PROCEEDINGS OF SCIENCE

Measurements of R(D(*)) and other missing energy decays at Belle II

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The Belle II experiment and SuperKEKB energy-asymmetric e^+e^- collider have already successfully completed Phase 1 and 2 of commissioning with first collisions seen in April 2018. The design luminosity of SuperKEKB is 8×10^{35} cm^{-2}s^{-1} and the Belle II experiment aims to record 50 ab^{-1} of data, a factor of 50 more than the Belle experiment. With this much data, decays sensitive to physics beyond the Standard Model can be studied with unprecedented precision. We present prospects for studying lepton flavor non-universality in $B \to D^{(*)}\tau\nu$ modes. Prospects for other missing energy modes sensitive to physics beyond the Standard Model such as $B^+ \to \tau^+\nu$ and $B \to K^{(*)}\nu\overline{\nu}$ are also discussed.

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1. Introduction

In this era of high-luminosity experiments, we can continue to study smaller and more subtle discrepancies between experiment and Standard Model (SM) expectations. With a design instantaneous luminosity of 8×10^{35} cm^{-2}s^{-1} – 40 times the instantaneous luminosity of KEKB at Belle–SuperKEKB and the Belle II experiment have a key role to play in studying beyond SM physics and existing flavour anomalies. In these proceedings we focus on prospects for the $R(D^{(*)})$ anomaly and the rare decay modes $B \to \tau\nu$ and $B \to K^{(*)}\nu\overline{\nu}$. These modes are good candidates for studying possible new physics, and the first statistically significant measurements in the latter two modes are eagerly anticipated.

Since first collisions in April 2018, Phase 2 studies of the Belle II detector have been ongoing. About 500 pb^{-1} of data has been collected with a near-complete Belle II arrangement: all outer detectors and a partial central vertex detector[1]. Additional parts of the vertex detector are currently being installed ready for Belle II Phase 3 data collection, starting in early 2019. Data collection will continue until 2025, and at least 50 ab^{-1} of data is expected at the $\Upsilon(4S)$ resonance.

2. Full Event Reconstruction for Missing Energy

As Belle II is an almost hermitic detector surrounding an e^+e^- interaction, $B\overline{B}$ signal events can be well constrained by reconstructing all visible final state particles. For early rare decay analyses, we consider reconstructing both the signal B and a tag B meson decaying in a purely hadronic mode, which - when combined with the known centre-of-mass energy of the e^+e^- collision - allows us to also indirectly measure the missing energy and momentum from neutrino(s) in the signal decay. At Belle II, this is achieved using the Full Event Interpretation[2], an update to Belle's Full Reconstruction algorithm.

In brief, the Full Event Interpretation (FEI) is a collection of multivariate classifiers. From an initial classifier on tracks and vertex information, further classifiers are trained to reconstruct intermediate particles and the final B meson. The FEI allows reconstruction of 55 hadronic B decay channels - 24 more channels than Belle's equivalent Full Reconstruction - and also increases the number of D and D^* channels from 30 to 43 to further increase the number of B decay chains reconstructed. Overall, the FEI improves the tag reconstruction efficiency to 0.5% compared to Belle's 0.2% in Monte Carlo studies, despite increased background expected at Belle II.

Additional studies of FEI performance on Belle II's Phase 2 data are in progress.

3. Belle II Prospects

3.1 $\mathbf{B \to D^{(*)}\tau\nu}$ and $\mathbf{R(D^{(*)})}$

Current discrepancies between experimentally-measured $R(D^{(*)})$ and the expected SM values give tantalising hints of possible lepton flavour universality violation, especially when combined with additional 2-3σ anomalies in other channels such as the similar $R(J/\Psi)$ at LHCb. The current HFLAV world average experimental combination of $R(D)$ and $R(D^*)$ is at 3.78σ from the SM[3], including measurements from Belle, BaBar, and LHCb. Belle II will be able to make a simultaneous measurement of $R(D)$ and $R(D^*)$ at higher precision than before, shedding new light on this flavour puzzle. A projection of the expected uncertainty of Belle II measurements of $R(D)$ and $R(D^*)$ at 50 ab^{-1} is shown in Figure 1, with additional predictions in Table 1. Belle II at 5 ab^{-1} is expected to have smaller uncertainty than the current world average.

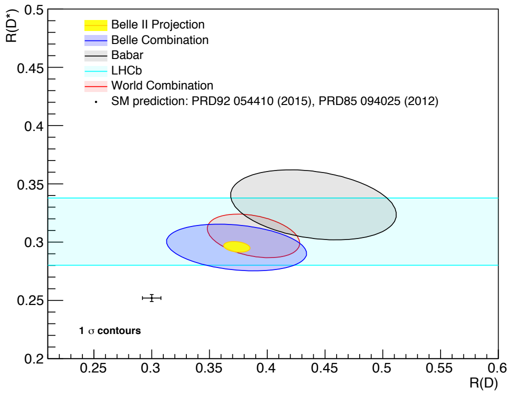

Figure 1: Projection of $R(D^*)$ and $R(D)$ uncertainties for the full Belle II dataset (yellow), compared to current experimental status and world averages. Figure also seen in [4].

	Observable	Uncertainty	
		stat.	syst.
1 ab^{-1}	$\mathscr{B}(B \to \tau\nu)$	29%	13%
5 ab^{-1}	$\mathscr{B}(B \to \tau\nu)$	13%	7%
	$R(D)$	6.0%	3.9%
	$R(D^*)$	3.0%	2.5%
	$P_\tau(D^*)$	0.18	0.08
50 ab^{-1}	$\mathscr{B}(B \to \tau\nu)$	4%	5%
	$R(D)$	2.0%	2.5%
	$R(D^*)$	1.0%	2.0%
	$P_\tau(D^*)$	0.06	0.04

Table 1: Prospects for uncertainties on $B \to D^{(*)}\tau\nu$ and $B \to \tau\nu$ observables at Belle II from Monte Carlo studies with hadronic FEI B tags. Data summarised from [4].

Theory uncertainties in $|V_{cb}|$ and the $B \to D^{(*)}l\nu$ form factors largely cancel in $R(D^{(*)})$. The remaining predicted systematic uncertainty in these measurements is dominated by uncertainty in decays involving excited D resonances (often labelled D^{**}), which contribute to $B \to D^{(*)}\tau\nu$ backgrounds via missing soft pions in reconstruction. Studies of both $B \to D^{**}\tau\nu$ and $B \to D^{**}l\nu$ decays are planned to help further reduce these uncertainties in the long term. Some additional excited D background may also be removed by taking advantage of improved vertexing at Belle II.

With the full Belle II dataset, measurement of additional observables in $B \to D^{(*)}\tau\nu$ will also be possible. Both the tau polarisation $P_\tau(D^*)$ and q^2 distribution will be available, and if the $R(D(^*))$ anomalies continue, this polarisation may be able to give insight into the type of new physics effects causing the differences from the Standard Model. In particular, at 50 ab^{-1} $P_\tau(D^*)$ may be able to discriminate between scalar, vector, or tensor New Physics[4].

3.2 $\mathbf{B}^+ \to \tau^+\nu$

Although the $B^+ \to \tau^+\nu$ channel has been observed as a world average, no single experiment has reached 5σ discovery individually. The most recent Belle result has 24% uncertainty[5], and higher luminosity at Belle II will allow us to improve on this result.

The Belle II measurement of $B \to \tau\nu$ – one of many “golden mode” studies[4] – will be made using FEI hadronic B tag and a one-prong tau decay in the signal B. Correctly reconstructed events will have no additional charged tracks and will not have missed any neutral particles arising from B decays. At Belle and BaBar, the number of beam background photons is small, and so the energy in the calorimeter unassigned to any particles in the decay gives an indication of the number of neutral particles that may have been missed in reconstruction. This calorimeter energy distribution will thus peak at 0 for correctly reconstructed signal events. At 40 times the luminosity, additional constraints are needed at Belle II to reject beam background photons from consideration in this extra neutral energy distribution. Such constraints include the use of calorimeter cluster timing information to identify and cut out photons that are not consistent with e^+e^- bunch crossing times.

Despite the complication of additional beam background, we still expect to see some improvement in reconstruction efficiency of $B \to \tau\nu$ events at Belle II compared to Belle, due to improved detector precision and the FEI tag reconstruction. Prospects for measurements of $B \to \tau\nu$ with different amounts of Belle II data are shown in Table 1. A SM $B \to \tau\nu$ 5σ discovery is predicted around 2.6 ab^{-1}.

3.3 $\mathbf{B \to K(*)\nu\overline{\nu}}$

In the longer term, $B \to K^{(*)}\nu\overline{\nu}$ is a rare decay channel with a lot of potential for SM and new physics studies. Measurements of these modes will be possible at Belle II, and the exact factorisation of hadrons and leptons in this decay allows precise experimental measurement of the $B \to K^{(*)}$ form factors. New Physics could also enhance the branching ratio of this mode, and the neutrino final state provides a window into right-handed operators. Interpreted as a measurement of $B \to K^{(*)} + invisible$, this decay channel also constrains weakly interacting dark matter scenarios[6].

Monte Carlo studies for this decay mode use the FEI Hadronic B tag, event shape constraints, and quality constraints on the K or K^* to determine an appropriate signal region. The current Standard Model estimate of the branching ratio for this decay has 10% uncertainty, which could be matched in experiment with the full 50 ab^{-1} dataset at Belle II. Evidence of a SM branching ratio is expected at 4 ab^{-1} and 5σ discovery is predicted with approximately 18 ab^{-1} of Belle II data.

4. Conclusion

The Belle II physics program has the opportunity to produce precision studies on a large number of new rare modes and known flavour anomalies. Results for $B \to \tau\nu$ and $R(D^{(*)})$ of interest to the global flavour community will be available at or by 5 ab^{-1}, currently anticipated in 2021.

References

[1] P. Branchini, *The Belle II Experiment: Status and Prospects*, *Universe* **4** (2018) 101.

[2] T. Keck, F. Abudinen, F. U. Bernlochner, R. Cheaib, S. Cunliffe, M. Feindt et al., *The Full Event Interpretation – An exclusive tagging algorithm for the Belle II experiment*, `1807.08680`.

[3] HEAVY FLAVOR AVERAGING GROUP collaboration, Y. Amhis et al., *Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2016*, *Eur. Phys. J.* **C77** (2017) 895 [`1612.07233`].

[4] The BELLE-II Collaboration, *The Belle II Physics book*, `1808.10567`.

[5] BELLE collaboration, B. Kronenbitter, M. Heck, P. Goldenzweig, T. Kuhr, A. Abdesselam, I. Adachi et al., *Measurement of the branching fraction of $B^+ \to \tau^+\nu_\tau$ decays with the semileptonic tagging method*, *Phys. Rev. D* **92** (2015) 051102.

[6] C. Bird, P. Jackson, R. Kowalewski and M. Pospelov, *Dark matter particle production in $b \to s$ transitions with missing energy*, *Physical Review Letters* **93** (2004) 1 [`hep-ph/0401195`].