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

F. Abudinén, 35 I. Adachi, 24, 21 R. Adak, 18 K. Adamczyk, 74 L. Aggarwal, 81 P. Ahlborg, 110 H. Ahmed, 84 J. K. Ahn, 55 H. Aihara, 128 N. Akopov, 2 A. Aloisio, 99, 28 F. Ameli, 32 L. Andricke, 64 N. Anh Ky, 46, 15 D. M. Asner, 4 H. Atmacan, 112 V. Aulchenko, 5, 76 T. Aushev, 71 V. Aushev, 90 T. Aziz, 91 V. Babu, 13 S. Bacher, 74 H. Bae, 128 S. Baehr, 52 S. Bahinipati, 37 A. M. Bakich, 127 P. Bambade, 107 Sw. Banerjee, 117 S. Bansal, 81 M. Barrett, 24 G. Batignani, 102, 31 J. Baudot, 108 M. Bauer, 52 A. Baur, 13 A. Beaulieu, 131 J. Becker, 52 P. K. Behera, 40 J. V. Bennett, 121 E. Bernier, 33 F. U. Bernlochner, 110 M. Bertemes, 43 E. Bertholet, 93 M. Bessner, 114 S. Bettarini, 102, 31 V. Bhattacharya, 36 B. Bhuyan, 38 F. Bianchi, 104, 34 T. Bilka, 8 S. Bilokon, 60 D. Biswas, 117 A. Bobrov, 5, 76 D. Bodrov, 71, 58 A. Bolz, 13 A. Bondar, 5, 76 G. Bonvicini, 133 A. Bozek, 74 M. Bracko, 119, 89 P. Branchini, 33 N. Braun, 52 R. A. Briere, 6 T. E. Browder, 114 D. N. Brown, 117 A. Budano, 33 L. Burmistrov, 107 S. Bussino, 103, 33 M. Campajola, 99, 28 L. Cao, 13 G. Caria, 120 G. Casarosa, 102, 31 C. Cecchi, 101, 30 D. Červenkov, 8 M.-C. Chang, 17 P. Chang, 72 R. Cheaib, 13 V. Chekalian, 63 C. Chen, 48 Y. Q. Chen, 124 Y.-T. Chen, 72 B. G. Cheon, 23 K. Chilikin, 58 K. Chirapatpimol, 9 H.-E. Cho, 23 K. Cho, 54 S.-J. Cho, 135 S.-K. Choi, 22 S. Choudhury, 39 D. Cinabro, 133 L. Corona, 102, 31 L. M. Cremaldi, 121 D. Cuesta, 108 S. Cunliffe, 13 T. Czank, 130 N. Dash, 40 F. Battolla, 13 E. De La Cruz-Burelo, 7 G. de Marino, 107 G. De Nardo, 99, 28 M. De Nuccio, 13 G. Di Pietro, 33 R. de Sangro, 27 B. Deschamps, 110 M. Destefanis, 104, 34 S. Dey, 93 A. De Yta-Hernandez, 7 A. Di Canto, 4 F. Di Capua, 99, 28 S. Di Carlo, 107 J. Dingfelder, 110 Z. Doležal, 8 J. Domínguez Jiménez, 98 T. V. Dong, 15 M. Dorigo, 105, 35 K. Dort, 51 D. Dossett, 120 S. Dubey, 114 S. Duell, 110 G. Dujany, 108 S. Eidelman, 5, 58, 76 M. Elachitch, 110 E. Fast, 5 J. E. Fast, 80 T. Ferber, 13 D. Ferlewick, 120 T. Fillinger, 108 G. Finocchiaro, 27 S. Fiore, 32 P. Fischer, 115 A. Fodor, 65 F. Forti, 102, 31 A. Frey, 19 M. Friedl, 43 B. G. Fulsom, 80 M. Gabriel, 63 A. Gabrielli, 105, 35 N. Gabysev, 5, 76 E. Ganiev, 105, 35 M. Garcia-Hernandez, 7 R. Garg, 81 A. Garmash, 5, 76 V. Gaur, 132 A. Gaz, 100, 29 U. Gebauer, 19 A. Gellrich, 13 J. Gemmler, 52 T. Geßler, 51 D. Getzkow, 51 R. Giordano, 99, 28 A. Giri, 39 A. Glazov, 13 B. Gobbo, 35 R. Godang, 125 P. Goldenzwieg, 52 B. Golob, 116, 89 P. Gomis, 47 G. Gong, 124 P. Grace, 109 W. Gradl, 50 E. Graziani, 33 D. Greenwald, 92 T. Gu, 123 Y. Guan, 112 K. Gudkova, 5, 76 C. Hadjivasiliou, 80 S. Halder, 91 K. Hara, 24, 21 T. Hara, 24, 21 O. Hartbrich, 114 K. Hayasaka, 75 H. Hayashi, 70 S. Hazra, 91 C. Hearty, 111, 45 M. T. Hedges, 114 I. Heredia de la Cruz, 7, 12 M. Hernández Villanueva, 13 A. Hershenhorn, 111 T. Higuchi, 130 E. C. Hill, 111 H. Hirata, 67 M. Hoek, 50 M. Holmann, 120 S. Hollitt, 109 T. Hotta, 79 C.-L. Hsu, 127 Y. Hu, 44 K. Huang, 72 T. Humair, 63 T. Iijima, 67, 69 K. Inami, 67 G. Inguglia, 43 J. Irakkathil Jabbar, 52 A. Ishikawa, 24, 21 R. Itoh, 24, 21 M. Iwasaki, 78 Y. Iwasaki, 21 S. Iwata, 97 P. Jackson, 109 W. W. Jacobs, 41 I. Jaegle, 113
R. J. Sobie,131,45 A. Soffer,93 A. Sokolov,42 Y. Soloviev,13 E. Solovieva,58 S. Spataro,104,34 B. Spruck,50 M. Starič,89 S. Stefkova,13 Z. S. Stottler,132 R. Stroili,100,29 J. Strube,80 J. Stypula,74 R. Sugiyama,128 M. Sumihama,20,79 K. Sumisawa,24,21 T. Sumiyoshi,97 D. J. Summers,121 W. Sutcliffe,110 K. Suzuki,67 S. Y. Suzuki,24,21 H. Svidras,13 M. Tabata,10 M. Takahashi,13 M. Takizawa,83,25,86 U. Tamponi,34 S. Tanaka,128 T. Tsuboyama,24,21 K. Tanida,49 H. Tanigawa,128 N. Taniguchi,24 Y. Tao,113 P. Taras,106 F. Tenchini,102,31 R. Tiwary,91 D. Tonelli,35 E. Torassa,29 N. Toutounji,127 K. Trabelsi,107 T. Uglov,58,71 K. Unger,52 Y. Unno,23 K. Uno,75 S. Uno,24,21 P. Urquijo,120 Y. Ushiroda,24,21,128 Y. V. Usov,5,76 S. E. Vahsen,114 R. van Tonder,110 G. S. Varner,114 K. E. Varvell,127 A. Vinokurova,5,76 L. Vitale,105,35 V. Vorobyev,5,58,76 A. Vossen,14 B. Wach,63 E. Waheed,24 H. M. Wakeling,65 K. Wan,128 W. Wan Abdullah,118 B. Wang,63 C. H. Wang,73 E. Wang,123 M.-Z. Wang,72 X. L. Wang,18 A. Warburton,65 M. Watanabe,75 S. Watamuki,135 J. Webb,120 S. Wehle,13 M. Welsch,110 C. Wessel,110 J. Wiechczynski,74 P. Wieduwilt,19 H. Windel,63 E. Won,55 L. J. Wu,44 X. P. Xu,87 B. D. Yabsley,127 S. Yamada,24 W. Yan,124 S. B. Yang,55 H. Ye,13 J. Yelton,113 I. Yeo,54 J. H. Yin,55 M. Yonenaga,97 Y. M. Yook,44 K. Yoshinobu,75 T. Yoshinobu,75 C. Z. Yuan,44 G. Yuan,124 Y. Yusa,75 L. Zani,1 J. Z. Zhang,44 Y. Zhang,124 Z. Zhang,124 V. Zhilich,5,76 J. Zhou,18 Q. D. Zhou,67,68,69 X. Y. Zhou,59 V. I. Zhukova,58 and V. Zhulanov,5,76

(Belle II Collaboration)

1Aix Marseille Université, CNRS/IN2P3, CPPM, 13288 Marseille, France
2Alikhanyan National Science Laboratory, Yerevan 0036, Armenia
3Beihang University, Beijing 100191, China
4Brookhaven National Laboratory, Upton, New York 11973, U.S.A.
5Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090, Russian Federation
6Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, U.S.A.
7Centro de Investigacion y de Estudios Avanzados del Instituto Politcnico Nacional, Mexico City 07360, Mexico
8Faculty of Mathematics and Physics, Charles University, 121 16 Prague, Czech Republic
9Chiang Mai University, Chiang Mai 50202, Thailand
10Chiba University, Chiba 263-8522, Japan
11Chonnam National University, Gwangju 61186, South Korea
12Consejo Nacional de Ciencia y Tecnologia, Mexico City 03940, Mexico
13Deutsches Elektronen–Synchrotron, 22607 Hamburg, Germany
14Duke University, Durham, North Carolina 27708, U.S.A.
15Institute of Theoretical and Applied Research (ITAR), Duy Tan University, Hanoi 100000, Vietnam
16ENEA Casaccia, I-00123 Roma, Italy
Department of Physics, Fu Jen Catholic University, Taipei 24205, Taiwan

Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443, China

II. Physikalisches Institut, Georg-August-Universität Göttingen, 37073 Göttingen, Germany

Gifu University, Gifu 501-1193, Japan

The Graduate University for Advanced Studies (SOKENDAI), Hayama 240-0193, Japan

Gyeongsang National University, Jinju 52828, South Korea

Department of Physics and Institute of Natural Sciences, Hanyang University, Seoul 04763, South Korea

High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan

J-PARC Branch, KEK Theory Center, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan

Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8530, Japan

INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy

INFN Sezione di Napoli, I-80126 Napoli, Italy

INFN Sezione di Padova, I-35131 Padova, Italy

INFN Sezione di Perugia, I-06123 Perugia, Italy

INFN Sezione di Pisa, I-56127 Pisa, Italy

INFN Sezione di Roma, I-00185 Roma, Italy

INFN Sezione di Roma Tre, I-00146 Roma, Italy

INFN Sezione di Torino, I-10125 Torino, Italy

INFN Sezione di Trieste, I-34127 Trieste, Italy

Indian Institute of Science Education and Research Mohali, SAS Nagar, 140306, India

Indian Institute of Technology Bhubaneswar, Satya Nagar 751007, India

Indian Institute of Technology Guwahati, Assam 781039, India

Indian Institute of Technology Hyderabad, Telangana 502285, India

Indian Institute of Technology Madras, Chennai 600036, India

Indiana University, Bloomington, Indiana 47408, U.S.A.

Institute for High Energy Physics, Protvino 142281, Russian Federation

Institute of High Energy Physics, Vienna 1050, Austria

Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

Institute of Particle Physics (Canada), Victoria, British Columbia V8W 2Y2, Canada

Institute of Physics, Vietnam Academy of Science and Technology (VAST), Hanoi, Vietnam
47 Instituto de Fisica Corpuscular, Paterna 46980, Spain
48 Iowa State University, Ames, Iowa 50011, U.S.A.
49 Advanced Science Research Center, Japan Atomic Energy Agency, Naka 319-1195, Japan
50 Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany
51 Justus-Liebig-Universität Gießen, 35392 Gießen, Germany
52 Institut für Experimentelle Teilchenphysik, Karlsruher Institut für Technologie, 76131 Karlsruhe, Germany
53 Kitasato University, Sagamihara 252-0373, Japan
54 Korea Institute of Science and Technology Information, Daejeon 34141, South Korea
55 Korea University, Seoul 02841, South Korea
56 Kyoto Sangyo University, Kyoto 603-8555, Japan
57 Kyungpook National University, Daegu 41566, South Korea
58 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow 119991, Russian Federation
59 Liaoning Normal University, Dalian 116029, China
60 Ludwig Maximilians University, 80539 Munich, Germany
61 Luther College, Decorah, Iowa 52101, U.S.A.
62 Malaviya National Institute of Technology, Jaipur, Jaipur 302017, India
63 Max-Planck-Institut für Physik, 80805 München, Germany
64 Semiconductor Laboratory of the Max Planck Society, 81739 München, Germany
65 McGill University, Montréal, Québec, H3A 2T8, Canada
66 Moscow Physical Engineering Institute, Moscow 115409, Russian Federation
67 Graduate School of Science, Nagoya University, Nagoya 464-8602, Japan
68 Institute for Advanced Research, Nagoya University, Nagoya 464-8602, Japan
69 Kobayashi-Maskawa Institute, Nagoya University, Nagoya 464-8602, Japan
70 Nara Women’s University, Nara 630-8506, Japan
71 National Research University Higher School of Economics, Moscow 101000, Russian Federation
72 Department of Physics, National Taiwan University, Taipei 10617, Taiwan
73 National United University, Miao Li 36003, Taiwan
74 H. Niewodniczanski Institute of Nuclear Physics, Krakow 31-342, Poland
75 Niigata University, Niigata 950-2181, Japan
76 Novosibirsk State University, Novosibirsk 630090, Russian Federation
77 Okinawa Institute of Science and Technology, Okinawa 904-0495, Japan
78 Osaka City University, Osaka 558-8585, Japan
79 Research Center for Nuclear Physics, Osaka University, Osaka 567-0047, Japan
80 Pacific Northwest National Laboratory, Richland, Washington 99352, U.S.A.
81 Panjab University, Chandigarh 160014, India
82 Punjab Agricultural University, Ludhiana 141004, India
83 Meson Science Laboratory, Cluster for Pioneering Research, RIKEN, Saitama 351-0198, Japan
84 St. Francis Xavier University, Antigonish, Nova Scotia, B2G 2W5, Canada
85 Seoul National University, Seoul 08826, South Korea
86 Showa Pharmaceutical University, Tokyo 194-8543, Japan
87 Soochow University, Suzhou 215006, China
88 Soongsil University, Seoul 06978, South Korea
89 J. Stefan Institute, 1000 Ljubljana, Slovenia
90 Taras Shevchenko National Univ. of Kiev, Kiev, Ukraine
91 Tata Institute of Fundamental Research, Mumbai 400005, India
92 Department of Physics, Technische Universität München, 85748 Garching, Germany
93 Tel Aviv University, School of Physics and Astronomy, Tel Aviv, 69978, Israel
94 Toho University, Funabashi 274-8510, Japan
95 Department of Physics, Tohoku University, Sendai 980-8578, Japan
96 Tokyo Institute of Technology, Tokyo 152-8550, Japan
97 Tokyo Metropolitan University, Tokyo 192-0397, Japan
98 Universidad Autonoma de Sinaloa, Sinaloa 80000, Mexico
99 Dipartimento di Scienze Fisiche, Università di Napoli Federico II, I-80126 Napoli, Italy
100 Dipartimento di Fisica e Astronomia, Università di Padova, I-35131 Padova, Italy
101 Dipartimento di Fisica, Università di Perugia, I-06123 Perugia, Italy
102 Dipartimento di Fisica, Università di Pisa, I-56127 Pisa, Italy
103 Dipartimento di Matematica e Fisica, Università di Roma Tre, I-00146 Roma, Italy
104 Dipartimento di Fisica, Università di Torino, I-10125 Torino, Italy
105 Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
106 Université de Montréal, Physique des Particules, Montréal, Québec, H3C 3J7, Canada
107 Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
108 Université de Strasbourg, CNRS, IPHC, UMR 7178, 67037 Strasbourg, France
109 Department of Physics, University of Adelaide, Adelaide, South Australia 5005, Australia
110 University of Bonn, 53115 Bonn, Germany
111 University of British Columbia, Vancouver, British Columbia, V6T 1Z1, Canada
112 University of Cincinnati, Cincinnati, Ohio 45221, U.S.A.
113 University of Florida, Gainesville, Florida 32611, U.S.A.
114 University of Hawaii, Honolulu, Hawaii 96822, U.S.A.
115 University of Heidelberg, 68131 Mannheim, Germany
116 Faculty of Mathematics and Physics, University of Ljubljana, 1000 Ljubljana, Slovenia
117 University of Louisville, Louisville, Kentucky 40292, U.S.A.
118 National Centre for Particle Physics, University Malaya, 50603 Kuala Lumpur, Malaysia
119 Faculty of Chemistry and Chemical Engineering,
    University of Maribor, 2000 Maribor, Slovenia
120 School of Physics, University of Melbourne, Victoria 3010, Australia
121 University of Mississippi, University, Mississippi 38677, U.S.A.
122 University of Miyazaki, Miyazaki 889-2192, Japan
123 University of Pittsburgh, Pittsburgh, Pennsylvania 15260, U.S.A.
124 University of Science and Technology of China, Hefei 230026, China
125 University of South Alabama, Mobile, Alabama 36688, U.S.A.
126 University of South Carolina, Columbia, South Carolina 29208, U.S.A.
127 School of Physics, University of Sydney, New South Wales 2006, Australia
128 Department of Physics, University of Tokyo, Tokyo 113-0033, Japan
129 Earthquake Research Institute, University of Tokyo, Tokyo 113-0032, Japan
130 Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa 277-8583, Japan
131 University of Victoria, Victoria, British Columbia, V8W 3P6, Canada
132 Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, U.S.A.
133 Wayne State University, Detroit, Michigan 48202, U.S.A.
134 Yamagata University, Yamagata 990-8560, Japan
135 Yonsei University, Seoul 03722, South Korea
Abstract

We report a measurement of the branching fraction of the semileptonic decay $B^- \to D^0 \ell^- \bar{\nu}_\ell$ (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 \(B \rightarrow X_c \ell \nu\), where \(X_c\) is a hadronic system with charm, \(\ell\) is a light charged lepton (electron or muon) and \(\nu\) 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 \(b \rightarrow c\) semileptonic mode such as \(B \rightarrow D^{*} \ell \nu\) or \(B \rightarrow D \ell \nu\). 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 \(B^- \rightarrow D^0 \ell^- \overline{\nu}_\ell\) \[5\], 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 \(D^0 \rightarrow K^- \pi^+\) 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 \(\Upsilon(4S)\) resonance.
This data set corresponds to an integrated luminosity of 62.8 fb$^{-1}$ and contains $N_{\bar{B}B} = (68.21 \pm 0.06_{\text{stat}} \pm 0.75_{\text{sys}}) \times 10^6 \ Upsilon(4S) \to \bar{B}B$ events as determined from a fit to event-shape variables \cite{9}.

Different samples of Monte Carlo (MC) simulated events are used throughout this analysis. These include a sample of $\Upsilon(4S) \to \bar{B}B$ events in which $B$ mesons decay generically, generated with EvtGen \cite{10} and a sample of continuum $e^+e^- \to q\bar{q}$ events ($q = u,d,s,c$) simulated with KKMC \cite{11}, interfaced with PYTHIA \cite{12}. Full detector simulation based on GEANT4 \cite{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 \cite{14}.

Prior to physics analysis, charged particle trajectories are reconstructed in the vertex detector and the central drift chamber \cite{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 \cite{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 $B^- \to D^0 \ell^- \bar{\nu}_\ell$ 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,

$$\cos\theta_{BY} = \frac{2E_B^*E_Y^* - m_B^2 - m_Y^2}{2|p_B^*||p_Y^*|}, \quad (1)$$
FIG. 1. $\cos\theta_{\ell\nu}$ distributions for selected $B^- \rightarrow D^0\ell^-\bar{\nu}_\ell$ (left) and $B^- \rightarrow D^0\mu^-\bar{\nu}_\mu$ 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 $E_Y^\ell$, $|p_Y^\ell|$, 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 $E_B^\ell$, $|p_B^\ell|$ are the c.m. energy and momentum, respectively, of the $B$. The latter are inferred from the beam 4-momenta. For correctly reconstructed $B^- \rightarrow D^0\ell^-\bar{\nu}_\ell$ candidates, the value of $\cos\theta_{\ell\nu}$ ranges within the interval $[-1, 1]$. However, due to the finite beam-energy spread, final-state radiation, and detector resolution, the $\cos\theta_{\ell\nu}$ 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 $\cos\theta_{\ell\nu}$ ranging between $-4$ and $4$.

To reduce the sizeable background of $B^0 \rightarrow D^{*-}(\bar{D}^0\pi^-)\ell^+\nu_\ell$ and $B^+ \rightarrow \bar{D}^{*0}(\bar{D}^0\pi^0)\ell^+\nu_\ell$ decays, an active veto is applied. For $B^0 \rightarrow D^{*-}(\bar{D}^0\pi^-)\ell^+\nu_\ell$, this is done by combining a slow ($p < 0.35$ GeV) pion of correct charge with the $D^0$ of a $B^+ \rightarrow D^0\ell^+\nu_\ell$ 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 $B^+ \rightarrow \bar{D}^{*0}(\bar{D}^0\pi^0)\ell^+\nu_\ell$ decays, we combine the $D^0$ with a neutral pion candidate and reject the $B^- \rightarrow D^0\ell^-\bar{\nu}_\ell$ candidate, if $\Delta M$ is in the interval $[0.141, 0.145]$ GeV and the opening angle between $D^0$ and $\pi^0$ is below 17 degrees. We reconstruct neutral pions from $\pi^0 \rightarrow \gamma\gamma$ 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 $\pi^0$ mass is required to be in the interval $[0.120, 0.145]$ GeV.

Fig. 1 shows the $\cos\theta_{\ell\nu}$ distributions of $B^- \rightarrow D^0\ell^-\bar{\nu}_\ell$ and $B^- \rightarrow D^0\mu^-\bar{\nu}_\mu$ candidates after applying the selections described in this section.
FIG. 2. Result of the fit to the $B^- \rightarrow D^0 e^- \bar{\nu}_e$ (left) and $B^- \rightarrow D^0 \mu^- \bar{\nu}_\mu$ 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.

| Channel          | Signal     | $D^*$     | Other $B\bar{B}$ | Continuum |
|------------------|------------|-----------|------------------|-----------|
| $B^- \rightarrow D^0 e^- \bar{\nu}_e$ | $19543 \pm 648$ | $65502 \pm 960$ | $59233 \pm 2450$ | $79697 \pm 1970$ |
| $B^- \rightarrow D^0 \mu^- \bar{\nu}_\mu$ | $18869 \pm 636$ | $67595 \pm 843$ | $64899 \pm 2101$ | $102308 \pm 1808$ |

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 $B^- \rightarrow D^0 e^- \bar{\nu}_e$ and $B^- \rightarrow D^0 \mu^- \bar{\nu}_\mu$ 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 [%] |
|-----------------------|----------------|------------------------|
| $B^- \to D^0 e^- \bar{\nu}_e$ | 30.12          | 2.34 ± 0.08            |
| $B^- \to D^0 \mu^- \bar{\nu}_\mu$ | 30.36          | 2.24 ± 0.08            |

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

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

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

4. RESULTS AND SYSTEMATIC UNCERTAINTY

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

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

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

where $N_{B\bar{B}}$ is the number of $\Upsilon(4S)$ events in the sample, $f_{+-}$ is the $B^+$ production fraction at the $\Upsilon(4S)$, $\mathcal{B}(D^0 \to K^- \pi^+)$ is the $D^0$ subdecay branching fraction and $\epsilon$ 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 $B^- \to D^0 \ell^- \bar{\nu}_\ell$ 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 $\bar{J}/\psi \to \ell^+\ell^-$ 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 $N_{\text{sig}}$ caused by lepton-identification.

The uncertainty on the branching fraction of the hadronic decay mode $B(D^0 \to K^-\pi^+)$ = (3.950 ± 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

$$N_{B^\pm} = 2 \times N_{BB} \times f_{+\mu}$$

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

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

The uncertainties on $f_{+\mu}$ and $N_{BB}$ 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 $\epsilon$ 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 $w = v_B \cdot v_{D(\ast)}$. 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 $B^- \to D^0\ell^-\nu_\ell$ and $\bar{B}^0 \to D^{**}\ell^-\nu_\ell$ in the parameterization of Caprini, Lellouch and Neubert (CLN) [20] by 1 $\sigma$ 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. [II] 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 $B^- \to D^0\ell^-\nu_\ell$ in 62.8 fb$^{-1}$ of Belle II data. The results in the electron and muon samples are

$$B(B^- \to D^0e^-\bar{\nu}_e) = (2.34 \pm 0.08_{\text{stat}} \pm 0.07_{\text{syst}})\%,$$

$$B(B^- \to D^0\mu^-\bar{\nu}_\mu) = (2.24 \pm 0.08_{\text{stat}} \pm 0.08_{\text{syst}})\%.$$
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

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

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

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

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