Recent BaBar results on $CP$ violation in $B$ decays

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Motivation and outline

CP violation studies showed good agreement with the SM by now

\[ L = 1.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]
\[ \int L \, dt \sim 430 \text{ fb}^{-1} \text{ @ Y}(4S)+\text{off-resonance (~10\%)} \]

This talk is concentrated on γ measurements

See other BaBar talks for more CPV results
γ measurements from $B \rightarrow D^{(*)}K^{(*)}$

Related variables (depend on the $B$ meson decay channel):

$$r_B = \frac{|A_{b \rightarrow u}|}{|A_{b \rightarrow c}|}$$

- $r_B \sim 0.1$ For charged $B$ mesons
- $r_B \sim 0.3$ For neutral $B$ mesons

$\delta_B$ strong phase ($CP$ conserving)

Advantages:
- Only tree decays.
- Largely unaffected by the New Physics scenarios
- Clear theoretical interpretation

Disadvantages:
- Rare decays and low $r_B$

Experimentally not easy to measure.
Three ways to extract the information:
- GLW
- ADS
- Dalitz
\( \gamma/\phi_3 \) measurements with GLW

**GLW Method**

Many \( D^0 \) Modes reconstructed:

\[
\begin{align*}
CP^+ & : D^0_{CP^+} \to K^+ K^- , \pi^+ \pi^- \\
CP^- & : D^0_{CP^-} \to K_s^0 \pi^0, K_s^0 \omega, K_s^0 \phi \\
CA & : D^0 \to K^- \pi^+
\end{align*}
\]

4 observables (3 independent):

\[
\begin{align*}
A_{CP^\pm} &= \frac{\Gamma(B^- \to D^0_{CP^\pm} K^-) - \Gamma(B^+ \to D^0_{CP^\pm} K^+)}{\Gamma(B^- \to D^0_{CP^\pm} K^-) + \Gamma(B^+ \to D^0_{CP^\pm} K^+)} \\
R_{CP^\pm} &= 2 \frac{\Gamma(B^- \to D^0_{CP^\pm} K^-) + \Gamma(B^+ \to D^0_{CP^\pm} K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to D^0 K^+)}
\end{align*}
\]

3 unknowns:

\[
\begin{align*}
R_{CP^\pm} &= 1 + r_B^2 \pm 2r_B \cos \gamma \cos \delta_B \\
A_{CP^\pm} &= \frac{\pm 2r_B \cos \gamma \cos \delta_B}{R_{CP^+}}
\end{align*}
\]


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**Energy substituted mass**

\[
m_{ES} = \sqrt{E_{beam}^2 - p_B^2}
\]

**Signal**

**Background**

Typical experimental resolution

\(~2.6\) MeV/c^2

**Beam-energy difference**

\[\Delta E = E_B - E_{beam}\]

Typical experimental resolution

\([15-20]\) MeV

**Event shape moments**

angles of thrust axes

**Proper time interval**

non-signal B variables

Information is usually combined into Fisher discriminant or Neural Net
GLW method results

BaBar 425 fb$^{-1}$
(467 MBB)

Simultaneous fit to the subsamples corresponding to different D decays

$A_{CP+} = 0.25 \pm 0.06 \pm 0.02$

$A_{CP-} = -0.09 \pm 0.07 \pm 0.02$

$R_{CP+} = 1.18 \pm 0.09 \pm 0.05$

$R_{CP-} = 1.07 \pm 0.08 \pm 0.04$

Direct CPV at 3.6$\sigma$ in $B \rightarrow D_{CP+} K$ decays!

ML fit to $\{m_{ES}, \Delta E, \text{Fisher(event shape variables)}\}$

$N_{CP+} = 477 \pm 28$

$N_{CP-} = 506 \pm 26$
\(\gamma/\phi_3\) extraction from the GLW method results

Frequentist interpretation gives:

<table>
<thead>
<tr>
<th>(\gamma) mod 180°</th>
<th>(r_B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>68% CL</td>
<td>[11.3, 22.7]</td>
</tr>
<tr>
<td></td>
<td>[80.9, 99.1]</td>
</tr>
<tr>
<td></td>
<td>[157.3, 168.7]</td>
</tr>
<tr>
<td>95% CL</td>
<td>[7.0, 173.0]</td>
</tr>
</tbody>
</table>

Large value of \(r_B\) is favored (but large uncertainty: less than 2\(\sigma\) from 0)
**γ/φ_3** measurements with ADS

**ADS Method**

*D. Atwood, I. Dunietz, A. Soni, PRL 78, 3357 (1997).*

**D^0** Modes:

*K^{+}π^-, K^{+}π^-π^0*

Interplay between Doubly-Cabibbo-Suppressed and Cabibbo allowed **D** meson decay

\[ \mathbb{V}_{cb} \rightarrow B^+ \rightarrow D^0 K^+ \rightarrow D^{0} \rightarrow f \]  

\[ \mathbb{V}_{ub} \rightarrow B^+ \rightarrow D^0 K^+ \rightarrow D^{0} \rightarrow f \]  

Same final state

**B^+ \rightarrow D^0 K^+, D \rightarrow K^{+}π^-**  

Same sign

**B^+ \rightarrow D^0 K^+, D \rightarrow K^{-}π^+**  

Opposite sign

New set of variables:

\[ R^+ = \frac{\Gamma([K^-π^-][K^+])}{\Gamma([K^+π^-][K^+])} \left[ \text{opposite sign events yield} \right] \frac{1}{\text{ same sign events yield}} \]  

\[ R^- = \frac{\Gamma([K^+π^-][K^-])}{\Gamma([K^-π^+][K^-])} \left[ \text{opposite sign events yield} \right] \frac{1}{\text{ same sign events yield}} \]  

These variables do not suffer of mutual statistical correlations.

**R^+ = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D + \gamma)\**

\[ R^- = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D - \gamma) \]

**Parameters:**

\{γ; r_B; δ_B\}

Can be measured by BaBar (and others)

**External Inputs:**

\{r_D; δ_D; k_D\}

\[ r_D = \frac{|A_{C \rightarrow u}|}{|A_{C \rightarrow s}|} \]

\[ k_D e^{iδ_D} = \frac{\int A_D \bar{A}_D e^{i(δ(m) - δ(m))} dm}{\sqrt{\int |A_D|^2 dm \int |\bar{A}_D|^2 dm}} \]

**k_D(D \rightarrow K π) = 1**

\( k_D \) and \( δ_D \) can be measured at charm factories using the Quantum-Correlated Measurements

**CLEOc, arXiv:1001.1840**

**k_D(Kππ^0)**
Simultaneous fit to $m_{ES}$ and NN (based on Event shape and tagging variables) for both decay chains.

$$B^+ \rightarrow D^{(*)}K^+, D \rightarrow K\pi$$

$B^+ \rightarrow D^*K^+$ results:

$$D_{D^{0}K}^* \quad D_{D^{*}K}^*$$

$R_{D^{0}K}^* (10^{-2}) = 0.5 \pm 0.8 \quad 0.9 \pm 1.6$

$R_{D^{*}K}^* (10^{-2}) = 3.7 \pm 1.8 \quad 1.9 \pm 2.3$

$$R^- = (0.2 \pm 0.6 \pm 0.2) \times 10^{-2} \quad R^+ = (2.2 \pm 0.9 \pm 0.3) \times 10^{-2}$$

These measurements allowed us to reconstruct $r_B$ and gamma

$$r_B = (9.5^{+5.1}_{-4.1}) \% \quad r_B^* = (9.6^{+3.5}_{-5.1}) \%$$

This can be interpreted as a limit $r_B < 16 \%$ @ 90% C.L.
New result with the reprocessed data.

BaBar is the only experiment for a moment to use a $\pi^0$ in the ADS chain

Simultaneous fit to $m_{ES}$ and $Fisher$ (based on event shape and tagging variables) for both decay chains.
ADS results (D→Kππ^0)

<table>
<thead>
<tr>
<th>Fit</th>
<th>R^+</th>
<th>R^-</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDF</td>
<td>+1.0*10^{-3}</td>
<td>1.1*10^{-3}</td>
</tr>
<tr>
<td></td>
<td>-1.8*10^{-3}</td>
<td></td>
</tr>
<tr>
<td>same sign peaking bkg</td>
<td>2*10^{-4}</td>
<td>5*10^{-4}</td>
</tr>
<tr>
<td>opposite sign peaking bkg</td>
<td>+0</td>
<td>+0</td>
</tr>
<tr>
<td></td>
<td>-3.6*10^{-3}</td>
<td>-3.6*10^{-3}</td>
</tr>
<tr>
<td>Data-MC difference</td>
<td>6*10^{-4}</td>
<td>6*10^{-4}</td>
</tr>
<tr>
<td>BR uncertainties</td>
<td>2*10^{-4}</td>
<td>6*10^{-4}</td>
</tr>
<tr>
<td>Efficiency ratio</td>
<td>1*10^{-4}</td>
<td>4*10^{-4}</td>
</tr>
<tr>
<td>os &lt;-&gt; ss crossfeed</td>
<td>1*10^{-4}</td>
<td>4*10^{-4}</td>
</tr>
<tr>
<td>Total</td>
<td>+1.2*10^{-3}</td>
<td>+1.6*10^{-3}</td>
</tr>
<tr>
<td></td>
<td>-4.1*10^{-3}</td>
<td>-3.9*10^{-3}</td>
</tr>
</tbody>
</table>

We measured:

\[ R^+ = \left( 5 \pm ^{12}_{-10} \pm ^{2}_{-4} \right) \times 10^{-2} \]

\[ R^- = \left( 12 \pm ^{12}_{-10} \pm ^{3}_{-5} \right) \times 10^{-2} \]

Statistical errors dominate over systematical ones.

This measurement allows us to put a limit \( r_B < 14\% \) at 90% probability, thus, making the results competitive with the channels without \( \pi^0 \)

This channel is less precise for gamma measurements (subject to lower \( k_D \)).
Conclusions

$CP$ violation in $B$ decays from BaBar:

- The structure of SM is well confirmed by the experiment
- Several analyses completed recently
- The results are being updated to the full (and reprocessed) data sample
- Some results with more than 3 sigma evidence are obtained in gamma sector.
- More information in other BaBar talks.
Backup
BaBar detector and recorded luminosity

3.1 GeV $e^+$ & 9 GeV $e^-$ beams

$$L = 1.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

$$\int L \, dt \sim 430 \text{ fb}^{-1} @ Y(4S) + \text{off-resonance} (~10\%)$$

with $>96\% \ Y(4S) \rightarrow BB$
(coherent production $L=1$)