Charmless Hadronic B Decays with BaBar

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On Behalf of the BaBar Collaboration

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Charmless B Decays

- Many such decays are dominated by $b \to s$ penguins

- Tree amplitudes subdominant in SM
- New Physics can appear in loops – affecting:
  - CP-violating asymmetries ($A_{CP}$) in decays
  - Altered polarizations in $B \to VV$ decays (angular analysis)
  - Altered branching fractions
The BaBar Experiment

- PEP-II asymmetric $e^+e^-$ collider at SLAC
- 9.0 GeV $e^-$ on 3.1 GeV $e^+$
- Operating at Upsilon(4S) resonance

- BaBar took data from 1999-2008
- Analyses based on final dataset:
  - ~470M $B\bar{B}$ pairs
Common Analysis Techniques

• Suppress dominant “continuum” background: $e^+e^- \rightarrow q\bar{q}$ (q=u,d,s,c)

\[ m_{ES} = \sqrt{\frac{s}{4} - p_B^2} \]

\[ \Delta E = E_B - \frac{1}{2}\sqrt{s} \]

• Multivariate Fisher discriminant or neural network (NN) to distinguish event shape:

• $B\bar{B}$ backgrounds: generally small, but some can look similar to signal – dangerous!

• Measurements extracted using multivariate maximum-likelihood (ML) fits
B$^+ \rightarrow \rho^0 K^{*+}$ and $B^+ \rightarrow f_0 K^{*+}$: Motivation

- Measure BF, $A_{CP}$, polarization
- $B^+ \rightarrow \rho^0 K^{*+}$ not yet observed

- $B^+ \rightarrow \rho^0 K^{*+}$ is VV decay, angular distribution given by

$$1 - \frac{f_L}{4}\sin^2 \theta_K^* \sin^2 \theta_\rho + f_L \cos^2 \theta_K^* \cos^2 \theta_\rho$$

- $f_L$: longitudinal polarization fraction
- Naïve factorization:
  - $f_L = (1 - m_V^2/m_B^2) \sim 0.9$
  - Works for $B \rightarrow \rho \rho$, not for other $B \rightarrow VV$ decays
  - “polarization puzzle” – recent work in QCDF to resolve issue
B$^+ \rightarrow \rho^0 K^*$ and B$^+ \rightarrow f_0 K^*$: Analysis

- Reconstruct $\rho/f_0 \rightarrow \pi^+\pi^-$, $K^* \rightarrow K_S \pi^+$ and $K^+\pi^0$
- ML fit to 7 variables: $m_{ES}$, $\Delta E$, NN, invariant masses, and $\cos(\theta)$
- Background: continuum + 9 BB categories.
- Fit simultaneously for BF’s, $A_{CP}$’s, and $f_L$

$$A_{CP} = \frac{N^- - N^+}{N^- + N^+}$$

### Graphs

- **K$^*+ \rightarrow K_S \pi^+$ only**
- **$f_0$ and $\rho^0$**
- **$\pi^+\pi^-$ invariant mass**
- **$K_S^0\pi^+$ invariant mass**
- **$|\cos(\theta_{K_S^0\pi^+})|$**

**References:**

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**Authors:** Brian Lindquist

**Title:** Charmless Hadronic B Decays with BaBar

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B$^+ \to \rho^0 K^*$ and B$^+ \to f_0 K^*$: Results

B$^+ \to \rho^0 K^*$:
- $N(Sig) = 85 \pm 24 \ (K_S\pi^+) \ , \ 67 \pm 31 \ (K^+\pi^0)$
- $BF = (4.6 \pm 1.0 \pm 0.4)x10^{-6}$ consistent with prediction
  - $5.3 \sigma$ significance (incl. syst.) – first observation
- $A_{CP} = 0.31 \pm 0.13 \pm 0.03$
- $f_L = 0.78 \pm 0.12 \pm 0.03$ larger than other $\rho K^*$ modes

B$^+ \to f_0 K^*$:
- $N(Sig) = 69 \pm 14 \ (K_S\pi^+) \ , \ 91 \pm 20 \ (K^+\pi^0)$
- $BF \times BF(f_0 \to \pi^+\pi^-) = (4.2 \pm 0.6 \pm 0.3)x10^{-6}$
- $A_{CP} = -0.15 \pm 0.12 \pm 0.03$
$B^0 \rightarrow (\rho^0/f_0)K^{*0}$ and $B^0 \rightarrow \rho^- K^{*+}$

- Reconstruct $\rho/f_0 \rightarrow \pi\pi$, $K^{*0} \rightarrow K^+\pi^-$, $K^{*+} \rightarrow K^+\pi^0$
- ML fit to 7 variables: $m_{ES}$, $\Delta E$, Fisher, invariant masses, and $\cos(\theta)$
- $f_2(1270)K^0$ events extrapolated from $m_{\pi\pi}$ sideband
- Also measure scalar and tensor $K^*$ states in a "high-mass" region (not in this talk)
B^0 \rightarrow (\rho^0/f_0)K^*0 and B^0 \rightarrow \rho^-K^{*+}: Results

- First 5 \sigma observations of B^0 \rightarrow \rho^-K^{*+} and B^0 \rightarrow f_0K^*0!

\[ B(B^0 \rightarrow \rho^-K^{*+}) = (10.3 \pm 2.3 \pm 1.3) \times 10^{-6} \]
\[ f_L(\rho^-K^{*+}) = 0.38 \pm 0.13 \pm 0.03 \]
\[ A_{ch}(\rho^-K^{*+}) = + 0.21 \pm 0.15 \pm 0.02 \]
\[ B(B^0 \rightarrow \rho^0K^*0) = (5.1 \pm 0.6 \pm 0.8) \times 10^{-6} \]
\[ f_L(\rho^0K^*0) = 0.40 \pm 0.08 \pm 0.11 \]
\[ A_{ch}(\rho^0K^*0) = - 0.06 \pm 0.09 \pm 0.02 \]
\[ B(B^0 \rightarrow f_0K^*0) \times B(f_0 \rightarrow \pi\pi) = (5.7 \pm 0.6 \pm 0.3) \times 10^{-6} \]
\[ A_{ch}(f_0K^*0) = + 0.07 \pm 0.10 \pm 0.02 . \]

- Experiment: 
  \[ f_L(\rho^-K^{*+}) \lesssim f_L(\rho^0K^*0) \lesssim f_L(\rho^+K^{*0}) < f_L(\rho^0K^{*+}) \]

- QCDF: 
  \[ f_L(\rho^0K^*0) < f_L(\rho^+K^{*0}) < f_L(\rho^-K^{*+}) < f_L(\rho^0K^{*+}) \]

More precision needed to really test Exp/Theory

New for DPF!
B→φφK: Motivation

- B→φφK and B→η_c(→φφ)K can interfere at m_φ ~ m(η_c):

  ![Diagram showing tree and penguin diagrams interfering with each other]

- In SM, tree and penguin carry (approx.) the same weak phase
  - No significant CP-violation in SM

- New physics in loop of penguin diagram could have different CP-violating phase
  - Large direct CP-violation possible!
B$\rightarrow\phi\phi K$: Backgrounds

- Peaking backgrounds from B$\rightarrow\phi KKK$, $f_0 KKK$, and 5K
- Measured in sidebands in $m_{\phi_1}$–$m_{\phi_2}$ plane.
- Extrapolated into signal region based on MC $m_{\phi_1}$–$m_{\phi_2}$ distributions
**B→ϕϕK: Results**

- ML fit in $m_{ES}$, $\Delta E$, Fisher, $m_{\phi_1}$, $m_{\phi_2}$

- For $m_{\phi\phi}<2.85$ GeV:
  - $BF(B^+\rightarrow \phi\phi K^+)=(5.6\pm0.5\pm0.3)x10^{-6}$
  - $BF(B^0\rightarrow \phi\phi K^0)=(4.5\pm0.8\pm0.3)x10^{-6}$
  - $A_{CP}(B^+\rightarrow \phi\phi K^+) = -0.10\pm0.08\pm0.02$

- ML fit in bins of $m_{\phi\phi}$

- $A_{CP}$ in $\eta_c$ region ($2.94<m_{\phi\phi}<3.02$):
  - $A_{CP} = -0.09\pm0.10\pm0.02$

  **Consistent with SM**
$B^0 \to K^+\pi^-\pi^0$: Motivation

- “$K \pi$ puzzle”
- Naively, we expect:
  - $A_{CP}(B^0 \to K^+\pi^-) = A_{CP}(B^+ \to K^+\pi^0)$
- Experimentally, we find:
  - $A_{CP}(B^+ \to K^+\pi^0) = 0.050 \pm 0.025$
  - $A_{CP}(B^0 \to K^+\pi^-) = -0.098 \pm 0.012$

- Is there a similar “$K^* \pi$” puzzle?
- Measure $B^0 \to K^*+\pi^-$
- Many resonances interfere
- Full amplitude analysis accounts for interference between resonances

5.3 $\sigma$ difference!

Color-suppressed tree, EW penguin – SM or NP?

5.3 $\sigma$ difference!
**B^0 \rightarrow K^+\pi^-\pi^0**: Analysis

- Large backgrounds: continuum + 19 BB background categories
- ~10% of signal events misreconstructed – explicitly modeled in fit
- Amplitude model with interference:

\[
A(m_{K^+\pi^-}, m_{K^+\pi^0}) = \sum_{i=1}^{N} c_i F_i(m_{K^+\pi^-}, m_{K^+\pi^0})
\]

- e.g. relativistic Breit-Wigner
- Complex coeff. (fit param.)

3670 signal events
$B^0 \rightarrow K^+\pi^-\pi^0$: Results

- $\text{BF}(B^0 \rightarrow K^+\pi^-\pi^0) = (38.5 \pm 1.0 \pm 3.9) \times 10^{-6}$

- $A_{CP}(K^+\pi^-) = -0.29 \pm 0.11 \pm 0.02$

- When combined with $B^0 \rightarrow K_S\pi^+\pi^-$:
  - $A_{CP}(K^+\pi^-) = -0.24 \pm 0.07 \pm 0.02$
  - 3.1 $\sigma$ evidence of direct CP-violation

Brian Lindquist                   Charmless Hadronic B Decays with BaBar  
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**B^+ \rightarrow K^+\pi^0\pi^0: Introduction**

- \( B^+ \rightarrow K^+\pi^0 \) can provide another piece to \( K^*\pi \) set of measurements
- Is \( A_{CP}(B^+ \rightarrow K^*+\pi^0) = A_{CP}(B^0 \rightarrow K^*+\pi^-) \) ?

- World’s first inclusive \( B^+ \rightarrow K^+\pi^0\pi^0 \) measurement:
  - \( BF = (16.2 \pm 1.2 \pm 1.5) \times 10^{-6} \)
  - \( A_{CP} = -0.06 \pm 0.06 \pm 0.04 \)

- Two \( \pi^0 \)'s lead to large fraction of misreconstructed events – full Dalitz plot amplitude analysis difficult
- Measure resonances in a two-body fashion

**Preliminary Result**

N(sig) = 1220 ± 85
B⁺ → K⁺π⁺π⁻: Resonances

- Measure K⁺π⁺, f₀K⁺, and χ_c0K⁺
- Contributions from nonresonant K⁺π⁺π⁻ and other resonances extrapolated from m_{ππ} and m_{Kπ} sidebands

<table>
<thead>
<tr>
<th>Decay</th>
<th>BF</th>
<th>A_CP</th>
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<tbody>
<tr>
<td>B⁺ → K⁺π⁻</td>
<td>(8.2 ± 1.5 ± 1.1) × 10⁻⁶</td>
<td>−0.06 ± 0.24 ± 0.04</td>
</tr>
<tr>
<td>B⁺ → f₀(→ π⁺π⁻)K⁺</td>
<td>(2.79 ± 0.57 ± 0.51) × 10⁻⁶</td>
<td>0.18 ± 0.18 ± 0.04</td>
</tr>
<tr>
<td>B⁺ → χ_c0K⁺</td>
<td>(182 ± 78 ± 32) × 10⁻⁶</td>
<td>−0.96 ± 0.37 ± 0.04</td>
</tr>
</tbody>
</table>
Summary

• Charmless hadronic B decays provide a wealth of measurements ($A_{CP}$, polarization, etc.) that are probes of new physics

• We measure:
  – Polarization $f_L$ in $\rho^0K^*$, $\rho^-K^*$, and $\rho^0K^0$
  – $A_{CP} = -0.09 \pm 0.10 \pm 0.02$ in $\eta_c$ region of $\phi\phi K^+$
  – $3.1 \sigma$ evidence for direct CP-violation in $B^0 \rightarrow K^{*+}\pi^-$
  – BF’s and $A_{CP}$’s for resonances in $B^+ \rightarrow K^+\pi^0\pi^0$

• No clear evidence for new physics, but “polarization puzzle” and “$K\pi$” puzzle need better understanding

• Many measurements remain statistically limited

• The future lies with LHCb, Belle-II, and SuperB!
  – Belle II/Super B expect $\sim 100x$ statistics of present B factories