Time-dependent CP violation in $b \to s \gamma$ transitions at Belle II
Outline

1. Motivation
2. Time-dependant evolution
3. Analysis strategies
4. Electroweak FCNCs
5. TDCPV of $B^0 \rightarrow K^0_S \pi^0 \gamma$
6. $K^0_S$ reconstruction
7. Photon polarization
8. Predictions for Belle II
9. Summary
Motivation:

In Standard Model \( b \to s \gamma \) depend on \( b \) flavor

\[
\begin{align*}
{b} & \quad \rightarrow \quad s \ Y_L \\
\bar{b} & \quad \rightarrow \quad \bar{s} \ Y_R
\end{align*}
\]

❖ allowed
❖ suppressed by \( m_s/m_b \)

Presence of significant mixing-induced CP violation would indicate the presence of right handed currents and clear hint of new physics.

- This type of new physics does not require a new phase.
1. Fully reconstructed one of B mesons which decays to CP eigenstates
2. Tag-side determines its flavour (efficiency ≈ 30%)
3. Proper time ($\Delta t$) is measured from decay-vertex difference ($\Delta z$).
### Inclusive analysis strategies for $b \rightarrow X_s \gamma$

#### Fully inclusive:
- Exploit clean decay environment on Belle II
- Can be fully hadronic tag (have full event information)
- ...or semi-leptonic tag (don't have full event)

#### Sum-of-exclusives:
- Reconstruct, the 'X' from many exclusive decays:
  \[ X_s \rightarrow K\pi\pi, 3K\pi\pi, K\eta\pi \\] (n>1, m≥1)
- Know flavor of B
- Know isospin

<table>
<thead>
<tr>
<th>reco. method</th>
<th>tagging</th>
<th>effi.</th>
<th>$S/B$</th>
<th>$q$</th>
<th>$p_B$</th>
<th>$A_{CP}$</th>
<th>$\Delta_{0+}$</th>
<th>$\Delta A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>sum-of-exclusive</td>
<td>none</td>
<td>high</td>
<td>moderate</td>
<td>$s$ or $d$</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>fully-inclusive</td>
<td>had. $B$</td>
<td>very low</td>
<td>very good</td>
<td>$s$ and $d$</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>SL $B$</td>
<td>very low</td>
<td>very good</td>
<td>$s$ and $d$</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>moderate</td>
<td>good</td>
<td>$s$ and $d$</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>none</td>
<td>very high</td>
<td>very bad</td>
<td>$s$ and $d$</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>
Electroweak FCNCs

We can write the amplitude including RH contribution as:

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O_i(\mu) \]

We have a constraint from inclusive branching ratio measurement:

\[ \mathcal{M}(b \rightarrow s\gamma) \simeq -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left( C_{7\gamma}^{\text{SM}} + C_{7\gamma}^{\text{NP}} \langle \mathcal{O}_{7\gamma} \rangle + C_{7\gamma}^{\text{NP}} \langle \mathcal{O}'_{7\gamma} \rangle \right) \propto \mathcal{M}_L \]

\[ \mathcal{M}_R \simeq C_{7\gamma}^{\text{NP}} \]

We have a constraint from inclusive branching ratio measurement:

\[ Br(B \rightarrow X_s\gamma) \propto |C_{7\gamma}^{\text{SM}} + C_{7\gamma}^{\text{NP}}|^2 + |C_{7\gamma}^{\text{NP}}|^2 \]

The polarization measurement carries information on

\[ \frac{\mathcal{M}_R}{\mathcal{M}_L} \simeq \frac{C_{7\gamma}^{\text{NP}}}{C_{7\gamma}^{\text{SM}} + C_{7\gamma}^{\text{NP}}} \]

Wilson coefficients
(calculated perturbatively; encode short-distance physics)

Products of field operators
(non-perturbative hadronic matrix elements; Heavy quark expansion in inverse powers of \( m_b \))
Time dependent CP violation analysis of $B^0 \rightarrow K^0_S \pi^0 \gamma$

Prediction:

Current world average:

- $b \rightarrow s \gamma_R$ is helicity suppressed ($m_s/m_b$) wrt $b \rightarrow s \gamma_L$
- $B^0 \rightarrow f_{CP} \gamma_R$ interferes with $B^0 \rightarrow B^0\text{-bar} \rightarrow f_{CP} \gamma_R$ only for helicity suppressed $b \rightarrow s \gamma_R$ decay
- TDCPV analysis is sensitive to the decay rate of $b$ into “wrongly” polarized $\gamma$.
- New physics can enhance the $b \rightarrow s \gamma_R$ decay rate

BaBar ($N_{BB} = 467 \times 10^6$) [PRD 78 (2008) 071102]
Belle ($N_{BB} = 535 \times 10^6$) [PRD 74 (2006) 111104(R)]
**$K^0_s$ reconstruction**

- The reconstruction of $K^0_s$ is the only source of information to determine the vertex position of $B^0_{\text{sig}}$.

- The channel of $K^0_s$ reconstruction is $K^0_s \rightarrow \pi^+ \pi^-$

- The $K^0_s$ flight direction is extrapolated backwards and matched to the estimated region in which the $e^+ e^-$ collisions take place.

*Table*

<table>
<thead>
<tr>
<th>$K^0_s$</th>
<th>$\pi^0$</th>
<th>$\gamma$</th>
<th>$B^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon^{\text{reco}}$</td>
<td>58.6%</td>
<td>53.7%</td>
<td>83.4%</td>
</tr>
</tbody>
</table>
Photon polarization

Indirect probe of photon polarization by measuring:

\[ A_{CP}(t) \equiv \frac{\Gamma(B(t) \to f_{CP}\gamma) - \Gamma(B(t) \to f_{CP}\gamma)}{\Gamma(B(t) \to f_{CP}\gamma) + \Gamma(B(t) \to f_{CP}\gamma)} \approx -2 \left( \frac{m_\gamma}{m_\rho} \right) \sin(2\beta) \sin(\Delta m t) \]

Photon polarization


- \( B^0 \to X_s \gamma_R \)
- \( \overline{B}^0 \to X_s \gamma_L \)

If a helicity flip occurs, the photon will also flip its helicity, producing \( B^0 \to X_s \gamma_L \).

No common final state for \( B^0 \) and \( \overline{B}^0 \)-bar

- Suppression of asymmetry \( S \) due to interference between \( B^0 \) mixing and decay diagrams
- TD CP asymmetry measurements give an indirect measurement of photon polarization.
Predictions for Belle II

### Observables

<table>
<thead>
<tr>
<th>Observable</th>
<th>Belle 0.71 ab⁻¹</th>
<th>Belle II 5 ab⁻¹</th>
<th>Belle II 50 ab⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Br}(B \to X_s \gamma)^\text{lep-tag}$</td>
<td>5.3%</td>
<td>3.9%</td>
<td>3.2%</td>
</tr>
<tr>
<td>$\text{Br}(B \to X_s \gamma)^\text{had-tag}$</td>
<td>13%</td>
<td>7.0%</td>
<td>4.2%</td>
</tr>
<tr>
<td>$\text{Br}(B \to X_s \gamma)^\text{sum-of-ex}$</td>
<td>10.5%</td>
<td>7.3%</td>
<td>5.7%</td>
</tr>
<tr>
<td>$\Delta_0^+(B \to X_s \gamma)^\text{sum-of-ex}$</td>
<td>2.1%</td>
<td>0.81%</td>
<td>0.63%</td>
</tr>
<tr>
<td>$\Delta_0^+(B \to X_{s+d}\gamma)^\text{had-tag}$</td>
<td>9.0%</td>
<td>2.6%</td>
<td>0.85%</td>
</tr>
<tr>
<td>$A_{\text{CP}}(B \to X_s \gamma)^\text{sum-of-ex}$</td>
<td>1.3%</td>
<td>0.52%</td>
<td>0.19%</td>
</tr>
<tr>
<td>$A_{\text{CP}}(B^0 \to X_s^0 \gamma)^\text{sum-of-ex}$</td>
<td>1.8%</td>
<td>0.72%</td>
<td>0.26%</td>
</tr>
<tr>
<td>$A_{\text{CP}}(B^+ \to X_s^+ \gamma)^\text{sum-of-ex}$</td>
<td>1.8%</td>
<td>0.69%</td>
<td>0.25%</td>
</tr>
<tr>
<td>$A_{\text{CP}}(B \to X_{s+d}\gamma)^\text{lep-tag}$</td>
<td>4.0%</td>
<td>1.5%</td>
<td>0.48%</td>
</tr>
<tr>
<td>$A_{\text{CP}}(B \to X_{s+d}\gamma)^\text{had-tag}$</td>
<td>8.0%</td>
<td>2.2%</td>
<td>0.70%</td>
</tr>
<tr>
<td>$\Delta A_{\text{CP}}(B \to X_s \gamma)^\text{sum-of-ex}$</td>
<td>2.5%</td>
<td>0.98%</td>
<td>0.30%</td>
</tr>
<tr>
<td>$\Delta A_{\text{CP}}(B \to X_{s+d}\gamma)^\text{had-tag}$</td>
<td>16%</td>
<td>4.3%</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

### Table: WA (2017) Cross-Sections

<table>
<thead>
<tr>
<th>Channel</th>
<th>WA (2017)</th>
<th>5 ab⁻¹</th>
<th>50 ab⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi K^0$</td>
<td>0.022</td>
<td>0.021</td>
<td>0.012</td>
</tr>
<tr>
<td>$\phi K^0$</td>
<td>0.12</td>
<td>0.14</td>
<td>0.048</td>
</tr>
<tr>
<td>$\eta' K^0$</td>
<td>0.06</td>
<td>0.04</td>
<td>0.032</td>
</tr>
<tr>
<td>$\omega K^0$</td>
<td>0.21</td>
<td>0.14</td>
<td>0.08</td>
</tr>
<tr>
<td>$K_S^0 \pi^0 \gamma$</td>
<td>0.20</td>
<td>0.12</td>
<td>0.10</td>
</tr>
<tr>
<td>$K_S^0 \eta^0$</td>
<td>0.17</td>
<td>0.10</td>
<td>0.09</td>
</tr>
</tbody>
</table>

### Diagram: $K^+ \gamma S_{\text{CP}}$ vs $C_{\text{CP}}$
Summary

1. Belle II provides a large dataset + improved detector and physics software (Flavor tagging and Vertex reconstruction).
2. Unique possibilities for modes with final state with neutral particles ($\pi^0, \gamma$)
3. For $b \rightarrow s \gamma$ transitions we can safely assume that all the channels will be dominated by the statistical uncertainties.
4. For most of the penguin dominated modes Belle II is projected to reduce the WA errors by a factor of:
   - 2 to 3 already with 5 ab$^{-1}$
   - 8 with 50 ab$^{-1}$
Backup
Belle II Nano-Beam

KEKB Achieved | SuperKEKB
---|---
RF frequency f [MHz] | 508.9
# of Bunches N | 1584
Horizontal emittance εx [nm] | 18
Beta at IP βx*/βy* [mm] | 1200/5.9 | 32/0.27 | 25/0.30
beam-beam param. 〈y | 0.129 | 0.090 | 0.088 | 0.081
Bunch Length Sz [mm] | 6.0
Horizontal Beam Size sx* [μm] | 150
Vertical Beam Size sy* [nm] | 0.94
Half crossing angle φ [mrad] | 11
Beam energy Eb [GeV] | 3.5 | 8 | 4 | 7.007
Beam currents lb [A] | 1.64 | 1.19 | 3.6 | 2.6
Lifetime t [min] | 133
Luminosity L [cm⁻²s⁻¹] | 2.1 x 10³⁴ | 8 x 10³⁵
Interaction vertex

- Distribution of the longitudinal component of the interaction vertex is much smaller than the bunch length.

- The nano beam scheme is working!