Analyzing cosmic-ray muons in the experimental paths of the "Mathematical High School" Project

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Abstract. The Mathematical High School (MHS) Project is a research project involving 160 high schools and 26 Italian universities in which experimental research paths are deepened to explore mathematics as a universal language and as a link between the various areas of both humanistic and scientific knowledge. These activities are developed with the collaboration of internationally recognized research institutions. In particular, in the MHS schools, the research group of the Mathematics Department of the University of Salerno in collaboration with INFN (National Institute of Nuclear Physics) Naples division, offers laboratory activities of data analysis on cosmic rays. Students, guided by the researchers, use the CRC (Cosmic Rays Cube), a portable muon detector, to carry out an experimental activity, from the data taking to the analysis. They study what cosmic rays are, where they come from and, in particular, the characteristics of comic-ray muons produced in the Earth atmosphere. Mathematics becomes the instrument to interpret data collected by the detector, measure the muon flux and reconstruct their direction. Using dedicated software, students experience the activity of the researchers. Working in team, they deal with high-profile scientific issues usually not developed in the curricular educational paths.

1. Introduction

In Italy, the Guidelines of the Education System issued by the Ministry of Education specify the learning objectives of the various disciplines. For higher scientific institutes, they specify the importance of sharing knowledge in interdisciplinary terms by declining various suggestions and operational indications in the guidelines of each discipline. The intent is to overcome the fragmentation of knowledge that inevitably derives from an increasingly rich and in-depth cultural world in each area. However, the teaching times that are marked by institutional commitments, checks and reports, often make it difficult for teachers to build transversal paths.

In this regard, the Mathematics Department of the University of Salerno (Italy) has developed a didactic research project the "Mathematical High School" Project (MHS) that experimentally began in some institutes in 2015 with the coordination of the Mathematics Department, and currently involves 26 Italian universities. The activities take place in more than 160 institutes of the whole national territory. The aim of the project is to provide students with interdisciplinary laboratory activities that build bridges between scientific and humanistic cultures having mathematics as the universal language of knowledge and as the substrate of all the paths that are proposed [1]. The activities are developed by professors and researchers of universities and research centers in collaboration and are proposed in extracurricular times in collaboration with the schools' teachers. In the period of lockdown due to the COVID-19 pandemic, all the paths have been reworked to be carried out in distance learning.

Among the activities proposed to the third-year students, we find an interdisciplinary path developed in collaboration between the Mathematics Department of the University of Salerno and the National Institute of Nuclear Physics in Naples (INFN – Napoli Unit), a research-project in astroparticle physics.

The project focuses on the study of astroparticles and on the reproduction in the classroom of some experiments thanks to very advanced technologies in which students work in groups and experience the role of researchers in a constructivist methodology [2], [3]. This choice is in line with both national and international indications relating to the use of technologies in education as described in [4], [5],[6],[7],[8],[9],[10],[11].

2. The Project

As part of the educational path of the Mathematical High School Project, the module of physics and science of the Mathematical High School Project consists of 10 hours of activities divided into four meetings for each class of the three-year period. The activity presented in this paper takes place in third classes and the data we have collected and analyze refer to the workshops carried out in the 2019-2020 and 2020-2021 school years. Due to the COVID-19 lockdown restrictions, educational activities have been carried out in some paths with remote e-Learning activities, in others in mixed mode with some meetings in presence and others in online platform.

The students who attended in presence, even if only in part, were able to work physically with the Cosmic Ray Cube (CRC), a portable muon detector designed by the Gran Sasso National Laboratories that was brought by researchers to the classes for the detection of muons. Those who attended remotely studied how the muon detector was built and how it works. All students subsequently analyzed the data through the dedicated apps and through calculation software.

3. The Cosmic Ray Cube

The CRC is a portable detector for cosmic muons. The telescope, using the most innovative technologies that are normally used in particle physics experiments, is able to visualize the passage of particles contained in cosmic-ray showers that continuously arrive on the Earth. It has a compact structure and allows the measure the flow of particles at various altitudes and their angular distribution.

The detection of muons within the CRC takes place thanks to the use of instruments commonly used in real experiments. The main parts are: plastic scintillators (able to convert into light the energy released by the interaction of a charged particle), optical wavelength shifter fibers, WLS, (that collect light signals and convert them into light of different wavelengths), and Silicon photomultipliers, SiPM (capable of converting the light collected by the fibers into an easily digitizable electrical signal [12]).

The CRC is also equipped with LEDs that, thanks to a sophisticated acquisition electronics, light up when the particles pass, allowing the observer to follow the trajectory. The detector consists of four modules. Each module consists of 2 layers, each of them consists of 6 scintillator bars. The 2 layers are superimposed and positioned orthogonally to each other.

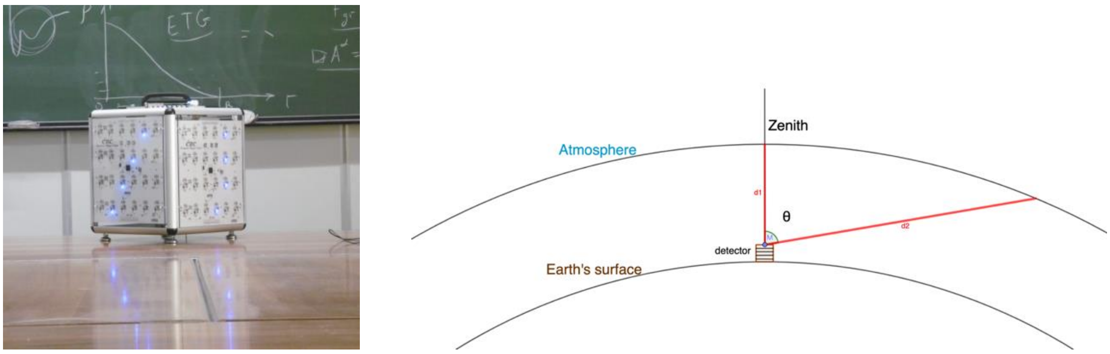

Figure 1. On the left the CRC, on the right the representation of the paths (d_1 and d_2) taken by two muons produced in the atmosphere and directed towards the detector placed on the earth's surface. One follows a vertical path (d_1-θ=0°), the other one follows a path (d_2) inclined of a θ angle with respect to the zenith.

4. Data analysis

4.1. CRC as a tracker

The students were able to observe on the XZ and YZ faces of the CRC the illumination of the LEDs corresponding to the scintillator bars crossed by the particles and understood how to reconstruct the trajectory of the muons. Details of this work are described in [6]. We have also deepened some aspects of the Cartesian geometry of space by exploiting the potential of the visualization of apps, calculation software and spreadsheets and we have studied an application to the concept of straight line in space (which is part of the school curriculum of mathematics) in trace reconstruction with an effective didactic impact as achieved through laboratory experimentation in active teaching activities text.

4.2. CRC as a counter

In the second workshop activity, the students used the CRC as a counter. Muons that arrive perpendicular to the Earth's surface (they arrive along the direction of the local zenith), travel the shortest distance in the atmosphere, while, for high angles of incidence, with respect to the zenith, the distance to travel is longer. The greater is the theta angle, the greater is the distance traveled, the greater is the probability that the muons decay before reaching the Earth's surface and the flux is lower.

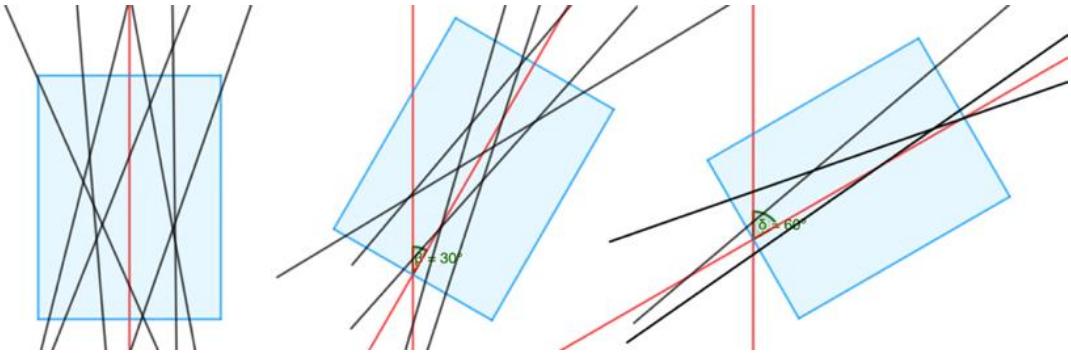

Figure 2. On Representation of the experimental configuration. The detector, initially positioned with the axis parallel to the local zenith (a) collect vertical particles, can be inclined at increasingly greater angles: 30° (b), 60° (c) up to 90°, to detect particles with increasing angle of incidence.

The students calculated the muon rate (R) as the ratio of the number of particles (C) to the time interval (T). The rate, R = C / T (particles/ minute), is measured for each angle and the relative statistical error is associated the relative statistical error. They then drew a graph with the rate as a function of θ on the y-axis, and θ on the x-axis. Counts were preliminarily normalized to 1 for comparison with the $\cos^2\theta$ function. We expect that the ratio as a function of theta follows this mathematical function. For the sake of synthesis, the description of the activities related to the errors is omitted in this paper, and the data of one of the sessions of this experiment is reported below.

Angle Measurement	Number of particles	Muon rate	Function value $\cos^2\theta$
0	78	1,00	1,00
15	62	0,79	0,93
30	42	0,54	0,75
45	29	0,37	0,50
60	24	0,31	0,25
90	12	0,15	0,00

In the graph were compared the normalized counts (the blue dots) with the values of the function $\cos^2\theta$ (the yellow line). For each angle, repeated measurements were made and a good agreement with theoretical expectations was observed, the students noticed the decreasing trend of the number of muons intercepted by the CRC as a function of the angle of inclination of the detector.

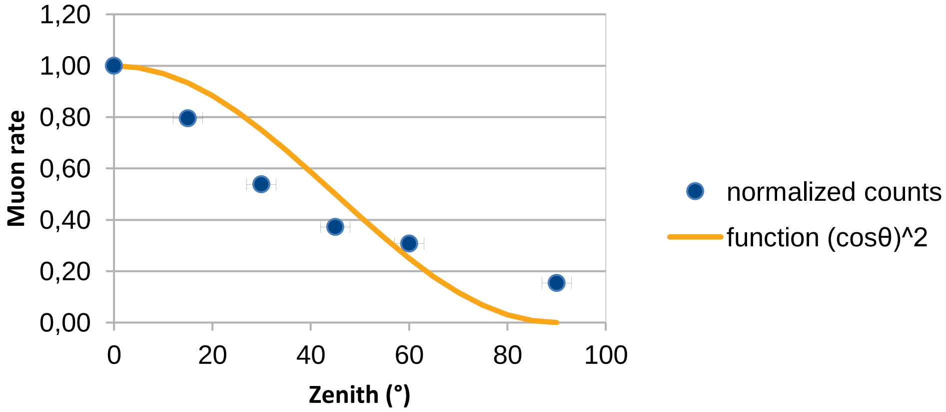

Figure 3. Muon rate as function of the zenith angle (the blue dots) compared with the values of the function $\cos^2\theta$ (the yellow line), the theoretical expectation.

In describing the previous stages of the work, we have said many times that the CRC detects cosmic ray muons. It can detect also other charged cosmic-ray particles as electrons and positrons (these are the particles which mostly reach the Earth's surface together with muons), but we usually use the CRC asking that at least one led per module is on. This means that the particles we collect in this configuration have passed through all four modules and there is a very high probability that they are muons. In fact, muons penetrate any matter better than any other known particles, except neutrinos. As electrons and positrons, they do not interact strongly and they very rarely undergo hard collisions with atomic nuclei. Moreover, being their mass about 200 times higher than electrons and positrons mass, they do not radiate as much energy during passage through matter as electrons and positrons do.

Muons lose less energy than other particles during their path. This makes muons very penetrating particles capable of crossing also many meters of rock without being absorbed by matter. To better understand this concept, students verified how the rate of detected particles changes by changing the "trigger mode" of the CRC, that is by changing the conditions necessary for the crossing particles to be counted. In addition to counting the particles that cross all four modules, we also saved those that only go through only three or two modules. As we expected, decreasing the number of requested modules, the number of counted particles increases. We are detecting also electrons and positron in these last two configurations. We cannot detect them if we ask four modules because they are stopped by the first scintillator modules (from top to bottom) and cannot reach the last one. They can reach the bottom module only if they are very very energetic.

Can we shield the penetrating muons in some way? To answer this question, we placed thin layers (for a total of 2 cm thick) of lead above the telescope. Thanks to its high density, lead can stop muons. As expected, we observed a small decrease of the muon flux, but this measurement can be improved choosing the right distance between lead and CRC.

At the beginning, it was very difficult for students to understand the concept of particle absorption in matter and the different behavior of different particles, but in the end they were very excited to be able to predict what they were going to measure.

5. Questionnaire analysis

To have feedback on the didactic effectiveness of the activities, two questionnaires were administered to the students, one before starting the path and one at its end. The results of the questionnaires administered in the first year were published in [8].

We did not observe significant differences between the questionnaire results of face-to-face and remote activities and therefore they were analyzed together. In the preliminary questionnaire the students showed a high degree of interest in the contents of the course. The questionnaire carried out at the end of the activity confirmed the previous answer with a small increase in appreciation. The evaluation was found to be independent of the propensity to future scientific studies of the participating students and from the potential relapse in terms of knowledge for their future.

In the second part of the questionnaire, the students had to answer open questions related to the topics of the Course. We experienced different answers in the two school years. In the first year in fact the students had never dealt with particles in class and therefore the questionnaire made before starting the activity highlighted quite generic answers or even non-answers. In the second year, the classes had previously participated to the activities of the International Cosmic Day ICD organized by the INFN and, after a few months, they remembered the topics they met at the ICD although with some inaccuracy.

In the questionnaires at the end of the course, all the students of the two years have shown to know adequately the topics addressed and to use a rigorous and scientific language.

6. Results and conclusions

The educational activity resulted to be perfectly consistent with the purposes of this Project, which aims to create cultural bridges between the various areas of knowledge, from the scientific world to the humanistic and the technological ones. With regard to the cognitive aspect, the continuous interaction between professors, researchers and students brought to the acquisition of new contents and calculation methodologies, but also the acquisition and development of a critical sense necessary to interpret the effectiveness less than a methodological approach to a real phenomenon to be explored to determine its characteristics and outline a scientific model.

From the meta-cognitive point of view, on the other hand, a virtuous behavior towards laboratory activity was found in the students. Students analyzed the historical evolution of the particle physics, met the protagonists, observed that scientific knowledge is described with a mathematical language and translated and analyzed thanks to the use of new technologies to overcome the limits of research.

Working in groups, even for remote activities, the students acquired a teamwork model with respect for the roles and a language both in interpersonal relationships and in the dissemination phase [13]. They underlined how it is easier for them to remember contents and becoming passionate when they work with engaging, dynamic and technological environments as protagonists in team with researchers and teachers.

7. Acknowledgements

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