**Electroweak Penguin**

**B Decays:**

\[ b \rightarrow s,d \gamma \text{ and } b \rightarrow s,d \ell \ell \]

Penguins being inspected carefully for new physics.
b→s,d Penguin Operators

The general Hamiltonian of b→s transitions is given by:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu)]$$

- C7 “photon penguin”
- C8 “gluon penguin”
- C9 “Z penguin”
- C10 “W box”

C7’, C9’, C10’ = opposite helicity projection of C7, C9, C10

Plus:
CS, CP = scalar and pseudoscalar FCNCs (e.g. Higgs penguin)

In SM, “t-penguins” dominate b→s; u- and c-penguins non-negligible for b→s, b→d, s→d, etc. could all have different C_i from new physics
Inclusive $b \to s \gamma$ Rate

“Total Branching Fraction” → PBF at $E_\gamma$ (min) = 1.6 GeV
Requires (model-dependent) extrapolation of spectral shape

Excellent agreement with Standard Model predictions at 10% level
Constrains $|C7|^2 + |C7'|^2$

Theory uncertainty could improve to ~5%

Experimental uncertainty:
- Systematics limited from large background subtraction
- Could improve to 5% with 500-1000 fb$^{-1}$
Direct CP asymmetry generally constrained to < 5%
Isospin asymmetry precision ~5%
All measurements statistics limited for foreseeable future

First ever CP asymmetry measurement of $b \rightarrow (s+d)\gamma$
First ever isospin breaking measurement of $b \rightarrow s\gamma$

Optimal $b \rightarrow s\gamma$ asymmetries truncate photon spectrum. (For ACP, $E_\gamma > 2.1$ GeV)
Does this spoil SM comparison?
$b \rightarrow d \gamma$ Branching Fractions

\[ \bar{B}[B \rightarrow (\rho, \omega) \gamma] = \frac{1}{2} \left\{ \mathcal{B}(B^+ \rightarrow \rho^+ \gamma) + \frac{\tau_{B^+}}{\tau_{B^0}} \left[ \mathcal{B}(B^0_d \rightarrow \rho^0 \gamma) + \mathcal{B}(B^0_d \rightarrow \omega \gamma) \right] \right\} \]

Central value

90% C.L. upper limit

Combined significance
Belle+BaBar = 2.6 $\sigma$

5$\sigma$ observation expected for 1 ab$^{-1}$/experiment
B → ργ CKM Impact

\[
\frac{\overline{B}[B \to (\rho/\omega)\gamma]}{B(B \to K^*\gamma)} = \left| \frac{V_{td}}{V_{ts}} \right|^2 \left( \frac{1 - m_\rho^2/M_B^2}{1 - m_{K^*}^2/M_B^2} \right)^3 \zeta^2 [1 + \Delta R]
\]

For \( \rho^0\gamma \), \( \Delta R \) is negligible and form factor ratio \( \zeta^2 \sim 1.2 \pm 0.1 \)

What, if anything, can be done to improve the estimate of the form factor ratio \( (B \to \rho/B \to K^*) \)?

Until Bs mixing is observed, this will be the most experimentally precise estimator of \( V_{td}/V_{ts} \)

Taken at face value, an intriguingly low \( |V_{td}/V_{ts}| \) is inferred.
The Physics of $b \to s \ell \ell$

3 separate penguin diagrams, 3 body decay has non-trivial kinematic distributions

- $C_7$: photon penguin from $b \to s \gamma$
- $C_9$: (mostly) Z penguin
- $C_{10}$: (mostly) W box unique to $b \to s \ell \ell$

Also sensitive to $C_{i'}$, CS, CP

$$\mathcal{M}(b \to s \ell^+ \ell^-) = \frac{G_F \alpha}{\sqrt{2\pi}} V_{ts}^* V_{tb} \left\{ C_9^{\text{eff}} [\bar{s} \gamma_\mu L b] [\bar{\ell} \gamma^\mu \ell] + C_{10} [\bar{s} \gamma_\mu L b] [\bar{\ell} \gamma^\mu \gamma_5 \ell] \right\}$$

$$-2\hat{m}_b C_7^{\text{eff}} \left[ \bar{s} i \sigma_{\mu\nu} \frac{\hat{q}'}{\hat{s}} R b \right] \left[ \bar{\ell} \gamma^\mu \ell \right]$$

$BF(b \to s \mu \mu) = 4.2 \pm 0.7 \times 10^{-6}$

15% uncertainty in inclusive rate
Pole at $q^2 \approx 0$ for $K^{*}ee$ (nearly on-shell $B \rightarrow K^{*}\gamma$)

$$\frac{\mathcal{B}(B \rightarrow K^{*}e^{+}e^{-})}{\mathcal{B}(B \rightarrow K^{*}\mu^{+}\mu^{-})} = 1.33$$

Huge long-distance contribution from $B \rightarrow$ charmonium decays

What $q^2$ range is insensitive to long distance contributions, LD-SD interference??

C9, C10 dominant at high $s$, C7 dominant at low $s$, sign of C7 matters

Generally decreases with $s$
**Inclusive $b \rightarrow s \ell \ell$ Rate**

Agreement with Standard Model predictions at 10% level
Total rate constrains $|C9|^2 + |C10|^2$

Other observables:
- Partial rate vs. $q^2$
- AFB
- ACP
- ACP in AFB

Sums over exclusive final states $K(Ks) + n\pi + \ell\ell$
- Cuts on $M(Xs)$ to suppress $B$ backgrounds
  \[ M(Xs) < 2 \text{ GeV}. \] 
  Does this spoil the inclusive predictions??

$70 \pm 14$ events in $140 \text{ fb}^{-1}$ (Belle)
**B → K(*)ll Total Rates**

BaBar and Belle branching fractions agree with SM predictions. Experimental uncertainty already better than theory. Difference between BaBar and Belle becoming significant?

\[ \text{difference} = 2.6\sigma \]

\[ \text{difference} = 1.9\sigma \]

Smallest B branching fractions ever measured:

- 45±12 K*ll events in 208 fb\(^{-1}\) above photon pole (BaBar)
- 79±11 K*ll events in 253 fb\(^{-1}\) Above photon pole (Belle)
b → sμμ = B_s → μμ turned sideways

Sensitive to “neutral Higgs penguin” for SUSY with large tan β, scalar penguins CS, CP

Ratio \( R(K) = \frac{BF(B \to K\mu\mu)}{BF(B \to K\text{ee})} \)
isolates Yukawa enhancement in muon mode

In SM, equal to unity with very high precision

Also contributes to \( R(K^*) \)
(=1 above the photon pole)

(My BaBar + Belle) average
RK < 1.85 90%CL

Complementary to Tevatron \( B_s \to \mu\mu \) limit,
but \( B_s \to \mu\mu \) will be the bellwether for foreseeable future

Hiller & Kruger hep-ph/0310219
Angular asymmetry of lepton (anti-lepton) angle with B (anti-B) momentum in dilepton rest frame

Varies with dilepton q²

Theoretically clean(??) probe of relative size and phase of C₇/C₉/C₁₀

What is form factor uncertainty of A_{FB}??

Can be dramatically modified by new physics

Zero of A_{FB} provides simple, precise (15%) relation between C₇ and C₉ (for LHCb/SuperB)
Raw AFB appears to have SM sign for C10*Re(C9) at high q^2
Need quantitative, efficiency corrected measurement
**B → K*±±± - AFB at Future Experiments**

\[ \hat{s} = \left( m_{\mu\mu}/m_B \right)^2 \]

LHCb: 4400 K*⁰ μμ events/year, S/B > 0.4

\( A_{FB}(\hat{s}) \) reconstructed using toy MC
(two years data, background subtracted)
Zero point located to ±0.04

ATLAS: 2000 events, S/B = 7 (30 fb⁻¹)

\(^{\text{C}_9, \text{C}_{10} \text{ q}^2 \text{ independent terms}} \)
can be determined with accuracies of 11\% and 13\%, respectively at 5 ab⁻¹.

\( \Delta q_0 \sim 11\% \)

\( s_0 \) can be measured with an accuracy of 5\% at 50 ab⁻¹.

What range of q² has comparable theory error?
We know from $B \to VV$ studies that triple diff. Dist. of all three angles ($\theta(l)$, $\theta(K^*)$, $\phi$) is useful

Kruger&Matias (hep-ph/0502060) predicted features of this distribution integrated over low $q^2$ region $< 6 \text{ GeV}^2$
### b→ dll decays

SM rate for B → πll (few 10^{-8}) may eventually be observable at B factories

- Expected yields in 200 fb^{-1}

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>Background</th>
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</thead>
<tbody>
<tr>
<td>B → πll</td>
<td>2.0</td>
<td>4.8</td>
</tr>
<tr>
<td>B → ρll</td>
<td>1.5</td>
<td>141.2</td>
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- With no improvements to the analysis, estimated ~2σ significance for B → πll with luminosity of 1 ab^{-1} and the assumed BF

- B → πll looks feasible (with enough data)

- B → ρll may require significantly more work to reduce backgrounds
  - Does the B → ρll branching fraction tell us anything B → πll does not?
Summary

\( b \rightarrow s \gamma \) penguin decays:
- precision constraints on C7, C7'
- rates are systematics limited
- asymmetries are statistics limited and theoretically precise

\( b \rightarrow d \gamma \) penguin decays:
- nearing observation of exclusive decays
- improved theory precision would have a big impact on CKM constraints

\( b \rightarrow s \lll \) penguin decays:
- total rates: exp. error comparable to theory error
- rich set of new constraints on penguin operators emerging from partial rates
- angular asymmetries (lepton angle and possibly K* polarization?)
- e/\( \mu \) rate asymmetries

\( b \rightarrow d \lll \) penguin decays:
- \( B \rightarrow \pi \lll \) may eventually be observable by B factories