Radiative Penguin Decays at the B Factories

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Outline:

- **Introduction**  
  CKM, SM, New Physics, Belle and BaBar, Analysis

- **B → (ρ/ω) γ**  
  Analysis, Results and the Tevatron

- **b → s γ**  
  A new technique

- **Bs → φ γ, γ γ**  
  The Y(5S) run at Belle

- **Summary**

...
Current state of CKM Flavor Physics:

- CP violation in the Standard Model is consistently accounted for by the CKM matrix:
Radiative penguin decays:

Decays where leading contribution is Penguin, thus BF $\sim 10^{-4} - 10^{-7}$

- New physics contributions can enter at the same level as SM contributions!
- Thus, observables can shift w.r.t. the SM prediction.
- If no conclusive difference between measurements and SM predictions are found, constraints on new physics contributions can be extracted (e.g. exclusion regions in $m_{H^+} - \tan \beta$ plane from $b \to s\gamma$)

Excluded regions at 95% C.L. (colored) for MSSM 2-Higgs Doublet Model of type II (PRD 48, 2342 (1993))
**Design Goal:** Study time dependent CP-violation in the B-meson system  
→ Run asymmetric at Υ(4S) resonance

**Basic Machine Parameters:**

<table>
<thead>
<tr>
<th></th>
<th>8 GeV electrons on 3.5 GeV positrons</th>
<th>9 GeV electrons on 3.1 GeV positrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energies</td>
<td>8 GeV electrons on 3.5 GeV positrons</td>
<td>9 GeV electrons on 3.1 GeV positrons</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td>605 fb(^{-1})</td>
<td>411 fb(^{-1})</td>
</tr>
<tr>
<td>Peak Luminosity</td>
<td>(17.1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1})</td>
<td>(12.0 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1})</td>
</tr>
</tbody>
</table>
**B meson reconstruction:** Use two standard variables:

\[
m_{ES} = M_{bc} = \sqrt{E_{Beam}^* - |p_B^*|^2}
\]

Resolution ~ 3 MeV

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

Resolution ~ 50 MeV

---

**Background suppression - The Name of the Game!**

\[\pi^0 \rightarrow \gamma\gamma \text{ and } \eta \rightarrow \gamma\gamma \text{ suppression:}
\]

High-energy photon usually comes from these decays in background events.

**Continuum (e^+e^- → light quark):** Event shape variables and angular information

Also, use tagging information, i.e. Leptons, Kaons (…) from the other B
**Overview**

Radiative Penguin Decays at the B Factories

**Sensitive to far side of Unitarity Triangle:**

\[
\frac{B(B \to (\rho, \omega)\gamma)}{B(B \to K^*\gamma)} = \left| \frac{V_{td}}{V_{ts}} \right|^2 \left( \frac{1 - m_{\rho,\omega}^2/m_B^2}{1 - m_{K^*}^2/m_B^2} \right)^3 \left( \frac{T_{1,0}^{\rho,\omega}}{T_{1,0}^{K^*}} \right)^2 [1 + \Delta R]
\]

Form factor ratio \((\xi = 1.17 \pm 0.09)^{-1}\)

Measures same side of UT triangle as \(B_d/B_s\) mixing, but with rather different underlying physics:

\[b \to u, c, t \to s \rightarrow \bar{s} \to \bar{u}, \bar{c}, \bar{t} \to \bar{b}\]

From the Tevatron:

\[
\sqrt{\frac{\Delta m_d}{\Delta m_s}} \propto \left| \frac{V_{td}}{V_{ts}} \right| = 0.2060 \pm 0.0007^{+0.0081}_{-0.0060}
\]

**Background Rejection**

**Fits**
**Continuum background rejection:**

- **Shape variables**: Fox-Wolfram Moments, Legendre moments, thrust angle
- **B decay properties**: cosine of B decay angle $\cos \theta_B$, $\Delta z$
- **Tagging related variables**: Presence and properties of Leptons, Kaons, Pions in the rest-of-the-event

1) Construct Fisher from shape variables.
2) Build likelihoods for Fisher output, $\cos \theta_B$ and $\Delta z$, where available (not 1-track $\rho^+$ mode).
3) Depending on a tagging quality variable, cut on product likelihood ratio.

At ~40% signal efficiency, achieve ~95% continuum background rejection efficiency.

Combine all variables with separating power into a neural network (including $\Delta z$ – even for 1-track $\rho^+$ mode).

At ~50% signal efficiency, achieve ~98.5% continuum background rejection.
Signal extraction with an unbinned maximum likelihood fit:

- Variables used:
  - $m_{ES}$ ($M_{bc}$),
  - $\Delta E$,
  - Neural network output,
  - Cosine of the Helicity angle,
  - Second decay angle in the $B \to \omega \gamma$ decay,

Based on theory assumptions, build simultaneous fit models:

- For all three modes ($\rho^+$, $\rho^0$, $\omega$):

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

- For the two $\rho$ modes ($\rho^+$, $\rho^0$), since the inclusion of $\omega$ is controversial:

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

Fit datasets simultaneously, only 1 signal yield parameter instead of 2 or 3.
**B → (ρ/ω) γ Results**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>Signif.</th>
<th>Efficiency (%)</th>
<th>$B \times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow ρ^+ γ$</td>
<td>8.5</td>
<td>1.6 (1.6)</td>
<td>3.86 ± 0.23</td>
<td>$0.55^{+0.42+0.09}_{-0.36-0.08}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow ρ^0 γ$</td>
<td>20.7</td>
<td>5.2 (5.2)</td>
<td>4.30 ± 0.28</td>
<td>$1.25^{+0.37+0.07}_{-0.33-0.06}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow ω γ$</td>
<td>5.7</td>
<td>2.3 (2.6)</td>
<td>2.61 ± 0.21</td>
<td>$0.56^{+0.34+0.05}_{-0.27-0.10}$</td>
</tr>
<tr>
<td>$B \rightarrow (ρ, ω) γ$</td>
<td>36.9</td>
<td>5.1 (5.4)</td>
<td>—</td>
<td>$1.32^{+0.34+0.10}_{-0.31-0.09}$</td>
</tr>
</tbody>
</table>

**Results**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$n_{sig}$</th>
<th>Signif.</th>
<th>$\epsilon$(%)</th>
<th>$B(10^{-6})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow ρ^+ γ$</td>
<td>42.0±14.0</td>
<td>3.8σ</td>
<td>11.0</td>
<td>$1.10^{+0.37}_{-0.33} ± 0.09$</td>
</tr>
<tr>
<td>$B^0 \rightarrow ρ^0 γ$</td>
<td>38.7±10.6</td>
<td>4.9σ</td>
<td>14.1</td>
<td>$0.79^{+0.22}_{-0.20} ± 0.06$</td>
</tr>
<tr>
<td>$B^0 \rightarrow ω γ$</td>
<td>11.0±6.7</td>
<td>2.2σ</td>
<td>7.9</td>
<td>$0.40^{+0.24}_{-0.20} ± 0.05$</td>
</tr>
<tr>
<td>$B \rightarrow (ρ/ω) γ$</td>
<td>350 fb$^{-1}$</td>
<td>6.4σ</td>
<td>1.25±0.25</td>
<td>$±0.24 ± 0.08$</td>
</tr>
<tr>
<td>$B \rightarrow ρ γ$</td>
<td>316 fb$^{-1}$</td>
<td>6.0σ</td>
<td>1.36±0.29</td>
<td>$±0.27 ± 0.09$</td>
</tr>
</tbody>
</table>
**Comparison of Belle and BaBar with theory:**

**CKM results:**

Using only the two rho modes:

\[
\left| \frac{V_{td}}{V_{ts}} \right| = 0.208^{+0.023}_{-0.022} \pm 0.016
\]

First error experimental and second theoretical.

**Branching Fraction (10^{-6})**

- (\rho^+, \rho^0, \omega) \gamma (combined)
- (\rho^+, \rho^0) \gamma (combined)
- \rho^+\gamma
- \rho^0\gamma
- \omega\gamma

**Branching Fractions |Vtd/Vts| Isospin**

- **Bd/Bs mixing**
  - BaBar, 316 fb^{-1}
    - PRL 98, 151802 (2007)
  - Belle, 350 fb^{-1}
    - PRL 96, 221601 (2006)
  - Ball, Jones, Zwicky
    - PRD 75, 054004 (2007)
  - derived from B. J. Z.
Combining Belle and BaBar

| Experiment $\mathcal{B}(10^{-6})$ | $1.25^{+0.25}_{-0.24} \pm 0.08$ |
| Babar | $1.32^{+0.34+0.10}_{-0.31-0.09}$ |
| Belle | $1.28^{+0.20}_{-0.19} \pm 0.06$ |

**In excellent agreement with $B_d/B_s$ mixing**

For comparison, from CDF:

$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.2060 \pm 0.0007^{+0.0081}_{-0.0060}$$

8.4% exp. error

7.4% theo. error

4% total error

95% prob. intervals

- BR($B \rightarrow p/\omega \gamma$)
- BR($B \rightarrow K^* \gamma$)
- $\Delta m_d$
- $\Delta m_s$

First error experimental and second theoretical.
Measure the isospin violation between $\rho^+\gamma$ and $\rho^0\gamma$ ($\sim \cos \alpha$):

$$\Delta = \frac{\Gamma(B^+ \to \rho^+\gamma)}{2\Gamma(B^0 \to \rho^0\gamma)} - 1 = -0.35 \pm 0.27$$

$\Delta$ is shown in the graph as a function of $\Delta(\rho\gamma)$ for different models:

- SM (green)
- BaBar (blue)
- EMFV (dark blue)
- MFV (light blue)
- SM at 68% C.L.
- EMFV at 68% C.L.
- MFV at 68% C.L., $C_7 > 0$

The graph also includes a data point from Babar PRL 98, 151802 (2007).

**New Physics:**

SM expectations (e.g.): $\mathcal{B}(B \to X_s \gamma) \ [E_\gamma > 1.6 \text{ GeV}] = (3.15 \pm 0.23) \times 10^{-4}$ (NNLO)

$A_{CP}(B \to X_s \gamma) < 1\%$ (SUSY: up to 20%)

**Photon Spectrum:**

At the quark level: 2-body decay

b quark bound inside B meson:

Moments of Photon Energy Spectrum carry information:

1\textsuperscript{st} moment: $\langle E^B_\gamma \rangle \approx \frac{m_b}{2}$

2\textsuperscript{nd} moment: $\langle (E^B_\gamma)^2 \rangle - \langle E^B_\gamma \rangle^2 \approx \mu^2 \approx E_{kin}^2 (b)$

This information can be used to extract $V_{cb}$ and $V_{ub}$ from semileptonic $b \to c$ and $b \to u$ transitions
Two established experimental methods:

- **“Fully Inclusive”**
  - Ignore \(X_s\) system.
  - Reconstruct only the \(\gamma\).
  - **Pros:**
    - No sensitivity to \(X_s\) fragmentation.
    - Theoretically clean.
  - **Cons:**
    - High background.
    - \(E_\gamma\) measured in \(Y(4S)\) rest frame.

- **“Sum of Exclusive”**
  - Fully reconstruct subset of all \(X_s\) final states.
  - **Pros:**
    - Lower background.
    - Good \(E_\gamma\) resolution in B rest-frame.
  - **Cons:**
    - \(X_s\) fragmentation systematic.
    - Missing \(X_s\) decay modes.
New approach: Fully reconstructed tag B:

Hadronic decay of one B meson fully reconstructed:
- 4-momentum, charge and flavor known, thus measurement of Isospin and CP asymmetry!
- With 4-momentum of Y(4S), also 4-momentum of signal B meson known. Thus, photon energy can be measured in signal B rest frame!

Analysis:
- Veto photons from $\pi^0$, $\eta$, $\rho$ decays.
- Suppress continuum with a Fisher discriminant (12 variables, mostly event shape).
- Determine partial branching fractions in bins of $E_\gamma$, using fits to $m_{ES}$.
**$E_\gamma$ Moments:**

- Measurement of photon energy moments as a function of minimum energy.
- Good agreement, different methods, independent data samples.

**1st $E_\gamma$ Moment**

<table>
<thead>
<tr>
<th>$E_{\text{cut}}$ (GeV)</th>
<th>Value</th>
<th>$\sigma_{\text{stat}}$</th>
<th>$\sigma_{\text{syst}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>2.289 ± 0.058 ± 0.026</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>2.315 ± 0.036 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>2.371 ± 0.025 ± 0.011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>2.398 ± 0.016 ± 0.006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>2.427 ± 0.010 ± 0.007</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**2nd $E_\gamma$ Moment**

**Partial Branching Fractions:**

- Statistical error dominates.
- Systematic error will shrink with more data.

<table>
<thead>
<tr>
<th>$E_{\text{cut}}$ (GeV)</th>
<th>Value</th>
<th>$\sigma_{\text{stat}}$</th>
<th>$\sigma_{\text{syst}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>366 ± 85 ± 59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>339 ± 64 ± 47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>278 ± 48 ± 34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>248 ± 38 ± 26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>207 ± 30 ± 19</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Branching Fractions:

Measured: \[ BF(B \to X_s \gamma) [E_\gamma > 1.9 \text{ GeV}] = (3.66 \pm 0.85 \pm 0.59) \times 10^{-4} \]

Extrapolated: \[ BF(B \to X_s \gamma) [E_\gamma > 1.6 \text{ GeV}] = (3.91 \pm 0.91 \pm 0.63) \times 10^{-4} \]

Using: PRD 73, 073008 (2006)
Producing $B_s$ mesons:

Belle collected 23.6 fb$^{-1}$ running at the Y(5S) resonance.
This corresponds to about 2.6x10$^6$ $B_s$ mesons (~20% uncertainty)

Two radiative penguin decays looked at:

$B_s \rightarrow \phi \gamma$

SM prediction: $BF = (4 \pm 1) \times 10^{-5}$

PRD 75, 054004 (2007)

$B_s \rightarrow \gamma \gamma$

BF = (0.5 - 1.0) x 10$^{-6}$

PRD 56, 5805 (1997)
JHEP 0208 054 (2002)

Can be enhanced by new physics by up-to an order of magnitude!
**B_{s} meson reconstruction:**

- **φ candidates:** Select K⁺ K⁻ pairs with invariant mass of 12 MeV around the nominal φ mass.
- **B_{s} candidates:** Standard m_{ES} (M_{bc}) and ΔE reconstruction.

**Background suppression:**

- **High-energy γ from π⁰/η decays:** Veto by combining high energy photon candidate with other photons in the event.
- **Continuum background (e⁺e⁻ to light quark pairs) suppression:** Use event topology by utilizing modified Fox-Wolfram moments:

**Final unbinned maximum likelihood fit:**

- Use three variables:

<table>
<thead>
<tr>
<th></th>
<th>m_{ES} (M_{bc}),</th>
<th>ΔE</th>
<th>cos(θ_{Helicity})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal:</td>
<td>Smoothed MC-histogram</td>
<td>1 - cos²(θ_{Helicity})</td>
<td></td>
</tr>
<tr>
<td>Background:</td>
<td>ARGUS</td>
<td>1st order Polynomial</td>
<td>Constant</td>
</tr>
</tbody>
</table>
**Results:**

- (18 ± 6) signal events found:
  \[ \mathcal{B} (B_S \rightarrow \phi \gamma) = (5.7^{+1.8}_{-1.5} + 1.2^{+1.7}_{-1.7}) \times 10^{-5} \]

- Significance (including systematics): 5.5σ.

- Signal region projection plots:

  ![Signal region projection plots](image)

  - m_{ES}
  - ΔE
  - cosθ

**First observation of a radiative Bs penguin decay!**

**Final fit finds no signal:**

<table>
<thead>
<tr>
<th>m_{ES} (M_{bc})</th>
<th>ΔE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal: Smoothened MC-histogram</td>
<td></td>
</tr>
<tr>
<td>Background: ARGUS 1st order Polynomial</td>
<td></td>
</tr>
</tbody>
</table>

\[ \mathcal{B} (B_S \rightarrow \gamma \gamma) < 8.6 \times 10^{-6} \] (90% CL)
Very interesting results in $B \rightarrow (\rho/\omega)\gamma$:

- The BaBar and Belle measurements lead to a first extraction of $|V_{td}/V_{ts}|$ from penguin decays!

$$\frac{V_{td}}{V_{ts}} = 0.202^{+0.017}_{-0.016} \pm 0.015$$

- In excellent agreement with Tevatron measurement. With increased statistics:
  - More precise determination of $|V_{td}/V_{ts}|$, even theory limited if calculations don’t improve…
  - Determination of $|V_{td}/V_{ts}|$ from single modes and measurements of other observables (direct CP violation, Isospin violation).

A promising new method for $b \rightarrow s\gamma$:

- Recent progress in both experiment and theory
  - Very good agreement between different experimental approaches.

- Photon energy spectrum measured in B rest frame.

- Soon: measurement of isospin and CP asymmetry.

The $Y(5S)$ run at Belle produces interesting new results:

- First measurement of a radiative penguin decay of the $B_s$ meson:

$$\mathcal{B}(B_s \rightarrow \phi\gamma) = (5.7^{+1.8}_{-1.5} +1.2^{+1.7}_{-1.7}) \times 10^{-5}$$

- Six times better upper limit on $\mathcal{B}(B_s \rightarrow \gamma\gamma) < 8.6 \times 10^{-6}$

More constraints on new physics to come before LHC!
Backup slides
In background events, the high energy photon comes mostly from \(\pi^0 \to \gamma \gamma\) or \(\eta \to \gamma \gamma\) decays.

Strategy:

- Combine high-energy photon with all other photons in the event.
- Build 2-dim PDF from invariant two-photon mass and second photon energy.
- Construct likelihoods for signal and background.
- Cut on likelihood ratios.
Sensitive to the Unitarity Triangle angle alpha:

\[ \alpha \equiv \arg \left( -\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right) \]

Thus:

Isospin violation between \( \rho^+\gamma \) and \( \rho^0\gamma \):

\[ \frac{\Gamma(B^+ \to \rho^+\gamma)}{2\Gamma(B^0 \to \rho^0\gamma)} - 1 \sim \cos \alpha \]
## Systematics

<table>
<thead>
<tr>
<th>Source of error</th>
<th>$\rho^+\gamma$</th>
<th>$\rho^0\gamma$</th>
<th>$\omega\gamma$</th>
<th>$\rho\gamma$</th>
<th>$(\rho/\omega)\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking efficiency</td>
<td>1.0</td>
<td>2.0</td>
<td>2.0</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Particle identification</td>
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<td>4.0</td>
<td>2.0</td>
<td>2.9</td>
<td>2.7</td>
</tr>
<tr>
<td>Photon selection</td>
<td>1.9</td>
<td>2.6</td>
<td>1.7</td>
<td>2.2</td>
<td>2.1</td>
</tr>
<tr>
<td>$\pi^0$ reconstruction</td>
<td>3.0</td>
<td>-</td>
<td>3.0</td>
<td>1.9</td>
<td>2.5</td>
</tr>
<tr>
<td>$\pi^0$ and $\eta$ veto</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>$NN$ efficiency</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$NN$ shape</td>
<td>0.4</td>
<td>0.3</td>
<td>2.3</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Signal PDF shapes</td>
<td>4.8</td>
<td>3.3</td>
<td>2.4</td>
<td>3.1</td>
<td>2.6</td>
</tr>
<tr>
<td>$B$ background PDFs</td>
<td>3.9</td>
<td>2.9</td>
<td>9.7</td>
<td>2.6</td>
<td>2.7</td>
</tr>
<tr>
<td>$B\bar{B}$ sample size</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>$B(\omega \rightarrow \pi^+\pi^-\pi^0)$</td>
<td>-</td>
<td>-</td>
<td>0.8</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Sum in quadrature</td>
<td>8.1</td>
<td>7.4</td>
<td>11.6</td>
<td>6.7</td>
<td>6.7</td>
</tr>
</tbody>
</table>
Projections to all 4 dimensions:

- **$\Delta E$**
  - BABAR
- **$m_{ES}$**
  - BABAR
- **$\rho^0 \gamma$**
- **Helicity**
  - BABAR

Use 4 dimensions (5 for $\omega \gamma$)
Belle running at the Y(5S)

From: J. Wicht, EPS HEP2007, Manchester, UK

- Beam energies increased by 2.7%
  - smooth running!
- Two samples:
  - June 2005: 1.86 fb\(^{-1}\).
  - June 2006: 21.7 fb\(^{-1}\).
- Today's results: 23.6 fb\(^{-1}\).

\[ \sigma_{bb}^{Y(5S)} = (0.302 \pm 0.015) \text{ nb} \]
\[ f_s = (19.5^{+3.0}_{-2.3})\% \]
PDG2007
\[ f_{B^*_sB^*_s} = (93^{+7}_{-9})\% \]

N\(_{B_s}\) (23.6 fb\(^{-1}\)) = 2.6x10\(^6\)
\(~20\% uncertainty\)

Belle running at the Y(5S)