Some Recent Results from $BABAR$

Jack Ritchie
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(representing the $BABAR$ collaboration)

Progress on Rare FCNC $B$ decays
Outline

I. The *BABAR* Experiment

II. Rare FCNC Decays
   i. $b \rightarrow s\gamma$
   ii. $b \rightarrow d\gamma$ (including $B^0 \rightarrow \gamma\gamma$)
   iii. $b \rightarrow sll\bar{l}$ (where $l = e, \mu, \tau$ or $\nu$)

III. Conclusion
$\bar{B}B$ production at PEP-II

$\Upsilon(4S)$ decays $\approx 100\%$ to $\bar{B}B$

$\bar{B}B$ production at PEP-II

Continuum ($u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, \tau^+\tau^-$) events are backgrounds to most $B$ decay measurements.

Rich program including CPV, CKM parameters, rare $B$ decays, charm, $\tau$ decays, bottomonium,…

$\geq 450$ publications so far
BABAR at SLAC

- 1.5 T solenoid
- Silicon vertex tracker
  - 5 layer, double-sided
- Drift chamber
  - Tracking + dE/dx
  - 40 stereo layers
- DIRC particle ID
  - Quartz bars, 11000 PMTs
- CsI(Tl) calorimeter
  - 6580 crystals
- Instrumented Flux Return
  - Iron + resistive plate chambers and limited streamer tubes

CM boost $\beta\gamma \approx 0.56$
9 GeV $e^-$, 3.1 GeV $e^+$
$b \rightarrow s\gamma$ in the Standard Model

- First penguin – 1993 CLEO observation of $B \rightarrow K^*\gamma$
- Heavy-quark hadron duality $\Rightarrow B(B \rightarrow X_s\gamma) \cong B(b \rightarrow s\gamma)$
- Theoretically clean prediction in the Standard Model
  - Next-to-next-leading order (NNLO) calculation ($E_{\gamma} > 1.6$ GeV)
    \[
    B(B \rightarrow X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}
    \]  
    Misiak et al., PRL 98, 022002(2007)
  - Small (7%) SM theory uncertainty $\Rightarrow$ constraint on New Physics
- $E_{\gamma}$ spectrum reflects $b$ quark’s mass, Fermi motion and gluon brem
  - Input to shape function parameters for $|V_{ub}|$ from $b \rightarrow ul^-\nu$ endpoint and used in extraction of $|V_{cb}|$ from $b \rightarrow cl^-\nu$

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New Physics in $b \rightarrow s\gamma$

- Sensitive to new heavy particles in the loops
  - charged Higgs, superpartners, etc

- Leading-order and next-to-leading order calculations for many models

- Experiment vs theory BF $\Rightarrow$ strong constraints on New Physics

$M_{H^\pm} > 295$ GeV

2-Higgs doublet model (type II); (as in MSSM)

Haisch, arXiV:0805.2141
Experimental Issues for $B \rightarrow X_s \gamma$

- **Two experimental techniques**
- **Fully Inclusive**
  - Only look at the $\gamma$ from the signal $B$ decay
  - Continuum rejection via event shape and either lepton tag (rejection $\sim 10^{-5}$ for 2.5% signal eff) or reconstructing the other $B$
- **"Semi-inclusive"** (sum of exclusive modes)
  - Reconstruct many final states (38 in BABAR)
  - Dominant systematic from the missing fraction ($\approx 45\%$)
- **Suppress $B$ backgnd with $E_\gamma$ min cut**
  - Compromise between experimental vs theoretical uncertainties

\[
E_\gamma^* \approx \frac{m_b^2 - m_s^2}{2m_b} \approx \frac{m_b}{2}
\]
Experimental Issues for $B \to X_s \gamma$

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Experimental Status for $B \rightarrow X_s \gamma$

Comparison of measurements extrapolated to $E_\gamma > 1.6$ GeV by the Heavy Flavor Averaging Group.

Updates are in progress for these BaBar measurements.
Direct CP Violation ($A_{CP}$) in $B \rightarrow X_s\gamma$

$$A_{CP} = \frac{\Gamma(B \rightarrow X_{s+d}\gamma) - \Gamma(\bar{B} \rightarrow X_{\bar{s}+\bar{d}\gamma})}{\Gamma(B \rightarrow X_{s+d}\gamma) + \Gamma(\bar{B} \rightarrow X_{\bar{s}+\bar{d}\gamma})} \approx 0$$

A strong SM prediction, so a good NP test.

0.056 $\pm$ 0.060 $\pm$ 0.018 optimized region
2.1 < $E_\gamma$ < 2.8 GeV

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• Suppressed w.r.t. $b \rightarrow s \gamma$ by $|V_{td}/V_{ts}|^2 \approx 0.04$

• Sensitivity to New Physics via loops
  – CKM suppression may not hold

• Complementary to $B_s$ and $B_d$ mixing for determining $|V_{td}/V_{ts}|$
  – Less precise, but
  – Possible different sensitivity to New Physics in box (mixing) vs radiative penguin diagrams.

• $|V_{td}/V_{ts}|$ determination can be based on exclusive ratio $\frac{B(B \rightarrow \rho \gamma)}{B(B \rightarrow K^{*}\gamma)}$
  – Depends on ratio of form factors
  – Ratio of inclusive rates is theoretically cleaner
  – BABAR has recently reported a semi-inclusive measurement
$B \rightarrow X_{d/s} \gamma$

Seven modes with one $\pi \leftrightarrow K$

$B \rightarrow X_{d}\gamma$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow \pi^+\pi^-\pi^+$</td>
<td>$B^0 \rightarrow K^+\pi^-\pi^+$</td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^+\pi^0\pi^+$</td>
<td>$B^+ \rightarrow K^+\pi^+\pi^-\pi^+$</td>
</tr>
<tr>
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</table>

Continuum rejection via event shape (neural net) – 99% rejection with good signal eff (≈25%)  
Extract signals via 2-d maximum likelihood fits  
Correct for missing modes  
  – Simple in low-mass bin; mostly missing $K^0$ modes  
  – Fragmentation model for high-mass (dominant systematic error)

Hadronic mass bins:  
0.5-1.0 GeV (all $\rho,\omega, K^*$)  
1.0-2.0 GeV (nonresonant)

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

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

Signal peaks at  
$M_{ES} = M_B$  
$\Delta E = 0$

Seven modes with one $\pi \leftrightarrow K$

$B \rightarrow X_{d/s} \gamma$
**$B \to X_{d/s}\gamma$ Results**

<table>
<thead>
<tr>
<th>$0.5 &lt; M_X &lt; 1.0$ GeV</th>
<th>$1.0 &lt; M_X &lt; 2.0$ GeV</th>
<th>$0.5 &lt; M_X &lt; 2.0$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(B \to X_d\gamma) \times 10^6$</td>
<td>$1.3 \pm 0.3 \pm 0.1$</td>
<td>$7.9 \pm 2.0 \pm 2.2$</td>
</tr>
<tr>
<td>$B(B \to X_s\gamma) \times 10^6$</td>
<td>$38 \pm 2 \pm 2$</td>
<td>$192 \pm 8 \pm 29$</td>
</tr>
<tr>
<td>$\frac{B(B \to X_d\gamma)}{B(B \to X_s\gamma)}$</td>
<td>$0.033 \pm 0.009 \pm 0.003$</td>
<td>$0.040 \pm 0.009 \pm 0.010$</td>
</tr>
</tbody>
</table>

- Correct to full $M_X$ range using Kagan-Neubert spectrum (ratio insensitive)

\[
|V_{td}/V_{ts}| = 0.199 \pm 0.022({\text{stat}}) \pm 0.024({\text{syst}}) \pm 0.002({\text{th}})
\]
Search for $B^0 \rightarrow \gamma\gamma$

- Leading order Standard Model calculation

$$B(B^0 \rightarrow \gamma\gamma) = (3.1^{+6.4}_{-1.6}) \times 10^{-8}$$


- Possible enhancement from New Physics in loop
- Never observed, best prior limit from Belle

$$B(B^0 \rightarrow \gamma\gamma) < 6.2 \times 10^{-7} \ (90\% \ CL)$$

PRD 73,051107(2006)

- New $BABAR$ search based on 430 fb$^{-1}$ (full dataset)
- Simple signature, but significant backgrounds from $\pi^0$ and $\eta$ decays in continuum events
$B^0 \rightarrow \gamma\gamma$ Background Rejection

Most rejection from likelihood ratios $(\pi^0, \eta)$ and neural net

Net rejection $\sim 10^{-3}$ for cuts with 27% signal efficiency
$B^0 \rightarrow \gamma\gamma$ Results

**BABAR** Preliminary

- Events / (0.003 GeV/c^2)
- $-0.30 \leq \Delta E \leq 0.13$ GeV

$N_{\text{signal}} = 21^{+13}_{-12}$ events (1.9$\sigma$)

$B(B^0 \rightarrow \gamma\gamma) = (1.7 \pm 1.1 \pm 0.2) \times 10^{-7}$

Set limit by integrating likelihood function to 90%

- Smear by 12% systematic error

90% CL upper limit

$B(B^0 \rightarrow \gamma\gamma) < 3.3 \times 10^{-7}$
$b \to s \, l^+l^-$

- More complex than $b \to s \, \gamma$
  - W-box and Z-penguin amplitudes important
  - $c\bar{c}$ resonances in dilepton spectrum (removed by cuts on $M_{ll}$)

- More observables
  - dilepton mass spectrum ($q^2 = M_{ll}^2$)
  - forward–backward asymmetry ($A_{FB}$)
  - New Physics may induce large effects in these observables

- Standard Model estimates made at NNLO
  - Reliable for inclusive $b \to s \, l^+l^-$
  - Form factor uncertainties affect exclusive processes
$b \rightarrow s \ l^+l^-$

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  - W-box and Z-penguin amplitudes important
  - cG resonances in dilepton spectrum (removed by cuts on $M_{ll}$)

- More observables
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- Standard Model estimates made at NNLO
  - Reliable for inclusive $b \rightarrow s \ l^+l^-$
  - Form factor uncertainties affect exclusive processes
$b \rightarrow s \ l^+ l^-$ Experimental Issues

• Fully inclusive measurements not possible
  – Semi-inclusive analysis via sum of exclusive states ($K l^+ l^- + n \pi$)
  – Exclusive $B \rightarrow K l^+ l^-$ and $B \rightarrow K^* l^+ l^-$ easier, but involve form factors

• Interference from $B \rightarrow K^(*) J/\psi$ and $B \rightarrow K^(*) \psi(2S)$
  – Remove with cuts on $l^+ l^-$ mass
  – Provide important control samples (same topology, known BFs)

• Main backgrounds from $B$ and $D$ semileptonic decays
  – Suppress using event shape, vertex info, missing energy

• Bkg from $B \rightarrow D \pi (D \rightarrow K^(*) \pi) + \pi \rightarrow \mu$ mis-ID
  – Veto $K^(*) \pi$ mass close to $D$

• Extract signal with maximum likelihood fits

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**$b \to s \ell^+\ell^-$ Branching Fraction Summary**

- **Good agreement between experiment and Standard Model theory**
  - Experimental errors smaller than theory errors for exclusive modes
  - With current statistics, all BF vs $q^2$ measurements consistent with SM
- **Semi-inclusive measurements not updated to full datasets (yet)**

![Graph showing branching fractions for various decay modes](image)
$A_{FB}$ in $b \rightarrow s \ell^+\ell^-$

Lepton forward–backward asymmetry ($A_{FB}$)

\[
A_{FB}(q^2) = \frac{1}{dB} \int d \cos \theta_l \frac{d^2B}{dq^2 d \cos \theta_l} \text{sgn}(\cos \theta_l)
\]

Sensitive to interference effects due to New Physics that might not affect BFs - e.g., relative signs of Wilson coefficients

$C_7 = -C_7(SM)$

$C_9 C_{10} = -C_9 C_{10}(SM)$

$C_7 = -C_7(SM)$

$C_9 C_{10} = -C_9 C_{10}(SM)$

Lepton pair CM
$A_{FB}$ in $B \rightarrow K^* \ell^+ \ell^-$

Lepton forward–backward asymmetry ($A_{FB}$)

$A_{FB}(q^2) = \frac{1}{\frac{d^2B}{dq^2}} \int d \cos \theta_\ell \frac{d^2B}{dq^2 d \cos \theta_\ell} \text{sgn}(\cos \theta_\ell)$

$A_{FB}$ determined from ML fit
- Along with $K^*$ polarization ($F_L$)
- Fit validation with $B \rightarrow K^* J/\psi$ and $B \rightarrow K^* \psi(2S)$

$\frac{1}{\Gamma} \frac{d \Gamma}{d \cos \theta_\ell} = \frac{3}{4} F_L (1 - \cos^2 \theta_\ell)$

$+ \frac{3}{8} (1 - F_L)(1 + \cos^2 \theta_\ell) + A_{FB} \cos \theta_\ell$

Lepton pair CM

$0.1 < q^2 < 6.25 \text{ GeV}^2$

$q^2 > 10.24 \text{ GeV}^2$

BABAR 349 fb$^{-1}$

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$A_{FB}$ Measurements in $B \rightarrow K^* l^+ l^-$

- Experiments are consistent
- Consistent with SM
  - Tend to be high at low $q^2$
- $BABAR$ result will be updated to full data + other improvements
- Clearly need higher statistics
Search for $B \rightarrow K \nu \bar{\nu}$

- Standard Model branching fraction $\approx 4 \times 10^{-6}$
- Sensitive to multiple New Physics scenarios
  - Significant enhancements possible (MSSM, unparticles, extra dimn); Yamada, PRD 77,014025; Aliev JHEP 07:072; Colangeo PRD 73, 115006.
- New search using full BaBar dataset
- Reconstruct tag $B$ in $B \rightarrow D^{(*)}\nu$
- Decision trees for bkngd rejection
  - Missing energy, event info kinematics, Tag B info
  - 26 (38) inputs for $K^+(K^0)$ mode
Search for $B \rightarrow K \nu \bar{\nu}$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_{bkgd}$</th>
<th>$N_{obs}$</th>
<th>$N_{excess}$</th>
<th>$N_{sig}$ at SM BF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+$</td>
<td>$17.6 \pm 2.6 \pm 0.9$</td>
<td>$19.4^{+4.4}_{-4.4}$</td>
<td>$1.8^{+6.2}_{-5.1}$</td>
<td>$2.9 \pm 0.4$</td>
</tr>
<tr>
<td>$K^0$</td>
<td>$3.9 \pm 1.3 \pm 0.4$</td>
<td>$6.1^{+4.0}_{-2.2}$</td>
<td>$2.2^{+4.1}_{-2.8}$</td>
<td>$0.5 \pm 0.1$</td>
</tr>
</tbody>
</table>

BABAR preliminary

$B(B^+ \rightarrow K^+ \nu \bar{\nu}) < 1.3 \times 10^{-5}$

$B(B^0 \rightarrow K^0 \nu \bar{\nu}) < 5.6 \times 10^{-5}$
First Search for $B \rightarrow K \tau^+ \tau^-$

### Branching Fraction

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching Fraction $(0.6 \leq q^2/m_b \leq 1.0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow X_s e^+ e^-$</td>
<td>$5.8 \times 10^{-7}$</td>
</tr>
<tr>
<td>$B \rightarrow X_s \mu^+ \mu^-$</td>
<td>$5.8 \times 10^{-7}$</td>
</tr>
<tr>
<td>$B \rightarrow X_s \tau^+ \tau^-$</td>
<td>$2.5 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

$X_s = K \approx 50\%$

- **SM rate inaccessible, but**
  - NP may enhance, $(m_\tau/m_\mu)^2=280$
  - Important to identify experimental issues/prospects for future expts

**Hiller, PRD 70, 034018(2004)**

**BABAR Preliminary**

- **Background est**
- **Observe 47 events with $65\pm7$ est bkg**

**90% CL**

$$B(B^+ \rightarrow K^+ \tau^+ \tau^-) < 3.3 \times 10^{-3}$$

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Summary/Conclusions

• There has been lots of progress, and continues to be lots of activity, in the study of rare FCNC B decays
  – The flow of results from BABAR (and Belle) will continue as final analyses are completed over the next year or two.

• These processes are important
  – Reliable Standard Model calculations possible
  – Sensitive to New Physics through loops

• No current result is inconsistent with the SM

• Several key measurements are statistically limited, so a complete study of these processes will require much larger data samples.
Backup/Extra Slides
Isospin Asymmetry

\[ A_I = \frac{B(B^0 \rightarrow K^{(*)0} l^+ l^-) - \frac{\tau_0}{\tau_+} B(B^\pm \rightarrow K^{(*)\pm} l^+ l^-)}{B(B^0 \rightarrow K^{(*)0} l^+ l^-) + \frac{\tau_0}{\tau_+} B(B^\pm \rightarrow K^{(*)\pm} l^+ l^-)} \]

- Expected near 0 for all \( q^2 \)
- Measurements
  - Consistent with 0 at high \( q^2 \)
  - Favor less than 0 at low \( q^2 \)
  - Belle 2.2\( \sigma \) below 0
  - \textit{BABAR} 3.9\( \sigma \) below 0
Direct CP Asymmetry

\[ A_l = \frac{B(\overline{B} \to \overline{K}^{(*)} l^+ l^-) - B(B \to K^{(*)} l^+ l^-)}{B(\overline{B} \to \overline{K}^{(*)} l^+ l^-) + B(B \to K^{(*)} l^+ l^-)} \]

Test for direct CP violation; less than 1% in Standard Model
Lepton Flavor Asymmetry

\[ R_{K^{(*)}} = \frac{B(B \rightarrow K^{(*)} \mu^+ \mu^-)}{B(B \rightarrow K^{(*)} e^+ e^-)} \]

\( \cong 1 \) in SM (for \( K^* \) if \( q^2 > 0.1 \text{ GeV}^2 \))

Enhanced in models with two-Higgs doublets, including SUSY with a neutral Higgs at large \( \tan \beta \)