Questioning
Fundamental
Physical Principles

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CERN

Experimental prospects for T and CPT symmetries tests in the *B* meson system.

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Outline

- **Introduction**
- **Part 1:**
  - BaBar results from 2012
  - Implications for future studies
  - Naive estimates of the precision obtainable
- **Part 2:**
  - di-lepton+hadronic results (results from 2004-2006)
  - A double CP-tagged measurement beyond Belle II
- **Summary**

For background see the following:

Banuls & Bernabeu [PLB **464** 117 (1999); PLB **590** 19 (2000)]
Alverex & Szynkman [hep-ph/0611370]
Bernaneu, Martinez-Vidal, Villanueva-Perez [JHEP **1208** 064 (2012)]
Bevan, Inguglia, Zoccali [arXiv:arXiv:1302.4191]
Applebaum et al, [arXiv:1312.4164]
Schubert et al., arXiv:1401.6938
Ed. A. Bevan et al "Physics of the B Factories", *to be submitted to Springer/EPJC* soon

INTRODUCTION

Introduction: Formalism

- Need to test a S=(T, CP, CPT) conjugate process, and compare a state or process to its conjugate; e.g. for T

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

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

- The problem resides in identifying conjugate pairs of processes that can be experimentally distinguished.
  - Given strong and EM conserve these symmetries we want to identify weak decays that can be transformed under CP, T, CPT, we want to focus on conjugate pairs of decays accessible only via weak interactions.

Formalism

- We can consider entangled mesons produced at the Φ, ψ(3770), ϒ(4S), ϒ(5S) in terms of flavour and CP eigen-states.

$$|\psi_{flav}\rangle = \frac{1}{\sqrt{2}}\left(|P_1\rangle|\overline{P}_2\rangle - |\overline{P}_1\rangle|P_2\rangle\right)$$

$$|\psi_{CP}\rangle = \frac{1}{\sqrt{2}}\left(|P_{1,+}\rangle|P_{2,-}\rangle - |P_{1,-}\rangle|P_{2,+}\rangle\right)$$

- Here we care about B mesons, so these are

$$B^0 \quad \overline{B}^0 \quad B_+ \quad B_-$$

- There are 16 combinations of decays of mesons described by these two bases: and three symmetries of interest: T, CP, and CPT: 48 combinations in all.
  - These lead to 15 distinct *testable* asymmetries

Asymmetry Codex

- Class 1:
  - 4 distinct CP asymmetry tests
- Class 2:
  - 4 distinct T asymmetry tests
- Class 3:
  - 4 distinct CPT asymmetry tests
- Class 4:
  - 1 dual CP and T test (like a Kabir test)
- Class 5:
  - 1 dual CP and CPT test
- Class 6:
  - 1 dual T and CPT test

Part 1

Part 2

- Class 1 asymmetry pairings:

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

- Class 2 asymmetry pairings:

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

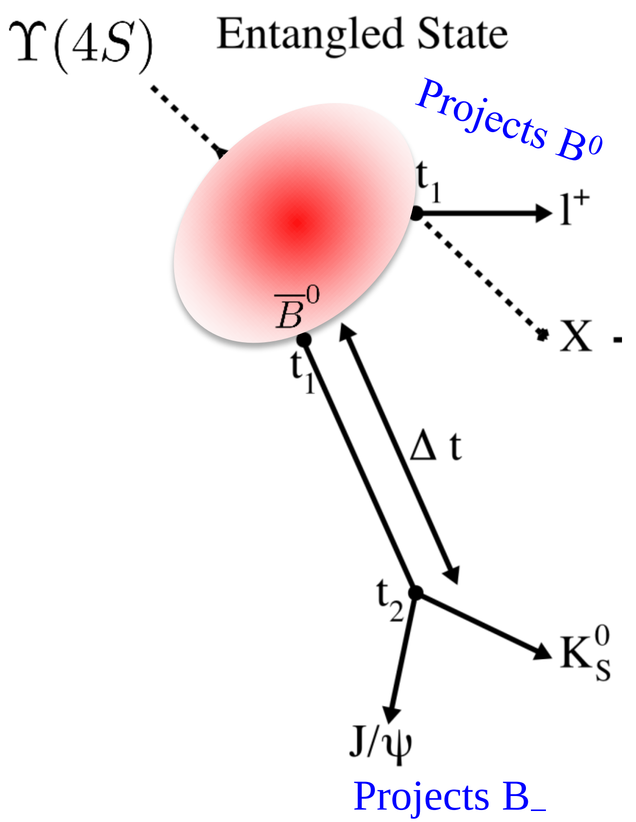
- Class 3 asymmetry pairings:

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

Formalism

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

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



1) At time t_1 the wave function collapses into the state:

$$B^0\overline{B}^0$$

2) The B^0 promptly decays to a flavor state via: l^+X.

3) The second B evolves naturally thereafter until it too decays.

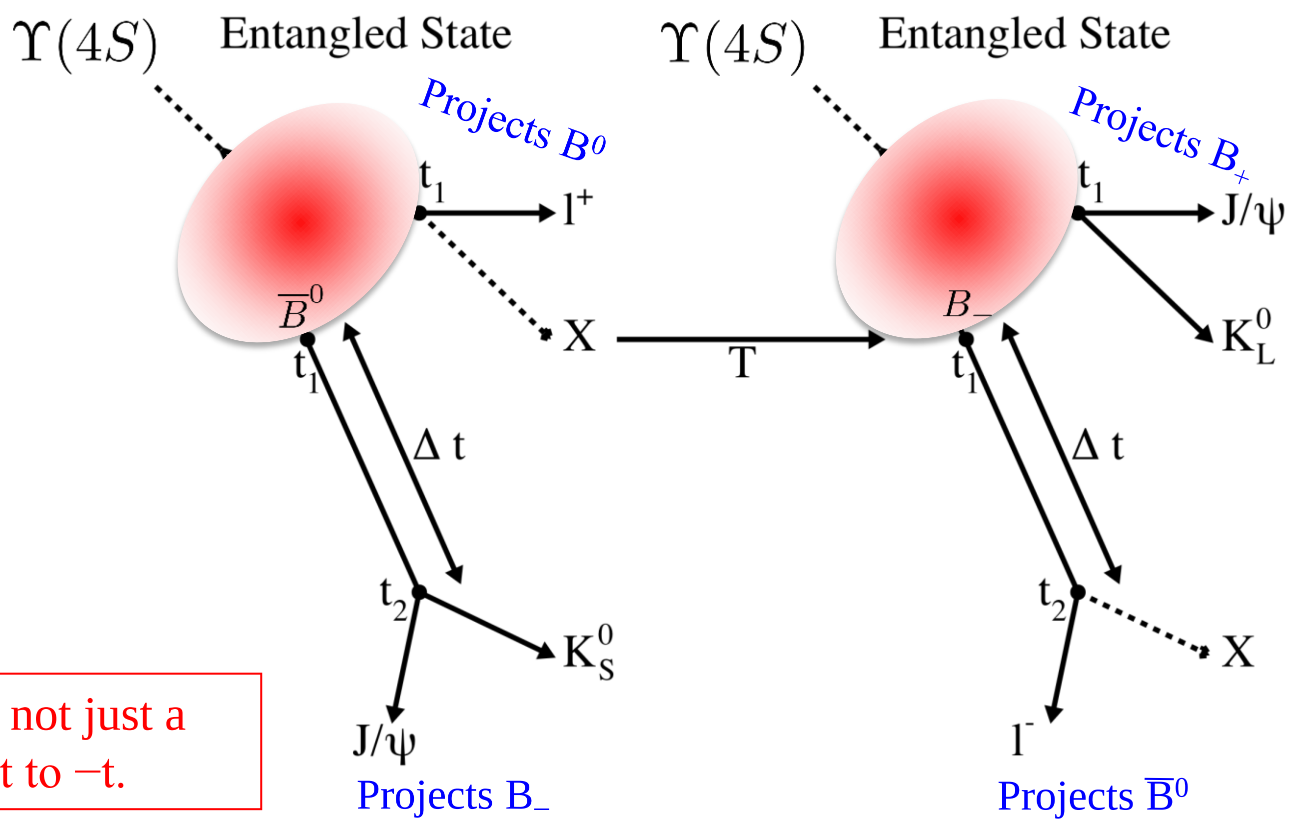
4) At some later time t_2 the second B decays as a B_-.

$$\Delta t = t_2 - t_1$$

Formalism

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

$$\overline{B}^0 \longrightarrow B_- \xrightarrow{\mathrm{T}} B_- \longrightarrow \overline{B}^0$$



This is not just a flip of t to −t.

$$\Delta t = t_2 - t_1$$

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

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

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

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

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 $\Delta\Gamma$=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.

Normal ordering: Tag decay before CP decay
Reversed ordering: CP decay before Tag decay

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 $\Delta C^{\pm} \sim 0$.

This part is concerned with asymmetries of Class I, II and III.

PART 1

Event Selection: CP filters

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

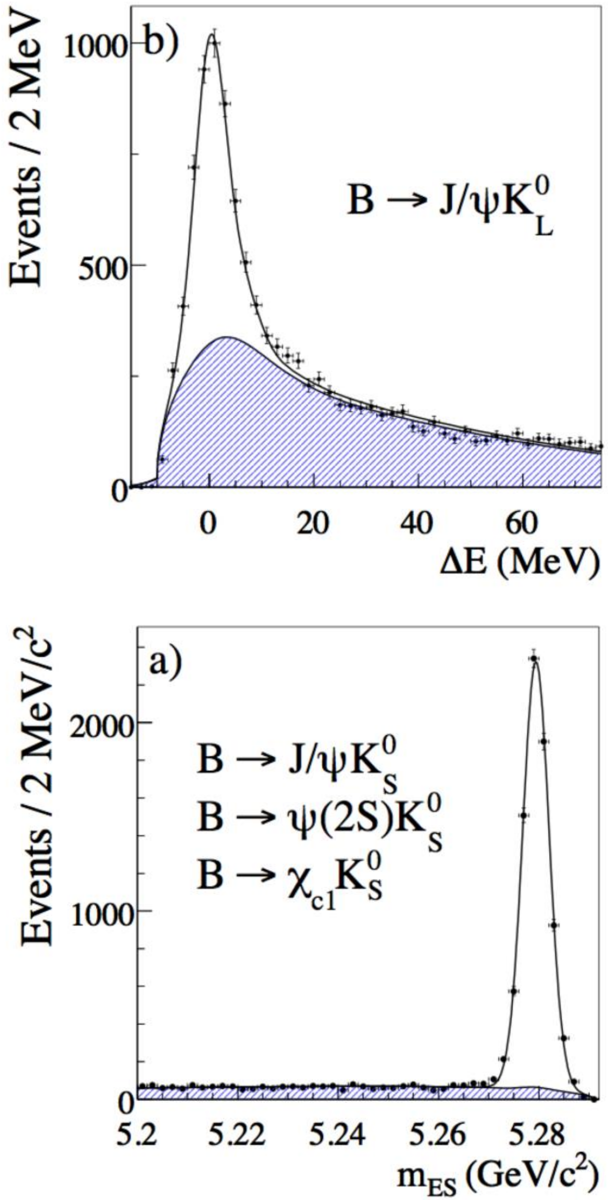
- CP even filter:

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

- 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.



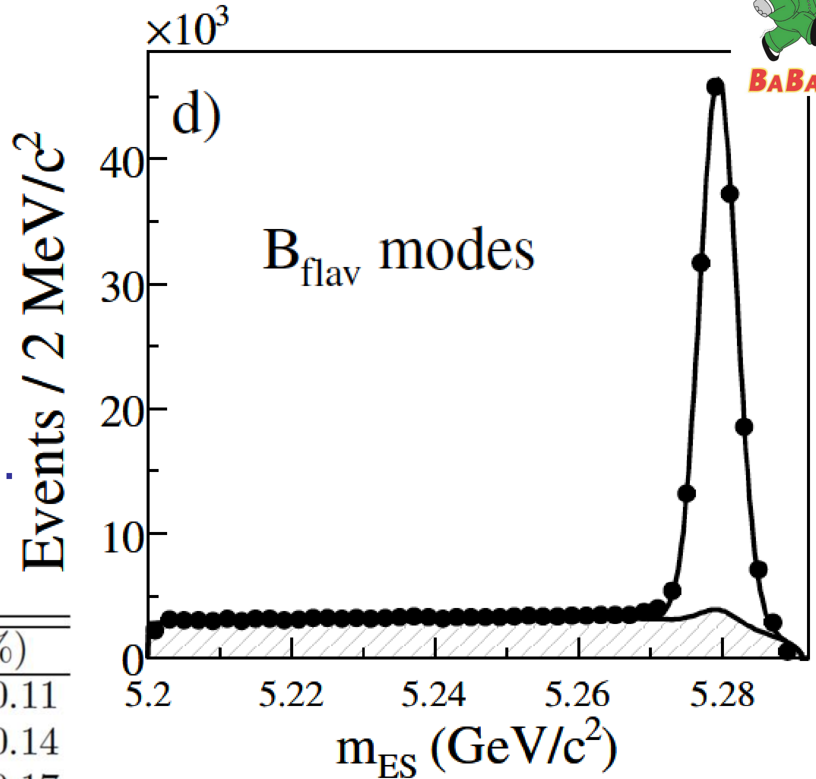
Event Selection: Flavor filters

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

- The set of "tag" modes used is:

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

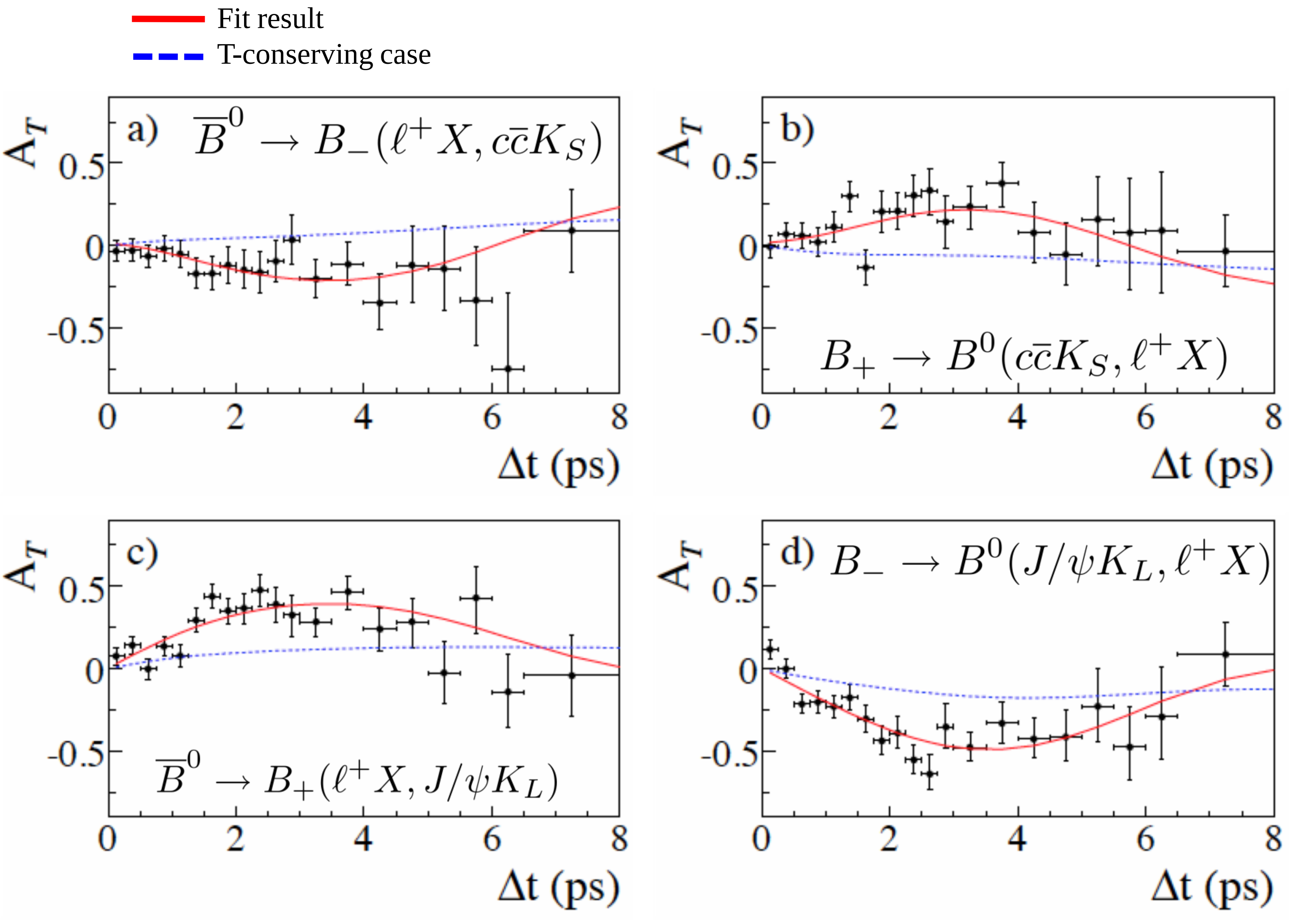
- which characterise "tag" performance and give the $B^0(\overline{B}^0)$ filter projections.



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

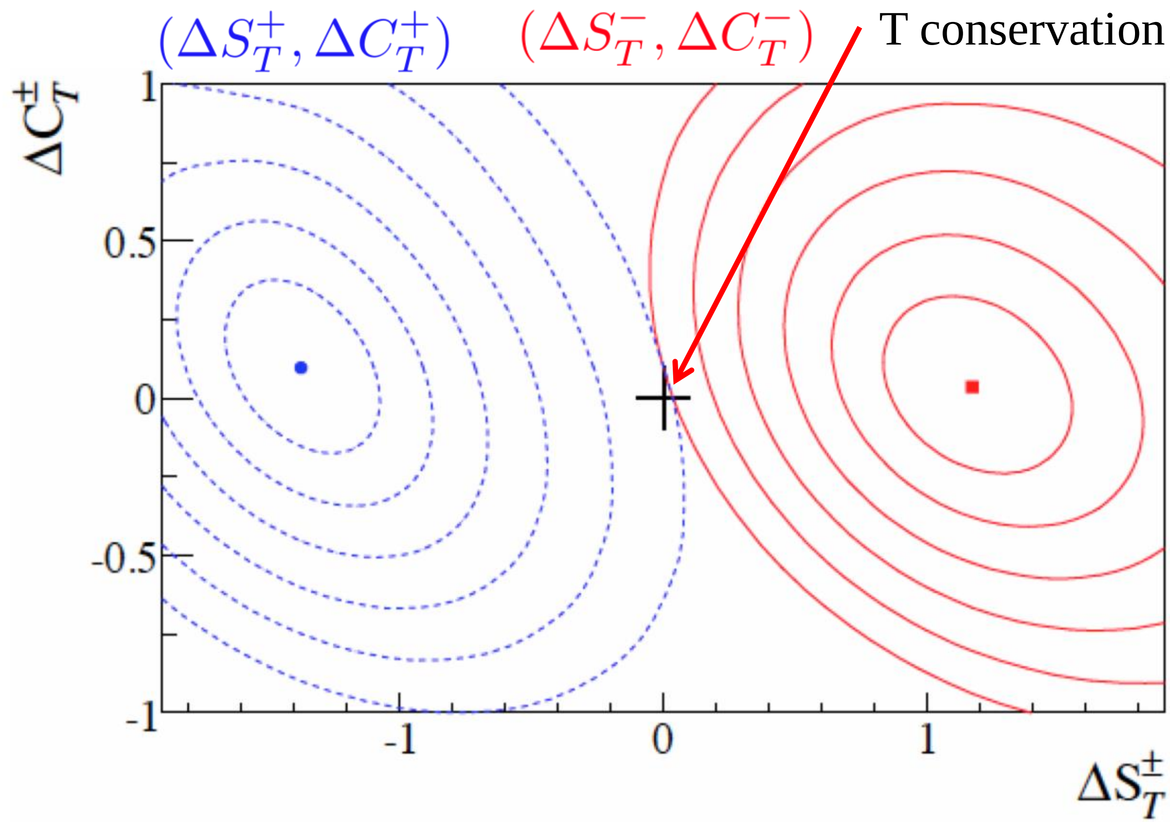
Parameter	Result
$\Delta S_T^+ = S^-_{\ell^-,K^0_L} - S^+_{\ell^+,K^0_S}$	$-1.37 \pm 0.14 \pm 0.06$
$\Delta S_T^- = S^+_{\ell^-,K^0_L} - S^-_{\ell^+,K^0_S}$	$1.17 \pm 0.18 \pm 0.11$
$\Delta C_T^+ = C^-_{\ell^-,K^0_L} - C^+_{\ell^+,K^0_S}$	$0.10 \pm 0.14 \pm 0.08$
$\Delta C_T^- = C^+_{\ell^-,K^0_L} -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

- First measurement of T violation in B decays.
- Observed level of T-violation balances CP violation.
- CPT is conserved.

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).

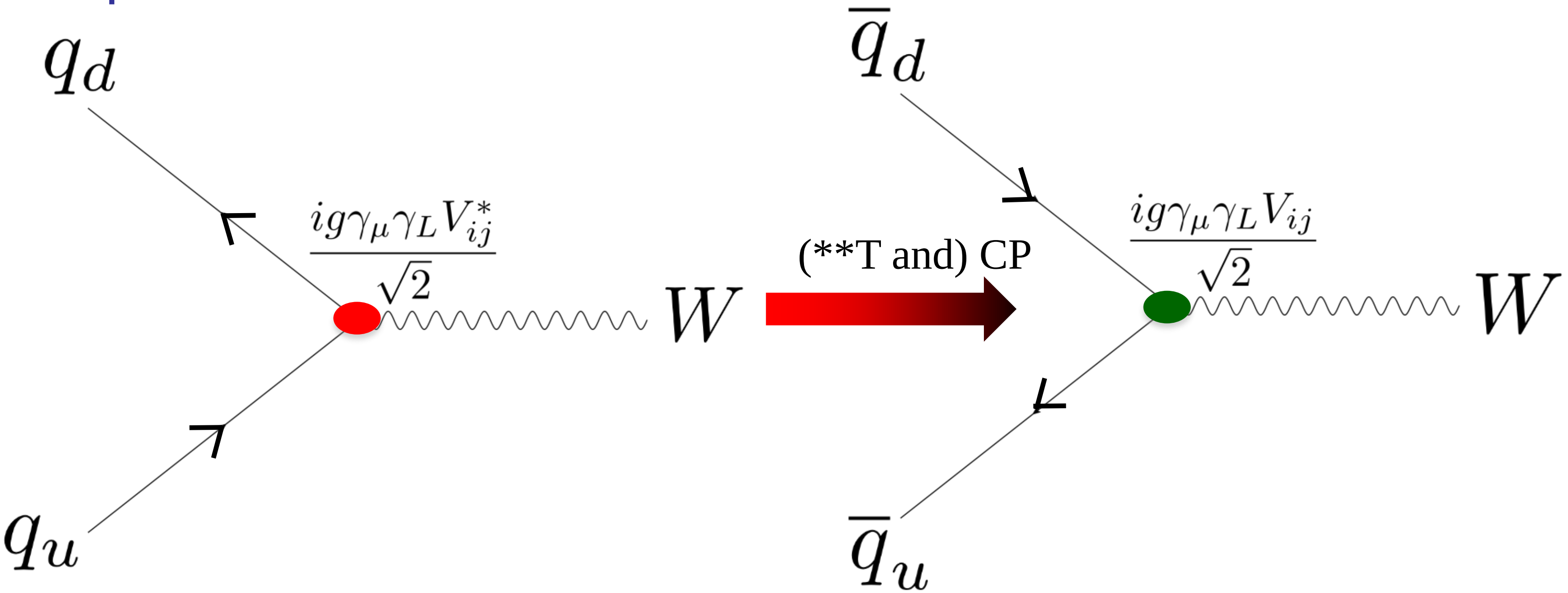
CL = 0.317, 4.55×10^{-2}, 2.70×10^{-3}, 6.33×10^{-5}, 5.73×10^{-7}, 1.97×10^{-9}

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

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

Can we learn anything about the SM?

- We need a weak phase difference for symmetry violation, in particular we use the convention



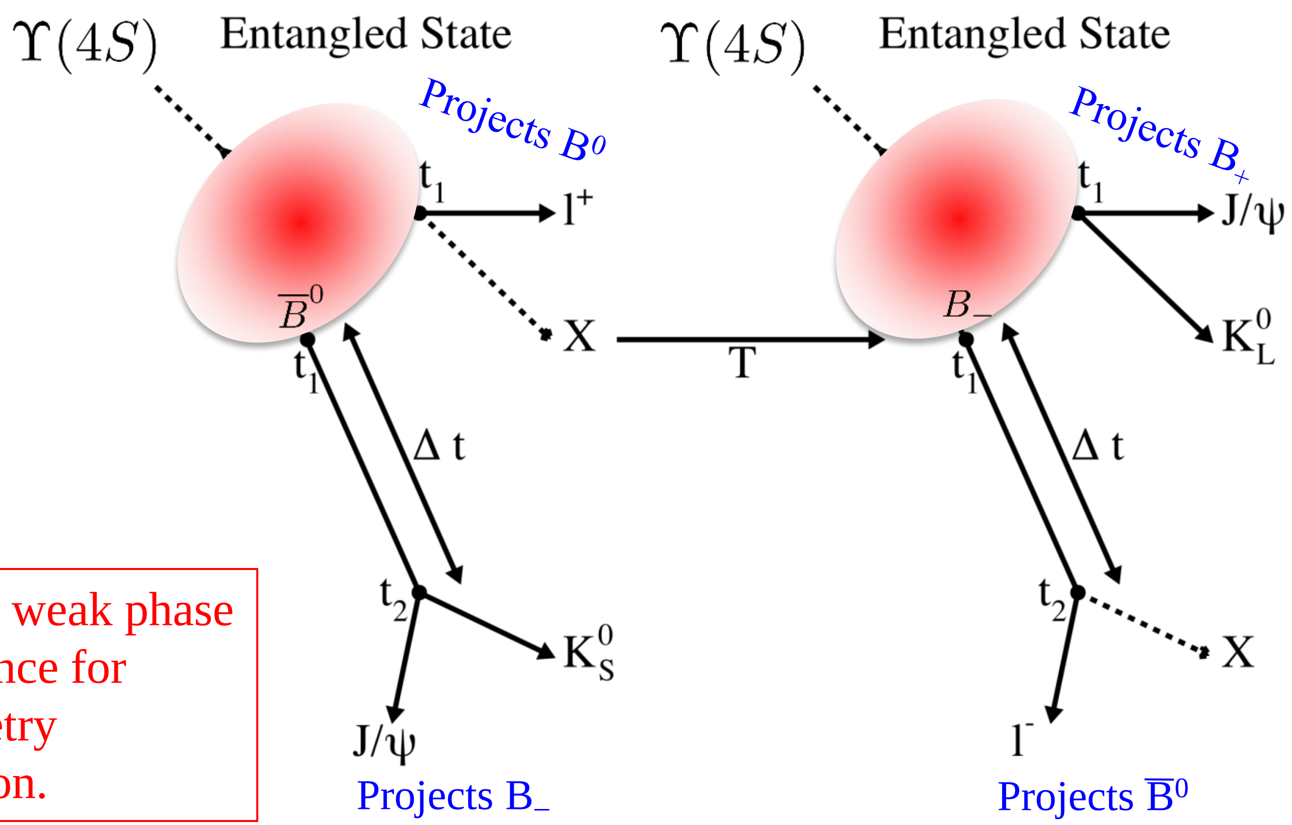
- If we consider this convention we see that V_{ij} is conjugted under T and CP and invariant under CPT.
  - So weak phases measured under CP are also measurable under T.

** by virtue of chosen filter states

Formalism

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

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



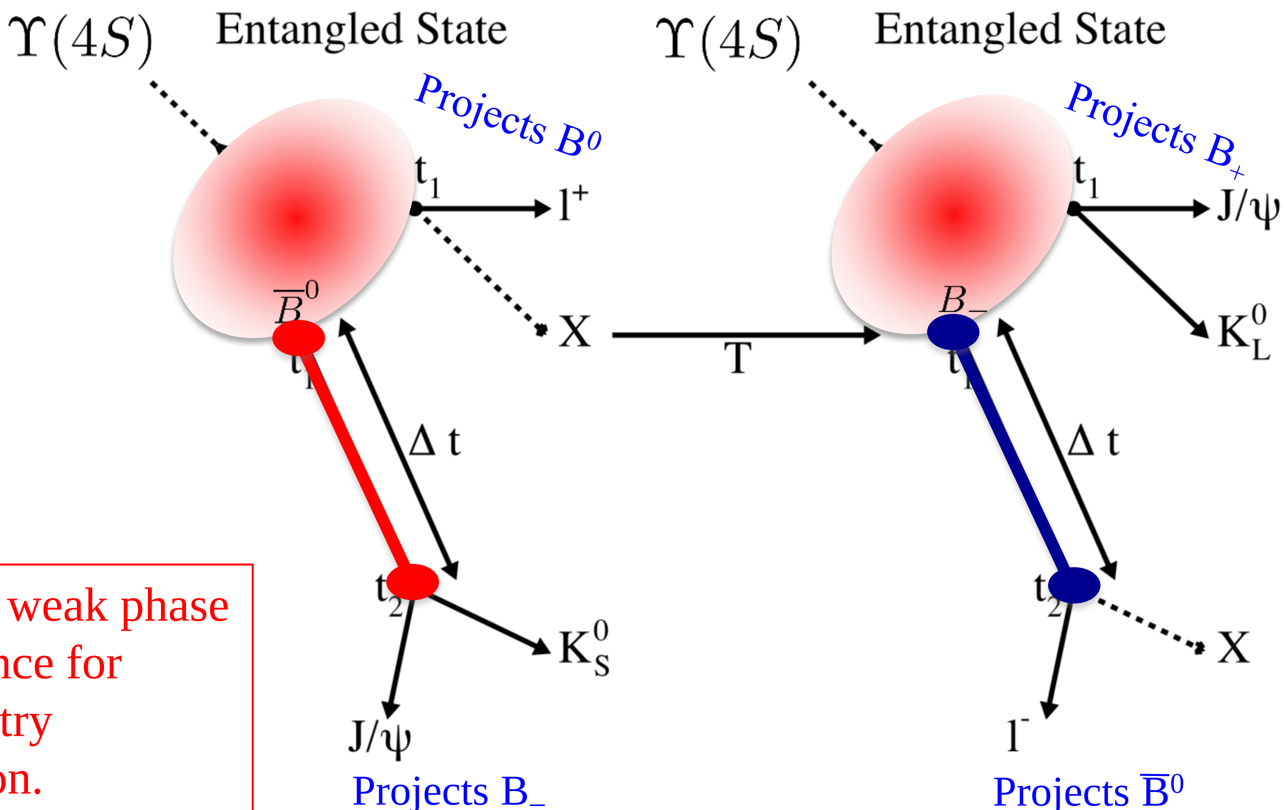
Need a weak phase difference for symmetry violation.

$$\Delta t = t_2 - t_1$$

Formalism

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

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



Need a weak phase difference for symmetry violation.

$e^{i\Phi W}=e^{i2\beta}$

$$\Delta t = t_2 - t_1$$

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

Other CP filter basis pairs

- There are other CP filter bases:
  - B_+ is a B decay filtering a CP-even state.
  - B_- is a B decay filtering a CP-odd state.
- The literature so-far uses the filters

$$\left.\begin{array}{l} B_+ \rightarrow c\bar{c}K^0_L \\ B_- \rightarrow c\bar{c}K^0_S \end{array}\right\}$$

• Convenient experimental basis, draws on the sin2β analysis = also good for experimentalists.

• $\{K_L, K_S\}$ basis is almost exact (up to CPV in kaons: ε_K)

Other CP filter basis pairs

- Many other CP states are measurable:
  - The even-odd filter selector is the $\{K_L, K_S\}$ pairing; we can replace the Charmonium with other states to widen the remit of these tests: e.g.

$$
\begin{aligned}
\{+1,-1\} &= \{B_+ \to \omega K^0_L, B_- \to \omega K^0_S\} \\
\{+1,-1\} &= \{B_+ \to \eta' K^0_S, B_- \to \eta' K^0_L\} \\
\{+1,-1\} &= \{B_+ \to \phi K^0_L, B_- \to \phi K^0_S\} \\
\{+1,-1\} &= \{B_+ \to K^0_S K^0_S K^0_L, B_- \to K^0_S K^0_S K^0_S\}
\end{aligned}
$$

  - These differ from the Charmonium decays as the weak phase difference enters through a loop, or loop dominated process.
  - They also measure sin2β.
  - The data are available to start making these tests.

AB, Inguglia, Zoccali arXiv:1302.4191

Other CP filter basis pairs

- s-penguin channels vs charmonium

Mode	BaBar/Belle Est. $\sigma(\Delta S^{\pm})$	BaBar/Belle Est. Significance $n\sigma$	Belle II Est. $\sigma(\Delta S^{\pm})$	Belle II 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 $50ab^{-1}$.

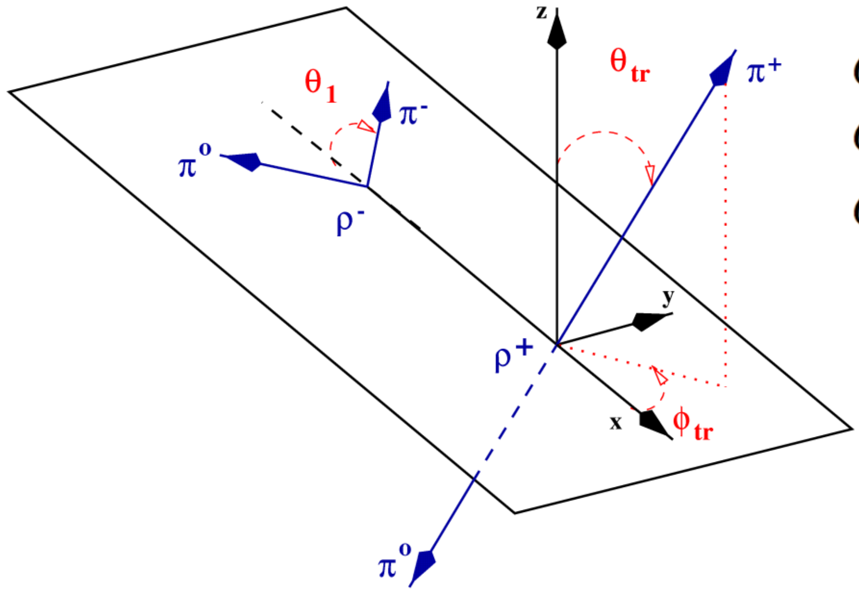
- Extrapolations are based on BaBar results from PRD 072009 (2009), PRD 79, 052003 (2009), and PRD 112010 (2012).

Other CP filter basis pairs

- Any CP filter pair would work: propose using the CP-even and CP-odd filter basis of a $0^- \rightarrow 1^{\pm}1^{\pm}$ decay:

$$|\mathcal{M}|^2 = |\underbrace{A_L + A_{\rm par}}_{\text{CP even}} + \underbrace{A_{\rm perp}}_{\text{CP odd}}|^2$$

- Instead of $\{K_S, K_L\}$ we have $\{f_{perp}, f_L+f_{par}\}$



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

See the following references for details of time-dependent angular analyses:

I. Dunietz, H. R. Quinn, A. Snyder, W. Toki and H. J. Lipkin, Phys. Rev. D 43 (1991) 2193.
G. Kramer and W. F. Palmer, Phys. Rev. D 45 (1992) 193.
Ed. A. Bevan et al, "Physics of the B Factories", Chapter 12.

AB, Inguglia, Zoccali arXiv:1302.4191

Other CP filter basis pairs

- The angular distribution is given by

See the Physics of the B factories for more details, or experimental results on B decays to $\phi K_S\pi^0$ or B_s to $J/\psi\phi$

$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_{tr} d\phi_{tr}} = \frac{9}{8\pi}\sum_{i=1}^{6}\alpha_i^{tr} g_i^{tr}(\cos\theta_1, \cos\theta_{tr}, \cos\phi_{tr})$$

$$\begin{aligned}
\alpha_1^{tr} &= \frac{|A_L|^2}{\sum\limits_{-1,0,+1}|A_h|^2} = f_L \\
\alpha_2^{tr} &= \frac{|A_\parallel|^2}{\sum\limits_{-1,0,+1}|A_h|^2} = f_\parallel \\
\alpha_3^{tr} &= \frac{|A_\perp|^2}{\sum\limits_{-1,0,+1}|A_h|^2} = f_\perp \\
\alpha_4^{tr} &= \frac{Im(A_\perp A_\parallel^*)}{\sum\limits_{-1,0,+1}|A_h|^2} = \sqrt{f_\perp f_\parallel}\sin(\phi_\perp - \phi_\parallel) \\
\alpha_5^{tr} &= \frac{Re(A_\parallel A_L^*)}{\sum\limits_{-1,0,+1}|A_h|^2} = \sqrt{f_\parallel f_L}\cos(\phi_\parallel) \\
\alpha_6^{tr} &= \frac{Im(A_\perp A_L^*)}{\sum\limits_{-1,0,+1}|A_h|^2} = \sqrt{f_\perp f_L}\sin(\phi_\perp)
\end{aligned}$$

$$\begin{aligned}
g_1^{tr} &= \cos^2\theta_1 \sin^2\theta_{tr}\cos^2\phi_{tr} \\
g_2^{tr} &= \frac{1}{2}\sin^2\theta_1\sin^2\theta_{tr}\sin^2\phi_{tr} \\
g_3^{tr} &= \frac{1}{2}\sin^2\theta_1\cos^2\theta_{tr} \\
g_4^{tr} &= -\eta\frac{1}{2}\sin^2\theta_1\sin 2\theta_{tr}\sin\phi_{tr} \\
g_5^{tr} &= \frac{1}{2\sqrt{2}}\sin 2\theta_1\sin^2\theta_{tr}\sin 2\phi_{tr} \\
g_6^{tr} &= -\eta\frac{1}{2\sqrt{2}}\sin 2\theta_1\sin 2\theta_{tr}\cos\phi_{tr}
\end{aligned}$$

$$\begin{aligned}
A_L &= A_L(0)e^{-im\Delta t}e^{-|\Delta t|/2\tau}\left(\cos\frac{\Delta m\Delta t}{2} + i\eta\lambda_L\sin\frac{\Delta m\Delta t}{2}\right) \\
A_\parallel &= A_\parallel(0)e^{-im\Delta t}e^{-|\Delta t|/2\tau}\left(\cos\frac{\Delta m\Delta t}{2} + i\eta\lambda_\parallel\sin\frac{\Delta m\Delta t}{2}\right)
\end{aligned}$$

CP even

$$A_\perp = A_\perp(0)e^{-im\Delta t}e^{-|\Delta t|/2\tau}\left(\cos\frac{\Delta m\Delta t}{2} - i\eta\lambda_\perp\sin\frac{\Delta m\Delta t}{2}\right)$$

CP odd

$$\eta = +1(-1) \text{ for } B(\overline{B})$$

Other CP filter basis pairs

- Decays of interest for future measurements:

$$\begin{aligned} B &\to J/\psi K^* \\ B &\to \phi K^* \\ B &\to D^* D^* \\ B &\to \rho\rho \\ B &\to \rho K^* \\ &\ldots \end{aligned}$$

- Experimental precision is a balance between the CP-odd and CP-even components (i.e. B_- and B_+ filters).

- This means we want to study decays that are NOT dominated by the longitudinal polarisation.

- D*D*, J/ψK*, $\rho^0\rho^0$ are all good starting points.

	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

This part is concerned with asymmetries of Class IV, V and VI.

PART 2

- Class IV Asymmetry: CP and T Violating

$$A_{CP,T} = \frac{\Gamma(B^0 \to \overline{B}^0) - \Gamma(\overline{B}^0 \to B^0)}{\Gamma(B^0 \to \overline{B}^0) + \Gamma(\overline{B}^0 \to B^0)}$$

Signature: e.g. same sign di-lepton and hadronic tag events

- Class V Asymmetry: CP and CPT Violating

$$A_{CP,CPT} = \frac{\Gamma(B^0 \to B^0) - \Gamma(\overline{B}^0 \to \overline{B}^0)}{\Gamma(B^0 \to B^0) + \Gamma(\overline{B}^0 \to \overline{B}^0)}$$

Signature: e.g. opposite sign di-lepton and hadronic events

- Class VI Asymmetry: T and CPT Violating

$$A_{T,CPT} = \frac{\Gamma(B_- \to B_+) - \Gamma(B_+ \to B_-)}{\Gamma(B_- \to B_+) + \Gamma(B_+ \to B_-)}$$

Signature: $(N^{KLKL} - N^{KSKS})/(N^{KLKL} + N^{KSKS})$
i.e. Double CP tagged events.

Class IV and V asymmetries

- The CP, T and CP, CPT asymmetries go hand in hand:

$$A_{CP,T} = \frac{\Gamma(B^0 \to \overline{B}^0) - \Gamma(\overline{B}^0 \to B^0)}{\Gamma(B^0 \to \overline{B}^0) + \Gamma(\overline{B}^0 \to B^0)}$$

Experimental signature: double tags of the same type: same sign di-lepton, or same sign hadronic tags.

$$\begin{tikzcd} B^0 \arrow[dr] & \overline{B}^0 \arrow[r] & \ell^- X \\ & \overline{B}^0 \arrow[r] & \ell^- X \end{tikzcd}$$

+C.C.

- The time-dependence is similar to the previous classes.

Class IV and V asymmetries

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$$A_{CP,T} = \frac{\Gamma(B^0 \to \overline{B}^0) - \Gamma(\overline{B}^0 \to B^0)}{\Gamma(B^0 \to \overline{B}^0) + \Gamma(\overline{B}^0 \to B^0)}$$

Experimental signature: double tags of the same type: same sign di-lepton, or same sign hadronic tags.

$$\begin{tikzcd} B^0 \arrow[d, no head] & \overline{B}^0 \arrow[r] & \ell^- X \\ {} \arrow[r] & \overline{B}^0 \arrow[r] & \ell^- X \end{tikzcd}$$

+C.C.

$$A_{CP,CPT} = \frac{\Gamma(B^0 \to B^0) - \Gamma(\overline{B}^0 \to \overline{B}^0)}{\Gamma(B^0 \to B^0) + \Gamma(\overline{B}^0 \to \overline{B}^0)}$$

Experimental signature: double tags of the opposite type: opposite sign di-lepton, or opposite sign hadronic tags.

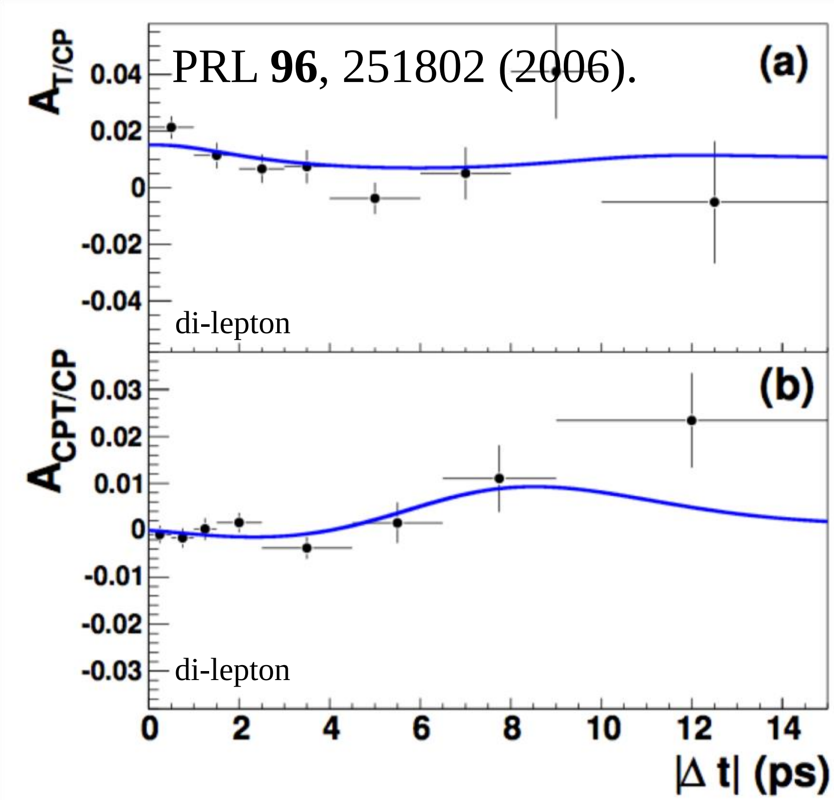
$$\begin{tikzcd} B^0 \arrow[d, no head] & \overline{B}^0 \arrow[r] & \ell^- X \\ {} \arrow[r] & B^0 \arrow[r] & \ell^+ X \end{tikzcd}$$

+C.C.

- The time-dependence is similar to the previous classes.

Class IV and V asymmetries

- Both BaBar and Belle measured these asymmetries



$$= \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

$$\simeq 2\frac{\mathrm{Im}\,\mathrm{z}\sin(\Delta\mathrm{m}\Delta\mathrm{t}) - \mathrm{Re}\,\mathrm{z}\sinh(\frac{\Delta\Gamma\Delta\mathrm{t}}{2})}{\cosh(\frac{\Delta\Gamma\Delta\mathrm{t}}{2}) + \cos(\Delta m\Delta\mathrm{t})}$$

$$\begin{aligned} |q/p| - 1 &= (-0.8 \pm 2.7(\mathrm{stat.}) \pm 1.9(\mathrm{syst.})) \times 10^{-3}, \\ \mathrm{Im}\,\mathrm{z} &= (-13.9 \pm 7.3(\mathrm{stat.}) \pm 3.2(\mathrm{syst.})) \times 10^{-3}, \\ \Delta\Gamma \times \mathrm{Re}\,\mathrm{z} &= (-7.1 \pm 3.9(\mathrm{stat.}) \pm 2.0(\mathrm{syst.})) \times 10^{-3}\,\mathrm{ps}^{-1} \end{aligned}$$

- Both asymmetries are found to be compatible with zero.

BaBar:
[di-lepton] PRL **88**, 231801 (2002), PRL **96**, 251802 (2006), [hadronic] PRL **92**, 181801 (2004) , PRD **70**, 012007 (2004).

Belle:
[di-lepton] PRD **73**, 112002 (2006).

What about the LHC?

- The LHC experiments: ATLAS, CMS and LHCb can contribute to this programme by measuring $A_{CP,T}$ and $A_{CP,CPT}$: (c.f. CPLEAR's approach with flavor tagging)

$$A_{CP,T} = \frac{\Gamma(B^0 \to \overline{B}^0) - \Gamma(\overline{B}^0 \to B^0)}{\Gamma(B^0 \to \overline{B}^0) + \Gamma(\overline{B}^0 \to B^0)} \qquad A_{CP,CPT} = \frac{\Gamma(B^0 \to B^0) - \Gamma(\overline{B}^0 \to \overline{B}^0)}{\Gamma(B^0 \to B^0) + \Gamma(\overline{B}^0 \to \overline{B}^0)}$$

- The time-dependent CP studies in place for $B_{(s)}$ decays requires flavour tagging; so one can identify the initial flavor filter using those techniques:
  - Q is a few % at most.
- The final decay filter can be a hadronically or SL tagged event state.
- Would be interesting to see what LHCb can produce for D, B_d and B_s using this approch.
- ATLAS & CMS should be able to do B_d and B_s.

Class VI Asymmetry

- This one has not been measured yet (a job for Belle ~~II~~ 3)

$$A_{T,CPT} = \frac{\Gamma(B_- \to B_+) - \Gamma(B_+ \to B_-)}{\Gamma(B_- \to B_+) + \Gamma(B_+ \to B_-)}$$

Scenario 1:

$$\begin{array}{l} B_- \quad B_+ \longrightarrow \eta_{CP} = +1 \\ \hookrightarrow B_+ \longrightarrow \eta_{CP} = +1 \end{array}$$

Scenario 2:

$$\begin{array}{l} B_+ \quad B_- \longrightarrow \eta_{CP} = -1 \\ \hookrightarrow B_- \longrightarrow \eta_{CP} = -1 \end{array}$$

- i.e. compare rates of decays to double CP tagged events using any of the aforementioned CP basis pairs.
- e.g. for Charmonium decays we have:

$$A_{T,CPT} = \frac{\Gamma[(J/\psi K_L)(J/\psi K_L)] - \Gamma[(J/\psi K_S)(J/\psi K_S)]}{\Gamma[(J/\psi K_L)(J/\psi K_L)] + \Gamma[(J/\psi K_S)(J/\psi K_S)]}$$

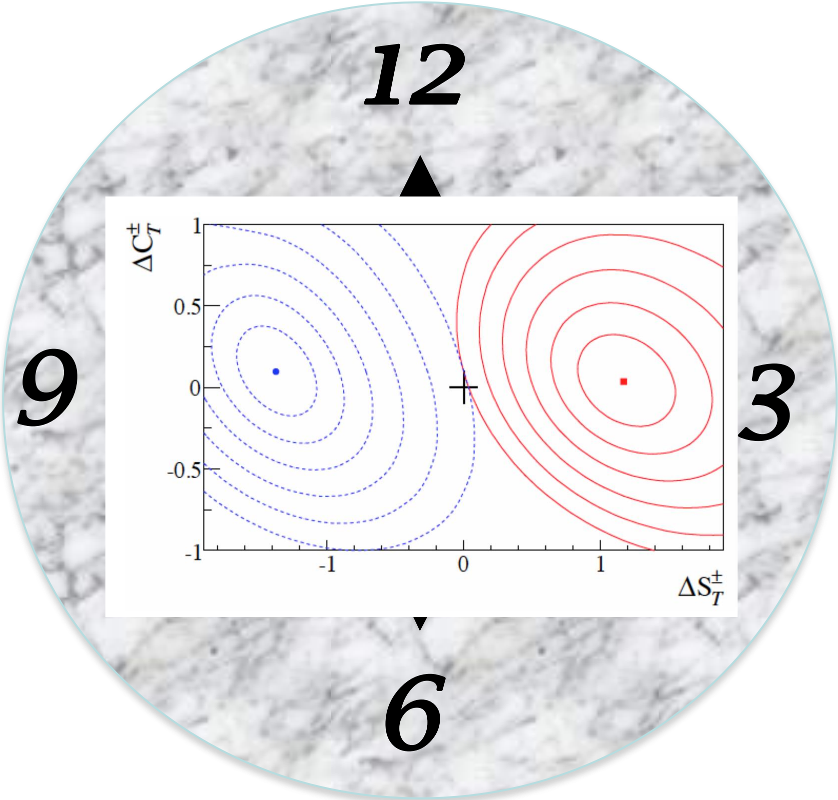
Class VI Asymmetry

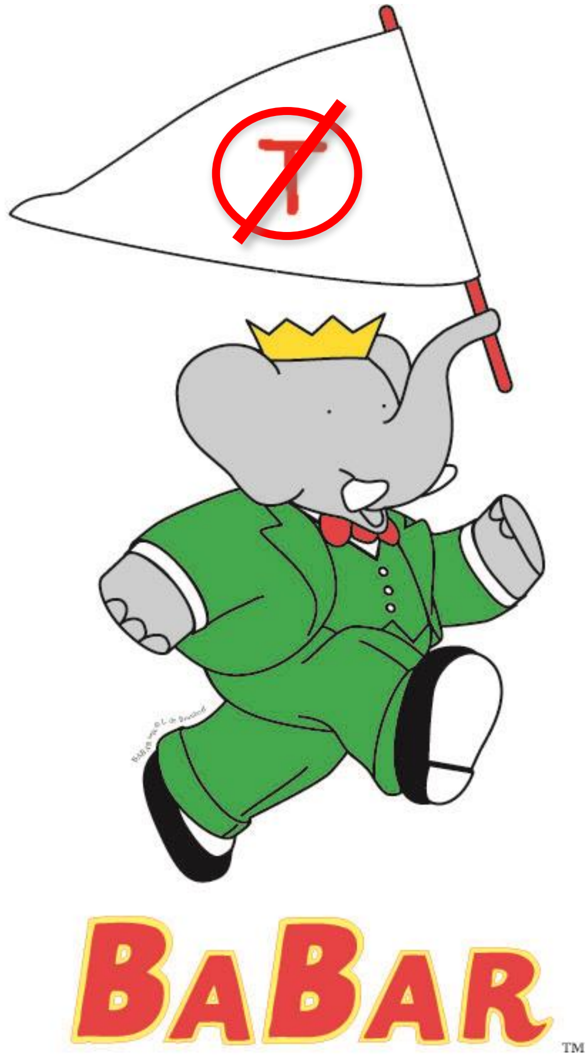
- BaBar has 6750 (5813) J/ψ K_S (K_L) events in their data.
- Expect ~725K (625K) single tagged events in 50ab^{-1}.
- Estimate that there will be:
  - 11 double tagged (J/ψ K_S)(J/ψ K_S) events at Belle II
  - 9 double tagged (J/ψ K_L)(J/ψ K_L) events at Belle II
  - Will need *"Super"Belle II (= **Belle 3**)* for a precision test of this asymmetry.
  - Probably a few hundred ab^{-1} would be needed to start measuring this asymmetry.
  - Could get more signal events if hadronic J/ψ decays are used given that the di-lepton BR is only 12%.
- The corresponding test in kaons Γ(3π,3π) vs Γ(2π,2π) events at KLOE (2) is more viable.

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?
  - The set of CP, T and CPT tests over-constrain our understanding of these symmetries in weak interactions.
- The $A_{T,\ CPT}$ double tag asymmetry measurement is more than a decade away (need a Super Belle II):
  - This is a dual T, CPT asymmetry measurement.
  - Equivalent to a double $K_S(2\pi)$ vs $K_L(3\pi)$ comparison at a Φ factory.
- Systematic treatment of these asymmetries at the B Factories over constrains the weak interaction behaviour in terms of CP, T, and CPT.
- The LHC can contribute via measurements of $A_{CP,T}$ and $A_{CP,CPT}$.

Back up slides




BABAR
TM

Dealing with detector resolution

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

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

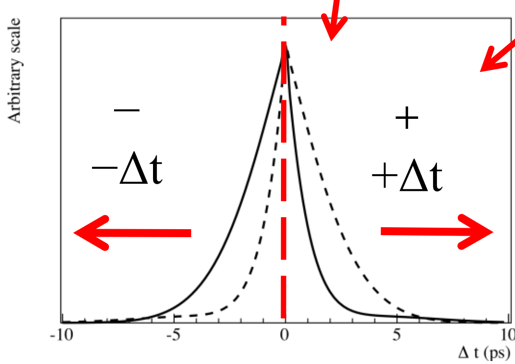
–

$-\Delta t$ (reversed ordering)

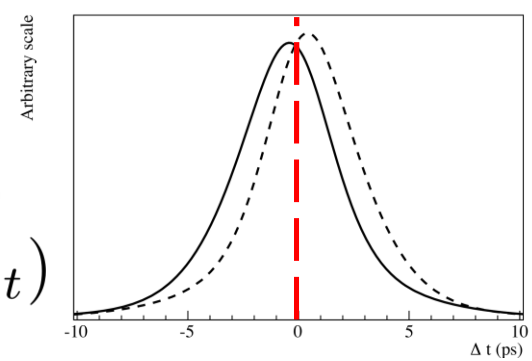
+

$+\Delta t$ (normal ordering)

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



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



Implications …

- CP filters:
  - Tree decays: $b \rightarrow c\bar{c}s$ i.e. $B \rightarrow J/\psi K_{S/L}$ which measure sin2β [BaBar result in backup slides].
  - Loop decays: $b \rightarrow s$ penguins e.g. $B \rightarrow (\eta', \omega, \ldots)K_{S/L}$ 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

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

- 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 $\sin 2\beta_{\text{eff}}$:

(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.

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

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

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

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

$\eta_c K_{S,L}$

$J/\psi K^*$

$\ldots$

u c t

d s b

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

$\phi K_{S,L}$

$\omega K_{S,L}$

ϕK^*

$\ldots$

Measures sin2β

AB, Inguglia, Zoccali arXiv:1302.4191

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

- From the CKM matrix perspective...

Measures sin2β

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

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

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

$\eta_c K_{S,L}$

$J/\psi K^*$

$\ldots$

u c t

d s b

$D^* D^*$

$\ldots$

Measures sin2β

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

$\phi K_{S,L}$

$\omega K_{S,L}$

ϕK^*

$\ldots$

Measures sin2β

AB, Inguglia, Zoccali arXiv:1302.4191

B decays at the ϒ(4S)

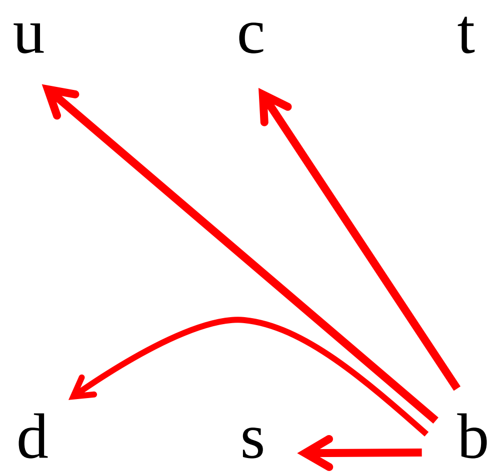
- From the CKM matrix perspective...

Measures sin2β

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

Measures $\sin 2\alpha_{\text{eff}}$

$\rho^0\rho^0$
$\ldots$



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

D^*D^*
$\ldots$

Measures sin2β

Measures sin2β

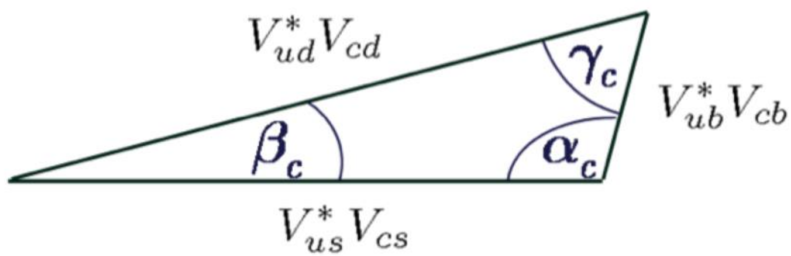
- There is at least one route to test each transition type from a *b* quark.

AB, Inguglia, Zoccali arXiv:1302.4191

IMPLICATIONS FOR D DECAYS

A brief look at charm

- The charm cu triangle has one unique element: β_c



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

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

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

- Precision measurement of mixing phase in many channels (<2°)
- Constrain $\beta_{c,\mathrm{eff}}$ using a $D \to \pi\pi$ Isospin analysis
  - Search for NP and constrain $\beta_{c,\mathrm{eff}} \sim 1^\circ$.
  - 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.

$D^0 \to K^+K^-$	$D^0 \to K^0_S\pi^0$	$D^0 \to K^0_L\pi^0$
$D^0 \to K^0_SK^0_S$	$D^0 \to K^0_S\omega$	$D^0 \to K^0_L\omega$
$D^0 \to \pi^+\pi^-$	$D^0 \to K^0_S\eta$	$D^0 \to K^0_L\eta$
$D^0 \to \pi^0\pi^0$	$D^0 \to K^0_S\eta'$	$D^0 \to K^0_L\eta'$
$D^0 \to \rho^+\rho^-$	$D^0 \to K^0_S\pi^+\pi^-$ (NR)	$D^0 \to K^0_L\pi^+\pi^-$ (NR)
$D^0 \to \rho^0\rho^0$	$D^0 \to K^0_S\rho^0$	$D^0 \to K^0_L\rho^0$
$D^0 \to \phi\pi^0$	$D^0 \to K^0_SK^+K^-$ (NR)	$D^0 \to K^0_LK^+K^-$ (NR)
$D^0 \to \phi\rho^0$	$D^0 \to K^0_S\phi$	$D^0 \to K^0_L\phi$
$D^0 \to f^0(980)\pi^0$	$D^0 \to K^0_Sf^0$	$D^0 \to K^0_Lf^0$
$D^0 \to \rho^0\pi^0$	$D^0 \to K^0_Sa^0$	$D^0 \to K^0_La^0$
$D^0 \to a^0\pi^0$		
$D^0 \to K^0_SK^0_SK^0_S$		
$D^0 \to K^0_LK^0_SK^0_S$		
$D^0 \to K^0_LK^0_LK^0_S$		
$D^0 \to K^0_LK^0_LK^0_L$		

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

D decays at the ψ(3770)

- 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

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

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

D decays at the ψ(3770)

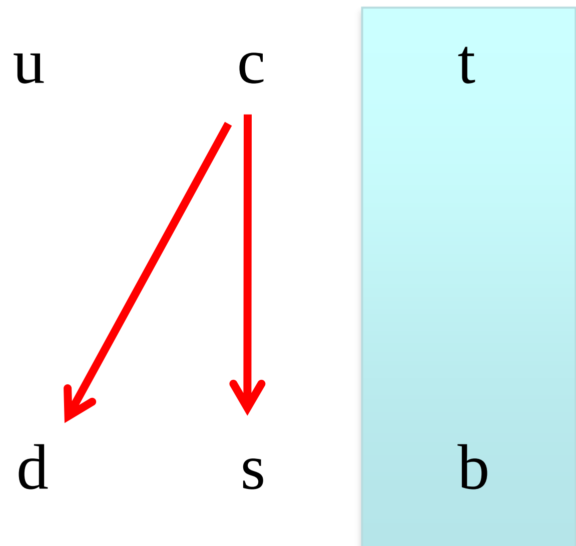
- From the CKM matrix perspective...

Measures mixing phase (null tests)

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

Measures β_c

$$\boxed{\begin{array}{r} K^+K^- K_{S,L} \\ \rho^-\rho^+ \\ \rho^0\rho^0 \\ \eta^{(\prime)} K_{S,L} \\ \ldots \end{array}}$$



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

- 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.**

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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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	$B^0 \to B_- \,(\ell^- X, \mathcal{B}_\perp)$

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