Performance of the Muon Identification at LHCb

The LHCb Collaboration

Abstract
The performance of the LHCb muon identification is extracted from the 2011 data using $J/\psi \rightarrow \mu^+\mu^-$, $\Lambda \rightarrow p\pi^-$ and $D^* \rightarrow \pi D^0(K\pi)$ decays. At high transverse momentum, efficiencies at the level of 98% are obtained for an incorrect pion identification below 0.6%, using the less stringent criterium. A continuous variation of those levels can be obtained by tuning a cut on the difference of log-likelihoods, according to the purity levels needed for each analysis.

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1 Introduction

The LHCb detector \[1\] is a dedicated heavy flavour experiment, designed to exploit the high \( pp \to c\bar{c} \) and \( pp \to b\bar{b} \) 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 CP and new physics sensitive decays. 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 as low as reasonable 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.

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 preshower, a scintillator pad detector, 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 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 total absorber thickness in front of station M2, including the calorimeters, is approximately 6.6 interaction lengths. The major part of the system is equipped with multi-wire proportional cham-
Figure 1: Schematic view of the LHCb experiment, displaying one event recorded in 2011, where 2 muons are identified (purple tracks). This turned out to be the best $B_s^0 \rightarrow \mu^+\mu^-$ candidate of 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 in such a way 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 are placed in such way that they 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 20ns 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.

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).

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 [4].

<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 with IsMuon true, the muon identification can be further improved by a
selection based on the difference of the log-likelihood for the muon and non-muon hypothe-
ses (muDLL). The likelihoods are computed as the cumulative probability distributions
of the average squared distance $D^2$ 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 is defined as:

$$D^2 = \frac{1}{N} \sum_{i=0}^{N} \left\{ \left( \frac{x_{\text{closest},i} - x_{\text{track}}}{\text{pad}_x} \right)^2 + \left( \frac{y_{\text{closest},i} - y_{\text{track}}}{\text{pad}_y} \right)^2 \right\}$$

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$_{x,y}$ correspond to one half
of the pad sizes in the $x,y$ directions.
The $D^2$ distributions for muons depend on the multiple scattering and, therefore, on the momentum and transverse momentum (or pseudo-rapidity) distributions of the analyzed sample. In order to avoid a dependence of the muon likelihood on the calibration sample (with particular $p$ and $p_T$ spectra), the tuning of the muon likelihood is performed separately in momentum bins and muon detector regions. The non-muon likelihood is built 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. The tuning is done separately in the 4 muon system regions due to their different granularity. The likelihood for each hypothesis is then defined event-by-event as the integral of the $D^2$ 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 and selected as described in Section 4. The non-muon likelihood has been calibrated with a Monte Carlo sample of decays $\Lambda \rightarrow p\pi^-$. We do not expect a significant reduction of discriminating power from the use of simulation in the likelihood determination.

The $D^2$ distributions for muons, protons, pions and kaons obtained from data is 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.

For each track passing the IsMuon requirement there is still another muon discriminating variable called Nshared, defined as the number of additional tracks in the event which are selected by the IsMuon requirement due to at least one hit shared with the current track and that have a $D^2$ value smaller than the $D^2$ value of this current track. This was designed to reduce the fraction of misidentification due to nearby muons keeping a high efficiency for true muons. Analyses which do want to reduce the probability of incorrectly identifying hadrons as muons due to this source usually select muons requiring Nshared=0, but looser requirements are also possible, as can be seen from the Nshared 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 (red full circles), protons (blue open circles), kaons (green open squares) and pions (black full squares).
4 Method for the extraction of efficiencies and misidentification rates

In order to extract the performance of the muon identification from data, we use 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. 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. In order to reduce further this type of background, one of the muons is required to have IsMuon true, \( p > 6 \text{ GeV}/c \) and \( p_T > 1.5 \text{ GeV}/c \). This is defined as the *tag* muon while the one being probed is required to have \( p_T > 0.8 \text{ GeV}/c \).

Protons are selected from the \( \Lambda \rightarrow p\pi^- \) 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/c² 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/c² 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 muons of the \( J/\psi \) sample are used. 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.

The mass distributions of the two-body decay samples used in this study are presented in Fig. 4. 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.
Figure 4: Fit 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 (bottom left) and pions (bottom right) from $D^0$.

Table 2: Number of tracks in the 2011 samples used to extract the muon identification performance. The number of signal tracks correspond to the number of tracks in the signal window subtracted from the number of background candidates.

<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 muonID (e.g. IsMuon true or DLL greater than a given cut), we use:

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

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

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

$N_{\text{true,false}}$ 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.
The signal mass window is defined as the interval 3060-3120 MeV/c$^2$ and a linear back-
ground shape is fitted to data in the mass ranges 2900-3000 MeV/c$^2$ and 3200-3295 MeV/c$^2$.

For the proton misidentification probability, the same method is used, for sig-
nal events with an invariant mass $m_{\proton\pi}$ in the range 1111-1121 MeV/c$^2$ and the side-
bands defined as the intervals 1099-1104 and 1128-1133 MeV/c$^2$. The kaon and pion
misidentification probabilities are obtained with Eq. 2, and $S_{\text{true,false}}$ 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 in the range 1810-1920 MeV/c$^2$. A double Gauss-
ian shape is used to describe the signal events and a third order Chebychev polynomial is
taken as probability density function for the background events. The signal mass window
is defined as the range 1851-1883 MeV/c$^2$.

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 per-
formance 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=\text{true} requirement, $\epsilon_{IM}$, is the efficiency of finding hits
within the fields of interest in the muon chambers for tracks extrapolated to the 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 significative 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 $P_{IM}^{p}$, $P_{IM}^{\pi}$ and $P_{IM}^{K}$ are given in Figs. 5(b), 5(c)
and 5(d). 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 $P_{IM}$ with increasing transverse momentum is expected,
since tracks with higher transverse momentum traverse the detector at higher polar angles,
in the lower occupancy regions. Nevertheless, 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 misid.
At low momentum, decays in flight are the dominant source 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, $P^\pi_{IM}$ and $P^K_{IM}$ 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

![Graphs showing IsMuon efficiency and misidentification probabilities as a function of momentum, in ranges of transverse momentum: $\epsilon_{IM}$ on the top left (a), $P^p_{IM}$ on the top right (b), $P^\pi_{IM}$ on the bottom left (c) and $P^K_{IM}$ on the bottom right (d).](image-url)
for the misidentification probabilities are \( P_{\mu}^{\text{IM}} = (1.033 \pm 0.003)\% \), \( P_{\pi}^{\text{IM}} = (1.025 \pm 0.003)\% \) and \( P_{\text{K}}^{\text{IM}} = (1.111 \pm 0.003)\% \). The average efficiency and misid probabilities, integrated over momentum, are also given in Table 3 for 5 different \( p_T \) bins.

Although the LHCb detector has been designed to operate at the luminosity of \( \mathcal{L} = 2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1} \), at which the probability of having one interaction per beam crossing is maximal with respect to higher numbers, in the 2011 run the experiment operated on a much higher multiplicity environment. The behavior of \( \epsilon_{\text{IM}} \) and \( P_{\text{IM}} \) was evaluated also as a function of the number of tracks which contain hits in the tracking subsystems, from the VELO to the tracking stations. These are called long tracks. The results are shown in Fig. 6. No significant decrease of \( \epsilon_{\text{IM}} \) is observed while, as expected, an increase of the misidentification probabilities is seen. \( P_{\mu}^{\text{IM}} \) increases by a factor 2.7 from the lowest to the highest multiplicity interval at the lowest momentum bin. At high momentum, the difference is much less important. For pions and kaons, the increase at low momentum is around 2.

The efficiency \( \epsilon_{\text{IM}} \) was also analysed separately for the opposite charge muons. As seen in Fig. 7, 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 only 0.09%.

### 5.2 Muon likelihoods discrimination

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. 8. The misidentification probabilities are also shown in Fig. 8 for the same momentum ranges. Here, black markers show 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.

As a figure of merit, requiring muDLL \( \geq 1.74 \), a cut that provides a final muon efficiency of 93.2% (95% with respect to the IsMuon efficiency), 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 efficiency is also shown directly as a function of the

<table>
<thead>
<tr>
<th>( p_T ) interval (( \text{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 ± 0.005</td>
<td>6.2 ± 0.1</td>
<td>4.3 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>0.8 &lt; ( p_T &lt; 1.7 )</td>
<td>96.94 ± 0.07</td>
<td>0.737 ± 0.003</td>
<td>2.19 ± 0.01</td>
<td>1.93 ± 0.1</td>
</tr>
<tr>
<td>1.7 &lt; ( p_T &lt; 3.0 )</td>
<td>98.53 ± 0.05</td>
<td>0.149 ± 0.004</td>
<td>0.61 ± 0.01</td>
<td>0.93 ± 0.01</td>
</tr>
<tr>
<td>3.0 &lt; ( p_T &lt; 5.0 )</td>
<td>98.51 ± 0.06</td>
<td>0.12 ± 0.02</td>
<td>0.40 ± 0.01</td>
<td>0.72 ± 0.01</td>
</tr>
<tr>
<td>5.0 &lt; ( p_T )</td>
<td>98.51 ± 0.07</td>
<td>0.33 ± 0.02</td>
<td>0.69 ± 0.01</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6: IsMuon efficiency $\epsilon_{IM}$ (a) and $P_{IM}$ for protons (b), pions (c) and kaons (d) as a function of momentum for different ranges of event long track multiplicity.

misidentification probabilities in Fig. [9]

The momentum dependence of $\epsilon_{mDDL}$ and of $P_{mDDL}$ for particles satisfying this cut are shown in Fig. [10] compared to the IsMuon requirement alone and a tighter cut, muDDL $\geq$ 2.25, which reduces the total efficiency for the $J/\psi$ detached calibration sample to 90% of the IsMuon efficiency. Again, since the performance is integrated over $p_T$, variations from these values are expected for different samples.
### Figure 7: 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.

5.3 Performance of the combined DLL

By combining the muon system information with the RICH and CALO capabilities on particle identification, we expect to improve the performance. For a direct comparison, the efficiency as a function of the misidentification probabilities corresponding to the same DLL cuts are shown in Figs. [11][13] together with the performance of the muDLL alone, for different momentum ranges. In particular, the average misidentification rates corresponding to a cut which provides an average efficiency of 93.2%, obtained with DLL$\geq$1.15, are around 0.22%, 0.65% and 0.38% for the protons, kaons, and pions respectively. 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 optimized for the proton-muon separation. 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 95-90% level.

5.4 Nshared performance

As mentioned in Section 3, after requiring IsMuon=True, an additional way of reducing the incorrect identification probability of hadrons as muons, in particular at high occupancy, is to use a cut on Nshared. The muon efficiency $\epsilon_{N\text{shared}}$ is shown as a function of the proton and kaon misidentification probabilities in [14]. The momentum dependency of $\epsilon_{N\text{shared}}$ and the misid rates for Nshared=0 is given in Fig. [15].
Figure 8: The efficiency $\epsilon_{\text{muDLL}}$ as a function of muon DLL cut for muons (top left) and misidentification probabilities for protons (top right), pions (bottom left) and kaons (bottom right). The black solid circles show the average values integrated over $p > 3$ GeV/c, the blue open circles for particles in the range $3 < p < 10$ GeV/c, the red squares for $10 < p < 20$ GeV/c and the green open squares for $p > 20$ GeV/c.

5.5 Systematic checks

We studied the effect of the trigger unbias strategy and of the method chosen to evaluate the efficiency or misidentification probabilities.

For the efficiency, instead of requiring the selected tag-and-probe sample to be triggered independently of the $\mu_{\text{probe}}$, we required alternatively a muon trigger due to the
Figure 9: Efficiency $\epsilon_{\text{muDLL}}$ as a function of the proton (a), kaon (b) and pion (c) misidentification probabilities shown for the whole samples and the three different momentum ranges of Fig [8].

For $\epsilon_{\text{IsMuon}}$ the two average evaluations agree within $\sim 0.2\%$, taken as the systematic error due to the trigger unbias choice. We also determined the efficiency by determining the signal yields satisfying and not satisfying the muon identification requirement using a full fit, including a linear or exponential pdf for the background and using a different method, the one described in Section 4 used to evaluate the proton misidentification rate. The results obtained agree within the per mil and typically no systematic error is quoted related to the method.

For the proton misidentification probabilities, we varied the probability density functions describing the signal and the background and the method, using the method taken as baseline for the efficiency determination, and the results obtained agree within the
Figure 10: Efficiency (top left), proton misidentification probability (top right), pion misidentification probability (bottom left) and kaon misidentification probability (bottom right) as a function of the particle momentum for the IsMuon requirement alone (black circles) and with the additional cuts $\text{muDLL} \geq 1.74$ (red triangles) and $\text{muDLL} \geq 2.25$ (blue open circles).

For the pion and kaon misidentification probabilities, we studied the effect of requiring that the trigger is independent of the track being probed. The ratio between the IsMuon misidentification probabilities obtained with this requirement and the baseline requirement explained in Section 4 is shown in Fig. 16. The ratios are compatible with 1 within statistical uncertainties.
Figure 11: Average efficiency $\epsilon_{\text{DLL}}$ as a function of the proton misidentification probability for particles with momentum in the ranges $p > 3$ GeV/c (a), $3 < p < 10$ GeV/c (b), $10 < p < 20$ GeV/c (c) and $p > 20$ GeV/c (d). Open markers show the combined DLL performance compared to the muon DLL performance with solid markers.

Statistical uncertainties and no systematic error is quoted to the trigger uncertainty. 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 12: Average efficiency $\epsilon_{\text{DLL}}$, compared to $\epsilon_{\text{muDLL}}$, as a function of the corresponding average kaon misidentification probability for particles with momentum in the ranges $p > 3$ GeV/c (a), $3 < p < 10$ GeV/c (b), $10 < p < 20$ GeV/c (c) and $p > 20$ GeV/c (d). Open markers show the combined DLL performance compared to the muon DLL performance with solid markers.
Figure 13: Average efficiency $\epsilon_{\text{DLL}}$ as a function of the pion misidentification probability for particles with momentum in the ranges $p > 3$ GeV/c (a), $3 < p < 10$ GeV/c (b), $10 < p < 20$ GeV/c (c) and $p > 20$ GeV/c (d). Open markers show the combined DLL performance compared to the muon DLL performance with solid markers.
Figure 14: Efficiency $\epsilon_{\text{shared}}$ as a function of the proton (a), kaon (b) and pion (c) misidentification probabilities shown for the whole samples and for three different momentum ranges.
Figure 15: Efficiency (a), proton (b), pion (c) and kaon (d) misidentification probabilities for the simultaneous requirement of IsMuon true and Nshared=0 (red open circles), compared to the IsMuon requirement alone (black circles).
Figure 16: (a) Ratio between $P_{\pi}^{IM}$ 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.
6 Conclusions

We have measured the performance of the muon identification procedure in the LHCb experiment, using 1 fb$^{-1}$ of data taken in 2011. The muon identification efficiency was observed to be robust against the operation conditions and presents a reasonably weak dependence on momentum and transverse momentum.

Hadron misidentification probabilities present a stronger dependence with the operation conditions, however the highest factors are observed only for low momentum particles. Above that the variations are always smaller than a factor 2.

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. In addition, a difference of log-likelihoods for the muon and non-muon hypothesis is defined for the particles passing the loosest selection. A cut based on the values of this difference can be tuned, according the purity levels needed in each physics analysis.

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