CP Violation in the $B$ System: The Measurement of $\sin 2\beta$
1973: M. Kobayashi and T. Maskawa realized the connection

**CP violation ⇒ third generation of quarks**

**Cabibbo-Kobayashi-Maskawa** matrix $V$:
Transition matrix between quark-flavor and mass eigenstates

- Couplings of the W boson to the flavor-changing charged quark currents
- Complex matrix described by 4 independent real parameters (e.g. three angles, one phase)

**Wolfenstein parametrization:**

$$
V = \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) - A\lambda^2 & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
$$

- $\lambda \sim 0.22$
- $A \sim 0.83$

**CP violation in the Standard Model ⇔ $\eta \neq 0$**
The Unitarity Triangle

The CKM Matrix is complex and unitary

\[
\begin{pmatrix}
V_{ud}^* & V_{cd}^* & V_{td}^* \\
V_{us}^* & V_{cs}^* & V_{ts}^* \\
V_{ub}^* & V_{cb}^* & V_{tb}^*
\end{pmatrix}
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
= \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}
\]

9 unitarity relations

\[\Rightarrow V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\]

The Rescaled Unitarity Triangle

The Rescaled Unitarity Triangle is a useful representation of the unitarity of the CKM matrix (consistency of the KM model).

\[CP \text{ Violation } \iff \gamma \neq 0 \text{ or } \pi \]

\[\propto \text{ area of the Triangle}\]

Experimentally: constraints on the coordinates of the apex of the Rescaled Triangle in the complex plane.

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The Neutral B Meson Systems

\[ \Delta m_d \approx 0.5 \text{ ps}^{-1} \]
\[ 1/\Gamma_d = 1.56 \text{ ps} \]
\[ |\Delta \Gamma_d|/2\Gamma_d \ll 1 \]
\[ \Delta m_d/\Gamma_d \approx 0.75 \]

\[ \Delta m_s > 14 \text{ ps}^{-1} \]
\[ 1/\Gamma_s = 1.47 \text{ ps} \]
\[ \Delta \Gamma_s/2\Gamma_s \approx -0.10 \]
\[ \Delta m_s/\Gamma_s \approx 20 - 40 \]
Mixing Parameters of B Systems

Empirically, for both B systems

\[ (\Delta m)^2 - \frac{1}{4}(\Delta \Gamma)^2 = 4|M_{12}|^2 - |\Gamma_{12}|^2 \]

\[ \Delta m \Delta \Gamma = 4\text{Re}(\Gamma_{12}^* M_{12}) \]

\[ \Delta \Gamma \simeq 2 \frac{\text{Re}(\Gamma_{12}^* M_{12})}{|M_{12}|} = 2|M_{12}| \text{Re} \left( \frac{\Gamma_{12}}{M_{12}} \right) \]

\[ \frac{q}{p} = -2 \frac{M_{12}^* - i\frac{1}{2} \Gamma_{12}^*}{\Delta m - i\frac{1}{2} \Delta \Gamma} \]

\[ \frac{q}{p} \simeq - \frac{M_{12}^*}{|M_{12}|} \left[ 1 + \frac{1}{2} \frac{\text{Im}(\Gamma_{12}^* M_{12})}{|M_{12}|^2} \right] = - \frac{M_{12}^*}{|M_{12}|} \left[ 1 - \frac{1}{2} \text{Im} \left( \frac{\Gamma_{12}}{M_{12}} \right) \right] \]

again one finds the condition for no CP violation in mixing: \( \text{Im}(\Gamma_{12}^* M_{12}) = 0 \)
In contrast to the neutral kaon system, the common decay states are only a small fraction all B decays, and they contribute with alternating signs.

In the SM, $\Gamma_{12}$ can be approximated by the absorptive part of the box diagram:

$$\frac{\Gamma_{12}^d}{M_{12}^d} \approx -\frac{3\pi}{2 S_0(m_t^2/m_W^2)} \frac{m_b^2}{m_W^2} \left(1 + \frac{8}{3} \frac{m_c^2}{m_b^2} \frac{V_{cb} V_{cd}^*}{V_{tb} V_{td}^*}\right)$$
Width Difference

\[ \frac{\Delta \Gamma}{\Delta m} \simeq \text{Re} \left( \frac{\Gamma_{12}}{M_{12}} \right) \propto -\frac{3\pi}{2} \frac{m_b^2}{m_t^2} \sim -3 \times 10^{-3} \]

using \( \Delta m_d \simeq 0.72\Delta \Gamma_d \) one gets \( \frac{\Delta \Gamma_d}{\Gamma_d} \approx -4 \times 10^{-3} \)

(order of magnitude)

The ratio \( \frac{\Delta \Gamma}{\Delta m} \) is independent from CKM factors, and \( \sim \) applies to both \( B^0 \) and \( B_s \) systems.

\[ \Gamma_s \sim \Gamma_d \]

\[ \frac{\Delta \Gamma_s}{\Gamma_s} \sim \left( \frac{\Delta m_s}{\Delta m_d} \right) \frac{\Delta \Gamma_d}{\Gamma_d} \]

not necessarily small

very small

can be large (>40)

Note: in \( B_s \) system, common final states are not Cabibbo-suppressed

Conclusion

\( \Delta \Gamma_d \) is a very small quantity and can be safely neglected in most calculations.

\( \Delta \Gamma_s \) can be as large as 5-10\%, and needs to be taken into account.

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Indirect CP Violation

\[ \delta_d \equiv \frac{1 - |q/p|^2}{1 + |q/p|^2} = \frac{2 \text{Re } \varepsilon_B}{1 + |\varepsilon_B|^2} \]

null is CP is conserved in mixing

In the Standard Model, one gets

\[ \delta_d \simeq \frac{1}{2} \text{Im} \left( \frac{\Gamma_{12}}{M_{12}} \right) \simeq -4\pi \frac{m_c^2}{m_t^2} \frac{R_c}{R_t} \sin \beta \]

\[ \delta_d \sim -5 \times 10^{-4} \]

order of magnitude! not a way to measure \( \sin \beta \)!

\[ \delta_s \] is further suppressed by a factor \( |V_{td}/V_{ts}|^2 \sim 10^{-2} \)

Therefore, for both systems, expect very small effects of CP violation in mixing

to an excellent approximation

\[ \frac{q}{p} \simeq -\frac{M_{12}^*}{|M_{12}|} = -e^{-i\varphi_M} \]

where \( \varphi_M \) is the mixing phase

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More Parameterizations

The usual Wolfenstein parameterization at order $O(\lambda^4)$

$$V_{CKM} = \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - (\rho + i\eta)) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)$$

This is good enough for the B0 system, but not for the Bs system

$$V_{CKM} = \begin{pmatrix}
1 - \lambda^2/2 & \frac{\lambda}{8} & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 - \frac{(1/8 + A/2)\lambda^4}{A\lambda^2} & A\lambda^2 \\
A\lambda^3(1 - (\rho + i\eta)(1 - \lambda^2/2)) & -A\lambda^2 & 1 - \frac{A^2\lambda^4}{2}
\end{pmatrix} + O(\lambda^6)$$

(one possible parameterization)
Unitarity Triangle(s)

\[ V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* = 0 \]

\[ \beta \equiv \arg \left[ -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right] \]
\[ \gamma \equiv \arg \left[ -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right] \]
\[ \alpha \equiv \pi - \beta - \gamma \]

\[ V_{td}V_{ud}^* + V_{ts}V_{us}^* + V_{tb}V_{ub}^* = 0 \]

\[ \delta \gamma \approx \lambda^2 \eta \sim \mathcal{O}(10^{-2}) \]
\[ \beta' \approx \beta + \delta \gamma \]
\[ \gamma' \approx \gamma - \delta \gamma \]

\[ \overline{\rho} \equiv (1 - \lambda^2/2) \rho \]
\[ \overline{\eta} \equiv (1 - \lambda^2/2) \eta \]
The base of the Unitarity Triangle

\[ V_{cd} V_{cb}^* = R_c e^{i \phi_{c\bar{c}d}} \]

\[ R_c \approx A \lambda^3 \]

In the B systems, to a very good approximation, \( q/p \) is a pure phase, with

\[
\left( \frac{q}{p} \right)_{q=d,s} \simeq -\frac{M_{12}^*}{|M_{12}|} = \frac{V_{tq} V_{tb}^*}{V_{tq}^* V_{tb}} e^{2i \xi_B}
\]

therefore \( q/p \) is a pure phase, with

\[
\arg \left[ \left( \frac{q}{p} \right)_{q=d,s} \right] \simeq -2 \phi_M^q + 2 \phi_{c\bar{c}d} + 2 \xi_B
\]

\[
\left\{ \begin{array}{l}
\phi_M^d = \beta \\
\phi_M^s = -\delta \gamma
\end{array} \right.
\]

(very small)
Consider the decay $B^0 \rightarrow f_{CP}$

$$\langle f_{CP}|H|\bar{B}^0 \rangle = \sigma_{f_{CP}} e^{-2i\xi_B} \frac{\langle f_{CP}|(CP)H(CP)^\dagger|B^0 \rangle}{\langle f_{CP}|H|B^0 \rangle} \langle f_{CP}|H|B^0 \rangle$$

$\langle f_{CP}|(CP)H(CP)^\dagger|B^0 \rangle$ is obtained from $\langle f_{CP}|H|B^0 \rangle$ by complex-conjugating the CKM matrix elements

$$\frac{A_{f_{CP}}}{\bar{A}_{f_{CP}}} = \sigma_{f_{CP}} e^{-2i\xi_B} e^{-2i\phi_{c\bar{c}d}} \sum_j a_j e^{i\delta_j} e^{-i\phi_j} = \sum_j a_j e^{i\delta_j} e^{i\phi_j}$$

and:

$$\lambda_{f_{CP}} = \sigma_{f_{CP}} e^{-2i(\phi_M - \phi_{f_{CP}})} \sum_j a_j e^{i\delta_j} e^{-i\phi_j}$$

The $\phi_j$ are weak phases relative to $V_{cd} V_{cb}^*$ for $B^0$ decays

$$\phi_M = \beta$$

$$\phi_M = -\delta\gamma$$

for $B_s$ decays

Case of a dominating amplitude with weak phase $\phi_{f_{CP}}$

$$|\lambda_{f_{CP}}| = 1$$

$$\text{Im} \lambda_{f_{CP}} = -\sigma_{f_{CP}} \sin 2(\phi_M - \phi_{f_{CP}})$$
Three Types of CP Violation

★ CP violation in $B$ mixing (known as **indirect CP violation**)

\[ \{|B_L\rangle, |B_H\rangle\} \neq \{|B_{CP=+1}\rangle, |B_{CP=-1}\rangle\} \iff \frac{|q|}{|p|} \neq 1 \]

★ CP violation in the decay (known as **direct CP violation**)

\[ C_{fCP} = \frac{1 - |\lambda_{fCP}|^2}{1 + |\lambda_{fCP}|^2} \neq 0 \]

\[ \iff |A_{fCP}| \neq |\bar{A}_{fCP}| \]

interfering decay amplitudes

with different weak
and strong phases

(only type of CP violation
for charged modes)

★ CP violation in the interference
of the decays with and without mixing
(known as **mixing-induced CP violation**)

\[ S_{fCP} = \frac{2\text{Im}\lambda_{fCP}}{1 + |\lambda_{fCP}|^2} \neq 0 \]

\[ \iff \text{arg} \lambda_{fCP} \neq 0, \pi \]

(not only for CP modes)

---

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interference between $B^0 \rightarrow J/\psi K^0$ and $\bar{B}^0 \rightarrow J/\psi \bar{K}^0$
possible thanks to $K^0\bar{K}^0$ mixing

$$\lambda_{J/\psi K^0_{S,L}} = \sigma_{J/\psi K^0_{S,L}} \left( \frac{q}{p} \right)_d \left( \frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}} \right) \left( \frac{q}{p} \right)_K$$

$$\lambda_{J/\psi K^0_{S,L}} = \mp e^{-2i\beta}$$

$B^0$ mixing  Decay  $K^0$ mixing

$$a_{J/\psi K^0_{S,L}}^{CP} = \pm \sin 2\beta \sin (\Delta m_d t)$$

Theoretically clean way to measure $\sin 2\beta$
Clear exp. signatures
Relatively large BF
**Golden Channel:** $B \rightarrow J/\psi K_{S,L}$

**Question:** Why “theoretically clean”?

**Main contributing amplitudes**

- Dominant diagram: color-suppressed tree
- Leading Penguin contribution has same weak phase as Tree

\[
A(B \rightarrow J/\psi K) = V_{cb}V_{cs}^*(T + P^{(c)} - P^{(t)}) + V_{ub}V_{us}^*(P^{(u)} - P^{(t)}) \\
\propto \lambda^2 \times \text{small}
\]

\[
\left| \frac{A_{J/\psi K^0}}{A_{J/\psi K^0_S}} - 1 \right| \lesssim 10^{-2}
\]

**Answer:** in SM expect very little direct $CP$ violation

(but independent experimental checks are needed)
The Charmonium System

\[
\begin{align*}
&\bar{D}_s D_s^* \\
&\bar{D}_s D_s^* \\
&\bar{D}_s D_s \\
&\bar{D} D \\
&\eta_c \\
&h_c \\
&\psi' \\
&\chi_{c1} \\
&\chi_{c2} \\
&1P_1 \\
&1S_0 \\
&3S_1 \\
&3P_J \\
&J^{PC} \ldots \, 1^{++} \\
&0^{--} \\
&1^{--} \\
&0^{++} \\
&1^{++} \\
&2^{++} \ldots
\end{align*}
\]
Early Measurements of $\sin 2\beta$
At LEP

\[ \sin 2\beta = 3.2^{+1.8}_{-2.0} \pm 0.5 \]

\[ \sin 2\beta = 0.84^{+0.82}_{-1.04} \pm 0.16 \]
ALEPH: a $J/\psi$ $K_s$ Candidate

but very small sample

At the Z, also access to the $B_s$ physics
At the Tevatron

CDF Run 1 (110 pb⁻¹)

\[ \sin 2\beta = 0.79 \pm 0.39 \pm 0.16 \]

CDF ~400 events

Time-dependent and time-integrated meas.

CDF preliminary

\[
\frac{0}{-20} -15 -10 -5 0 5 10 15 20
\]

\[
0 S_0 K/JB \psi \rightarrow \text{MB / MM (0)}
\]

\[
-20 -15 -10 -5 0 5 10 15 20
\]

\[
0 S_0 K/JB \psi \rightarrow \text{MB / MM (0)}
\]

\[
B^0 \rightarrow J/\psi K_S^0
\]

\[
(M_{\mu\mu\pi\pi} - M_{B^0}) / \sigma_M
\]

CDF PR D61 (2000)

Precision lifetime sample 202 ± 18 events

Low \( c\tau \) reso 193 ± 26 events

\[
\Delta m_d \text{ fixed}
\]

\[
\Delta m_d \text{ floating}
\]

\[
\begin{align*}
\sin 2\beta & \approx -0.47 \sin 2\beta \\
A_{J/\psi K^0_S}^{\text{int}} & = -\frac{x_d}{1 + x_d} \sin 2\beta
\end{align*}
\]

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Physics at the Y(4S)
The Y(4S) Region

The cleanest way to produce B mesons

$e^+e^-$ collisions around $\sqrt{s} = 10.58$ GeV

production of $B\bar{B}$ pairs with a cross section of 1.1 nb over a continuum of ~3 nb

$\frac{b\bar{b}}{c\bar{c}} \approx 1.1$ nb

$\frac{c\bar{c}}{d\bar{d}, s\bar{s}} \approx 1.3$ nb

$\frac{d\bar{d}, s\bar{s}}{u\bar{u}} \approx 0.3$ nb

$\frac{u\bar{u}}{50\%/50\%} B^+B^- \& B^0\bar{B}^0$
Quantum Mechanics of the Y(4S)

\[ e^+e^- \rightarrow \gamma(4S) \rightarrow B^0 \bar{B}^0 \]

\[ J^{PC} = 1^{--} \]

two pseudoscalar bosons in a P-wave
antisymmetric wave function

\[ t \equiv \frac{t_1 + t_2}{2} \]
\[ \Delta t \equiv t_2 - t_1 \]

\[ \begin{align*}
| \gamma(4S) \rightarrow B^0 \bar{B}^0 \rangle & \sim | B^0, p^* \rangle | \bar{B}^0, -\bar{p}^* \rangle - | \bar{B}^0, \bar{p}^* \rangle | B^0, -p^* \rangle \\
& \sim | B_H, p^* \rangle | B_L, -\bar{p}^* \rangle - | B_L, \bar{p}^* \rangle | B_H, -p^* \rangle
\end{align*} \]

\[ \begin{aligned}
| \{ \gamma(4S) \rightarrow B \bar{B}^0 \} \rangle_{\text{phys}}(t, \Delta t) & \sim e^{-2i\omega t} \left[ e^{+i\Delta\omega \Delta t/2} | B_H, p^* \rangle | B_L, -\bar{p}^* \rangle - e^{-i\Delta\omega \Delta t/2} | B_L, \bar{p}^* \rangle | B_H, -p^* \rangle \right] \\
\text{with} & \quad \omega = M - \frac{i}{2} \Gamma \\
\text{and} & \quad \Delta\omega = \Delta m - \frac{i}{2} \Delta\Gamma
\end{aligned} \]
Quantum Coherence

quantum coherence (due to synchronous evolution) for $\Delta t = 0$ the system is the superposition of

$$\begin{align*}
\text{one } B^0 & \quad \text{one } \overline{B}^0 \\
\text{one } B_{CP=+1} & \quad \text{one } B_{CP=-1} \\
\text{one } B_H & \quad \text{one } B_L
\end{align*}$$

an EPR situation

the measure of the flavor (or CP) of one meson (e.g. from its decay products) determines the flavor (or CP) at the same proper time (it is opposite)

this property is exploited for B flavor tagging

For the study of time evolution, one needs to measure $\Delta t$

$$\begin{align*}
p^* &= 340 \text{ MeV/c} \\
(\beta\gamma)^* &= 0.064
\end{align*}$$

flight distance $d^* \sim 30 \mu m$

even with infinite resolution, only $t$ can be measured since the actual position of the Y(4S) in the luminous region is not known

In the Y(4S) CoM frame, only time integrated measurements are possible
Time-Integrated Measurements

Because $\Delta t$ is an algebraic quantity, only $\Delta t$-even quantities can be obtained with a time-integrated measurement.

- Flavor mixing is $\Delta t$-even
  \[ a_{\text{mix}}(\Delta t) \sim \cos(\Delta m \Delta t) \]

- a time-integrated measurement is possible

- $CP$ asymmetries are $\Delta t$-odd
  \[ a^{CP}(\Delta t) \sim \sin(\Delta m \Delta t) \]
  \[ \int_{-\infty}^{+\infty} a^{CP}(\Delta t) d\Delta t = 0 \]

Time-dependent $CP$ studies at the Y(4S) require:
- the measurement of $\Delta t$
- of the order of 100 million B mesons (or more)

ARGUS, 1987
Discovery of BB mixing
\[ \chi_d = 0.17 \pm 0.05 \]
Evolution for $B^0 (\bar{B}^0)$ state at $t_{CP} = 0$

**Incoherent**

**Coherent**

For coherent source, integrated asymmetry is zero: must do a time-dependent analysis
Oddone’s Clever Idea (1987)

why not produce the Y(4S) with a boost?
One could deduce the $\Delta t$ from the distance between the two B vertices along the boost axis.
What we need is a beam-energy asymmetric B Factory with luminosity of order $5 \times 10^{33}$

Duh!
Who’s that guy?
It’s a theorist idea!

But Pier is an experimentalist
Then he’s even crazier than a theorist!

10 years later, two asymmetric B Factories: PEP-II at SLAC and KEK-B at KEK...
PEP II/BABAR at SLAC

PEP II
Asymmetric
B Factory

Luminosity records
(as of May 26, 2003)

PEP-II/BABAR at SLAC

design peak: \(3 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}\)
best peak: \(6.1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}\)
total recorded: \(123.3 \text{ fb}^{-1}\)
since last fall: \(28.9 \text{ fb}^{-1}\)
best month: \(7.4 \text{ fb}^{-1}\)

9 GeV e\(^-\) on 3.1 GeV e\(^+\)
KEK-B Storage Rings

Located in the 3 km Tristan tunnel at KEK

KEK-B/Belle at KEK

- design peak: $10 \times 10^{33}$ cm$^{-2}$s$^{-1}$
- best peak: $10.6 \times 10^{33}$ cm$^{-2}$s$^{-1}$
- total recorded: 146.1 fb$^{-1}$
- since last fall: 56.6 fb$^{-1}$
- best month: 11.4 fb$^{-1}$

8 GeV $e^-$ $\times$ 3.5 GeV $e^+$
$\gamma(4S)$ boost: $\beta \gamma = 0.425$ 
$\pm 11$ mrad crossing angle
Interaction Regions

PEP-II

KEK-B

head-on collisions

small crossing angle (11 mrad)
The BABAR Detector

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Belle Detector

SC solenoid
1.5T

CsI(Tl) 16X₀

TOF counter

8GeV e⁻

Aerogel Cherenkov cnt.
n=1.015~1.030

3.5GeV e⁺

Tracking + dE/dx
small cell + He/C₂H₅

Si vtx. det.
3 lyr. DSSD

µ / Kₗ detection
14/15 lyr. RPC+Fe
Introduction to Time-Dependent CP Analyses at B Factories
Analysis Technique at B Factories

PEP-2 (SLAC)

- $E_{e^-} = 9$ GeV, $E_{e^+} = 3.1$ GeV
- $\sqrt{s} = 10.58$ GeV
- $\langle \beta \gamma \rangle_{\Upsilon(4S)} = 0.56$

**B-Flavor Tagging**

**Exclusive B Meson Reconstruction**

**Vertexing & Time Difference Determination**

\[ \Delta t \equiv t_{\text{rec}} - t_{\text{tag}} \]

\[ \Delta t \approx \Delta z / c \langle \beta \gamma \rangle_{\Upsilon(4S)} \]

\[ \langle \Delta z \rangle_{BB} \approx 260 \mu m \]
$B^0 \rightarrow J/\psi (\rightarrow \mu^+\mu^-) K_S^0$

with **kaon tag**
A Fully Reconstructed Event

A candidate in the mode

\[ B^0_{\text{CP}} \rightarrow \psi(2S) K_S^0, \quad K_S^0 \rightarrow \pi^+ \pi^- \]

with: \( \psi(2S) \rightarrow \mu^+ \mu^- \)

The other \( B \) meson is **fully-reconstructed** in the mode:

\[ \overline{B}^0 \rightarrow D^{*+} \pi^- \]

\[ D^{*+} \rightarrow D^0 \pi_s^- \]

\[ D^0 \rightarrow K^- \pi^+ \]
Kinematics at the Y(4S)

☆ Exclusive reconstruction: B candidate from tracks and clusters in the event

\[ P = (E, \vec{p}) \quad \text{boost back} \quad P^* = (E^*, \vec{p}^*) \]

in the lab

in the center-of mass frame (CoM)

☆ Define two largely independent analysis variables

The beam-energy substituted mass

\[ m_{ES} \equiv \sqrt{E_{\text{beam}}^* - p_{\text{beam}}^*} \]

with

\[ E_{\text{beam}}^* = \sqrt{s}/2 \]

half-CoM energy

The energy difference

\[ \Delta E \equiv E^* - E_{\text{beam}}^* \]

☆ Uncertainties

\[ \sigma_{m_{ES}}^2 = \frac{1}{4} \sigma_s^2 + \left[ \frac{p^*}{m_B} \right]^2 \sigma_{p^*}^2 \approx \frac{1}{4} \sigma_s^2 \]

dominated by beam energy spread

\[ \sigma_{\Delta E}^2 = \frac{1}{4} \sigma_s^2 + \sigma_{E^*}^2 \approx \sigma_{E^*}^2 \]

dominated by energy resolution

\[ \sigma_{m_{ES}} \approx 2.6 \text{ MeV}/c^2 \]
\[ \sigma_{\Delta E} \approx 10 \leftrightarrow 40 \text{ MeV} \]
Signal Region and Sidebands

**Signal Region**: typically 3-sigma around the B mass in $m_{ES}$ and around 0 in $\Delta E$

**Sideband Region**: defined outside the signal region in order to estimate backgrounds

Also: use off-resonance data

$B^0 \rightarrow J/\psi K^0_S$
Flavor Specific Final States: Neutrals

Self-tagging modes

Nov 1999- June 2002 data
82 fb$^{-1}$ on-peak – 89 million BB pairs

$B^0 \rightarrow D^{(*)-} \pi^+/\rho^+/a_1^+$
$B^0 \rightarrow J/\psi K^{*0}(\rightarrow K^+\pi^-)$

$N_{\text{tag}} = 23618$
Purity $= 84\%$

$N_{\text{tag}} = 1757$
Purity $= 96\%$

Also: charged modes, an important control sample
$CP = -1$ Sample

Samples of $B$ decays to $CP$-eigenstates with charmonium

\[
\begin{align*}
B^0 & \rightarrow J/\psi (\rightarrow \ell^+ \ell^-) K_S^0 \\
B^0 & \rightarrow J/\psi K_S^0 (\rightarrow \pi^0 \pi^0) \\
B^0 & \rightarrow \psi(2S) (\rightarrow \ell^+ \ell^-, J/\psi \pi \pi) K_S^0 \\
B^0 & \rightarrow \chi_{c1} (\rightarrow J/\psi \gamma) K_S^0
\end{align*}
\]

and also:

\[
B^0 \rightarrow \eta_c (\rightarrow K_S^0 K^\mp \pi^\mp) K_S^0
\]

Note: the $\eta_c$ has $CP= -1$, that is opposite to the $J/\psi$ but the decay is S-wave rather than P-wave.
**CP Sample**

**Mixed CP Sample**

\[ B^0 \rightarrow J/\psi \ K^{*0}_{CP} (\rightarrow K^0_S \pi^0) \]

P to VV decay mode

angular analysis is used to disentangle
the CP-odd and CP-even components

mostly CP-even

**CP=+1 Sample**

\[ B^0 \rightarrow J/\psi \ K^0_L \]

K-longss are identified in either the
EM Calo or the muon system, but their
energy is not measured.

\[ \text{signal: 988 purity 55\%} \]
Belle LP2003, 140/fb

$M_{bc}(\text{GeV}/c^2)$

Events/(0.002 GeV/c^2)

$CP=-1$ Sample

$CP=+1$ Sample
B Flavor Tagging

Underlying physics processes: exploit charge correlations

- primary leptons
- fast track, secondary leptons
- kaon(s)
- soft pions

\[ B^0 \to D^{(*)-} \ell^+ \nu \]
\[ B^0 \to D^- \pi^+, D^- \to K^{(*)} \ell^- \bar{\nu} \]
\[ B^0 \to \bar{D}X, \bar{D} \to K^+ X' \]
\[ B^0 \to D^{*-} X^+, D^{*-} \to \bar{D}^0 \pi^- \]

apply momentum cut e.g. \( p^*_\ell > 1 \text{ GeV}/c \)

Multivariate techniques (Neural Network) used to combine information in an optimal way

- event topology
- track and event kinematics
- particle identification

Tagging categories based on the physics (BABAR) or NN output (Belle)
Tagging Performances

Tagging performance are measured from the data:
- tagging efficiencies and mis-tagging probabilities determined with physical quantities in simultaneous fits
- cross-checks with independent high statistics control samples
- Monte-Carlo used for optimizations and second-order effects

<table>
<thead>
<tr>
<th>Physics Category</th>
<th>Efficiency $\varepsilon$ (%)</th>
<th>Wrong-Tag Fraction $w$ (%)</th>
<th>$Q = \varepsilon \times (1 - 2w)^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton</td>
<td>9.1 ± 0.2</td>
<td>3.3 ± 0.6</td>
<td>7.9 ± 0.3</td>
</tr>
<tr>
<td>Kaon I</td>
<td>16.7 ± 0.2</td>
<td>9.9 ± 0.7</td>
<td>10.7 ± 0.4</td>
</tr>
<tr>
<td>Kaon II</td>
<td>19.8 ± 0.3</td>
<td>20.9 ± 0.8</td>
<td>6.7 ± 0.4</td>
</tr>
<tr>
<td>Inclusive</td>
<td>20.0 ± 0.3</td>
<td>31.6 ± 0.9</td>
<td>0.9 ± 0.7</td>
</tr>
<tr>
<td>All</td>
<td>65.6 ± 0.5</td>
<td></td>
<td>28.1 ± 0.7</td>
</tr>
</tbody>
</table>

$\varepsilon = 65.6 \pm 0.5\% \quad Q = 28.1 \pm 0.7\%$

Tagging performance at Belle very similar
1. Reconstruct $B_{\text{rec}}$ vertex from $B_{\text{rec}}$ daughters

2. Reconstruct $B_{\text{tag}}$ direction from $B_{\text{rec}}$ vertex & momentum, beam spot, and $\Upsilon(4S)$ momentum = pseudotrack

3. Reconstruct $B_{\text{tag}}$ vertex from pseudotrack plus consistent set of tag tracks

4. Convert from $\Delta z$ to $\Delta t$, accounting for (small) $B$ momentum in $\Upsilon(4S)$ frame

Result: High efficiency (97%) and $\sigma(\Delta z)_{\text{rms}} \sim 180 \mu m$ versus $<|\Delta z|> \sim \beta \gamma c t = 260 \mu m$
Time Resolution Function

Event-by-event \( \sigma(\Delta t) \) from vertex errors

Signal MC: \( \Delta t \) resolution function

\[ \frac{\Delta t_{\text{meas}} - \Delta t_{\text{true}}}{\sigma(\Delta t)} \]

Asymmetric RF: Tracks from long-lived charm in tag vertex

Empirical Models with parameters fit to data: Gaussian convolved with an exponential [lifetime] or Triple Gaussian [mixing, CP]

G. Hamel de Monchenault – Experimental Aspects of CP Violation
Differential event rate, as a function of the difference between the proper decay times of the two B mesons in the final state

\[
\frac{d}{d\Delta t} N(\Upsilon(4S) \rightarrow B\bar{B} \rightarrow f_{\text{tag}}, f_{\text{rec}}) \propto \frac{1}{\Gamma} e^{-\Gamma|\Delta t|} \left\{ 1 - C_{f_{\text{tag}}, f_{\text{rec}}} \times \cos(\Delta m \Delta t) + S_{f_{\text{tag}}, f_{\text{rec}}} \times \sin(\Delta m \Delta t) \right\}
\]

with

\[
C_{f_{\text{tag}}, f_{\text{rec}}} = \frac{|a_m|^2 - |a_u|^2}{|a_m|^2 + |a_u|^2}
\]

and

\[
S_{f_{\text{tag}}, f_{\text{rec}}} = \frac{2 \text{Im}(a_u^* a_m)}{|a_m|^2 + |a_u|^2}
\]

where one defines

\[
a_u \equiv \bar{A}_{f_{\text{tag}}} A_{f_{\text{rec}}} - A_{f_{\text{tag}}} \bar{A}_{f_{\text{rec}}}
\]

\[
a_m \equiv \frac{q}{p} \bar{A}_{f_{\text{tag}}} A_{f_{\text{rec}}} - \frac{p}{q} A_{f_{\text{tag}}} \bar{A}_{f_{\text{rec}}}
\]

Note - since t is not measured, integrate:

\[
\int_{|\Delta t/2|}^{\infty} e^{-2\Gamma t} dt = \frac{1}{\Gamma} e^{-\Gamma|\Delta t|}
\]

\[
\Delta \Gamma = 0
\]

\[
z = 0
\]
$f_{\text{tag}}$ is Flavor Specific

\[ \lambda_f \equiv \frac{q \overline{A}_f}{p A_f} \quad (\text{if } A_f \neq 0) \quad \text{and} \quad \overline{\lambda}_f \equiv \frac{p A_f}{q \overline{A}_f} \quad (\text{if } \overline{A}_f \neq 0) \]

flavor tagging \[
\left\{ \begin{array}{c}
B^0\text{tag ( + ) } \iff \lambda_{f\text{tag}} \approx 0 \\
\overline{B}^0\text{tag ( - ) } \iff \overline{\lambda}_{f\text{tag}} \approx 0
\end{array} \right.
\]

\[
\frac{d}{d\Delta t} \mathcal{N}(f_{\text{rec}}, \text{tag} = \pm) \propto \frac{1}{\Gamma} e^{-\Gamma|\Delta t|} \left\{ 1 \mp C_{f\text{rec}} \times \cos(\Delta m \Delta t) \pm S_{f\text{rec}} \times \sin(\Delta m \Delta t) \right\}
\]

with \[
C_{f\text{rec}} \equiv \frac{1 - |\lambda_{f\text{rec}}|^2}{1 + |\lambda_{f\text{rec}}|^2} \quad \text{and} \quad S_{f\text{rec}} \equiv \frac{2 \text{Im } \lambda_{f\text{rec}}}{1 + |\lambda_{f\text{rec}}|^2}
\]

- familiar expressions, but with $\Delta t$ as time variable
- in the general case, there are non-trivial interference terms
The production point of the $B$ meson is known with good accuracy.

Control of the resolution function at negative times.

The proper time is deduced from the distance in $z$ between the 2 $B$ vertices.

Fit the parameters of the resolution function together with the lifetime.

G. Hamel de Monchenault – Experimental Aspects of CP Violation
Lifetime Measurements

**BABAR**

20.7 fb$^{-1}$

**Proof of principle for time-dependent analyses at B Factories**

G. Hamel de Monchenault – Experimental Aspects of CP Violation
Case of a Flavor Eigenstate, $f_{\text{flav}}$

$B_{\text{rec}}$ is reconstructed in a flavor-specific mode

$$\lambda_{f_{\text{flav}}} \equiv \frac{q}{p} \frac{A_{f_{\text{flav}}}}{A_{\bar{f}_{\text{flav}}}} \quad \Rightarrow \quad |\lambda_{f_{\text{flav}}}| \ll 1$$

Two categories of events:

- **UnMixed** (+): $f_{\text{flav}}$ and $f_{\text{tag}}$ have opposite flavor
- **Mixed** (−): $f_{\text{flav}}$ and $f_{\text{tag}}$ have same flavor

**perfect**

- flavor tagging
- &
- time resolution

**unmixed**

rate

$$\approx \frac{1}{\Gamma} e^{-\Gamma|\Delta t|} \{ 1 \pm \cos(\Delta m \Delta t) \}$$

**realistic**

- mis-tagging probability
- &
- finite time resolution

**mixed**
hadronic sample

\[ \pi / \Delta m_d \]

29.7 fb\(^{-1} \)
Sample used to determine from the data the probabilities of incorrect $B$-flavor tagging and parameters of the time-resolution function.

\[ a_{\text{mix}}(\Delta t) \sim (1 - 2\omega) \cos(\Delta m \Delta t) \otimes R(\Delta t) \]

(very) simplified fit function

\[ \sim 1 - 2\omega \]

hadronic sample

folded asymmetry

\[ \sim \pi / \Delta m_d \]
B_{rec} is reconstructed in a CP final state

\[ \lambda_{f_{CP}} \equiv \frac{q}{p} \frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} \] complex CP-parameter characterizes interference between decay with or without mixing

\[ |\lambda_{f_{CP}}| \approx 1 \]

\[ \begin{aligned} C_{f_{CP}} &\approx 0 \\ S_{f_{CP}} &\approx \text{Im} \lambda_{f_{CP}} \end{aligned} \]

- **perfect** flavor tagging & time resolution
- **realistic** mis-tagging probability & finite time resolution

\[ \text{rate} \approx \frac{1}{\Gamma} e^{-\Gamma |\Delta t|} \{ 1 \pm \text{Im} \lambda_{f_{CP}} \times \sin(\Delta m \Delta t) \} \]
$\sin 2\beta = 0.741 \pm 0.067_{(\text{stat})} \pm 0.033_{(\text{syst})}$

$\lambda_{J/\psi K_S^0} = -e^{-2i\beta}$

$\lambda_{J/\psi K_L^0} = +e^{-2i\beta}$
Control Sample: Flavor Specific

expect no "CP" asymmetry

Input $B_{flav}$ sample to CP fit

consistent with no asymmetry
same conclusion with charged sample
Pure Gold: Lepton Tags

\[ e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B_{\text{rec}} B_{\text{tag}} \]

\[ B_{\text{rec}} \rightarrow J/\psi K^0, \ldots \]

\[ B_{\text{tag}} \rightarrow \ell^+ X \]

\[ B_{\text{tag}} \rightarrow \ell^- X \]

\[ \text{N(BB pairs)} = 88 \text{ million!} \]

\[ \sin 2\beta = 0.79 \pm 0.11 \]
**sin2β per Charmonium Mode**

Very good consistency between the various measurements.
Belle LP2003, 140/fb

![Graph showing raw asymmetry](image)

\[ CP = +1 \] sample
\[ (c\bar{c})K_S^0 \]
\[ \sin 2\beta = 0.73 \pm 0.06 \]

\[ CP = -1 \] sample
\[ J/\psi K_L^0 \]
\[ \sin 2\beta = 0.80 \pm 0.13 \]

\[ \sin 2\beta = 0.733 \pm 0.057 \pm 0.028 \]
Precision Test of the KM Model

Main experimental constraints on the apex of the UT

- **Indirect CP violation** in the kaon system
- Measurements of $|V_{ub}|$ (b → u transitions)
- $B^0$ mixing frequency and ratio of $B_s$ to $B^0$ mixing frequencies

remarkable consistency!

$$\sin 2\beta_{\text{indirect}} = 0.715 \pm 0.055$$

World average (*BABAR*+Belle+...)

$$\sin 2\beta = 0.739 \pm 0.048$$

*Heavy Flavor Averaging Group LP 2003*
Search for Direct CPV in $J/\psi K$

Search for direct CP Violation in the Golden Sample

from $C_{J/\psi K_S}$ and $S_{J/\psi K_S}$, measure:

$$|\lambda_{J/\psi K_S}| = 0.948 \pm 0.051 \pm 0.030$$  \hspace{1cm} \text{BABAR}$$

$$|\lambda_{(c\bar{c})K_S}| = 1.007 \pm 0.041 \text{ (stat)}$$  \hspace{1cm} \text{Belle}$$

In fact: cannot disentangle direct CPV from indirect CPV in mixing with this measurement

consistent with no direct CP violation

Search for direct CP violation in isospin-related charged mode

in 20.7 fb$^{-1}$ select $\sim 1300$ candidates

$$A_{J/\psi K} = \frac{N(J/\psi K^-) - N(J/\psi K^+)}{N(J/\psi K^-) + N(J/\psi K^+)}$$

$$A_{J/\psi K} = 0.003 \pm 0.030 \text{ (stat)} \pm 0.004 \text{ (syst)}$$

again, no hint of direct CP violation...

Search for Indirect $CP$ Violation

Study asymmetry in same-sign dilepton sample

$$a_T^{\text{exp}}(\Delta T) = \frac{\dot{N}(\ell^+\ell^+, \Delta t) - \dot{N}(\ell^-\ell^-, \Delta t)}{\dot{N}(\ell^+\ell^+ , \Delta t) + \dot{N}(\ell^-\ell^-, \Delta t)} = a_T \times \frac{S(\Delta t)}{S(\Delta t) + B(\Delta t)}$$

with

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

**BABAR**

Sample backgrounds $B(\Delta t)$

Signal $S(\Delta t)$

20381 events

Measurement region > 200$\mu$m

$$a_T = (0.5 \pm 1.2 \pm 1.4)\%$$


previous (less precise) studies by OPAL, ALEPH, CLEO
Limit on $\Delta \Gamma$ & Search for $CP$, $T$, and $CPT$ Violation in Mixing

Using the Hadronic Sample (CP + Flavor Samples)

- **Simultaneous fit** to time-dependence of CP Sample and Flavor Sample, including tagged and untagged events.

- No assumption made on width difference, indirect $CP$ violation, direct $CP$ violation, $CPT$ conservation.
  
  - Exploit all the information from the time distribution.
  - Prototype of future analyses in BABAR for the simultaneous determination of lifetimes, mixing and time-dependent $CP$ asymmetries.

- Subtle effects to deal with:
  - Detector charge asymmetries
  - Doubly-CKM-Suppressed Decays (including interference rec/tag sides)

Hadronic sample: not as statistically powerful as the dilepton sample for study of $CP$ and $CPT$ in mixing, but complementary.

Best way to deal with subtle correlations.
Doubly CKM-Suppressed Decays

\( B \rightarrow DX \) decays receive contribution from \( b \rightarrow u \) transitions at \( O(10^{-4}) \)

\[
\begin{align*}
B^0 & \left\{ \begin{array}{c}
\bar{b} \\
 d
\end{array} \right\} \xrightarrow{W^+} \left\{ \begin{array}{c}
\bar{c} \\
 d
\end{array} \right\} \pi^+ \\
& \sim V_{ub}^* V_{cd} / V_{cb}^* V_{ud} \sim 0.02
\end{align*}
\]

On the rec side

Exploit interference
\( B^0 \rightarrow D^{(*)-} \pi^+ \) \( \xrightarrow{\text{relative weak phase}} B^0 \rightarrow \overline{B}^0 \rightarrow \pi^+ D^{(*)-} \sim 2\beta + \gamma \)

Very small time-dependent asymmetry
exclusive and semi-inclusive analyses
Unknown amplitude ratio and strong phase
need experimental determination

Similarly:
\( B_s (\overline{B}_s) \rightarrow D_s^- K^+ \)
promising way to measure \( \sin(\gamma) \) at LHCb/BTeV

G. Hamel de Monchenault – Experimental Aspects of CP Violation
Doubly CKM-Suppressed Decays

On the tag side

Effect of $b \to u$ is small and partially accounted for by measured mis-tag rates

- affects only kaon tags ($\to$ wrong-sign kaons), lepton tags unaffected

Residual time-dependent interference effect

- corrections on $C_{J/\psi K_S}$ and $S_{J/\psi K_S}$ that depend for each tagging mode on the size and phase of the amplitude ratio

Systematic errors

$$\sigma_{DCKM}(\sin 2\beta) \approx 0.008$$

$$\sigma_{DCKM}(|\lambda_{J/\psi K_S}|) \approx 0.024$$

marginal (total syst. 0.034)

dominant (total syst. 0.030)
Back to Time-Dependent Rates

Differential event rate, as a function of the difference between the proper decay times of the two B mesons in the final state

\[
\frac{d}{d\Delta t} \mathcal{N}(\Upsilon(4S) \to B\bar{B} \to f_{\text{tag}}, f_{\text{rec}}) \propto \frac{1}{\Gamma} e^{-\Gamma|\Delta t|} \left\{ \cosh \left( \frac{\Delta \Gamma \Delta t}{2} \right) + \sigma \sqrt{1 - T_{f_{\text{tag}}, f_{\text{rec}}}^2} \sinh \left( \frac{\Delta \Gamma \Delta t}{2} \right) \right. \\
\left. - C_{f_{\text{tag}}, f_{\text{rec}}} \times \cos(\Delta m \Delta t) + S_{f_{\text{tag}}, f_{\text{rec}}} \times \sin(\Delta m \Delta t) \right\}
\]

with

\[
C_{f_{\text{tag}}, f_{\text{rec}}} = \frac{|a_m|^2 - |a_u|^2}{|a_m|^2 + |a_u|^2} \quad \quad S_{f_{\text{tag}}, f_{\text{rec}}} = \frac{2 \text{Im}(a_u^*a_m)}{|a_m|^2 + |a_u|^2}
\]

and

\[
T_{f_{\text{tag}}, f_{\text{rec}}}^2 \equiv C_{f_{\text{tag}}, f_{\text{rec}}}^2 + S_{f_{\text{tag}}, f_{\text{rec}}}^2 \leq 1
\]

let \( \Delta \Gamma \neq 0 \)

now, we have

\[
a_u \equiv A_{f_{\text{tag}}}A_{f_{\text{rec}}} - A_{f_{\text{tag}}} \bar{A}_{f_{\text{rec}}}
\]

\[
a_m \equiv \sqrt{1 - z^2} \left( \frac{q}{p} A_{f_{\text{tag}}} \bar{A}_{f_{\text{rec}}} - \frac{p}{q} A_{f_{\text{tag}}} A_{f_{\text{rec}}} \right) + z \left( A_{f_{\text{tag}}} A_{f_{\text{rec}}} + A_{f_{\text{tag}}} \bar{A}_{f_{\text{rec}}} \right)
\]

Life seems to be significantly more complicated!

fortunately, fitted quantities largely uncorrelated

G. Hamel de Monchenault – Experimental Aspects of CP Violation
Results of Full Time-Dependent Fit

Preliminary results

\[
\begin{align*}
\text{sign}(\text{Re } \lambda_{CP}) \times \Delta \Gamma / \Gamma &= -0.008 \pm 0.037 \pm 0.018 \quad [\pm 0.084, +0.068] \\
|q/p| &= 1.029 \pm 0.013 \pm 0.011 \quad [+1.001, +1.057] \\
(\text{Re } \lambda_{CP} / |\lambda_{CP}|) \times \text{Re } z &= 0.014 \pm 0.035 \pm 0.034 \quad [-0.072, +0.101] \\
\text{Im } z &= 0.038 \pm 0.029 \pm 0.025 \quad [-0.028, +0.104]
\end{align*}
\]

- Direct limit on $\Delta \Gamma / \Gamma$
- Test of CPT invariance
- Study for indirect $T/CP$ violation in $B$ mixing

Cross-checks

\[
\begin{align*}
\Delta m & \quad \sin 2\beta \quad \text{consistent with published values} \\
|\overline{A}_{CP} / A_{CP}| & \quad \text{consistent with no direct CPV (4.5%)}
\end{align*}
\]

G. Hamel de Monchenault – Experimental Aspects of CP Violation
Constraints on $CP/T$ and $CPT$ in Mixing
Promising ways to look for New Physics

- Measure/constrain angle $\alpha$
  - $B \to \pi/\rho/\omega \ell\nu, \ldots$
  - $B \to D K^{(*)}$
  - $B \to D K_S^{0}$
  - $B \to K\pi$
  - $B \to D^*\pi$

- Measure/constrain angle $\gamma$
  - $B \to \pi^+\pi^-$
  - $B \to \rho^+\rho^-$

- Measure $\sin2\beta$ in several decays sensitive to different short-distance physics
  - $B^0 \leftrightarrow \bar{B}^0$, $\Delta m (\phi_M = -\beta)$
  - $B \to K^*\gamma + \rho/\omega \gamma$

- Improve UT side measurements
  - $B \to J/\psi \ K_S^{0}$
  - $b \to c \bar{c} \ s$
  - $B \to \phi \ K_S^{0}$
  - $b \to s \bar{s} \ s$
  - $B \to D^{*\pm} D^{\mp}$
  - $b \to c \bar{c} \ d$
  - $B \to J/\psi \ \pi^0$
**B → φK**

- **B± → φ K±**
  - Beam energy-substituted mass
  - ~175 events

- **B → φ K^+_S**
  - KK mass
  - ~50 events

- **φ → K^+K^-**
  - φ helicity

- **Internal penguin**

- **Flavor-singlet penguin**

**Pure penguin decay, therefore potentially a place to look for New Physics**

- **In SM, expect**  \[ S_{φK^0_S} = \sin 2β \]
Belle mostly penguin, possible tree pollution

Strongly disagrees with Standard Model expectation!
First evidence for New Physics?

Belle 2003 (preliminary)
\[ S_{\phi K_S^0} = -0.96 \pm 0.50 \pm 0.09 \]
\[ C_{\phi K_S^0} = +0.15 \pm 0.29 \pm 0.07 \]

BABAR 2003 (preliminary)
\[ S_{\phi K_S^0} = +0.45 \pm 0.43 \pm 0.07 \]
\[ C_{\phi K_S^0} = -0.38 \pm 0.37 \pm 0.12 \]

In agreement with SM Evidence for New Physics not confirmed by BABAR
Hint of New Physics?

$B \rightarrow \phi K^0_S$

Belle at Lepton-Photon 2003

Standard Model expectation

-2ln(L/L_{max}) vs S(\phi K^0_S)

likelihood function from fit

unphysical region

B^0 \rightarrow \phi K^0_S

bad tags

0.0 < r \leq 0.5

good tags

0.5 < r \leq 1.0

Raw Asymmetry vs \Delta t (ps)
### Charmonium versus s Penguin

<table>
<thead>
<tr>
<th>Charmonium Modes</th>
<th>( \sin(2\beta_{\text{eff}}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPAL 98</td>
<td>0.736 ± 0.049</td>
</tr>
<tr>
<td>ALEPH 00</td>
<td>0.733 ± 0.057 ± 0.028</td>
</tr>
<tr>
<td>CDF 00</td>
<td>0.79 ± 0.44</td>
</tr>
<tr>
<td>BABAR 02</td>
<td>0.741 ± 0.067 ± 0.034</td>
</tr>
<tr>
<td>Belle 03</td>
<td>(-0.96 ± 0.05)</td>
</tr>
<tr>
<td>Average (charmonium)</td>
<td>(0.736 ± 0.049)</td>
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</thead>
<tbody>
<tr>
<td>BABAR 03</td>
<td>0.02 ± 0.34 ± 0.03</td>
</tr>
<tr>
<td>Belle 03</td>
<td>0.43 ± 0.27 ± 0.05</td>
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<th>( K K K_S^0 )</th>
<th>( \sin(2\beta_{\text{eff}}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle 03</td>
<td>0.51 ± 0.26 ± 0.05</td>
</tr>
<tr>
<td>Average (s penguin)</td>
<td>(0.24 ± 0.15)</td>
</tr>
<tr>
<td>Average (All)</td>
<td>(0.695 ± 0.047)</td>
</tr>
</tbody>
</table>
$b \rightarrow c \bar{c} d$

$\bar{B}^0 \left\{ \begin{array}{c} b \rightarrow c \bar{c} d \\
\bar{d} \rightarrow \bar{c} c d \end{array} \right\}$

$J/\psi$

$\pi^0$

Tree: color- and Cabibbo-suppressed

Penguin: competing weak phase?

If penguin contribution negligible

$S_{J/\psi \pi^0} = - \sin 2\beta$

$\bar{B}^0 \left\{ \begin{array}{c} b \rightarrow c \bar{c} d \\
\bar{d} \rightarrow \bar{c} c d \end{array} \right\}$

$D^{(*)-}$

$D^{(*)+}$

Cabibbo-suppressed tree

$b \rightarrow d$ penguin

$D^* - D^+$ not CP eigenstate

If penguins are negligible

$C_{-+} = C_{+-} = 0$

$S_{--} = S_{+-} = - \sin 2\beta$
\[ B \rightarrow D^{*+}D^{*-} \]

\[ b \rightarrow c \bar{c} d \]

★ Sample  \[ N_{D^{*+}D^{*-}} = 126 \pm 13 \]
(before flavor-tagging)

★ Vector-Vector decay (L=0,1,2)
possible mix of CP = +1 and CP = −1

Transversity analysis
 mostly CP-even

\[ R_\perp = 0.07 \pm 0.06 \text{ (stat) } \pm 0.03 \text{ (syst)} \]

define CP-even parameter \( (\lambda_{D^*D^*})_+ \)

★ If penguin contribution negligible
\[ \text{Im} (\lambda_{D^*D^*})_+ = -\sin 2\beta \]
\[ |(\lambda_{D^*D^*})_+| = 1 \]
$K_s \pi^0$ Time-Dependent

$b \rightarrow d\bar{d}s$

$B \rightarrow K^0_S \pi^0$

process dominated by $b \rightarrow d\bar{d}s$ Penguin

possible small pollution by CKM and color-suppressed $b \rightarrow u\bar{u}s$ Tree

$S^0_{K_S^0 \pi^0} = 0.48^{+0.38}_{-0.47} \pm 0.11$

$C^0_{K_S^0 \pi^0} = 0.40^{+0.27}_{-0.28} \pm 0.10$

$S_{K_S^0 \pi^0}$ (fixing $C_{K_S^0 \pi^0} = 0$) = $0.41^{+0.41}_{-0.48} \pm 0.11$

consistent with sin2$\beta$ (Standard Model expectation)

BABAR, 113/fb (124 million BB pairs)

$N_{K_S^0 \pi^0} = 123 \pm 16$

(needs specific vertexing)
Comparison of Various “sin2β”

very promising way to contradict the Standard Model
(obviously more statistics needed!)