PROCEEDINGS OF SCIENCE

Missing Energy B Decays at the Belle II Experiment

Mario Merola[*] **on behalf of the Belle II Collaboration**
Università di Napoli Federico II and INFN Napoli, Italy
E-mail: `mario.merola@na.infn.it`

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}. 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 the semileptonic and leptonic ~~B~~ meson decays $B\to X_u\ell\nu$, $B\to D^{(\star)}\tau\nu$, and $B\to\ell\nu(\gamma)$~~, and~~ the rare process $B\to K^{(*)}\nu\bar{\nu}$~~, which~~ provides one of the cleanest experimental probes of the favour-changing neutral current process $b\to s\nu\bar{\nu}$. This report discusses the expected sensitivities of ~~Belle II for these decays~~.

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[*] Speaker.

1. Introduction

In the past years, the Belle and ~~BaBar~~ experiments, operating at the electron-positron colliders KEKB (Tsukuba, Japan) and PEP-II (Stanford, US) respectively, have offered important insights into the flavour sector of particle physics. The achievements of the two collaborations, which collected together an integrated luminosity of about 1.5 ab^{-1}, ~~culminated in~~ the ~~nobel~~ prize for physics awarded ~~in 2008~~ to Kobayashi and Maskawa for their theory of ~~CP~~ violation. In order to answer some of the ~~still~~ open~~ed~~ questions in the flavour physics sector ~~and to unveil~~ the nature of the tensions ~~occurring~~ in the current observations, ~~a~~ ~~larger amount of~~ data is needed. For this purpose the KEKB collider ~~and the Belle detector have~~ been upgraded to reach an instantaneous luminosity of $8 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ ~~and~~ to cope with the ~~expected overwhelming~~ level of backgrounds.

In the SuperKEKB collider, beams of electrons and positrons with energy of 7 GeV and 4 GeV, respectively, will mainly collide at a centre-of-mass energy of 10.58 GeV ~~corresponding~~ to the peak of Y(4S) resonance (~~data~~ taking at other Y(nS) resonances is also scheduled~~)~~. At the design luminosity, the machine will produce 10^{10} ~~B~~ pairs per year, ~~becoming therefore~~ the most prolific B-factory ever built. The gain of a factor of 40 in luminosity foreseen by the SuperKEKB collider with respect to its predecessor KEKB, is obtained by means of higher beam currents ($\sim$2×) and strong beam~~s~~ squeezing at the interaction point ($\sim$20×). To achieve this big improvement and at the same time keep ~~under control~~ the beam instabilities, the machine has faced several upgrades involving the radio frequency cavities, the dipole and quadrupole magnets, the beam pipe, and the interaction point (IR) optics ~~(~~nano-beam scheme [1]~~)~~.

The Belle detector underwent important upgrades ~~involving~~ the Vertex Detector (VXD) ~~with the addition~~ ~~of~~ two layers of pixel silicon detector, the Central Drift Chamber (CDC) ~~with~~ smaller cell sizes, ~~the addition of~~ new particle identification devices (PID) in the endcaps (Aerogel Ring Imaging Cherenkov detector), ~~new~~ faster electronics for the Electromagnetic Calorimeter (ECL), and the replacement of the ~~RPCs~~ in the endcap of the muon and K_L detectors (KLM) with scintillators instrumented with silicon photomultipliers. The mechanical structure and the superconducting solenoid providing a magnetic field of 1.5 T are left unchanged. These features lead to several improvements of the detector performances, from the vertex resolution and efficiency of K_S and slow pions reconstruction (VXD, CDC), to the pion/kaon separation (PID) and machine background rejection (ECL). Furthermore, the improved hermeticity of the Belle II detector allows ~~to precisely measure B decays with missing energy reconstructing the neutrino momentum~~, as ~~it~~ will be detailed in the next section.

The first collisions have been recorded on April 26th 2018 with the Phase-2 Belle II detector ~~(i.e. without the VXD)~~ and the data taking ~~is expected to~~ continue until the mid ~~of~~ July. Afterwards, the ~~Vertex Detector~~ will be installed and from February 2019 Belle II will start taking data with ~~the full~~ detector configuration (Phase-3).

2. Reconstruction of missing energy B decays at Belle II

The Belle II experiment offers unique capabilities to study the B decays with neutrinos in the final state, with respect to ~~the~~ hadron colliders. The center-of-mass energy of the collisions is precisely known, within few MeV, and running at Y(4S) resonance peak produces a very clean sample of B meson pairs, with ~~a~~ relatively low tracks multiplicity and detector occupancy. In addition, the Belle II detector is capable of high reconstruction efficiencies ~~of~~ both charged and neutral particles. These features allow the full reconstruction of one of the two B mesons (called B$_{\text{tag}}$), in order to infer the ~~4~~-momentum of the other B meson (B$_{\text{sig}}$). An advanced technique Belle II uses to reconstruct the B$_{\text{tag}}$, via hadronic or semileptonic B decays, is the Full Event Interpretation (FEI). It is an extension of the Full Reconstruction used in Belle [2] and makes use of thousands exclusive decay modes to train several multivariate classifiers ~~(MVCs)~~ in a hierarchical approach, starting from final-state particles as leptons, charged pions, kaons and photons, to the intermediate particles, as $D^{(*)}_{(s)}$ and $J/$~~Ψ~~ mesons, ~~K_S~~ and ~~neutral pions~~, ending with the reconstruction of the B meson candidate. It has been shown, ~~on~~ the Belle II ~~full~~ simulation and considering the hadronic tagging modes, that the FEI has improved the Belle FR ~~performances increasing~~ the tagging efficiency ~~by about a factor of 2,~~ from 0.2% to 0.5%, at ~~the~~ fixed B$_{\text{tag}}$ purity of 25%.

The continuum background events $e^+e^- \rightarrow q\bar{q}, \tau^+\tau^-$, ~~contaminating~~ the $B\bar{B}$ pairs data sample, are usually strongly ~~reduced~~ exploiting their different topology (back-to-back) with respect to the more ~~spherical and~~ isotropic $B\bar{B}$ events. The so called "continuum suppression" makes use of the CLEO cones and Kakuno-Super-Fox-Wolfram moments [3, 4] and it is ~~largely~~ employed in B ~~mesons'~~ decay ~~studies.~~

It is worth introducing here the ~~quantity called~~ E_{ECL} (or E_{Extra}) which almost all of the missing energy B decay studies rely on. It is defined as the residual energy deposited in the ~~Electromagnetic Calorimeter~~ once we have subtracted all the clusters associated ~~to~~ the B$_{\text{tag}}$ and ~~to the signal~~. It is expected to peak at 0 GeV for correctly reconstructed $\Upsilon(4S)$, while it shows a broader distribution, peaking at larger values, for mis-reconstructed signal events or for background events, ~~which present extra deposits in the calorimeter.~~ It has been verified with the Belle II full simulation that the impact of the photon~~s~~ background coming from the beams and the interaction region (synchrotron radiation, radiative Bhabha, two-photons processes) on E_{ECL} can be ~~reduced and kept under control~~ exploiting the ~~peculiar~~ features of the background calorimetric clusters ~~against~~ the energy deposits coming from the $\Upsilon(4S)$.

3. Semileptonic B decays and $|V_{ub}|$ determination

The $|V_{ub}|$ determinations from inclusive ($B \rightarrow X_u l\bar{\nu}$) and exclusive ($B \rightarrow \pi\ell\nu$ for example) measurements exhibit a clear tension (Fig. 1, left). The inclusive studies of $B \rightarrow X_u l\bar{\nu}$, where X_u is any hadronic final state coming from the fragmentation of the u quark, are typically based on measurements of partial branching fractions in various fiducial kinematic regions. The $|V_{ub}|$ determinations show a slight dependency on the fiducial region which may be due to differences in theory treatment or to experimental mismodelling of the signal and background components (the most important ~~background~~ is $B \rightarrow X_c l\bar{\nu}$~~)~~.

Belle II has performed a full simulation study of one of the most promising exclusive decay $B \rightarrow \pi\ell\nu$. This measurement represents also a precise test of Lattice QCD (LQCD) predictions since the $|V_{ub}|$ extraction relies on the B decays form factors calculated in LQCD [5]. Two different strategies have been explored for this study using the hadronic tagging of the B meson with FEI~~,~~ or considering an inclusive tagging (the so called untagged method). In the last case instead of explicitly reconstructing the companion B, firstly the signal B candidates are reconstructed with kinematical and angular requirements on pions and leptons, and then a selection is applied on clusters and tracks not used for the signal reconstruction (the Rest Of Event ~~of the signal~~). The details of the analysis are omitted in this report (as well for the next sections), at the end the signal yield measurement relies ~~basically~~ on the reconstructed missing mass squared $m^2_{miss} = m^2_\nu$, which is expected to peak at 0 GeV^2/c^4. The extrapolated uncertainties on the $|V_{ub}|$ in the tagged and untagged analyses with the increasing Belle II collected dataset are depicted in Fig. 1 (right). Here the current LQCD estimation refers to the world average by the Flavour Lattice Averaging Group (FLAG) [6], the 5 years projection assume a factor of 2 reduction of the lattice QCD uncertainty on the semileptonic form factors, while the 10 years projection assumes a factor of 5 reduction. In addition, these estimates assume that the electromagnetic corrections contribute ~~with~~ 1% ~~of~~ uncertainty added in quadrature to the QCD uncertainty. In conclusion, the expected uncertainty on the $|V_{ub}|$ measurement with the full Belle II dataset of 50 ab^{-1} from inclusive and exclusive semileptonic decays is of the order of 3% and 2%, respectively.

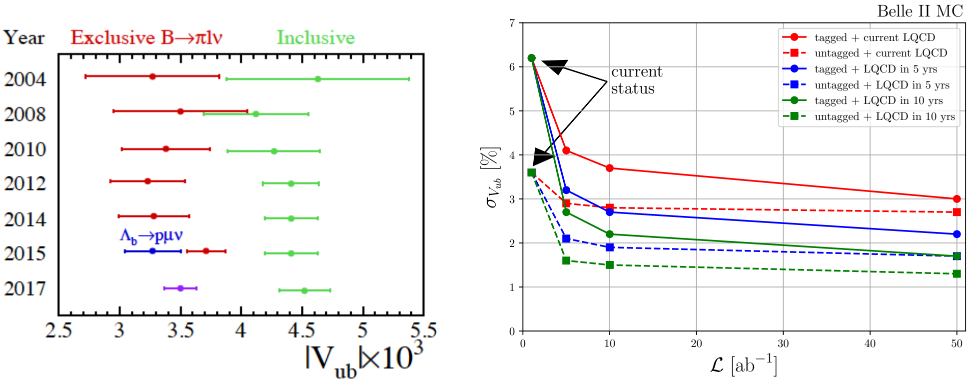

Figure 1: $|V_{ub}|$ determinations from exclusive and inclusive semileptonic B meson decays (left). Projections of $|V_{ub}|$ error to various luminosity values and LQCD error forecasts for $B \to \pi \ell \nu$ tagged and untagged modes (right).

4. Semileptonic B decays into charmed mesons and R(D$^{(*)}$)

The semileptonic B decays $B \to D^{(*)} \ell \nu$ are a clear test of the Standard Model, as New Physics can largely affect both the ~~B~~ranching ~~R~~atio and the τ polarization, through diagrams involving a charged Higgs boson [7] or leptoquarks [8]. The observables $R_{D^{(*)}} = Br(B \to D^{(*)} \tau \nu)/Br(B \to D^{(*)} \ell \nu)$, where $\ell = \mu, e$, are usually considered, as ~~they allow to reduce~~ the experimental uncertainties on the tagging efficiencies ~~and~~ the theoretical uncertainties on the semileptonic form factors and ~~on~~ the $|V_{cb}|$ ~~CKM matrix element~~. The current world average of the two ratios [9], combining measurements performed by Belle, BaBar and LHCb, is $R_D = 0.397 \pm 0.040(stat.) \pm 0.028(syst.)$ and $R_{D^*} = 0.310 \pm 0.015(stat.) \pm 0.008(syst.)$, ~~resulting~~ above the SM expectations [10] of $R_D = 0.299 \pm 0.003$ and $R_{D^*} = 0.257 \pm 0.003$ ~~with a deviation of up to~~ 4σ. The Belle measurements using hadronic or semileptonic tag are based on ~~the residual energy in the calorimeter~~ E_{ECL}, ~~and on~~ the squared missing mass M^2_{miss} and the angle between the reconstructed signal B and the $D^* \ell$ system $\cos\theta_{B\text{-}D^*\ell}$ to separate the signal mode $B \to D^{(*)} \tau \nu$ and the normalization $B \to D^{(*)} \ell \nu$. One of the

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

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 errors respectively.

most important systematic uncertainties affecting the measurements originate from the 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 τ polarization is defined as $P_\tau(D^{(*)}) = (\Gamma^+ - \Gamma^-)/(\Gamma^+ + \Gamma^-)$, where $\Gamma^{+(-)}$ is the decay rate with the τ helicity +1/2 (-1/2). The most recent Belle measurement [11] is in agreement with the SM within 2σ.

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 at Belle II. In Fig. 2 the expected precisions with 50 ab^{-1} at Belle II are compared with the current measurements and with the SM predictions. It is worth ~~to stress~~ that with the first ~~5 : 10~~ ab^{-1} collected by Belle II within about 2 years from the start of the phase 3, we will be able to potentially observe a 5σ discrepancy ~~with~~ the SM expectations. NP scenarios will be tested as well studying differential branching fraction distributions, for example as function of the momentum transfer to the lepton pair, $q^2 = (p_\tau + p_\nu)^2 = (p_B - p_{D^{(*)}})^2$.

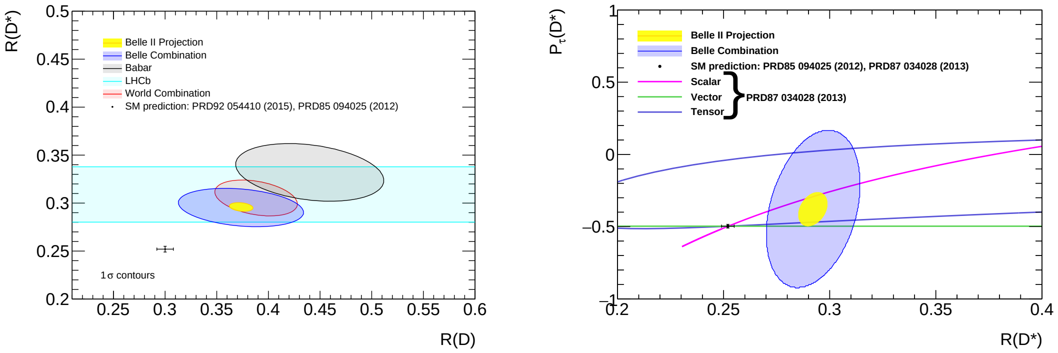

Figure 2: Expected Belle II constraints on the R_D ~~vs~~ R_{D^*} plane (left) and the R_{D^*} vs $P_\tau(D^*)$ plane (right) compared to existing experimental constraints. The SM predictions are indicated by the black points with theoretical error bars.

5. Leptonic B decays

The branching fractions of $B^- \to \ell^- \bar{\nu}_\ell$ are hierarchical in the lepton masses due to the helicity ~~conservation~~ ~~in~~ the B meson decay, in absence of new physics. The predicted values in the SM ~~obtained from~~ [12, 9] are ~~found to be~~ Br(~~τ~~) $= (7.7 \pm 0.6) \times 10^{-5}$, $Br(\mu) = (3.5 \pm 0.3) \times 10^{-7}$, $Br(e) = (8.1 \pm 0.6) \times 10^{-12}$. NP contributions, as predicted by the Higgs double models [13], can

	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

Table 2: Expected uncertainties on the $B \to \tau\nu$ branching fraction for different luminosity scenarios with hadronic and semileptonic tag methods.

increase or decrease their values depending on the interference with the SM processes, which is mediated by a charged W boson.

5.1 $B \to \tau\nu$

The tauonic mode has been measured by Belle and BaBar, and the last Belle measurement [14], combining the results obtained in the hadronic and semileptonic tag, reached a precision of 24% on the ~~Branching Ratio~~. The Belle II experiment has carried ~~on~~ a study of measurement prospects with full simulation, reconstructing the B$_{\mathrm{tag}}$ in hadronic modes with the FEI, and reconstructing the tau lepton in four ~~1~~-prong decay modes, specifically $\mu\nu\bar{\nu}$, $e\nu\bar{\nu}$, $\pi\nu$, $\pi\pi^0\nu$. The most important part of the event selection is the reduction of the beam background photons component exploiting the properties of the calorimeter clusters originated 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. 3, left)~~, and a toy~~ MC study has shown that with 1 ab^{-1} Belle II will be able to measure ~~the~~ $B^- \to \tau^-\bar{\nu}$ ~~Branching Ratio with~~ ~~a~~ 29% ~~precision~~, ~~corresponding to 3.4σ (statistical only)~~. 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 Branching Ratio of the backgrounds peaking in E_{ECL} and the tagging efficiencies. Nevertheless most of these uncertainties will be strongly reduced with increasing luminosity as they ~~rely on~~ control samples~~ in data~~.

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 [15], see Fig. 3. 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 ~~to~~ the advanced decay reconstruction techniques used in the new experiment.

In conclusion, the current extrapolations indicate that Belle II will be able to observe the $B \to \tau\nu$ decay with a significance above the 5σ level after collecting about 3 ab^{-1} of data.

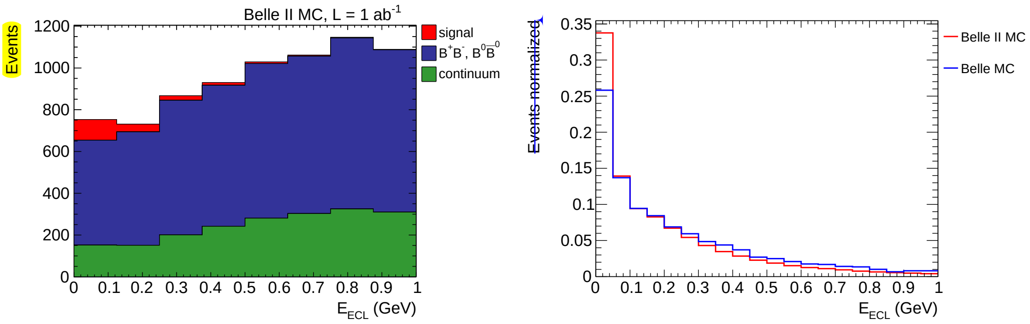

Figure 3: Left: $E_{\rm ECL}$ distribution for signal (red), $B\overline{B}$ background (blue) and continuum (green). The events are normalised to an integrated luminosity of 1 ab^{-1}. Right: Comparison of signal $E_{\rm ECL}$ distribution for Belle II (red) and the Belle measurement with hadronic tag (blue).

5 ab^{-1}	50 ab^{-1}
+0.56 -0.53	+0.18 -0.17

Table 3: Expected absolute statistical error in 10^{-6} at Belle II for a simulated branching fraction of $B \to \ell\nu\gamma = 5.0 \times 10^{-6}$.

5.2 $B \to \mu\nu$ and radiative $B \to \ell\nu\gamma$

Despite ~~the~~ ~~very small Branching Ratio,~~ ~~$\mathcal{O}$~~(10^{-7}), the $B \to \mu\nu$ decay is very promising at Belle II, ~~presenting a very clear~~ topology, ~~as~~ the muon is monochromatic in the signal B rest frame. This feature has been exploited by the Belle [16, 17] searches using both tagged and untagged techniques, to separate the signal from other B decays. The projections based on the Belle measurement show that Belle II should reach the 5σ observation of this channel with only approximately 6 ab^{-1}.

The radiative decay lifts the helicity suppression of the purely leptonic B decays up to a $Br \sim 10^{-5}$. These decays allow the measurement of a very important input to QCD factorization schemes for non-perturbative calculation of non-leptonic B meson ~~decays. In fact, the~~ emission of the photon probes the first inverse moment λ_B of the light-cone distribution amplitude of the B meson [18]. A recent study performed on Belle MC has shown that the Belle II FEI tagging algorithm can increase the signal yield by a factor of three with the same dataset size, ~~with respect~~ to the Belle ~~predictions.~~ In Table 3 the projections of the statistical uncertainties on the $B \to \ell\nu\gamma$ ~~Branching Ratio~~ expected at Belle II are shown.

6. Search for $B \to K^{(*)}\nu\overline{\nu}$

The $B \to K^{(*)}\nu\overline{\nu}$ ~~decays~~ are prohibited at tree level in the SM ~~and can~~ only occur through a flavour-changing neutral current box or penguin diagram. NP models [19, 20, 21, 22] might contribute to the loops or at tree level increasing the ~~Branching Ratio of~~ $10^{-6} \div 10^{-5}$ ~~even~~ by a factor of 50. Experimental searches have been carried on by both Belle and BaBar Collaborations [23, 24] and no evidence for signal has been found. Fig. 4 summarizes the current upper limits and the SM expectations.

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

Table 4: Sensitivities to the $K^{(*)}\nu\bar{\nu}$ modes.

Belle II has performed a full simulation study reconstructing the $\mathrm{B_{tag}}$ meson with FEI in hadronic decay modes, and selecting the signal channel $K^{*+} \to K^+\pi^0$. 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 estimated in ~~a~~ signal region of E_{ECL}. The beam background impact on the measurement has been evaluated as well, comparing the Belle II simulation superimposed to nominal background with a background-free configuration: a negligible effect has been observed both in terms of 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 4. With about 18 ab^{-1}, Belle II will be able to reach the 5σ observation of the $B \to K^{(*)}\nu\bar{\nu}$ channels, and with the full dataset the fraction of longitudinally polarized K^*, helpful in distinguishing ~~among~~ different NP scenarios, may also be measured ~~at the 20% -level precision.~~

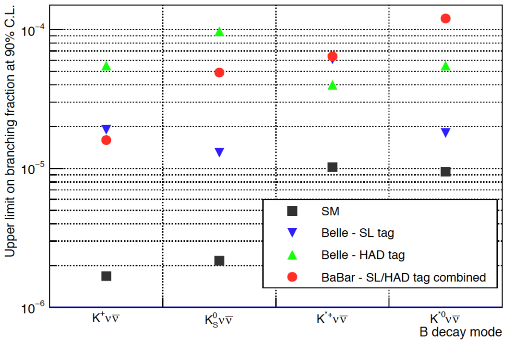

Figure 4: Experimental upper limits and expected ~~Branching Ratio in the SM~~ for the decays $B \to K^{(*)}_{(S)}\nu\bar{\nu}$.

7. Conclusions

The important upgrades the e^+e^- KEKB collider and the Belle detector underwent will allow ~~to collect~~ 10^{10} $B\bar{B}$ pairs per year at the peak instantaneous luminosity of $8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$~~; and to~~ efficiently identify and reconstruct the charged and neutral particles produced in the collisions. Furthermore, the advanced reconstruction techniques being developed ~~at~~ Belle II will allow ~~to measure the~~ missing energy decays of the B meson with an unprecedented precision. Within the first two years of data taking, corresponding to an integrated luminosity of 5 ~~÷~~ 10 ab^{-1}, Belle II will possibly address the ~~Lepton Flavour Universality~~ by precisely measuring $R_{D^{(*)}}$, ~~and~~ the $|V_{ub}|$ ~~puzzle from~~ inclusive and exclusive semileptonic B decays $B \to X_u l\bar{\nu}$. It will also have strong discovery potential ~~in~~ rare processes suppressed in the SM, as $B \to \tau\nu$, $B \to \mu\nu$, $B \to \ell\nu\gamma$, 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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