Search for the Decay Modes $B^+ \rightarrow D^+K^0$ and $B^+ \rightarrow D^+K^{*0}$ with the $BaBar$ Experiment

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On behalf of the $BaBar$ Collaboration

ICHEP 2010 – Paris
Measurement of $\gamma$ angle in CKM triangle:
Still challenging, large uncertainty
Flagship analysis in $BaBar$

Measurement with $B^+ \rightarrow \tilde{D}^0 K^+$:

- $B^+ \rightarrow \bar{D}^0 K^+$
- $B^+ \rightarrow D^0 K^+$

Sensitivity on $\gamma$ then driven by:

$$r_{D^0 K^+} = \frac{|A(B^+ \rightarrow D^0 K^+)|}{|A(B^+ \rightarrow \bar{D}^0 K^+)|} = \frac{|V_{cs} V_{ub}^*|}{|V_{us} V_{cb}^*|} \times \frac{|C + A|}{|T + C|}$$

$\Rightarrow$ Amplitudes must be under control

Motivations (2)

**Annihilation diagram:**

- Expected amplitude: $A \sim (\sin \theta_c)^5$
- No hadronic annihilation decay seen so far:
  
  $\text{BF}(B^+ \to D^+ K^0) < 5 \times 10^{-6} @ 90\% \ C.L.$,

  [$\text{BaBar}, 226 \times 10^6 \ B\bar{B}, \text{PRD} 72, 011102 (2005)$]

- Ordinarily neglected in theoretical calculations

**But...**

- **Weak process** may be enhanced by **strong rescattering effect**
  
  $PRL \ 78, \ 3999 \ (1997)$

- Branching ratio may reach non-negligible value

Negligibility of annihilation diagram must be confirmed
Check with $B^+ \to D^+ K^{(*)0}$ (proceed through annihilation only)
Reconstruction of $B^+ \to D^+ K^{(*)0}$

$B$ mesons from $e^+e^- \rightarrow Y(4S) \rightarrow \bar{B}B$ with PEPII accelerator (SLAC), reconstructed with $BaBar$ detector

$B^+ \rightarrow D^+ K^0$

- $D^+$
  - $K^- \pi^+ \pi^+$
  - $K^0_s \pi^+$
  - $K^- \pi^+ \pi^+ \pi^0$
  - $K^0_s \pi^+ \pi^0$
- $K^0 \rightarrow K^0_s$

$B^+ \rightarrow D^+ K^{*0}$

- $D^+$
  - $K^- \pi^+ \pi^+$
  - $K^0_s \pi^+$
- $K^{*0} \rightarrow K^+ \pi^-$

4-vectors of decay daughters summed to build mother candidate and mass-constrained

Main backgrounds:
- $e^+e^- \rightarrow$ quark anti-quark (quark=u,d,c,s)
- $e^+e^- \rightarrow B^0 \bar{B}^0$ and $B^+B^- :$ generic $B$ decays,
- $B$ decays with similar final states (peaking background in signal region)

For $D^+ K^0$:
- $B^0 \rightarrow D^- \rho^+$ ($\rho^+ \rightarrow \pi^+ \pi^0$)
- $B^0 \rightarrow \bar{D}^0 K^0$
- $B^0 \rightarrow \bar{D}^{*0} K^0$

For $D^+ K^{*0}$:
- $B^0 \rightarrow D^- \rho^+$
- $B^0 \rightarrow D^- K^{*+}$
- $B^0 \rightarrow D^- a_1^+$
Selection of $B^+ \rightarrow D^+K^{(*)0}$

Selections $\Rightarrow$ maximizing $S/\sqrt{S+B}$ with high statistics Monte-Carlo simulations

Assume branching fraction of $B^+\rightarrow D^+K^{(*)0} = 5\times10^{-6}$ (previous upper limit by BaBar)

- Tracks origin constrained to same vertex
- Mass of $D^+$ candidates
- Mass, energy, shower shape, momentum of $\pi^0$ candidates
- Mass of $K_s^0$ candidates
- Peaking background rejected with $K_s^0$-related variables:
  - Helicity angle $\theta_{K_s}^{Hel}$
  - Flight Angle $\alpha_{K_s}$
- Mass of $K^*$
- Helicity angle of $K^*\rightarrow K\pi$ similar to
- $B^+$ built by combining $D^+$ and $K^{(*)0}$, constraining them to same origin vertex
- Angular distribution $\cos(\theta_B)$

PRD 72, 011102 (2005)
Selection of $B^+ \rightarrow D^+ K^{(*)0}$ (2)

Use kinematics of $e^+ e^- \rightarrow Y(4S) \rightarrow \overline{B}B$ for selection of $B$ signal

**Beam-Energy Substituted Mass**

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

- $\sigma \approx 2.5$ MeV

**Energy Difference**

$$\Delta E = E_B^* - E_{beam}^*$$

- $\sigma \approx 15$ MeV

- Keep $B$ candidates with $\Delta E$ close to zero (yellow band)

Eventually keep only 1 $B$ / event:
- [D$^+$ mass closest to PDG value] or [$\Delta E$ closest to 0]

Overall efficiency on signal MC:
- $B^+ \rightarrow D^+ K^0$ : 5 – 21 %
- $B^+ \rightarrow D^+ K^{*0}$ : $\sim$10 %

SLAC-418, LBL-5379 (1993)
Largest background from $e^+ e^- \rightarrow q\bar{q}$, $q=u,d,s,c$ (produce very high momentum mesons $D^+$, $K^{(*)0}$)

Different event topologies

Described by shape variables: $L_0$, $L_2$, $|\cos(\theta_{\text{thrust}})|$

(e+e-→q̅q MC distributions checked with off-resonance data)

Use time difference $|\Delta t|$ between the two B’s

Combined in a Fisher discriminant:

$$F = a_0 + a_1 \cdot L_0 + a_2 \cdot L_2 + a_3 \cdot |\cos(\theta_{\text{thrust}})| + a_4 \cdot |\Delta t|$$
Extraction of Number of Signal Events

2D maximum likelihood fit: $m_{ES}$ x Fisher

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$N_{sig}$</th>
<th>$N_{BB}$</th>
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<td>$K\pi\pi$</td>
<td>$-11.9 \pm 6.7$</td>
<td>$70 \pm 27$</td>
<td>$2690 \pm 57$</td>
<td>$-4.2 \pm 2.4$</td>
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<td>$K\pi\pi\pi^0$</td>
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<td>$111 \pm 51$</td>
<td>$6516 \pm 94$</td>
<td>$20 \pm 20$</td>
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<td>$K_0^\pi\pi$</td>
<td>$0.6 \pm 5.3$</td>
<td>$20 \pm 14$</td>
<td>$381 \pm 23$</td>
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<td>$K_0^{0}\pi\pi^0$</td>
<td>$-6.7 \pm 4.5$</td>
<td>$36 \pm 22$</td>
<td>$1270 \pm 41$</td>
<td>$-14 \pm 9.2$</td>
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Background yields compatible with expectations

Signal yield compatible with 0

Projections of $m_{ES}$ for Fisher > 0:

Fit projection, signal, $BB$, $q\bar{q}$, peaking background

BaBar preliminary
### Uncertainties on Branching Ratio

#### Statistical unc.

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| $B^+ \to D^+ K^{*0}$ |                  |                     |                   |       |
| $K\pi\pi$   | $-15.6 \pm 8.7$  | $463 \pm 63$        | $6338 \pm 98$    | $-5.0 \pm 2.9$ |
| $K^0_S\pi$  | $-11.4 \pm 3.5$  | $35 \pm 15$         | $547 \pm 27$     | $-33 \pm 10.2$  |

#### Systematic unc.

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<td>PDF - MC</td>
<td>$+0.8$</td>
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Data-MC PDF shapes:

- Continuum background | 0.2 | 0.4 | 1.4 | 0.5 | 0.1 | 1.7
- $B\overline{B}$ background | 0.7 | 1.6 | 2.5 | 5.0 | 1.0 | 4.4
- Signal | $< 0.05$ | 9.2 | 5.6 | 0.9 | 0.9 | 3.1

Efficiency error:

- Reconstruction efficiency (MC) | 0.1 | 0.6 | $< 0.05$ | 0.9 | 0.1 | 0.5
- Data-MC | 0.2 | 0.8 | $< 0.05$ | 0.5 | 0.2 | 0.3
- Peaking background | $< 0.05$ | 0.5 | 0.2 | 0.2 | $< 0.05$ | 0.1
- $B$ errors | 0.3 | 0.3 | $< 0.05$ | 0.4 | $< 0.05$ | 0.1

Combined | +1.1 | +11.3 | +8.2 | +9.0 | +1.5 | +6.4
|         | $-1.3$ | $-11.8$ | $-9.3$ | $-12.5$ | $-1.8$ | $-7.4$
No signal observed in $B^+ \rightarrow D^+ K^{(*)0}$

Combination of BR measured with the different $D^+$ modes:

- $\mathcal{B}(B^+ \rightarrow D^+ K^0) = (-3.8^{+2.5}_{-2.4}) \times 10^{-6}$,
- $\mathcal{B}(B^+ \rightarrow D^+ K^{*0}) = (-5.3 \pm 2.7) \times 10^{-6}$

Upper limit set on BR using Bayesian approach

Likelihood $\mathcal{L}_i^{\text{final}}$ of BR for each decay mode “$i$”: $\mathcal{L}_i^{\text{final}} = \mathcal{L}_i * \mathcal{G}_i$

$\mathcal{G}_i$ = Gaussian with width equal to systematic uncertainty

$\mathcal{L}_i^{\text{final}}$ finally combined in one likelihood $\mathcal{L}^{\text{total}}$

Confidence Level measured by integrating $\mathcal{L}^{\text{total}}$ (flat prior for BR $\geq 0$)

$BR_{BB} < 2.9 \times 10^{-6}$ at 90% C.L.

$BR_{BB} < 3.0 \times 10^{-6}$ at 90% C.L.

$[\text{hep-ex}]$arxiv:1005.0068, Submitted to Phys. Rev. D
Conclusion

- Measurement of $B^+ \rightarrow D^+ K(\ast)\,^0$ branching ratios of interest for
  - CKM angle $\gamma$ measurement
  - constraining QCD models for annihilation diagrams

- Search with whole $BaBar$ dataset $465 \times 10^6 \, \bar{B}\bar{B}$

- Uncertainty dominated by statistical uncertainty

- No signal observed

- **Upper limit** set on branching ratio with Bayesian statistics

  $BR_{B \rightarrow DK} < 2.9 \times 10^{-6}$ at 90% C.L.

  $BR_{B \rightarrow DK^*} < 3.0 \times 10^{-6}$ at 90% C.L.

- Improvement of limit for $B^+ \rightarrow D^+ K^0$ ($5.5 \times 10^{-6}$)
  First search for $B^+ \rightarrow D^+ K^{*0}$

- Strengthens hypothesis of negligible contributions from annihilation diagrams
Backup Slides
The first variable is the cosine of the angle between the $B$ thrust axis and the thrust axis of all the other reconstructed charged tracks and neutral energy deposits (rest of the event), where the thrust axis is defined as the direction that maximizes the sum of the longitudinal momenta of all the particles. The second and third variables are the event shape moments $L_0 = \sum_i p_i$, and $L_2 = \sum_i p_i |\cos \theta_i|^2$, where the index $i$ runs over all tracks and energy deposits in the rest of the event; $p_i$ is the momentum and $\theta_i$ is the angle with respect to the thrust axis of the $B$ candidate. These three variables are calculated in the CM.
**BaBar Data**

**Production of BB pairs through Y(4S)**

Off resonance data, no B produced

**bb resonance Y(4S). Production of BB pairs through Y(4S) → BB**