LIP-STUDENTS-22-25

Measuring The Sky

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Abstract. Atmosphere is swarming with particles invisible to the eye. They are subatomic particles whose effects on materials can be measured as they pass through them. One of these particles is muons. They are created after a particle called primary particle enters the atmosphere and interacts with the air. Their angular and energy distribution varies depending on altitude and latitude. In this work, an experiment to construct angular and energy distribution of muons at the sea level is devised and a corresponding simulation by means of Geant4 simulation toolkit and CRY software is presented.

Keywords: Muons, Cosmic Showers, Geant4, CRY

1 Introduction

The atmosphere is subject to a plethora of particles from the space such as protons, gamma rays, neutrons, alpha particles and so on. A particle entering the atmosphere is called primary particle. As it travels through the air in the atmosphere, it interacts with the particles of the air and generates other particles. These other particles create other particles and this cascade of multiplication of primary particle in number is oriented in the direction of the primary particle meanwhile dispersing wider in thickness as it traverses longer. This process brings about a vast variety of particles defined as cosmic shower. The energy and angular distribution of each species of these particles differ at different altitude and latitude. Difference in altitude is a result of the cross section of its generating interaction and particle's lifetime. As the cross section of its generating interaction increases the number of particle will raise. On the other hand, short decay time will reduce the number of particles before they reach the ground[1]. Muons can be produced by variety of processes. μ^- decay via the process $\mu^- \to e^- \bar{\nu}_e \nu_\mu$ with almost 100% branching ratio and μ^+ decay via the same process charge conjugated, $\mu+ \to e^+ \nu_e \bar{\nu}_\mu$ [**pdg**]. All those taken into account, the flux of muons at energy E and angle θ is:

$$I(E,\theta) = I_0 N (E_0 + E)^{-n} \times \left(1 + \frac{E}{\epsilon}\right)^{-1} \cos^{n-1}\theta \quad (1)$$

where I_0 is the energy integrated flux at the angle 0° with normalisation constant N and ϵ is a parameter to account for pions and kaons decaying to muons at high energy[1].

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2 Experimental Setup

The aim of the experiment is to measure angular and energy distribution of muons. The experimental setup to accomplish this is explained here. There are a variety of environmental factors when performing the experiment. The experiment must take place at the sea level to be consistent with the simulation. The detectors must be placed in a open area where there will be no obstruct except for the air for muons coming from above to lose energy.

In the experiment, there are two parallel EJ-200 scintillators placed as in the figure 1:

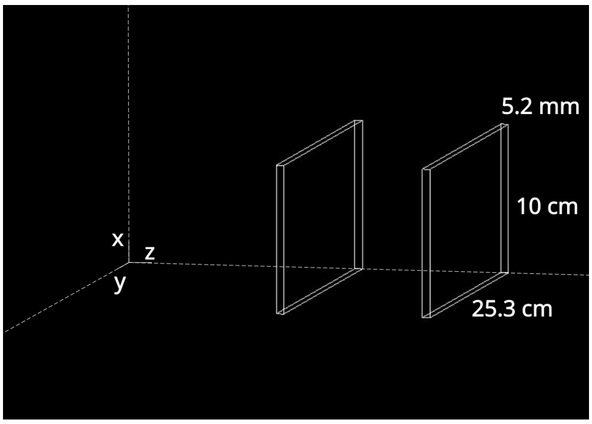

Figure 1: Placement of the scintillators in the space

Here +z axis points towards the ground so particles go towards +z. The scintillators that are going to be used in the experiment can be seen in the figure 2

The area of the plane of scintillators is 253 cm^2 . The number of muons passing through 1 cm^2 per minute is 1 [2]. Therefore, it is expected that there will be 253 muons passing through a detector at sea level per minute. EJ-200 scintillators use polyvinyltoluene [(2-$CH_3C_6H_4CHCH_2)_n$]. Since a plastic scintillator is used, energy resolution will be

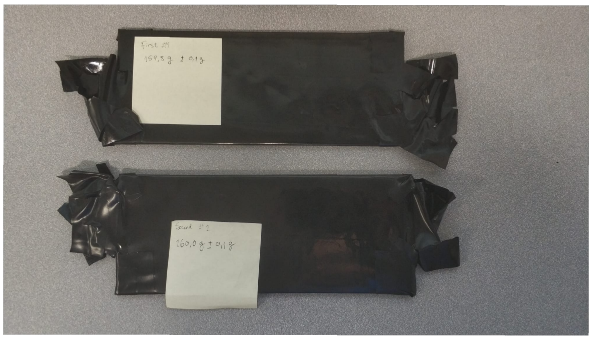

Figure 2: View of the two scintillation detectors in the simulation framework. The dimensions of the detectors are shown

inferior. However, the number of incidents that are not registered by the scintillators will be less.

In figure 1, if a particle comes from the direction perpendicular to the planes of scintillators, it will pass through both scintillators. To select the particles passing through both scintillators in the setup of experiment, scintillators will be connected to PMTs and a NIM, which is capable of selecting events in time-coincidence at the both detectors.

3 Simulation

The depicted experiment was simulated using Geant4 and CRY software. Geant4 is a toolkit to simulate passage of particles through materials using Monte Carlo algorithm[3]. Cry is a software to simulate the effect of cosmic-ray particle showers at either sea level, 2100 m, or 11300 m to be utilised as an input for transport or detector simulations[4]. CRY software is used to create the cosmic shower at the sea level and Geant4 is used to simulate the development of the nuclear interactions on the detector system setup as seen in the figure 1.

To maintain the consistency with the experiment following considerations are attended in CRY runs: The shower is created on a 1 m^2 area lying on xy plane shown in figure 1. On this area, there are muons travelling towards the detectors from different positions and with different momenta. As consequence, a simulation of the position and momenta of muons at the sea level was created on this 1 m^2 area above the detectors. Distance between this plane and the detectors is a variable. The experiment takes place at the sea level. Latitude is that of Lisbon, Portugal, 38.717°. Only particles created are muons. This will reduce the number of muons reaching the farther detector as some muons will decay and the particles decaying to muons will be omitted. Notwithstanding, this will not affect the resolution of the experiment. The decay products of muons are not of interest in this experiment and neither are the particles decaying to muons. The number of particles created was 5×10^4. Date was not taken into account due to its negligible effect.

As an output, CRY software yielded whether the particle is a muon or antimuon(charge of the particle), their kinetic energy, and position on that 1 m^2 area. The simulation can be seen in the figure 3

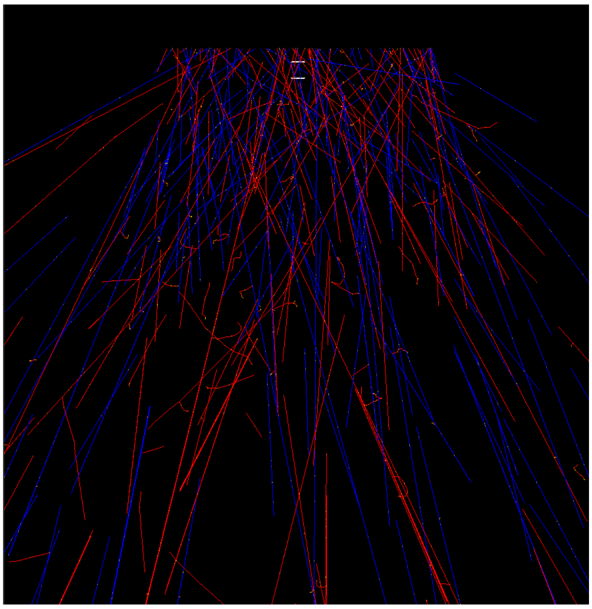

Figure 3: A frame from the simulation of the muon cosmic ray with the detectors in the middle

In this figure two white lines are the detector system as depicted in figure 1. The line above where the particles are emitted from is the 1 m^2 area specified for CRY run. Blue lines are the muons and red lines are the antimuons.

CRY software had Geant4 bindings but they were significantly outdated at the time of this simulation. The CRY software's bindings for Geant4 were written for Geant4 4.2, yet the current version was 11.0.3. Any attempt to run the bindings would result in a plenitude of deprecated API errors. As a result, CRY output was acquired in .csv file. Then, this file is converted to a form Geant4 could interpret. Generally, particles in Geant4 are generated using G4ParticleGun but to import the CRY output to Geant4, a more sophisticated approach was required. For this G4GeneralParticleSource class is used. This class is just defined and after the simulation is run, the particle setting is supplied by Geant4 commands. Geant4 can read commands from a file called Geant4 macro. A python code is written to convert the CRY output to Geant4 macro.

In Geant4, the detectors are set up according to their specifications remarked in the section 2 Experimental Setup. All interactions of muons are added to physics list of Geant4. As an output file a root file is set to visualise the histogram of particle energies.

4 Results

In the simulations, the distance between the detectors was coded to be 6 cm. The distance between the centre of mass of the detector system and the origin was coded to be 8 cm. These are variable in the code and can be manipulated on demand to find the most suitable distances.

The energy distribution of deposited energy by the muons on the detector closer to the simulated shower can be observed on the figure 4:

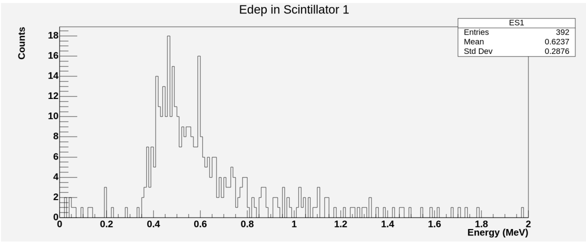

Figure 4: Energy deposition on the top detector at the angle 0°

The measured energy may deviate from the muons' energy before they interact with the detectors because of energy straggling in scintillators. In addition, since the simulation takes all interactions into account such as muon-electron scattering (delta-ray production), or muon multiple scattering and backscattering, there are incidents where energy deposited was between 0 and minimum ionising particle energy.

The energy distribution of deposited energy by the muons on the detector farther to the simulated shower can be observed on the figure 5:

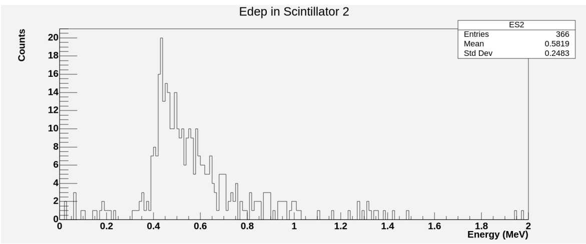

Figure 5: Energy deposition on the bottom detector at the angle 0°

The number of counts on this figure is less than the one that demonstrates the energy deposited on the detector closer to the cosmic ray shower simulation. In the atmosphere such minute changes in altitude will not make a difference. The muon flux will be almost the same 10 cm above and 10 cm below. Because contrary to this simuation, in the atmosphere, muons decay to other particles while other particles may decay to muons. As a result, as the distance from the source plane of CRY simulation increases, the number of counts in the GEANT4 simulation decreases. This effect was explained above and here data confirms that inference. This reduction in the number of counts do not affect the the angular distribution.

The energy distribution of deposited energy by the muons on the detector closer to the simulated shower in coincidence can be observed on the figure 6:

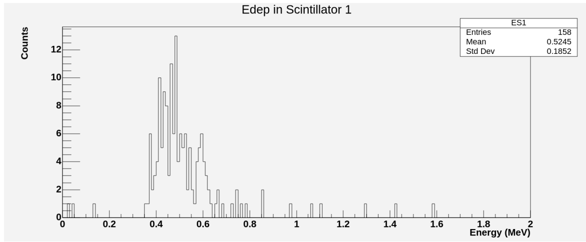

Figure 6: Energy deposition on the top detector at the angle 0° in coincidence with the bottom detector

Here, a significant descent in the counts implies that the selection process takes place successfully. More than half of the particles pass through only both of the scintillators.

Angular distribution of the muons at the sea level is verified in the figure 6 along with the prediction of the model in the equation 1.

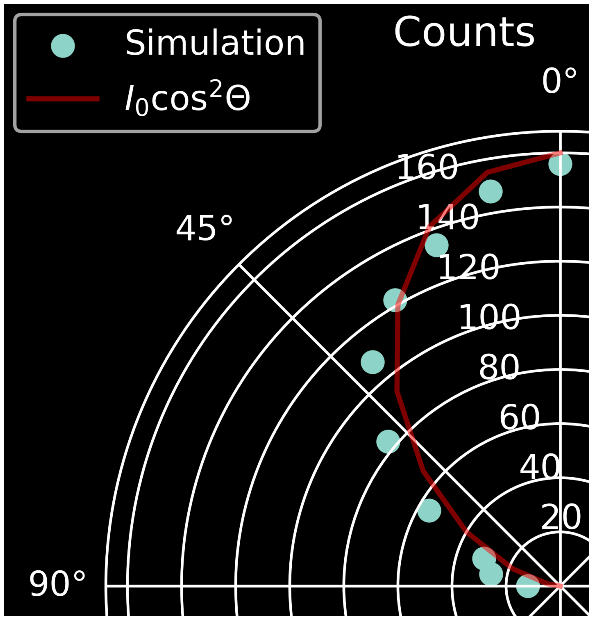

Figure 7: Angular distribution of cosmic muons at the sea level according to cosine law (line plot) and GEANT4 simulation of that (scatter plot)

The graph is drawn to resemble the setting of the experiment in real life: 0° angle points upwards representing the skywards direction. 90° angle points towards the horizon. The radial distance confers the the count measured at this angle. In accord with the prediction of the cosine law, as the inclination of direction the detectors are facing increases, less and less particles are registered.

There exists a systematic error in the distribution. This is a consequence of the choice of the experimental setup. To illustrate this, a different perspective of the detector system can be seen in the figure 8:

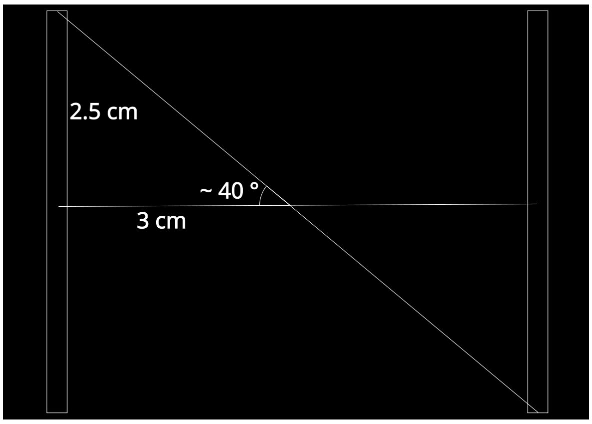

Figure 8: The placement of the detectors for angular distribution measurement

The two columns on the sides represent the detectors. If the detectors are oriented at 60 °for example, then detections at this angle are considered to have arisen due to muons passing through at exactly 60 °. However, this gives rise to an error because muons that pass through at angles other than 60 °are also detected, but they are still considered to have arrived at 60 °. To illustrate this, consider the diagonal line in the figure represents how a muon may pass through both detectors at 40 °to the direction that the detectors face. The horizontal line in the figure represents the direction that we assume the muons arrived at (which is the same as the direction that the detectors face). This phenomenon happens up to 40 °of difference between the actual arrival angle of the muons and the angular orientation of the detectors, for 6 cm distance between the detectors. Beyond 40 °, the muons cannot not pass through in coincidence. This event causes the error observable in the figure 7. One practical solution is to increase the distance between the detectors for it is a variable in the code of the simulation. As the distance increases the angle between the diagonal line and the angle of interest will decrease making the angular distribution less error-prone. However, caution must be practised because as the distance between the detectors increase, the probability of a muon passing through one detector to pass through the other

detector will decrease. Therefore, the number of counts recorded in coincidence will fall.

Acknowledgements

Hereby, I would like to express my deepest thanks to my supervisor Tomás Sousa and my professor Daniel Galaviz.

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