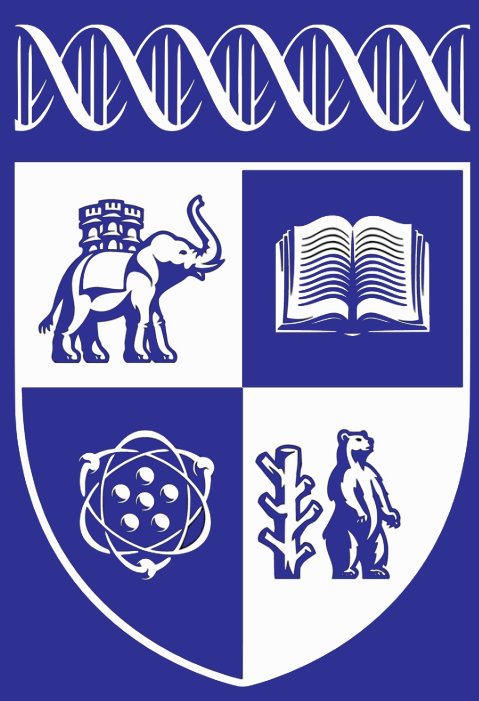
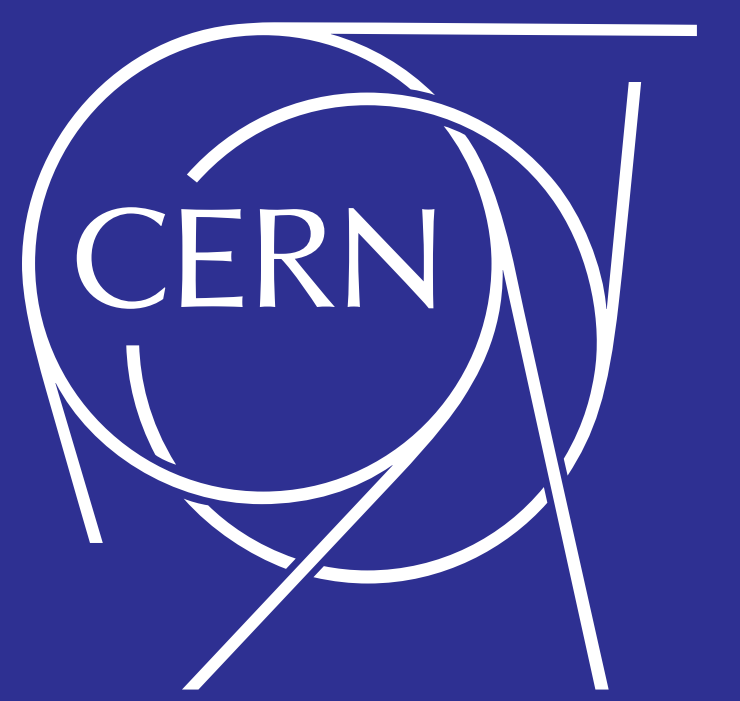




CP-Averaged Branching Fractions for $B^0 \rightarrow D^-(K^+\pi^-\pi^-)h^+$, $h = \pi, K$ with Leptonic Normalisation $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ in LHCb Run-3

Collected experimental measurements of $B^0 \rightarrow D^-K^+$ and $B^0 \rightarrow D^-\pi^+$ remain below the theoretical QCD expectations, supporting the existing $b \rightarrow c\bar{u}q$ branching fraction and ratio tension.

Gabriel Hagen Antunes



Motivation and the branching fraction tension

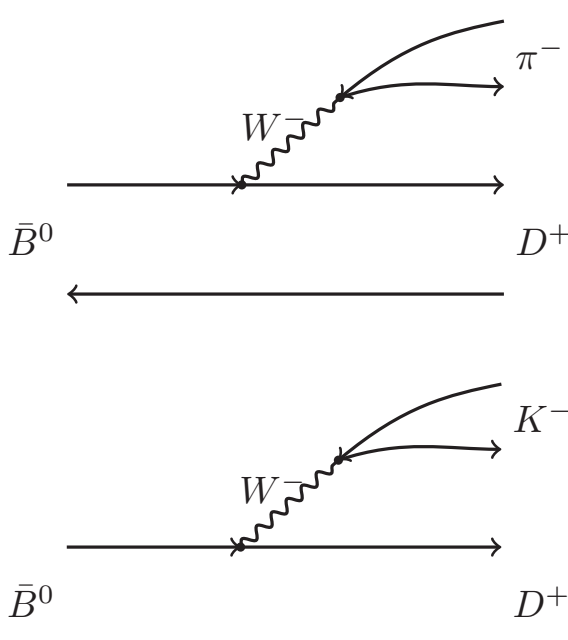
- Flavour physics tests the CKM description of $SU(2)_L$ weak quark interactions and the $SU(3)_C$ QCD formation of hadronic final states [1].
- Colour-allowed $B^0 \rightarrow D^-h^+$ test QCDF in non-leptonic B-decays [2].
- Improved theory and measurements revealed the $b \rightarrow c\bar{u}q$ anomaly, in which rates lie systematically 4.4σ below QCDF predictions [3,4].
- Thus motivating Run-3 LHCb measurements to directly improve yields and reduce statistical uncertainty ($\propto 1/\sqrt{N}$) to observe the same suppression.
- The puzzle's origins could be attributed to hidden experimental effects, possible BSM amplitude effects, or underestimated QCD uncertainties.
- The Run-3 trigger/upgrade enables use of the $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ clean normalisation channel to avoid those that share the same anomaly [5].

Theory and QCD factorisation

- The two tree-dominated charged-current $b \rightarrow c\bar{u}q$, $q = d, s$ modes are very clean as competing topologies are suppressed.
- QCDF amplitudes are split into the emitted-meson decay constant f_h , the $B \rightarrow D$ form factor, and the effective coefficient a_1 absorbing non-factorisable residuals [2]:

$$A(B \rightarrow Dh) \propto V_{cb}V_{uq}^* a_1(Dh) f_h F_0^{B \rightarrow D}(m_h^2).$$

- Both mainly differ by CKM factors and as $|V_{us}| < |V_{ud}|$, $A(DK) \propto V_{us}^*$ is Cabibbo-suppressed relative to $A(D\pi) \propto V_{ud}^*$ [1].



Simultaneous mass spectra fits and validation

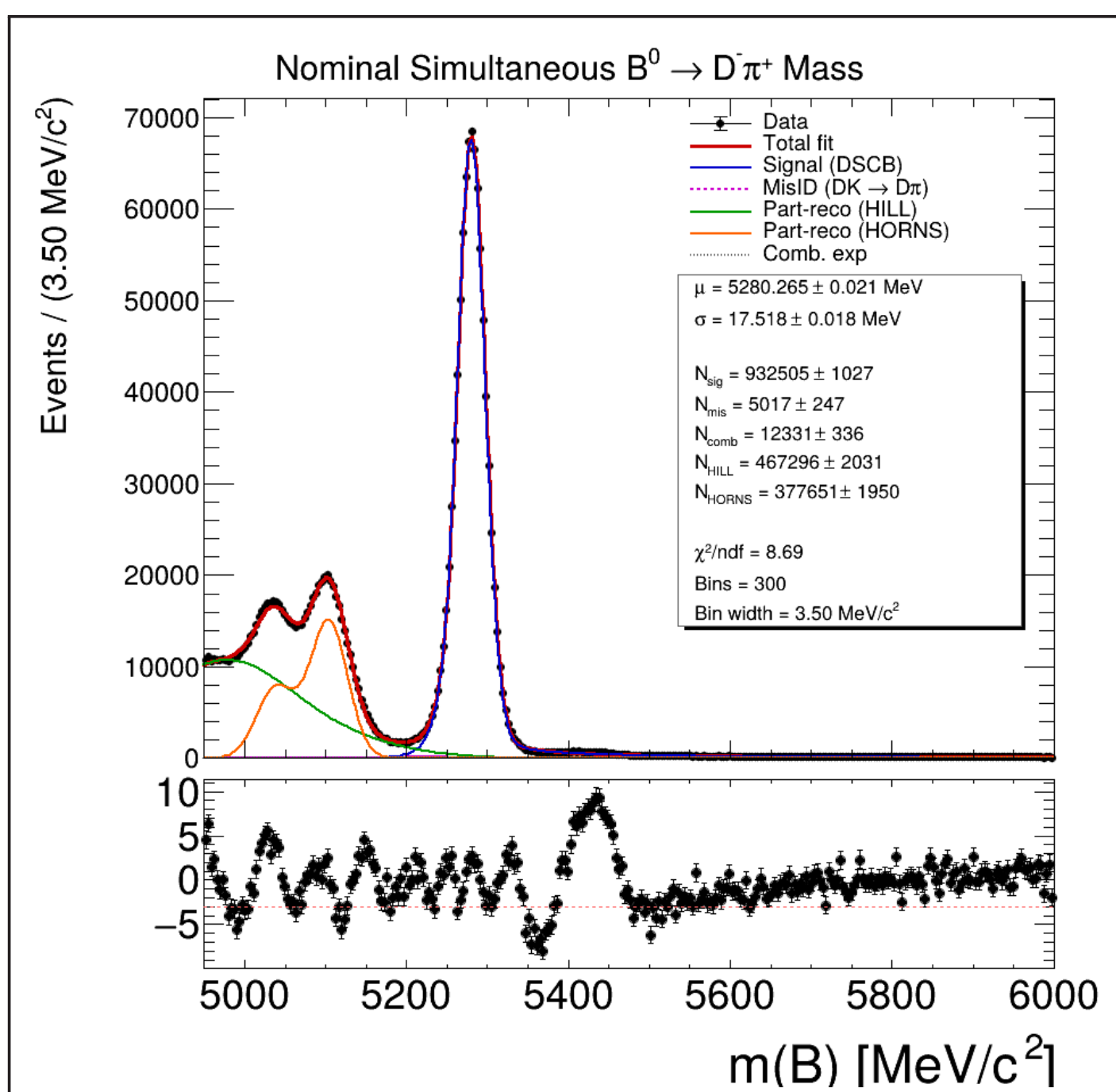


Fig 1. $N_{\text{sig}}(D\pi) = 932,505 \pm 1,027$.

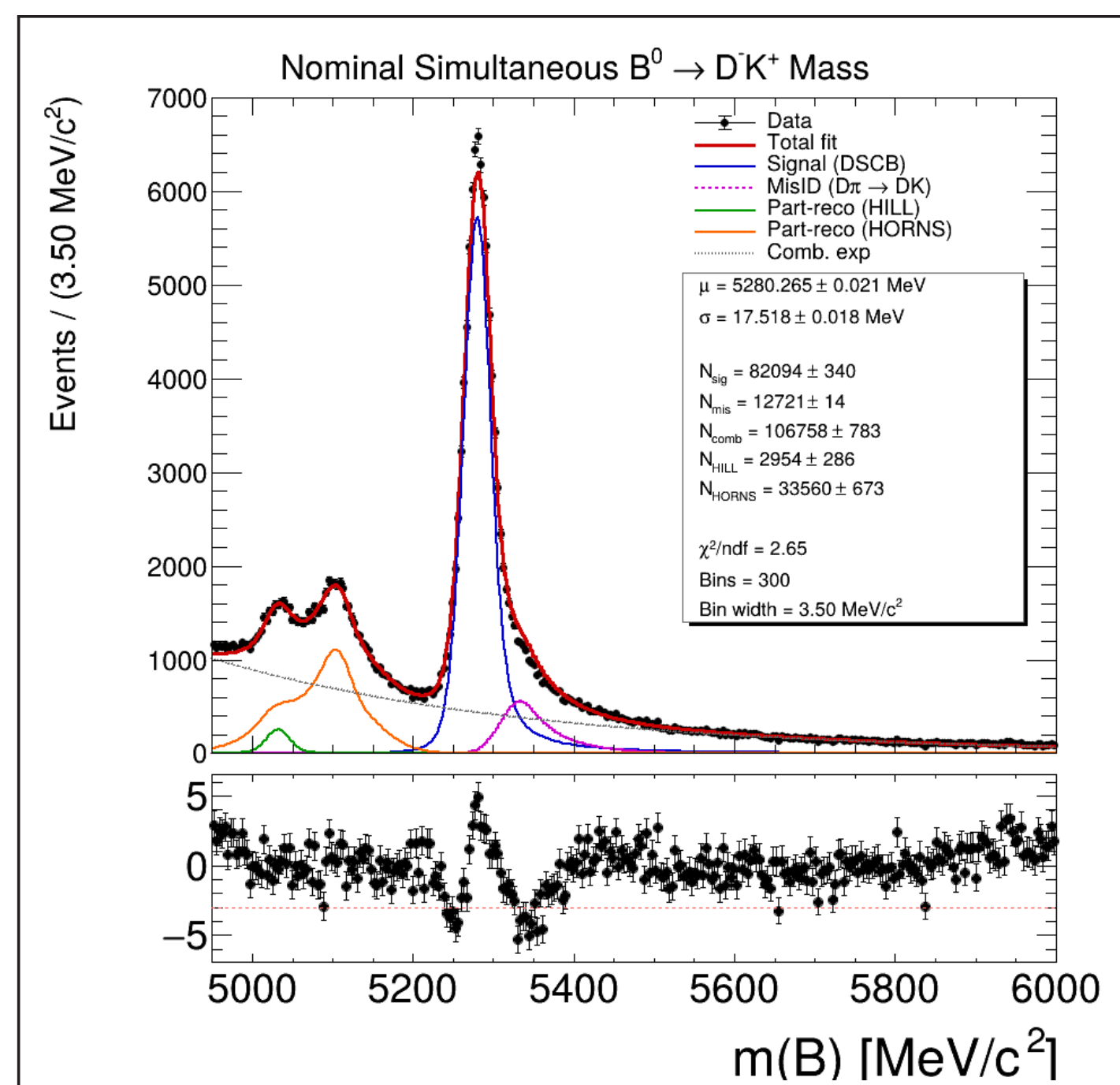


Fig 2. $N_{\text{sig}}(DK) = 82,094 \pm 340$.

- Signal yields extracted from binned invariant-mass fits to the reconstructed B -candidate mass.
- Equivalent to minimising $-\ln \mathcal{L}(\theta) = -\sum_i \ln \left(\frac{\nu_i(\theta)^{n_i} e^{-\nu_i(\theta)}}{n_i!} \right)$
- Extended density: $\mathcal{P}(m) = \sum_{i \in \text{comp}} N_i S(m; \theta_i)$.
- Challenging misID shapes due to misidentified bachelor hadron, most prevalent in DK modelled by wrong mass-hypothesis control samples.
- Shapes constrained using PID calibration efficiencies [6]: $\bar{\epsilon}_{\text{PID}} = \frac{\sum_i \epsilon_i w_i C_i}{\sum_i w_i C_i}$ so yields are linked as $N_{\text{mis}}^{DK} = N_{\text{sig}}^{D\pi} \frac{\epsilon(\pi \rightarrow K)}{\epsilon(\pi \rightarrow \pi)}$, $N_{\text{mis}}^{D\pi} = N_{\text{sig}}^{DK} \frac{\epsilon(K \rightarrow \pi)}{\epsilon(K \rightarrow K)}$.
- Other components include DSCB signal (true candidates), HILLS/HORNS partially reconstructed background (missing neutral particles or soft pions) and exponential/decaying combinatorial background (random tracks).
- Validation through various fits and diagnostic pulls / χ^2/ndf :
 - Individual fits provide starting values/shapes and baseline validation.
 - Stable nominal simultaneous fit with shared μ, σ used as inputs.
 - Magnet-polarity 4-way simultaneous fit to test detector stability
 - An analytic DSCB-misID cross-check fit to estimate model sensitivity.
- Normalisation channel is stable $N_{\text{sig}}(J/\psi K^+) = 133,218 \pm 739$, when fitted with a flexible DSCB signal and a second-order Chebyshev polynomial.

The Run-3 LHCb detector at CERN

- LHCb is a single-arm forward spectrometer designed for precision studies of beauty and charm hadrons from pp collisions at $\sqrt{s} = 13.6$ TeV [5].
- Upgrades leading to Run-3 increased luminosity 5 times, requiring the use of a fully software-based trigger with 40 MHz bunch-crossing rate [5].
- Trigger: HLT1 selects tracks/vertices; HLT2 determines real candidates.
- To reconstruct the 4-track candidates, require:
 - precise vertexing by VELO to minimise background,
 - good momentum reconstruction by the tracker to refine resolution,
 - crucial efficient kaon-pion separation by RICH to lower cross-feed as modes differ only by the bachelor hadron, and
 - efficient muon identification to cleanly reconstruct the control channel.

Selections to isolate $B^0 \rightarrow D^-(K^+\pi^-\pi^-)h^+$

- Cuts are applied on D-mass, vertex quality, flight-distance, impact-parameter, DIRA and machine-learning multivariate MVA / XGBoost.
- Selected via 1D Punzi-type figure-of-merit scan over the response.
- RICH PID separates candidates into a more pion-like sample ($\text{PIDK} < 0$) and a cleaner kaon-like sample ($\text{PIDK} > 5$) to suppress cross-feed.

Efficiency

- Most factors cancel in the total efficiency. Remaining differences arise from final-state content, hadronic interactions, and PID requirements.
- Relative efficiency between modes $\epsilon_{\text{rel}}(h) = \frac{\epsilon(B^0 \rightarrow D^-h^+)}{\epsilon(B^+ \rightarrow J/\psi K^+)} \approx \epsilon(\mu) S_\pi^2 S_h$.
- Simplifications aren't exact: error propagates into systematic uncertainties as π are treated as μ , and different vertex kaons are treated as equal.

Branching fraction and comparison

- Yields are charge-inclusive, so the measured observable is the CP-averaged branching fraction.

$$\frac{\mathcal{B}(B^0 \rightarrow D^-h^+)}{\mathcal{B}(B^+ \rightarrow J/\psi K^+)} = \frac{f_u}{f_d} \frac{N_{Dh}}{N_{J/\psi K}} \frac{\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)}{\mathcal{B}(D^- \rightarrow K^+\pi^-\pi^-)} \frac{1}{\epsilon_{\text{rel}}(h)}$$

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

- $D\pi$ is stable/robust across all fit variants, agreeing with existing averages within 1σ [1,4].
- DK lies 2.6σ above existing averages. It's more sensitive to $D\pi \rightarrow DK$ misID [1,4].
- Both rates remain 3.6σ and 6.2σ below QCDF expectations respectively [2,3].
- Ratio $R_{K/\pi}$ is below QCDF by 3.4σ , but above measurements by circa 1.7σ [1,3,4].

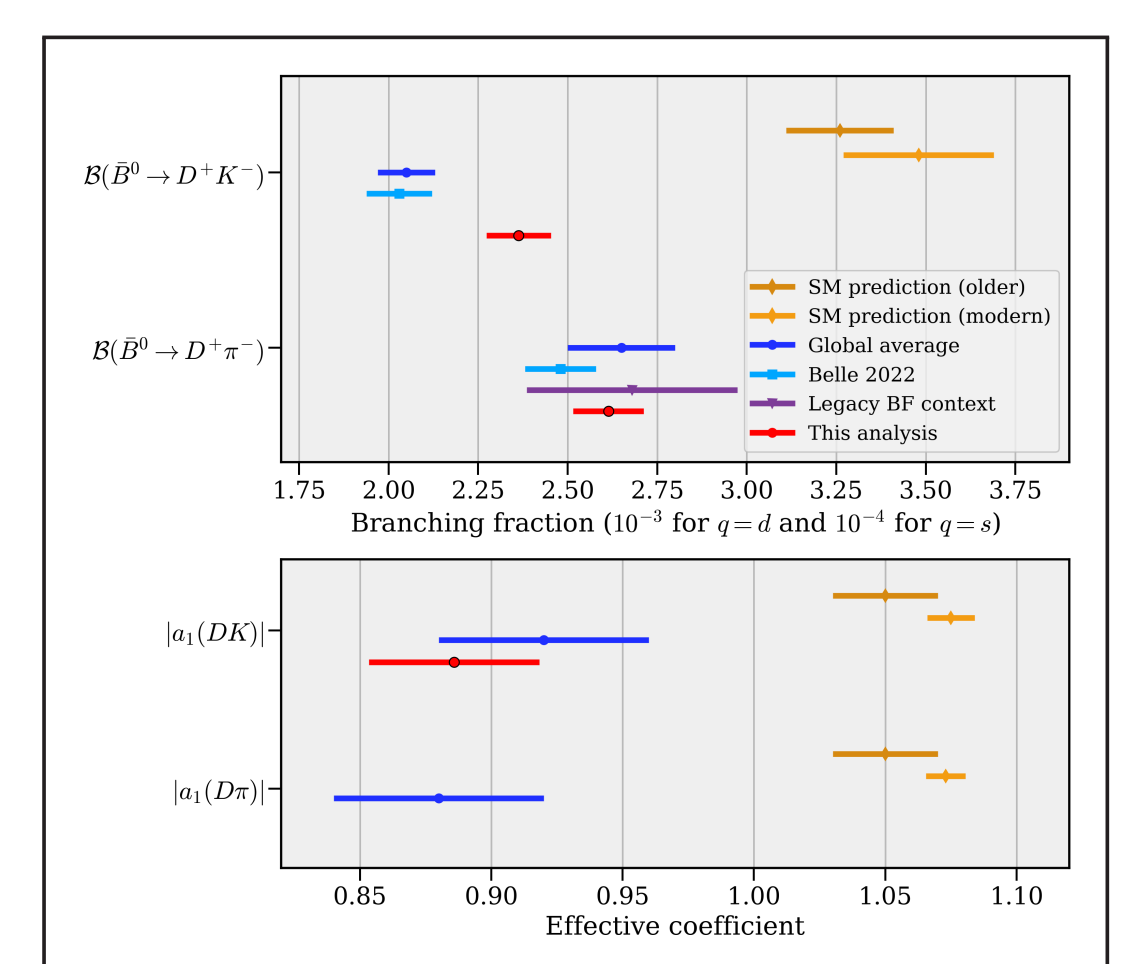


Fig 3. $\mathcal{B}$ comparison.

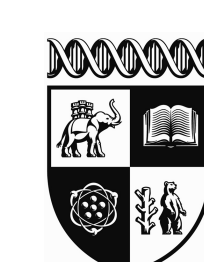
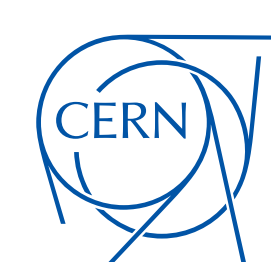
Conclusion

- Run-3 LHCb data support the existing $b \rightarrow c\bar{u}q$ branching-fraction tension, but DK results remain limited by misID and efficiency systematics.
- Uncertainties are dominated by external inputs, relative-efficiency assumptions and model dependence, not by the fit statistics.
- Future work: further efficiency modelling, more misID modelling from other modes, low-mass backgrounds, full systematic uncertainties and a projection to LHCb's full integrated luminosity.

KEY REFERENCES

- [1] S. Navas et al., *Review of Particle Physics*, Phys. Rev. D 110, 030001, 2024.
- [2] M. Beneke et al., *QCD factorization for exclusive, non-leptonic B meson decays*, Nucl. Phys. B 591, 313–418, 2000.
- [3] M. Bordone et al., *A puzzle in $B^0 \rightarrow D^{(*)+} \{ \pi^-, K^- \}$ decays*, Eur. Phys. J. C 80, 951, 2020.
- [4] E. Waheed et al., *Study of $B^0 \rightarrow D^+ h^-$ ($h = K/\pi$) decays at Belle*, Phys. Rev. D 105, 012003, 2022.
- [5] R. Aaij et al., *The LHCb Upgrade II*, JINST 19, P05065, 2024.
- [6] R. Aaij et al., *Selection and processing of calibration samples to measure the PID performance of LHCb*, EPJ Techniques and Instrumentation 6, 1, 2019.

ACKNOWLEDGEMENTS



Thanks to my supervisor, Nicole Skidmore, and the Department of Physics at the University of Warwick.

CONTACT

Gabriel Hagen Antunes
Department of Physics
University of Warwick
Coventry CV4 7AL, United Kingdom
gabriel.hagen-antunes@warwick.ac.uk