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Performance of the particle identification system at LHCb

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Effective particle identification (PID) is crucial for LHCb to meet its ambitious physics objectives after "Upgrade I". To handle the higher luminosity and pile-up conditions of Run 3, LHCb has significantly upgraded its core PID subsystems, which include the Ring Imaging Cherenkov detectors, electromagnetic and hadronic calorimeters, and muon stations. This document provides an updated assessment of the PID performance following these upgrades, with a focus on charged hadrons and leptons. The results demonstrate that the enhanced subsystems offer reliable and robust PID capabilities under the challenging operational conditions of Run 3, ensuring LHCb's ability to continue producing world-class physics results in the near future.

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1. Introduction

The LHCb experiment [1] is a dedicated heavy-flavour physics experiment at the Large Hadron Collider (LHC), with the primary objective of searching for indirect evidence of New Physics through the study of CP violation and rare decays of beauty and charm hadrons. To address its unique physics goals, the LHCb detector was designed as a single-arm forward spectrometer, offering precise vertexing, tracking and momentum resolution, along with exceptional particle identification (PID) capabilities. The latter are crucial for producing world-leading results in the field of flavour physics, enabling the differentiation of final states with identical topologies, the suppression of backgrounds, the optimization of trigger bandwidth, and the efficient flavor tagging of neutral B mesons at production. In LHCb, three key subsystems are essential for PID: two Ring Imaging Cherenkov (RICH) detectors, the Electromagnetic (ECAL) and Hadronic (HCAL) calorimeters, and the four muon stations. All of these subsystems recently underwent significant upgrades to accommodate the increased luminosity and higher average number of visible proton-proton collisions per bunch crossing (μ) after "Upgrade I". This document presents an update on the PID performance following these upgrades.

2. PID strategy in LHCb

The three PID subsystems offer complementary information for the identification of charged and neutral particles. The RICH detectors excel in charged particle identification, particularly effective at distinguishing between hadrons with momenta in the range of 2.6 and 100 GeV/c. The ECAL and HCAL calorimeters, on the other hand, contribute primarily to the identification of photons, electrons, and both charged and neutral hadrons. Muon stations specialize in identifying muons due to their high penetrating power. For charged particles, the information from these subsystems is combined into high-level variables in two primary ways: $\Delta\text{LL}(x-\pi)$, representing the difference in log-likelihood for a track x under the kaon, proton, electron, muon, or pion hypothesis; and PROBNN_x, corresponding to the output of a Neural Network (NN) trained on simulation to distinguish between the particle species x against all the others. This variable integrates additional tracking information beyond that used in the log-likelihood approach and is tuned on real data. For neutral particles two PID variables are mostly used: `IsNotH` and `IsPhoton`, corresponding to dedicated NNs trained to distinguish photons from charged hadrons and π^0 clusters, respectively. This last aspect becomes particularly challenging at increasing μ, since the higher cluster pile-up in the calorimeters complicates the separation between the signatures of different particles. In these proceedings, only the performance of $\Delta\text{LL}(x-\pi)$ will be discussed, as the performance of the other variables is still under validation.

Particle identification performance is not perfectly modeled in simulation, therefore, to keep the associated systematic uncertainties subdominant, most measurements rely on a data-driven determination of these quantities. To make this possible, LHCb has developed a set of trigger lines referred collectively as TURCAL stream, that are fully dedicated to calibration purposes and that allow to collect data samples of high rate and high purity modes for each particle species. Thanks to the flexibility of the newly introduced full-software trigger, it is possible to do so while ensuring proper online alignment and calibration, providing datasets with offline reconstruction quality out-

Species	Primary channels
$K^\pm$	$D^{*+} \to D^0(\to K^-\pi^+)\pi^+$
$p^\pm$	$\Lambda^0 \to p\pi^-$
$\pi^\pm$	$D^{*+} \to D^0(\to K^-\pi^+)\pi^+$
$e^\pm$	$B^+ \to K^+ J/\psi(\to e^+e^-)$
$\mu^\pm$	Detached $J/\psi \to \mu^+\mu^-$

Table 1: Decay modes used for the data-driven determination of charged PID efficiencies in LHCb. Additional modes needed to enlarge the covered phase space region of these decays are currently under study and not reported here for simplicity. The inclusion of charge-conjugate processes is implied throughout this proceeding unless explicitly stated.

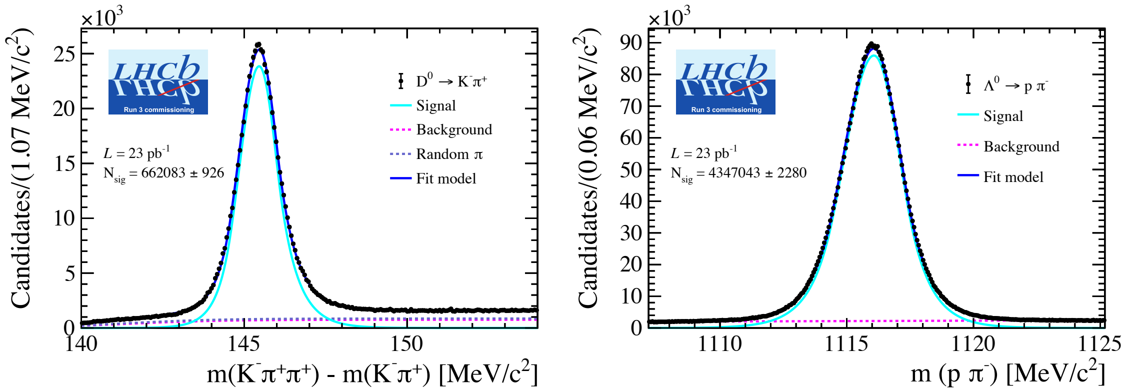

Figure 1: Invariant mass fits of $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ (left) and $\Lambda^0 \to p\pi^-$ (right) decay candidates [3]. The data is represented by the black dots, while in cyan and blue are shown the signal and total distributions respectively, as obtained from the fits.

of-the-box. The PID performance is then obtained from data using the tag-and-probe method. This method relies on the fact that, in a decay that can be selected cleanly using mainly kinematics, the use of particle identification on only one of the final state particles is sufficient to cleanly select the decay channels of interest. The other particle can therefore be used to probe PID efficiencies directly from data. An exception to this procedure is made when studying $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ and $\Lambda^0 \to p\pi^-$ decays. In these channels, the desired signal purity can be achieved without requiring additional PID information. Table 1 summarizes the list of the primary channels used to study the charged PID performance of kaon, protons, pion, electrons and muons. Additional channels are considered for systematic studies, but not reported here. Figure 1 shows the fit to the $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ and $\Lambda^0 \to p\pi^-$ calibration channels. The purities observed are comparable to those observed during Run 2 [2].

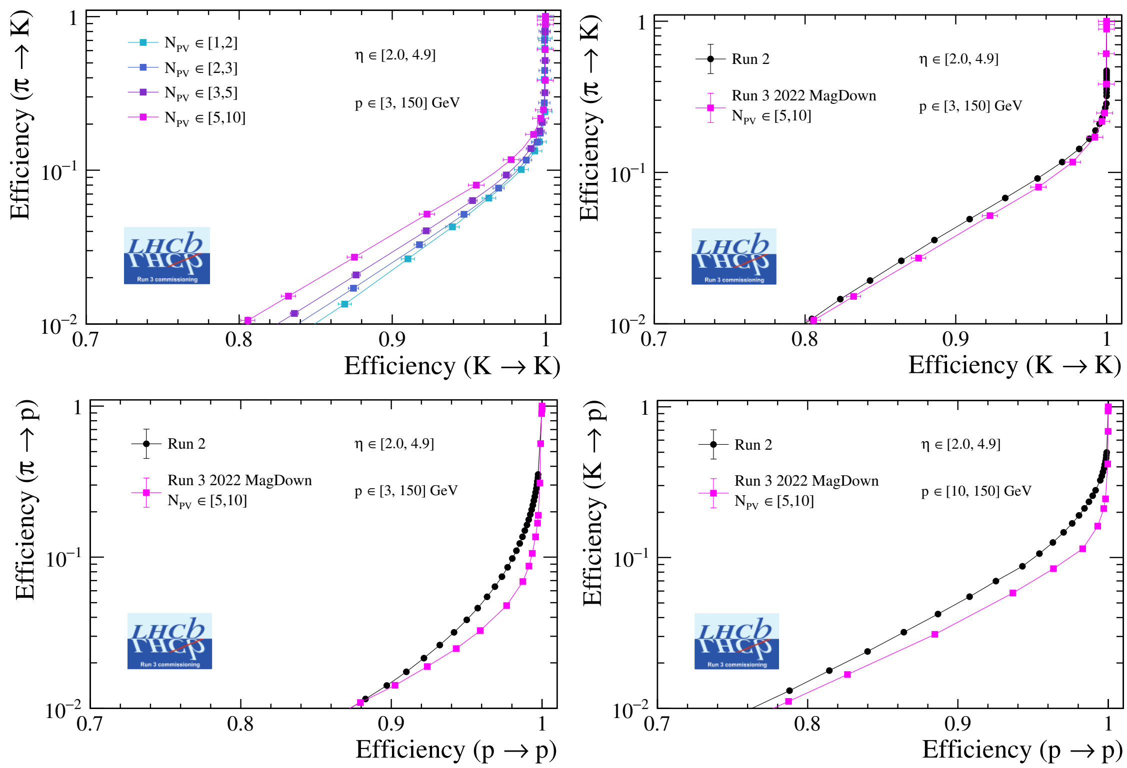

Figure 2: (Top left) Probability of a kaon (x-axis) or a pion (y-axis) to be identified as kaon as a function of the number of reconstructed primary vertices. (Top right and bottom row) Comparison between the efficiency and mis-identification probability of kaons, protons and pions as obtained in Run 2 (black) or in Run 3 for high multiplicity events (magenta). All curves are obtained scanning identification and mis-identification probabilities as a function of $\Delta\mathrm{LL}(x-\pi)$ [3].

3. Charged PID performance

The performance of the $\Delta\mathrm{LL}(x-\pi)$ variable is evaluated by comparing efficiencies and mis-identification probabilities of a given species as a function of momentum, number of primary vertices ($\mathrm{N_{PV}}$) or average μ. The charge hadron performance, summarized in Figure 2, clearly reflects the many improvements of the RICH systems with respect to the Run 2. In particular, two features are worth to be highlighted: the relative stability of the PID performance with the increase of the detector occupancy, and the increased ability of our detector the discriminate between kaons, protons and pions with respect to Run 2, even under much higher pile-up conditions. The PID performance for electrons and muons is shown in Figure 3. When compared against the results obtained in Run 2 and shown in Figure 2 of Ref.[5], the PID efficiencies probabilities obtained from 2024 data show similar performances. The probability of a pion being misidentified as a muon (electron) under the same conditions ($\Delta\mathrm{LL}(e-\pi) > 5$) also remains consistent, at approximately 1% or lower. Additionally, for both lepton species no significant dependence on the event pile-up is observed.

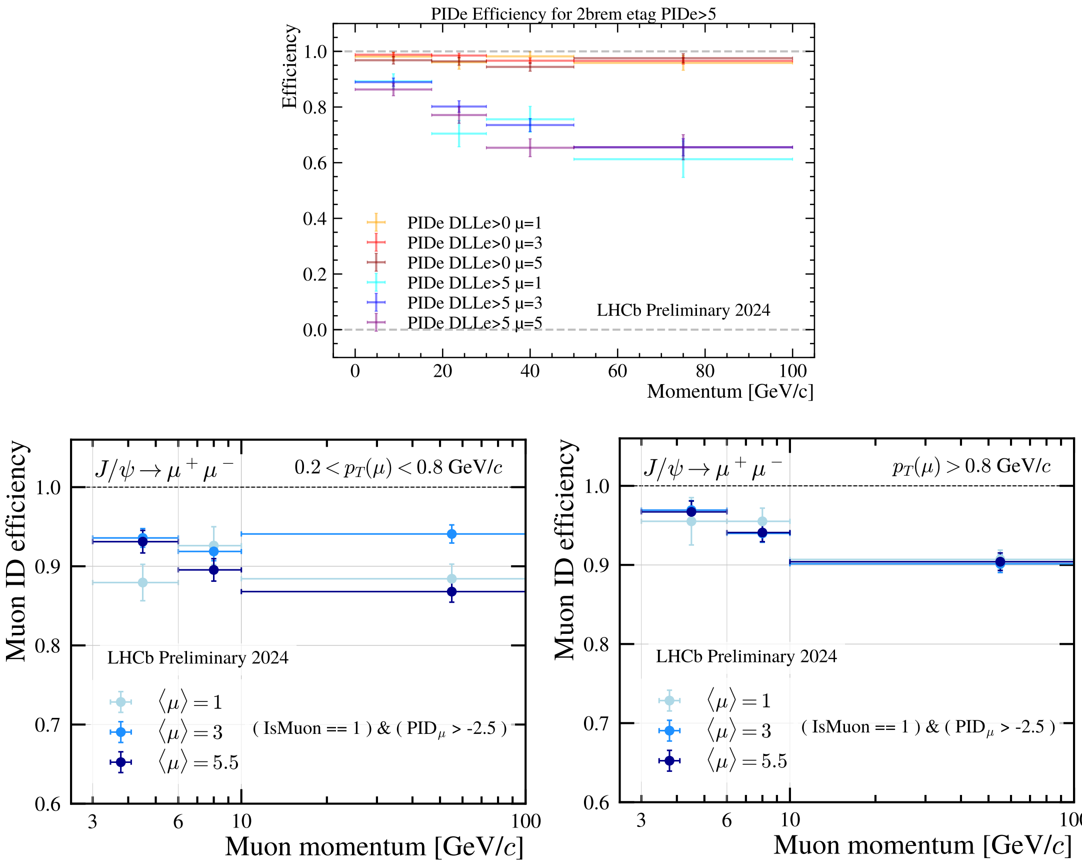

Figure 3: (Top row) Particle identification performance as a function of the electron's momentum and average μ [4]. Only events where bremsstrahlung clusters were consistent with originating from the two final-state electrons were considered. (Bottom row) Particle identification performance as a function of the muon's momentum and event average μ, in two bins of the muon's transverse momentum: $0.2 < p_T(\mu) < 0.8$ GeV/c (left) and $p_T(\mu) > 0.8$ GeV/c (right) [4]. The selection criteria consist of a combination of $\Delta\mathrm{LL}(x - \pi) > -2.5$, along with the requirement that the muon satisfies the `IsMuon` condition [6].

4. Conclusions

Achieving excellent particle identification is essential for LHCb to meet its ambitious physics objectives after "Upgrade I". The recent upgrades of the RICH detectors, calorimeters, and muon systems have proven effective in maintaining robust PID performance under the increased luminosity and pile-up conditions of Run 3. This proceeding presented an overview of the upgraded system's performance, with a focus on the data-driven evaluation of charged particle PID for hadrons and leptons. Preliminary results indicate that LHCb's PID performance is comparable to that of the previous runs, despite the more challenging environment of Run 3. This ensures that LHCb will remain well-positioned to deliver high-precision measurements and explore new physics in the years to come.

References

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