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Measurement of the $B^- \to D^0\ell^-\bar{\nu}_\ell$ Branching Fraction in 62.8 fb^{-1} of Belle II data

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Abstract

We report a measurement of the branching fraction of the semileptonic decay $B^- \to D^0 \ell^- \overline{\nu}_\ell$ (and its charge conjugate) using 62.8 fb^{-1} of $\Upsilon(4S) \to B\bar{B}$ data recorded by the Belle II experiment at the SuperKEKB asymmetric-energy e^+e^- collider. The neutral charm meson is searched for in the decay mode $D^0 \to K^-\pi^+$ and combined with a properly charged identified lepton (electron or muon) to reconstruct this decay. No reconstruction of the second B meson in the $\Upsilon(4S)$ event is performed. We obtain $\mathcal{B}(B^- \to D^0\ell^-\bar{\nu}_\ell) = (2.29 \pm 0.05_{\text{stat}} \pm 0.08_{\text{syst}})\%$, in agreement with the world average of this decay. We also determine the ratio of the electron to muon branching fractions to be $R(e/\mu) = 1.04 \pm 0.05_{\text{stat}} \pm 0.03_{\text{syst}}$ and observe no deviation from lepton universality.

1. INTRODUCTION

The magnitude of the Cabibbo-Kobayashi-Maskawa (CKM) [1, 2] matrix element $|V_{cb}|$ squared determines the transition rate of b- into c-quarks and the precise knowledge of this fundamental parameter of the Standard Model (SM) [3] is crucial for the ongoing precision-B-physics programme at the Belle II experiment and elsewhere. The CKM element $|V_{cb}|$ is measured from semileptonic B meson decays $B \to X_c \ell \nu$, where X_c is a hadronic system with charm, ℓ is a light charged lepton (electron or muon) and ν is the associated neutrino. These determinations can be *inclusive*, *i.e.*, sensitive to all $X_c \ell \nu$ final states within a given region of phase space, or *exclusive*, *i.e.*, based only on a single $b \to c$ semileptonic mode such as $B \to D^* \ell \nu$ or $B \to D \ell \nu$. Pursuing both approaches is important as the two avenues involve different theoretical and experimental uncertainties and consistency between both is a powerful cross-check of our understanding. However, inclusive and exclusive measurements of $|V_{cb}|$ are at odds for many years now, an issue which is often referred to as the *inclusive vs. exclusive problem* [4].

In this paper we describe the measurement of the branching fraction of the decay $B^- \to D^0 \ell^- \overline{\nu}_\ell$ [5], a mode which is expected to yield a precise determination of the CKM element $|V_{cb}|$ from the Belle II data. Neutral D mesons are searched for in the decay mode $D^0 \to K^- \pi^+$ and combined with an identified lepton (electron or muon) of the same charge as the kaon to reconstruct this decay. To maximize the statistical power of the early Belle II data, this analysis is untagged, *i.e.*, we do not place any constraint on the second B meson in the $\Upsilon(4S)$ event. The paper is organized as follows: Sect. 2 describes the real data and simulated data sets used throughout this analysis. The experimental procedure is described in Sect. 3. Finally, Sect. 4 contains the results of this analysis.

2. THE BELLE II DETECTOR AND DATA SAMPLE

The Belle II detector [6, 7] operates at the SuperKEKB asymmetric-energy electron-positron collider [8], located at the KEK laboratory in Tsukuba, Japan. The detector consists of several nested detector subsystems arranged around the beam pipe in a cylindrical geometry. The innermost subsystem is the vertex detector, which includes two layers of silicon pixel detectors and four outer layers of silicon strip detectors. Currently, the second pixel layer is installed in only a small part of the solid angle, while the remaining vertex detector layers are fully installed. Most of the tracking volume consists of a helium and ethane-based small-cell drift chamber (CDC). Outside the drift chamber, a Cherenkov-light imaging and time-of-propagation detector provides charged-particle identification in the barrel region. In the forward endcap, this function is provided by a proximity-focusing, ring-imaging Cherenkov detector with an aerogel radiator. Further out is the ECL electromagnetic calorimeter, consisting of a barrel and two endcap sections made of CsI(Tl) crystals. A uniform 1.5 T magnetic field is provided by a superconducting solenoid situated outside the calorimeter. Multiple layers of scintillators and resistive plate chambers, located between the magnetic flux-return iron plates, constitute the K_L and muon identification system (KLM).

The data used in this analysis were collected in the years 2019 and 2020 at a center-of-mass (c.m.) energy of 10.58 GeV, corresponding to the mass of the Υ(4S) resonance.

This data set corresponds to an integrated luminosity of 62.8 fb^{-1} and contains $N_{B\bar{B}} = (68.21 \pm 0.06_{\text{stat}} \pm 0.75_{\text{sys}}) \times 10^6$ $\Upsilon(4S) \to B\bar{B}$ events as determined from a fit to event-shape variables [9].

Different samples of Monte Carlo (MC) simulated events are used throughout this analysis. These include a sample of $\Upsilon(4S) \to B\bar{B}$ events in which B mesons decay generically, generated with EvtGen [10] and a sample of continuum $e^+e^- \to q\bar{q}$ events ($q = u, d, s, c$) simulated with KKMC [11], interfaced with PYTHIA [12]. Full detector simulation based on GEANT4 [13] is applied to MC events. The Monte Carlo samples used in this analysis correspond to an integrated luminosity of 300 fb^{-1}. The lepton reconstruction efficiencies and the hadron misidentification rates in simulation are adjusted to match the real performance of the Belle II lepton identification system.

The data samples are processed using the Belle II software framework basf2 [14].

Prior to physics analysis, charged particle trajectories are reconstructed in the vertex detector and the central drift chamber [15]. Photons are reconstructed from ECL clusters unmatched to charged particle tracks. Hadronic events are selected by requiring at least three charged particles, a visible energy above 4 GeV, and a ratio R_2 of the second to the zeroth Fox-Wolfram moments below 0.3 [16].

3. EXPERIMENTAL PROCEDURE

3.1. Reconstruction

We require charged particle tracks to originate from the interaction point (IP): The distance of closest approach between each track and the interaction point must be less than 2 cm along the z direction (parallel to the beams) and less than 0.5 cm in the transverse $r - \phi$ plane. We further require charged particles to be within angular acceptance of the central drift chamber and to have associated CDC hits.

Charged leptons (electron or muons) are required to have a c.m. momentum greater than 0.6 GeV. Electrons are identified based on their energy and shower shape in the ECL calorimeter. Muons are found based on the information of the instrumented return yoke KLM. We attempt to recover bremsstahlung photons radiated from an electron track by searching within a cone around the lepton direction. If such photons, with an energy between 50 MeV and 150 MeV, are found they are added to the electron candidate to correct the 4-momentum.

Neutral D meson candidates are searched for in the decay mode to $K^-\pi^+$, $D^0 \to K^-\pi^+$. D^0 candidates are accepted within a $K\pi$ invariant mass window from 1.857 GeV to 1.872 GeV.

Candidates for the decay $B^- \to D^0\ell^-\overline{\nu}_\ell$ are obtained by combining an appropriately charged lepton with a neutral D candidate. The mass of the $Y = D^0\ell$ system is required to exceed 3.15 GeV. For each B candidate, we calculate the angle between the Y and the B meson in the c.m. frame of the collision,

$$\cos\theta_{BY} = \frac{2\,E^*_B E^*_Y - m^2_B - m^2_Y}{2|p^*_B||p^*_Y|}, \tag{1}$$

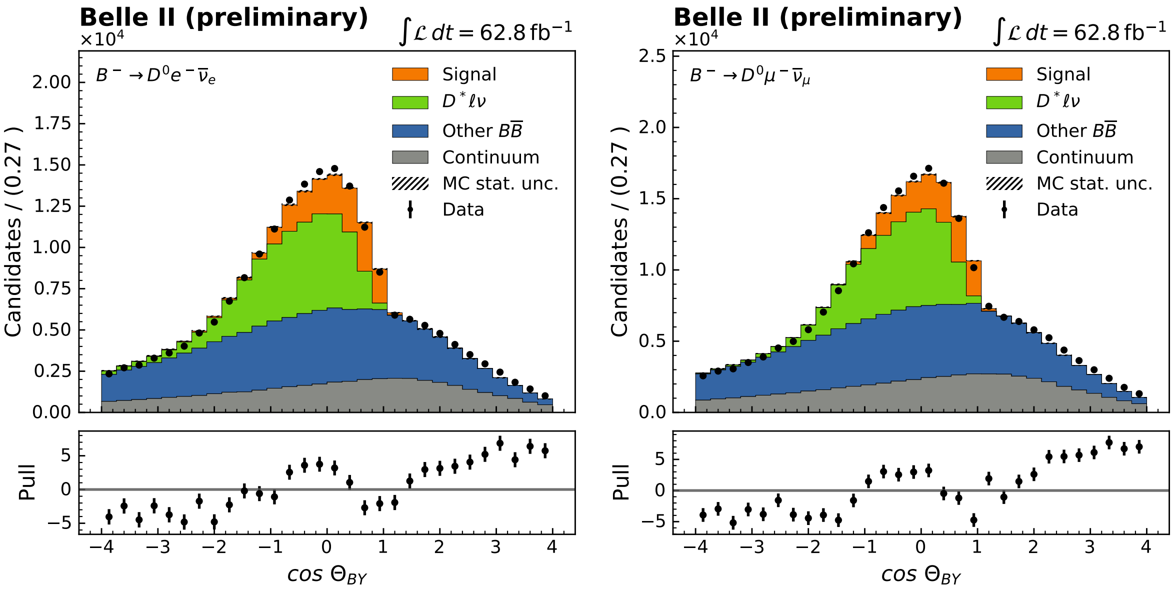

FIG. 1. $\cos\theta_{BY}$ distributions for selected $B^- \to D^0 e^- \overline{\nu}_e$ (left) and $B^- \to D^0 \mu^- \overline{\nu}_\mu$ candidates (right). The stacked histograms are MC simulated events scaled to the real data luminosity of 62.8 fb^{-1}. The real data is shown by points with error bars.

where E^*_Y, $|p^*_Y|$, and m_Y are the c.m. energy, momentum, and invariant mass, respectively, of the $D^0\ell$ system, m_B is the nominal B mass [17], and E^*_B, $|p^*_B|$ are the c.m. energy and momentum, respectively, of the B. The latter are inferred from the beam 4-momenta. For correctly reconstructed $B^- \to D^0\ell^-\overline{\nu}_\ell$ candidates, the value of $\cos\theta_{BY}$ ranges within the interval $[-1, 1]$. However, due to the finite beam-energy spread, final-state radiation, and detector resolution, the $\cos\theta_{BY}$ distributions of signal events are smeared beyond this range. For background candidates, values outside of the $[-1, 1]$ interval are allowed. In the rest of the analysis, we retain B candidates with a value of $\cos\theta_{BY}$ ranging between -4 and 4.

To reduce the sizeable background of $B^0 \to D^{*-}(\bar{D}^0\pi^-)\ell^+\nu_\ell$ and $B^+ \to \bar{D}^{*0}(\bar{D}^0\pi^0)\ell^+\nu_\ell$ decays, an active veto is applied. For $B^0 \to D^{*-}(\bar{D}^0\pi^-)\ell^+\nu_\ell$, this is done by combining a slow ($p < 0.35$ GeV) pion of correct charge with the D^0 of a $B^+ \to \bar{D}^0\ell^+\nu_\ell$ candidate. If, for any slow pion candidate in the event, the mass difference $\Delta M = M(D^*) - M(D)$ is found to be in the interval $[0.144, 0.148]$ GeV, the B^+ candidate is rejected. For $B^+ \to \bar{D}^{*0}(\bar{D}^0\pi^0)\ell^+\nu_\ell$ decays, we combine the D^0 with a neutral pion candidate and reject the $B^- \to D^0\ell^-\overline{\nu}_\ell$ candidate, if ΔM is in the interval $[0.141, 0.145]$ GeV and the opening angle between D^0 and π^0 is below 17 degrees. We reconstruct neutral pions from $\pi^0 \to \gamma\gamma$ and require different energies of the photon daughters depending on the region of the detector the photon signature originated from. We require $E > 0.080$ GeV for the forward end-cap, $E > 0.030$ GeV for the barrel region and $E > 0.060$ GeV for the backward end-cap. The π^0 mass is required to be in the interval $[0.120, 0.145]$ GeV.

Fig. 1 shows the $\cos\theta_{BY}$ distributions of $B^- \to D^0 e^- \overline{\nu}_e$ and $B^- \to D^0 \mu^- \overline{\nu}_\mu$ candidates after applying the selections described in this section.

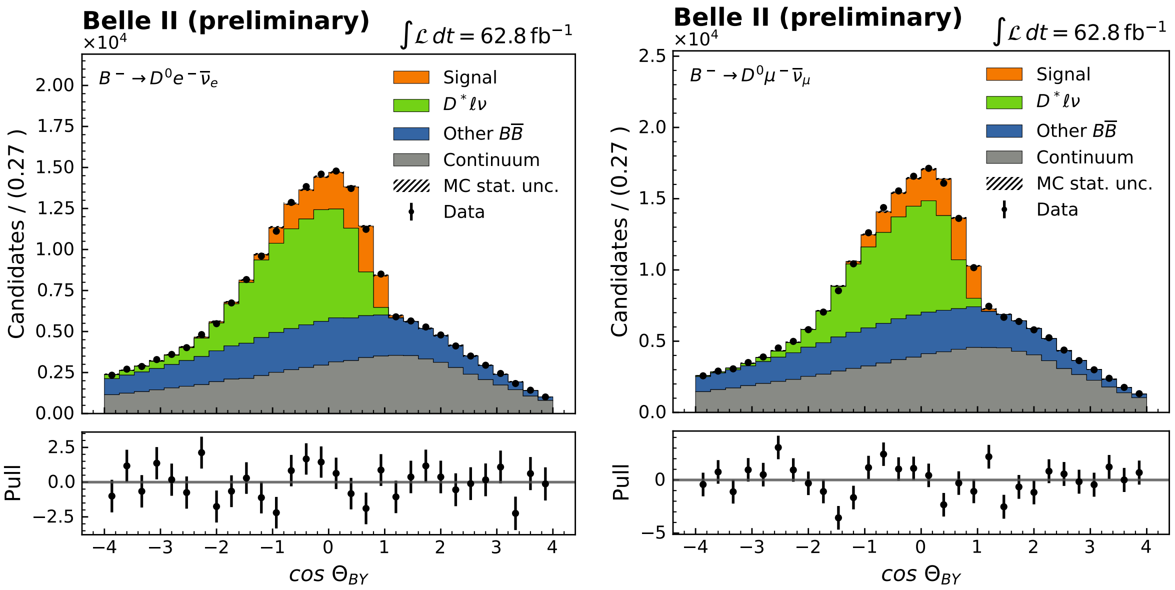

FIG. 2. Result of the fit to the $B^- \to D^0 e^- \overline{\nu}_e$ (left) and $B^- \to D^0 \mu^- \overline{\nu}_\mu$ samples (right). The stacked histograms are MC simulated events scaled to match the result of the fit. The real data is shown by points with error bars.

	Fitted Yields			
Channel	Signal	D^*	Other $B\overline{B}$	Continuum
$B^- \to D^0 e^- \overline{\nu}_e$	19543 ± 648	65502 ± 960	59233 ± 2450	79697 ± 1970
$B^- \to D^0 \mu^- \overline{\nu}_\mu$	18869 ± 636	67595 ± 843	64899 ± 2101	102308 ± 1808

TABLE I. The fitted yield for each MC component determined from a maximum likelihood fit in $\cos\theta_{BY}$. The uncertainties are statistical only.

3.2. Signal extraction

To extract the amount of signal in the selected sample, we perform separate fits to the $\cos\theta_{BY}$ distributions of $B^- \to D^0 e^- \overline{\nu}_e$ and $B^- \to D^0 \mu^- \overline{\nu}_\mu$ candidates. We use a maximum likelihood technique using Poisson statistics of both real and MC simulated data [18]. The MC shape of the signal, D^* downfeed, background from $B\bar{B}$ events and continuum background distributions is kept, while the respective normalizations are free parameters in both fits.

The fit results are shown in Table I. We find $19,543 \pm 628$ $(18,869 \pm 636)$ events in the electron (muon) channel. In Fig. 2 the stacked MC components are scaled according to the fit results and the collision data is shown by points with error bars.

Channel	Efficiency [%]	Branching fraction [%]
$B^- \to D^0 e^- \overline{\nu}_e$	30.12	2.34 ± 0.08
$B^- \to D^0 \mu^- \overline{\nu}_\mu$	30.36	2.24 ± 0.08

TABLE II. Branching fractions of $B^- \to D^0 \ell^- \overline{\nu}_\ell$ determined in the electron and muon samples. The uncertainties are statistical only.

	Relative uncertainty [%]	
Source	$B^- \to D^0 e^- \overline{\nu}_e$	$B^- \to D^0 \mu^- \overline{\nu}_\mu$
$N_{B^\pm}$	1.61	1.61
$\mathcal{B}(D^0 \to K^- \pi^+)$	0.78	0.78
Tracking	2.07	2.07
Lepton identification	1.41	2.38
MC efficiency (statistical)	0.09	0.09
$D\ell\nu$ form factor	0.15	0.15
$D^*\ell\nu$ form factor	0.44	0.44
Continuum shape	0.37	0.37
Sum	3.14	3.68

TABLE III. Relative systematic uncertainty on the measurement of the $B^- \to D^0 \ell^- \overline{\nu}_\ell$ branching fraction in the two samples.

4. RESULTS AND SYSTEMATIC UNCERTAINTY

4.1. $B^- \to D^0 \ell^- \overline{\nu}_\ell$ branching fraction

The fit result quoted in the previous section can be converted into a measurement of the $B^- \to D^0 \ell^- \overline{\nu}_\ell$ branching ratio by using

$$N_{\text{sig}} = 2 \times N_{B\bar{B}} \times f_{+-} \times \mathcal{B}(B^- \to D^0 \ell^- \overline{\nu}_\ell) \times \mathcal{B}(D^0 \to K^- \pi^+) \times \epsilon \,, \tag{2}$$

where $N_{B\bar{B}}$ is the number of $\Upsilon(4S)$ events in the sample, f_{+-} is the B^+ production fraction at the $\Upsilon(4S)$ [17], $\mathcal{B}(D^0 \to K^- \pi^+)$ is the D^0 subdecay branching fraction [17] and ϵ is the overall selection criteria efficiency of this analysis as determined from MC simulation. The results obtained in the two samples are collected in Table II.

4.2. Systematic uncertainty

The relative systematic uncertainties affecting the $B^- \to D^0 \ell^- \overline{\nu}_\ell$ branching fraction measurement are listed in Table III. We assume no correlation among the individual sources of uncertainty and sum them in quadrature to obtain the total systematic uncertainty. The methods used for obtaining these uncertainties are detailed below.

To correct for mismodelling of the lepton-identification in the MC compared to collision events, we apply momentum-and polar-angle-dependent corrections. In independent studies of $J/\psi \to \ell^+\ell^-$ and $K_S \to \pi^+\pi^-$ decays, correction factors are obtained for the reconstruction efficiency of leptons, and the mis-identification of hadrons as leptons. Due to limited sample size in the control samples, the lepton-identification correction factors are associated with statistical and systematic uncertainties. By resampling the correction factors with Gaussian distributions, while accounting for systematic correlations, we generate 500 sets of correction values. The 500 sets are used to estimate the systematic uncertainty on N_{sig} caused by lepton-identification.

The uncertainty on the branching fraction of the hadronic decay mode $\mathcal{B}(D^0 \to K^-\pi^+) = (3.950 \pm 0.031)\%$ [19] enters the result of the signal yield as a systematic uncertainty.

The number of charged $B^\pm$ mesons in the data sample is calculated as

$$N_{B^\pm} = 2 \times N_{B\bar{B}} \times f_{+-} \tag{3}$$

with $N_{B\bar{B}} = (68.21 \pm 0.06_{\mathrm{stat}} \pm 0.75_{\mathrm{sys}}) \times 10^6$ and

$$f_{+-} = \frac{\Gamma\left(\Upsilon(4S) \to B^+B^-\right)}{\Gamma\left(\Upsilon(4S)\right)_{\mathrm{tot}}} = 0.514 \pm 0.006. \tag{4}$$

The uncertainties on f_{+-} and $N_{B\bar{B}}$ are added in quadrature to estimate the impact on the measured branching fraction.

We account for the effect of finite MC sample sizes on the selection efficiency ϵ with the binomial standard error.

A $e^+e^- \to \tau^+\tau^-$ performance study measures discrepancies in the track finding efficiency between MC and collision data. In accordance with the performance study, a relative systematic uncertainty of 0.69 % is assigned for each of the three charged final state tracks to account for the track efficiency discrepancy.

The form factors describe the dependency of the decay rate on the kinematic variable $w = v_B \cdot v_{D^{(*)}}$. The form factors impact on the shape of signal and D^* components has to be taken into account. We separately vary the form factor parameters of the decays $B^- \to D^0\ell^-\overline{\nu}_\ell$ and $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ in the parameterization of Caprini, Lellouch and Neubert (CLN) [20] by 1 σ around their central values [21] to estimate the corresponding systematic uncertainty. The form factor uncertainty quoted in Table III corresponds to the quadratic sum of these individual variations.

Finally, the discrepancies between data and MC in the sidebands of the pre-fit $\cos\theta_{BY}$ distributions in Fig. 1 are partly explained by mismodelling of the continuum MC. We estimate the effect of this mismodelling on the measured branching fractions by reweighing the continuum MC using collision data recorded below the $\Upsilon(4S)$.

5. SUMMARY

We have measured the branching fraction of the decay $B^- \to D^0\ell^-\overline{\nu}_\ell$ in 62.8 fb^{-1} of Belle II data. The results in the electron and muon samples are

$$\mathcal{B}(B^- \to D^0 e^-\overline{\nu}_e) = (2.34 \pm 0.08_{\mathrm{stat}} \pm 0.07_{\mathrm{syst}})\% \;, \tag{5}$$

$$\mathcal{B}(B^- \to D^0 \mu^-\overline{\nu}_\mu) = (2.24 \pm 0.08_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}})\% \;, \tag{6}$$

where the first error is statistical and the second systematic.

The weighted mean of both modes yields to this combined value of the branching fraction

$$\mathcal{B}(B^- \to D^0\ell^-\overline{\nu}_\ell) = (2.29 \pm 0.05_{\rm stat} \pm 0.08_{\rm syst})\% \; , \tag{7}$$

in agreement with the world average value of $(2.35 \pm 0.03_{\rm stat} \pm 0.09_{\rm syst})\%$ [21]. For the ratio between the e and μ channels, the uncertainties related to $N_{B^\pm}$ and $\mathcal{B}(D^0 \to K^-\pi^+)$ cancel and we obtain

$$R(e/\mu) = \frac{\mathcal{B}(B^- \to D^0 e^-\overline{\nu}_e)}{\mathcal{B}(B^- \to D^0\mu^-\overline{\nu}_\mu)} = 1.04 \pm 0.05_{\rm stat} \pm 0.03_{\rm syst} \; . \tag{8}$$

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