Prospects for Rare Decays at Belle II

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Outline
- Motivation and Introduction (Belle II and SuperKEKB)
- $b \rightarrow (s,d) \gamma$
- $b \rightarrow (s,d)l^+l^-$
- $b \rightarrow (s,d) \nu\nu$
- Double radiative decays
- Status and Summary
Motivation

Success of B-factories:

(Belle and BaBar) had a successful operational period with a total recorded sample over 1.5 ab\(^{-1}\) (1.25 x 10\(^9\) B-meson pairs).

- Observation of CPV in B meson system and confirmation of CKM picture.
- Still room for NP.

Advantages of SuperKEKB and Belle II

- Very clean sample of quantum correlated B-meson pairs.
- Low background environment \(\rightarrow\) efficient reconstruction of neutrals (\(\pi^0\), \(\eta\), ..)
- Dalitz plot analyses, missing mass analyses straight-forward.
- Systematics quite different from those at LHCb. If true NP is seen by one of the experiments, confirmation by the other would be important.
- Belle II goal: to increase the sample sizes over what Belle has achieved by a factor of 50 (> 5.0 x 10\(^{10}\) B-meson pairs).
SuperKEKB

- Upgraded from KEKB
  - which is the world’s highest luminosity e+e- machine.

- Design Luminosity : \(8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}\)
  - 40 times larger than KEKB.
    - 20 times smaller beam size
    - 2 times larger beam current
    - Large number of upgrades to RF, magnet, vacuum, etc. systems

- Asymmetric energy : \(7\text{GeV}(\text{e}^-) \times 4\text{GeV}(\text{e}^+)\)
  - Boost factor smaller to reduce beam background.

- Accelerator commissioning : June 2016 (successful.)
  - Phase 2: Starts in Nov 2017 (w/o vtx)
  - Phase 3 / Run 1: Fall 2018 (full det.)

*Gray: recycled
Colored: newly installed
• All sub-detectors are upgraded from Belle II:
  • Except for ECL crystals and a part of Barrel KLM
• First Pixel layer closer to IP → Better vertex resolution
• Larger Vertex Detector → Better $K_s$ efficiency for TDCPV in $B \rightarrow K_s \pi^0 \gamma$
• TOP and ARICH provide better $K/\pi$ separation.
• Similar or better performance than Belle even under 20 times higher backgrounds.
The inclusive $\bar{B} \rightarrow X_q \gamma$ decays provide important constraints on masses and interactions of many possible BSM scenarios.

The inclusive $\bar{B} \rightarrow X_q \gamma$ B.F. is sensitive to $|C_7|$ and in the new physics models such as 2HDM type II and SUSY.

Very precise prediction is available (for the CP- and isospin-averaged branching ratios) for $E_\gamma > 1.6$ GeV:

$$\mathcal{B}_{s\gamma}^{SM} = (3.36 \pm 0.23) \times 10^{-4} \quad 6.8\% \text{ precision}$$

$$\mathcal{B}_{d\gamma}^{SM} = (1.73^{+0.12}_{-0.22}) \times 10^{-5}$$

(Misiak et. al PRL 114, 221801 (2015))
Exp. and theory are consistent – puts a strong limit on new physics.

Evaluation of constraint on BSM scenario depends crucially on both the central value and the uncertainties on the B.F.

(Misiak et. al PRL 114, 221801 (2015))

The newest Belle result with fully inclusive method has only 7.3% uncertainty.

→ Charged Higgs mass > 580 GeV at 95% CL
Mission at Belle II is to reduce the systematic uncertainty with huge data.

Conservatively estimated, 3.9% total error will be reachable with 50 ab$^{-1}$ which is comparable to uncertainty due to non-perturbative effect (which is hard to reduce) in theory. [Misiak et. al PRL 114, 221801 (2015)].

We can also measure the BF with $E_\gamma$ > 1.6 GeV (w/o extrapolation).
**$\bar{B} \rightarrow X_q \gamma$ : Rate Asymmetry**

- In addition to BFs, asymmetry in decay rates (isospin asym. and CP asym.) are also sensitive to BSM contributions.

- Isospin asymmetry (IA) can be defined as:
  \[
  a_I^0 = \frac{c^2 V \Gamma(\bar{B}^0 \rightarrow \bar{V}^0 \gamma) - \Gamma(B^- \rightarrow V^- \gamma)}{c^2 V \Gamma(\bar{B}^0 \rightarrow \bar{V}^0 \gamma) + \Gamma(B^- \rightarrow V^- \gamma)} \quad \text{for } c^2_{\rho} = 2 \text{ and } c^2_{K^*} = 1
  \]

- To accumulate more statistics, CP-averaged IAs can be defined as: $\bar{a}_I = (a_I^0 + a_I^0)/2$

  \[
  \begin{align*}
  \bar{a}_I^{SM}(K^*\gamma) &= (4.9 \pm 2.6)\% \\
  \bar{a}_I^{SM}(\rho\gamma) &= (5.2 \pm 2.8)\% \\
  \bar{a}_I^{exp}(K^*\gamma) &= (5.2 \pm 2.6)\% \\
  \bar{a}_I^{exp}(\rho\gamma) &= (30^{+13}_{-16})\% \\
  \end{align*}
  \]

  PRD 88 (2013), 094004 | HFAG 2015  

  slight tension with considerable uncertainty

- The observable with reduced uncertainty
  \[
  \delta_{a_I} = 1 - \frac{\bar{a}_I(\rho\gamma)}{\bar{a}_I(K^*\gamma)} \sqrt{\frac{\Gamma(B \rightarrow \rho\gamma)}{\Gamma(B \rightarrow K^*\gamma)}} \left| \frac{V_{ts}}{V_{td}} \right|
  \]

  \[
  \begin{align*}
  \delta_{a_I}^{SM} &= 0.10 \pm 0.11 \\
  \delta_{a_I}^{exp} &= -4.0 \pm 3.5 \quad \rightarrow \text{Can be improved at Belle II with more statistics.}
  \end{align*}
  \]

The sensitivity of $\delta_{a_I}$ to BSM physics has been studied in PRD 88 (2013), 094004 in a model-independent fashion.
The direct CP asymmetry in the time-integral rates is defined as:

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{X}) - \Gamma(B \to X)}{\Gamma(\bar{B} \to \bar{X}) + \Gamma(B \to X)}$$

SM predicts quite different asymmetries for $\bar{B} \to X_s\gamma$ and $\bar{B} \to X_d\gamma$.

$$A_{CP}(B \to X_s\gamma) = (+0.44^{+0.24}_{-0.14}) \times 10^{-2}$$

$$A_{CP}(B \to X_d\gamma) = (-10.2^{+3.3}_{-5.8}) \times 10^{-2}$$

However, the sum of $b \to s\gamma$ and $b \to d\gamma$ is predicted to be very small (close to zero, thanks to the unitarity of the CKM matrix).

Further, difference of $A_{CP}(B \to X_s\gamma)$ between charged and neutral B mesons $\Delta A_{CP}$ is sensitive to phases in $C_7$ and $C_8$.

- In the SM, phases in $C_7$ and $C_8$ are zero $\to \Delta A_{CP} = 0$.

If either is deviated from null, clear NP signal!

Theory refs:
T. Hurth, E. Lunghi and W. Porod, Nucl.Phys. B704 (2005) 56–74, M. Benzke et. al, PRL 106, 141801 (2011)
\( \overline{B} \to X_q \gamma : \text{Rate Asymmetry} \)

- In asymmetry (difference) measurements, most of systematic error cancels out, so both are still statistically dominated at Belle II with 50 ab\(^{-1}\).
- Uncertainty in \( A_{\text{CP}} \) to be \( \pm 0.61 \% \to 3.4\sigma \) if the central value not change.

\[
A_{\text{CP}}(\overline{B} \to X \gamma) \quad \text{Belle II Prospects}
\]

- Uncertainty in \( \Delta A_{\text{CP}} \) to be \( \pm 0.37 \% \to 13.5\sigma \) if the central value not change [from BaBar’s measurement \( \Delta A_{\text{CP}}(X_s \gamma) = +(5.0 \pm 3.9 \pm 1.5)\% \) [Belle II : +(5.0 \pm 0.37)\%]
Time dependent CPV

• Mixing-induced CP asymmetry in an exclusive $b \to s\gamma$ CP eigenstate mode such as $B \to K^*(K_s\pi^0)\gamma$ is an excellent probe for particular class of NP scenario.

• In the SM, expected asymmetry $|S_{CP}| \approx \frac{2m_s}{m_b}\sin(2\phi_1) \sim$ a few %.

• New physics with right handed current increases the fraction of right handed photon.
  • Interfere with the SM occurs and large TDCPV possible

• Studies of these asymmetries are thus considered to be one of the most promising methods to search for non-SM right-handed currents
Time dependent CPV

- At Belle II, significant improvement in the determination of $A_{CP}(t)$ in $K_s\pi^0\gamma$ is expected.
  - Belle II vertex detector is larger than Belle (6cm → 11.5cm).
  - 30% more $K_s$ with vertex hits available.
  - Effective tagging efficiency is 13% better (conservative estimation).

- Expected errors for $S$ measurements of $K_s\pi^0\gamma$ and $\rho^0\gamma$.

| Mode  | 5 ab$^{-1}$ | 50 ab$^{-1}$ |
|-------|-------------|--------------|
| $K_s\pi^0\gamma$ | 0.09 | 0.030 |
| $\rho^0\gamma$ | 0.19 | 0.064 |

$16\sigma$ deviation with 50 ab$^{-1}$. 
**Ratio of $B \rightarrow K\mu\mu$ and $B \rightarrow Kee$**

- $B \rightarrow K\ell\ell$ proceeds via one loop diagram, and LU holds in SM.

- LHCb reported $2.6\sigma$ deviation of ratio of BFs from unity.

  $$R(K) = 0.745^{+0.090}_{-0.074} \pm 0.036$$

  PRL 11, 151601 (2014)

- However, electron mode is challenging at LHCb, especially for high $q^2$.

- At Belle II:
  - electron and muon modes have similar efficiency.
  - Both low and high $q^2$ regions are possible.
  - All ratios $R(K)$, $R(K^*)$, $R(X_s)$ are possible.
The errors reach to 0.04 for all K, K* and Xs modes in Belle II. Errors are still statistical dominant (systematic error ~ 0.4%)
Angular Analysis of $B \rightarrow K^* \ell^+ \ell^-$

- Demonstrated that Belle can make a contribution to the $b \rightarrow s \ell^+ \ell^-$ puzzle
- Found 2.6$\sigma$ deviation from the Standard Model prediction
- Shows $P_5'$ anomaly is unlikely to be a statistical fluctuation
- No significant lepton flavor non-universality is found

See Simon Wehle’s talk in this conference

| $q^2$ (GeV$^2$/c$^4$) | Belle | LHCb (3 fb$^{-1}$) | Belle II |
|------------------------|-------|-------------------|----------|
| 0.1 – 4                | 0.416 | 0.109             | 0.059    |
| 4 – 8                  | 0.277 | 0.099             | 0.040    |
| 10.09 – 12             | 0.344 | 0.155             | 0.049    |
| 14.18 – 19             | 0.248 | 0.092             | 0.033    |

• Belle II and LHCb will be comparable for this process.
• electron mode more efficiently
• Belle II will be also be able to do isospin comparison ($K^*$, $K^*$ or ground states $K$).
Inclusive measurement is theoretically cleaner than exclusive.

Measurement of BF and $A_{FB}$ in $B \rightarrow X_s \ell^+ \ell^-$ at Belle.

Sum-of-exclusive method is utilized.

Tension in low $q^2$ region.

Measurement can be improved at Belle II.

Decay amplitude can be expressed in terms of $C_7$, $C_9$, and $C_{10}$.

Precise theory prediction available.

T. Huber, J. Virto, A. Ishikawa
In the SM:

- SM predictions (\cite{1} JHEP 02 184, 2015) updated BELLE2-MEMO-2016-007\cite{2} [D M Straub]

| Mode           | $\mathcal{B}$ [10^{-6}] Ref. | $\mathcal{B}$ [10^{-6}] Ref. |
|----------------|-------------------------------|-------------------------------|
| $B^+ \rightarrow K^+ \nu \bar{\nu}$ | $3.98 \pm 0.43 \pm 0.19$ | $4.68 \pm 0.64$ |
| $B^0 \rightarrow K_S^0 \nu \bar{\nu}$ | $1.85 \pm 0.20 \pm 0.09$ | $2.17 \pm 0.30$ |
| $B^+ \rightarrow K^{*+} \nu \bar{\nu}$ | $9.91 \pm 0.93 \pm 0.54$ | $10.22 \pm 1.19$ |
| $B^0 \rightarrow K^{*0} \nu \bar{\nu}$ | $9.19 \pm 0.86 \pm 0.50$ | $9.48 \pm 1.10$ |

- NP scenario can be tested:
  - Non-standard Z-coupling
  - New sources of missing energy.
• Belle very recently updated $b \rightarrow (s,d) \nu \bar{\nu}$ measurement.  
(See P.Goldenzweig’s talk in this conference)

• Brighter prospects for Belle II to observe this decay.

• Belle II extrapolation based on previous Belle measurement (hadronic tag) 
  Phys. Rev. D87 111103 (2013) [BELLE2-MEMO-2016-008].

• Assumes 100% more had. tag eff. and 30% more $K_s$ reco. eff.

\[
\begin{array}{|c|c|c|c|c|c|c|c|}
\hline
\text{Mode} & \mathcal{B} \left[10^{-6}\right] & \text{Efficiency} & N_{\text{Backg.}} & N_{\text{Sig-exp.}} & N_{\text{Backg.}} & N_{\text{Sig-exp.}} & \text{Statistical} & \text{Total Error} \\
& \left[10^{-4}\right] & \text{Belle} & 711 & 711 & 50 & 50 & \text{error} & \text{error} \\
\hline
B^+ \rightarrow K^+ \nu \bar{\nu} & 4.68 & 5.68 & 21 & 3.5 & 2960 & 245 & 20\% & 22\% \\
B^0 \rightarrow K^0_s \nu \bar{\nu} & 2.17 & 0.84 & 4 & 0.24 & 560 & 22 & 94\% & 94\% \\
B^+ \rightarrow K^{+} \nu \bar{\nu} & 10.22 & 1.47 & 7 & 2.2 & 985 & 158 & 21\% & 22\% \\
B^0 \rightarrow K^{0} \nu \bar{\nu} & 9.48 & 1.44 & 5 & 2.0 & 704 & 143 & 20\% & 22\% \\
B \rightarrow K^* \nu \bar{\nu} \text{ combined} & & & & & & & & 15\% & 17\% \\
\hline
\end{array}
\]

(We can include semileptonic tagging)
Major upgrade at KEK represents an essentially new experiment:
   • Many detector components and electronics replaced, software and analysis also improved.

Belle II has a rich physics program, complementary to existing experiments and energy frontier programs.

With the better detector Belle II and higher luminosity machine SuperKEKB, we can intensely search for NP with Radiative and EW Penguin decays.

Accelerator commissioning: June 2016 (successful.) → Phase 2: Starts in Nov 2017 (w/o vtx) → Phase 3 / Run 1: Fall 2018 (full det.).

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Double-radiative B decays

\[ B_q \rightarrow \gamma \gamma : \]

**SM prediction**

- \( \text{Br}(B_s \rightarrow \gamma \gamma)_{SM} \in [0.5, 3.7] \times 10^{-6} \)
- \( \text{Br}(B_d \rightarrow \gamma \gamma)_{SM} \in [1.0, 9.8] \times 10^{-8} \)

Bosch and Buchalla, JHEP 08 (2002) 054

- With the above comparison, Belle II will be able to discover \( B_d \rightarrow \gamma \gamma \) with the anticipated 50 ab\(^{-1}\) at \( \Upsilon(4S) \).
- Furthermore, in an appropriately large data at \( \Upsilon(5S) \) \( B_s \rightarrow \gamma \gamma \) can be observed.

\[ B \rightarrow X_s \gamma \gamma : \]

- \( B \rightarrow X_s \gamma \gamma \) decays are suppressed by \( \alpha_s/4\pi \) compared to \( B \rightarrow X_s \gamma \).
  \[ \text{Br}(B \rightarrow X_s \gamma\gamma)_{SM}^{0.02} = (1.7 \pm 0.7) \times 10^{-7} \]
  Asatryan et al., PRD 93, 014037 (2016) should be observable at Belle II.

- Measurements of the double-radiative decay mode would allow to put bounds on 1PI type corrections.
- One can study more complicated distributions like, double differential rate \( (d^2\Gamma/dE_1dE_2) \) and forward backward asymmetry \( \rightarrow \) sensitive to BSM physics.