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Belle II status and prospects for studies of neutral currents

On behalf of Belle II Collaboration

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Abstract: The Belle II experiment at the SuperKEKB energy-asymmetric electron-positron collider is a substantial upgrade of the B factory facility at the Japanese KEK laboratory. Belle II collected a sample of 362 fb^{-1} at the $\Upsilon(4S)$ resonance between 2019 and the 2022, with a maximum peak luminosity of $4.7 \cdot 10^{34}\ \mathrm{cm}^{-2}s^{-1}$. We report the recent measurements which involve neutral current transitions in B meson decays. In particular, we present the branching fractions measurements of the radiative decays $B \to K^*\gamma$ and the fully inclusive $B \to X_s\gamma$, the search for $B^+ \to K^+\nu\bar{\nu}$ decays, the measurement of the branching fractions of $B \to J/\psi(\to \ell\ell)K$ and $B \to K^*\ell\ell$. We also present the future prospects and the expected improvements for all the listed measurements. Finally, we show the perspectives of the search for $B \to K^*\tau\tau$ and the searches of lepton flavor violating channels $B \to K^{(*)}\ell\ell'$, with $\ell = e, \mu, \tau$.

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1 Introduction

The flavour chaning neutral current $b \to s$ transitions are suppressed in the Standard Model (SM) and therefore sensitive to Beyond the Standard Model (BSM) amplitudes. The SM branching fractions are $O(10^{-5} - 10^{-7})$, predicted with 10 – 30% uncertainties. Angular distributions and ratios of amplitudes can be used to improve the precision and eventually have access to new physics properties.

Belle II [1] and SuperKEKB [2] produce an optimal environment to study the neutral currents. Belle II has similar and good performance in electron and muon channels, in term of efficiency, fake rate and particle identification capability. This is a key feature to perform lepton flavour universality (LFU) tests and lepton flavour violation (LFV) searches in the $b \to s\ell\ell^{(\prime)}$ sector, where ℓ indicates a charged lepton. On the other hand, the $b \to s\gamma$ and $b \to s\nu\bar{\nu}$ transitions represent a unique opportunity for Belle II, because of the almost complete hermeticity of the detector, the possibility to exploit the $\Upsilon(4S)$ initial state constraint and the relatively low combinatorial background of the SuperKEKB collisions. Finally, the neutral current transitions with τ lepton production represent a great opportunity for Belle II, given the τ reconstruction performance and the hermeticity.

One of the key tools of Belle II for the channels with missing energy in the final state is the B-tagging, a set of reconstruction techniques to identify the $\Upsilon(4S) \to B\overline{B}$ events exploiting the initial state knowledge to constraint the missing information in the signal side. It consists in reconstructing the parter B meson, called B_{tag}, produced in association with the signal one, to infer the properties of the signal. We refer to hadronic or semileptonic tagging according to the channels used for the B_{tag} reconstruction. The B-tagging algorithm is called Full Event Interpretation (FEI) [3], a boosted decision tree (BDT)-based tagging algorithm which exploits a hierarchical approach to reconstruct $O(10^4)$ decay chains on the tag side. The efficiency for the hadronic (semileptonic) tag is 0.5% (2%) and the purity about 30% (10%).

2 Fully inclusive $B \to X_s\gamma$

We present the measurement the $B \to X_s\gamma$ branching ratio as a function of the photon energy in the range 1.8 GeV $< E_\gamma <$ 2.7 GeV, where $X_s\gamma$ is the inclusive final state involving a photon and a strange hadron, performed on a 189 fb^{-1} Belle II sample [4]. The decays are reconstructed using the hadronic B-tagging, requiring a γ in the signal side with a threshold energy 1.4 GeV. The main challenge of the analysis is to suppress the background without breaking the inclusivity of the measurement. The backgrounds are suppressed using a BDT and the residual X_d background is removed using the simulation. The signal is extracted using a fit to the tag side $M_{\text{bc}} = \sqrt{E^{*2}_{\text{beam}} - p^{*2}_B}$ distribution (where $*$ means evaluated in the $\Upsilon(4S)$ frame, p_B is the B momentum, E_{beam} is the beam energy), as a function of E_γ. The result is competitive with previous measurements performed with hadronic B-tagging.

The prospects of this measurements with larger statistics depend on the chosen photon energy threshold [5]. With lower threshold the background will he higher, while with higher threshold the theoretical systematic uncertainties will be higher. However, some improvements are expected both on background suppression side and using additional tagging methods, which will allow to reach the percent level precision. To make further improvements, the use of more complex observables, like ratios or asymmetries, will be needed.

3 Measurement of $B \to K^*\gamma$ branching fractions

We present the measurement of the branching fraction of $B \to K^*\gamma$, where K^* indicates both $K^{*+}(892)$ and $K^{*0}(892)$, performed on a 63 fb^{-1} Belle II sample [6]. The decays are identified reconstructing only the signal B in the event. The misreconstructed γ background is suppressed with an energy selection, and with a veto on γ from π^0 and η decays. The $e^+e^- \to q\overline{q}$ background is suppressed with an MVA. The misreconstructed K^* background is suppressed using the K^* helicity angle distribution. A fit to $\Delta E = E^*_B - E^*_{\text{beam}}$ (where E_B is the energy of the B meson) is used to extract the signal, excluding higher-mass K^* resonances. The results are $\mathcal{B}(B^0 \to K^{*0}(K^+\pi^-)\gamma) = 4.5 \pm 0.3 \pm 0.2) \times 10^{-5}$, $\mathcal{B}(B^0 \to K^{*0}(K^0_S\pi^0)\gamma) = 4.4 \pm 0.9 \pm 0.6) \times 10^{-5}$, $\mathcal{B}(B^+ \to K^{*+}(K^+\pi^0)\gamma) = 5.0 \pm 0.5 \pm 0.4) \times 10^{-5}$, $\mathcal{B}(B^+ \to K^{*+}(K^0_S\pi^+)\gamma) = 5.4 \pm 0.6 \pm 0.4) \times 10^{-5}$, where the first uncertainty is statistical and the second systematic, compatible with the world averages [10].

This measurement is performed as the cleanest exclusive channel in $B \to X_s\gamma$ sector, and is a first step toward asymmetry measurements of radiative decays. In the latters several systematic uncertainties cancel out, and projections based on Belle result [7] shows that a precision below the percent level can be reached with a sample with an integrated luminosity of few ab^{-1} [5].

4 Search for $B^+ \to K^+\nu\overline{\nu}$ decays

The search of $B^+ \to K^+\nu\overline{\nu}$ decay is a unique opportunity for Belle II. This decays has never been observed before and SM amplitude [8] can receive sizeable contribution from BSM amplitudes. The measurement is performed on a sample with an integrated luminosity of 63 fb^{-1} [9]. The reconstruction is performed with an inclusive tagging approach, reconstructing the B_{sig} using the highest p_T track compatible with a K^+, and assigning the rest of the event to the B_{tag}. The procedure is validated on $B^+ \to J/\psi(\to \mu\mu)K^+$ decays. Two BDT in cascade are used to suppress the background exploiting the event shape, kinematics and vertex features.

No signal is observed and the observed upper limit is $4.1 \cdot 10^{-5}$ at the 90% C.L. The result is also recasted in term of signal strength or $\mathcal{B}(B^+ \to K^+\nu\overline{\nu}) = (1.9 \pm 1.3\,(\text{stat})^{+0.08}_{-0.07}\,(\text{syst})) \cdot 10^{-5}$, compatible with the SM prediction and the previous results [10].

The projection with larger samples [5] shows that a 5σ observation can be achieved with an integrated luminosity of 5 ab^{-1} with an expected 50% efficiency improvement coming from the use of exclusive tagging approaches in combination with the inclusive one. Moreover, additional channels (K^*, K^0_S) will be investigated.

5 Measurement of $R_K(J/\psi)$

We present the measurements of the branching fraction of $B \to J\psi(\to \ell\ell)K$, $\ell = e, \mu$ and $K = K^+, K^0_S$, performed on a 189 fb^{-1} Belle II sample [11]. The ratios $R_K(J/\psi) = \mathcal{B}(B \to J\psi(\to \mu^+\mu^-)K)/\mathcal{B}(B \to J\psi(\to e^+e^-)K)$ are also measured. These channels have no sensitivity on BSM, so $R_K(J/\psi) \approx 1$ is expected. This analysis is used to validate the measurement of $B \to K^*\ell\ell$. The yields are extracted from a fit to $(\Delta E, M_{bc})$ distribution. The results are $R_{K^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008$, $R_{K_S^0}(J/\psi) = 1.042 \pm 0.042 \pm .008$, where the first uncertainty is statistical and the second systematic, in agreement with the expectations.

6 Measurement of $B \to K^*\ell\ell$ branching fractions

We present the measurement of the branching fractions $\mathcal{B}(B \to K^*\ell^+\ell^-)$ (where $\ell = e, \mu$ and $K^* = K^{*+}(892), K^{*0}(892)$) performed on a sample with an integrated luminosity of 189 fb^{-1} [12]. The backgrounds are suppressed using a BDT combined with a veto on the dilepton invariant mass for the $J/\psi, \psi(2S) \to \ell\ell$ background. An extended maximum likelihood fit is performed to the $(\Delta E, M_{bc})$ distribution. The results are $\mathcal{B}(B \to K^*\mu^+\mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \cdot 10^{-6}$, $\mathcal{B}(B \to K^*e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \cdot 10^{-6}$, $\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \cdot 10^{-6}$, where the first uncertainty is statistical and the second systematic, compatible with the world average [10].

These results prepare the ground for the measurement of $R_{K^{(*)}} = \mathcal{B}(B \to \mu^+\mu^-K^{(*)})/\mathcal{B}(B \to e^+e^-K^{(*)})$, which will require a larger sample.

7 $B \to K^*\tau\tau$ perspectives

The measurement of $B \to K^*\tau\tau$ is complementary to the previously discussed measurement, investigating the new physics in the third generation. The SM branching ratio is expected to be $O(10^{-7})$, but BSM amplitudes can enhance the signal of several order of magnitude [13]. Currently the decay has been never observed and an upper limit at $O(10^{-3})$ is available [14]. Prospects extrapolating from the current upper limit with a larger samples shows that Belle II can investigate the branching ratios down to 10^{-4} with 5 ab^{-1}, using hadronic and semileptonic B-tagging and reconstructing the τ leptons both in leptonic and hadronic decays [5].

8 Perspectives of Lepton Flavor Violation searches in $B \to K^{(*)}\ell\ell'$ sector

Several measurement have been performed in past years by BaBar, LHCb and Belle collaborations in the $B \to K^{(*)}\ell\ell'$ sector, where $\ell = e, \mu, \tau$, peforming searches of Lepton Flavor Violation, setting upper limits that span from 10^{-5} to 10^{-9} level. Belle II is planning to join the effort in the searches of new physics in this sector. Focusing on $B \to K^{(*)}\tau\ell$, the use of the hadronic or semileptonic tag allow to avoid the explicit reconstruction of the τ lepton. The signal is extracted from the τ recoil mass distribution, obtained from the B_{tag} and the signal K track information. The recent results performed on Belle sample using the FEI are very promising [15].

9 Conclusions

Belle II radiative decays measurement are on par with the world best measurements. In the close future, exploring a sample of few ab^{-1} will be possible to explore the asymmetries observables and improve the new physics sensitivity. $B \to K\nu\nu$ sector represents a unique opportunity for Belle II and a sample of few ab^{-1} will allow to observe the decays or have access to BSM amplitudes. Despite the anomalies in $b \to s\ell\ell$ sector disappeared [16], the performed $B \to K^*\ell\ell$ measurements remain relevant to prepare the ground for rare decays searches like $B \to K^*\tau\tau$ and LFV $B \to K^{(*)}\ell\ell'$ decays.

Belle II is currently facing a long shutdown period, required for several upgrades of the detector and the collider. Data taking will resume at the end of 2023.

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