Inclusive $B$ decays and exclusive radiative decays by Belle

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for the Belle Collaboration (Nagoya University)

11 Sep 2014
Introduction

- Electroweak/radiative $B$ decays are sensitive to new physics.
  - New particles may enter in the loop and alter physical observables.

$\mathbf{b \to s \gamma (b \to d \gamma)}$

$\mathbf{b \to s l^+ l^-}$

- In this talk:
  1. $\mathcal{B}(B \to X_s \gamma)$ with sum-of-exclusives
  2. $A_{CP}(B \to X_{s+d} \gamma)$
  3. $A_{FB}(B \to X_s l^+ l^-)$ with sum-of-exclusives

- All results are based on the complete $\Upsilon(4S)$ Belle data samples of 711 fb$^{-1}$. 

<table>
<thead>
<tr>
<th>Time [year]</th>
<th>Integrate luminosity [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td>2002</td>
<td>600</td>
</tr>
<tr>
<td>2004</td>
<td>1000</td>
</tr>
<tr>
<td>2006</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td></td>
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</tbody>
</table>
$\mathcal{B} (B \rightarrow X_s \gamma)$ with sum of exclusives

- $X_s$ reconstruction: **sum-of-exclusives approach**
  - As many $X_s$ final states as possible are reconstructed and summed to get the inclusive branching fraction.

- 38 exclusive $X_s$ states (~70% of total)

**Bkg suppression**

- Continuum $e^+ e^- \rightarrow qq$ ($q = u, d, s, c$)
  - Suppressed using a Neural Network (Topological and kinematic variables)
- Peaking bkg from $D$ decays: $B \rightarrow D^{(*)} \rightarrow \rho^+ \rightarrow \pi^+ \pi^0$
Signal extraction

- Branching fraction is extracted by $M_{bc}$ fit in 19 $M_{Xs}$ bins
  
  - $M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - |\vec{p}_B|^2}$
  
  - $0.6 < M_{Xs} < 2.8$ GeV/c$^2$
Result of $\mathcal{B}(B \to X_s \gamma)$

- With $M_{X_s} < 2.8$ GeV/c$^2$ ($E_\gamma > 1.9$ GeV)

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

- Calibration of $X_s$ hadronization
  - Signal efficiency depends on model.
  - Pythia parameters are tuned by comparing data with MC.

- Missing modes uncertainty
  - Estimated using different Pythia parameters

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B\bar{B}$ 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>Total</td>
<td>9.3</td>
</tr>
</tbody>
</table>
• Extrapolated BF to $E_\gamma > 1.6$ GeV to compare with the SM prediction

$$\mathcal{B}(B \to X_s \gamma) = (3.74 \pm 0.18 \pm 0.35) \times 10^{-4} \ (E_\gamma > 1.6 \text{ GeV})$$ \textbf{Preliminary}

– Consistent with the SM prediction within 1.3$\sigma$.

• $\mathcal{B}(B \to X_s \gamma)_{\text{SM}} = (3.15 \pm 0.23) \times 10^{-4}$ with NNLL ($E_\gamma > 1.6$ GeV)

@ PRL 98, 022002 (2007)

Constraint to $M_{H^+}$ v.s. $\tan \beta$

Only from this result

Most precise result with sum-of-exclusives!
\[ A_{CP}(B \rightarrow X_{s+d}\gamma) = \frac{\Gamma(\bar{B} \rightarrow X_{s+d}\gamma) - \Gamma(B \rightarrow X_{s+d}\gamma)}{\Gamma(\bar{B} \rightarrow X_{s+d}\gamma) + \Gamma(B \rightarrow X_{s+d}\gamma)} \]

- Cancellation due to unitarity,
- Negligible theory error

**Inclusive analysis**

- Only reconstruct photon and charged lepton for tagging.
  - \(1.7 < E_m^* < 2.8\) GeV
  - \(1.10 < p_l^* < 2.25\) GeV/c

\[ A_{CP} = \frac{N^+ - N^-}{N^+ + N^-} \] (using tag-lepton)
Background

Background suppression

- Mass veto for $\pi^0(\eta) \rightarrow \gamma\gamma$
- BDT for continuum suppression

Background calibration

- Topological variables
- Kinematic variables
- Isolation and calorimeter variables for $\gamma$

- $\pi^0/\eta$ bkg is calibrated from MC with correction factors in momentum bins.
- Correction factor is estimated from $B \rightarrow X\pi^0/\eta$ in data and MC.
  - $C_i = \frac{N_{on} - \alpha_{off} \cdot N_{off}}{N_{MC}}$

### Signal vs. Background

<table>
<thead>
<tr>
<th>Category</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>21.2%</td>
</tr>
<tr>
<td>$\pi^0 \rightarrow \gamma\gamma$</td>
<td>49.5%</td>
</tr>
<tr>
<td>$\eta \rightarrow \gamma\gamma$</td>
<td>7.9%</td>
</tr>
<tr>
<td>Other BB</td>
<td>9.0%</td>
</tr>
<tr>
<td>Continuum</td>
<td>12.4%</td>
</tr>
</tbody>
</table>

2nd photon is lost in $1.7 < E_\gamma^* < 2.8$ GeV

Off-resonance data, 90 fb$^{-1}$, below Y(4S)

$2.0 < p_\eta < 2.1$ GeV/c
Wrong tag fraction and correction

Wrong tag factors:

- $A_{CP}^{true} = \frac{1}{1-2w} A_{CP}^{meas}$
  - $B\bar{B}$ mixing
  - lepton from $D$ decays
  - $K/\pi$ miss-identified as lepton

<table>
<thead>
<tr>
<th>factor</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$w_{oscilation}$</td>
<td>$0.0913 \pm 0.0015$</td>
</tr>
<tr>
<td>$w_{2nd-lepton}$</td>
<td>$0.0431 \pm 0.0036$</td>
</tr>
<tr>
<td>$w_{misID}$</td>
<td>$0.0069 \pm 0.0034$</td>
</tr>
<tr>
<td>$w_{(total)}$</td>
<td>$0.1413 \pm 0.0052$</td>
</tr>
</tbody>
</table>

Bias

- Asymmetry from detector
  - Lepton ID: $A_{det} = (0.11 \pm 0.07)\%$
  - Tracking: $A_{det} = (-0.01 \pm 0.21)\%$

- Asymmetry from BB bkg: $A_{bkg} = (-0.14 \pm 0.78)\%$

→ Measured $A_{CP}^{meas}$ is corrected for wrong tags and bias.
Photon spectrum in $B \rightarrow X_{s+d} \gamma$

- Measure as function of $E_\gamma$ threshold.
  - Statistically dominated
  - Leading systematic comes from BB bkg asymmetry
- Stable for different thresholds
Result of $A_{CP}(B \rightarrow X_{s+d}\gamma)$

- $A_{CP}(B \rightarrow X_{s+d}\gamma) = (2.23 \pm 4.02 \pm 0.78\%)$
  - Consistent with SM.
  - Most precise measurement of $A_{CP}$.
$A_{FB}(B \rightarrow X_s l^+ l^-)$ with sum of exclusive

- Forward-backward Asymmetry ($A_{FB}$) can be expressed with three Wilson coefficients ($C_7, C_9, C_{10}$).

\[ A_{FB} \equiv \frac{N(\cos \theta > 0) - N(\cos \theta < 0)}{N(\cos \theta > 0) + N(\cos \theta < 0)} \propto -\text{Re} \left[ \left( 2C_\text{eff}^7 + \frac{q^2}{m_b^2} C_\text{eff}^9 \right) C^{*}_{10} \right] \]

- $l^+l^-$: $e^+e^-$ or $\mu^+\mu^-$

- $X_s := K^\pm/K_S + \text{up to } 4\pi \text{ (at most } 1\pi^0 \text{)}$
  
  \[
  \begin{align*}
  \begin{bmatrix} K \\ K \pi \end{bmatrix} & : K, K_S \\
  \begin{bmatrix} K\pi \\ K\pi \end{bmatrix} & : K\pi, K_S\pi, K\pi^0, K_S\pi^0 \\
  \begin{bmatrix} K2\pi \end{bmatrix} & : K2\pi, K_S2\pi, K\pi\pi^0, K_S\pi\pi^0 \\
  \begin{bmatrix} K3\pi \end{bmatrix} & : K3\pi, K_S3\pi, K2\pi\pi^0, K_S2\pi\pi^0 \\
  \begin{bmatrix} K4\pi \end{bmatrix} & : K4\pi, K_S4\pi, K3\pi\pi^0, K_S3\pi\pi^0
  \end{align*}
  \]

- $M_{X_s} < 2.0 \text{ GeV/c}^2$

- 10 flavor specific states for $A_{FB}$ measurement ($\sim 50\%$ of total).
- Neural network for suppression of continuum and BB bkg.
- Veto Charmonium: $J/\Psi$ and $\Psi(2S)$. 
Signal extraction

- Divide data into $4q^2$ regions to perform a fit.
- Correct $A_{FB}^{raw}$ to $A_{FB}^{true}$.

\[ A_{FB}^{true} = \alpha^{\mu\mu} \times A_{FB}^{raw,\mu\mu} = \alpha^{ee} \times \beta \times A_{FB}^{raw,ee} \]

\( \alpha \): scale factor due to rec. efficiency
\( \beta \): correction due to different Charmonium veto range.

- \( \alpha \) is derived using MC with various sets of $C_7, C_9, C_{10}$

\[ B \rightarrow X_s e^+ e^+ \]

\[ B \rightarrow X_s \mu^+ \mu^+ \]

Rec. Eff.
Fitting for $A_{FB}(B \rightarrow X_s l^+ l^-)$

- Unbinned maximum likelihood fit to $M_{bc}$ for each $q^2$ bin.

  Sum of all $q^2$ bin

- Dominant systematics
  - $\alpha$ correction, peaking bkg.

\[
\begin{align*}
B \rightarrow X_s e^+ e^- & \quad \text{forward} \\
B \rightarrow X_s e^+ e^- & \quad \text{backward} \\
B \rightarrow X_s \mu^+ \mu^- & \quad \text{forward} \\
B \rightarrow X_s \mu^+ \mu^- & \quad \text{backward}
\end{align*}
\]

- Total
  - Signal + cross feed
  - Non-peaking B.G.
  - Peaking B.G.

1. Leakage from $B \rightarrow J/\Psi (\Psi(2S)) X_s$ veto.
2. Double miss ID from $B \rightarrow D^{(*)} n\pi$
3. Swapped mis ID in $B \rightarrow J/\Psi (\Psi(2S)) X_s$
Result of $A_{FB}(B \to X_S l^+ l^-)$

- $A_{FB}$ are consistent with the SM.
  - The deviation of the 1$^{\text{st}}$ bin is 1.8$\sigma$.
  - Exclude $A_{FB} < 0$ at $q^2 > 10.2$ GeV$^2$/c$^2$ at 2.3$\sigma$.
- First measurement of inclusive $A_{FB}$ with sum-of-exclusives

![Graph showing the result of $A_{FB}$ vs. $q^2$]

*arXiv:1402.7134; submitted to PRL*
Summary

- $\mathcal{B}(B \to X_s \gamma)$ with sum-of-exclusives
  - Extrapolated BF to $E_\gamma > 1.6$ GeV
    $$\mathcal{B}(B \to X_s \gamma) = (3.74 \pm 0.18 \pm 0.35) \times 10^{-4}$$
  - Most precise result with sum-of-exclusives

- $A_{CP}(B \to X_{s+d} \gamma)$
  - $A_{CP}(B \to X_{s+d} \gamma) = (2.23 \pm 4.02 \pm 0.78)\%$
  - Most precise result.

- $A_{FB}(B \to X_s l^+ l^-)$ with sum-of-exclusives
  - Exclude $A_{FB} < 0$ at $q^2 > 10.2$ GeV$^2$/c$^2$ at $2.3\sigma$.
  - First measurement of inclusive $A_{FB}$ with sum-of-exclusives