Status and prospects for rare decays at Belle II

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(On behalf of the Belle II collaboration)

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Outline

- Introduction
- Measurement of $B \rightarrow K^* \gamma$ branching fraction
- Study of $B \rightarrow X_s \gamma$
- Study of $B^+ \rightarrow K^+ \ell^+ \ell^-$
- Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$
- Summary & outlook
SuperKEKB accelerator and Belle II experiment

- $e^-(7\text{ GeV}) \leftrightarrow e^+(4\text{ GeV})$
- $\sqrt{s} = 10.58\text{ GeV} = m(\Upsilon(4S))$
- $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) > 96\%$
- Clean environment; well defined initial state
- Efficient neutral reconstruction capability ($\gamma$, $\pi^0$, $\eta$, $K_S^0$, $K_L^0$)
- Excellent vertexing and flavour tagging performance
Belle II status

- Collected 213 fb$^{-1}$ of data since 2019
- Today’s results: 63 fb$^{-1}$ at $\Upsilon(4S) + 9$ fb$^{-1}$ off-resonance (60 MeV below the $\Upsilon(4S)$)

- World record of luminosity:
  $L = 3.1 \times 10^{34} \text{cm}^{-2}\text{sec}^{-1}$
- Despite the pandemic, data taking has been very successful:
  $12 \text{fb}^{-1}/\text{week}, 40.3 \text{fb}^{-1}/\text{month}$

Tentative long-term operation plan

- Long-term target:
  $L_{\text{int}} \sim 50 \text{ab}^{-1}$,
  $L_{\text{peak}} \sim 6 \times 10^{35} \text{cm}^{-2}\text{sec}^{-1}$
Radiative and electroweak penguin $B$ decays

- $B$-decays with flavor changing neutral currents (FCNC), $b \rightarrow s(d)$ transitions

- Forbidden at tree level in the SM and can only proceed via suppressed loop or box-level amplitudes

- BSM model allowing FCNC at tree level or new particles appearing in loop can change branching fractions and/or other observables

Radiative and electroweak penguin decays in SM

Potential BSM contributions

- e.g. Charged Higgs
- e.g. Leptoquark
Multivariate analyzer

- A boosted decision tree (BDT) to suppress background from light quark (u, d, s and c) pairs (denoted as $q\bar{q}$ events)
  - Use event shape variables and vertex information as input
  - A requirement on the BDT output removes most of the $q\bar{q}$ background

$q\bar{q}$ background is $\sim 10^6$ times more abundant than signal events
Measurement of $B \to K^*\gamma$ branching fraction

- $b \to s\gamma$ electroweak amplitude
- Sensitive to new physics particles that can enter the loop
- SM prediction of branching fraction suffers from large uncertainties owing to form factors

- Other observables:

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{K}^*\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(B \to K^*\gamma) + \Gamma(B \to K^*\gamma)}$$

$$\Delta_{+0} = \frac{\Gamma(B^0 \to K^*\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)}$$

- Reliably predicted due to form-factor cancellation
- The latest measurement by Belle reported evidence for isospin violation with a significance of 3.1 standard deviations:

$$\Delta_{+0} = [+6.2 \pm 1.5(\text{stat}) \pm 0.6(\text{syst}) \pm 1.2(\text{f+−/f00})]\%$$

\(B \rightarrow K^*\gamma\): Analysis overview

- All final states are explicitly reconstructed,
  \[K^* \rightarrow K^+\pi^-, K_S^0\pi^0, K^+\pi^0, K_S^0\pi^+ (K_S^0 \rightarrow \pi^+\pi^-, \pi^0 \rightarrow \gamma\gamma)\]

- Signal yield is obtained from an unbinned maximum likelihood (ML) fit to \(\Delta E (= E_B^* - \sqrt{s}/2)\) distribution

Dominant background:

- \(q\bar{q}\) events with \(\gamma\) from \(\pi^0, \eta\) decay
  \(\rightarrow \pi^0, \eta\) veto using kinematic information by combining hard and soft-photons

  \(\rightarrow q\bar{q}\) suppression with BDT
  
  Bkg rejection: 70 - 90 %
  Signal loss: 10 - 21 %
Studies ongoing for the measurement of $CP$ and isospin asymmetries

<table>
<thead>
<tr>
<th>Mode</th>
<th>B.F ($ \times 10^{-5}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K^{*0}[K^+\pi^-]\gamma$</td>
<td>$4.5 \pm 0.3 \pm 0.2$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^{*0}[K^0\pi^0]\gamma$</td>
<td>$4.4 \pm 0.9 \pm 0.6$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*+}[K^+\pi^0]\gamma$</td>
<td>$5.0 \pm 0.5 \pm 0.4$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*+}[K^0\pi^+]\gamma$</td>
<td>$5.4 \pm 0.6 \pm 0.4$</td>
</tr>
</tbody>
</table>
Study of $B \rightarrow X_s \gamma$ with untagged method

- Strong constraint on the Charged Higgs is obtained from $B (B \rightarrow X_s \gamma)$: $M_{H^\pm} < 590$ GeV


- Reconstruct only $\gamma$ in the signal-side $B$ meson
- Untagged method: No explicit reconstruction of recoil-side $B$ meson
  $\rightarrow$ Higher efficiency & lower purity
  $\rightarrow$ Subtract expected background contributions
Study of $B \rightarrow X_s \gamma$ with untagged method

- Photon energy ($E^*_\gamma$) spectrum is used to extract signal after background suppression
- Monochromatic spectrum is expected for signal
- $q\bar{q}$ is estimated from the off-resonance data
- $B\bar{B}$ background is obtained from simulation
- Background subtracted plot on the bottom

Excess clearly visible in the signal region
Study of $B^+ \rightarrow K^+ \ell^+ \ell^-$

- Tension between the observed and SM-predicted ratio:
  
  \[ R_K \equiv \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} \]

  suggests a lepton universality violation

  arXiv:2103.11769

  \[ \rightarrow \] Important to have independent measurement of $B^+ \rightarrow K^+ \ell^+ \ell^-$ (with $\ell = e, \mu$)

- $B^+ \rightarrow K^+ \ell^+ \ell^-$ is reconstructed from both electron and muon modes

  \[ \rightarrow \] Similar electron and muon reconstruction performances, unlike LHCb

- Background suppression with BDT using event shape variables and vertex information

- Signal selection using two kinematic variables:

  \[ M_{bc} = \sqrt{E_{beam}^* - \vec{p}_B^*}^2, \quad \Delta E = E_B^* - E_{beam}^* \]
Study of $B^+ \rightarrow K^+ \ell^+ \ell^-$

- 2D unbinned ML fit to $M_{bc} - \Delta E$

![Graph showing the fit results](image)

Signal yield $= 8.6^{+4.3}_{-3.9} \pm 0.4$ with $2.7\sigma$ significance
Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ with a novel inclusive tagging

- $B^+ \rightarrow K^+ \nu \bar{\nu}$ decay is not observed yet:

  SM prediction: $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$

  (Prog.Part.Nucl.Phys. 92 (2017) 50 – 91)

  Upper limit on $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) < (1.6 \pm 0.5) \times 10^{-5}$

  (BaBar 429 fb$^{-1}$, Phys.Rev.D 87 (2013) 11, 112005)

- Complementary probe of BSM physics scenarios proposed to explain anomalies observed in $b \rightarrow s \ell \bar{\ell}$ transitions (arXiv: 2005.03734), including recent measurement of $R_K$ by LHCb (arXiv: 2103.11769)

- Many other BSM models can be constrained like dark matter, leptoquarks and axions

$B^+ \rightarrow K^+ \nu \bar{\nu}$: Analysis strategies

- All previous studies used an explicit reconstruction of the $B_{\text{tag}}$ followed by the signal reconstruction.

- Reconstruction efficiency suffers because of the low tagging efficiency:
  - Hadronic tagging: $\varepsilon_{\text{sig}} \cdot \varepsilon_{\text{tag}} \sim 0.04\%$
  - Semileptonic tagging: $\varepsilon_{\text{sig}} \cdot \varepsilon_{\text{tag}} \sim 0.2\%$

- Inclusive tagging:
  - Exploit distinct topology and kinematics to achieve higher signal efficiency ($\sim 4\%$)
  - Higher efficiency & lower purity

*Technique used first time in this channel!*
$B^+ \rightarrow K^+ \nu \bar{\nu}$: Analysis procedure

- Select highest $p_T$ track as signal kaon candidate
- Use of nested statistical-learning discriminators: BDT$_1$ & BDT$_2$ (topology, rest-of-event, missing energy, vertex separation,...)
- Validate the BDT using data of $B^+ \rightarrow K^+ J/\psi \rightarrow (\mu^+ \mu^-)$ decays where the muons are removed and the kaon momentum is reweighed to mimic the signal
- Signal strength is extracted by binned ML fit on the 2D ($p_T(K^+)$, BDT) histogram
- Use off-resonance data to constrain the yield from $q\bar{q}$ processes
$B^+ \rightarrow K^+ \nu \bar{\nu}$: Results

- Measured branching fraction
  \[
  \mathcal{B}(B^\pm \rightarrow K^\pm \nu \bar{\nu}) = [1.9^{+1.3}_{-1.3} \text{(stat)}^{+0.8}_{-0.7} \text{(syst)}] \times 10^{-5}
  \]

- No significant signal observed; setting upper limit on branching fraction:
  \[
  \mathcal{B}(B^\pm \rightarrow K^\pm \nu \bar{\nu}) < (4.1 \pm 0.5) \times 10^{-5} \text{ @ 90\% CL}
  \]

arXiv:2104.12624 (Accepted to PRL!)

- Inclusive approach outperforms semileptonic tagging by 10-20% and hadronic tagging by 3.5x at given luminosity\footnote{assuming the total uncertainty in the branching-fraction scales with $1/\sqrt{L}$}.

- This result based on the novel inclusive tagging approach already has an impact on the global picture of these decays.

- Studies on additional channels $B^0 \rightarrow K^{*0} \nu \bar{\nu}$ and $B^0 \rightarrow K_S^0 \nu \bar{\nu}$ etc. using more data are in preparation!

\footnote{assuming the total uncertainty in the branching-fraction scales with $1/\sqrt{L}$}
Summary and outlook

- First results from Belle II on radiative and electroweak penguin decays with $(63 \pm 9) \text{ fb}^{-1}$ demonstrate the high capabilities of the experiment
  - Measurement of $B \rightarrow K^* \gamma$ branching fraction BELLE2-CONF-PH-2021-014
  - Study of $B \rightarrow X_s \gamma$ BELLE2-NOTE-PL-2021-004
  - Study of $B^+ \rightarrow K^+ \ell^+ \ell^-$ BELLE2-NOTE-PL-2021-014
  - Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ with the inclusive tagging method arXiv:2104.12624 (Accepted to PRL!)

- The result on $B^+ \rightarrow K^+ \nu \bar{\nu}$ based on a novel inclusive tagging approach already has an impact on the global picture of these decays
- Belle II has recorded $213 \text{ fb}^{-1}$ of data by 2021 summer
- $3 \times$ larger sample ready to be analysed while aiming for $400 \text{ fb}^{-1}$ by 2022 summer ($50 \text{ ab}^{-1}$ over 10 years)
- Interesting results are coming in the near future with more and more channels and improved analysis techniques!

Stay tuned!
Extra Slides
Summary of the Sensitivities: $B \rightarrow K^*\gamma$

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle 0.71 ab$^{-1}$ (0.12 ab$^{-1}$)</th>
<th>Belle II 5 ab$^{-1}$</th>
<th>Belle II 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \theta_+(B \rightarrow K^*\gamma)$</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>
## Summary of the Sensitivities: $B \rightarrow X_s \gamma$

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle 0.71 ab$^{-1}$</th>
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<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>$\text{Br}(B \rightarrow X_s \gamma)_{\text{sum-of-ex}}$</td>
<td>10.5%</td>
<td>7.3%</td>
<td>5.7%</td>
</tr>
<tr>
<td>$\Delta_{0+}(B \rightarrow X_s \gamma)_{\text{sum-of-ex}}$</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>$A_{\text{CP}}(B \rightarrow X_s \gamma)_{\text{sum-of-ex}}$</td>
<td>1.3%</td>
<td>0.52%</td>
<td>0.19%</td>
</tr>
<tr>
<td>$A_{\text{CP}}(B^0 \rightarrow X_s^0 \gamma)_{\text{sum-of-ex}}$</td>
<td>1.8%</td>
<td>0.72%</td>
<td>0.26%</td>
</tr>
<tr>
<td>$A_{\text{CP}}(B^+ \rightarrow X_s^+ \gamma)_{\text{sum-of-ex}}$</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>$\Delta A_{\text{CP}}(B \rightarrow X_s \gamma)_{\text{sum-of-ex}}$</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 of the Sensitivities: $R_K$

### Summary of the Sensitivities: $B^+ \rightarrow K^+ \nu \bar{\nu}$

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<th>Belle II 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Br}(B^+ \rightarrow K^+ \nu \bar{\nu})$</td>
<td>$&lt; 450%$</td>
<td>$30%$</td>
<td>$11%$</td>
</tr>
<tr>
<td>$\text{Br}(B^0 \rightarrow K^{*0} \nu \bar{\nu})$</td>
<td>$&lt; 180%$</td>
<td>$26%$</td>
<td>$9.6%$</td>
</tr>
<tr>
<td>$\text{Br}(B^+ \rightarrow K^{*+} \nu \bar{\nu})$</td>
<td>$&lt; 420%$</td>
<td>$25%$</td>
<td>$9.3%$</td>
</tr>
<tr>
<td>$F_L(B^0 \rightarrow K^{*0} \nu \bar{\nu})$</td>
<td>$-$</td>
<td>$-$</td>
<td>$0.079$</td>
</tr>
<tr>
<td>$F_L(B^+ \rightarrow K^{*+} \nu \bar{\nu})$</td>
<td>$-$</td>
<td>$-$</td>
<td>$0.077$</td>
</tr>
<tr>
<td>$\text{Br}(B^0 \rightarrow \nu \bar{\nu}) \times 10^6$</td>
<td>$&lt; 14$</td>
<td>$&lt; 5.0$</td>
<td>$&lt; 1.5$</td>
</tr>
<tr>
<td>$\text{Br}(B_s \rightarrow \nu \bar{\nu}) \times 10^5$</td>
<td>$&lt; 9.7$</td>
<td>$&lt; 1.1$</td>
<td>$-$</td>
</tr>
</tbody>
</table>