PROCEEDINGS OF SCIENCE

A Simulation Study of the GRAPES-3 Sensitivity to Primary Cosmic Ray Composition with the Expanded Muon Telescope.

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The GRAPES-3 extensive air shower consisting of a dense scintillator array and a 560 m square area tracking muon detector is designed to study the cosmic ray energy spectrum and composition over the knee region. Another muon telescope similar to the existing one is under construction and is expected to be operational within a year's time since the muon content is a sensitive parameter of the cosmic Ray primary composition, with the doubling of the area of the expanded muon detector, the mass separation of the different primary composition rays is expected to be improved at low energy when the muon density is low. Here we present our simulation studies of the sensitivity of the expanded muon telescope to the primary composition over 10-100 TeV. We used Corsika for shower simulation and GEANT-4 for simulating the detector response.

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1. Introduction

Cosmic Rays are high energy particles that originate in our own galaxy and beyond. The approximated composition of the cosmic rays states that protons stand at (~ 85%), followed by alpha particles(~ 12%), which are further followed by elements with nuclear charge Z≥ 3(~ 3%). As mentioned, they are particles with great energies so on entering the Earth's atmosphere, they collide with the atmospheric nuclei, thus producing secondary particles like pions and kaons which have a very short lifetime and decay quickly. On decaying these pions and kaons give rise to particles like gamma and muons. The gamma so produced, by means of pair production give rise to electrons and positrons which further produce gamma by bremsstrahlung. In this way a cascade of secondary particles is formed known as Extensive Air Shower (EAS). Muons produced by pions and kaons, lose very less energy and whatever energy they lose it's mostly by ionization. As a consequence of this muons easily reach the earth's surface . Some of them even reach beneath the surface of the Earth, and are very important in investigating different parameters related to cosmic rays. So the Primary Cosmic Rays(PCRs) do not reach the ground directly. So the direct study of cosmic rays(up to 100TeV) is done by satellite or balloon based experiments, but at higher energies the flux of cosmic rays falls steeply [1, 2], so in that case indirect measurement comes into picture. GRAPES-3 is one of the many experiments involving indirect measurement of cosmic rays. It is explained in detail in the next section.

Cosmic Rays have a very wide energy spectrum which goes from 10^8 GeV - 10^{20} GeV. The main primaries are Proton(H), Helium(He), Nitrogen(N), Aluminium(Al) and Iron(Fe). The proton and helium are combined as the lighter mass category while carbon, oxygen and nitrogen as the medium mass and lastly, aluminium- upto iron as the heavier mass. Now, since the energy spectrum is so wide, the contribution of different primary changes as the energy changes, i.e. at low energies proton might be dominant but at higher energies iron might be the dominant one.

2. GRAPES-3 Experiment

The GRAPES-3 (Gamma Ray Astronomy at PeV Energies Phase-3) experiment, is located at the Cosmic Ray Laboratory, Ooty, Tamil Nadu. The experiment runs at an altitude of 2200m above mean sea level and its geographical co-ordinates are 11.4°N latitude and 76.7°E longitude. The main detector used to measure different parameters of EAS, is an array of scintillator detectors. There are 400 plastic scintillators spread over an area of 25,000 m^2. The area of each detector is 1m^2 and the inter-detector distance is 8m [3] , which makes it very compact and dense, hence it is possible to observe the primary cosmic rays in TeV-Pev energy range [2]. Each detector in this array has four blocks of organic scintillators, each of area 50cm × 50cm and 5 cm thickness. These detector are designed to measure both density and arrival of the EAS particles. Earlier the detectors used were trapezoidal in shape, but due to some limitations like low photon collection and large non-uniform response due to the geometry, there was the development of a better design by coupling wavelength shifting fibers on the scintillator surface. The large area tracking muon telescope or the GRAPES-3 muon telescope (G3MT) is designed to record the muon component of the Extensive Air Shower(EAS). The details of the G3MT are discussed in section 3 of this paper.

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Figure 1: GRAPES-3 Experimental site in Ooty [6].

3. The GRAPES-3 Muon Telescope (G3MT)

The G3MT is one of the two detectors used at GRAPES-3, having 16 independent modules each with an area of $35m^2$. The total area of the G3MT is $560m^2$. The basic detection element of G3MT is the proportional counter(PRC). Each PRC, is a mild steel, zinc coated cuboidal tube of dimension 600cm × 10cm × 10cm, filled with P10 (90% Ar and 10% CH_4) gas at a density 1.67 kg/m^3, pressure of 1.09 *bar* and a temperature of 295 K, having a tungsten wire placed at it's center. The G3Mt has 16 independent modules shown in figure 2. Each module has 4 layers, where each layer has 58 PRCs [4, 5]. The bottom-most layer is called layer 0, whereas the top-most layer is the 3rd layer.The alignment of the PRC's in layer 0 and layer 2 is in East-West direction and in the layers 1 and 3 in Noth-South direction. The alignment is done in such a way to reconstruct muon tracks in two dimensional orthogonal vertical planes. In-between two adjacent layers a concrete block of 15cm thickness is placed so to shield the electromagnetic and hadronic component of the EAS. On top of the 3rd layer a total of 2m thick, 13 concrete layers are placed in an inverted pyramid shape. A total of 3712 proportional counters are arranged in 16 modules. Four modules of G3MT together are known as a station or a supermodule. The G3MT has an energy threshold of secθ GeV, where θ is the zenith angle of the incidence muon.

Recently the construction of the new muon telescope with similar area as the old one, has been completed at GRAPES-3. The GEANT-4 reconstructed new muon module is shown in figure 2. [6]

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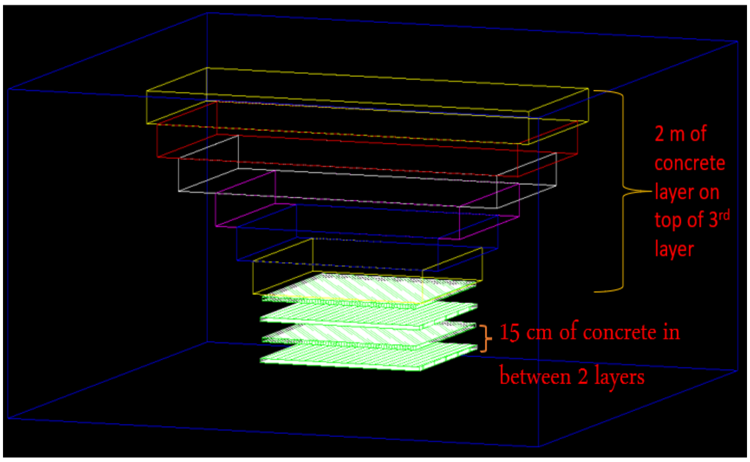

Figure 2: A GEANT-4 Reconstructed New Muon Module, with 59 proportional counter in each layer.

In the new muon telescope there are 59 proportional counters in each layer of a module, making a total of 3776 PRCs with 70% more sky coverage. Also, the new G3MT has all the stations or supermodules housed under a single roof. The rest of the features of the new G3MT are quite similar to the old one. Combining the new G3MT with the old G3Mt we get, expanded muon telescope. This is done so that the detection area for muons will be doubled which would enable more efficient measurement of cosmic ray composition.

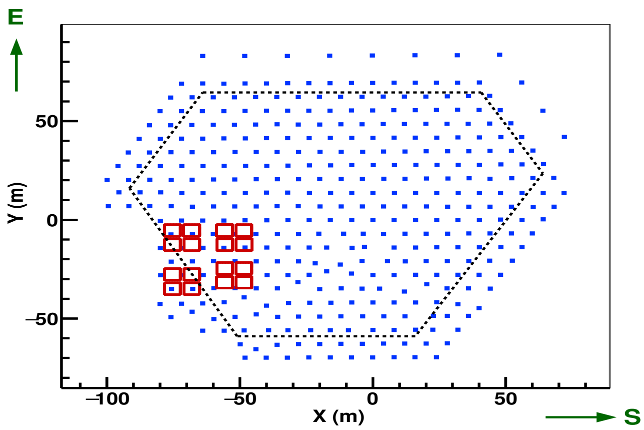

Figure 3: GRAPES-3 Array showing scintillator detectors by blue squares and sixteen independent muons of the old muon telescope by red big squares.This picture has been taken from the article "Vetoing the high energy showers in the GRAPES-3 experiment whose cores lie outside the array" [8].

4. Monte Carlo Simulation

The Simulation data that has been taken, is done using CORSIKA version 7.6900 [10], with QGSJET-II-04 and FLUKA [7] as the high and low energy hadronic interaction model respectively [10]. The electromagnetic interactions are treated by EGS4 model. The simulation is done with the proton, helium, nitrogen, aluminium and iron as the major primaries.
The CORSIKA generated files(DAT files) are converted to ROOT files using G3Analysis tool.

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5. Composition Study Comparing Data and Simulation

Since the composition of Cosmic Rays is energy dependent, meaning there will be different primaries dominating at different energies. For example, at lower energies proton as a primary is dominant but as the energy increases other heavier elements are more dominant. To study the energy dependent composition we can compare the actual data plots with the simulation of the five major primaries i.e. H(proton), He,N,Al,Fe and find out the contribution of each primary as a function of energy. Although it is a complex process and needs deep study. In this paper, we have graphically tried to look into the contribution of the different primaries (H, He, N, Al, Fe) in the cosmic ray composition for different shower size(N_e) bins, from $10^{3.6}$ to $10^{4.6}$ (3.6-4.6 in log_{10} scale) with a bin width of $10^{0.2}$ [11]. We have compared the muon multiplicity distributions(MMD) of the real data for the year 2014 for the 16 modules of the G3MT, with the CORSIKA simulated data of the five primaries i.e., Proton, Helium, Nitrogen, Aluminium and Iron.

5.1 Selection Cuts for the Analysis

The selection criteria were as follows:

- $0.2 < \text{showerage}(x) < 1.8$, since there is a lot of fluctuation below 0.2 and above 1.8(due to shower age converging to its limits)
- $\theta < 45°$, i.e. zenith angle less than 45 degrees, since at larger angles the length of path traversed by the cosmic rays increases, thereby increasing more interactions so more energy loss, hence reduced flux.
- Considered only those EAS the core of which lie within the fiducial area(shown by black dotted lines in figure 2). Table 1 shows the x, y co-ordinates of the fiducial area.

x (m)	y (m)
-91.5	16.0
-64.0	64.5
40.8	64.5
64.0	23.5
16.0	-59.0
-51.0	-59.0

Table 1: X and Y Co-ordinates of the Fiducial Area

Figure 4-9 are preliminary plots showing the comparison of muon multiplicity distribution of the observed data with the simulated data.

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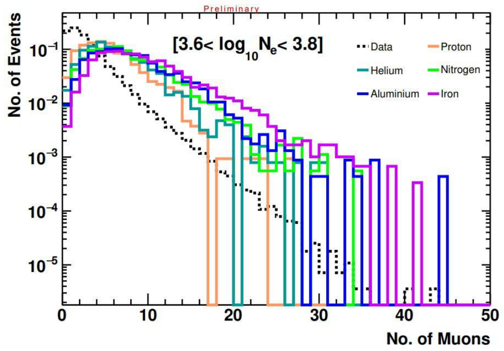

Figure 4: MMD for Shower Size bin 3.6-3.8

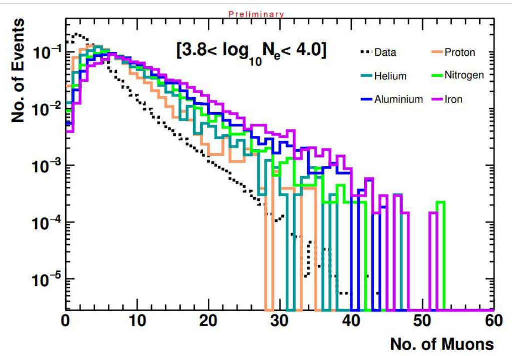

Figure 5: MMD for Shower Size bin 3.8-4.0

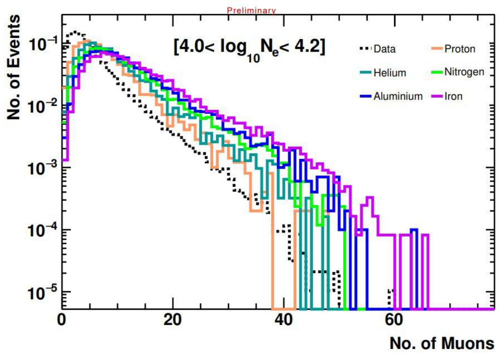

Figure 6: MMD for Shower Size bin 4.0-4.2

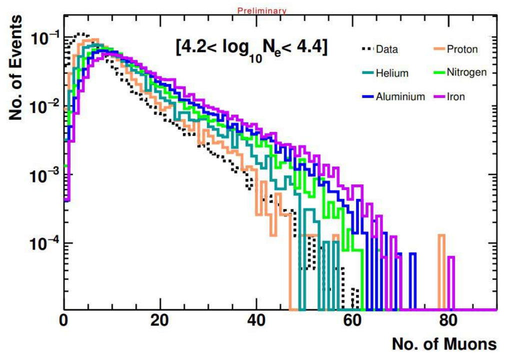

Figure 7: MMD for Shower Size bin 4.2-4.4

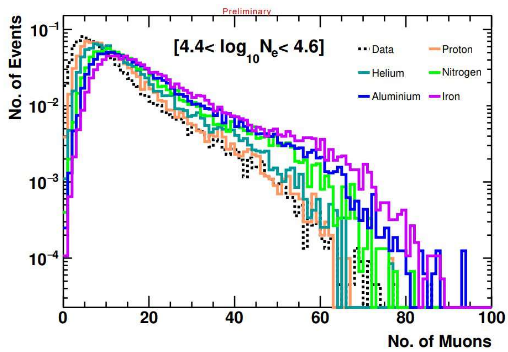

Figure 8: MMD for Shower Size bin 4.4-4.6

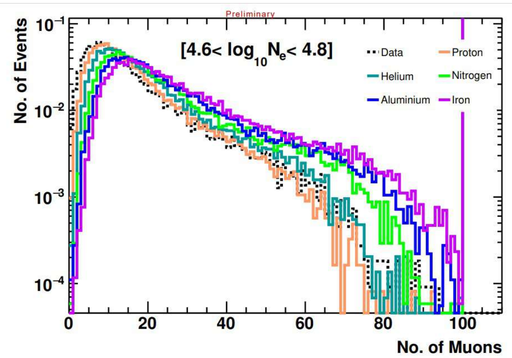

Figure 9: MMD for Shower Size bin 4.6-4.8

We also plotted a preliminary graph of Mean Muon multiplicity as a function of Shower shower size, shown in figure 10.

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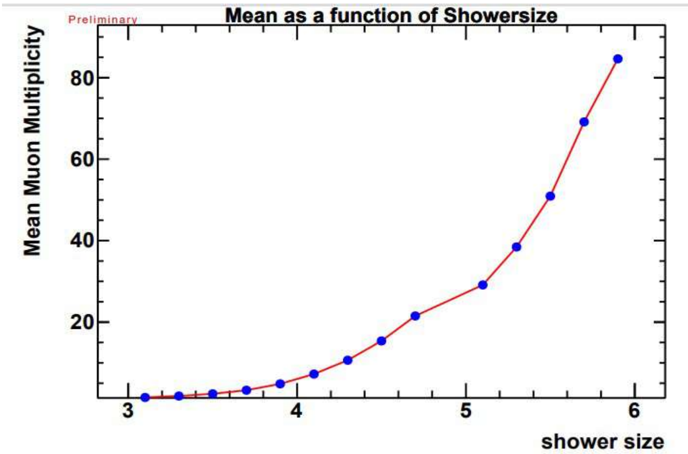

Figure 10: Mean Muon Multiplicity as a function of Shower Size.

6. Increased Sensitivity to Primary Cosmic Ray Composition with the Expanded Muon Telescope

With the Expanded Muon Telescope the detection area of the muons is doubled, so in this paper we have plotted the MMD for old muon telescope and the expanded muon telescope and compared the same to note the increased sensitivity towards primary cosmic ray composition.[work under progress]

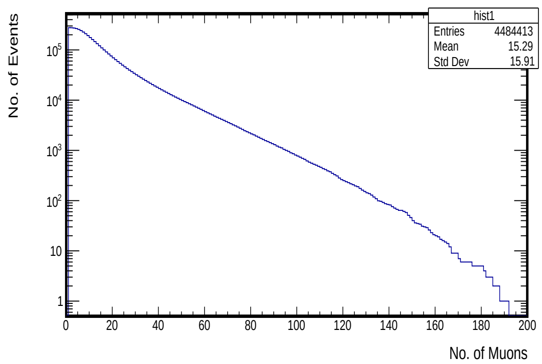

Figure 11: Muon Multiplicity with the old muon telescope.

This is just a place holder, the graph to be put here is under works and will be uploaded soon.

Figure 12: Muon Multiplicity with the Expanded muon telescope.

7. Conclusion

In this paper we have compared the Muon Multiplicity Distributions (MMDs) from the existing muon telescope and simulations. These plots show that the observed MMD can not be explained only by proton or iron primaries and it requires intermediate mass primaries. To observe the increased sensitivity to the primary cosmic ray composition with the expanded muon telescope (old + new), we plotted the total muon multiplicity of the old muon telescope and the extended

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muon telescope, as shown in the figure 11 and 12 respectively. Once the new Muon Telescope is operational, we would extend the simulation studies with the expanded muon telescope and the simulation results will be compared with the data.

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