Studies of missing energy decays of B meson at Belle II

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The Belle II experiment at the SuperKEKB collider is a major upgrade of the KEK "B factory" facility in Tsukuba, Japan. The machine is designed for an instantaneous luminosity of 8×10^{35} $cm^{-2}s^{-1}$, and the experiment is expected to accumulate a data sample of about 50 ab^{-1} in five years of running. With this amount of data, decays sensitive to physics beyond the Standard Model can be studied with unprecedented precision. One promising set of modes are physics processes with missing energy such as $B^+ \to \tau^+ \nu$, $B \to D^{(*)} \tau \nu$, and $B \to K^{(*)} \nu \bar{\nu}$ decays.

The $B \to K^{(*)} \nu \bar{\nu}$ decay provides one of the cleanest experimental probes of the flavour-changing neutral current process $b \to s \nu \bar{\nu}$, which is sensitive to physics beyond the Standard Model. However, the missing energies of the two neutrinos in the final state makes the measurement challenging and requires full reconstruction of the spectator B meson in $e^+ e^- \to \Upsilon(4S) \to B \bar{B}$ events. Observation of the $B \to K^{(*)} \nu \bar{\nu}$ decay will become possible with the large data set to be collected by the upgraded Belle II experiment running at the Super-KEKB accelerator in Japan. A challenge of this analysis will be understanding and suppressing backgrounds. This talk discusses such backgrounds and the expected sensitivity of Belle II for this rare decay.

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1. Strategies for new physics searches in B final states with missing energy

Searches for physics beyond the Standard Model (SM) can be performed at accelerator experiments both at the energy and at the intensity frontier. In the first case, state predicted by New Physics (NP) models are searched for as real particles, making this approach limited by the energy of the beam(s). In the second case, NP effects due to non-standard particles, produced as virtual intermediate states, are searched for. In such case, to observe deviations from the SM predictions high statistics samples are needed. In the intensity frontier context, the Belle II experiment, at the SuperKEK accelerator in Japan, will search for NP effects by exploiting a pletora of B, D, τ, and Υ decay modes, with 50 ab^{-1} collected in 5 years of data-taking. With respect to its predecessors, BaBar and Belle, the detector will have to work in an higher luminosity environment (factor of 40 with respect to Belle) resulting in an higher statistic sample but also higher rate of radiation hitting the detector components coming from beam-beam, intra-beam, and beam-material interactions. Such processes are referred to as "machine background". In ordet to keep same or better performances with respect to Belle, an upgrade of such detectot is ongoing and data taking is foreseen to start in the first half of 2018. In e^+e^- collisions at the $\Upsilon(4S)$ mass, final states containing only charged and neutral $B\bar{B}$ pairs will be produced. Thanks to the clean environment due to a well defined initial state, a good and efficient reconstruction of decays with both charged and neutral particles, and a full solid angle detector which ensure high detector hermeticity, the Belle II experiment is an ideal environment to search for decays with missing energy in the final state in which NP states can contribute both as intermediate particles and as new sources of missing energy. One of the experimental methods used for this purpose is called Full Event Interpretation (FEI) in which one of the B's is reconstructed in semileptonic or hadronic modes (tag side) and on the other side the signal signature (signal side) is searched for. The FEI algorithm, already in use at Belle, has been improved both in terms of reconstruction algorithm and of number of reconstructed decay modes, resulting in a factor of 2 improvement in efficiency with respect to the Belle performances. An overview on the Belle II studies for $B \to D^{(*)}\tau\nu$, $B \to \tau\nu$, and $B \to K^{(*)}\nu\bar{\nu}$ will be described in the following.

2. Search fo $B \to D^{(*)}\tau\nu$

The $B \to D^{(*)}\tau\nu$ transition is a tree level process mediated, in the SM, by the W boson. NP scenarios predict the existence of new charged boson, e.g. a charged Higgs, that can replace the W. Deviation from the SM expectation for the branching fracstion's ratio $R(D^{(*)}) = \frac{\mathscr{B}(B \to \bar{D}^{(*)}\tau^+\nu)}{\mathscr{B}(B \to \bar{D}^{(*)}\ell\bar{\nu})}$, with $(\ell = e, \mu)$, have been searched for by the BaBar, Belle, and LHCb collaborations. The experimental results for R_{D^*}, along with the SM expectations [1], are summarised on the left plot of Fig. 1. In the R_{D^*}- R_D plane, the most recent experimental world average is 4.08 σ away from the SM expectations. The current measurements are statistically limited, while the dominant systematic uncertainties arises from the limited signal MC samples and the limited knowledge of dominant backgrounds (involving soft pions produced in the D^* decay). Large signal MC samples and dedicated measurement for background characterisation with large data samples, along with improved tracking algorithm to recover efficiency in the low momentum range, are foreseen at Belle II. Studies of the q^2 distributions and precise measurements of the τ polarisation, both essential to distinguish
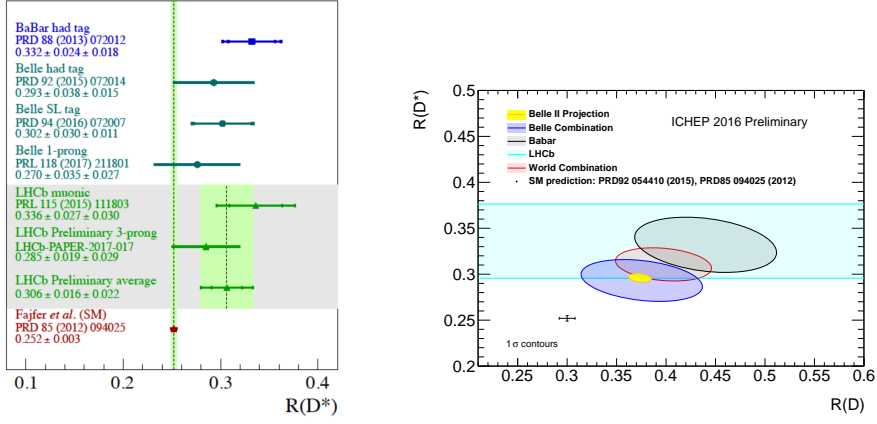
Figure 1: Left: experimental results and SM expectations for $R(D^*)$. Right: expected Belle II constraints on R_D and R_{D^*} compared to existing experimental constraints, as of ICHEP 2016, and SM prediction.

among NP models, will also be feasible. Extrapolating the existing BaBar and Belle results, the following precision with the full Belle II statistics are expected: $\frac{\sigma(R_D)}{R_D} = 2.0\%(\text{stat.}) \pm 2.5\%(\text{syst.})$, $\frac{\sigma(R_{D^*})}{R_{D^*}} = 1.0\%(\text{stat.}) \pm 2.0\%(\text{syst.})$. The expected Belle II constraints on R_D and R_{D^*}, compared to existing experimental measurements as of ICHEP 2016 and to the SM predictions, are shown on the right plot of Fig. 1.

3. Search fo $B \rightarrow \tau\nu$

As $B \rightarrow D^{(*)}\tau\nu$, also $B \rightarrow \tau\nu$ decay is a tree level process mediated in the SM by a W, which can be replaced by non-standard charged bosons. The branching fraction of the purely leptonic decay depends on the CKM element $|V_{ub}|$ and on the form factor f_B. Using the values in Ref. [3], the branching ratio SM prediction is $\mathscr{B}(B \rightarrow \tau\nu) = (0.77 \pm 0.06) \times 10^{-4}$. This has to be compared to the BaBar and Belle world average $\mathscr{B}(B \rightarrow \tau\nu) = (1.06 \pm 0.19) \times 10^{-4}$, obtained by using both hadronic and semileptonic tag [4]. Combining the available results, the branching fraction measurement exceeds the 5 σ significance. Moreover the world average is consistent with the SM expectation at the 2 σ level. The measurements are statistically limited. The dominant systematic effects are due to disagreement between data and simulation and to the estimation of the parameterisation of signal and background shape in the fit for the yield extraction. Some of them are statistical in origin. An analysis using the Belle II full simulation, with the hadronic B reconstruction technique, has been performed. Extrapolating the systematic effects from the most recent Belle analyses and considering the full Belle II statistics, uncertainties of the order of 6% on the branching fraction are expected from both the hadronic and the semilptonic analysis.

4. Search fo $B \rightarrow K^{(*)}\nu\bar{\nu}$

The $B \rightarrow K^{(*)}\nu\bar{\nu}$ decay happens through a flavour changing neutral current, prohibited at tree level in the SM. NP contributions (from new mediators in the box or in the penguin diagrams or due to new sources of missing energy) may be comparable to the SM ones. The process is also
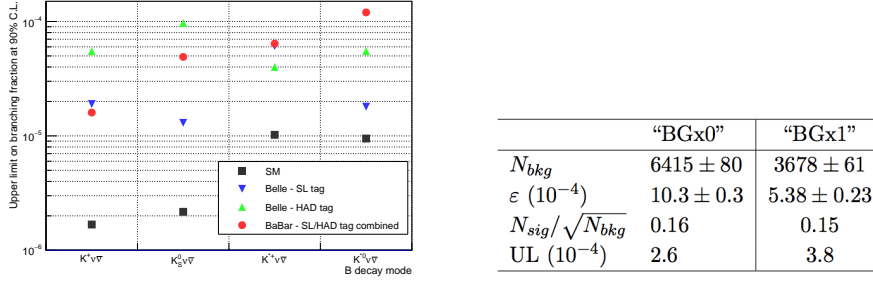
	"BGx0"	"BGx1"
N_{bkg}	6415 ± 80	3678 ± 61
$\varepsilon \ (10^{-4})$	10.3 ± 0.3	5.38 ± 0.23
$N_{sig}/\sqrt{N_{bkg}}$	0.16	0.15
UL (10^{-4})	2.6	3.8

Figure 2: Left: measured upper limit and expected branching fraction in the SM for $B \to K^{(*)} \nu \bar{\nu}$. Right: number of generic events (N_{bkg}), signal selection efficiency (ε), signal significance ($N_{sig}/\sqrt{N_{bkg}}$ with arbitrary normalization of the signal), and expected upper limit (UL) at 90% C.L at 1 ab^{-1} for "BGx0" and "BGx1" configurations. The errors reported and the ones used in the Upper limit estimation are statistical only.

theoretically clean due to the absence of long-distant hadronic effects. Experimental searches have been performed with the BaBar and Belle data with both hadronic and semileptonic tag [5] and no evidence for signal has been found. In the left plot of Fig. 2 the experimental upper limits and the SM expectations [6] are shown. The upper limits are less than 1 order of magnitude away from SM predictions. An analysis on Belle II full simulation using hadronic tag B reconstruction and selecting $K^{*+} \to K^+ \pi^0$ to establish the machine background impact has been performed. After applying selection criteria on kinematics and event shape variables, signal efficiency and background yield have been estimated in a signal region of the extra neutral energy recorded in the electromagnetic calorimeter, not associated to the tag side nor to the signal side. Analysis results on samples of simulated physics events superimposed to nominal machine background ("BGx1" configuration) and on machine background-free samples ("BGx0" configuration) have been compared. Negligible impact of machine background both in terms of variable distribution and signal significance has been observed, as shown in the table reported in Fig 2. Extrapolation on full Belle II statistics of the Belle hadronic and semileptonic tag analyses, assuming two times better tag B reconstruction efficiency, shows that the 5 σ observation will be feasible with about 18 ab^{-1}. The predicted precision, incorporating both statistical and systematic effects, with the full statistics is of the order of 10% for all charged and neutral $K^{(*)} \nu \bar{\nu}$ channels. The fraction of longitudinally polarized K^*, helpfull in distinguishing among different NP scenarios, may also be measured with full statistics at the 20%-level precision.

5. Conclusions

As discussed in this contribution, Belle II will be a unique or very competitive environment to study *B* decays with missing energy in the final state, sensitive to indirect NP effects. Belle II will have a factor of 40 in luminosity (and much higher machine background) with respect to the first generation B-factories, BaBar and Belle. Full simulation studies, with the current knowledge of the machine background rates, have proved the detector performances and the reconstruction algorithms to be robust against machine background. Improvements on the analysis strategy and larger
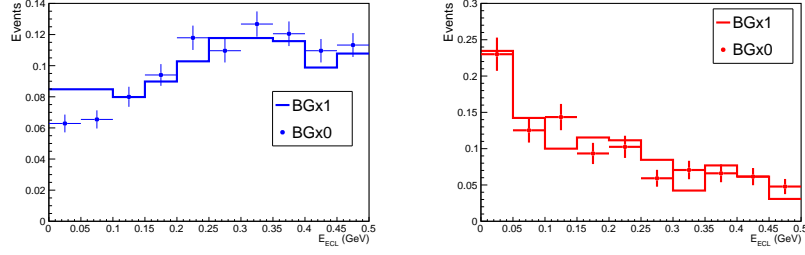
Figure 3: Extra neutral energy distribution for B^+B^- generic decay sample (left) and signal MC sample (right) for simulated events not superimposed to machine background (crosses) and simulated events superimposed to the nominal machine background (full histogram).

data samples will allow to approach the SM predictions for $B \to K^{(*)}\nu\bar{\nu}$ and to further investigate deviations from or consistency with the SM predictions in the case of the $B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$ channels. A detailed discussion of the Belle II detector and machine background measurements, software tools, and physics program will be published in 2017 in the "B2TIP report".

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