Radiative $B$ Meson Decays at Belle and Belle II

Markus Röhrken
DESY

On behalf of the Belle and Belle II Collaborations

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Overview

- Belle II BF measurement of $B \rightarrow K^*\gamma$ decays.
- Comparison to Belle’s $B \rightarrow K^*\gamma$ measurement.
- Prospects on time-dependent measurements of $B \rightarrow K^*\gamma$ at Belle II.
- Measurement of the direct $CP$ asymmetry of inclusive $B \rightarrow X_s\gamma$ decays with a lepton tag at Belle.
- Untagged analysis and photon energy spectrum of inclusive $B \rightarrow X_s\gamma$ decays at Belle II.
- Prospect of inclusive $B \rightarrow X_s\gamma$ measurements at Belle II.
Introduction to Radiative $B$ Meson Decays

• Rare heavy flavor decays mediated by radiative penguin transitions provide sensitive probes for physics BSM:

Radiative SM penguin  Examples of new physics entering the loops

• Sensitive to Wilson coefficients $C_7$ and $C_7'$.

• Observables:
  o Branching fractions: $|C_7|^2 + |C_7'|^2$
  o Direct $CP$ asymmetries: $\text{Im}(C_7)$
  o Mixing-induced $CP$ asymmetries
    + angular observables: $C_7'$
    (Right-handed currents, photon polarization)
  o Isospin asymmetries: Long distance effects.
  o Inclusive photon energy spectra: $m_b$
  o …

• Various analysis approaches:
  o Exclusive decays (e.g. $B \rightarrow K^*\gamma$)
  o Sum-of-exclusive (adding many modes)
  o Inclusive $B \rightarrow X_s\gamma$

• Global fits:

Global fits. Examples of new physics entering the loops.
The KEKB collider and the Belle experiment have been operated as an asymmetric-energy $B$ factory until 2010.

To date, Belle provides the largest data sample of $B$ mesons produced in $e^+e^-$ annihilations.

The KEKB collider and the Belle detector have been upgraded to SuperKEKB and Belle II, that are designed to operate at 40x higher instantaneous luminosity.
The Belle II Experiment

KL and muon detector:
- Resistive Plate Counter (barrel outer layers)
- Scintillator + WLSF + MPPC (end-caps)

Particle Identification
- Time-of-Propagation counter (barrel)
- Prox. focusing Aerogel RICH (twd)

Electrons (7 GeV)

Beryllium beam pipe
- 2 cm diameter

Vertex Detector
- 2 layers DEPFET + 4 layers DSSD

Central Drift Chamber
- He(50%):C$_2$H$_6$(50%), small cells, long lever arm, fast electronics

EM Calorimeter:
- CsI(Tl), waveform sampling (barrel)

Positrons (4 GeV)

[SupperKEKB, Belle II TDR, arXiv:1011.0352]
Exclusive Radiative $B$ Decays
Belle II Measurement of $B \to K^* \gamma$

- Belle II performed a BF measurement of exclusive $B \to K^* \gamma$ decays using 62.8 fb$^{-1}$. [BELLE2-CONF-PH-2021-014]

- Neutral and charged $B$ mesons are reconstructed in 4 decay modes, by combination of $K^*$ mesons with hard $\gamma$'s.

\[
\begin{align*}
B^0 & \to K^{*0} \left[ K^+ \pi^- \right] \gamma \\
B^+ & \to K^{*+} \left[ K^+ \pi^0 \right] \gamma \\
B^0 & \to K^{*0} \left[ K_S^0 \pi^0 \right] \gamma \\
B^+ & \to K^{*+} \left[ K_S^0 \pi^+ \right] \gamma
\end{align*}
\]

- The dominant sources of background are $e^+e^- \to q\bar{q} (q = u, d, s, c)$ continuum events and photons from the decays of light neutral hadrons like $\pi^0$ and $\eta$ mesons.

  - The continuum background is suppressed using a BDT trained on event shape variables.

  - The photons from $\pi^0$ and $\eta$ decays are veto-ed by a MVA classifier trained on kinematic variables.
Belle Measurement of $B \rightarrow K^* \gamma$

- $B \rightarrow K^* \gamma$ measurement by Belle using $772 \times 10^6 B \bar{B}$.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_B^{\ell}$</th>
<th>$N_S^{\ell}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K_S^0 \pi^0 \gamma$</td>
<td>$349 \pm 23 \pm 15$</td>
<td></td>
</tr>
<tr>
<td>$B^0 \rightarrow K^+ \pi^- \gamma$</td>
<td>$2295 \pm 56 \pm 27$</td>
<td>$2339 \pm 56 \pm 30$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+ \pi^0 \gamma$</td>
<td>$572 \pm 32 \pm 12$</td>
<td>$562 \pm 31 \pm 11$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K_S^0 \pi^+ \gamma$</td>
<td>$745 \pm 32 \pm 8$</td>
<td>$721 \pm 32 \pm 9$</td>
</tr>
</tbody>
</table>

- Evidence for isospin violation at the 3.1σ level.
- Belle results still more precise than Belle II to date.
Belle II Measurement of $B \to K^\ast \gamma$

- The signal is extracted by unbinned ML fits to the $\Delta E$ distributions (with $\Delta E = E_B^\ast - E_{\text{beam}}^\ast$):
  - Signal: Cruijff + Gaussian functions.
  - Self-cross-feed (SCF): Cruijff.
  - Continuum bkg.: Chebyshev polynomial.
  - Partially reconstructed $B$ decays: Gaussian

- Belle II using 62.8 fb$^{-1}$:

- The results agree with the world averages at the 1-2$\sigma$ level:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Signal yield</th>
<th>Efficiency (%)</th>
<th>$B_{\text{meas}} \ 10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to K^{*0}[K^+\pi^-]\gamma$</td>
<td>454 ± 28</td>
<td>15.22 ± 0.03</td>
<td>4.5 ± 0.3 ± 0.2</td>
</tr>
<tr>
<td>$B^0 \to K^{*0}[K_S^0\pi^0]\gamma$</td>
<td>50 ± 10</td>
<td>1.73 ± 0.01</td>
<td>4.4 ± 0.9 ± 0.6</td>
</tr>
<tr>
<td>$B^+ \to K^{*+}[K^+\pi^0]\gamma$</td>
<td>169 ± 18</td>
<td>4.84 ± 0.02</td>
<td>5.0 ± 0.5 ± 0.4</td>
</tr>
<tr>
<td>$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$</td>
<td>160 ± 17</td>
<td>4.23 ± 0.02</td>
<td>5.4 ± 0.6 ± 0.4</td>
</tr>
</tbody>
</table>

[BELLE2-CONF-PH-2021-014]
Prospects of \( B \to K^* \gamma \) Time-Dependent Measurements

- Radiative penguins \( b \to s \gamma \) provide unique probes to the photon polarization:

- \( W^- \) bosons couple only to left-handed quarks, chirality flip suppressed: 
  \[ b \to \gamma_L + \frac{m_s}{m_b} \gamma_R \]
  \[
  \rightarrow \text{Photon is dominantly left-handed (right-handed) in } b (\bar{t}) \text{ decays.}
  \]

- New physics effects can give rise to a right-handed photon polarization:

New heavy particles and flavor couplings
(SUSY, extended Higgs sector, …)

Models restoring the Left\(\leftrightarrow\)Right symmetry
and right-handed interactions \( (W_{R}^{\pm}, V_{CKM}^{R}) \).
Prospects of $B\rightarrow K^*\gamma$ Time-Dependent Measurements

- Principle of time-dependent measurements:

- Current status on time-dep. $CP$ violation:

- Prospects at Belle II:

<table>
<thead>
<tr>
<th>Observables</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>$\Delta_{0\pm}(B \rightarrow K^*\gamma)$</td>
<td>2.0%</td>
<td>0.70%</td>
<td>0.53%</td>
</tr>
<tr>
<td>$A_{CP}(B^0 \rightarrow K^{*0}\gamma)$</td>
<td>1.7%</td>
<td>0.58%</td>
<td>0.21%</td>
</tr>
<tr>
<td>$A_{CP}(B^+ \rightarrow K^{*+}\gamma)$</td>
<td>2.4%</td>
<td>0.81%</td>
<td>0.29%</td>
</tr>
<tr>
<td>$\Delta A_{CP}(B \rightarrow K^*\gamma)$</td>
<td>2.9%</td>
<td>0.98%</td>
<td>0.36%</td>
</tr>
<tr>
<td>$S_{K^{*0}\gamma}$</td>
<td>0.29</td>
<td>0.090</td>
<td>0.030</td>
</tr>
</tbody>
</table>

[The Belle II Physics Book, BELLE2-PAPER-2018-001]
Inclusive Radiative $B$ Decays
Inclusive Measurements

Several tagging techniques are possible at the $B$ factory experiments for inclusive analyses.

• Important effects:

- Tagging efficiencies, achievable signal yields
- Purities of the tagged samples
- Amount of accessible physics information

<table>
<thead>
<tr>
<th>Fully inclusive, no tagging</th>
<th>Lepton tagging</th>
<th>Semileptonic tagging</th>
<th>Hadronic tagging</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow \text{anything}$</td>
<td>$B \rightarrow lX$</td>
<td>$B \rightarrow D(\ast) \nu n \pi$</td>
<td>$B \rightarrow \text{hadrons, e.g. } B \rightarrow D(\ast) n \pi$</td>
</tr>
<tr>
<td>$\epsilon \approx \mathcal{O}(10%)$</td>
<td>$\epsilon \approx \mathcal{O}(1%)$</td>
<td>$\epsilon \approx \mathcal{O}(0.2%)$</td>
<td>$\epsilon \approx \mathcal{O}(0.1%)$</td>
</tr>
</tbody>
</table>

Measurement of the Direct CP Asymmetry w/ a Lepton Tag by Belle

- Belle performed a measurement of the direct CP asymmetry in $\bar{B} \rightarrow X_{s+d}\gamma$ decays with a lepton tag.

- Reconstruct only one high-energetic photon on the signal side.

- From the tagging side, reconstruct only the high-momentum lepton from the second $B$ meson from the $\Upsilon(4S)$ decay.

- The $B$ flavor can be inferred from the charge of the lepton.

- Definition of the direct CP asymmetry:

$$A_{CP}(\bar{B} \rightarrow X_{s+d}\gamma) \equiv \frac{\Gamma(\bar{B} \rightarrow X_{s+d}\gamma) - \Gamma(B \rightarrow X_{\bar{s}+\bar{d}}\gamma)}{\Gamma(\bar{B} \rightarrow X_{s+d}\gamma) + \Gamma(B \rightarrow X_{\bar{s}+\bar{d}}\gamma)}$$

- In the SM, the direct CP asymmetry is predicted to vanish.

- In BSM models, the direct CP asymmetry could be as large as 10%.
The dominant background originates from $e^+e^- \rightarrow q\bar{q} \ (q = u, d, s, c)$ continuum events and is suppressed by a BDT classifier trained on event shape variables:

- The $\bar{B} \rightarrow X_{s+d}\gamma$ signal is obtained by subtracting the continuum and $B\bar{B}$ contributions:

The result using $772 \times 10^6 B\bar{B}$ is:

$$A_{CP}(\bar{B} \rightarrow X_{s+d}\gamma) = (2.2 \pm 3.9 \pm 0.9)\% \quad \text{PRL 114, 151601 (2015)}$$
Observation of Inclusive $B \to X_s \gamma$ Decays by Belle II

- Belle II performed a measurement of the inclusive $B \to X_s \gamma$ photon energy spectrum without any tagging.

- Reconstruct only the hard photon from the $B \to X_s \gamma$ decay. In the reconstruction, ignore any other particles in the event.

- Veto photons from light neutral hadrons ($\pi^0 \to \gamma \gamma$ and $\eta \to \gamma \gamma$).

- Suppress continuum background using global event shape variables.

- The remaining continuum background is subtracted using off-resonance data.

- Estimate/subtract the $B \bar{B}$ background from MC simulations.

- Determine the photon energy spectrum.
Observation of Inclusive $B \to X_s \gamma$ Decays by Belle II

• Belle II with 62.8 fb$^{-1}$:

• An excess of events is seen in the region expected for photons from $B \to X_s \gamma$ decays.
Prospects for Inclusive $B \rightarrow X_s \gamma$ at Belle II

- Prospects:

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

Summary

• Radiative B meson decays are very sensitive to physics BSM (2HDM, SUSY, Left↔Right symmetric models, …).

• All results are in agreement with the SM.

• Belle II started producing physics results. First results on exclusive and inclusive $b \to s\gamma$ mediated decays have been presented.
Supplementary Slides
• Sensitive observables are the inclusive $B \rightarrow X_s \gamma$ decay rate and the corresponding photon energy spectra.

• Inclusive $B \rightarrow X_s \gamma$ measurements are as well important for the estimation of SM parameters like $m_b$ or $|V_{ub}|$. 