Rare B and B_s decays at Belle

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We report on recent measurements for rare decays of B and B_s mesons at the Belle experiment; $B^+ \to K^+\tau^\pm\ell^\mp$, $B^0 \to K^{*0}e^+e-$, $B^0 \to K^{*0}\tau^+\tau^-$, $B_s^0 \to \pi^0\pi^0$, $B_s^0 \to \ell^\mp\tau^\pm$ and $B \to ha'$ where $\ell \in e,\ \mu$, $h \in \pi^\pm,\ K^\pm,\ D_s^\pm,\ D^0$, and a' is invisible. These highly suppressed decays are excellent tests of the Standard Model, and despite data-taking ceasing more than a decade ago, we show the Belle dataset is still capable of producing world-leading results. The B decay measurements were performed on a dataset of 711 fb^{-1} taken at the $\Upsilon(4S)$ resonance, corresponding to 772 million B meson pairs, while the measurements of decays of B_s mesons were performed on a dataset of 121 fb^{-1} taken at the $\Upsilon(5S)$ (or $\Upsilon(10860)$) resonance, corresponding to 8.3 million B_s meson pairs.

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1. Introduction

Rare decays of $B_{(s)}$ mesons are a very sensitive probe for new physics (NP). These rare decays include decays with $b \to s$ transitions, which are highly GIM suppressed, as well as decays forbidden in the Standard Model (SM), such as those that violate the conservation of lepton flavour. Decays involving τ leptons are highly sensitive to NP effects that couple to higher masses, or effects that are exclusive to the third generation of matter. Searches for rare decays can generally be interpreted as indirect searches for new mediators, however at B factory experiments like Belle, direct searches for new particles are also possible.

In the SM, lepton flavour is always conserved. However, we know from observations of neutrino oscillations that this is not always the case in nature. Currently, it is unknown if there is lepton flavour violation (LFV) in decays with charged leptons, and if any experiment were to find LFV in the charged sector, it would be direct evidence of NP.

2. Search for $B_s^0 \to \ell^\mp\tau^\pm$

The purely leptonic decays $B_s^0 \to e^\mp\tau^\pm$ and $B_s^0 \to \mu^\mp\tau^\pm$ are forbidden in the SM. Belle searched for these decays with its 121 fb^{-1} dataset collected at the $\Upsilon(5S)$ resonance [1]. The analysis used a semileptonic tag method to reconstruct one B_s meson and searched for peaks in the centre-of-mass frame ℓ momentum consistent with the decay $B_s \to \ell\tau$. The analysis used the `b2bii` [2] software package to convert the Belle dataset into a format that can be used by the Belle II analysis software, and relies on classifiers trained with FastBDT [3] to reject background events.

The signal reconstruction efficiency for both the electron and muon channels was around 0.03%, and the analysis set upper limits on the branching fractions of 1.4×10^{-3} and 7.3×10^{-4} for the electron and muon channels respectively. Analyses of B_s^0 branching fractions have a large systematic uncertainty on f_s, the fraction of $b\bar{b}$ pairs that result in $B_s^0\overline{B}_s^0$ pairs, and so upper limits on $f_s \times \mathcal{B}(B_s^0 \to \ell^\pm\mu^\mp)$ are also reported, with values of 5.5×10^{-4} and 2.9×10^{-4} for the e and μ cases respectively. The result in the electron channel is the first measurement to date, while the muon channel's sensitivity is an order of magnitude less than a 2019 study by LHCb [4].

3. Search for $B^+ \to K^+\tau^\pm\ell^\mp$

In light of recent B physics anomalies that challenge the SM assumption of lepton flavour universality [5], there has been an increase in interest in leptoquarks. These particles could mediate quark-level processes such as $b \to s\tau\ell$; evidence for which could be found by finding events consistent with $B^+ \to K^+\tau^\pm\ell^\mp$. A search for this channel was recently conducted by Belle [6].

As any decays containing τ must contain neutrinos, τ can't be fully reconstructed. Because of that, this analysis used the recoiling mass from the combined $B_{\text{tag}} + K\ell$ system. The tag-side B meson was reconstructed using the Full Event Interpretation (FEI) [7, 8] algorithm, which was developed for Belle II but can be applied to Belle data thanks to `b2bii`. The FEI is the main driver of signal reconstruction efficiency, which lies between 0.046% and 0.074% depending on the charge and flavour of ℓ.

This search set upper limits on branching fractions of 0.59, 1.51, 2.45, and 1.53×10^{-5} for $B^+ \to K^+\tau^+\mu^-$, $B^+ \to K^+\tau^+e^-$, $B^+ \to K^+\tau^-\mu^+$, and $B^+ \to K^+\tau^-e^+$ respectively. These represent the most sensitive search for these channels to date, superseding results from BaBar [9] and LHCb [10].

4. Angular analysis of $B^0 \to K^{*0}e^+e^-$

The $b \to s\ell\ell$ vertex can be approximated with the effective Hamiltonian

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\sum_{i=1}^{10}(C_iO_i + C_i'O_i') \tag{1}$$

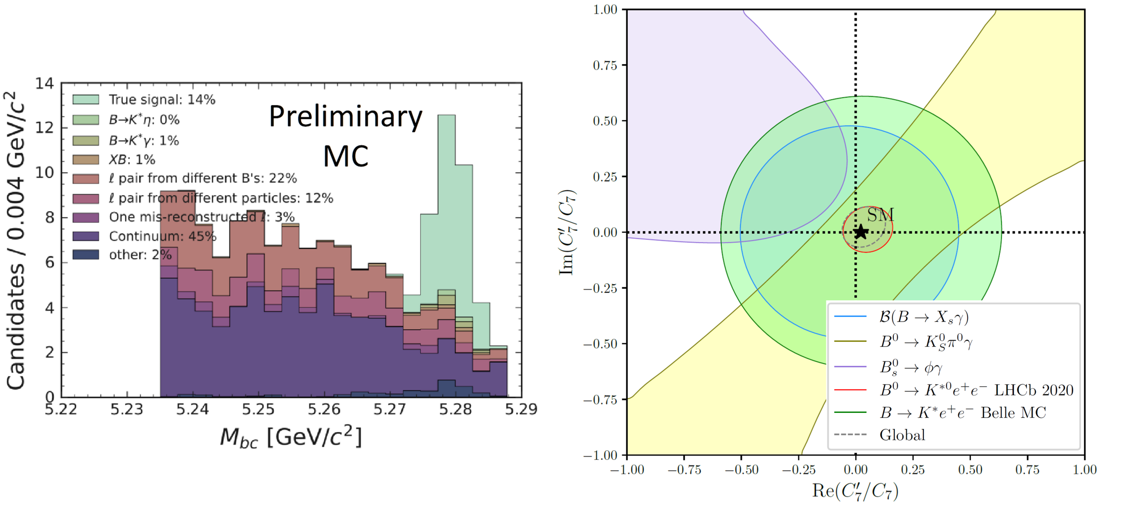
where the Wilson coefficients C_i dominate the differential decay rate at different q^2 regions. In this formalism, the operators O_i encode various long-distance Lorentz interaction structures and q^2 is the square of the dilepton invariant mass. At $q^2 < 1$ GeV$^2/c^4$, $C_7^{(\prime)}$ has an enhanced contribution. In the SM, these coefficients are 0 at $q^2 = 0$, and so one can probe them quite sensitively in q^2 regions where they dominate. The $C_7^{(\prime)}$ coefficient is related to the angular variables $A_T^{\rm Re}$, $A_T^{\rm Im}$, and $A_T^{(2)}$, which appear in the full differential decay rate described in [11].

Since the last angular analysis of $B^+ \to K^+e^+e^-$ at Belle, new machine-learning based lepton identification methods have been developed, which allow the upcoming analysis to reconstruct the signal channel with greater efficiency for the same background rate as compared to the previous analysis at Belle. The analysis method was able to be validated on Monte Carlo produced with non-SM angular variables, and good linearity was shown when extracting these variables on simulated datasets. The analysis is performed in the region $0.0008 < q^2 < 1.12$ GeV$^2/c^2$ to match the 2015 study from LHCb [12]. At the time of writing, the unblinded result has not been published. In Figure 1a we demonstrate the projected power of the analysis method's background rejection and signal retention, as well as the projected sensitivity to the Wilson coefficients $C_7^{(\prime)}$ given the expected values from the SM in Figure 1b. While this study doesn't have the statistical power that the previous LHCb study has thanks to the greater statistics afforded by the LHC, it demonstrates that Belle can still produce comparable results and plays a role in developing key methods that can be applied to the Belle II dataset.

5. Search for $B^0 \to K^{*0}\tau^+\tau^-$

The decay $B^0 \to K^{*0}\tau^+\tau^-$ is highly suppressed in the SM, with a predicted SM branching fraction of $\sim 10^{-7}$ [13]. This means that other rare NP processes can still significantly enhance the rate at which this decay occurs.

This decay was searched for at Belle [14] using a tagged analysis that relied on the NeuroBayes full reconstruction algorithm [15] to reconstruct the tag-side B meson. Due the τ pair present in this decay, there are always at least two neutrinos, making the channel quite difficult to reconstruct. The signal was extracted from fits to the calorimeter energy that was not associated with the reconstruction of the signal or tag side B mesons. Validation of the analysis method was performed by extracting $\mathcal{B}(B^0 \to D^-\ell^+\nu_\ell)$, which was found to be in agreement with the world average.



(a) **(b)**

Figure 1: Estimates to the $B^+ \to K^+e^+e^-$ signal and background yield and $C_7^{(\prime)}$ sensitivity (given the SM expectation) based on Monte Carlo studies.

Branching fractions down to 3.1×10^{-3} were excluded for $B^0 \to K^{*0}\tau^+\tau^-$, and was the first direct limit that has been set on this decay.

6. Search for $B \to ha'$ where $h \in \pi^\pm,\ K^\pm,\ D_s^\pm,\ D^0$

There are a rich variety of NP models that can be probed through decays of B mesons with missing energy, including those containing axion-like particles (ALPs), dark baryons, and long-lived dark scalars. Many constraints on these models are derived from searches for SM decays such as $B \to K\nu\bar{\nu}$, with explicit searches for these kinds of channels only appearing the literature more recently.

We reported on an upcoming search at Belle for $B \to ha'$ where $h \in \pi^\pm,\ K^\pm,\ D_s^\pm,\ D^0$ where a' in invisible. As these processes are two-body decays, one can easily search for new resonances with the momentum of the recoiling hadron h in the frame of reference of the signal-side B meson, which is inferred thanks to the well-known beam four momentum and the momentum of the tagged B meson.

The projected sensitivity that of Belle based on studies on simulated events is already of interest to the wider community [16] with unblinding of data expected to occur later this year.

7. Search for $B_s \to \pi^0\pi^0$

Recently, there has been some tension between the predicted branching fraction of the decay $B_s^0 \to \pi^+\pi^-$ and a measurement by LHCb, suggesting either our understanding of QCD needs to be revisited, or there is some non-QCD process affecting this anomaly. A strength of the Belle experiment over LHCb is its ability to reconstruct neutral final-state particles cleanly, which means that Belle can measure $B_s^0 \to \pi^0\pi^0$ to complement the result from LHCb. Furthermore, this channel has not been measured since a study by the L3 collaboration in 1995 [17].

The Belle search for $B_s^0 \to \pi^0\pi^0$ [18] was performed on the 121 fb^{-1} dataset collected at the $\Upsilon(5S)$ resonance. The signal yield was extracted from a 3-dimensional fit to M_{bc}, ΔE and the output of a neural network that was trained to separate signal and background events. An best fit and 90% C.I. upper limit on $\mathcal{B}(B_s^0 \to \pi^0\pi^0)$ were found to be $(2.8 \pm 2.8 \pm 0.5) \times 10^{-6}$ and 7.7×10^{-6} respectively, and the best fit and 90% C.I. upper limit on $f_s \times \mathcal{B}(B_s^0 \to \pi^0\pi^0)$ are reported to be $(0.6 \pm 0.6 \pm 0.1) \times 10^{-6}$ and 1.5×10^{-6}.

Channel	Belle result	Previous best
$B_s^0 \to e^\mp\tau^\pm$	14.1×10^{-4}	—
$B_s^0 \to \mu^\mp\tau^\pm$	7.3×10^{-4}	4.2×10^{-5} (LHCb, 2019)
$B^+ \to K^+\tau^+\mu^-$	5.9×10^{-6}	3.9×10^{-5} (LHCb, 2020)
$B^+ \to K^+\tau^+e^-$	1.51×10^{-5}	3.0×10^{-5} (BaBar, 2012)
$B^+ \to K^+\tau^-\mu^+$	2.45×10^{-5}	4.8×10^{-5} (BaBar, 2012)
$B^+ \to K^+\tau^-e^+$	1.53×10^{-5}	3.0×10^{-5} (BaBar, 2012)
$B^0 \to K^{*0}\tau^+\tau^-$	3.1×10^{-3}	—
$B^+ \to \pi^+a'$	$\sim 10^{-6}$	1.4×10^{-5} (Belle, 2017)†
$B^+ \to K^+a'$	$\sim 10^{-6}$	1.6×10^{-5} (BaBar, 2013)†
$B^+ \to D_s^+a'$	$\sim 10^{-5}$	—
$B^0 \to D^0a'$	$\sim 10^{-5}$	—
$B_s^0 \to \pi^0\pi^0$	7.7×10^{-6}	2.1×10^{-4} (L3, 1995)

Table 1: Comparison between the results from Belle presented in this work and the next best (or better) measurements from other collaborations. All results are 90% confidence level upper limits. Limits marked with a $\dagger$ are derived from searches for $B \to h\nu\bar{\nu}$ where $h \in \pi, K$.

8. Summary

Despite Belle's data-taking ceasing more than a decade ago, the vast number of possible decay channels of the $B_{(s)}$ meson, coupled with the advances in analysis and software techniques developed for its successor, the Belle II experiment, mean that world-leading results can still be extracted from the Belle dataset. We report on studies of the channels $B_s^0 \to \ell^\mp\tau^\pm$, $B^+ \to K^+\tau^\pm\ell^\mp$, $B^0 \to K^{*0}e^+e^-$, $B^0 \to K^{*0}\tau^+\tau^-$, $B_s^0 \to \pi^0\pi^0$ and a search for new invisible particles in two-body B decays, and summarise the branching fraction sensitivities of these studies in Table 1. The large overlap between the cohort of Belle analysts and Belle II analysts means that future results on the large projected dataset of Belle II will be able to leverage the expertise and methods used on Belle data in these studies.

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