Measurement of the branching fractions of the decays

\[ B_s^0 \rightarrow \bar{D}^0 K^- \pi^+ \] and

\[ B^0 \rightarrow \bar{D}^0 K^+ \pi^- \]

The LHCb collaboration†

Abstract

The first observation of the decay \( B_s^0 \rightarrow \bar{D}^0 K^- \pi^+ \) is reported. The analysis is based on a data sample, corresponding to an integrated luminosity of 1.0 fb\(^{-1}\) of \( pp \) collisions, collected with the LHCb detector. The branching fraction relative to that of the topologically similar decay \( B^0 \rightarrow \bar{D}^0 \pi^+ \pi^- \) is measured to be

\[
\frac{\mathcal{B} (B_s^0 \rightarrow \bar{D}^0 K^- \pi^+)}{\mathcal{B} (B^0 \rightarrow \bar{D}^0 \pi^+ \pi^-)} = 1.18 \pm 0.05 \text{ (stat.)} \pm 0.12 \text{ (syst.)}.
\]

In addition, the relative branching fraction of the decay \( B^0 \rightarrow \bar{D}^0 K^+ \pi^- \) is measured to be

\[
\frac{\mathcal{B} (B^0 \rightarrow \bar{D}^0 K^+ \pi^-)}{\mathcal{B} (B^0 \rightarrow \bar{D}^0 \pi^+ \pi^-)} = 0.106 \pm 0.007 \text{ (stat.)} \pm 0.008 \text{ (syst.)}.
\]

Submitted to Phys. Rev. D.

© CERN on behalf of the LHCb collaboration, license CC-BY-3.0.

†Authors are listed on the following pages.
LHCb collaboration

R. Aaij, C. Abellan Beteta, B. Adeva, M. Adinolfi, C. Adrover, A. Affolder, Z. Ajaltouni, J. Albrecht, F. Alessio, M. Alexander, S. Ali, G. Alkhazov, P. Alvarez Cartelle, A.A. Alves Jr, S. Amato, S. Amerio, Y. Amhis, L. Anderlini, J. Anderson, R. Andreassen, R.B. Appleby, O. Aquines Gutierrez, F. Archilli, A. Artamonov, M. Artuso, E. Aslanides, G. Auriemma, S. Bachmann, J.J. Baack, C. Baesso, V. Balagura, W. Baldini, R.J. Barlow, C. Barschel, S. Barsuk, W. Barter, Th. Baucer, A. Bay, J. Beddow, F. Bedeschi, I. Bediaga, S. Belogurov, K. Belous, I. Belyaev, E. Ben-Haim, G. Bencivenni, S. Benson, J. Benton, A. Bereznyo, R. Bernet, M. Better, M. van Beuzekom, A. Bien, S. Bifani, T. Bird, A. Bizzeti, P.M. Bjornstad, T. Blake, F. Blanch, J. Blouw, S. Blusk, V. Bocci, A. Bondar, N. Bondar, W. Bonivento, S. Borghi, A. Borgia, T.J.V. Bowcock, E. Bowen, C. Bozzi, T. Brambach, J. van den Brand, J. Bressieux, D. Brett, M. Britsch, T. Britton, N.H. Brook, H. Brown, I. Burducea, A. Bursche, G. Busetto, J. Buytaert, S. Cadeddu, O. Calliot, M. Calvi, M. Calvo Gomez, A. Camboni, P. Campana, D. Campora Perez, A. Carbone, G. Carboni, R. Cardinale, A. Cardini, H. Carranza-Mejia, L. Carson, K. Carvalho Alkiba, G. Casse, L. Castillo Garcia, M. Cattaneo, Ch. Canet, M. Charles, Ph. Charpentier, P. Chen, N. Chiapolini, M. Chrzaszcz, K. Ciba, X. Cid Vidal, G. Ciezarek, P.E.L. Clarke, M. Clemencic, H.V. Cllifi, J. Closier, C. Coka, V. Coco, J. Cogan, E. Coger, P. Collins, A. Comerma-Montells, A. Contu, A. Cook, M. Coombes, G. Coquerel, G. Corti, B. Couturier, G.A. Cowan, D.C. Craik, S. Cullen, P. Currie, C. D’Ambrosio, P. David, P.N.Y. David, A. Davis, I. De Bonis, K. De Bruyn, S. De Capua, M. De Cian, J.M. De Miranda, L. De Paula, W. De Silva, P. De Simone, D. Decamp, M. Deckenhoff, L. Del Buono, N. Deléage, D. Derkach, O. Deschamps, F. Dettori, A. Di Canto, F. Di Ruscio, H. Dijkstra, M. Dogaru, S. Donlevy, F. Dordi, A. Dosil Suárez, D. Dossett, A. Dovbnya, F. Dupertuis, R. Dzhelyadin, A. Dzirura, A. Dzyuba, S. Easo, U. Egede, V. Egorychev, S. Eidelman, D. van Eijk, S. Eisenhardt, U. Eitschberger, R. Ekelof, L. Eklund, I. El Rifai, Ch. Elsasser, D. Elsky, A. Falabella, C. Fälder, G. Fardell, C. Farinelli, S. Farry, V. Fave, D. Ferguson, V. Fernandez Albor, F. Ferreira Rodrigues, M. Ferro-Luzzi, S. Filipov, M. Fiore, C. Fitzpatrick, M. Fontana, F. Fontanelli, R. Forty, O. Francisco, M. Frank, C. Frei, M. Frosini, F. Furcas, E. Furfaro, A. Gallas Torreira, D. Galli, M. Gandelman, P. Gandini, Y. Gao, J. Garofoli, P. Garosi, J. Garra Tico, L. Garrido, C. Gaspar, R. Gauld, E. Gersabeck, M. Gersabeck, T. Gershon, Ph. Ghie, V. Gibson, V.V. Gligorov, C. Göbel, D. Golubkov, A. Golutvin, A. Gomes, H. Gordon, M. Grabalosa Gándara, R. Graciani Diaz, L.A. Granado Cardoso, E. Graugés, G. Graziani, A. Grecu, E. Greening, S. Gregson, P. Griffith, O. Grünberg, B. Gu, E. Gushchin, Yu. Guz, T. Gys, C. Hadjiiska, G. Haefeli, C. Haen, S.C. Haines, S. Hall, T. Hampson, S. Hansmann-Menzemer, N. Harnew, S.T. Harnew, J. Harrison, T. Hartmann, J. He, V. Heijne, K. Hennessy, P. Henrard, J.A. Hernando Morata, E. van Herwijnen, E. Hicks, D. Hill, M. Hoballah, C. Hombach, P. Hopchev, W. Hulsbergen, P. Hunt, T. Huse, N. Hussain, D. Hutchcroft, D. Hynds.
V. Iakovenko, M. Idzik, P. Ilten, R. Jacobsson, A. Jaeger, E. Jans, P. Jaton, A. Jawahery, F. Jing, M. John, D. Johnson, C.R. Jones, C. Joram, B. Jost, M. Kaballo, S. Kandybei, M. Karacson, T.M. Karbach, I.R. Kenyon, U. Kerzel, T. Ketel, A. Keune, B. Khanji, O. Kochebina, I. Komarov, R.F. Koopman, P. Koppenburg, M. Korolev, A. Kozlinskiy, L. Kravchuk, K. Kreplin, M. Kreps, G. Kroker, P. Krokovny, F. Kruse, M. Kucharczyk, V. Kudryavtsev, T. Kvaratskheliya, V.N. La Thi, D. Lacarrere, G. Lafferty, A. Lai, D. Lambert, R.W. Lambert, E. Lanciotti, C. Lanfranchi, C. Lattes, S. Leo, I.V. Machikhiliyan, A. Martín Sánchez, D. Martínez Santos, D. Martín Tostes, A. Massafferri, R. Matev, Z. Mathe, C. Matteuzzi, E. Mauriès, A. Mazurov, J. McCarthy, A. McNab, R. McNulty, B. Meadows, F. Meier, M. Meissner, M. Merk, D.A. Milanes, M.N. Minard, J. Molina Rodríguez, S. Monteil, D. Moran, P. Morawska, M.J. Morello, R. Mountain, I. Mous, F. Muheim, K. Müller, R. Muresan, B. Muryn, B. Muster, P. Naik, T. Nakada, R. Nandakumar, I. Nasteva, M. Needham, N. Neufeld, A.D. Nguyen, T.D. Nguyen, C. Nguyen-Mau, M. Nicol, V. Niess, R. Niet, N. Nikitin, T. Nikodem, A. Nomerotski, A. Novoselov, A. Oblakowska-Mucha, V. Obraztsov, S. Oggero, S. Ogilvy, O. Okhrimenko, R. Oldeman, M. Orlandea, J.M. Otalora Goicochea, P. Owen, A. Oyanguren, B.K. Pal, A. Palano, M. Palután, J. Panman, A. Papanestis, M. Pappagallo, C. Parkes, C.J. Parkinson, G. Passaleva, G.D. Patel, M. Patel, G.N. Patrick, C. Patrignani, C. Pavel-Nicorescu, A. Pazos Alvarez, A. Pellegrino, G. Penso, M. Pepe Altarelli, S. Perazzini, D.L. Perego, E. Perez Trigo, A. Pérez-Calero Yzquierdo, P. Perret, M. Perrin-Terrin, G. Pessina, K. Petridis, A. Petrolini, A. Phan, E. Picatoste Ollooi, B. Pietrzyk, T. Pilia, D. Pinci, S. Place, M. Plo Casasus, F. Polci, G. Polok, A. Poluektov, E. Polycarpov, A. Popov, D. Popov, B. Popovici, C. Potterat, A. Powell, J. Prisciandaro, V. Pugatch, A. Puig Navarro, G. Puzzi, W. Qian, J.H. Rademacker, B. Rakotomiaramanana, M.S. Rangel, I. Raniuk, N. Rauschmayr, G. Raven, S. Redford, M.M. Reid, A.C. dos Reis, S. Ricciardi, A. Richards, K. Rinnert, V. Rives Molina, D.A. Roa, M. Robbe, E. Rodrigues, P. Rodriguez Perez, S. Roise, V. Romanovsky, A. Romero Vidal, J. Rouvinet, T. Ruf, F. Ruffini, H. Ruiz, P. Ruiz Valls, G. Sabatino, J.J. Saborido Silva, N. Sagidova, P. Sail, B. Saitta, V. Salustino Guimarães, C. Salzmann, B. Sanmartín Sedes, M. Sannino, R. Santacesaria, C. Santamaria Rios, E. Santovetti, M. Sapunov, A. Sarti, C. Satriano, M. Satta, M. Savrie, D. Savrini, P. Schaack, M. Schiller, H. Schindler, M. Schupp, M. Schilling, B. Schmidt, O. Schneider, A. Schopper, M.-H. Schune, R. Schwenners, B. Sciascia, A. Scibba, M. Seco, A. Semennikov, K. Sederowska, I. Sepp, N. Serra, J. Serrano, P. Seyfert, M. Shapkin, I. Shapoval, P. Shatalov, Y. Shcheglov, P. Shcheglov, A. Shires, R. Silva Coutinho, T. Skwarnicki.
N.A. Smith1, E. Smith2,4,8, M. Smith3, M.D. Sokoloff5,6, F.J.P. Soler50, F. Soomro18, D. Souza45, B. Souza De Paula2, B. Spaan9, A. Sparkes49, P. Spradlin60, F. Stagni37, S. Stahl11, O. Steinkamp39, S. Stoica28, S. Stone38, B. Storaci39, M. Straticiuc28, U. Straumann39, V.K. Subbiah37, L. Sun56, S. Swientek9, V. Syropoulos41, M. Szczekowski27, P. Szczyptk38,37, T. Szumlak26, S. T’Jampens4, M. Teklishyn7, E. Teodorescu28, F. Teubert37, C. Thomas54, E. Thomas37, J. van Tilburg11, V. Tisserand4, M. Tobin38, S. Tolk41, D. Tonelli37, S. Topp-Joergensen54, N. Torri44, E. Tournefier4,52, S. Tournerie38, M.T. Tran38, M. Tresch39, A. Tsaregorodtsev6, P. Tsopelas40, N. Tuning40, M. Ubeda Garcia37, A. Ukleda27, D. Urner53, U. Uwer11, V. Vagnoni14, G. Valenti14, R. Vazquez Gomez35, P. Vazquez Regueiro36, S. Vecchi16, J.J. Velthuis45, M. Veltri17,9, G. Veneziano38, M. Vesterinen37, B. Viaud7, D. Vieira2, X. Vilasis-Cardona35,n, A. Vollhardt39, D. Volyanskyy10, D. Voong45, A. Vorobyev29, V. Vorobyev33, C. Volf60, H. Voss10, R. Wald60, R. Wallace12, S. Wandernoth11, J. Wang58, D.R. Ward46, N.K. Watson44, A.D. Webber53, D. Websdale52, M. Whitehead47, J. Wicht37, J. Wiechczynski25, D. Wiedner11, L. Wiggers40, G. Wilkinson54, M.P. Williams47,48, M. Williams55, F.F. Wilson48, J. Wishahi9, M. Witke25, S.A. Wotton46, S. Wright46, S. Wu3, K. Wylie37, Y. Xie49,37, F. Xing54, Z. Xing58, Z. Yang3, R. Young39, X. Yuan3, O. Yushchenko34, M. Zangoli14, M. Zavertyaev10,a, F. Zhang3, L. Zhang58, W.C. Zhang12, Y. Zhang3, A. Zhelezov11, A. Zhokhov10, J. Wieczynski37, S. Zhong30, L. Zhong3, A. Zvyagin37.

1Centro Brasileiro de Pesquisas Fisicas (CBPF), Rio de Janeiro, Brazil
2Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
3Center for High Energy Physics, Tsinghua University, Beijing, China
4LAPP, Université de Savoie, CNRS/IN2P3, Annecy-Le-Vieux, France
5Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France
6CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
7LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
8LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France
9Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
10Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
11Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
12School of Physics, University College Dublin, Dublin, Ireland
13Sezione INFN di Bari, Bari, Italy
14Sezione INFN di Bologna, Bologna, Italy
15Sezione INFN di Cagliari, Cagliari, Italy
16Sezione INFN di Ferrara, Ferrara, Italy
17Sezione INFN di Firenze, Firenze, Italy
18Laboratori Nazionali dell’INFN di Frascati, Frascati, Italy
19Sezione INFN di Genova, Genova, Italy
20Sezione INFN di Milano Bicocca, Milano, Italy
21Sezione INFN di Padova, Padova, Italy
22Sezione INFN di Pisa, Pisa, Italy
23Sezione INFN di Roma Tor Vergata, Roma, Italy
24Sezione INFN di Roma La Sapienza, Roma, Italy
25Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
26AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
27National Center for Nuclear Research (NCBJ), Warsaw, Poland
28Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
29Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
30Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia

v
Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia
Institute for High Energy Physics (IHEP), Protvino, Russia
Universitat de Barcelona, Barcelona, Spain
Universidad de Santiago de Compostela, Santiago de Compostela, Spain
European Organization for Nuclear Research (CERN), Geneva, Switzerland
Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
Physik-Institut, Universität Zürich, Zürich, Switzerland
Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands
NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
University of Birmingham, Birmingham, United Kingdom
H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, University of Warwick, Coventry, United Kingdom
STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Imperial College London, London, United Kingdom
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
Department of Physics, University of Oxford, Oxford, United Kingdom
Massachusetts Institute of Technology, Cambridge, MA, United States
University of Cincinnati, Cincinnati, OH, United States
University of Maryland, College Park, MD, United States
Syracuse University, Syracuse, NY, United States
Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to
Institut für Physik, Universität Rostock, Rostock, Germany, associated to

P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia
Università di Bari, Bari, Italy
Università di Bologna, Bologna, Italy
Università di Cagliari, Cagliari, Italy
Università di Ferrara, Ferrara, Italy
Università di Firenze, Firenze, Italy
Università di Urbino, Urbino, Italy
Università di Modena e Reggio Emilia, Modena, Italy
Università di Genova, Genova, Italy
Università di Milano Bicocca, Milano, Italy
Università di Roma Tor Vergata, Roma, Italy
Università di Roma La Sapienza, Roma, Italy
Università della Basilicata, Potenza, Italy
LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain
IFIC, Universitat de Valencia-CSIC, Valencia, Spain
Hanoi University of Science, Hanoi, Viet Nam
Università di Padova, Padova, Italy
Università di Pisa, Pisa, Italy
Scuola Normale Superiore, Pisa, Italy
1 Introduction

The precise measurement of the angle $\gamma$ of the CKM Unitarity Triangle [12] is one of the primary objectives in contemporary flavour physics. Measurements from the experiments BaBar, Belle and LHCb are based mainly on studies of $B^+ \to D K^+$ decays, where the notation $D$ implies that the neutral $D$ meson is an admixture of $D^0$ and $\bar{D}^0$ states. Each experiment currently gives constraints on $\gamma$ with a precision of $\sim 15^\circ$ [3–5]. Significant reduction of this uncertainty is well motivated and the use of additional channels to further improve the precision is of great interest.

The decay $B^0 \to D K^+ \pi^-$, including the resonant contribution from $B^0 \to D K^{*0}$, is one of the modes with the potential to make significant impact on the overall determination of $\gamma$ [6]. A first measurement of $CP$ observables in $B^0 \to D K^{*0}$ decays has been reported by LHCb [7]. This decay is particularly sensitive to $\gamma$ owing to the interference of $b \to c \bar{u}s$ and $b \to u \bar{c}s$ amplitudes, which for this decay are of similar magnitude. It has been noted that an amplitude analysis of $B^0 \to D K^+ \pi^-$ decays can further improve the sensitivity and also resolve the ambiguities in the result [8, 9].

The decays $B^0 \to D^0 K^+ \pi^-$ and $B_s^0 \to D^0 K^- \pi^+$ can be mediated by the decay diagrams shown in Fig. 1. Both $B^0$ and $B_s^0$ decays are flavour-specific, with the charge of the kaon identifying the flavour of the decaying $B$ meson, though the charges are opposite in the two cases. In addition to these colour-allowed tree-level diagrams, colour-suppressed tree-level diagrams contribute to $B^0 \to D^0 K \pi$ decays ($K \pi$ denotes the sum over both charge combinations). Both colour-allowed and colour-suppressed diagrams contribute to the CKM-suppressed $B^0 \to D^0 K \pi$ modes.

A first study of the decay $B^0 \to D^0 K^+ \pi^-$ has been performed by BaBar [10], giving a branching fraction measurement $B(B^0 \to D^0 K^+ \pi^-) = (88 \pm 15 \pm 9) \times 10^{-6}$, where the contribution from the $B^0 \to D^{*-} K^+$ decay is excluded. There is no previous branching fraction measurement for the inclusive three-body process $B^0 \to D^0 K^- \pi^+$, although that of the resonant contribution $D^0 K^{*0}$ has been measured by LHCb [11]. Since the $B_s^0 \to D^0 K^- \pi^+$ and the related $B^0 \to D^0 K^- \pi^+$ decays form potentially serious backgrounds to the $B^0 \to D^+ K^- \pi^-$ channel, measurements of their properties will be necessary to reduce systematic uncertainties in the determination of $\gamma$.

In this paper the results of a study of neutral $B$ meson decays to $D^0 K \pi$, includ-

Figure 1: Decay diagrams for (a) favoured $B^0 \to D^0 K^+ \pi^-$ decays and (b) favoured $B_s^0 \to D^0 K^- \pi^+$ decays.
ing inspections of their Dalitz plot distributions, are presented. The $D^0K^+\pi^-$ and $D^0K^-\pi^+$ final states are combined, and the inclusion of charge conjugate processes is implied throughout the paper. In order to reduce systematic uncertainties in the measurements, the topologically similar decay $D^0\pi^+\pi^-$, which has been studied in detail previously [12,13], is used as a normalisation channel. In this paper, $D\pi\pi$ denotes the $D^0\pi^+\pi^-$ final state and $DK\pi$ denotes the sum over the $D^0K^+\pi^-$ and $D^0K^-\pi^+$ final states. The neutral $D$ meson is reconstructed using the $D^0\rightarrow K^+\pi^-$ final state; therefore the signal yields measured include small contributions from $D^0\rightarrow K^+\pi^-$ decays, but such contributions are expected to be small and are neglected hereafter. The analysis uses a data sample, corresponding to an integrated luminosity of 1.0 fb$^{-1}$ of $pp$ collisions at a centre-of-mass energy of 7 TeV, collected with the LHCb detector during 2011.

2 Detector, trigger and selection

The LHCb detector [14] is a single-arm forward spectrometer covering the pseudorapidity range $2<\eta<5$, designed for the study of particles containing $b$ or $c$ quarks. The detector includes a high precision tracking system consisting of a silicon-stripe vertex detector surrounding the $pp$ interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined tracking system provides a momentum measurement with relative uncertainty that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, and impact parameter (IP) resolution of 20 µm for tracks with high transverse momentum ($p_T$). Charged hadrons are identified using two ring-imaging Cherenkov (RICH) detectors [15]. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The LHCb trigger [16] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage that applies a full event reconstruction. In this analysis, signal candidates are accepted if one of the final state particles created a cluster in the hadronic calorimeter with sufficient transverse energy to fire the hardware trigger. Events that are triggered at the hardware level by another particle in the event are also retained.

The software trigger requires a two-, three- or four-track secondary vertex with a high sum of the transverse momentum, $p_T$, of the tracks and a significant displacement from the primary $pp$ interaction vertices (PVs). At least one track should have $p_T > 1.7$ GeV/c and impact parameter $\chi^2$, $\chi^2_{IP}$, with respect to the primary interaction greater than 16. The $\chi^2_{IP}$ is the difference between the $\chi^2$ of the PV reconstruction with and without the considered track. A multivariate algorithm [17] is used for the identification of secondary vertices consistent with the decay of a $b$ hadron.

Candidates that satisfy the software trigger selection and are consistent with the decay chain $B^0(s) \rightarrow D^0K^+\pi^-$, $D^0 \rightarrow K^+\pi^-$ are selected, with requirements similar to those in
the LHCb study of the decay $B^0_{(s)} \rightarrow D^0 K^+ K^−$ \[18\]. The $D^0$ candidate invariant mass is required to satisfy $1844 < m_{K\pi} < 1884 \text{MeV}/c^2$. Tracks are required to be consistent with either the kaon or pion hypothesis, as appropriate, based on particle identification (PID) information primarily from the RICH detectors \[15\]. All other selection criteria were tuned on the $D^0 \pi^+ \pi^−$ channel. The large yield available for the $B^0 \rightarrow D^0 \pi^+ \pi^−$ normalisation sample allows the selection to be based on data, though the efficiencies are determined using simulated events. In the simulation, $pp$ collisions are generated using PYTHIA 6.4 \[19\] with a specific LHCb configuration \[20\]. Decays of hadronic particles are described by EVTGEN \[21\] in which final state radiation is generated using PHOTOS \[22\]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit \[23\] as described in Ref. \[24\].

Loose selection requirements are applied to obtain a visible signal peak in the $D^0 \pi^+ \pi^−$ normalisation channel. The selection includes criteria on the quality of the tracks forming the signal candidate, their $p_T$, and $\chi^2_{IP}$. Requirements are also placed on the corresponding variables for candidate composite particles ($D^0, B^0_{(s)}$) together with restrictions on the consistency of the decay fit ($\chi^2_{vertex}$), the flight distance significance ($\chi^2_{flight}$), and the cosine of the angle between the momentum vector and the line joining the PV under consideration to the $B^0_{(s)}$ vertex ($\cos \theta_{\text{dir}}$) \[11\].

A boosted decision tree (BDT) \[25\] that identifies $D^0 \rightarrow K^+ \pi^−$ candidates is used to suppress backgrounds from $b$-hadron decays to final states that do not contain charmed particles and backgrounds where the $D^0$ does not decay to the $K^+ \pi^−$ final state. This “$D^0$ BDT” \[26,27\] is trained using a large high-purity sample obtained from $B^+ \rightarrow D^0 \pi^+$ decays. The BDT takes advantage of the kinematic similarity of all $b$-hadron decays and avoids using any topological information from the $B^0_{(s)}$ decay. Properties of the $D^0$ candidate and its daughter tracks, containing kinematic, track quality, vertex and PID information, are used to train the BDT.

Further discrimination between signal and background categories is achieved by calculating weights, using the sPlot technique \[28\], for the remaining $D^0 \pi^+ \pi^−$ candidates. The weights are based on a simplified fit to the $B$ candidate invariant mass distribution from the $D\pi\pi$ data sample. The weights are used to train a neural network \[29\] to maximise the separation between the categories. A total of 10 variables are used in the network. They include the $p_T$, $\chi^2_{IP}$, $\chi^2_{vertex}$, $\chi^2_{flight}$ and $\cos \theta_{\text{dir}}$ of the $B^0_{(s)}$ candidate, the output of the $D^0$ BDT and the $\chi^2_{IP}$ of the two pion tracks that originate from the $B^0_{(s)}$ vertex. The $p_T$ asymmetry and track multiplicity in a cone with half-angle of 1.5 units in the plane of pseudorapidity and azimuthal angle (measured in radians) \[30\] around the $B^0_{(s)}$ candidate flight direction are also used. The input quantities to the neural network only depend weakly on the kinematics of the $B^0_{(s)}$ decay. A requirement on the network output is imposed that reduces the combinatorial background by an order of magnitude while retaining about 70 % of the signal.

To improve the $B^0_{(s)}$ candidate invariant mass resolution, the four-momenta of the tracks from the $D^0$ candidate are adjusted \[31\] so that their combined invariant mass matches the world average value \[32\]. An additional $B^0_{(s)}$ mass constraint is applied in the
calculation of the Dalitz plot coordinates, $m^2(DK)$ and $m^2(D\pi)$, which are used in the determination of event-by-event efficiencies. The coordinates are calculated twice: once each with a $B^0$ and a $B^0_s$ mass constraint. A small fraction ($\sim 1\%$ within the fitted mass range) of candidates with invariant masses far from the $B^0_s$ peak fail one or both of these mass-constrained fits, and are removed from the analysis.

To remove the large background from $B^0 \to D^{*-} \pi^+$ decays, candidates in both samples are rejected if the mass difference $m_{D\pi} - m_D$ (for either pion charge in the combinations $D^0\pi^+\pi^-$ and $D^0K\pi$) lies within $\pm 2.5$ MeV/$c^2$ of the nominal $D^{*-}D^0$ mass difference $^{32}$. Candidates in the $DK\pi$ sample are also rejected if the mass difference $m_{DK} - m_D$ calculated under the pion mass hypothesis satisfies the same criterion. A potential background contribution from $B^0_s \to D^{\pm} K^{\mp}$ decays is removed by requiring that the pion from the $D^0$ candidate together with the kaon and the pion do not form an invariant mass in the range 1850–1885 MeV/$c^2$. Further $DK\pi$ candidates are rejected by requiring that the kaon from the $D^0$ candidate together with the kaon and the pion do not form an invariant mass in the range 1955–1975 MeV/$c^2$, which removes potential background from $B^0 \to D^* \pi^\pm$ decays. A muon veto is applied to all four final state tracks to remove potential background from $B^0_s \to J/\psi K^{*0}$ decays and $D^0$ candidates are required to travel at least 1 mm from the $B^0$ decay vertex to remove charmless backgrounds that survive the $D^0$ BDT requirement. Candidates are retained for further analysis if they have an invariant mass in the range 5150–5600 MeV/$c^2$ for $D\pi\pi$ or 5200–5600 MeV/$c^2$ for $DK\pi$. After all selection requirements are applied, fewer than 1\% of events with at least one candidate also contain a second candidate. Such multiple candidates are retained and treated in the same manner as other candidates; the associated systematic uncertainty is negligible.

### 3 Determination of signal yields

The signal yields are obtained from unbinned maximum likelihood fits to the invariant mass distributions. In addition to signal contributions and combinatorial background, candidates may be formed from misidentified or partially reconstructed $b$-hadron decays. Contributions from partially reconstructed decays are reduced by the lower bounds on the invariant mass regions used in the fits. Sources of misidentified backgrounds are investigated using simulation. Most potential sources are found to have broad invariant mass distributions, and are absorbed in the combinatorial background shapes used in the fits described below. Backgrounds from $\Lambda^0_b \to D^0\pi^\pm$ $^{33}$ and $B^0 \to D^0\pi^+\pi^-$ decays may, however, give contributions with distinctive shapes in the mass distributions of $D\pi\pi$ and $DK\pi$ candidates, respectively, and are therefore explicitly modelled in the fits.

The $D\pi\pi$ fit includes a double Gaussian shape to describe the signal, where the two Gaussian functions share a common mean, together with an exponential component for partially reconstructed background, and a probability density function (PDF) for $\Lambda^0_b \to D^0\pi^\pm$ decays. This PDF is modelled using a smoothed non-parametric function obtained from simulated data, reweighted so that the $D^0\pi^+$ invariant mass distribution matches that observed in data. The shape of the combinatorial background is essentially
linear, but is multiplied by a function that accounts for the fact that candidates with high invariant masses are more likely to fail the $B^0_{(s)}$ mass constrained fit. There are ten free parameters in the $D\pi\pi$ fit: the double Gaussian peak position, the widths of the two Gaussian shapes and the relative normalisation of the two Gaussian functions, the linear slope of the combinatorial background, the exponential shape parameter of the partially reconstructed background, and the yields of the four categories. The result of the fit to the $D\pi\pi$ candidates is shown in Fig. 2(a) and yields $8558 \pm 134$ $B^0 \to D^0\pi^+\pi^-$ decays.

The $DK\pi$ fit includes a second double Gaussian component to account for the presence of both $B^0$ and $B^0_s$ decays. The peaking background PDF for $B^0 \to D^0\pi^+\pi^-$ is modelled using a smoothed non-parametric function derived from simulation, reweighted in the same way as described for $\Lambda_b \to D^0\pi\pi$ above. The dominant partially reconstructed backgrounds in the $DK\pi$ fit are from $B^0_s$ decays and these extend into the $B^0$ signal region. Instead of an exponential component, a background PDF for $B^0_s \to D^0 K^-\pi^+$ decays is included, modelled using a smoothed non-parametric function obtained from simulation. Studies using simulated data show that this function can account for all resonant contributions to the $B^0_s \to D^0 K^-\pi^+$ final state. The function describing the combinatorial background has the same form as for the $D\pi\pi$ fit. The $DK\pi$ fit has eight free parameters; the parameters of the double Gaussian functions are constrained to be identical for the $B^0$ and $B^0_s$ signals, with an offset in their mean values fixed to the known $B^0_s$ mass difference. The relative width of the broader to the narrower Gaussian component and the relative normalisation of the two Gaussian functions are constrained within their uncertainties to the values obtained in simulation. The result of the fit is shown in Fig. 2(b) and yields $815 \pm 55$ $B^0 \to D^0 K^+\pi^-$ and $2391 \pm 81$ $B^0_s \to D^0 K^-\pi^+$ decays. All background yields in both fits are consistent with their expectations within uncertainties, based on measured or predicted production rates and branching fractions and background rejection factors determined from simulations.
4 Calculation of branching fraction ratios

The ratios of branching fractions are obtained after applying event-by-event efficiencies as a function of the Dalitz plot position. The branching fraction for the $B^0 \to \bar{D}^0 K^+\pi^-$ decay is determined as

$$R_{B^0} \equiv \frac{B(B^0 \to \bar{D}^0 K^+\pi^-)}{B(B^0 \to \bar{D}^0 K^-\pi^+)} = \frac{N_{\text{corr}}(B^0 \to \bar{D}^0 K^+\pi^-)}{N_{\text{corr}}(B^0 \to \bar{D}^0 K^-\pi^+)}$$

(1)

and the branching fraction of the $B^0_s \to \bar{D}^0 K^-\pi^+$ mode is determined as

$$R_{B^0_s} \equiv \frac{B(B^0_s \to \bar{D}^0 K^-\pi^+)}{B(B^0_s \to \bar{D}^0 K^+\pi^-)} = \left(\frac{f_s}{f_d}\right)^{-1} \frac{N_{\text{corr}}(B^0_s \to \bar{D}^0 K^-\pi^+)}{N_{\text{corr}}(B^0_s \to \bar{D}^0 K^+\pi^-)},$$

(2)

where the efficiency corrected yield is $N_{\text{corr}} = \sum_i W_i/\epsilon_i^{\text{tot}}$. Here the index $i$ runs over all candidates in the fit range, $W_i$ is the signal weight for candidate $i$, determined using the procedure described in Ref. [28], from the fits shown in Fig. 2 and $\epsilon_i^{\text{tot}}$ is the efficiency for candidate $i$ as a function of its Dalitz plot position. The ratio of fragmentation fractions is $f_s/f_d = 0.256 \pm 0.020$ [34]. The statistical uncertainty on the branching fraction ratio incorporates the effects of the shape parameters that are allowed to vary in the fit and the dilution due to event weighting. Most potential systematic effects cancel in the ratio.

The PID efficiency is measured using a control sample of $D^+ \to \bar{D}^0 \pi^-$, $\bar{D}^0 \to K^+\pi^-$ decays to obtain background-subtracted efficiency tables for kaons and pions as a function of their $p$ and $p_T$ [15, 35]. The kinematic properties of the particles in signal decays are obtained from simulation in which events are uniformly distributed across the phase space, allowing the PID efficiency for each event to be obtained from the tables, while taking into account the correlation between the $p$ and $p_T$ values of the two tracks. The other contributions to the efficiency (detector acceptance, selection criteria and trigger effects) are determined from phase space simulation, and validated using data. All are found to be approximately constant across the Dalitz plane, apart from some modulations seen near the kinematic boundaries and, for the $DK\pi$ channels, a variation caused by different PID requirements on the pion and the kaon. The efficiency for each mode, averaged across the Dalitz plot, is given in Table 1 together with the contributions from geometrical acceptance, trigger and selection requirements and particle identification.

The Dalitz plots obtained from the signal weights are shown in Fig. 3. The $B^0 \to \bar{D}^0 \pi^+\pi^-$ plot, Fig. 3(a), shows contributions from the $\rho^0(770)$ and $f_2(1270)$ resonances (upper diagonal edge of the Dalitz plot) and from the $D^-_2(2460)$ state (horizontal band), as expected from previous studies of this decay [12, 13]. The $B^0 \to \bar{D}^0 K^+\pi^-$ plot, Fig. 3(b), shows contributions from the $K^*(892)$ (upper diagonal edge) and from the $D^-_2(2460)$ (vertical band) resonances, as also expected [10]. The $B^0_s \to \bar{D}^0 K^-\pi^+$ plot, Fig. 3(c), shows contributions from the $\bar{K}^*(892)$ (upper diagonal edge) and from the $D^-_{s2}(2573)$ (horizontal band) states. The former contribution is as expected [11]. The decay $B^0_s \to D^-_{s2}(2573)\pi^+$ has not been observed previously but is expected to exist given the observation of the $B^0_s \to D^-_{s2}(2573)\mu^+\nu X$ decay [36].
Table 1: Summary of the efficiencies for $D\pi\pi$ and $DK\pi$ in phase space simulation. Contributions from geometrical acceptance ($\epsilon_{\text{geom}}$), trigger and selection requirements ($\epsilon_{\text{trig&sel}}$) and particle identification ($\epsilon_{\text{PID}}$) are shown. The geometrical acceptance is evaluated for $B$ mesons produced within the detector acceptance. Values given are in percent.

| Decay                | $\epsilon_{\text{geom}}$ | $\epsilon_{\text{trig&sel}}$ | $\epsilon_{\text{PID}}$ | $\epsilon_{\text{tot}}$ |
|----------------------|----------------------------|-------------------------------|--------------------------|--------------------------|
| $B^0 \to D\pi\pi$   | 44.7                       | 1.32                          | 89.3                     | 0.53                     |
| $B^0 \to DK\pi$     | 46.6                       | 1.25                          | 74.8                     | 0.44                     |
| $B^0_s \to DK\pi$   | 46.5                       | 1.25                          | 75.0                     | 0.44                     |

Figure 3: Efficiency corrected Dalitz plot distributions for (a) $B^0 \to D^0\pi^+\pi^-$, (b) $B^0 \to D^0 K^+\pi^-$ and (c) $B^0_s \to D^0 K^-\pi^+$ candidates obtained from the signal weights.

5 Systematic uncertainties and cross-checks

Systematic uncertainties are assigned to both branching fraction ratios due to the following sources (summarised in Table 2). Note that all uncertainties are relative. The variation of efficiency across the Dalitz plot may not be correctly modelled in simulation. A two-dimensional polynomial is used to fit the variation across the Dalitz region of each of the four contributions to the efficiency (detector acceptance, selection criteria, PID and trigger effects). These polynomials are used to generate 1000 simulated pseudo-experiments, varying the fit parameters within their uncertainties. Each set of simulations is used to calculate the efficiency corrected yield. The standard deviation from a Gaussian fit to these yields is used to provide a systematic uncertainty for each decay mode. This leads to a systematic uncertainty of 3.4\% (3.1\%) for $R_{\bar{B}^0}$ ($\bar{R}_{B^0}$). The $DK\pi$ fit model is varied by scaling the signal PDF width ratio to account for the different masses of the $B^0$ and $B^0_s$ mesons, replacing the PDFs of the background components with unsmoothed versions, adding components for potential background from $B^0 \to D^0 K^+\pi^0$ and $\Lambda^0 \to D^0 p\pi^+$ decays, and replacing the double Gaussian signal components with double Crystal Ball functions. The $D\pi\pi$ fit model is varied by replacing the PDF of the $\Lambda^0 \to D^0 p\pi^+$ component with an unsmoothed version, varying the slope of the combinatorial background and
replacing the exponential partially reconstructed background component with a PDF for $B^0 \to \bar{D}^0\pi^+\pi^-$ decays. Combined in quadrature, these contribute 6.3% (4.3%) to $R_{B^0}$ ($R_{B^0}$). Variations in the $D^{*\pm}$, $D^{\pm}$ and $D_s^{\pm}$ vetoes contribute to $R_{B^0}$ ($R_{B^0}$), at the level of < 0.1%, 2.0% and 0.2% (1.0%, 0.5% and 0.2%), respectively. In addition, the possible differences in the data to simulation ratios of trigger and PID efficiencies between the two channels (both 1.0%) and the limited statistics of the simulated data samples used to calculate efficiencies (2.0%) affect both $R_{B^0}$ and $R_{B^0}$. The uncertainty on the quantity $f_s/f_d$ (7.8%) affects only $R_{B^0}$. The total systematic uncertainties are obtained as the quadratic sums of all contributions.

A number of cross-checks are performed to test the stability of the results. Based upon the hardware trigger decision, candidates are separated into three groups: events in which a particle from the signal decay created a cluster with enough energy in the calorimeter to fire the trigger, events that were triggered independently of the signal decay and those events that were triggered by both the signal decay and the rest of the event. The data sample is divided by dipole magnet polarity. The neural network and PID requirements are both tightened and loosened. The PID efficiency is evaluated using the kinematic properties from $\bar{D}^0\pi^+\pi^-$ data instead of from simulation. The requirement for the $B^0$ mass constrained fits to converge is removed. All cross-checks give consistent results.

### 6 Results and conclusions

In summary, the decay $B^0 \to \bar{D}^0K^-\pi^+$ has been observed for the first time, and its branching fraction relative to that of the $B^0 \to \bar{D}^0\pi^+\pi^-$ decay is measured to be

$$\frac{B(B^0 \to \bar{D}^0K^-\pi^+)}{B(B^0 \to \bar{D}^0\pi^+\pi^-)} = 1.18 \pm 0.05 \text{ (stat.)} \pm 0.12 \text{ (syst.)}. \quad (8)$$
The current world average value of $\mathcal{B} (B^0 \rightarrow \bar{D}^0 \pi^+ \pi^-) = (8.4 \pm 0.4 \pm 0.8) \times 10^{-4}$ \cite{12} assumes equal production of $B^+ B^-$ and $B^0 \bar{B}^0$ at the $\Upsilon(4S)$ resonance and uses the $D^0$ branching fraction $\mathcal{B} (D^0 \rightarrow K^- \pi^+ ) = (3.80 \pm 0.07)\%$. Using the current world average values of $\Gamma (\Upsilon(4S) \rightarrow B^+ B^- ) / \Gamma (\Upsilon(4S) \rightarrow B^0 \bar{B}^0 ) = 1.055 \pm 0.025$ \cite{32} and $\mathcal{B} (D^0 \rightarrow K^- \pi^+ ) = (3.88 \pm 0.05)\%$ \cite{32}, the branching fraction of the normalisation channel becomes $\mathcal{B} (B^0 \rightarrow \bar{D}^0 \pi^+ \pi^- ) = (8.5 \pm 0.4 \pm 0.8) \times 10^{-4}$. This corrected value gives

$$ \mathcal{B} (B^0_s \rightarrow D^0 K^- \pi^+ ) = (1.00 \pm 0.04 (\text{stat.}) \pm 0.10 (\text{syst.}) \pm 0.10 (\mathcal{B})) \times 10^{-3}, $$

where the third uncertainty arises from $\mathcal{B} (B^0 \rightarrow \bar{D}^0 \pi^+ \pi^- )$. The $B^0 \rightarrow \bar{D}^0 K^+ \pi^-$ decay has also been measured, with relative branching fraction

$$ \frac{\mathcal{B} (B^0 \rightarrow \bar{D}^0 K^+ \pi^- )}{\mathcal{B} (B^0 \rightarrow \bar{D}^0 \pi^+ \pi^- )} = 0.106 \pm 0.007 (\text{stat.}) \pm 0.008 (\text{syst.}). $$

Using the corrected value of $\mathcal{B} (B^0 \rightarrow \bar{D}^0 \pi^+ \pi^- )$ gives

$$ \mathcal{B} (B^0 \rightarrow \bar{D}^0 K^+ \pi^- ) = (9.0 \pm 0.6 (\text{stat.}) \pm 0.7 (\text{syst.}) \pm 0.9 (\mathcal{B})) \times 10^{-5}, $$

which is the most precise measurement of this quantity to date. Future studies of the Dalitz plot distributions of these decays will provide insight into the dynamics of hadronic $B$ decays. In addition, the $B^0 \rightarrow D K^+ \pi^-$ decay may be used to measure the $CP$ violating phase $\gamma$.

\section*{Acknowledgements}

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); NSFC (China); CNRS/IN2P3 and Region Auvergne (France); BMBF, DFG, HGF and MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (The Netherlands); SCSR (Poland); ANCS/IFAI (Romania); MinES, Rosatom, RFBR and NRC “Kurchatov Institute” (Russia); MinECo, XuntaGal and GENCAT (Spain); SNSF and SER (Switzerland); NAS Ukraine (Ukraine); STFC (United Kingdom); NSF (USA). We also acknowledge the support received from the ERC under FP7. The Tier1 computing centres are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (The Netherlands), PIC (Spain), GridPP (United Kingdom). We are thankful for the computing resources put at our disposal by Yandex LLC (Russia), as well as to the communities behind the multiple open source software packages that we depend on.

\section*{References}

\begin{enumerate}
  \item N. Cabibbo, \emph{Unitary symmetry and leptonic decays}, \textit{Phys. Rev. Lett.} \textbf{10} (1963) 531.
\end{enumerate}
[2] M. Kobayashi and T. Maskawa, *CP violation in the renormalizable theory of weak interaction*, Prog. Theor. Phys. **49** (1973) 652.

[3] BaBar collaboration, J. P. Lees et al., *Observation of direct CP violation in the measurement of the Cabibbo-Kobayashi-Maskawa angle $\gamma$ with $B^{\pm} \to D^{(*)}K^{(*)\pm}$ decays*, Phys. Rev. **D87** (2013) 052015, arXiv:1301.1029

[4] K. Trabelsi, *Study of direct CP in charmed $B$ decays and measurement of the CKM angle $\gamma$ at Belle*, arXiv:1301.2033, proceedings of CKM 2012, the 7th International Workshop on the CKM Unitarity Triangle.

[5] LHCb collaboration, R. Aaij et al., *A measurement of $\gamma$ from a combination of $B^{\pm} \to Dh^{\pm}$ analyses*, arXiv:1305.2050, submitted to Phys. Lett. B.

[6] M. Gronau, *Improving bounds on $\gamma$ in $B^{\pm} \to DK^{\pm}$ and $B^{\pm,0} \to DX^{\pm,0}$*, Phys. Lett. **B557** (2003) 198, arXiv:hep-ph/0211282

[7] LHCb collaboration, R. Aaij et al., *Measurement of CP observables in $B^0 \to DK^{*0}$ with $D \to K^+K^-$*, JHEP **03** (2013) 067, arXiv:1211.5205

[8] T. Gershon, *On the measurement of the Unitarity Triangle angle $\gamma$ from $B^0 \to DK^{*0}$ decays*, Phys. Rev. **D79** (2009) 051301, arXiv:0810.2706.

[9] T. Gershon and M. Williams, *Prospects for the measurement of the Unitarity Triangle angle $\gamma$ from $B^0 \to DK^+\pi^-$ decays*, Phys. Rev. **D80** (2009) 092002, arXiv:0909.1495

[10] BaBar collaboration, B. Aubert et al., *Measurement of branching fractions and resonance contributions for $B^0 \to D^0 K^+\pi^-$ and search for $B^0 \to D^0 K^+\pi^-$ decays*, Phys. Rev. Lett. **96** (2006) 011803, arXiv:hep-ex/0509036.

[11] LHCb collaboration, R. Aaij et al., *First observation of the decay $\bar{B}_s^0 \to D^0 K^{*0}$ and a measurement of the ratio of branching fractions $B(\bar{B}_s^0 \to D^0 K^{*0})/B(\bar{B}_s^0 \to D^0 \rho^0)$*, Phys. Lett. **B706** (2011) 32, arXiv:1110.3676.

[12] Belle collaboration, A. Kuzmin et al., *Study of $\bar{B}_s^0 \to D^0 \pi^+\pi^-$ decays*, Phys. Rev. **D76** (2007) 012006, arXiv:hep-ex/0611054.

[13] BaBar collaboration, P. del Amo Sanchez et al., *Dalitz-plot analysis of $B^0 \to \bar{D}^0 \pi^+\pi^-$*, PoS **ICHEP2010** (2010) 250, arXiv:1007.4464

[14] LHCb collaboration, A. A. Alves Jr. et al., *The LHCb detector at the LHC*, JINST **3** (2008) S08005.

[15] M. Adinolfi et al., *Performance of the LHCb RICH detector at the LHC*, Eur. Phys. J. **C73** (2013) 2431, arXiv:1211.6759.
[16] R. Aaij et al., *The LHCb trigger and its performance in 2011*, JINST 8 (2013) P04022 [arXiv:1211.3055].

[17] V. V. Gligorov and M. Williams, *Efficient, reliable and fast high-level triggering using a bonsai boosted decision tree*, JINST 8 (2013) P02013 [arXiv:1210.6861].

[18] LHCb collaboration, R. Aaij et al., *Observation of $B^0 \to \bar{D}^0 K^+ K^-$ and evidence for $B_{s}^0 \rightarrow \bar{D}_s^0 K^+ K^-$*, Phys. Rev. Lett. 109 (2012) 131801 [arXiv:1207.5991].

[19] T. Sjöstrand, S. Mrenna, and P. Skands, *PYTHIA 6.4 physics and manual*, JHEP 05 (2006) 026 [arXiv:hep-ph/0603175].

[20] I. Belyaev et al., *Handling of the generation of primary events in GAUSS, the LHCb simulation framework*, Nuclear Science Symposium Conference Record (NSS/MIC) IEEE (2010) 1155.

[21] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. A462 (2001) 152.

[22] P. Golonka and Z. Was, *PHOTOS Monte Carlo: a precision tool for QED corrections in Z and W decays*, Eur. Phys. J. C45 (2006) 97 [arXiv:hep-ph/0506026].

[23] GEANT4 collaboration, J. Allison et al., *Geant4 developments and applications*, IEEE Trans. Nucl. Sci. 53 (2006) 270; GEANT4 collaboration, S. Agostinelli et al., *GEANT4: A simulation toolkit*, Nucl. Instrum. Meth. A506 (2003) 250.

[24] M. Clemencic et al., *The LHCb simulation application, GAUSS: design, evolution and experience*, J. of Phys.: Conf. Ser. 331 (2011) 032023.

[25] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification and regression trees*. Wadsworth international group, Belmont, California, USA, 1984.

[26] LHCb collaboration, R. Aaij et al., *First evidence for the annihilation decay mode $B^+ \to D^+_s \phi$*, JHEP 02 (2013) 43 [arXiv:1210.1089].

[27] LHCb collaboration, R. Aaij et al., *First observations of $B^0 \to D^+ D^-, D^+_s D^- \text{ and } D^0 \bar{D}^0$ decays*, Phys. Rev. D87 (2013) 092007 [arXiv:1302.5854].

[28] M. Pivk and F. R. Le Diberder, *sPlot: a statistical tool to unfold data distributions*, Nucl. Instrum. Meth. A555 (2005) 356 [arXiv:physics/0402083].

[29] M. Feindt and U. Kerzel, *The NeuroBayes neural network package*, Nucl. Instrum. Meth. A559 (2006) 190.

[30] LHCb collaboration, R. Aaij et al., *Observation of CP violation in $B^\pm \to DK^\pm$ decays*, Phys. Lett. B712 (2012) 203 [arXiv:1203.3662].
[31] W. D. Hulsbergen, Decays chain fitting with a Kalman filter, Nucl. Instrum. Meth. A552 (2005) 566, arXiv:physics/0503191.

[32] Particle Data Group, J. Beringer et al., Review of particle physics, Phys. Rev. D86 (2012) 010001.

[33] LHCb collaboration, Studies of beauty baryons decaying to $D^0\pi^−$ and $D^0pK^−$, LHCb-CONF-2011-036.

[34] LHCb collaboration, R. Aaij et al., Measurement of the fragmentation fraction ratio $f_s/f_d$ and its dependence on $B$ meson kinematics, JHEP 04 (2013) 1, arXiv:1301.5286.

[35] LHCb collaboration, R. Aaij et al., Measurement of $b$-hadron branching fractions for two-body decays into charmless charged hadrons, JHEP 10 (2012) 37, arXiv:1206.2794.

[36] LHCb collaboration, R. Aaij et al., First observation of $B_s^0 \rightarrow D_{s2}^{*+} X \mu^−\bar{\nu}$ decays, Phys. Lett. B698 (2011) 14, arXiv:1102.0348.

[37] T. Skwarnicki, A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances, PhD thesis, Institute of Nuclear Physics, Krakow, 1986, DESY-F31-86-02.