PROCEEDINGS OF SCIENCE

Rare B decays from Belle II

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We present the latest Belle II and Belle results on rare B decays, based on data samples of 365 and 711 fb^{-1}, respectively, collected at the $\Upsilon(4S)$ resonance. Rare B decays, in particular flavor-changing neutral currents (FCNC) of the type $b \to s$, provide unique sensitivity to a wide range of new-physics scenarios. Belle II and Belle are achieving world-leading precision and are probing intriguing anomalies in $B^+ \to K^+ \nu\bar{\nu}$ that have generated broad interest within the particle-physics community. We discuss several new FCNC measurements, as well as results on $B^+ \to \mu^+ \nu_\mu$, which set the current most stringent limits on branching fractions and impose new constraints on theoretical models.

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1. Introduction

Flavor changing neutral currents (FCNC) are forbidden at tree-level in the standard model (SM) of particle physics. They only occur at loop-level, heavily suppressed through the GIM mechanism and small CKM amplitudes. In precision measurements, this makes them sensitive to potential small amplitudes from beyond-the-standard-model (BSM). Of particular interest are FCNC of the type $b \to s$ in B meson decays, which benefit from the relatively large B mass $m_B \sim 5\,\text{GeV}$, allowing to apply perturbation theory in $1/m_B$ for precise theory predictions.

Belle II is the successor experiment of Belle, located at the second-generation B factory SuperKEKB, at which B mesons are produced exclusively and in pairs through decays of the bottonium resonance $\Upsilon(4S) \to B\overline{B}$. Measurements just below the $\Upsilon(4S)$ resonance mass allow to experimentally access important backgrounds from light quark $q = u, d, s, c$ and tau lepton pair production. The SuperKEKB lepton collider energy is precisely known and the Belle II spectrometer covers close to 4π of the solid angle. This enables two types of reconstructions for B mesons: In an exclusive reconstruction of a collision, first one B meson is reconstructed in a generic hadronic or semileptonic decay mode. We call this B meson the tagged B meson B_{tag}. Together with the known collider kinematics, this puts stringent kinematic constrains on the reconstruction of the second B meson B_{sig} in a specified signal decay mode, e.g. in the so-called beam-constrained mass M_{bc}. [1] By contrast, an inclusive reconstruction starts from reconstructing a B meson in the signal decay mode B_{sig}. The remaining tracks and clusters in the collision are assigned to a so-called rest-of-event (ROE) and no explicit reconstruction of the second B meson is required. Therefore, an inclusive reconstruction yields higher signal efficiencies compared to an exclusive reconstruction, at the cost of a less pure selection. Subsequently, multivariate methods are employed on quantities of both the B_{sig} and the ROE for signal-background separation. Topological features of reconstructed B meson decays are particularly powerful discriminants. While pseudo-scalar B mesons are almost at rest in the center-of-mass frame and decay isotropically, light quark jets are highly boosted and exhibit a back-to-back topology.

Uniquely, the experimental setup of Belle II allows for the search of B meson decay modes involving multiple neutrinos, such as $B \to K\nu\overline{\nu}$. The presence and kinematics of the undetected neutrinos can be inferred from the missing energy-momentum in the collision.

2. Inclusive Measurement of $B \to X_s\nu\overline{\nu}$ using Hadronic B Tagging at Belle II [2]

FCNCs in B meson decays of the type $B \to X_s\nu\overline{\nu}$ are heavily suppressed in the SM and proceed via penguin and box diagrams. Neither involves the exchange of intermediate photons, unlike in the related decays to charged leptons $B \to X_s\ell^+\ell^-$, which carry significant theoretical uncertainties due to the breakdown of factorization caused by photon exchange [3]. This complication does not affect $B \to X_s\nu\overline{\nu}$ decays, leading to relatively precise rate predictions for these processes. Long-distance contributions via intermediate tau leptons $B \to \nu\tau(\to \nu X_s)$ are subdominant.

We follow an exclusive reconstruction strategy and reconstruct the signal B meson B_{sig} in a total of 30 exclusive final states, which amount to 93% of the branching fraction $\mathcal{B}(B \to X_s\nu\overline{\nu})$. These include one K^+ or K_S^0 and up to 4 pions, as well as three K^+ or K_S^0 and up to one pion. In both cases, we include at most one neutral pion π^0. Decay modes with pairs of kaons are omitted to suppress contributions from $b \to d$ with resonant strangonium states $s\bar{s}$.

To suppress further backgrounds, we require that there are no extra tracks, π^0 or K^0_S, that the energy carried by extra photons is $E^{\gamma}_{\text{extra}} < 1.3$ GeV and that the polar angle of the missing momentum lays inside the central drift chamber (CDC) acceptance. For the remaining collisions, we train a boosted decision tree (BDT) for signal-background separation. Its inputs include kinematic and topological features of B_{sig}, B_{tag} and the missing momentum, as well as of veto charm mesons, reconstructed from signal kaon candidates and pions.

For the signal extraction, we employ a binned maximum-likelihood fit in the BDT output η and the reconstructed X_s mass m_{X_s}. In the signal region, we require $\eta > 0.86$ and $m_{X_s} < 2.0$ GeV and exclude the charm enriched region $1.84 < m_{X_s} < 1.89$ GeV. We use three bins in m_{X_s}, which are enriched in K, K^* and non-resonant decays respectively. For each mass bin we find no significant evidence for signal (see Table 1). In total we obtain $\mathcal{B} = 8.8^{+8.5}_{-8.2}(\text{stat.})^{+12.6}_{-10.8}(\text{syst.})$, yielding an upper limit of $3.2 \cdot 10^{-4}$ on the branching fraction at 90% confidence level. This constitutes the best upper limit measured up to date.

			$\mathcal{B}$ $[10^{-5}]$		
M_{X_s} $[\text{GeV}/c^2]$	$\epsilon[10^{-3}]$	N_{sig}	central value	UL_{obs}	UL_{exp}
$[0, 0.6]$	2.93	6^{+18+19}_{-17-16}	$0.3 \pm 0.8^{+0.9}_{-0.7}$	2.2	2.0
$[0.6, 1.0]$	1.32	36^{+27+31}_{-26-26}	$3.5^{+2.6+3.1}_{-2.5-2.6}$	9.5	6.6
$[1.0, m_B]$	0.62	24^{+44+62}_{-43-53}	$5.1^{+9.2+12.9}_{-8.8-11.0}$	31.2	26.7
Full range	0.97	66^{+64+95}_{-62-81}	$8.8^{+8.5+12.6}_{-8.2-10.8}$	32.2	24.4

Table 1: Efficiencies and upper limits on $B \to X_s \nu\bar{\nu}$ in three mass regions.

3. Reinterpreting $B \to K^+\nu\bar{\nu}$ at Belle II in BSM Scenarios [4]

Belle II recently observed first evidence for $B \to K^+\nu\bar{\nu}$ in a combination of exclusive and inclusive reconstruction, with an observed branching fraction 2.7σ above the SM expectation.[5] The measurement generated significant interest from the particle physics community and several theory models were proposed that can describe the tensions with the SM. These include models involving leptoquarks and additional bosons, right-handed neutrinos, light dark matter, the Higgs portal, and other models (see, e.g., refs. [6–10]).

The measurement in [5] uses SM signal templates and reweighting these to an alternate BSM model must take into account experimental acceptances and efficiencies. Traditional approaches involve re-simulating the collisions, which is computationally expensive and only possible by Belle II members. To enable SM-independent evaluations of the observations, Belle II recently published the full model-independent likelihood, allowing to correctly reinterpret the results in alternate models.

In practice, the joint number-density in the observables and the momentum-transfer q^2 was extracted using the `redist` python package[1] and published in sufficiently fine binning. Knowledge

[1] https://github.com/lorenzennio/redist

Parameters	Mode	68% HDI	95% HDI
$\lvert C_{\mathrm{VL}} + C_{\mathrm{VR}}\rvert$	11.3	[7.82, 14.6]	[1.86, 16.2]
$\lvert C_{\mathrm{SL}} + C_{\mathrm{SR}}\rvert$	0.00	[0.00, 9.58]	[0.00, 15.4]
$\lvert C_{\mathrm{TL}}\rvert$	8.21	[2.29, 9.62]	[0.00, 11.2]

Table 2: $B^+ \to K^+\nu\overline{\nu}$ reinterpretation: posterior mode and HDI for the WET Wilson coefficients.

of the kinematic theory predictions then suffices to re-weight the published number-density and repeat the signal extraction in a fit. We demonstrate the method by reweighting the SM templates to a weak-effective field theory (WET), which yields 3 parameters of interest in terms of vector, scalar and tensor Wilson coefficients. Each of the latter leads to distinct predicted spectra in q^2, resulting in experimental distinguishing power of its contributions. Table 2 summarizes the extracted values of the posterior mode for the Wilson coefficient parameters and their highest density credible intervals (HDI). We observe an increased vector contribution over the SM expectation, which is expected from the observed excess in signal decays. Intriguingly, our measurement also yields a non-zero tensor contribution, which is vanishing in the SM.

4. $B^0 \to K^{*0}\tau^+\tau^-$ with Hadronic Tag at Belle II [11]

FCNC of the type $B^0 \to K^{*0}\tau^+\tau^-$ may be sensitive to similar BSM amplitudes as $B \to K\nu\overline{\nu}$, as well as to models proposed for the $b \to c\tau\nu_\tau$ anomalies. The measurement is particularly challenging due to up to four neutrinos in the final state and the low-momentum K^{*0} which features no peaking observables.

We again follow an exclusive hadronic reconstruction strategy with $B_{\mathrm{sig}} \to K^{*0}\tau^+\tau^-$ reconstructed in $K^{*0} \to K^+\pi^-$ and combinations of four types of tau decays: semileptonic decays to electrons or muons and hadronic decays to a pion or a rho meson with $\rho \to \pi\pi^0$. We require two reconstructed B mesons of opposite flavor and use the same-flavor sideband as control region. A single candidate is selected by the reconstructed K^{*0} mass and the sample is split into four signal categories according to the τ decays. We prefer first the ρ then semileptonic categories, i.e. if at least one tau candidate decays to ρ then we assign the collision to the ρ category. This approach prevents the π^0 from contributing to the ROE reconstruction.

We train a BDT for signal-background separation, including the tau kinematics as inputs. Since the tau decays differ in their number of final state neutrinos and kinematics, we need to separately train one BDT for each signal category. For signal extraction, we employ a binned maximum-likelihood fit in the each of the four BDT outputs with shared signal strength parameter. We find no significant evidence for signal and measure $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) = [-0.15 \pm 0.86(\mathrm{stat.}) \pm 0.52(\mathrm{syst.})] \cdot 10^{-3}$, yielding the best current upper limit of $1.8 \cdot 10^{-3}$ at 90% confidence level.

5. $B^+ \to K^+\tau^+\tau^-$ with Hadronic Tag at Belle and Belle II [12]

In a measurement of the closely related decay mode $B^+ \to K^+\tau^+\tau^-$, we determine the signal yield by counting the excess events over the expected background yield, as extrapolated from sidebands.

We follow a hadronic exclusive reconstruction strategy with tau leptons decaying semileptonically to electrons or muons. A single candidate is formed by combining a kaon candidate with two oppositely charged leptons. Backgrounds from $B^+ \to J/\psi(\to \ell^+\ell^-)K^+$ and $\gamma \to e^+e^-$ are suppressed by strict kinematic constraints on the reconstructed di-lepton mass. For the signal region, we require opposite-charge kaon-lepton masses $M(K^+\ell^-) > 1.9\,\mathrm{GeV}/c^2$, which strongly suppresses charm backgrounds of the type $B^+ \to \overline{D}^{(*)0}(\to K^+\ell^-\overline{\nu}_\ell)\ell^+\nu_\ell$. We determine the signal yield by counting the excess events in the signal region over the background expectation, extrapolated from sidebands with low q^2, M_{bc} and large E_{extra}. We find no evidence for signal in either Belle or Belle II data and set a combined exclusion limit of $\mathcal{B} < 0.87 \cdot 10^{-3}$ at 90% confidence level, a factor 2.6 better than previous bounds.

6. Search for $B^+ \to \mu^+\nu_\mu$ with Inclusive Tag at Belle and Belle II [13]

In the SM, $B^+ \to \mu^+\nu_\mu$ proceeds via the annihilation of the B constituent $\overline{b}$ and u quarks, suppressed by helicity and the small magnitude of V_{ub}. Similarly to FCNC, the rare nature of the decay makes it sensitive to potential BSM contributions.

We employ an inclusive reconstruction strategy, not requiring a full reconstruction of the accompanying B meson. However, knowledge of $\vec{p}_{B_{\mathrm{tag}}} = -\vec{p}_{B_{\mathrm{sig}}}$ allows us to boost into the rest frame of $B^+ \to \mu^+\nu_\mu$, in which we expect a monochromatic muon at $p^{\mu}_{B_{\mathrm{sig}}} = 2.64\,\mathrm{GeV}/c$. The incomplete coverage of the 4π solid angle and the presence of unreconstructed particles such as neutrinos and K^0_L mesons limit the ROE reconstruction, which in turn affects the resolution of the muon momentum in the signal B rest frame. To correct for these detector-level effects, we derive a calibration function from simulation that maps the reconstructed $p^{z}_{B_{\mathrm{tag}}}$ onto the mean of its true distribution. The corrected $p^{z}_{B_{\mathrm{tag}}}$ is then used to determine the transverse momentum and an overall scaling factor is applied to minimize the difference between corrected and generated $p^{\mu}_{B_{\mathrm{sig}}}$.

This procedure is validated in $B^+ \to \overline{D}^0(\to K^+\pi^-)\pi^+$, where the fully reconstructed B meson allows an independent determination of $\vec{p}^{\,\pi^+}_{B_{\mathrm{sig}}}$. The signal is extracted in a maximum-likelihood fit of $p^{\mu}_{B_{\mathrm{sig}}}$, binned in the output of a BDT trained for signal-background suppression. We measure $\mathcal{B} = [4.36 \pm 1.89(\mathrm{stat.}) \pm 1.03(\mathrm{syst.})] \cdot 10^{-7}$ and improve the best upper limits to $\mathcal{B} < [7.13\,(\mathrm{bay.}), 6.24\,(\mathrm{freq.})] \cdot 10^{-7}$ at 90% confidence level.

We interpret the result as an exclusion in the parameter spaces of type II and III two-Higgs-doublet models, as well as of sterile neutrinos. Further, we measure the partial branching fraction of $B \to X_u\ell\nu_\ell$ for $p^{\mu}_{B_{\mathrm{sig}}} > 2.2\,\mathrm{GeV}$ near its kinematic endpoint. The extracted value is extrapolated to the full phase space and agrees with previous measurements at improved precision. Finally, we model weak annihilation as a flat plus peaking component, combined by a single floating fraction. Its contribution is found to be strongly anti-correlated with that of $B \to X_u\ell\nu_\ell$ and becomes significant only in regions where the distribution resembles that of $B \to X_u\ell\nu_\ell$.

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