Results and Prospects of Radiative and Electroweak Penguin Decays at Belle II

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KEK
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Radiative and Electroweak Penguin decays in SM

- Radiative and Electroweak penguin decays are flavor-changing neutral current (FCNC), which proceeds via one-loop diagrams in the standard model (SM) and thus suppressed.

- New physics (NP) can appear in the loop or mediate FCNC at tree level.

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NP contributions

- e.g. Charged Higgs
- e.g. Leptoquark
- Asymmetric $e^-(7 \text{ GeV}) e^+ (4 \text{ GeV})$ collider.
- CM-energy is at $\Upsilon(4S)$ resonance, 10.58 GeV $\rightarrow$ Produce $B \bar{B}$-pair efficiently.
- Precise study of $b, c, \tau$ to search NP in the clean experimental environment.
Status of SuperKEKB and Belle II

- New world record of luminosity:
  - $L = 3.1 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$
  - 12 fb$^{-1}$/week, 40.3 fb$^{-1}$/month
  (KEKB : $2.1 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$, 8 fb$^{-1}$/week, 29.4 fb$^{-1}$/month)

- Total integrated luminosity : 213 fb$^{-1}$
  - >120 fb$^{-1}$ in Feb-June 2021
  - Today’s results:
    - 62.8 fb$^{-1}$ at $\Upsilon(4S)$ + 9 fb$^{-1}$ at off-resonance
    (off-resonance = 60 MeV below the $\Upsilon(4S)$)
Radiative Penguin Decays $b \to s\gamma$

- Relatively large branching fraction, $O(10^{-5})$
- Great sensitivity to new heavy particle which can enter the loop.
  - Strong constraint on the Charged Higgs is obtained from $\text{Br}(B \to X_s\gamma)$:
    $$M_{H^\pm} < 590 \text{ GeV (Type II, 2HDM)}$$

Contents

- Measurement of branching fractions of $B \to K^*\gamma$
  BELLE2-CONF-PH-2021-014
- Observation of $B \to X_s\gamma$
  BELLE2-NOTE-PL-2021-004
The cleanest exclusive mode in $b \to s \gamma$ modes.

All final states are explicitly reconstructed,

- $K^* : K^+\pi^-, K_S^0\pi^0, K^+\pi^0, K_S^0\pi^+ (K_S^0 \to \pi^+\pi^-, \pi^0 \to \gamma\gamma)$, $0.817 < M_{K^*} < 0.967$ GeV ($\sim$3σ)
- $\gamma$ : Cluster of the electromagnetic calorimeter (ECL), $2.25 < E_{\gamma}^{\text{CM-frame}} < 2.85$ GeV

Dominant background

- $q\bar{q}$ ($q = u, d, s, c$) events with $\gamma$ from $\pi^0, \eta$ decay
  - $\pi^0, \eta$ veto using kinematic information of combination of hard-/soft-photon.
  - Suppressed with MVA using event-shape variables.
Signal yield is obtained from unbinned maximum likelihood (ML) fit to $\Delta E$ distribution: $\Delta E = E_B^{CM-frame} - \sqrt{s}/2$

- **Signal**: Cruijff function + Gaussian.
- **Self-cross-feed (SCF)**: Cruijff function.
- **Background (Bkg)** has two components
  - $q\bar{q}$: Chebyshev polynomial.
  - Shifted peaking $B\bar{B}$ (e.g. $B \to K\pi\pi\gamma$): Gaussian

The measured values are consistent with the world average values within 1$\sigma$ (2$\sigma$) for neutral (charged) modes.

Plan to upgrade for the measurement of CP- and Isospin- asymmetry.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\text{Br (fit)} \times 10^{-5}$</th>
<th>$\text{Br (PDG)} \times 10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to K^{*+} [K^+\pi^-]_{\gamma}$</td>
<td>$4.5 \pm 0.3$(stat) $\pm 0.2$(syst)</td>
<td>$4.18 \pm 0.25$</td>
</tr>
<tr>
<td>$B^0 \to K^{*0} [K_S^0 \pi^0]_{\gamma}$</td>
<td>$4.4 \pm 0.9$(stat) $\pm 0.6$(syst)</td>
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<tr>
<td>$B^+ \to K^{*+} [K^+\pi^0]_{\gamma}$</td>
<td>$5.0 \pm 0.5$(stat) $\pm 0.4$(syst)</td>
<td>$3.92 \pm 0.22$</td>
</tr>
<tr>
<td>$B^+ \to K^{*+} [K_S^0 \pi^+]_{\gamma}$</td>
<td>$5.4 \pm 0.6$(stat) $\pm 0.4$(syst)</td>
<td></td>
</tr>
</tbody>
</table>
Observation of $B \rightarrow X_s \gamma$ with untagged method

- Reconstruct only $\gamma$ in the signal side B-meson.
- **Untagged method** : No explicit reconstruction of other side B-meson.
  - Higher efficiency & lower purity than tagging method.
  - **Subtract expected background contributions.**

- Photon energy spectrum is used to extract signal component after the background suppression.
  - Monochromatic spectrum is expected for signal.
  - Continuum ($q\bar{q}$) is estimated from data of off-resonance.
  - $B\bar{B}$ is estimated from simulation.

- Excess is clearly visible in the expected region.
Electroweak Penguin Decays $b \to s\ell^+\ell^-, b \to s\nu\bar{\nu}$

- Lepton Flavor Universality (LFU) violation in $b \to s\ell^+\ell^-$ is drawing attention recently.
  - Evidence of LFU violation on $B^+ \to K^+\ell^+\ell^-$ from LHCb. arXiv:2103.11769

- Shed further light on the anomalies by independent measurements on $b \to s\ell^+\ell^-$ and search for $b \to s\nu\bar{\nu}$.
  - $b \to s\nu\bar{\nu}$ provide complementary prove of NP that explain $b \to s\ell^+\ell^-$ anomalies. arXiv:2103.16558

Contents

- Study of $B^+ \to K^+\ell^+\ell^-$
  BELLE2-NOTE-PL-2021-014

- Search for $B^+ \to K^+\nu\bar{\nu}$ using an inclusive tagging
  arXiv:2104.12624
Study of $B^+ \rightarrow K^+ \ell^+ \ell^-$

- $B^+ \rightarrow K^+ \ell^+ \ell^-$ is reconstructed from both electron and muon modes.
  - Electron can be reconstructed at similar level of muon at Belle II.
- Background is suppressed with MVA using event shape, vertex information...

- 2D unbinned ML fit, $(M_{bc}, \Delta E)$:
  
  $$M_{bc} = \sqrt{s/4 - |p_B^{CM-frame}|^2}$$

- Signal yield: $8.6^{+4.3}_{-3.9} \pm 0.4$

Measurement of important observables is planed using more upcoming data!
Search for $B^+ \rightarrow K^+ \nu \bar{\nu}$ with an inclusive tagging

- Two undetectable neutrinos in the final state.
- $b \rightarrow s\nu \bar{\nu}$ decays are not observed yet.
  - SM: $Br(B^+ \rightarrow K^+ \nu \bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$ \cite{Phys.Part.Nucl.Phys.92(2017)50-91}
  - Upper limit on $Br(B^+ \rightarrow K^+ \nu \bar{\nu}) : < 1.6 \times 10^{-5}$ \cite{Phys.Rev.D87(2013)11,112005}
    - Previous measurements are performed by reconstructing the other side B-meson.

- **Inclusive tagging method**:
  - No explicit reconstruction of other side B-meson
    - Higher efficiency & lower purity.
    - Exploit distinct kinematics of signal event.
      *This method has not been used for this process!*
$B^+ \rightarrow K^+\nu\bar{\nu}$: Analysis procedure

- Select highest $p_T$ track as signal Kaon, $K^\pm$
- Train MVA (BDT) to suppress backgrounds using event shape, missing energy, $\Delta E$ of the other side B-meson…
  - Two BDT-classifiers are trained, BDT$_1$ and BDT$_2$.
  - Select events with BDT$_1$ > 0.9 and then train BDT$_2$.
- BDT performance is validated using data of control mode $B^+ \rightarrow K^+J/\psi(\rightarrow \mu^+\mu^-)$.
- Signal strength is extracted by binned ML fit on the 2D ($p_T(K^+)$, BDT$_2$) histogram.
  - Continuum components are constrained using off-resonance data.
Result of branching fraction is

\[ Br(B^+ \to K^+ \nu \bar{\nu}) = [1.9^{+1.3}_{-1.2} \text{(stat)}^{+0.8}_{-0.7} \text{(syst)}] \times 10^{-5} \]

- Competitive with previous results taking into account the difference in the integrated luminosity.

No significant signal is observed and an upper limit is set on the branching fraction.

\[ Br(B^+ \to K^+ \nu \bar{\nu}) = 4.1 \times 10^{-5} \ (90\% \ CL) \]

The capability of the inclusive tagging approach is demonstrated from the measurement.

- Study on additional channels \((B^0 \to K^0 \nu \bar{\nu}, B^0 \to K_S^0 \nu \bar{\nu})\) using more data is in preparation!
Belle II has recorded 213 fb\(^{-1}\) of data by 2021 summer.

First results on radiative and electroweak penguin decays with (63+9) fb\(^{-1}\) demonstrate the high capabilities of the Belle II.

- Measurement of branching fractions of \(B \rightarrow K^{*} \gamma\). BELLE2-CONF-PH-2021-014
- Observation 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

Interesting results are upcoming in near future using more data.

- >3 times more on tape!
- Aiming for ~400 fb\(^{-1}\) by 2022 summer (BaBar : 424 fb\(^{-1}\) at \(\Upsilon(4S)\)) and 50 ab\(^{-1}\) over ~10 years.