The Search for Time-Dependent $CP$-Asymmetries in the Neutral $B$-Meson System

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The Nature of Particle Physics

- As particle physicists, we study the fundamental constituents of matter and their interactions.

- Our understanding of these issues is built upon certain fundamental principles
  - The laws of physics are the same everywhere
  - The laws of physics are the same at all times
  - The laws of physics are the same in all inertial reference frames (the special theory of relativity)
  - The laws of physics should describe how the wave function of a system evolves in time (quantum mechanics)

- These principles do not tell us what types of fundamental constituents exist, or how they interact, but they restrict the types of theories that are allowed.

- In the past 30 years, we have developed a Standard Model of particle physics to describe the electromagnetic, weak nuclear, and strong nuclear interactions of constituents in terms of quantum field theories.
Special Relativity

- **Energy and momentum**
  - Energy and momentum form a four-vector \((t, x, y, z)\). The Lorentz invariant quantity defined by energy and momentum is mass:
    \[
    E^2 - p_x^2 c^2 - p_y^2 c^2 - p_z^2 c^2 = m^2 c^4
    \]
  - For the special case when an object is at rest so that its momentum is zero
    \[
    E = mc^2
    \]

- When a particle decays in laboratory, we can measure the energy and momenta of its decay products (its daughter particles), albeit imperfectly.

- The energy of the parent is exactly the sum of the energies of its daughters energies. Similarly, each component of the parent’s momentum is the sum of the corresponding components of the daughters’ momenta.

From the reconstructed energy and momentum of the candidate parent, we can calculate its invariant mass
Classical Field Theory (E&M)

Coulomb’s Law
\[ F_T = \frac{q_T q_i}{r_i^2} \hat{r}_i \]

Electric Field
\[ F_T = q_T \mathbf{E} \]

Magnetic Field
\[ F_T = q_T \mathbf{v}_T \times \mathbf{B} \]

\[(\mathbf{E}, \mathbf{B}) \longrightarrow (\phi, \mathbf{A}) \longrightarrow A^\mu \]

\[ \mathbf{E} = -\nabla \phi - \frac{d\mathbf{A}}{dt}; \quad \mathbf{B} = \nabla \times \mathbf{A} \]

Maxwell’s Equations:

\[ \nabla \cdot \mathbf{E} = \rho/\epsilon \quad \nabla \cdot \mathbf{B} = 0 \]

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \nabla \times \mathbf{B} = \mu \mathbf{J} + \mu_0 \epsilon \frac{\partial \mathbf{E}}{\partial t} \]

couple changing electric and magnetic fields

and

predict that accelerating charges produce electromagnetic radiation which travels at a fixed speed in vacuum, which is the speed of light.
Fields and Quanta

Electromagnetic fields transfer energy and momenta from one charged particle to another.

Electromagnetic energy/momentum is quantized:

\[ E = h \nu \]
\[ P = h \nu / c \]

These quanta are called photons:

\[ \gamma \]

Relativistic Quantum Field Theory:

\[ A^\mu \leftrightarrow \gamma \]

Perturbation Theory — Feynman Diagrams

\[ \mathcal{M} \sim e \frac{1}{q^2} e \sim \frac{\alpha}{q^2} \]
\[ \sigma, \Gamma \sim |\mathcal{M}|^2 \]
The Strong Nuclear Interactions of Quarks and Gluons

\[
\begin{pmatrix}
  u \\
  d
\end{pmatrix} \quad \begin{pmatrix}
  c \\
  s
\end{pmatrix} \quad \begin{pmatrix}
  t \\
  b
\end{pmatrix} \quad Q = +2/3 \\
Q = -1/3
\]

Each quark carries one of three strong charges, and each antiquark carries an anticharge. For convenience, we call these charges colors:

\[ u_r, u_g, u_b \quad \bar{u}_r, \bar{u}_g, \bar{u}_b \]

Strong Force, Color Charges

\[ \Rightarrow \text{Strong Field} \iff \text{gluons} \]

\[ \begin{cases}
  \text{gluons carry} \\
  \text{color-anticolor} \\
  \text{quantum numbers}
\end{cases} \]

\[ \alpha_s = \frac{g^2}{4\pi} \sim \frac{12\pi}{(33 - 2n_f)/\log(Q^2/\Lambda^2)} \]

\[ \Lambda \sim 240 \text{MeV} \]

low \( Q^2, \alpha_s \to 1 \), infrared slavery
high \( Q^2, \alpha_s \ll 1 \), ultraviolet freedom
Baryons and Mesons

- Quarks are never observed as free particles.
  - **baryons** consist of three quarks, each with a different color (strong nuclear) charge
    
    - proton = \( uud \)
    - neutron = \( udd \)
  - **mesons** consist of quark-antiquark pairs with canceling color-anticolor charges
    
    \[
    \begin{align*}
    \pi^+ &= u\bar{d}; & D^0 &= c\bar{u} \\
    K^- &= s\bar{u}; & B^0 &= \bar{b}d \\
    K^0 &= s\bar{d}; & J/\Psi &= c\bar{c} \\
    K^0_S &= (s\bar{d} + s\bar{d}) / \sqrt{2}
    \end{align*}
    \]

- Baryons and mesons (collectively called **hadrons**) have net color charge zero.

- A Van der Waals-type of strong interaction creates an attractive force which extends a short distance to bind nucleii together.
Weak Charged Current Interactions

As a first approximation, the weak charged current interaction couples fermions of the same generation. The Standard Model explains coupling between quark generations in terms of the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

\[
\begin{pmatrix}
d \\ s \\ b
\end{pmatrix} \rightarrow \begin{pmatrix} d' \\ s' \\ b'
\end{pmatrix} =
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
d \\ s \\ b
\end{pmatrix}
\]

This matrix is approximately diagonal, but it allows for mixing between generations and introduces a relative phase in the quantum mechanical amplitudes for decay of some particles and their antiparticles.
Particle-Antiparticle Mixing

A second order weak charged current process, often referred to as a box diagram amplitude, provides a mechanism by which \( B^0 \) particles oscillate into \( \bar{B}^0 \) antiparticles, and vice versa.

- Particles decay exponentially with characteristic times
  \[ N(t) = N_0 e^{-t/\tau} \]

- Neutral \( B \)-mesons mix sinusoidally with characteristic times
  \[ N_{mix} = N_0 e^{-t/\tau} \sin \left( t/t_{mix} \right) \]

- Experimentally,
  \[ t_{mix} \approx 1.4 \tau, \]
  which makes its observation relatively easy.
CP Violation

- Both $B^0$ particles and $B^0$ antiparticle can decay to common final states, as indicated below.

- The $J/\Psi K^0_S$ final state is invariant under charge and parity conjugation; that is, it remains $J/\Psi K^0_S$.

- The Standard Model predicts that the CKM phase will produce a time-dependent asymmetry in the decay rates of the $B^0$ and $\bar{B}^0$ to this final state, and that the asymmetry will vary sinusoidally.
From flavor eigenstates to weak eigenstates

The time evolution of a $B^0$ or $\bar{B}^0$ is determined by Schrödinger’s Equation:

$$i \frac{\partial}{\partial t} \begin{pmatrix} |B^0\rangle \\ |\bar{B}^0\rangle \end{pmatrix} = \begin{bmatrix} M - i\Gamma/2 & M_{12} - i\Gamma_{12}/2 \\ M_{12}^* - i\Gamma_{12}^*/2 & M - i\Gamma/2 \end{bmatrix} \begin{pmatrix} |B^0\rangle \\ |\bar{B}^0\rangle \end{pmatrix}$$

With

$$H = a I + b_x \sigma_x + b_y \sigma_y + b_z \sigma_z,$$

$$CP \iff \sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

Diagonalizing $H$, Schrödinger’s Equation has solutions of the form $e^{-i\omega t} = e^{-i(m - i\gamma/2)t}$ with eigenvalues

$$m_{H,L} = M \pm \text{Re} [(M_{12} - i\Gamma_{12})(M_{12}^* - i\Gamma_{12}^*)]^{1/2}$$

$$\gamma_{H,L} = \Gamma \pm \text{Im} [(M_{12} - i\Gamma_{12})(M_{12}^* - i\Gamma_{12}^*)]^{1/2}$$

for eigenstates

$$|B_L\rangle = p |B^0\rangle + q |\bar{B}^0\rangle$$

$$|B_H\rangle = p |B^0\rangle - q |\bar{B}^0\rangle$$

with

$$\frac{q}{p} = \frac{1 + \epsilon_B}{1 - \epsilon_B} = \left(\frac{M_{12}^* - i\Gamma_{12}^*}{M_{12} - i\Gamma_{12}}\right)^{1/2} = e^{2i\phi_M} \left(\frac{\sqrt{M_{12}^*}}{M_{12}}\right)$$
Mixing Formalism

\(|B^\circ(t)\rangle\) and \(|\bar{B}^\circ(t)\rangle\) can be written in terms of the weak eigenstates:

\[
|B^\circ(t)\rangle = \frac{1}{\sqrt{2}} \left[ |B_L\rangle e^{-(\Gamma_H/2 + im_H)t} + |B_H\rangle e^{-(\Gamma_L/2 + im_L)t} \right]
\]

\[
= e^{-(\Gamma/2 - im)t} \left[ \cos \left( \frac{\Delta m}{2} t \right) |B^\circ\rangle + \left( \frac{q}{p} \right) i \sin \left( \frac{\Delta m}{2} t \right) |\bar{B}^\circ\rangle \right]
\]

\[
|\bar{B}^\circ(t)\rangle = \frac{1}{\sqrt{2}} \left[ |B_L\rangle e^{-(\Gamma_H/2 + im_H)t} - |B_H\rangle e^{-(\Gamma_L/2 + im_L)t} \right]
\]

\[
= e^{-(\Gamma/2 - im)t} \left[ \left( \frac{q}{p} \right) i \sin \left( \frac{\Delta m}{2} t \right) |B^\circ\rangle + \cos \left( \frac{\Delta m}{2} t \right) |\bar{B}^\circ\rangle \right]
\]

where \(m \equiv (m_H + m_L)/2\) and \(\Gamma = \Gamma_H = \Gamma_L\).

For any final state \(f\), there are now four decay amplitudes:

\[
\langle f|\mathcal{H}|B^\circ(t)\rangle = e^{-(\Gamma/2 - im)t} \left[ \mathcal{A}_f \cos \left( \frac{\Delta m}{2} t \right) + \mathcal{A}_f \left( \frac{q}{p} \right) i \sin \left( \frac{\Delta m}{2} t \right) \right]
\]

\[
\langle f|\mathcal{H}|\bar{B}^\circ(t)\rangle = e^{-(\Gamma/2 - im)t} \left[ \mathcal{A}_f \cos \left( \frac{\Delta m}{2} t \right) + \mathcal{A}_f \left( \frac{q}{p} \right) i \sin \left( \frac{\Delta m}{2} t \right) \right]
\]

\[
\langle f|\mathcal{H}|B^\circ(t)\rangle = e^{-(\Gamma/2 - im)t} \left[ \mathcal{A}_{\bar{f}} \left( \frac{q}{p} \right) i \sin \left( \frac{\Delta m}{2} t \right) + \mathcal{A}_{\bar{f}} \cos \left( \frac{\Delta m}{2} t \right) \right]
\]

\[
\langle f|\mathcal{H}|\bar{B}^\circ(t)\rangle = e^{-(\Gamma/2 - im)t} \left[ \mathcal{A}_{\bar{f}} \left( \frac{q}{p} \right) i \sin \left( \frac{\Delta m}{2} t \right) + \mathcal{A}_{\bar{f}} \cos \left( \frac{\Delta m}{2} t \right) \right]
\]

where the decay amplitudes for the pure \(B^\circ\) and \(\bar{B}^\circ\) states are

\[
\mathcal{A}_f \equiv \langle f|\mathcal{H}|B^\circ\rangle \quad \mathcal{A}_{\bar{f}} \equiv \langle f|\mathcal{H}|\bar{B}^\circ\rangle
\]

\[
\mathcal{A}_{\bar{f}} \equiv \langle f|\mathcal{H}|B^\circ\rangle \quad \mathcal{A}_{\bar{f}} \equiv \langle f|\mathcal{H}|\bar{B}^\circ\rangle
\]

The decay rate to a particular final state depends on all the amplitudes which can produce it:

\[
\frac{d\Gamma}{dt} \propto |\sum A|^2
\]
Mixing Asymmetries

\[ A(t) \equiv \frac{d\Gamma / dt - d\Gamma^* / dt}{d\Gamma / dt + d\Gamma^* / dt} \]
\[ = \frac{(1 - |\kappa|^2) \cos(\Delta m t) - 2i \sin(\Delta m t) \text{Im}(\kappa)}{1 + |\kappa|^2} \]

where \( \kappa \equiv (q/p)(A_f / A_f) \). For \( B^\circ, \bar{B}^\circ \to CP \) eigenstates where only one tree-level amplitude contributes,

\[ \frac{A_f}{A_f} \to \frac{|A_t|e^{-i\phi_t}}{|A_t|e^{i\phi_t}} = e^{-2i\phi_t} \]

in which case the decay asymmetry becomes

\[ A(t) \to \sin(\Delta m t) \sin 2(\phi_t - \phi_m) (-1)^{CP} \]

where the superscript is the \( CP \) eigenvalue of \( f \). Experimentally, \( \zeta / f \times \Gamma \approx 0.7 \), which makes it possible to observe the time dependence of this asymmetry. The BELLE and \( \text{BABAR} \) experiments will do this using asymmetric \( e^+e^- \to \Upsilon(4S) \to B^\circ\bar{B}^\circ \) events:
Weak Phases in the Standard Model

In the Standard Model, the Cabibbo-Kobayashi-Maskawa (CKM) matrix transforms the flavor eigenstates to weak eigenstates at the quark level:

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} = \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

In general, a unitary matrix has \(N^2 \) (9) independent parameters, and \(N(N - 1)/2 \) (3) can be taken as Euler angles. The remaining parameters are phases. Of these, \(2N - 1 \) (5) are relative phases which can be absorbed in the quark fields. The CKM matrix can therefore be described in terms of three rotation angles and one phase.

\[
V_{PDG} = \begin{pmatrix}
  c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}s_{13} \\
 s_{12}s_{13} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}s_{13}
\end{pmatrix}
\]

Lincoln Wolfenstein introduced an approximation where the elements of the CKM matrix are expressed in powers of the Cabibbo angle, \(\lambda\).

\[
V_W = \begin{pmatrix}
  1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\
  \lambda & 1 - \frac{1}{2} \lambda^2 - iA^2\lambda^4\eta & A\lambda^2 \\
 A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]

The CKM matrix should be unitary:

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

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

\[ \frac{V_{ub}^*}{|\lambda V_{cb}|} \to A \lambda^2 \]

\[ \frac{V_{cs}V_{cb}}{|\lambda V_{cb}|} = 1 \]

\[ A(t) \to \sin(\Delta m t) \sin(2(\phi_t - \phi_M)) \]

\[ 2\phi_M = \text{Arg} \left( \frac{M_{12}^*}{M_{12}} \right) = \text{Arg} \left( \frac{V_{td}V_{tb}^*}{V_{tcb}V_{tbs}^*} \right) \to \text{Arg} \left( \frac{V_{td}^*}{V_{td}} \right) \]

For \( B^0 \to \Psi K_S^0 \) (BR \( \approx 3 \times 10^{-4} \)),

\[ \frac{\bar{A}_f}{A_f} \propto \left( \frac{V_{cb}V_{cs}}{V_{tcb}V_{tcs}^*} \right) \Rightarrow 2\phi_t \to 0 \]

\[ \Rightarrow 2(\phi_t - \phi_M) \to \text{Arg} \left( \frac{V_{td}^*}{V_{td}} \right) \approx 2\beta \]

Similarly,
for \( B^0 \to \pi^+\pi^- \), (BR \( \approx 2 \times 10^{-5} \)), \( \phi_M - \phi_t = -\alpha \) and
for \( B_s \to \rho^0 K^0 \), (BR \( \approx \mathcal{O}(10^{-6}) \)), \( \phi_M - \phi_t = -\gamma \).
Unitarity Triangle Parameters

In the Standard Model, $\rho$ and $\eta$ are constrained by data from $K^0$ decay ($\epsilon$), $B$ and charm decays, and from $B_d^0 - \overline{B}_d^0$ mixing. In addition, theoretical calculations of hadronic matrix elements are used. The shaded area in the figure below corresponds to that allowed for the apex of the unitarity triangle. These measurements indirectly constrain the phase the of $CKM$ matrix. But they do not establish the existence of the phase or establish the unitarity of the $CKM$ matrix. Rather, they assume these features.

Measuring the time-dependent $CP$ asymmetries in $B^0$ and $B_S$ decay can directly establish the $CKM$ phase as the origin of $CP$ violation. Checking experimentally that $\alpha + \beta + \gamma = 180^\circ$ will test the unitarity of the $CKM$ matrix. Comparing the angles derived by these $CP$ asymmetry measurements with those determined from ratios of branching ratios, the $B^0 - \overline{B}^0$ mixing rate, etc. will provide further tests of the Standard Model.
Producing B-Mesons for CP Violation Studies

- The B-factories at SLAC (California) and KEK (Japan) produce B-mesons via $e^+e^-$ annihilation.

\[
\begin{align*}
(e^+e^-) & \rightarrow \text{hadronic events} \\
& \rightarrow \upsilon(4s) \\
& \rightarrow B_0 + B_0 \\
& \rightarrow B^0 + \bar{B}^0
\end{align*}
\]

- At the upsilon(4s) resonance, $e^+e^- \rightarrow \upsilon(4s) \rightarrow B\bar{B}$, approximately 25% of all hadronic events are $B\bar{B}$. 

\[r = \frac{\#(\text{multihadron candidates})}{\#(B\bar{B})} \}

\[0.00 \rightarrow \frac{0.09}{0.05} \rightarrow \frac{0.09}{0.05}
\]

\[E_{\text{cm}} - M_{\upsilon(4s)} \text{[MeV]} \]

Physics 841, January 2001           Michael D. Sokoloff
$CP$ Asymmetries in $e^+e^- \rightarrow \Upsilon(4S)$

- The $\Upsilon(4S)$ is a pure ($CP = -1$) state. At BABAR ($BELLE$) it will be moving with $\beta\gamma = 0.56$ (0.43) along the $z$–axis.
  - The $B^o\overline{B}^o$ state is coherent until one $B$ decays.
  - At this point, one is a $B^o$ and the other a $\overline{B}^o$. For the evolution equations presented earlier, this is time $t = 0$.
  - Time $t$ is measured from $\Delta z$ between the two $B$ decay vertices. $t$ can be $< 0$ or $> 0$.
  - $\langle |\Delta z| \rangle \sim \beta\gamma c\tau_B \sim 250 \mu m$ (200 $\mu$m). Measurement errors on $\Delta z$ depend on both the tagging and $CP$ decays. The convoluted $\sigma(\Delta z)$ is typically $< 80 \mu m$.

The relative decay rates, $\Gamma(B_{CP}) \propto e^{-|\Gamma| t} [1 \pm \sin 2\beta \sin(\Delta m t)]$, for events which “start” life as $B^o (-)$ and $\overline{B}^o (+)$ assuming $\beta = 0.5$; $\Delta m/\Gamma = 0.7$.

plots courtesy of Brian Meadows
Design Parameters:

- $l = 3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- 9 GeV $e^-$ on 3.1 GeV $e^+$
- 0.75 A $e^-$ on 2.14 A $e^+$
- 1658 bunches in each ring
- Head-on collisions
The \textbf{BaBar} Detector

Measure the \textit{trajectories} and \textit{momenta} of charged particles traveling in a magnetic field.

Measure the \textit{energy} of photons and electrons.

Identify \textit{muons} which traverse large amounts of material without interacting.

Measure the \textit{speeds} of particle using Cherenkov radiation and ionization density.

\begin{itemize}
  \item \textbf{Silicon Vertex Tracker:} tracking, $\Delta z$
  \item \textbf{DIRC PID} $p/K/\pi$
  \item \textbf{Drift Chamber} tracking, $dE/dx$
  \item \textbf{Instrumented Flux Return} $\mu$, neutral hadron ID
  \item \textbf{Electromagnetic Calorimeter:} good resolution, low energy reach for $\pi^0$, $\gamma$'s
\end{itemize}

1.5T Solenoid
Silicon Vertex Tracker

- 5 double-sided layers, $\phi/z$
- $r = 32\text{mm}$ to $144\text{mm}$
- $15\mu\text{m} (\phi)$ to $19\mu\text{m} (z)$ resolution
- $60\mu\text{m}$ z vertex resolution
- radiation hard to $2\text{MRad}$

Resolution measured using cosmic rays:
The Drift Chamber

- 40 layers, alternating axial and stereo superlayers
- Low density: 80% He, 20% Isobutane, Al wires
- dE/dx resolution of 7%
- <140 mm position resolution
Particle Identification Using Ionization

- Ionization (dE/dx) is measured in each of 40 layers in the drift chamber.
- A truncated mean value is used as the best estimate of the average ionization rate.
- Recent improvements bring the average fractional resolution for Bhabhas close to the design value of 7%.
  - improved feature extraction from the digitized signals;
  - improved understanding of the gas gain;
  - Software corrections for bias due to using truncated mean, as a function of track dip angle.
The DIRC

The Detector of Internally Reflected Cherenkov Light is used to identify charged particles. The Cherenkov angle depends on the speed of the particles.

The Cherenkov angle difference for K and $\pi$ at 4 GeV/c is $\sim 6.5$ mrad. The design specifies $3\sigma$ separation at this energy.

Cherenkov angle resolution should be 2.6 mrad for backward positrons from Bhabha events. It is approaching the design specification.
Electromagnetic Calorimeter

- 7000 CsI crystals in barrel and forward endcap
- Reconstruct photons above 20 MeV
- Energy resolution of $\frac{\sigma(E)}{E} = 1\% / \sqrt[4]{E(\text{GeV})} \oplus 1.2\%$
Finding the Constituents
(July 2000 data)

The first $B$-meson decay we will try to study is

$$B^0 \rightarrow J/\Psi K_S^0$$

with

$$J/\Psi \rightarrow \mu^+\mu^-$$

or

$$J/\Psi \rightarrow e^+e^-$$

and

$$K_S^0 \rightarrow \pi^+\pi^-$$
A Sample Event

$B^0 \rightarrow J/\psi \ K^0_s \ \text{with} \ K^0_s \rightarrow \pi \ \bar{\pi}^+$
Summer 2000 Results

$B^0 \to J/\psi \ K^0_s$ with $K^0_s \to \pi^+\pi$

Flavor-tagged sample of $B^0 \to J/\psi \ K^0_s$ used in $\sin2\beta$ analysis

Combined with analogous sample of $B^0 \to J/\psi(2S) \ K^0_s$ for the Osaka result:

$$\sin2\beta = +0.12 \pm 0.37 \pm 0.09$$
Summer 2000 Results & Projections for Full First Run

Some projected results for the full 23 fb\(^{-1}\) sample
(Estimated errors for combined results shown in brown)

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<td>(\tau_{B^0}) (ps)</td>
<td></td>
<td>±0.014 (0.9%)</td>
<td>±0.022(1.5%)</td>
<td>1.548 ± 0.032(2.1%)</td>
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<td>1.506 ± 0.052</td>
<td>±0.030(2.0%)</td>
<td>±0.016(1.1%)</td>
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</tr>
<tr>
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<td>±0.029</td>
<td>±0.022</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>(\tau_{B^+}) (ps)</td>
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<td>±0.018 (1.1%)</td>
<td>±0.027(1.7%)</td>
<td>1.653 ± 0.028(1.7%)</td>
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<tr>
<td>(\Delta m_d) (h ps(^{-1}))</td>
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<td></td>
<td>±0.011</td>
<td>±0.018</td>
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<tr>
<td>sin2(\beta)</td>
<td>0.12 ± 0.37</td>
<td>±0.2</td>
<td>?</td>
<td>0.9 ± 0.4</td>
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</tbody>
</table>

(sin2\(\beta\) projection assumes additional modes will be used)
Summary and Conclusions
[with December, 2000 updates]

- The Standard Model of particle physics predicts time-dependent asymmetries in the decay rates for $B^0 \rightarrow J/\psi \ K^0_s$ and its charge conjugate decay.

- B-factories (PEP-II at SLAC and KEK-B in Japan) are designed to produce $30 \times 10^6 \ b\bar{b}$ pairs per year. [3.6 x $10^6$ produced by PEP-II in the month of October, 2000]

- The BaBar experiment at SLAC is able to detect B-meson decays with good efficiency and good resolution. BaBar’s detectors are rapidly approaching design specifications. BaBar is on schedule to measure time-dependent $CP$-violation within a year ($\approx 200$ reconstructed with very little background). [Approx. 140 reconstructed as of July, 2000.] Peak luminosity is already $10^{33} \ cm^{-2} \ sec^{-1}$. [It was greater than $3 \times 10^{33} \ cm^{-2} \ sec^{-1}$ as of October, 2000]

- BaBar should be able to measure $CP$-violation in many decay modes in the next few years, enough to test the Standard Model (thousands in $B^0 \rightarrow J/\psi \ K^0_s$ and thousands in additional decay modes).

- Understanding $CP$-violation in neutral B-meson decays may provide a better understanding of the origin of the most obvious matter-antimatter asymmetry in the universe -- the predominance of matter over antimatter.