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Prospects for rare B decays at Belle II

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Abstract

Rare and flavour-changing neutral current decays of the B meson are an important probe in the search for physics beyond the Standard Model. There have recently been several anomalies in rare B decays, and lepton-universality measurements, specifically involving the $b \to s\ell^+\ell^-$ quark transition. These results tend towards a non-Standard-Model interpretation. The Belle II experiment is a next-generation b physics experiment located at SuperKEKB, an upgraded B factory e^+e^- collider, in Tsukuba, Japan. The first collisions are expected in early 2018 with full physics data expected in 2019. This document describes prospects for several rare B decays at Belle II including $b \to s\ell^+\ell^-$ processes and others, such as $b \to (s,d)\gamma$ and $b \to s\nu\bar{\nu}$. Areas where the Belle II program is complementary to that of the currently running LHCb experiment are highlighted.

1. Introduction

Rare and flavour-changing neutral current (FCNC) decays of the beauty quark are sensitive to the effects of undiscovered new particles, if they exist, that are not included in the Standard Model of particle physics (SM). As FCNC are forbidden at tree-level in the SM, these decays proceed by higher-order loop-level diagrams (as shown in Figure 1). However any potential new physics (NP) contribution does not suffer the same restriction and can occur at a comparable size. As these NP diagrams contain virtual particles that can be off-mass-shell, the mass scale in the search for NP with these decays is typically many times larger than searches involving direct production. Furthermore, several recent measurements of these decay processes [1–4][1] are in tension with SM predictions, which has generated much interest [5–9][2].

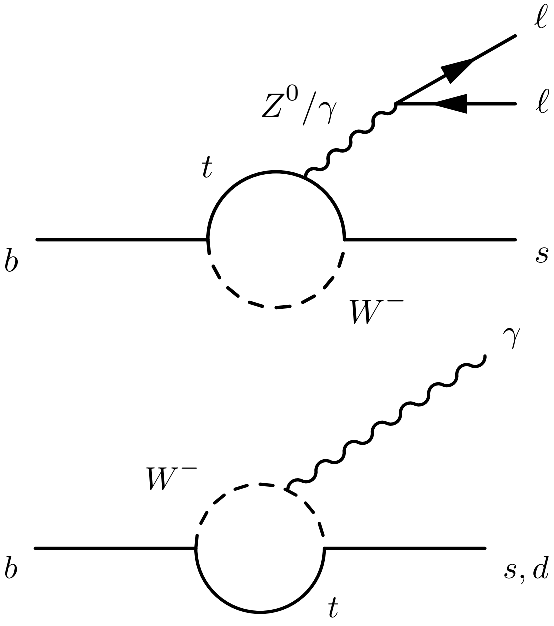

Figure 1: *The leading order Feynman diagrams for the FCNC $b \to s\ell\ell$ (where ℓ represents e, μ, τ or ν) and $b \to (s,d)\gamma$ in the SM.*

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[1] The result of Ref. [4] is also presented at this conference, talk by S. Sandilya.

[2] The analysis of Ref. [6] is also presented at this conference, talk by W. Altmannshofer.

The Belle II experiment [10] is a hermetic detector currently being commissioned at the SuperKEKB accelerator [11] at the KEK laboratory in Tsukuba, Japan. The first data are expected in early 2018, with a target dataset of 50 ab^{-1} of e^+e^- collisions by 2025. This dataset should contain approximately 50×10^9 $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ events. Measurements of rare and FCNC decays are an integral part of the Belle II physics program.

2. Previous and current *b* physics experiments

The Belle II experiment is a second-generation B factory. The first generation of B factories were the Belle and BaBar experiments [12] at the KEKB and PEP-III accelerators at KEK and the SLAC National Accelerator Laboratory, respectively. Following the first-generation B factories, the LHCb experiment [13] at the LHC at CERN has been taking data since 2009. The LHC produces pp collisions at high-energy and cannot exploit the $\Upsilon(4S)$ resonance, however $pp \to b\bar{b}$ quark pair-production is copious in the forward region and LHCb utilises a single-arm forward spectrometer detector design [13]. These three experiments have produced many noteworthy results, several examples that are not discussed elsewhere in this document are described in Refs [14–19].

3. The next-generation experiment: Belle II at SuperKEKB

3.1. Description

The SuperKEKB accelerator complex [11] is an upgrade of KEKB. The accelerator beams are asymmetric in energy: 7 GeV for electrons (defining the forward direction) and 4 GeV for positrons. The accelerator is designed to achieve a factor 40 increase in instantaneous luminosity with respect to KEKB. This is due to a more focused beam crossing and higher beam current, achieved by: new superconducting magnets [20] at the interaction point, a new positron dampening ring, and upgraded beam optics.

The Belle II detector [10] has been upgraded from Belle to cope with the much higher luminosity and higher expected beam backgrounds. Around the collision point, the silicon vertex detector has one more layer than Belle, with the addition of two inner layers of depleted field-effect transistor pixel detectors. The vertexing detectors are surrounded by the Belle II wire drift chamber that is larger than in Belle. Two new particle identification systems have been installed utilising Cherenkov radiation: in aerogel blocks in the forward endcap and totally internally reflected inside quartz bars in the barrel. The thallium-doped caesium iodide electromagnetic calorimeter has been reused from Belle although the readout and electronics have been totally replaced. The superconducting coil magnet is reused and will provide a 1.5 T magnetic field for charge assignment and to measure tracking momentum of charged particles. The inner barrel layers and the endcap of K_L^0 and muon detector have been replaced with plastic scintillator, the outer barrel layers reuse the original resistive plate chambers from Belle.

3.2. Status as of August 2017

The design data schedule is shown in Figure 2. In early 2018 the accelerator is scheduled to provide e^+e^- collisions at reduced luminosity for detector commissioning[3]. The vertexing pixel detector and silicon vertex detector components will not be installed for this phase. In 2019 the full vertexing detector will be installed and the accelerator will provide physics collisions[4].

4. Theoretical framework and motivation

Figure 1 shows the leading order SM contributions to $b \to s$ processes. However, in order to interpret results in a model-independent way, the theory community typically works in a general expansion of an effective Hamiltonian,

$$\mathcal{H}_{\text{eff}} \propto \sum_{i=1,..10,S,P} (C_i\mathcal{O}_i + C_i'\mathcal{O}_i'),$$

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[3] Operationally, and in Belle II literature, this is referred to as "Phase 2" for historic reasons.

[4] Referred to as "Phase 3". Should be thought of as physics run 1.

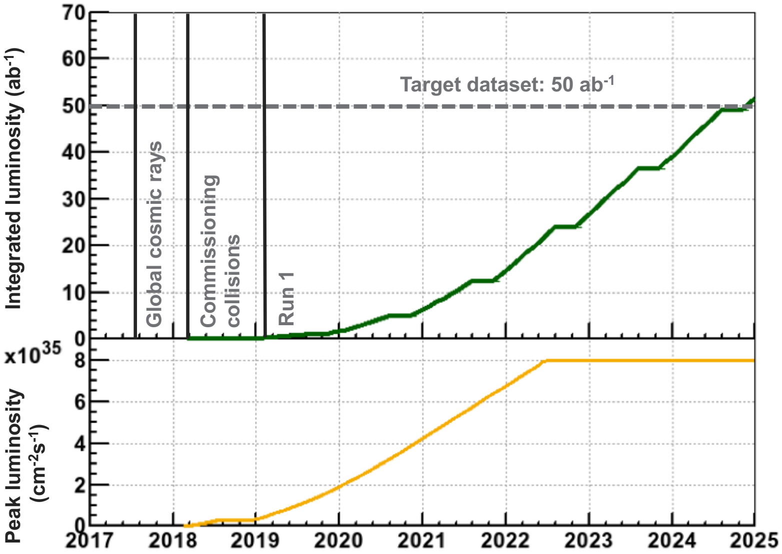

Figure 2: *The scheduled integrated and peak luminosities of SuperKEKB. Approximately* 10^9 $B\bar{B}$ *pairs per* ab^{-1} *of data at the* $\Upsilon(4S)$ *resonance will be collected. Adapted from* [21].

in terms of effective operators, $\mathcal{O}_i^{(\prime)}$, containing the non-pertubative low-energy effects and so-called "Wilson coefficients", C_i. The primes denote the chiral partner operator that is suppressed in the SM. The Wilson coefficients may be expressed as:

$$C_i = C_i^{\mathrm{SM}} + C_i^{\mathrm{NP}},$$

the sum of the SM (calculable with pertubative techniques) and NP (to be determined) contributions.

There are 24 operators and coefficients in the full expansion[5]. However, there are three which are most relevant for $b \to s$:

$$\begin{aligned}
\mathcal{O}_9 &\propto (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell);\\
\mathcal{O}_{10} &\propto (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell);\\
\mathcal{O}_7 &\propto m_b(\bar{s}\sigma_{\mu\nu} P_R b)F^{\mu\nu}.
\end{aligned}$$

These are the vector, axial vector, and radiative photon operators respectively, and are shown schematically in Figure 3. This theoretical procedure is appealing as it allows model-independent global fits to the C_i^{NP}, searching for *generic NP* based on the *form of the interaction* with SM fermions.

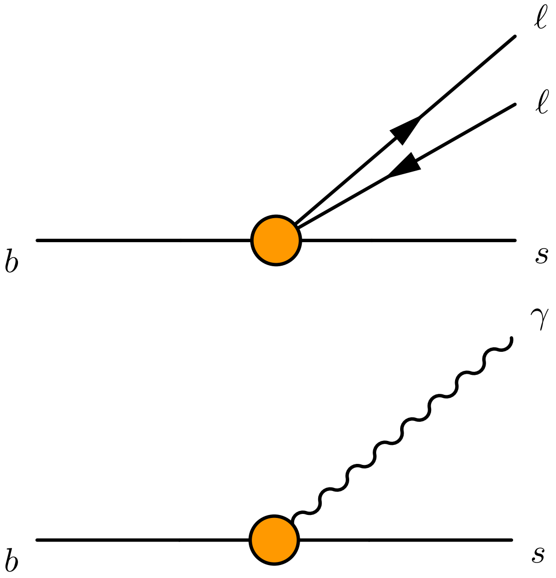

Figure 3: *A diagrammatic representation of the effective (axial) vector operators* $\mathcal{O}_9$ *(*$\mathcal{O}_{10}$*) and radiative photon operator* $\mathcal{O}_7$ *(upper and lower respectively).*

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[5] More detail is available in many references, for example Ref. [22].

Furthermore, many observables are then constructed in such a way as to divide out or otherwise remove the hadronic uncertainties. Such observables are called "theoretically clean" or "form-factor independent". Finally, it is also possible to separate this whole framework by lepton flavour such that

$$C_i \longrightarrow C_i^{\mu} \text{ and } C_i^{e}$$

allowing for a lepton-flavour-dependent determination of any NP. This final step is relevant given recent results [1, 2, 4], analyses may be found in Refs [6–8].

5. Inclusive measurements and full event interpretation

Inclusive decays, where the hadronic part of the decay is not specified, are denoted $B \to X(\gamma, \ell\ell)$ with X representing all hadrons. Their measurements should be contrasted with measurements of exclusive decays to a specific hadronic final state (such as $B \to K^*\gamma$, for example).

In terms of theory, SM predictions of inclusive decays are complementary to exclusive as they typically suffer less, or orthogonal, uncertainty due to hadronic form-factors. Predictions for the branching fractions of $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$ in the SM are calculated to a precision of around 7% [23–25] which should be compared to the SM prediction for the branching fractions of $B \to K^*\gamma$ and $B \to K^*\mu^+\mu^-$ at $20 - 23\%$ [25, 26].

Experimentally, there are two approaches for inclusive analyses: fully inclusive and the so-called "sum-of-exclusive" methods. These are described in the following subsections.

In addition, decays with neutrinos in the final state are often reconstructed in the B factories as part of the full $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ event such that the missing energy is precisely known.

5.1. Sum-of-exclusive approach

The sum-of-exclusive reconstruction method is where the X is specifically reconstructed to several final states. This method is the only way to specify the transition as $b \to s$ (or $b \to d$) since X_s (X_d) can be specified by the presence (absence) of a kaon in the final state. For example, X_s can be reconstructed as $Kn\pi$ and $3Km\pi$ where $n \geq 1$ and $m \geq 0$. Furthermore, the flavour and momentum of the parent B is known without the need to perform full event interpretation (discussed in the following section). The sum-of-exclusive analyses therefore have relatively high efficiency to select signal events.

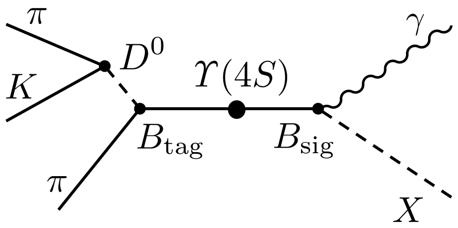

Figure 4: *A schematic of a hadronically tagged decay where full event reconstruction is possible. In this example the tag decay is $B \to D^0(\to K\pi)\pi$, however several decay chains with high branching fractions or efficiencies are included [27]. The signal is able to be constructed from missing energy (i.e. neutrinos) or as an inclusive decay if only a photon or (pair of) leptons are reconstructed.*

5.2. Full event interpretation

Fully inclusive measurements, and processes with neutrinos or other missing energy often rely on "tagging" the other B decay (the B_{tag}) from the $\Upsilon(4S)$. This is shown schematically in Figure 4. Such analyses are challenging for LHCb due to the detector geometry and the production mechanism $pp \to b\bar{b}$. Hermetic detectors, such as BaBar, Belle, and Belle II are able to precisely reconstruct $\Upsilon(4S) \to B\bar{B}$ decays and therefore better suited to performing such measurements. This is illustrated qualitatively in Figure 5.

There are two further approaches to reconstruct the full event, dependent on the final state of the B_{tag} decay. The B_{tag} decay may be reconstructed in a fully hadronic final state, in which case the momentum of the signal B is

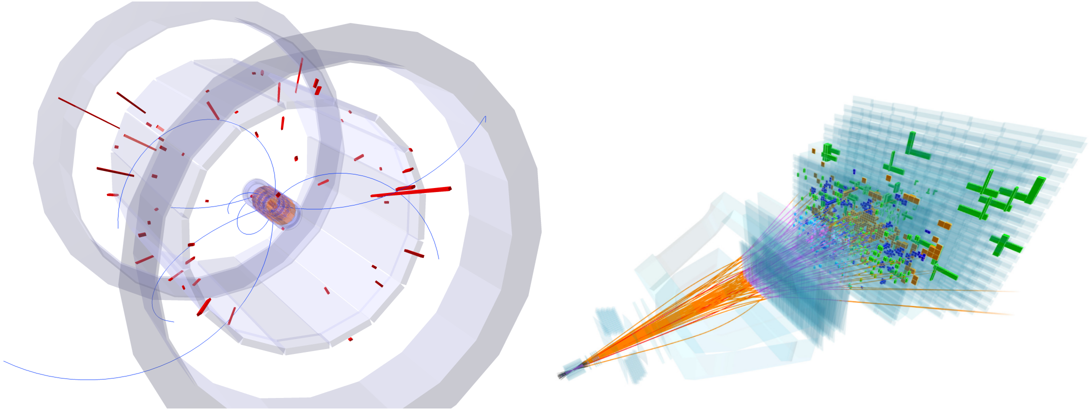

Figure 5: *Examples of event displays from Belle II simulation (left) and LHCb data (right). Belle II is hermetic and can exploit the clean* $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ *production. LHCb does not have full coverage and the production mechanism* $p^+p^- \to b\bar{b}$ *is less well known. Belle II is therefore better suited to perform fully inclusive measurements and measure processes with neutrinos in the final state. Right-hand figure from [28].*

known precisely, independent of the signal decay. However, fully reconstructed hadronic decays suffer from low branching fractions with respect to semi-leptonic decays. Thus semi-leptonic tagging has a somewhat higher efficiency at the expense of losing the full momentum (and parent charge) information in most signal decays. Newer full event interpretation (FEI) algorithms have been developed for Belle II [27] which include several final states and utilise advances in machine learning. The efficiencies of FEI are shown in Table 1.

6. Prospects at Belle II

6.1. Inclusive $b \to (s, d)\gamma$

The inclusive radiative penguin measurements provide important constraints on many possible NP scenarios such as models with extended Higgs sectors and supersymmetry [25, 30]. Measurements of the branching fraction of $B \to X_s\gamma$ ($B \to X_d\gamma$) from the first generation of B factories have been combined [31] to give a precision of about 4% (30%). These averages are in very good agreement with the SM predictions which are calculated to around 7% precision [24]. With Belle II, the single experiment precision for $B \to X_s\gamma$ measured with a semi-leptonic tag is expected to quickly overtake the the combination, and should be known to less than 3% uncertainty. The full precision is expected to reach percent-level. For $B \to X_d\gamma$, the precision will be improved to around 15% with 50 ab^{-1}. In the case of X_d this improvement is due both to a larger data sample, and to the upgraded particle identification system which will aid discrimination against the large background from $B \to X_s\gamma$ processes (namely where a kaon track is misidentified as a pion).

It is also possible to construct the CP-asymmetry, defined in general as:

$$A_{\text{CP}} \equiv \frac{\Gamma\left[\bar{B} \to \bar{f}\right] - \Gamma\left[B \to f\right]}{\Gamma\left[\bar{B} \to \bar{f}\right] + \Gamma\left[B \to f\right]},$$

where Γ is the partial width for *any* decay of a B meson to a final state f, as well as the isospin asymmetry, defined as:

$$\Delta_{0+} \equiv \frac{\Gamma\left[B^0 \to f^0\right] - \Gamma\left[B^\pm \to f^\pm\right]}{\Gamma\left[B^0 \to f^0\right] + \Gamma\left[B^\pm \to f^\pm\right]}.$$

Another related observable is the difference of CP-violation between the charged and neutral B meson decays:

$$\Delta A_{\text{CP}} \equiv A_{\text{CP}}\left[B^\pm \to f^\pm\right] - A_{\text{CP}}\left[B^0 \to f^0\right].$$

These observables can be defined for an in-

Parent	Tagging	Belle II FEI	Belle MC Belle II FEI	Belle
$B^{\pm}$	Hadronic	0.61%	0.49%	0.28%
	Semi-leptonic	1.45%	1.42%	0.67%
B^0	Hadronic	0.34%	0.33%	0.18%
	Semi-leptonic	1.25%	1.33%	0.63%

Table 1: *Tagging efficiencies for Belle II FEI algorithms determined with simulation of the Belle II and Belle detectors and the original Belle efficiency evaluated on data. Taken from [27, 29].*

clusive decay, such as $B \to X_s\gamma$ as,

$$A_{\mathrm{CP}} = \frac{\Gamma\left[\bar{B} \to X_s\gamma\right] - \Gamma\left[B \to X_{\bar{s}}\gamma\right]}{\Gamma\left[\bar{B} \to X_s\gamma\right] + \Gamma\left[B \to X_{\bar{s}}\gamma\right]},$$

$$\Delta_{0+} = \frac{\Gamma\left[B^0 \to X_s\gamma\right] - \Gamma\left[B^{\pm} \to X_s\gamma\right]}{\Gamma\left[B^0 \to X_s\gamma\right] + \Gamma\left[B^{\pm} \to X_s\gamma\right]},$$

$$\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}\left[B^{\pm} \to X_s^{\pm}\gamma\right] - A_{\mathrm{CP}}\left[B^0 \to X_s^0\gamma\right].$$

In all cases, the flavour and CP state of the parent B is determined from the tag.

Such observables have reduced experimental systematic effects, as well as reduced theoretical uncertainty from hadronic form-factors. Experimental measurements are therefore more precise than the branching fractions, for example A_{CP} and Δ_{0+} for $B \to X_s\gamma$ are both around 2% [32,33], for $B \to X_d\gamma$ they are around 30%. With 50 ab^{-1} at Belle II, measurements are expected to reach sub-percent-level precision for A_{CP} and Δ_{0+} in $B \to X_s\gamma$, and around percent level precision for $B \to X_d\gamma$. Figure 6 shows the precision on A_{CP} and ΔA_{CP} as a function of integrated luminosity collected at the $\Upsilon(4S)$ resonance.

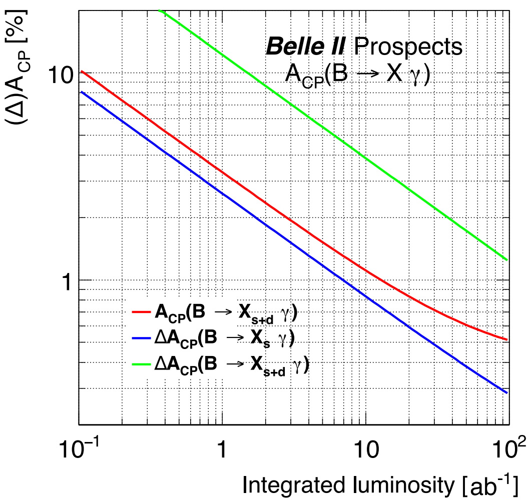

Figure 6: *Sensitivity to A_{CP} and ΔA_{CP} in $B \to X_{(s,\,d)}\gamma$ decays. To appear in [29].*

6.2. Lepton (non) universality and inclusive $b \to s(e^+e^-,\ \mu^+\mu^-)$

Recent experimental tests of lepton universality in $b \to s\ell^+\ell^-$ decays have shown deviation from the SM predictions [1,2]. Deviations are not too far from statistical significance and are therefore the source of much discussion within the community [5–8]. In addition to these measurements a somewhat longstanding discrepancy in the angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ [3] has been explored for both $B \to K^*e^+e^-$ and $B \to K^*\mu^+\mu^-$ by Belle [4].

In global fits to the Wilson coefficients [6–8], these discrepancies prefer a non-zero C_9^{NP}. In terms of NP interpretations, models with an extended electroweak sector, such as a new vector boson Z', have been suggested. There has been some debate in the theory community about possible non-NP explanations for these deviations, such as underestimated hadronic uncertainty, or an underestimated contribution from high-order diagrams involving charm quarks in the $b \to s\mu^+\mu^-$ transition [34].

References [1, 2] present the measurement of lepton universality ratios conventionally defined,

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}\left[B \to K^{(*)}\mu^+\mu^-\right]}{\mathcal{B}\left[B \to K^{(*)}e^+e^-\right]},$$

where $\mathcal{B}$ is the branching fraction. In the SM these ratios are predicted to be very close to unity within the region of the

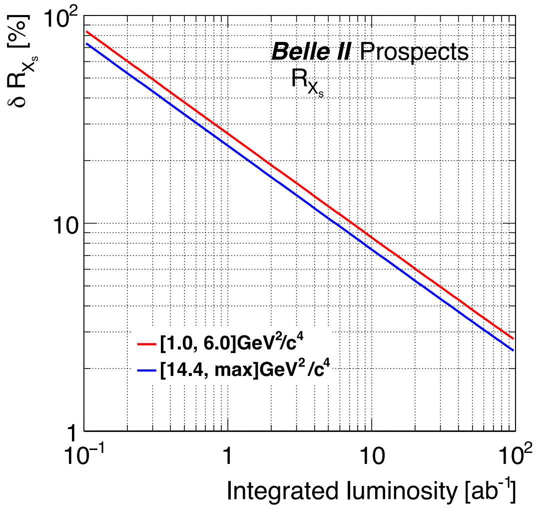

Figure 7: *Sensitivity to an inclusive lepton universality ratio defined in Equation 1, for two regions of squared invariant mass of the lepton pair. To appear in [29].*

squared invariant mass of the lepton pair, $1 < q^2 < 6\ \mathrm{GeV}^2/c^4$ [35]. Belle II will not overtake the precision of these measurements but will perform an independent verification. With approximately 10 ab^{-1} (3 ab^{-1}) Belle II will reach the current precision of R_K (R_{K^*}). However an analogous definition in terms of the inclusive decays,

$$R_{X_s} \equiv \frac{\mathcal{B}\left[B \to X_s\mu^+\mu^-\right]}{\mathcal{B}\left[B \to X_s e^+e^-\right]}, \qquad (1)$$

can be made. Such an observable would be challenging for LHCb, but could be measured with percent-level precision at Belle II as shown in Figure 7.

It is also possible to measure the differential branching fraction ($\mathrm{d}\mathcal{B}/\mathrm{d}q^2$), A_{CP}, and perform an angular analysis for these inclusive $B \to Xe^+e^-$ and $B \to X\mu^+\mu^-$ decays. In contrast to the angular analysis of the exclusive $B \to K^*\mu^+\mu^-$ decay with many observables, in an inclusive angular analysis it is only possible to measure the forward-backward asymmetry of the leptons (A_{FB}). Current precision [36–38] is around 30% for $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$, and 20% for A_{FB} and A_{CP}. Belle II will reach a precision of around 7% for $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$ and $2-3\%$ for A_{FB} and A_{CP}. Figures 8 and 9 show the sensitivity for the former two of these observables.

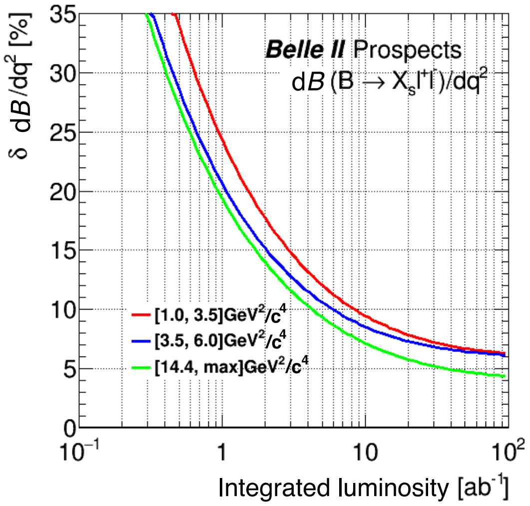

Figure 8: *Sensitivity to the differential branching fraction ($d\mathcal{B}/dq^2$) in $B \to X_s\ell^+\ell^-$ decays, for three regions of squared invariant mass of the lepton ($\ell = e, \mu$) pair. To appear in [29].*

6.3. $b \to s\nu\bar{\nu}$

Assuming that the $B \to K^*\nu\bar{\nu}$ decay occurs at the rates predicted by the SM [39, 40],

$$\mathcal{B}\left[B^+ \to K^+\nu\bar{\nu}\right] = (4.7 \pm 0.6) \times 10^6;$$
$$\mathcal{B}\left[B^0 \to K^{*0}\nu\bar{\nu}\right] = (9.5 \pm 1.1) \times 10^6,$$

Belle II will observe the process and measure the branching fraction with $10-11\%$ uncertainty in 50 ab^{-1}. This decay mode is of similar interest to $B^0 \to K^{*0}\mu^+\mu^-$ in terms of sensitivity to $C_{9,10}^{\mathrm{NP}}$, however probing $B \to K^*\nu\bar{\nu}$ decays also provides orthogonal information. For $B \to K^*\nu\bar{\nu}$, the factorisation of hadronic effects is exact (since neutrinos are electrically neutral) and could be used to extract $B \to K$ hadronic form-factors to high accuracy [29]. It is also possible that $B \to K^*\nu\bar{\nu}$ can provide model-dependent information to disentangle possible NP effects behind the current anomalies [39].

Experimentally, it is possible to use full event reconstruction and construct the sum of the missing energy and missing momentum in the e^+e^- centre-of-momentum frame. The distribution of this variable is shown in Figure 10.

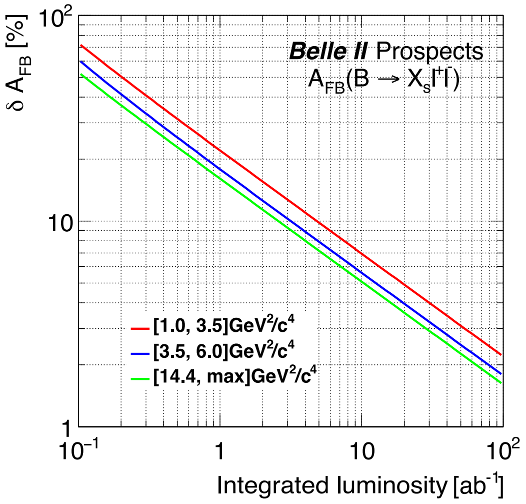

Figure 9: *Sensitivity to the forward-backward asymmetry of the leptons* (A_{FB}) *in* $B \to X_s \ell^+\ell^-$ *decays, for three regions of squared invariant mass of the lepton* ($\ell = e, \mu$) *pair. To appear in* [29].

Such a variable is promising for separating signal from background, either for a counting analysis or as the independent variable in a maximum likelihood fit. Assuming observation at Belle II, it should also be possible to measure fraction of longitudinal polarisation of the K^* in $B \to K^*\nu\bar{\nu}$ to around 20% precision.

6.4. $b \to (s,d)\tau^+\tau^-$

Decays with the $b \to (s,d)\tau^+\tau^-$ transition are thus-far unobserved. Current experimental limits [41, 42] are of the order of 10^{-3} which is rather far from the SM predictions [43, 44] of,

$$\begin{aligned} \mathcal{B}\left[B_s^0 \to \tau^+\tau^-\right] &= (7.73 \pm 0.49) \times 10^{-7}; \\ \mathcal{B}\left[B^0 \to \tau^+\tau^-\right] &= (2.22 \pm 0.19) \times 10^{-8}; \\ \mathcal{B}\left[B^+ \to K^+\tau^+\tau^-\right] &= (1.22 \pm 0.10) \times 10^{-7}. \end{aligned}$$

Assuming these SM branching fractions, Belle II will be able to set limits of around 10^{-6} and 10^{-5} for $B^0 \to \tau^+\tau^-$ and $B^+ \to K^+\tau^+\tau^-$ respectively. The sensitivity to $B_s \to \tau^+\tau^-$ decays is highly dependent on SuperKEKB running at the $\Upsilon(5S)$ resonance, which has not yet been finalised.

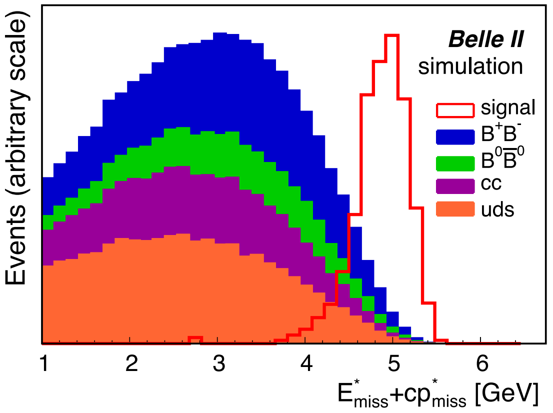

Figure 10: *The distribution of the missing energy and missing momentum in the centre-of-momentum frame for* $B \to K^*\nu\bar{\nu}$ *signal decays (red) and various background categories (solid colour stack by cross-section). To appear in* [29].

7. Conclusions

The Belle II experiment at SuperKEKB will collect first collisions commissioning data in 2018. Full-detector physics data are expected in 2019. At time of writing, the Belle II detector has been rolled into the collision point at SuperKEKB and is taking cosmic ray commissioning data.

Rare radiative and electroweak penguin processes have recently shown deviations from SM predictions, and form an integral part of the Belle II physics program. Belle II will have access to several decay modes that are challenging at the LHCb experiment, such as $B \to K^*\nu\bar{\nu}$ and inclusive decays. Belle II will provide independent verification of the deviations observed by LHCb, such as lepton universality in $B \to K^*(e^+e^-, \mu^+\mu^-)$ decays.

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