Mini-review on radiative and leptonic rare B decays

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## Contents

- **Radiative penguins:**
  - $b \rightarrow s \gamma$ inclusive
  - $b \rightarrow s \gamma$ exclusive
  - $b \rightarrow d \gamma$
- **Semileptonic penguins:**
  - $b \rightarrow s \ell^+ \ell^-$ inclusive
  - $b \rightarrow s \ell^+ \ell^-$ exclusive
  - Forward-backward asymmetry in $B \rightarrow K^* \ell^+ \ell^-$
  - $b \rightarrow s \nu \bar{\nu}$
- **Annihilation trees and penguins (purely leptonic and radiative)**
  - $B \rightarrow \ell \nu, \ell^+ \ell^-, \nu \bar{\nu}, \gamma \gamma,...$

- **Not covered: lepton-flavor violating modes (LFV)**
  - No surprises, limits are in expected ranges
Color code, BF units

BABAR measurement: $\pi = 3.12 \pm 0.08$

Belle measurement: $\pi = 3.16 \pm 0.07$

CLEO measurement: $\pi = 2.98 \pm 0.19$

HFAG 2005 average: $\pi = 3.15 \pm 0.05$

Brand new at Moriond 2006: $\pi = 3.12 \pm 0.08$

SM prediction: $\pi = 3.141 \pm 0.001$

- All branching fractions are given in units of $10^{-6}$ (HFAG convention)
- All limits are at the 90% confidence level
The main players...

Collected ~330 fb\(^{-1}\), Analyses based on 88–232 M BB

Collected ~560 fb\(^{-1}\), Analyses based on 111–386 M BB
Radiative Penguins
**Motivation**

- **Probe new physics!**
  - BF: measurement of Wilson coefficient $|C_7|$.
  - CP-asymmetry: look for new phases in $b \rightarrow s\gamma$ loop.
- **Study dynamics of $b$ quark inside $B$ meson.**
  - $b$ motion is universal $\Rightarrow$ applicable to other decays!

**Methods**

**Fully inclusive:**

- Look for hard photon from $b \rightarrow s\gamma$, nothing else.
- Huge backgrounds!
  - Suppress with various methods, then subtract with off-resonance data.
- Lepton tag to suppress background
  - Used by BABAR analysis (semileptonic decay of other $B$)
  - 5% efficiency for $\times 1200$ reduction in background!

**Semi-inclusive:**

- Sum of exclusive modes ($B \rightarrow K[n\pi]\gamma$ etc.)
  - Belle '01: 16 modes, BABAR '05: 38 modes!
- Large uncertainty from extrapolation to missed modes ($K_L$ etc.)
- Assume isospin symmetry (i.e. $K_L = K_S$, $K^+\pi^- = K^0\pi^0$, etc.)
New HFAG average of these measurements using a common shape function for the extrapolation to low photon energies and taking into account the correlated error from $b \to d\gamma$ contamination:

Calculation of extrapolation factors by O. Buchmüller and H. Flächer, hep-ph/0507253

Standard Model prediction (NLO):

$$\text{BF}(b \to s\gamma) = 321 \pm 43 \pm 27^{+18}_{-10}$$

• $E(\gamma)>2.0$ GeV

$$\text{BF}(b \to s\gamma) = 355 \pm 32 \pm 30^{+11}_{-31}$$

• $E(\gamma)>1.8$ GeV

$$\text{BF}(b \to s\gamma) = 367 \pm 29 \pm 34$$

• Lepton-tagged

$$\text{BF}(b \to s\gamma) = 335 \pm 19^{+56}_{-41}$$

• $E(\gamma)>1.9$ GeV

$$\text{BF}(b \to s\gamma) = 335 \pm 19^{+56}_{-41}$$

• 38 modes covering ~55%

$$\text{BF}(b \to s\gamma) = 355 \pm 24^{+9}_{-10}$$

• $E(\gamma)>1.6$ GeV

⇒ Depressing agreement between theory and experiment!
Spectra in $\Upsilon(4S)$ rest frame:

- CLEO
  - PRL 87 (2001) 251807
  - $9.1 \text{ fb}^{-1}$ on $\Upsilon(4S)$
  - $-4.4 \text{ fb}^{-1}$ off $\Upsilon(4S)$
  - (continuum subtraction)
  - $E_\gamma > 2.0 \text{ GeV}$

- Semi-inclusive analysis allows spectrum measurement in B rest frame $[\text{via } M(X_s)]$!
  - No smearing from B momentum
  - Better energy resolution (1–5 MeV!)

- $81.9 \text{ fb}^{-1}$ on $\Upsilon(4S)$
  - $-9.6 \text{ fb}^{-1}$ off $\Upsilon(4S)$
  - (continuum subtraction)
  - $E_\gamma > 1.9 \text{ GeV}$

- $140 \text{ fb}^{-1}$ on $\Upsilon(4S)$
  - $-15 \text{ fb}^{-1}$ off $\Upsilon(4S)$
  - (continuum subtraction)
  - $E_\gamma > 1.8 \text{ GeV}$

- $\gamma$ spectrum gives direct access to fundamental parameters governing the b quark inside the B meson!
  - e.g. OPE parameters in kinetic scheme:
    - $m_b = (4.59 \pm 0.04) \text{ GeV}$ (b quark mass in B)
    - $\mu^2 = (0.40 \pm 0.04) \text{ GeV}^2$ (b quark momentum squared in B)

- Valuable for $b \rightarrow c \ell \nu$, $b \rightarrow u \ell \nu$ analyses (extraction of $V_{ub}$ and $V_{cb}$)

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- Semi-inclusive analysis allows spectrum measurement in B rest frame $[\text{via } M(X_s)]$!
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**b → sγ inclusive: CP asymmetry**

\[ A_{CP}(b \rightarrow s\gamma) = (2.5 \pm 5.0 \pm 1.5)\% \]

PRL 93 (2004) 031803

\[ A_{CP}(b \rightarrow s\gamma) = (0.2 \pm 5.0 \pm 2.6)\% \]

PRL 93 (2004) 021804

**Semi-inclusive** (pseudo-reconstruction) technique: negligible contamination from \( b \rightarrow d\gamma! \)

**HFAG**

\[ A_{CP}(b \rightarrow s\gamma) = (0.4 \pm 3.6)\% \]

New result from BABAR inclusive lepton-tagged analysis:

\[ A_{CP}(b \rightarrow [s+d]\gamma) = (-11.0 \pm 11.5 \pm 1.7)\% \]

hep-ex/0507001

- Charge from lepton tag (dilution from B mixing)
- No distinction \( b \rightarrow s\gamma \) vs. \( b \rightarrow d\gamma \)...
- Note: in the limit of U-spin symmetry, \( A_{CP}(b \rightarrow [s+d]\gamma) \) is strictly zero in SM by unitarity!

Hurth, Lungi, Porod, NPB 704 (2005) 56
Established kaon resonance modes:

- $B \to K^*(892)\gamma$ (CLEO, BABAR, Belle)
- $B \to K^+_1(1270)\gamma$ (Belle [charged only])
- $B \to K^{*}_2(1430)\gamma$ (CLEO, Belle [neutral only], BABAR)

Good agreement with theory (which is less precise!)

Established $K^{(*)}X\gamma$ modes (mostly resonant):

- $B \to K\pi\gamma$ (CLEO, BABAR, Belle)
- $B \to K\pi\pi\gamma$ (Belle, BABAR [new, summer ‘05])
- $B \to K^*(892)\pi\gamma$ (Belle)
- $B \to K\rho\gamma$ (Belle, evidence)
- $B \to K\eta\gamma$ (Belle [charged only], BABAR [new, MORIOND ‘06])
- $B \to K\phi\gamma$ (Belle)

Belle has been leading the field, but BABAR is rapidly catching up!
**Motivation:**

- Resonance interference between various $K\pi\pi\gamma$ modes allows a measurement of the photon polarization in the $b \to s\gamma$ transition [Gronau et al., PRL 88 (2002) 051802]

- Standard Model predicts (mostly) left-handed photon [Atwood, Gronau, Soni, PRL 79 (1997) 185], but up to 10% right-handed amplitude from QCD operators [Grinstein et al., PRD 71 (2005) 011504]

- But we first need to sort out the messy resonances!

**Results:**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield</th>
<th>Branching Fraction ($10^{-5}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+\pi^-\pi^+\gamma$</td>
<td>899 ± 38</td>
<td>2.95 ± 0.13 ± 0.19</td>
</tr>
<tr>
<td>$K^+\pi^-\pi^0\gamma$</td>
<td>572 ± 31</td>
<td>4.07 ± 0.22 ± 0.31</td>
</tr>
<tr>
<td>$K^0\pi^+\pi^+\gamma$</td>
<td>176 ± 20</td>
<td>1.85 ± 0.21 ± 0.12</td>
</tr>
<tr>
<td>$K^0\pi^+\pi^0\gamma$</td>
<td>164 ± 15</td>
<td>4.56 ± 0.42 ± 0.30</td>
</tr>
</tbody>
</table>

- Detailed study of resonance structure still in progress
- $K_1(1270)$ clearly visible
- Polarization analysis requires “clean” $K_1(1400)$ in $K\pi^\pm\pi^0$ modes
- We probably have to wait for a Super-B-factory for this measurement!
**BABAR: B → K\(\eta\gamma\) and K\(\eta'\gamma\)**

- Reconstruction channels \(\eta \rightarrow \gamma \gamma\) and \(\eta \rightarrow 3\pi\), \(\eta' \rightarrow \eta \pi \pi\), \(\eta' \rightarrow \rho \gamma\).
- Standard continuum background suppression with Fisher discriminant.
- Unbinned maximum likelihood fit on \(m_{ES}\), \(\Delta E\) (and resonance masses, Fisher for some modes)

\[
\begin{align*}
\text{BF}(B^+ \rightarrow K^+\eta \gamma) &= 10.0 \pm 1.3 \pm 0.5 \ (10\sigma) \\
\text{BF}(B^0 \rightarrow K^0\eta \gamma) &= 11.3 \pm 2.8 \pm 0.6 \ (5.3\sigma)
\end{align*}
\]

Also:

\[
\text{A}_{CP}(B^+ \rightarrow K^+\eta \gamma) = (-7.5 \pm 12.0 \pm 0.5)\%
\]

- First limits on this channel!
- Expected to be suppressed w.r.t. \(K^+\eta \gamma\) due to well-known destructive penguin interference

\[
\begin{align*}
\text{BF}(B^+ \rightarrow K^+\eta' \gamma) < 4.2 \\
\text{BF}(B^0 \rightarrow K^0\eta' \gamma) < 6.6
\end{align*}
\]
Direct CP violation in excl. $b \rightarrow s \gamma$

- Firmly in the few-percent range – precision measurements!
- Hadronic uncertainties with respect to inclusive $b \rightarrow s \gamma$, but asymmetries still expected to be small.
- Not much room left for new physics here!
- Also measured: isospin asymmetries, compatible with SM prediction.

\[ A_{\text{CP}}(B \rightarrow K^*\gamma) = (-1.5 \pm 4.4 \pm 1.2)\% \]

PRD 69 (2004) 112001

\[ A_{\text{CP}}(B \rightarrow K^*\gamma) = (-1.3 \pm 3.6 \pm 1.0)\% \]

PRD 70 (2004) 112006
Indirect CP violation in $b \rightarrow s \gamma$

Motivation:
- $B$-$\bar{B}$ interference gives access to photon polarization in the $b \rightarrow s \gamma$ transition, predicted to be lefthanded in the SM [Atwood, Gronau, Soni, PRL 79 (1997) 185]
- Therefore small interference effect in SM, $S(B^0 \rightarrow K^{*0} \gamma) \approx -2(m_s/m_b)\sin 2\phi_1 \approx -0.06 \times \sin 2\phi_1$.
- Ideal channel is $B^0 \rightarrow K^{*0}(K_S\pi^0)\gamma$, but $S$ parameter should be the same for all $B^0 \rightarrow K_S\pi^0 \gamma$ [Atwood, Gershon, Hazumi, Soni, PRD 71 (2005) 076003]
- Experiments indeed favor small $S$, but errors are still large!

$S(B^0 \rightarrow K^{*0}[K_S\pi^0] \gamma) = 0.01 \pm 0.52 \pm 0.11$

$S(B^0 \rightarrow K_S\pi^0 \gamma) = 0.08 \pm 0.41 \pm 0.10$

$S(B^0 \rightarrow K^{*0}[K_S\pi^0] \gamma) = -0.21 \pm 0.40 \pm 0.05$

$S(B^0 \rightarrow K_S\pi^0 \gamma) = 0.08 \pm 0.41 \pm 0.10$

PRD 72 (2005) 051103

HFAG
HEP 2005
PRELIMINARY
• CKM-suppressed counterpart of \( b \rightarrow s \gamma \), suppressed by \( |V_{td}/V_{ts}|^2 \approx 0.04 \).
  - But additional annihilation diagram!
• Even more sensitive to new physics!
• Within SM: extract value for \( |V_{td}/V_{ts}|^2 \).
  - The B factories’ \( \Delta m_s \)!
  - But only exclusive measurements are possible ⇒ hadronic uncertainties.
• Huge backgrounds as for \( b \rightarrow s \gamma \), in addition substantial backgrounds from \( b \rightarrow s \gamma \) itself!
• The big news of 2005 (first observation)!
Belle: $b \to d \gamma$

First observation in 2005!

measurement finalized and submitted for publication

- Very sophisticated background suppression necessary:
  - $\pi^0$ and $\eta$ rejection, $K^*\gamma$ veto, $\rho/\omega$ helicity
  - Vertex displacement from other $B$
  - Flavor-tag algorithm (continuum is flavorless)
- Combine variables with event-shape Fisher in likelihood ratio, apply flavor-tag quality dependent cut.

Fit for signal, $K^*\gamma$ contamination, continuum, other $B$ bgr.

$$\mathcal{B}(B^+ \to \rho^+\gamma) = 0.55 \pm^{+0.42}_{-0.36} \pm^{+0.09}_{-0.08} \ (1.6\sigma)$$

$$\mathcal{B}(B^0 \to \rho^0\gamma) = 1.25 \pm^{+0.37}_{-0.33} \pm^{+0.07}_{-0.06} \ (5.2\sigma)$$

$$\mathcal{B}(B^0 \to \omega\gamma) = 0.56 \pm^{+0.34}_{-0.27} \pm^{+0.05}_{-0.10} \ (2.3\sigma)$$

Combined fit, assuming isospin:

$$\mathcal{B}(B \to (\rho/\omega)\gamma) = \frac{1}{2} \left\{ \mathcal{B}(B^+ \to \rho^+\gamma) \right\} + \frac{\tau_{B^+}}{\tau_{B^0}} \left[ \mathcal{B}(B^0 \to \rho^0\gamma) + \mathcal{B}(B^0 \to \omega\gamma) \right]$$

$$\mathcal{B}(B^0 \to [\rho,\omega]\gamma) = 1.32 \pm^{+0.34}_{-0.31} \pm^{+0.10}_{-0.09} \ (5.1\sigma)$$
**Analysis similar to Belle, uses neural network to combine background suppression variables.**

**Combined fit, assuming isospin:**

\[ \text{BF}(B^0 \rightarrow [\rho,\omega] \gamma) = 0.6 \pm 0.3 \pm 0.1 \ (2.1\sigma) \]

or:

\[ \text{BF}(B^0 \rightarrow [\rho,\omega] \gamma) < 1.2 \]

**BF}(B^+ \rightarrow \rho^+ \gamma) < 1.8 \ (1.9\sigma)\]

**BF}(B^0 \rightarrow \rho^0 \gamma) < 0.4 \ (0.0\sigma)\]

**BF}(B^0 \rightarrow \omega \gamma) < 1.0 \ (1.5\sigma)\]

**Plot by Jeff Berryhill, BABAR rad. penguin group**

**BABAR: b \rightarrow d \gamma**

**published limits**

PRL 94 (2005) 011801 (211M BB)
$b \to d \gamma$: extraction of $|V_{td}/V_{ts}|$

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

form factor ratio:
$$\zeta^2 \approx 0.85 \pm 0.1$$

different dynamics (weak annihilation diagram)
$$\Delta R \approx 0.1 \pm 0.1$$

$|V_{td}/V_{ts}| = 0.199^{+0.026}_{-0.025} \text{(exp.)}^{+0.018}_{-0.015} \text{(theor.)}$

a non-trivial constraint for the unitarity triangle!

In comparison with “new-physics-free” tree-only UT:

$|V_{td}/V_{ts}| < 0.19$
Semileptonic Penguins

\[ b \rightarrow s \ell \ell, \ \bar{\nu} \ell, \ \bar{\nu} \]

\[ b \rightarrow s \ell, \nu \ell, \nu \]
The physics of $b \rightarrow s \ell^+ \ell^-$ is governed by the Wilson coefficients $C_7$, $C_9$, and $C_{10}$ that describe the strength of the corresponding local (short-distance) operators in the effective Hamiltonian.

- $O_7$: electromagnetic operator
- $O_9$: semileptonic vector operator
- $O_{10}$: semileptonic axialvector operator

Wilson coefficients are experimental observables.

Contributions from new physics appear as deviations from the SM values, which have been calculated to NNLO.

Experimental information on Wilson coefficients:

- $BF(b \rightarrow s \gamma)$ determines $|C_7|$ with an uncertainty of about 20% (exp. + theor.)
- Does not give information on sign!

- $BF(b \rightarrow s \ell^+ \ell^-)$ constrains $C_9$ and $C_{10}$
  - Donut shaped constraint
  - No information on sign and magnitude of $C_9$, $C_{10}$!

Need differential decay rates and asymmetries to learn more about $C_i$'s!

- Inclusive decay rate as function of lepton $q^2$.
- Forward-backward asymmetry in exclusive $B \rightarrow K^* \ell^+ \ell^-$.
**b → sℓ⁺ℓ⁻ inclusive: sign of C₇**

Gambino, Haisch, Misiak, PRL 94 (2005) 061803

<table>
<thead>
<tr>
<th>q² range</th>
<th>BF(b → sℓ⁺ℓ⁻)</th>
<th>weighted average</th>
<th>SM</th>
<th>C₇ → -C₇</th>
</tr>
</thead>
<tbody>
<tr>
<td>q² &gt; (2m_μ)²</td>
<td>4.1 ± 1.1</td>
<td>5.6 ± 2.0</td>
<td>4.5 ± 1.0</td>
<td>4.4 ± 0.7</td>
</tr>
<tr>
<td>1 &lt; q² &lt; 6 GeV²</td>
<td>1.5 ± 0.6</td>
<td>1.8 ± 0.9</td>
<td>1.6 ± 0.5</td>
<td>1.57 ± 0.16</td>
</tr>
</tbody>
</table>

Experiments clearly favor SM-sign for C₇!

SUGRA example with C₇ → -C₇

SM case

Goto et al., PRD 55 (1997) 4273
**b → sℓ⁺ℓ⁻** exclusive

- All individual exclusive modes established by now, except $K^{*+}$ modes and $K^0e^+e^-$ mode.
- Belle values in general higher than BABAR – just statistics?

---

**Charge and lepton-flavor averaged measurements:**

### BABAR

- $BF(B \rightarrow K\ell^+\ell^-) = 0.34 \pm 0.07 \pm 0.03$
- $BF(B \rightarrow K^*\ell^+\ell^-) = 0.78^{+0.19}_{-0.17} \pm 0.12$
- $BF(B \rightarrow K^*\ell^+\ell^-) = 1.65^{+0.23}_{-0.22} \pm 0.11$

### BELLE

- $BF(B \rightarrow K\ell^+\ell^-) = 0.550^{+0.075}_{-0.070} \pm 0.027$
- $BF(B \rightarrow K^*\ell^+\ell^-) = 2.75^{+0.27}_{-0.23} \pm 0.11$

---

**Lepton and charge/isospin asymmetries:**

- no surprises so far...

(see Refs. for values)
All individual exclusive modes established by now, except $K^{*+}$ modes and $K^0e^+e^-$ mode.

Belle values in general higher than BABAR – just statistics?
b → sℓ⁺ℓ⁻: Wilson coefficients (cont’d)

Now that we know the sign of $C_7$, how can we learn where exactly we sit on the $C_9$-$C_{10}$ donut?

**forward-backward asymmetry $A_{FB}(q^2)$!**

- measurable in exclusive $B \rightarrow K^*\ell^+\ell^-$ decays
- induced by interference between vector ($C_7$, $C_9$) and axial vector ($C_{10}$) couplings ($γ$, $Z$, and $W$ contributions)

### Definition of $A_{FB}(q^2)$:

$$A_{FB}(q^2) = \frac{\Gamma(q^2, \cos θ_{B\ell^-} > 0) - \Gamma(q^2, \cos θ_{B\ell^-} < 0)}{\Gamma(q^2, \cos θ_{B\ell^-} > 0) + \Gamma(q^2, \cos θ_{B\ell^-} < 0)}$$
Belle: $A_{FB}(q^2)$ for $B \to K^*\ell^+\ell^-$

- Measurement based on $114 \pm 13$ $B \to K^*\ell^+\ell^-$ decays (44% pure)
  - $K^* \to K^+\pi^-, K_S\pi^+, K^+\pi^0$.
- Analysis in terms of leading-order coefficients $A_7, A_9, A_{10}$
  - $(C_7 = A_7 + \text{higher-order terms, etc.})$
- Maximum-likelihood fit to normalized double-differential decay width, $(1/\Gamma) d^2\Gamma / ds \, d\cos\theta$, using 8 event categories (signal, 3 cross-feeds, 4 backgrounds, of which dilepton dominant).
- Fix $A_7 = -0.330$ (SM value), fit for $A_9/A_7$ and $A_{10}/A_7$.
  - Repeat fit also for $A_7 = +0.330$, gives worse fit.
- Null test with $B \to K\ell^+\ell^-$. 

**Fit result ($A_7$ fixed):**

$$A_9/A_7 = -15.3 \pm 3.4 \pm 1.1$$

$$A_{10}/A_7 = 10.3 \pm 5.2 \pm 1.8$$

**SM:**

$$A_9/A_7 = -12.33, \quad A_{10}/A_7 = 12.82$$

95% C.L. ($A_7$ free):

$$-1401 < A_9 A_{10}/A_7^2 < -26.4$$

**SM:**

$$A_9 A_{10}/A_7^2 = -158.1$$

See K. Ikado’s talk for details!

New BABAR result: covered by Jeff Berryhill!
**b → sνν: B⁺ → K⁺νν**

- **Theoretically very clean mode** (no photon penguin, no hadronic long-distance effects (charmonium resonances)).
- **Experimentally challenging** (2 neutrinos in final state)
  - Need “recoil analysis”: reconstruct one B fully, look for difficult decay in event-remainder.

Belle analysis identical to B → τν search, see later.

BABAR result finalized and published.

- Use ~480k B → D(⁎)0ℓ⁺ν and ~180k B → D(⁎)⁰X⁺_{had} events (X⁺_{had} = up to 5 pions/kaons)
- Look for exactly one opposite-charged track identified as a kaon
- Cut on extra energy found in el.-magn. Calorimeter: E_{extra} < 250 MeV.

**SM:** \[ BF(B⁺ → K⁺νν) = 3.8^{+1.2}_{-0.6} \]

BF(B⁺ → K⁺νν) < 36
hep-ex/0507034

(275M BB)

BF(B⁺ → K⁺νν) < 52
PRL 94 (2005) 101801

(89M BB)
Annihilation Penguins and Trees
(leptonic and purely radiative decays)
Thomas Schietinger

Mini-review on radiative and leptonic rare B decays

Moriond, 11–18 March 2006

Analysis:

- Look for $\tau \to e\nu\nu$, $\mu\nu\nu$, $\pi\nu$, $\pi\pi^0\nu$, $\pi\pi\pi\nu$, decays in recoil of fully reconstructed B decays
  - Belle: 400k $B \to D^{(*)0}h^+$ and $D^{(*)0}D_s^{(*)+}$ events
  - BABAR: $\sim 400k$ $B \to D^{(*)0}\ell^+\nu$ events
    (+ hadronic events from previous analysis)
- Cut on extra energy in em. Calorimeter ($E_{\text{extra}}$).
- Use double-tag events (fully reconstructed $\Upsilon(4S)$ decays) to validate $E_{\text{extra}}$ simulation.

See K. Ikado’s talk for details!

$B \to \tau\nu$

$BF(B \to \tau\nu) < 180$

or

$BF(B \to \tau\nu) = 81^{+58}_{-45}$

or

$BF(B \to \tau\nu) = 92^{+51}_{-41}$

$BF(B \to \tau\nu) < 260$

$BF(B \to \tau\nu) = 93$

Tantalizingly close to observation! Stay tuned for updates!
B → τν: what does it mean?

SM context: independent constraint for CKM matrix

e.g UTfit:

Beyond SM context: constraints on charged Higgs mass and tanβ.

...or CKMfitter (in combination with constraint from B mixing):

![Graph showing constraints on charged Higgs mass and tanβ.](image)
**B → µν and B → eν**

- **Helicity-suppressed** with respect to B → τν (1/225 for B → µν, 10⁻⁷ for B → eν).
- No new measurements since 2004.

**Analysis**

- One highly energetic lepton, charmonium veto.
- Large missing E and p.
- Define signal window on kinematics of companion B.
- Cut on lepton momentum in B rest frame.

- B(B → µν) < 2.0
  - (152M B̅B)
  - hep-ex/0408132

- B(B → eν) < 5.4
  - (65M B̅B)
  - BELLE-CONF-0247
  - (prehistoric)

- B(B → µνγ) < 23
  - also

- B(B → eνγ) < 22

- SM: B(B → µν) = 0.4

B → µνγ and B → eνγ

**BF(B → µν) < 2.0**

**BF(B → eν) < 5.4**

**BF(B → µνγ) < 23**

**BF(B → eνγ) < 22**

**BF(B → µν) ≈ 0.00001**

**BF(B → eν) ≈ 0.00001**
**BABAR**: \( B \rightarrow \tau^+ \tau^- \)

- **First ever limit on this channel!**
  - One of the last big loopholes for theorists is finally being constrained!
  - Constrains in particular leptoquark couplings and \( \tan\beta \) enhancements in SUSY.

- **Experimentally very challenging!**
  - 2–4 neutrinos in every signal event...

**Analysis**

- **Completely reconstruct** one \( B \) in the channel \( B \rightarrow D^{(*)}X \),
  \( X = \) combination of charged and neutral \( \pi \)'s and \( K \)'s
  \( \Rightarrow 280k \) events

- In the event remainder, look for two “simple” \( \tau \) decays
  (one charged particle per decay):
  - \( \tau \rightarrow \ell \nu \nu, \pi \nu, \rho \nu \), covers 51% of all \( \tau^+ \tau^- \) decays.

- **Remove all** \( K_L, K_S \) and \( K^\pm \).

- Kinematics of charged daughter momenta and residual energy in calorimeter are fed into a **neural network** to separate signal from background.

- 263 ± 19 events survive selection, expect 281 ± 40 from sidebands/simulation \( \Rightarrow \) no signal present.

**BF(B → τ⁺τ⁻) < 3200**

**SM:** BF(B → τ⁺τ⁻) = 0.12

(for \( f_B = 200 \) MeV and \( V_{td} = 0.07 \))
No new results from the B factories ⇒ the Tevatron is taking the lead!

New Tevatron averages

\[ BF(B \rightarrow \mu^+\mu^-) < 0.032 \]
\[ BF(B_s \rightarrow \mu^+\mu^-) < 0.12 \]

Already puts stringent limits on SUSY models!

SM:
\[ BF(B \rightarrow \mu^+\mu^-) = 0.0001 \]
\[ BF(B_s \rightarrow \mu^+\mu^-) = 0.0035 \]
**$B \to \nu\bar{\nu}$**

...or any other invisible mode (e.g. neutralinos, large extra dimensions).

Analysis on 126k $B \to D^{(*)}\ell\nu$ recoil events (66% purity).

Belle result finalized, submitted to PRD.

**$B \to \gamma\gamma$**

Belle result finalized, submitted to PRD.

Preliminary limit on $BF(B_s \to \gamma\gamma)$: see A. Drutskoy talk!

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$BF(B \to \nu\bar{\nu}) < 220$

PRL 93 (2004) 091802

**$BF(B \to \nu\bar{\nu}) < 0.62$**

*hep-ex/0507036 (submitted to PRD)*

SM: $BF(B \to \nu\bar{\nu}) \approx 0$

Also:

**$BF(B \to \nu\bar{\nu}\gamma) < 47$**

$BF(B \to \gamma\gamma) < 1.7$

PRL 87 (2001) 241803

SM: $BF(B \to \gamma\gamma) = 0.03$

Update expected soon!
Conclusions

● **Tremendous progress** in the past couple of years!

● Dawn of a new era: **CKM fits with rare radiative/leptonic decays!**
  
  – We have $|V_{ub}|$ from $B \rightarrow \tau \nu$, $|V_{td}|$ from $B \rightarrow \rho/\omega \gamma$, constraints are beginning to impact CKM fits in non-trivial way!
  
  – (We also have $[-0.06 \times] \sin^2 \phi_1$ from $B \rightarrow K^* \gamma$!)

● We’re on the brink of observing $B \rightarrow \tau \nu$.

● Still no deviations from SM, but too early to tell for these channels.

● At last **ALL modes** are being constrained experimentally!
  
  – $B \rightarrow \tau \tau$ was a huge gap!
    
    (Mercilessly exploited by theorists to construct crazy models.)

● **Photon polarization in $b \rightarrow s \gamma$** probably requires **Super-B factory**.
  
  – Window of opportunity for LHCb?
    
    ($\Lambda_b \rightarrow \Lambda \gamma$ promising, if $\Lambda_b$’s are polarized at the LHC)
Back up material
Asymmetric B factories

$e^+e^- \rightarrow \gamma(4S) \rightarrow B^0\bar{B}^0$ or $B^\pm\bar{B}^\mp$

- $\gamma(4S)$ is the first bottomonium resonance that can decay to $B$ mesons.
- $\sim50\% B^0\bar{B}^0$, $\sim50\% B^\pm\bar{B}^\mp$ mesons (no $B_s$ or $B_c$!)
- The $B^0\bar{B}^0$ system is entangled!
  $\Rightarrow$ Always one $B^0$ and one $\bar{B}^0$!

Why asymmetric?

symmetric: $B^0$ $\bar{B}^0$ $\sim 30 \text{ \mu m}$

asymmetric: $\bar{B}^0$ $B^0$ $\sim 200 \text{ \mu m}$

$\Rightarrow$ Boost gives better time resolution and a reference "$t_0$"!
Reconstruction of B meson

**B factory physics:**
\[ e^+e^- \rightarrow \gamma(4S) \rightarrow B^0\bar{B}^0 \text{ or } B^\pm\bar{B}^\mp \text{ and nothing else in a given event!} \]
⇒ The total energy of the B is given by the energy of the beam. Use this information when reconstructing the B!

Two variables, evaluated in the CM system:
\( E_B, p_B \) are reconstructed B energy and momentum

**Beam-constrained mass:**
\[ M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2} \]
(independent of particle assignments!)

**Energy difference:**
\[ \Delta E = E_B - E_{\text{beam}} \]
(corresponds to traditional invariant mass)
Suppression of “continuum” background

Main background for rare B decays:

\[ e^+e^- \rightarrow q\bar{q} \text{ “continuum”} \]

(q = u,d,s,c)

Suppression through event shape variables:
- Thrust angle
- “Super-Fox-Wolfram” moments (Belle)
- “virtual calorimeter” (CLEO/BABAR) etc.

General idea is always the same:

B event: spherical shape (B mesons almost at rest in CM)

continuum event: jet-like structure