Rare decays: A window on new physics

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Abstract. We report on the extrapolated measurements related to the flavour-changing-neutral-current(FCNC) $b \to s$ and $b \to d$ transitions with the Belle II data. The branching fraction(BF) and raw asymmetry measurements of the exclusive decay $\bar{B} \to X_q\gamma$, time-dependent CP asymmetry in the transition $b \to s\gamma$, angular analysis of $B \to K^*ll$ and $B \to X_sll$ are discussed. We also report on the searches for the decay $B \to h\nu\nu$. Most of these analyses are extrapolated with 5 and 50 ab^{-1} Belle II data.

Keywords: Belle II, Branching fraction, CP asymmetry, B meson, FCNC decay

1 Introduction

B-factories had 10 years of the successful operational period and accumulated 1.5 ab^{-1} data (1.25 $\times 10^9$ $B\bar{B}$pairs). The major achievements of Belle include observation of CP violation in B meson system and confirmation of CKM picture, first evidence for mixing in the D meson system, first evidence for exotic states X(3872) and so on. Belle II, as a next generation flavor factory, aims to search for New Physics (NP) in the flavour sector and to further reveal the nature of QCD. Belle II is expected to gather 50 ab^{-1} of data in e^+e^- collisions by 2025 [1].

FCNC $b \to s$ and $b \to d$ processes continue to be of great importance to precision flavor physics (FP). Final states having color singlet leptons and photons are both theoretically and experimentally clean. Also, radiative and electroweak (EW) penguin B decays are an ideal place to search for NP. Belle II physics program in this area will focus on the process such as inclusive measurements of $B \to X_{s,d}\gamma$, $B \to X_{s,d}ll$ as well as decay $B \to K^{(*)}\nu\nu$ [2]. The fully-inclusive measurements with final states containing pairs of photons, neutrinos or taus are possible at Belle II. It will provide an independent test of the anomalies recently uncovered by the LHCb and Belle experiments in the angular analysis of $B \to K^*\mu^+\mu^-$ and in the determination of $R(K)$.

2 $\bar{B} \to X_q\gamma$ decay

2.1 Branching Fraction

The inclusive $\bar{B} \to X_{s,d}\gamma$ decays provide important constraints on masses and interactions of many possible beyond Standard Mechanism (BSM) scenarios such as models with extended Higgs sector or super-symmetric (SUSY). Also, it is sensitive to $|C_7|$ co-efficient. Precise SM prediction [3] is available (for the CP and isospin asymmetry (IA) branching ratios) for gamma threshold energy (E_γ) greater than 1.6 GeV are as :

$$Br_{s\gamma} = (3.36 \pm 0.23)10^{-4} \qquad Br_{d\gamma} = (1.73^{+0.12}_{-0.22})10^{-5}, \tag{1}$$

and experimental obtained results [4] are as :

$$Br_{s\gamma} = (3.27 \pm 0.14)10^{-4} \qquad Br_{d\gamma} = (1.41 \pm 0.57)10^{-5}. \tag{2}$$

Though experiment and theory are consistent and put a strong limit on NP, experimental measurements are systematically dominated. The Belle measurement on fully inclusive method is systematic dominated [5]. This systematics can be reduced with large Belle II data samples. The extrapolated Belle II prospects on BF will be 3.9% with full 50 ab^{-1} as shown in Fig. 1 [2].

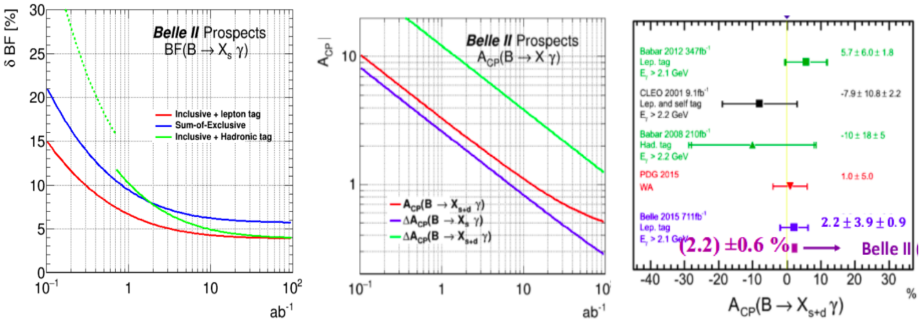

Fig. 1: Belle II exceptions on BF and CP uncertainty of $B \to X_s\gamma$ decays.

2.2 Rate Asymmetry

In addition to BFs, asymmetry in decay rates (IA and CP asymmetry) are also sensitive to BSM contributions. The SM predictions on A_{CP} of the decays $B \to X_{s,d}\gamma$ are given in the Ref. [6, 7]. The direct CP asymmetry and their IA are defined as:

$$A_{CP} = \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)}, \tag{3}$$

$$\Delta A_{CP}(B \to X_q\gamma) = A_{CP}(B^+ \to X_q^+\gamma) - A_{CP}(B^0 \to X_q^0\gamma). \tag{4}$$

The existing measurements of A_{CP} are measured by BaBar [8] and Belle [9] by using the sum-of-exclusive method and BaBar also measured ΔA_{CP} for fully inclusive method [10]. Belle II can be measured both A_{CP} and ΔA_{CP} using the same technique as BaBar, yet with a much larger data set. A reduction of the systematic uncertainties is therefore crucial at Belle II. The obtained previous results and expected Belle II results are shown in Fig. 1 [2].

3 $b \to s\gamma$ transitions (Time dependent CP asymmetry)

The observable IA, sensitive to BSM, can be defined as :

$$a_I^{0-} = \frac{c_V^2 \Gamma(\bar{B^0} \to \bar{V^0}\gamma - \Gamma(B^- \to V^-\gamma))}{c_V^2 \Gamma(\bar{B^0} \to \bar{V^0}\gamma + \Gamma(B^- \to V^-\gamma))} \tag{5}$$

where $c_{\rho^0} = \sqrt{2}$ and $c_{K^{*0}} = 1$ are isospin-symmetry factors [2]. To accumulate more statistics one can define CP-averaged IAs through $\bar{a}_I = \bar{a}_I^{0-} + a_I^{0+}/2$. The most up-to-date theoretical predictions [11] for the IAs are

$$\bar{a}_I^{SM}(K^*\gamma) = (4.9 \pm 2.6)\%, \quad \bar{a}_I^{SM}(\rho\gamma) = (5.2 \pm 2.8)\% \tag{6}$$

and these are consistent with the HFLAV average [12] which are as:

$$\bar{a}_I^{exp}(K^*\gamma) = (5.2 \pm 2.6)\%, \quad \bar{a}_I^{exp}(\rho\gamma) = (30^{-13}_{+16})\%. \tag{7}$$

The observable,

$$1 - \delta_{aI} = \frac{\bar{a}_I(\rho\gamma)}{\bar{a}_I(K^*\gamma)} \sqrt{\frac{\bar{\Gamma}(B \to \rho\gamma)}{\bar{\Gamma}(B \to K^*\gamma)}} \left|\frac{V_{ts}}{V_{td}}\right| \tag{8}$$

where δ_{aI} is close to zero, and the quantity $(1 - \delta_{aI}^{SM})= 0.90 \pm 0.11$ shows a reduced uncertainty with respect to the individual CP-averaged IAs. The experimental average $\delta_{aI}^{exp} = -4.0 \pm 3.5$ can be improved at Belle II through more statistics as well as taking into account experimental correlations. In the SM, expected mixing-induced CP asymmetries (S) are as follows:

$$S_{K^*(K_S^0\pi^0)\gamma} = -2\frac{m_s}{m_b} \sin 2\phi_1 = afew\%, \quad S_{\rho(\pi^+\pi^-)\gamma} = 0. \tag{9}$$

The expected uncertainties on S are 0.03% (0.09%) and 0.06% (0.19%) for the decay modes $K^*(K_S^0\pi^0)\gamma$ and $\rho^0(\pi^+\pi^-)\gamma$ respectively with 50 (5) ab^{-1} Belle II data sample [2].

4 Measurements of R_K, R_{K^*}, and R_{X_s}

The decay $B \to K^*ll$ proceeds via one loop diagram and lepton universality holds in SM. Interestingly, in the recent years several measurements have shown possible deviations from the SM for this decay [13]. The Lepton Flavor Universality (LFU) ratios $R_K(R_{K^*})$ are defined as the ratios $\frac{\Gamma[B\to K(K^*)\mu\mu]}{\Gamma[B\to K(K^*)ee]}$ and R_{X_s} as $\frac{\Gamma[B\to X_s\mu\mu]}{\Gamma[B\to X_s ee]}$. The electron mode is challenging at LHCb, especially for high q^2 (invariant mass squared of the two leptons) region but Belle II is having similar efficiency for electron and muon modes. Thus, the measurements at both low and high q^2 regions and the ratios R_K, R_{K^*}, and R_{X_s} are possible at Belle II. An additional q^2 ϵ (1.0, 6.0) GeV^2/c^2 bin is considered, which is favored

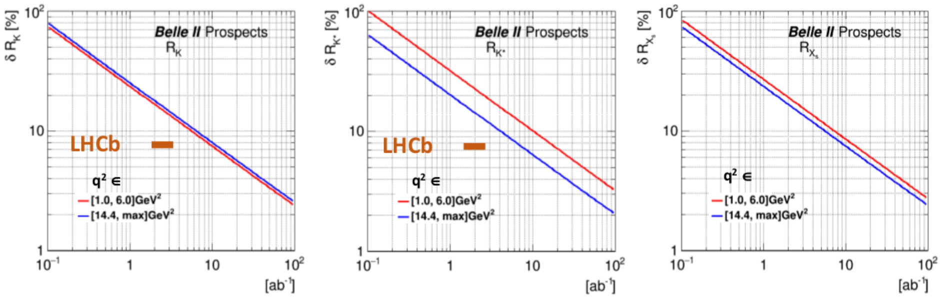

Fig. 2: Expected uncertainty of R measurement at Belle II.

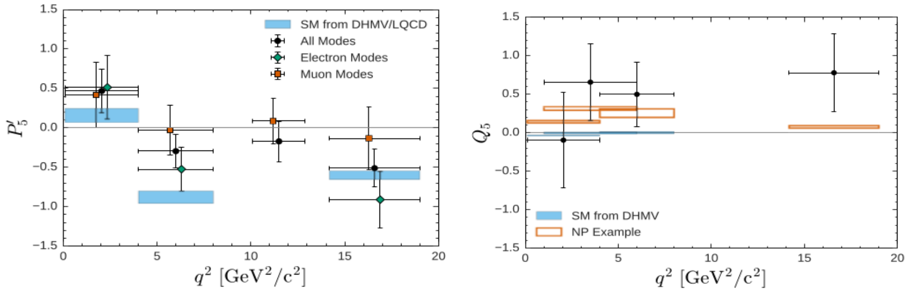

Fig. 3: (left) P_5observables for combined, electron and muon modes and (right) Q_5 observables compared with SM and NP scenario.

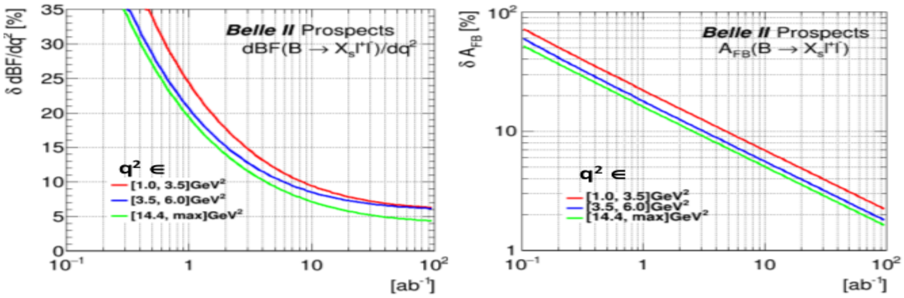

Fig. 4: Belle II exceptions on BF and A_{FB} uncertainty of $B \to X_s ll$ decays.

for theoretical predictions [14]. To maximize the potency of limited statistics, a data-transformation technique is utilized [15, 16]. The result is shown in Fig. 3, where it is also compared with SM predictions [17, 18]. The largest deviation is 2.6σ , observed in q^2 ϵ (4.0, 8.0) GeV^2 /c^2 bin of P_5 for the muon mode [19]. This tension is coincidental to the P_5 anomaly earlier reported by LHCb [20, 15]. In the same region the electron modes deviate by 1.3σ and the combination deviates by 2.5σ. The observables P_5 and Q_5 are presented in Fig. 3, where they are compared with SM and NP scenario [21]. The results show no significant deviation from zero. A global fit performed including these measurements [19] suggests for lepton-universality violation [22]. Belle II and LHCb will be comparable for this $b \to sll$ process. The Belle II projection for P_5 anomaly for different q^2 regions are listed in Table1. In the low q^2 region the uncertainty will be 4% with 50 ab^{-1} [2] which will be comparable with LHCb 22 fb^{-1} result. The Belle II excepted uncertainty on BF and A_{FB} uncertainty of $B \to X_s ll$ decays are shown in Fig. 4 [2].

q^2 (GeV^2/c^4)	Belle	Belle II
0.1-4	0.42	0.06
4-8	0.28	0.04
10.09-12	0.34	0.05
14.18-19	0.25	0.03

Table 1: Expected uncertainty on P_5 at Belle II in bins of q^2.

5 Search for $b \to s\nu\nu$ transitions

The decays $B \to h\nu\nu$ (where h refers to K^+, K^0_S , K^{*+} , K^{*0} , π^+ , π^0 , ρ^+ or ρ^0 [23]) are theoretically clean due to the exchange of a Z boson alone, in comparison to other $b \to s$ transitions where the virtual photon also contributes [24]. The SM predicted BF is given in the Ref. [24]. Previously, the decays $B \to h\nu\nu$ have been searched in Belle utilizing the hadronic tag method [25] and in BaBar using both hadronic [26] and semi-leptonic (SL) tag [27]. The recent Belle analysis updated this measurement with SL tag method and set most stringent limits till date in most channels [28]. The SM predicted the $K^{(*)}$ mode is a golden channel for Belle II and extrapolated by assuming Belle hadronic and SL tag analyses as

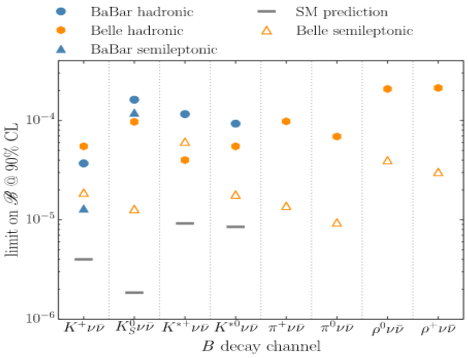

Fig. 5: Belle II exceptions on BF uncertainty of $B \to h\nu\nu$ decays.

100%. The precision on the BF of few decay modes are listed in Table 2 at 50 ab^{-1} Belle II data set. The BF of $B \to K(*)\nu\nu$ is measurable at Belle II with about 10% uncertainty [2].

Mode	stat. only	Total
$B^+ \to K^+\nu\nu$	10%	11%
$B^+ \to K^{*+}\nu\nu$	8%	9%
$B^+ \to K^{*0}\nu\nu$	8%	10%

Table 2: Expected uncertainty on K modes at Belle II.

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