Measurement of the branching fraction of $B \to X_s \gamma$ and $A_{CP}$ in $B \to X_{s+d} \gamma$ from Belle

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Introduction

- Electroweak penguins: $b \rightarrow s/d\gamma$ are FCNC, forbidden at tree level
- Observables: $BF$, $A_{CP}$, $A_{FB}$, Isospin asymmetry
  - Could be modified by new physics
- Precise SM predictions for inclusive $b \rightarrow s\gamma$
  - Motives to perform semi-inclusive or inclusive analysis
- Problems: large BG, missing exclusive modes, fragmentation modeling, etc.

This talk: 2 analysis with complete $\gamma(4S')$ Belle data set of 711 fb$^{-1}$ (and 90 fb$^{-1}$ continuum)

- $\mathcal{B}(B \rightarrow X_s\gamma)$
- $A_{CP}(B \rightarrow X_{s+d}\gamma)$
**BF(B → X_sγ), semi-inclusive**

- Current theory estimate @ NNLL ($E^*_γ > 1.6$ GeV):
  \[ \mathcal{B}(B \to X_sγ)_{SM} = (3.15 \pm 0.23) \times 10^{-4} \]
  (PRL 98, 022002 (2007))

- Using signal model by Kagan-Neubert (KN) with:
  \[ m_b = 4.44 \text{ GeV}/c^2, \quad \mu^2_π = 0.750 \text{ GeV}^2 \]

\[ E^*_γ > 1.8 \text{ GeV} \]

- 1 or 3 K/Ks (at most 1 Ks)
- up to 4 π/π\(^0\) (at most 2 π\(^0\))
- at most 1 η

\[ 0.6 \leq M_{X_s} \leq 2.8 \text{ GeV}/c^2 \]

In total 38 exclusive $X_s$ states (70% of total)
Selection and signal extraction

- Veto $D$ decays → peaking bkg $B \rightarrow D^{(*)}(K\pi\pi)\rho^+(\pi^+\pi^0)$
- Continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) suppressed using a Neural Network
  - Topological and kinematic variables

- BF extracted in 19 $M_{X_s}$ bins on $M_{bc}$:
  $$M_{bc} \equiv \sqrt{E_{beam}^2 - |\vec{p}_B|^2}$$

1.4 ≤ $M_{X_s}$ ≤ 1.5 GeV

1.9 ≤ $M_{X_s}$ ≤ 2.0 GeV

Signal selection efficiency ~2.1%
\( B \to X_s \gamma \) (sum of exclusives), result

- Measured BF for:
  \[ E_\gamma^* > 1.8 \text{ GeV and } 0.6 \leq M_{X_s} \leq 2.8 \text{ GeV/c}^2 \]

\[ \mathcal{B}(B \to X_s \gamma) = (3.51 \pm 0.17 \pm 0.33) \times 10^{-4} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( BB ) counting</td>
<td>1.37</td>
</tr>
<tr>
<td>Detector response</td>
<td>2.98</td>
</tr>
<tr>
<td>Background rejection</td>
<td>3.38</td>
</tr>
<tr>
<td>( M_{bc} ) PDF</td>
<td>5.06</td>
</tr>
<tr>
<td>Hadronization model</td>
<td>6.66</td>
</tr>
<tr>
<td>Missing mode</td>
<td>1.59</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>9.3</strong></td>
</tr>
</tbody>
</table>
Extrapolation to $E_{\gamma}^* > 1.6$ GeV for comparison with theory

$$\mathcal{B}(B \to X_s \gamma) = (3.74 \pm 0.18 \pm 0.35) \times 10^{-4}$$
**CP asymmetry in $B \to X_{(s+d)}\gamma$**

\[
A_{CP} = \frac{\Gamma(\bar{B} \to f) - \Gamma(B \to f)}{\Gamma(\bar{B} \to f) + \Gamma(B \to f)}
\]

Channel | $A_{CP}$ (SM)  
--- | ---  
$B \to X_s\gamma$ | [-0.6%, +2.8%]  
$B \to X_d\gamma$ | [-62%, +14%]  
$B \to X_{s+d}\gamma$ | 0  

PRL 106, 141801 (2011)

- Cancellation due to unitarity, theory error becomes negligibly small!

\[
A_{CP,q} = \frac{\Delta_q}{2\Gamma(B \to f)} \quad \rightarrow \quad \Delta_q \propto \Im(V_{uq}V_{ub}^*V_{cq}V_{cb}^*)
\]

$\Delta_s = -\Delta_d$  


- Inclusive analysis:
  - Only reconstruct photon and charged lepton for tagging.

\[\gamma\quad B \leftarrow \gamma(4S') \rightarrow \bar{B} \rightarrow \ell^- \quad X'\]

**Using tag-lepton**

\[
A_{CP} = \frac{N^+ - N^-}{N^+ + N^-}
\]
Selection

- Photon energy: $1.7 \leq E_\gamma^* \leq 2.8$ GeV
- Charged tag-lepton: $1.10 \leq p_\ell^* \leq 2.25$ GeV/c
- Mass veto for $\pi^0(\eta) \rightarrow \gamma\gamma$
- BDT for continuum suppression:
  - Topological variables (thrust, Fox-Wolfram moments, ...)
  - Kinematic variables (missing mass, transverse energy, ...)

![Graphs showing BDT output with signal and continuum data]
Background calibration

- Calibrate $\pi/\eta$ BG: fit to reconstructed $m_{\gamma\gamma}$, correction in $p_{\pi^0/\eta}$ bins:

$$C_i = \frac{N_{on} - N_{off}}{N_{MC}}$$

Example

$2.0 \leq p_\eta \leq 2.1 \text{GeV}/c$

\begin{itemize}
  \item Signal \hspace{1cm} 21.2%
  \item $\pi^0 \rightarrow \gamma\gamma$ \hspace{1cm} 49.5%
  \item $\eta \rightarrow \gamma\gamma$ \hspace{1cm} 7.9\%
  \item Other BB \hspace{1cm} 9.0\%
  \item Continuum \hspace{1cm} 12.4\%
\end{itemize}

2nd photon is lost

Off-resonance data, 90 fb$^{-1}$, below $\Upsilon(4S)$
Wrong tag and systematic asymmetries

Effects that would affect measurement (central value) of $A_{CP}$

- Wrong tag factors: $A_{CP} = \frac{1}{1 - 2\omega} A_{CP}^{meas}$

\[ B^0 \to B^0 \chi_d = 18.7\% \]

\[ \omega = \omega_{osc} + \omega_{2nd} + \omega_{misID} \]

\[ = 0.1413 \pm 0.0052 \]

- Lepton detection: tag-and-probe in

\[ B \to X J/\Psi (\ell^+ \ell^-) \]

\[ \varepsilon^\pm = \frac{N_{pass}}{N_{pass} + N_{fail}} \]

\[ A_{det} = \frac{\varepsilon^+ - \varepsilon^-}{\varepsilon^+ + \varepsilon^-} = (0.10 \pm 0.22)\% \]

- Asymmetry in BB bkg: measured in data:

\[ E_\gamma^* < 1.7 \text{ GeV} \]

\[ A_{bkg} = \frac{N^+ - N^-}{N^+ + N^-} = (-0.14 \pm 0.78)\% \]
Subtracted $B \to X_{(s+d)} \gamma$ photon spectrum

- Background subtracted spectrum:
- Asymmetry calculated as:
  $$A_{CP}^{\text{meas}} = \frac{N^+ - N^-}{N^+ + N^-}$$
- Measure as function of $E_\gamma^*$ threshold:

<table>
<thead>
<tr>
<th>$E_\gamma^*$ thresh</th>
<th>$(A_{CP} \pm \text{stat} \pm \text{syst}) \times 10^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7 GeV</td>
<td>1.3 ± 4.4 ± 3.5</td>
</tr>
<tr>
<td>1.8 GeV</td>
<td>2.4 ± 4.3 ± 2.6</td>
</tr>
<tr>
<td>1.9 GeV</td>
<td>1.0 ± 4.1 ± 1.9</td>
</tr>
<tr>
<td>2.0 GeV</td>
<td>2.1 ± 4.0 ± 1.2</td>
</tr>
<tr>
<td>2.1 GeV</td>
<td>2.2 ± 4.0 ± 0.8</td>
</tr>
<tr>
<td>2.2 GeV</td>
<td>1.5 ± 4.0 ± 0.5</td>
</tr>
</tbody>
</table>
Result for $A_{\text{CP}}$ in $B \to X_{(s+d)} \gamma$

- Most precise measurement of $A_{\text{CP}}$
  - Statistically dominated
  - Leading systematic comes from BB bkg asymmetry
- Consistent with SM and other experiments

![Graph showing $A_{\text{CP}}$ for different experiments with $E_{\gamma}^* > 2.1$ GeV]
Summary

• Branching fraction $B \to X_s \gamma$, sum of exclusives
  – Old Belle measurement: 5.8 fb$^{-1}$ and 16 hadronic states
  – Reconstruct 38 exclusive modes
  – Systematics dominated
  – Consistent with SM: $\mathcal{B}(B \to X_s \gamma) = (3.74 \pm 0.18 \pm 0.35) \times 10^{-4}$

• First Belle measurement of CP asymmetry in $B \to X_{(s+d)} \gamma$
  – Measured as a function of $E_\gamma^*$
  – Most precise result to date, statistics dominated
  – Consistent with SM: $E_\gamma^* > 2.1\text{GeV}$ \quad $A_{\text{CP}} = (2.2 \pm 4.0 \pm 0.8) \times 10^{-2}$

• Prospects for Belle 2
  – $\text{BF}(B \to X_s \gamma)$ new studies and data samples can help to achieve a better understanding of hadronization
  – $A_{\text{CP}}(B \to X_{s+d} \gamma)$ will reduce the statistical uncertainty
BACKUP
Belle @ KEKB-B factory

- Asymmetric e+e- collider

On resonance: \( \sqrt{s} = 10.58\text{GeV} \) \( e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B} \) \( 710\text{fb}^{-1} \)

Off resonance: \( \sqrt{s} = 10.52\text{GeV} \) \( e^+e^- \rightarrow q\bar{q}(q = u, d, s, c) \) \( 90\text{fb}^{-1} \)
Wrong tag factor

\[ A_{CP}^{\text{meas}} = (1 - 2\omega) A_{CP}^{\text{true}} \]

\[ \omega = \omega_{\text{osc}} + \omega_{2nd} + \omega_{\text{misID}} \]

Oscillation probability of \( B^0 \)

\[ \omega_{\text{osc}} = \chi_d \cdot f_{00} \]

\[ \omega_{\text{osc}} = (0.0913 \pm 0.0015) \]

\[ \omega_{\text{misID}} = (0.0069 \pm 0.0034) \]

\[ \omega_{2nd} = (0.0431 \pm 0.0036) \]

Mainly \( \pi/K \) faking \( \mu \)

Semileptonic decays of charm

\[ \bar{B} \to DX \quad D \to Yl^+\nu \]
Reconstructed $B \to X_s \gamma$ modes

<table>
<thead>
<tr>
<th>Mode ID</th>
<th>Final state</th>
<th>Mode ID</th>
<th>Final state</th>
<th>Mode ID</th>
<th>Final state</th>
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<tr>
<td>2</td>
<td>$K_s\pi^+$</td>
<td>17</td>
<td>$K^+\pi^0\pi^0$</td>
<td>32</td>
<td>$K_s\eta\pi^+\pi^0$</td>
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<td>$KKK$</td>
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<tr>
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<td>$KKK_s$</td>
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<td>$K^+K^+K^-\pi^-$</td>
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<td>$K^+K^-K_s\pi^+$</td>
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<tr>
<td>8</td>
<td>$K_s\pi^+\pi^0$</td>
<td>23</td>
<td>$K^+\eta$</td>
<td>38</td>
<td>$K^+K^+K^-\pi^0$</td>
</tr>
<tr>
<td>9</td>
<td>$K^+\pi^+\pi^-\pi^-$</td>
<td>24</td>
<td>$K_s\eta$</td>
<td></td>
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</tr>
<tr>
<td>10</td>
<td>$K_s\pi^+\pi^+\pi^-$</td>
<td>25</td>
<td>$K^+\eta\pi^-$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>$K_s\pi^+\pi^0$</td>
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<td>$K_s\eta\pi^+$</td>
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<tr>
<td>12</td>
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<td>$K^+\eta\pi^0$</td>
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<td>30</td>
<td>$K_s\eta\pi^+\pi^-$</td>
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<td></td>
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</tbody>
</table>
Table 9.12: The partial branching ratio on $M_{X_s}$

<table>
<thead>
<tr>
<th>$M_{X_s}$ bin (GeV/c^2)</th>
<th>$BR (10^{-6})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6-0.7</td>
<td>-0.1±0.1±0.0</td>
</tr>
<tr>
<td>0.7-0.8</td>
<td>0.3±0.1±0.1</td>
</tr>
<tr>
<td>0.8-0.9</td>
<td>19.8±0.5±0.9</td>
</tr>
<tr>
<td>0.9-1.0</td>
<td>15.7±0.5±0.7</td>
</tr>
<tr>
<td>1.0-1.1</td>
<td>2.9±0.3±0.2</td>
</tr>
<tr>
<td>1.1-1.2</td>
<td>4.8±0.5±1.5</td>
</tr>
<tr>
<td>1.2-1.3</td>
<td>18.7±0.8±1.1</td>
</tr>
<tr>
<td>1.3-1.4</td>
<td>21.8±1.0±1.3</td>
</tr>
<tr>
<td>1.4-1.5</td>
<td>21.2±1.0±1.4</td>
</tr>
<tr>
<td>1.5-1.6</td>
<td>22.0±1.4±1.3</td>
</tr>
<tr>
<td>1.6-1.7</td>
<td>22.4±1.1±1.5</td>
</tr>
<tr>
<td>1.7-1.8</td>
<td>24.8±1.4±1.7</td>
</tr>
<tr>
<td>1.8-1.9</td>
<td>26.7±2.2±1.9</td>
</tr>
<tr>
<td>1.9-2.0</td>
<td>26.3±2.9±2.3</td>
</tr>
<tr>
<td>2.0-2.1</td>
<td>23.3±3.1±4.5</td>
</tr>
<tr>
<td>2.1-2.2</td>
<td>21.0±2.6±4.9</td>
</tr>
<tr>
<td>2.2-2.4</td>
<td>40.3±7.2±11</td>
</tr>
<tr>
<td>2.4-2.6</td>
<td>27.9±8.6±11</td>
</tr>
<tr>
<td>2.6-2.8</td>
<td>11.5±11±13</td>
</tr>
</tbody>
</table>

(a) Partial branching ratio. The first solid error is the statistical one and the second dashed error is a quadratic sum of the statistical and systematic errors.