Measurement of cos2\(\beta\) at BABAR

Resolving Ambiguity from sin2\(\beta\)

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on behalf of the
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CKM Physics

- CKM matrix describes weak couplings in quarks
  \[
  \begin{pmatrix}
  d' \\
  s' \\
  b'
  \end{pmatrix}
  =
  \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
  \end{pmatrix}
  \begin{pmatrix}
  d \\
  s \\
  b
  \end{pmatrix}
  \]

- Primary goal of the B-factories is to measure these parameters (magnitudes and phases) in as many ways as possible, over constraining the Standard Model parameter space.

In this convention, only $V_{ub}$ and $V_{td}$ contain phases of order 1.
Time-Dependent Measurement

- $\Upsilon(4S)$ decays to $B^0\bar{B}^0$ coherently.

- Center-of-mass boosted $\beta\gamma=0.56$, separating two $B$ vertices.

- Interference between decay and decay via mixing resulting in CP asymmetry.

\[
A_{CP} = \frac{\Gamma(B^0_{\text{phys}}(t) \rightarrow f_{CP}) - \Gamma(B^0_{\text{phys}}(t) \rightarrow f_{CP})}{\Gamma(B^0_{\text{phys}}(t) \rightarrow f_{CP}) + \Gamma(B^0_{\text{phys}}(t) \rightarrow f_{CP})} = S \cdot \sin(\Delta m_d t) - C \cdot \cos(\Delta m_d t)
\]

\[
S = 2\eta_f \frac{\text{Im}(\lambda)}{1 + |\lambda|^2} \quad \lambda = \frac{q}{p} \frac{\bar{A}_f}{A_f} \quad ; \quad S = \eta_f \sin 2\beta \quad \text{if} \quad \frac{\bar{A}_f}{A_f} \quad \text{has no non-trivial phase.}
\]
Ambiguity in $\beta$

- $\sin 2\beta$ has been measured pretty precisely using charmonium-$K^0$ decays.
- Four-fold ambiguity in $\beta$.
- Solution $\beta=21^\circ (+180^\circ)$ is consistent with other constraints in SM, but there is room for new phase in mixing so that it might not be the right solution.
- Measuring (the sign of) $\cos 2\beta$ can resolve the ambiguity.
- Idea: Use the decay modes that have more than one amplitude contributing with different strong phases and the strong phase difference can either be measured or calculated.
Resolving Ambiguity in $2\beta$ at BABAR

• First attempt: $B^0/\bar{B}^0 \to J/\psi K^{*0}$: use angular analysis to resolve $|A_0|e^{\delta_0}$, $|A_\parallel|e^{\delta_\parallel}$, $|A_\perp|e^{\delta_\perp}$ amplitudes and use P-wave/S-wave interference in $K\pi$ to resolve strong phase ambiguity.
  
  – [PRD 71, 032005] (not in this talk)

• Time-dependent Dalitz analysis in $B^0/\bar{B}^0 \to D^{(*)0}/\bar{D}^{(*)0} h^0$ with $D^0 \to K^0_S \pi^+ \pi^-$ (⇒ this talk).

• Time-dependent analysis in $B^0/\bar{B}^0 \to D^*+D^*-K^0_S$ in partial phase space (⇒ this talk).

• Time-dependent Dalitz analysis in $B^0/\bar{B}^0 \to K^+K^-K^0$
  
  – See Denis Dujmic's talk later today.
Color-Suppressed $B \rightarrow D^{(*)0} h^0$ Decays

- $B^0$ decay

\[ \begin{array}{c}
\bar{b} \\
B^0 \\
d \\
\bar{d} \\
\bar{D}^0 \\
\bar{c} \\
u \\
D^0 \\
d \\
\pi^0 \\
\end{array} \quad \text{via mixing} \quad \begin{array}{c}
b \\
D^0 \\
c \\
\bar{u} \\
\bar{D}^0 \\
\bar{d} \\
d \\
\pi^0 \\
\end{array} \]

\[ D^0 / \bar{D}^0 \rightarrow K^0_S \pi^+ \pi^- \] to reach a common final state.

- $P_\pm = \frac{1}{2} e^{-\Gamma t} |A|^2 \cdot \left[ (|A_{\bar{D}}|^2 + |A_D|^2) \mp (|A_{\bar{D}}|^2 - |A_D|^2) \cos(\Delta mt) \right.
\left. \pm 2 \eta_{h0} (-1)^L \text{Im} \left( e^{-2i\beta} A_D A^*_\bar{D} \right) \sin(\Delta mt) \right]$

\[ \text{Im} \left( e^{-2i\beta} A_D A^*_\bar{D} \right) = \text{Im}(A_D A^*_\bar{D}) \cos 2\beta - \text{Re}(A_D A^*_\bar{D}) \sin 2\beta \]

- Strong phases in $D^0$ and $\bar{D}^0$ amplitudes are different at a given point on the Dalitz plot $\Rightarrow \text{Im}(A_D A^*_\bar{D}) \neq 0$

- Need to model $D^0 / \bar{D}^0 \rightarrow K^0_S \pi^+ \pi^-$ amplitudes.

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Dalitz Plot Model

- **Isobar model**

\[
A_D(m_{+}^{2}, m_{-}^{2}) = \sum_{r} a_{r} e^{i\phi_{r}} A_{r}(m_{+}^{2}, m_{-}^{2}) + a_{NR} e^{i\phi_{NR}}
\]

- **Parameters determined from a large D*→D^0π sample.**

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Amplitude</th>
<th>Phase (deg)</th>
<th>Fit fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>K^*(892)^-</td>
<td>1.781 ± 0.018</td>
<td>131.0 ± 0.8</td>
<td>0.586</td>
</tr>
<tr>
<td>K_0^*(1430)^-</td>
<td>2.45 ± 0.08</td>
<td>−8.3 ± 2.5</td>
<td>0.083</td>
</tr>
<tr>
<td>K_2^*(1430)^-</td>
<td>1.05 ± 0.06</td>
<td>−54.3 ± 2.6</td>
<td>0.027</td>
</tr>
<tr>
<td>K^*(1410)^-</td>
<td>0.52 ± 0.09</td>
<td>154 ± 20</td>
<td>0.004</td>
</tr>
<tr>
<td>K^*(1680)^-</td>
<td>0.89 ± 0.30</td>
<td>−139 ± 14</td>
<td>0.003</td>
</tr>
<tr>
<td>K^*(892)^+</td>
<td>0.180 ± 0.008</td>
<td>−44.1 ± 2.5</td>
<td>0.006</td>
</tr>
<tr>
<td>K_0^*(1430)^+</td>
<td>0.37 ± 0.07</td>
<td>18 ± 9</td>
<td>0.002</td>
</tr>
<tr>
<td>K_2^*(1430)^+</td>
<td>0.075 ± 0.038</td>
<td>−104 ± 23</td>
<td>0.000</td>
</tr>
<tr>
<td>ρ(770)</td>
<td>1 (fixed)</td>
<td>0 (fixed)</td>
<td>0.224</td>
</tr>
<tr>
<td>ω(782)</td>
<td>0.0391 ± 0.0016</td>
<td>115.3 ± 2.5</td>
<td>0.006</td>
</tr>
<tr>
<td>f_0(980)</td>
<td>0.482 ± 0.012</td>
<td>−141.8 ± 2.2</td>
<td>0.061</td>
</tr>
<tr>
<td>f_0(1370)</td>
<td>2.25 ± 0.30</td>
<td>113.2 ± 3.7</td>
<td>0.032</td>
</tr>
<tr>
<td>f_2(1270)</td>
<td>0.922 ± 0.041</td>
<td>−21.3 ± 3.1</td>
<td>0.030</td>
</tr>
<tr>
<td>ρ(1450)</td>
<td>0.52 ± 0.09</td>
<td>38 ± 13</td>
<td>0.002</td>
</tr>
<tr>
<td>σ</td>
<td>1.36 ± 0.05</td>
<td>−177.9 ± 2.7</td>
<td>0.093</td>
</tr>
<tr>
<td>σ'</td>
<td>0.340 ± 0.026</td>
<td>153.0 ± 3.8</td>
<td>0.013</td>
</tr>
<tr>
<td>Non Resonant</td>
<td>3.53 ± 0.44</td>
<td>128 ± 6</td>
<td>0.073</td>
</tr>
</tbody>
</table>

[PRL 95, 121802 (2005)]
B→D*(*)0h0  Modes

• Used modes:  \(D^0\pi^0, D^0\eta, D^0\eta', D^0\omega, D^{*0}\pi^0, D^{*0}\eta\)

\[\eta \rightarrow \gamma\gamma \quad \eta \rightarrow \gamma\gamma, \pi^+\pi^-\pi^0 \quad \eta' \rightarrow \pi^+\pi^-\eta \quad \omega \rightarrow \pi^+\pi^-\pi^0\]

\(D^{*0} \rightarrow D^0\pi^0\)

• Use a Fisher discriminate to reduce the major background, continuum event (thrust angle, Legendre polynomial, B flight angle, event thrust, sphericity. Also exploit \(\omega\) decay angles)

• Cut |ΔE|<80 MeV for \(h^0\rightarrow\gamma\gamma\) modes,

  |ΔE|<40 MeV for \(h^0\rightarrow\pi\pi\pi^0\) modes.
Event Yield

- Fit to $m_{ES}$, $m_{D^0}$, $\Delta t$ and Dalitz variables simultaneously.
- $(m_{ES}, m_{D^0})$ discriminate peak and background with/without a real $D^0$.
- Fake $D^0$ Dalitz distribution modeled empirically from sideband.
- Peaking background determined from simulation.
- Data = 311 M $B\bar{B}$ pairs.
  
  signal = 384±28 events
Dalitz Distribution

$B^0$—tagged

$\bar{B}^0$—tagged
Preliminary Results

- Fit for $\cos 2\beta$, $\sin 2\beta$ and $|\lambda|$: $\cos 2\beta = 0.54 \pm 0.54 \pm 0.08 \pm 0.18$
  $\sin 2\beta = 0.45 \pm 0.35 \pm 0.05 \pm 0.07$
  $|\lambda| = 0.975^{+0.093}_{-0.085} \pm 0.012 \pm 0.002$

- Fix $\sin 2\beta$ at world average and $|\lambda|=1$:
  $\cos 2\beta = 0.55 \pm 0.52 \pm 0.08 \pm 0.18$

- Largest systematic error from Dalitz model.

- Generate toys with $\sin 2\beta=\sin 2\beta_{WA}$, and $\cos 2\beta= \pm(1-\sin^2 2\beta)^{1/2}$; compare fit distributions and data fit result:
  $\cos 2\beta= +(1-\sin^2 2\beta)^{1/2}$ is favored at 87% C.L.
**B→D*+D*-K^0 Decays**

- Tree-dominated process. If ignoring penguin, asymmetry amplitude = $\mathcal{D} \sin 2\beta$.
  - $\mathcal{D}$ is dilution due to possible resonances of different $J^P$ and non-resonance.

- Again, there is a varying strong phase over the DDK Dalitz plot. Integrate half of the Dalitz plot: (we don't know the detail of Dalitz model)

$$A(t) \equiv \frac{\Gamma_{B^0} - \Gamma_{B^0}}{\Gamma_{B^0} + \Gamma_{B^0}} = \eta_y \frac{J_c}{J_0} \cos(\Delta m_d t) - \left( \frac{2J_{s1}}{J_0} \sin 2\beta + \eta_y \frac{2J_{s2}}{J_0} \cos 2\beta \right) \sin(\Delta m_d t)$$

$$\eta_y = -1 (+1) \quad \text{for} \quad m^2(D^{*+}K^0) < (>) m^2(D^{*-}K^0)$$

$$J_0 = \int |A|^2 + |\bar{A}|^2 \quad J_c = \int |A|^2 - |\bar{A}|^2 \quad J_{s1} = \int \text{Re}(\bar{A}A^*) \quad J_{s2} = \int \text{Im}(\bar{A}A^*)$$

over the region where $m^2(D^{*+}K^0) < m^2(D^{*-}K^0)$
Branching Fraction Results

- Modes: $D^{*+} \to D^0 \pi^+$, $D^+ \pi^0$; $D^0 \to K^- \pi^+$, $K^- \pi^+ \pi^0$, $K^- \pi^+ \pi^- \pi^+$; $D^+ \to K^- \pi^+ \pi^+$.

Data = 230 M $B \bar{B}$ pairs

$D^+_s(2536)$: $12.3 \pm 4.0$ events

$\mathcal{B}(B^0 \to D^{*+} D^*^- K_S^0) = (4.4 \pm 0.4 \pm 0.7) \times 10^{-3}$

$\mathcal{B}(B^0 \to D^{*-} D^+_s(2536)) \times \mathcal{B}(D^+_s(2536) \to D^{*+} K_S^0) = (4.1 \pm 1.3 \pm 0.6) \times 10^{-4}$

4.6σ significance
Time-Dependent Results

\[ \frac{J_c}{J_0} = 0.76 \pm 0.18 \text{(stat)} \pm 0.07 \text{(syst)} \]

\[ \frac{2J_{s1}}{J_0} \sin 2\beta = 0.10 \pm 0.24 \text{(stat)} \pm 0.06 \text{(syst)} \]

\[ \frac{2J_{s2}}{J_0} \cos 2\beta = 0.38 \pm 0.24 \text{(stat)} \pm 0.05 \text{(syst)} \]

- Large \( J_c/J_0 \Rightarrow \) sizable broad \( D_{s1}^+ \)
- [PRD 61, 054009 (2000)] predicts \( J_{s2} > 0 \) (factorization+heavy hadron chiral perturbation theory)
- Our data show \( J_{s2} \cos 2\beta > 0 \) at 94% confidence level.

Chih-hsiang Cheng, Caltech
Conclusions

• BABAR has measured (the sign of) cos2β using $D^{(*)0}h^0$ ($D^0 \rightarrow K_S\pi^+\pi^-$) and $D^+D^-K_S$ decays. The sign is determined to be positive at 87% and 94% confidence level.

• See another cos2β measurement using $B^0 \rightarrow K^+K^-K^0$ decays in D. Dujmic's talk later today.

• Combining these results and Belle's result, $\beta=69^\circ \pm 180^\circ$ is excluded at a very high confidence level. Standard Model is still intact.