1 Introduction

The activities of the LHCb-LNF group in the Muon sub-detector in year 2009 can be summarized as follows:
- the completion of the commissioning of the stations behind the calorimeters (M2-M5);
- the installation of the detectors (MWPC and GEM) on M1 and the commissioning of the station;
- the completion of the production of spare MWPC detectors in the LNF-LHCb clean room, as well as the recovery of old ones at CERN, so to prepare a reserve of detectors for the running of the experiment;
- the preparation of the Roadmap for selected key measurements of LHCb paper, and the activity of simulation and analysis of MonteCarlo samples, in particular for the muon-id, for the study of early physics with $J/\Psi$, and for the rare channel $B_s \rightarrow \mu\mu$;
- a first look to 2009 LHC data, in particular for the determination of the efficiency and timing of the Muon System and of the muon-id performances and calibration.

Futhermore, the whole group has participated to the cosmic rays and to the LHC collision runs and to their first analysis.

2 Installation of the M1 station

During 2009 a considerable effort has been spent to install and commit the M1 station, in order to cope with the start of the LHC run. This required a lot of qualified manpower from the Frascati group. The M1 station, being inserted between the RICH2 and the Preshower detectors, has very little room (some 40 cm) for the installation and deserves special attention to the mechanical issues. Moreover, the station has to comply with severe limitations to the material budget, being in front of the calorimeters, and to face the presence of approximately 40% of the total amount of electronic channels of the whole Muon detector, for a total of 276 chambers and 32256 physical channels. The high electronics density, which requires air-cooling and foresees a large amount of cables ($\sim 2350$), makes the whole project a real challenge.

The installation and testing of the services was completed in February 2009. This required exact routing and check of all the cables (low voltage, high voltage, signal and control cables) and gas piping. Moreover, a further task was to build the system for moving the cable chain and its
suspension, which has been conceived to sustain the approximately 2 t of cables hanging from the walls. Last but not least, all of the mechanical supports needed to fix the chambers to the wall have been designed and machined between the end of 2008 and the beginning of 2009.

2.1 **M1 GEM detectors commissioning**

The central part of the first station of the LHCb Muon System, in the region closer to the beam pipe, is instrumented with Triple-GEM detectors with pad readout. In total, 24 Triple-GEM detectors, assembled in pairs to increase efficiency and redundancy, cover an area of about 0.6 m$^2$, for a total of 2304 digital readout channels. A special gas mixture with 40% CF4 is used to ensure that the Triple-GEM detectors have the required time resolution (better than 3 ns, rms). The Triple-GEM detectors, designed and assembled by INFN Cagliari and Laboratori Nazionali di Frascati, have been installed in the experimental cavern during Spring 2009 and after a commissioning phase they have started to be regularly in operation since the beginning of October when an intensive cosmic rays campaign took place. In November 2009, when the first proton-proton collisions occurred in LHCb, Triple-GEM detectors were operating at a gain of about 5000, a setting very close to nominal working point. The GEMs, together with the MWPC present in the rest of the muon system, allowed triggering on muons coming from the pp collisions. Since the end of November, the GEM detectors have been operated continuously and without any problem during the LHC operations. Many collision events have been recorded with proton beams both at 450 GeV and at 1.18 TeV, providing us with a muon sample in excess of 30k events. Approximately 20% of these muons have a hit in the GEM detectors.

In Fig. 1 the final M1 station installed can be seen, together with a detail of GEM detectors around the beam pipe.

![Figure 1: The M1 station installed (left) and a detail of the GEM detectors (right).](image)

2.2 **M1 MWPC detectors commissioning and spare production**

Chamber installation started by the end of February, and was completed by the end of June. Operation on the apparatus required good coordination with the other subdetector teams (specifically calorimeter and RICH), for sharing the access to the same detector regions. Moreover, since two
layers of chambers were mounted on each side of the support wall, chamber alignment and test of the detector basic functionality (noise and dead channels, gas connection) for the innermost layer were performed before starting the installation of the second layer. A second phase of chamber tests followed, asynchronous with the chamber installation. This consisted of testing the whole signal path, from chambers to the DAQ system, first with noise and pulse runs, and finally with cosmics. At the same time, the automated system for the wall movement was built. After a very carefully alignment of the wall, the final and crucial task was the closure of the M1 detector, which was achieved by the first week of July. Regular data taking campaigns with cosmics started early in September.

During 2009, the production and test of the spare MWPC for the experiment continued at the LNF site. A total of 37 new chambers have been built during 2009: 4 for region 2 of M4 and M5, 22 for region 3 of M1 to M5 and 11 for region 4 of M1 and M5. After construction, the detectors have been tested against gas leaks, checked and trained with HV, equipped and tested with FEE electronics, and sent to CERN.

3 Commissioning and calibration of the Muon System

The LHCb muon trigger architecture relies on 1248 Trigger Sectors (TS) originated by 122,112 front-end channels. These physical channels are merged to generate 25,920 logical channels both in the chamber front-end and in the Intermediate Boards (IB) system. Logical channels are grouped in Trigger Sector in the Off Detector Electronics (ODE) system. The last two items (IB and ODE systems) are under LNF responsibility and have been tested and installed on 2007; cabling was entrusted to LNF as well. The commissioning of stations M2 to M5 was successfully completed during 2009, together with that of station M1. Commissioning procedure followed four phases which required a lot of qualified manpower, mainly provided by Cagliari and Frascati: connectivity test with noise, pulse time alignment, and optical link test to trigger and DAQ systems. As of mid December 2009, no trigger sectors were missing, and very few noisy spots appears in the readout channels.

During year 2009 data taking runs on cosmic rays have been regularly performed, to test the overall performances of the data acquisition and trigger systems after integration of of the various subdetectors. A typical pad map obtained with cosmic ray run is shown in Fig. 2.

Moreover, the analysis of cosmic ray data was crucial for time and space alignment of the muon detector, in view of the data acquisition with proton collisions. In Frascati the activity was focussed on the calibration of the time response of the muon chambers.

4 Time calibration and muon chamber efficiency with data from LHC collisions

In the first round of LHC collisions at a c.m. energy of 0.9 TeV, and at a maximum luminosity of few units of $10^{26}$ cm$^{-2}$ s$^{-1}$, LHCb has collected approximately 500,000 triggers, part of them due to beam-gas interactions. A very short run has been performed also at 2.36 TeV, the highest energy ever reached in the world.

Since the muon system is used for triggering purposes, the time response of the stations has to be calibrated in order to give signals falling well within a 25 ns time coincidence window for a track generated at the interaction point. The average time of flight between two adjacent muon stations is 4 ns; on top of that one has also to account for obvious hardware delays which can vary...
The status of the time calibration was finally checked on real muons from collisions. Only data acquired with a calorimeter trigger have been used, not to bias the observed time spectra. The time spectrum of the muon hits from all of the stations is shown in Fig. 3. The core resolution from data is 3.6 ns, while the efficiency for having 5 muon hits within the same bunch crossing is ~ 95%. The efficiency value drops to ~ 44% without using the calibration constants evaluated on cosmics. The previous results demonstrate the effectiveness of the time calibration procedure developed on cosmics.

Parallel to the calibration of timing, the Frascati group has developed a method for the monitoring of the muon chamber efficiency on real collision data. As a first step, a procedure to select a pure sample of muon candidates was defined. This procedure select tracks reconstructed by the tracking detectors of LHCb, with momentum above 3 GeV/c. Each track is extrapolated through the Muon Stations and is selected within the geometrical acceptance of the detector. For each Muon Station it is selected the closest hit to the impact point of the extrapolated tracks within a search window that takes into account of the extrapolation errors due to the multiple
scattering. The tracks are selected as muon candidates if at least 3 hits over the 4 stations M2, M3, M4 and M5 are found.

Looking at the first data delivered by LHC in November 2009 (450 GeV/c protons beams), the efficiency values for M1 to M5 are shown in Fig. 4, for tracks with momentum above 8 GeV/c.

![Figure 3: Muon hit time measured on stations M1-M5, collision data.](image)

From the MC it is known that about 30% of the selected muons comes from decay in flight after the tracking detectors and before the first muon station: this entails that the collected sample has a contamination due to muons with a non tracked kink. The search windows have been therefore increased to minimize the inefficiency due to \( \mu \)'s with large kinks keeping the purity of the sample \( \approx 80\% \).

Furthermore, a preliminary analysis of muon candidates extracted from the muon-id algorithm, and originating from collisions at 0.9 TeV c.m. energy shows already a very good agreement
of distributions between data and Montecarlo, as can be seen in Fig. 5.

Figure 5: A comparison between data and Montecarlo for the muon momentum (left) and for the angular distribution (right).

5 Software activities

The software activities in 2009 of the LHCb-LNF group were mainly focused in finalizing the analysis using the full LHCb Monte Carlo production and starting to look to the performances of the Muon System with the first data. In particular, several members of the LNF group have participated actively in the preparation of the document (Roadmap for selected key measurements of LHCb) for the six main analysis that LHCb plans to perform with the first years of data taking.

5.1 Preparation for data analysis

In 2009 the LHCb-LNF group has been involved in the preparation of the following analysis:

1. the study of the muon-id and its calibration with real data;
2. the search for the $B_s \rightarrow \mu^+ \mu^-$ rare decay;
3. the measurement of the ratio of the cross sections $\sigma(J/\Psi)/\sigma(\psi(2S))$.

The study of the $B_s \rightarrow \mu^+ \mu^-$ rare decay is considered top priority for the LHCb collaboration since it will be competitive with the Tevatron results already with 0.2 fb$^{-1}$ of integrated luminosity (which is what LHCb expects to collect in the 2010 run). However, this measurement requires a deep understanding of the detector behaviour and rely on the calibration of many quantities (momentum scale, momentum resolution, particle ID, flavour tagging, proper time resolution).

Already with first data, a set of easiest measurements has been foreseen, such as the determination of $\sigma(J/\Psi)/\sigma(\psi(2S))$, where both $J/\Psi$ and $\psi(2S)$ decays in muon pairs.

We underline the fact many of the six key LHCb measurements contains muons in the final state, making the Muon Detector one of the main LHCb detectors for the first years.
Search for New Physics with the LHCb detector

Due to its sensitivity to New Physics contributions, the Branching Ratio $BR\left(\mathcal{B}_{s} \rightarrow \mu^{+}\mu^{-}\right)$ is one of the most interesting measurements that the LHCb experiment can perform with the first data. The Standard Model predictions are $BR(\mathcal{B}_{s} \rightarrow \mu^{+}\mu^{-}) = (3.35 \pm 0.32) \times 10^{-9}$ while the current upper limit given by Tevatron is $BR < 36 \times 10^{-9} @ 90\%$ CL, with a statistics of 3.7 fb$^{-1}$, which is still one order of magnitude higher than predictions.

LHCb collecting data at 7 TeV c.m., has the potential to exclude at 90\% CL any value of the BR down to the SM value with approximately 3-4 fb$^{-1}$ of integrated luminosity, corresponding to 2 nominal years ($10^7$ sec) running at $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$.

The expected limit at the end of Tevatron, $\sim 2 \times 10^{-8}$, is overtaken by LHCb with less than 0.2 fb$^{-1}$ even considering that LHC will run in 2010 and 2011 at reduced energy (3.5+3.5 TeV) (see Fig. 6).

One of the crucial points of this analysis is the control of the background mainly coming from hadrons mistakenly identified as muons.

The responsibility of the LHCb-LNF group is to develop the muon-id algorithms and all the related tools for monitoring and calibrate the muon-id with data. The studies of the muon-id performance for muons belonging to the phase space interesting for the $\mathcal{B}_{s} \rightarrow \mu\mu$ analysis continued in 2009.

In particular, the use of data samples coming from the modes $J/\Psi \rightarrow \mu^{+}\mu^{-}$ and $\Lambda \rightarrow \pi p$ have been implemented in the LHCb official software, to extract and to monitor the muon-id through all the data taking.

Moreover, it is worthwhile to mention that the interference between $B^0$ decays to $J/\Psi \phi$ with or without $B^0 \rightarrow \overline{B}^0$ oscillation could give rise rise to a non-zero CP violating phase $\phi_{J/\Psi \phi}$. This mode is one of the strongest test of the Standard Model and a window for new physics, as possibly shown by Tevatron results, although affected by a large error.

As in the previous rare decay channel, LHCb is able already with 0.2 fb$^{-1}$, hopefully collected in 2010 run, to overcome present Tevatron measurement. A detailed comprehension of the perfor-
mances of the Muon System is therefore crucial also for this kind of measurement. The statistical sensitivity expected at LHCb as a function of integrated luminosity is shown in Fig. 7.

\[ \sigma(J/\psi(2S)) \] as a function of integrated luminosity (fb$^{-1}$). Uncertainties on $\sigma(bb)$ and BRvis($B^0_s \to J/\psi \phi$)

**Figure 7:** Sensitivity expected at LHCb for the CP phase of the $B^0_s \to J/\psi \phi$ decay.

5.3 Measurement of the ratio of the $\sigma_{J/\psi}/\sigma_{\Psi(2S)}$

The measurement of this ratio even at a center-of-mass energy of 7 TeV is one of the parameters needed to theorists to understand the charmonium production mechanisms in the framework of the NRQCD theories.

The theoretical uncertainty on the production of charmonium at the LHC is dominated by arbitrary assumptions made on the $\Psi(2S)$ production mechanisms and even a measurement within an error of 20% will be a useful benchmark for Montecarlo tuning.

In first data at low luminosity the sample of $J/\psi$ and $\Psi(2S)$ will be already huge (a plot of the $J/\psi$ invariant mass is shown in Fig. 8).

The main experimental challenge of such a measurement is to keep under control the efficiencies and the angular acceptances in LHCb.

However, selecting only events with $\mu\mu$ in the final state we would expect a partial cancellation of the trigger, reconstruction and muon-id efficiencies, with a ratio constant or slowly dependent on the kinematics and on the geometrical variables. Preliminary results show that such a measurement is affected by a systematic error ranging up to 20%, allowing for an unknown value of the polarization.

A direct measurement of the polarization of the $J/\psi$ is under study.

5.4 Control samples for the Muon Detector monitoring and muon-id calibration

Since the assessment of the quality of the muon reconstruction, the evaluation of the muon-id and mis-id efficiencies and of its calibration play a fundamental role in several key first year physics
measurements, the effort of the LHCb-LNF group has been focused on developing the strategy and tools for calibrating with data the muon-id procedure and to extract in-situ the performance.

Two main calibration samples have been chosen after a detailed study: the inclusive $J/\Psi \rightarrow \mu\mu$ decay, as a source of muons, and the $\Lambda(1115.6) \rightarrow \pi p$ decay as a source of hadrons decaying and non-decaying in flight. For each channel different luminosity scenarios, with corresponding selections, have been identified. The expected purity and the rates have been optimized against computing and performance requirements: the allowed rate cannot exceed 5 Hz per channel and the S/B needs to be maximized while keeping the sample unbiased for muon-id studies.

Results are shown in Fig. 8 for $J/\Psi$ and $\Lambda$, corresponding to nearly 20 minutes of running in a starting low luminosity scenario at $\sim 10^{31}$ cm$^{-2}$ s$^{-1}$ with rate of the order of 10 Hz.

The $J/\Psi$ are selected by requiring a well identified muon, paired with a long track of opposite charge: geometrical constraints are applied, leaving the non identified track unbiased for particle ID studies (tag and probe method). Lambdas are selected exploiting the golden kinematics in the $\Lambda \rightarrow \pi p$ decay: since the production cross section is really large, strong geometrical (pointing) and kinematic ($p_T$, IM) cuts can be placed on the proton and the pion, leading to a pure sample of pions and protons for particle id studies.

The Armenteros Podolansky distribution (momentum asymmetry vs transverse momentum of the two daughter tracks) is used to disentangle the $\Lambda - \bar{\Lambda}$ ambiguity, allowing a clear separation of pions and protons.

With those selected sample a monitoring of the muon-id performances is possible: an error of the order 1-2% is easily achievable, and distribution of ID and mis-ID (for protons) efficiencies vs $P$ or $P_T$ can be made.

![Figure 8: The $J/\Psi$ and the $\Lambda$ invariant mass peaks at LHCb.](image-url)
6 Conference Talks

- A. Sarti, Rare B decays at LHC, Meeting IFAE2009, Bari, Aprile 2009.

7 Publications

- M. Calvi et al., Calibration of the flavour tagging with $B^+ \to J/\Psi K^+$ and $B^0 \to J/\Psi K^*$ control channels at LHCb, CERN-LHCb-2009-020.
- M. Calvi et al., Lifetime unbiased selection of $B_s \to J/\Psi \phi$ and related control channels: $B^+ \to J/\Psi K^+$ and $B^0 \to J/\Psi K^*$, CERN-LHCb-2009-025.
- A. Carbone et al., Invariant Mass Line shape of $B \to hh$ decays at LHCb, CERN-LHCb-2009-031.
- B. Adeva et al., Roadmap for selected key measurements of LHCb, arXiv:0912.4179.
- G. Sabatino, Charmonium production at LHCb: measurement of the $\Psi’$ to $J/\Psi$ production ratio at LHCb with first data, Tesi di Dottorato, Universita’ di Tor Vergata, Roma, Dicembre 2009.