A Search for CP(T) Violation in B Decays at OPAL

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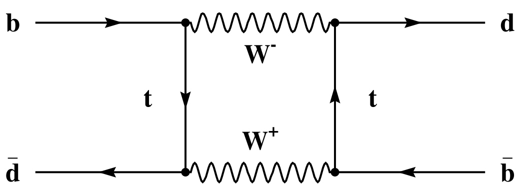
→ New inclusive results using reconstructed secondary vertices.

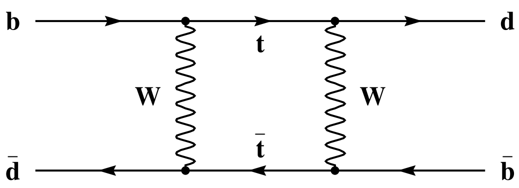
Probes of CP Violation in the B System

Two experimental approaches:

1. Search for inclusive effects which are easier to observe. Though smaller in magnitude and more difficult to interpret theoretically, may give superior distinction between Standard Model and superweak CP violation (this analysis).
2. Consider exclusive channels which may have large asymmetries and straightforward theoretical descriptions (e.g. measurement of $\sin 2\beta$ in $B^0 \rightarrow J/\psi K^0_s$ decays).

We can apply both of these methods to study CP violation in $Z^0 \rightarrow b\bar{b}$ decays at LEP as "Proof of Principle" for future B-Factories. Look for indirect CP violation (i.e. through $B^0\bar{B}^0$ mixing) . . . predicted to have larger effects than direct CP violation.





Inclusive CP(T) Tests

Indirect CP violation is possible in B^0 system if weak eigenstates B^0 and $\bar{\mathrm{B}}^0$ differ from mass eigenstates B_1 and B_2:

$$|\mathrm{B}_1> \;=\; \frac{(1+\epsilon_B+\delta_B)|\mathrm{B}^0> + (1-\epsilon_B-\delta_B)|\bar{\mathrm{B}}^0>}{\sqrt{2\left(1+|\epsilon_B+\delta_B|^2\right)}}$$

$$|\mathrm{B}_2> \;=\; \frac{(1+\epsilon_B-\delta_B)|\mathrm{B}^0> - (1-\epsilon_B+\delta_B)|\bar{\mathrm{B}}^0>}{\sqrt{2\left(1+|\epsilon_B-\delta_B|^2\right)}}$$

ϵ_B parameterizes indirect CP violation, and δ_B parameterizes CPT violation.

- A non-zero value of ϵ_B gives rise to a time-dependent rate asymmetry, A(t), in the Standard Model:

$$\mathrm{A}(\mathrm{t}) \;\equiv\; \frac{\mathrm{B}^0(\mathrm{t}) - \bar{\mathrm{B}}^0(\mathrm{t})}{\mathrm{B}^0(\mathrm{t}) + \bar{\mathrm{B}}^0(\mathrm{t})},$$

  where $\mathrm{B}^0(\mathrm{t})$ and $\bar{\mathrm{B}}^0(\mathrm{t})$ are the decay rates of B^0 and $\bar{\mathrm{B}}^0$ mesons.

- CPT invariance implies that $\tau_b = \tau_{\bar{b}}$. If CPT violation occurred, lifetimes of b and $\bar{\mathrm{b}}$ hadrons could be different:

$$\tau_{b/\bar{b}} \;=\; \left[1 \pm \frac{1}{2}\left(\frac{\Delta\tau}{\tau}\right)_b\right]\tau_{av},$$

  where τ_{av} is the average and $(\Delta\tau/\tau)_{\mathrm{b}}$ is the fractional difference in lifetimes.

Inclusive CP(T) Tests cont'd.

For an unbiased selection of B^0 and $\bar{\mathrm{B}}^0$ mesons, the time-dependent inclusive decay rate asymmetry can be rewritten in terms of proper decay time t:

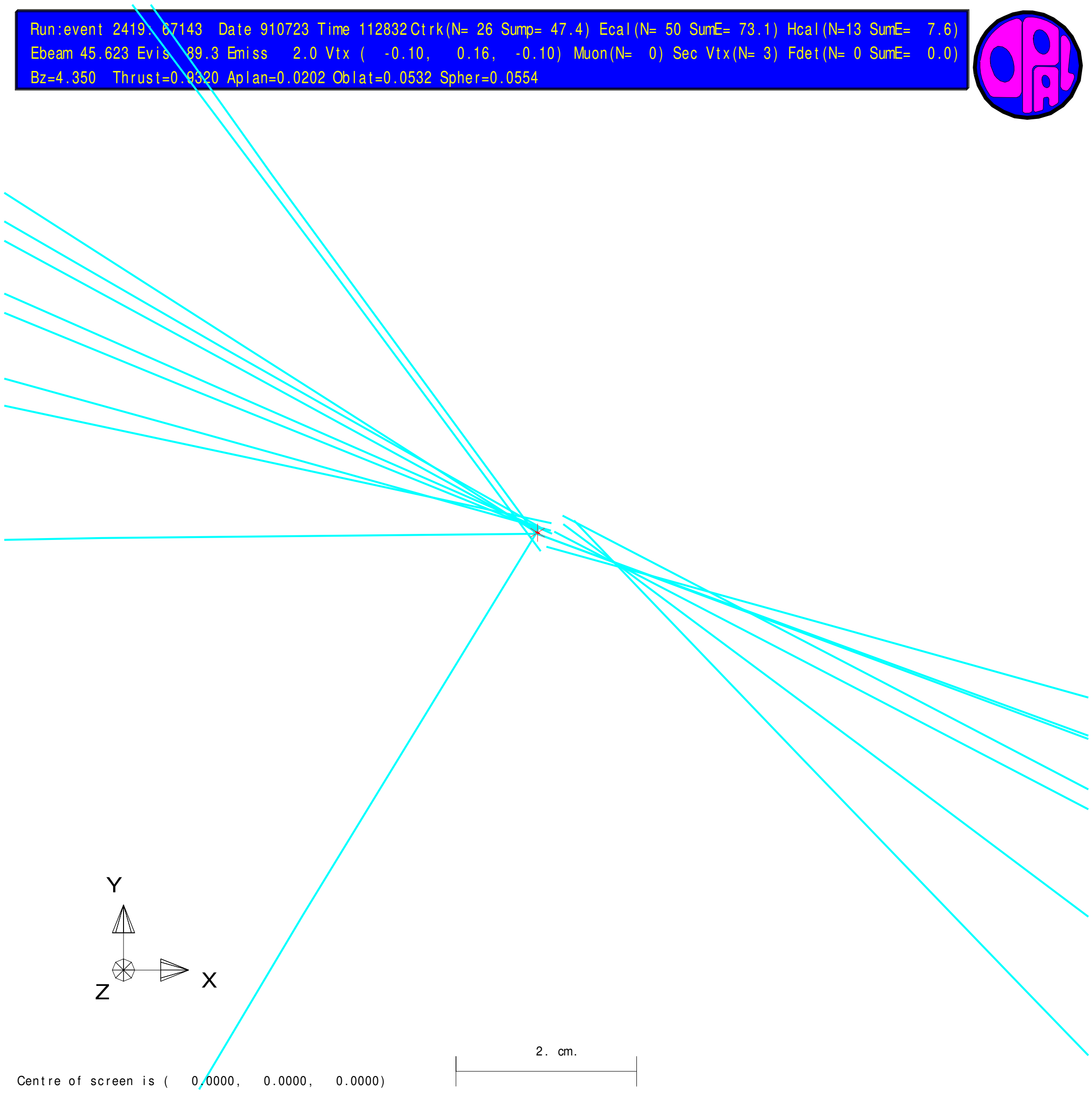
$$A(t) \quad = \quad a_{cp}\left[\frac{\Delta m_d \tau_{\mathrm{B}^0}}{2}\sin(\Delta m_d t) - \sin^2\left(\frac{\Delta m_d t}{2}\right)\right],$$

where $\mathrm{a_{cp}}$ is the CP-violating observable, $\Delta\mathrm{m_d}$ is the B^0 oscillation frequency, and τ_{B^0} is the B^0 lifetime.
For $|\epsilon_B| << 1$, the parameter $\mathrm{a_{cp}}$ is related to ϵ_B by: $Re(\epsilon_B) = a_{cp}/4$.

- Divide events into 2 hemispheres defined by plane $\perp$ to thrust axis and containing the $\mathrm{e^+e^-}$ interaction point.
- Tag $\mathrm{b\bar{b}}$ events via the presence of a displaced secondary vertex or a high momentum lepton. (ϵ_{hemi} of 37 % for $\mathrm{b\bar{b}}$ events, non-b impurity of 13%).
- Reconstruct the b hadron proper decay time, t, in the opposite hemisphere by forming a secondary vertex, measuring the decay length from the primary vertex, and estimating the b hadron energy.
- Extract $\mathrm{a_{cp}}$ via a binned χ^2 fit of the observed time-dependent asymmetry in bins of reconstructed proper time.

Close-up View of a Typical $\mathrm{b\bar{b}}$ Event

Two displaced secondary vertices are apparent. . .



The e^- direction points into the page.

The x coordinate points towards the center of the LEP ring.

Production Flavor Tagging: I

The production flavor estimate, $\mathrm{Q_T}$, in the tagged hemisphere is the output of a neural net with the following inputs:

1. Jet charge of highest energy jet, $\mathrm{Q_{jet}}$, with (with momentum weight $\kappa = 0.5$).
2. Vertex charge, $\mathrm{Q_{vtx}}$.
3. Error on vertex charge, $\sigma_{\mathrm{Q_{vtx}}}$.
4. The product of lepton charge and output of neural network used to select $\mathrm{b} \to \mathrm{l}$ decays, a lepton tag.

Separate networks with fewer inputs were trained for events with only a vertex or a lepton.

The variable $\mathrm{Q_T}$ is defined as follows:

$$\begin{aligned} Q_T &= \frac{N_b(x) - N_{\bar{b}}(x)}{N_b(x) + N_{\bar{b}}(x)} \\ |Q_T| &= 1 - 2\eta. \end{aligned}$$

$N_b(x)$ and $N_{\bar{b}}(x)$ are the numbers of MC b and $\bar{\mathrm{b}}$ hadron hemispheres with a given value of ANN output x and η is the mistag probability.

- $\mathrm{Q_T} > 0 \to \mathrm{b\ hadron}$ more likely than $\bar{\mathrm{b}}\ \mathrm{hadron}$.
- $\mathrm{Q_T} < 0 \to \bar{\mathrm{b}}\ \mathrm{hadron}$ more likely than $\mathrm{b\ hadron}$.
- $\mathrm{Q_T} = 0 \to$ both equally likely.

Production Flavor Tagging: II

To estimate b hadron flavor in the measurement hemisphere, use $\mathrm{Q_T}$ along with the jet charge, $\mathrm{Q_M}$ (with momentum weight $\kappa = 0$), in the measurement hemisphere to form a composite variable, $\mathrm{Q_2}$:

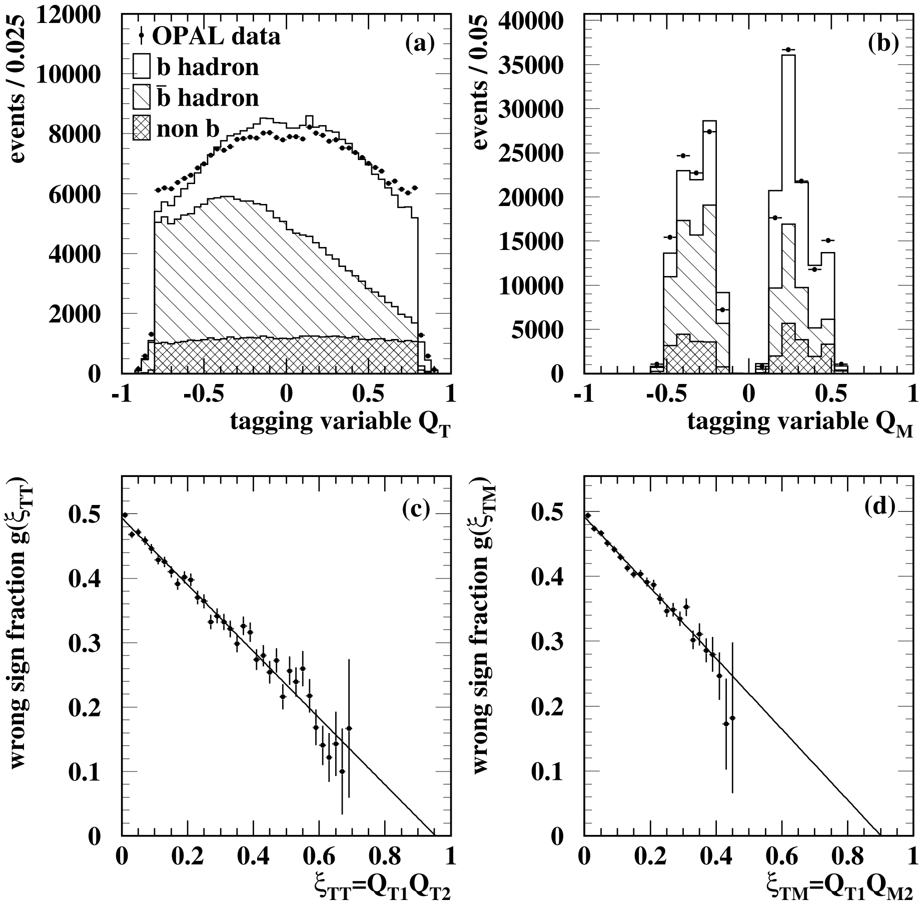
$$Q_2 = 2\left[\frac{(1-Q_T)(1+Q_M)}{(1-Q_T)(1+Q_M)+(1+Q_T)(1-Q_M)}\right] - 1.$$

- $\mathrm{Q_2} > 0 \rightarrow$ tagged as a b hadron.
- $\mathrm{Q_2} < 0 \rightarrow$ tagged as a $\bar{\mathrm{b}}$ hadron.

Of a sample of 2.4 million hadronic $\mathrm{Z^0}$ decays, 394119 events remain after flavor tagging.

- Detector effects result in charge asymmetry in $\mathrm{Q_{jet}}$ and $\mathrm{Q_{vtx}}$. Compensate by subtracting offsets determined from data before calculating $\mathrm{Q_T}$ and $\mathrm{Q_M}$.

Flavor Tag Performance



- Sharp drop at $|Q_T| = 0.8$ due to irreducible fraction of lepton mistags due to B^0 and B^0_s mixing.
- Data and MC discrepancies not important as long as Q_T values in data describe mistag probabilities well. For double-tagged hemispheres, look at the "wrong-sign fraction" for a given value of the product of the two tag outputs. Q_T is correct to $\sim 2.6\%$ and Q_M is correct to $\sim 10\%$.

Proper Decay Time Reconstruction: I

First, reconstruct hadron decay length in measurement hemisphere:

- Form a "seed" secondary vertex using two tracks with largest impact parameter (relative to the primary vertex) in the highest energy jet.
- Add all good-quality tracks ($p > 0.5$ GeV, $|d_0| < 1$ cm, $\sigma_{d_0} < 0.1$ cm) consistent with "seed" vertex via an iterative procedure.
- Secondary vertex must have at least 3 tracks, and an invariant mass of at least 0.8 GeV (assuming all tracks are pions).
- Require the secondary vertex to be kinematically consistent with a long-lived particle originating from the primary vertex to further eliminate badly reconstructed or fake secondary vertices.
- Acceptable secondary vertices found in about 70% of hemispheres for both signal and background.
- Calculate decay length L between primary and secondary vertices using jet axis as a constraint.

Proper Decay Time Reconstruction: II

Then, calculate the b hadron energy:

- Estimate energy of the b jet by treating even as 2-body decay of a Z^0 into a b-jet of mass m_b and another object.
- Estimate fragmentation energy using charged track weights w_i tuned with the vertex finder described above and unassociated ECAL clusters weighted according to their angle w.r.t. jet axis.
- Thus, $\mathrm{E_b} = \mathrm{E_{bjet}} - \mathrm{E_{bfrag}}$.

The b hadron decay proper time t can then be extracted:

$$t = \frac{m_b L}{\sqrt{E_b^2 - m_b^2}}.$$

- Proper time resolution described by 2 Gaussians in MC, one with RMS width 0.33 ps and the other with RMS width 1.3 ps. About 65% of events are contained in the narrower Gaussian.
- Resolutions are an average over all true decay proper times t. Non-Gaussian effects apparent in small slices of t due to contamination by primary vertex tracks, but not critical in this analysis (not very dependent on accurate decay time resolution).

Fit and Results for ϵ_{B}

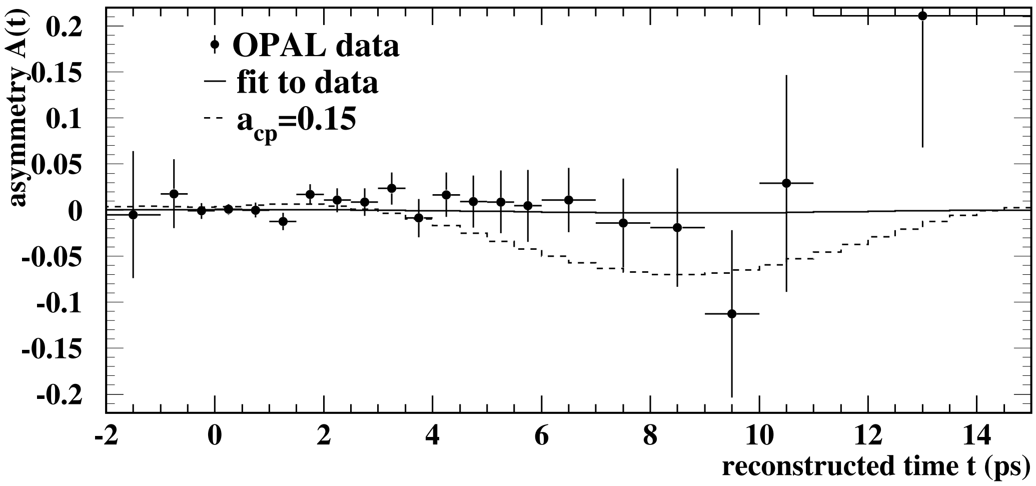
1. For each of 34 time bins i (in the range -2 to 15 ps), calculate asymmetry in 10 bins j of $|\mathrm{Q}_2|$:

$$A_{ij}^{obs} = \frac{N_{ij}^{b} - N_{ij}^{\bar{b}}}{< |Q_2| >_{ij} (N_{ij}^{b} + N_{ij}^{\bar{b}})}.$$

2. Average the 10 estimates of $\mathrm{A}_{\mathrm{ij}}^{\mathrm{obs}}$ in each bin i, weighting by $(\sigma_{\mathrm{A}_{\mathrm{ij}}^{\mathrm{obs}}})^{-2}$ to get $\mathrm{A}_{\mathrm{i}}^{\mathrm{obs}}$.

3. Perform a binned χ^2 fit to reconstructed proper time, accounting for non-B^0 background, the B^0 lifetime, and detector effects which smear the time resolution:

$$a_{cp} = 0.005 \pm 0.055 \pm 0.013.$$
$$Re(\epsilon_B) = 0.001 \pm 0.014 \pm 0.003$$



Systematic Uncertainties on $\mathrm{a_{cp}}$

Source	$\Delta\mathrm{a_{cp}}$	$\Delta\mathrm{c_{cp}}$
B^0 lifetime	0.002	0.000
Δm_d value	0.001	0.001
B^0 fraction	0.002	0.002
Flavor tagging offsets	0.003	0.013
Flavor tagging mis-tag	0.009	0.005
b fragmentation	0.008	0.006
Time resolution	0.002	0.000
Total	0.013	0.015

If the reconstruction efficiency for B^0 decays to different numbers of charm hadrons isn't the same, expected asymmetry could take the form:

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

Repeat fit letting both $\mathrm{a_{cp}}$ and $\mathrm{c_{cp}}$ vary:

$$a_{cp} = 0.002 \pm 0.055$$
$$c_{cp} = 0.026 \pm 0.027$$

Differences in ϵ are not significant, as $\mathrm{a_{cp}}$ does not change much.

Fit and Results for $(\Delta\tau/\tau)_{\mathrm{b}}$

Measure fractional difference between b and $\bar{\mathrm{b}}$ hadron lifetimes.

1. Divide data into 20 bins of Q_2 (related to $\mathrm{b}/\bar{\mathrm{b}}$ hadron purity).
2. Do a simultaneous fit of the reconstructed proper time distrbutions to the expected proper time distribution to extract τ_{avg} and $(\Delta\tau/\tau)_{\mathrm{b}}$. The expected distribution accounts for time resolution effects, non-$\mathrm{b}\bar{\mathrm{b}}$ background, the lifetimes of b and $\bar{\mathrm{b}}$ hadrons, and a background component with a lifetime τ_{bg}.

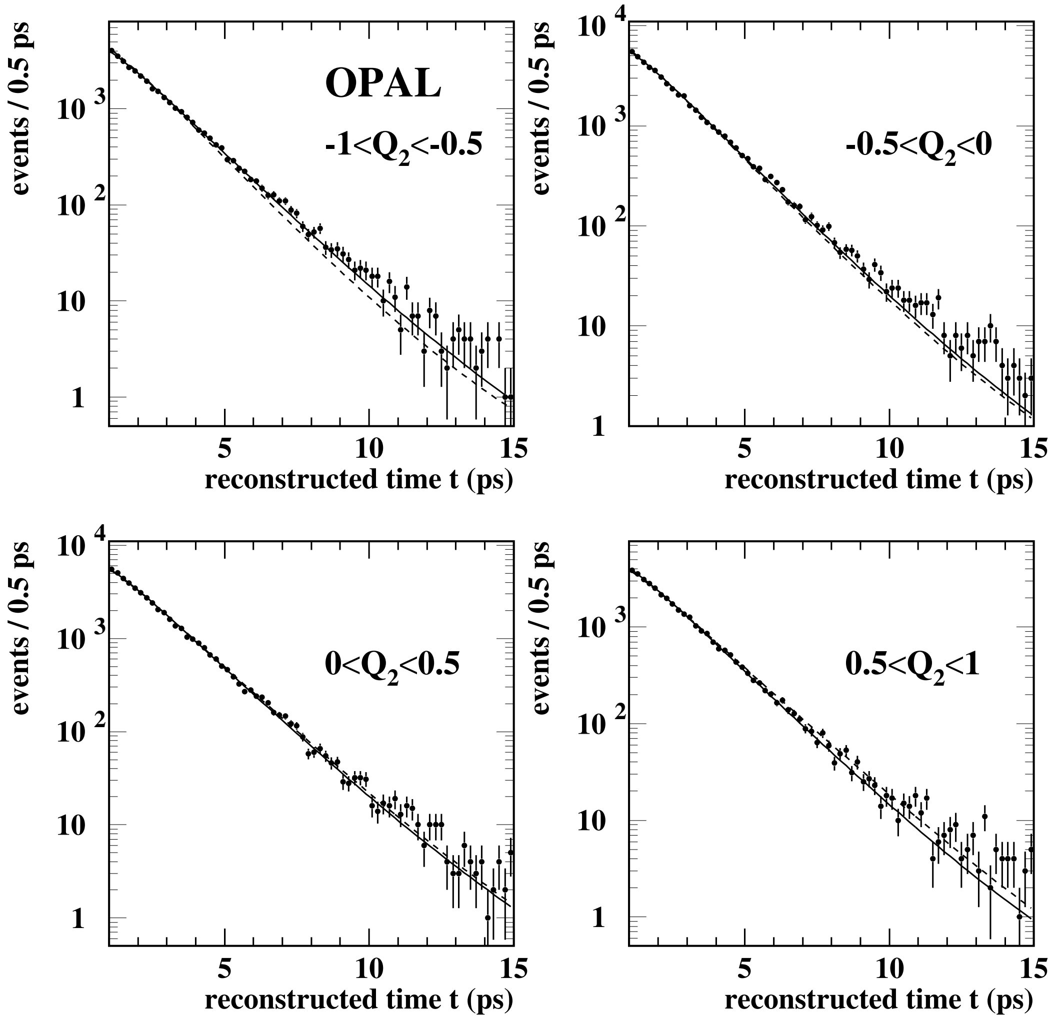
The fit result is:

$$(\Delta\tau/\tau)_b = -0.001 \pm 0.012 \pm 0.008$$

- The uncertainty in the flavor mistag rate dominates the systematic uncertainty on $(\Delta\tau/\tau)_{\mathrm{b}}$.
- The result for τ_{avg} has a large systematic uncertainty due to the time resolution function and should not be interpreted as a measurement of the average b-hadron lifetime.

Reconstructed Proper Time Distributions

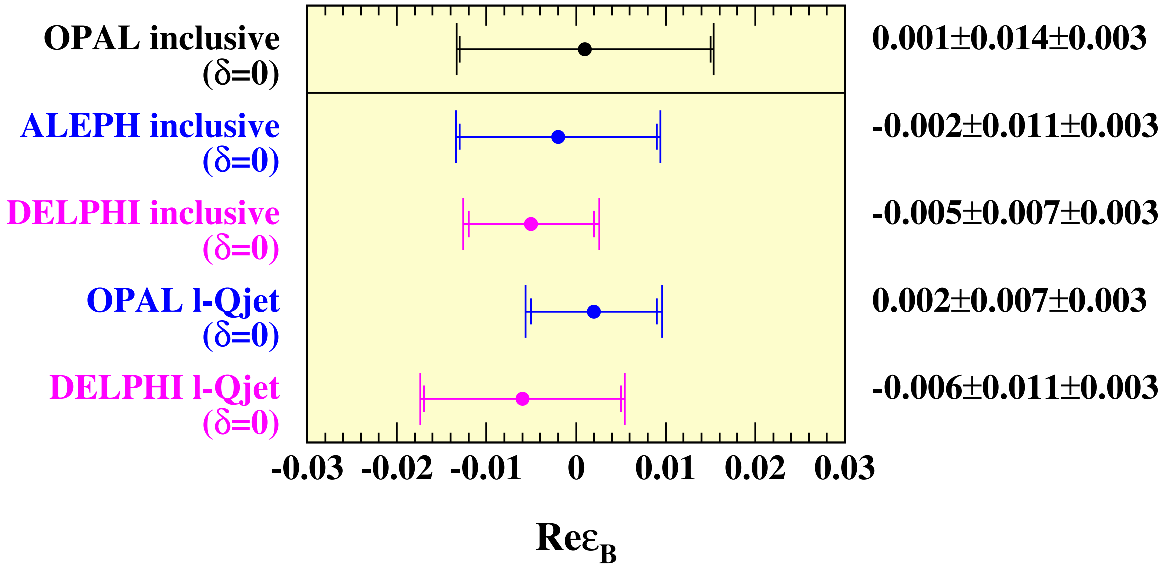
Data are shown by the points with error bars and the fit prediction by the solid lines. The expected distributions for $(\Delta\tau/\tau)_{\mathrm{b}} = 0.2$ are shown by the dotted lines.



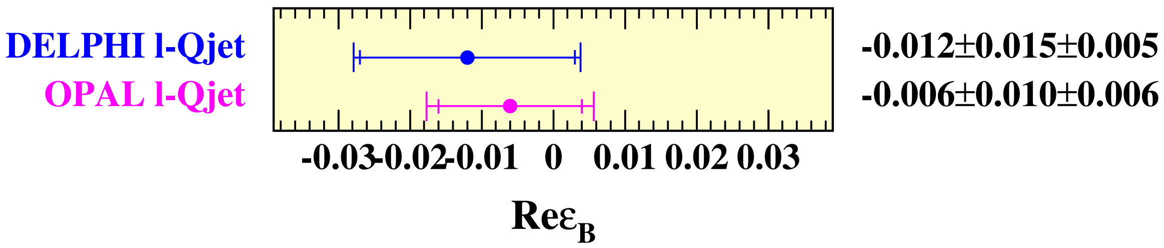
Inclusive CP(T) Results from LEP

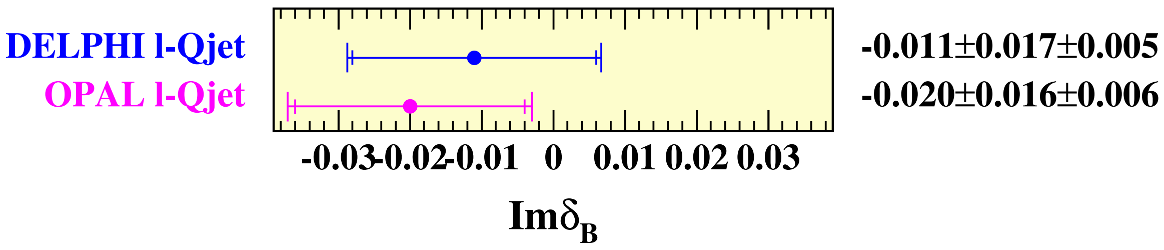
New OPAL result agrees well with previous published (OPAL lepton-jet charge) and preliminary (ALEPH,DELPHI) results.

Standard Model predicts $\mathrm{Re}(\epsilon_{\mathrm{B}}) \sim 10^{-3}$, could be an order of magnitude larger in superweak models. . . still some way to go.



If CPT violation is allowed. . .





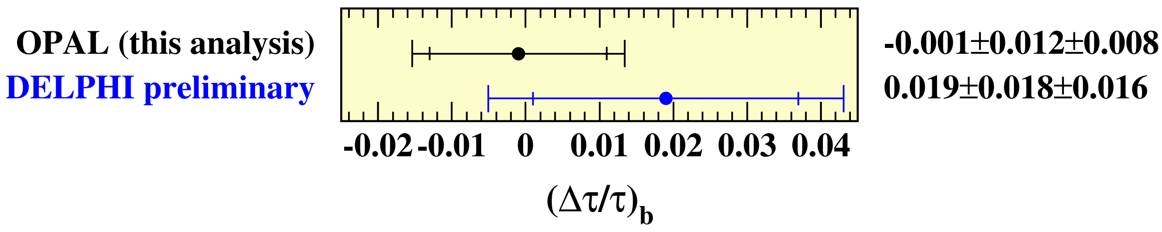
Conclusion

→ No evidence for CP or CPT violation from inclusive B decays.

$$Re(\epsilon_B) \quad = \quad 0.001 \pm 0.014 \pm 0.003$$

→ First analysis submitted for publication to test equality of b and $\bar{\mathrm{b}}$ hadron lifetimes:

$$(\Delta\tau/\tau)_b \quad = \quad -0.001 \pm 0.012 \pm 0.008.$$



Details of Flavor Tag

- JET CHARGE:

$$Q_{jet} = \frac{\Sigma_i (p_i^l)^\kappa q^i}{\Sigma_i (p_i^l)^\kappa q^i},$$

where p_i^l is the longitudinal momentum component w.r.t. jet axis and q_i is the charge of track i.

- VERTEX CHARGE:

$$\begin{aligned} Q_{VTX} &= \Sigma_i w_i q_i \\ \sigma_{Q_{VTX}} &= \Sigma_i w_i (1 - w_i) q_i^2, \end{aligned}$$

where w_i is the weight for track i to have come from a secondary instead of a primary vertex. Weights are derived from an ANN with inputs p_i, $(p_t)_i$ w.r.t. jet axis, and impact parameter.

- LEPTON TAG: $\mathrm{Q_l \cdot S}$ where S is the output of an ANN to select $b \to l$ decays. Lepton tag is diluted by mixing, cascade b decays, c decays and fake leptons.

Q_{jet} and Q_{VTX} aren't charge symmetric due to detector effects resulting in difference in the rate and reconstruction of + and - tracks. Offsets evaluated from inclusive T-tagged samples.

Mistag Probabilities

For double T-tagged events: $\xi_{\mathrm{TT}} = \mathrm{Q}_{\mathrm{T1}}\mathrm{Q}_{\mathrm{T2}}$.

- Negative if both (or neither) hemisphere is tagged correctly.
- Positive if one hemisphere is tagged incorrectly.

The wrong-sign fraction for a given value of ξ_{TT} can be written as:

$$\begin{aligned} g(\xi_{TT}) &= \frac{f(\xi_{TT})}{f(\xi_{TT}) + f(-\xi_{TT})} \\ &= \frac{1-\xi_{TT}}{2} \end{aligned}$$

provided $\xi_{\mathrm{TT}} > 0$ and Q_{T} correctly describes mistag probabilities. Fit $\mathrm{g}(\xi_{\mathrm{TT}})$ to a line. Use error on fit as systematic uncertainty in the mistag probability.

Also look at: $\xi_{\mathrm{TM}} = \mathrm{Q}_{\mathrm{T1}}\mathrm{Q}_{\mathrm{M2}}$.

CP(T) Tests in Semileptonic B Decays

Tag flavor with lepton charge. Investigate the difference of time-dependent assymetries of decay probabilities:

$$D(t) = \frac{\Gamma(\bar{\mathrm{B}}^0(\mathrm{t}) \to \bar{\mathrm{f}}) - \Gamma(\bar{\mathrm{B}}^0(\mathrm{t}) \to \mathrm{f})}{\Gamma(\bar{\mathrm{B}}^0(\mathrm{t}) \to \bar{\mathrm{f}}) + \Gamma(\bar{\mathrm{B}}^0(\mathrm{t}) \to \mathrm{f})} - \frac{\Gamma(\mathrm{B}^0(t) \to f) - \Gamma(\mathrm{B}^0(t) \to \bar{f})}{\Gamma(\mathrm{B}^0(t) \to f) + \Gamma(\mathrm{B}^0(t) \to \bar{f})}$$

$$D(t) = -4Re(\epsilon_B) \cdot (1 - \cos \Delta mt) + 4Im(\delta_B) \cdot \sin \Delta mt.$$

The imaginary part of δ_{B} parameterizes indirect CPT violation.