

Test of a SiPM-scintillator-based muon detector at the Gran Sasso National Laboratory

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Abstract. The aim of the present work was to determine the characteristics of a tracking scintillation detector by measuring cosmic muons above- and underground at the Gran Sasso National Laboratory (LNGS). The detector has been designed for demonstrational purposes and had never been involved in scientific research before. It is a compact, layered detector using plastic scintillator bars and silicon photomultipliers (SiPM). In the present setup no energy information is used. In the underground laboratory we had to deal with a very low rate of muons (6 orders of magnitude less than on the surface). For this reason we optimized the trigger configuration. During the evaluation process we designed and optimized a maximum-likelihood line fitting method which is able to deal with the high dark count rate and the non optimized detection efficiency of the detector. We also carried out simulations to calculate the actual flux and intensity from the measured ones. Finally, we compared our results with the literature and they were found to be in agreement.

1. Introduction

The primary role of underground laboratories such as LNGS is to provide a low background environment suitable for the low cross-section experiments conducted inside. Precise detectors capable of detecting the background (such as cosmic muons) can serve as a veto-system in many of the performed experiments, and therefore are under constant development.

The detector we worked with can be used for muon track reconstruction. As it wasn't involved in scientific research before, a lot of work was done to understand its properties, and to prepare it for data collection. From the measured data and the found properties the angular intensity aboveground and the flux above- and underground was determined.

2. Setup

In the detector the cosmic ray detection is based on scintillation. The used scintillator bars are made from extruded polystyrene (STYRON 663W) doped with PPO and POPOP made by Fermilab [1]. The polystyrene bars are extruded in the form of $64 \times 4 \times 1$ cm³ bricks with a hole at the longest symmetry axis. In this hole a wavelength shifter fiber is inserted which is used to collect the light at one end of the scintillator. This is important for the photodetection,

which in this case is more sensitive to the shifted wavelength. For photon detection silicon photomultipliers (SiPMs) were used. The used SiPMs made by AdvanSiD (ASD-SiPM1S-M) have an array of 10×10 Geiger-mode avalanche photodiodes (GM-APD) with a total size of 1 mm^2 . These diodes are capable of detecting few photons, but only in counting mode (without energy information).

The detector (figure 1) is built in a way to have a naturally built-in Cartesian coordinate system. There are 10 layers of scintillator bars on top of each other. Every layer is composed of two orthogonal half-layers one below the other (figure 2). Each half-layer consists of 16 parallel bars, so the whole detector has 320 bars connected to 320 SiPMs. Each bar is 1 cm high so a layer is 2 cm. The distance between the layers is 10.9 cm.

A signal coming from a SiPM is preamplified and the analogue sum of a half-layer is collected on the controller board present on the top of the detector. The triggering mechanism uses this summed value and gives a trigger when the selected half-layers have signals above a predefined threshold. When the trigger occurs, the digitized signals of each SiPM are driven to LED matrices present on two panels. This way the passing particles become visible in real-time. For data analysis the digitized signals can be acquired through a PC. Seeing the bars which the muon has crossed gives the possibility to reconstruct the three dimensional track of the detected particle.



Figure 1. The muon telescope.

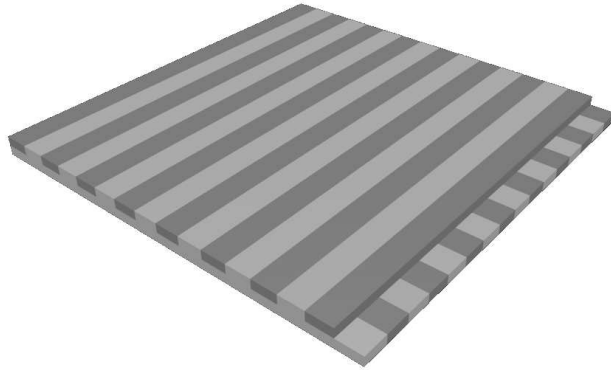


Figure 2. Illustration of the orthogonal half-layers

3. Data analysis

3.1. Performance of the detector

The noise rate for each bar was evaluated by collecting about 13 million events underground. Assuming that practically all of the signals underground are noise events, the rate can be calculated by counting how many times a given SiPM was giving a signal.

For evaluating the efficiency of each bar about 100 000 muons were measured aboveground. After fitting the lines of muons and selecting the events caused by muons, the efficiencies were calculated by counting how many times a given SiPM was giving a signal out of the times a muon passed the relevant bar. In the line fitting method the efficiencies of the bars are used, therefore prior efficiency values were estimated from vertical tracks.

The efficiency is strongly dependent on the zenith angle of the muon tracks, because the more inclined the angle of the track is, the longer the muon travels through the bars. The angular dependence of the efficiency of each bar was measured using the method described before, but restricting it to muons that come from certain solid angles.

3.2. Line fitting and sorting algorithm

In the present work the trajectories of muons are assumed to be straight lines. In our case the widely used method of least squares cannot be applied, because of the high noise rates and the fact, that the information about the track is not a set of points in space but bars.

For this reason a maximum likelihood method was used: for numerous lines where the muon could have passed through the detector the probability of measuring the given dataset is calculated. The line for which this probability is the highest will be the fitted line. The probability can be determined from the efficiency and noise rate of each bar.

Underground the ratio of measured muons to random coincidences is 1:300 000. Therefore it is crucial to differentiate the two. An event was claimed to be caused by a muon, if there are at least 7 signals on the fitted line and no more than 9 elsewhere.

4. Simulations

Two simulations were carried out. In the first one a 100 million random coincidences were simulated based on the measured noise rates. After fitting and selecting them, none of them was claimed to be a muon event. This means, as there were 33 million events collected underground, that the used selection criteria is strong enough to use in further data analysis.

In the second simulation measured datasets caused by muons coming from different directions were simulated, based on the noise rates and the angular dependent efficiencies. For each incoming solid angle range it was calculated how many times it was measured to come from different solid angle ranges. This can be represented as a matrix called the efficiency matrix (figure 3). The figure shows that most of the simulated muons were measured in the solid angle where they came from (purple line). Although, a few were measured in other directions too. Note, that the purple colour refers to only 18%, so about 80% of the simulated muons weren't measured, because they weren't triggered.

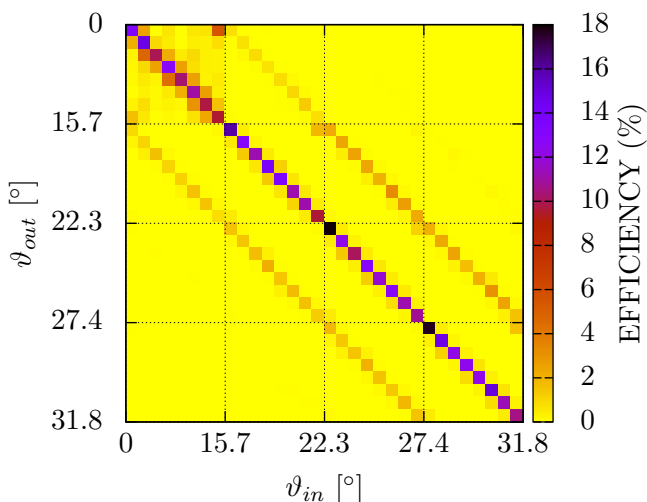


Figure 3. A part of the efficiency matrix, which shows in what percentage were simulated muons coming from given solid angles (columns), measured in different solid angles (rows). Within the dotted lines the solid angles are in the same zenith angle range. The 8 pixels in them refer to 8 different azimuthal angle range. The figure shows 4×4 different zenith angle ranges, subdivided into 8×8 azimuthal angle ranges each.

5. Results

With the previously described efficiency matrix ($\mathcal{E}$), having the measured data in each solid angle ($\mathbf{N}_m$) the corrected data ($\mathbf{N}$) can be calculated by inverting the efficiency matrix:

$$\mathcal{E} \cdot \mathbf{N} = \mathbf{N}_m \quad \Rightarrow \quad \mathcal{E}^{-1} \cdot \mathbf{N}_m = \mathbf{N} \quad (1)$$

The corrected data can be used to calculate the zenith angle dependence of the angular intensity. These calculated intensity values can be seen compared to the values calculated from the measured rates (figure 4).

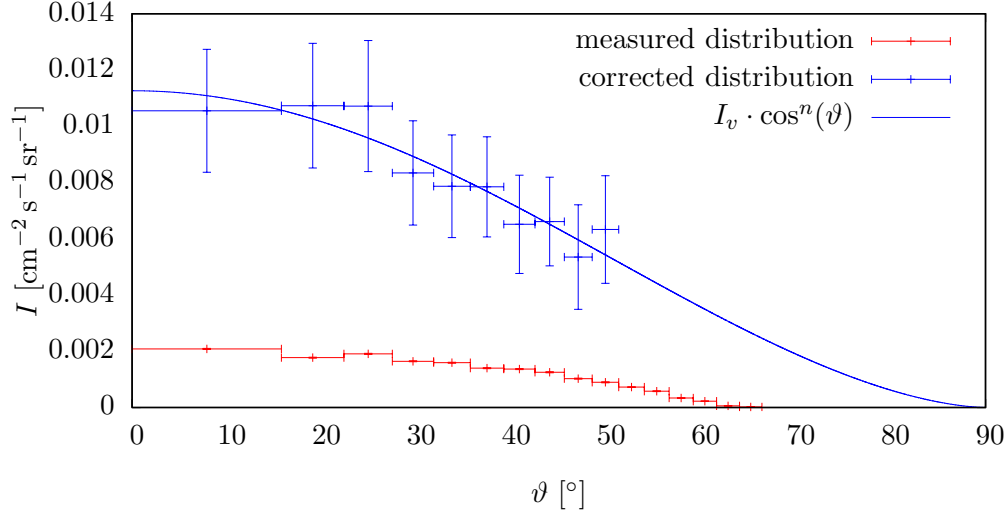


Figure 4. The zenith angle dependence of the angular intensity of muons at the surface. The fitted vertical angular intensity is $I_v = (1.1 \pm 0.2) \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ and the fitted exponent is $n = 1.7 \pm 0.2$.

By integrating the fitted angular intensity the aboveground flux of the muons was calculated: $F_a = (1.9 \pm 0.3) \times 10^{-2} \text{ cm}^{-2} \text{ s}^{-1}$. The flux at the Gran Sasso Laboratory can be estimated from the count rates above- and underground. Table 1 shows the measured muons.

Table 1. Collected muon data under- and aboveground

	registered events	muons	T [s]	measured count rate [s^{-1}]
underground	32 848 892	95	3 610 429	2.631×10^{-5}
aboveground	169 397	80 792	6158	1.312×10^1

The underground muon reduction was estimated by dividing the count rates: $(2.0 \pm 0.2) \times 10^{-6}$. This assumes that the muon angular and energy distribution is the same in both locations. Multiplying this with the aboveground flux, we get the underground flux: $F_u = (3.8 \pm 0.7) \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$. This is compatible within uncertainty with the official data of the Gran Sasso Laboratory: $F = (3.41 \pm 0.01) \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$ [2].

Acknowledgments

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References

- [1] Pla-Dalmau A, Bross A D and Rykalin V V 2003 Extruding plastic scintillator at Fermilab
- [2] Bellini G *et al.* (Borexino) 2012 *JCAP* **1205** 015 (*Preprint* 1202.6403)