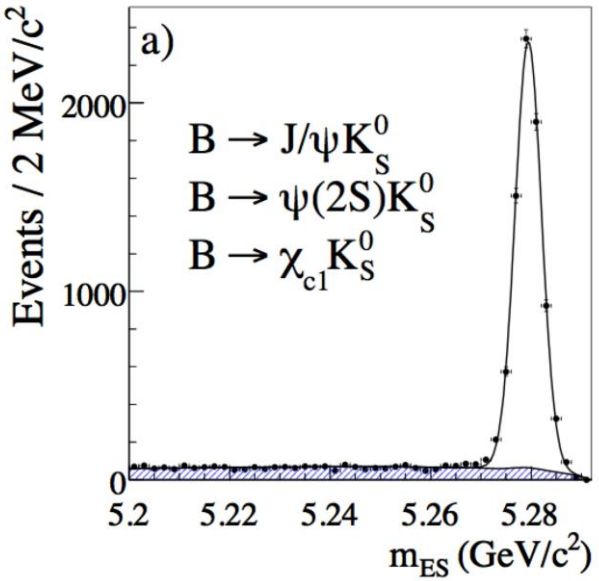
$$B \to J/\psi K_L$$

- CP odd filters:

$$\begin{aligned} B &\to J/\psi K_S \\ &\to \psi(2S) K_S \\ &\to \chi_{c1} K_S \end{aligned}$$

- Drop K* and η_c modes from the CP selection.





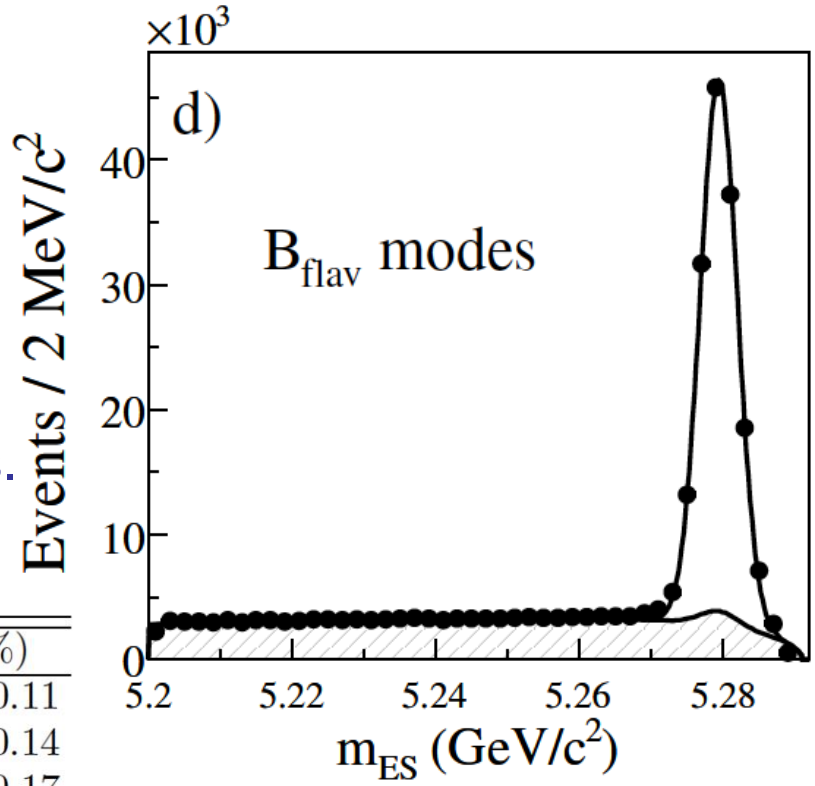
Event Selection: Flavor filters

- The same as for the sin2β CPV measurement in *Phys.Rev. D**79**:072009 (2009)*

- The set of "tag" modes used is:

$$B \to D^{(*)-}(\pi^+,\ \rho^+, a_1^+)$$

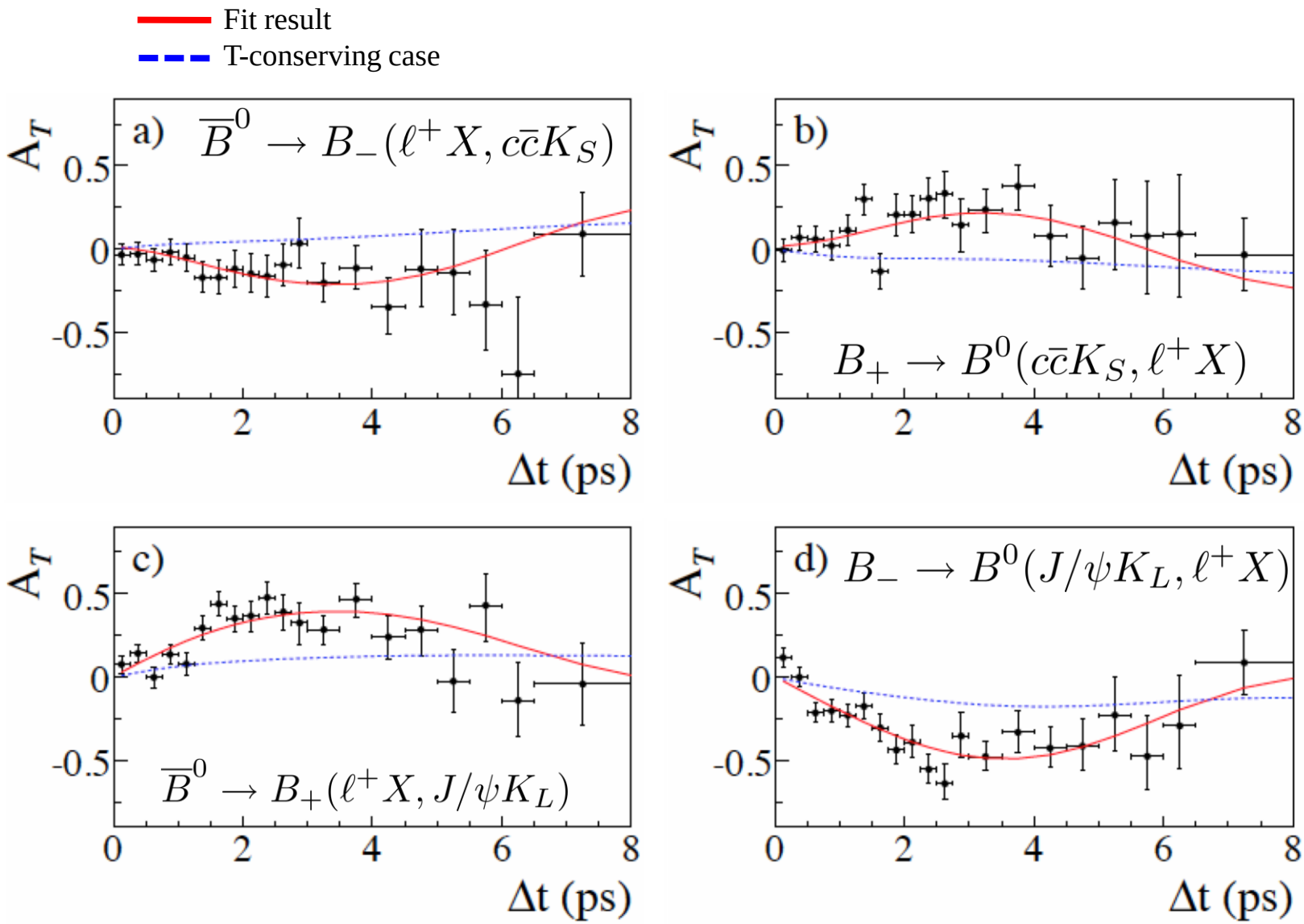
- which characterise "tag" performance and give the $B^0(\overline{B}^0)$ filter projections.



Category	ε (%)	w (%)	Δw (%)	Q (%)
Lepton	8.96 ± 0.07	2.8 ± 0.3	0.3 ± 0.5	7.98 ± 0.11
Kaon I	10.82 ± 0.07	5.3 ± 0.3	-0.1 ± 0.6	8.65 ± 0.14
Kaon II	17.19 ± 0.09	14.5 ± 0.3	0.4 ± 0.6	8.68 ± 0.17
KaonPion	13.67 ± 0.08	23.3 ± 0.4	-0.7 ± 0.7	3.91 ± 0.12
Pion	14.18 ± 0.08	32.5 ± 0.4	5.1 ± 0.7	1.73 ± 0.09
Other	9.54 ± 0.07	41.5 ± 0.5	3.8 ± 0.8	0.27 ± 0.04
All	74.37 ± 0.10			31.2 ± 0.3

Overall
$Q = 31.2\%$

Experimental results



Phys. Rev. Lett. 109, 211801 (2012) [arXiv:1207.5832]

Experimental results

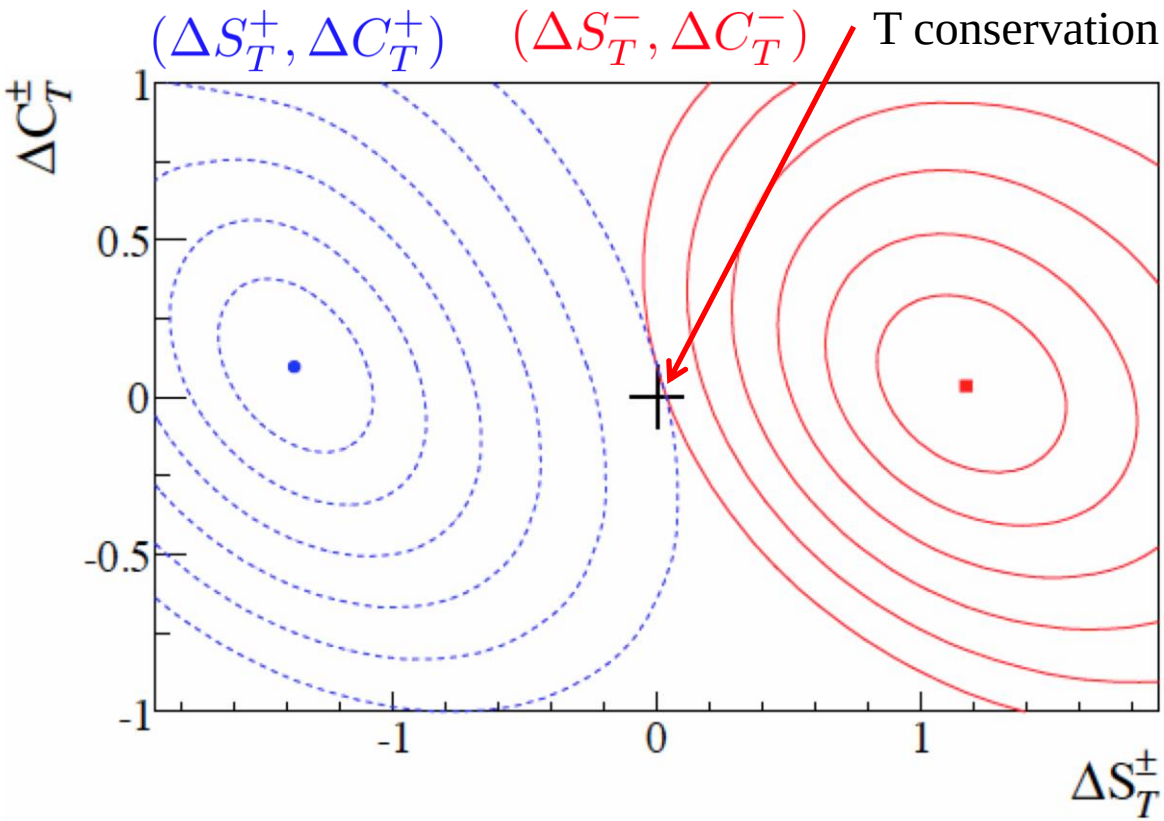
Parameter	Result
$\Delta S_T^+ = S^-_{\ell^-,K_L^0} - S^+_{\ell^+,K_S^0}$	$-1.37 \pm 0.14 \pm 0.06$
$\Delta S_T^- = S^+_{\ell^-,K_L^0} - S^-_{\ell^+,K_S^0}$	$1.17 \pm 0.18 \pm 0.11$
$\Delta C_T^+ = C^-_{\ell^-,K_L^0} - C^+_{\ell^+,K_S^0}$	$0.10 \pm 0.14 \pm 0.08$
$\Delta C_T^- = C^+_{\ell^-,K_L^0} - C^-_{\ell^+,K_S^0}$	$0.04 \pm 0.14 \pm 0.08$
$\Delta S_{CP}^+ = S^+_{\ell^-,K_S^0} - S^+_{\ell^+,K_S^0}$	$-1.30 \pm 0.11 \pm 0.07$
$\Delta S_{CP}^- = S^-_{\ell^-,K_S^0} - S^-_{\ell^+,K_S^0}$	$1.33 \pm 0.12 \pm 0.06$
$\Delta C_{CP}^+ = C^+_{\ell^-,K_S^0} - C^+_{\ell^+,K_S^0}$	$0.07 \pm 0.09 \pm 0.03$
$\Delta C_{CP}^- = C^-_{\ell^-,K_S^0} - C^-_{\ell^+,K_S^0}$	$0.08 \pm 0.10 \pm 0.04$
$\Delta S_{CPT}^+ = S^-_{\ell^+,K_L^0} - S^+_{\ell^+,K_S^0}$	$0.16 \pm 0.21 \pm 0.09$
$\Delta S_{CPT}^- = S^+_{\ell^+,K_L^0} - S^-_{\ell^+,K_S^0}$	$-0.03 \pm 0.13 \pm 0.06$
$\Delta C_{CPT}^+ = C^-_{\ell^+,K_L^0} - C^+_{\ell^+,K_S^0}$	$0.14 \pm 0.15 \pm 0.07$
$\Delta C_{CPT}^- = C^+_{\ell^+,K_L^0} - C^-_{\ell^+,K_S^0}$	$0.03 \pm 0.12 \pm 0.08$
$S^+_{\ell^+,K_S^0}$	$0.55 \pm 0.09 \pm 0.06$
$S^-_{\ell^+,K_S^0}$	$-0.66 \pm 0.06 \pm 0.04$
$C^+_{\ell^+,K_S^0}$	$0.01 \pm 0.07 \pm 0.05$
$C^-_{\ell^+,K_S^0}$	$-0.05 \pm 0.06 \pm 0.03$

- Observed level of T-violation balances CP violation.
- First direct measurement of T violation in B decays.
- Interpretation is unambiguous.

Phys. Rev. Lett. 109, 211801 (2012) [arXiv:1207.5832]

Experimental results

- Observation of T-violation can be seen in the following:



- Fit result is 14σ from the T conserving case (assuming Gaussian errors).

CL = 0.317, 4.55×10^{-2}, 2.70×10^{-3}, 6.33×10^{-5}, 5.73×10^{-7}, 1.97×10^{-9}

$-2\Delta\ln\mathcal{L}$ = 2.3, 6.2, 11.8, 19.3, 28.7, 40.1

Phys. Rev. Lett. 109, 211801 (2012) [arXiv:1207.5832]

Experimental results

- Recall that $\Delta S^{\pm}$ are related to sin2β, so we can compare CP violation with T non-invariance for this parameter:

$$\Delta S^{-} \quad : \qquad \beta_{SM} = (17.9^{+3.9}_{-3.6})^{\circ}$$
$$\Delta S^{+} \quad : \qquad \beta_{SM} = (21.6^{+3.2}_{-2.9})^{\circ}$$

- c.f. beta measured from the standard CP analysis:

$$S \quad : \qquad \beta_{SM} = (21.7 \pm 1.2)^{\circ}$$

- As expected all results of β are in agreement with each other, however a more precise comparison of these results is called for.

This is my interpretation of the results.

Dealing with detector resolution

- Given that detector resolution may smear out information about the sign of Δt, heavyside step functions are used to compute

$$\mathcal{H}_{\alpha,\beta}(\Delta t_{\rm rec}) \propto h^{+}_{\alpha,\beta}(\Delta t)H(\Delta t) \otimes \mathcal{R}(\delta t;\sigma_{\Delta t_{\rm rec}}) + h^{-}_{\alpha,\beta}(-\Delta t)H(-\Delta t) \otimes \mathcal{R}(\delta t;\sigma_{\Delta t_{\rm rec}})$$

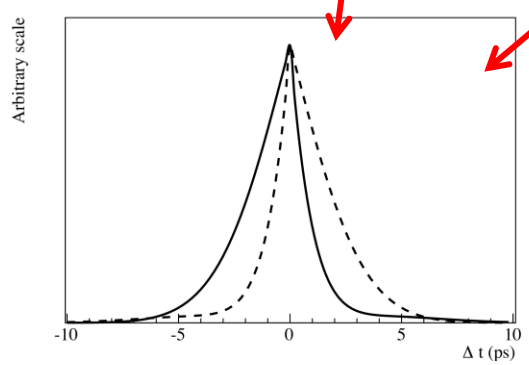
$-$ (reversed ordering)

$-\Delta t$

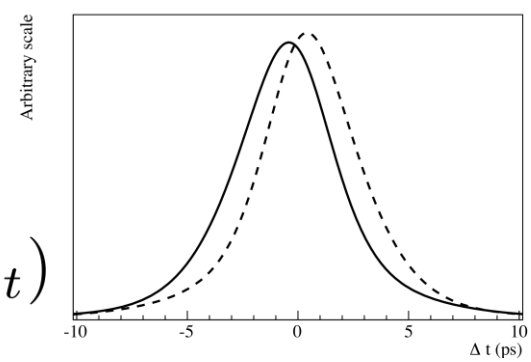
$+$ (normal ordering)

$+\Delta t$

$$h^{\pm}_{\alpha,\beta}(\Delta t) \propto (1-\omega_\alpha)g^{\pm}_{\alpha,\beta}(\Delta t) + \omega_\alpha g^{\pm}_{\overline{\alpha},\beta}(\Delta t)$$



$\otimes\mathcal{R}(\delta t;\sigma_{\Delta t})$



CP and CPT asymmetries

- Similar pairings for these discrete symmetry transformations

Reference		CP-conjugate	
Transition	Final state	Transition	Final state
$\overline{B}^0 \to B_-$	$(\ell^+X, J/\psi K_S)$	$B^0 \to B_-$	$(\ell^-X, J/\psi K_S)$
$B_+ \to B^0$	$(J/\psi K_S, \ell^+X)$	$B_+ \to \overline{B}^0$	$(J/\psi K_S, \ell^-X)$
$\overline{B}^0 \to B_+$	$(\ell^+X, J/\psi K_L)$	$B^0 \to B_+$	$(\ell^-X, J/\psi K_L)$
$B_- \to B^0$	$(J/\psi K_L, \ell^+X)$	$B_- \to \overline{B}^0$	$(J/\psi K_L, \ell^-X)$

Reference		CPT-conjugate	
Transition	Final state	Transition	Final state
$\overline{B}^0 \to B_-$	$(\ell^+X, J/\psi K_S)$	$B_- \to B^0$	$(J/\psi K_L, \ell^+X)$
$B_+ \to B^0$	$(J/\psi K_S, \ell^+X)$	$\overline{B}^0 \to B_+$	$(\ell^+X, J/\psi K_L)$
$B^0 \to B_-$	$(\ell^-X, J/\psi K_S)$	$B_- \to \overline{B}^0$	$(J/\psi K_L, \ell^-X)$
$B_+ \to \overline{B}^0$	$(J/\psi K_S, \ell^-X)$	$B^0 \to B_+$	$(\ell^-X, J/\psi K_L)$

As with the T symmetry, there are distinct conjugate parings used to test the reference vs conjugate probabilities.

A non-zero difference in these probabilities results in a non-conservation of the symmetry.

In the case of CP, where there is a definite eigen-value we can say that the symmetry is violated.