Review of rare $B$ decay results from $BABAR$ and Belle

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Overview

• Introduction
• The BABAR and Belle experiments
• Charmless hadronic $B$ decays:
  – branching fractions
  – charge asymmetries
• Radiative $B$ decays
• $B$ charmless decays to pairs of vector mesons
• Summary & conclusion
Brief historical perspective

- **1990's:**
  CLEO (and ARGUS) started to explore rare $B$ decays:
  - observation of $b \to u$ transitions (semileptonic)
  - $b \to s\gamma$
  - $B^0 \to h^+ h^- \to B \to K^+ \pi^- \ (\sim 17 \times 10^{-6})$
    $\to B \to \pi^+ \pi^- \ (\sim 4 \times 10^{-6})$
  - $B \to \eta' K$ larger than first expected ($\sim 70 \times 10^{-6}$)

- **1999:** $BABAR$ and Belle start data taking
  - high luminosity $B$ factories
  - in $\sim 5$ years, accumulated a combined sample of $>500M$ $B\bar{B}$
  - ideal for the study of rare decays
What do we call rare $B$ decays?

- $B$ decays suppressed relative to $b \to c$ transitions:
  - they occur mostly via $b \to u$ (tree) or $b \to s(d)$ (penguin loop) transitions $\Rightarrow$ BF $< 10^{-4}$
  - competing tree and penguin amplitudes
- Examples of possible diagrams:

```
Tree
```

```
Penguin
```
Why are rare B decays interesting?

1) Tests of the standard model (SM)
   - small amplitude processes
   - sensitivity to CP violation (phases in mixing and decay)
   - constraints on CKM parameters: sides & angles

2) Sensitivity to physics beyond the SM
   - heavy (non-SM) particles can enter the loop
   - put constraints on theoretical models (e.g. SUSY)
PEP-II and KEK-B

- Asymmetric B factories
- Run at $\Upsilon(4S)$ CM energy (10.58GeV)
- Peak luminosities:
  PEP-II: $9.2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
  KEK-B: $14.2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$

\[ L_{\text{int}} = 254 \text{fb}^{-1} \]

\[ L_{\text{int}} = 350 \text{fb}^{-1} \]
BABAR and Belle detectors

- Multipurpose detectors:
  - Tracking
  - PID
  - Calorimeter
  - Muon/KL detector

**BABAR**

- Drift Chamber
  - 40 layers

- Silicon Vertex Tracker
  - 5 double-sided layers

- **DIRC** (PID)
  - 144 quartz bars

- Electro-Magnetic Calorimeter
  - 6580 CsI(TI) crystals

- 1.5T Solenoid
  - (superconducting)

- **Tracking**:
  - $\sigma(p_\perp/p_\perp) = 0.13\% p_\perp \oplus 0.45\%$

- **DIRC**:
  - $K/\pi$ separation $\geq 3.5\sigma$ for $p<3.5$ GeV/c

- **EMC**:
  - $\sigma_{e/E} = 2.3\% E^{1.4} \oplus 1.9\%$
Analysis techniques (I)

- **Experimental challenge**: isolate tiny signal in very large background (100s M events)

- Variables used to identify the signal:
  - $B$ kinematics (exploit the known total energy of the $B$ candidate)
    - **$B$ mass**: $m_{ES} = \sqrt{\frac{1}{4}s - |p_B|^2}$
    - $m_{ES}$ (BABAR) = $m_{hc}$ (Belle)

- **Energy**: $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$

  - $B$ candidate energy
  - CM energy

- $m_{ES}$ resolution ≈ 2-3 MeV/c²
- $\Delta E$ resolution ≈ 20-50 MeV

- secondary resonance mass(es), etc...
Analysis techniques (II)

- **Backgrounds:**
  - combinatoric $e^+e^- \rightarrow q\bar{q}$ ($q=u,d,s,c$) (dominant background)
    ➔ event shape variables
  - other $B$ decays

- **Signal extracted with ML fit on discriminating variables**
Branching fractions (BF)

- ~50 charmless hardonic B decays have been observed
- Useful to test and help develop phenomenological models
- Examples:
  - flavor SU(3)
    e.g. Chiang et al.
    PRD68, 074012
    PRD69, 034001
  - QCD factorization
    e.g. Beneke & Neubert
    Nucl. Phys. B675, 333
  - ...

Plots from Heavy Flavor Averaging Group:
http://www.slac.stanford.edu/xorg/hfag/
Setting bounds on the tree contribution in $B^0 \rightarrow \eta' K_S$

- **Time-dependent results in $B^0 \rightarrow \eta' K_S$**

<table>
<thead>
<tr>
<th></th>
<th>BABAR (232M)</th>
<th>Belle (275M)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>0.30±0.14±0.02</td>
<td>0.65±0.18±0.04</td>
<td>0.43±0.11</td>
</tr>
<tr>
<td>$C$</td>
<td>-0.21±0.10±0.02</td>
<td>0.19±0.11±0.05</td>
<td>-0.04±0.08</td>
</tr>
</tbody>
</table>

- Compare with charmonium value: $\sin^2 \beta = 0.73±0.04$

=> difference $\Delta S_{\text{exp}} = S - \sin^2 \beta = -0.30±0.12$

- Estimate of the tree contribution in $B^0 \rightarrow \eta' K_S$ is necessary in the interpretation of the time-dependent results

- Flavor SU(3) is used to set bounds on time-dependent CP asymmetry in $B \rightarrow \eta' K_S$:

  $$\Delta S_{\text{th}} = S(\eta'K_S) - \sin^2 \beta < |\xi_{\eta'K_S}|$$

- $\xi_{\eta'K_S}$ function of BF for related decay modes
B decays to pairs of light isoscalar mesons

- $\Delta S_{th} = S(\eta' K_S) - \sin 2\beta < |\xi_{\eta' K_s}|$

- $\xi_{\eta' K_s}$ function of the BF for flavor SU(3) related decay modes $B^0 \rightarrow \eta' \eta', \eta' \eta, \eta' \pi^0, \eta' \pi^0, \text{etc...}$
  [Gronau et al., PLB596 (2004) 107]

- Current limit: $\Delta S_{th} < \sim 0.1$
  (compare to $\Delta S_{exp} \sim 0.3$)

- If measure $\Delta S_{exp} > 0.1$
  => signature for new physics

- $\Delta S_{th}$ will improve with better BF measurements
Charge asymmetries (direct CP)

- Many self-tagging (i.e. B flavor identified by final state) rare decays have competing tree and penguin amplitudes.
- Interference between two decay amplitudes can lead to direct CP violation $A_{CP}$:
  
  $$A_{CP} = \frac{\Gamma(\bar{B}\to\bar{f})-\Gamma(B\to f)}{\Gamma(\bar{B}\to\bar{f})+\Gamma(B\to f)} \sim \sin \Delta \phi_{\text{weak}} \sin \Delta \delta_{\text{strong}}$$

- $A_{CP}$ can be sizable if both weak and strong phases $\neq 0$.
- Strong phases difficult to estimate => large theoretical uncertainties on predictions.
\[ B^0 \rightarrow K^+\pi^- \]

- Observation of direct CP violation in \( B^0 \rightarrow K^\pm\pi^{\mp} \) decays

<table>
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<tr>
<th></th>
<th>( N_{BB} )</th>
<th>( N_{K\pi} )</th>
<th>( A_{CP} )</th>
<th>signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BABAR</td>
<td>227M</td>
<td>1606±51</td>
<td>-0.133±0.030±0.009</td>
<td>4.2( \sigma )</td>
</tr>
<tr>
<td>Belle</td>
<td>275M</td>
<td>2140±53</td>
<td>-0.101±0.025±0.005</td>
<td>3.9( \sigma )</td>
</tr>
</tbody>
</table>

Significant asymmetry in signal region
$B^\pm \to \eta^{(')} h^\pm$

- Why $A_{CP}$ in $B^+ \to \eta K^+/\pi^+$ may be large:
  - $\eta$-$\eta'$ mixing enhances $B \to \eta'K$ and suppresses $B \to \eta K$
    => in $\eta K$ interference between amplitude can be sizable
    => possible source of large direct CP violation
  - predicted in 1979! [Bander, Silverman, Soni, PRL 43, 242]

- Based on 89M $B \bar{B}$ pairs, BABAR saw ~2$\sigma$ significant $A_{CP}$:
  $A_{CP}(\eta K^+) = -0.52 \pm 0.24$ and $A_{CP}(\eta \pi^+) = -0.44 \pm 0.18$ [PRL 92, 061801]

- BABAR and Belle obtained new preliminary measurements:

<table>
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<tr>
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<th>$N_{BB}$</th>
<th>$A_{CP}(\eta K^+)$</th>
<th>$A_{CP}(\eta \pi^+)$</th>
<th>$A_{CP}(\eta \bar{\pi}^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>152M</td>
<td>-0.49$\pm$0.31$\pm$0.07 +0.07$\pm$0.15$\pm$0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BABAR</td>
<td>232M</td>
<td>-0.20$\pm$0.15$\pm$0.01 -0.13$\pm$0.12$\pm$0.01 +0.14$\pm$0.16$\pm$0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>My average</td>
<td></td>
<td>-0.25$\pm$0.14</td>
<td>-0.05$\pm$0.09</td>
<td></td>
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</table>

(BABAR: $BF(B \to \eta' \pi^+) = (4.0 \pm 0.8 \pm 0.4) \times 10^{-6}$ signif. 5.4$\sigma$)

=> Results compatible with no asymmetry (and with large $A_{CP}$)
Charge asymmetries: summary

- Several modes used to look for direct CP violation
- Errors as low as ±0.02

\[ A_{CP} = -0.109 \pm 0.019 \]

Observation of direct CP violation (5.7sigma)

Improved averages with new BABAR result
Radiative penguin decays

- $b \to s(d)\gamma$ proceed through EW penguin loop

**Inclusive decays**
- Branching fractions:
  - theoretically clean (no hadronization) $\text{BF}_{\text{th}} = (3.6\pm0.3) \times 10^{-4}$
  - experimentally difficult (fight background)
    $\Rightarrow \text{BF}_{\text{exp}} = (3.5\pm0.3) \times 10^{-4}$
  - sensitive to new physics entering the loop
- Charge asymmetries:
  - experimental errors cancel
  - sensitive to new physics in loop and to new phases

**Exclusive decays**
- experimentally easier
- theoretical uncertainties from hadronization
$A_{CP}$ in inclusive $b \to s \gamma$

- Theory prediction (SM):
  - small due to single dominant amplitude
  - $A_{CP} = 0.0044 + 0.0024 - 0.0014$

- Results:
  - **BABAR (89M BB):**
    $A_{CP} = 0.025 \pm 0.050 \pm 0.015$
  - **Belle (152M BB):**
    $A_{CP} = 0.002 \pm 0.050 \pm 0.030$

- Results statistics limited, and in agreement with SM
Search for $b \to d \gamma$ exclusive decays

- **Used in determination of $V_{td}$**
- $B^0 \to \omega \gamma$ and $B \to \rho \gamma$ expected to dominate
  - SM predictions: $BF \sim (0.9-2.7) \times 10^{-6}$
- **Results ($x 10^{-6}$)**
  (upper limits at 90% C.L.)

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</thead>
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<tr>
<td>$\rho^+ \gamma$</td>
<td>&lt;1.8</td>
<td>&lt;2.2</td>
</tr>
<tr>
<td>$\rho^0 \gamma$</td>
<td>&lt;0.4</td>
<td>&lt;0.8</td>
</tr>
<tr>
<td>$\omega \gamma$</td>
<td>&lt;1.0</td>
<td>&lt;0.8</td>
</tr>
<tr>
<td>$(\rho, \omega) \gamma$</td>
<td>&lt;1.2</td>
<td>&lt;1.4</td>
</tr>
</tbody>
</table>

$\Rightarrow |V_{td}|/|V_{ts}| < 0.19$ @90% C.L.

- **Upper limits in range of SM predictions**
Other radiative decay results

- Other radiative decay results not covered in this talk:
  - inclusive photon spectrum
    $\Rightarrow b$-quark mass
  - $B \rightarrow K^*\gamma$
    - direct CP
    - time-dependent CP
  - $b \rightarrow s l^+ l^-$
    - $\text{BF} \& A_{\text{CP}}$ results in agreement with SM predictions
    - $\text{BF}(B \rightarrow K l^+ l^-) = (0.57\pm 0.07) \times 10^{-6}$
      smallest BF measured in $B$ decays
      $1 \times 10^{-6}$
Polarization in charmless $B \rightarrow VV$

- $B$ (spin-0) decays to two spin-1 particles:
  - spin-related configurations $\Rightarrow 3$ amplitudes
  - 11 observables:
    - **Polarization** fractions
    - Direct $CP$ asymmetries
    - triple product asymmetries
- In SM
  - $A_{00}$ is the natural spin configuration
  - $A_{++}$ and $A_{--}$ suppressed by $m_{res}/m_B$ (one for each spin flip)
  - expect strong longitudinal polarization

$$f_L = \frac{|A_{00}|^2}{(|A_{00}|^2 + |A_{++}|^2 + |A_{--}|^2)} \sim 1$$
$B^0 \rightarrow \phi K^{*0}$

- In $B^0 \rightarrow \phi K^{*0}$ decays, measure
  
  **BABAR** (227M BB) \( f_L = 0.52 \pm 0.05 \pm 0.02 \) (PRL93, 231804)
  
  **Belle** (86M BB) \( f_L = 0.43 \pm 0.09 \pm 0.04 \) (PRL91, 201801)

- But $f_L \sim 1$ for tree-dominated $B \rightarrow VV$ decays ($\rho \rho$, $\omega \rho^+$)

- Other penguin dominated modes still statistics limited
Polarization in $B \to VV$: summary

- The polarization puzzle in $B^0 \to \phi K^{*0}$ remains: $f_L(\phi K^{*0}) \sim 0.5$
- For tree-dominated $VV$ mode: $f_L(\text{tree}) \sim 1$
- Currently no convincing explanation
- Possible scenarios:
  - poorly understood SM strong interaction effects?
  - effects from new physics?
- Additional measurements will help solve this problem
Summary

• We have presented recent highlights of the study of rare $B$ decays:
  
  – several measurements of branching fractions
    • useful to contraint phenomenological models
  
  – Search for direct CP violation in $B$ decays:
    • Direct CP observed in $B^0 \rightarrow K^\pm \pi^\mp$ decays
    • many other measurements (non significant)

  
  – Radiative decays

  
  – $B \rightarrow VV$ decays
    • rich program, and puzzle in polarization results
Conclusion

- Rare $B$ decays are a very rich source of information on
  - the standard model
  - physics beyond the standard model
- The experiments at the $B$ factories have produced many new results with their current data samples
- Many more rare-$B$ decay results to come with a combined $>1000\text{fb}^{-1}$ by 2006!