Recent Belle and Belle II results on radiative and EWP decays

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(On behalf of the Belle II collaboration)
Motivation

- $b \rightarrow s(d)$ flavour changing neutral current (FCNC) transitions forbidden at tree level in the Standard Model (SM)
- Mediated by loop/box diagrams
- Resulting B decays are rare $\mathcal{B}_{SM} = \mathcal{O}(10^{-7} - 10^{-4})$
- Precise predictions for ratios, angular observables and asymmetries

Look for variations/enhancements in FCNC due to BSM contributions

- New interactions at tree level diagrams
- New particles in loop corrections

Many opportunities to probe the SM and explore BSM physics
Belle II at SuperKEKB

Asymmetric $e^+e^-$ collisions at SuperKEKB accelerator at Japan

Collected 424 fb$^{-1}$ of dataset so far (363 fb$^{-1}$ on $\Upsilon(4S)$ resonance and 61 fb$^{-1}$ below/above)

- Close to full solid-angle (~4$\pi$) coverage
- Low background
- Known initial kinematics
- Good charged particle reconstruction

★ Similar advantages for Belle as well
Belle II: advantage for radiative and EWP

ECL

\[ \gamma = \frac{\sigma_E}{E} = 2\% \ (E > 1 \text{ GeV}) \]

eID: 85\% at 0.1\% \pi\text{ fake}

KLM

mulD: 90\% at 5-10\% \pi\text{ fake}

High photon detection efficiency and good electron and muon identification efficiency

Inclusive and missing energy decays

\( \mathcal{O}(1\%) \)

Tagging efficiencies, achievable yields

\( \mathcal{O}(10\%) \)

Purities of the tagged samples

Hadronic tagging

\[ B \to D^{(*)}n\pi \]

\( \mathcal{O}(100\%) \)

Fully inclusive, no tagging

\[ B \to \text{anything} \]
Let’s start with....
Fully inclusive $B \to X_s \gamma$: Belle II

- $\mathcal{B}(B \to X_s \gamma)$ measurement as the most effective way to search for or constrain NP in $b \to s\gamma$
- Only possible in the clean environment of B-factories

- Fully inclusive $\mathcal{B}(B \to X_s \gamma)$ measurement at Belle II using 189 fb$^{-1}$ of dataset in bins of $E^B_\gamma$

- Partner $B$ (tag) meson reconstruction in the event via hadronic tagging
  - Lower background, isolated $X_S$ system, access to $E^B_\gamma$
  - Reduced statistics (efficiency < 1%)

$E^B_\gamma$: photon energy in $B_{\text{sig}}$ rest frame
B $\rightarrow X_S \gamma$: Selection and signal extraction strategy

- Background suppression:
  - Veto $\gamma$ from $\pi^0$ and $\eta$ in signal region
  - Other backgrounds using boosted decision tree (BDT) classifier

- Simultaneous fit to tag-side $B$ mass in bins of $E^B_{\gamma}$

- Non-signal $B$ subtracted using simulation

- $b \rightarrow d\gamma$ contribution removed assuming same shape and selection efficiency as $B \rightarrow X_S \gamma$

\[ M_{bc} = \sqrt{E_{beam}^2 - |\vec{p}_B|^2} \]
B → Xsγ: results

<table>
<thead>
<tr>
<th>$E^B_\gamma$ threshold (GeV)</th>
<th>$\mathcal{B}(B → Xs\gamma)(10^{-4})$</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>
<tr>
<td>2.1</td>
<td>2.49 ± 0.46 ± 0.35</td>
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- Provided partial branching fractions in bins of $E^B_\gamma$

- We are already competitive with BaBar results with 10% less data
  - BaBar hadronic tag result for $E^B_\gamma > 1.9$ GeV (210 fb$^{-1}$): $(3.66 ± 0.85 ± 0.60) \times 10^{-4}$

- Dominant systematics comes from background modelling (limited size of the simulation propagated) and fit assumptions
Moving towards......
Preparatory work towards $R_{K^{(*)}}$ : Belle II

$B(B \rightarrow K^{*}l^+l^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}$

- Similar performance for $e$ and $\mu$ channels
- Belle II predicts 3% precision of $R_{K^{(*)}}$ at 50 ab$^{-1}$, it would provide a crucial clarification in a different experimental environment compared to LHCb
Search for $B \rightarrow K^{*0}\tau\tau$ decays: Belle

- SM expected BF $\mathcal{O}(10^{-7})$
- Current sensitivity is far from $\mathcal{B}_{SM}$

<table>
<thead>
<tr>
<th>Decay</th>
<th>BF U.L. @90% CL</th>
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<tbody>
<tr>
<td>$B_{S} \rightarrow \tau\tau$</td>
<td>$5.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$B^{+} \rightarrow K\tau\tau$</td>
<td>$2.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>$B^{0} \rightarrow K^{*0}\tau\tau$</td>
<td>$3.1 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

- Tag-side $B$ decays hadronically
- $\tau \rightarrow l\nu\bar{\nu}$, $\pi\nu$ modes are considered
- Signal extraction from fit to the $E_{ECL}^{extra}$: gives peak at zero for signal events

$N_{sig} = -4.9 \pm 6.0$

No signal observed, UL is provided at 90% CL
**B → Kτl search: Belle**

- LFV $B \to K\tau l$ decays are more interesting to simultaneously explain $R_{K^{(*)}}$ and $R_{D^{(*)}}$ anomalies
  - Sensitivity is entering now the $10^{-6}$ regime

**Search at Belle**

- Uses full 711 fb$^{-1}$ of Belle dataset
- Tag-side $B$ decays hadronically
- Signal $B$ reconstruction from $K$ and lepton ($e$, $\mu$)
- Signal extraction from the recoil-mass of $B_{\text{sig}}$ and $B_{\text{tag}}$: should give a peak at $\tau$ mass for signal events
- Background is suppressed using BDT
No significant signal is observed, UL is provided at 90% CL

World’s best limit on $B \to K\tau l$ decays
Summary

- $b \rightarrow s$ transitions offer powerful probe of the SM and physics beyond

- $b \rightarrow s$ studies are important part of Belle II physics program
  - Unique access to radiative and missing energy modes

- Measurements with 189 fb$^{-1}$ Belle II dataset were presented today
  - BF of inclusive $B \rightarrow X_s \gamma$ decays and preparatory measurements for LFU test

- Measurements with 711 fb$^{-1}$ Belle dataset were also presented
  - Search for $B^0 \rightarrow K^{*0} \tau\tau$: no signal observed, provided UL at 90% CL
  - Search of LFV decay $B \rightarrow K \tau l$ decays: currently provides world’s best limits

**Belle II: twice the dataset already available, data taking will restart in early 2024. Many exciting results are coming, stay tuned!**
Belle II prospects for $R_K^{(*)}$

Uncertainties are from:
Belle JHEP 03 105 (2021)

Uncertainties are from:
Belle PRL 126, 161801 (2021)

Current LHCb precision for
$q^2 \in [1,6] \text{ GeV}/c^2$ (9 fb-1): stat. dominated

Belle II can provide 3% precision at 50 ab-1
$B \to K^*(892)l^+l^-$: results

\[
\begin{align*}
\mathcal{B}(B \to K^* \mu^+ \mu^-) &= (1.19 \pm 0.31_{-0.07}^{+0.08}) \times 10^{-6} \\
\mathcal{B}(B \to K^* e^+ e^-) &= (1.42 \pm 0.48 \pm 0.09) \times 10^{-6}
\end{align*}
\]

- Results are consistent with the W.A., but precision is limited by the sample size
- Performance is similar between muon and electron channels
- Main systematics sources are:
  - Total number of $B\bar{B}$ pair: 2.9%
  - Data-MC differences in $\pi^0$ reconstruction efficiency: 3.4%
$B \to J/\psi(l^+l^-)K$: results

\[
A_I(B \to J/\psi(\mu^+\mu^-)K) = -0.006 \pm 0.015 \pm 0.030 \\
A_I(B \to J/\psi(e^+e^-)K) = -0.022 \pm 0.016 \pm 0.030 \\
R_{K^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008 \\
R_{K^0}(J/\psi) = 1.042 \pm 0.042 \pm 0.008
\]

- Results are consistent with the W.A.
- Similar efficiencies for muon and electron modes: uncertainty on $R_K$ will be equally contributed by the these flavour modes
- Main systematics sources are:
  - BF of $\Upsilon(4S) \to B^0\bar{B}^0, B^+B^-$: 2.6%
  - Data-MC differences in $K_S^0$ reconstruction efficiency: 3.0%
Belle II at SuperKEKB

- Asymmetric $e^+e^-$ collisions at centre-of-mass energy 10.58 GeV corresponding to $\Upsilon(4S)$ resonance mass

- $B\bar{B}$ at threshold production: $\mathcal{B}(\Upsilon(4S) \rightarrow B\bar{B}) > 96\%$

- Instantaneous luminosity world record: $4.7 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ (June 2022)

- Target instantaneous luminosity: $6 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$

- Collected 428 fb$^{-1}$ of dataset so far (362 fb$^{-1}$ on $\Upsilon(4S)$ resonance and 66 fb$^{-1}$ below)

- Target dataset: 50 ab$^{-1}$
Measurement of \( B \to J/\psi(l^+l^-)K \)

- Not an EW penguin process but a control channel for \( B \to Kl^+l^- \)
- \( R_K(J/\psi) = \frac{\mathcal{B}(B \to J/\psi(\rightarrow \mu^+\mu^-)K)}{\mathcal{B}(B \to J/\psi(\rightarrow e^+e^-)K)} \)
- Reconstructed four channels: \( B^+ \to J/\psi(l^+, l^-)K^+ \) and \( B^0 \to J/\psi(l^+l^-)K^0_S; \ l = e, \mu \)
  \[ \Delta E = E_B - \sqrt{S}/2 \]

\[
R_{K^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008 \\
R_{K^0}(J/\psi) = 1.042 \pm 0.042 \pm 0.008
\]

- Systematics uncertainties have been reduced compared to most precise measurements from Belle (JHEP03(2021)105)

\[ N_{\text{sig}} = 4578 \pm 62 \]

\[ N_{\text{sig}} = 3706 \pm 62 \]
Preparatory work towards $R_{K^{(*)}}$ measurement

- Following decays are reconstructed ($l = e, \mu$) with 189 fb$^{-1}$ of dataset
  - $B^+ \rightarrow K^{*+}l^+l^-$ with $K^{*+} \rightarrow K_S^0\pi^+, K^+\pi^0$
  - $B^0 \rightarrow K^{*0}l^+l^-$ with $K^{*0} \rightarrow K^+\pi^-$

- Background suppression:
  - Veto $\gamma K^*$ and $q^2$ regions containing $B \rightarrow J/\psi K^*, \psi(2S)K^*$
  - Remaining background with BDT

$$B(B \rightarrow K^*l^+l^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}$$

- Result is consistent with the W.A., but precision is limited by the sample size
  $$B(B \rightarrow K^*\mu\mu)_{WA} = (1.06 \pm 0.09) \times 10^{-6}$$
  $$B(B \rightarrow K^*ee)_{WA} = (1.19 \pm 0.20) \times 10^{-6}$$

- Observation of these decays is the first step towards LFU test ($R_{K^{(*)}}$)
Today’s focus

- Inclusive branching fraction (BF) measurement of $B \rightarrow X_s\gamma$

  Requires good photon detection efficiency

- Towards $R_K^{(*)}$ measurement
  - BF of $B \rightarrow K^{*}(892)\ell^+\ell^-$ decays
  - Study of control mode $B \rightarrow J/\psi(\ell^+\ell^-)K$

- Search for LFV $B \rightarrow K\tau\ell$ decays at Belle

  Requires good $e$ and $\mu$ identification
$B \rightarrow K\tau\ell$ search at Belle: results

No significant signal is observed for any of the 4 modes!
Reconstruction techniques at B factories

- A typical $B\bar{B}$ event generates ~10 tracks and ~10 photons
- Measurement of inclusive decays or decays with $\nu$ in the final state suffer from missing kinematic information
- $B$-factory advantage: information from partner $B$ (tag) provides insight of signal $B$

\[
\begin{align*}
\mathcal{O}(1\%) & \quad \text{Tagging efficiencies, achievable yields} \\
\mathcal{O}(10\%) & \quad \text{Purities of the tagged samples, physics observables}
\end{align*}
\]

Hadronic tagging

$B \rightarrow D^{(*)}n\pi$

Fully inclusive, no tagging

$B \rightarrow$ anything