Rare Leptonic B and $b \rightarrow s l^+ l^-$ Decays at B-factories

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(representing BaBar)

Recent results from BaBar and Belle
Topics

Flavor changing neutral currents

\[ B \rightarrow K^{(*)} \ell^+ \ell^- \text{ - recent BABAR} \]
\[ B \rightarrow \pi \ell^+ \ell^- \text{ - recent Belle} \]
\[ B \rightarrow K^{(*)} \nu \bar{\nu} \text{ - recent BABAR} \]
\[ B^0 \rightarrow \ell^+ \ell^- \]
\[ B^\pm \rightarrow \ell^\pm \nu \]

(\text{where } \ell = \mu \text{ or } e)
Enormous luminosities have led to major advances in the study of rare B decays.

Jack Ritchie
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Heavy Quarks and Leptons 2008
Melbourne, Australia
Short-distance physics appears in the Wilson coefficients. \(C_7, C_9, C_{10}\) important for \(b \to s l^+ l^-\).

Magnitude of \(|C_7| \approx 0.33\) known from \(B \to X_S \gamma\), but sign not constrained.

\(|C_9|^2 + |C_{10}|^2\) constrained by \(b \to s l^+ l^-\) branching fraction, but not relative sign.

New physics may modify the \(C\)'s or introduce additional terms (e.g., scalar, pseudoscalar).
\[ b \to s \ l^+l^- \]  Experimental Issues

- Fully inclusive measurements not possible
  - Semi-inclusive analysis via sum of exclusive states \( (K \ l^+l^- + n\pi) \)
  - Exclusive \( B \to K \ l^+l^- \) and \( B \to K^* \ l^+l^- \) for most studies
  - Ten sub-modes: \( \{ K^\pm, K_S^0, K^\pm \pi^\mp, K^\pm \pi^0, K_S^0 \pi^\pm \} \times [e^\pm e^\mp, \mu^\pm \mu^\mp] \)

- Interference from \( B \to K^{(*)} J/\psi \) and \( B \to K^{(*)} \psi(2S) \)
  - 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 (combined in neural nets, or other method)

- Background from \( B \to D \pi (D \to K^{(*)} \pi) \) with \( \pi \to \mu \) mis-ID
  - Veto based on \( K^{(*)} \pi \) mass close to \( D \) mass

- Extract signal with maximum likelihood fit
  - Fit versus \( M_{ES} \), with mode-dependent \( \Delta E \) cut

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

\[ M_{ES} = M_{bc} = \sqrt{E_{beam}^{*2} - P_B^{*2}} \]
$B \rightarrow K^{(*)} l^+ l^-$ Signals

349 fb$^{-1}$

$ΔE$ cuts applied

combinatorics

fake muons

cross-feed and peaking bkgs

signal
$B \rightarrow K^{(*)} l^+ l^- q^2$ regions

$q^2 = m_{ll}^2$

$B \rightarrow K^* l^+ l^-$

$B \rightarrow K l^+ l^-$

$0.1 < q^2 < 7.02$

$10.24 < q^2 < 12.96$

$B_A B_A R$ preliminary

$q^2 > 14.06$


$J/\psi$

$pole$

$\psi(2S)$
$B \rightarrow K^{(*)} l^+ l^-$ Branching Fractions

**new BaBar preliminary (349 fb⁻¹)**

\[
B(B \rightarrow K^{*} l^+ l^-) = (11.1^{+1.9}_{-1.8} \pm 0.7) \times 10^{-7} \\
B(B \rightarrow Kl^+ l^-) = (3.9 \pm 0.7 \pm 0.2) \times 10^{-7}
\]

Consistent with theory. Next level of SM tests from rate asymmetries and angular information (as functions of $q^2 = s = m_{ll}^2$)
\[ A_{CP} \equiv \frac{\mathcal{B}(\bar{B} \to \bar{K}^{(*)} \ell^+ \ell^-) - \mathcal{B}(B \to K^{(*)} \ell^+ \ell^-)}{\mathcal{B}(\bar{B} \to \bar{K}^{(*)} \ell^+ \ell^-) + \mathcal{B}(B \to K^{(*)} \ell^+ \ell^-)} \]

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

**BaBar preliminary (349 fb\(^{-1}\))**

<table>
<thead>
<tr>
<th>Mode</th>
<th>combined (q^2)</th>
<th>(0.1 &lt; q^2 &lt; 7.02) (GeV(^2/c^4))</th>
<th>(q^2 &gt; 10.24) (GeV(^2/c^4))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^+ \to K^+ \ell^+ \ell^-)</td>
<td>(-0.18^{+0.18}_{-0.18} \pm 0.01)</td>
<td>(-0.18^{+0.19}_{-0.19} \pm 0.01)</td>
<td>(-0.09^{+0.36}_{-0.39} \pm 0.02)</td>
</tr>
<tr>
<td>(B^0 \to K^{*0} \ell^+ \ell^-)</td>
<td>(0.02^{+0.20}_{-0.20} \pm 0.02)</td>
<td>(-0.23^{+0.38}_{-0.38} \pm 0.02)</td>
<td>(0.17^{+0.24}_{-0.24} \pm 0.02)</td>
</tr>
<tr>
<td>(B^+ \to K^{*+} \ell^+ \ell^-)</td>
<td>(0.01^{+0.26}_{-0.24} \pm 0.02)</td>
<td>(0.10^{+0.25}_{-0.24} \pm 0.02)</td>
<td>(-0.18^{+0.45}_{-0.55} \pm 0.04)</td>
</tr>
<tr>
<td>(B \to K^{*} \ell^+ \ell^-)</td>
<td>(0.01^{+0.16}_{-0.15} \pm 0.01)</td>
<td>(0.01^{+0.21}_{-0.20} \pm 0.01)</td>
<td>(0.09^{+0.21}_{-0.21} \pm 0.02)</td>
</tr>
</tbody>
</table>

All results consistent with zero.
Enhanced in models with two-Higgs doublets, including SUSY with a neutral Higgs at large \( \tan \beta \)
$B \rightarrow K^{(*)} l^+ l^-$ Isospin Asymmetry

\[
A_I \equiv \frac{B(B^0 \rightarrow K^{(*)0} \ell^+ \ell^-) - (\frac{m_\tau}{\tau_+})B(B^\pm \rightarrow K^{(*)\pm} \ell^+ \ell^-)}{B(B^0 \rightarrow K^{(*)0} \ell^+ \ell^-) + (\frac{m_\tau}{\tau_+})B(B^\pm \rightarrow K^{(*)\pm} \ell^+ \ell^-)}
\]

Small in Standard Model, with some variation at low- $q^2$.

Some sensitivity to the sign of $C_7$
$B^0$ vs $B^\pm \rightarrow K^{(*)} l^+ l^-$ Comparison

$BABAR$ preliminary

$0.1 < q^2 < 7.02$

$B(B^\pm \rightarrow K^{\pm} \ell^+ \ell^-) = (2.5^{+0.52}_{-0.47} \pm 0.1) \times 10^{-7}$

$B(B^0 \rightarrow K^0 \ell^+ \ell^-) < 0.9 \times 10^{-7}$ (90% CL)

$B(B^0 \rightarrow K^{*0} \ell^+ \ell^-) = (2.6^{+1.1}_{-1.0} \pm 0.2) \times 10^{-7}$

$B(B^\pm \rightarrow K^{*\pm} \ell^+ \ell^-) = (9.8^{+2.6}_{-2.4} \pm 0.6) \times 10^{-7}$
$B \rightarrow K^{(*)} l^+ l^-$ Isospin Asymmetry

In low-$q^2$ bin, $A_I$ is significantly less than zero:
- $3.0 \sigma$ for $K l^+ l^-$
- $2.7 \sigma$ for $K^* l^+ l^-$
- $4.0 \sigma$ combined

combined $q^2$

$A_I(K \ell^+ \ell^-) = -0.37^{+0.27}_{-0.34} \pm 0.04$

$A_I(K^* \ell^+ \ell^-) = -0.12^{+0.18}_{-0.16} \pm 0.04$
\[ B \rightarrow K^* l^+ l^- \] Angular Analysis

Angular distributions as functions of \( q^2 \) are particularly sensitive to possible new physics.

\( K^* \) longitudinal polarization \( F_L \)

From distribution of the angle \( \theta_K \) between the \( K \) and \( B \) in the \( K^* \) rest frame

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_K} = \frac{3}{2} F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L) (1 - \cos^2 \theta_K)
\]

Lepton forward-backward asymmetry \( A_{FB} \)

From distribution of the angle \( \theta_\ell \) between the \( l^+ \) and \( B \) in the \( l^+ l^- \) rest frame

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4} F_L (1 - \cos^2 \theta_\ell) + \frac{3}{8} (1 - F_L) (1 + \cos^2 \theta_\ell) + A_{FB} \cos \theta_\ell
\]
$B \to K^{*}l^{+}l^{-}$ Angular Analysis

Two $q^2$ bins:
- low - $0.1 < q^2 < 6.25$ GeV$^2$
- high - $q^2 > 10.24$ GeV$^2$
  except $12.96 < q^2 < 14.06$

Three Step Fit Procedure:
1. Combine $K^{*}l^{+}l^{-}$ modes, fit for yields.
2. Fix yields. For $m_{ES}>5.27$, fit $\cos(\theta_K)$ for $F_L$.
3. Fix $F_L$, fit $\cos(\theta_l)$ for $A_{FB}$.

Angular PDFs
- Signal weighted by detector eff from MC
- Combinatorial bkg from sidebands in data

BABAR preliminary (349 fb$^{-1}$)
Results submitted to PRL arXiv: 0804.4412

\[ A_{FB}^{low q^2} = 0.24^{+0.18}_{-0.23} \pm 0.05 \]
\[ A_{FB}^{high q^2} = 0.76^{+0.52}_{-0.32} \pm 0.07 \]
\[ F_L^{low q^2} = 0.35 \pm 0.16 \pm 0.04 \]
\[ F_L^{high q^2} = 0.71^{+0.20}_{-0.22} \pm 0.04 \]

Fit method tested on \( B \to J/\psi K^* \) events, for which BF \( s \) and \( K^* \) polarization are known, and \( A_{FB} = 0 \). Also, \( A_{FB} \) consistent with zero for \( B \to K l^+ l^- \).
$A_{FB}$ from Belle and BaBar

Belle approach differs from BaBar
- For events in the signal box, fits for ratios of Wilson coefficients using $(q^2, \cos \theta_E)$ distribution
- $F_L$ not determined, $A_{FB}$ from projected fit result

Belle and BaBar results consistent
- low-$q^2$ $A_{FB}$ favors flipped-sign $C_7$
- high-$q^2$ $A_{FB}$ strongly disfavors flipped-sign $C_9C_{10}$

BaBar $F_L$ result also favors flipped-sign $C_7$

Belle 357 fb$^{-1}$, PRL 96, 2511801 (2006)
$B \rightarrow \pi l^+l^-$

Same diagrams as $b \rightarrow s l^+l^-$, suppressed by $|V_{td}/V_{ts}|^2 \approx 0.04$

$SM$ expectation:
\[ B(B^+ \rightarrow \pi^+ l^+ l^-) = 3.3 \times 10^{-8} \]
\[ B(B^0 \rightarrow \pi^0 l^+ l^-) = 1.7 \times 10^{-8} \]

Aliev and Savci, RPD 60, 104005 (1999)

New Belle result - submitted to PRD(RC), arXiv: 0804.3656

- from 657M $B\bar{B}$ pairs ($\approx 607$ fb$^{-1}$)
- continuum and $B$ semi-leptonic bkgs rejected with likelihood ratios that include shape, vertex and other info
- Unbinned max likelihood fits in $\Delta E - m_{bc}$ for each sub-mode
### $B \to \pi l^+l^-$ Limits

#### 90% Confidence Level Upper Limits

<table>
<thead>
<tr>
<th>Mode</th>
<th>NEW Belle</th>
<th>BABAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to \pi^+l^+l^-$</td>
<td>$&lt; 4.9 \times 10^{-8}$</td>
<td>$&lt; 12 \times 10^{-8}$</td>
</tr>
<tr>
<td>$B^0 \to \pi^0l^+l^-$</td>
<td>$&lt; 15.4 \times 10^{-8}$</td>
<td>$&lt; 12 \times 10^{-8}$</td>
</tr>
<tr>
<td>$B \to \pi l^+l^-$</td>
<td>$&lt; 6.2 \times 10^{-8}$</td>
<td>$&lt; 9.1 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

Belle - arXiv: 0804.3656  

For the $\pi^+$ mode, the experimental limit is close to SM level.

**Standard Model**

\[ B(B^+ \to \pi^+l^+l^-) = 3.3 \times 10^{-8} \]
\[ B(B^0 \to \pi^0l^+l^-) = 1.7 \times 10^{-8} \]
New BaBar $K^*\nu\bar{\nu}$ analysis: 413 fb$^{-1}$
- Reconstruct “tag” $B$ via $B \to D^{(*)}l^{\pm}\nu$
- Reconstruct $K^* (K^+\pi^-, K_S\pi^+, K^+\pi^0)$
- Extract signal via fit of $E_{extra}$

New BaBar $K\nu\bar{\nu}$ analysis: 319 fb$^{-1}$
- Reconstruct tag $B$ via $B \to D^{(*)}l^{\pm}\nu$
- Use a Random Forest algorithm to separate signal and background

$B \to K^{(*)}\nu\bar{\nu}$

$K^* \to K^+\pi^-$

$K^{*+} \to K_S\pi^+(K_S \to \pi^+\pi^-)$
**$B \to K^{(*)}\nu\bar{\nu}$ Limits**

**SM expectation:**

\[ B(B \to K^*\nu\bar{\nu}) = 1.3 \times 10^{-5} \]
\[ B(B \to K\nu\bar{\nu}) = 0.4 \times 10^{-5} \]

Buchalla et al., RPD 63, 014015 (2000)

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### 90% Confidence Level Upper Limits

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<tr>
<th>Mode</th>
<th><strong>Belle</strong></th>
<th><strong>BABAR</strong></th>
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<tr>
<td>$B^+ \to K^{*+}\nu\bar{\nu}$</td>
<td>$&lt; 14 \times 10^{-5}$</td>
<td>$&lt; 9 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B^0 \to K^{*0}\nu\bar{\nu}$</td>
<td>$&lt; 34 \times 10^{-5}$</td>
<td>$&lt; 21 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B \to K^+\nu\bar{\nu}$</td>
<td>$&lt; 1.4 \times 10^{-5}$</td>
<td>$&lt; 4.2 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B \to K^0\nu\bar{\nu}$</td>
<td>$&lt; 16 \times 10^{-5}$</td>
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Belle 492 fb$^{-1}$ - PRL 99, 221802 (2007)

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new prelim
$B^0 \rightarrow l^+l^-$ Status

Same diagrams as $b \rightarrow d l^+l^-$ in Standard Model
- $\mu$ and $e$ modes helicity suppressed
- possible large enhancement from non-SM scalar currents (e.g., MSSM); window for New Physics

<table>
<thead>
<tr>
<th>mode</th>
<th>SM</th>
<th>90% CL limits (Belle, BABAR)</th>
</tr>
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<tbody>
<tr>
<td>$\tau^+\tau^-$</td>
<td>$\approx 10^{-7}$</td>
<td>$&lt; 4.1 \times 10^{-3}$, PRL 96, 241802 (2006) 210 fb$^{-1}$</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>$\approx 10^{-10}$</td>
<td>$&lt; 1.6 \times 10^{-7}$, PRD 68, 111101 (2003) 78 fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$&lt; 5.2 \times 10^{-8}$, PRD 77, 032007 (2008) 347 fb$^{-1}$</td>
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<td>$&lt; 1.8 \times 10^{-8}$, CDF PRL 100, 101802 (2008)</td>
</tr>
<tr>
<td>$e^+e^-$</td>
<td>$\approx 10^{-15}$</td>
<td>$&lt; 1.9 \times 10^{-7}$, PRD 68, 111101 (2003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$&lt; 1.1 \times 10^{-7}$, PRD 77, 032007 (2008)</td>
</tr>
</tbody>
</table>
**B⁺ → ℓ⁺ν Status**

Depends on \( f_B |V_{ub}| \)
- with \( |V_{ub}| \) from \( b \rightarrow ul\nu \), measures \( f_B \)

\[
B(B^+ \rightarrow \ell^+\nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_{B^+}
\]

Enhancements possible (e.g., MSSM charged Higgs)

<table>
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<th>SM</th>
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</tr>
</thead>
<tbody>
<tr>
<td>( \tau^+\nu )</td>
<td>( \approx 10^{-4} )</td>
<td>See Matthew Barrett’s talk</td>
</tr>
</tbody>
</table>
| \( \mu^+\nu \) | \( \approx 5 \times 10^{-7} \) | \( < 1.6 \times 10^{-6} \), Phys.Lett. B 647, 67 (2007) 253 fb\(^{-1}\) \[
\]
|                          |       | \( < 6.6 \times 10^{-6} \), PRL 92, 221803 (2004) 81 fb\(^{-1}\) |
| \( e^+\nu \) | \( \approx 10^{-11} \) | \( < 9.8 \times 10^{-7} \), Phys.Lett. B 647, 67 (2007) |
Summary

- The B-factory experiments have made great progress in rare B-decay studies

- $b \rightarrow s l^+l^-$ decays are experimentally accessible and provide a rich menu of observables
  - ... but results so far are statistically limited
  - Asymmetry and angular measurements beginning to be important

- The significant isospin asymmetry observed at low-$q^2$ (by BaBar) is unexpected

- $A_{FB}$ measurements from both Belle and BaBar seem to favor the “flipped-sign” $C_7$ scenario and strongly disfavor a flipped-sign $C_9C_{10}$ scenario.

- Progress has been made toward SM-level in $B \rightarrow \pi l^+l^-$ and $B \rightarrow K^{(*)} \nu \bar{\nu}$