CP(T) violation in incl. B decays at OPAL

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- Introduction: CP violation in inclusive B decays
- OPAL CP(T) violation analysis:
  - Analysis method
  - Flavour tagging
  - Results for CP violation
  - Equality of b and $\overline{\mathrm{b}}$ hadron lifetimes
- Summary and conclusion: results from other experiments

Results presented here are from abstract 43, published as CERN-EP/98-195, accepted by Eur Phys J.

Paper also includes $\mathrm{B}^+/\mathrm{B}^0$ lifetime analysis–covered in session 5.

Introduction

CP violation known in $K^0 - \overline{K^0}$ system, but small.

- In Standard Model, CP violation comes from phase in CKM matrix.
- Implies potentially large CP effects in $B^0 - \overline{B^0}$ system.

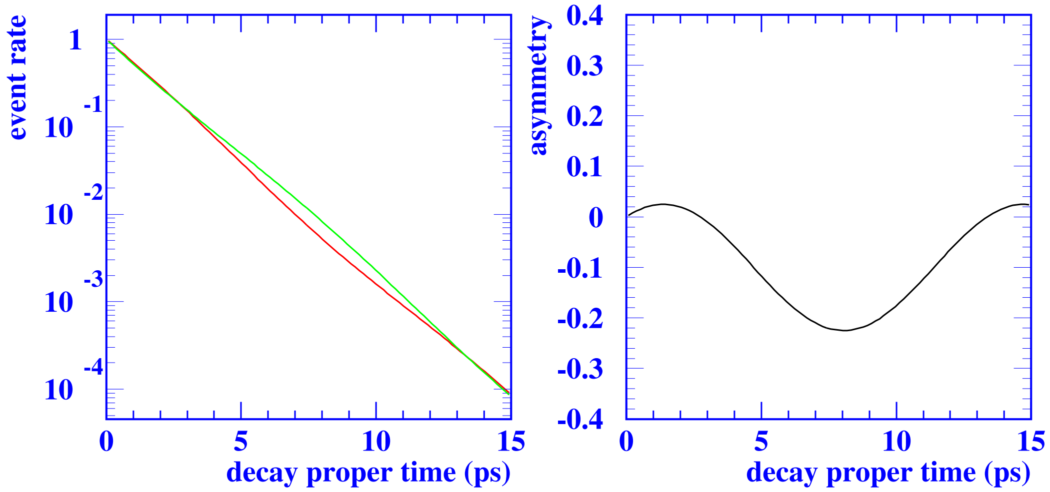
Fashionable to look in exclusive decays ($\sin 2\beta$), can also look in inclusive b decays—smaller effects but much higher statistics.

As in K^0 system, indirect CP violation can occur in B^0 system, if weak eigenstates B^0 and $\bar{B}^0$ differ from mass eigenstates B_1 and B_2:

$$
\begin{aligned}
|B_1> &= (1+\epsilon_B)|B^0> + (1-\epsilon_B)|\bar{B}^0> \\
|B_2> &= (1+\epsilon_B)|B^0> - (1-\epsilon_B)|\bar{B}^0>
\end{aligned}
$$

ϵ_B parameterises indirect CP violation.

Time evolution of B^0 and $\bar{B}^0$ are not the same:

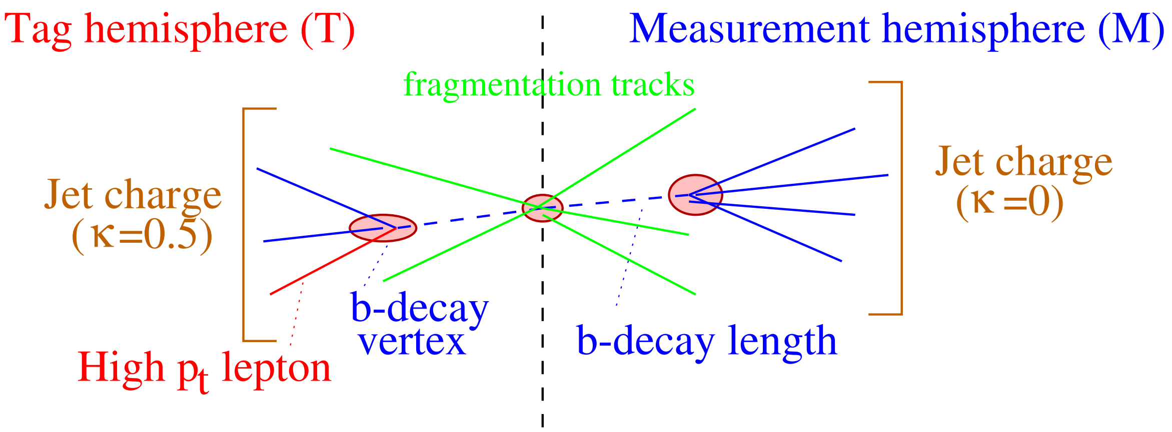


Expect an asymmetry in numbers of produced B^0 and $\bar{B}^0$ decaying at time t.

- Tag production flavour and decay time of inclusive b decays (no effect in B^+,Λ_b, only very small effect in B_s).

Analysis Method

Exploit the structure of $Z^0 \rightarrow b\bar{b}$ decays—two back-to-back jets, each containing one b hadron.



Tag hemisphere (T):

- Look for displaced vertex or high momentum lepton to identify $b\bar{b}$ event.
- Use properties of tag hemisphere to identify b hadron production flavour.
- Infer production flavour in M hemisphere (always b opposite $\bar{b}$).

Measurement hemisphere (M):

- Reconstruct decay length L and energy E of b hadron by looking for secondary vertex, determine proper time t of b decay.
- Also use jet charge in this hemisphere to help $b/\bar{b}$ determination.

Analysis uses T-M asymmetric double tag events, where both a b-tag (T) and proper time (M) are available.

Use double-tagging techniques (as in LEP R_b) to determine b-purity of selected sample ($87.9 \pm 2.6\,\%$) with minimal dependence on MC simulation.

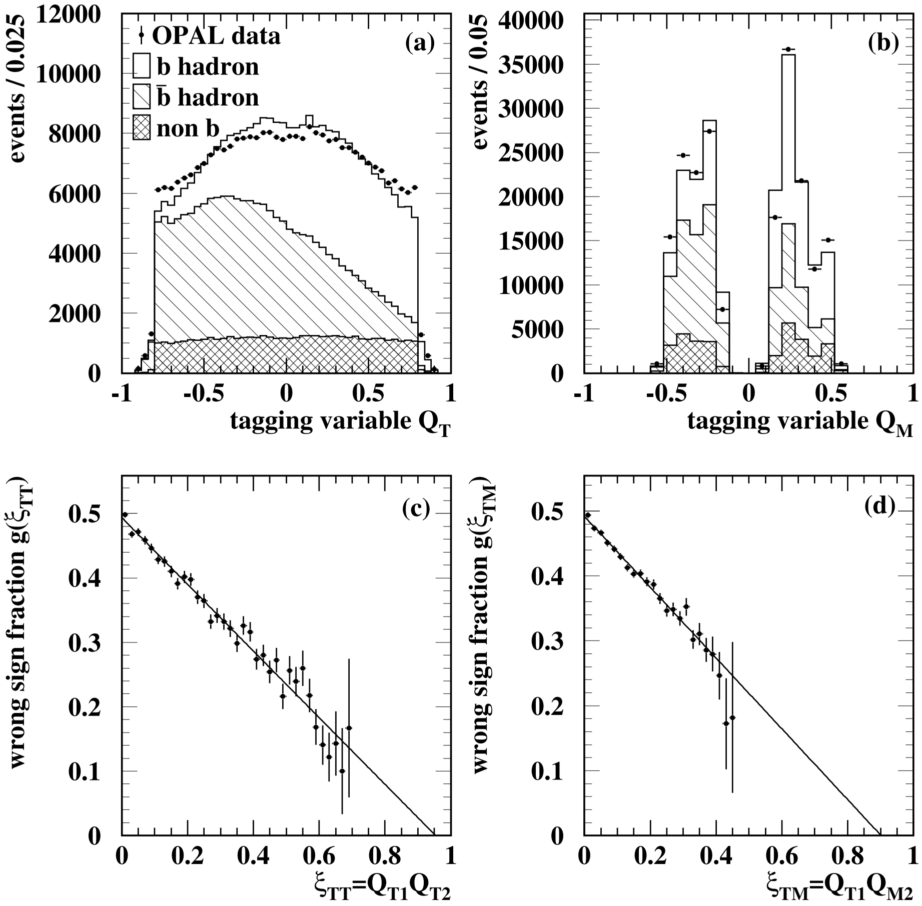
b flavour tagging

b hadron production flavour ($\mathrm{b}/\overline{\mathrm{b}}$) determined using T-hemisphere variables:

- Jet charge ($\kappa = 0.5$): $Q_{\mathrm{jet}} = \sum_i (p_i^l)^\kappa q_i / \sum_i (p_i^l)^\kappa$
- Secondary vertex charge (if existing): $Q_{\mathrm{vtx}} = \sum_i w_i q_i$.
- Lepton charge (if existing): p, p_t used to determine reliability.

Combined using neural network: T-hemisphere production flavour tag Q_{T}.

Add M-hemisphere $\kappa = 0$ jet charge (Q_{M}) to get event tag variable Q_2.



All Q defined so $|Q| = 1 - 2\eta$ where η is mistag rate. Mistags tested on data in double tagged events (determine Q_{T} in each hemisphere).

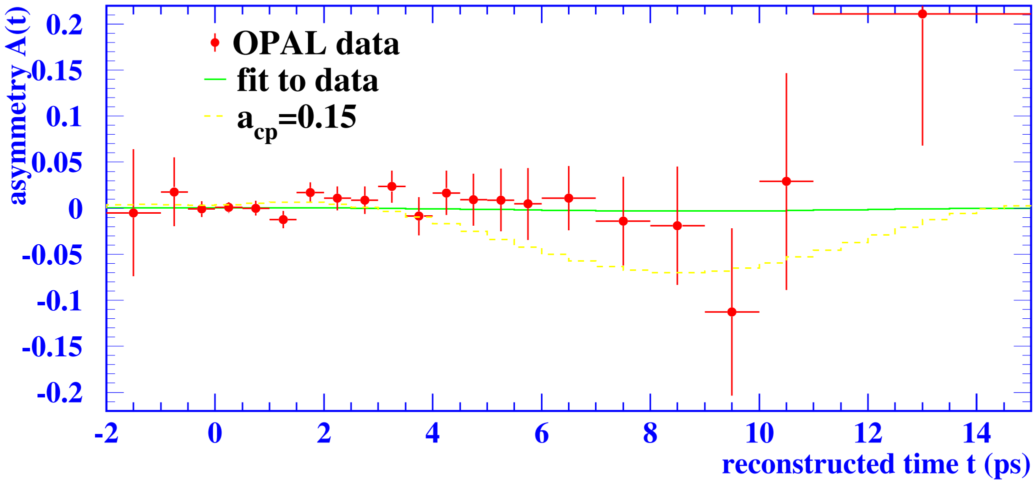
Fit and results: CP violation

Final data sample of 394 119 events with b production flavour tagged and b hadron decay time measured.

Measure production flavour asymmetry as function of b decay time:

$$A(t) = a_{\rm cp} \left\{ \frac{\Delta m_{\rm d} \tau_{\rm B^0}}{2} \sin(\Delta m_{\rm d} t) - \sin^2\left(\frac{\Delta m_{\rm d} t}{2}\right) \right\}$$

Parameter $a_{\rm cp}$ measures indirect CP violation and is related to $\mathrm{Re}(\epsilon_{\rm B})$.



Result is $a_{\rm cp} = 0.005 \pm 0.055$.

Assumed equal efficiencies for all b hadron decay modes—in particular for $b \to$ 0 charm, 1 charm and 2 charm hadrons.

Larger CP violating effects may be present in decays to different numbers of charm hadrons, which cancel out in inclusive asymmetry. Test with:

$$A(t) = c_{\rm cp} \sin(\Delta m_{\rm d} t) - a_{\rm cp} \sin^2\left(\frac{\Delta m_{\rm d} t}{2}\right)$$

Result is $a_{\rm cp} = 0.002 \pm 0.055$, $c_{\rm cp} = 0.026 \pm 0.027$.

CPT violation: b-lifetimes

- Basic result of CPT invariance is equality of particle and antiparticle total decay rates, and hence lifetimes.
- True even in presence of CP violation ($\mathrm{Re}(\epsilon_\mathrm{B}) \neq 0$).

Test this using the same data sample:

- Perform average b hadron lifetime analysis as function of production flavour tag.
- Big systematic in lifetime analysis is from resolution function (reconstructed vs true proper time).
- But this largely cancels when looking for a difference—can get a precise result:

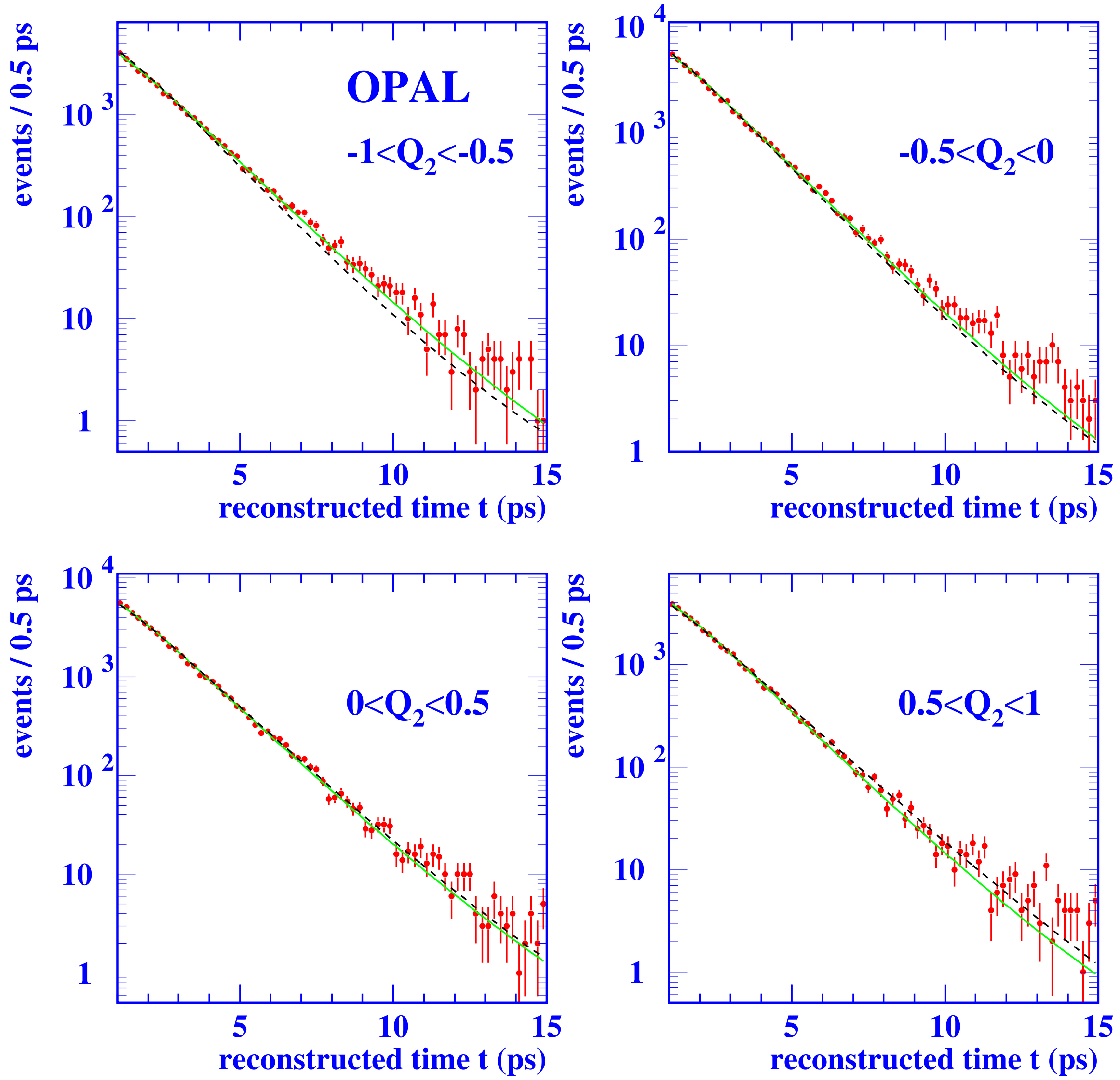
$$\tau_\mathrm{b} = \left\{1 + \frac{1}{2}\left(\frac{\Delta\tau}{\tau}\right)_\mathrm{b}\right\}\tau_\mathrm{av}$$
$$\tau_{\bar{\mathrm{b}}} = \left\{1 - \frac{1}{2}\left(\frac{\Delta\tau}{\tau}\right)_\mathrm{b}\right\}\tau_\mathrm{av}$$

2-parameter fit for $(\Delta\tau/\tau)_\mathrm{b}$ and τ_av.

Use same analysis, tagging and reconstruction as for CP violation analysis.

Fit and results: lifetime difference

Fit displayed in 4 bins of $b/\overline{\mathrm{b}}$ hadron purity (actually done in 20 bins):



Fit result is

$$\left(\frac{\Delta\tau}{\tau}\right)_{\mathrm{b}} = -0.001 \pm 0.012$$

No evidence for different b and $\overline{\mathrm{b}}$ hadron lifetimes.

Excess of data at large t is due to resolution function imperfections—seen in all samples. Constraints on $(\Delta\tau/\tau)_{\mathrm{b}}$ come mainly from low t.

Systematic errors

Systematic errors are small—looking for asymmetries and ratios not absolute values, so many effects cancel.

Source	$\Delta a_{\rm cp}$	$\Delta c_{\rm cp}$	$\Delta((\Delta\tau/\tau)_{\rm b})$
B^0 lifetime	0.002	0.000	-
$\Delta m_{\rm d}$ value	0.001	0.001	-
B^0 fraction	0.002	0.002	-
Flavour tagging offsets	0.003	0.013	0.001
Flavour tagging mis-tag	0.009	0.005	0.008
b fragmentation	0.008	0.006	0.000
Time resolution	0.002	0.000	0.001
Total systematic	0.013	0.015	0.008

Final results:

$$a_{\rm cp} = 0.005 \pm 0.055 \pm 0.013$$

$$c_{\rm cp} = 0.026 \pm 0.027 \pm 0.015$$

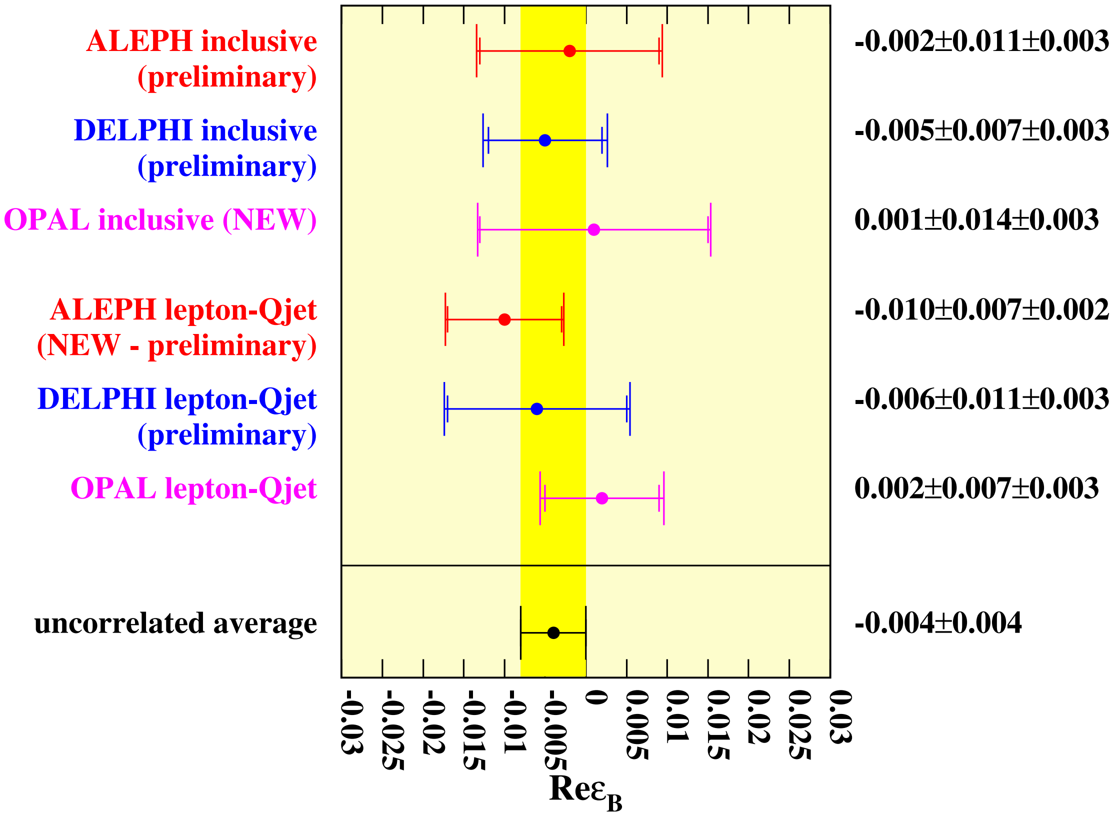
$$\Rightarrow \mathrm{Re}(\epsilon_{\rm B}) = 0.001 \pm 0.014 \pm 0.003$$

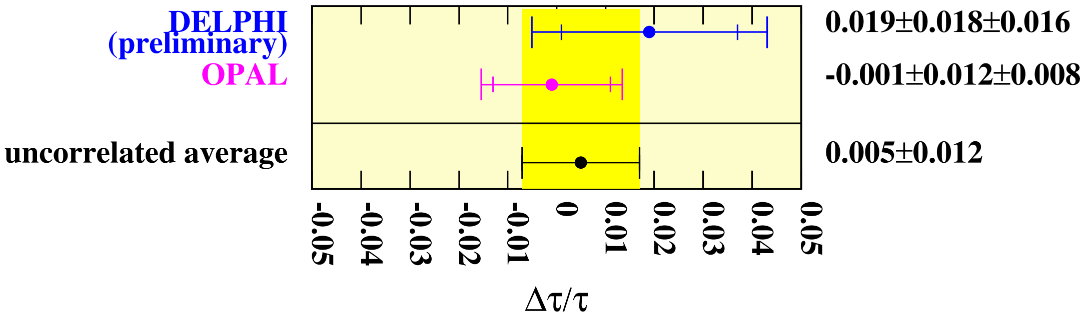
$$\left(\frac{\Delta\tau}{\tau}\right)_{\rm b} \equiv \frac{\tau(\mathrm{b\ hadron}) - \tau(\overline{\mathrm{b}}\ \mathrm{hadron})}{\tau(\mathrm{average})} = -0.001 \pm 0.012 \pm 0.008$$

This is the only published result on b/$\overline{\mathrm{b}}$-lifetime difference.

No sign of CP or CP(T) violating effects have been seen. . .

Summary and conclusions





No evidence of CP(T) violation yet. . .

Expect $\mathrm{Re}(\epsilon_B) \sim 10^{-3}$ in Standard Model, but could be 10^{-2} in (now disfavoured) superweak models.

Most data from LEP is now analysed, wait for B-factories.