Rare Decays at B Factories

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Luminosity at the B Factories

On-resonance samples:
- $4S$: 711 fb\(^{-1}\)
- $5S$: 121 fb\(^{-1}\)
- $3S$: 3.0 fb\(^{-1}\)
- $2S$: 24 fb\(^{-1}\)
- $1S$: 5.7 fb\(^{-1}\)

Off-resonance: 87 fb\(^{-1}\)

PEP-II for BaBar

On-resonance samples:
- $4S$: 433 fb\(^{-1}\)
- $3S$: 30 fb\(^{-1}\)
- $2S$: 14 fb\(^{-1}\)

Off-resonance: 54 fb\(^{-1}\)

KEKB for Belle

~770 M BB

~470 M BB
Rare Decays, Loops and Penguins

• Flavor changing neutral current (FCNC) processes are forbidden at tree level → loops make them sensitive to potential contributions from new physics.
  – Radiative penguins, e.g., $b \to s\gamma$:
  
  – Electroweak penguins or box diagrams, e.g., $b \to s\ell\ell, b \to s\nu\overline{\nu}$:
  
  – Hadronic penguins, e.g., $b \to sg$:
Outline

• Radiative penguins: $b \rightarrow s\gamma$
  – Exclusive:
    • $B \rightarrow K\eta^{(l)}\gamma$
    • $B \rightarrow K\phi\gamma$
    • $B \rightarrow K^*\gamma$
  – Inclusive

• Electroweak penguins: $b \rightarrow s\ell^+\ell^-, b \rightarrow s\nu\bar{\nu}$
  – Exclusive:
    • $B \rightarrow K^{(*)}\ell\ell$
    • $B \rightarrow K\nu\bar{\nu}$
  – Inclusive

• Hadronic penguins: $b \rightarrow sg, b \rightarrow sq\bar{q}$
  – Exclusive:
    • $B \rightarrow \eta^{(l)}K^{(*)}$
    • $B \rightarrow \eta'\rho$
    • $B \rightarrow \eta'f_0$
  – Inclusive: $B \rightarrow X_s\eta^{(l)}$
Radiative Penguins: $b \rightarrow s\gamma$

- Extensions of the Standard Model can have particles that contribute in the loops...

- Search for beyond SM contributions in:
  - Branching fractions
    - Inclusive measurements $\Rightarrow$ more experimental uncertainty, smaller theoretical uncertainties.
    - Exclusive measurements $\Rightarrow$ smaller experimental uncertainty, larger theoretical uncertainties (hadronic uncertainties).
  - CP asymmetries
  - Isospin asymmetries
Exclusive $B \rightarrow K^*(892)\gamma$

383M BB
PRL 103, 211802 (2009)

- Branching fractions:
  \[ B(B^0 \rightarrow K^{*0}\gamma) = (4.47 \pm 0.10 \pm 0.16) \times 10^{-5} \]
  \[ B(B^+ \rightarrow K^{*+}\gamma) = (4.22 \pm 0.14 \pm 0.16) \times 10^{-5} \]

- CP asymmetry:
  \[ \mathcal{A} = \frac{\Gamma(\bar{B} \rightarrow K^{*}\gamma) - \Gamma(B \rightarrow K^{*}\gamma)}{\Gamma(\bar{B} \rightarrow K^{*}\gamma) + \Gamma(B \rightarrow K^{*}\gamma)} \]

  Measured:
  \[ \mathcal{A} = -0.003 \pm 0.017 \pm 0.007 \]
  \[ -0.033 < \mathcal{A} < 0.028 \quad (90\% \text{ CL}) \]

- Isospin asymmetry:
  \[ \Delta_{0-} = \frac{\Gamma(\bar{B}^0 \rightarrow K^{*0}\gamma) - \Gamma(B^- \rightarrow K^{*-}\gamma)}{\Gamma(\bar{B}^0 \rightarrow K^{*0}\gamma) + \Gamma(B^- \rightarrow K^{*-}\gamma)} \]

  Measured:
  \[ \Delta_{0-} = 0.066 \pm 0.021 \pm 0.022 \]
  \[ 0.017 < \Delta_{0-} < 0.116 \quad (90\% \text{ CL}) \]
In SM, photon polarizations in $b \rightarrow s\gamma$ depend on $b$ flavor:

- Presence of mixing-induced CP violation would indicate the presence of right handed currents and clear hints of new physics.
  - This type of new physics does not require a new phase.
Exclusive $B \to K\eta\gamma$

$\mathcal{B}(B^+ \to \eta K^+\gamma) = (7.7 \pm 1.0 \pm 0.4) \times 10^{-6}$

$A_{CP} = (-9.0^{+10.4}_{-9.8} \pm 1.4) \times 10^{-2}$

$\mathcal{B}(B^0 \to \eta K^0\gamma) = (7.1^{+2.1}_{-2.0} \pm 0.4) \times 10^{-6}$

First time dependent CPV search in this mode:

$S = -0.18^{+0.49}_{-0.46} \pm 0.12$

$C = -0.32^{+0.40}_{-0.39} \pm 0.07$

Similar mode, $B^0 \to K^0_S \rho^0 \gamma$ measured at Belle w/ 657 M BB [PRL 101, 251601 (2008)]:

$S(B^0 \to K^0_S \rho^0 \gamma) = 0.11 \pm 0.33^{+0.05}_{-0.09}$

$C(B^0 \to K^0_S \rho^0 \gamma) = -0.05 \pm 0.18 \pm 0.06$

In both cases, analyses need improved statistics. Potentially promising for Super B factories!
Exclusive $B \rightarrow K\eta'\gamma$, $B \rightarrow K\phi\gamma$

$B \rightarrow K\eta'\gamma$

657M BB
arXiv: 0810.0804, Submitted to PRD(RC)

$B(B^0 \rightarrow K^0\eta'\gamma) \leq 6.4 \times 10^{-6}$ (90% CL)

$B(B^+ \rightarrow K^+\eta'\gamma) = (3.6 \pm 1.2 \pm 0.4) \times 10^{-6}$

First evidence w/ 3.3$\sigma$ significance

$B \rightarrow K\phi\gamma$

772M BB
Preliminary, arXiv: 0911.1779

$B(B^+ \rightarrow \phi K^+\gamma) = (2.34 \pm 0.29 \pm 0.23) \times 10^{-6}$

$B(B^0 \rightarrow \phi K^0\gamma) = (2.66 \pm 0.60 \pm 0.32) \times 10^{-6}$

First observation w/ 5.4$\sigma$ significance

Time dependent analysis ongoing...
Inclusive $b \to s\gamma$

- Fully inclusive measurement (only the $\gamma$ w/ $E_{\text{CM}} > 1.4$ GeV is reconstructed):
  - Divided into two streams:
    - MAIN - without lepton tag
    - LT – w/ lepton tag, reduces $qq$ background
  - A data sample of 68 fb$^{-1}$ taken below $\gamma(4S)$ is used to subtract $e^+e^-$ → $qq$ backgrounds from 605 fb$^{-1}$ on-resonance sample.

Left: photon energy distributions in data for on resonance, off resonance, and continuum subtracted samples.

Right: photon energy signal / background distributions. $\pi^0$ and $\eta$ backgrounds dominate.
Inclusive $b \to s\gamma$

: control regions (no yield expected)

• Untagged and tagged spectra are combined:
  – Corrected for selection efficiency.
  – Including statistical correlations between tagged/untagged spectra.

\[ \mathcal{B}(B \to X_s\gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4} \]

1.7 GeV < $E_\gamma$ < 2.8 GeV

657M BB
PRL 103, 241801 (2009)
Inclusive $b \rightarrow s\gamma$

$\mathcal{B}(B \rightarrow X_s\gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$

$1.7 \text{ GeV} < E_\gamma < 2.8 \text{ GeV}$

Consistent with NNLO SM calculations [Misiak et al., PRL 98, 022002 (2007)]:

$\mathcal{B}_{SM}(B \rightarrow X_s\gamma; E_\gamma > 1.6\text{GeV}) = (3.15 \pm 0.23) \times 10^{-4}$
\[ b \to s\gamma \] measurements can place strong constraints on some NP models: e.g., type II two-Higgs doublet models (THDM) [Ulrich Haisch, arXiv:0805.2141]
Electroweak Penguins \( b \rightarrow s\ell\ell, b \rightarrow s\nu\bar{\nu} \)

- **Observables:**
  - Branching fractions
    - Large theoretical form factor uncertainties
  - Longitudinal polarization fraction \((F_L)\)
    \[
    \frac{d\Gamma}{d\cos\theta_{K^*}} = \frac{3}{2} F_L \cos^2 \theta_{K^*} + \frac{3}{4} (1 - F_L)(\sin^2 \theta_{K^*})
    \]
  - Forward backward asymmetry \((A_{FB})\)
    \[
    \frac{d\Gamma}{d\cos\theta_{B\ell}} = \frac{3}{4} F_L \sin^2 \theta_{B\ell} + \frac{3}{8} (1 - F_L)(1 + \cos^2 \theta_{B\ell}) + A_{FB} \cos \theta_{B\ell}
    \]
Branching Fractions for $B \rightarrow K^{(*)} \ell \ell$

**657M BB** PRL 103, 171801 (2009)

$B(B \rightarrow K^* \ell^+\ell^-) = (10.7^{+1.1}_{-1.0} \pm 0.9) \times 10^{-7}$

$B(B \rightarrow K\ell^+\ell^-) = (4.8^{+0.5}_{-0.4} \pm 0.3) \times 10^{-7}$

**383M BB** PR D73, 092001 (2009)

$B(B \rightarrow K^* \ell^+\ell^-) = (7.8^{+1.9}_{-1.7} \pm 1.1) \times 10^{-7}$

$B(B \rightarrow K\ell^+\ell^-) = (3.4 \pm 0.7 \pm 0.2) \times 10^{-7}$

Lines are SM predictions w/ various form factor models.

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$B(B \rightarrow K^* \ell^+\ell^-)$

$B(B \rightarrow K\ell^+\ell^-)$

$B(B \rightarrow K^* \ell^+\ell^-)$

$B(B \rightarrow K\ell^+\ell^-)$
**$F_L$, and $A_{FB}$ for $B \rightarrow K^* \ell \ell$**

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

\[
\frac{d\Gamma}{d\cos \theta_{B\ell}} = \frac{3}{4} F_L \sin^2 \theta_{B\ell} + \frac{3}{8} (1 - F_L) (1 + \cos^2 \theta_{B\ell}) + A_{FB} \cos \theta_{B\ell}
\]

*Wrong sign $C_7$??*

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**657M BB**

PRL 103, 171801 (2009)

**383M BB**

PR D79, 031102 (2009)

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- **J/ψ ($\psi'$) veto regions**
- **SM expectation ($C_7 = C_7^{SM}$)**
- **Sign-flipped $C_7$ ($C_7 = -C_7^{SM}$)**

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Mar. 3 2010 - La Thuile  
K. Nishimura - Rare Decays at B Factories
Inclusive $B \rightarrow X_s \ell \ell$

- Opposite sign $c_7$ would enhance branching fraction of $B \rightarrow X_s \ell \ell$
  - Modest form factor uncertainties relative to $K^{(*)} \ell \ell$
  - Belle update with sum-of-exclusive technique,

$X_s = K + n\pi$, $n = 0-4$

657M BB Preliminary

$M_{X_s} < 2$ GeV $10\sigma$ significance

1 GeV $< M_{X_s} < 2$ GeV $3\sigma$ significance

Large backgrounds:

Combinatorial from continuum & semileptonic B decays

Leakage after $J/\psi$ and $\psi'$ vetoes, mis-id in $X_s \pi^+ \pi^-$, other $\psi$ states, $X_s \ell \ell$

Mar. 3 2010 - La Thuile
Branching Fraction for $B \to X_s \ell \ell$

$B(B \to X_s \ell \ell) = (3.33 \pm 0.80^{+0.19}_{-0.24}) \times 10^{-6}$

*Total branching fraction is for $q^2 > 0.2 (\text{GeV/c}^2)^2$ & extrapolated to entire $M_{X_s}$ region


$B_{SM}(B \to X_s \ell \ell) = (4.2 \pm 0.7) \times 10^{-6}$

No enhancement $\Rightarrow$ opposite sign $C_7$ is not favored by the inclusive measurement.
Searches for $B \rightarrow K \nu \overline{\nu}$

- Previous best upper limits (90% CL):
  - BaBar, semileptonic tagging:
    \[ B(B^+ \rightarrow K^+ \nu \overline{\nu}) < 4.5 \times 10^{-5} \]
  - Belle, using full hadronic reconstruction of one B:
    \[ B(B^+ \rightarrow K^+ \nu \overline{\nu}) < 1.4 \times 10^{-5} \]
    \[ B(B^0 \rightarrow K^0 \nu \overline{\nu}) < 16 \times 10^{-5} \]
New BaBar $B \rightarrow K \nu \bar{\nu}$ w/ semileptonic tagging

- Method:
  - Tag one B using $D(\ast) \ell \nu$ ($\sim 1\%$ efficiency)
  - Look for a lone K ($K_s$ plots shown, $K^+$ in backup)
  - Multivariate technique (bagged decision tree) to select events

$B \rightarrow K \nu \bar{\nu}$, 90% CL

$B^+ \rightarrow K^+ \nu \bar{\nu} < 1.3 \times 10^{-5}$
$B^0 \rightarrow K^0 \nu \bar{\nu} < 5.6 \times 10^{-5}$


$$B(B \rightarrow K \nu \bar{\nu}) = (3.8^{+1.2}_{-0.6}) \times 10^{-6}$$
Hadronic Penguins

- Final states with $\eta$ and $\eta'$ particularly interesting:
  - Interference patterns in dominant amplitudes
  - Sensitive to flavor singlet contributions
- Branching fractions:
  - A history of unexpected or unexpectedly large signals
Exclusive \[ B \rightarrow \eta'(\rho, f_0, K^*(892), K^*(1430)) \]

Observation of \[ \eta'^+ \rho^+ \], \[ \eta'^+ K^*_2(1430)^{(0,+)} \] ! Evidence for \[ \eta'^+ K^*(0,+)^* \] !
Exclusive $B \rightarrow \eta'(\rho, f_0, K^*(892), K^*(1430))$

**BaBar Preliminary**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$Y$ (events)</th>
<th>$Y_0$ (events)</th>
<th>$\epsilon$ (%)</th>
<th>$\prod B_s$ (%)</th>
<th>$S$ (σ)</th>
<th>$B$ (10$^{-6}$)</th>
<th>$B$ U.L. (10$^{-6}$)</th>
<th>$A_{\text{ch}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta'\rho^0$</td>
<td>37±15</td>
<td>9±5</td>
<td>23.4</td>
<td>17.5</td>
<td>2.0</td>
<td>1.5±0.8±0.3</td>
<td>2.8</td>
<td>–</td>
</tr>
<tr>
<td>$\eta'f_0$</td>
<td>8±8</td>
<td>4±2</td>
<td>25.9</td>
<td>17.5</td>
<td>0.5</td>
<td>0.2$^{+0.4}_{-0.3}$±0.1</td>
<td>0.9</td>
<td>–</td>
</tr>
<tr>
<td>$\eta'\rho^+$</td>
<td>128±22</td>
<td>15±8</td>
<td>14.3</td>
<td>17.5</td>
<td>5.8</td>
<td>9.7$^{+1.9}_{-1.8}$±1.1</td>
<td>–</td>
<td>0.26±0.17±0.02</td>
</tr>
<tr>
<td>$\eta'K^0$</td>
<td>–</td>
<td>4.0</td>
<td>3.1$^{+0.9}_{-0.8}$±0.3</td>
<td>4.4</td>
<td>0.02±0.23±0.02</td>
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<tr>
<td>$\eta'K^+$</td>
<td>–</td>
<td>3.8</td>
<td>4.8$^{+1.6}_{-1.4}$±0.8</td>
<td>7.2</td>
<td>–0.26±0.27±0.02</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$\eta'(K\pi)^0$</td>
<td>3.8</td>
<td>5.6</td>
<td>7.4$^{+1.5}_{-1.4}$±0.6</td>
<td>–</td>
<td>−0.19±0.17±0.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta'(K\pi)^+$</td>
<td>–</td>
<td>2.9</td>
<td>6.0$^{+2.2}_{-2.0}$±0.9</td>
<td>9.3</td>
<td>0.06±0.20±0.02</td>
<td></td>
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</tr>
<tr>
<td>$\eta'K_2^*(1430)^0$</td>
<td>5.3</td>
<td>5.3</td>
<td>13.7$^{+8.0}_{-5.9}$±1.2</td>
<td>–</td>
<td>0.14±0.18±0.02</td>
<td></td>
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</tr>
<tr>
<td>$\eta'K_2^*(1430)^+$</td>
<td>7.2</td>
<td>7.2</td>
<td>28.0$^{+4.6}_{-4.3}$±2.6</td>
<td>–</td>
<td>0.15±0.13±0.02</td>
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</tr>
</tbody>
</table>

- No significant direct CP asymmetry in any modes.
- Results for $\eta'\rho^+$ generally favor pQCD and QCDF predictions over SCET
- **Unexpected enhancements** of $K_2^*(1430)$ over $K^*(892)$
Inclusive $B \rightarrow X_s \eta$

- Sum of exclusive modes: $B \rightarrow X_s \eta \ (p^{cm}_\eta > 2.0 \text{ GeV}/c)$

$B \rightarrow X_s \eta (p^{cm}_\eta > 2.0 \text{ GeV}/c) \rightarrow \gamma \gamma \rightarrow K n \pi (n \leq 4, n_{\pi^0} \leq 1)$

Belle Preliminary

Signal yield ($M_{X_s} > 1.0 \text{ GeV}/c^2$) = $749 \pm 48 \pm 7$

$17.6\sigma$ statistical significance
**B → X_s η Branching Fraction**

**Belle partial branching fraction for X_s mass range 0.4 – 2.6 GeV/c^2:**

\[
\mathcal{B}(B \rightarrow X_s \eta)^* = (25.5 \pm 2.7\text{ (stat)} \pm 1.6\text{ (sys)}^{+3.8}_{-14.1}\text{ (model)}) \times 10^{-5}
\]

*assuming JETSET hadronization.

Signals beyond the known K*(892,1430) contributions in both Xs η and Xs η' modes

657M BB
Preliminary, arXiv: 0910.4751

**PDG average for B(B → X_s η')**

\[
(42.0 \pm 9.0) \times 10^{-5}
\]

**B → X_s η', QCD anomaly?**

BaBar (2004)
Conclusion

• Rare B decays provide a valuable tool to test Standard Model predictions.
• Both Belle and BaBar have accumulated a large set of data with which to study these decays…
  – We can look forward to many final results using the entirety of the Belle and BaBar data sets…
  – …but many modes require significantly improved statistics:
    • Super B factories may reveal and elucidate the nature of new physics!
      ➔ More on SuperKEKB in Bostjan’s talk on Friday.
B$\to$K(*)$\ell\ell$: Isospin Asymmetry

$$A_I \equiv \frac{\tau_{B^+}/\tau_{B^0} \times B(K^{(*)0} \ell^+\ell^-) - B(K^{(*)\pm} \ell^+\ell^-)}{\tau_{B^+}/\tau_{B^0} \times B(K^{(*)0} \ell^+\ell^-) + B(K^{(*)\pm} \ell^+\ell^-)}$$

$q^2 < 8.68 \text{ GeV}^2/c^2$

- $A_I(K^* \ell\ell) = -0.29^{+0.16}_{-0.16} \pm 0.03 \quad 1.40\sigma$
- $A_I(K \ell\ell) = -0.31^{+0.17}_{-0.14} \pm 0.05 \quad 1.75\sigma$
- $A_I(K^{(*)} \ell\ell) = -0.30^{+0.12}_{-0.11} \pm 0.04 \quad 2.24\sigma$

$q^2 = 0.1 - 7.02 \text{ GeV}^2/c^2$

- $A_I(K^* \ell\ell) = -0.56^{+0.17}_{-0.15} \pm 0.03 \quad 2.7\sigma$
- $A_I(K \ell\ell) = -1.43^{+0.56}_{-0.85} \pm 0.05 \quad 3.2\sigma$
- $A_I(K^{(*)} \ell\ell) = -0.64^{+0.15}_{-0.14} \pm 0.03 \quad 3.9\sigma$

A$_I$ deviates from zero at low-q$^2$?

*Slide from T. Iijima, Lepton-Photon 2009*
Branching fraction and lepton flavor ratio

- $\mathcal{B} \sim 10^{-6}$ or less
  also measured by CDF
  (CDF PRD79,011104(2009), 924 pb$^{-1}$)

- Differential BF
  sensitive to Wilson coefficients
  (but suffer from form-factor uncertainty)

- Lepton flavor ratio: sensitive to SUSY neutral Higgs at large $\tan \beta$

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

<table>
<thead>
<tr>
<th></th>
<th>Belle</th>
<th>BaBar</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_K$</td>
<td>$1.03 \pm 0.19 \pm 0.06$</td>
<td>$0.96^{+0.44}_{-0.34} \pm 0.05$</td>
</tr>
<tr>
<td>$R_{K^*}$</td>
<td>$0.83 \pm 0.17 \pm 0.05$</td>
<td>$1.10^{+0.42}_{-0.32} \pm 0.07$</td>
</tr>
</tbody>
</table>

($R_{K^*}^{SM} = 0.75$ due to photon pole)

Inclusive $B \to X_s \ell^+\ell^-$ are yet to be updated
(Last results were 152 M (Belle) / 88 M (BaBar))
CDF $B \rightarrow K^{(*)}\ell^+\ell^-$ (924 pb$^{-1}$)
CDF Collaboration, T. Aaltonen et al., PRD 79, 011104 (2009)

\[ B(B^+ \rightarrow K^+\mu^+\mu^-) = (5.9 \pm 1.5 \pm 0.4) \times 10^{-7} \]
\[ B(B^0 \rightarrow K^{*0}\mu^+\mu^-) = (8.1 \pm 3.0 \pm 1.0) \times 10^{-7} \]
\[ \frac{B(B_s^0 \rightarrow \phi\mu^+\mu^-)}{B(B \rightarrow J/\psi\phi)} < 2.6 (2.3) \times 10^{-3} (95(90)\% \text{ CL}) \]
$B \rightarrow K^* \ell^+ \ell^-$ and Wilson coefficients

- Forward-backward asymmetry ($A_{FB}$) and Wilson coefficients

\[ A_{FB}(q^2) = -C_{10}^{\text{eff}} \xi(q^2) \left[ \text{Re}(C_9^{\text{eff}})F_1 + \frac{1}{q^2} C_7^{\text{eff}} F_2 \right] \]  

(similar to $\gamma-Z$ interference at high energy)

- Wilson coefficients to identify type of new physics

| $C_7$  | for magnetic penguin operator $[\frac{e}{8\pi^2} m_b \bar{s}_i \sigma^{\mu\nu}(1 + \gamma_5) b_i F_{\mu\nu}]$  
|        | (size is determined from $b \rightarrow s\gamma$, but sign is from $b \rightarrow s\ell^+\ell^-$)  
| $C_9$  | for vector electroweak operator $[(\bar{b}s)_{V-A}(\bar{\ell}\ell)_V]$  
| $C_{10}$ | for axial-vector electroweak operator $[(\bar{b}s)_{V-A}(\bar{\ell}\ell)_A]$  

- Angular distributions to extract FB asymmetries

$K^*$ longitudinal polarization $F_L$ from kaon angle $\theta_K$

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

Forward-backward asymmetry $A_{FB}$ from lepton angle $\theta_\ell$

\[ \frac{3}{4} F_L (1 - \cos^2 \theta_\ell) + \frac{3}{8} (1 - F_L) (1 + \cos^2 \theta_\ell) + A_{FB} \cos \theta_\ell \]
$B \rightarrow X_s \ell^+ \ell^-$ and Wilson coefficients

\[
\frac{d\Gamma(b \rightarrow s \ell^+ \ell^-)}{dq^2} = \left( \frac{\alpha_{\text{em}}}{4\pi} \right)^2 \frac{G_F^2 m_b^5 |V_{ts}^* V_{tb}|^2}{48 \pi^3} (1 - q^2)^2 \\
\times \left[ (1 + 2q^2) \left( |C_9^{\text{eff}}|^2 + |C_{10}^{\text{eff}}|^2 \right) + 4 \left( 1 + \frac{2}{q^2} \right) |C_7^{\text{eff}}|^2 + 12 \text{Re} \left( C_7^{\text{eff}} C_9^{\text{eff}} \right) \right] + \text{corr.}
\]

- Inclusive differential branching fraction is sensitive to Wilson coefficients (no form factor uncertainties of $B \rightarrow K^* \ell^+ \ell^-$)

- **Opposite-sign $C_7$ makes the branching fraction larger** (in SM, $C_7 < 0$ and $C_9 > 0$)

- Fully inclusive measurement is not feasible so far, sum-of-exclusive technique has been used by Belle/BaBar
New BaBar $B \to K \nu \bar{\nu}$ w/ semileptonic tagging

- Method:
  - Tag one $B$ using $D^{(*)} \ell \nu$ (~1% efficiency)
  - Look for a lone $K$
  - Multivariate technique (bagged decision tree) to select events


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

$\mathcal{B}(B^0 \to K^0 \nu \bar{\nu}) < 5.6 \times 10^{-5}$

SM Prediction:
[Buchalla, PRD 63, 014015 (2001)]:

$\mathcal{B}(B \to K \nu \bar{\nu}) = (3.8^{+1.2}_{-0.6}) \times 10^{-6}$
Upper limits on $B \rightarrow K\nu\bar{\nu}$

Decision tree outputs in signal region:

<table>
<thead>
<tr>
<th>CL</th>
<th>$K^+$</th>
<th>$K^0$</th>
<th>$K^+ &amp; K^0$ For $p^* (K^+)&lt;1.5 \text{ GeV/c}$</th>
<th>$K^+ &amp; K^0$ For $p^* (K^+)&gt;1.5 \text{ GeV/c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>90%</td>
<td>$1.3 \times 10^{-5}$</td>
<td>$5.6 \times 10^{-5}$</td>
<td>$1.4 \times 10^{-5}$</td>
<td>$3.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>95%</td>
<td>$1.6 \times 10^{-5}$</td>
<td>$6.7 \times 10^{-5}$</td>
<td>$1.7 \times 10^{-5}$</td>
<td>$4.6 \times 10^{-5}$</td>
</tr>
</tbody>
</table>


$$B(B \rightarrow K\nu\bar{\nu}) = \left(3.8^{+1.2}_{-0.6}\right) \times 10^{-6}$$
Modes including $\eta$, $\eta'$

- $\text{Br}(\eta'K) \gg \text{Br}(\eta K)$
  -- a long-standing issue
- $A_{CP}(\eta K) > A_{CP}(\eta'K)$?
- Input to SU(3)-based calculation for $\Delta S = S_{\bar{c}c\bar{s}s} - S_{\eta'K, \phi K}$

BaBar: 467 M BB

- $A_{CP}(B^+ \to \eta K^+) = -0.36 \pm 0.11 \pm 0.03$
- Evidence for three decay modes.
  $\text{Br}(B^0 \to \eta K^0) = (1.15^{+0.43}_{-0.38} \pm 0.09) \times 10^{-6}$
  $\text{Br}(B^0 \to \eta \omega) = (0.94^{+0.35}_{-0.30} \pm 0.19) \times 10^{-6}$
  $\text{Br}(B^0 \to \eta' \omega) = (1.01^{+0.46}_{-0.38} \pm 0.09) \times 10^{-6}$

*Slide from T. Iijima, Lepton-Photon 2009*
\[ B^- \rightarrow \ell^- \bar{\nu} \]

- Within SM, proceed via W annihilation.

\[ \mathcal{B}(B^- \rightarrow \ell^- \bar{\nu}) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left( 1 - \frac{m_\ell^2}{m_B^2} \right)^2 f_B^2 |V_{ub}|^2 \tau_B \]

**Helicity suppression**

\[ Br(B \rightarrow e \nu) \ll Br(B \rightarrow \mu \nu) \ll Br(B \rightarrow \tau \nu) \]

\[ \sim 10^{-11} \ll \sim 10^{-7} \]

**Determination of \( f_B |V_{ub}| \)**

\[ f_B = 190 \pm 13 \text{ MeV} \quad \text{HPQCD, 0902.1815v2} \]

\[ |V_{ub}| = (4.32 \pm 0.16 \pm 0.29) \times 10^{-3} \quad \text{HFAG ICHEP08} \]

\[ Br_{SM}(\tau \nu) = (1.20 \pm 0.25) \times 10^{-4} \]

Sensitive also to NP (charged Higgs)

*Slide from T. Iijima, Lepton-Photon 2009*
### B\(^-\) → τ \(\bar{\nu}\)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Hadronic tag (MBB)</th>
<th>Semileptonic tag (MBB)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Belle</strong></td>
<td>1.79 ±0.56 ±0.46 -0.49 -0.51</td>
<td>1.65 ±0.38 ±0.35 -0.37 -0.37</td>
</tr>
<tr>
<td><strong>BaBar</strong></td>
<td>1.8 ±0.9 ±0.4 (bkg) ±0.2 (other)</td>
<td>1.8 ±0.8 ±0.1</td>
</tr>
</tbody>
</table>

*Slide from T. Iijima, Lepton-Photon 2009*
**Constraint on Charged Higgs**

Naïve world average

\[ \text{Br}(\tau\nu) = [1.73 \pm 0.35] \times 10^{-4} \]

**Effect of Charged Higgs**


\[ \text{Br} = \text{Br}_{SM} \times r_H \]

\[ r_H = \left( 1 - \frac{m_B^2 \tan \beta^2}{m_H^2} \frac{1}{1 + \varepsilon_0 \tan \beta} \right)^2 \]

\[ \tan \beta = \frac{v_u}{v}, \quad \text{SUSY Loop correction} \]

\[ \varepsilon_0 = 0 \text{ for Type-II 2HDM} \]

\[ \text{Br}_{SM}(\tau\nu) = [1.20 \pm 0.25] \times 10^{-4} \]

Based on fB from HPQCD and \(|V_{ub}|\) from HFAG (BLNP, ICHEP08)

**Constraint on charged Higgs**

Type-II 2HDM

95% CL excluded

*Slide from T. Iijima, Lepton-Photon 2009*
Comparison to CKM fit

Naïve world average

$$\text{Br}(\tau\nu) = [1.73 \pm 0.35] \times 10^{-4}$$

$$\text{Br}(\tau\nu)_{\text{CKM fit}} = \left[ 0.786^{+0.179}_{-0.083} \right] \times 10^{-4}$$

Output of a CKM fit without including $B \rightarrow \tau\nu$ in the fit (CKM fitter, ICHEP08)

The measured Br is 2.4 $\sigma$ higher than the value predicted by the CKM fit.

*Slide from T. Iijima, Lepton-Photon 2009*
Combined charged Higgs bound from B-factories

completely covering expected exclusion region by ATLAS
**Time Dependent CPV in $B^0$ decays**

\[ \Gamma_{B^0}(\Delta t) \]
\[ \Gamma_{\bar{B}^0}(\Delta t) \]

\[ A_{CP}(\Delta t) = \frac{\Gamma_{\bar{B}^0}(\Delta t) - \Gamma_{B^0}(\Delta t)}{\Gamma_{\bar{B}^0}(\Delta t) + \Gamma_{B^0}(\Delta t)} = S \sin \Delta m \Delta t + A \cos \Delta m \Delta t \]

- $S = -\xi_{CP} \sin 2\phi_1 = +\sin 2\phi_1$
- $A \sim 0$

($\xi_{CP}$: CP eigenvalue $\pm 1$)

**N.B.** Time integrated mixing-induced asymmetries vanish