Nuclear Instruments and Methods in Physics Research A 764 (2014) 142–149

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

An extensive air shower trigger station for the *Muon Portal* detector

F. Riggi [a,b,*], A.A. Blancato [a], P. La Rocca [a,b], S. Riggi [c], G. Santagati [a,b]

[a] *Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy*
[b] *INFN Sezione di Catania, Catania, Italy*
[c] *INAF, Osservatorio Astrofisico di Catania, Catania, Italy*

ARTICLE INFO

Article history:
Received 29 March 2014
Received in revised form
5 July 2014
Accepted 11 July 2014
Available online 22 July 2014

Keywords:
Muon tomography
Cosmic rays
Extensive air showers

ABSTRACT

The *Muon Portal* project (⟨http://muoni.oact.inaf.it:8080/⟩ [1]; Riggi et al., 2013 [2,5,7]; Lo Presti et al., 2012 [3]; La Rocca et al., 2014 [4]; Bandieramonte et al., 2013 [6]; Pugliatti et al., 2014 [8]) aims at the construction of a large area detector to reconstruct cosmic muon tracks above and below a container, to search for hidden high-Z materials inside its volume by the muon tomography technique. Due to its sensitive area (about 18 m^2), with four *XY* detection planes, and its good tracking capabilities, the prototype under construction, which should be operational around mid-2015, also allows different studies in cosmic ray physics, including the detection of muon bundles. For such purpose, a trigger station based on three scintillation detectors operating in coincidence close to the main muon tracker has been built. This paper describes the design and preliminary results of the trigger station, together with the physics capabilities of the overall setup.

1. Introduction

Muon tomography [9] is a technique employing the scattering of secondary cosmic muons inside a material, to reconstruct a 3D image as close as possible to the real objects inside the volume to be inspected. Due to the dependence of the scattering angle on the atomic number Z of the material, this technique is particularly promising to search for the presence of high-Z materials inside large volumes – such as containers – even in the presence of additional low- and medium-Z objects.

To reach a good precision in the reconstruction of the tomographic image a good tracking muon detector is required, able to reconstruct on an event-by-event basis the track of each muon before and after traversing the volume, even in the presence of multiple hits generated by the detector structure and the surrounding environment.

Among the various projects currently exploited in the world [10–12], the *Muon Portal* Collaboration [1–8] aims at the construction of a real size prototype (6 m × 3 m sensitive area, ~7 m height) of a particle detector for cosmic muons, which was originally designed for muon tomography applications, hence based on several (four) X–Y horizontal position-sensitive planes located some distance apart, able to reconstruct incoming muon tracks. Apart from tomographic applications, this facility may act as a general purpose cosmic muon detector. Due to the its envisaged sensitive area and tracking capabilities, basic physics research programs in cosmic rays may be carried out with this setup in addition to its original application.

Precision measurements of muon angular distributions, short- and long-term monitoring of the secondary cosmic ray flux, investigation of its periodicities, influence of catastrophic events in the Sun (i.e. Forbush decreases) on the cosmic ray flux, detection of multi-muon events and large muon bundles, time and orientation correlation to other muon detectors, as well as studies of muon flux anisotropies are a few among the many possible physics studies within reach of this setup.

The study of muon bundles in particular is of current interest both for underground experiments and for experiments located at the sea level or moderate altitudes. Muon bundles are high multiplicity quasi-parallel tracks mainly originating from pion and kaon decays, produced during the development of an extensive air shower. Observed for the first time more than 50 years ago, they are currently of interest for many experiments, such as MACRO at LNGS [13], ALEPH [14], DELPHI [15] and L3+C [16] at LEP, the EMMA multi-muon array [17], ALICE [18], ATLAS [19] and CMS [20] experiments at the CERN LHC. The physics interest in the study of muon bundles relies on the chemical composition of primary cosmic rays, test of interaction models and deviations from current Monte Carlo generators.

The sensitive area of the *Muon Portal* detector is relatively large and its tracking capabilities and spatial resolution are such as to

* Corresponding author at: Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy.
E-mail address: francesco.riggi@ct.infn.it (F. Riggi).

http://dx.doi.org/10.1016/j.nima.2014.07.027
0168-9002/

allow a good separation of muon tracks. Another possible analysis of interest is the study of muon flux anisotropy, since at shower energies between 10^{11} eV and 10^{14} eV, several underground [21–23] and ground [24–26] array experiments have reported evidences for anisotropies in the arrival direction distribution, either of solar origin (due to the diffusion of cosmic rays inside the heliosphere) or of sideral nature, exhibiting for instance a deficit around Right Ascension RA = 12 h, Declination Dec = 20° and an excess around RA = 6 h, Dec = −24°. Though most of these studies may be carried out also in an inclusive mode by the *Muon Portal* detector, triggering on extensive air showers would give the possibility to sort out the collected events, allowing to correlate the muon properties (muon angular distributions, muon multiplicity in the bundle, etc.) to that of the shower, namely to its energy and incoming orientation. A simple trigger station for extensive air showers would be very useful in this respect. Such station may be simply built by a proper set of detectors operating in coincidence some distance apart, from a few meters to a few hundred meters. Increasing the relative distance between them gives access to more energetic showers. In order to reconstruct the arrival direction of the incoming shower, triangulation methods may be applied to a minimum set of three non-aligned detectors, measuring the differences in the arrival times of the secondary particles in each detector.

This paper reports the design and operational parameters of a trigger station based on three scintillator discs (1 m diameter), viewed by large area photomultipliers and operating in coincidence, at small relative distances, to trigger on low energy extensive air showers. The use of proper electronics to tag the arrival times of the particles also allows us to operate the station at larger distances between the individual detectors. Section 2 summarizes the main properties of the *Muon Portal* detector, while Section 3 reports the design of the trigger station and the preliminary tests of its working conditions. Section 4 discusses the result of a first set of about 2×10^4 shower events. Section 5 reports also the results of CORSIKA simulations of extensive air showers carried out to determine the primary energy range at which the station might be sensitive, depending on the distance between individual detectors.

2. Overview of the *Muon Portal* project

The *Muon Portal* project [1–8] is a prototype of a particle detector for the inspection of harbor containers through the technique of muon tomography (see Fig. 1). The experimental setup is based on four *XY* detector planes, each providing the *X* and *Y* position measurements, two placed below and two above the volume to be inspected. The size of each plane is optimized to fit that of a real TEU (twenty-foot equivalent units) container, namely 5.9 m × 2.4 m × 2.4 m.

To favor the detector assembly and its maintenance, each plane is divided into six modules of size 1 m × 3 m, arranged to cover the detector area with minimal dead surfaces. Each module is hosted inside a casing providing the mechanical support for the detector planes. The mechanical structure is designed to minimize the amount of material traversed by the cosmic ray muons.

Each module is segmented into 100 strips of extruded plastic scintillators UPS-923A (analogues of BC400, NE114) (1 cm × 1 cm × 300 cm), provided by Amcrys [27] with two embedded wavelength-shifting (WLS) fibres Y11(200), provided by Kuraray [28], to collect the light produced inside the scintillator bars. All fibers are coupled at one end to Silicon Photomultipliers (SiPMs), designed ad hoc for the project by STMicroelectronics [29] to maximize the light yield with reasonable cost requirements.

More details concerning the detector geometry, electronic readout and channel reduction mechanism can be found in Refs. [4–8].

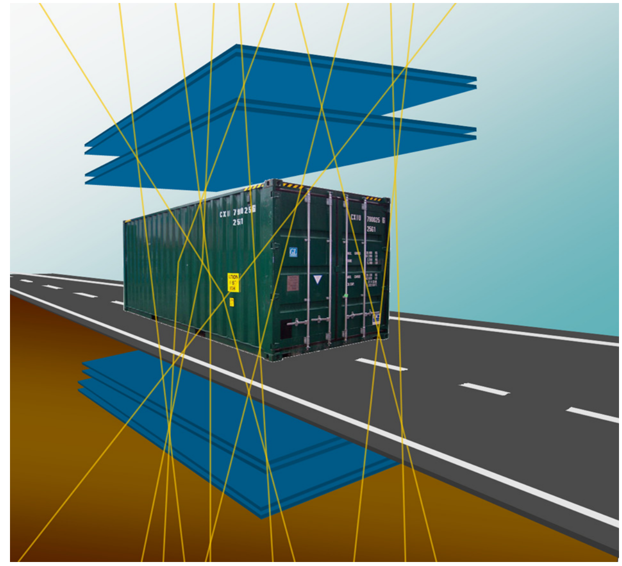

Fig. 1. Artist view of the Muon Portal detector illustrating the inspection of a container through the reconstruction of muon tracks above and below its volume.

The expected detector acceptance $\mathcal{A}$ to a flux of cosmic ray muons has been evaluated from GEANT4 detector simulations, taking into account the geometry of the detector planes (sensitive area and relative distances) and the surrounding material, and realistic angular and energy distributions of secondary cosmic muons, as derived from CORSIKA [30] simulations of extensive air showers. This results in a value of about $\mathcal{A} = 10\ \mathrm{m}^2$ sr, corresponding to a number of expected events of $\sim 2 \times 10^5$ for a scanning time of $\Delta t = 5$ min and a standard cosmic ray flux $\phi_\mu = 1\ \mathrm{cm}^{-2}\ \mathrm{min}^{-1}$ for horizontal detectors [31].

Reconstruction of the tomographic image inside a container is accomplished in the *Muon Portal* by various algorithms, which have been extensively tested against simulated events [32] under different scenarios, demonstrating the capability of the setup to locate and identify the presence of small high-Z objects (for instance a cube with side 5 cm, hence a volume of the order of 100 cm^3), over a container volume of 34 m^3.

Apart from muon tomography, the *Muon Portal* has in itself the potential to detect single and multi-muon events over a large sensitive area and with a good angular resolution, due to its four *XY* detection planes. The distance between top and bottom planes may be adjusted between 5 and 6 m.

When the *Muon Portal* is used simply as a muon detector (that is without any heavy material interposed between the detection planes), the amount of multiple scattering is very small, so that a good angular resolution (of the order of 0.1°) may be achieved by the 4 *X–Y* hit position (at 6 m distance between top and bottom planes). The value was estimated by GEANT4 simulations, taking into account the spatial resolution on the *X*- and *Y*-coordinates in the four detection planes of the *Muon Portal* and their relative distances, and a realistic description of the material used as a support for the detection planes.

Single rates of the order of 500 Hz may be expected with the fully operational detector, allowing a large number of events ($\sim 4 \times 10^7$/day) to be collected. This should give a reasonable statistics also on multi-muon events and any orientation-dependent cosmic ray study.

3. Design of the trigger station and preliminary tests

Reconstruction of cosmic air showers produced in the atmosphere by the interaction of high energy particles, mainly protons,