CP Violation at BaBar & Belle

Sören Prell
Iowa State University

31st SLAC Summer Institute
Topical Conference
August 6-8, 2003
Outline

• CP violation in the Standard Model
• The BaBar and Belle detectors
• CP violation measurements
  – $\beta / \phi_1$
    • $B \to J/\psi K_s$
    • $B \to J/\psi \pi^0, D^*D, D^*D^*$
    • $B \to \phi K_s, \eta' K_s$
  – $\alpha / \phi_2$
    • $B \to \pi\pi$
    • $B \to \rho\pi$
  – $\gamma / \phi_3$
    • $B \to DK$
    • $B \to D^{(*)}\pi$

• Summary and Conclusion
Macroscopic CP Violation

- Universe is matter dominated
  - Where has the anti-matter gone?

- Generation of a net baryon number requires (Sakharov conditions):
  1. Baryon number violating processes (e.g. proton decay)
  2. Non-equilibrium state during the expansion
  3. C and CP symmetry violation (different decay rates for particles and antiparticles)

- How is CP violation described in the Standard Model and how do we measure it?

\[ \Rightarrow \frac{N(\text{anti-Baryon})}{N(\text{Baryon})} \leq 10^{-4} - 10^{-6} \]
The Weak Interactions of Quarks

- Coupling strength at vertex is $gV_{ij}$
  - universal Fermi weak coupling $g$
  - $V_{ij}$ depends on quark flavors $i,j$
  - complex phase $\eta$ leads to different $b \rightarrow u$ and $t \rightarrow d$ amplitudes for quarks and anti-quarks

$$V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} e^{-i\gamma} \\
-V_{cd} & V_{cs} & V_{cb} \\
V_{td} e^{-i\beta} & -V_{ts} & V_{tb}
\end{pmatrix}$$

\[\begin{array}{ccc}
1-\lambda^2/2 & \lambda & A\lambda^3(\rho-\eta)
\\
-\lambda & 1-\lambda^2/2 & A\lambda^2
\\
A\lambda^3(1-\rho-\eta) & -A\lambda^2 & 1
\end{array}\] + $O(\lambda^4)$

(Cabbibo-Kobayashi-Maskawa matrix)

$\lambda = 0.221 \pm 0.002$
$A = 0.83 \pm 0.06$
$\bar{\rho} = 0.22 \pm 0.10$
$\bar{\eta} = 0.35 \pm 0.05$
The B Unitarity Triangle

\[ V^\dagger V = 1 \rightarrow V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0 \]

- angles \( \alpha, \beta \) and \( \gamma \) in SM related to single weak phase \( \eta \)
- test SM by over-constraining the Unitarity Triangle
Is CKM matrix the (only) source of $\mathcal{C}\mathcal{P}$?

• Why should we expect other (New Physics) mechanisms for $\mathcal{C}\mathcal{P}$?
  - difficult for CKM CP violation to generate the observed matter/anti-matter asymmetry in the universe

• There must be something else!
CP Observable

- Need non-zero expectation value of a CP odd observable
  - requires two interfering amplitudes

- CP violation in B decays manifests itself in
  - Different (time-integrated or time-dependent) rates of decay for $B$ and $\bar{B}$ for specific final states

- Sometimes easy to interpret as some weak phase, sometimes interpretation hard (direct CP violation, penguin pollution, etc.)
CP in Decay (direct CP)

- Different decay rates for $B \rightarrow f$ and $\bar{B} \rightarrow \bar{f}$

\[
A_{\text{CP}} = \frac{N(B \rightarrow f') - N(\bar{B} \rightarrow \bar{f}')}{N(B \rightarrow f') + N(\bar{B} \rightarrow \bar{f}')} 
\]

- Need 2 decay amplitudes with different weak phase and different strong phase:

Difficult to interpret: measure $a$ and $\bar{a}$, but need $a_1$, $a_2$, $\phi$, $\delta$

No CP violation

Direct CP violation!
CP violation arises from interference of 2 amplitudes with different phases

- In B decays, we have 2 types of amplitudes:
  - Decay amplitudes
  - Mixing amplitudes
- 3 possible manifestations of CP violation:
  - Interference between 2 decay amplitudes (Direct CP violation)
  - Interference between 2 mixing amplitudes
  - Interference between mixed and unmixed decays
$B^0 \leftrightarrow \bar{B}^0$ Oscillations

$B^0 \leftrightarrow \bar{B}^0$ Oscillation via 2nd order weak transition

- Involve $V_{td} = |V_{td}| e^{i \beta}$

$\text{Prob}(B^0 \rightarrow B^0) \propto \exp(-t/\tau_B)(1 + \cos \Delta m t)$

$\text{Prob}(B^0 \rightarrow \bar{B}^0) \propto \exp(-t/\tau_B)(1 - \cos \Delta m t)$

$\Delta m_d = m_{B_H} - m_{B_L}$

Start with a pure beam of $B^0$ mesons → a $\bar{B}^0$ component develops with time

Proper time (ps)
B^0\bar{B}^0 Oscillation Measurements

\[ A_{\text{mixing}}(\Delta t) = \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})} \approx (1 - 2\langle w \rangle) \times \cos(\Delta m \Delta t) \]

B^0\bar{B}^0 oscillation frequency precisely determined from flavor specific final states:

\[ \Delta m = 0.502 \pm 0.006 \text{ ps}^{-1} \]

(HFAG average)
Interference of 2 different Paths to the same Final State induced by B Mixing

- Consider pure $B^0$ initial state ($\bar{B}^0$ is the same)

$$\Delta m \Delta t = 0: \quad P(B^0 \rightarrow B^0) = 0 \rightarrow \text{no mixing, no interference}$$

$$\Delta m \Delta t = \pi: \quad P(B^0 \rightarrow \bar{B}^0) = 1 \rightarrow \text{full mixing, no interference}$$

$$\Delta m \Delta t = \pi/2: \quad P(B^0 \rightarrow \bar{B}^0) = 1/2 \rightarrow \text{maximal interference, resulting in CP violation}$$
CP violation results from interference between decays with and without mixing.

\[ \lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} = |\lambda_{f_{CP}}| e^{-i2\varphi_{CP}} \]

Time-dependent CP asymmetry:

\[ A_{f_{CP}}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})} = C_{f_{CP}} \cos (\Delta m_d t) + S_{f_{CP}} \sin (\Delta m_d t) \]

\[ C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2} \]
\[ S_{f_{CP}} = \frac{-2 \text{Im} \lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2} \]

\[ \lambda_{f_{CP}} \neq \pm 1 \Rightarrow \text{Prob}(\bar{B}^0_{\text{phys}}(t) \to f_{CP}) \neq \text{Prob}(B^0_{\text{phys}}(t) \to f_{CP}) \]
PEP-II & KEKB Asymmetric B Factories

- Decay time determined from decay distance between B decays $\Delta z = \Delta t (c \beta \gamma)$
- In $\Upsilon(4S)$ CMS daughter B’s travel only $\Delta z \sim 20 \mu m$
- Boost at PEP-II / KEKB decay gives much larger separation $<|\Delta z|> \sim 250/200 \mu m$ (BaBar/Belle)
- measurable with high resolution Silicon Vertex Detectors (typical resolution 200 $\mu m$)

$E_+ = 3 \text{ GeV}$
$E_- = 9.1 \text{ GeV}$
$\beta \gamma = 0.56$

$E_+ = 3.5 \text{ GeV}$
$E_- = 8 \text{ GeV}$
$\beta \gamma = 0.43$
The BaBar & Belle Detectors

Multi-purpose $4\pi$ detectors
- Precision vertexing with silicon strip detectors
- Tracking with central drift chamber
- PID (BaBar: DIRC, Belle: Aerogel+TOF)
- Super-conducting coil
- EM CsI calorimeter
- Muon detection with RPCs

Integrated Luminosity
- BaBar 131/ fb, Belle 159/ fb
- ~ 80/ fb analyzed per experiment
  (1/ fb ~ 1.15 million $B\bar{B}$ events)
Golden Decay Mode: $B^0 \rightarrow J/\psi \ K^0_S$

- Relatively ‘large’ branching fraction ie. $O(10^{-4})$
- Clear experimental signature
- Theoretically clean way to measure $\sin 2\beta$

\[ \lambda_{J/\psi K^0_{L,S}} = \eta \ e^{-i2\beta} \]

$\eta = -1 \ (+1)$ for $J/\psi \ K^0_{S(L)}$

Single weak phase = no direct $CP$

\[ C = 0, \ S = \sin 2\beta \]

\[ \Gamma(B^0 \rightarrow f_{CP}) \propto e^{-t/\tau} \ [1 + \eta \sin 2\beta \sin \Delta m \Delta t] \]
\[ \Gamma(\bar{B}^0 \rightarrow f_{CP}) \propto e^{-t/\tau} \ [1 - \eta \sin 2\beta \sin \Delta m \Delta t] \]

\[ A_{CP}(t) = -\eta \sin 2\beta \sin(\Delta m \Delta t) \]
Measurement of $\sin 2\beta$

Flavor tagging and $\Delta t$ reconstruction same as for mixing analysis:

$\Delta t = t_{\text{rec}} - t_{\text{tag}}$

$\approx \Delta z / \langle \beta \gamma \rangle c$

Coherent $B\bar{B}$ production (p-wave)

Reconstruction of $B$ decays to CP eigenstates
Tagged $B_{CP}$ candidates

- **88M $B\bar{B}$**
  - 1506 events
  - Purity 94%

- **85M $B\bar{B}$**
  - 1230 events
  - Purity 63%

- **J/$\psi$ $K_L$ signal**
  - 988 events
  - Purity 55%

- **J/$\psi$ $X$ bkgd**
  - Non-J/$\psi$ bkgd

- **J/$\psi$ $X$ bkgd**
  - 1728 events
  - Purity 94%
B⁰ Flavor Tagging

- Reconstruct one B in a decay mode accessible to B⁰ and B̅⁰ e.g J/ψKₜ – Need to know B flavor at production!

- Determine flavor of other B (tag B) from its charged decay products
  - Lepton, Kaon tagging
    - B̅⁰(b→l⁻,K⁻), B⁰(b→l⁺,K⁺)
  - Soft and hard pion tagging
    - B̅⁰ → D⁺⁺π⁻
    - B⁰: fast π⁻, soft π⁺
    - B⁰: fast π⁺, soft π⁻
CP Analysis: $\Delta t$ Distributions

**perfect**
flavor tagging & time resolution

$$B_{tag}^0 = \bar{B}^0$$

**realistic**
mis-tagging & finite time resolution

$$B_{tag}^0 = B^0$$

### Determine flavor mis-tag rates $w$ and $\Delta t$ resolution function $R$ from large control samples of $B^0 \rightarrow D^{(*)}\pi/\rho/\alpha_1, J/\psi K^*, D^* l\nu$

**CP PDF**

$$f_{CP, \pm}(\Delta t) = e^{-|\Delta t|/\tau_{B_d}} \times \left[ 1 \mp \eta_f \sin 2\beta (1 - 2w) \sin(\Delta m_d \Delta t) \right] \otimes R$$

**Mixing PDF**

$$f_{mixing, \pm}(\Delta t) = e^{-|\Delta t|/\tau_{B_d}} \times \left[ 1 \pm (1 - 2w) \cos(\Delta m_d \Delta t) \right] \otimes R$$
$\sin^2\beta$ from BaBar

$\sin^2\beta = 0.755 \pm 0.074$

$\eta_{cp} = -1$

$\sin^2\beta = 0.723 \pm 0.158$

$\eta_{cp} = +1$

$\sin^2\beta = 0.741 \pm 0.067 \pm 0.034$
$\sin^2 \beta$ from Belle

$q = +1 \rightarrow B^0 \text{ tag } \xi = \text{CP eigenvalue}$

$q = -1 \rightarrow \bar{B}^0 \text{ tag } (-1 \text{ for } J/\psi K_S, +1 \text{ for } J/\psi K_L)$

$\sin^2 \beta = 0.719 \pm 0.074 \pm 0.035$
One solution for $\beta$ is in good agreement with measurements of sides of Unitarity Triangle.

Error on $\sin 2\beta$ is dominated by statistics $\rightarrow$ will decrease $\sim 1/\sqrt{\text{Luminosity}}$ for a while.

$\sin 2\beta = 0.731 \pm 0.056$ (BaBar & Belle)
Beyond the Standard Model

If at least 2 amplitudes with a weak phase difference contribute $|\lambda|$ could be different from 1

(tree amplitude and leading penguin amplitude for $B \to J/\psi K_S$ have same weak phase in SM)

$$A_{\text{CP}} = C_{\text{f}_{\text{CP}}} \cos \Delta m_d \Delta t + S_{\text{f}_{\text{CP}}} \sin \Delta m_d \Delta t$$

$$\lambda_{\text{f}_{\text{CP}}} = \frac{q \cdot \overline{A}_{\text{f}_{\text{CP}}}}{p \cdot A_{\text{f}_{\text{CP}}}}$$

$$= |\lambda_{\text{f}_{\text{CP}}}| e^{-i2\phi_{\text{CP}}}$$

$$C_{\text{f}_{\text{CP}}} = \frac{1 - |\lambda_{\text{f}_{\text{CP}}}|^2}{1 + |\lambda_{\text{f}_{\text{CP}}}|^2}$$

$$S_{\text{f}_{\text{CP}}} = \frac{-2 \text{Im} \lambda_{\text{f}_{\text{CP}}}}{1 + |\lambda_{\text{f}_{\text{CP}}}|^2}$$

$|\lambda| = 0.949 \pm 0.045$ (BaBar & Belle)

No evidence of direct CP violation due to decay amplitude interference!
\[
\sin 2\beta \text{ from } B^0 \rightarrow D^*+D^*^- \text{ and } B^0 \rightarrow D^*+D^-
\]

- Tree amplitude dominant, top or up penguin diagram (internal loop) with different phases are color-suppressed

\[
\lambda^3 \text{ + color suppressed}
\]

- \(\sin 2\beta\)
S and C in $B^0 \rightarrow D^*+D^-$ (BaBar)

133 ± 13 signal events (81/fb)

Not a CP eigenstate!

Separate C and S for $D^*+D^-$ and $D^*+D^-$

$D^*-D^+$/ $D^*+D^-$ rate asymmetry
$A = -0.03 ± 0.11 ± 0.05$

If penguins negligible, expect
$C_{-+} = C_{+-} = 0$
$S_{-+} = S_{+-} = -\sin 2\beta$

More data needed, to see penguin effect!

$B^0 \rightarrow D^*-D^+$
$S_{-+} = -0.24 ± 0.69 ± 0.12$
$C_{-+} = -0.22 ± 0.37 ± 0.10$

$B^0 \rightarrow D^*+D^-$
$S_{+-} = -0.82 ± 0.75 ± 0.14$
$C_{+-} = -0.47 ± 0.40 ± 0.12$
$\sin 2\beta$ in $B^0 \to D^{*+} D^{*-}$ (BaBar)

- $D^{*+}D^{*-}$ is vector-vector final state with CP-even (S- and D-wave) and CP-odd (P-wave) contributions
- Get CP-odd fraction $R_\perp$ from $\theta_{tr}$ distribution

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_{tr}} = \frac{3}{4} (1 - R_\perp) \sin^2 \theta_{tr} + \frac{3}{2} R_\perp \cos^2 \theta_{tr}$$

$R_\perp = 0.063 \pm 0.055 \pm 0.009$

~94% CP even
sin2\(\beta\) from \(B^0 \rightarrow D^*+D^*\) (BaBar, 81/fb)

156 ± 14 signal events (88M B\(\bar{B}\))

Measure CP-parameter \(\lambda_+\) for CP-even component:

\[
\text{Im}(\lambda_+) = 0.05 \pm 0.29 \pm 0.10
\]

\[
|\lambda_+| = 0.75 \pm 0.19 \pm 0.02
\]

If no penguin contribution, expect:

\[
\text{Im}(\lambda_+) = -\sin2\beta, \quad |\lambda_+| = 1
\]

2.5 \(\sigma\) away from ‘no penguin’ SM
If no penguins, expect $S = -\sin 2\beta$, $C = 0$

Need more data to see tree/penguin interference

<table>
<thead>
<tr>
<th></th>
<th>BaBar</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>$0.05 \pm 0.49 \pm 0.16$</td>
<td>$-0.93 \pm 0.49 \pm 0.08$</td>
</tr>
<tr>
<td>$C$</td>
<td>$0.38 \pm 0.41 \pm 0.09$</td>
<td>$+0.25 \pm 0.39 \pm 0.06$</td>
</tr>
</tbody>
</table>

$40 \pm 7$ events
Sin2$\beta$ with (pure) Penguins

- pure penguin decay $B \rightarrow \phi K$
  - dominated by top quark in loop, up quark contribution is highly suppressed

\[
\begin{align*}
BR(B^+ \rightarrow \eta' K^+) &= (8.8 \pm 1.1) \times 10^{-6} \\
BR(B^0 \rightarrow \eta' K^0) &= (8.4 \pm 1.6) \times 10^{-6}
\end{align*}
\] (HFAG averages)

- SM top penguin has no weak phase and expected time-dependent CP asymmetry is $\sin 2\beta$

- new physics may show up due to new (virtual) heavy particles replacing top quark or W in the loop
### B → φK Results

<table>
<thead>
<tr>
<th></th>
<th>BaBar</th>
<th>Preliminary</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi K_S$</td>
<td>$S = -0.18 \pm 0.51 \pm 0.06$</td>
<td>$C = -0.80 \pm 0.38 \pm 0.11$</td>
<td>$S = -0.73 \pm 0.64 \pm 0.22$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$C = 0.56 \pm 0.41 \pm 0.16$</td>
</tr>
<tr>
<td>$K^+K^-K_S$</td>
<td>$S = 0.49 \pm 0.43 \pm 0.11 \pm 0.33 \pm 0.00$</td>
<td>$C = 0.40 \pm 0.33 \pm 0.10 \pm 0.26 \pm 0.00$</td>
<td>$S = -0.18 \pm 0.51 \pm 0.22$</td>
</tr>
<tr>
<td>$\phi K^+$</td>
<td>$A = 0.04 \pm 0.09 \pm 0.01$</td>
<td>$A = 0.01 \pm 0.12 \pm 0.05$</td>
<td>$A = 0.04 \pm 0.09 \pm 0.01$</td>
</tr>
</tbody>
</table>

**BaBar & Belle:**

2σ discrepancy between $S$ and $\sin 2\beta$ for $\phi K_S$

3rd error for $K^+K^-K_S$ from error in CP-odd fraction
Another penguin: $B \to \eta'K$

- Gluonic top penguin dominates
  - up penguin and tree have different weak phase ($\gamma$), but are suppressed by $\lambda^2 \sim 0.04$

\[ BR(B^+ \to \eta'K^+) = (78 \pm 5) \times 10^{-6} \]
\[ BR(B^0 \to \eta'K^0) = (60.8 \pm 5.6) \times 10^{-6} \]

(HFAG averages)
\[ B^0 \rightarrow \eta' K_S \]

<table>
<thead>
<tr>
<th>( B^0 \rightarrow \eta' K_S )</th>
<th>( B^+ \rightarrow \eta' K^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S = 0.02 \pm 0.34 \pm 0.03 )</td>
<td>( S = 0.71 \pm 0.37 \pm 0.06 )</td>
</tr>
<tr>
<td>( C = 0.10 \pm 0.22 \pm 0.03 )</td>
<td>( C = -0.26 \pm 0.22 \pm 0.03 )</td>
</tr>
</tbody>
</table>

\( \eta' K^+ \)

| \( A = 0.04 \pm 0.05 \pm 0.01 \) | \( A = -0.02 \pm 0.07 \pm 0.01 \) |

BaBar: 2\( \sigma \) discrepancy between S and \( \sin 2\beta \)
Belle: no discrepancy
$b \to s$ Penguin Averages

$S = 0.19 \pm 0.20$

~ 2.6 $\sigma$ smaller than charmonium modes

A statistical fluctuation or a hint of new physics...

Expectation from $J/\psi K_S$
\[ \alpha \text{ from } B \rightarrow \pi^+\pi^- \]

**Tree**

\[ \lambda^3 \]

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

\[ d \rightarrow \bar{u} \]

\[ u \rightarrow u \]

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

If no penguin, expect:

\[ \lambda_{\pi\pi} = e^{-2i\alpha} \]

\[ S_{\pi\pi} = \sin(2\alpha) \]

\[ C_{\pi\pi} = 0 \]

**Penguin**

\[ \lambda^3 \]

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

\[ d \rightarrow \bar{u} \]

\[ u \rightarrow u \]

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

**Tree + Penguin:**

\[ \lambda_{\pi\pi} = e^{-2i\alpha} \frac{1 + |P/T| e^{i(\delta+\gamma)}}{1 + |P/T| e^{i(\delta-\gamma)}} \]

\[ S_{\pi\pi} = \sqrt{1 - C_{\pi\pi}^2} \sin(2\alpha_{\text{eff}}) \]

\[ C_{\pi\pi} \propto \sin \delta \]

**Time evolution**

\[ q=+1 (B^0 \text{ tag}), q=-1 (\bar{B}^0 \text{ tag}) \]

\[ \frac{d\Gamma}{d\Delta t} \propto e^{\frac{|\Delta|}{\tau}} [1 + q(S_{\pi\pi} \sin \Delta m\Delta t - C_{\pi\pi} \cos \Delta m\Delta t)] \]

August 7, 2003

Sören Prell
B → π⁺π⁻ Results

85M B̅B

88M B̅B

S_{ππ} = -1.23 ± 0.41^{+0.08}_{-0.07}
C_{ππ} = -0.77 ± 0.27 ± 0.08

3.4 σ evidence for CP violation

S_{ππ} = +0.02 ± 0.34 ± 0.05
C_{ππ} = -0.30 ± 0.25 ± 0.04

Consistent with no CP violation
BaBar & Belle averages

\[ S_{\pi\pi} = -0.47 \pm 0.26 \]
\[ C_{\pi\pi} = -0.49 \pm 0.19 \]

\(~ 2.2 \sigma\) discrepancy between BaBar and Belle \(B \to \pi^+\pi^-\) results

Need to resolve with more data!
How to get $\alpha$ from $B \to \pi^+\pi^-$?

- $\alpha$ can be determined with isospin analysis
  - Need $\text{Br}(B^+ \to \pi^+\pi^0)$, $\text{Br}(B^0 \to \pi^0\pi^0)$, $\text{Br}(\bar{B}^0 \to \pi^0\pi^0)$

\[2\alpha_{\text{eff}} = 2\alpha + \kappa_{\pi\pi}\]

\[
\frac{1}{\sqrt{2}} A(B^0 \to \pi^+\pi^-) A(B^0 \to \pi^0\pi^0) = \tilde{A}(\bar{B}^0 \to \pi^0\pi^0)
\]

- $B^0/\bar{B}^0 \to \pi^0\pi^0$ not seen, yet
  - Need $\sim 2/ab$ to resolve large/small $|\kappa_{\pi\pi}|$ solutions (at 95% CL level)
  - Limit on $\alpha$ can be obtained with model input (SU(3) symmetry, QCD factorization)

$\text{Br}(B^0 \to \pi^+\pi^-) = (4.8 \pm 0.5) \times 10^{-6}$

$\text{Br}(B^\pm \to \pi^\pm\pi^0) = (5.6 \pm 0.9) \times 10^{-6}$

$A_{\text{CP}}(B^\pm \to \pi^\pm\pi^0) = 0.05 \pm 0.15$

$\text{Br}(B^0 \to \pi^0\pi^0) < 3.6 \times 10^{-6}$ (90%CL)

$[\text{Br}(B^0 \to \pi^0\pi^0) = (2.0 \pm 0.7) \times 10^{-6}]$

$|\alpha_{\text{eff}} - \alpha| < 54^\circ$ (90% CL)
$B \rightarrow \rho^+ \pi^-$

- Tree and penguin amplitudes contribute
  - Same Feynman diagrams as in $B^0 \rightarrow \pi^+ \pi^-$

- Not a CP eigenstate
  - Separate C and S for $\rho^+ \pi^-$ and $\rho^- \pi^+$
  - $\rho^+ \pi^-$ and $\rho^- \pi^+$ yield asymmetry $A$

Time-dependent rate

$$f_{\rho^\pm \pi^\mp}(\Delta t) = (1 \pm A) \left[ 1 + q \left\{ \left( S \pm \Delta S \right) \sin \Delta m \Delta t - \left( C \pm \Delta C \right) \cos \Delta m \Delta t \right\} \right]$$

$N(\rho\pi) = 428 \pm 34$ in 81(fb)
$B \to \rho^+\pi^-$ Results (BaBar 81/fb)

- $A_{\rho\pi} = -0.18 \pm 0.08 \pm 0.03$
- $S_{\rho\pi} = 0.19 \pm 0.24 \pm 0.03$
- $\Delta S_{\rho\pi} = 0.15 \pm 0.25 \pm 0.03$
- $C_{\rho\pi} = 0.36 \pm 0.18 \pm 0.04$
- $\Delta C_{\rho\pi} = 0.28 \pm 0.18 \pm 0.04$

The (usual) C’s are

- $C(B^0 \to \rho^+\pi^-) = 0.62 \pm 0.26 \pm 0.06$
- $C(B^0 \to \rho^-\pi^+) = 0.11 \pm 0.17 \pm 0.04$

~ $2\sigma$ hint of direct CP violation
\( \gamma \) from \( B^+ \to D^0 K^+ \)

Interference of \( b \to c \) tree and \( b \to u \) tree

- Single charm quark ensures absence of penguin contribution
- Common final state for \( D^0 \) and \( \bar{D}^0 \) e.g. CP eigenstates
  - \( D_1 \) (CP-even): \( K^+ K^- , \pi^+ \pi^- \)
  - \( D_2 \) (CP-odd): \( K_S \pi^0, K_S \omega, K_S \eta, K_S \eta' \)

\[ b \to u \] transition is color-suppressed

- Expect up to \( \sim 10\% \) CP asymmetry (depending on the relative strong phase)

\[ r \equiv \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} = 0.1 - 0.2 \]
Extract $\gamma$ with $B^+ \rightarrow DK^+$

- Reconstruct $D^0$ in Cabibbo-favored modes and CP-modes (Cabibbo-suppressed)

\[
\sqrt{2} A(B^+ \rightarrow D^0K^+) = A(B^- \rightarrow D^0K^-)
\]

- Experimental difficulties:
  - $D\pi$ final state has higher branching ratio (need good K ID)
  - All hadronic final states are common for $D^0$ and $\bar{D}^0$!
    - Solution: use at least 2 doubly Cabibbo-suppressed D final states instead of CP eigenstates

Can’t measure with hadronic D decays!

Rate for $B^+ \rightarrow D^0K^+(D^0 \rightarrow K^-\pi^+)$ and $B^+ \rightarrow \bar{D}^0K^+(\bar{D}^0 \rightarrow K^-\pi^+)$ are about the same!
B $\rightarrow$ $D_{\text{CPK}}$

Measure CP asymmetries and Cabibbo-suppression

$$A_{1,2} = \frac{\text{Br}(B^- \rightarrow D_{1,2}K^-) - \text{Br}(B^+ \rightarrow D_{1,2}K^-)}{\text{Br}(B^- \rightarrow D_{1,2}K^-) + \text{Br}(B^+ \rightarrow D_{1,2}K^-)} = \frac{\pm 2r \sin \delta \sin \gamma}{1 + r^2 \pm 2r \cos \delta \cos \gamma}$$

$$R_{1,2} = \frac{\text{Br}(D_{1,2}K^-) / \text{Br}(D_{1,2}\pi^-)}{\text{Br}(D^0K^-) / \text{Br}(D^0\pi^-)} = 1 + r^2 \pm 2r \cos \delta \cos \gamma$$

$r$ can’t be determined cleanly from $A_{1,2}$ and $R_{1,2}$, but

$$\frac{R_1 - R_2}{2} = 2r \cos \delta \cos \gamma$$

$$\frac{A_1 - A_2}{2} \sim 2r \sin \delta \sin \gamma \quad O(r^2)$$

Error $O(r^2)$ for hadronic $D$ decays (DCSD).
### B → D_{CPK} Results

<table>
<thead>
<tr>
<th></th>
<th>CP even</th>
<th>CP odd</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preliminary</strong></td>
<td><strong>A_{1} = 0.17 ± 0.23 ± 0.08</strong>&lt;br&gt;<strong>A_{2} = -0.19 ± 0.17 ± 0.05</strong>&lt;br&gt;<strong>R_{1} = 1.06 ± 0.26 ± 0.17</strong>&lt;br&gt;<strong>R_{2} = 1.41 ± 0.27 ± 0.15</strong>&lt;br&gt;<strong>A_{1} = 0.06 ± 0.19 ± 0.04</strong>&lt;br&gt;<strong>R_{1} = 1.21 ± 0.25 ± 0.14</strong>&lt;br&gt;<strong>A_{2} = 0.17 ± 0.23 ± 0.08</strong>&lt;br&gt;<strong>R_{1} = 1.06 ± 0.26 ± 0.17</strong>&lt;br&gt;<strong>R_{2} = 1.41 ± 0.27 ± 0.15</strong></td>
<td><strong>A_{1} = 0.17 ± 0.23 ± 0.08</strong>&lt;br&gt;<strong>A_{2} = -0.19 ± 0.17 ± 0.05</strong>&lt;br&gt;<strong>R_{1} = 1.06 ± 0.26 ± 0.17</strong>&lt;br&gt;<strong>R_{2} = 1.41 ± 0.27 ± 0.15</strong>&lt;br&gt;<strong>A_{1} = 0.06 ± 0.19 ± 0.04</strong>&lt;br&gt;<strong>R_{1} = 1.21 ± 0.25 ± 0.14</strong>&lt;br&gt;<strong>A_{2} = 0.17 ± 0.23 ± 0.08</strong>&lt;br&gt;<strong>R_{1} = 1.06 ± 0.26 ± 0.17</strong>&lt;br&gt;<strong>R_{2} = 1.41 ± 0.27 ± 0.15</strong></td>
</tr>
<tr>
<td><strong>BaBar (DK)</strong></td>
<td><strong>Belle (DK)</strong></td>
<td><em><em>Belle (DK</em>)</em>*</td>
</tr>
</tbody>
</table>

#### From DK results,

\[
2r \sin \delta \sin \gamma \sim \frac{A_{1} - A_{2}}{2} = 0.15 \pm 0.12 \quad [O(r^{2})]
\]

\[
2r \cos \delta \cos \gamma = \frac{R_{1} - R_{2}}{2} = -0.14 \pm 0.19
\]
\[ \gamma \text{ from } B^0 \rightarrow D^{(*)0}K^{(*)0} \]

- **\(K_S\) modes:** \(D^{(*)0}K_S\)
  - Time-dependent CP asymmetry sensitive to \(\sin(2\beta + \gamma \pm \delta)\)
  - Both amplitudes are about \(O(\sim \lambda^3)\)

- **Self-tagging modes with \(K^{*0} \rightarrow K^+\pi^-\)**
  - Ratio \(r = \text{Br}(B^0 \rightarrow D^{(*)0}\overline{K}^*)/\text{Br}(B^0 \rightarrow D^{(*)0}K^*)\) sensitive to relative contribution of \(V_{ub}\) and \(V_{cb}\) diagrams
  - Expect \(r \sim 0.2\)
B^0 \rightarrow D^{(*)0}K^{(*)} Results (Belle 78/fb)

Observe b\rightarrow c transition, but not b\rightarrow u transition transition, yet

\[ BR(B^0 \rightarrow \bar{D}^0 K^{*0}) = (4.8 \pm 1.1 \pm 0.5) \times 10^{-5} \]
\[ BR(B^0 \rightarrow D^0 K^{*0}) < 1.8 \times 10^{-5} \]

\[ V_{cb} \]

\[ V_{ub} \]

\[ V_{cb} / V_{ub} \text{ (interference)} \]
\[ BR(B^0 \rightarrow (D / \bar{D}^0)K^0) = (5.0 \pm 1.3 \pm 0.6) \times 10^{-5} \]

Modes with D^{*0} not observed, yet

\[ BR(B^0 \rightarrow \bar{D}^{*0}K^0) < 6.6 \times 10^{-5} \]
\[ BR(B^0 \rightarrow \bar{D}^{*0}K^{*0}) < 6.9 \times 10^{-5} \]
\[ BR(B^0 \rightarrow D^{*0}K^{*0}) < 4.0 \times 10^{-5} \]

27.0 \pm 7.3 'CP' events

41.0 \pm 8.4 'self-tag' events

More events needed for \( \gamma \) measurement!
\[ \gamma \text{ from } B^0 \rightarrow D^{(*)+}\pi^- \]

- Large branching fractions, but \( b \rightarrow u \) diagram strongly suppressed
- Expect time-dependent CP asymmetry amplitude to be small
  \[ S^\pm = 2r \sin(2\beta + \gamma \pm \delta), \quad |S^\pm| \sim 0.04 \]
  - Cannot fit for \( |r(*)|^2 = Br(B^0 \rightarrow D^{(*)+}\pi^-)/Br(B^0 \rightarrow D^{(*)-}\pi^+) \), use BaBar measurements of \( Br(\bar{B}^0 \rightarrow D_s^{(*)+}\pi^-) \) and SU(3)
    - \( |r| = 0.021^{+0.004}_{-0.005}, \quad |r^*| = 0.017^{+0.005}_{-0.007} \) [\( \pm 30\% \) error from SU(3)]
  - Tag-side \( b \rightarrow c,u \) interference for non-lepton tags is same order as CP amplitude under study
$\gamma$ from $B^0 \rightarrow D^{(*)+}\pi^-$ (BaBar 81/fb)

Fully reco’ed B’s: Preliminary

5200 $D^+\pi^-$ (purity 85%)
4750 $D^{*+}\pi^-$ (purity 94%)

$2|r| \sin(2\beta+\gamma) \cos \delta = -0.02 \pm 0.04 \pm 0.02$
$2|r*|\sin(2\beta+\gamma) \cos \delta* = -0.07 \pm 0.04 \pm 0.02$
$2|r| \cos(2\beta+\gamma) \sin \delta = 0.03 \pm 0.07 \pm 0.04$
$2|r*|\cos(2\beta+\gamma) \sin \delta* = 0.03 \pm 0.07 \pm 0.04$

Fit $|\sin(2\beta+\gamma)|,|\cos \delta(*)|$: $|\sin(2\beta+\gamma)| > 0.69$ (68% CL)

$\delta(*)$ is strong phase difference between two amplitudes for $D^{(*)+}\pi^-$
$\gamma$ from $B^0 \rightarrow D^{*+}\pi^-$ (BaBar 81/fb)

Partially reco’ed $D^{**}\pi^-$: $D^{**}\rightarrow (D^0) \pi^+$
use lepton and kaon tags

Fit $|\sin(2\beta+\gamma)|$, $|\cos \delta(*)|$: $|\sin(2\beta+\gamma)| > 0.75$ (90% CL)

$2 |r*|\sin(2\beta+\gamma) \cos \delta^* = -0.063 \pm 0.024 \pm 0.017$
$2 |r*|\cos(2\beta+\gamma) \sin \delta^* = -0.004 \pm 0.037 \pm 0.020$
\( \gamma \) from \( B^0 \to D^{(*)+}\pi^- \) (BaBar 81/fb)

Combined results from fully-reconstructed \( D^{(*)+}\pi^- \) samples and partially-reconstructed \( D^{*+}\pi^- \) sample:

Preference for ‘small \( \beta \)’ solution in \( \bar{\eta} > 0 \) half-plane

\[
\sin(2\beta + \gamma) > 0.76 \ (90\% \ CL) \\
\sin(2\beta + \gamma) > 0 \ (99.5\% \ CL)
\]

August 7, 2003

Sören Prell
Summary

• CP violation in the B system is established
  – Sin2β is > 13σ away from zero
  – Most precise constraint on apex of Unitarity Triangle

• Consistency: tree vs. penguin for sin2β
  – 2.6σ discrepancy; more data needed

• Measurements of α and γ have larger uncertainties (theoretical and/or experimental)
  – α / φ2
    • Need to control penguins in ππ, ρπ, etc. (need B0 → π0π0)
  – γ / φ3
    • DK modes are theoretically clean, but need much more data
    • Dπ becomes interesting, will be limited by (theoretical) error on |λ(*)|

• Need better precision on α and γ to constrain Unitarity Triangle
Conclusions

• Standard Model CKM prediction of only one complex phase as single source of $CP$ violation has not been disproved, yet

• Current experimental measurements of $CP$ violation in weak interactions of quarks are unlikely to explain the $CP$ asymmetry observed in the universe.

• New physics and its contribution to $CP$ violation in B decays are still possible, but remain to be discovered...