Charmless twobody $B$ decays
Branching fraction and direct CP measurements at the B Factories

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Workshop on the Unitarity Triangle
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Outline

1. Introduction
2. Two charged particles
3. One charged particle
4. No charged particle
5. Conclusion
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Motivation

- several interfering topologies
- amplitudes related by isospin and SU(3)
- sensitivity to weak phases:
  \( \alpha \) from \( \pi \pi \)
  \( \gamma \) from \( K \pi \)

Amplitude computations:
- QCD FA
- pQCD
- SCET
- Charming Penguins
Overview of results

Babar

- six analysis groups cover $B$ and $A$ measurements at the same time
- all analysis except $B_{h^+h^-}$ updated for ICHEP with full dataset, 227 million $B\bar{B}$ pairs

Belle

- different responsibilities for $B$ and $A$
- $B$ generally updated with 85 million $B\bar{B}$ pairs
- $A$ generally updated with 275 million $B\bar{B}$ pairs
- exception: $B_{\pi^0\pi^0}$
Measurement strategy

Want to measure branching fractions $B$ in rare decays $\mathcal{O}(10^{-6} - 10^{-5})$ and asymmetries $A$

- Identify contributing components:
  → Signal, B background, continuum

- Identify discriminating variables:
  → $m_{ES}$, $\Delta E$, $F$, $\theta_C$, ...

- Model distributions from
  → control sample, off-resonance, sideband, simulation

- (Un)binned maximum likelihood fit to extract yields

$$
L = \exp \left( - \sum_i n_i \right) \prod_{j=1}^{N} \left[ \sum_i n_i P_i(\vec{x}_j; \vec{\alpha}_i) \right]
$$

$i$ components, $j$ events, $\vec{\alpha}_i$ parameters of the fit
Continuum suppression at Babar

Event shape variables to distinguish spherical and jet-like topology: cut on \( \cos \theta_S \)

With \( \theta_i \equiv \angle(B, (p_{i}^*)) \) use “Fisher”

\[
F = a_0 \sum_i p_{i}^* + a_2 \sum_i p_{i}^* \cos^2 \theta_i
\]

Alternatively use Neural Network, e.g. with tagging information
Continuum suppression at Belle

- Fox-Wolfram moments: \[ H_l = \sum_{i,j} \frac{\vec{p}_i \cdot \vec{p}_j}{s} P_l(\cos \theta_{i,j}) \]

- Super FW: \[ \sum_{l=2,4} \alpha_l \frac{h_{so}[l]}{h_{so}[0]} + \sum_{l=1}^{4} \beta_l \frac{h_{oo}[l]}{h_{oo}[0]} \]

- Modified SFW: \[ \sum_{l=0}^{4} \alpha_{cl} h_c so[l] + \sum_{l=0,2,4} \left( \alpha_{nl} h_n so[l] + \alpha_{ml} h_m so[l] \right) + \sum_{l=0}^{4} \beta_l h_{oo}[l] \]

- MSFW combined with \( \sum |p_T| \) into a \( F \) discriminant
- MSFW and \( \cos \theta_B \) combined into a likelihood function
- b-flavor tagging confidence \( r \) combined into multi-dimensional likelihood-ratio
- make an optimized CUT → does not enter the ML fit
Common systematic uncertainties

- Estimate of $\pi^0$ and tracking efficiency (using control samples)
- Energy resolution affects the $\Delta E$ signal PDF
- Higher multiplicity B background
- Fixing PDF parameters for signal from Monte Carlo
This talk is not full of angles ($\alpha \leftrightarrow \phi_2$, etc.) ...
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but I use the following:

- $^{6}\mathcal{B}_{\pi\pi^0}^{227} = 5.8 \pm 0.6 \pm 0.4$ is the CP averaged branching fraction $\times 10^6$
  measured with 227 million $B\bar{B}$ pairs by Babar

- $^{2}\mathcal{A}_{\pi\pi^0}^{275} = -2 \pm 5 \pm 2$ is the charge asymmetry or direct CP in percent
  measured with 275 million $B\bar{B}$ pairs by Belle
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joined fit for three modes ($\pi^+\pi^-$, $K^+\pi^-$, $K^+K^-$)

assign pion mass to all charged tracks

separate kaons and pions with

- PID Cherenkov angle in the DIRC, used in the ML fit
- KID N. of photoelectrons in the ACC and dE/dx in CDC, $\mathcal{L}$ ratio cut

B backgrounds neglected in Babar and small in Belle

cross-feed between the modes
Interest foremost in the time-dependent asymmetry measurement (see talk by Hirokazu Ishino) to extract $\alpha$

- branching fraction measurements are currently systematics limited and not updated to the full dataset
- similar selection efficiencies (38% vs. 35%)

$$\mathcal{B}_{\pi^+\pi^-}^{88} = 4.7 \pm 0.6 \pm 0.2$$

$$\mathcal{B}_{\pi^+\pi^-}^{85} = 4.4 \pm 0.6 \pm 0.3$$

$$\mathcal{B}_{\pi^+\pi^-} = 4.6 \pm 0.4$$
$K/\pi$ separation: Cherenkov angle $\theta_C$

- New technique, imaging reflected light
- $\theta_C$ distribution is parameterized and used in the fit with charged tracks
- Critical for disentangling $\pi^\pm$ and $K^\pm$
- $\Rightarrow$ direct CP in $B^0 \to K^+\pi^-$
Direct CP violation in $B^0 \to K^+\pi^-$

$^6B_{K\pi}^{88} = 17.9 \pm 0.9 \pm 0.7$

Summer'04 : first observation of direct CP violation (by both exp.!) $n_{K\pi} = 1606 \pm 51$

$B^0 \to K^+\pi^-(910)$ background subtracted

$\bar{B}^0 \to K^-\pi^+(696)$ signal enhanced

$2A_{K\pi}^{227} = -13.3 \pm 3.0 \pm 0.9$

$2A_{K\pi}^{275} = -10.1 \pm 2.5 \pm 0.5$

$\implies 2A_{K\pi} = -10.9 \pm 1.9$
$A_{K\pi}$ Cross checks and systematics

- Toy Monte Carlo shows no intrinsic bias
- Consistent in different Kaon momentum ranges
- No $K/\pi$ or $+/−$ efficiency asymmetry
- Consistent in different run periods

<table>
<thead>
<tr>
<th>Sample</th>
<th>$N_{B\bar{B}}$</th>
<th>$n_{K\pi}$</th>
<th>$A_{K\pi}$</th>
<th>$A^{b}_{K\pi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999–2001</td>
<td>21.1</td>
<td>142 ± 15</td>
<td>$-0.240 \pm 0.102$</td>
<td>0.006 ± 0.026</td>
</tr>
<tr>
<td>2002</td>
<td>66.4</td>
<td>479 ± 27</td>
<td>$-0.102 \pm 0.055$</td>
<td>$-0.008 \pm 0.015$</td>
</tr>
<tr>
<td>2003</td>
<td>34.1</td>
<td>241 ± 19</td>
<td>$-0.109 \pm 0.079$</td>
<td>0.007 ± 0.021</td>
</tr>
<tr>
<td>2004</td>
<td>104.9</td>
<td>743 ± 33</td>
<td>$-0.142 \pm 0.044$</td>
<td>0.004 ± 0.012</td>
</tr>
</tbody>
</table>

- Standard Model does not predict $A_{K\pi} = 0$

Dominant source of systematic uncertainty:
background asymmetry $A^{bckgnd}_{K\pi} = 0.001 \pm 0.008$
No evidence for the decay $B^0 \rightarrow K^+ K^-$

- expected to be suppressed
- selection efficiency differs, 36% and 20%

Latest CP fit yield: $3 \pm 12$ in 68k events

$^6 B_{KK}^{88} < 0.6$  \hspace{2cm} $^6 B_{KK}^{85} < 0.7$
Radiative corrections

- see also talks by L. Cavoto and E. Baracchini at the RadCor Workshop on Monday

- Branching fraction measurements $h^+ h^-$ are systematics limited

- Not updated to the full dataset

- Main problem: efficiency estimate with correct description of final state radiation

- Inclusion of out-of-the-box PHOTOS might not be ideal (e.g. pions and kaons are treated the same)
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$B^+ \rightarrow h^+\pi^0$

$B^+ \rightarrow \pi^+\pi^0$ and $B^+ \rightarrow K^+\pi^0$ signal

- Combined fit to extract two signal components
- appear separated in $\Delta E$ distribution
- tight cut to suppress B background
- peak position used to calibrate energy scale for $\pi^0\pi^0$
$B^+ \rightarrow h^+\pi^0$

$B^+ \rightarrow \pi^+\pi^0$ and $B^+ \rightarrow K^+\pi^0$ signal

Continuum background
\[ B^+ \rightarrow h^+ \pi^0 \]

\[ B^+ \rightarrow \pi^+ \pi^0 \] and \[ B^+ \rightarrow K^+ \pi^0 \] signal

\[ \mathcal{B}_{\pi\pi^0}^{227} = 5.8 \pm 0.6 \pm 0.4 \]
\[ \mathcal{B}_{K\pi^0}^{227} = 12.0 \pm 0.7 \pm 0.6 \]
\[ \mathcal{A}_{\pi\pi^0}^{227} = -1 \pm 10 \pm 2 \]
\[ \mathcal{A}_{K\pi^0}^{227} = 6 \pm 6 \pm 1 \]

\[ \mathcal{B}_{\pi\pi^0}^{85} = 5.0 \pm 1.2 \pm 0.5 \]
\[ \mathcal{B}_{K\pi^0}^{85} = 12.0 \pm 1.3 \pm 1.1 \]
\[ \mathcal{A}_{\pi\pi^0}^{275} = -2 \pm 5 \pm 2 \]
\[ \mathcal{A}_{K\pi^0}^{275} = 4 \pm 5 \pm 2 \]

No CP asymmetry in \( B^+ \rightarrow K^+ \pi^0 \)
Select $\tau^+ \tau^-$ events with $\tau^+ \rightarrow e^+ \nu \bar{\nu}$ and $\tau^- \rightarrow (\pi^-, \rho^-) \nu$

Corrections applied to account for inaccuracies in MC
- high energy tail of the energy deposited in the calorimeter
- hadronic split-offs

Compare to efficiencies (double ratio) of std $\pi^0$ cuts
Discrepancy is $< 3\%$

For $B_{\pi^0\pi^0}$ Belle reports 6% systematics obtained from

\[
\frac{\eta \rightarrow \pi^0 \pi^0 \pi^0 \text{ data}}{\eta \rightarrow \gamma \gamma \text{ MC}}
\]
$B^+ \rightarrow K^0_S h^+$

$K^0_S$ reconstructed as $K^0_S \rightarrow \pi^+ \pi^-; \text{ cut on } m_{\pi^+ \pi^-} \text{ and decay time; }$

$\delta \epsilon / \epsilon = 2.8\%, 4.4\%$

No B background, approx. 20k events sample

Babar sees evidence $(3.5\sigma)$ for the decay mode $B^+ \rightarrow K^0_S K^+$

$6B^{227}_{K^0\pi} = 26.0 \pm 1.3 \pm 1.0$

$6B^{85}_{K^0\pi} = 22.0 \pm 1.9 \pm 1.1$

$2A^{227}_{K^0\pi} = -8.7 \pm 4.6 \pm 1.0$

$2A^{152}_{K^0\pi} = 5 \pm 5 \pm 1$

$6B^{227}_{K^0K} = 1.45 \pm 0.50 \pm 0.11$

$6B^{85}_{K^0K} < 3.3$

$2A^{227}_{K^0K} = 15 \pm 34 \pm 3$
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$B^0 \rightarrow \pi^0\pi^0$

BF expected to be small (color suppr.?) and f.s. contains only $\gamma$'s
Bkg from continuum and $B^+ \rightarrow \rho^+ (\rightarrow \pi^+\pi^0)\pi^0$

*Markus Cristinziani*  
Charmless twobody B decays
$B^0 \rightarrow \pi^0 \pi^0$

BF expected to be small (color suppr.?) and f.s. contains only $\gamma$’s
Bkg from continuum and $B^+ \rightarrow \rho^+ (\rightarrow \pi^+ \pi^0) \pi^0$

- ML fit: $N_{\pi^0\pi^0} = 61 \pm 17$ at $5.0\sigma$
- data, ML fit, $q\bar{q}$ and $\rho\pi^0$

$^6 B_{\pi^0\pi^0}^{227} = 1.17 \pm 0.32 \pm 0.10$

$^{2}A_{\pi^0\pi^0}^{227} = 12 \pm 56 \pm 6$
\[ B^0 \rightarrow \pi^0 \pi^0 \]

BF expected to be small (color suppr.?) and f.s. contains only \( \gamma \)'s.

Bkg from continuum and \( B^+ \rightarrow \rho^+ (\rightarrow \pi^+ \pi^0) \pi^0 \)

- ML fit: \( N_{\pi^0 \pi^0} = 61 \pm 17 \) at 5.0\( \sigma \)
- ML fit: \( N_{\pi^0 \pi^0} = 82 \pm 16 \) at 5.8\( \sigma \)

\[ 6B_{\pi^0 \pi^0}^{2^{277}} = 1.17 \pm 0.32 \pm 0.10 \]
\[ 6B_{\pi^0 \pi^0}^{2^{275}} = 2.3^{+0.4+0.2}_{-0.5-0.3} \]
\[ 2A_{\pi^0 \pi^0}^{2^{277}} = 12 \pm 56 \pm 6 \]
\[ 2A_{\pi^0 \pi^0}^{2^{275}} = 44 \pm 53 \pm 17 \]
$B^0 \rightarrow K^0_S \pi^0$

$b \rightarrow s$ penguin transition; time-dependent CP violation yields $\sin 2\beta_{\text{eff}}$, see talk by Steve Wagner

- use of invariant and missing mass
  - smaller correlation
  - better background suppression (high momentum $\pi^0$)
- $\cos \theta^*_B$ variable in ML fit
- $\epsilon = 34\%$ vs $21\%$
- systematics from $\epsilon(\pi^0)$ and $\epsilon(K^0_S)$

$^6B^{227}_{K^0\pi^0} = 11.4 \pm 0.9 \pm 0.6$

$^6B^{85}_{K^0\pi^0} = 11.7 \pm 2.3 \pm 1.3$
First observation of $B^0 \rightarrow K^0 \bar{K}^0$

Established a $b \rightarrow d\bar{s}s$ penguin transition

Seen by Babar with $4.5\sigma$ significance (hep-ex/0408080)

$\mathcal{B}_{K^0\bar{K}^0}^{227} = 1.19 \pm 0.38 \pm 0.13$
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Summary of branching fractions and asymmetries

Branching Ratio x 10^6

Asymmetry
Isospin analysis

With isospin decomposition we can relate the amplitudes

\[ A^{+-}(B^0 \to \pi^+\pi^-), \ A^{+0}(B^+ \to \pi^+\pi^0) \text{ and } A^{00}(B^0 \to \pi^0\pi^0) \]

\[
\frac{1}{\sqrt{2}} A^{+-} + A^{00} = A^{+0} \\
\frac{1}{\sqrt{2}} \bar{A}^{+-} + \bar{A}^{00} = A^{0-} \\
\]

\[ \text{arg}(A^{+-}/\bar{A}^{+-}) = 2\Delta\alpha = 2(\alpha - \alpha_{\text{eff}}) \]

- Crucial observation: \( B^+ \to \pi^+\pi^0 \) is pure tree, thus \( |A^{+0}| = |A^{0-}| \)
- Obtain a common base of the triangles with \( \bar{A}^{ij} \equiv e^{i2\gamma} \bar{A}^{ij} \)
- Can determine the penguin pollution \( \Delta\alpha \) and extract \( \alpha \)
**First isospin analysis possible in the $\pi\pi$ system**

- Full isospin analysis is possible with $C_{\pi^0\pi^0}$ measured
- Input quantities
  - 3 branching fractions
  - 2 asymmetries

\[ \Delta \alpha \equiv |\alpha - \alpha_{\text{eff}}| < 35^\circ \text{ at } 90\% \text{ CL} \]
Patterns in $K\pi$ branching fractions

- Ratios $R_x \sim 1$ in the Standard Model
- deviations are sensitive to different corrections to the dominant penguin amplitudes

\[
R_c \equiv \frac{2B^{0+}}{B^{+0}} = 1.00 \pm 0.08
\]
\[
R_n \equiv \frac{B^{+-}}{2B^{00}} = 0.79 \pm 0.08
\]
\[
R \equiv \frac{B^{+-}}{\tau B^0} / \frac{B^{+0}}{\tau B^+} = 0.82 \pm 0.06
\]
\[
R_L \equiv 2 \frac{B^{0+}}{\tau B^+} + \frac{B^{00}}{\tau B^0} = 1.12 \pm 0.07
\]

- Fleischer-Mannel bound (from R) : $\gamma < 75^\circ$ (95% CL)
Patterns of $B \to K\pi$ Asymmetries

Using simple isospin (ignoring $P_{EW}$)

⇒ Can relate asymmetries in charged and neutral $B \to K\pi$ decays

With $\Delta^{\mu\nu} \equiv |A(B \to K^{\mu}\pi^{\nu})|^2 - |A(\bar{B} \to K^{\mu}\pi^{\nu})|^2$

$$\Delta^{0+} + \Delta^{+-} = 2\Delta^{+0} + 2\Delta^{+-}$$

- $A^{0+}$ is small: annihilation and penguin
- $A^{00}$ is not small: color suppressed and penguin

$$A_{th}^{00} = \frac{1}{2} A^{+-} \times B^{+-} - A^{+0} \times B^{+0}$$

$$B^{00} = -0.13 \pm 0.05$$

- In good agreement with the (experimentally difficult) measurement $A_{exp}^{00} = -0.09 \pm 0.14$
Summary

- Results are generally in good agreement, often using different techniques.
- Discovery of direct CP violation in $B^0 \rightarrow K^+\pi^-$ decays confirmed by both experiments.
- $B^0 \rightarrow \pi^0\pi^0$ is large and makes the isospin analysis challenging.
- Hadronic uncertainties “cancel” in the R ratios in $B \rightarrow K\pi$.
- Need to understand radiative corrections in more depth.
- Most of the measurements are statistics limited, thus we benefit from the anticipated duplication rate of the datasets.
Backup
### Interpretation of $A_{K\pi}$ within the Standard Model

<table>
<thead>
<tr>
<th>Model</th>
<th>$A_{K\pi}$ (%)</th>
<th>Error(%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>pQCD</td>
<td>-19</td>
<td></td>
<td>Keum et al., PRD 63, 054008 (2001)</td>
</tr>
<tr>
<td>Charm. Penguins</td>
<td>-8</td>
<td>3</td>
<td>Ciuchini et al., PLB 515, 33 (2001)</td>
</tr>
<tr>
<td>CKMfitter</td>
<td>-10</td>
<td>3.5</td>
<td>Charles et al., hep-ph/0406184</td>
</tr>
<tr>
<td>Data WA</td>
<td>-11</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

- Range of predictions [-20%,+5%] covers data
- Theory error $\sim 10\%$
- Consistent result with CKM Fit
- No sign of new physics here
Measurement of $\alpha$ in $B \rightarrow \pi\pi$

- Core of solution at CKM fit value is fairly precise
- $2\sigma$ not so good
- Most of the information comes from the $C(\pi^0\pi^0)$ measurement