Measurements of $\sin^2\varphi_1$

at Belle and BaBar

5th International Conference on Hyperons,
Charm, and Beauty Hadrons
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Daniel R. Marlow
Princeton University/Belle Collaboration
Talk Outline

• Physics of $\varphi_1$, a simple picture.
• The Tools: Accelerators and Detector
• Indirect CP Violation Measurement/Analysis
• Results from Belle and BaBar
• Other $\varphi_1$ modes
The Kobayashi-Maskawa Mixing Scheme

Quark mixing is described via

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

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 Unitarity of the CKM mixing matrix can be represented as a triangle in the complex plane.

To obtain sensitivity to the phases that give rise to CP violation, one needs some sort of interference.

\[ V_{ud} \approx V_{tb} \approx 1 \]
Why do some call it $\sin 2\phi_1$?

In my first recollection of the unitarity triangle (mid 80’s), it was called the “Bjorken triangle.” The sketch above was drawn by Bjorken at a 1987 D0 workshop. I would be personally interested to know how and when the more common, “$\alpha, \beta, \gamma$” notation came into being.
Indirect CP Violation

In many measurements we obtain the requisite interference using state mixing, i.e.,

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

\[ |B^0(t)\rangle \propto \cos\left(\frac{\Delta m t}{2}\right)|B^0\rangle + ie^{-2i\phi_1}\sin\left(\frac{\Delta m t}{2}\right)|\bar{B}^0\rangle \]

\[ |\bar{B}^0(t)\rangle \propto ie^{2i\phi_1}\sin\left(\frac{\Delta m t}{2}\right)|B^0\rangle + \cos\left(\frac{\Delta m t}{2}\right)|\bar{B}^0\rangle \]

\[ |B^0_{\pm}\rangle \equiv \frac{1}{\sqrt{2}}\left[|B^0\rangle \pm |\bar{B}^0\rangle\right] \]

CP Eigenstates

\[ B_0^0 \rightarrow J/\Psi K_S \quad \text{CP odd} \]

\[ B_0^0 \rightarrow J/\Psi K_L \quad \text{CP even} \]
Indirect CP Violation

If we choose $\varphi_1=45^\circ$, then $e^{\pm 2i\varphi_1} = \pm i$

\[ |B^0(t)\rangle \propto \cos\left(\frac{\Delta m t}{2}\right)|B^0\rangle + \sin\left(\frac{\Delta m t}{2}\right)|B^0\rangle \]

\[ |\bar{B}^0(t)\rangle \propto -\sin\left(\frac{\Delta m t}{2}\right)|B^0\rangle + \cos\left(\frac{\Delta m t}{2}\right)|\bar{B}^0\rangle \]
Indirect CP Violation

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

CP eigenvalue

Interference from mixing.

Mixing Coefficient

No mixing
Effect of Resolution

The resulting signature of CP violation is mainly a mean shift between the $B^0$ and $\bar{B}^0$ samples.
Asymmetric $e^+e^-$ Colliders

**KEK:** KEK- 8.0 x 3.5 GeV/$c$
Lumi: Design $10^{34}$ cm$^{-2}$s$^{-1}$
    Achieved $7.2\times10^{33}$ cm$^{-2}$s$^{-1}$

**SLAC:** PEP II 9.0 x 3.1 GeV/$c$
Lumi: Design $3\times10^{33}$ cm$^{-2}$s$^{-1}$
    Achieved $3.1\times10^{33}$ cm$^{-2}$s$^{-1}$

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## 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>$7.2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$</td>
<td>$4.6 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$</td>
</tr>
<tr>
<td><strong>Shift</strong></td>
<td>141 pb$^{-1}$</td>
<td>105 pb$^{-1}$</td>
</tr>
<tr>
<td><strong>24 hour</strong></td>
<td>395 pb$^{-1}$</td>
<td>303 pb$^{-1}$</td>
</tr>
<tr>
<td><strong>month</strong></td>
<td>8617 pb$^{-1}$</td>
<td>6661 pb$^{-1}$</td>
</tr>
<tr>
<td><strong>Integrated</strong></td>
<td>87.0 fb$^{-1}$</td>
<td>92.0 fb$^{-1}$</td>
</tr>
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As of ~June 21, 2002  Comparisons not quite apples to apples.
Particle Detection

\[ e^+ e^- \rightarrow B^0 \bar{B}^0 \]

CP eigenstate

\[ \rightarrow J/\Psi K_s \]

Hadron Identification

\[ K^+ X^- \]

tag

Lepton Identification

\[ l^+ l^- \]

Momentum Measurement

\[ \rightarrow \pi^+ \pi^- \]
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
   - $\sin 2\phi_1$
$J/\psi \, K_s(\pi^+\pi^-)$

457 Events
~3% Background

30 fb$^{-1}$ sample

$$\Delta E \equiv E^*_\text{cand} - E^*_\text{beam}$$

$$m_{bc} = \sqrt{(E^*_\text{beam})^2 - \left(\sum_{\text{cand}} \vec{p}\right)^2}$$

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CP Even Mode: $B \rightarrow J/\Psi K_L$

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

767 candidates
60% signal purity

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## Charmonium Event Sample Summary

<table>
<thead>
<tr>
<th>Mode</th>
<th>BaBar (38 fb(^{-1}*))</th>
<th>Belle (42 fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Events</td>
<td>Purity</td>
</tr>
<tr>
<td>(J/\Psi K_S(\pi^+\pi^-))</td>
<td>693</td>
<td>96%</td>
</tr>
<tr>
<td>(J/\Psi K_S(\pi^0\pi^0))</td>
<td>123</td>
<td>89%</td>
</tr>
<tr>
<td>(\Psi(2S)K_S)</td>
<td>119</td>
<td>89%</td>
</tr>
<tr>
<td>(\chi_{c1}K_S)</td>
<td>60</td>
<td>94%</td>
</tr>
<tr>
<td>(\eta_cK_S)</td>
<td>119</td>
<td>89%</td>
</tr>
<tr>
<td>(J/\Psi K_L)</td>
<td>742</td>
<td>57%</td>
</tr>
</tbody>
</table>

*BaBar luminosity scaled by raw tagging efficiency—i.e., 56 fb\(^{-1}\) \(\times 0.675 = 38\) fb\(^{-1}\)
Flavor Tagging

Hierarchical Tagging Categories

For electrons, muons and Kaons use the charge correlation

\[ I^- \rightarrow \bar{B}^0 \]
\[ I^+ \rightarrow B^0 \]

Lepton Tag

Kaon Tag

Multivariate analysis exploiting the other kinematic information of the event, e.g.,
- Momentum spectrum of the charged particles
- Information from non-identified leptons and kaons
- Soft \( \pi \) from \( D^* \) decay

Neural Network

Each category is characterized by the probability of giving the wrong answer (mistag fraction \( \nu \))
Flavor Tagging Belle

BaBar requires a minimum level of reliability of the tagging information, before including an event in their sample, Belle accepts all events, weighting them according to the reliability of the tagging information.
Flavor Tagging

Although the techniques of the two experiments differ in detail, both ultimately rely on data to determine their wrong-tag fractions, which have a direct effect on the fitted value of the CP asymmetry.

<table>
<thead>
<tr>
<th>Effective Tagging Efficiency</th>
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<tr>
<td>BaBar</td>
<td>$(25.1 \pm 0.8)%$</td>
</tr>
<tr>
<td>Belle</td>
<td>$(27.0 \pm 1.0)%$</td>
</tr>
</tbody>
</table>
The $B$ lifetime is of the same order as the vertex resolution, so the effect is quite subtle.
Test of Vertex Resolution

\[ B^0 \rightarrow J / \Psi K^{*0} \]

\[ l^+l^- \text{ (CP Vtx)} \]
Fitting

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

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

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

Response function

\[ + P_{\text{bkg}}(\Delta t' - \Delta t) \otimes R_{\text{bkg}}(\Delta t) \times f_{\text{bg}} \]
The Fitted Result

\[ \sin 2\varphi_1 = 0.82 \pm 0.12 \pm 0.05 \]
Time Dependent Asymmetries

\[ \sin 2\beta = 0.76 \pm 0.10 \]

\[ \sin 2\beta = 0.73 \pm 0.19 \]
World Average of $\sin 2\phi_1$ Measurements

It looks like CDF had it right!

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B→η’K Results

Belle has looked for a time-dependent CP asymmetry

\[ A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0 \rightarrow \eta' K_S) - \Gamma(B^0 \rightarrow \eta' K_S)}{\Gamma(\overline{B}^0 \rightarrow \eta' K_S) + \Gamma(B^0 \rightarrow \eta' K_S)} \equiv A_{\eta'K_S} \cos(\Delta m\Delta t) + S_{\eta'K_S} \sin(\Delta m\Delta t) \]

In the simplest case, we expect \( A_{\eta'K_S} = 0 \) and \( S_{\eta'K_S} = \sin 2\phi_1 \), but the larger-than-expected measured by CLEO and confirmed by Belle and BaBar suggests that there may be something more going on, possibly leading to \( A_{\eta'K_S} \neq 0 \) and \( S_{\eta'K_S} \neq \sin 2\phi_1 \).
Yields: $B \rightarrow \eta' K_S$

- $\eta' \rightarrow \eta \pi \pi$
- $\eta' \rightarrow \rho \gamma$

$B \rightarrow \eta' K^+$

(a) $\eta' K^-$

(b) $\eta' K^+$
$B \rightarrow \eta' K$

Asymmetries

\[ A_{\eta'K_s} = 0.13 \pm 0.32^{+0.09}_{-0.06} \]

\[ S_{\eta'K_s} = 0.28 \pm 0.55^{+0.07}_{-0.08} \]

$B \rightarrow \eta' K^\pm$ Counting Asymmetry

\[ A_{\eta'K^\pm} \equiv \frac{N(B^-) - N(B^+)}{N(B^-) + N(B^+)} \]

\[ = (-1.5^{+7.2}_{-6.8} \pm 0.9)\% \]
Conclusions

• The first angle of the unitarity triangle is now well determined:

\[ \sin 2\varphi_1 = 0.78 \pm 0.08 \]

• Other modes are beginning to show sufficient statistical accuracy to facilitate meaningful comparison.

• Belle and BaBar provide one another with tough competition.