Measurements of the CP angle $\alpha$

with the BaBar experiment

Alexandre V. Telnov
Princeton University
for the BaBar Collaboration

XXXIII International Conference on High Energy Physics
Moscow, Russia
Session 8: CP violation, Rare decays, CKM
Friday, July 28, 2006, 10:06
Theoretical and experimental introduction to the CKM angle $\alpha$

New $BaBar$ results; their interpretation and implications for $\alpha$:

$$B \rightarrow \pi^+ \pi^-, \pi^0 \pi^0, \pi^- \pi^0$$

$$B \rightarrow \rho^0 \rho^0, \rho^\pm \rho^0, \rho^+ \rho^-$$

$$B^0 \rightarrow (\rho \pi)^0$$

Summary and outlook

Current $BaBar$ dataset: 347 million $B\bar{B}$ pairs ($\pm 1.1\%$)
Measuring $\alpha$

$\mathcal{A}_{CP}(t)$ in $b \to u\bar{u}d$ decay to a CP eigenstate \textit{at the tree level}:

$\mathcal{A}_{CP}(t)$ in $b \to u\bar{u}d$ decay to a CP eigenstate \textit{at the tree level}:

Measure $180^\circ - \beta - \gamma = \alpha \equiv \arg \left[ \frac{-V_{td} V_{tb}^*}{V_{ud} V_{ub}^*} \right]$ (in SM)

\textbf{Penguins:} $\mathcal{A}_{CP}(t) \Rightarrow \sin(2\alpha_{\text{eff}})$; $\alpha_{\text{eff}} = \alpha - \Delta \alpha$; direct $\mathcal{A}_{CP} \neq 0$

Measure $180^\circ - \beta - \gamma = \alpha \equiv \arg \left[ \frac{-V_{td} V_{tb}^*}{V_{ud} V_{ub}^*} \right]$ (in SM)

\textbf{Penguins:} $\mathcal{A}_{CP}(t) \Rightarrow \sin(2\alpha_{\text{eff}})$; $\alpha_{\text{eff}} = \alpha - \Delta \alpha$; direct $\mathcal{A}_{CP} \neq 0$
**Isospin analysis in $B \rightarrow \pi\pi, \rho\rho$**

$S = \sin(2\alpha + 2\Delta\alpha)\sqrt{1 - C^2}$

In $B \rightarrow \rho\rho$, there are 3 such relations (one for each polarization):

6 unknowns, 6 observables in $\pi\pi$ (there is no vertex to measure $S_{\pi^0\pi^0}$)
5 observables in $\rho\rho$ (or 7, when both $C_{\rho^0\rho^0}$ and $S_{\rho^0\rho^0}$ are measured)

4-fold ambiguity in $2\Delta\alpha$: either triangle can flip up or down

Neglecting EW penguins, $\pm 0$ is a pure tree mode, and so the two triangles share a common side:

$A_{hh} = e^{i\gamma T} + e^{-i\beta P}$

$\tilde{A}_{hh} = e^{-i\gamma T} + e^{i\beta P}$

$A(B^+ \rightarrow h^+ h^0) = \tilde{A}(B^- \rightarrow h^- h^0)$
Simultaneous ML fit to $B^0 \rightarrow \pi^+ \pi^-$, $K^+ \pi^-$, $\pi^+ K^-$, $K^+ K^-$
Using DIRC Cherenkov angle to separate pions and kaons
Additional $\pi\pi/K\pi/KK$ separation from $\Delta E$

Also measure $A_{K^+ \pi^-}$: see talk by Emanuele Di Marco at 12:12 today

**DIRC:** 144 quartz bars
0.84 x 4$\pi$ coverage; 97% eff. @ 3 GeV/c
12$\sigma$ $\pi/K$ separation at 1.5 GeV/c, 2$\sigma$ at 4.5 GeV/c

**Calibration sample:** $B^- \rightarrow \pi^- D^0$, $D^0 \rightarrow \pi^+ K^-$
New *BaBar* results: $B^0 \rightarrow \pi^+ \pi^-$ \hspace{1cm} (1)

Measurements of the $CP$ angle $\alpha$ with the *BaBar* experiment

**Preliminary**

*New BaBar results:*

- $N_{\pi^+ \pi^-} = 675 \pm 42$
- $m_{ES}$
- $\Delta t$
- Asymmetry

**sPlot:** Builds a histogram of $x$ excluding it from the Maximum-Likelihood fit, assigning a weight to each event, keeping all signal events, getting rid of all background events, and keeping track of the statistical errors in each $x$ bin.

New *BaBar* results: $B^0 \rightarrow \pi^+ \pi^-$ (2)

*BaBar* has observed a $3.6\sigma$ evidence for CP violation in $B^0 \rightarrow \pi^+ \pi^-$

$S_{\pi\pi} = -0.53 \pm 0.14 \pm 0.02$

$C_{\pi\pi} = -0.16 \pm 0.11 \pm 0.03$

$(S,C) = (0.0, 0.0)$ is excluded at a confidence level of 0.99970 ($3.6\sigma$)
The $B \rightarrow \pi^\pm \pi^0, \pi^0 \pi^0$ analysis

Simultaneous fit to $B^0 \rightarrow \pi^+ \pi^0, K^+ \pi^0$ (using DIRC Cherenkov angle to separate pions and kaons)

$B^0 \rightarrow \pi^0 \pi^0$: branching fraction and time-integrated direct CP asymmetry

new: in addition to $\pi^0 \rightarrow \gamma \gamma$, we use merged $\pi^0$ and $\gamma \rightarrow e^+e^-$ conversions

$\Rightarrow$ 10% efficiency increase per $\pi^0$ (4% from merged $\pi^0$, 6% from $\gamma$ conversions)

merged $\pi^0$:

the two photons are too close to one another in the EMC to be reconstructed individually; can be recovered using

$$M^2_{\pi^0} \approx E^2_{\pi^0} (S_{\pi^0} - S_{\gamma}),$$

where $S$ is the second EMC moment of the merged $\pi^0 \rightarrow \gamma \gamma$

$\gamma \rightarrow e^+e^-$ conversions: result from interactions with detector elements

The control sample: $\tau \rightarrow \rho \nu$

Measurements of the CP angle $\alpha$ with the BaBar experiment

Alexandre V. Telnov (Princeton University)
New BaBar results: \( B \rightarrow \pi^\pm \pi^0, \pi^0 \pi^0 \)

- \( N_{\pi^\pm \pi^0} = 572 \pm 53 \)
- \( N_{\pi^0 \pi^0} = 140 \pm 25 \)

\[
\mathbf{Br}_{\pi^\pm \pi^0} = (5.12 \pm 0.47 \pm 0.29) \times 10^{-6}
\]

\[
\mathbf{Br}_{\pi^0 \pi^0} = (1.48 \pm 0.26 \pm 0.12) \times 10^{-6}
\]

\[
C_{\pi^0 \pi^0} = -0.33 \pm 0.36 \pm 0.08
\]
An interpretation of the new $B \rightarrow \pi\pi$ results

|Δα| < 41° at 90% C.L.

This is a frequentist interpretation: we use only the $B \rightarrow \pi\pi$ isospin-triangle relations in arriving at these constraints on $\Delta\alpha = \alpha - \alpha_{\text{eff}}$ and on $\alpha$ itself.

Here is one of the possible solutions to the Gronau-London isospin triangle in $B \rightarrow \pi\pi$ according to the central values of the latest BaBar results:

Measurements of the $CP$ angle $\alpha$ with the BaBar experiment

Alexandre V. Telnov (Princeton University)
**B → ρρ** angular analysis

**B → ρρ** is a vector-vector state; angular analysis is required to determine CP content:

Longitudinal: \( A_0 = -\frac{1}{\sqrt{3}} S + \frac{2}{\sqrt{3}} D \)  

pure \( CP = +1 \)

Transverse \( A_{+1} = \frac{1}{\sqrt{3}} S + \frac{1}{\sqrt{6}} D + \frac{1}{\sqrt{2}} P \)

transverse is not a \( CP \) eigenstate

Fortunately, the fraction \( f_L \) of the helicity-zero state in \( B → ρρ \) decays is very close to 1:

\[
f_L(B^0 \rightarrow ρ^+ ρ^-)_{WA} = 0.967^{+0.023}_{-0.028}
\]

\[
f_L(B^\pm \rightarrow ρ^\pm ρ^0)_{WA} = 0.96 \pm 0.06
\]

New BaBar results:

3.0 $\sigma$ evidence for $B^0 \rightarrow \rho^0 \rho^0$

Incremental improvements in the event selection and the analysis technique
Results are statistically consistent with the previous BaBar analyses

$$N_{\rho^0 \rho^0} = 98^{+32}_{-31} \pm 22$$

$$\text{Br}(B^0 \rightarrow \rho^0 \rho^0) = (1.16^{+0.37}_{-0.36} \pm 0.27) \times 10^{-6}$$

$$f_L(B^0 \rightarrow \rho^0 \rho^0) = 0.86^{+0.11}_{-0.13} \pm 0.05$$

The systematic error is dominated by interference with $B^0 \rightarrow a_1^\pm (1260) \pi^\mp$ and by PDF parameter uncertainties

$$\text{Br}(B^0 \rightarrow a_1^\pm (1260) \pi^\mp) \times \text{Br}(a_1^\pm (1260) \rightarrow \pi^+ \pi^- \pi^\mp) = (16.6 \pm 1.9 \pm 1.5) \times 10^{-6}$$

Also measure:

$$\text{Br}(B^0 \rightarrow \rho^0 f_0) \times \text{Br}(f_0 \rightarrow \pi^+ \pi^-) < 0.68 \times 10^{-6} \text{ (at 90\% C.L.)}$$

$$\text{Br}(B^0 \rightarrow f_0 f_0) \times \text{Br}^2(f_0 \rightarrow \pi^+ \pi^-) < 0.33 \times 10^{-6} \text{ (at 90\% C.L.)}$$
New BaBar results: $B^\pm \to \rho^\pm \rho^0$

Based on 232 million $B\bar{B}$ pairs; BaBar-PUB-06/052

Measurements of the $CP$ angle $\alpha$ with the BaBar experiment

Alexandre V. Telnov (Princeton University)

$\mathcal{B}r_{\rho^\pm \rho^0} = \left(16.8 \pm 2.2 \pm 2.3\right) \times 10^{-6}$

$f_L(B^\pm \to \rho^\pm \rho^0) = 0.905 \pm 0.042^{+0.023}_{-0.027}$

The systematic error is dominated by modeling of backgrounds, signal misreconstruction, and by statistical PDF uncertainties

The new BaBar measurement in $B^\pm \to \rho^\pm \rho^0$ allows the $\rho\rho$ isospin triangle to close


PDG 2004: $(26 \pm 6) \times 10^{-6}$

Belle: $(31.7 \pm 7.1^{+3.8}_{-6.7}) \times 10^{-6}$

Previous BaBar: $(22.5^{+5.7}_{-5.4} \pm 5.8) \times 10^{-6}$
New **BaBar results**: $B^0 \rightarrow \rho^+ \rho^-$

**Measurements of the $CP$ angle $\alpha$ with the $BaBar$ experiment**

**Reduced systematics thanks to**

$Br(B^0 \rightarrow a_1^+ \rho^+) \times Br(a_1^+ \rightarrow \pi^+ \pi^- \pi^0) < 30 \times 10^{-6} (90\% \text{ C.L.})$

**New $BaBar$ results**: $B^0 \rightarrow \rho^+ \rho^-$

<table>
<thead>
<tr>
<th>$Br(B^0 \rightarrow \rho^+ \rho^-)$</th>
<th>$(23.5 \pm 2.2 \pm 4.1) \times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\rho^+ \rho^-}$</td>
<td>$615 \pm 57$</td>
</tr>
<tr>
<td>$S_{\text{long}}$</td>
<td>$-0.19 \pm 0.21^{+0.05}_{-0.07}$</td>
</tr>
<tr>
<td>$C_{\text{long}}$</td>
<td>$-0.07 \pm 0.15 \pm 0.06$</td>
</tr>
</tbody>
</table>

**Asymmetry**

**BaBar-CONF-06/016**

**Reduced systematics thanks to**

hep-ex/0605024, accepted by PRD
An interpretation of the new $B \rightarrow \rho \rho$ results

Due to the new $B^0 \rightarrow \rho^0 \rho^0$ BF result, the constraint on $\alpha$ from $B \rightarrow \rho \rho$ has become less stringent.

This is a frequentist interpretation: we use only the $B \rightarrow \rho \rho$ branching fractions, polarization fractions and isospin-triangle relations in arriving at these constraints on $\Delta \alpha = \alpha - \alpha_{\text{eff}}$ and $\alpha$.

As datasets increase, determination of both $C$ and $S$ will become possible in $B^0 \rightarrow \rho^0 \rho^0$, leading to an improvement in the precision of the the $\rho \rho$ isospin analysis.
Measurements of the $CP$ angle $\alpha$ with the $BaBar$ experiment

Alexandre V. Telnov (Princeton University)

$B^0 \rightarrow (\rho \pi)^0$: Dalitz-plot analysis

$B^0 \rightarrow (\rho \pi)^0$ is not a $CP$ eigenstate

An isospin-pentagon analysis method exists but is not fruitful

$\Rightarrow$ Time-dependent Dalitz-plot analysis assuming isospin symmetry,
measuring 26 coefficients of the bilinear form factors


$A(B^0 \rightarrow \pi^+ \pi^- \pi^0) = f_+ A(\rho^+ \pi^-) + f_- A(\rho^- \pi^+) + f_0 A(\rho^0 \pi^0)$

$\tilde{A}(\overline{B}^0 \rightarrow \pi^+ \pi^- \pi^0) = f_+ \tilde{A}(\rho^+ \pi^-) + f_- \tilde{A}(\rho^- \pi^+) + f_0 \tilde{A}(\rho^0 \pi^0)$

Interference in the corners of the Dalitz plot provides information on strong phases between resonances

The $\rho(1450)$ and $\rho(1700)$ resonances are also included in this analysis
New BaBar results: \( B^0 \rightarrow (\rho \pi)^0 \) (1)

Measurements of the \( CP \) angle \( \alpha \) with the BaBar experiment

Alexander V. Telnov (Princeton University)
New *BaBar* results: $B^0 \to (\rho \pi)^0$ (2)

$$S_{\rho\pi} = 0.01 \pm 0.12 \pm 0.028$$

$$C_{\rho\pi} = 0.154 \pm 0.090 \pm 0.037$$

$$A_{\rho\pi} = -0.142 \pm 0.041 \pm 0.015$$

A more physically intuitive way to represent direct-CP quantities:

$$A^{+-}_{\rho\pi} = 0.03 \pm 0.07 \pm 0.03$$

$$A^{-+}_{\rho\pi} = -0.38^{+0.15}_{-0.16} \pm 0.07$$

Parameters from the quasi-two-body description of $B \to \rho\pi$:

$$\Delta S_{\rho\pi} = 0.06 \pm 0.13 \pm 0.029$$

$$\Delta C_{\rho\pi} = 0.377 \pm 0.091 \pm 0.021$$

For results on Direct CP Violation, attend talk by Emanuele Di Marco at 12:12 today.
An interpretation of the new $B^0 \rightarrow (\rho\pi)^0$ results

The relative phase between the amplitudes of $B^0 \rightarrow \rho^- \pi^+$ and $B^0 \rightarrow \rho^+ \pi^-$

$$\delta_{+-} = \text{arg}(A^+*A^-): \quad \delta_{+-} = \arg(A^+*A^-) : \quad B^0 \rightarrow \rho^- \pi^+$$

The constraint on $\alpha$ from $B^0 \rightarrow (\rho\pi)^0$ is relatively weak – but free from ambiguities!
Recap of new results

$B^0 \rightarrow (\rho\pi)^0$: see page 18

$S_{\pi\pi} = -0.53 \pm 0.14 \pm 0.02$
$C_{\pi\pi} = -0.16 \pm 0.11 \pm 0.03$

$CP$ violation at 3.6$\sigma$

$Br_{\rho^0\rho^0} = (1.16^{+0.37}_{-0.36} \pm 0.27) \times 10^{-6}$
First evidence, at 3.0$\sigma$

$Br_{\rho^+\rho^-} = (23.5 \pm 2.2 \pm 4.1) \times 10^{-6}$

$f_L(B^0 \rightarrow \rho^0\rho^0) = 0.86^{+0.11}_{-0.13} \pm 0.05$

$Br_{\rho^+\rho^-} = (16.8 \pm 2.2 \pm 2.3) \times 10^{-6}$

$f_L(B^\pm \rightarrow \rho^\pm\rho^0) = 0.905 \pm 0.042^{+0.023}_{-0.027}$

$Br(B^0 \rightarrow a_1^\pm \rho^\mp) \times Br(a_1^\pm \rightarrow \pi^+\pi^-\pi^\pm) < 30 \times 10^{-6} (90\% \text{ C.L.})$

$Br(B^0 \rightarrow a_1^\pm (1260)\pi^\mp) \times Br(a_1^\pm (1260) \rightarrow \pi^\mp\pi^\pm) = (16.6 \pm 1.9 \pm 1.5) \times 10^{-6}$

Measurements of the $CP$ angle $\alpha$ with the $BaBar$ experiment

Alexandre V. Telnov (Princeton University)
Global fits for the value of $\alpha$

Please see talks by S. T’Jampens (CKMfitter) and V. Vagnoni (UTfit) for details.

Two interpretations currently exist that convert the $B \rightarrow \pi\pi, \rho\pi, \rho\rho$ measurements to constraints on $\alpha$:


CKMfitter talk: 17:30 tomorrow

UTfit talk: 17:48 tomorrow

Measurements of the $CP$ angle $\alpha$ with the $BaBar$ experiment

Alexandre V. Telnov (Princeton University)
The *BaBar* experiment has observed evidence of

- Time-dependent *CP* violation in \( B^0 \rightarrow \pi^+ \pi^- \)
- The decay process \( B^0 \rightarrow \rho^0 \rho^0 \)

and improved the precision of other measurements related to the extraction of \( \alpha \).

The ability of existing *B*-meson factories to measure the angle \( \alpha \) with a precision of a few degrees crucially depends on the developments in measuring the branching fractions and *CP* parameters in \( B^0 \rightarrow \rho^0 \rho^0 \) and \( B^0 \rightarrow \pi^0 \pi^0 \).

The extraction of \( \alpha \) depends significantly on the statistical and theoretical treatment; The larger of the *CKMfitter* and *UTfit* 68.3% C.L. intervals is \( \alpha \in [86, 114]^\circ \) (*CKMfitter*)