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Mainz Institute for Theoretical Physics

Workshop on T violation and CPT tests in neutral-meson systems

15-16th April 2013

Future experiments on $\mathcal{T}$ violation and CPT tests in the B^0 (and D^0) systems

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AB, Inguglia, Zoccali arXiv:1302.4191

Overview

- (Brief) recap on the context of formalism/results
- Implications for future studies of weak interactions under T symmetry.
- Naive estimates of the precision obtainable
- Summary

Caveat: some extrapolations done based on BaBar data, as I am also a BaBar collaborator. Belle would yield similar precisions.

Formalism

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

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

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:

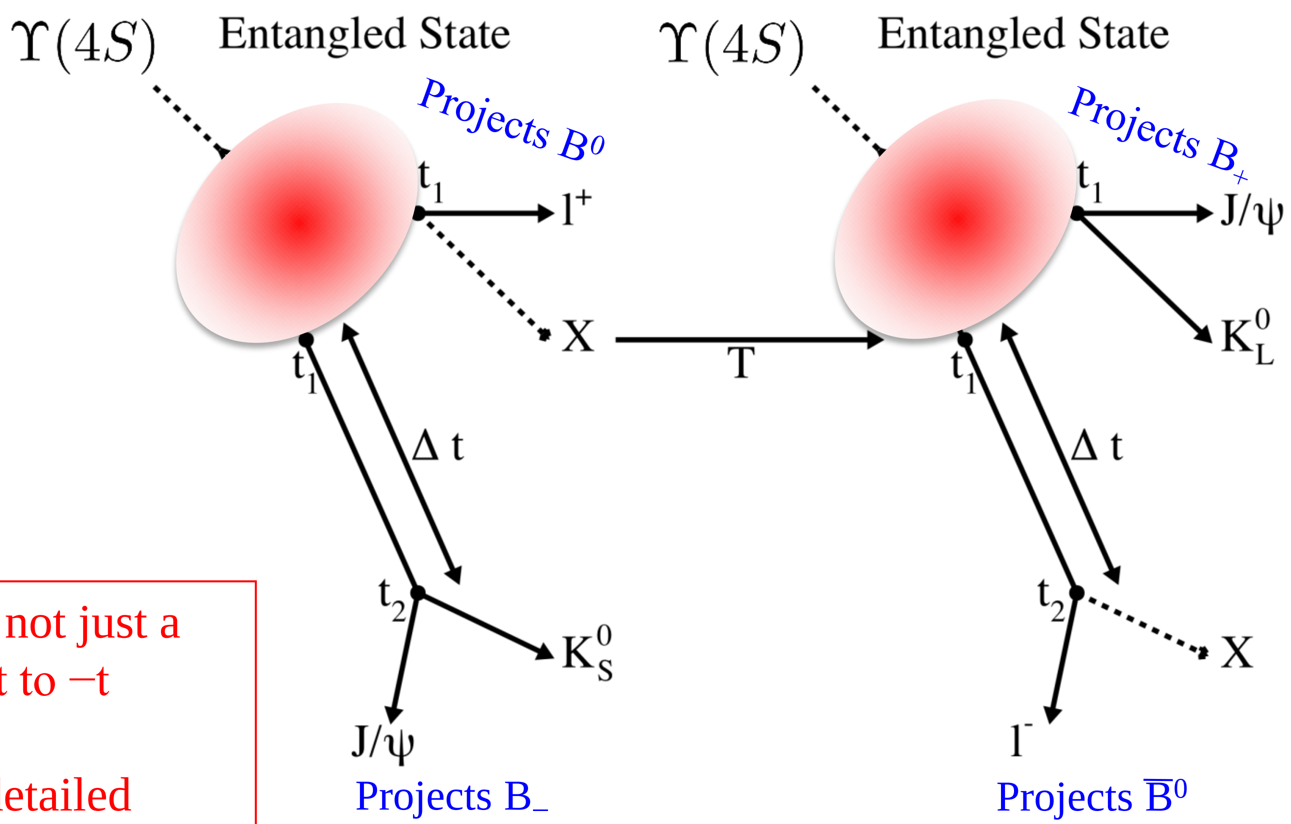
$$\Phi = \frac{1}{\sqrt{2}}\left(P_1^0 \overline{P}_2^0 - \overline{P}_1^0 P_2^0\right)$$

- 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.

Time-evolution

- Assuming ΔΓ=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

- Assuming ΔΓ=0 (good for B_d decays)

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

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

Time-evolution

- Assuming $\Delta\Gamma=0$ (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.

$$A_T \simeq \frac{\Delta C^{\pm}_T}{2}\cos\Delta m\Delta t + \frac{\Delta S^{\pm}_T}{2}\sin\Delta m\Delta t$$

- In the SM (for the charmonium modes)

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

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

Event Selection: CP filters

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

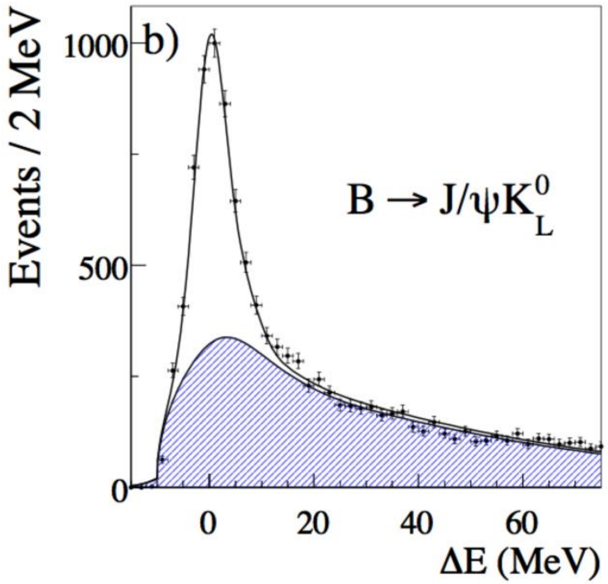
- CP even filter:

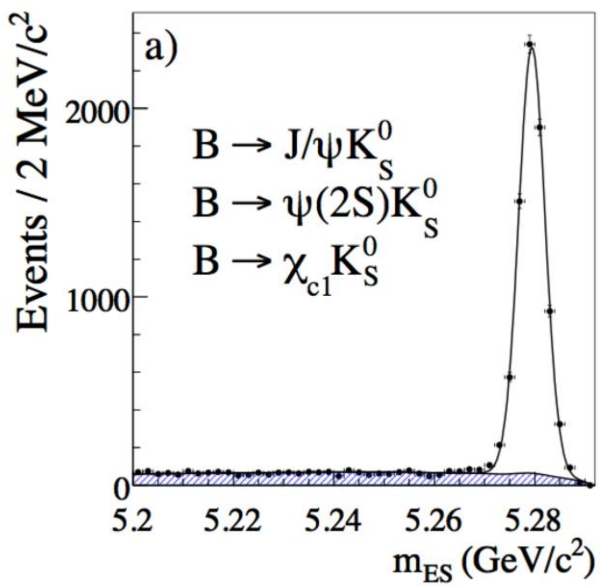
$$B \to J/\psi K_L$$

- 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.





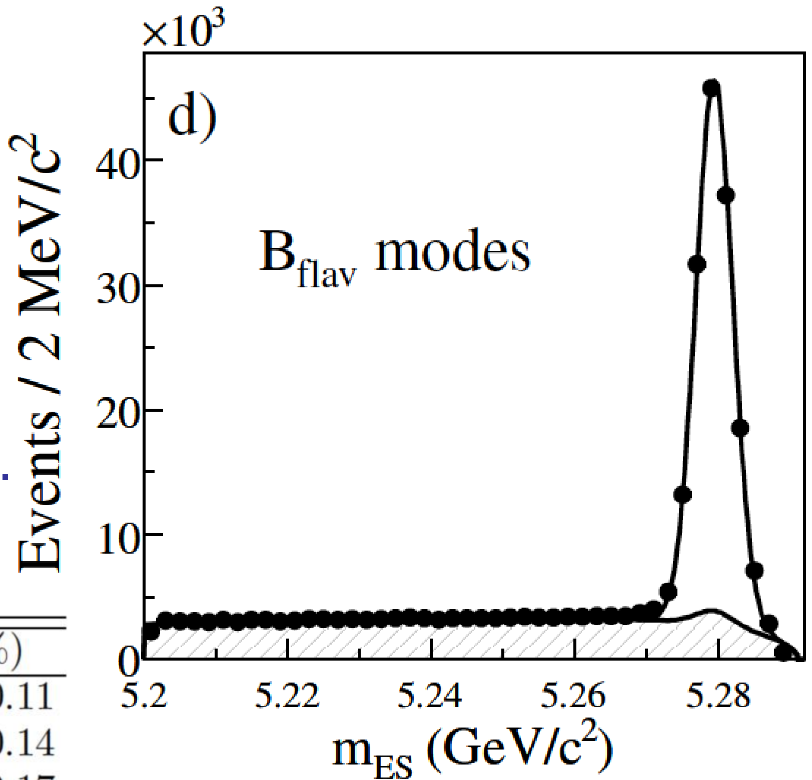
Event Selection: Flavor filters

- 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.

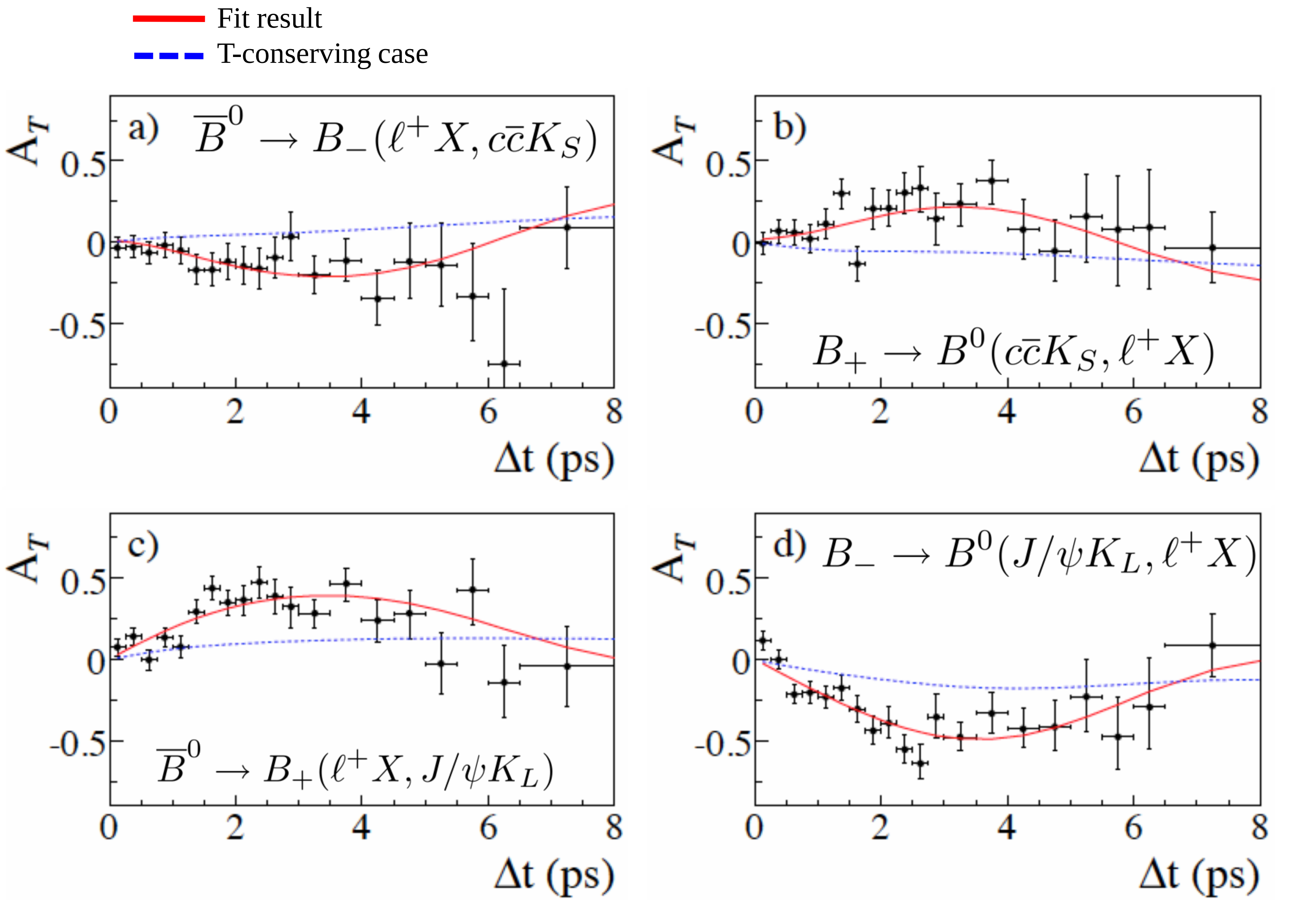


Category	ε (%)	w (%)	Δw (%)	Q (%)
Lepton	8.96 ± 0.07	2.8 ± 0.3	0.3 ± 0.5	7.98 ± 0.11
Kaon I	10.82 ± 0.07	5.3 ± 0.3	-0.1 ± 0.6	8.65 ± 0.14
Kaon II	17.19 ± 0.09	14.5 ± 0.3	0.4 ± 0.6	8.68 ± 0.17
KaonPion	13.67 ± 0.08	23.3 ± 0.4	-0.7 ± 0.7	3.91 ± 0.12
Pion	14.18 ± 0.08	32.5 ± 0.4	5.1 ± 0.7	1.73 ± 0.09
Other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

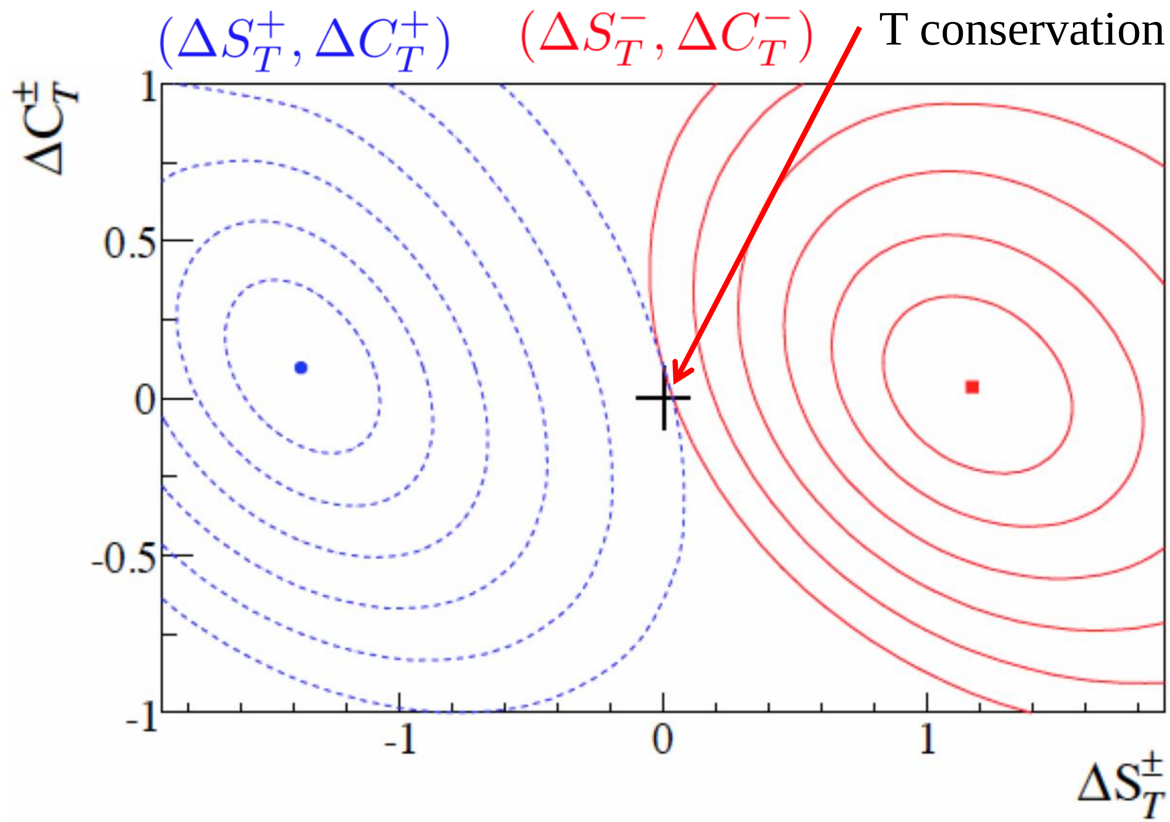
Parameter	Result
$\Delta S_T^+ = S^-_{\ell^-,K_L^0} - S^+_{\ell^+,K_S^0}$	$-1.37 \pm 0.14 \pm 0.06$
$\Delta S_T^- = S^+_{\ell^-,K_L^0} - S^-_{\ell^+,K_S^0}$	$1.17 \pm 0.18 \pm 0.11$
$\Delta C_T^+ = C^-_{\ell^-,K_L^0} - C^+_{\ell^+,K_S^0}$	$0.10 \pm 0.14 \pm 0.08$
$\Delta C_T^- = C^+_{\ell^-,K_L^0} -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

- 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.

IMPLICATIONS FOR B DECAYS

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

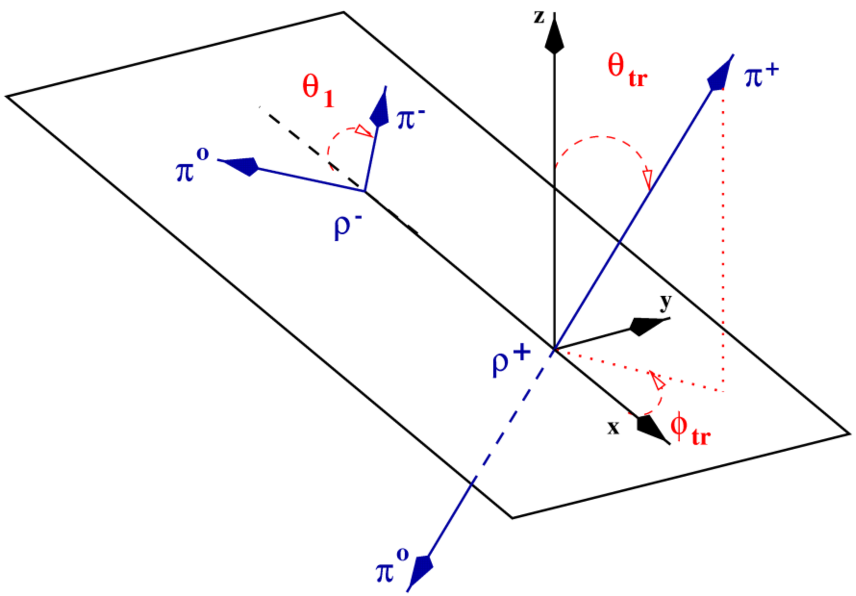
Implications …

- 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. $B \to (\eta', \omega, \ldots)K_{S/L}$ 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 $J/\psi K^*$, 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
$\overline{B}^0 \to B_-$	$(\ell^+ X, J/\psi K_S)$	$B_- \to \overline{B}^0$	$(J/\psi K_L, \ell^- X)$
$B_+ \to B^0$	$(J/\psi K_S, \ell^+ X)$	$B^0 \to B_+$	$(\ell^- X, J/\psi K_L)$
$\overline{B}^0 \to B_+$	$(\ell^+ X, J/\psi K_L)$	$B_+ \to \overline{B}^0$	$(J/\psi K_S, \ell^- X)$
$B_- \to B^0$	$(J/\psi K_L, \ell^+ X)$	$B^0 \to B_-$	$(\ell^- X, J/\psi K_S)$

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:

$$B \to VV$$

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 $\Upsilon(4S)$

- From the CKM matrix perspective...

Measures sin2β

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

u c t

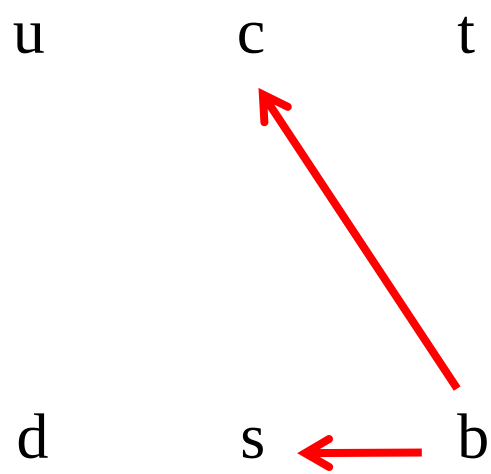
d s b

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

AB, Inguglia, Zoccali arXiv:1302.4191

B decays at the $\Upsilon(4S)$

- From the CKM matrix perspective...



Measures sin2β

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

$\psi(2S) K_{S,L}$

$\chi_{c1} K_{S,L}$

$\eta_c K_{S,L}$

$J/\psi K^*$

$\ldots$

$\eta^{(\prime)} K_{S,L}$

$\phi K_{S,L}$

$\omega K_{S,L}$

ϕK^*

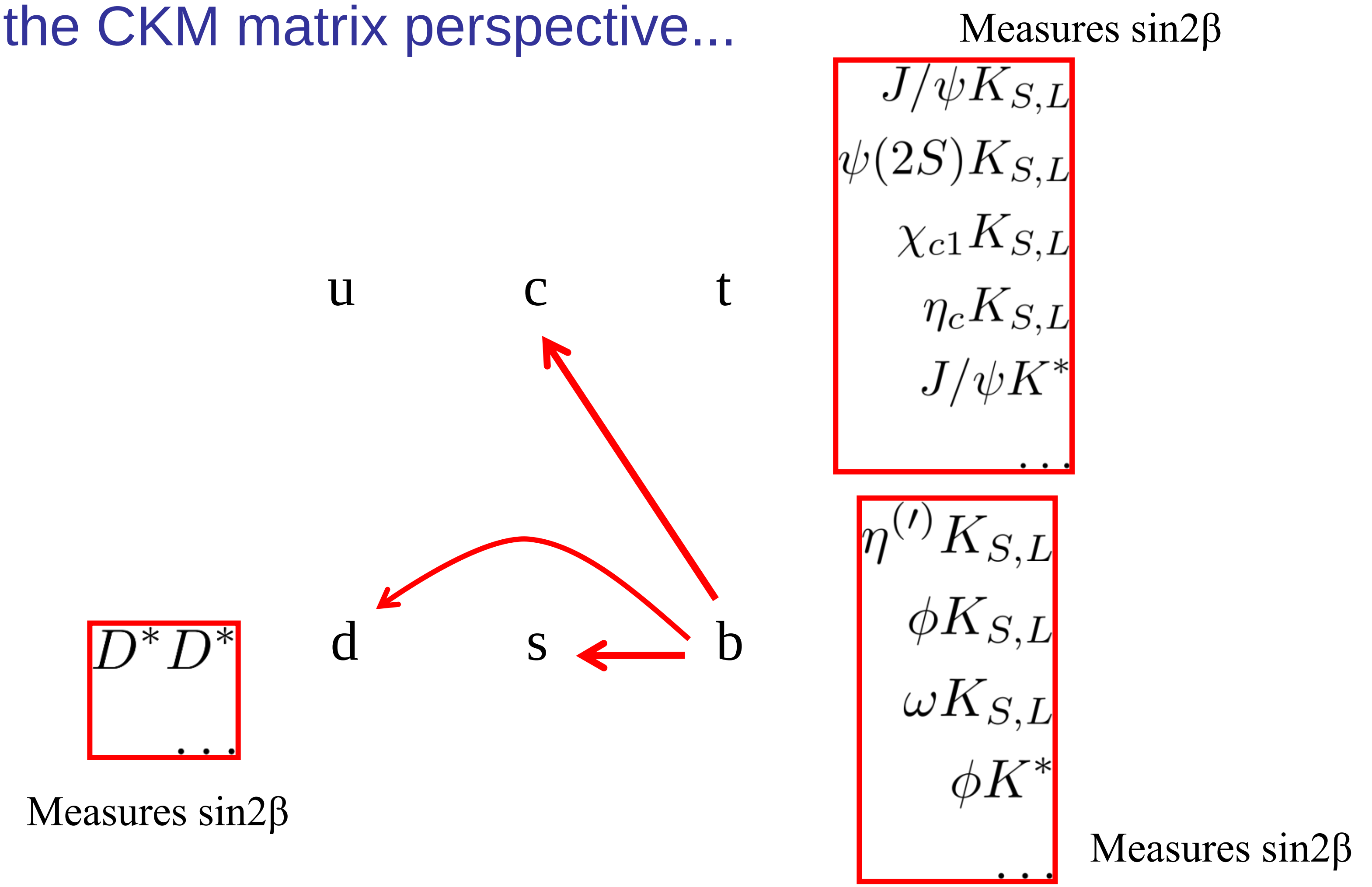
$\ldots$

Measures sin2β

AB, Inguglia, Zoccali arXiv:1302.4191

B decays at the $\Upsilon(4S)$

- From the CKM matrix perspective...



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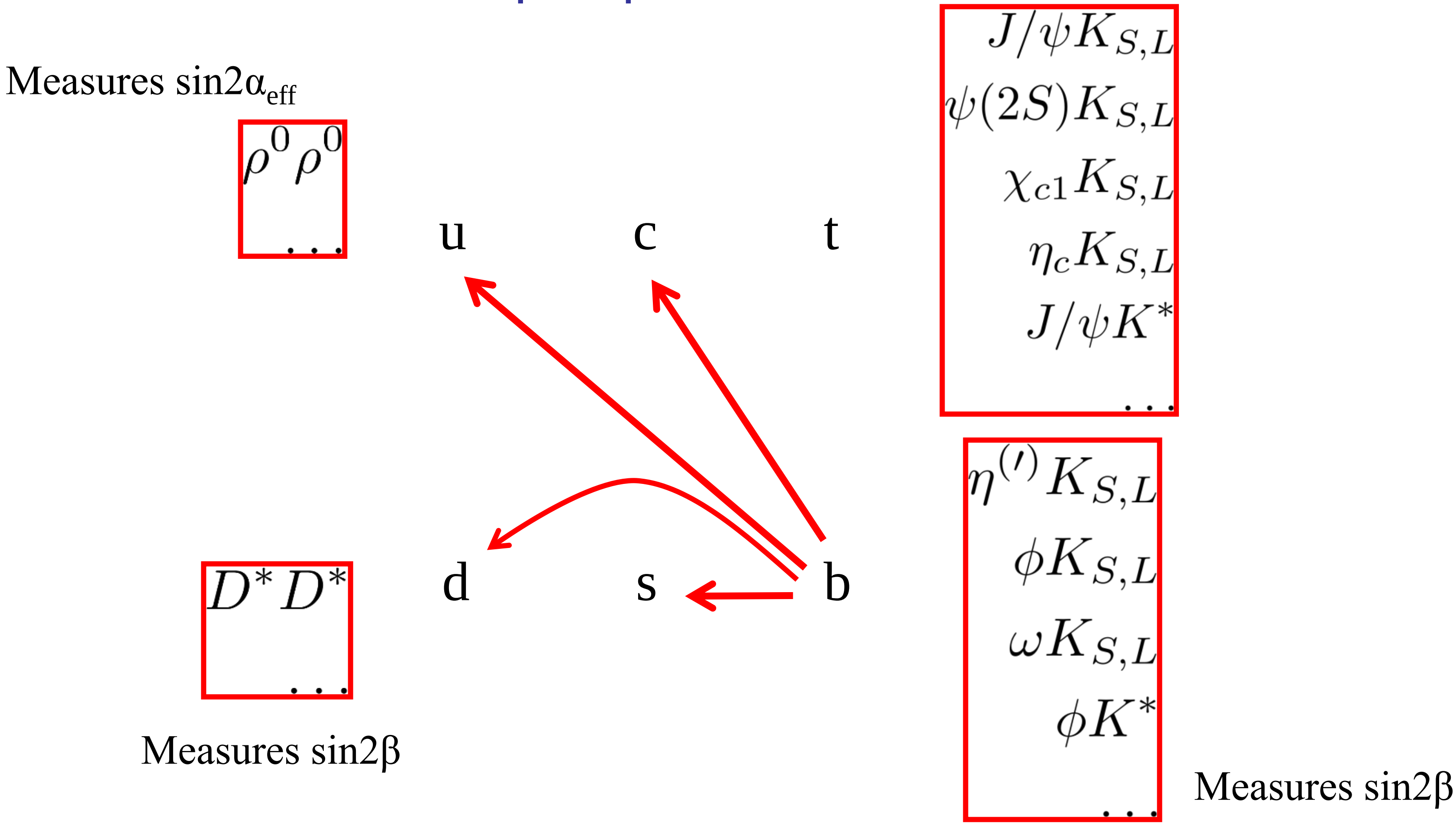
B decays at the $\Upsilon(4S)$

- From the CKM matrix perspective...

Measures sin2β



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

AB, Inguglia, Zoccali arXiv:1302.4191

Naive estimates of results

- Want to perform naive extrapolation for B factory potential to measure T-symmetry non-conservation.
- Use the charmonium data (CP vs T) to estimate this.
  - Experimental precision dominated by K_L modes.

Full CP sample	15481	76	0.687 ± 0.028	0.024 ± 0.020
$J/\psi K^0_S(\pi^+\pi^-)$	5426	96	0.662 ± 0.039	0.017 ± 0.028
$J/\psi K^0_S(\pi^0\pi^0)$	1324	87	0.625 ± 0.091	0.091 ± 0.063
$\psi(2S)K^0_S$	861	87	0.897 ± 0.100	0.089 ± 0.076
$\chi_{c1}K^0_S$	385	88	0.614 ± 0.160	0.129 ± 0.109
$\eta_c K^0_S$	381	79	0.925 ± 0.160	0.080 ± 0.124
$J/\psi K^0_L$	5813	56	0.694 ± 0.061	-0.033 ± 0.050
$J/\psi K^{*0}$	1291	67	0.601 ± 0.239	0.025 ± 0.083
$J/\psi K^0_S$	6750	95	0.657 ± 0.036	0.026 ± 0.025
$J/\psi K^0$	12563	77	0.666 ± 0.031	0.016 ± 0.023
$\eta_f = -1$	8377	93	0.684 ± 0.032	0.037 ± 0.023
1999-2002 data	3079	78	0.732 ± 0.061	0.020 ± 0.045
2003-2004 data	4916	77	0.720 ± 0.050	0.045 ± 0.036
2005-2006 data	4721	76	0.632 ± 0.052	0.027 ± 0.037
2007 data	2765	75	0.663 ± 0.071	-0.023 ± 0.049
Lepton	1740	83	0.732 ± 0.052	0.074 ± 0.038
Kaon I	2187	78	0.615 ± 0.053	-0.046 ± 0.039
Kaon II	3630	76	0.688 ± 0.056	0.068 ± 0.039
KaonPion	2882	74	0.741 ± 0.086	0.013 ± 0.061
Pion	3053	76	0.711 ± 0.132	0.016 ± 0.090
Other	1989	74	0.766 ± 0.347	-0.176 ± 0.236
$B_{\rm flav}$ sample	166276	83	0.021 ± 0.009	0.012 ± 0.006
B^+ sample	36082	94	0.021 ± 0.016	0.013 ± 0.011

From PRD 79:072009,2009

Naive estimates of results

- Want to perform naive extrapolation for B factory potential to measure T-symmetry non-conservation.
- Use the charmonium data (CP vs T) to estimate this.
  - Experimental precision dominated by K_L modes.
  - Assuming S=0 to get an indicative value, we would naively expect

$$\sigma(\Delta S^{\pm}) \sim 0.16(\mathrm{stat.})$$

  - BaBar finds

$$\sigma(\Delta S^{+}) \sim 0.14(\mathrm{stat.})$$
$$\sigma(\Delta S^{-}) \sim 0.18(\mathrm{stat.})$$

  - Compatible with naive expectations, and the asymmetry between the results is a reflection of non-zero S (ΔS, or if you prefer Im λ).

Applying this logic to other modes

- s-penguin channels vs charmonium

	BaBar/Belle		Belle II	
Mode	Est. $\sigma(\Delta S^{\pm})$	Est. Significance $n\sigma$	Est. $\sigma(\Delta S^{\pm})$	Est. Significance $n\sigma$
$c\bar{c}K^0$	0.16 (actual = 0.14, 0.18)	9 (actual = 14)	0.022	62
$\eta' K^0$	0.56	2.5	0.08	17
ϕK^0	1.84	1.2	0.17	8
ωK^0 (no K_L analysis yet)	1.95	0.7	0.27	5

- Naive estimates, one should do a little better (as in the Charmonium case as S~0.7.
- Take significance estimates with a pinch of salt, seem to underestimate.
- BaBar/Belle **might** be able to establish evidence for T symmetry non-conservation with data in hand for $\eta' K^0$ modes.
- Belle II **should** observe T symmetry non conservation in all modes given $50ab^{-1}$.

- Extrapolations are based on BaBar results from PRD 072009 (2009), PRD 79, 052003 (2009), and PRD 112010 (2012).

Applying this logic to other modes

- Example: B to D*D*

Based on Phys.Rev. D79 (2009) 032002

$$
\begin{aligned}
S_+ &= -0.76 \pm 0.16 \pm 0.04 \\
C_+ &= +0.00 \pm 0.12 \pm 0.02 \\
S_\perp &= -1.80 \pm 0.70 \pm 0.16 \\
C_\perp &= +0.41 \pm 0.49 \pm 0.08\,,
\end{aligned}
$$

These results can be used to estimate the precision of the $\Delta S\pm$ observables in a T-symmetry test. The S_+ is the combination of longitudinal and || amplitudes (CP even), and S_{perp} the is the CP odd component.

	BaBar/Belle		Belle II	
Mode	Est. $\sigma(\Delta S^\pm)$	Est. Significance $n\sigma$	Est. $\sigma(\Delta S^\pm)$	Est. Significance $n\sigma$
$c\bar{c}K^0$	0.16 (actual = 0.14, 0.18)	9 (actual = 14)	0.022	62
D^*D^*	2.0	0.7	0.29	4.8

- Given the crudeness of the estimate, I would expect Belle II to be able to observe a significant asymmetry.

Applying this logic to other modes

- Example of a B to VV mode: $B \to \phi K^*(\to K_S \pi^0)$
- The time-dependence is more complicated (e.g. see PRD 78 (2008) 092008):

Scalar contribution: $$S_{00} = -\sqrt{1 - \mathcal{A}_{00}^2} \times \sin(2\beta + 2\Delta\phi_{00}) \, ,$$

Vector (J=1) / Tensor (J=2) contributions:

$$\begin{aligned}
S_{J0} &= -\sqrt{1 - \mathcal{A}_{J0}^2} \times \sin(2\beta + 2\Delta\delta_{0J} + 2\Delta\phi_{00}) \\
S_{J\parallel} &= -\sqrt{1 - \mathcal{A}_{J\parallel}^2} \times \sin(2\beta + 2\Delta\delta_{0J} - 2\Delta\phi_{\parallel J} + 2\Delta\phi_{00}) \\
S_{J\perp} &= +\sqrt{1 - \mathcal{A}_{J\perp}^2} \times \sin(2\beta + 2\Delta\delta_{0J} - 2\Delta\phi_{\perp J} + 2\Delta\phi_{00}).
\end{aligned}$$

So one has three values of S, related to the different contributions, including interference effects which complicate the interpretation of the observables in the context of the CKM matrix.

$B \to \phi K^*(\to K_S \pi^0)$

- Measurements of $\sin 2\beta_{eff}$:

(CP = +1) $\sigma(S_{A_L}) = {}^{+0.26}_{-0.34}$

(CP = +1) $\sigma(S_{A_{||}}) = {}^{+0.22}_{-0.30}$

(CP = −1) $\sigma(S_{A_\perp}) = {}^{+0.23}_{-0.32}$

3 of the 6 effective measurements of sin2β from this measurement. These results are correlated with each other, but can be used to estimate the precision on $\Delta S^{\pm}$ for this VV decay.

	BaBar/Belle		Belle II	
Mode	Est. $\sigma(\Delta S^{\pm})$	Est. Significance $n\sigma$	Est. $\sigma(\Delta S^{\pm})$	Est. Significance $n\sigma$
$c\bar{c}K^0$	0.16 (actual = 0.14, 0.18)	9 (actual = 14)	0.022	62
$\phi K^*(K^0\pi^0)$	1.14	1.5	0.13	10.3

- Expect better significance than the VP decay, but a more complicated analysis is required.
- NOTE: for B→VV decays the CP basis is exact unlike the K_L/K_S one.

What can Belle II do with 50/ab?

- Expect to observe non-zero asymmetries and establish T non-conservation in a number of different modes.

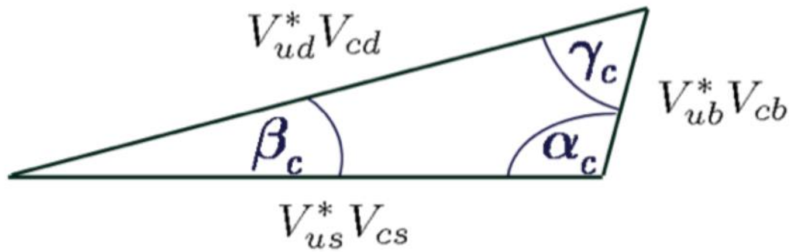
- With the exception of Charmonium decays (already demonstrated by BaBar), observation is not possible with current statistics.

- Caveats:
  - Statistical error extrapolation, and naive estimates only.
  - Charmonium determination will have syst. error contribution that needs to be investigated.
  - Extrapolations take no account of improved vertex detector for Belle II and are based on BaBar results.
  - One could play games with $\rho^0\rho^0$, but more data is really needed here to resolve the CP even/odd fraction.

IMPLICATIONS FOR D DECAYS

A brief look at charm

- The charm cu triangle has one unique element: β_c



$$\begin{aligned}\alpha_c &= \arg\left[-V_{ub}^*V_{cb}/V_{us}^*V_{cs}\right].\\ \beta_c &= \arg\left[-V_{ud}^*V_{cd}/V_{us}^*V_{cs}\right],\\ \gamma_c &= \arg\left[-V_{ub}^*V_{cb}/V_{ud}^*V_{cd}\right],\end{aligned}$$

$$\begin{aligned}\alpha_c &= (111.5 \pm 4.2)^\circ\\ \beta_c &= (0.0350 \pm 0.0001)^\circ\\ \gamma_c &= (68.4 \pm 0.1)^\circ\end{aligned}$$

$$V_{ud}^*V_{cd} + V_{us}^*V_{cs} + V_{ub}^*V_{cb} = 0$$

- Precision measurement of mixing phase in many channels (<2°)
- Constrain $\beta_{c,eff}$ using a $D \to \pi\pi$ Isospin analysis
  - Search for NP and constrain $\beta_{c,eff} \sim 1^\circ$.
  - Can only fully explore in an e^+e^- environment.
  - Data from the charm threshold region completes the set of 5 $|V_{ij}|$ to measure: needs Belle II and BES III to perform an indirect test of the triangle.

AB, Inguglia, Meadows, PRD **84** 114009 (2011)

A brief look at charm

- Time-dependent CP violation follows in a similar way to B physics (analogy with B_S decays). Phenomenologically we measure either the phase of mixing, or β_c
- Many modes can be studied for CPV, and a number can be studied for T symmetry non-invariance.

$$D^0 \to K^+K^-$$
$$D^0 \to K^0_S K^0_S$$
$$D^0 \to \pi^+\pi^-$$
$$D^0 \to \pi^0\pi^0$$
$$D^0 \to \rho^+\rho^-$$
$$D^0 \to \rho^0\rho^0$$
$$D^0 \to \phi\pi^0$$
$$D^0 \to \phi\rho^0$$
$$D^0 \to f^0(980)\pi^0$$
$$D^0 \to \rho^0\pi^0$$
$$D^0 \to a^0\pi^0$$
$$D^0 \to K^0_S K^0_S K^0_S$$
$$D^0 \to K^0_L K^0_S K^0_S$$
$$D^0 \to K^0_L K^0_L K^0_S$$
$$D^0 \to K^0_L K^0_L K^0_L$$

$$D^0 \to K^0_S\pi^0$$
$$D^0 \to K^0_S\omega$$
$$D^0 \to K^0_S\eta$$
$$D^0 \to K^0_S\eta'$$
$$D^0 \to K^0_S\pi^+\pi^- \text{ (NR)}$$
$$D^0 \to K^0_S\rho^0$$
$$D^0 \to K^0_S K^+K^- \text{ (NR)}$$
$$D^0 \to K^0_S\phi$$
$$D^0 \to K^0_S f^0$$
$$D^0 \to K^0_S a^0$$

$$D^0 \to K^0_L\pi^0$$
$$D^0 \to K^0_L\omega$$
$$D^0 \to K^0_L\eta$$
$$D^0 \to K^0_L\eta'$$
$$D^0 \to K^0_L\pi^+\pi^- \text{ (NR)}$$
$$D^0 \to K^0_L\rho^0$$
$$D^0 \to K^0_L K^+K^- \text{ (NR)}$$
$$D^0 \to K^0_L\phi$$
$$D^0 \to K^0_L f^0$$
$$D^0 \to K^0_L a^0$$

See AB, Inguglia, Meadows, PRD **84** 114009 (2011) for a discussion of CPV measurements, and illustrationusing D to hh decays.

- From the CKM matrix perspective...

Measures mixing phase (null tests)

$$\boxed{\begin{array}{r} \pi^+\pi^- K_{S,L} \\ \phi\rho^0 \\ 3K^0 \\ \phi K_{S,L} \\ \ldots \end{array}}$$

u	c	t
d	s	b

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

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

D decays at the ψ(3770)

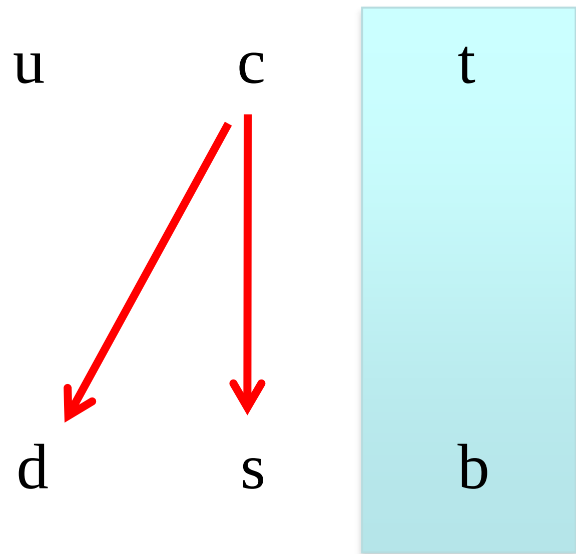
- From the CKM matrix perspective...

Measures mixing phase (null tests)

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

Measures β_c

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



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

- 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)

Naive estimates of results

- Some work has been done in looking at the precision of CP-symmetry violation measurements in a charm environment, but these need to be extended to T-symmetry measurements.

- Remember that in the SM the asymmetries in charm are expected to be ~0 (within experimental precision), so one will want to identify any large anomalies (related to a non-zero ΔA_{CP} from LHCb perhaps?) to study further.

- The potential is there for a tau-charm analysis of T-symmetry non-invariance, but we lack an experiment capable of doing that...

- Is it worth resurrecting the Berkelman idea of studying CP violation at a symmetric machine and seeing if BES III, or a successor, could be modified to do these tests?
  - See K. Berkelman **Mod.Phys.Lett. A10 (1995) 165-172.**

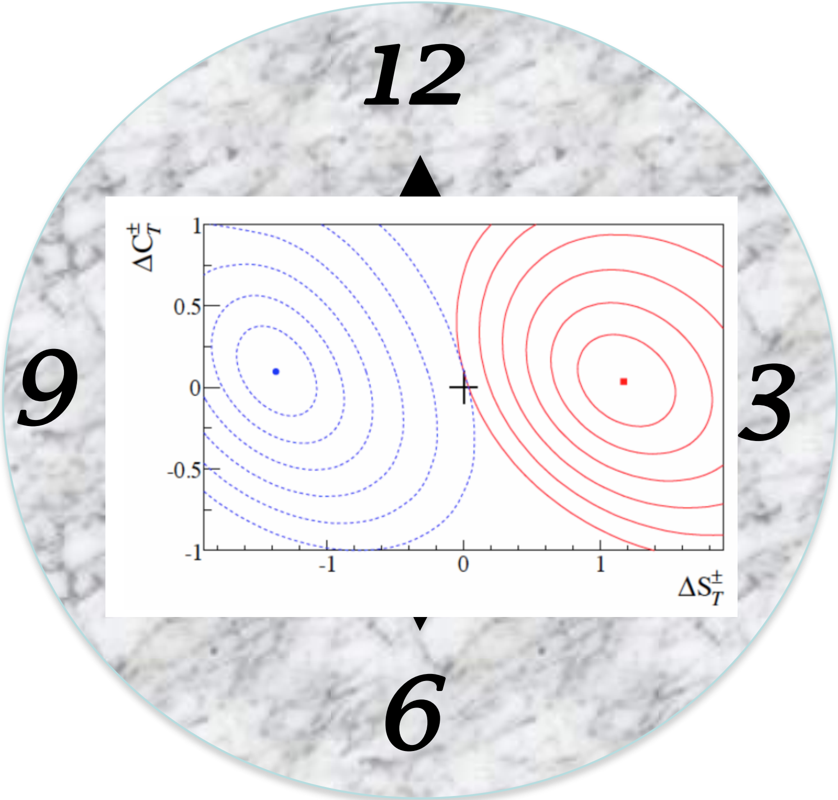
Summary

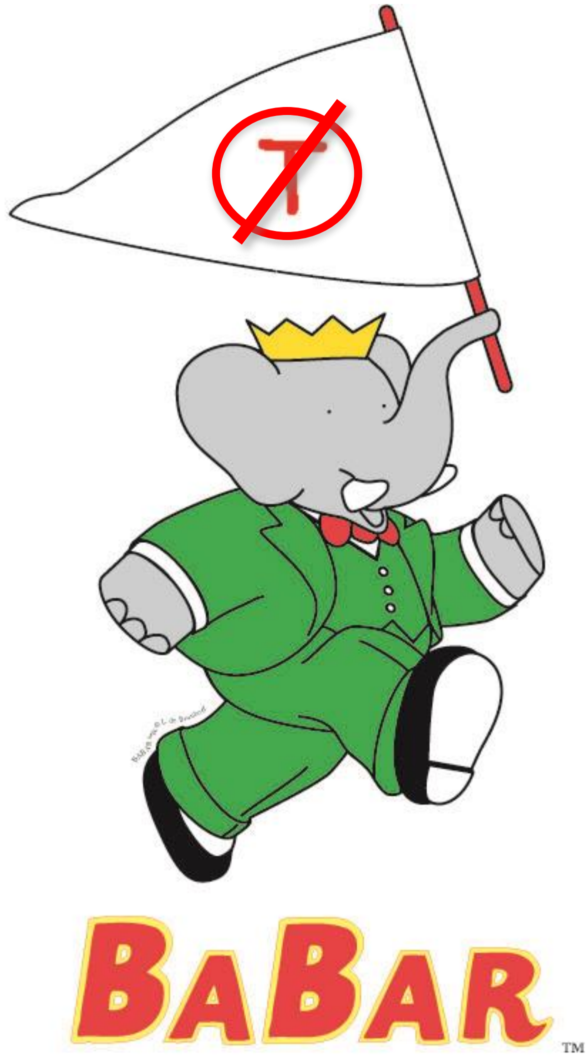
- BaBar, Belle and Belle II can now start to systematically probe the question:
  - Does the Kobayashi-Maskawa mechanism work under the T symmetry as well as the CP one?
  - Combined these two provide a test of CPT.

- 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.

Back up slides




T
BABAR

Dealing with detector resolution

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

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

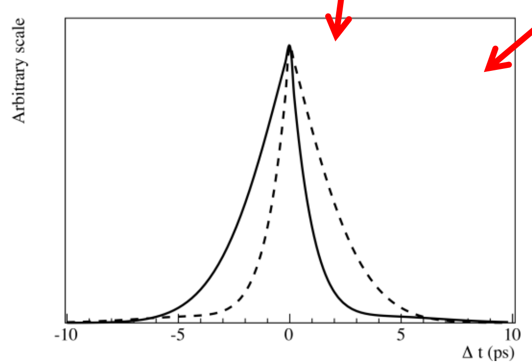
$-$

$-\Delta t$ (reversed ordering)

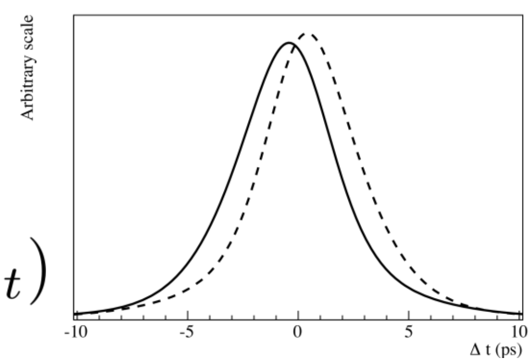
$+$

$+\Delta t$ (normal ordering)

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



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



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.