The muon spectrometer of the ALICE experiment at LHC

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***Abstract*— The muon spectrometer of the ALICE experiment is a dedicated device to study heavy quark production in heavy ion collisions via their decay into muons. After more than 10 years of R&D and production, all large pieces of the muon spectrometer are installed in the ALICE experimental hall, while all detectors and their electronics are almost ready for installation.**

***Index Terms*— CERN, LHC, ALICE, heavy ion, QGP, heavy flavour, quarkonia, spectrometer, muon.**

I. INTRODUCTION

ALICE [1] (A Large Ion Collider Experiment) is a detector designed for the study of nucleus-nucleus collisions at the CERN Large Hadron Collider (LHC). Its physics program will address question concerning QCD (Quantum ChromoDynamics) of hot and dense nuclear matter produced in central heavy ion collisions at a nucleon-nucleon center of mass energy $\sqrt{s_{NN}} = 5.5$ TeV. The main goal of ALICE is to characterize a deconfined state of matter called the Quark-Gluon Plasma (QGP) [2]. The understanding of nucleus-nucleus data needs to study also p-p and p-nucleus collisions as reference on vacuum processes and on the effects due to cold nuclear matter matter, respectively.

The properties of the medium created in heavy ion collisions can be probed via hard processes such as the production of quarkonia (J/Ψ or Υ), which is expected to be affected by in-medium effects: decreased by color screening [3] or increased by coalescence [4] in a deconfined medium. Furthermore, as measured for light quarks [5], theoretical calculations [6] predict energy loss for heavy quarks in hot and dense nuclear medium. A general review of heavy flavour physics in heavy ion collisions is given in Ref. [7].

The ALICE detector is composed of three parts:

- a barrel part ($-0.9 \leq \eta \leq 0.9$) with detectors allowing to identify and measure hadrons, electrons and photons in a magnetic field (up to 0.5 T) produced by a solenoid magnet;
- a forward part ($3.4 \leq \eta \leq 5.1$ and $\eta \approx 8.7$) which consists of different detectors devoted to event characterization and to provide the interaction trigger;
- a muon spectrometer ($-4.0 < \eta < -2.4$) to study the muon tagged events.

All detectors are designed to work in an environment with large particle multiplicities: theoretical models predict between 2000 and 6000 charged particle per rapidity unit at mid-rapidity for the most central Pb-Pb collisions.

The role of the ALICE muon spectrometer [8] is to study the production of quarkonia and heavy quarks via their muonic decays.

To reach this physics goal, quarkonia should be reconstructed with the maximum efficiency over their whole p_T range and with a mass resolution of the order of 70 MeV/c^2 for the J/ψ family ($m_{J/\psi} \approx 3$ GeV/c^2) and 100 MeV/c^2 for the Υ one ($m_\Upsilon \approx 10$ GeV/c^2). This implies that the momentum of muons from Υ decay must be determined at the percent level.

The muon spectrometer (Fig. 1), with an angular acceptance of $[2^0, 9^0]$ with respect to the beam axis over the full azimuthal range, consists of a front absorber, a beam shielding, a set of high resolution tracking chambers, a dipole magnet, a muon filter and a trigger system.

II. ABSORBERS

The front absorber is a huge passive piece, starting at 0.9 m from the interaction point (IP). Most of the hadrons emitted in the acceptance of the muon spectrometer are stopped in the front absorber. This decreases the initial forward particle flux by a factor 100 and reduces the yield of muons coming from pion and kaon decays. The front absorber is a 4.1 m long cone made of carbon, concrete and steel ($\approx 10\,\lambda_{int}$). Low Z materials are close to the IP minimizing multiple scattering which deteriorates the invariant mass resolution.

Tracking and trigger chambers are protected by mean of a beam shielding. It consists of an assembly of tungsten, lead and stainless-steel surrounding the beam pipe with an open geometry to absorb particles produced at very small angle as weel as secondaries generated in the beam pipe. The beam pipe is a 0.8 mm thick beryllium tube (with a diameter of 59.6 mm) up to 40 cm from the IP, followed by a stainless-steel tube.

An additional absorber, called muon filter, is located just after the last tracking chamber (at 14.5 m from the IP) to reduce the particle flux on trigger chambers. It consists of a 1.2 m thick iron wall.

The presence of the front absorber and the muon filter introduces a muon momentum threshold of 4 GeV/c, allowing a good rejection of soft muons.

III. TRIGGER SYSTEM

The trigger system is composed of two stations of two detector planes of about 6×6 m^2 located respectively at 16.1 m

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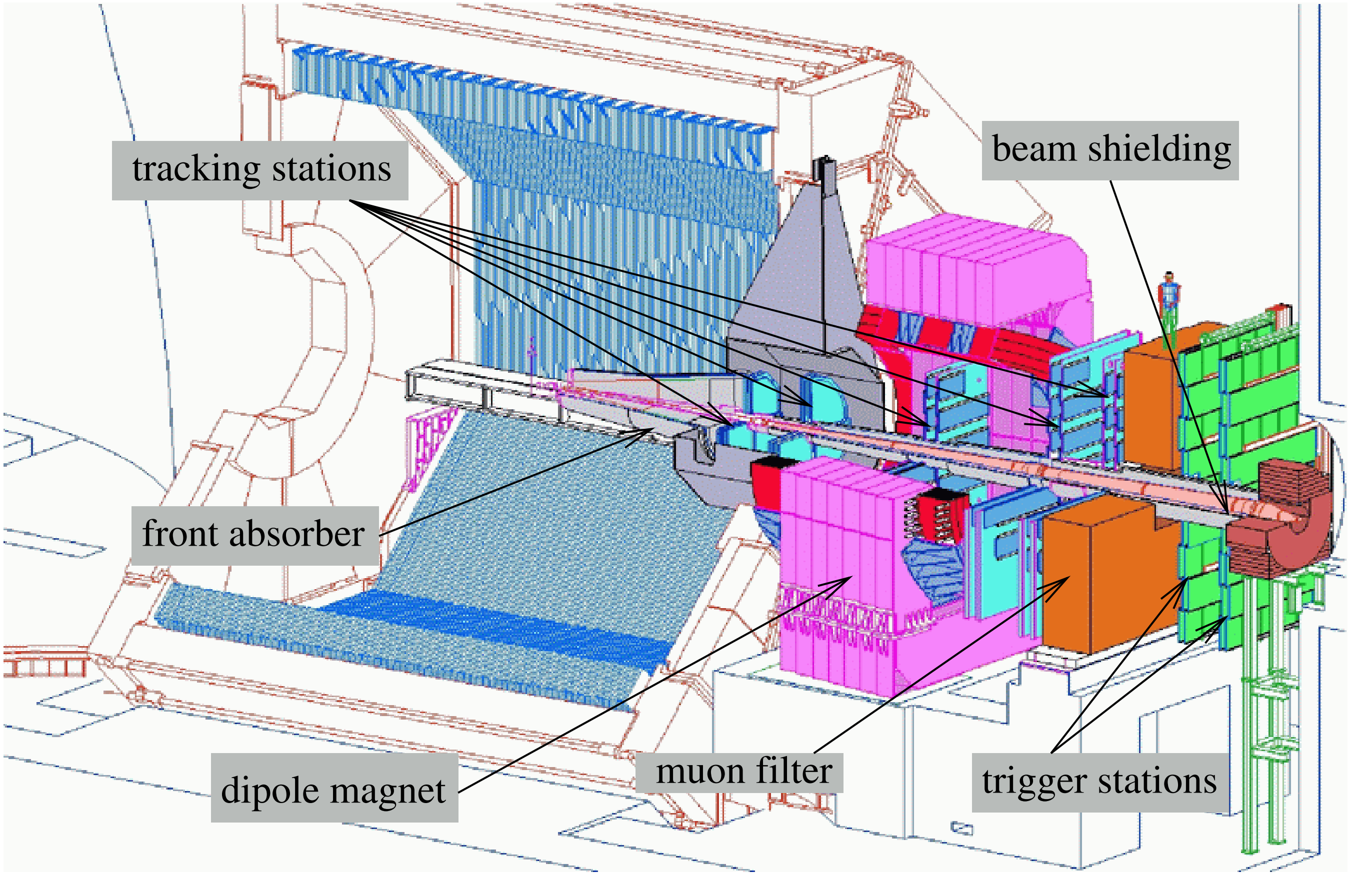

Fig. 1. Schematic 3D view of the muon spectrometer of the ALICE experiment.

and 17.1 m from the IP. The detectors are RPCs (Resistive Plate Chambers) working in streamer mode at a high voltage value of about 8 kV [9]. The system consists of 72 RPCs with a typical size of 2.8×0.7 m^2. Since the charged particle multiplicity is expected to be maximum close to the beam and decreasing with radius, the readout strips have three different widths (about 1, 2 and 4 cm). The strips of the different detection planes are projective to the interaction point. Two perpendicular strip planes equip each RPC (one on each side of the gas gap) allowing a three dimensional hit reconstruction. The total number of channels is close to 21000.

The muon trigger is part of the level 0 (L0) of the general ALICE trigger system [10]. A muon trigger decision is issued each 25 ns (corresponding to the 40 MHz LHC clock) and delivered to the central trigger processor within 800 ns after the collision.

The front-end electronics of the RPCs is based on the 8-channels ADULT chip [11] (A DUaL Threshold technique) using a set of two discriminators with two different thresholds. This ASIC allows to pick up prompt RPC signals (2 ns rise time and 5 ns width) with a time resolution of about 1 ns [12]. About 2700 specific front-end boards are needed to equip all the detectors. Each 25 ns the "local" trigger electronics (234 boards), located in racks at about 20 m from the RPCs, samples all the signals delivered by the front-end electronics. The role of the "local" trigger electronics is to store all front-end signals (bit-patterns) in a pipeline memory for further readout and to identify single muon tracks with a transverse momentum above a pre-defined threshold (using a look-up-table) by means of a dedicated algorithm located in FPGAs (Field Programmable Gate Arrays). The "regional" (16 boards) and next the "global" (1 board) trigger boards collect the information from the "local" boards in order to select single or dimuon events from the whole system.

RPCs equipped with its front-end electronics have been tested at CERN with muons from SPS (Super Proton Synchrotron) combined with γ background from GIF (Gamma Irradiation Facility using a 137-Cesium source). A specific "mini-trigger" test consisting of four RPCs in ALICE-like conditions [13] (two stations of two detection planes), coupled to the trigger electronics, shows that the efficiency of the trigger system (Fig. 2) is higher than 98% in a wide RPC high voltage range, even in the presence of a high γ background.

IV. Dipole Magnet

The momentum of charged particle is measured by its deviation from a straight line in the vertical (y, z) plane (bending plane), where z correspond to the beam axis. This deviation is due to the magnetic field produced by a warm dipole starting at 7.4 m from the IP and with an overall magnet length of 5 m.

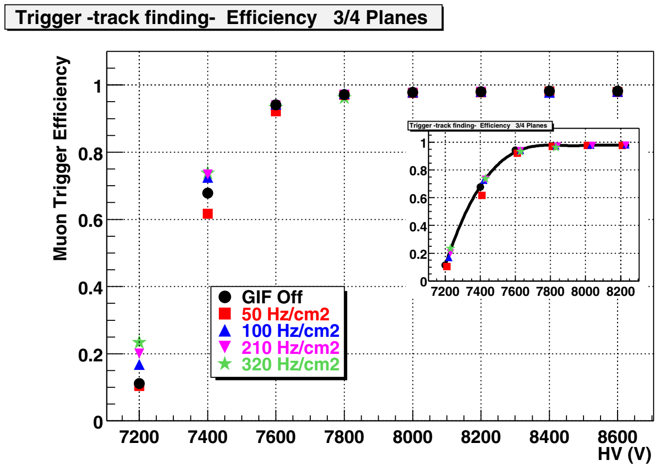

Fig. 2. Efficiency of the muon trigger test experiment with different level of background (created by the γ source of GIF) as a function of the high voltage applied to the RPCs. The efficiency is measured with respect to hodoscopes (scintillators associated with photomultipliers).

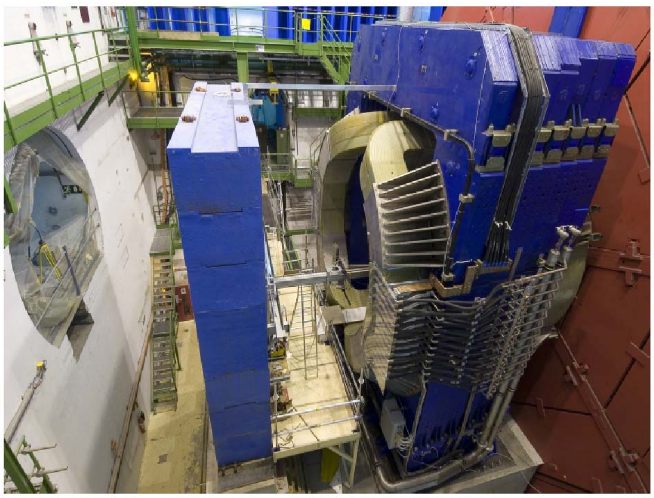

Fig. 3. Picture of the dipole magnet (right) and the muon filter (left) in the final position in the ALICE cavern.

The required mass resolution is obtained by a nominal field of 0.7 T and a field integral of 3 T m, requiring an electrical power consumption of 3.8 MW (at the current of 6000 A). This huge piece of about 850 tons is now placed in its final position, as shown in Fig. 3, and the field mapping was done in the summer of 2005.

V. Tracking system

The tracking system is composed of five stations of two detection planes located (distance are given from the IP) in front of (5.4 and 6.4 m), inside (9.8 m) and after (12.9 and 14.2 m) the dipole magnet. To reach the goal of $\Delta p/p < 1\%$ for muons produced by Υ decay, a spatial resolution of 100 μm is required for hits in the bending plane, vertical one (y, z), while a spatial resolution of 1 mm is enough in the non-bending plane, horizontal one (x, z), the z axis corresponding the beam axis. Furthermore, the tracking chambers must be able to operate in the high hit multiplicity environment produced in the most central Pb-Pb collisions, resulting in a hit density of 5×10^{-2} cm^{-2} for the most exposed part of the first station. For these reasons, multi-wire proportional chambers (gas mixture: 80% Ar + 20% CO_2) with segmented cathode planes, called Cathode Pad Chambers (CPC), have been chosen with two types of technologies:

- a quadrant geometry for stations 1 and 2 (total of 16 quadrants) with an anode-cathode gap of 2.1 mm for station 1 and 2.5 mm for station 2, three different pad sizes per chamber (from 4×6 mm^2 to 5×30 mm^2), with the electronics on the surface of the chamber,
- a slat geometry for station 3, 4 and 5 (total of 160 slats) with an anode-cathode gap of 2.5 mm, three different pad sizes from 5×25 mm^2 to 5×100 mm^2, with the electronics on the side of the chamber.

The total area of the tracking chambers is about 100 m^2 with 1.1×10^6 electronics channels.

The front-end electronics is based on the 16-channel MANAS chip (Multiplexed ANAlogic Signal processor) developed with the following functionalities: charge amplifier, filter and shaper. Four MANAS are mounted on a front-end MANU card (MAnas NUmerical) with two 12-bit ADCs and a dedicated MARC chip (Muon Arm Readout Chip) designed to control the MANAS, perform zero suppression, buffer the data and communicate with the Digital Signal Processor (DSP). Each MANU card is associated with 64 cathode pads, and about 17000 cards are needed to equip the full tracking system. Each DSP collects the data from 26 MANU via a bus. Data are assembled in clusters by the CROCUS boards (Concentrator ReadOut Cluster Unit System), located in racks at about 20 m from the chambers, and sent to the data acquisition via an optical DDL (Detector Data Link). The transfer is done in 240 μs after the trigger signal.

Tracking chambers with their front-end electronics were tested at CERN with pions from the PS (Proton Synchrotron) and muons from SPS. The results obtained for slats (see Fig. 4) show that the spatial resolution of the chambers (measured with final electronics) is within the requirement: 97 μm [14] in the bending plane with 100 GeV/c muons from SPS and 467 μm [15] in the non-bending plane with 7 GeV/c pions from PS, with an efficiency of about 97%. Similar results are obtained for the quadrants [16].

The alignment of the tracking chambers will be performed by the GMS [17] (Geometry Monitoring System) which is based on two kinds of devices. The first one (BCAM device) will measure distances between stations, station and wall, and the planarity of each chamber. It is a two-point imaging system based on two boxes equipped with laser diodes, a lens and a CCD sensor. Each box is illuminated by the other allowing to measure distances greater than 1 m with a spatial resolution of $\sigma_{x,y} = 0.5$ μm in the transverse plane and a relative

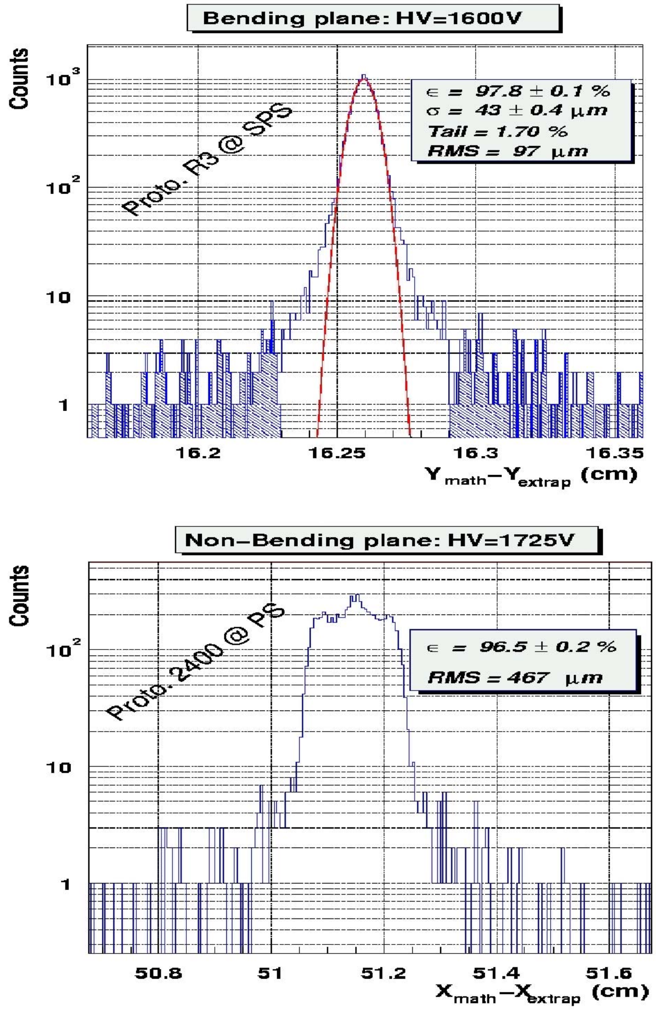

Fig. 4. Spatial resolution of a slat CPC in the bending plane obtained with 100 GeV/c muons from SPS (upper plot) and in the non-bending plane for 7 GeV/c pions from PS (lower plot). The residuals (Δx and Δy) are calculated as the difference between the CPC response (labeled "math") and the extrapolation (labaled "extrap") obtained with an external tracking system using Silicon Strip Chambers.

resolution of $\sigma_z/z = 4 \times 10^{-5}$ for the longitudinal coordinate. The second system (PROX device) will measure the distance between chambers of the same station. Its principle is based on the comparison of a coded mask on a support (illuminated by IR LED) and its image recorded on another support by a CCD sensor associated with a lens. The spatial resolution in the transverse plane is $\sigma_{x,y} = 1$ μm, the relative resolution of the longitudinal coordinate is $\sigma_z/z = 4 \times 10^{-4}$, and the angle resolution is $\sigma_\alpha = 0.2$ mrad.

The GMS, as illustrated in Fig. 5, will use a total of 100 optical lines to monitor the position of the different chambers with an accuracy of 20 μm, and 160 other optical lines to monitor the planarity of each chamber. Simulations show that the contribution of GMS resolution on the dimuon mass resolution does not exceed 15 MeV/c^2 for $m_{\mu\mu} = 10$ GeV/c^2.

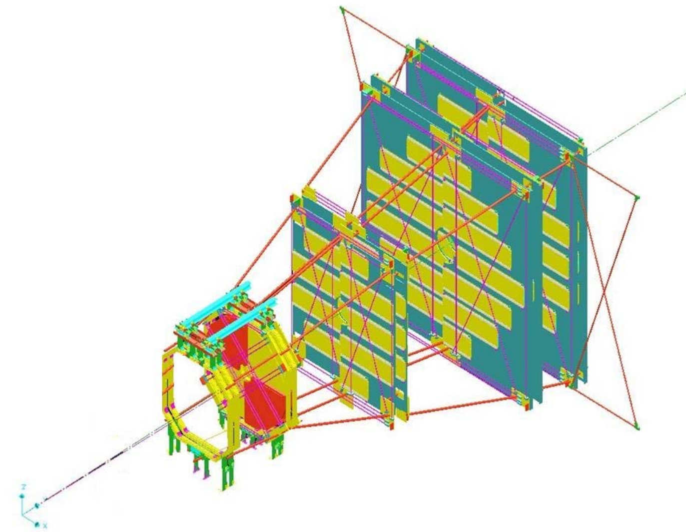

Fig. 5. Schematic 3D view of the tracking chamber alignment setup (GMS).

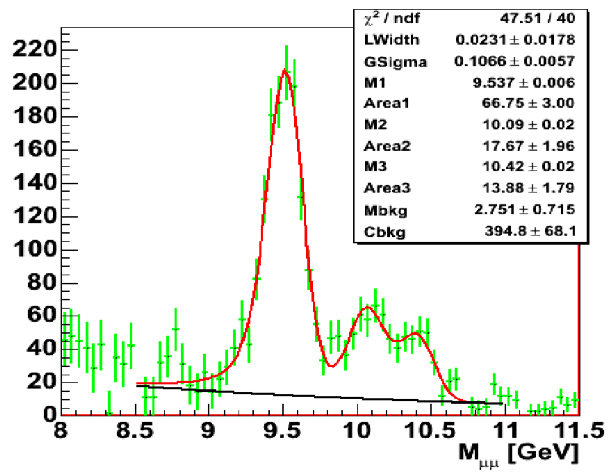

Fig. 6. Invariant mass spectrum of correlated dimuon pairs (background subtracted) expected in the Υ mass region for the most central Pb-Pb collisions after one month of running with a luminosity of 5×10^{26} cm^{-2}s^{-1}.

VI. Physics performance

By taking into account all detector response in the simulation codes, the physics performance have been extensively studied [18]. Fig. 6 [19] shows, the mass spectrum of correlated muon pairs in the Υ mass region expected for the most central Pb-Pb collisions after one month of running at a luminosity of 5×10^{26} cm^{-2}s^{-1}. As required, the ALICE muon spectrometer will be able to separate the different states of the Υ family. With such performance, this apparatus will be able to address questions about the production of heavy quarks and quarkonia in hot and dense nuclear matter.

VII. Conclusion

The muon spectrometer of the ALICE experiment is designed to identify and to reconstruct muons produced in p-p, p-nucleus and nucleus-nucleus collisions at the future LHC at CERN. The performances of each part of the spectrometer fulfill the requirements allowing to reach a dimuon mass resolution of $\sigma_{m_{\mu\mu}} < 100$ MeV/c^2 at $m_{\mu\mu} = 10$ GeV/c^2 and to separate Υ family states. All the large passive pieces (absorbers, dipole magnet and large detector support structure) are assembled on the surface or in final position in the ALICE cavern. Most of the detectors and their electronics are produced and will be ready for installation in 2006. In summary, the ALICE muon spectrometer is on track to be ready for data taking in 2007 with the first p-p collisions.

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