

# CP-Averaged Branching Fractions for $B^0 \rightarrow D^- h^+$ with Leptonic Normalisation in LHCb Run-3 – Final Report

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This analysis presents a stable measurement of the CP-averaged branching fractions for the tree-dominated decays  $B^0 \rightarrow D^- h^+$ ,  $h \in (\pi, K)$  using Run-3 LHCb data at  $\sqrt{s} = 13.6$  TeV that remains below QCDF expectations and that supports the existing  $b \rightarrow c\bar{u}q$  tension. Simultaneous maximum-likelihood invariant-mass fits extract the charge-inclusive yields, which are then normalised by the semi-leptonic  $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$  to obtain the following results

- $\bar{B}(B^0 \rightarrow D^- \pi^+) = (2.614 \pm 0.003_{\text{stat}} \pm 0.098_{\text{ext}}) \times 10^{-3}$
- $\bar{B}(B^0 \rightarrow D^- K^+) = (2.363 \pm 0.010_{\text{stat}} \pm 0.089_{\text{ext}}) \times 10^{-4}$ ,
- $R_{K/\pi} = 0.09040 \pm 0.00039_{\text{stat}} \pm 0.00231_{\text{ext}}$

The  $DK$  results lie  $2.61\sigma$  above the global average and Belle 2022 measurements, and the  $D\pi$  lies within  $0.82\sigma$  and  $0.96\sigma$ , respectively. However, both remain  $3.60\sigma$  and  $6.16\sigma$  below the QCDF estimate.

## I. Introduction

Flavour physics describes transitions between different quark species, and measurements of these processes are among the strongest tests of the incomplete Standard Model (SM). In the quark sector, charged-current weak interactions are governed by the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which sets the relative amplitude at which up- and down-type quarks change flavour and contains the only irreducible complex phase responsible for charge-parity (CP) violation within the SM [1, 2, 3]. Weak heavy-flavour decays are sensitive to both the CKM structure of the underlying transition and to the strong interaction that determines how the quarks reorganise into the experimentally observable

final-state hadrons. In current experiments, precise measurements of charge-parity (CP) asymmetries, decay rates, and oscillations of beauty mesons ( $B$ ) are used to probe the reliability of the CKM flavour description and the hadronic QCD framework [3]. The Particle Data Group (PDG) emphasises that improving the precision of these measurements across the sector is essential for validating the SM and constraining possible beyond-the-SM (BSM) physics. [3] At the same time, as postulated by Sakharov, CP violation is necessary for baryogenesis [4], yet the amount of CP violation from the CKM mechanism is too small to explain the observed matter-antimatter asymmetry in the Universe.

Among these processes, the colour-allowed  $B^0 \rightarrow D^- h^+$  decays with  $h = (\pi, K)$  are especially useful because they are dominated by  $b \rightarrow c\bar{u}q$  tree-level transitions, where  $q = d, s$ , and in the heavy quark limit belong to one of the theoretically cleanest classes of non-leptonic tree-level  $B$  decays [5, 6]. For this channel, QCD factorisation (QCDF) predicts that the decay amplitude is the product of a short-distance coefficient, the decay constant of the emitted light meson, and a  $B \rightarrow D$  form factor, with all remaining non-factorisable residuals absorbed into an effective coefficient  $a_1$  [5]. Earlier analyses generally concluded that this factorisation framework provided a good description of the colour-allowed decays  $B \rightarrow Dh$  without revealing large non-factorisable  $SU(3)$ -breaking effects within the available precision [6]. In charged-conjugate notation, CLEO measured  $\mathcal{B}(\bar{B}^0 \rightarrow D^+ \pi^-) = (26.8 \pm 1.2 \pm 2.4 \pm 1.2) \times 10^{-4}$  while Belle found the ratio  $\mathcal{B}(\bar{B}^0 \rightarrow D^+ K^-)/\mathcal{B}(\bar{B}^0 \rightarrow D^+ \pi^-) = 0.068 \pm 0.015 \pm 0.007$  [7, 8]. In this picture,  $a_1$  is expected to be close to unity, so these decays provide a clean probe of the QCDF framework when compared with precise branching-fraction measurements.

However, as theoretical descriptions and experimental results have improved, tension between the two has emerged, defining the form of the  $b \rightarrow c\bar{u}q$  anomaly [9, 10, 11]. The QCDF framework began to incorporate semi-leptonic form factors and better treatments for perturbative corrections [9]. The corresponding modern Belle measurements by themselves do not indicate a sharp inconsistency as the tensions are a discrepancy with the sharpened theoretical predictions and not with other measurements; the branching fractions have only shifted downward by about 7.5% or by  $0.65\sigma$  relative to the CLEO/Belle era averages, while the ratio has increased by about 20.4%, corresponding to  $0.83\sigma$  [12]. In a global average analysis, the clearest branching-fraction discrepancy is in  $\bar{B}^0 \rightarrow D^+ K^-$ , with the QCDF expectations  $(3.26 \pm 0.15) \times 10^{-4}$ ,  $(3.48_{-0.28}^{+0.14}) \times 10^{-4}$  [10, 11] following the above descriptions in order. The experimental average is  $(2.05 \pm 0.08) \times 10^{-4}$  [13], which is consistent with the recent Belle measurement [12], and gives a  $7.1\sigma$  and  $4.9\sigma$  discrepancy,

respectively [10, 11]. The same pattern appears for the effective coefficients  $a_1(Dh)$  in the  $D\pi$  and  $DK$ , in which theoretical expectations are  $1.073^{+0.005}_{-0.010}$  and  $1.075^{+0.007}_{-0.011}$  but experimental measurements are  $0.88 \pm 0.04$  and  $0.92 \pm 0.04$ , which correspond to differences 18.0% and 14.4%, respectively [10]. In general, this pattern, in which expectations for the decays increased while the measured rates remained systematically lower, is observed throughout the  $b \rightarrow c\bar{u}q$  channel, but in this analysis the focus is entirely on the pseudoscalar system [9, 10, 14, 11].

There are three main ways to interpret this observed discrepancy; however, this analysis will not determine which explanation is correct. The first is the presence of an unaccounted-for systematic experimental effect, which is not favoured, as the tension has been observed across global experiments and is not particular to the LHC or a single analysis [7, 15, 12]. The second is possible genuine BSM effects that modify the leading-order  $b \rightarrow c\bar{u}q$  amplitudes and have been investigated in both weak-effective-theory fits and simple new-particle mediator models. Finally, a more conservative possibility is that the strong-interaction uncertainties have been underestimated, particularly in finite-mass effects, QCD-based soft-gluon terms and form factors used to normalise non-leptonic rates [9, 10, 14]. Recent global studies have shown that explaining the anomaly solely through SM perturbations would require shifts far larger than currently estimated within the soft-gluon range, but an  $SU(3)$  analysis indicates that the symmetry breaking can accommodate the observed patterns [11, 14].

The goal of this dissertation is to directly improve the experimental CP-averaged branching fraction inputs  $\bar{\mathcal{B}}(B^0 \rightarrow D^- h^+)$  for pseudoscalar channels using Run-3 LHCb data. This measurement can be used to test whether the system exhibits the same branching fraction and  $a_1$  pattern observed in the  $b \rightarrow c\bar{u}q$  decays. The timing is particularly favourable because to get a more precise measurement, the statistical uncertainty that scales as  $1/\sqrt{N}$  needs to be reduced, and Run 3 is particularly advantageous in this respect. The LHCb Upgrade 1 fully renewed the detector with a software-based trigger, enabling it to operate at an instantaneous luminosity approximately 5 times that of previous runs, thereby providing higher statistical precision and tighter control of the underlying systematic effects [16]. The LHCb experiment was further optimised to reconstruct beauty-hadron decays through improved tracking, vertexing, and hadron-identification systems, which is especially important for fully hadronic  $B^0 \rightarrow D^- h^+$  decays that require precise  $\pi/K$  separation and displaced-vertex reconstruction to improve efficiency and background control [16, 17]. These measurements require invariant-mass fits to



Figure 1: Tree-level external- $W$  emission topologies for  $\bar{B}^0 \rightarrow D^+ h^-$ .

extract signal yields, which are then normalised to a clean semi-leptonic control mode  $B^+ \rightarrow J/\psi K^+$  that does not share the underlying anomaly and can now be efficiently selected with the fully software-based trigger [16].

## II. Theory

This section reviews the quark-level structure, the tree-level topology and the weak-interaction description of  $B^0 \rightarrow D^- h^+$  modes with  $h = (\pi, K)$ , the factorisation picture used to compute their amplitudes and rates, and the definition of CP-averaged branching fractions that are measured in this analysis. For convenience, the weak effective Hamiltonian is written for a decaying  $b$  quark, so the charge-conjugate amplitudes are used  $\bar{B}^0 \rightarrow D^+ h^-$ . The reconstructed modes  $B^0 \rightarrow D^- h^+$  used for the processes follow by charge conjugation, and all branching fractions are assumed to be CP-averaged.

### A. The tree-level topology and QCD factorisation for $B \rightarrow Dh$

The relevant valence-quark content is  $\bar{B}^0 = b\bar{d}$ ,  $D^+ = c\bar{d}$ ,  $\pi^- = d\bar{u}$ ,  $K^- = s\bar{u}$ . At the quark level, the underlying charged-current interaction for  $B^0 \rightarrow D^- h^+$  is  $b \rightarrow c\bar{u}q$  where  $q = d, s$ , mediated by a virtual  $W^-$  gauge boson. The dominant mechanism in the nonleptonic  $B$  decays follows the colour-allowed external- $W$  emission tree topology, where the bottom quark  $b$  emits a virtual  $W^-$  boson that weakly transitions to a charm quark  $c$ , while the spectator down antiquark  $\bar{d}$  combines with the charm quark to form the  $D^+$  meson. The virtual  $W^-$  subsequently materialises as  $\bar{u}q$ , and then hadronises into the emitted light meson  $\pi^-$  or  $K^-$ , as seen in Figure 1.

For the specific final state  $D^+ h^-$ , the decay is dominated by the above topology, and there are no secondary tree-level contributions that involve the same quark contents of the mesons. Weak-exchange or annihilation topologies would require the spectator quark to contribute in the weak interaction and are therefore expected to be suppressed by a power of  $\Lambda_{\text{QCD}}/m_b$ . Loop-level penguin operators also do not provide a sufficiently strong

leading amplitude to compete with the tree-level contribution in  $b \rightarrow c\bar{u}q$ . Overall, these hadronic processes are one of the cleanest classes of non-leptonic  $B$  decays. [5, 18, 9].

The strength of the  $b \rightarrow c\bar{u}q$  transition is determined by the elements of the CKM matrix  $V$ , a  $3 \times 3$  unitary matrix that relates the quark mass and weak-interaction eigenstates. The coupling of  $b$  to  $c$  via a charged-current interaction is denoted by  $V_{cb}$ , while  $V_{ud}$  and  $V_{us}$  describe the corresponding couplings of an up quark to a down or strange quark, respectively. The CKM factors that describe the amplitudes of the relevant decays for this analysis are thus  $V_{cb}V_{ud}^*$  for  $D^+\pi^-$  final state and  $V_{cb}V_{us}^*$  for  $D^+K^-$ . Unitarity,  $V^\dagger V = I$ , implies several closed triangle relations in the complex plane, most commonly  $V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0$  whose sides and angles are physical observables, determined by various weak decays. Since  $|V_{us}| < |V_{ud}|$ , the kaon mode is Cabibbo-suppressed relative to the pion mode even before hadronic effects are taken into account, just by the smaller magnitude of its CKM factor [1, 2, 3].

At energy scales  $\mu$  well below  $W^-$  mass  $m_W \sim 80$  GeV, the resulting weak interaction is described locally by the effective Hamiltonian obtained by integrating the heavy fields, which is a sum of four-quark operators, multiplied by Wilson coefficients  $C_1$  and  $C_2$  [5].

$$\mathcal{H}_{\text{eff}}^{b \rightarrow c\bar{u}q} = \frac{G_F}{\sqrt{2}} V_{cb}V_{uq}^* [C_1(\mu)O_1^q(\mu) + C_2(\mu)O_2^q(\mu)] + \text{h.c.}, \quad (1)$$

where low-energy QCD contributions are contained in the operators in the standard basis,

$$O_1^q = (\bar{c}_\alpha b_\beta)_{V-A} (\bar{q}_\beta u_\alpha)_{V-A}, \quad O_2^q = (\bar{c}_\alpha b_\alpha)_{V-A} (\bar{q}_\beta u_\beta)_{V-A} \quad (2)$$

with left-handed weak current  $(\bar{q}_1 q_2)_{V-A} \equiv \bar{q}_1 \gamma_\mu (1 - \gamma_5) q_2$  and colour indices  $\alpha, \beta$  [5].

Historically, to evaluate hadronic matrix elements of the four-quark operator, an approximation to two simpler current matrix elements was used, one describing the  $B \rightarrow D$  transition and another quantifying the creation of the light meson from the vacuum [19]. For  $\bar{B}^0 \rightarrow D^+ h^-$  transitions, this naive picture can be justified in the heavy-quark limit  $m_b \gg \Lambda_{\text{QCD}}$  using QCDF such that low-energy physics is contained in the decay constant  $f_h$  of the emitted bachelor hadron and the form factor, while high-energy QCD corrections are absorbed into a computable coefficient such as  $a_1$  [5, 18].

For the pseudoscalar modes, the tree amplitude may be schematically factorised as

$$\mathcal{A}(\bar{B}^0 \rightarrow D^+ h^-) = i \frac{G_F}{\sqrt{2}} V_{cb}V_{uq}^* a_1(Dh) f_h (m_B^2 - m_D^2) F_0^{B \rightarrow D}(m_h^2), \quad (3)$$

where  $F_0^{B \rightarrow D}$  is the scalar form factor and  $a_1(Dh)$  is the effective coefficient [5, 9]. Finally, the residual non-factorisable physics enter as smaller corrections in  $\alpha_s$  and  $\Lambda_{\text{QCD}}/m_b$ .

Eq. (3) makes the dominant contributions of the hadronic modes obvious. In the simplest approximation, the smaller  $DK$  rate is driven by the CKM suppression  $|V_{us}| < |V_{ud}|$ , with small corrections from differences in form factors, kinematics, and decay constants. Since the tree-level amplitude dominates and other topologies are suppressed, measurements of the branching fractions provide a clean test of how accurately QCDF describes the non-leptonic decays [5, 18, 9]. The recent global measurements and QCDF calculation described in Sect. I have demonstrated an anomaly between the two rates in  $b \rightarrow c\bar{u}q$  decays, and the CP-averaged branching fractions in this analysis are used as experimental input for comparison with those results [9, 10, 12, 20, 11].

## B. Branching fractions and fragmentation fractions

For any decay channel  $f$ , the branching fraction is defined as the ratio of the partial decay width  $\Gamma(B \rightarrow f)$  to the total width of the parent hadron  $\Gamma_{\text{tot}}$  [3]. The reconstructed data used in this analysis are charge-inclusive; thus, individual  $B^0$  and  $\bar{B}^0$  decays are not separated, and the relevant observable is the CP-averaged branching fraction.

$$\bar{\mathcal{B}}(B^0 \rightarrow D^- h^+) \equiv \frac{1}{2} [\mathcal{B}(B^0 \rightarrow D^- h^+) + \mathcal{B}(\bar{B}^0 \rightarrow D^+ h^-)]. \quad (4)$$

Additionally, possible corrections from  $B^0$ - $\bar{B}^0$  are neglected, since the effective decay-time acceptance of the LHCb detector is lower than the  $B_0$  lifetime. The branching fractions are fully time-integrated, and any residual effects from such mixing are insignificant compared to the current systematic uncertainties.

Experimentally,  $\mathcal{B}$  is measured through the relation to the yields

$$N_f = N_{b\bar{b}} f_q \mathcal{B}(B_q \rightarrow f) \left( \prod_i \mathcal{B}_i \right) \varepsilon_f, \quad (5)$$

where  $N_{b\bar{b}}$  is the number of  $b\bar{b}$  produced,  $f_q$  is the fragmentation fraction,  $\mathcal{B}_i$  are the daughter branching fractions, and  $\varepsilon_f$  is the total efficiency. For the respective signal and normalisation channels used in this dissertation,

$$N_{Dh} = N_{b\bar{b}} f_d \bar{\mathcal{B}}(B^0 \rightarrow D^- h^+) \mathcal{B}(D^- \rightarrow K^+ \pi^- \pi^-) \epsilon_{Dh}, \quad (6)$$

$$N_{J/\psi K} = N_{b\bar{b}} f_u \mathcal{B}(B^+ \rightarrow J/\psi K^+) \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) \epsilon_{J/\psi K}. \quad (7)$$

Taking the ratio of these yields, rearranging and cancelling  $N_{b\bar{b}}$  gives

$$\overline{\mathcal{B}}(B^0 \rightarrow D^- K^+) = \mathcal{B}(B^+ \rightarrow J/\psi K^+) \frac{f_u}{f_d} \frac{N_{DK}}{N_{J/\psi K}} \frac{\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)}{\mathcal{B}(D^- \rightarrow K^+ \pi^- \pi^-)} \frac{1}{\epsilon(h)}, \quad (8)$$

where the relative efficiency is defined as

$$\epsilon_{\text{rel}}(h) \equiv \frac{\epsilon_{Dh}}{\epsilon_{J/\psi K}} \equiv \frac{\epsilon(B^0 \rightarrow D^- h^+)}{\epsilon(B^+ \rightarrow J/\psi K^+)} \quad (9)$$

The inputs for Eq. (8) are the PDG world-average branching fractions [13]:

- $\mathcal{B}(B^+ \rightarrow J/\psi K^+) = (1.026 \pm 0.031) \times 10^{-3}$ ,
- $\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) = (5.93 \pm 0.06) \times 10^{-2}$ ,
- $\mathcal{B}(D^- \rightarrow K^+ \pi^- \pi^-) = (9.38 \pm 0.16) \times 10^{-2}$ ,

The fragmentation fractions  $f_u$  and  $f_d$  denote the probability that the produced  $b$  hadronise into the  $B^+$  and  $B^0$  mesons, respectively, and their ratio  $f_u/f_d = 1.00 \pm 0.02$  expected under isospin symmetry and other kinematic dependences [21, 22]. Additionally, the run ranges for the signal and normalisation candidate collections differ, so  $N_{J/\psi K}$  needs to be rescaled to the effective luminosity-scaled control yield  $N_{J/\psi K}^{\text{eff}}$ . Finally, the only remaining inputs to the equation are the three yields and their corresponding efficiency.

### III. Detector

#### A. LHC complex, LHCb design and its components

The setup used to collect the data comprises the accelerator complex and the LHCb detector used in Run-3, which is suitable for precisely measuring  $\mathcal{B}(B^0 \rightarrow Dh)$ .

During Run-3, protons are accelerated through CERN's injector chain into the Large Hadron Collider (LHC), delivering proton-proton collisions at a chosen centre-of-mass energy of  $\sqrt{s} = 13.6$  TeV, which provide large beauty-flavour production cross-sections [23, 24, 17]. At these energies, the collisions create several heavy-quark pairs via gluon-gluon fusion, and in such a high-occupancy environment, the detector must distinguish and reconstruct  $B$ -hadron decays while suppressing significant combinatorial backgrounds from unrelated tracks that can mimic genuine signal events.

The LHCb is a  $b$ - and  $c$ -hadron detector, designed as a single-arm forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$  [17]. The detector is built as a forward spectrometer because  $b\bar{b}$  pairs are boosted along the beam direction in the laboratory frame,

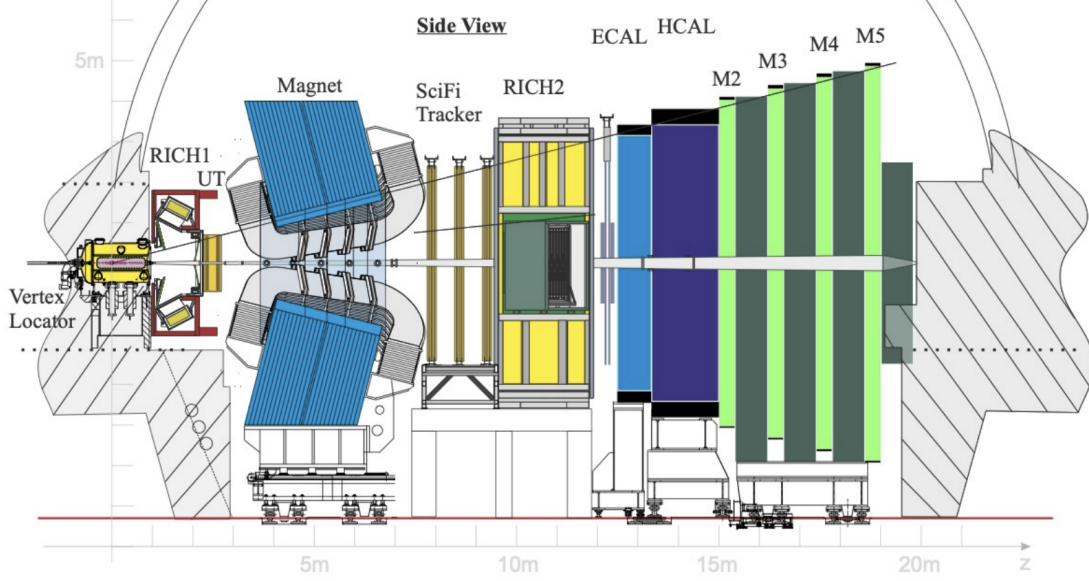


Figure 2: Schematic view of the LHCb single-arm forward spectrometer in Run-3 [16].

resulting in a forward-peaked hadron distribution, as heavy flavours are produced at small angles to the beam. LHCb is designed to measure rare heavy-flavour hadron processes together with CP violation. Therefore, its forward acceptance (the covered phase-space region) allows LHCb to record a large fraction of beauty hadrons while maintaining precise vertexing, momentum measurement, and particle identification (PID) [17].

The detector incorporates various components, as illustrated in Fig. 2. Particles produced at the interaction point are first measured by the vertex locator (VELO), which delivers a precise reconstruction of the  $pp$  primary vertex (PV) as well as the displaced secondary vertices (SV) of long-lived beauty-flavour hadrons with measurable lifetimes. Charged particles traverse the Upstream Tracker (UT) and are then deflected by a dipole magnet toward the three downstream SciFi trackers, which together determine the momentum from the curvature of their trajectories in the magnetic field. The two Ring-Imaging Cherenkov (RICH) detectors identify hadrons by measuring Cherenkov angles with different radiators, and the calorimeters (ECAL for electromagnetic and HCAL for hadronic particles) measure and identify energies of hadrons, electrons, and photons using particle showers. Muons are detected by dedicated muon detectors placed behind absorber materials, which is important for the normalisation channel [17, 16].

Upgrades to the detector were carried out during the second long shutdown (LS2) to fully exploit the higher luminosity provided by the LHC during Run-3 [16]. Crucially, all subsystems employed a triggerless readout architecture, selecting events solely through software at a bunch-crossing rate of 40 MHz [16], with real-time decay reconstruction to improve the flexibility and quality of event selection. The complete redesign

of the hardware-based Level-0 trigger removed limitations imposed by previous trigger thresholds and boosted statistical precision by increasing signal yields and efficiencies, particularly for hadronic modes [16]. Before the upgrade, large fractions of raw detector information were stored and later reconstructed separately; however, this became infeasible at the increased rates due to storage constraints. To resolve this issue, the new software trigger works in two stages: first, a high-rate trigger (HLT1) selects possible candidate events via fast tracking and pattern recognition of PVs using a small set of measurements. These accepted events are buffered while the calibration and alignment constants are derived. Second, a slower reconstructor (HLT2) takes the selected events as input to determine which real candidates are assembled using additional measured parameters [16]. With the upgrade, only reconstructed decays and their corresponding observables are stored, so the ROOT files used in this analysis contain candidate-level quantities rather than raw information. To secure compatibility with increased occupancy and new architecture, the VELO, trackers and RICH detectors were also improved [16]. Overall, this increases LHCb’s sensitivity to CP-violating processes and unusual decays.

The VELO enables reconstruction of the initial proton intersection and subsequent SV from decays of produced heavy-flavour hadrons, which travel a few millimetres in the lab frame before decaying due to their lifetimes. For  $B$ -physics analysis, these vertices must be precisely separated to suppress combinatorial background using an accurately measured distance. The system was replaced during LS2, resulting in improvements in radiation tolerance, spatial resolution, mechanical stability, cooling, and precision in track-position measurement. The upgraded VELO has a spatial resolution of approximately  $5\text{ }\mu\text{m}$ , supporting precise vertexing, decay-time measurements, and impact-parameter measurements needed for lifetime and time-based analyses [25, 26]. The detector maintained stable performance through Run-3, with excellent vertexing efficiency and impact-parameter resolution despite increased track multiplicities [26, 27]. High-resolution vertices are essential for hadronic selection to reject background, so VELO enhancements directly affect systematic uncertainty in branching-fraction measurements and stability of fitted yields.

High track multiplicities, with numerous charged-particle tracks, require efficient trackers capable of robust pattern recognition and high efficiency across LHCb’s acceptance. The new Upstream Tracker (UT), located upstream of the dipole magnet, and the Scintillating Fibre Tracker, downstream, are used to track the trajectories of such charged particles using their Lorentz curvature and accommodate the increased occupancies from higher luminosity [28]. The UT determines track parameters and improves pattern recog-

nition prior to the magnet, while the three SciFis complete trajectory determination. A 4 Tm magnet bends charged particle paths for good momentum resolution across the required kinematic range [16, 29]. Refined resolution directly narrows the  $B$ -mass peak and is necessary to separate the signal from the background in hadronic invariant-mass fits [17, 16, 29]. Tracking efficiency significantly affects the relative efficiency factor in Eq. 8, making it essential for systematic control.

Efficient kaon-pion separation is required for measuring  $B^0 \rightarrow D\pi$  and  $B^0 \rightarrow DK$  decays, as these modes share topologies but differ by the bachelor hadron. Incorrect identification results in cross-feed between channels, distorting invariant-mass spectra. The two RICH detectors achieve this separation by measuring Cherenkov angles from charged particles passing through radiators, ensuring  $\pi/K/p$  discrimination over a wide momentum range. RICH1, using  $C_4F_{10}$ , is placed upstream, and RICH2, with  $CF_4$ , extends coverage to higher momenta downstream [30]. PID is summarised by variables such as PIDK, which represents the difference in logarithmic likelihood between the hypotheses during reconstruction; positive values indicate more kaon-like tracks. [17, 31]

Muons are identified by matching reconstructed tracks with hits in downstream muon detectors located behind absorber material. Most hadrons shower before reaching the muon stations, whereas muons traverse them and leave identifiable signatures. This method improves the resolution of the  $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$  peak by strongly suppressing hadronic backgrounds, providing a clean control sample for yield normalisation and mass calibration. Such detectors play a limited role in  $D\pi$  and  $DK$  modes, but are important for overall event reconstruction and the LHCb experiment as a whole [32, 16].

## B. Initial online selections and observables

For this analysis, the observables used for yield extraction and offline selection are derived directly from all detector components. The hadronic candidates are formed by combining four charged tracks (two  $\pi^-$ , one  $K^+$ , the bachelor  $h^+$ ), first fitting a third displaced charm vertex  $D^- \rightarrow K^+\pi^-\pi^-$  to its three corresponding tracks, and then combining this  $D^-$  candidate with the bachelor track to reconstruct the initial  $B^0$  decay SV. Each track's momentum is obtained from its curvature in the magnetic dipole field using the specific tracking detectors. In contrast, the PV and SV positions and their uncertainties are obtained from vertex fits, with VELO dominating the resolution. From fitted momenta, invariant masses  $m(D)$  and  $m(B)$  are measured by assigning a mass hypothesis to specific

tracks and are mainly influenced by tracking performance and momentum calibration.

Several vertex-related observables are used to assess topological consistency and suppress combinatorial backgrounds, both of which are strongly affected by VELO performance. The vertex qualities  $\chi_D^2/\text{dof}$ ,  $\chi_B^2/\text{dof}$  are produced by the vertex fitter to quantify whether the input and output tracks originate from a single point. The flight distance is calculated by the displacement vector  $\vec{x}_{\text{SV}} - \vec{x}_{\text{PV}}$ , and its significance  $FD\chi^2$  determines how far the hadrons have travelled from the PV before they decay. The significance of the impact parameter  $IP\chi^2$  measures the distance of closest approach between the candidate trajectory and the PV. The *DIRA* pointing requirement is the cosine of the angle between the  $B$  momentum and its flight direction, which should be close to unity for true decays.

Finally, events are classified as  $D\pi$  or  $DK$  using the RICH likelihood PID response on the bachelor track, with explicit PID requirements on the daughter tracks to enforce the second  $D$  decay topology [17, 31, 33]. The resulting samples are stored in blocks corresponding to the present experimental conditions and used to construct binned  $m(B)$  spectra for the invariant-mass fits. The only differences between them are their assigned bachelor mass hypothesis and PID. The magnet’s dipole field can be reversed to probe detector asymmetries, thereby flipping the track-bending direction through various regions of the spectrometer. In the normalisation channel, candidates are formed by combining two oppositely charged muon tracks into the common  $J/\psi \rightarrow \mu^+\mu^-$  vertex, which are then combined with a bachelor kaon track to reconstruct the  $B^+$  decay SV. Observables similar to those in the hadronic channels are measured in this process [32].

## IV. Method

The primary objective of this analysis is to measure the branching fractions  $\bar{\mathcal{B}}(B^0 \rightarrow D^- h^+)$  for  $h = (\pi, K)$  using Run-3 data. Stable signal yields are extracted from hadronic decay channels and normalised through the high-purity control mode  $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ . Implementing a fully software-based trigger facilitates the use of the normalisation channel, thereby avoiding hadronic normalisations that share the same  $b \rightarrow c\bar{u}q$  dynamics as the signal [16]. Any effect of neutral-meson mixing in the  $B^0$ - $\bar{B}^0$  system is neglected, since the measurements are fully time-integrated. Furthermore, the yields are charge-inclusive, resulting in CP-averaged branching fractions.

In practice, the normalisation relation in Eq. (8) reduces the measurement to a limited set of experimental inputs: the fitted signal yields  $N_{D\pi}$  and  $N_{DK}$ , the fitted control-

| Sample block                            | Run range                   | Runs | Raw total | Selected total |
|-----------------------------------------|-----------------------------|------|-----------|----------------|
| Block 7 down: $D\pi$                    | 307589 $\rightarrow$ 308098 | 509  | 1,956,966 | 987,426        |
| Block 7 down: $DK$                      | 307589 $\rightarrow$ 308098 | 509  | 543,117   | 122,937        |
| Block 8 up: $D\pi$                      | 308104 $\rightarrow$ 308540 | 436  | 1,179,814 | 593,751        |
| Block 8 up: $DK$                        | 308104 $\rightarrow$ 308540 | 436  | 327,189   | 73,521         |
| $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ | 320529 $\rightarrow$ 321444 | 915  | 719,129   | 297,512        |

Table 1: Run ranges and event counts from preselection and offline cuts

channel yield  $N_{J/\psi K}$  evaluated at the same effective luminosity, and the corresponding relative efficiencies  $\epsilon_{\text{rel}}$  between the hadronic and semi-leptonic modes. The main experimental challenge is the cross-feed between the  $D\pi$  and  $DK$  selections, which arises from the misID of the bachelor hadron. Since both modes share the same topology, the hadronic mass fits explicitly include a misID component alongside the signal peak, combinatorial background, and partially reconstructed backgrounds. The signal yields are extracted using binned extended maximum-likelihood fits to the reconstructed  $B$ -candidate mass  $m(B)$ . Three complementary fit configurations are used: two separate individual fits provide a baseline validation and a set of initial conditions; a simultaneous two-channel fit takes advantage of the shared peak parameters of the core signal ( $\mu, \sigma$ ); and a simultaneous four-category fit, split by magnet polarity, tests the stability of the model in the subdivision of the data set.

### A. Datasets and their final offline selections

The analysis is based on  $pp$  collision data at  $\sqrt{s} = 13.6$  TeV, collected by the LHCb detector as described in Sect. III.B.. Candidate samples reconstructed by the fully software trigger are split into three ROOT datafiles according to the final-state hypothesis from PID acquired by the RICH and muon detectors: two hadronic signal modes  $B^0 \rightarrow D^-(K^+\pi^-\pi^-)h^+$  and a normalisation mode  $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ . [34, 31]

Both hadronic channels use identical reconstruction and offline selection frameworks and share the same run-number windows, as shown by Table 1, thereby preserving consistent detector conditions. In addition, both the  $D\pi$  and  $DK$  files are split by the magnet polarity of their measurement block, allowing explicit probing of residual or RICH PID-related differences, which are more relevant in the  $DK$  sample. They can also be used in the polarity-split stability tests described later, but when combined, the overall distortions should partially cancel.

Several offline cuts are applied to both samples to further suppress the combinatorial

background while retaining high signal efficiency prior to fitting, reducing the number of candidates by 49.6% for the  $D\pi$  samples and by 77.4% for the  $DK$  samples. The charm candidate is constrained to be consistent with a real  $D^- \rightarrow K^+\pi^-\pi^-$  decay by tightly restricting the  $D^-$ -mass within 20 MeV/ $c^2$  of its known mass 1869.65 MeV/ $c^2$  to reduce random combinations of three-track decays. Further topological cuts exploit the displaced nature of  $b$ -hadron decays. Candidates are required to have a large flight-distance significance  $FD\chi^2$  to take advantage of the significant lifetime of  $B$ ; small impact-parameter significance  $IP\chi^2$ , and small vertex-fit quality  $\chi_B^2/\text{dof}$  and  $\chi_D^2/\text{dof}$  to enforce well-constructed vertices. A pointing requirement, expressed through cosine DIRA, is also imposed and should be close to one to enforce consistency between the momentum vector and the direction of flight towards the PV.

Since the two signal modes differ only in the bachelor hadron, the bachelor PID defines the two samples. Pions are selected with  $PIDK < 0$ , and for kaons, a restriction to  $PIDK > 5$  is applied to obtain a cleaner sample with the requirement also applied to the  $D^- \rightarrow K^+\pi^-\pi^-$  final-state tracks to suppress cross-feed from mis-reconstructed charm decays. Beyond these baseline selections, two machine-learning-based multivariate classifier outputs, an MVA and an XGBoost response, are used to further suppress background. Both compute signal-likeness scores, with higher values corresponding to consistent displaced two-vertex  $b \rightarrow c$  decays. The final working point is then selected using a one-dimensional Punzi-type figure-of-merit scan over the cut response.

$$\mathcal{F} = \frac{S}{a/2 + \sqrt{B}}, \quad (10)$$

where  $S$  is estimated by a signal proxy window around the  $m(B^0)$  peak and  $B$  from sideband regions scaled into the signal window. The final offline requirements are chosen to maximise  $\mathcal{F}$  while maintaining stable fit behaviour and are displayed in Table 2.

In contrast, the high-purity control mode  $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$  is taken from a different, shorter run period. The control candidates were reconstructed over a shorter data-taking period and must therefore correspond to a smaller integrated luminosity. Thus, for comparison, the fitted yield must be rescaled by a factor of circa 1.039 before entering Eq. (8). Table 3 displays the set of similar baseline selections that is used to obtain an even cleaner channel, reducing the number of candidates by 59.6%. These are constrained to good-quality track and vertex fits, correct muon identification, sufficient transverse momentum  $p_T$  to suppress soft combinatorial contributions, and a  $PIDK > 5$

| Selection applied                   | Requirement                                                                |
|-------------------------------------|----------------------------------------------------------------------------|
| $B^0$ mass range (300 bins)         | $4950 < m(B^0) < 6000 \text{ MeV}/c^2$                                     |
| $D^-$ mass window                   | $ m(D^-) - 1869.65  < 20 \text{ MeV}/c^2$                                  |
| $B^0$ and $D^-$ vertex quality      | $\chi^2/\text{dof} < 10$                                                   |
| $B^0$ flight-distance significance  | $FD\chi^2 > 70$                                                            |
| $B^0$ impact-parameter significance | $IP\chi^2 < 15$                                                            |
| Pointing requirement                | $\text{DIRA} > 0.9995$                                                     |
| MVA multivariate selection          | $\text{MVA} > 0.90$                                                        |
| XGB multivariate selection          | $\text{XGB} > 0.50$                                                        |
| Bachelor PIDK                       | $D\pi$ : $\text{PIDK} \leq 0$ ; $DK$ : $\text{PIDK} \geq 5$                |
| $D$ -daughter PIDK                  | $K^+$ : $\text{PIDK} \geq 5$ ; $\pi^-$ : $\text{PIDK} \leq 0$ (both pions) |
| MisID control PIDK (templates)      | $D\pi$ : $\text{PIDK} \leq -3$ ; $DK$ : $\text{PIDK} \geq 10$              |

Table 2: Final selection used to build the  $B^0 \rightarrow D^- h^+$  mass spectra.

| Selection applied                  | Requirement                                                         |
|------------------------------------|---------------------------------------------------------------------|
| $B^+$ fit window (100 bins)        | $5175 < m(B^+) < 5450 \text{ MeV}/c^2$                              |
| $J/\psi$ mass window               | $ m(J/\psi) - 3096.9  < 80 \text{ MeV}/c^2$                         |
| $B^+$ flight-distance significance | $FD\chi^2 > 100$                                                    |
| $B^+$ vertex quality               | $\chi^2_{B^+}/\text{dof} < 20$                                      |
| Bachelor-kaon PID                  | $\text{PIDK} > 5$                                                   |
| Muon identification                | Muon confirmation and $\text{PID}_\mu > 0$ (both muons)             |
| Track quality                      | $\chi^2/\text{dof} < 10$ for kaon and both muons                    |
| Track transverse momentum          | $p_T(\mu^\pm) > 250 \text{ MeV}/c$ , $p_T(K^+) > 250 \text{ MeV}/c$ |
| Exposure rescaling                 | $N_{J/\psi K}^{\text{eff}} = (951/915) N_{J/\psi K}$                |

Table 3: Final selection used to build the  $B^+ \rightarrow J/\psi K^+$  mass spectra.

kaon-like track.

## B. Misidentification control samples and PID-calibration constraints

The selections  $B^0 \rightarrow D^- \pi^+$  and  $B^0 \rightarrow D^- K^+$  are intrinsically linked by a cross-feed between the samples due to the mistaken identity of the bachelor hadron. A fraction of true  $B^0 \rightarrow D^- \pi^+$  decays is reconstructed in the  $DK$  sample when the bachelor pion is assigned a kaon mass and passes the kaon PID requirement, and vice versa to a lesser extent. These contributions appear as shifted, peak-like distributions and must be explicitly included in the mass model to prevent absorption from other components, as the decays share the same underlying topology.

The misID shapes are constructed from two clean PID-constrained control samples under the opposite bachelor-mass hypothesis. Identical run ranges, kinematic, and topo-

logical requirements are used to reflect the same detector and selections as in the nominal samples and to ensure that the resulting shapes accurately capture the relevant features. The only difference is a tighter bachelor PID region ( $\pi$ :  $PIDK < -5$ ;  $K$ :  $PIDK > 8$ ) used to obtain a purer sample before re-massing to isolate the kinetic distortions. The shifted mass distributions are fitted into finer  $m(B)$  bins and then converted into unit-normalised templates for use as fixed-shape PDFs in simultaneous hadronic fits. By construction, this approach is fully data-driven.

The misID cross-feed components in fits should be constrained in fits, following the standard LHCb PID-calibration procedure, rather than floated independently. At the LHCb, PID efficiencies are derived from dedicated raw data calibration samples, in which the candidate particles of the dedicated channel are fixed from the decay kinematics, prior to the implementation of PID separation by the RICH detector [33]. The measured efficiencies, therefore, provide a data-driven calibration of the PID selection requirements. These are measured in bins of variables that parametrise the PID response, typically including track momentum, pseudorapidity, and occupancy, which are then reweighted to match the kinematics of the desired reference sample [33]. The standard weight for a bin  $i$  is given by

$$w_i = \frac{R_i C}{C_i R}, \quad \bar{\epsilon}_{\text{PID}} = \frac{\sum_i \epsilon_i w_i C_i}{\sum_i w_i C_i}, \quad (11)$$

where  $C_i$  and  $R_i$  denote the count of calibration and reference tracks and  $\epsilon_i$  is the PID efficiency measured for that bin [33]. For this dissertation, the kinematic constraints used to reweight each bin were supplied externally from the corresponding analysis inputs, while the PID efficiencies were obtained from the calibration data and were not derived in this analysis.

The PID efficiencies are used to relate the misID yields from true  $B^0 \rightarrow D^- h$  candidates in the simultaneous fit. The corresponding yields are therefore linked as

$$N_{\text{mis}}^{DK} = N_{\text{sig}}^{D\pi} \frac{\epsilon(\pi \rightarrow K)}{\epsilon(\pi \rightarrow \pi)}, \quad N_{\text{mis}}^{D\pi} = N_{\text{sig}}^{DK} \frac{\epsilon(K \rightarrow \pi)}{\epsilon(K \rightarrow K)}, \quad (12)$$

where the efficiency ratios are taken from PID calibration. In the simultaneous fits, these are implemented as Gaussian constraints in the extended likelihood discussed in Sect. IV.C.. This is done to prevent unnatural normalisations between overlapping background components and to improve the overall stability of the fit.

Additionally, the normalisation channel is validated using the same incorrect bachelor-

mass hypothesis-handling as above. Under the pion hypothesis, the reconstructed mass peak is shifted downwards and broadened, with only a small 3.05% fraction remaining within  $\pm 10 \text{ MeV}/c^2$  of the real  $B^+$  mass signal peak. This behaviour confirms that the re-massing procedure works as expected and that misID  $B^+ \rightarrow J/\psi K^+$  decays are far from the signal peak, preventing significant cross-feed in the sample.

### C. Validation of binned maximum-likelihood fits on histograms

Yield extraction is performed using binned histograms of the reconstructed  $B$ -candidate mass. For hadronic fits, 300 uniform bins are used to cover the fixed range  $4950 < m(B) < 6000 \text{ MeV}/c^2$ , corresponding to a bin width of  $3.50 \text{ MeV}/c^2$ . This was chosen to be smaller than the detector mass resolution for fully reconstructed  $B$  decays,  $\mathcal{O}(20)$ , to avoid over-discretising, but it needs to remain sufficiently large to suppress instabilities arising from low-statistics fluctuations in regions where multiple components overlap. For the control mode  $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ , two binning configurations are used as consistency checks: a wide-range fit in  $5100 < m(J/\psi K) < 5600 \text{ MeV}/c^2$  with 120 bins and a narrower nominal fit in  $5175 < m(J/\psi K) < 5450 \text{ MeV}/c^2$  with 200 bins.

In each bin  $i$ , the observed number of candidates  $n_i$  is Poisson-distributed with expectation  $\nu_i(\theta)$  defined by the integral of the probability density function (PDF) of the model over that bin. The yields are extracted with a binned extended maximum-likelihood fit [35, 36], which consists of minimising the negative logarithmic likelihood

$$-\ln \mathcal{L}(\theta) = -\sum_i \ln \left( \frac{\nu_i(\theta)^{n_i} e^{-\nu_i(\theta)}}{n_i!} \right) \quad (13)$$

so that the fit determines both the component shapes and their total event counts as the yields are entered explicitly. Each component shape is normalised throughout the range so that the expected counts satisfy  $\sum_i \nu_i = \sum_k N_k$ , where  $N_k$  are the component yields. For the simultaneous fits, a Gaussian constraint is enforced with efficiencies determined from PID calibration ratios and thus the full likelihood is constrained to the extended likelihood.

The quality of the fits is assessed through the pull distributions (defined as the Poisson-normalised difference between the observed and expected counts), a diagnostic  $\chi^2/\text{ndf}$  (squared sum of the bins per degree of freedom), and the numerical convergence information returned by *RooFit*, in particular the minimiser status, covariance quality and the estimated distance to the minimum (EDM) [36].

### D. Mass-fit model components

For each hadronic histogram, the reconstructed candidate mass is modelled as a sum of physically motivated components, each represented by a PDF  $S$ , with independent shapes and yield  $N$ . The total extended density model is

$$\mathcal{P}(m) = \sum_{comp} N_{comp} S(m; \theta_{comp}) \quad (14)$$

where each shape term is unit-normalised over the range, and so that  $\int \mathcal{P}(m) dm = \sum_i N_i$ .

The component structure follows the standard LHCb approach for  $B \rightarrow Dh$  mass fits [37, 38]. The signal peak is modelled using a double-sided Crystal Ball (DSCB), consisting of a Gaussian core with asymmetric tails and is flexible enough to capture the detector’s dominant tracking and momentum resolution while remaining robust to the small number of non-Gaussian effects in the tails. On the low-mass side, the signal resolution is degraded primarily by final-state radiation and energy loss. A simple Gaussian could also be used, but doing so typically forces background components in overlapping regions to absorb outliers. The cross-feed from bachelor misidentification is described by the data-driven templates discussed in Sect. IV.B.. The misID contributions appear as shifted, peak-like structures; they can’t be absorbed reliably and must be explicitly included to avoid bias in the yields, particularly for the  $DK$  channel.

The combinatorial background generally arises from random combinations of tracks that satisfy the offline selection requirements, and is modelled with a falling exponential, or, in alternative checks, with a low-order (Chebyshev) polynomial [37]. There is a bias towards candidates built from tracks with moderate kinematics that populate the low-mass region, as heavier candidates require several high-momentum tracks. The exponential provides a stable two-parameter description determined from the sideband regions without introducing unnecessary flexibility. Additionally, partially reconstructed backgrounds arise from real  $b$ -hadron decays that contain at least one undetected final-state particle (a neutral hadron, a photon, or a soft pion). The missing momentum produces broad shapes with a shifted  $m(B^0)$  below the true  $B^0$  mass. These have characteristic endpoints and smoothly extend to the signal peak (4950–5200 MeV/ $c^2$ ), forming features whose shapes depend on the underlying decay topology and the missing particle. In practice, there are several physically motivated parametrisations to account for these, determined by phase space and the masses of intermediate states. In our case, the HILL (smooth shoulders from missing photons) and HORN (pronounced shoulders from missing soft pions) PDFs

provide sufficient flexibility to describe this observed behaviour while remaining stable. The yields are floated in the fit, and the most sensitive shape parameters are taken from the individual fits to reduce degeneracies and improve stability.

For the normalisation channel  $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ , the nominal mode consists of a DSCB to flexibly accommodate the high-statistics core and second-order Chebyshev polynomials rather than an exponential, since there is only mild curvature in the combinatorial background. In the wider-range model, a lower-mass partially reconstructed contribution is additionally fitted by an ARGUS threshold function [39]. This displaced peak, well below the true  $B^+$  mass, is sufficiently separated from the signal to be removed without affecting the nominal signal yield. The agreement between the two configurations confirms that the extracted control yield is not sensitive to the exact fitted range or binning choice.

### E. Fit configurations and yield extraction procedure

The two hadronic selections are coupled by the bachelor's misID, so the spectra cannot be independently treated once PID is applied. For this reason, the nominal yield extraction is performed by using a simultaneous fit to the two channels, allowing the core signal-shape parameters to be shared, while still permitting the background compositions and normalisations to differ.

The hadronic spectra  $B^0 \rightarrow D^-\pi^+$  and  $B^0 \rightarrow D^-K^+$  are first fitted independently after applying the final common selection. These serve two practical purposes. First, they verify that each channel can be well described in isolation by a physically motivated model, so that low-mass regions are absorbed by the partially reconstructed components rather than by signal distortions. Second, they provide stable starting values for simultaneous fits and enable a direct comparison of fitted peak parameters. In each binned extended maximum-likelihood individual fit, the yields of each component (signal  $N_{\text{sig}}$ ; misID  $N_{\text{mis}}$ ; partially reconstructed  $N_{\text{HILL}}$ ,  $N_{\text{HORNS}}$ ; combinatorial  $N_{\text{comb}}$ ) are freely floated, together with the DSCB core parameters ( $\mu, \sigma$ ) and the tail parameters. The shape of the misID is fixed to the data-driven templates described in Sect. IV.B.; however, the yield is unconstrained, allowing the fit to adjust the relative sizes of the cross-feed and the smooth background to provide a baseline description without imposing the PID calibration.

The nominal branching-fraction inputs are then obtained from a simultaneous two-channel fit in which the mean  $\mu$  and width  $\sigma$  of the DSCB are shared between the samples.

Since both samples were reconstructed from the same run ranges and detector conditions, they should share the same dominant mass calibration and resolution. The remaining parameters are channel-specific, if there is a clear physics motivation to stabilise the fit: DSCB tail parameters are floated independently to absorb small non-Gaussian differences between the two bachelor hypotheses; the combinatorial slopes fitted independently to account for different background composition; and the and the partially reconstructed yields are floated separately with their least stable shape parameters fixed from the individual fits to reduce degeneracy in the low mass region.

For the simultaneous fits, the misID treatment is tightened. The shape remains fixed to the data-driven template, but these yields are constrained through Eq. (12). The required efficiency ratios are taken from the PID calibration ratios introduced in Sect. IV.B. and are implemented as Gaussian constraint parameters in the likelihood fits. These stabilise the separation between the true signal and the misidentified candidates, which is particularly important in the  $DK$  spectrum.

In practice, the simultaneous fit is performed in stages to improve numerical stability and convergence of correlated parameters. First, the dominant signals and combinatorial yields  $N_{\text{sig}}$ ,  $N_{\text{comb}}$  are floated to obtain a well-behaved minimum. Subsequently, the remaining yields are released to refine the background normalisations. Finally, the Gaussian constraints from PID calibration are imposed, and a full fit is performed with Hessian error calculations. These fitted results, together with the uncertainties, define the input variables  $N_{D\pi}$  and  $N_{DK}$  used in Eq. (8)

## F. Fit validation and stability checks

The nominal branching fractions are derived from the simultaneous two-channel fit. Robustness is assessed by testing reasonable variations in the fit configurations to ensure convergence is independent of these choices. Stability and reliability are evaluated by repeating the fits under controlled modifications to modelling assumptions and running conditions, verifying that yields and peak parameters remain stable within expected uncertainties. For instance, variations in the fitted mass ranges, number of bins, combinatorial background PDFs, and the fixed/floated parameter choices are a good idea. However, emphasis must be placed on misID components, as they can seriously bias the extracted yield ratios if mismodeled, and on whether the model well represents the system when split by the magnet’s polarity. [34]

The first validation is provided by a four-category simultaneous fit in which data are split by magnet polarity ( $D\pi_{\text{down}}$ ,  $D\pi_{\text{up}}$ ,  $DK_{\text{down}}$ , and  $DK_{\text{up}}$ ) primarily to verify that the mass distributions can fit the same model, and secondarily to test whether any possible polarity-dependent distortions are visible beyond normalisation differences that detector asymmetries could drive. The peak positions of the signal  $\mu$  and the resolution  $\sigma$  are shared, whereas the yield parameters are separated. To quantify the agreement between the samples, a raw magnet-polarity yield asymmetry is defined as

$$A(Dh) \equiv \frac{N_{\text{up}}^{Dh} - N_{\text{down}}^{Dh}}{N_{\text{up}}^{Dh} + N_{\text{down}}^{Dh}}, \quad (15)$$

These are expected to be dominated by differences in sample sizes between the two blocks rather than by genuine distortions. An agreement in the  $\mathcal{O}(1)$  percentage-level asymmetries indicates that splitting the samples only changes the general normalisation, as expected, and does not provide evidence of additional shape biases. This only serves as validation, and no separate systematic uncertainty is assigned to test this if the fitted yields remain consistent within the uncertainty.

A second, more important, dedicated stress test requires changing the data-driven misID template to an analytic DSCB parametrisation, which is weakly constrained to the expected location of the misID component, as discussed at the end of Sect. IV.B.. The three fits above were repeated exactly, using the same selections, structure and staged fitting to assess the model's robustness to differences in compartmental structure. The same PID calibration is applied to the relevant components using Gaussian constraints. This variation isolates the sensitivity of the results to the overlapping misID tails from the data-driven misID. A larger change is expected in the  $DK$  channel as it is more exposed to cross-feed of the high-statistic  $D\pi$  mode. The residual difference between the extracted yields should contribute to the systematic uncertainty associated with the misID modelling.

## G. Efficiency determination

The measurements require the relative efficiency between the hadronic and normalisation modes, as defined in Eq. (9). Generally, each total efficiency factorises into acceptance, reconstruction, offline selection, trigger, and PID contributions ( $\varepsilon = \varepsilon_{\text{acc}} \varepsilon_{\text{trig}} \varepsilon_{\text{reco}} \varepsilon_{\text{sel}} \varepsilon_{\text{PID}}$ ). Most of these factors are presumed to cancel in the first approximation, as all relevant signal and normalisation modes are fully reconstructed charged-track three- or four-track

final state with similar topologies, trigger lines and offline selections. The remaining differences arise mainly from the different final-state particle content and from the tighter kaon–pion separation required in the hadronic channels [17, 16].

The control mode contains two muons and a bachelor kaon, whereas the hadronic mode contains two pions, one kaon from the  $D^-$  decay, and the bachelor hadron. Following the LHCb tracking-performance recommendations, the single-muon tracking efficiency is taken to be  $\varepsilon(\mu) = 0.969$ , as obtained from dedicated muon control samples.[40] The efficiency ratio is simplified by assuming that the pions behave as muons, so that the pion tracking efficiency can be expressed as  $\varepsilon(h) = \varepsilon(\mu) S_h$ , where  $S_h$  is the type-dependent survival factor that is from the proportion of pions and kaons that undergo hadronic interactions in the detector material before reaching the end of the tracing volume. In the fiducial region, circa 15% of pions and 12.7% of kaons interact hadronically before 9410mm, implying  $S_\pi \simeq 0.850$  and  $S_K \simeq 0.873$ . [41]

Under these assumptions, the common efficiency factors cancel, so the dominant efficiency is associated with the bachelor hadron.

$$\varepsilon_{\text{rel}}(h) = \frac{\varepsilon_{\text{sig}}(h)}{\varepsilon_{\text{norm}}} = \frac{\varepsilon(\pi)^2 \varepsilon(K) \varepsilon(h)}{\varepsilon(\mu)^2 \varepsilon(K)} = \frac{\varepsilon(\mu)^3 S_\pi^2 S_h}{\varepsilon(\mu)^2} = \varepsilon(\mu) S_\pi^2 S_h \begin{cases} \varepsilon_{\text{rel}}(\pi) = 1.68 \\ \varepsilon_{\text{rel}}(K) = 1.64 \end{cases} \quad (16)$$

This simplification is not exact, and two key assumptions underlie the construction. Pions are treated as muons, up to an average hadronic survival correction, so that differences across multiple spectral regions are neglected. The bachelor kaon in the control channel appears in the SV, and its kinematics are assumed to have the same tracking efficiency as those of the hadronic daughter kaon that originates from a third vertex. The remaining mismatches in momentum, material interactions, and PID responses are thus propagated into the systematic uncertainty of efficiency.

## H. Branching-fraction calculation and uncertainty treatment

Finally, the CP-averaged branching fractions are obtained from the fitted hadronic signal yields, normalised to the luminosity-scaled effective yield of the control channel. These are then combined with the decay daughter branching fractions, the fragmentation fraction and the relative efficiencies to calculate the branching fraction using Eq. (8).

The statistical uncertainties comprising the fitting methods on the hadronic sample are given by the three yields. Each systematic contribution should then be assigned to

account for any imperfections of the model, such as variations in the misID components, binning, the fit range, and the overall background model, to verify that no instabilities are present. The external uncertainty is taken from the normalisation yields, the relative efficiencies and the external inputs.

## V. Results

This section presents the invariant-mass fitted charge-inclusive yields and the resulting CP-averaged branching fraction  $\overline{\mathcal{B}}(B^0 \rightarrow D^- h^+)$  for  $h = (\pi, K)$  obtained from invariant-mass fits to the Run-3 data. The results follow from the full selection, model construction, and fitting procedures discussed in the previous sections. The nominal hadronic results are extracted via a simultaneous fit to the  $D\pi$  and  $DK$  histograms using the data-driven misidentification model, following a prior-independent fit to fix certain model parameters. Finally, the polarity-split fit is used as a stability test, and the simultaneous analytic-misID is used to estimate the model's dominant dependence. The two obtained yields are combined with the fitted yield of the normalisation mode  $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ , the relative efficiency, and the external inputs described above to calculate the branching fractions and their uncertainty.

### A. Wrong-mass control samples and nominal fit results

The wrong mass-hypothesis control plots show the expected cross-feed shapes between the  $D\pi$  and  $DK$  selections as seen in Figure 3. The  $D\pi \rightarrow DK$  sample forms a broad structure  $-52.95 \text{ MeV}/c^2$  below the PDG  $B^0$  mass peak centred at  $\mu_{D\pi \rightarrow DK} = 5226.77 \pm 0.33 \text{ MeV}/c^2$ , with width  $\sigma_{D\pi \rightarrow DK} = 35.18 \pm 0.41 \text{ MeV}/c^2$ , and has a high-mass tail that extends to the  $DK$  signal region. In contrast, the  $DK \rightarrow D\pi$  contribution lies  $+54.54 \text{ MeV}/c^2$  above the nominal  $B^0$  mass with a more separated peak ( $\mu_{DK \rightarrow D\pi} = 5334.26 \pm 0.08 \text{ MeV}/c^2$  and  $\sigma_{DK \rightarrow D\pi} = 24.16 \pm 0.09 \text{ MeV}/c^2$ ). Since the  $D\pi$  signal is much larger than the true  $DK$  yield and the low-mass tail of the misID component overlaps with the signal, any small misidentification of the bachelor will bias the yields, and thus predicts  $N_{mis}(DK)$  is much more sensitive to any mismodelling.

The individual hadronic fits show that each channel is reasonably described by the model in isolation, and the fitted yields are listed in Table 4. Both returned a tight, clean signal peak, but the means differ significantly by  $0.73 \pm 0.08 \text{ MeV}/c^2$ , which, when averaged, lies 0.016% above the PDG mass, indicating a small mass-scale offset. In

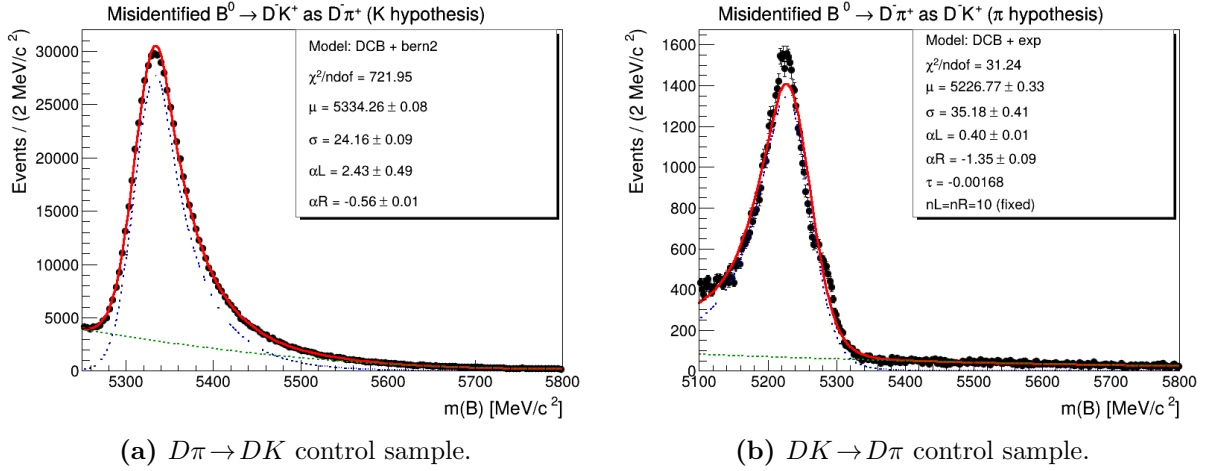


Figure 3: The misID control sample fits when reconstructed under the wrong bachelor mass hypothesis. The resulting peak-like shapes are then used as fixed misID PDF in the nominal  $D\pi/DK$  mass fits.

| Individual fits                | $B^0 \rightarrow D^- \pi^+$ | $B^0 \rightarrow D^- K^+$ |
|--------------------------------|-----------------------------|---------------------------|
| $\mu$ [MeV/c <sup>2</sup> ]    | $5280.196 \pm 0.018$        | $5280.927 \pm 0.078$      |
| $\sigma$ [MeV/c <sup>2</sup> ] | $17.603 \pm 0.015$          | $16.799 \pm 0.078$        |
| $N_{\text{sig}}$               | $934,988 \pm 851$           | $81,939 \pm 497$          |
| $N_{\text{mis}}$               | $102 \pm 191$               | $9,685 \pm 307$           |
| $N_{\text{HILL}}$              | $488,311 \pm 818$           | $2,718 \pm 572$           |
| $N_{\text{HORNS}}$             | $359,099 \pm 113$           | $30,573 \pm 619$          |
| $N_{\text{comb}}$              | $12,131 \pm 391$            | $112,466 \pm 624$         |
| $\chi^2/\text{ndf}$            | 9.37                        | 1.50                      |

Table 4: Summary of the individual hadronic fits used as starting values for the simultaneous fits.

the  $DK$  spectrum, the misID contribution is visibly significant, while the combinatorial absorbed most of the background. In contrast, in the  $D\pi$  channel, the misID yield is negligible, and the low-mass structure is dominated by the two-peaked HORN (soft pion) and the broad HILL (photon) component. Although some residual disturbance is observed in the pulls, which gives an inflated  $\chi^2/\text{ndf} = 9.37$ , the signal peak is well described and was then used to set the initial parameters for the simultaneous fit and to provide a good baseline description of the two spectra. These independent fits already show that the hadron modes are limited and sensitive to their background structure.

The results of the nominal simultaneous two-channel fit are shown in Fig. 4. The shared peak parameters are  $\mu = 5280.265 \pm 0.021$  MeV/c<sup>2</sup>,  $\sigma = 17.518 \pm 0.018$  MeV/c<sup>2</sup>, and the fitted component yields are listed in Table 5. The common mean is only 0.010% higher than the PDG average and is much closer to the individual  $D\pi$  than to the  $DK$ , which now differ by  $-0.297$  MeV/c<sup>2</sup>, indicating improved global consistency that stabilised the mass scale, while barely changing the signal yields. The inputs for the primary branching-fraction calculation are  $N_{\text{sig}}(D\pi) = 932,505 \pm 1,027$ ,  $N_{\text{sig}}(DK) = 82,094 \pm 340$ . and are

| Nominal simultaneous fit      | $B^0 \rightarrow D^- \pi^+$           | $B^0 \rightarrow D^- K^+$          |
|-------------------------------|---------------------------------------|------------------------------------|
| Shared $\mu$ [MeV/ $c^2$ ]    | $5280.265 \pm 0.021$                  | $5280.265 \pm 0.021$               |
| Shared $\sigma$ [MeV/ $c^2$ ] | $17.518 \pm 0.018$                    | $17.518 \pm 0.018$                 |
| $N_{\text{sig}}$              | <b><math>932,505 \pm 1,027</math></b> | <b><math>82,094 \pm 340</math></b> |
| $N_{\text{mis}}$              | $5,017 \pm 247$                       | $12,721 \pm 14$                    |
| $N_{\text{HILL}}$             | $467,296 \pm 2,031$                   | $2,954 \pm 286$                    |
| $N_{\text{HORNS}}$            | $377,651 \pm 1,950$                   | $33,560 \pm 673$                   |
| $N_{\text{comb}}$             | $12,331 \pm 336$                      | $106,758 \pm 783$                  |
| $\chi^2/\text{ndf}$           | 8.69                                  | 2.65                               |

Table 5: Summary of the nominal simultaneous fit results to the  $D\pi$  and  $DK$  spectra.

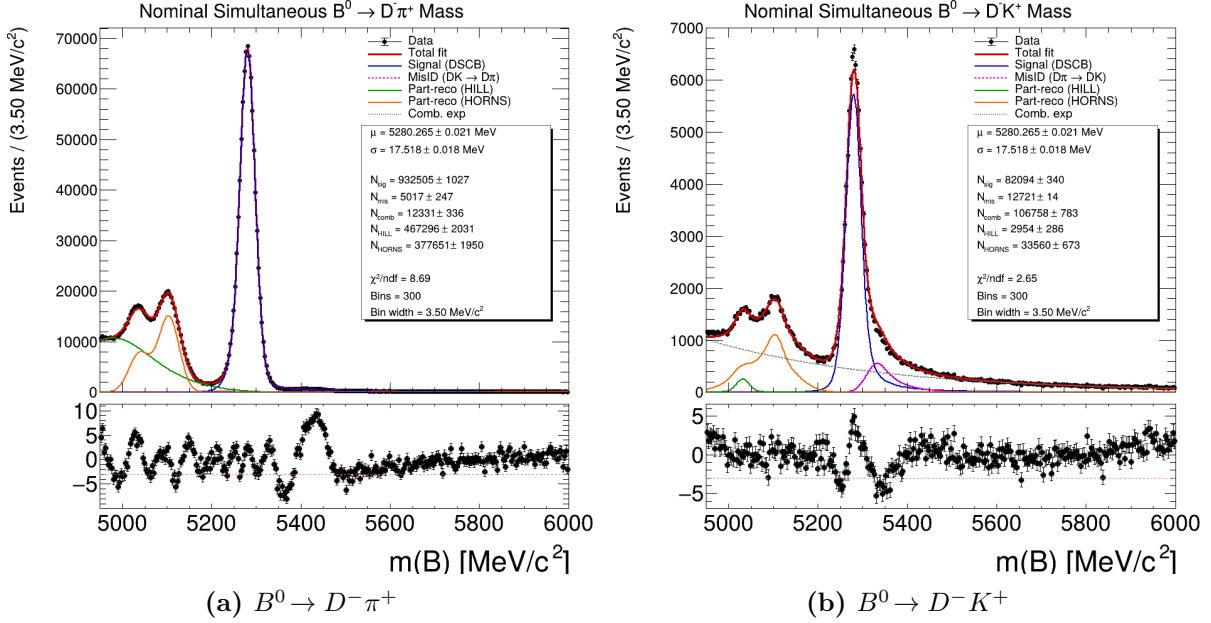


Figure 4: Nominal simultaneous invariant-mass fits for  $B^0 \rightarrow D^- \pi^+$  and  $B^0 \rightarrow D^- K^+$  with PID-calibration yield constraints showing the full model and the relevant pulls.

consistent with those from the individual fit yields by 0.27% and 0.19% corresponding to  $1.9\sigma$  and  $0.3\sigma$ , respectively, thus indicating that the simultaneous fit does not redistribute the signal. The  $N_{\text{mis}}(D\pi)$  increased by a factor of 50, but remains small relative to  $N_{\text{sig}}$ , and thereby resolves the poorly determined, unconstrained component in the individual fit. The effective misID fractions are about 1.36% for  $D\pi \rightarrow DK$  and 6.11% for  $DK \rightarrow D\pi$ . As predicted by the misID control channels, the wrong mass tail from  $D\pi \rightarrow DK$  overlaps with the  $DK$  signal, so  $N_{\text{mis}}$  impacts the stability more than in the reverse situation for  $D\pi$ . Numerically, the fit converges well with EDM =  $1.01 \times 10^{-4}$  and great covariance quality. Similar to the individual fits, the  $D\pi$  exhibits an inflated  $\chi^2/\text{ndf} = 8.69$  from low-mass residual oscillatory disturbances, but the pull distributions remain well behaved in the peak region for both channels, therefore motivating the dedicated stability probes below. The simultaneous fit improved the distribution of the components and

resolved discrepancies between the background components without biasing the signal count.

The normalisation channel  $B^+ \rightarrow J/\psi K^+$  is shown in Fig. 5a. In the nominal window, the fit converges with  $\chi^2/\text{ndf} = 0.98$ , and returns the peak mean  $\mu_{J/\psi K} = 5279.113 \pm 0.038 \text{ MeV}/c^2$ , resolution  $\sigma_{J/\psi K} = 8.492 \pm 0.044 \text{ MeV}/c^2$ , and the fitted yields  $N_{J/\psi K} = 133,218 \pm 739$ ,  $N_{\text{bkg}}(J/\psi K) = 164,294 \pm 759$ . The signal peak is narrow, the background is smooth, and the pulls fluctuate around zero, making this a very clean control mode for branching-fraction extraction, despite a small mass difference. The resolution is substantially tighter than in the hadronic channels; the mean is very close to the PDG  $B^+$  mass and is significantly lower than the fitted hadronic means. Thus, the systematic uncertainty is mostly determined by the  $B^0 \rightarrow D^- h^+$  decays. Compared to the wider mass-range fit, the extracted results are statistically identical; the  $\chi^2/\text{ndf}$  and EDM values are higher, so the control yield is not sensitive to the exact choice of fit window.

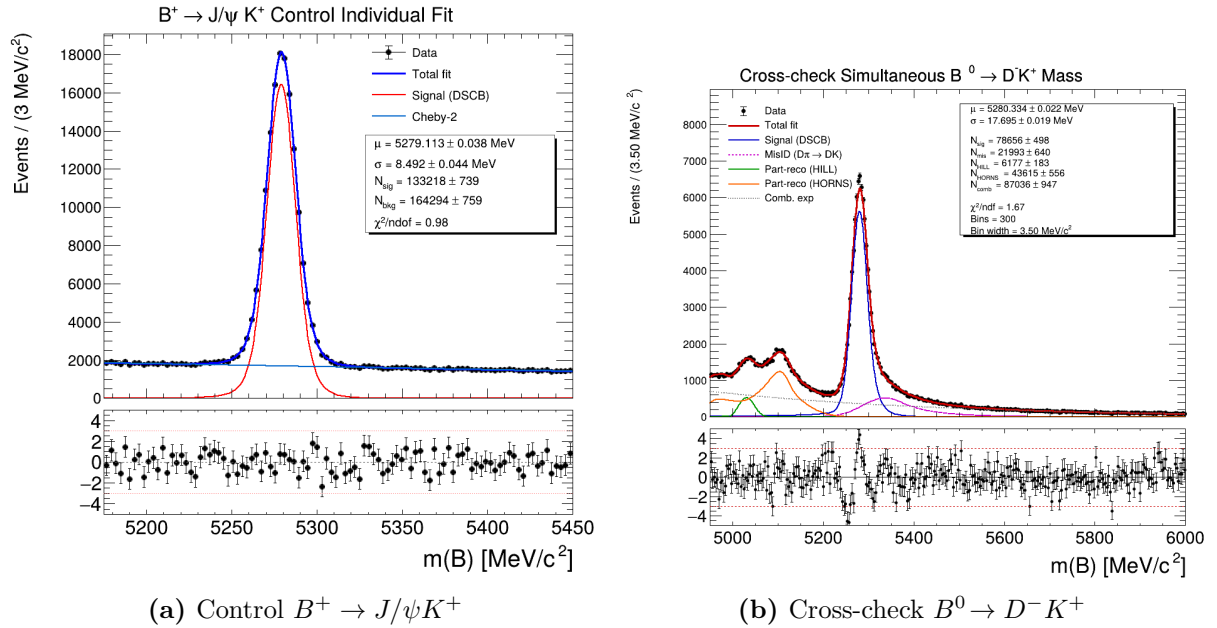


Figure 5: (a)  $B^+ \rightarrow J/\psi K^+$  control-channel invariant-mass fit in the range 5175–5450  $\text{MeV}/c^2$ . (b) Cross-check simultaneous invariant-mass fits for  $B^0 \rightarrow D^- K^+$  with the analytic misID.

## B. Stability tests and model dependence

The four-category polarity-split fit provides a direct probe of whether the nominal result and the model itself are stable under data subdivision due to detector conditions. The extracted signal yields are listed in Table 6. The sum of the two same polarity signals yields is 926,194 for  $D\pi$  and 75,273 for  $DK$ , which differ from the nominal simultaneous

| Fit configuration | $N_{\text{sig}}(B^0 \rightarrow D^- \pi^+)$ | $N_{\text{sig}}(B^0 \rightarrow D^- K^+)$ |
|-------------------|---------------------------------------------|-------------------------------------------|
| Individual        | $934,988 \pm 851$                           | $81,939 \pm 497$                          |
| <b>Nominal</b>    | <b><math>932,505 \pm 1,027</math></b>       | <b><math>82,094 \pm 340</math></b>        |
| Split polarity    | $926,194 \pm 1,033$                         | $75,273 \pm 329$                          |
| Split down        | $579,374 \pm 818$                           | $47,018 \pm 260$                          |
| Split up          | $346,820 \pm 632$                           | $28,255 \pm 201$                          |
| Cross-check       | $925,576 \pm 1,069$                         | $78,656 \pm 498$                          |

Table 6: Comparison of fitted signal yields across the relevant fit variants used in this analysis.

fit by  $-0.68\%$  and  $-8.31\%$ , respectively. Using Eq. 15, the raw asymmetries are  $A(D\pi) = -0.2511 \pm 0.0011$ ,  $A(DK) = -0.2493 \pm 0.0042$ . These are consistent within  $0.41\sigma$  of one another and only differ by  $0.18\%$  or  $0.42\sigma$ , so polarity-dependent distortions are not a dominant issue, and thus these fits are taken as a validation of the nominal strategy.

The most important cross-check is to rerun the same fitting procedure as above, replacing the data-driven misID component with a semi-constrained DSCB to isolate discrepancies between components. The corresponding  $DK$  fit is shown in Fig. 5b, and the signal yields are listed in Table 6. The common signal peak is largely unchanged, shifting the mean and width by only  $+0.069 \text{ MeV}/c^2$  and  $+0.177 \text{ MeV}/c^2$ , respectively, but it significantly alters the component yields. The  $D\pi$  signal yield differs by only  $-0.74\%$  despite the sizeable redistribution of the background components, whereas the  $DK$  yield shifts by  $-4.19\%$  because the kaon mode is more sensitive to the misID modelling. For the  $DK$  channel, the misID yield increases by about  $73\%$ , and the fit quality improves, with  $\chi^2/\text{ndf} = 1.67$  compared to worsened  $16.27$  for  $DK$ , but still remains stable. Repeating the split-polarity fit for this cross-check model changes  $N_{\text{sig}}(D\pi)$  by  $-1.47\%$ ,  $N_{\text{sig}}(DK)$  by  $2.21\%$  relative to the nominal simultaneous fit, while leaving the asymmetries statistically unchanged with respect to the nominal 4 channel fit, where the  $A(DK)$  changing by  $0.4\sigma$ . Yield differences are driven by model dependence rather than magnet polarity.

Together, these tests show that any residual uncertainty is primarily associated with the division between the low-mass components rather than with  $\mu$  and  $\sigma$ . The  $D\pi$  signal is the most stable measurement in the analysis, despite a discrepancy in the low-mass region, whereas the  $DK$  yield varies under both changes to the misID model and any polarity subdivisions.

### C. Branching fractions and comparison with existing results

Using the nominal simultaneous yields, the fitted normalisation yield, the relative efficiencies of Sect. IV.G., and the external branching-fraction inputs of Sect. II.B., the

| Configuration    | $\overline{\mathcal{B}}(B^0 \rightarrow D^- K^+) [10^{-4}]$ | $\overline{\mathcal{B}}(B^0 \rightarrow D^- \pi^+) [10^{-3}]$ |
|------------------|-------------------------------------------------------------|---------------------------------------------------------------|
| Individual       | $2.359 \pm 0.014 \pm 0.089$                                 | $2.621 \pm 0.002 \pm 0.099$                                   |
| <b>Nominal</b>   | <b><math>2.363 \pm 0.010 \pm 0.089</math></b>               | <b><math>2.614 \pm 0.003 \pm 0.098</math></b>                 |
| Split polarity   | $2.415 \pm 0.010 \pm 0.091$                                 | $2.575 \pm 0.003 \pm 0.097$                                   |
| Cross-check      | $2.264 \pm 0.014 \pm 0.086$                                 | $2.594 \pm 0.003 \pm 0.098$                                   |
| Belle 2022       | $2.03 \pm 0.05 \pm 0.07 \pm 0.03$                           | $2.48 \pm 0.01 \pm 0.09 \pm 0.04$                             |
| Global Average   | $2.05 \pm 0.08$                                             | $2.51 \pm 0.08$                                               |
| QCDF Expectation | $3.94^{+0.24}_{-0.20}$                                      | $3.26 \pm 0.15$                                               |

Table 7: Branching fractions obtained from the different fit strategies relevant in this study and external branching fraction from [12, 13, 10, 9].

CP-averaged branching fractions are obtained as

$$\overline{\mathcal{B}}(B^0 \rightarrow D^- \pi^+) = (2.614 \pm 0.003_{\text{stat}} \pm 0.098_{\text{ext}}) \times 10^{-3}, \quad (17)$$

$$\overline{\mathcal{B}}(B^0 \rightarrow D^- K^+) = (2.363 \pm 0.010_{\text{stat}} \pm 0.089_{\text{ext}}) \times 10^{-4}, \quad (18)$$

with the corresponding branching-fraction ratio

$$R_{K/\pi} \equiv \frac{\overline{\mathcal{B}}(B^0 \rightarrow D^- K^+)}{\overline{\mathcal{B}}(B^0 \rightarrow D^- \pi^+)} = 0.09040 \pm 0.00039_{\text{stat}} \pm 0.00231_{\text{ext}}. \quad (19)$$

These are stated first, with their statistical uncertainty propagated from the mass-fit models, and the second is their external uncertainty from other inputs, including the control fit. The branching-fraction values obtained from the other fit models are summarised in Table 7.

An estimate of the residual model dependence is then obtained from the analytical misID cross-check. Taking the difference with respect to the nominal fits gives the fit model variations of  $0.020 \times 10^{-3}$  and  $0.099 \times 10^{-4}$  for the  $D\pi$  and  $DK$  branching fractions, respectively, and for their ratio, 0.00314. Numerically, the dependence is modest for the pion mode but more pronounced for the kaon mode, as expected from the wrong-mass misID study and the stability tests. Thus, the absolute branching fraction for the  $DK$  is more sensitive than the one for  $D\pi$ .

Finally, Fig. 6 presents the results beside the current experimental averages and the QCDF expectations that were discussed in Sect. I. [12, 13, 9, 10, 11]. The measured  $D\pi$  branching fraction is close to both the global averages and the Belle 2022 value by  $0.82\sigma$  and  $0.96\sigma$ , respectively. However, the measured  $DK$  branching fraction is much larger than the experimental results, and lies  $2.61\sigma$  above the global average and the Belle 2022 measurement. Nevertheless, for both channels, the measured rates remain

far below the expectations of the older and modern SMs. The present results reduce the discrepancies by  $3.60\sigma$  in the  $D\pi$  and  $6.16\sigma$  in the  $DK$ , but do not eliminate them. The corresponding effective coefficients are  $|a_1(D\pi)| = 0.8740 \pm 0.0005_{\text{stat}} \pm 0.0300_{\text{ext}}$  and  $|a_1(DK)| = 0.8858 \pm 0.0018_{\text{stat}} \pm 0.0324_{\text{ext}}$  with an discrepancy of 0.0033 and 0.0187 when compared to the cross-check analytic result, that correspond to  $0.08\sigma$  and  $0.41\sigma$  for the  $D\pi$  and  $DK$  channels, respectively. Compared with the existing experimental average, the values are fully consistent, differing only by  $0.12\sigma$  for  $D\pi$  and  $0.66\sigma$  for  $DK$ . In contrast, when compared to the modern QCDF expectations, both remain significantly smaller by  $6.44\sigma$  and  $5.62\sigma$ , respectively. The value of this coefficient mirrors the pattern seen in the branching fraction and, therefore, supports the conclusion that the Run-3 follows the same  $b^- \rightarrow c\bar{u}q$  anomaly as the previous experiments. Finally, the branching ratio below the QCDF expectation by  $-0.0305$ , but it is larger than both Belle 2022 and global average ratios by 0.0085 and 0.0087, respectively. These three ratios correspond to differences  $3.4\sigma$ ,  $1.6\sigma$ , and  $1.8\sigma$  and thus follow the same tension pattern.

Overall, the results of this study show that once a sensible description of the troubling low-mass structure is included, the pion mode is stable. However, the kaon mode remains more directly limited by the treatment of the  $D\pi \rightarrow DK$  misID component. The nominal simultaneous results are used as the main result, but the polarity-split fit serves as a detector-stability check, and the analytic misID fits provide the most relevant estimate of the residual model component dependence.

#### D. Are the results reasonable and what are the next steps?

The fit behaviour and results presented in this dissertation are physically reasonable. The control channel is extremely clean and free of potential misidentifications; the signal peaks across the hadronic fits are stable and narrow; the shared mass scaled in the simultaneous fit is well-behaved; and the polarity-split fit reveals no hidden detector-driven discrepancies. The variations in the  $D\pi$  signal yields are minor across all the tests. The main limitations stem from the branching fractions, which are much more sensitive and fragile than the yield extractions, where values can change even when the signals are correct. The results depend directly on the relative efficiencies, which were calculated by assuming that the muons behave like pions up to some factor and that bachelor and daughter hadrons share the same kinematics. In addition, the  $DK$  mode yields depend on the misID contribution, which originates from a much larger sample. The low-mass

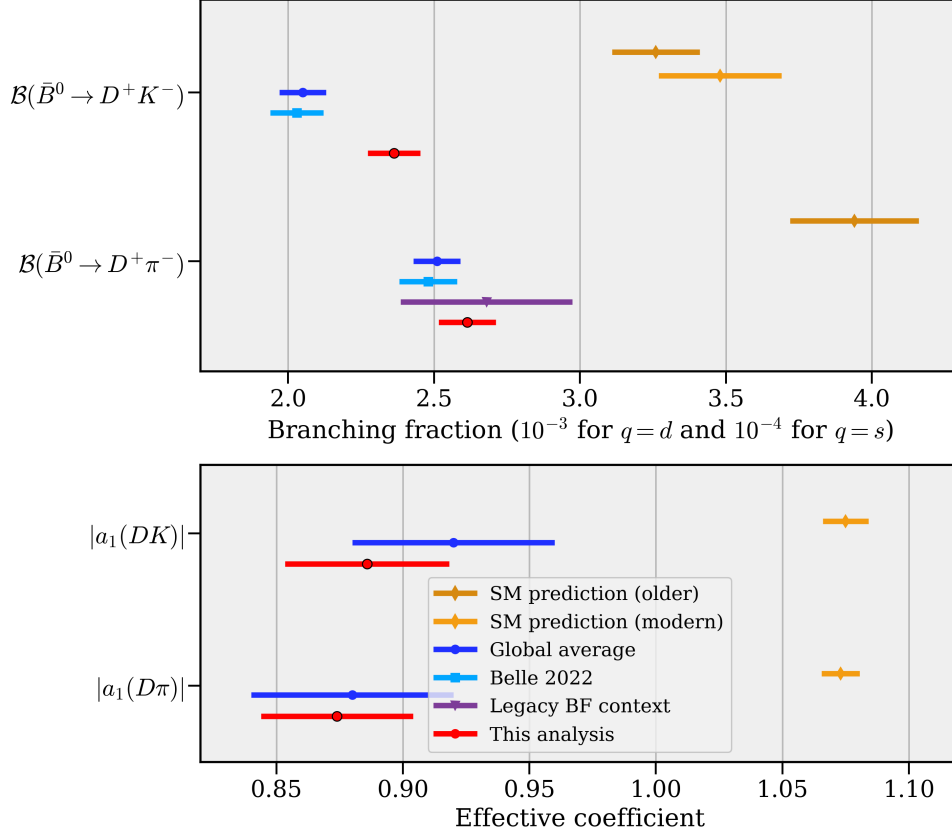


Figure 6: Summary of branching fractions and extracted  $|a_1|$  coefficients for  $\bar{B}^0 \rightarrow D^+ h^-$  decays [12, 13, 9, 10, 11]

region of the hadronic spectra is not fully accounted for by the current background and misID components, so any variations in the normalisations could bias the signal yields. Finally, the quoted central values don't account for the full uncertainty in the fit, as the systematic uncertainty was not fully evaluated.

An additional source of uncertainty could be peak contamination due to other misidentified decays. For example, the channel  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  can enter the  $D\pi$  sample when the daughter  $\Lambda_c^+ \rightarrow p K^- \pi^+$  is reconstructed under the  $D^+ \rightarrow K^- \pi^+ \pi^+$  hypothesis. The proton is misidentified as a pion, and overall, the tracks and vertices could satisfy the offline selections, thereby producing a small peak-like structure near the  $B^0$  signal region. The expected corresponding effect in the  $DK$  sample should be much smaller, as the bachelor pion would need to satisfy the kaon PID requirement. For this reason, the results presented should be interpreted as an intermediate Run-3 measurement rather than a fully precise determination. Much more work can be done to resolve other possible peak contributions and, finally, to project the model across the full data-taking time range.

## VI. Conclusion

This dissertation has presented a measurement of the CP-averages branching fraction of the decays  $B^0 \rightarrow D^- \pi^+$  and  $B^0 \rightarrow D^- K^+$  using data collected from the Run-3 LHCb at  $\sqrt{s} = 13.6$  TeV. These channels arise from the dominant colour-allowed tree-level transition  $b \rightarrow c\bar{u}q$  and provide a clean setting to test the flavour structure of the weak interaction within the Standard Model and the accuracy of the QCD factorisation expectations for hadronic  $B$  decays. The relevant yields were extracted from extended maximum-likelihood invariant-mass fits across multiple fit configurations, with the nominal result obtained from simultaneous fits to the hadronic  $D\pi$  and  $DK$  spectra that shared signal-peak parameters and used a data-driven template to control cross-feed between the channels arising from candidate misidentification. The extracted non-leptonic yields  $N_{\text{sig}}(D\pi) = 932,505 \pm 1,027$ ,  $N_{\text{sig}}(DK) = 82,094 \pm 340$ , are normalised to the clean control channel  $B^+ \rightarrow J/\psi K^+$  to obtain  $\overline{\mathcal{B}}(B^0 \rightarrow D^- \pi^+) = (2.614 \pm 0.003_{\text{stat}} \pm 0.098_{\text{ext}}) \times 10^{-3}$ ,  $\overline{\mathcal{B}}(B^0 \rightarrow D^- K^+) = (2.363 \pm 0.010_{\text{stat}} \pm 0.089_{\text{ext}}) \times 10^{-4}$  and  $R_{K/\pi} = 0.09040 \pm 0.00039_{\text{stat}} \pm 0.00231_{\text{ext}}$ . Relative to the QCDF expectation, both channels are suppressed with the discrepancy reduced by  $3.60\sigma$  and  $6.16\sigma$  for  $D\pi$  and  $DK$ , respectively. However, they are consistent with the global average  $0.82\sigma$  for  $D\pi$ , and slightly more deviated  $2.61\sigma$  for  $DK$ . The branching-fraction ratio follows the same anomaly, lying above the experimental measurements but below the QCDF expectation. To conclude, the measurements in this analysis solidify the underlying systematic suppression of the pseudoscalar  $b \rightarrow c\bar{u}q$  decays relative to modern QCDF predictions, while remaining consistent with previous experiments.

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