CP violation in B decays at LEP

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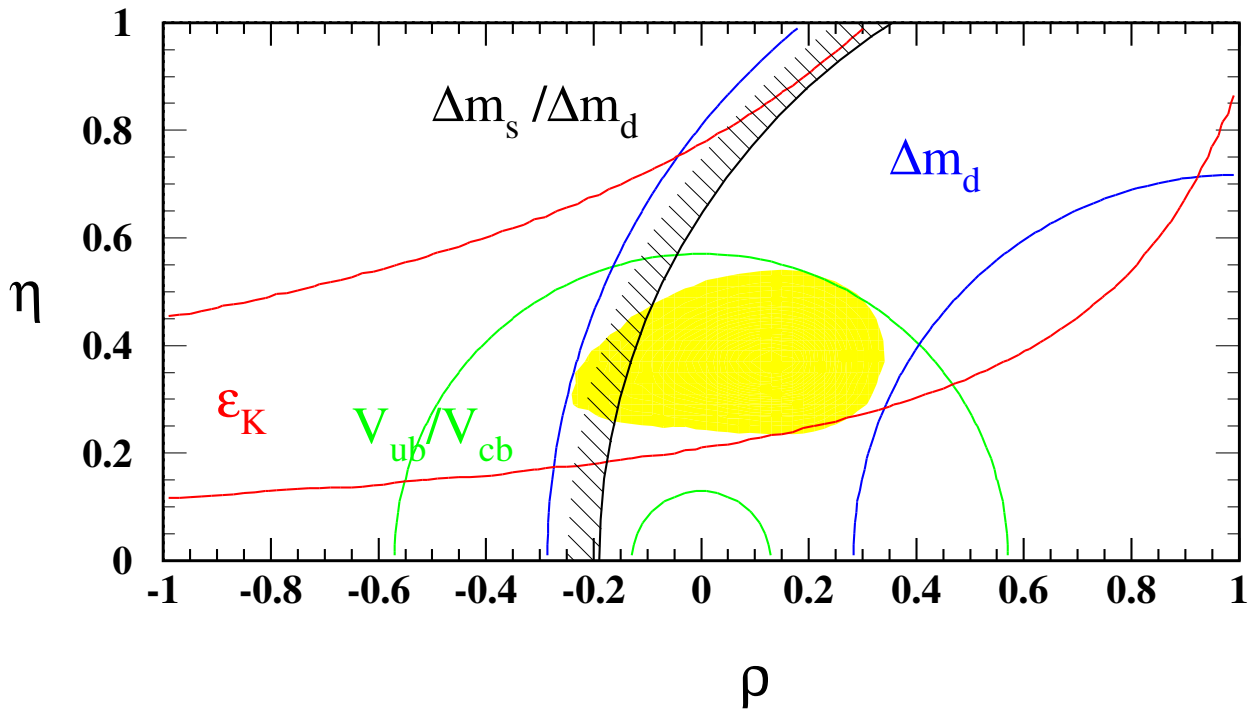
- Introduction: CP violation in B decays.
- $\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^0_\mathrm{s}$ to get $\sin 2\beta$: OPAL analysis.
- Inclusive CP(T) violation tests:
  other results from LEP (ALEPH, DELPHI, OPAL) on:
  - semileptonic B decays
  - fully inclusive B decays
  - equality of B and $\overline{\mathrm{B}}$ hadron lifetimes.
- Summary and Conclusion.

Introduction

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

In Standard Model, CP violation comes from phase in CKM matrix.

This implies potentially large CP effects in $\mathrm{B}^0 - \overline{\mathrm{B}^0}$ system.



CP violation driven by angles α, β, γ.

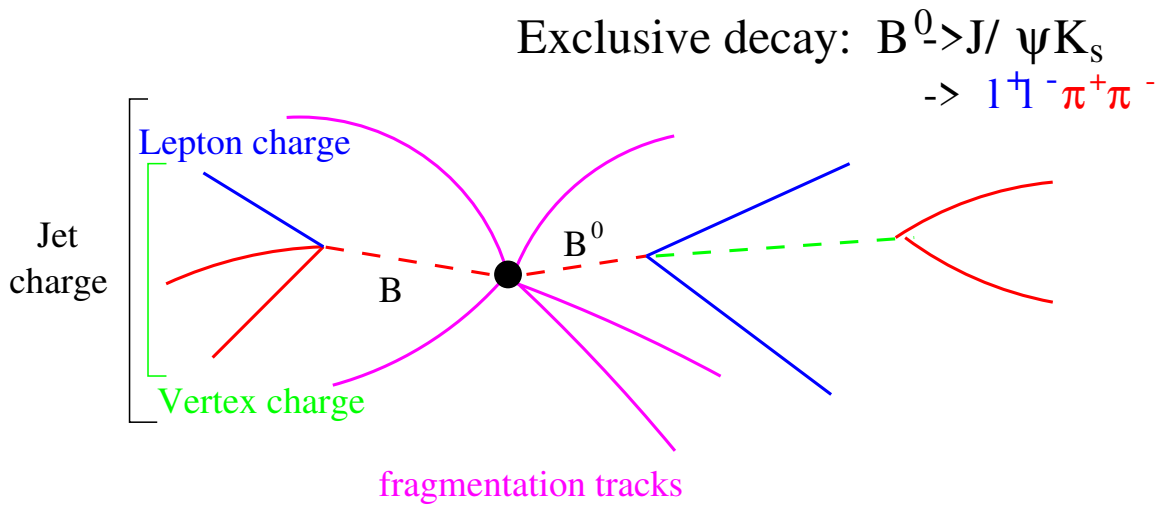
Two methods to learn about CP violation in B system:

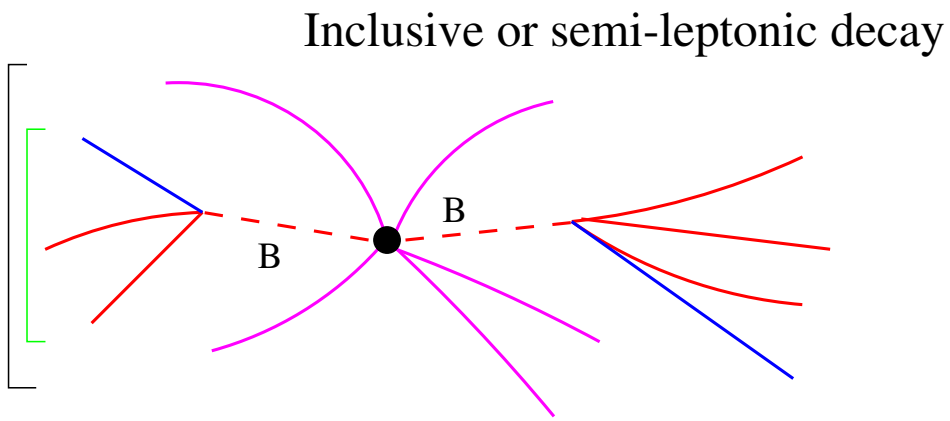
- Study exclusive channels with potentially large asymmetries and clean theoretical interpretation.
- Look for inclusive effects—easier to see, but smaller and hard to interpret theoretically.

'Gigabucks' being spent on new facilities. . . what can we learn at LEP. . . ?

Analyses performed at LEP

- LEP ran on Z^0 peak from 1989–1995, giving approx 4 million $Z^0 \to q\overline{q}$ decays (0.9 million $Z^0 \to b\overline{b}$).
- Characteristic decay topology of two back-to-back jets, each containing one B hadron decay and some fragmentation particles.
- Precise B decay length measurement with silicon microvertex detectors—time dependent measurements (decay length $\sim 3\,\mathrm{mm}$).
- B production flavour inferred from other B hadron jet, and fragmentation tracks in same jet.





CP violation in $B^0 \to J/\psi K^0_s$ decays

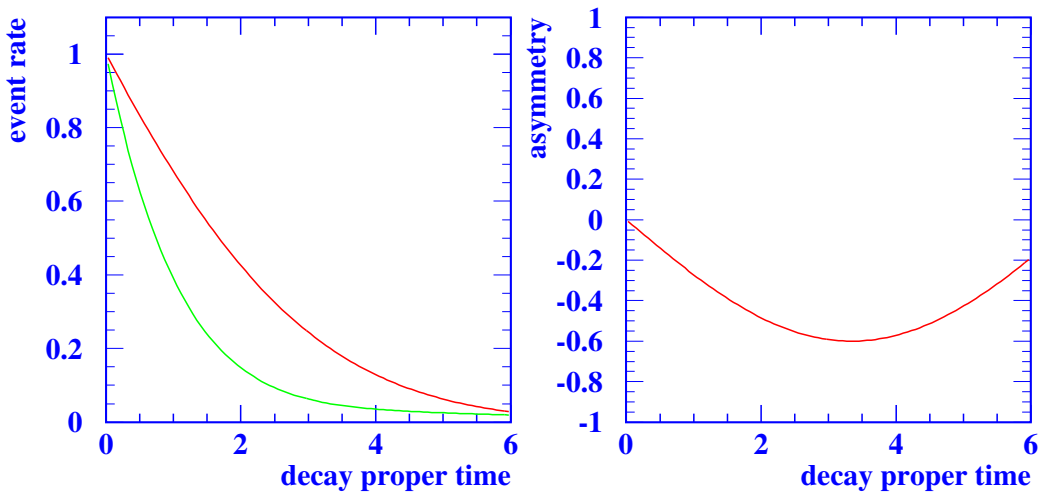
'Golden' decay mode is $B^0 \to J/\psi K^0_s$ (eigenstate CP=-1), very clean channel and well understood theoretically.

$$B^0 \to J/\psi K^0_s \to \ell^+\ell^-\pi^+\pi^-$$
$$B^0 \to \bar{B}^0(\text{mixed}) \to J/\psi K^0_s \to \ell^+\ell^-\pi^+\pi^-$$

Two routes to same final state, with different weak phases:
. . . interference. . . CP violation.

Count number of produced B^0 and $\bar{B}^0$ decaying at time t. Expect an asymmetry:

$$A(t) = \frac{n_{B^0}(t) - n_{\bar{B}^0}(t)}{n_{B^0}(t) + n_{\bar{B}^0}(t)} = -\sin 2\beta \sin \Delta m t$$



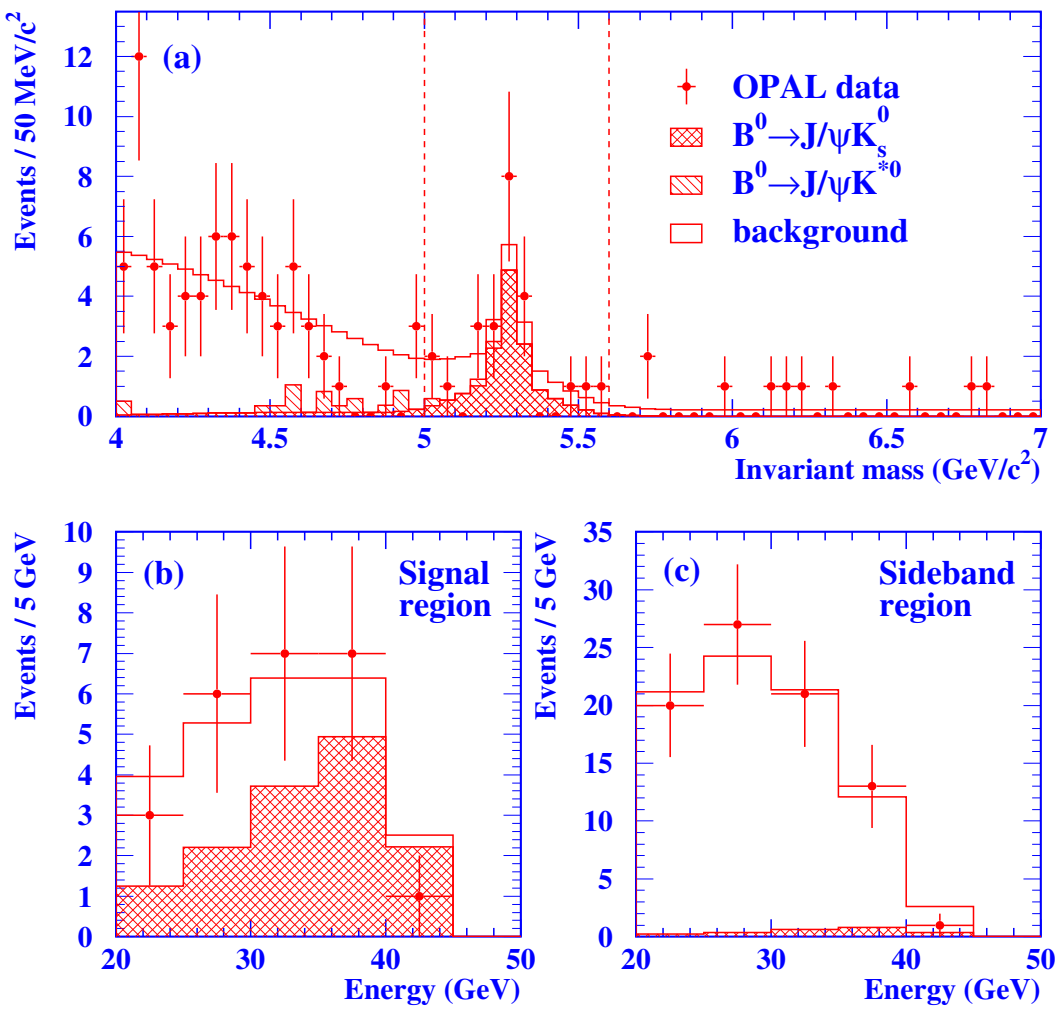
Largest asymmetry around decay time $t = 3\,\text{ps}$.

Reconstructing $B^0 \to J/\psi K^0_S$ decays

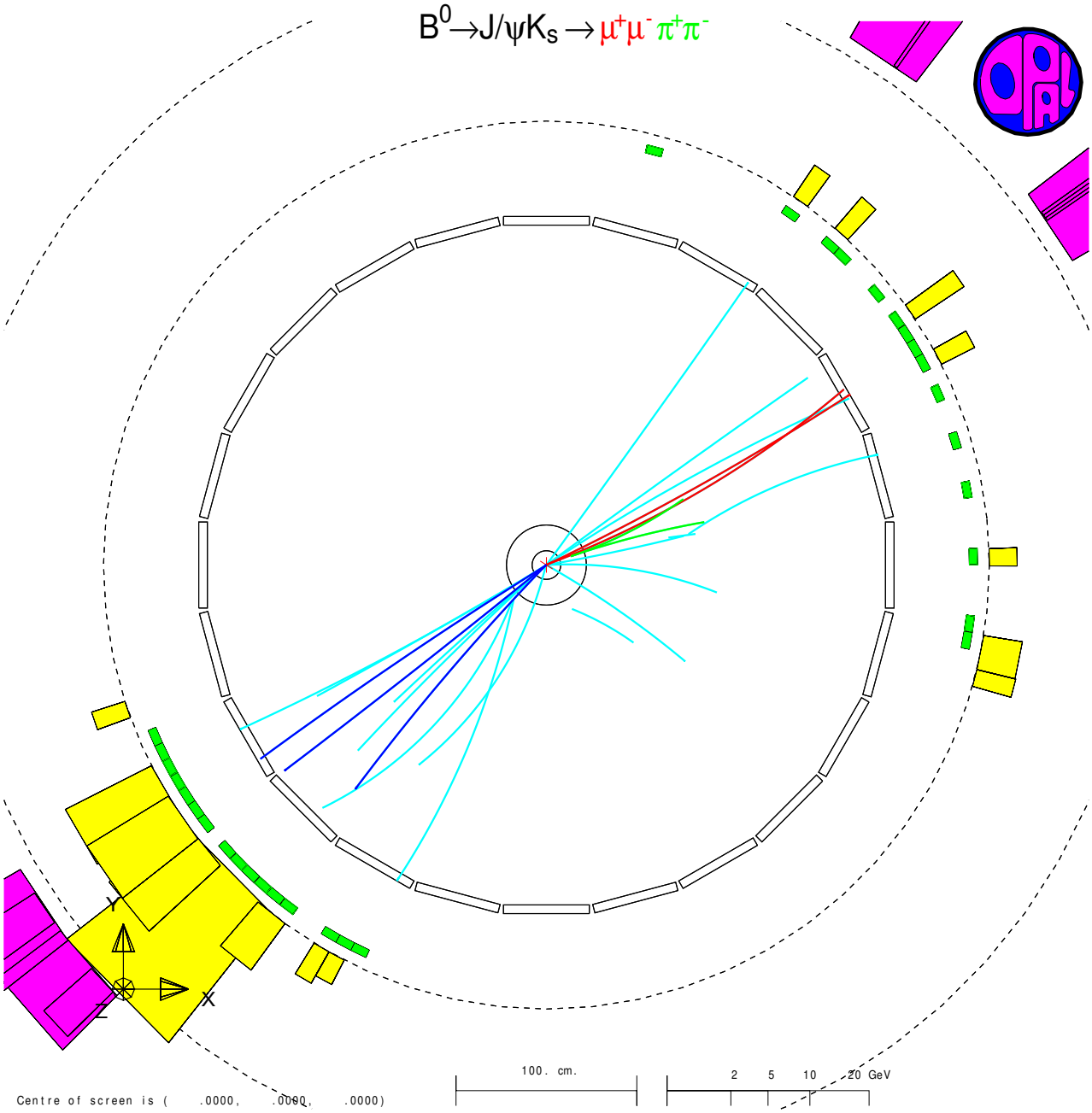
Branching ratio $B^0 \to J/\psi K^0_S \to \ell^+\ell^-\pi^+\pi^-$ is only 3×10^{-5}.

- Reconstruct J/ψ in leptonic decay to electrons or muons.
  —J/ψ vertex gives B^0 decay point, measure distance from primary vertex and get decay proper time of B^0.
- Reconstruct K^0_S in decay to $\pi^+\pi^-$ somewhere in tracking system (typical decay length 30 cm—striking signature).

Reconstruction efficiency is around 20 %—expect a handful of events:



Reconstructed $J/\psi K^0_s$ event



Production flavour tagging

Tag whether the $\mathrm{J}/\psi\mathrm{K}^0_\mathrm{s}$ was produced as B^0 or $\bar{\mathrm{B}}^0$.

Three pieces of information are used to tag production flavour:

- Opposite side jet charge tags flavour of other b-hadron in event (anticorrelated with signal B^0). Use momentum weight $\kappa = 0.5$.
- Same side jet charge tags flavour of signal B^0 from information in fragmentation tracks—B^0 decay products are excluded from the jet charge. Use momentum weight $\kappa = 0.4$.
- Opposite side vertex charge tags flavour of other b-hadron if it is B^+ or B^-. A significantly separated secondary vertex can be reconstructed in 40% of events.

The information from all these tags is combined in a neural network algorithm to form a single tagging variable Q_B, quantifying the confidence of the tag:

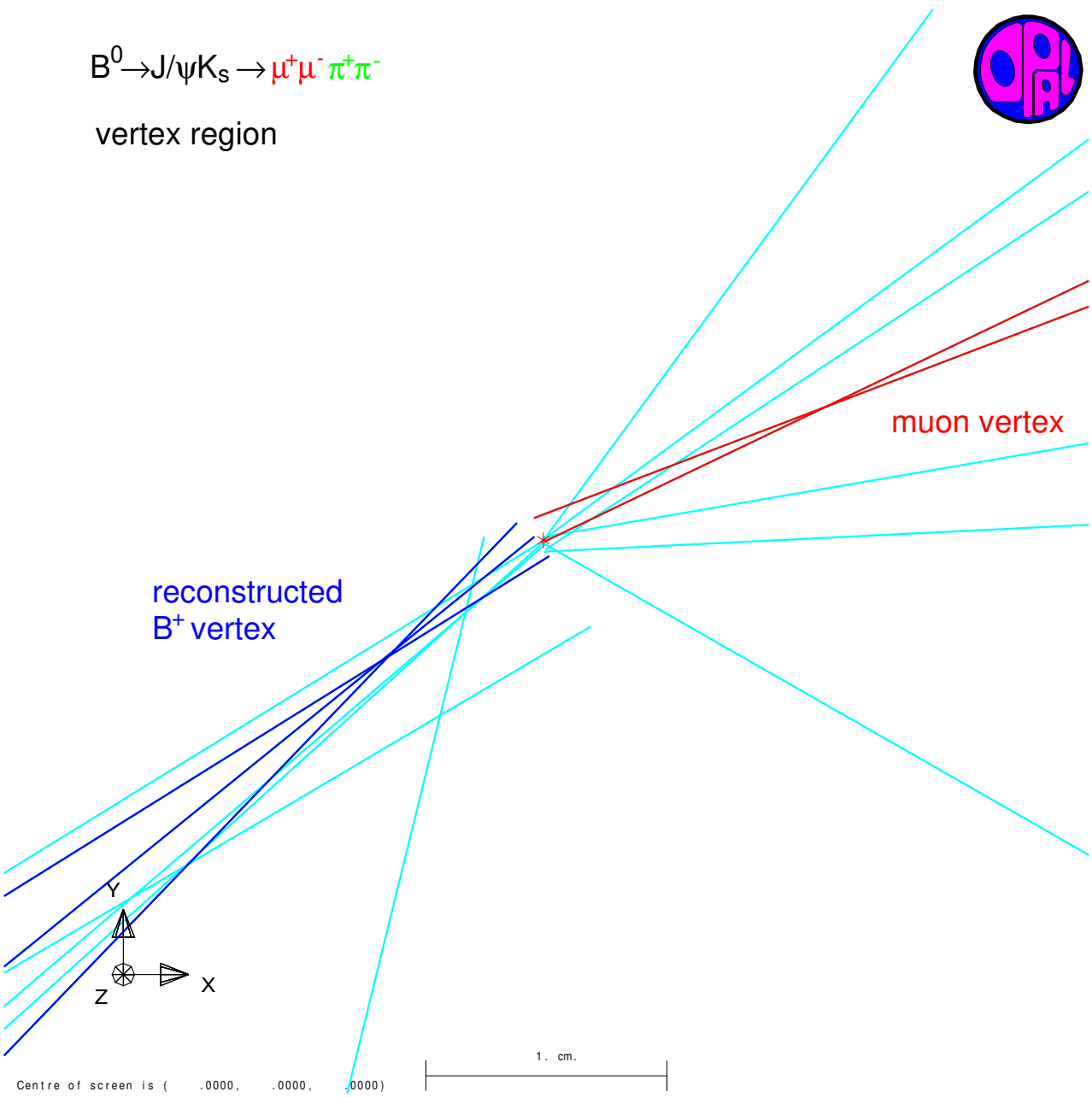
$Q_\mathrm{B} = +1$	Definitely produced as B^0.
$Q_\mathrm{B} = -1$	Definitely produced as $\bar{\mathrm{B}}^0$. and all values in between...
$Q_\mathrm{B} = 0$	Equally likely to be B^0 or $\bar{\mathrm{B}}^0$.

Monte Carlo is used to translate jet/vertex charges to Q_B.

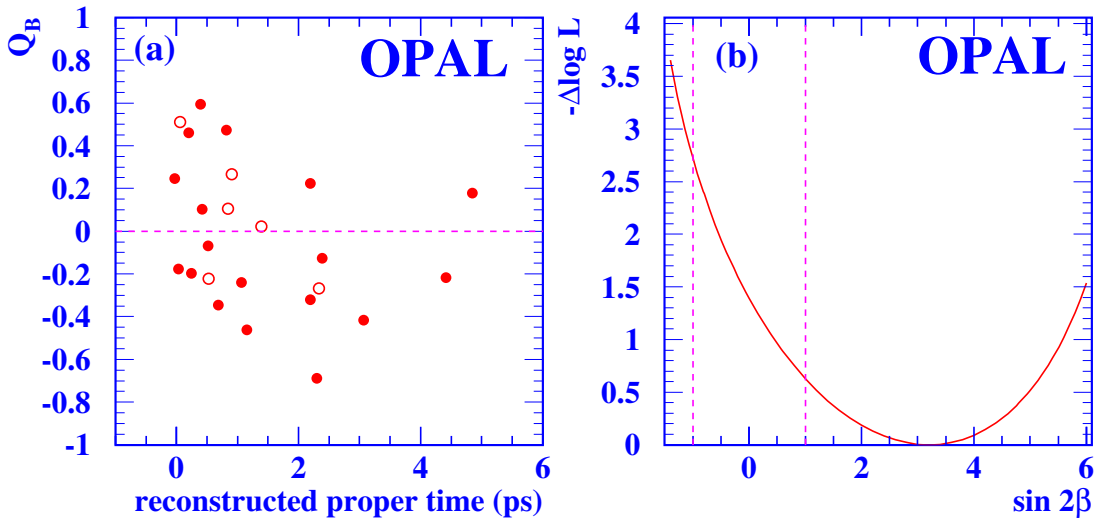
Data/Monte Carlo agreement of tag performance checked using:

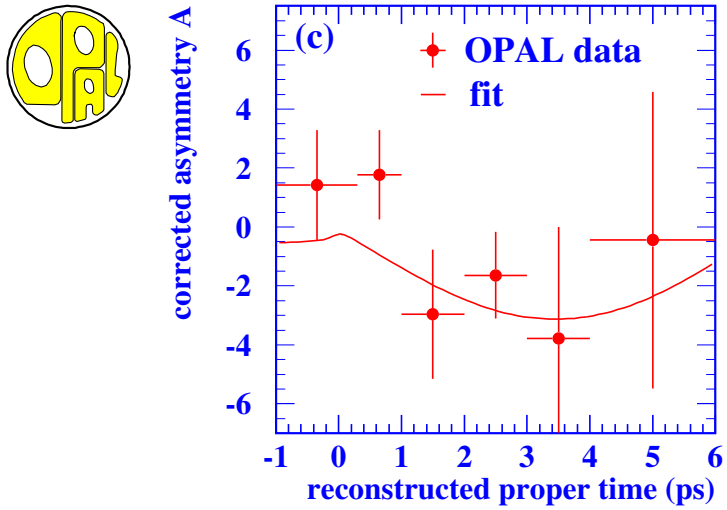
- lepton b-tagged events for opposite side tags.
- $\mathrm{B}^0 \to \mathrm{D}^{*\pm}\ell$ events for same side (another channel where B^0 is fully reconstructed—check by performing Δm_d oscillation analysis).

$B^0 \to J/\psi K^0_s$ opposite tagged B^+



Results





Unbinned likelihood fit for $\sin 2\beta$, using $t_{\rm rec}$, σ_t, $Q_{\rm B}$ and f_{bac} in each event.

From the fit to 24 candidates, get:

$$\sin 2\beta = 3.2^{+1.8}_{-2.0}$$

Systematics and Cross Checks

Main systematic errors from background, signal shape and flavour tagging, many scale with statistics and $\sin 2\beta$ value.

Source	$\delta(\sin 2\beta)$
Background level/content	± 0.33
Signal shape	± 0.13
Background asymmetry	± 0.03
Flavour tagging	$^{+0.34}_{-0.27}$
Physics inputs (Δm_d, τ_{B^0}	± 0.10
Background lifetime (± 0.4 ps)	$^{+0.01}_{-0.02}$
Total	$^{+0.50}_{-0.46}$

Cross checks:

- Tighten mass cuts or remove events with $f_{bac} > 0.5$, result stable.
- Remove poorly tagged events $|Q_{\mathrm{B}}| < 0.25$, result stable.
- CP asymmetry of sideband: $\sin 2\beta = 0.38^{+0.45}_{-0.49}$
  $\sin 2\beta = 0.12 \pm 0.30$ with looser cuts—consistent with zero.
- Fit for B^0 lifetime: $1.2^{+0.5}_{-0.4}$ ps (world average 1.56 ± 0.06 ps).

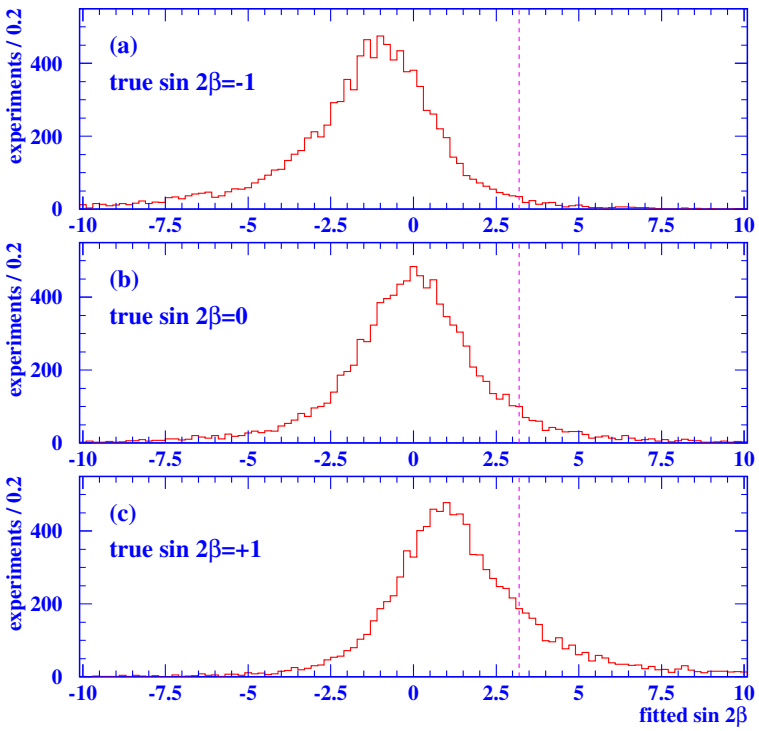
From a time dependent fit to 24 candidates, obtain the result:

$$\sin 2\beta = 3.2^{+1.8}_{-2.0}(\mathrm{stat}) \pm 0.5(\mathrm{syst})$$

First direct study of CP violation in the $\mathrm{B}^0 \to \mathrm{J}/\psi \mathrm{K}^0_{\mathrm{s}}$ system (CERN EP/98-01), now also result from CDF (see later talk of S. Tkaczyk).

Interpretation

Toy Monte Carlo experiments with 24 candidates, same background and tagging dilution as expected in data.



Result is not improbable for some true values of $\sin 2\beta$.

Calculate probabilities to observe a result at least this far from the true value, if the true value is x, based on log-likelihood differences to minimum.

True $\sin 2\beta$	fit $\sin 2\beta > 3.2$	data $\Delta \log L$	probability
+1	19.3%	0.61	21.1%
0	7.1%	1.33	7.7%
-1	2.1%	2.27	1.5%

Inclusive CP(T) tests in B decays

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

$$|\mathrm{B}_1> = (1+\epsilon+\delta)|\mathrm{B}^0> + (1-\epsilon-\delta)|\bar{\mathrm{B}^0}>$$
$$|\mathrm{B}_2> = (1+\epsilon-\delta)|\mathrm{B}^0> + (1-\epsilon+\delta)|\bar{\mathrm{B}^0}>$$

ϵ parameterises indirect CP violation, and δ parameterises CPT violation.

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

$$\left.\begin{array}{l}\mathrm{B}^0 \to \mathrm{B}^0 \\ \bar{\mathrm{B}^0} \to \bar{\mathrm{B}^0}\end{array}\right\} = \frac{\exp(-t/\tau)}{\tau}\frac{(1+\cos\Delta m_\mathrm{d} t \mp 4\mathrm{Im}\delta \sin\Delta m_\mathrm{d} t)}{k_{\mathrm{B}^0}, k_{\bar{\mathrm{B}^0}}}$$

$$\left.\begin{array}{l}\mathrm{B}^0 \to \bar{\mathrm{B}^0} \\ \bar{\mathrm{B}^0} \to \mathrm{B}^0\end{array}\right\} = \frac{\exp(-t/\tau)}{\tau}\frac{(1-\cos\Delta m_\mathrm{d} t)}{2}\frac{(1\mp 4\mathrm{Re}\epsilon)}{k_{\mathrm{B}^0}, k_{\bar{\mathrm{B}^0}}}$$

k_{B^0} and $k_{\bar{\mathrm{B}^0}}$ are (different) normalisation constants.

By tagging production and decay flavour of B^0, and measuring decay time t, can untangle the four different components for B^0 (neglect B^0_s).

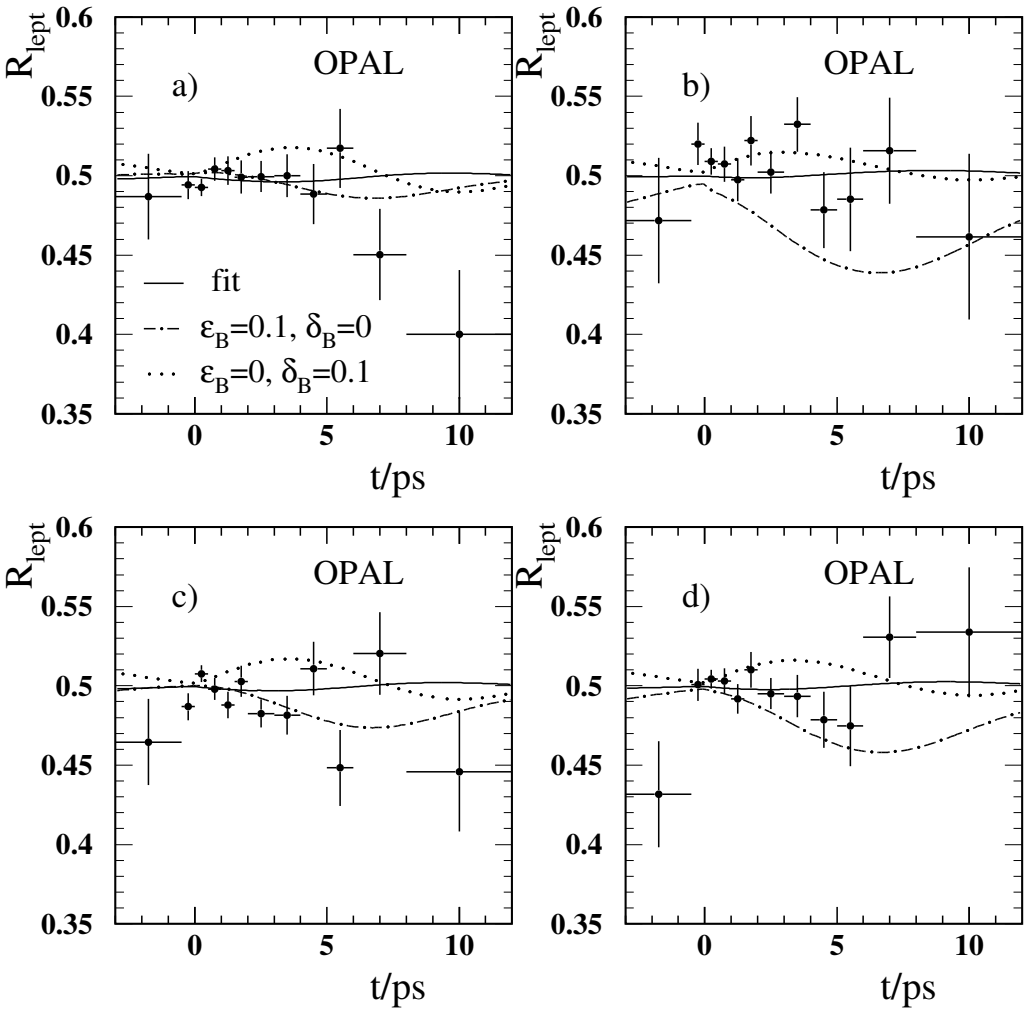
- CP violation ($\mathrm{Re}\epsilon_\mathrm{B}$) gives $\cos\Delta m_\mathrm{d} t$ term.
- CPT violation ($\mathrm{Im}\delta_\mathrm{B}$) gives $\sin\Delta m_\mathrm{d} t$ term.

Can be done as an extension of B^0 oscillation analysis, tagging B decay flavour with lepton charge, and production flavour with jet charge.

CP(T) tests in semileptonic B decays

Fit for $\mathrm{Re}\epsilon_\mathrm{B}$ and $\mathrm{Im}\delta_\mathrm{B}$ as additional parameters in lepton-jet charge B^0 oscillation analysis (OPAL Z. Phys. C 76 (1997) 401).

Looking for difference in behaviour of positive and negative lepton events: $R_\mathrm{lept}(t)$ is fraction of negative leptons at time t.



$$\mathrm{Re}\epsilon_\mathrm{B} = -0.006 \pm 0.010 \pm 0.006, \quad \mathrm{Im}\delta_\mathrm{B} = -0.020 \pm 0.016 \pm 0.006$$

Constraining $\mathrm{Im}\delta_\mathrm{B} = 0$ gives $\mathrm{Re}\epsilon_\mathrm{B} = 0.002 \pm 0.007 \pm 0.003$

Similar limits from preliminary DELPHI inclusive lepton analysis (HEP 97-449)

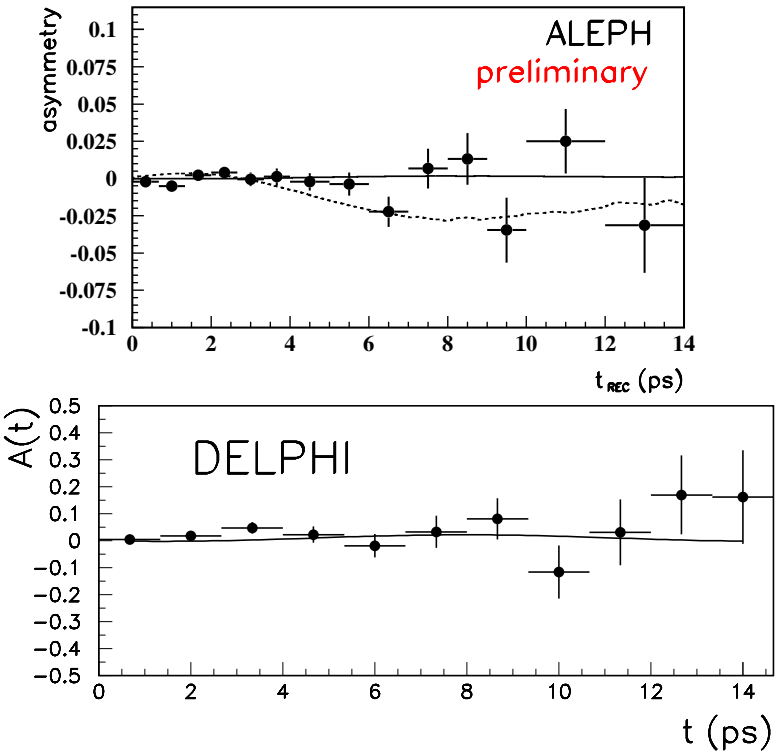
CP test in fully inclusive B decays

In inclusive B decay reconstruction, can measure the decay time but not decay flavour.

Can still get production flavour from opposite side of event (jet, vertex, lepton, kaon charge)—measure production flavour asymmetry as function of time:

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

Parameter a_{d} measures indirect CP violation and can be related to $\mathrm{Re}\epsilon_{\mathrm{B}}$.



$$\mathrm{Re}\epsilon_{\mathrm{B}} = -0.002 \pm 0.011 \pm 0.003 \quad \text{(ALEPH prel ICHEP 98-936)}$$

$$= -0.005 \pm 0.007 \pm 0.003 \quad \text{(DELPHI prel HEP 97-449)}$$

$$= 0.001 \pm 0.014 \pm 0.003 \quad \text{(OPAL CERN-EP/98-195)}$$

Statistics dominates . . . main systematics from flavour tagging and $\mathrm{b\overline{b}}$ purity.

Inclusive B decays (ctd)

More generally, have two terms in asymmetry

(I. Dunietz, FERMILAB-PUB-97/323-T):

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

Only for completely unbiased selection $c_{\rm d} = a_d \, \Delta m_d \tau / 2$.

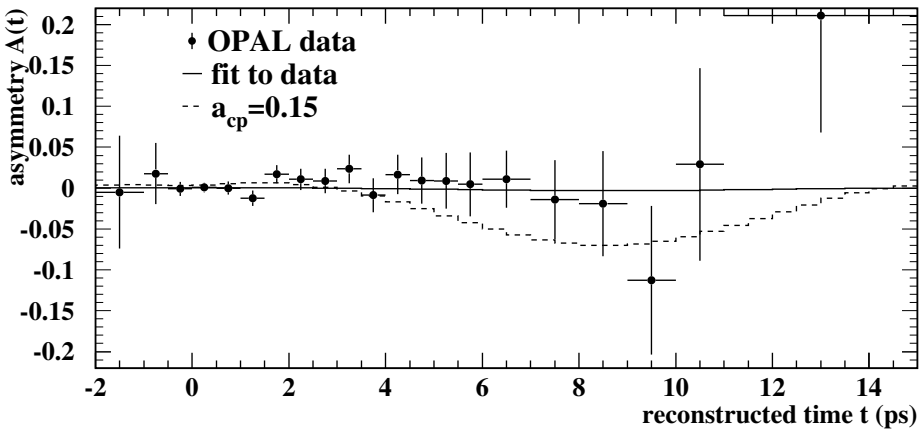
This requires equal reconstruction efficiencies for charmless, single charm and double charm B decays (not true in practice).

Test by fitting $c_{\rm d}$ as a separate parameter:

$c_{\rm d} = 0.03 \pm 0.01$ (stat only) (Dunietz analysis, DELPHI data)

$= 0.026 \pm 0.027 \pm 0.015$ (OPAL)

No significant evidence for asymmetry.

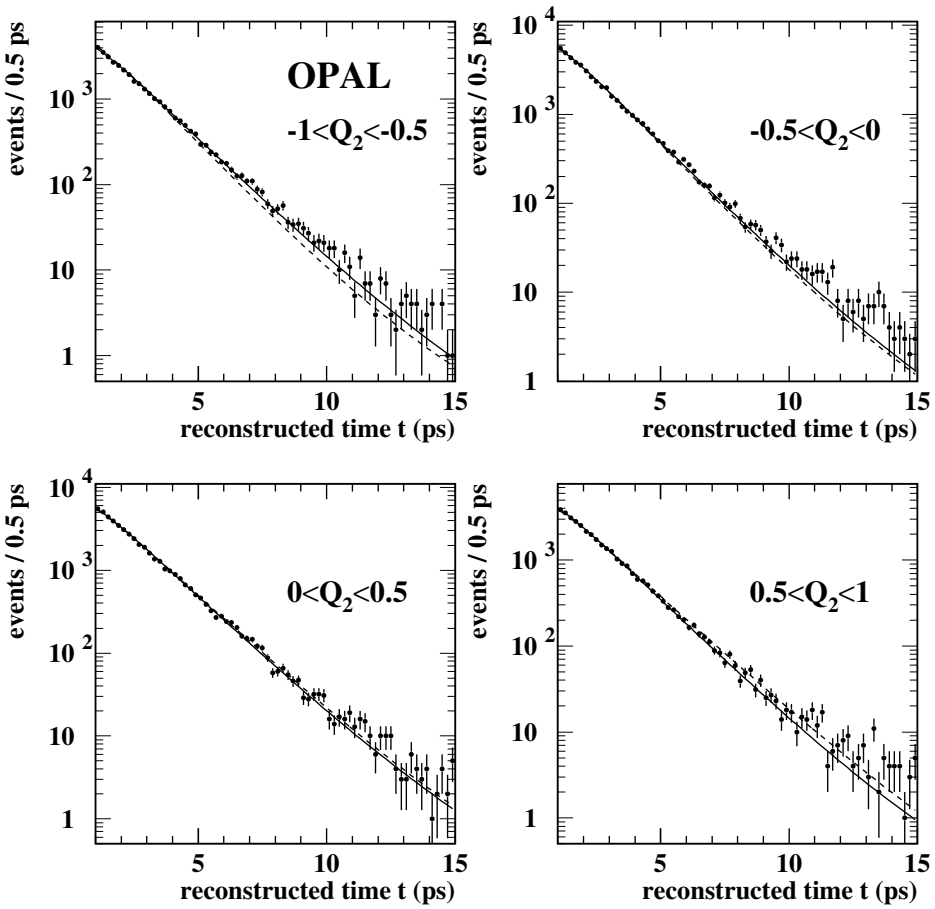


In future experiments/analyses, could deliberately bias reconstruction efficiency to increase sensitivity (some cancellation between charmless, single and double charm in completely inclusive asymmetry.)

CPT limits via B lifetime

CPT invariance implies particle and antiparticle lifetimes are equal—can be tested for B hadrons.

Measure average B lifetime in samples tagged as B or $\overline{\mathrm{B}}$ in opposite hemisphere using jet, vertex, lepton and kaon (DELPHI) charges.



$$\frac{\Delta\tau}{\tau} = \frac{\tau(\mathrm{B\ hadron}) - \tau(\overline{\mathrm{B}}\ \mathrm{hadron})}{\tau(\mathrm{average})}$$

$$= 0.019 \pm 0.018 \pm 0.016 \text{ (DELPHI prel. HEP 97-449)}$$

$$= -0.001 \pm 0.012 \pm 0.008 \text{ (OPAL CERN-EP/98-195)}$$

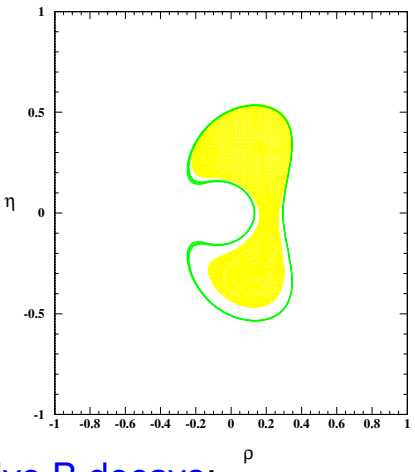
Lifetime difference consistent with zero in both cases.

Summary and Conclusion

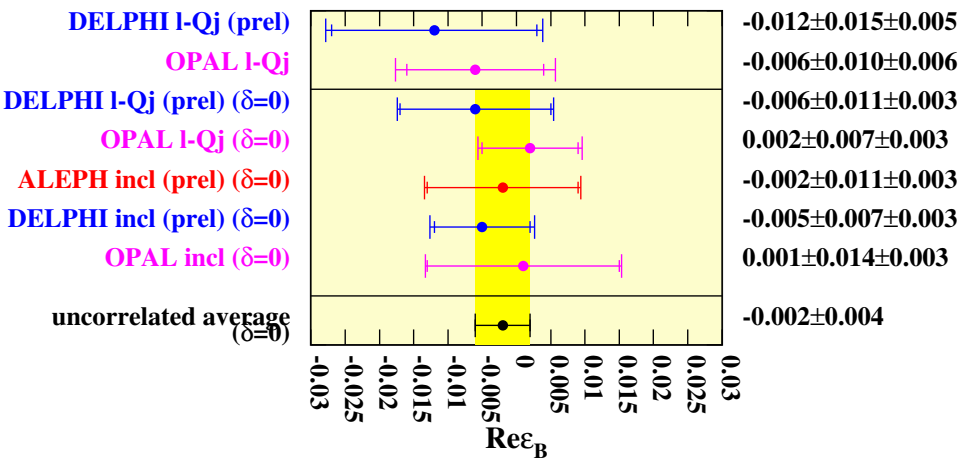
First direct constraint on $\sin 2\beta$ from OPAL study of $\mathrm{B}^0 \to \mathrm{J}/\psi \mathrm{K}^0_\mathrm{s}$ decays:

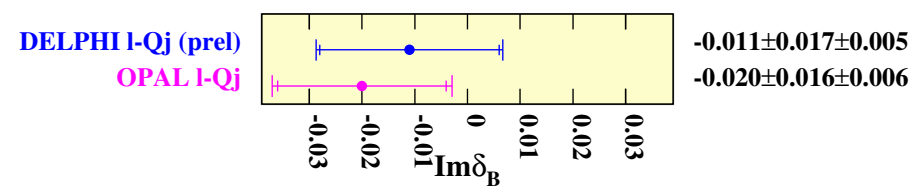
$$\sin 2\beta = 3.2^{+1.8}_{-2.0}(\mathrm{stat}) \pm 0.5(\mathrm{syst})$$

Effect on ρ-η plane if constraint from kaon system (ϵ_k) is not used (i.e. η no longer constrained to be positive):



No evidence of CP or CPT violation from inclusive B decays:





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.