Talk Outline

• Introduction
• KEK-B & Belle
• Time-dependent CP Violation Measurement/Analysis in the context of the Gold-Plated Modes
• Other $\sin 2\varphi_1$ Modes
• $B^0 \rightarrow \pi^+\pi^-$
• Conclusion
The gold-plated mode determines the angle $\phi_1$ which is also called $\beta$.
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 Y(4S)
- Luminosity
  - target:  $10^{34}$ cm$^{-2}$s$^{-1}$
  - achieved: $9.5 \times 10^{33}$ cm$^{-2}$s$^{-1}$

World record for any accelerator class!
KEKB Performance

Integrated/day

500 pb⁻¹ day⁻¹

Total Integrated

~78 fb⁻¹

World’s largest sample!
Belle Detector

- SC solenoid 1.5T
- CsI(Tl) 16X₀
- TOF counter
- 8GeV e⁻
- 3.5GeV e⁺
- Aerogel Cherenkov cnt. n=1.015~1.030
- Tracking + dE/dx small cell + He/C₂H₅
- μ / K_L detection 14/15 lyr. RPC+Fe
- Si vtx. det. 3 lyr. DSSD
An international collaboration involving about 10 Countries, 50 Institutes, & ~300 People
Time-Dependent CP Violation

For a decay $B^0 \rightarrow f$ where $f$ is a CP eigenstate, there are two “indistinguishable” decay paths

Working through the algebra, yields a time-dependent CP asymmetry

$$A_{CP}(\Delta t) = \frac{\Gamma(B^0 \rightarrow f) - \Gamma(\bar{B}^0 \rightarrow f)}{\Gamma(B^0 \rightarrow f) + \Gamma(\bar{B}^0 \rightarrow f)}$$

$$= -\xi_f \sin(\Delta m\Delta t) \sin 2(\phi_M + \phi_D)$$

Where $\phi_M$ and $\phi_D$ are the weak phases for the mixing and decay diagrams, respectively and

$$CP|f\rangle = \xi_f |f\rangle$$

$$\xi_f = \pm 1$$

For $B \rightarrow J/\psi K_s$ and related modes., $\phi_D = 0$ and $\phi_M = \phi_1$
The Measurement

- Measure momenta
- ID leptons & K’s
- Measure vertices

\[ B^0 \pm \mu^\pm \pm e^\pm \pm e^\pm \pm \bar{B}^0 \pm \Delta z \pm J/\Psi \pm \mu^+ \pm \mu^- \pm CP \pm D^0 \]
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
   - $\sin 2\phi_1$
B Reconstruction

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

457 Events

\(~3\%\) Background

29 fb\(^{-1}\) sample

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

\[m_{bc} = \sqrt{(E_{\text{beam}}^*)^2 - \left(\sum_{\text{cand}} \vec{p}\right)^2}\]
CP Even Mode ($B \to J/\psi K_L$) Reconstruction

- Assume $B^0 \to J/\psi K_L$ (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 $p_B^* = |\vec{p}_{J/\psi}^* + \vec{p}_{K_L}^*|$

See talk by Vahsen
B → J/ΨK_L Reconstruction

\[ p_B^* = |\vec{p}_{J/Ψ}^* + \vec{p}_{K_L}^*| \]

78 fb\(^{-1}\) Sample
# Charmonium CP Mode Summary

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\xi_f$</th>
<th>$N_{rec}$</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$</td>
<td>-1</td>
<td>1285</td>
<td>0.98</td>
</tr>
<tr>
<td>$J/\psi(\ell^+\ell^-)K_S^0(\pi^0\pi^0)$</td>
<td>-1</td>
<td>188</td>
<td>0.82</td>
</tr>
<tr>
<td>$\psi(2S)(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$</td>
<td>-1</td>
<td>91</td>
<td>0.96</td>
</tr>
<tr>
<td>$\psi(2S)(J/\psi\pi^+\pi^-)K_S^0(\pi^+\pi^-)$</td>
<td>-1</td>
<td>112</td>
<td>0.91</td>
</tr>
<tr>
<td>$\chi_{c1}(J/\psi\gamma)K_S^0(\pi^+\pi^-)$</td>
<td>-1</td>
<td>77</td>
<td>0.96</td>
</tr>
<tr>
<td>$\eta_c(K_S^0K^-\pi^+)K_S^0(\pi^+\pi^-)$</td>
<td>-1</td>
<td>72</td>
<td>0.65</td>
</tr>
<tr>
<td>$\eta_c(K^+K^-\pi^0)K_S^0(\pi^+\pi^-)$</td>
<td>-1</td>
<td>49</td>
<td>0.72</td>
</tr>
<tr>
<td>$\eta_c(\rho\pi)K_S^0(\pi^+\pi^-)$</td>
<td>-1</td>
<td>21</td>
<td>0.94</td>
</tr>
<tr>
<td>All with $\xi_f = -1$</td>
<td></td>
<td>1895</td>
<td>0.94</td>
</tr>
<tr>
<td>$J/\psi(\ell^+\ell^-)K^{*0}(K_S^0\pi^0)$</td>
<td>-1(19%)/+1(81%)</td>
<td>101</td>
<td>0.92</td>
</tr>
<tr>
<td>$J/\psi(\ell^+\ell^-)K_L^0$</td>
<td>+1</td>
<td>1330</td>
<td>0.63</td>
</tr>
<tr>
<td>All</td>
<td></td>
<td>3326</td>
<td>0.81</td>
</tr>
</tbody>
</table>

78 fb$^{-1}$ Sample
Flavor Tagging

One needs 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., $B^0 \to D^{(*)-} \pi^+$)
  - Low-momentum $\pi^\pm$ (from D*’s).

- Need to take into account multiple tags and correlations.
Flavor Tagging

\[ q = \pm 1; \quad 0 < r < 1 \iff \text{tag reliability} \]

\[ r = 1 - 2w \]
The $B$ lifetime is of the same order as the vertex resolution, so the effect is quite subtle.
Fitting

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

Signal

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

Background

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

Response function

\[ + P_{\text{bkg}}(\Delta t' - \Delta t) \otimes R_{\text{bg}}(\Delta t) \times f_{\text{bg}} \]
The Fitted Result: 78 fb$^{-1}$ Sample

\[ \sin 2\varphi_1 = 0.719 \pm 0.074 \pm 0.035 \]

\[ \text{cf BaBar} \quad \sin 2\beta = 0.741 \pm 0.067 \pm 0.034 \]
Other $\varphi_1$ Modes $b \to \bar{s}ss$

In the SM, the phase for these decays is $\sim 0$, so the time-dependent asymmetry should be $\sim \sin 2\varphi_1$ with direct CPV. Given the anomalously large rate, however, there might be more to the story . . .

\[ B(B^0 \to \eta' K^0) = 5.8 \times 10^{-5} \]
Other $\phi_1$ Modes: $b \to \bar{ss}s$

- $B^0 \to \pi^+ \pi^-$
- $B^0 \to \eta' K_S$
  - $\pi^+ \pi^- \eta, \rho \gamma$
- $B^0 \to \pi^+ \pi^-$
- $B^0 \to \phi K_S$
  - $\gamma \gamma$
- $B^0 \to K^+ K^- K_S$
  - $(K^+ K^- \neq \phi)$

$M_{bc}$ (GeV/c$^2$)
Other $\phi_1$ Modes: $b \to \bar{s}ss$

Raw CP asymmetries

\[
\begin{align*}
S_{\eta'K} &= 0.71 \pm 0.37 \pm 0.06 \\
A_{\eta'K} &= 0.26 \pm 0.22 \pm 0.03 \\
S_{\phi K} &= -0.73 \pm 0.64 \pm 0.22 \\
A_{\phi K} &= -0.56 \pm 0.41 \pm 0.16 \\
S_{KKK} &= 0.49 \pm 0.43 \pm 0.11^{+0.33}_{-0.00} \\
A_{KKK} &= -0.40 \pm 0.33 \pm 0.10^{+0.00}_{-0.26}
\end{align*}
\]

Uncertainty in CP ± fractions

\[ w = (3^{+16}_{-3})\% \]
Onward to $\phi_2$
Measuring $2\phi_2$ with $B \to \pi^+\pi^-$

Interference between the tree-level and penguin decay graphs is a little bit too much of a good thing!

$$\Gamma(\Delta t) = \frac{e^{-\Delta t/\tau_B}}{4\tau_B} [1 + q(S_{\pi\pi} \sin \Delta m \Delta t + A_{\pi\pi} \cos \Delta m \Delta t)]$$

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

Population difference between the $q=+1$ and $q=-1$ samples.
Particle ID

\[ \Gamma(B^0 \rightarrow K^+\pi^-) \approx 4\Gamma(B^0 \rightarrow \pi^+\pi^-) \]

Need to augment kinematic suppression with particle ID.

for \( \pi^+\pi^- \),
\[ \pi \text{ eff.} = 0.91 \]
\[ K \text{ fake rate} = 0.10 \]
Continuum Suppression

- Event topology
  - Modified Fox-Wolfram
  - Fisher Discriminant
- Angular distribution of B flight direction
- Combine into likelihood
  \[ LR = \frac{L_S}{L_S + L_{q\bar{q}}} \]

Note: The likelihood cut depends on the flavor-tagging class.
$$B^0 \rightarrow \pi^+ \pi^-$$

Kinematic Selection

$$B^0 \rightarrow K^\pm \pi^\mp$$

$$\Delta E = 45 \text{ MeV} \approx 2 \sigma_{\Delta E}$$

LR $> 0.825$

LR $< 0.825$
$A_{\pi\pi} = +0.77 \pm 0.27 \pm 0.08$

$S_{\pi\pi} = -1.23 \pm 0.41 \pm 0.08$
The resulting signature of CP violation is mainly a mean shift between the $B^0$ and $\bar{B}^0$ samples.
The log likelihood functions are not well behaved (parabolic), which is not surprising since the central values lie outside of the physically allowed region.
Statistical Error

The MINOS errors are significantly smaller than the toy-MC pull distributions. After considerable internal discussion, we decided to adopt the larger MC errors as the most indicative of the actual statistical uncertainty.

Green arrows indicate MINOS errors.
How Often Are We Outside the Physical Region?

Events outside physical region: 60.1%
Events outside ellipse: 16.6%

Physical region $A_{\pi\pi}^2 + S_{\pi\pi}^2 \leq 1$

"Toy MC" ensemble.

$A_{\pi\pi} = 0.539$  $S_{\pi\pi} = -0.822$
Confidence Regions; Evidence for $CP$ Violation

- Feldman-Cousins frequentist approach.
- Acceptance regions obtained from MC pseudo-experiments.
- Systematic errors also included.
- Confidence Level (CL) at each point is calculated.

CL for CP conservation: $3.4\sigma$
Future Prospects (as seen in the past!)

Projection of Luminosity Accumulation

1/fb

- 33/fb
- 75/fb
- 130/fb
- 315/fb
- 440/fb

- Installation of Ante-chambers and Crab cavities
- Energy switch
Summary & Conclusions

• CP violation in the B system has been observed at the >6σ level.
  
  \[ \sin 2\varphi_1 = 0.719 \pm 0.074 \pm 0.035 \]

• Measurements of CP asymmetries in \( b \rightarrow s\bar{s}s \) are approaching significance.

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

  \[ A_{\pi\pi} = +0.77 \pm 0.27 \pm 0.08 \quad S_{\pi\pi} = -1.23 \pm 0.41 \pm 0.08 \]
The End
Additional Slides
$B^0 \rightarrow K^+\pi^-$ control sample

Positively-identified kaons (opposite use of PID)

LR > 0.825

LRmin < LR ≤ 0.825

1371 candidates
Mixing fit using $B^0 \rightarrow K^+ \pi^-$

$\Delta m_d = 0.55^{+0.05}_{-0.07}$ ps$^{-1}$

Consistent with the world average $(0.489 \pm 0.008)$ ps$^{-1}$

PDG2002
But What About the CP Violating Phase?

As noted, it is there, but we can’t get at it in a standard mixing measurement since it disappears when we “project out” the flavor eigenstates.
Lifetime Measurements

c.f. (PDG2002)

\( \pi\pi : \tau_B = (1.42 \pm 0.14) \) ps

\( K\pi : \tau_B = (1.46 \pm 0.08) \) ps

Evidence that background treatment is correct
Null Asymmetry Tests

Null asymmetry

\[ A = -0.015 \pm 0.022 \]
\[ S = 0.045 \pm 0.033 \]
\[ S_{K\pi} = 0.08 \pm 0.16 \]
\[ A_{K\pi} = -0.03 \pm 0.11 \]
Monte Carlo pseudo experiments are used to check various things. In particular, we studied the linearity of the fitting procedure and the determination of the statistical error.
### Systematic Uncertainties

<table>
<thead>
<tr>
<th>source</th>
<th>$A_{\pi\pi}$ $+$error</th>
<th>$A_{\pi\pi}$ $-$error</th>
<th>$S_{\pi\pi}$ $+$error</th>
<th>$S_{\pi\pi}$ $-$error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background fractions</td>
<td>+0.058</td>
<td>−0.048</td>
<td>+0.044</td>
<td>−0.055</td>
</tr>
<tr>
<td>Vertexing</td>
<td>+0.044</td>
<td>−0.054</td>
<td>+0.037</td>
<td>−0.012</td>
</tr>
<tr>
<td>Fit bias</td>
<td>+0.016</td>
<td>−0.021</td>
<td>+0.052</td>
<td>−0.020</td>
</tr>
<tr>
<td>Wrong tag fraction</td>
<td>+0.026</td>
<td>−0.021</td>
<td>+0.015</td>
<td>−0.016</td>
</tr>
<tr>
<td>$\tau_B, \Delta m_d, A_{K\pi}$</td>
<td>+0.021</td>
<td>−0.014</td>
<td>+0.022</td>
<td>−0.022</td>
</tr>
<tr>
<td>Resolution function</td>
<td>+0.019</td>
<td>−0.020</td>
<td>+0.010</td>
<td>−0.013</td>
</tr>
<tr>
<td>Background shape</td>
<td>+0.003</td>
<td>−0.015</td>
<td>+0.007</td>
<td>−0.002</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.08</strong></td>
<td><strong>0.08</strong></td>
<td><strong>0.08</strong></td>
<td><strong>0.07</strong></td>
</tr>
</tbody>
</table>

* Actual estimations were done before seeing the fit result, as we adopted a blind analysis technique.
Muon Identification

The dilepton decay modes are a big part of the reason of why the "gold-plated" modes are given that name.

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

plus tag-side \( \mu \)

The gaps are instrumented with RPCs.