Recent Results from Belle

HEP Seminar
SUNY Stony Brook

Daniel Marlow
Princeton University
April 1, 2002
Talk Outline

• Introduction/Review (with apologies to the experts)
• The KEK-B Collider
• The Belle Detector
• Indirect CP Violation Measurement/Analysis
• New result on $B^0 \rightarrow \pi^+\pi^-$
• Conclusions
The Kobayashi-Maskawa Mixing Scheme

Quark mixing is described via

\[
M = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\approx \begin{pmatrix}
1 - \lambda^2 / 2 & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda & 1 - \lambda^2 / 2 & A\lambda^2 \\
A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]

Where the second matrix is the Wolfenstein parameterization.

The “d b” unitarity relation yields

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

\[
V_{td} + V_{ub}^* \approx A\lambda^3
\]
The gold-plated mode determines the angle $\phi_1$ which is also called $\beta$. 

$$ V_{ud} \approx V_{tb} \approx 1 $$
**Direct CP Violation**

*Direct* CP violation is perhaps the simplest case. Consider the CP mirror processes:

\[ B \rightarrow f \text{ and } \bar{B} \rightarrow \bar{f} \]

The CP asymmetry is defined as

\[ A_{CP} \equiv \frac{\Gamma(B \rightarrow f) - \Gamma(\bar{B} \rightarrow \bar{f})}{\Gamma(B \rightarrow f) + \Gamma(\bar{B} \rightarrow \bar{f})} \]

The decay amplitudes are

\[ A_f = |A_f| e^{i\phi_W} e^{i\phi_S} \text{ and } A_{\bar{f}} = |A_f| e^{-i\phi_W} e^{i\phi_S} \]

Note that the weak phase changes sign.
Direct CP Violation

Note that \[ |A_f|^2 = |A_f^-|^2 \implies \Gamma_f = \Gamma_{f^-} \] (no effect)

\( \implies \text{We need some sort of interference, two amplitudes, for example} \)

\[ A_f = |A_1| e^{i\phi_{w1}} e^{i\phi_{s1}} + |A_2| e^{i\phi_{w2}} e^{i\phi_{s2}} \]

\[ A_{f^-} = |A_1| e^{-i\phi_{w1}} e^{i\phi_{s1}} + |A_2| e^{-i\phi_{w2}} e^{i\phi_{s2}} \]

Yielding

\[ \Gamma_f = |A_1|^2 + |A_2|^2 + 2 |A_1| |A_2| \cos(\Delta \phi_w + \Delta \phi_s) \]

\[ \Gamma_{f^-} = |A_1|^2 + |A_2|^2 + 2 |A_1| |A_2| \cos(\Delta \phi_w - \Delta \phi_s) \]
Direct CP Violation

Despite its conceptual and experimental simplicity, there are two problems with direct CP violation:

- Cases where there are two comparable amplitudes that are large are (probably) rare.

- The strong phases are poorly understood, making it difficult to extract the weak (KM) phases that are of greatest interest.

One is thus led in the direction of asymmetric $e^+e^-$ B factories aimed at the study of indirect CP violation.
Indirect CP Violation

Here we look for decays of the form $B^0 \rightarrow f$ where $f$ is a CP eigenstate. The most promising candidate for this decay is

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

the so-called “gold-plated” mode. Note that the decay

$$\bar{B}^0 \rightarrow J / \Psi K_S$$

is also possible.
Indirect CP Violation

Thus we can provide the requisite interference using $B^0 \bar{B}^0$ state mixing, i.e.,

$$
\left| B^0(t) \right> = e^{-i(m-i\Gamma)/2} \times \left[ \cos\left(\frac{\Delta m t}{2}\right) \left| B^0 \right> + i \sin\left(\frac{\Delta m t}{2}\right) e^{-2i\phi_m} \left| \bar{B}^0 \right> \right]
$$
Indirect CP Violation

$A(t)$

$\frac{\pi}{2}$ $\pi$ $\Delta mt$

$\Gamma(t) = \frac{e^{-t/\tau_B}}{\tau_B} \times \left[ 1 \pm \xi_f \sin(\Delta mt) \sin 2\phi \right]$  

No mixing

Interference from mixing.
Indirect CP Violation

Before continuing, we stop to take note of the experimental situation. In the measurements to be described, we create $B^0\bar{B}^0$ pairs via the reaction

$$e^+e^- \rightarrow Y(4S) \rightarrow B^0\bar{B}^0$$

"Spectator" or "tagging" $B^0$ CP eigenstate
Flavor Tagging

Observation of CP violation requires that we know whether the decaying particle was initially a $B^0$ or a $\bar{B}^0$, but the final state (a CP eigenstate) does not tell us that. However, can infer the “flavor” of the decaying particle, by looking at what the “spectator” does: we need to know the “flavor” of the spectator $B^0$.

A positive lepton in the final state indicates that the decaying particle was a $B^0$. Kaons can also be used in this way.
Consider a frame where the $B^0$ and the $\bar{B}^0$ travel along \sim side-by-side.

\[
\Gamma(\Delta t) = \frac{e^{-\Delta t/\tau_B}}{\tau_B} \left[ 1 \pm \xi_f \sin(\Delta m \Delta t) \sin 2\phi \right]
\]

Only $\Delta t$ is measured.

Depends on sign of tag.

April 2002

Indirect CP Violation
Indirect CP Violation

$\Delta t$ can be negative.

$$\Gamma(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{\tau_B} \left[ 1 \pm \xi_f \sin(\Delta m \Delta t) \sin 2\phi \right]$$
The resulting signature of CP violation is mainly a mean shift between the $B^0$ and $\bar{B}^0$ samples.
CP Phases in the Gold-Plated Mode

Decay

\[ B^0 \rightarrow J/\Psi \, K_S \]

\[ \phi_D \approx 0 \]

Mixing

\[ \phi_M \approx \arg(V_{td}) \]

The KM phase comes from the mixing.
The Measurement

Need to:
- Measure momenta
- ID leptons & K’s
- Measure vertices

April 2002
KEKB is similar to PEP-II in many ways, although there is an important difference in the way in which the beams are brought into collision.
KEK B Asymmetric Collider

asymmetric $e^+e^-$ collider

- Two separate rings
  - $e^+$ (LER) : 3.5 GeV
  - $e^-$ (HER) : 8.0 GeV
- $E_{CM}$ : 10.58 GeV at $\Upsilon$(4S)
- Luminosity
  - target: $10^{34} \text{ cm}^{-2}\text{s}^{-1}$
  - achieved: $5.2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- $\pm 11$ mrad crossing angle
- Small beam sizes:
  - $\sigma_y \approx 3 \mu m$; $\sigma_x \approx 100 \mu m$
April 2002 CP Violation at Belle

Machine Performance

Summer ’01 shutdown

 Integrated/ day

Total Integrated

Reported here

Belle log total: 64065.2 pb⁻¹
April 2002 CP Violation at Belle

Typical Day.
KEKB/PEP II Luminosity Bakeoff

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>PEP-II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak</strong></td>
<td>$7.2 \times 10^{33}$ cm$^{-2}$s$^{-1}$</td>
<td>$4.6 \times 10^{33}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td><strong>Shift</strong></td>
<td>129 pb$^{-1}$</td>
<td>105 pb$^{-1}$</td>
</tr>
<tr>
<td><strong>24 hour</strong></td>
<td>364 pb$^{-1}$</td>
<td>303 pb$^{-1}$</td>
</tr>
<tr>
<td><strong>7 day</strong></td>
<td>2207 pb$^{-1}$</td>
<td>1789 pb$^{-1}$</td>
</tr>
<tr>
<td><strong>Integrated</strong></td>
<td>64.1 fb$^{-1}$</td>
<td>77.4 fb$^{-1}$</td>
</tr>
</tbody>
</table>

As of ~Mar. 30, 2002

Comparisons not quite apples to apples.
An international collaboration involving about 10 Countries, 50 Institutes, & 250 People

April 2002
Detector Performance

- Silicon Vertex Detector
  - $\sigma \approx 55\mu m$ for $1GeV/c \cdot 90^\circ$

- Central Drift Chamber
  - $\sigma_{p/p} \approx 0.35\% @ 1GeV/c$
  - $\sigma_{\pi}(dE/dx) \approx 7\%$

- $K^\pm$ id up to $p_{lab}=3.5$ GeV/c

- TOF ($\sigma \sim 95$ ps)

- Aerogel ($n = 1.01 \sim 1.03$)

- $\gamma$, $e^\pm$ with CsI crystals
  - $\sigma_{E/E_\gamma} \sim 1.5\% @ 1GeV$

- KL and $\mu^\pm$ with KLM (RPCs)
  - $\mu^\pm$: effic. $> 90\%$; $\sim 2\%$ fakes
$K_S^0 \rightarrow \pi^+ \pi^-$

$\sigma_{\text{eff}} = 4.6 \text{ MeV/c}^2$

Mass Reconstruction

April 2002 CP Violation at Belle
CsI EM Calorimeter Performance

$E_{\gamma} > 50$ MeV

$\pi^0$ Reconstruction

$\eta \rightarrow \gamma \gamma$ Reconstruction

$m = 133.4 \pm 0.1$ MeV
$\sigma = 5.64 \pm 0.10$ MeV

$m = 544 \pm 1$ MeV
$\sigma = 12 \pm 1$ MeV
The Silicon Vertex Detector

This small detector incorporates ~90,000 fully integrated data acquisition channels.
Vertex Detector

\[ \sigma \sim 55\mu m \text{ for } 1\text{GeV/c @ 90}^\circ \]

Occupancy at present luminosity \(~4\%\)

Upgraded SVD coming:

- 4 layers
- Radiation hard
- Level 1 trigger
- Summer ’02 installation

April 2002
The ToF has a resolution of $\sigma=100$ ps, which provides $\pi/K$ separation up to about 1.2 GeV/$c$, at which point the ACC array kicks in. The index of refraction of the counters varies as a function of angle, reflecting the boosted CM.
Muons are important for the same reason. They are identified by the way in which they penetrate the iron return yoke of the magnet.

\[ B^+ \rightarrow J/\Psi K^+ \]

\[ \rightarrow \mu^+ \mu^- K^+ \]

plus tag-side \( \mu \)

The gaps are instrumented with RPCs.
Software and Computing

• S/W framework (BASF)
  • written by small group of physicists
  • accommodates either FORTRAN or C++
  • most code is written by people under 30 (who are not to be trusted!) and is therefore in C++
  • data storage is “conventional.”

• Computing H/W
  • 650 GHz Pentium III (equivalent) at KEK
  • DST production throughput 2 fb$^{-1}$ per day
  • similar (~1/2?) aggregate CPU power in the provinces can be used for MC generation.

April 2002  CP Violation at Belle
Analysis Flowchart

1. CP mode reconstruction
   - Signal / Background

2. Flavor Tagging of other B
   - Wrong tag Fraction

3. Vertex reconstruction
   - $\Delta t = \Delta z/c\beta\gamma$, Resol.Func.

4. CP fit
   - $\sin 2\phi_1$
J/Ψ Reconstruction

- Require one lepton to be positively identified and the other to be consistent with lepton hypothesis.

- For $e^+e^-$, add any photon within .05 of electron direction.
B Reconstruction

$J/\psi \ K_s(\pi^+\pi^-)$

457 Events
~3% Background

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

\[ m_{bc} = \sqrt{\left(E_{\text{beam}}^*\right)^2 - \left(\sum_{\text{cand}} \vec{p}\right)^2} \]

April 2002
$B^0 \to J/\psi K_S; \quad K_S \to \pi^0 \pi^0$

Total events = 76
Bkgd \approx 9 evts (12\%)
ψ' Modes

ψ' → l⁺l⁻

Dileptons
Yield: 1542 ± 118.
Mean: 3684.50 (Fixed)
Width: 12.14 (Fixed)

ψ' → J/ψππ

J/ψ π⁺π⁻
Yield: 1515 ± 63.
Mean: 589.31 ± 0.13 MeV/c²
Width: 2.97 ± 0.14 MeV/c²

Both leptons tagged.

April 2002

CP Violation at Belle
Other Charmonium Modes

1st observation of inclusive $B \rightarrow \chi_{c2} X$

- $\chi_{c1}$ Yield: 2270. ± 85.
- $\chi_{c1}$ Mean: 413.6 MeV/c² (Fixed)
- $\chi_{c1}$ Width: 7.2 MeV/c² (Fixed)
- $\chi_{c2}$ Yield: 553. ± 67.
- $\chi_{c2}$ Mean: 460.0 MeV/c² (Fixed)
- $\chi_{c2}$ Width: 7.9 MeV/c² (Fixed)
CP Even Mode ($B^0 \rightarrow J/\psi K_L$) Reconstruction

- Assume $B^0 \rightarrow J/\psi K_L$ (2-body) kinematics.
- Look for $K_L$ recoiling from $J/\psi$
  - hits in RPCs
  - cluster in ECL
- Remove positively tagged background modes: $J/\psi K^+$, $J/\psi K^*$, etc.
- Plot $p_B^* = |p_{J/\psi}^* + p_{K_L}^*|$
$K_L^0$ Detection

$$P_{\text{miss}} = P_{4S} - \sum_{i=\gamma, h^\pm} P_i$$

Inclusive “$K_L$’s”

April 2002
$\vec{p}_B^* = \left| \vec{p}_{J/\Psi}^* + \vec{p}_{K_L}^* \right|$

61% signal purity
# CP Mode Summary

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_{ev}$</th>
<th>$N_{bkgd}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi(\ell^+\ell^-)K_S(\pi^+\pi^-)$</td>
<td>457</td>
<td>11.9</td>
</tr>
<tr>
<td>$J/\psi(\ell^+\ell^-)K_S(\pi^0\pi^0)$</td>
<td>76</td>
<td>9.4</td>
</tr>
<tr>
<td>$\psi(2S)(\ell^+\ell^-)K_S(\pi^+\pi^-)$</td>
<td>39</td>
<td>1.2</td>
</tr>
<tr>
<td>$\psi(2S)(J/\psi\pi^+\pi^-)K_S(\pi^+\pi^-)$</td>
<td>49</td>
<td>2.1</td>
</tr>
<tr>
<td>$\chi_{c1}(\gamma J/\psi)K_S(\pi^+\pi^-)$</td>
<td>24</td>
<td>2.4</td>
</tr>
<tr>
<td>$\eta_c(K^+K^-\pi^0)K_S(\pi^+\pi^-)$</td>
<td>23</td>
<td>11.3</td>
</tr>
<tr>
<td>$\eta_c(K_SK^+\pi^-)K_S(\pi^+\pi^-)$</td>
<td>41</td>
<td>13.6</td>
</tr>
<tr>
<td>$J/\psi K^*(0)(K_S\pi^0)$</td>
<td>41</td>
<td>6.7</td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td><strong>750</strong></td>
<td><strong>58.6</strong></td>
</tr>
<tr>
<td>$J/\psi(\ell^+\ell^-)K_L$</td>
<td>569</td>
<td>223</td>
</tr>
</tbody>
</table>
Flavor Tagging

We need to know the flavor of the spectator $B^0$.

- Track level tags
  - High momentum leptons
  - Medium momentum $K^\pm$
  - High-momentum $\pi^\pm$ (from e.g., $B^0 \rightarrow D^{(*)-} \pi^+$)
  - Low-momentum $\pi^\pm$ (from $D^{*}$’s).
- Need to take into account multiple tags and correlations.
Flavor Tagging

$q = \pm 1; \quad 0 < r < 1 \iff \text{tag reliability}$
The B lifetime is of the same order as the vertex resolution, so the effect is quite subtle.
Vertexing

• Common track requirements
  – # of associated SVD hits > 2
  – Use run-dependent IP
• For CP-side, use J/ψ → l⁺l⁻ tracks
  – Reject poorly fit events.
• For Tag-side, use tracks with:
  – |δz|<1.8mm, |σ_z|<500 μm, |δr|<500 μm
  – Iterate: discard worst track until fit is acceptable.
• Require |z_{CP} - z_{tag}|<2 mm (∼10 τ_B)
Test of Vertex Resolution

$B^0 \rightarrow J/\psi K^{*0}$

$K^-\pi^+$
(take as tag-side Vtx)

$l^+l^-$ (CP Vtx)

![Graph showing vertex resolution results with r.m.s. ± error]

$\text{r.m.s.}=123 \mu m$
$\sigma=97.1 \pm 4.8 \mu m$
Fitting

\[ P_{\text{sig}}(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{2\tau_B} \left[ 1 - \eta_f q(1 - 2w) \sin 2\varphi_1 \sin(\Delta m \Delta t) \right] \quad \text{Signal} \]

\[ P_{\text{bkg}}(\Delta t) = f_\tau \frac{e^{-|\Delta t|/\tau_{bg}}}{2\tau_{bg}} + (1 - f_\tau) \delta(\Delta t) \quad \text{Background} \]

\[ L_i = P_{\text{sig}}(\Delta t' - \Delta t) \otimes R_{\text{sig}}(\Delta t) \times (1 - f_{bg}) \]

Response function

\[ + P_{\text{bkg}}(\Delta t' - \Delta t) \otimes R_{\text{bkg}}(\Delta t) \times f_{bg} \]
The first order effect is a mean shift between positively and negatively tagged samples (Summer ’01 sample).

April 2002

CP Violation at Belle
The Fitted Result: Update

\[ \sin 2 \phi_1 = 0.82 \pm 0.12 \pm 0.05 \]
### Sources of Systematic Error

| Source                                    | Error  
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex algorithm</td>
<td>±0.04</td>
</tr>
<tr>
<td>Flavor tagging</td>
<td>±0.03</td>
</tr>
<tr>
<td>Resolution function</td>
<td>±0.02</td>
</tr>
<tr>
<td>$K_L$ background fraction</td>
<td>±0.02</td>
</tr>
<tr>
<td>Background shapes</td>
<td>±0.01</td>
</tr>
<tr>
<td>$\Delta m_d$ and $\tau_{B_0}$ errors</td>
<td>±0.01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>±0.06</td>
</tr>
</tbody>
</table>
Time-Dependent Asymmetry

One can plot the excess/deficit on a bin-by-bin basis.

First we start with a non-CP sample to look for false asymmetries.

\[ \xi_f = -1 \]

\[ \xi_f = +1 \]

combined
Subsample Dependence

$\sin^2 \phi_1$

- $q_0 = +1$ (B$^+$-tag)
- $q_0 = -1$ (B$^-$-tag)
- All

April 2002 CP Violation at Belle

0.875 - 1.000
0.750 - 0.875
0.500 - 0.750
0.000 - 0.500

0.96$^{+0.15}_{-0.17}$
1.54$^{+0.24}_{-0.28}$
0.27$^{+0.25}_{-0.25}$
-0.12$^{+0.58}_{-0.57}$

0.60$^{+0.19}_{-0.19}$
1.00$^{+0.15}_{-0.16}$
0.82$^{+0.12}_{-0.12}$
Comparison to other $\sin^2\phi_1$ Measurements

It looks like CDF had it right!
In the simplest case, CP violation occurs due to the interference between mixing and decay.
Extra decay graphs can give rise to direct CP violation, which complicates the situation.
$B \rightarrow \pi^+\pi^-$ decay

$$\Gamma(\Delta t) = \frac{e^{-\Delta t/\tau_B}}{\tau_B} \left[ 1 \pm \xi_f (S_{\pi\pi} \sin \Delta m \Delta t + C_{\pi\pi} \cos \Delta m \Delta t) \right]$$

Mean shift between q=+1 and q=-1 samples.

Population difference between the q=+1 and q=-1 samples.
In the 42 fb$^{-1}$ sample, we have observed an asymmetry in the rate for $B^0 \rightarrow \pi^+\pi^-$ vs. $\bar{B}^0 \rightarrow \pi^+\pi^-$. At present, this is only a $\sim 3\sigma$ effect, but if it persists with higher statistics, it will represent the first observation of direct CP violation in the B system.
**B → π⁺π⁻ decay**

$$\Gamma(\Delta t) = \frac{e^{-\Delta t / \tau_B}}{\tau_B} \left[ 1 \pm \xi f \left( S_{\pi \pi} \sin \Delta m \Delta t + C_{\pi \pi} \cos \Delta m \Delta t \right) \right]$$

- Mean shift between q=+1 and q=-1 samples.
- Population difference between the q=+1 and q=-1 samples.

\[
S_{\pi \pi} = -1.21^{+0.38}_{-0.27} \quad \text{(stat.)} \quad +0.16_{-0.13} \quad \text{(syst.)}
\]

\[
C_{\pi \pi} = +0.94^{+0.25}_{-0.31} \quad \text{(stat.)} \quad \pm 0.09 \quad \text{(syst.)}
\]
Future Prospects

Projection of Luminosity Accumulation

$\delta (\sin 2\phi_2) \approx 0.2$

Installation of Ante-chambers and Crab cavities
and Energy switch

April 2002

CP Violation at Belle
Conclusions

• CP violation in the B system has been observed at the $>6\sigma$ level.

\[ \sin 2\varphi_1 = 0.52 \pm 0.12 \pm 0.05 \]

• We see an indication of CP violation in $B \rightarrow \pi^+\pi^-$ decay.

• The KEKB accelerator is working very well and continues to improve.

• There will be lots of good physics to come.
Additional Slides
# Additional Topics

<table>
<thead>
<tr>
<th>Topic</th>
<th>Belle</th>
<th>BaBar</th>
<th>Include</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 K*ll</td>
<td>signal</td>
<td>B(Kll)&lt;0.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B(K*ll)&lt;2.5</td>
<td>Yes</td>
</tr>
<tr>
<td>Chi_c0, chi_c2</td>
<td>signals</td>
<td>no</td>
<td>No</td>
</tr>
<tr>
<td>1 D*D</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>2 phiK</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>B-&gt;gamma X_s</td>
<td></td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>5 Color suppressed modes</td>
<td>yes</td>
<td>no</td>
<td>Yes</td>
</tr>
<tr>
<td>3 B-&gt;pipi</td>
<td>yes</td>
<td>yes</td>
<td>Yes</td>
</tr>
<tr>
<td>D0 lifetime difference</td>
<td></td>
<td></td>
<td>maybe</td>
</tr>
</tbody>
</table>
Flavor Tagging

\[ B^0 \rightarrow D^{*+} \ell^\pm \nu \]

Data

Monte Carlo

April 2002 CP Violation at Belle
## Two Pseudoscalar Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_m$</th>
<th>$\Sigma$</th>
<th>$\epsilon$ [%]</th>
<th>$\mathcal{B}$ [\times 10^{-5}]</th>
<th>U.L. [\times 10^{-5}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to \pi^+\pi^-$</td>
<td>17.7 $^{+7.1}<em>{-6.4}$ $^{+0.3}</em>{-1.1}$</td>
<td>3.1</td>
<td>28.1</td>
<td>0.56 $^{+0.23}_{-0.20}$ $^{\pm 0.04}$</td>
<td>–</td>
</tr>
<tr>
<td>$B^+ \to \pi^+\pi^0$</td>
<td>10.4 $^{+5.1}<em>{-4.3}$ $^{+1.2}</em>{-1.6}$</td>
<td>2.7</td>
<td>12.0</td>
<td>0.78 $^{+0.38}<em>{-0.32}$ $^{+0.08}</em>{-0.12}$</td>
<td>1.34</td>
</tr>
<tr>
<td>$B^0 \to K^+\pi^-$</td>
<td>60.3 $^{+10.6}<em>{-9.9}$ $^{+2.7}</em>{-1.1}$</td>
<td>7.8</td>
<td>28.0</td>
<td>1.93 $^{+0.34}<em>{-0.32}$ $^{+0.15}</em>{-0.06}$</td>
<td>–</td>
</tr>
<tr>
<td>$B^+ \to K^+\pi^0$</td>
<td>34.9 $^{+7.6}<em>{-7.0}$ $^{+0.6}</em>{-2.0}$</td>
<td>7.2</td>
<td>19.2</td>
<td>1.63 $^{+0.35}<em>{-0.33}$ $^{+0.16}</em>{-0.18}$</td>
<td>–</td>
</tr>
<tr>
<td>$B^+ \to K^0\pi^+$</td>
<td>10.3 $^{+4.3}<em>{-3.6}$ $^{+0.4}</em>{-0.1}$</td>
<td>3.5</td>
<td>13.5</td>
<td>1.37 $^{+0.57}<em>{-0.48}$ $^{+0.19}</em>{-0.18}$</td>
<td>–</td>
</tr>
<tr>
<td>$B^0 \to K^0\pi^0$</td>
<td>8.4 $^{+3.8}<em>{-3.1}$ $^{+0.4}</em>{-0.6}$</td>
<td>3.9</td>
<td>9.4</td>
<td>1.60 $^{+0.72}<em>{-0.59}$ $^{+0.25}</em>{-0.27}$</td>
<td>–</td>
</tr>
<tr>
<td>$B^0 \to K^+K^-$</td>
<td>0.2 $^{+3.8}_{-0.2}$</td>
<td>–</td>
<td>24.0</td>
<td>–</td>
<td>0.27</td>
</tr>
<tr>
<td>$B^+ \to K^+\bar{K}^0$</td>
<td>0.0 $^{+0.9}_{-0.0}$</td>
<td>–</td>
<td>12.1</td>
<td>–</td>
<td>0.50</td>
</tr>
</tbody>
</table>
Constraints

\[ |\varepsilon_K| \]

\[ \Delta m_d \]

\[ |V_{ub}/V_{cb}| \]

\[ \sin 2\beta_{WA} \]
What if $|\lambda| \neq 1$?

In general we have

$$p_{\pm}(\Delta t) = \frac{\Gamma e^{-\Gamma |\Delta t|}}{2(1 + |\lambda|^2)} \left[ \frac{1 + |\lambda|^2}{2} \pm \text{Im} \lambda \sin(\Delta m \Delta t) \mp \frac{1 - |\lambda|^2}{2} \cos(\Delta m \Delta t) \right]$$

If $|\lambda|$ is allowed to float, (i.e. a $\cos(\Delta m \Delta t)$ term)

$$|\lambda| = 1.03 \pm 0.09$$

$$\sin 2\phi_1 = 0.99 \pm 0.14$$

The CPV asymmetry is unchanged.

Note: if $|\lambda| \neq 1$, then the gold-plated mode isn’t really gold plated.
**KL Details**

- **Two classes**: KLM+ECL and ECL only (397 and 172 entries, respectively)
  - Fitted yield is 346 events.
- **Background composition**: 71% non-CP modes.
  - The remainder is $\psi K_L \pi^0 (13\%)$, $\psi K_s (10\%)$ which are both CP=-1 and 5%($\psi K$, $\chi_{c1} K_s$, $\psi \pi^0$) which are CP=+1.
- $p_B^*$ background shape is used to find bkg level.
\[ B(B \rightarrow K \mu^+ \mu^-) = (0.99^{+0.40+0.13}_{-0.32-0.14}) \times 10^{-6} \]

\[ B(B \rightarrow K^* \mu^+ \mu^-) < 3.1 \times 10^{-6} \quad 90\% \text{ CL} \]

\[ B(B \rightarrow K e^+ e^-) < 1.3 \times 10^{-6} \quad 90\% \text{ CL} \]

\[ B(B \rightarrow K^* e^+ e^-) < 5.6 \times 10^{-6} \quad 90\% \text{ CL} \]
Particle ID
(dE/dx, ToF, & Aerogel)

\[ dE/dx \text{ meas. by CDC} \]
80% truncated mean of 50 layers
\[ 0.3 < P < 0.7 \text{ GeV} \]
\[ \sigma(dE/dx) = 6.8\% \]

Aerogel Cherenkov counter
\[ n = 1.010 - 1.03 \text{ depending on } \theta \]
\[ N_{p.e.} = 20.0 \text{ for } \beta = 1 \text{ part.} \]
(with \( n = 1.015 \))

Time-of-flight measurement
\[ \sigma_{TOF} = 120 \text{ psec} \]
Track matching eff.
\[ \simeq 90\% \]
April 2002 CP Violation at Belle

Belle: Aerogel

Barrel Module

Kaons (selected by ToF and dE/dx)

Bhabha e+/e−

Pulse Height (p.e.)

Beam Data

Monte Carlo
Particle ID (dE/dx, ToF, & Aerogel)

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

![Graph showing particle identification distributions for pions and kaons.](image)
Time-Dependent Asymmetry

One can plot the excess/deficit on a bin-by-bin basis.

First we start with a non-CP sample to look for false asymmetries.
Comparison to Other CKM Results
Other Modes

$B^+ \rightarrow \chi_{c0} K^+$

$\rightarrow \pi^+ \pi^-$

$B^+ \rightarrow \chi_{c0} K^+$

$\rightarrow K^+ K^-$

April 2002

CP Violation at Belle
What if $|\lambda| \neq 1$?

In general we have

$$p_{\pm}(\Delta t) = \frac{\Gamma e^{-\Gamma|\Delta t|}}{2(1 + |\lambda|^2)} \left[ \frac{1 + |\lambda|^2}{2} \pm \text{Im} \lambda \sin(\Delta m \Delta t) + \frac{1 - |\lambda|^2}{2} \cos(\Delta m \Delta t) \right]$$

If $|\lambda|$ is allowed to float, (i.e. a $\cos(\Delta m t)$ term)

$$|\lambda| = 1.03 \pm 0.09$$

$$\sin 2\phi_1 = 0.99 \pm 0.14$$

The CPV asymmetry is unchanged.

Note: if $|\lambda| \neq 1$, then the gold-plated mode isn’t really gold plated.
Likelihood Plots

$-2 \ln \left( \frac{L}{L_{\text{max}}} \right)$ vs $\sin 2\varphi_1$

- $\xi_f = -1$
- $\xi_f = +1$
- all modes

April 2002

CP Violation at Belle
Other Modes

Probing $\sin 2\phi_1$ with other modes.

We need a lot more data to get a measurement of $\sin 2\phi_1$ this way (cf GPM, where there are ~500 events).

April 2002
Other Modes

Probing $\sin 2\phi_1$ with other modes.

For $\phi K$ modes the decay amplitude is a pure penguin.

$21.6 \text{ fb}^{-1}$  \hspace{2cm} $8 \pm 3$ events
Two Body Modes

10.4 fb⁻¹

CP Violation at Belle
Branching Fraction Comparison

\[ \text{Br} \left(10^{-5}\right) \text{ (90\% CL)} \]

\[ \pi^+\pi^-: 0.56^{+0.23}_{-0.20} \pm 0.04 \ [3.1\sigma] \]

\[ \pi^+\pi^0: <1.34 \]

\[ K^+\pi^-: 1.93^{+0.34}_{-0.32} \pm 0.15 \ [7.8\sigma] \]

\[ K^+\pi^0: 1.63^{+0.35}_{-0.33} \pm 0.16 \ [7.2\sigma] \]

\[ K^0\pi^+: 1.37^{+0.57}_{-0.48} \pm 0.19 \ [3.5\sigma] \]

\[ K^0\pi^0: 1.60^{+0.72}_{-0.59} \pm 0.25 \ [3.9\sigma] \]

\[ K^+K^-: <0.27 \]

\[ K^+\bar{K}^0: <0.50 \]
$B \rightarrow K^{(*)} \ell \ell$

29.1 fb$^{-1}$

FCNCs are an ideal hunting ground for new physics.

A $B \rightarrow K\mu^+\mu^-$ signal is clearly seen.
## Yields and Limits

### Signal yields (29.1 fb⁻¹)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Signal</th>
<th>Background</th>
<th>stat. signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ke^+e^-$</td>
<td>$4.1^{+2.7}<em>{-2.1}^{+0.6}</em>{-0.8}$</td>
<td>$1.7 \pm 0.4$</td>
<td>2.5</td>
</tr>
<tr>
<td>$K^*e^+e^-$</td>
<td>$6.3^{+3.7}<em>{-3.0}^{+1.0}</em>{-1.1}$</td>
<td>$5.7 \pm 0.9$</td>
<td>2.5</td>
</tr>
<tr>
<td>$K\mu^+\mu^-$</td>
<td>$9.5^{+3.8}<em>{-3.1}^{+0.8}</em>{-1.0}$</td>
<td>$1.6 \pm 0.4$</td>
<td>4.7</td>
</tr>
<tr>
<td>$K^*\mu^+\mu^-$</td>
<td>$2.1^{+2.9}<em>{-2.1}^{+0.9}</em>{-1.0}$</td>
<td>$4.9 \pm 0.8$</td>
<td></td>
</tr>
</tbody>
</table>

### Upper limits (90% C.L.)

| $B \rightarrow Ke^+e^-$ | $< 1.3 \times 10^{-6}$ |
| $B \rightarrow K^*e^+e^-$ | $< 5.6 \times 10^{-6}$ |
| $B \rightarrow K^*\mu^+\mu^-$ | $< 3.1 \times 10^{-6}$ |
Putting it all together

\[ B^0 \rightarrow J/\Psi K_S \rightarrow (\mu^+ \mu^-)(\pi^+ \pi^-) \]

April 2002

CP Violation at Belle
Flavor Tagging

Two measures of tagging performance:

- $\varepsilon = \text{efficiency}$
- $w = \text{wrong-tag fraction}$

Amplitude of mixing oscillation depends on $w$

$\varepsilon_{\text{eff}} = 0.27 \pm 0.01$
Existing Constraints

Höcker et al.
hepex/0104062
225-259

$\sin 2\beta$ results are average prior to July 2001. They are \textit{not} included in the fit.
April 2002 CP Violation at Belle

Fit to Lifetime

$B \rightarrow D^{*} \ell \nu$

$\tau_{B^0} = 1.55 \pm 0.02 \text{ ps}$

$\tau_{B^-} = 1.64 \pm 0.03 \text{ ps}$
The Fitted Result

\[
\sin 2\phi_1 = 0.99 \pm 0.14 \pm 0.06
\]

PRL 87, 091802 (2001)