Performance of the Muon Identification at LHCb

The LHCb MuonID group†

Abstract

The muon identification procedure at LHCb is based on the pattern of the hits in the muon chambers. A momentum dependent binary requirement is used to reduce the probability of pions to the percent level, keeping a high muon efficiency. Then a likelihood is built for the muon and non-muon hypotheses. The performance of the LHCb muon identification is extracted from the data using muons and hadrons produced in the $J/\psi \rightarrow \mu^+\mu^-$, $\Lambda^0 \rightarrow p\pi^-$ and $D^{*+} \rightarrow \pi^+D^0(K^-\pi^+)$ decays. Muon efficiencies at the level of 95-98% are obtained with criteria which provide an incorrect pion identification below 0.6%. The probability of incorrect identification of kaons and protons are even lower.

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1 Introduction

The LHCb detector [1] is a dedicated heavy flavour experiment, designed to exploit the high \( pp \rightarrow c\bar{c} \) and \( pp \rightarrow b\bar{b} \) cross-sections at the LHC in order to perform precision measurements of CP violation and rare decays. Muons are present in the final state of many of the key decays, sensitive to new physics via CP violation observables or not. Moreover, they play a crucial role in the determination of the flavor tagging of the neutral \( B \) mesons and are also present in the signatures of interesting electroweak and strong processes. The muon identification procedure must be flexible enough to provide high muon efficiency while keeping the incorrect identification probability of light hadrons as muons (misidentification probabilities) at the lowest possible level. The pion misidentification is one of the major sources of combinatoric background for decays with muons in the final state. It is also important to keep the other hadron misidentification probabilities at low levels so that rare decays can be separated from more abundant hadronic decays with similar or identical topology.

This paper presents the performance of the muon identification in LHCb, obtained from the data taken in 2011, corresponding to approximately 1 fb\(^{-1}\). In Section 2, a brief description of the LHCb spectrometer and the muon detection system is given. The muon identification algorithm is discussed in Section 3. The method used to extract the muon efficiency and the misidentification probability from data is explained in Section 4. Finally, the performance results are presented in Section 5, followed by the conclusions in Section 6. In the appendix, performance plots similar to the ones shown in Section 5 for the pion sample are shown for the kaon and proton sample.

2 The LHCb experiment and the muon system

The LHCb detector [1] is a single-arm forward spectrometer. A vertex locator (VELO) determines with high precision the positions of the vertices of \( pp \) collisions (PVs) and the decay vertices of long-lived particles. The tracking system includes a silicon strip detector located in front of a dipole magnet with an integrated field of around 4 Tm, and a combination of silicon strip detectors and straw drift chambers placed behind the magnet, allowing the momentum determination of charged particles with a resolution of \( \sigma_p/p \sim 0.4(0.6)\% \) at a momentum scale of 3(100) GeV/c. Charged hadron identification is achieved with two ring-imaging Cherenkov (RICH) detectors. The calorimeter system consists of a scintillator pad detector, a preshower, an electromagnetic calorimeter and a hadronic calorimeter. It identifies high transverse energy hadron, electron and photon candidates and provides information for the trigger.

The muon system [2] is composed of five stations (M1-M5) of rectangular shape, placed along the beam axis. As shown in Figure Section 1, stations M2 to M5 are placed downstream the calorimeters and are interleaved with iron absorbers 80 cm thick to select penetrating muons. Station M1 is located in front of the calorimeters and is used to improve the transverse momentum measurement in the first level hardware trigger. The
Figure 1: Schematic view of the LHCb experiment, displaying one event recorded in 2011, where 2 muons are identified (purple tracks). This is one of the best $B^0_s \rightarrow \mu^+\mu^-$ candidates selected from the 2011 data [3]. The muon stations are seen as the five green vertical lines, the second one placed just after the calorimeters, shown as the rectangles with red and blue bars representing the energy deposition along the direction transverse to the beam.

The chambers are positioned to provide with their sensitive area a hermetic geometric acceptance to high momentum particles coming from the interaction point. In addition, the chambers of different stations form projective towers pointing to the interaction point. The detectors provide space point measurements of the tracks, providing binary (yes/no) information to the trigger processor and to the data acquisition (DAQ). The information is obtained by partitioning the detector into rectangular logical pads whose dimensions define the $x$, $y$ resolution in the plane perpendicular to the beam axis. Each station is divided into four regions, R1 to R4 with increasing distance from the beam axis. The linear dimensions of the regions R1, R2, R3, R4, and their segmentation scale in the ratio 1:2:4:8. Each muon plane is designed to perform with an efficiency above 99% in a 20 ns time window with a noise rate below 1 kHz per physical channel, what was achieved during operation, as described in [2].

The muon system provides information for the selection of high transverse momentum muons at the trigger level and for the offline muon identification. This document refers to the latter procedure, which uses only the information from the 4 stations located after the calorimeters. The muon identification in the trigger system is described in [4].
3 The muon identification procedure

The muon identification strategy in the LHCb experiment can be divided in two steps: a loose binary selection of muon candidates based on the penetration of the muons through the calorimeters and iron filters, which provides high efficiency while reducing the rate of hadrons to the percent level, and the computation of a likelihood for the muon and non-muon hypotheses, based on the pattern of hits around the extrapolation to the different muon stations of the charged particles trajectories reconstructed with high precision in the tracking system (tracks).

3.1 IsMuon binary selection

The binary selection, hereafter denominated IsMuon (true for tracks identified as muons and false otherwise), is defined according to the number of stations where a hit is found within a field of interest (FOI) defined around the track extrapolation. The number of stations required to be fired is a function of track momentum ($p$), as shown in Table 1. The size of the field of interest also depends on the particle momentum and are defined according to the expected multiple scattering suffered by a muon when traversing the material. They are parameterized separately for the 4 regions of the 4 different stations downstream the calorimeter in both $x$ and $y$ directions according to:

$$\text{FOI} = a + b \times \exp(-cp).$$

The parameters $a$, $b$ and $c$ have been determined using muons from a full detector Monte Carlo simulation [5].

<table>
<thead>
<tr>
<th>Momentum range</th>
<th>Muon stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3 \text{ GeV}/c &lt; p &lt; 6 \text{ GeV}/c$</td>
<td>M2+M3</td>
</tr>
<tr>
<td>$6 \text{ GeV}/c &lt; p &lt; 10 \text{ GeV}/c$</td>
<td>M2+M3+(M4 or M5)</td>
</tr>
<tr>
<td>$p &gt; 10 \text{ GeV}/c$</td>
<td>M2+M3+M4+M5</td>
</tr>
</tbody>
</table>

Table 1: Muon stations required to trigger the IsMuon decision as a function of momentum range.

For tracks passing the IsMuon requirement, the muon identification can be further improved by a selection based on the difference of the log-likelihood for the muon and non-muon hypotheses (muDLL).

3.2 Muon and non-muon likelihoods

The likelihoods are computed as the cumulative probability distributions of the average squared distance significance $D^2$ of the hits in the muon chambers with respect to the extrapolation of the tracks from the tracking system. True muons tend to have a
much narrower $D^2$ distribution, close to zero, than the other particles that are incorrectly selected by the IsMuon requirement.

The average squared distance significance is defined as:

$$D^2 = \frac{1}{N} \sum_{i=1}^{5} \left\{ \left( \frac{x_{\text{closest},i} - x_{\text{track}}}{\text{pad}_x} \right)^2 + \left( \frac{y_{\text{closest},i} - y_{\text{track}}}{\text{pad}_y} \right)^2 \right\}$$  \hspace{1cm} (1)$$

where the index $i$ runs over the fired stations, $(x_{\text{closest},i}, y_{\text{closest},i})$ are the coordinates of the closest hit to the track extrapolation for each station and pad$_x$, pad$_y$ correspond to one half of the pad sizes in the $x,y$ directions.

The $D^2$ distribution for muons depend on the multiple scattering and, therefore, on the momentum ($p$) and polar angle ($\theta$) distributions of the analyzed sample. In order to avoid a dependence of the muon likelihood on the calibration sample (with particular $p$ and $\theta$), the tuning of the muon likelihood is performed separately in momentum bins and muon detector regions (which correspond to 4 intervals of $\theta$).

The non-muon likelihood is calibrated with the $D^2$ distribution for protons, since the other charged hadrons (pions or kaons) selected by IsMuon will present a $D^2$ distribution with a component identical to the protons and a component very similar to the true muons, due to decays in flight before the calorimeter. For protons, the hits in the muon system found around the track extrapolation are essentially due to three sources: a random combination of hits, hits from muons produced in the collision which point to the same direction of the proton or from punch throughs. The first two are at first order uncorrelated to the proton momentum while the third one can present some momentum dependence, however less important than the dependence expected for muons. Moreover, since the IsMuon rate of protons is of the order of a few percent, the samples available are statistically limited for a calibration in momentum bins. Hence, the tuning of the non-muon likelihood is merely performed separately for the 4 muon system regions, due to their different granularity.

The likelihood for the muon (or non-muon) hypothesis is then defined, for each candidate, as the integral of the calibrated muon (or proton) $D^2$ probability density function from 0 to the measured value, $D^2_0$.

The results presented in this document are obtained with a muon likelihood calibrated with muons from $J/\psi \rightarrow \mu^+\mu^-$ decays selected from the data taken in 2010, as described in Section 4. The non-muon likelihood has been calibrated with a Monte Carlo sample of decays $\Lambda^0 \rightarrow p^+\pi^-$. The $D^2$ distributions for muons, protons, pions and kaons obtained from data are shown in Fig. 2(a). The muDLL distributions are shown in Fig. 2(b). More details about the selection of the particles used to make these plots and to extract the performance are given in Section 4.
3.3 Combined likelihoods

The muon and non-muon likelihoods presented in Section 3.2 can be combined to the likelihoods provided by the RICH systems and the calorimeters to provide an improved performance for muon identification.

The Cherenkov angle measurements measured in the two LHCb RICH detectors are combined with the track momentum using an overall event log-likelihood algorithm. For each track in the event, a likelihood is assigned to each mass hypothesis (electron, muon, pion, kaon and proton). The RICH likelihood can differentiate between muon and non-muon in particular at low momentum, below 5 GeV/c [6].

The energy deposition in the calorimeters also allows the evaluation of likelihoods for the muon (minimum ionizing particle), electron and hadron hypotheses [7].

A combined log-likelihood is then obtained for each track and for each of the different mass hypothesis by summing the logarithms of the likelihoods obtained using the muon, the RICH and the calorimeters. In this computation, the non-muon likelihood obtained in the muon system is assigned to the electron, pion, kaon and proton hypotheses. The difference of the combined log-likelihoods for the muon and pion hypotheses (combined DLL) is then used to identify the muons.

3.4 Nshared

The number of additional tracks in the event which share hits with the muon candidate can be used to further discriminate actual muon candidates from fake ones. In order to reduce the fraction of misidentification due to nearby muons keeping a high efficiency for true muons, only additional IsMuon candidates sharing at least one hit and with a smaller $D^2$ value for the square distance significance are counted to build the observable called from now on $N_{shared}$. Analyses which do want to reduce the probability of incorrectly identifying hadrons as muons due to this source usually select muons requiring $N_{shared}=0$, but looser requirements are also possible, as can be seen from the $N_{shared}$ distributions of muons, protons, pions and kaons shown in Fig. 3.
Figure 2: Average square distance distributions for muons, protons, pions and kaons (a) and the corresponding muon DLL distributions (b).

Figure 3: NShared distributions for muons, protons, kaons and pions.
4 Method for the extraction of efficiencies and misidentification rates

In order to extract the performance of the muon identification from data, muons, protons, pions and kaons from two body decays which have a clear signature and can be selected with high purity using only kinematical requirements are used. When necessary, the purity is improved by using a tag and probe technique where particle identification requirements are applied to one of the tracks (tag) while the other (probe) is used to the computation of the muon efficiency or of the hadron misidentification probabilities.

4.1 Selection of control samples

An abundant source of muons is provided in our experiment by the $J/\psi \rightarrow \mu^+\mu^-$ decay. By requiring the muons to have a high impact parameter with respect to the primary vertex and the reconstructed $J/\psi$ to have a large flight distance significance and good decay vertex quality ($\chi^2$), most of the combinatorial background originating from the tracks coming from the primary vertex is removed and the sample gets enriched by $B \rightarrow J/\psi X$ candidates. In order to reduce further the combinatorial background, one of the muons is required to have IsMuon true, $p > 6$ GeV/c and $p_T > 1.5$ GeV/c. This is defined as the tag muon while the one being probed is required to have $p_T > 0.8$ GeV/c.

Protons are selected from the $\Lambda^0 \rightarrow p^+\pi^-$ decays reconstructed using decay vertex quality criteria and detachment from the decay to the primary vertex. Besides, the invariant mass obtained by assigning the $\pi$ mass to the two daughters is required to be out of a window of 20 MeV/c$^2$ around the nominal $K^0_s$ mass.

The $D^{*+} \rightarrow \pi^+ D^0 (K^- \pi^+)$ decays are our source of pions and kaons. Once again relatively high impact parameter is required for the daughters while the $D^0$ flight direction is required to point to the primary vertex. To evaluate the pion misidentification probability, we require the kaon to satisfy a particle identification condition using a cut on the difference of $\pi$-$K$ log-likelihoods based on the RICH information. To evaluate the kaon misidentification probability we apply the RICH particle identification condition on the pion. Quality criteria are used for the $D^{*+}$ and $D^0$ decay vertices. A window of 25 MeV/c$^2$ around the nominal $D^0$ mass is used to exclude the doubly Cabibbo supressed mode (opposite charge) and the $K^+K^-$ and $\pi^+\pi^-$ decay channels.

To avoid our results to be biased by the trigger requirements, only events which are triggered independently of the probe tracks of the $J/\psi$ and $\Lambda^0$ samples are used, both in the hardware and software levels. For the $D^0 \rightarrow K^-\pi^+$ sample, a substantial fraction of the events would be lost by such requirement. We therefore require that the lowest level hardware trigger fires independently of the kaons and pions and that the high level trigger decision is based only on impact parameter and detachment from the primary vertex, with no particle identification requirement.

\footnote{To understand how it is possible to use events triggered independently of the candidate tracks, please refer to [8]}
The mass distributions of the two-body decay samples used in this study are presented in Fig. 4. The relative low purity of the $J/\psi$ sample is due to the fact that only one of the muons is required to be well identified as muon, passing the IsMuon requirement (tag and probe selection). On the bottom left plot, the $D^0$ candidates passed a selection including a PID requirement on the pion, so that the background is reduced and the pion is used in the extraction of the performance. On the bottom right plot, the kaon is selected using a PID requirement, and the pion is used to extract the performance (again using a tag and probe technique).

The total number of track candidates in each sample and the yields obtained from the mass fits in the signal windows are given in Table 2.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Candidate tracks ($\times 10^6$)</th>
<th>Signal tracks ($\times 10^6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>muons</td>
<td>23.2</td>
<td>2.4</td>
</tr>
<tr>
<td>protons</td>
<td>20.8</td>
<td>16.1</td>
</tr>
<tr>
<td>pions from $D^0$</td>
<td>14.8</td>
<td>11.7</td>
</tr>
<tr>
<td>kaons from $D^0$</td>
<td>16.8</td>
<td>12.3</td>
</tr>
</tbody>
</table>

### 4.2 Efficiency evaluation

As a baseline method to evaluate the efficiency $\epsilon_{\text{muonID}}$ of a generic muon identification requirement denoted in this section by $\text{muonID}$ (e.g. IsMuon true or DLL greater than a given cut), we use:

$$\epsilon_{\text{muonID}} = \frac{S_{\text{true}}}{S_{\text{true}} + S_{\text{false}}},$$

(2)

where $S_{\text{true}}$ and $S_{\text{false}}$ are the numbers of signal events satisfying and not satisfying $\text{muonID}$, extracted from data using

$$S_{\text{true,false}} = N_{\text{true,false}} - B_{\text{true,false}}.$$ (3)

$N_{\text{true,false}}$ are obtained by counting the number of $J/\psi$ candidates with invariant mass lying within a signal mass window around the $J/\psi$ mass and $B_{\text{true,false}}$, the number of background events within the same mass window, is computed by extrapolating the background mass fit to the sidebands of the $J/\psi$ mass distribution to the signal window.

For the proton misidentification probability, the same method is used.

The kaon and pion misidentification probabilities are also obtained with Eq. 2 but $S_{\text{true,false}}$ and $B_{\text{true,false}}$ are extracted directly from a full fit of the signal and background shapes to the invariant mass distribution of the $D^0$ candidates.
Figure 4: Fits of the mass distributions of the two-body decays used to extract the muon identification performance: muons from $J/\psi$ on the top left, protons from $\Lambda$ on the top right, and kaons and pions from $D^0$ (bottom).

5 Results

The muon identification performance is presented in terms of the muon efficiency and hadron misidentification probabilities for the different requirements. In all cases, the performance is evaluated for tracks pointing to a position within the geometrical acceptance of the muon detector.

5.1 IsMuon performance

The efficiency of the IsMuon requirement, $\epsilon_{IM}$, is the efficiency of finding hits within the fields of interest in the muon chambers for tracks extrapolated to the Muon system. In Fig. 5(a), $\epsilon_{IM}$ is shown as a function of the muon momentum, for different transverse momentum ranges. A weak dependency with transverse momentum is observed and in particular a drop of $\sim2\%$ is measured for the lowest $p_T$ interval. This efficiency drop is essentially due to tracks close to the inner edges of region R1 which in principle have their extrapolation points within M1 and M5 acceptance, but are in fact scattered outside the detector. For particles with $p_T$ above 1.7 GeV/c, the efficiency is above 97% in the whole momentum range, from 3 GeV/c to 100 GeV/c. The average efficiency obtained for the $\mu_{\text{probe}}$ in the $J/\psi$ calibration sample is $\epsilon_{IM}=(98.13 \pm 0.04)\%$. 
The misidentification probabilities $\mathcal{P}^p_{IM}$, $\mathcal{P}^\pi_{IM}$ and $\mathcal{P}^K_{IM}$ are also given in Fig. 5. The fraction of protons within the muon system which are identified as muons drops quickly with momentum for the lowest $p_T$ ranges, reaching a plateau at about 30-40 GeV/c. The observed decrease of $\mathcal{P}_{IM}$ with increasing transverse momentum is expected, since tracks with higher transverse momentum traverse the detector at higher polar angles, in the lower occupancy regions. The proton misidentification probability is at the range 0.5% for all $p_T$ ranges and momentum above 30 GeV/c. The pion and kaon misidentification probability have a similar behavior, increasing with decreasing $p_T$. Above 40 GeV/c, the pion misidentification probability is almost at the level of the proton misidentification probability. At low momentum, decays in flight are the dominant source.

**Figure 5:** IsMuon efficiency and misidentification probabilities, as a function of momentum, in ranges of transverse momentum: $\epsilon_{IM}$ on the top left, $\mathcal{P}^p_{IM}$ on the top right, $\mathcal{P}^\pi_{IM}$ on the bottom left and $\mathcal{P}^K_{IM}$ on the bottom right.
of incorrect identification. While the proton misidentification probability, within the $p_T$ intervals chosen, lies within 0.1-3.1%, the pion and kaon misidentification probability are within 0.2-5.6% and 0.6-4.5%. For momentum above 30 GeV/c, $P_{IM}^\pi$ and $P_{IM}^K$ are practically independent of $p_T$. Note that the correlation between $p$ and $p_T$ for the daughters of $D^0$ and detached $J/\psi$ is higher than the one for $\Lambda$, therefore for the latter there are enough particles in our samples to extract the performance at high $p_T$ even for the lowest momentum ranges. When integrated over the whole $p$ and $p_T$ spectra of our calibration samples, the average values for the misidentification probabilities are $P_{IM}^p = (1.033 \pm 0.003)\%$, $P_{IM}^\pi = (1.025 \pm 0.003)\%$ and $P_{IM}^K = (1.111 \pm 0.003)\%$. The average efficiency and misid probabilities, integrated over momentum, are also given in Table 3, for 5 different $p_T$ intervals. There aren’t enough candidates in the muon, pion and kaon samples for a measurement dependent on momentum in the lowest $p_T$ bin. Similarly for the protons, in the highest $p_T$ interval.

The LHCb detector has been designed to operate at the luminosity of $\mathcal{L} = 2 \times 10^{32}$ cm$^2$/s$^{-1}$, at which the probability of having one interaction per beam crossing is maximal with respect to higher numbers. However, in the 2011 run the experiment operated on a much higher multiplicity environment than previously anticipated. The behavior of $\epsilon_{IM}$ and $P_{IM}$ was evaluated as a function of the number of tracks which contain hits in the tracking subsystems, from the VELO to the tracking stations, as those shown in the event display of Fig. 1.

No significative decrease of $\epsilon_{IM}$ is observed while, as expected, an increase of the misidentification probabilities is seen. The probability $P_{IM}^p$ increases by a factor 2.7 for particles with momentum in the range 3 to 5 GeV/c, when comparing events with track multiplicity smaller than 40 and events with track multiplicity between 150 and 250, which is the highest interval of multiplicity analised. At high momentum, the difference is much less important. For pions and kaons, the increase at low momentum is around 2 and drops very quickly, becoming insignificant already at 20 GeV/c. The detailed behaviour as a function of momentum is shown in Section A in Fig. 15.

The efficiency $\epsilon_{IM}$ was also analysed separately for the opposite charge muons. As seen in Fig. 6, no difference between the efficiencies is seen up to the level of the statistical fluctuations. When integrating over the whole momentum range, the relative difference is $0.09\pm0.08\%$, compatible with zero within the statistical uncertainty.

<table>
<thead>
<tr>
<th>$p_T$ interval (GeV/c)</th>
<th>$\mu$</th>
<th>proton</th>
<th>pion</th>
<th>kaon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T &lt; 0.8$</td>
<td>$1.393 \pm 0.005$</td>
<td>$6.2 \pm 0.1$</td>
<td>$4.3 \pm 0.1$</td>
<td></td>
</tr>
<tr>
<td>$0.8 &lt; p_T &lt; 1.7$</td>
<td>$96.94 \pm 0.07$</td>
<td>$0.737 \pm 0.003$</td>
<td>$2.19 \pm 0.01$</td>
<td>$1.93 \pm 0.1$</td>
</tr>
<tr>
<td>$1.7 &lt; p_T &lt; 3.0$</td>
<td>$98.53 \pm 0.05$</td>
<td>$0.149 \pm 0.004$</td>
<td>$0.61 \pm 0.01$</td>
<td>$0.93 \pm 0.01$</td>
</tr>
<tr>
<td>$3.0 &lt; p_T &lt; 5.0$</td>
<td>$98.51 \pm 0.06$</td>
<td>$0.12 \pm 0.02$</td>
<td>$0.40 \pm 0.01$</td>
<td>$0.72 \pm 0.01$</td>
</tr>
<tr>
<td>$5.0 &lt; p_T$</td>
<td>$98.51 \pm 0.07$</td>
<td>$0.33 \pm 0.02$</td>
<td>$0.69 \pm 0.01$</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Average IsMuon efficiency and misid probabilities in different transverse momentum intervals (%).
Figure 6: Ratio between $\epsilon_{IM}$ for $\mu^+$ and $\mu^-$ as a function of momentum and integrated over transverse momentum, for the whole sample in black circles, for data taken with magnet polarity up in blue squares and magnet polarity down in red triangles.

5.2 Muon likelihoods

The muon identification efficiency ($\epsilon_{\text{muDLL}}$) is analysed as a function of a selection cut in the variable muDLL, for different momentum ranges, as shown in the top left part of Fig. 7. The misidentification probabilities are also shown in Fig. 7, for the same momentum ranges. The black solid line shows the average fractions, when integrated over the whole momentum range. All the curves start at the efficiency or misidentification probability corresponding to the IsMuon requirement.

The efficiency is also shown directly as a function of the misidentification probabilities in Fig. 8. Requiring muDLL\(\geq\)1.74, a cut that provides a muon efficiency of 95% with respect to the IsMuon efficiency (final muon efficiency of 93.2%), we obtain as final misidentification probabilities the values 0.21%, 0.78% and 0.52% for protons, kaons and pions respectively. These average values are given for our calibration samples, which have their particular momentum and $p_T$ spectrum and will be different for samples with different kinematic distributions.

The momentum dependence of $\epsilon_{\text{muDLL}}$ and of $P_{\text{muDLL}}$ for particles satisfying this cut are shown in Fig. 9, compared to the IsMuon requirement alone and a tighter cut, muDLL\(\geq\)2.25, which reduces the total efficiency for the $J/\psi$ calibration sample to 90% of the IsMuon efficiency. Again, since the performance is integrated over $p_T$, small variations from these values are expected for different samples, in particular for the misidentification probabilities, which present a stronger dependence with transverse momentum.
Figure 7: The efficiency $\epsilon_{\text{muDLL}}$ as a function of muon DLL cut for muons (top left) and misidentification probabilities (or efficiencies, as shown in the plots) for protons (top right), pions (bottom left) and kaons (bottom right). The black solid line shows the average values integrated over $p > 3$ GeV/c. The blue dotted line correspond to particles in the range $3 < p < 10$ GeV/c. The red dashed lines show results for $10 < p < 20$ GeV/c and the green dashed-dotted for $p > 20$ GeV/c.

5.3 Combined likelihoods

The combined DLL efficiency is shown as a function of the proton, kaon and pion misidentification probabilities in Fig. 10 and Fig. 11 together with the results obtained using the muDLL alone, allowing for a direct comparison of their performances. We observe that the superiority of the combined DLL performance with respect to the muon DLL alone is more important for pions and kaons, as expected, since the muon DLL is
Figure 8: Efficiency $\epsilon_{\text{muDLL}}$ as a function of the proton (top left), kaon (top right) and pion (bottom) misidentification probabilities shown for the whole samples and the three different momentum ranges of Fig 7.

optimized for the proton-muon separation. In particular, the average misidentification rates corresponding to a cut which provides an average efficiency of 93.2% (equivalent to the one obtained with muDLL$\approx$1.74, as shown in the previously) are around 0.22%, 0.65% and 0.38% for the protons, kaons and pions, respectively. The corresponding requirement on the combined DLL is CDLL$\approx$1.15.

Similar plots, showing the performance for different ranges of momentum are shown in Section A. The lower the momentum, more important is the gain of using the combined DLL. Moreover, the difference is only important for cuts which provide an efficiency below the 90-95% level.

For the remaining part of this document, the performance will be focused on the muon efficiency and pion misidentification probability, since pions are most copiously produced in the pp collisions and are thus the most relevant contribution to the combinatorial
Figure 9: Muon efficiency (top left) and misidentification probabilities for protons (top right), kaons (bottom left) and pions (bottom right) as a function of the particle momentum for the IsMuon requirement alone (black solid circles) and with the additional cuts $\mu_{DLL} \geq 1.74$ (red triangles) and $\mu_{DLL} \geq 2.25$ (blue open circles).

The probability of a kaon to be identified as a muon presents a behaviour very similar to the pion misidentification probability, as seen for the results presented so far. However, absolute values are different, hence the performance plots for the kaon sample are shown in the appendix, as are the ones produced for the proton sample. The latter are interesting because show the level of misidentification which is free from the contribution of decays in flight.
Figure 10: Average efficiency $\epsilon_{\text{DLL}}$ as a function of the pion (a) and kaon (b) misidentification probability for particles with momentum in the range $p > 3$ GeV/c. The dotted lines show the combined DLL performance, while the muon DLL performance is shown with a solid line.

Figure 11: Average efficiency $\epsilon_{\text{DLL}}$ as a function of the proton misidentification probability for particles with momentum in the range $p > 3$ GeV/c. The dotted lines show the combined DLL performance, while the muon DLL performance is shown with a solid line.

5.4 Nshared performance

As mentioned in Section 3, after requiring IsMuon, an additional way of reducing the incorrect identification probability of hadrons as muons, in particular at high occupancy, is the use of a cut on Nshared.

The muon efficiency $\epsilon_{\text{Nshared}}$ is shown as a function of the pion
Figure 12: Efficiency $\epsilon_{\text{Nshared}}$ as a function of the pion misidentification probability.

Figure 13: Muon efficiency (a) and pion misidentification probability for the simultaneous requirement of IsMuon true and Nshared=0 (red open circles), compared to the IsMuon requirement alone (black circles).

The black solid line shows the average values integrated over $p > 3$ GeV/c. The blue dotted line correspond to particles in the range $3 < p < 10$ GeV/c. The red dashed lines show results for $10 < p < 20$ GeV/c and the green dashed-dotted for $p > 20$ GeV/c. This can also be seen from Fig. 13, where the momentum dependency of the muon and pion efficiencies for Nshared=0 are illustrated. The same information is given in Section A for kaons and protons.
5.5 Systematic checks

The effect of the trigger and of the method chosen to evaluate the efficiency and misidentification probabilities were investigated.

Alternatively to the requirement of the $J/\psi \rightarrow \mu^+\mu^-$ sample being triggered independently of the probe muon, a muon trigger decision based on the tag muon was used to evaluate the Ismuon efficiency. The systematic uncertainty due to the choice of trigger strategy was taken as the difference between the two determinations, which is of 0.2%.

When performing a full fit to the signal and background components of the mass distributions used to extract the yields of signal events satisfying or not the muon identification requirements, the resulting efficiencies and proton misidentification probability rates agree within the statistical uncertainties with the results shown in Section 5.

For the pion and kaon misidentification probabilities, the effect of requiring that the trigger is independent of the track being probed was studied. The ratio between the IsMuon misidentification probabilities obtained with this requirement and the baseline requirement explained in Section 4 is shown in Fig. 14. The ratios are compatible with 1 within statistical uncertainties and no systematic error is quoted due to the trigger strategy. The systematic uncertainties due to the evaluation method are usually smaller than the statistical one, apart from some bins at low or high momentum where the two contributions are at the same level.

![Figure 14: (a) Ratio between $P_{\pi}$ obtained with the baseline trigger requirement and a trigger independent of the pion. (b) Same for the kaon. The ratios are given as a function of momentum and transverse momentum.](image)

6 Conclusions

We have measured the performance of the offline muon identification procedure used in the LHCb experiment, using 1 fb$^{-1}$ of data taken in 2011.

The algorithm is based on a binary selection based on the matching of muon hits with particle trajectory. For candidates satisfying this requirement, likelihoods for muon and
non-muon hypotheses are built with the pattern of hits around the trajectories, which can be used to refine the selection. An additional way of rejecting fake muon candidates is provided by a variable sensitive to hit sharing by nearby particles. The muon identification efficiency was observed to be robust against the operational conditions and presents a weakly dependence on momentum and transverse momentum. Hadron misidentification probabilities present a stronger dependence on hit or track multiplicity, however the highest increase factors are observed only for low momentum particles. At high momentum the variations are always smaller than a factor 2, for protons, and negligible for pions and kaons.

Average muon identification efficiencies at the 98% level are attainable for pion and kaon misidentification below the level of 1% at high transverse momentum, using the loosest identification criterium. The performance of additional requirements based on likelihoods or hits sharing can be tuned according to the needs of each analysis and reduce the misidentification probabilities dependence on track multiplicity.

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References


Appendix

A Additional performance plots

Figure 15: IsMuon efficiency $\epsilon_{IM}$ (top left) and $P_{IM}$ for protons (top right), pions (bottom left) and kaons (bottom right) as a function of momentum for different ranges of the number of trajectories reconstructed in the event (ntracks).
Figure 16: Average efficiency $\epsilon_{\text{DLL}}$ as a function of the pion (a) and kaon (b) misidentification probability for particles with momentum in the range $3 < p < 10 \text{ GeV}/c$. The dotted lines show the combined DLL performance, while the muon DLL performance is shown with a solid line.

Figure 17: Average efficiency $\epsilon_{\text{DLL}}$ as a function of the pion (a) and kaon (b) misidentification probability for particles with momentum in the range $10 < p < 20 \text{ GeV}/c$. The dotted lines show the combined DLL performance, while the muon DLL performance is shown with a solid line.
Figure 18: Average efficiency $\epsilon_{\text{DLL}}$ as a function of the pion (a) and kaon (b) misidentification probability for particles with momentum in the range $p > 20 \text{ GeV/c}$. The dotted lines show the combined DLL performance, while the muon DLL performance is shown with a solid line.
Figure 19: Average efficiency $\epsilon_{\text{DLL}}$ as a function of the proton misidentification probability for particles with momentum in the ranges $3 < p < 10$ GeV/$c$ (top left), $10 < p < 20$ GeV/$c$ (top right) and $p > 20$ GeV/$c$ (bottom). Dashed lines show the combined DLL performance compared to the muon DLL performance with solid lines.
Figure 20: Efficiency $\epsilon_{\text{Nshared}}$ as a function of the proton (a) and kaon (b) misidentification probabilities shown for the whole samples and for three different momentum ranges.
Figure 21: Proton (a) and kaon (b) misidentification probabilities for the simultaneous requirement of IsMuon true and Nshared=0 (red open circles), compared to the IsMuon requirement alone (black circles).