Electroweak and radiative penguin decays
at Belle II

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On behalf of the Belle II collaboration

CIPANP 2022, Aug 29 - Sep 04
- $b \to s(d)$ flavour changing neutral current transitions **not possible at tree level** in the Standard Model (SM).
- Branching fractions $\simeq 10^{-4} - 10^{-7} \Rightarrow “rare”$ decays.
- Highly sensitive to beyond-SM mediator contributions, affecting:
  - Branching fractions.
  - Angular distributions.
  - CP asymmetries.
  - Kinematics.

**Electroweak penguins:**

**Electroweak radiative penguin:**
Belle II at superKEKB (1/3)

**SuperKEKB**: 4.0 GeV $e^+$ - 7.0 GeV $e^-$ collider.

- Luminosity world record: $4.7 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$
  On June 22, 2022.

**Current status:**
- Collected 424 fb$^{-1}$ of data since 2019.
- Here we show studies based on 63 fb$^{-1}$ and 189 fb$^{-1}$ datasets.

**On-resonance data:**
- $\sqrt{s} = 10.58$ GeV.
- $\simeq 1\%$ of collisions produce $B\bar{B}$ pairs.
- Clean B sample.

**Off-resonance data:**
- 60 MeV below $\Upsilon(4S)$ resonance.
- $e^+e^- \rightarrow q\bar{q}$ events.
- Control sample for continuum background.
Belle II detector:

- Flavour universal: similar performances for electrons and muons.
- Optimized for high instantaneous luminosity.
- Collision of point-like particles and $4\pi$ detector coverage.
**Belle II at superKEKB (3/3)**

**Belle II detector:**
- Flavour universal: similar performances for electrons and muons.
- Optimized for high instantaneous luminosity.
- Collision of point-like particles and $4\pi$ detector coverage.

⇒ **Strengths:** Precision measurements, rare and partially invisible decays (ex: $B \rightarrow D \tau \bar{\nu}$). Just started a shutdown to upgrade the detector and improve the beampipe.
Some decays studied here have missing kinetic information in the final state of the signal $B$ meson (fully inclusive measurements or neutrinos in the final state).

Specific to $e^+e^-$ B-factories: use the accompanying $B$ meson (tag-side) to constrain the signal-side.

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**Purity of the tagged samples**

**Tagging efficiency**

**Inclusive tagging**

$B_{\text{tag}} \rightarrow \text{anything}$

$\varepsilon \approx \mathcal{O}(100\%)$

**Hadronic tagging**

$B_{\text{tag}} \rightarrow \text{hadrons (e.g } B \rightarrow D^* n \pi )$

$\varepsilon \approx \mathcal{O}(0.1\%)$

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The Full Event Interpretation

How to reconstruct the tag-side?

- Reconstruction using the Full Event Interpretation algorithm (FEI).
- Use final state particles to hierarchically reconstruct the most probable $B_{tag}$.
- Predefined $B$ meson decay lists are used (ex: fully hadronic decays).
- Probability of each candidate to be correct estimated by a multivariate classifier.
- Inclusive tagging does not need to use this algorithm.
Towards $R_K$, $R_{K^*}$ (1/2)

Belle II able to provide independent checks of $R_{K^*}$ anomalies ([JHEP 08(2017)055]) with enough data (few $ab^{-1}$). Here search with 189 $fb^{-1}$

$$R_{K^*} = \frac{\mathcal{B}(B \to K^* \mu^+ \mu^-)}{\mathcal{B}(B \to K^* e^+ e^-)}$$

- First step towards $R_{K^*}$: observation of $B \to K^*(892)l^+l^-$.  
- Reconstruct $K^*$ from $K^+$ or $K^0_S$ with $\pi^+$ or $\pi^0$.  
- Background suppression: dilepton mass suppression (e.g $J/\Psi \to ll$, photon conversion). Boosted Decision Tree (BDT) to suppress $e^+e^- \to q\bar{q}$.  
- Extract signal yield from 2-dimensional fit to $M_{bc}$ and $\Delta E$.  
- Precision for $e$ and $\mu$ channels in same ballpark ($\simeq 25 - 30\%$).

$$M_{bc} = \sqrt{E_{beam}^2 - p_B^*} \quad \Delta E = E_B^* - E_{beam}$$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Observed events</th>
<th>Branching Fraction ($\times 10^{-6}$)</th>
<th>World average ($\times 10^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to K^* e^+ e^-$</td>
<td>$22 \pm 6$</td>
<td>$1.42 \pm 0.48 \pm 0.09$</td>
<td>$1.19 \pm 0.20$</td>
</tr>
<tr>
<td>$B \to K^* \mu^+ \mu^-$</td>
<td>$18 \pm 6$</td>
<td>$1.19 \pm 0.31^{+0.08}_{-0.07}$</td>
<td>$1.06 \pm 0.09$</td>
</tr>
</tbody>
</table>
Towards $R_K$, $R_{K^*}$ (2/2)

Measurement of $B \rightarrow J/\Psi K$.

- Not a $b \rightarrow s$ transition, **but** an important control channel for $R_K$.
- Proceeds via a $b \rightarrow c$ tree level transition.
- Reconstruct $B^+ \rightarrow K^+ J/\Psi$ and $B^0 \rightarrow K^0_S J/\Psi$ decays with $J/\Psi \rightarrow e^+e^-/\mu^+\mu^-$.
- Signal yield extracted from fit to $M_{bc}$ and $\Delta E$.

\[
R_K(J/\Psi) = \frac{\mathcal{B}(B \rightarrow KJ/\Psi(\rightarrow \mu^+\mu^-))}{\mathcal{B}(B \rightarrow KJ/\Psi(\rightarrow e^+e^-))}
\]

\[
\epsilon_{B^+ \rightarrow K^+}/\epsilon_{B^0 \rightarrow K^0_S} = e : 30%/20%, \mu : 37%/25%.
\]

<table>
<thead>
<tr>
<th>Observable</th>
<th>Belle II</th>
<th>Belle (2021)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{K^+}(J/\Psi)$</td>
<td>$1.009 \pm 0.022 \pm 0.008$</td>
<td>$0.0994 \pm 0.011 \pm 0.010$</td>
</tr>
<tr>
<td>$R_{K^0_S}(J/\Psi)$</td>
<td>$1.042 \pm 0.042 \pm 0.008$</td>
<td>$0.0993 \pm 0.015 \pm 0.010$</td>
</tr>
</tbody>
</table>

[JHEP, 03, 105 (2021)]
Complementary to $b \rightarrow sll$. Avoids some theoretical uncertainties (no amplitude with virtual photon).

- **Challenges:**
  - Rare: $Br_{SM} = (4.6 \pm 0.5) \times 10^{-6}$ [arXiv: 1606.00916].
  - Two neutrinos in the final state $\Rightarrow$ unique to Belle II.
  - Previous analyses used tagged approaches: low efficiency.
    - No signal observed thus far.
    - $Br(B^+ \rightarrow K^+ \nu \bar{\nu}) < 1.6 \times 10^{-5}$ at 90% CL.
  - Here, an inclusive approach is used to search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ with 63 fb$^{-1}$.
    - **Single candidate:** single highest $p_T$ kaon track
    - **Rest of event:** remaining tracks and energy deposits (tag-side B meson).
    - Use two sequential BDTs trained on kinematics, event-topology, vertexing, etc. to suppress background.
- BDT performance on data tested using $B^+ \rightarrow K^+ J/\Psi (\mu^+ \mu^-)$.
- Signal from maximum likelihood fit in bins of $p_T(K^+)$ and BDT output.
- No statistically significant signal observed.
- Upper limit at 90% CL: $Br(B^+ \rightarrow K^+ \nu\bar{\nu}) < 4.1 \times 10^{-5}$.
- Belle II capable of providing world-leading measurements in the near future.
$B \to X_s \gamma$ with hadronic tagging (1/3)

$b \to s \gamma$ has higher rates and is sensitive differently to NP compared to $b \to s \nu \bar{\nu}$.
All $b \to s \gamma$ final states are considered ⇒ inclusive search. In addition to studying NP ($H^\pm$ mass), allows to extract:

- Several SM parameters (e.g. $m_b$) [RevModPhys.88.035008].
- Shape function describing the motion of $b$-quark inside $B$ meson [PRL 127, 102001].

Measurement:

- Inclusive measurement: only photon constrained on signal side.
- Large background contribution ⇒ challenging to suppress without losing "inclusiveness".
- Tag-side $B$ meson reconstructed with hadronic tagging ⇒ high purity sample, direct access to $E_B^\gamma$, photon energy in $B$ rest frame.
- Hadronic tagged study performed once by BaBar (210 fb$^{-1}$) [PRD 77, 051103].
\( B \to X_s \gamma \) with hadronic tagging (2/3)

- **Signal candidate**: Highest energy photon in event, \( E^B_\gamma > 1.4 \) GeV.
- **General background suppression**: BDT trained to suppress events compatible with \( e^+ e^- \to q\bar{q} \).
  \( \Rightarrow \) only use features uncorrelated to \( E^B_\gamma \) and \( M_{bc} \).
- **Signal-side background suppression (photon)**: Veto \( \eta \to \gamma\gamma \) and \( \pi^0 \to \gamma\gamma \).
- **Tag-side background suppression**: \( B_{tag} \) \( M_{bc} \) fits in bins of \( E^B_\gamma \) \( \Rightarrow \) correctly tagged events count.

Selection and fit validated on \( 1.4 < E^B_\gamma < 1.8 \) GeV.
$B \to X_s \gamma$ with hadronic tagging (3/3)

Still correctly tagged non-$B \to X_s \gamma$ background remaining.

⇒ Simulation used to estimate the size of this background.

<table>
<thead>
<tr>
<th>$E^B_\gamma$ threshold, GeV</th>
<th>Branching fraction ($\times 10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>3.54 ± 0.78 ± 0.83</td>
</tr>
<tr>
<td>2.0</td>
<td>3.06 ± 0.56 ± 0.47</td>
</tr>
</tbody>
</table>

- Main systematic effect comes from background data/simulation discrepancies.
- **Competitive with BaBar (210 fb$^{-1}$) measurement:**

  $3.66 \pm 0.55 \pm 0.60 \times 10^{-4}$ ($E^B_\gamma > 1.9$ GeV) [PRD 77, 051103]

- **Consistent with world average:** 3.49 ± 0.19 $\times 10^{-4}$
Summary

- $b \rightarrow s$ transitions are powerful tools to probe the SM.
- Belle II is at the center of the studies on these modes, thanks to its unique access to radiative and missing energy modes.

Measurements presented:

- $B \rightarrow K^* l^+ l^-$ and $B \rightarrow K J/\Psi$ ⇒ **First steps towards $R_K$.** (189 fb$^{-1}$)
- $B^+ \rightarrow K^+ \nu \bar{\nu}$ ⇒ **New approach, upper limit on branching fraction.** (63 fb$^{-1}$)
- $B \rightarrow X s \gamma$ ⇒ **First Belle II inclusive measurement of the branching fraction** (189 fb$^{-1}$)

Belle II will provide new exciting EW and Radiative penguins measurements using the full data collected before shutdown.

⇒ **Stay tuned !**
Thank you for listening!
Measurement of $B \to K^* \ell \ell$

$B \to K^* \mu^+ \mu^-$

$B \to K^* e^+ e^-$

Belle II (Preliminary)
\[ \int L \, dt = 189 \, fb^{-1} \]

Entries / [0.0033 GeV/c^2]

$M_{bc}$ [GeV/c^2]

Entries / [0.0078 GeV]

$\Delta E$ [GeV]

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Measurement of $B \rightarrow K^* l l$

$B \rightarrow K^* l^+ l^-$
Measurement of $B \rightarrow K^{*}\ell\ell$

<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>$R_K$ ([1.0, 6.0] GeV$^2$)</td>
<td>28%</td>
<td>11%</td>
<td>3.6%</td>
</tr>
<tr>
<td>$R_K$ (&gt; 14.4 GeV$^2$)</td>
<td>30%</td>
<td>12%</td>
<td>3.6%</td>
</tr>
<tr>
<td>$R_{K^*}$ ([1.0, 6.0] GeV$^2$)</td>
<td>26%</td>
<td>10%</td>
<td>3.2%</td>
</tr>
<tr>
<td>$R_{K^*}$ (&gt; 14.4 GeV$^2$)</td>
<td>24%</td>
<td>9.2%</td>
<td>2.8%</td>
</tr>
</tbody>
</table>

**Figure:** Prospects for Belle II sensitivity for $R_K / R_{K^*}$ measurements.
Angular analysis in $B \rightarrow K^*\ell\ell$

The differential decay rate is given by:

$$\frac{d\Gamma}{dq} \frac{d^4\Gamma}{dcos\theta_i dcos\theta_K d\phi dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) sin^2\theta_K + F_L cos^2\theta_K + \frac{1}{4} (1 - F_L) sin^2\theta_K cos2\theta_l - F_L cos^2\theta_K cos2\theta_l + S_3 sin^2\theta_K sin^2\theta_l cos2\phi + S_4 sin2\theta_K sin2\theta_l cos\phi + S_5 sin2\theta_K sin\theta_l cos\phi + S_6 sin^2\theta_K cos\theta_l + S_7 sin2\theta_K sin\theta_l sin\phi + S_8 sin2\theta_K sin2\theta_l sin\phi + S_9 sin^2\theta_K sin^2\theta_l sin2\phi \right]$$

- 8 independent observables in the lepton massless limit:
  - $F_L$: Fraction of the longitudinal polarization of the $K^*$.
  - $S_6$: The forward-backward asymmetry of the $\ell\ell$ system.
  - $S_{3,4,5,7,8,9}$: The remaining CP-averaged observables.
- $F_L$ and $S_i$ are function of $q^2$.
- $P_i'$ and $Q_i$:
  - $P_i'=4,5,7,8 = \frac{S_{j=4,5,7,8}}{\sqrt{F_L (1 - F_L)}}$
  - $Q_i = P_i'^\mu - P_i'^e$, $i = 4, 5$
- Any deviation from zero for $Q_i$ would indicate NP.
Measurement of $B \rightarrow J/\Psi K$
Measurement of $B \to J/\psi K$
Measurement of $B \rightarrow X_s \gamma$

TABLE I: Partial branching fraction measurement results and uncertainties. Note that signal efficiency and background modelling uncertainties are correlated (see Sections 7.2 and 7.3).

<table>
<thead>
<tr>
<th>$E_{\gamma}$ [GeV]</th>
<th>$\frac{1}{\Gamma_B} \frac{d\Gamma_{B}}{dE_{\gamma}} (10^{-4})$</th>
<th>Statistical</th>
<th>Systematic</th>
<th>Fit procedure</th>
<th>Signal efficiency</th>
<th>Background modelling</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8-2.0</td>
<td>0.48</td>
<td>0.54</td>
<td>0.64</td>
<td>0.42</td>
<td>0.03</td>
<td>0.49</td>
<td>0.09</td>
</tr>
<tr>
<td>2.0-2.1</td>
<td>0.57</td>
<td>0.31</td>
<td>0.25</td>
<td>0.17</td>
<td>0.06</td>
<td>0.17</td>
<td>0.07</td>
</tr>
<tr>
<td>2.1-2.2</td>
<td>0.13</td>
<td>0.26</td>
<td>0.16</td>
<td>0.13</td>
<td>0.01</td>
<td>0.11</td>
<td>0.01</td>
</tr>
<tr>
<td>2.2-2.3</td>
<td>0.41</td>
<td>0.22</td>
<td>0.10</td>
<td>0.07</td>
<td>0.05</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>2.3-2.4</td>
<td>0.48</td>
<td>0.22</td>
<td>0.10</td>
<td>0.06</td>
<td>0.06</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>2.4-2.5</td>
<td>0.75</td>
<td>0.19</td>
<td>0.14</td>
<td>0.04</td>
<td>0.09</td>
<td>0.02</td>
<td>0.09</td>
</tr>
<tr>
<td>2.5-2.6</td>
<td>0.71</td>
<td>0.13</td>
<td>0.10</td>
<td>0.02</td>
<td>0.09</td>
<td>0.00</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Measurement of $B \rightarrow X_s \gamma$