

Semileptonic and leptonic B decay results from early Belle II data

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The Belle II experiment at the SuperKEKB energy-asymmetric e^+e^- collider is a substantial upgrade of the B factory facility at the Japanese KEK laboratory. The design luminosity of the machine is $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ and the Belle II experiment aims to record 50 ab^{-1} of data, a factor of 50 more than its predecessor. From February to July 2018, SuperKEKB has completed a commissioning run, achieved a peak luminosity of $5.5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, and Belle II recorded a data sample of about 0.5 fb^{-1} . In this presentation we show first results from studying missing energy signatures, such as leptonic and semileptonic B meson decays based on this early Belle II data. We report first studies on re-measuring important standard candle processes, such as the abundant inclusive $B \rightarrow Xl\nu$ and $B \rightarrow D^*l\nu$ decays, and evaluate the performance of machine learning-based tagging algorithms. Furthermore, we also present an overview of the semileptonic B decays that will be measured in the upcoming years at Belle II and discuss prospects for important B-anomalies like $R(D)$ and $R(D^*)$, as well as other tests of lepton flavor universality.

I. INTRODUCTION

The Belle II [1] experiment is located at the SuperKEKB [2] accelerator in Tsukuba, Japan. The experiment is designed to perform a variety of high-precision measurements, among others, in the field of heavy flavour physics. In particular it is designed to study the decay of B mesons. The Belle II detector is an upgrade of the Belle detector and is designed to cope with the factor of 40 increased target luminosity of $\mathcal{L} = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ of SuperKEKB.

This manuscript contains three studies on the early Belle II data from the commissioning run: The performance of the Full Event Interpretation [3], the analysis of inclusive semileptonic $B \rightarrow Xev$ decays, and the analysis of exclusive semileptonic $B \rightarrow D^*e\nu$ decays. Additionally, two prospects of the Belle II physics program are briefly shown: The projection of the Belle II sensitivity on $R(D^{(*)})$ and the projected precision of different methods used to extract the CKM matrix element $|V_{ub}|$.

II. FULL EVENT INTERPRETATION PERFORMANCE

The Full Event Interpretation (FEI) is a new exclusive tagging algorithm developed for the Belle II experiment. It allows the measurement of otherwise inaccessible B decays by reconstructing the so-called B_{tag} meson. The algorithm reconstructs possible B_{tag} decay chains in a hierarchical approach and uses machine learning to identify plausible candidates and to reduce the combinatorics. For a detailed description of the FEI see [3]. Here we present the application of the FEI on the Belle II data sample of 500 fb^{-1} from the commissioning run. For this study only the hadronic decay chains are considered.

During the application of the FEI the following cuts on tracks and intermediate particles are applied: Tracks are required to originate from the interaction region $|dz| < 2 \text{ cm}$, $d_0 < 0.5 \text{ cm}$, and photons are required to have a energy of $E_\gamma > 0.10 \text{ GeV}$ in the forward, $E_\gamma > 0.09 \text{ GeV}$ in the barrel and $E_\gamma > 0.16 \text{ GeV}$ in the backward region. An invariant mass cut was performed on the intermediate states π^0 , D and J/Ψ of $0.08 \text{ GeV} < m(\pi^0) < 0.18 \text{ GeV}$, $1.70 \text{ GeV} < m(D) < 1.95 \text{ GeV}$ and $2.8 \text{ GeV} < m(J/\Psi) < 3.5 \text{ GeV}$ respectively. The D^* candidates are accepted if the energy release is $0 \text{ GeV} < Q < 3 \text{ GeV}$. The B candidates need to pass a cut on the beam-constrained mass $m_{bc} > 5.22 \text{ GeV}$, the missing energy $0.15 \text{ GeV} < \Delta E < 0.10 \text{ GeV}$, and on the thrust angle $\cos \theta_{\text{thrust}} < 0.9$. If multiple B candidates survive the selection cuts, the candidate with the highest signal probability is selected. After application of the FEI, the $e^+e^- \rightarrow q\bar{q}$ background was suppressed by a cut on the ratio of the two Fox-Wolfram moments $R_2 = F_2/F_0$, which encodes the topology of the event. To extract the number of reconstructed B mesons a fit was performed on the beam-constrained mass $m_{bc} = \sqrt{s/4 - |\vec{p}_{\text{tag}}^*|^2}$, where s is the center-of-mass energy and \vec{p}_{tag}^* the reconstructed momentum of the B_{tag} candidate. The fit result for charged and neutral B mesons is shown in Figure 1 for a signal probability output of the FEI $\mathcal{P}_{\text{FEI}} > 0.2$. The efficiency, which is defined as the fraction of correctly reconstructed B mesons of all $\Upsilon(4S)$ events and the purity, which is defined as the fraction of correctly reconstructed B mesons of all reconstructed B candidates, for two cuts on the FEI signal probability $\mathcal{P}_{\text{FEI}} > 0.2$ and $\mathcal{P}_{\text{FEI}} > 0.01$ is tabulated in Table I.

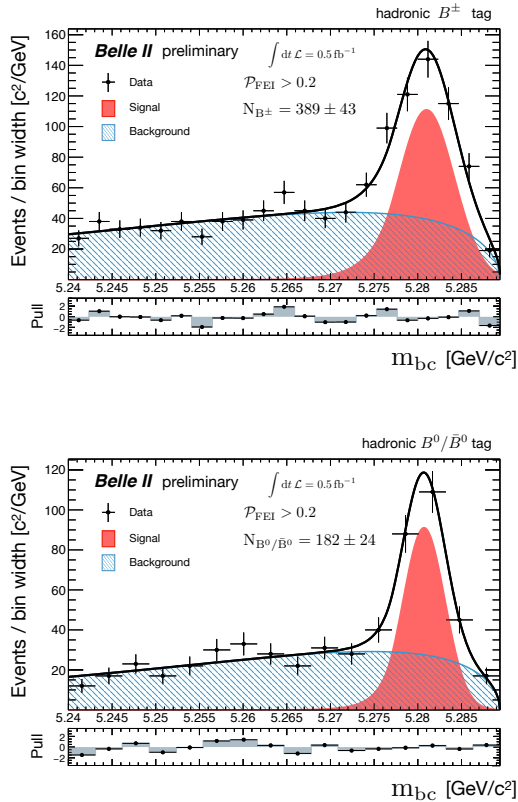


FIG. 1: Charged (top) and neutral (bottom) B meson m_{bc} distributions with a tight cut on the signal probability of $\mathcal{P}_{\text{FEI}} > 0.2$.

TABLE I: Efficiencies and purities of the FEI for two different signal probability cuts on the FEI output.

	Candidates	Efficiency	Purity
FEI Signal Probability $\mathcal{P} > 0.01$			
Charged Candidates	937±126	0.17%	24%
Neutral Candidates	394± 59	0.09%	25%
FEI Signal Probability $\mathcal{P} > 0.2$			
Charged Candidates	389± 43	0.07%	63%
Neutral Candidates	182± 24	0.03%	73%

III. ANALYSIS OF INCLUSIVE SEMILEPTONIC $B \rightarrow X l \nu$ DECAYS

We performed the analysis of inclusive $B \rightarrow X e \nu$ decays on the Belle II data sample of 500 fb^{-1} from the commissioning run, which is motivated by a similar analysis by the CLEO collaboration [4]. Due to the lack of an off-resonance data sample only the rediscovery of the decay can be achieved. Statements about V_{ub} , V_{cb} and branching fractions are not possible, because no background subtraction can be performed.

We select events by requiring one charged elec-

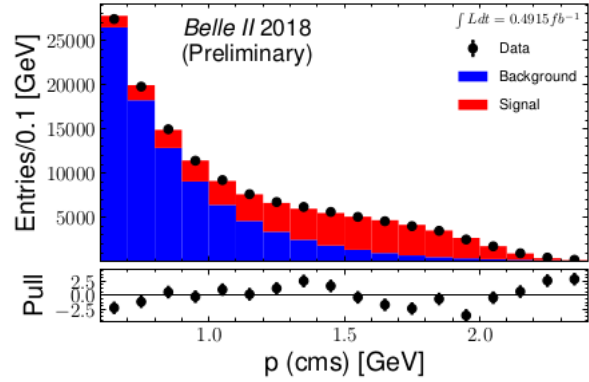


FIG. 2: Results of binned maximum likelihood template fits to the data using one component for the background pdf.

tron track originating from the interaction region $|dz| < 2 \text{ cm}$, $d_0 < 0.5 \text{ cm}$ with at least one hit in the CDC, a center-of-mass momentum of $0.6 \text{ GeV} < p^* < 3.3 \text{ GeV}$, a polar angle of the corresponding ECL cluster of $0.767 \text{ rad} < \theta_{\text{ECLcluster}} < 2.042 \text{ rad}$ which corresponds to the barrel region of the ECL, and a pseudo electron ID of $E_{\text{ECL}}/p_{\text{track}} > 0.9$. Background from non-resonant $e^+e^- \rightarrow q\bar{q}$ events is suppressed with the reduced Fox Wolfram moment $R_2 < 0.4$. Contamination of $J/\Psi \rightarrow e^+e^-$ decays is avoided by discarding events containing a reconstructed J/Ψ candidate with an invariant mass of $3 \text{ GeV} < m_{J/\Psi} < 3.14 \text{ GeV}$. The distribution of the center-of-mass momentum of the lepton after the event selection is shown in Figure 2. The fitted signal yield is 42181 ± 304 over a background yield of 89802 ± 374 .

IV. ANALYSIS OF EXCLUSIVE SEMILEPTONIC $B \rightarrow D^* l \nu$ DECAYS

The decay $B \rightarrow D^* e \nu$ has a large branching ratio of $\mathcal{B}(B \rightarrow D^* e \nu) = (5.05 \pm 0.14) \%$ making them an excellent candidate for a rediscovery with a data sample of 366 pb^{-1} from the commissioning run.

Events are selected as follows. The impact parameters of the π and K tracks are required to be close to the interaction region: $d_0 < 0.5 \text{ cm}$, $|z_0| < 3.0 \text{ cm}$. The center-of-mass momentum of the slow π from the $D^* \rightarrow D$ transition is selected as $p^*(\pi) < 0.4 \text{ GeV}$. The allowed invariant mass range for D candidates is $1.85 \text{ GeV} < m(D) < 1.88 \text{ GeV}$. The allowed mass difference between the D and D^* candidates is $0.144 \text{ GeV} < \Delta m < 0.148 \text{ GeV}$. Lepton tracks are required to have impact parameters of $d_0 < 2 \text{ cm}$ and $|z_0| < 5 \text{ cm}$ and a center-of-mass momentum of $1.2 \text{ GeV} < p_l^* < 2.4 \text{ GeV}$. Further, a pseudo electron ID of $E_{\text{ECL}}/p_{\text{track}} > 0.94$ is required. Background from non-resonant $e^+e^- \rightarrow q\bar{q}$ events is suppressed

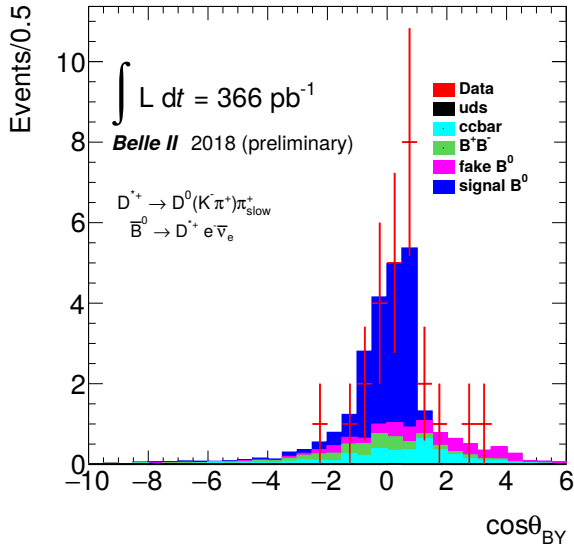


FIG. 3: The $\cos \Theta_{BY}$ distribution for $B \rightarrow D^* e \nu$ candidates in the data (points with error bars) overlaid with the combination of MC events. All cuts are applied. The MC histograms are scaled to the number of data events recorded.

with the reduced Fox Wolfram moment $R_2 < 0.25$.

The signal extraction is performed on the variable

$$\cos \Theta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - m_Y^2}{2p_B^* p_Y^*} \quad (1)$$

where E_Y^* , p_Y^* and m_Y are the center-of-mass energy, center-of-mass momentum and the invariant mass of the $D^* l$ system. Further M_B denotes the nominal B mass, and E_B^* and p_B^* the center-of-mass energy and momentum inferred from the beam energies. For correctly reconstructed candidates, ignoring detector resolution and mis-reconstructed events, this variable peaks in $\cos \Theta_{BY} \in [-1, 1]$. The distribution of this variable after the event selection is shown in Figure 3. We observe a total of 22 events, thereof 15 events in the signal region $\cos \Theta_{BY} \in [-1, 1]$ where we expect from MC that 13 events are signal.

V. FUTURE PROSPECTS OF BELLE II

Belle II has a rich physics program [5] which will be pursued in the future. Here two long standing tensions with the SM and how Belle II will be able to resolve them are shown.

The decays $B \rightarrow D^{(*)} \tau \nu$ are described at the quark level as $b \rightarrow c \tau \nu$ tree-level transitions that proceed in the SM through the exchange of a virtual W boson. The ratios, defined as

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu)}{\mathcal{B}(B \rightarrow D^{(*)} l \nu)} \quad (2)$$

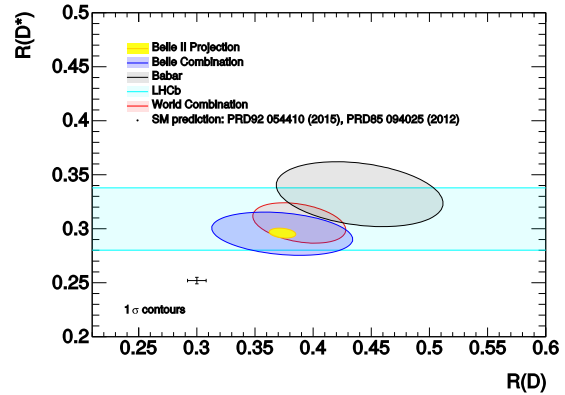


FIG. 4: Expected Belle II constraints on the $R(D)$ vs. $R(D^*)$ plane compared to existing experimental constraints from Belle. The SM prediction is indicated by the black point with theoretical error bars. The figure is taken from Reference [5] and does not include the latest Belle measurement from Reference [6].

with $l = e, \mu$, are excellent probes for new physics as theoretical uncertainties from form factors and the CKM matrix element $|V_{cb}|$ cancel. The observable has shown large tensions in the past and Belle II will be able to give a final answer if new physics, e.g. charged Higgs bosons [7, 8] or Leptoquarks [9], contribute to the process. The projection of the Belle II sensitivity in the $R(D)$ - $R(D^*)$ plane is shown in Figure 4.

The determination of the CKM matrix element $|V_{ub}|$ from semileptonic $B \rightarrow X_q l \nu$ decays exhibits a long-standing tension to the determination of $|V_{ub}|$ from exclusive $B \rightarrow \pi l \nu$ decays and global fits of the CKM unitarity triangle. With the full Belle II data sample the decay $B \rightarrow \tau \nu$ will become a competitive method to extract $|V_{ub}|$. The current experimental status and projections for 5 ab^{-1} and 50 ab^{-1} are shown in Table II.

VI. CONCLUSION

With the first 500 pb^{-1} recorded by Belle II during the 2018 commissioning run, we have successfully applied the newly developed algorithms and tools on real data. The FEI shows excellent performance, and we observe clear signals for inclusive $B \rightarrow X e \nu$ and exclusive $B \rightarrow D^* e \nu$ decays. With the target integrated luminosity of 50 ab^{-1} Belle II will be able to give a final answer on long standing tensions with the SM.

TABLE II: Expected errors in $|V_{ub}|$ measurements with the Belle full data sample, 5 ab^{-1} and 50 ab^{-1} Belle II data. Note that the statistical error quoted for exclusive $|V_{ub}|$ branching fraction, however a fit to the spectrum information is used to determine $|V_{ub}|$. We use the lattice-QCD projected precision for the future data sets. From Ref. [5].

	Statistical	Systematic	Total Exp.	Theory	Total
	(reducible, irreducible)				
$ V_{ub} $ exclusive (had. tagged)					
711 fb^{-1}	3.0	(2.3, 1.0)	3.8	7.0	8.0
5 ab^{-1}	1.1	(0.9, 1.0)	1.8	1.7	3.2
50 ab^{-1}	0.4	(0.3, 1.0)	1.2	0.9	1.7
$ V_{ub} $ exclusive (untagged)					
605 fb^{-1}	1.4	(2.1, 0.8)	2.7	7.0	7.5
5 ab^{-1}	1.0	(0.8, 0.8)	1.2	1.7	2.1
50 ab^{-1}	0.3	(0.3, 0.8)	0.9	0.9	1.3
$ V_{ub} $ inclusive					
605 fb^{-1} (old B tag)	4.5	(3.7, 1.6)	6.0	2.54.5	6.57.5
5 ab^{-1}	1.1	(1.3, 1.6)	2.3	2.54.5	3.45.1
50 ab^{-1}	0.4	(0.4, 1.6)	1.7	2.54.5	3.04.8
$ V_{ub} B \rightarrow \tau\nu$ (had. tagged)					
711 fb^{-1}	18.0	(7.1, 2.2)	19.5	2.5	19.6
5 ab^{-1}	6.5	(2.7, 2.2)	7.3	1.5	7.5
50 ab^{-1}	2.1	(0.8, 2.2)	3.1	1.0	3.2
$ V_{ub} B \rightarrow \tau\nu$ (SL tagged)					
711 fb^{-1}	11.3	(10.4, 1.9)	15.4	2.5	15.6
5 ab^{-1}	4.2	(4.4, 1.9)	6.1	1.5	6.3
50 ab^{-1}	1.3	(2.3, 1.9)	2.6	1.0	2.8

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- [1] T. Abe et al. (Belle II technical design report)(2010) arXiv:1011.0352 [hep-ex]
- [2] Y. Ohnishi et al. (Accelerator design at SuperKEKB) Progress of Theoretical and Experimental Physics **2013**, 03A011 (2013)
- [3] Keck, T., et al. Comput Softw Big Sci **3**, 6 (2019)
- [4] R. Fulton et al. (CLEO Collaboration) Phys. Rev. Lett. **64**, (1990)
- [5] E. Kou, P. Urquijo et al. (Belle II Collaboration) arXiv:1808.10567 [hep-ex]
- [6] A. Abdesselam et al. (Belle Collaboration) arXiv:1904.08794 [hep-ex]
- [7] S. P. Martin, arXiv:hep-ph/9709356 [hep-ph]
- [8] J. F. Gunion, H. E. Haber, G. L. Kane, and S. Dawson Front. Phys. 80, 1 (2000)
- [9] W. Buchmuller, R. Ruckl, and D. Wyler, Phys. Lett. **B191**, 442 (1987), [Erratum: Phys.Lett. **B448**, 320 (1999)]