Performance of the LHCb muon system

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ABSTRACT: The performance of the LHCb Muon system in detecting muons produced in LHC collision events is presented. The first collisions delivered by LHC allowed for a fast fixing of the detector setting with optimized working conditions of the muon chambers and precise time calibration. The detector performance and its stability across the full 2010 data taking with LHC running at \( \sqrt{s} = 7 \) TeV energy, are here evaluated. Particle rates, measured in the different detector regions for a wide range of luminosity and beam operation conditions, are compared with the values expected from simulation. Space and time alignment of the detector, chamber efficiency, time resolution and cluster size are carefully studied.

KEYWORDS: Muon spectrometers; Trigger detectors; LHC detectors

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### 1 Introduction

LHCb is an experiment dedicated to heavy flavour physics at the LHC. Its primary goal is to look for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons. The LHCb apparatus is provided with a performant vertex detector, a magnetic spectrometer and efficient particle identification systems.

Muon identification is assured by a large and complex system comprising 5 stations, 1380 chambers of 20 different types for a total of 122 k channels [1]. The detector and its associated readout electronics were designed to trigger with high efficiency on high $p_T$ muon tracks within a time window smaller than 25ns to unambiguously identify the LHC bunch crossing.
In the year 2009, before the LHC start-up, a first setting up of the detector was performed using cosmic rays [2]. The large data samples made available by the first LHC pp collisions at $\sqrt{s} = 7$ TeV energy, allowed for a rapid refinement of the detector settings with a significant improvement of detector performance.

After describing the muon system (section 2), we report the actions taken to optimize the detector performance (section 3) and summarize the main features of detector operation during the 2010 run, evaluating the effects of the small number of hardware failures and noisy channels on the data taking efficiency (section 4). The performance of the system is assessed by analysing differently selected samples of high momentum muons from minimum bias triggers and muon triggers and studying its behaviour in the wide range of beam conditions spanned during the data taking (section 5).

In section 6 we report the particle rates measured for beam operations evolving from single bunch crossing per orbit to 50 ns bunch crossing, verifying their scaling with luminosity and evaluating the amount of spillover from previous bunch collisions. The study of the response to muon tracks in terms of cluster size is reported in section 7. We then describe the time calibration and the resulting time resolution and timing efficiency of the detector (section 8). The performance in terms of spatial allignment is also analysed (section 9). Finally, an accurate measurement of the overall detector efficiency is presented, discussing different methods for background subtraction, and estimating systematic uncertainties (section 10).

2 The LHCb muon system

The LHCb apparatus [1] is a single-arm forward spectrometer, consisting of a series of sub-detectors aligned along the beam axis. A silicon-strip Vertex Locator (VELO) centered on the interaction point allows for precise vertex reconstruction. A dipole magnet provides the bending for momentum measurement. Four multi-layer stations placed upstream and downstream the magnet, insure the tracking. Silicon strips are used in the upstream station (TT) and in the downstream inner tracker (IT) while straw tubes are used in the downstream outer tracker (OT). Particle identification is provided by two ring imaging Cerenkov (RICH) detectors, by an electromagnetic and hadron calorimeter system (ECAL and HCAL) and by the Muon Detector.

The muon detector tracking system is designed to send binary (yes/no) information to the data acquisition (DAQ) and to the first level hardware muon trigger processors. The trigger (L0MU) is based on a stand-alone muon track reconstruction searching for hits inside fields of interest (FOI) in projective-tower elements and requiring tracks having a transverse momentum ($p_T$) above a given threshold.

The detector is composed of five stations (M1-M5) of rectangular shape, placed along the beam axis (see Fig. 1). The stations are equipped with multi-wire proportional chambers (MWPC), with the exception of the inner part of the first station equipped with triple-GEM detectors [3]. Each station consists of two mechanically independent halves (called A and C sides) that can be horizontally moved to access the beam pipe and the detector chambers for installation and maintenance. Stations M2 to M5 are placed downstream the calorimeters and are interleaved with 80 cm thick iron absorbers. Their information is used to identify penetrating muons both on-line
and off-line. Station M1 is instead located in front of the calorimeters and is only used in the L0MU trigger to improve the $p_T$ measurement up to a 20% resolution.

The geometry of the five stations is such that all their transverse dimensions scale with the distance from the interaction point and, for trigger purpose, the chambers are positioned to form, across the stations, adjacent projective towers pointing the beam crossing position. The chambers are partitioned into physical channels each one readout by one front-end (FE) channel. The size of the physical channels is constrained by constructional reasons, or requirements on their capacitance (related to noise) and rate capability (dead time). Appropriate combinations of physical channels are performed to build up rectangular "logical pads" with the $x$ and $y$ sizes required by the muon trigger and off line muon identification.

Each station is divided into four regions with increasing distance from the beam axis. The linear dimensions of the regions R1, R2, R3, R4, and the size of their logical pads, scale in the ratio 1:2:4:8. Since the dipole magnet provides bending in the horizontal plane, the logical pad segmentation of muon chambers is finer in the horizontal direction $x$ than in the vertical direction $y$, to allow a good estimate of the momentum. Stations M1 to M3 are used to define the track direction and to calculate the $p_T$ of the candidate muon and therefore have a higher $x$ granularity than stations M4 and M5, whose main purpose is the identification of penetrating particles. In the inner region of the first station M1, the pad size is 1 cm in $x$ and 2.5 cm in $y$. In the other stations the vertical size $y$ just scales projectively with their distance from the interaction point; the $x$ granularity instead is two times finer in station M2 and M3 and two times larger in M4 and M5.

The trigger L0MU requires a five-fold coincidence among all the stations, therefore the efficiency of each station must be $\geq 99\%$ to obtain a trigger efficiency of at least 95%, within a
time window smaller than 25 ns in order to unambiguously identify the bunch crossing (BX). To comply with this stringent requirement, excellent time resolution and redundancy of the detector are needed. These are ensured by a fast gas mixture, $\text{Ar}/\text{CO}_2/\text{CF}_4$ 40/55/5, and an optimized charge-collection geometry both for the MWPC and the GEM detectors. Moreover the signal of each chamber is the OR of the signals of more than one gas gap. In stations M2 to M5 the MWPC’s consist of four gas gaps arranged in two layers, each one composed of two hardware OR-ed gaps, with two independent readouts. In station M1, R2 to R4 the MWPC have only two gas gaps with independent readout to minimize the material in front of the electromagnetic calorimeter. In region M1R1 two superimposed three GEM chambers are used. In all cases, in standard running conditions, the two independent readout layers are OR-ed in the front-end electronics.

Since the requirements on spatial resolution and rate capability strongly vary in different stations and regions of the detector, different readout techniques were employed. In the high granularity regions R1,R2 of stations M2,M3 a double readout was adopted: narrow vertical wire-strips defining the $x$ resolution and larger cathode pads defining the $y$ resolution are readout via FE channels and sent to the trigger and DAQ. Logical pads can be obtained as an AND between wire and cathode pads. In all the other stations and regions, the chambers are segmented into anode or into cathode pads (generally smaller than the required logical pad). In the large low resolution external regions R4, anode pads are formed by soldering an appropriate number of adjacent wires. In the other regions, both in MWPCs and in GEM chambers, cathode pads are obtained with a segmented printed circuit board.

The readout electronics includes flexible logical units performing the OR of a variable number of FE channels in order to prepare the information needed by the L0MU trigger and to be sent to the DAQ system. Up to four adjacent physical pads are OR-ed by the FE electronics to build a logical pad. In the M1 station, where the channel occupancy is high, the signals from the logical pads are directly sent to the trigger and DAQ. In most of the other low occupancy regions, M2/3 R3/4 and M4/5 R2/3/4, several contiguous logical pads are further OR-ed to build larger logical channels in the form of vertical and horizontal strips, with the aim of reducing the number of optical links to the trigger and DAQ. Logical pads are then reconstructed by the coincidence of two crossing strips.

The FE boards house two 8-channel ASIC’s [4] (each one containing a wide-band current amplifier, a shaper and a single threshold fast discriminator in leading edge mode) processing the physical signals from the chambers with a typical integration time of 60 ns. The 122 k output channels are then OR-ed to generate the 26 k logical-channel signals by suitable logical units (DIALOG [5]). This last step is in fact fully performed by the DIALOG on the FE boards only in part of the detector and it is completed on special Intermediate Boards in regions where the logical channel spans more than one FE board. Eventually, the Off Detector Electronics (ODE) boards receive the signals from the logical channels. They are tagged with the identification number of the bunch crossing (BXID) and routed to the trigger processors via optical links without zero suppression. The fine time information inside the 25 ns gate, measured by a 4-bit TDC ASIC [6] on the ODE boards, is added to the data transmitted to the acquisition system.
3 Detector setting

The operating conditions of the chambers were optimized for each region through a procedure described elsewhere[7, 8] which aims at reaching a low and stable noise rate while minimizing ageing effects and cluster size. These conditions were satisfied by setting the thresholds to 6 noise r.m.s. and by choosing the minimal high voltage value allowing to obtain the required 99% efficiency. Although all the MWPCs have the same gas gap of 5mm, different HV (from 2.53 to 2.65 kV) were required in different regions, depending on the pad size and the readout technique.

The chamber setting was kept constant during the whole 2010 run, except for region M5R2 where voltage was reduced by 90V when a large increase in luminosity produced a jump of the HV trip rate. Thresholds were lowered correspondingly to maintain high efficiency at the price of a slight increase of the noise level.

The triple GEM detectors of M1R1 were operated with voltages of 435/425/415 V for the first part of the run. Voltages were later reduced twice by 5 V per gap for safer operations following the increasing luminosity.

4 Detector Operation in 2010

During 2010 the detector was operated to acquire some special calibration runs and many physics runs with p-p collisions events at \( \sqrt{s} = 7 \) TeV for an integrated luminosity of \( \sim 37 \text{pb}^{-1} \). To illustrate the detector operation performance, we show in Fig. 2 a typical map of muon hits in all the five stations during a physics run. The few holes present on the maps correspond to dead channels. Most of them were due to hardware problems in the readout chain known since the beginning of the data taking (and have been cured in the LHC shutdown after the 2010 data taking). They affected only 129 of the 55296 logical pads (0.2%). Detector failures occurred during the run, were mostly due to HV trips of single detector gaps and were recovered after some conditioning procedure.

The overall effect of dead channels on muon tracking efficiency over the full 2010 run has been estimated [9] by counting the fraction of muon tracks with momentum larger than 6 GeV/c crossing one of the dead channels in MonteCarlo minimum-bias events. It resulted to be below 1%. For M2–M5 stations, due to the large redundancy (four independent gaps per chamber), the effect of gap failures on the overall system efficiency was negligible (\(< 0.1 \%\)). In the case of M1, gap failures are more dangerous since there are only 2 gaps per chamber. However, this station is only used by the L0 trigger and not by the high level trigger and offline reconstruction. If detectors in a whole trigger sector are faulty, the corresponding link to the L0MU trigger can be forced to one for all events, with the effect of a slight degradation of the L0MU performance for the affected region. This procedure was used only in one case for a chamber in M1R1, when both its triple GEM detectors became very inefficient. This dead zone would have otherwise generated an overall tracking inefficiency of the order of 3%.

The noise in the detector should be below 1 kHz per physical channel in order to have a negligible rate (below 1 Hz) of fake muon triggers ([10]). Even lower rates are desirable to suppress the noise contribution to muon misidentification in the offline reconstruction. The level of detector noise was checked regularly with dedicated runs of random triggers in absence of beam and the

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noise rate per physical channel was computed for each detector region from the multiplicity of firing logical channels (for double readout regions) or logical pads. The fraction of channels having a noise rate larger than 10 kHz is typically lower than 0.1%, making always negligible the rate of L0MU triggers due to noise.

5 Data samples and track reconstruction

Due to the continuous progress of the LHC machine operations, the 2010 data span a wide range of luminosity values, from $10^{27}$ to $10^{32}$ Hz/cm$^2$. The filling scheme was accordingly evolving with

Figure 2: Illumination map of the five detector stations in a typical 2010 physics run. The log color scales give the number of hits per cm$^2$ for all the 55296 logical pads. Faulty channels giving no hits and a few noisy spots can be noticed.
time, from the single bunch collision per orbit of the first runs, to the 150 ns spaced bunch trains of the highest intensity runs with 344 bunch crossings per orbit (equivalent to a 3.9 MHz collision rate) and the first tests with 50 ns spaced bunches.

In order to test the muon detector response with these changing conditions, an appropriate set of sample runs over the full period was chosen and analysed. Some special runs with triggered events in a larger time gate (125 ns instead of the nominal 25 ns) were acquired for time alignment studies (time alignment events, TAE in the following).

For the measurement of particle rates, cluster size and time resolution, only events triggered by some minimum bias condition, independently of the muon detector response, were used:

- Minimum Bias trigger (L0MB), requiring the total energy released in the HCAL to be more than 320 MeV;
- “Microbias” single track trigger ($\mu$bias), requiring some hits compatible with a track in the VELO or first tracking stations;
- random triggers.

For spatial alignment studies (section 9) and detector efficiency measurements (section 10), when the statistics of muon tracks in the minimum bias samples was not adequate, events acquired with standard physics triggers were used. The samples chosen and the procedures adopted to avoid the bias introduced by the trigger will be there described.

Monte Carlo simulation was used to compare the observed detector performance with the expectation, and to verify the analysis procedures. Standard samples of LHCb Monte Carlo events simulating minimum bias $pp$ interactions and production of prompt $J/\psi$ decaying to $\mu^+\mu^-$ were used. Other special samples used for particular needs will be described on the next sections. The events were generated using PYTHIA 6.4 [11] to describe the $pp$ collisions and GEANT4 [12] for the LHCb detector simulation.

Standalone muon tracks (Mtracks) are reconstructed with an algorithm similar to the one used in the muon high level trigger [13]. Mtracks are reconstructed starting from the firing logical pads, that are clustered to obtain track hits. Muon hits aligned with the primary proton-proton collision point are selected by a combinatorial algorithm. The track hits are fitted to a straight line and quality cuts are applied depending on the measured quantities. Mtracks are then matched with the tracks reconstructed in the tracking detectors (Ttracks) when this is needed to improve momentum resolution or reduce background.

6 Rates

The rate capability was one of the key request for the choice of technology and design of the muon detector. Detailed simulations were developed [14] to evaluate the particle rates and radiation doses expected for the nominal LHCb operations at an energy of $\sqrt{s} = 14$ TeV and a luminosity of $2 \cdot 10^{32}$ Hz/cm$^2$. The detector was designed to stand a rate larger than a factor 3 (for M2–M5 stations) or 2 (for M1 station) with respect to these simulations, for the 10 years of planned LHCb operation. The 2010 data allowed to measure the actual rates at 7 TeV energy for a wide range of luminosities and to compare them with expectations [9].
The number of firing logical pads per unit surface and triggered event $r_T = dN_h/dSdN_T$ was computed for every chamber. The average rate was obtained for each detector region, after removing the few chambers with channels affected by some pathology (dead or noisy). From the rate seen by triggered events we can evaluate the rate of firing pads per visible interaction, by definition independent of luminosity, and the contribution not due to the triggered collision, that could be due to spillover from collisions in previous bunches, beam background or detector effects (residual noise, late cross talk or afterpulses).

Since the statistics for random triggers is very limited, the $\mu$bias trigger provides the least biased available trigger for this measurement.

For each sample run, the average number $\mu$ of interactions visible in the LHCb detector per beam crossing was evaluated from the fraction $f_0$ of beam crossing events not producing a $\mu$bias trigger

$$f_0 = P(0; \mu) = e^{-\mu}$$

where $P$ is the Poisson distribution. Then the rates are extrapolated at nominal luminosity using the measured values of $r_{\mu\text{bias}}$ and the formula

$$\frac{dN_{\mu\text{bias}}}{dt} = \sigma \times \frac{L}{p}$$

where $p$ is the pile–up factor $p = \mu/(1 - P(0; \mu))$ and the cross-section $\sigma$ was evaluated to be 65 mb with 10% uncertainty, from the first luminosity studies. The result is shown in Fig. 3.

![Figure 3: Average rate, extrapolated at the nominal luminosity, in the 20 muon detector regions for the 2010 sample runs.](image)

The scaling of rates is verified within a few percent across five order of magnitudes in luminosity. The only exception is the outer region of the last station M5, where a significant contribution from back–scattering is expected due to the limited shielding behind the detector. The contribution of backscattering depends on the beam conditions ($\mu$ and bunch spacing) of each run.
In Fig. 4 we compare the measured values of the average $R$ in each region with the predictions of two simulations: the MonteCarlo data previously mentioned, produced with the full GEANT simulation in the nominal LHCb configuration at $\sqrt{s} = 14$ TeV including spillover, and more recent MonteCarlo data produced in the 2010 configuration at $\sqrt{s} = 7$ TeV, not including spillover. The simulation at 7 TeV reasonably reproduces rates for the outer regions (except for the missing spillover contribution in M5), while underestimating them for the inner regions and M1 by up to a factor 2, that is however within the design safety factor.

The spillover contribution was estimated [9] from TAE data by using the bunch crossing identification number (BXID) and the fine time information of the 4–bit TDC in the ODE boards. In this case L0MB events were used, since the $\mu$ bias triggers were not available in the TAE mode.

As an example we report in Fig. 5 the time distribution measured for the hits of M5R2 region.

The space distribution of any–time signals (125 ns gate) normalized to the in–time (within the standard 25 ns gate) signal distribution, is shown in Fig. 6. The plots show excess of late hits, clearly not related to the amount of the in–time ones, notably in the up and down edges of the downstream stations. The effect is impressive in the last station M5 where the too small iron wall behind the detector (see Fig. 1) provides insufficient shielding from backscattered particles. It is worth to note that the effect of late hits is enhanced in regions where the rate of in–time hits is small and is depressed where the in–time particle flux is large (this is visible for instance in the left and right edges of M5, not fully shielded from in–time particles by calorimeters and upstream muon stations).

In the M5R4 region the total rate of hits in TAE events increases by a factor 10 with respect to the in–time rate (from 1.5 to 15 Hz/cm$^2$). The increase for the other regions can be seen in Fig. 7. The large effect measured for the downstream stations is essentially due to late (backscattered) particles. The smaller increase seen for station M1, instead, is mostly due to late cross talk signals from in–time particles$^1$. The overall spillover effect is somewhere large in terms of relative rate increase, but not worrying in terms of absolute occupancy level. It must be added that the extra rate

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$^1$This will be clarified in section 7 were the time behaviour of cross talk is studied. The effect of rate increase due to
Figure 5: Time distribution of the M5R2 hits for L0MB events acquired in TAE mode. The red vertical lines separate the consecutive 25 ns gates assigned with progressive BXID numbers. The structures at the gate boundaries are due to a known feature of the TDC giving an incorrect fine time measurement at the gate edges.

is mostly seen in the 25 ns following the bunch crossing, not affecting beam operations with 50 ns bunch crossing spacing. The rate level far from LHC bunch trains is compatible with the residual detector noise [9]. No evidence for significant beam backgrounds is thus observed.

Finally, a check for possible sources of particles outside collision events was performed. In Fig. 8 the rates seen in beam–beam collisions, empty–beam (beam gas interactions) and empty–empty (out of time) randomly triggered events are compared. Except for the low–rate external regions of M5, rates outside collisions are less than 10% of the collision rates. The rates seen in empty–empty events are dominated by the delayed hits from the collisions in the previous bunch.
Figure 6: Space distribution of the ratio between the rates in 125 ns and 25 ns. The contribution of late hits from backscattering is evident in the outer regions, notably for station M5.
Figure 7: In red: ratio of the rate in 125 ns time window to the rate in 25 ns; the out of scale value for M5R4 is about 10. In blue: ratio of total cluster size to in–time cluster size for track hits.

Figure 8: Comparison of rates seen in events with beam–beam crossing (bb), single beam (eb) and no beams (ee).
7 Cluster Size

The average cluster size of muon track hits is an essential parameter of the detector response, since it monitors the correct operation conditions of the chambers and affects the muon trigger performance.

Cluster size can be measured in terms of the average number of firing adjacent pads. Due to the finer segmentation of chambers in the bending coordinate, the average cluster size is significantly larger than 1 in $x$, dependently on the detector geometry of each region. A cross–talk between adjacent pads due to charge signal induction and to some capacitive coupling is expected. The cluster size values for standard operating conditions were in the past measured on test benches, for particles impinging perpendicularly to the chamber plane, and used to feed MonteCarlo simulations.

It is worth to note that the average cluster size of muon track hits, is smaller than the one for all the hits in the detector, as can be seen in Fig. 9. This effect is large in regions where most of the illumination is due to low energy particles from punch–through showers and backscattered particles. If clusters associated to a track are also required to be isolated, the cluster size is further reduced demonstrating an effect of hit coalescence. This effect is run dependent, being correlated with event pile–up. The isolation cut reduces the effect of pile–up though not fully suppressing it [9]. For this reason a run with a small $\mu$ value must be used to make a comparison with the cluster size measured on test benches.

![Figure 9: Average cluster size along $x$ in a low luminosity run for each detector region. Events are triggered by $\mu$bias or L0MB triggers. Cluster selections are described in the text.](image)

The purely geometrical effect due to the muon trajectory inside chambers was measured by plotting the average $x$ cluster size as a function of the angle between the track projection on the bending plane and the perpendicular to the chamber plane. A correction for this effect was performed by extrapolating to 0 angle, as shown in Fig. 10. The resulting average cluster sizes are in good agreement with the design values used in the simulation as can be seen in Fig. 11. The cluster sizes never exceed 1.35, a value well within the L0 trigger requirements [10].

\[ \text{Run 70686 } \mu = 0.02 \]

\[ \text{All Clusters} \]
\[ \text{Clusters on tracks} \]
\[ \text{Clusters on isolated tracks} \]

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2 The isolation condition requires non-adjacent firing pads in the non-bending direction ($y$ cluster size = 1) and no other firing channels in the same station within 7 logical pads in $x$ and 2 in $y$. 

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Figure 10: Average \(x\) cluster size for isolated track hits as a function of the track angle (in rad) for M2R1 (smallest logical pad region) and M5R4 (largest logical pad region). A linear fit is used to evaluate the cluster size for perpendicularly impinging tracks.

Figure 11: Average \(x\) cluster size at 0 angle in data and MC2010. To suppress the effect of pile-up, only isolated clusters and low-luminosity data are used.

The time behaviour of cross-talk hits was studied using TAE data. While the time distribution of the first pad in time in a cluster is almost fully contained in a 25 ns time window (so ensuring a high trigger efficiency), the other pads in the cluster can arrive significantly later as it is shown in Fig. 12. As a consequence, the cluster size (as the hit rate) measured in a 125 ns time window is larger with respect to the one measured in the 25 ns window. The importance of the effect is region dependent and is quantified in Fig. 7 for clusters associated to muon tracks. The late cross-talk signals are not normally acquired and thus do not affect the trigger performance, though contributing to background for future beam operations with 25 ns bunch spacing, and to dead time already with 50 ns bunch spacing.
Figure 12: Time delay distribution (normalized to 1) of pads in track clusters with respect to the first pad in time: (a) for the small cathod pad region M1R1; (b) for the large anode pad region M5R4.

8 Timing

The L0MU trigger requires muon hits to be recorded in each of the five stations within the 25 ns LHC gate associated to a beam–beam crossing. This timing constraint is the most stringent requirement for achieving the design 95% muon detection efficiency. To reach this goal, the detectors were conceived to have a time resolution better than 4 ns at their nominal settings, while the 122k read-out channels have to be time–aligned at the 1 ns r.m.s. level. Though, tails in the time response are expected to be one of the main sources of detector inefficiency.

The time alignment of the detector has been achieved in several steps. Test signals produced by a custom pulser system were used for a first equalization. Cosmic data collected in 2009 allowed to refine the intercalibration using physical signals. These two steps are described in detail in [2] and [15].

After the calibration with cosmic data, a satisfactory time resolution was already reached for all regions except the most inner ones where the statistics was a limit. The precise timing of the first beam particles allowed to quickly intercalibrate the channels of the highly illuminated inner regions. For the other regions, only a few channels exhibiting an anomalous shift in the time response due to some hardware interventions were identified and fixed.

The detector efficiency could then be optimized by a fine tuning of the channels time offset with respect to the 40 MHz LHCb clock. The single channel time distribution exhibits an asymmetric shape, with a longer tail for late times. This is due to the intrinsic chamber response (dependent on drift time and time walk with pulse height), to the effect of delayed cross–talk hits and to the effect of the longer path of low momentum tracks. This implies that, in order to minimize the fraction of signals falling outside the 25 ns gate, the average time should not be centered on the middle of the DAQ gate, but slightly before. The optimal offset is region dependent as is the shape of the time spectrum. Moreover, small shifts among regions were already introduced by the optimization of the HV and threshold settings.

The offset optimization was then independently performed for each detector region. Special
runs were acquired with L0MB triggered events in TAE mode, varying the global time offset in steps of 1 ns. For each data sample, standalone muon tracks were reconstructed requiring hits in all five stations. The optimal offset was chosen by maximizing the timing efficiency, defined as the probability that at least one of the track hits in a given station is found within the central 25 ns gate [9].

8.1 Time Performance

The detector time resolution and, most importantly, the timing efficiency for each detector region was estimated [9] by analysing two TAE event samples:

- The first sample was acquired at the beginning of the physics data taking (before applying the final intercalibration for region M1R1) with events triggered by L0MB;
- The second sample was acquired at the very end of physics data taking. At that time the L0MB triggers were downscaled by a factor 100 and the need of an adequate statistics required the use of the physics L0 triggers based on calorimeters (electron, photon, hadron triggers).

TAE events were fully reconstructed so that Mtracks could be required to have a good matching with a Ttrack having a momentum larger than 8 GeV/c to ensure muons to reach the M5 station. Ttracks were required to cross the muon detector at a safety distance from the inner and outer edges to avoid border effects. Clusters inside the few chambers with pathologic behaviour mentioned in section 4, were not considered for the timing efficiency calculation.

The time performance is evaluated from the distributions obtained with the BXID and the 4–bit TDC measurement for the most time centered hit in the track clusters. As an example, the distribution obtained with the second TAE sample for the M5R2 region is reported in Fig. 13.

![Figure 13](image)

**Figure 13**: Time distribution of the most time centered hit measured in M5R2 for L0MB events acquired in TAE mode. The vertical lines delimit the “efficient” hits assigned with the BXID number of the trigger.

The timing efficiencies obtained for the TAE sample acquired at the end of data taking are reported in Tab. 1. The overall efficiency is measured to be $98.83 \pm 0.09 \%$, a value well beyond
Table 1: Timing efficiency, in per cent, for each detector region, obtained from the TAE sample acquired at the end of data taking. The average efficiencies on the stations are also reported.

<table>
<thead>
<tr>
<th>Station</th>
<th>Average</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>99.48±0.07</td>
<td>98.4±0.4</td>
<td>99.50±0.10</td>
<td>99.78±0.10</td>
<td>99.77±0.26</td>
</tr>
<tr>
<td>M2</td>
<td>99.79±0.05</td>
<td>99.6±0.4</td>
<td>99.72±0.09</td>
<td>99.91±0.07</td>
<td>99.89±0.21</td>
</tr>
<tr>
<td>M3</td>
<td>99.82±0.04</td>
<td>99.5±0.4</td>
<td>99.72±0.09</td>
<td>99.91±0.06</td>
<td>100.00±0.17</td>
</tr>
<tr>
<td>M4</td>
<td>99.91±0.03</td>
<td>99.8±0.4</td>
<td>99.96±0.06</td>
<td>99.88±0.07</td>
<td>99.95±0.18</td>
</tr>
<tr>
<td>M5</td>
<td>99.75±0.05</td>
<td>99.7±0.5</td>
<td>99.67±0.10</td>
<td>99.84±0.07</td>
<td>99.86±0.20</td>
</tr>
</tbody>
</table>

requirements. The sensitivity of the measured values to the quality cuts, suggests that the efficiency could be systematically underestimated, by a few per mill, in the regions most affected by combinatorial background, namely region R1 and stations M1 and M5. On the other hand, the statistics of the available data samples does not allow to tighten the cuts, further improving the muon track sample purity.

The core time resolution was evaluated by a gaussian fit to the distributions around the maximum and has values between 3 and 4 ns, in line with expectations. The results obtained for the two TAE samples are compared in Fig. 14. Despite the different triggers used in the two samples, resulting in a different momentum spectrum and space distribution of the tracks, the results were found to be in very good agreement, except for region M1R1 where a more accurate intercalibration was used for the second sample. This demonstrates the excellent stability of the muon system along the 2010 run.

Figure 14: Core time resolution (upper plot) and timing efficiency (lower plot) measured for each region in the two TAE samples acquired before and after the bulk of 2010 LHCb physics data.
8.2 Stability of the time response

The stability of the absolute time scale in the long term is expected to be limited by two effects:

- the LHCb clock drifts with temperature; variations were compensated manually during the run in order to be stable within ± 0.5 ns;
- the variations of temperature and atmospheric pressure at the pit which affect the chamber gain and produce a time walk effect. The largest effect is expected from pressure variations, and is estimated to be equivalent to a ~ ± 20V change in HV [16], corresponding to ~ ± 0.4 ns.

The average time of track hits, measured as a function of time in the sample runs acquired across the 2010, is shown in Fig. 15 for various detector regions. The behaviour is consistent with the mentioned effects. Variations are at the level of ± 1 ns and are clearly correlated among regions. Residual uncorrelated variations are compatible with zero. There is no evidence for a dependence of the time drift on the detector illumination, that could be a hint for an ageing effect on the chamber gain.

![Figure 15: Variation of muon chambers time response during the 2010 run. The average time of the most time-centered track hit, in different stations and regions, is plotted as a function of the data-taking time. The values for optimal efficiency depend on the detector region and have been fixed at the start of data taking. Variations along the 7 months of operation do not exceed the ± 1 ns range.](image)

9 Spatial alignment

The spatial alignment of the muon detector must guarantee the design performance of trigger and offline muon identification. The L0MU trigger requires hits in all the 5 stations aligned on a track-segment having a $p_T$ above a given threshold. The hit alignment is determined through fields of interest (FOI) in the projective trigger-tower elements. Offline muon identification is less
demanding on the muon track-segment and requires the matching with a track reconstructed in the tracking system through the whole spectrometer.

Given the spatial resolution of the muon detector readout elements, the alignment accuracy needed in the system is driven by the trigger requirements in the inner regions of stations M1, M2 and M3. In particular in these stations the trigger FOI is defined by 1 pad only in the non-bending vertical coordinate $y$ and a misalignment can directly contribute to trigger inefficiency. In the bending coordinate $x$, the FOIs are composed of several pads and the main effect of a misalignment can be a bias in the $p_T$ calculation if the trigger algorithm does not use the true $x$ positions. The alignment of stations M4 and M5 is less important because in their case the $y$ FOI is as large as 3 pads and the hits are not used to calculate $p_T$. The detector mechanics was designed to reach a precision of the order of 1 mm in $x$ and $y$ directions. The alignment requirements along $z$ are much less demanding due to the forward geometry of the experiment.

During the installation, the supporting walls were kept in the open position and the muon chambers mounted with an accuracy of $\sim$ 1 mm along $x$ and $y$ coordinates, centered on their nominal positions, relative to reference targets placed on top of each half station. The measured rotations were zero within the precision of 1 mrad. After chamber installation, the half stations were closed around the beam pipe leaving a small safety distance between the A and C side; the two half stations being ideally positioned left–right symmetric and projective to the interaction point. The closed stations were then surveyed with respect to the LHCb cavern using four reference targets on each side, and the values stored in the geometry database used by the offline reconstruction program to define the absolute hit coordinates. The values measured by the survey for the 2010 collision run are reported in figure 16. The M1C half station shows a non negligible though small misalignment.

9.1 Space alignment measured with muon tracks

A study of the muon system alignment was performed using muon tracks with the purpose of checking the mechanical positioning and the survey measurements, preparing a tool for alignment monitoring after each intervention requiring the opening of the stations, and eventually correcting the geometry data base.

In this analysis, standalone muon track segments (Mtracks) are defined by at least four clusters in four different stations that are compatible with a straight line. Candidates with large clusters (number of pads $> 6$) are eliminated to avoid mis-reconstruction problems. Moreover stations with more than 300 hits are excluded. The Mtracks are required to match a good quality track reconstructed in all the tracking detectors ($long$ Ttrack) having a momentum $p > 6$ GeV/c. The matching condition requires a good $\chi^2$ between the parameters of Mtrack and Ttrack extrapolated to the M2 position. Matching segments are then merged together in a unique track that is required to have a good $\chi^2$.

The alignment procedure used is based on Kalman fit iterative method [17], that performs a minimization of the total $\chi^2$ of an ensemble of tracks while adjusting the detector positions. Only the positions of the muon half stations were allowed to vary since the tracking detectors were previously independently aligned using the same procedure. The iterative process starts assuming the muon detector in the positions measured by the survey and stops when the convergence is reached (total $\chi^2$ doesn’t improve significantly) usually after 4-5 iterations. In Tab. 2 are reported
Figure 16: Alignments of the ten muon half stations for the 2010 run. The average value $x$ of the inner edges (left) and the median $y$ (right), are shown as a function of the station $z$ position. The empty dots represent the survey measurements, the full dots are the positions found by the software global alignment. The error bars correspond to the statistical and systematic uncertainties, summed in quadrature.

Table 2: Misalignments of muon half stations M1 – M5, relative to the survey measurements, calculated in the LHCb reference system with the Kalman fit iterative method. The quoted uncertainties are the fit errors (first) and the systematic uncertainties (second) on the relative positions determined repeating the analysis with different track selections.

<table>
<thead>
<tr>
<th></th>
<th>C-side</th>
<th>A-side</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta x$ (mm)</td>
<td>$\Delta y$ (mm)</td>
</tr>
<tr>
<td>M1</td>
<td>$0.92\pm0.14\pm0.15$</td>
<td>$0.11\pm0.28\pm0.24$</td>
</tr>
<tr>
<td>M2</td>
<td>$-1.56\pm0.05\pm0.04$</td>
<td>$-0.89\pm0.12\pm0.13$</td>
</tr>
<tr>
<td>M3</td>
<td>$-2.41\pm0.08\pm0.05$</td>
<td>$-1.53\pm0.14\pm0.14$</td>
</tr>
<tr>
<td>M4</td>
<td>$-0.33\pm0.15\pm0.11$</td>
<td>$-1.59\pm0.17\pm0.09$</td>
</tr>
<tr>
<td>M5</td>
<td>$-2.14\pm0.18\pm0.12$</td>
<td>$0.18\pm0.20\pm0.11$</td>
</tr>
</tbody>
</table>

The misalignments relative to the survey, measured on a sample of $\sim 7000$ tracks, with an analysis performed fitting only the translational degrees of freedom along $x$ and $y$ of each half station. The absolute positions in the LHCb reference system are shown in figure 16 together with the survey measurements.

The systematic errors have been estimated repeating the analysis with different samples of tracks (having different momenta and hitting different detector regions) and using slightly different alignments for the tracking system. While the absolute positions of the stations show variations of the order of 1 mm both in $x$ and $y$, their relative positions are more stable. The results obtained with
the Kalman fit iterative method significantly differ from the survey measurements (in particular for the \(x\) position of M1, M2, M3 side C) and suggest to apply a correction to the geometry database. Studies on the additional degrees of freedom like rotations around \(y\) or \(x\) directions give results compatible with the survey. Due to the forward geometry of the experimental apparatus, shifts in \(z\) direction are as difficult to measure as unimportant, therefore the \(z\) values measured by the survey were assumed.

9.2 Alignment check with a standalone approach

A partial but very sensitive check of the detector alignment was performed with an independent method using standalone muon tracks. The attention was focused on the relative \(y\) alignment of the first three stations, which is of primary importance for trigger efficiency. It is worth to notice that the results obtained with this method are independent of possible small residual misalignments of the tracking system. The analysis procedure is hereafter summarized:

Trigger unbiased muon tracks are selected requiring events triggered by the Calorimeters. The track reconstruction algorithm is the same used in the previous analysis\(^3\) as well as the selection criteria. In addition we select tracks having only one cluster per station, composed by hits having the same \(y\) and we consider only tracks crossing the same region in all the stations (hitting pads with projectively corresponding size).

Selected tracks are analyzed only in the non bending plane \(yz\), assuming that their trajectories are straight lines originating in the interaction point. We look for \(\Delta y\) misalignments of the 4 half stations M1(A,C) and M3 (A,C) with respect to the straight line defined by the centres of the interaction zone and M2 hit pads.

A non-null value of \(\Delta y\) for each track can be due to a physical effect (like multiple scattering, decay kink or punch through) or to a detector misalignment. A misalignment of station \(M_i\) would shift the average value \(<\Delta y_{Mi}>\) for a sample of tracks by an amount equal to the misalignment. Also physical effects can locally generate \(<\Delta y> \neq 0\). In fact, while a uniform track hit distribution would symmetrically smear \(\Delta y\) giving an average value zero, the real distribution is strongly peaked at \(y=0\) and generates systematic effects. A study performed on simulated events shows large “apparent misalignments” for tracks samples hitting the “up” quadrants or the “down” quadrants. The effect increases with the pad size, ranging from \(~ \pm 1\) mm to \(~ \pm 10\) mm in the four regions. Nevertheless up/down biases have opposite sign and the detector is almost up/down symmetric so that, summing the two quadrants in the half station, the smearing asymmetries cancel almost completely and the detector misalignment can be disentangled and measured.

Systematic uncertainties have been estimated using simulated and real data events and comparing the results obtained with subsamples of tracks reconstructed in different detector regions. The uncertainties increase with the pad dimension (while the importance of the misalignments for muon identification and trigger decreases). For this reason only tracks crossing R1 and R2 were eventually considered. The results are reported in Tab. 3.

The largest misalignments are measured for M1 station. Combining the results of R1 and R2 we get \(\Delta y_{M1C} = 0.76 \pm 0.27\) mm and \(\Delta y_{M1A} = 1.02 \pm 0.27\) mm, which are consistent with

\(^3\)To cross-check the results, the combinatorial algorithm described in section 5 was also tested. Consistent results were obtained.
Table 3: Misalignments along $y$ of M1 and M3 stations relative to the alignment of M2 station to the interaction point, as measured with tracks crossing the three stations in R1 and in R2 regions. The first error is statistical, the second is systematic.

<table>
<thead>
<tr>
<th>$\Delta y$ (mm)</th>
<th>C-side</th>
<th>A-side</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R1</td>
<td>R2</td>
</tr>
<tr>
<td>M1</td>
<td>0.81±0.05±0.3</td>
<td>0.53±0.07±0.6</td>
</tr>
<tr>
<td>M3</td>
<td>0.48±0.02±0.3</td>
<td>0.56±0.04±0.6</td>
</tr>
</tbody>
</table>

the results of the previous analysis that, reported in the reference system here considered, give $\Delta y_{M1C} = 0.38 \pm 0.39$ mm and $\Delta y_{M1A} = 0.93 \pm 0.37$ mm. The deviations of M1 from projectivity along $y$ are small enough and are of the same order of the mechanical positioning precision and reproducibility.

10 Detector efficiency

The overall performance of the muon detector is quantified by the detection efficiency of muon tracks when the system is operated in the standard data taking conditions. The inefficiency introduced by dead channels, or other hardware failures occurred in the 2010 detector operation, has been quantified in section 3. Here the intrinsic efficiency of the system is evaluated after applying strict fiducial volume cuts and eliminating the few small zones where known problems are present.

The used procedure is described in detail in reference [9] and is here summarized:

- Different data sets are used for M1 and M2–M5 stations to select appropriate samples of trigger unbiased standalone muon tracks (Mtracks). To reach the needed purity of the sample, Mtracks are matched with a good quality, high momentum Ttrack and required to fulfill tight selection criteria (section 10.1).

- The presence of background hits affects the results and requires different procedures to correctly evaluate the true efficiency for M2-M5 stations and for M1 station where the occupancy is much higher (section 10.2).

- The efficiency for each station is estimated by searching clusters around the prediction defined by the Mtrack reconstructed using only the other 4 stations. The search of clusters around the prediction is repeated increasing the opening window from 1 up to $8\sigma$’s both in $x$ and $y$. The value of $\sigma$ being determined, region by region, by a gaussian fit to the central part of the distribution of the distance between the position predicted by the Mtrack and all clusters in that region. For M1 the prediction is defined by the Ttrack associated to the Mtrack in order to improve its quality. The values of $\sigma$ for the twenty regions are reported in Tab. 4.

If the quality of the Mtrack sample is good enough, if the residuals are well described by a gaussian shape and, more importantly, if the background subtraction is a stable and reliable procedure which works even when a search area as large as $16\sigma_x \times 16\sigma_y$ is considered, the efficiency measured as a function of the search opening window will show a correct saturation behaviour permitting a reliable estimate of the detector efficiency.
Table 4: Resolution along $x$ and $y$ of the distance between the muon track and the muon cluster in each region of the muon detector. The muon track is reconstructed skipping the station whose resolution must be evaluated.

<table>
<thead>
<tr>
<th>Region</th>
<th>$\sigma_x (mm) \times \sigma_y (mm)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>4 x 10</td>
</tr>
<tr>
<td>M2</td>
<td>15 x 30</td>
</tr>
<tr>
<td>M3</td>
<td>10 x 12</td>
</tr>
<tr>
<td>M4</td>
<td>15 x 16</td>
</tr>
<tr>
<td>M5</td>
<td>33 x 40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>$\sigma_x (mm) \times \sigma_y (mm)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>8 x 18</td>
</tr>
<tr>
<td>R2</td>
<td>25 x 50</td>
</tr>
<tr>
<td>R3</td>
<td>25 x 48</td>
</tr>
<tr>
<td>R4</td>
<td>48 x 64</td>
</tr>
</tbody>
</table>

10.1 Muon samples and track selection

Different data samples are used for M1 and for M2-M5 stations:

- For the efficiency of M2-M5 stations, data acquired in two fills, corresponding to an integrated luminosity of $1.2 \text{ nb}^{-1}$, were used. The first level hardware trigger (L0) required a high $p_T$ hadron or lepton detected in the calorimeter or in the muon system; the software high–level trigger (HLT1) required the OR of several independent algorithms. To remove the bias introduced by the trigger in the efficiency calculation, events where both L0 and HLT1 were fired irrespectively of the muon system information were selected. With this data sample, the majority of the muons reaching the muon stations and used for the analysis, originate from decays in flight of $\pi$’s or K’s.

- For the M1 efficiency measurement, kaons decaying at the end of the tracking system can generate a good Ttrack giving a poor quality M1 prediction, not adequate to the large occupancy of the station. To have a sample of true muons, events with a reconstructed $J/\psi \rightarrow \mu^+\mu^-$ were used. This sample corresponds to almost all data acquired in 2010 ($\sim 37 \text{ pb}^{-1}$). In the trigger algorithms, M1 information is used only for L0. The high level trigger, the reconstruction and the data stripping do not use it. To remove the L0 bias on the efficiency evaluation, in each $\mu^+\mu^-$ couple from a $J/\psi$, the muon which fired the L0 trigger was not considered in the analysis. Notice that the use of the $J/\psi$ sample for the analysis of M2-M5 station is not possible since the muon information is used to identify both muons in the HLT and in the reconstruction.

A tight selection is required to reach the purity of the Mtrack sample needed for a precise efficiency measurement and different conditions are required for the different stations.

In all cases when the efficiency of a station is evaluated, the Mtrack is validated by requiring the existence of at least one Ttrack matching within one standard deviation in $x$ and $y$, the clusters associated to the Mtrack in each of the other four stations used for the fit. These standard deviations are estimated by a gaussian fit to the central peak of the distribution of the distance in $x, y$ projection of the Ttrack prediction to the cluster position. Examples of these distributions for region R1 of stations M1, M2, M3 and M5 (when the efficiency of M4 is being measured) are shown in Fig. 17.

A momentum cut of 12 GeV/c (15 GeV/c) is applied to the Ttrack when M2 (M3, M4, M5) station is analysed. If more than one Ttrack matches the Mtrack candidate and at least one of them
has a momentum below the cut, the candidate is rejected. When evaluating the efficiency of M2 and M3, where the occupancy is relatively high and the fired hits are identified by crossing vertical and horizontal strips, further cuts on the local hit multiplicity are applied to avoid ghost combinations. Moreover, when analyzing the efficiency of M3 where the prediction resolution is poor due to the lower granularity of M4, a cluster size of 1 is required on M2 station. For the analysis of M1 station, the Mtrack sample selection starts from the Ttrack associated to a muon candidate from the \( J/\psi \) and a cut on momentum of 12 GeV/c is applied.

![Figure 17](image1.png)

**Figure 17**: The \( x \) difference between all the Ttracks extrapolated in region R1 of the station midplane and the clusters. The plots refer to the stations M1, M2, M3, M5, when the M4 station is excluded from the fit, being its efficiency under evaluation.

### 10.2 Background subtraction

The presence of background clusters affects the search results. The necessary background subtraction requires different procedures for M2-M5 and for M1 station where the occupancy is higher.

Assuming a Poissonian nature of the background, the mean value of the background and the efficiency in a given search window can be extracted by a fit to the distribution of the number of clusters found. If this method works, the background estimate in the neighbouring of the muon track takes automatically into account any possible correlation between muons and background, as in the case of delta rays or punch through in the calorimeter.

For stations M2-M5, a fully satisfactory result is obtained assuming a background with two Poissonian components. The probability of finding \( n \) clusters in the search window is described by the formula

\[
P(n) = \varepsilon \cdot \left[ r \cdot \frac{B_1^{n-1} \cdot e^{-B_1}}{(n-1)!} + (1 - r) \cdot \frac{B_2^{n-1} \cdot e^{-B_2}}{(n-1)!} \right] + (1 - \varepsilon) \cdot \left[ r \cdot \frac{B_1^{n-1} \cdot e^{-B_1}}{n!} + (1 - r) \cdot \frac{B_2^{n-1} \cdot e^{-B_2}}{n!} \right]
\] (10.1)

where \( \varepsilon \) is the efficiency, B1 and B2 are the two Poissonian components of the background and \( r \) their ratio.
Figure 18: Multiplicity of clusters found in the $8\sigma$ search window for the M3 regions. The thick line shows the results of the fit with the two components background described in equation 10.1.

As an example, in Fig. 18 are reported the results of the fit in the case of an opening window of $8\sigma_x$ and $8\sigma_y$ for the station M3. It is worth to add that a fit with only one Poissonian component for the background does not give an equally good representation of the high multiplicity bins, but the fitted values of the efficiency do not show any significant difference.

In the case of the more crowded station M1 where the $J/\psi$ muon sample is used, the cluster multiplicities are not very well fitted with the double poissonian function. Thus another, more direct, method is also used to evaluate the background and the efficiency. It exploits the $\phi$ rotation invariance of the primary interactions and assumes that the background correlated with the muon track is negligible. The background is estimated by counting the average number of clusters in the same search window but in the opposite quadrant, with respect to the track prediction. The soundness of the method is confirmed by comparing the number of clusters found in the opposite quadrant with the number of clusters in the track prediction quadrant having subtracted one cluster attributed to the muon track, as shown in Fig. 19.

The true efficiency $\varepsilon_t$ is then estimated by the formula:

$$\varepsilon_a = \varepsilon_t + (1 - \varepsilon_t) \cdot P_{bg} \quad (10.2)$$

where $\varepsilon_a$ is the apparent efficiency calculated as $N_{NCLUS>0}/N_{preds}$, being $N_{NCLUS>0}$ the number of tracks where at least one cluster has been found and $N_{preds}$ the total number of tracks predicted to fall in the search window; $P_{bg} = N_{NCLUS>0,OQ}/N_{preds}$ is the probability to find at least one cluster in the search window in the opposite quadrant.

The M1 efficiency extracted with this method and the one estimated with the two Poissonian background components are in very good agreement.
Figure 19: The cluster multiplicity in the $8\sigma$ search window diminished by 1 (histogram) and the cluster multiplicity in the corresponding window in the opposite quadrant (dots), for $J/\psi$ muons in the four regions of M1 station.

10.3 Check of the procedure

To evaluate that the whole procedure, from track selection to efficiency value determination, is robust and unbiased, a test has been made using simulated events. As an ideal sample of muon tracks the so-called Particle Gun muons have been considered. These muons are generated as starting from the average $pp$ interaction point with a predefined momentum and angular distribution. Since those events are practically background free and do not suffer from fakes in track reconstruction and selection, they allow to cleanly extract the efficiency measurable with the present method. Of course the absolute values of the efficiency, depending on the assumptions made in the digitization procedure and on geometrical effects, will not necessarily be in agreement with the values obtained with real data. The efficiencies obtained with Particle Gun events are then compared with the ones obtained with Minimum Bias (for M2-M5) and $J/\psi$ (for M1) Monte Carlo events, were all background components and detector effects are described. A satisfactory agreement is an overall check of the correctness of the procedure, in particular of the background subtraction.

The estimated values for the different stations and regions are reported in Tab. 5. The agreement is good apart from R3 and R4 regions of the M5 station where the efficiency extracted from the Minimum Bias is lower than the corresponding Particle Gun efficiency. This difference has to do with the track sample purity. In fact, part of the selected tracks are muons produced in the showers inside the calorimeter that are aligned with the hadron track initiating the shower. These muons have an unknown and sometime low momentum so that they can be absorbed between M4 and M5 causing artificial inefficiency in M5. This effect is region dependent since tracks crossing outer regions have, on average, lower momentum that those crossing inner regions. In fact using the Minimum Bias Monte Carlo events, the fraction of selected tracks having the muon with momentum lower than the minimum value required to reach M5 (6 GeV/c) is 0.2% in R1, 0.3% in R2,
0.7% in R3 and 1.5% in R4. Removing the tracks with momentum below 6 GeV/c, the efficiency reaches the value of 99.77 ± 0.07 in R1, 99.63 ± 0.04 in R2, 99.51 ± 0.08 in R3 and 99.8 ± 0.1 in R4 in the Minimum Bias sample, in agreement with the Particle Gun sample. To take into account such effect the real data results have been corrected for the ratio between the efficiencies with and without the 6 GeV/c cut, as extracted by the Minimum Bias Monte Carlo sample.

Table 5: Values of the Monte Carlo efficiency for Minimum Bias and J/ψ events compared to Particle Gun events.

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>PG</td>
<td>95. ± 1.</td>
<td>94.9 ± 0.4</td>
<td>95.0 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>J/ψ</td>
<td>93.5 ± 0.2</td>
<td>94.4 ± 0.1</td>
<td>94.7 ± 0.2</td>
</tr>
<tr>
<td>M2</td>
<td>PG</td>
<td>99.5 ± 0.2</td>
<td>99.67 ± 0.09</td>
<td>99.70 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>MB</td>
<td>99.56 ± 0.07</td>
<td>99.69 ± 0.04</td>
<td>99.61 ± 0.08</td>
</tr>
<tr>
<td>M3</td>
<td>PG</td>
<td>99.9 ± 0.4</td>
<td>99.73 ± 0.07</td>
<td>99.68 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>MB</td>
<td>99.64 ± 0.07</td>
<td>99.59 ± 0.05</td>
<td>99.70 ± 0.08</td>
</tr>
<tr>
<td>M4</td>
<td>PG</td>
<td>99.9 ± 0.2</td>
<td>99.61 ± 0.09</td>
<td>99.70 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>MB</td>
<td>99.58 ± 0.05</td>
<td>99.64 ± 0.03</td>
<td>99.65 ± 0.07</td>
</tr>
<tr>
<td>M5</td>
<td>PG</td>
<td>99.5 ± 0.3</td>
<td>99.73 ± 0.09</td>
<td>99.69 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>MB (p &gt; 6 GeV/c)</td>
<td>99.58 ± 0.07</td>
<td>99.46 ± 0.04</td>
<td>99.14 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>MB (p &gt; 6 GeV/c)</td>
<td>99.77 ± 0.07</td>
<td>99.63 ± 0.04</td>
<td>99.51 ± 0.08</td>
</tr>
</tbody>
</table>

10.4 Results

The behaviour of the efficiency as a function of the number of σ’s of the opening window has been analysed for each region of the muon system. In all cases a correct saturation is observed at 3-4σ demonstrating the reliability of the method. However the final value taken for the efficiency is the one at 8σ to allow for the presence of non gaussian tails in the prediction point.

In Fig. 20 is shown the behaviour of the efficiency as a function of the number of σ for the four regions of M2 station. In Fig. 21 the same is shown for the station M1, with the efficiencies obtained with equation 10.2. The efficiency values obtained for M1 with the two poissonian components fit to the cluster multiplicity distribution are in excellent agreement. For the final value of the M1 efficiency the average of the two estimates was assumed.

In Tab. 6 the final summary of the efficiencies with the statistical and systematic errors is reported. For M2-M5 the systematic errors due to background modeling have been estimated by changing the fit function from two poissonians to a single one. The efficiency varies less that 0.01% in all regions of M2-M5. For M1 where two orthogonal ways of estimating the background have been tested, a systematic uncertainty of half the difference between the two results has been assumed. Since the choice of evaluating the final efficiency at 8σ has a certain degree of arbitrariness, a systematic error has been assigned as half the difference between the efficiency value calculated at 4σ and 8σ, both in x and y projections. The uncertainty, due to MC limited statistics, of the correction applied on the M5 efficiency to take into account the absorption of muons between
Figure 20: The measured efficiency of M2 station as a function of the number of $\sigma$ of the search window. The four regions are shown: R1 (red circles), R2(green squares), R3(black triangles), R4(pink crosses).

Figure 21: The measured efficiency of M1 station as a function of the number of $\sigma$ of the search window. The four regions are shown: R1 (red circles), R2(green squares), R3(black triangles), R4(pink crosses).

M4 and M5 is included in the systematics. The different systematic sources have been added in quadrature.

The final estimates of the overall detector efficiency are compared in Fig. 22 with the results of section 8.1 where the contributions of timing tails to the inefficiency are evaluated. As already mentioned, the limited statistics of TAE data prevented to apply the same track selection for the two studies. The lower purity of the muon track sample for the timing analysis leads to an underestimate of the timing efficiency. The data were also acquired at different times, and this could explain the poorer performance of region M1R1 for the TAE data acquired at the end of the runs with a slightly lower high voltage (see section 4). Nevertheless, the region dependence of the two measurements is very similar, and for regions less affected by combinatorial background the timing efficiency is
Table 6: Efficiency values (%) of all the twenty regions with their statistical and systematic errors

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>98.66 ± 0.08 ± 0.08</td>
<td>99.37 ± 0.04 ± 0.08</td>
<td>99.70 ± 0.03 ± 0.06</td>
<td>99.85 ± 0.04 ± 0.02</td>
</tr>
<tr>
<td>M2</td>
<td>99.68 ± 0.05 ± 0.04</td>
<td>99.78 ± 0.03 ± 0.05</td>
<td>99.79 ± 0.04 ± 0.02</td>
<td>99.8 ± 0.1 ± 0.01</td>
</tr>
<tr>
<td>M3</td>
<td>99.35 ± 0.06 ± 0.05</td>
<td>99.79 ± 0.02 ± 0.04</td>
<td>99.85 ± 0.02 ± 0.01</td>
<td>99.86 ± 0.06 ± 0.01</td>
</tr>
<tr>
<td>M4</td>
<td>99.62 ± 0.03 ± 0.07</td>
<td>99.89 ± 0.01 ± 0.03</td>
<td>99.65 ± 0.04 ± 0.03</td>
<td>99.72 ± 0.09 ± 0.01</td>
</tr>
<tr>
<td>M5</td>
<td>99.64 ± 0.07 ± 0.10</td>
<td>99.82 ± 0.03 ± 0.04</td>
<td>99.90 ± 0.04 ± 0.12</td>
<td>100.0 ± 0.2 ± 0.1</td>
</tr>
</tbody>
</table>

found to be compatible or slightly better than the overall efficiency, indicating that the bulk of the detector inefficiency comes from signals falling outside the 25 ns LHC gate.

Figure 22: The results for total efficiency are compared with the estimates of timing efficiency from section 8.1. Errors are statistical only. For the regions more affected by combinatorial background, a systematic underestimation of the timing efficiency by a few per mill is probably present.

11 Conclusions

The muon detector was successfully operated during the first year of LHC physics. Its performance has been evaluated, showing that detector requirements in terms of cluster size, time resolution and efficiency, have been fulfilled. Notably, the whole detector chain demonstrated an excellent reliability and stability among the five orders of magnitude of luminosity experienced during 2010, with maximum particle rates comparable to the design values.

The inefficiency of muon detection due to a small number of dead channels has been estimated to be less than 1%. Thanks to a good monitoring system and maintenance work, temporary failures occurring during the run, mainly HV trips of single chamber gaps, accounted for per mill effects in the efficiency.
A careful timing intercalibration allowed to reach the wanted time resolution. The intrinsic performance in detecting high momentum muons, mainly determined by the chamber time resolution, has been evaluated after having excluded from the analysis the small regions with evident instrumental problems. All the 5 stations were operated with efficiencies well above the design requirement of 99%.

References