Measurements of $R(D^{(*)})$ and other missing energy $B$ decays at the Belle II experiment

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Abstract. The Belle II experiment at the SuperKEKB collider is a major upgrade of the KEK “B factory” facility in Tsukuba, Japan. The accelerator has already successfully completed the first phase of commissioning in 2016 and first electron positron collisions in Belle II have taken place in April 2018. The design luminosity of SuperKEKB is $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$ and the Belle II experiment is expected to accumulate a data sample of about 50 ab$^{-1}$, a factor of 50 more than the Belle experiment. With this amount of data, decays sensitive to physics beyond the Standard Model can be studied with unprecedented precision. This report discusses our prospects for studying lepton flavor non-universality with the modes $B \rightarrow D^{(*)}\tau\nu$, and the prospects for other missing energy modes sensitive to physics beyond the Standard Model, such as $B \rightarrow \tau\nu$ and $B \rightarrow K^{(*)}\nu\nu$, which provides one of the cleanest experimental probes of the flavour-changing neutral current process $b \rightarrow s\nu\nu$.

1. Introduction
In order to answer some of the open questions in the flavour physics sector, particularly to probe the nature of the tensions with the SM predictions in the current observations, the electron-positron collider KEKB (Tsukuba, Japan) has been upgraded to reach an instantaneous luminosity of $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$, in order to accumulate a sample of 50 ab$^{-1}$. In the SuperKEKB collider, beams of electrons and positrons collide with asymmetric energies of 7 and 4 GeV, respectively, corresponding to a centre-of-mass energy of 10.58 GeV (peak of the $\Upsilon(4S)$ resonance). Data taking at other $\Upsilon(nS)$ resonances is also scheduled. At the design luminosity, the machine will produce $10^{10}$ $B$ pairs per year, therefore becoming the most prolific $B$-factory ever built. Furthermore, the Belle detector has undergone a major upgrade, to cope with the significantly higher level of beam-induced backgrounds, while maintaining or improving the performance.

The first collisions have been recorded on April 26th 2018 with the Phase-2 Belle II detector, which is without the Vertex Detector (VXD), and the data taking continued until July. Afterwards, the almost complete VXD will be installed and starting from February 2019 Belle II will take data with this new detector configuration (Phase-3).

2. Reconstruction of missing energy $B$ decays at Belle II
An advanced technique that Belle II uses to fully reconstruct one of the two $B$ mesons (called $B_{\text{tag}}$), in order to infer the four-momentum of the other $B$ meson ($B_{\text{sig}}$), via hadronic or semileptonic $B$ decays, is the Full Event Interpretation (FEI). It is an extension of the Full
Reconstruction (FR) used in Belle [1] and makes use of thousands of exclusive decay modes to train several multivariate classifiers in a hierarchical approach. It has been shown, using the Belle II GEANT4-based [2] simulation and considering the hadronic-tagging modes, that the FEI has improved upon the Belle FR performance by increasing the tagging efficiency from 0.2% to 0.5%, at a fixed \(B_{\text{tag}}\) purity of 25% [3].

It is worth introducing here the observable \(E_{\text{ECL}}\) (or \(E_{\text{Extra}}\), upon which almost all of the missing energy \(B\) decay studies rely. It is defined as the residual energy deposited in the ECL once we have subtracted all the clusters associated with the \(B_{\text{tag}}\) and \(B_{\text{sig}}\). It is expected to peak at 0 GeV for correctly reconstructed \(\Upsilon(4S)\) decays, while it shows a broader distribution, peaking at larger values, for mis-reconstructed signal events or for background events. It has been verified with the Belle II full simulation that the impact of the photon background in the ECL coming from the beams and the interaction region (synchrotron radiation, radiative Bhabha and two-photon processes) can be controlled by exploiting the distinctive features of the background calorimetric clusters compared to the energy deposits coming from the \(T(4S)\).

### 3. Semileptonic \(B\) decays and \(R(D^{(*)})\)

The semileptonic \(B\) decays \(B \to D^{(*)}\tau\nu\) are a clear test of the Standard Model (SM), as New Physics (NP) can largely affect as both the branching fraction, \(B\), and the \(\tau\) polarisation, \(P_{\tau}\), through diagrams involving a charged Higgs boson [4] or leptoquarks [5]. The observables \(R_{D^{(*)}} = B(B \to D^{(*)}\tau\nu)/B(B \to D^{(*)}\ell\nu)\), where \(\ell = \mu, e\), are usually considered, as the ratio reduces the experimental uncertainties on the tagging efficiencies, the theoretical uncertainties on the semileptonic form factors and the uncertainty associated with \(|V_{cb}|\). The current world average of the two ratios [6], combining measurements performed by Belle, BABAR and LHCb, is \(R_D = 0.397 \pm 0.040(\text{stat.}) \pm 0.028(\text{syst.})\) and \(R_{D^{*}} = 0.310 \pm 0.015(\text{stat.}) \pm 0.008(\text{syst.})\), which are significantly above the SM expectations [7] of \(R_D = 0.299 \pm 0.003\) and \(R_{D^{*}} = 0.257 \pm 0.003\), corresponding to a deviation of approximately \(4\sigma\). The most recent average, including the latest results obtained by the LHCb Collaboration [8], reduces the discrepancy to \(3.62\sigma\). The Belle measurements using hadronic or semileptonic tags are based on \(E_{\text{ECL}}\) for the signal extraction, and on the squared missing mass \(M_{\text{miss}}^2\) and the angle between the reconstructed signal \(B\) and the \(D^{(*)}\ell\) system, \(\cos \theta_{B,D^{(*)}\ell}\), to separate the signal mode \(B \to D^{(*)}\tau\nu\) from the normalization mode \(B \to D^{(*)}\ell\nu\). The squared missing mass is defined as \(M_{\text{miss}}^2 = (p_{e^+e^-} - p_{\text{tag}} - p_{D^{(*)}} - p_{\ell})^2\), where \(p\) denotes the four-momentum of the \(e^+e^-\) beam, \(p_{\text{tag}}\), \(D^{(*)}\), and the charged lepton, respectively. One of the most important systematic uncertainties affecting the measurements originates from the limited knowledge of the \(B \to D^{(*)}\ell\nu\) background. For precision measurements at Belle II, dedicated measurements of \(B \to D^{(*)}\ell\nu\) with a large data sample are essential.

The \(\tau\) polarization is defined as \(P_{\tau}(D^{(*)}) = (\Gamma^+ - \Gamma^-)/(|\Gamma^+| + |\Gamma^-|)\), where \(\Gamma^+(-)\) is the decay rate with the \(\tau\) helicity +1/2 (-1/2). The most recent Belle measurement [9] is in agreement with the SM within \(2\sigma\).

Table 1 summarizes the estimates of the precision of \(R_{D^{(*)}}\) and \(P_{\tau}(D^{(*)})\) with 5 and 50 ab\(^{-1}\) collected at Belle II, based on existing results from Belle and the expected experimental improvements with the upgraded detector [3]. In Fig. 1 the expected precisions with 50 ab\(^{-1}\) of data collected by Belle II are compared with the current measurements and with the SM predictions. It is worth emphasizing that with the first 5 to 10 ab\(^{-1}\) collected by Belle II, which should be within about 2 years from the start of Phase-3, we will be able to potentially observe a 5\(\sigma\) discrepancy from the SM expectations. NP scenarios will also be tested by studying differential branching fraction distributions, for example as a function of the momentum transfer to the lepton pair, \(q^2 = (p_\tau + p_\nu)^2 = (p_B - p_{D^{(*)}})^2\).
Nevertheless most of these uncertainties will be strongly reduced with increasing luminosity as the background models, the extrapolating from the Belle measurement for the semileptonic tag, are summarized in Table 2. which corresponds to a significance of 3σ.

Table 1. Expected precision on $R_{D(*)}$ and $P_\tau(D^*)$ at Belle II, given as the relative uncertainty for $R_{D(*)}$ and absolute on $P_\tau(D^*)$. The two values refer to the statistical and systematic uncertainties, respectively.

|          | 5 ab$^{-1}$       | 50 ab$^{-1}$       |
|----------|-------------------|-------------------|
| $R_D$    | $(\pm 6.0 \pm 3.9\%)$ | $(\pm 2.0 \pm 2.5\%)$ |
| $R_{D*}$ | $(\pm 3.0 \pm 2.5\%)$ | $(\pm 1.0 \pm 2.0\%)$ |
| $P_\tau(D^*)$ | $0.18 \pm 0.08$ | $0.06 \pm 0.04$ |

Figure 1. Expected Belle II constraints on the $R_D$ vs. $R_{D*}$ plane (left) and the $R_D$ vs. $P_\tau(D^*)$ plane (right) compared to existing experimental constraints. The elliptical contours refer to the 1σ uncertainties on the measurements. The SM predictions are indicated by the black points with theoretical error bars.

4. Leptonic $B$ decays and $B \to \tau \nu$

The branching fractions of $B^- \to \ell^- \bar{\nu}_\ell$ are hierarchical in the lepton masses due to the helicity suppression of the $B$ meson decay, in the absence of NP. The SM expectation [6] are $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = (7.7 \pm 0.6) \times 10^{-5}$, $\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) = (3.5 \pm 0.3) \times 10^{-7}$, $\mathcal{B}(B^- \to e^- \bar{\nu}_e) = (8.1 \pm 0.6) \times 10^{-12}$. NP contributions, as predicted by Higgs doublet models [10], can increase or decrease these values depending on the interference with the SM processes.

The tauonic mode has been measured by Belle and BABAR, and the last Belle measurement [11], combining the results obtained in the hadronic and semileptonic tag, reached a precision of 24% on $\mathcal{B}$. The Belle II experiment has carried out a study of the measurement prospects with the full simulation [3], reconstructing the $B_{tag}$ in hadronic modes with the FEI, and reconstructing the tau lepton in four single-prong decay modes, specifically $\mu^- \nu_\mu$, $e^- \nu_e$, $\pi^- \nu_\tau$, and $\pi^- \pi^0 \nu_\tau$. The most important part of the event selection is the reduction of the beam-background photon component by exploiting the properties of the calorimeter clusters originating from physics photons: they are more energetic, in time with the bunch crossing, and usually are associated with few calorimeter crystals, while beam-induced photon showers exhibit a larger spread of energy deposits. The signal is extracted with a maximum likelihood fit to the $E_{ECL}$ distribution (Fig. 2, left). A toy MC study has shown that with 1 ab$^{-1}$ of data Belle II will be able to measure $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)$ with a relative precision of 29%, which corresponds to a significance of 3.4σ when only considering the statistical uncertainty. The measurement projections with 5 and 50 ab$^{-1}$, including the systematic uncertainties and extrapolating from the Belle measurement for the semileptonic tag, are summarized in Table 2.

The main expected contributions to the systematic uncertainties come from the knowledge of the background models, the $\mathcal{B}$ of the backgrounds peaking in $E_{ECL}$ and the tagging efficiencies. Nevertheless most of these uncertainties will be strongly reduced with increasing luminosity as...
Table 2. Expected uncertainties on the $B^- \rightarrow \tau^- \bar{\nu}_\tau$ branching fraction for different luminosity scenarios with hadronic and semileptonic tag methods.

| Integrated Luminosity (ab$^{-1}$) | 1     | 5     | 50    |
|-----------------------------------|-------|-------|-------|
| hadronic tag                      |       |       |       |
| statistical uncertainty (%)       | 29    | 13    | 4     |
| systematic uncertainty (%)        | 13    | 7     | 5     |
| total uncertainty (%)             | 32    | 15    | 6     |
| semileptonic tag                  |       |       |       |
| statistical uncertainty (%)       | 19    | 8     | 3     |
| systematic uncertainty (%)        | 18    | 9     | 5     |
| total uncertainty (%)             | 26    | 12    | 5     |

they can be determined from data control samples.

A dedicated study has been performed to evaluate the impact of the beam background on the measurement, and in particular on the $E_{ECL}$ resolution. The Belle II MC with superimposed nominal beam background has been compared to the Belle MC used for the measurement with hadronic tag [12], see Fig. 2. The comparison shows that the impact of the increased beam background is almost negligible, with a slightly better resolution at Belle II, thanks to the upgraded detector and the advanced decay reconstruction techniques used in the new experiment.

In conclusion, the full simulation study indicates that Belle II will be able to observe the $B^- \rightarrow \tau^- \bar{\nu}_\tau$ decay, using the hadronic tag, with a significance above the $5\sigma$ level after collecting about 3 ab$^{-1}$ of data.

Figure 2. Left: $E_{ECL}$ distribution for signal (red), $BB$ background (blue) and continuum (green). The events are normalised to an integrated luminosity of 1 ab$^{-1}$. Right: Comparison of signal $E_{ECL}$ distribution for Belle II (red) and the Belle measurement with hadronic tag (blue).

5. Search for $B \rightarrow K^{(*)} \nu \bar{\nu}$

The decays $B \rightarrow K^{(*)} \nu \bar{\nu}$ are prohibited at tree level in the SM, therefore they can only occur through a flavour-changing neutral current box or penguin diagram. NP models [13] might contribute to the loops or at the tree level, increasing the SM branching fractions, which span between $10^{-6}$ and $10^{-5}$, by a factor of 50. Experimental searches have been carried out by both Belle and BABAR Collaborations [14],[15] and no evidence for signal has been found.

Belle II has performed a full simulation study [3] reconstructing the $B_{tag}$ meson with FEI in hadronic decay modes, and selecting the signal channel $K^{(*)} \rightarrow K^+ \pi^0$. After applying selection criteria on kinematics and event-shape variables, in particular exploiting the missing energy and the missing momentum in the event, the signal efficiency and background yields have been...
Table 3. Expected sensitivities to the $K^{(*)}\nu\bar{\nu}$ modes with different Belle II datasets.

| Observables                  | 5 ab$^{-1}$ | 50 ab$^{-1}$ |
|------------------------------|-------------|--------------|
| $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$ | 30% 11%     |              |
| $\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$ | 26% 9.6%    |              |
| $\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu})$ | 25% 9.3%    |              |

estimated in the signal region of $E_{ECL}$. The beam background impact on the measurement has been evaluated as well, comparing the Belle II simulation superimposed with the nominal background to a background-free configuration: a negligible effect has been observed both in terms of the $E_{ECL}$ variable distribution and signal significance.

Projections with 5 and 50 ab$^{-1}$ collected at Belle II, with both hadronic and semileptonic tags, are reported in Table 3. With about 18 ab$^{-1}$, Belle II will be able to reach the $5\sigma$ observation of the $B \to K^{(*)}\nu\bar{\nu}$ channels, and with the full dataset the fraction of longitudinally polarized $K^*$, which is helpful in distinguishing different NP scenarios, may also be measured with a precision of 20%.

6. Conclusions

Major upgrades of the $e^+e^-$ KEKB collider and the Belle detector will allow the collection of $10^{10}$ $B\bar{B}$ pairs per year at the peak instantaneous luminosity of $8 \times 10^{36}$ cm$^{-2}$s$^{-1}$. In addition, Belle II can efficiently identify and reconstruct the charged and neutral particles produced in the collisions. Furthermore, the advanced reconstruction techniques being developed by Belle II will allow the measurement of missing energy decays of $B$ mesons with an unprecedented precision. Within the first two years of data taking, corresponding to an integrated luminosity of 5 to 10 ab$^{-1}$, Belle II will possibly address the lepton-flavour-universality violation by precisely measuring $R_{D^{(*)}}$, as well as the tension between measurements of $|V_{ub}|$ made using samples of inclusive and exclusive semileptonic $B$ decays $B \to X_u\nu\bar{\nu}$. It will also have a strong discovery potential for rare processes suppressed in the SM, such as $B \to \tau\nu$, and the flavour-changing neutral current decays $B \to K^{(*)}\nu\bar{\nu}$. A detailed discussion of the Belle II detector and machine background measurements, software tools, and physics program will be published in 2018 in the “Belle II physics book”.

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