CP violation in B decays at LEP

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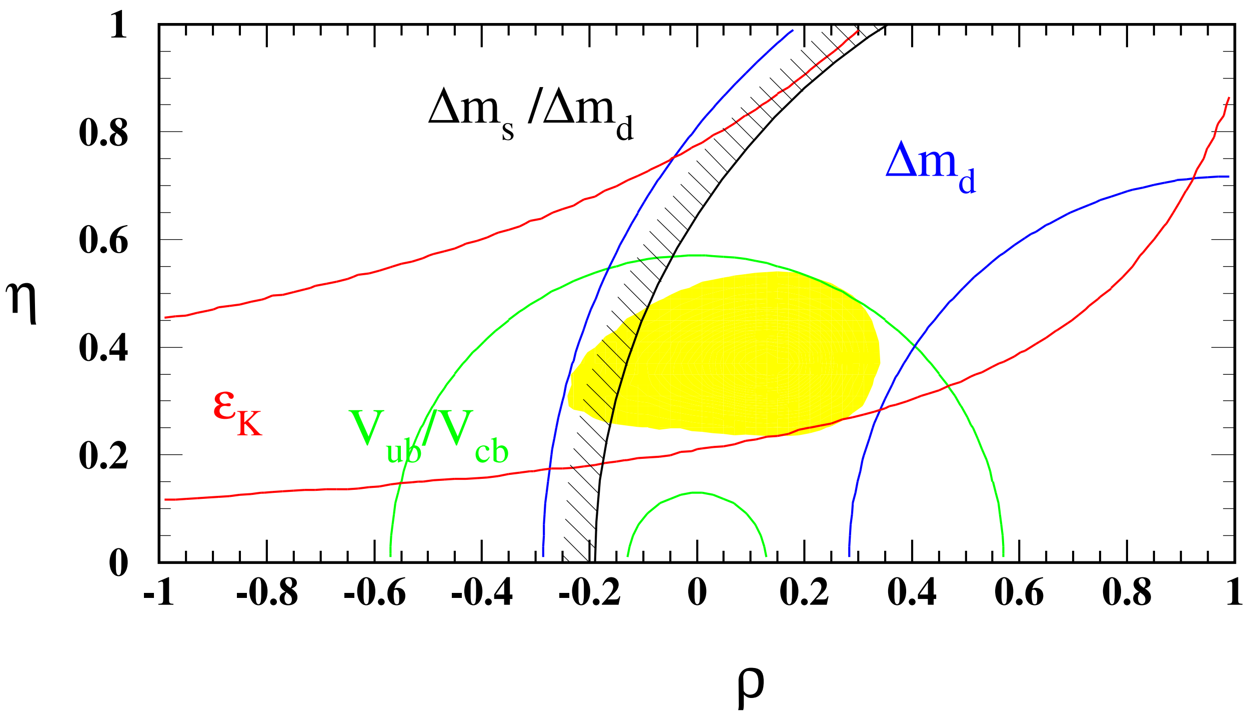
- Introduction: CP violation in B decays.
- $\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^0_\mathrm{s}$ to get $\sin 2\beta$: OPAL analysis.
- Inclusive CP violation tests: other results from LEP.
- Summary and Conclusion.

Introduction

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

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

This implies potentially large CP effects in $B^0 - \overline{B^0}$ 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 B-factories. . . what can we learn at LEP. . . ?

CP violation in $\mathrm{B^0} \rightarrow \mathrm{J}/\psi \mathrm{K^0_s}$ decays

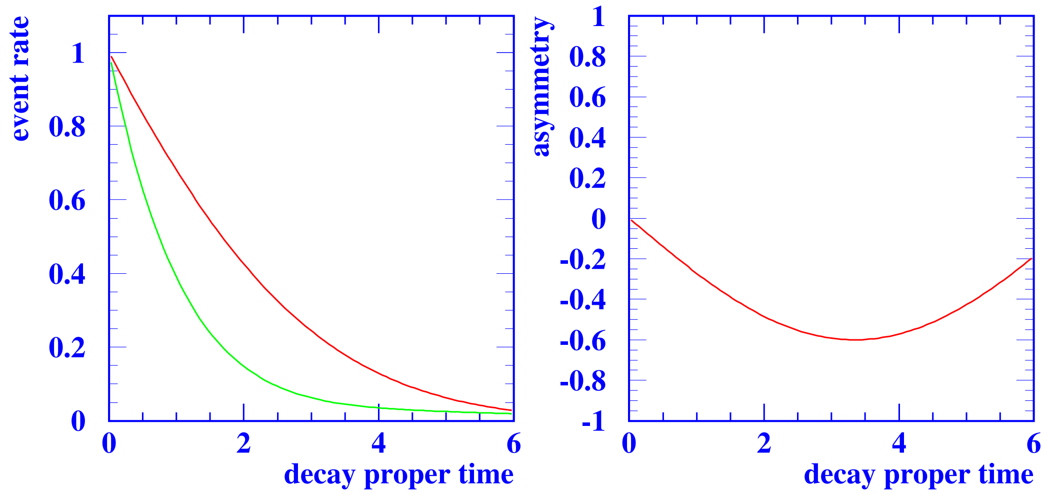
'Golden' decay mode is $\mathrm{B^0} \rightarrow \mathrm{J}/\psi \mathrm{K^0_s}$ (eigenstate CP=-1), very clean channel and well understood theoretically.

$$\begin{array}{llll} \mathrm{B^0} & \rightarrow & \mathrm{J}/\psi \mathrm{K^0_s} \rightarrow \ell^+\ell^-\pi^+\pi^- \\ \mathrm{B^0} & \rightarrow \bar{\mathrm{B}}^0(\mathrm{mixed}) \rightarrow & \mathrm{J}/\psi \mathrm{K^0_s} \rightarrow \ell^+\ell^-\pi^+\pi^- \end{array}$$

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

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

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



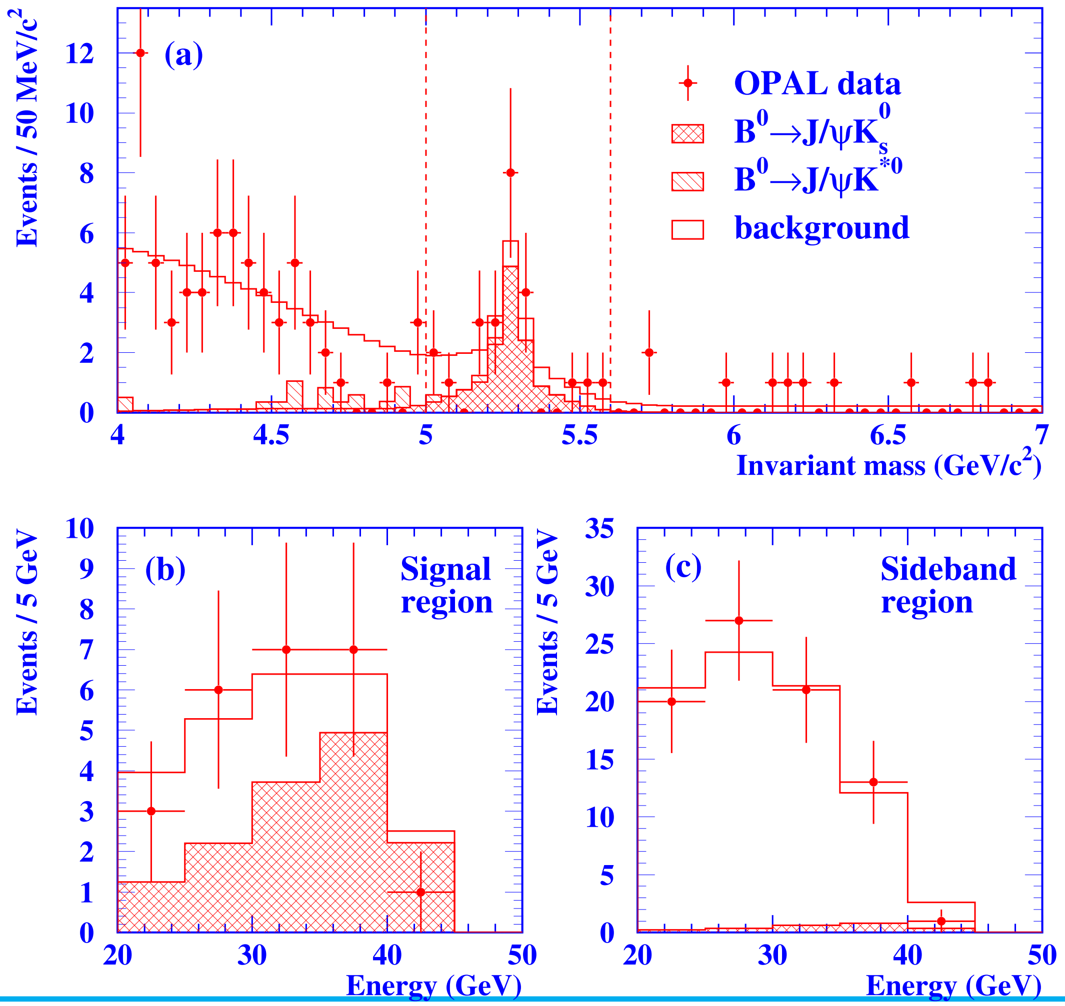
Largest asymmetry around decay time $t = 3\,\mathrm{ps}$.

Reconstructing $\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^0_\mathrm{s}$ decays

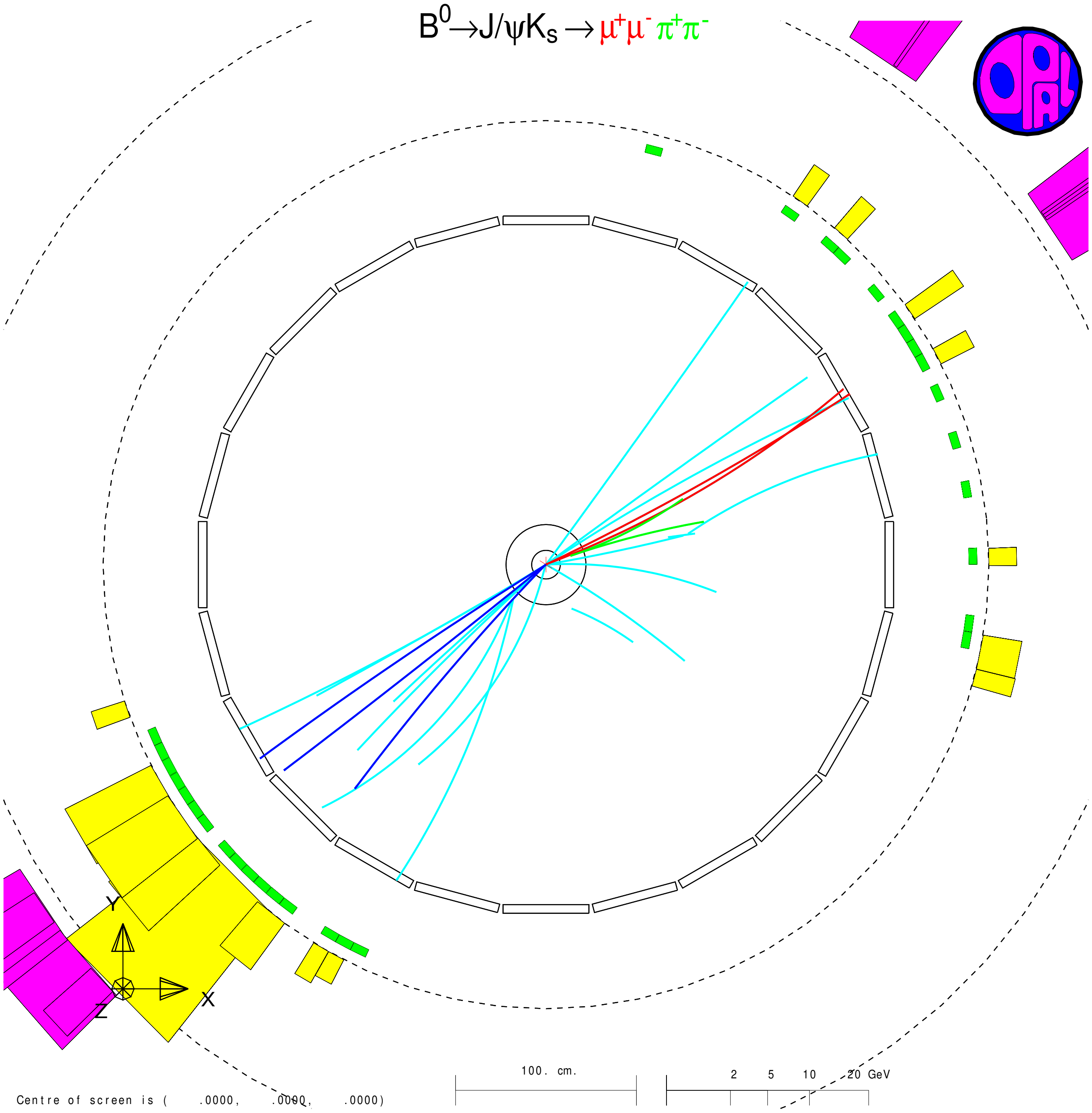
Branching ratio $\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^0_\mathrm{s} \to \ell^+\ell^-\pi^+\pi^-$ is only 3×10^{-5}.

- 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:



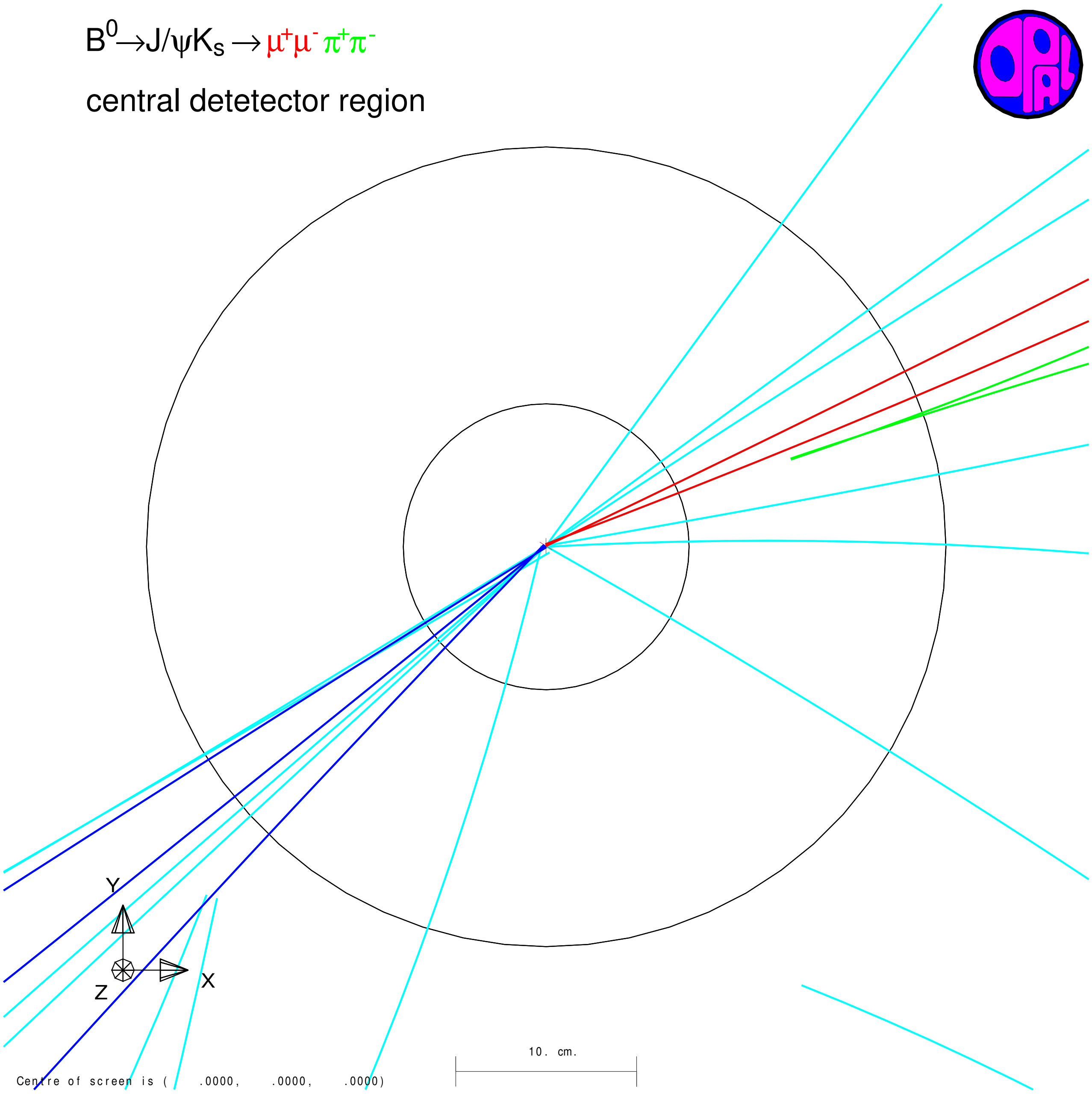
Reconstructed $J/\psi K^0_s$ event



Zooming in...

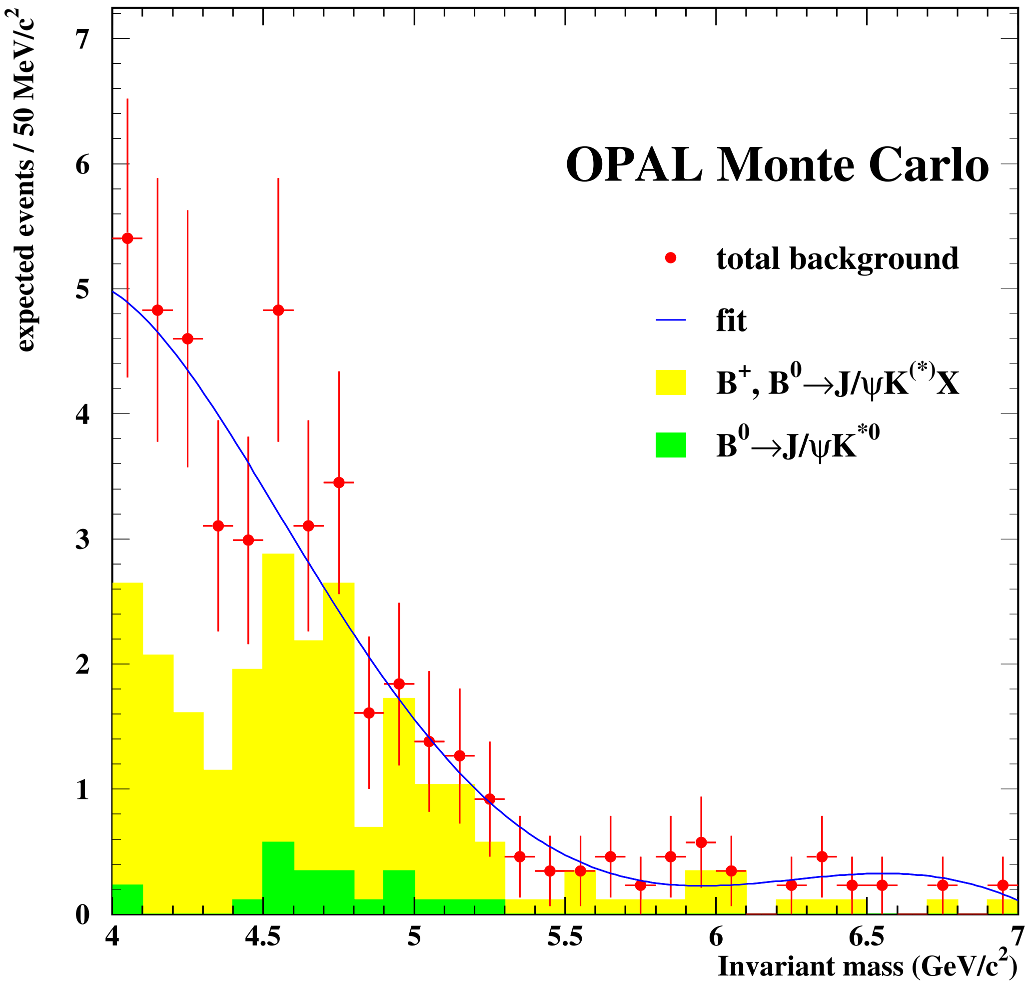
$B^0 \to J/\psi K_S \to \mu^+\mu^- \pi^+\pi^-$

central detetector region



Monte Carlo Background

Background is composed mainly of $\mathrm{B} \to \mathrm{J}/\psi\mathrm{X}$, with real K^0_s from B decay or fragmentation, or fake K^0_s.



Contribution from $\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^{*0}$ is mixture of CP eigenstates (± 1), estimate 0.7 events in signal region.

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 $\bar{\mathrm{B}}^0$.	

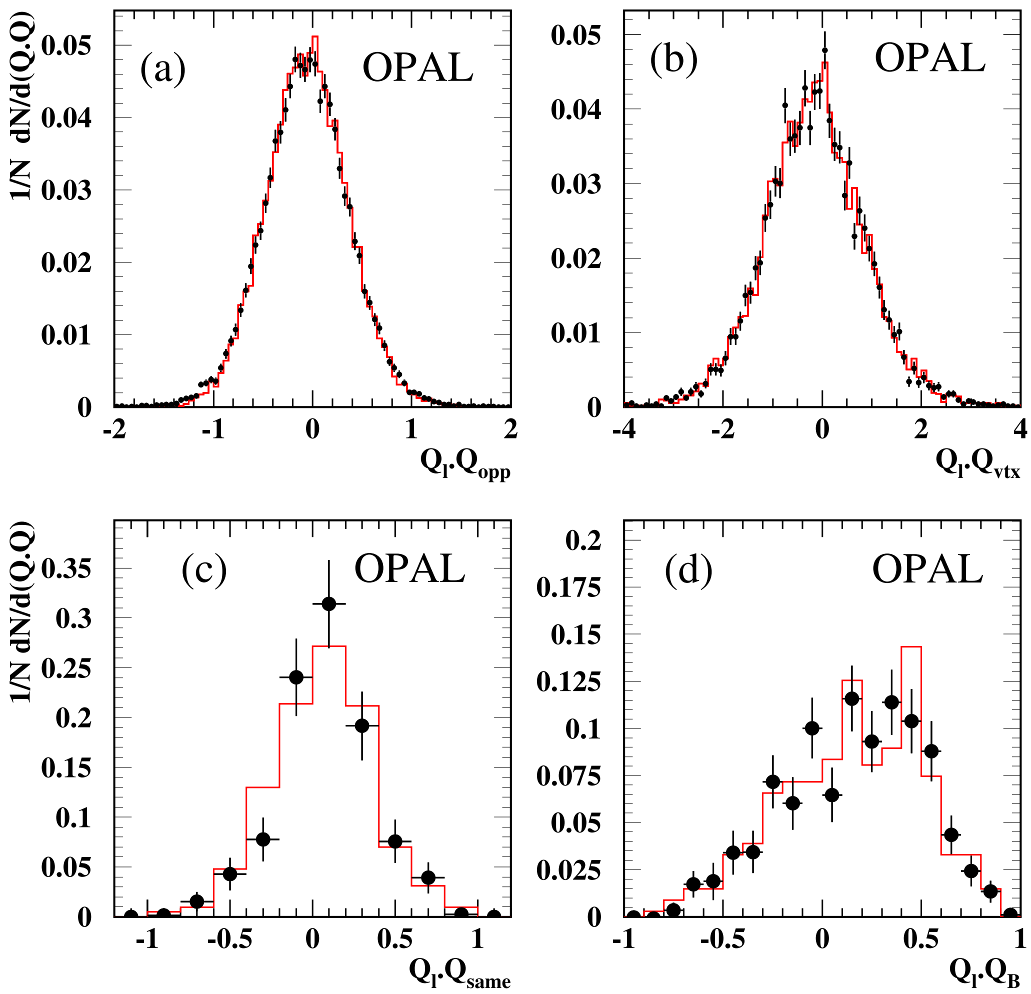
Monte Carlo is used to translate jet/vertex charges to Q_B.

Data/Monte Carlo agreement checked using lepton b-tagged events for opposite side, and $\mathrm{B}^0 \to \mathrm{D}^{*\pm}\ell$ events for same side.

Checking Q_{B} performance: I

Study product of lepton charge Q_ℓ with opposite side jet charge Q_{opp} or vertex charge Q_{vtx}.

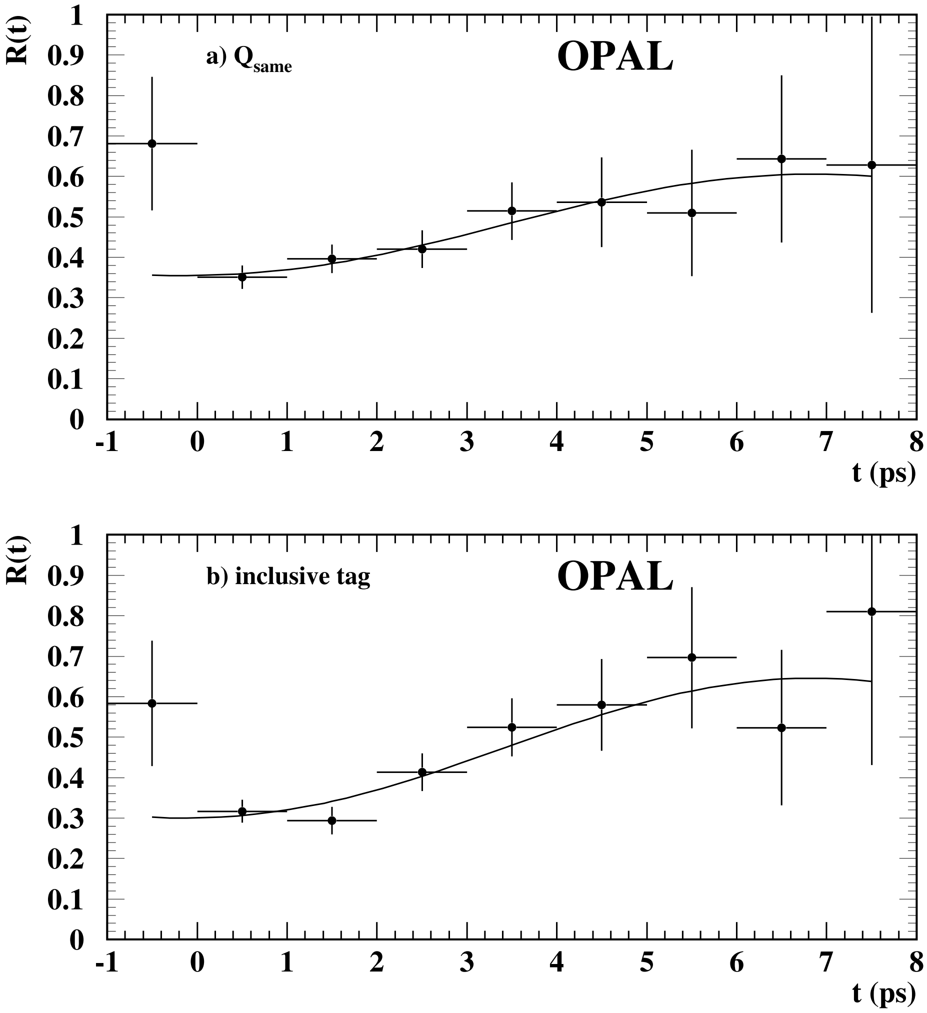
For same side jet charge, need sample of fully reconstructed B^0 decays to exclude decay products—use $\mathrm{B}^0 \to \mathrm{D}^{*\pm}\ell$ events.



Checking Q_{B} performance: II

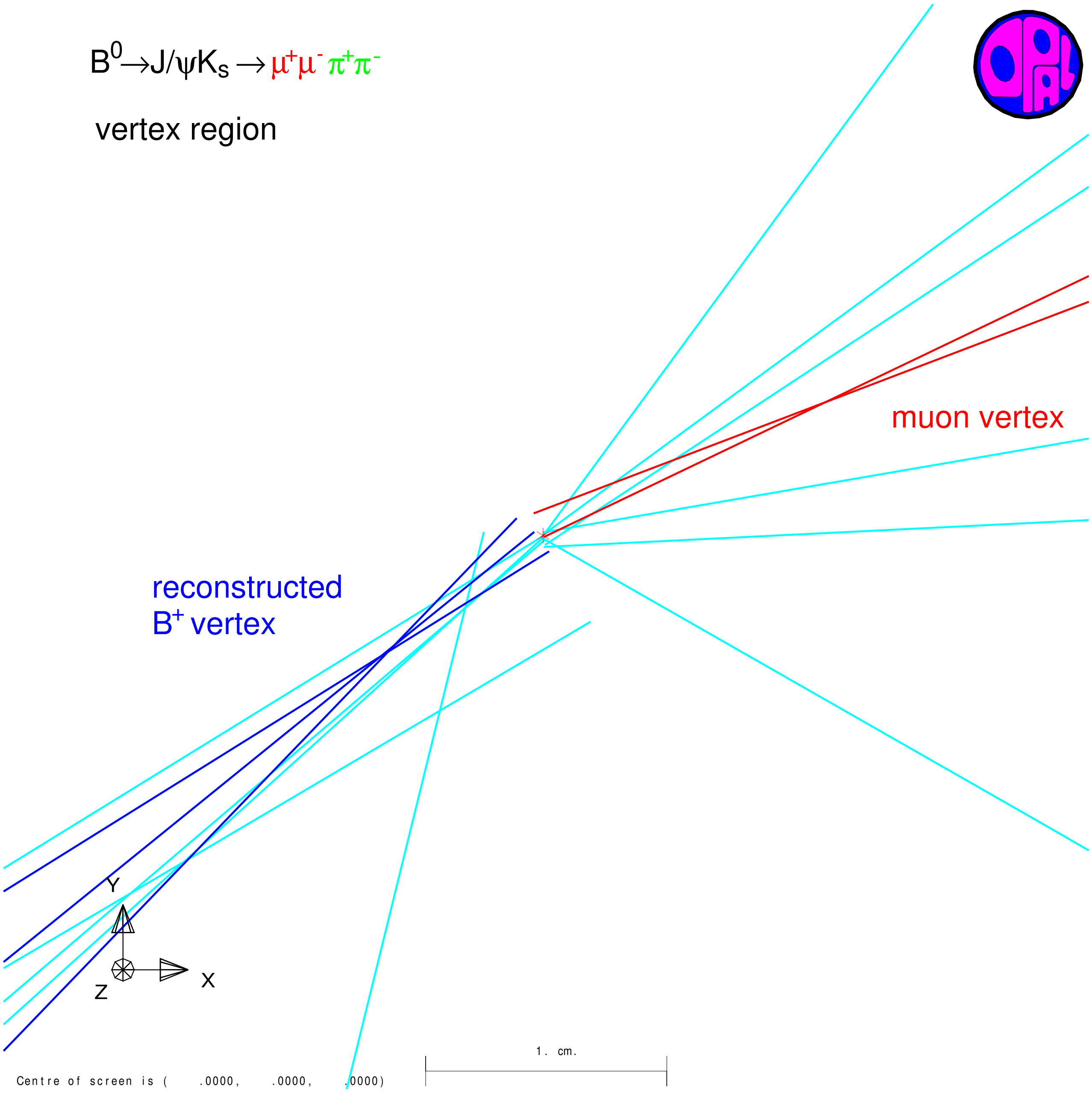
To check the modelling of same side jet charge, perform B^0 oscillation fit on $\mathrm{D}^{*\pm}\ell$ sample, using jet charge as production flavour tag.

Do the same for Q_{B} checking the combined tag.

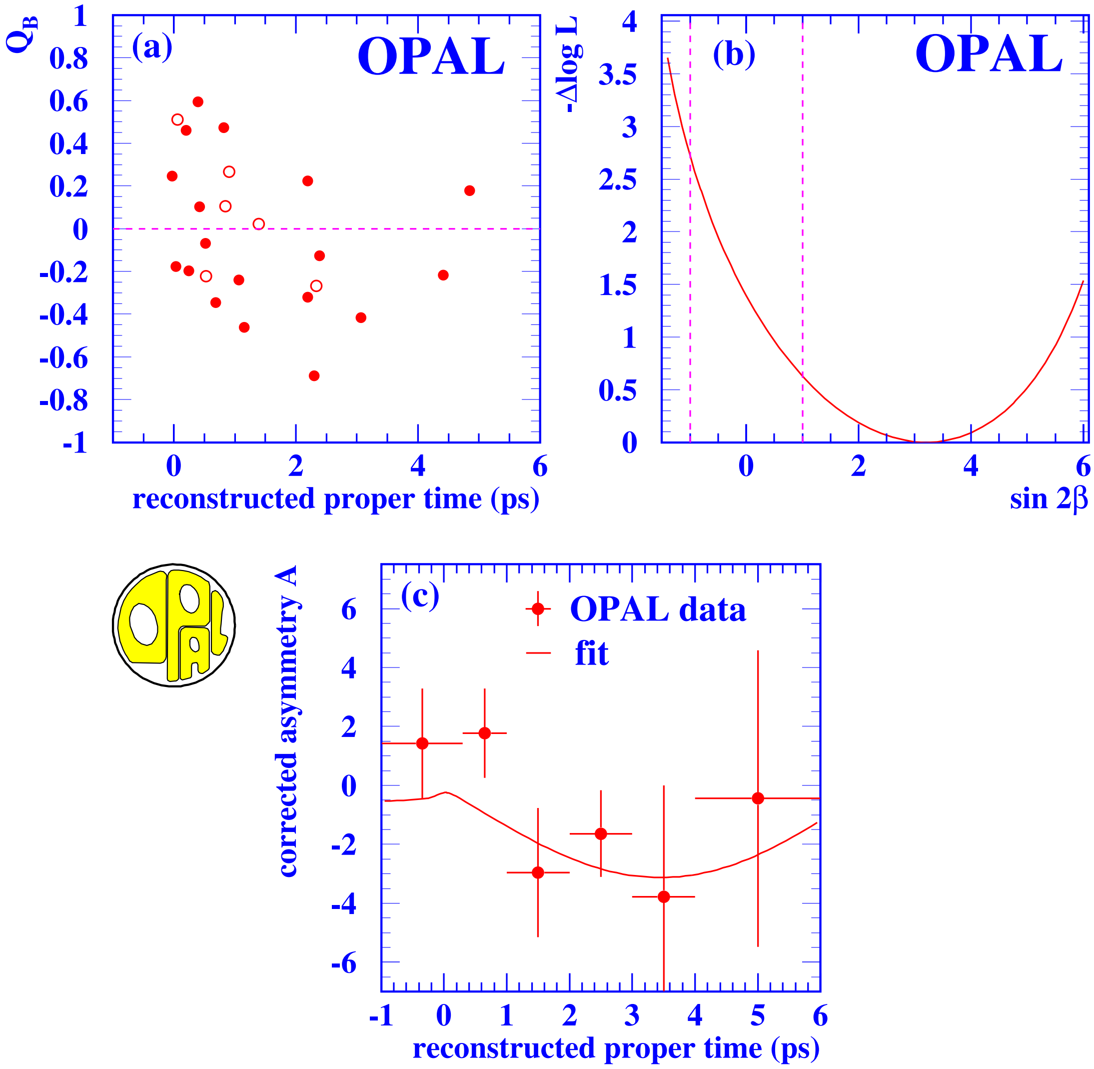


Fit tagging dilution in data and Monte Carlo—get consistent results, so Monte Carlo modelling of Q_{B} is reliable.

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



Results



Unbinned likelihood fit for $\sin 2\beta$, using t_{rec}, σ_t, Q_{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.

Source	$\delta(sin2\beta)$
Background level (data statistics)	$^{+0.06}_{-0.07}$
Background content	± 0.32
Signal shape	± 0.13
Background asymmetry	± 0.03
Proper time reconstruction	± 0.01
Jet and vertex charge modelling	$^{+0.31}_{-0.26}$
Jet charge offsets	$^{+0.14}_{-0.08}$
Vertex charge performance	± 0.01
Δm_d value	± 0.10
B^0 lifetime	± 0.01
Background lifetime (± 0.4 ps)	$^{+0.01}_{-0.02}$
Total	$^{+0.50}_{-0.46}$

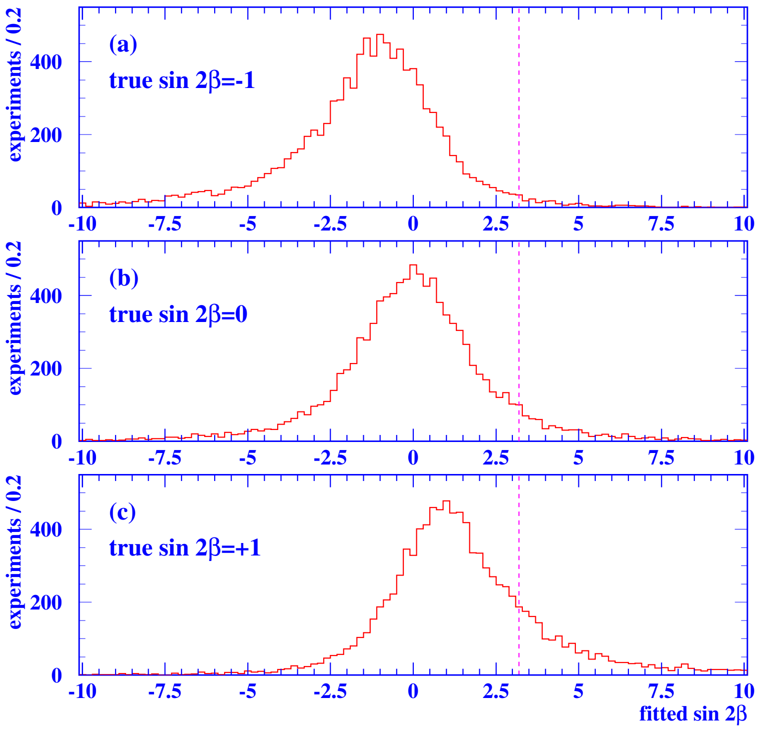
Many of these errors approximately scale with statistics and $\sin 2\beta$.

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).

Toy Monte Carlo Studies

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%

Result and interpretation

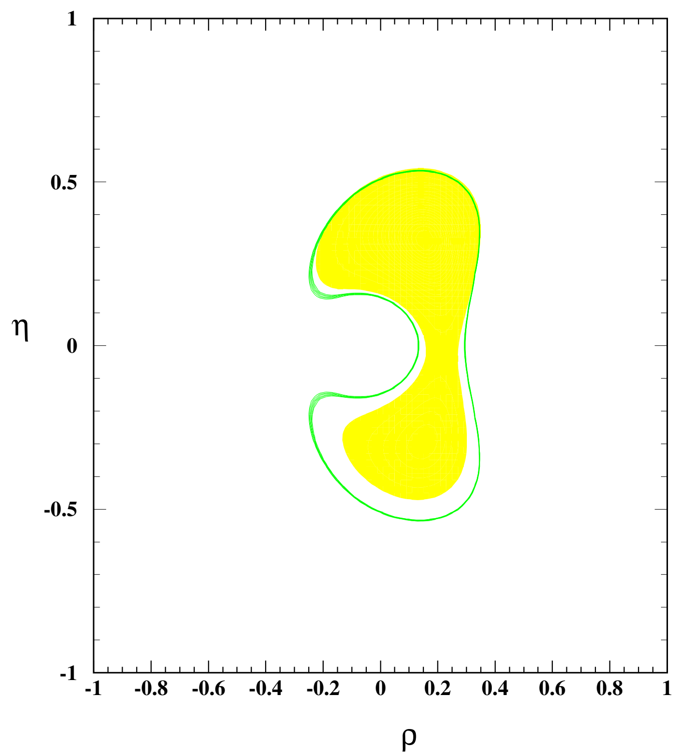
From a time dependent fit to 24 candidates, obtain the result:

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

The probabilities to obtain a result at least as far from the true value, if the true value is +1 ,0 or -1 are 21.1%, 7.7% and 1.5% respectively.

This is the 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). It can be combined with future results from CDF (see talk of Ken Kelley) and other LEP experiments.

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



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:

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

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 $\mathrm{B}^0_{\mathrm{s}}$).

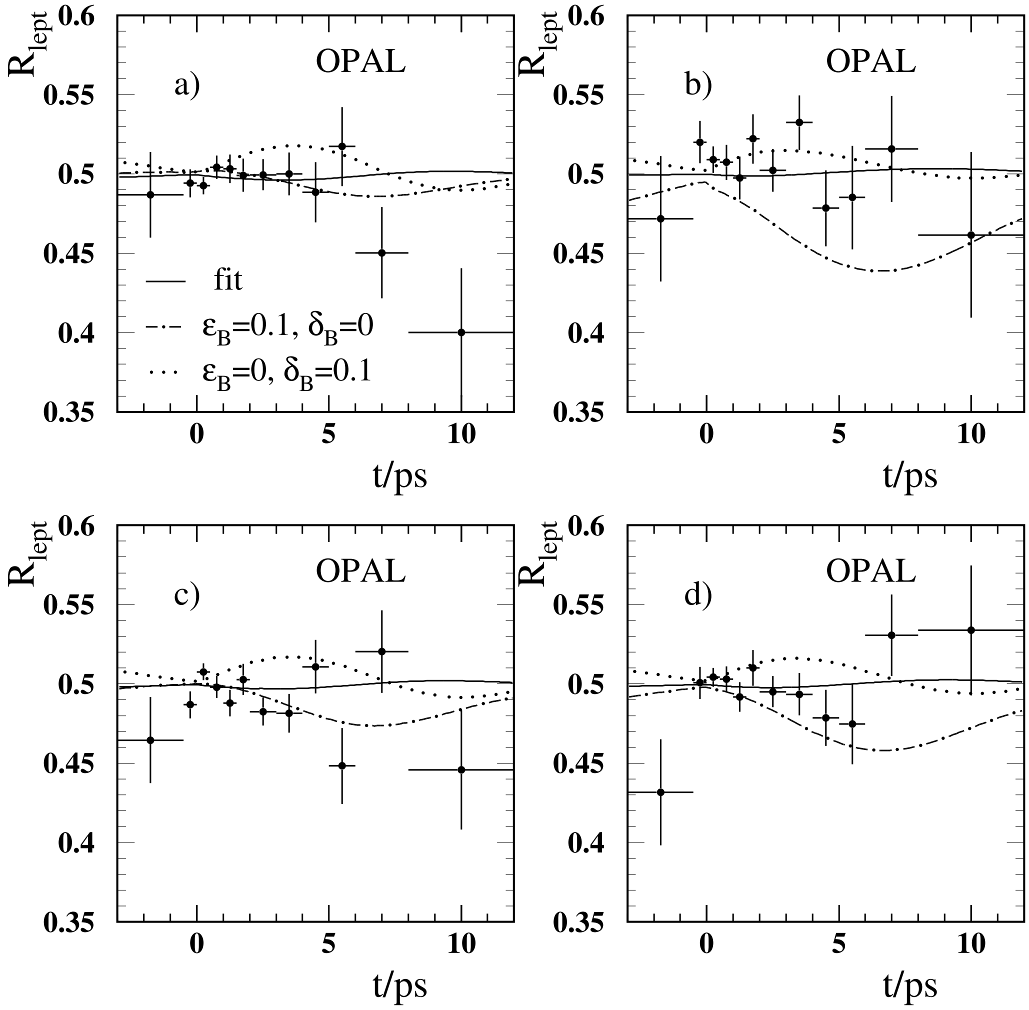
- CP violation ($\mathrm{Re}\epsilon_{\mathrm{B}}$) gives $\cos\Delta m_{\mathrm{d}}t$ term.
- CPT violation ($\mathrm{Im}\delta_{\mathrm{B}}$) gives $\sin\Delta m_{\mathrm{d}}t$ term.

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)

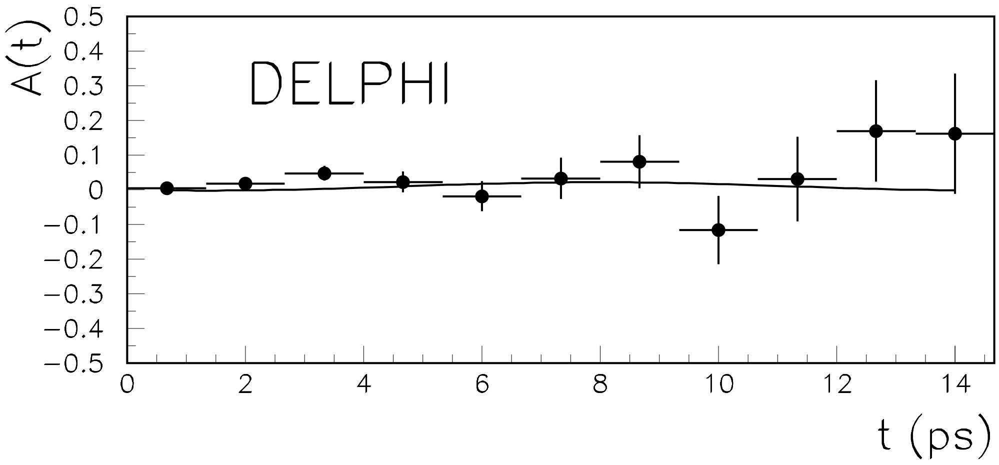
CP test in fully inclusive B decays

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 $\mathrm{Re}\epsilon_{\mathrm{B}}$.



DELPHI preliminary analysis (HEP 97-449) gets:

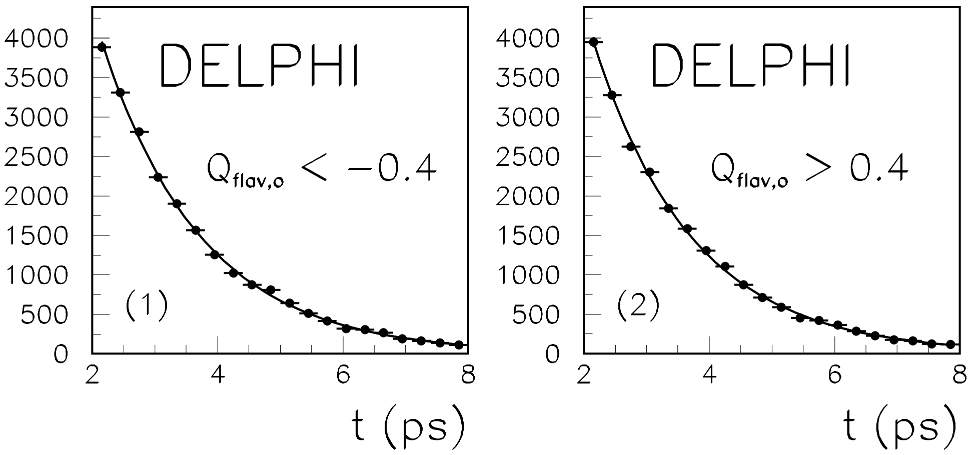
$$\mathrm{Re}\epsilon_{\mathrm{B}} = -0.005 \pm 0.007 \pm 0.003$$

Main systematics from flavour tagging and $\mathrm{b\bar{b}}$ purity.

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 charges.



$$\tau_{\mathrm{raw}}(\mathrm{B\ hadron}) = 1.609 \pm 0.013 \pm 0.025\,\mathrm{ps}$$
$$\tau_{\mathrm{raw}}(\overline{\mathrm{B}}\ \mathrm{hadron}) = 1.589 \pm 0.013 \pm 0.025\,\mathrm{ps}$$

Absolute lifetime is biased due to D lifetime and non $\mathrm{b\overline{b}}$ contamination.

Relevant quantity is difference in lifetimes:

$$\frac{\tau(\mathrm{B\ hadron}) - \tau(\overline{\mathrm{B}}\ \mathrm{hadron})}{\tau(\mathrm{average})} = 0.019 \pm 0.018 \pm 0.016$$

Lifetime different consistent with zero (2.5 % precision). First test of difference in B system (DELPHI preliminary: HEP 97-449).

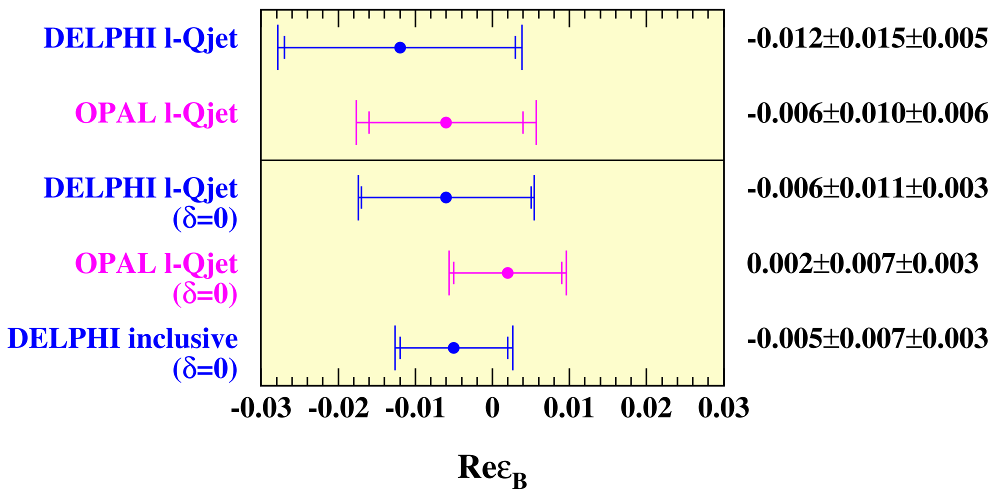
Summary and Conclusion

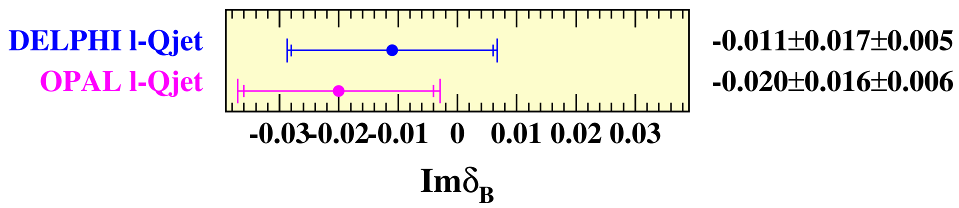
First direct constraint on $\sin 2\beta$ from OPAL study of $B^0 \to J/\psi K^0_s$ decays:

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

Favours positive values of $\sin 2\beta$; hope to combine with other 'current' experiments and say something significant.

Precise measurements will have to wait for B factories.





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.