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^2 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 one of its module is already operational. 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 cosmic rays is expected to be improved at low energy when the muon density is low. In this paper we present our simulation studies of the sensitivity of the expanded muon telescope to the primary composition over 10-100 TeV by studying muon multiplicity distributions (MMDs) . 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 charged particles that come from both within our galaxy and from beyond. Around 90% of the Primary Cosmic Rays (PCRs) are estimated to be composed of protons. Following protons, approximately 9% consist of alpha particles, and the remaining fraction, 1% is composed of elements with nuclear charge Z greater than or equal to 3. Upon entering the Earth's atmosphere, PCRs interact with atmospheric nuclei, resulting in the creation of secondary particles such as pions and kaons. These secondary particles possess extremely small lifetimes and rapidly undergo decay processes. When pions and kaons undergo decay, they can give rise to particles such as gamma rays and muons. Gamma rays, on interacting with matter, can produce electron-positron pairs through pair production. Additionally, electrons and positrons can emit gamma rays by bremsstrahlung. This process leads to the formation of a cascade of secondary particles, referred to as an Extensive Air Shower (EAS). Muons produced by pions and kaons undergo minimal energy loss, primarily through ionization. As a result, these muons can efficiently reach the Earth's surface and some can even penetrate beneath it. Their exceptional ability to retain energy makes them crucial for studying various parameters related to cosmic rays. Cosmic Rays have a very wide energy spectrum which range from 10^8 GeV - 10^{20} GeV with the main primaries are Proton (H), Helium (He), Nitrogen (N), Aluminium (Al) and Iron (Fe). Proton and Helium are combined as the lighter mass category while Carbon, Oxygen and Nitrogen as the medium mass and lastly, Aluminium - up to Iron as the heavier mass. Since the energy spectrum is so wide, the contribution of different primary varies as the energy varies, i.e. at low energies Proton might be dominant but at higher energies Iron might be the dominant one. The direct study of cosmic rays (up to 100 TeV) is done by satellite or balloon based experiments, however at higher energies the flux of cosmic rays falls steeply [1], so in that case indirect measurement comes into picture. GRAPES-3 is one of the the major EAS experiments involving indirect measurement of cosmic rays and is explained in detail in the next section.

In this article, we visually depict the contributions of various primary particles (Proton, He, N, Al and Fe) to the PCR with increasing energy (or increasing shower size) by using simulations and compared them with GRAPES-3 data. We have also compared the muon multiplicities in both expanded muon telescope and the old muon telescope using simulated data by taking Proton as the primary.

2. GRAPES-3 Experiment

The GRAPES-3 (or Gamma Ray Astronomy at PeV Energies Phase-3) experiment is located at the Cosmic Ray Laboratory (CRL), Ooty, Tamil Nadu, India. The experiment operates at an altitude of 2200 meters above mean sea level, with geographical co-ordinates 11.4°N latitude and 76.7°E longitude. To measure various parameters of EAS, the main detector used is an array of scintillator detectors. This array consists of 400 plastic scintillators spread over a 25,000 m^2 area. Each individual scintillator detector covers an area of 1 m^2, and the inter-detector distance is 8 m, making it highly compact and dense, hence it is possible to observe the PCRs in the TeV-PeV energy range [2]. Each detector in this array comprises of four blocks of plastic scintillator, each with an area of 50 cm × 50 cm and a thickness of either 5 cm or 3 cm. These detectors are designed to measure both the density and arrival of EAS particles. In addition to that, the experiment features the large-area tracking muon telescope, known as the GRAPES-3 muon telescope (G3MT), which is specifically designed to record the muon component of the EAS.

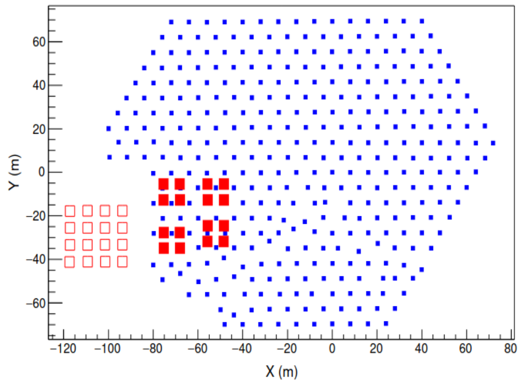

Figure 1: A schematic of the GRAPES-3 array. The blue filled squares represent the existing scintillator detectors and the red filled squares represent the old muon modules whereas the open red squares represent new muon modules. The picture is taken from Ref.[3].

3. The GRAPES-3 Expanded Muon Telescope

The GRAPES-3 Muon Telescope or the G3MT is one of the two detectors used at GRAPES-3, having 16 independent modules each with an area of 35 m^2. The total area of the G3MT is 560 m^2 [4]. Recently, the construction of the new muon telescope with similar area (560 m^2) as the old one, has been completed at GRAPES-3. The basic detection element of new muon telescope 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 its center. There are 16 independent modules, each having 4 layers, where each layer has 59 PRCs unlike the old muon telescope which has 58 PRCs [4]. The bottom-most and the top-most layers are called layer 0 and layer 3 respectively. The alignment of the PRCs in layer 0 and layer 2 is in East-West direction and in the layers 1 and 3 in North-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 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 3776 proportional counters are arranged in 16 modules. Four modules of the new muon telescope together are known as a station or a super-module. There are four such stations housed under the same roof. The new G3MT has an energy threshold of secθ GeV, where θ is the zenith angle of the incidence muon. A GEANT-4 reconstruction of a new muon telescope module is shown in Figure 2.

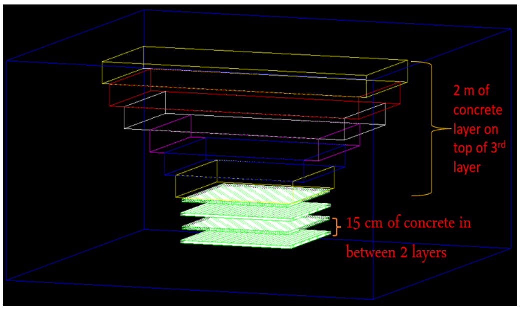

Figure 2: A GEANT-4 reconstructed new muon module, with 59 PRCs in each layer.

The new muon telescope has 70% more sky coverage than the old one. Combining the new muon telescope with the old muon telescope we call as the expanded muon telescope. By enlarging the detection area, the expanded muon telescope can capture a larger number of muons, leading to more data collection. This, in turn, enables a more efficient measurement of cosmic ray composition and facilitates the study of different aspects of cosmic rays.

4. Composition Study Comparing Data and Simulation

In an EAS, muons exhibit negligible energy loss via ionization, enabling their efficient penetration to the Earth's surface. The muon multiplicity, or the number of muons detected, plays an important role in investigating the composition of cosmic rays. In this paper, we have compared the muon multiplicity distributions (MMDs) of the real data collected with 16 modules of the G3MT in the year 2014, with the CORSIKA simulated data of the five primaries i.e., Proton, Helium, Nitrogen, Aluminium and Iron for different shower size (N_e) bins. The details of the simulation are described in the Section 4.1. Shower size is basically the number of secondary particles from an air shower at a particular atmospheric depth. With increasing energy, shower size also increases. Since we wish to study the energy dependent composition, we carried out the analysis from shower size $10^{3.0}$ to $10^{6.0}$ (i.e. 3.0 - 6.0 in $\log_{10}$ scale) with a bin width of $10^{0.2}$. However, in this paper we have included MMDs for the shower size bins 3.6 - 4.8 only.

4.1 Monte Carlo Simulation

The simulation datasets considered in this analysis are prepared using CORSIKA version 7.6900 [5], with QGSJET-II-04 and FLUKA [6] as the high and low energy hadronic interaction models, respectively. The electromagnetic interactions are treated by EGS4 model. The simulation is done with the Proton, Helium, Nitrogen, Aluminium and Iron as the major primaries [7]. The CORSIKA generated showers have been implemented in the GeneratePrimaries function of GEANT-4, by loading the particle gun with secondary particles from the shower [8]. The CORSIKA generated files (DAT files) are converted to ROOT files using G3Analysis tool.

4.2 Selection Criteria for the Analysis

The following selections are applied in this analysis.

- 0.2 < showerage (s) < 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 red dotted lines in Figure 1). 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

5. Results

The comparison of MMDs between real data and the five primaries Proton, Helium, Nitrogen, Aluminium and Iron is presented in this section. Figure 3 shows the MMD comparison for the shower size in the range of 3.6 - 4.8. Figures 4 - 9 show MMD comparison plots with shower size 3.6 to 4.8 in the bins of 0.2. The tracking information for muons has not been yet incorporated into our simulations. This is the reason for the excessive estimation of muon occurrences in our simulations as compared to the observed data.

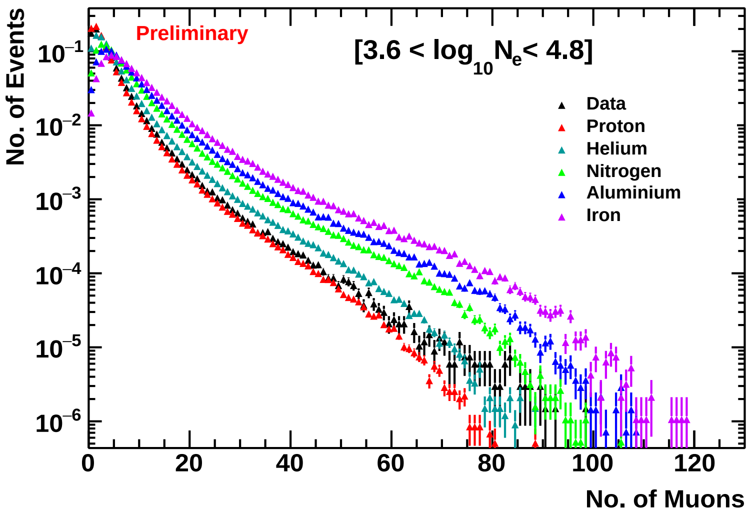

Figure 3: MMD comparison of data and five primaries (Proton, He, N, Al and Fe) for the Shower Size 3.6 - 4.8.

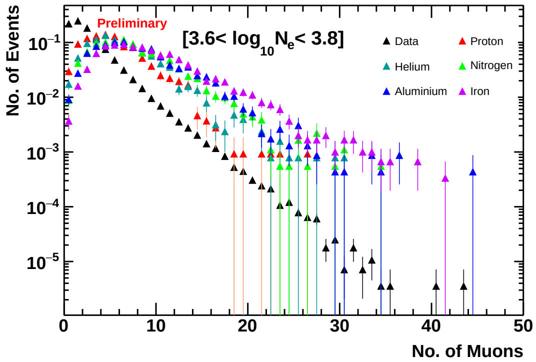

Figure 4: MMD in Shower Size bin 3.6 - 3.8

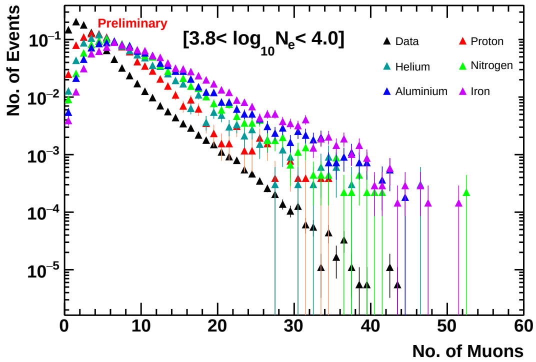

Figure 5: MMD in Shower Size bin 3.8 - 4.0

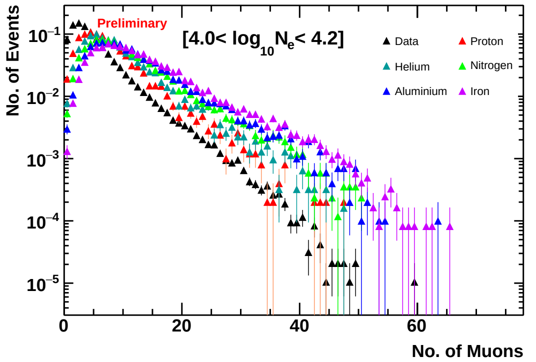

Figure 6: MMD in Shower Size bin 4.0 - 4.2

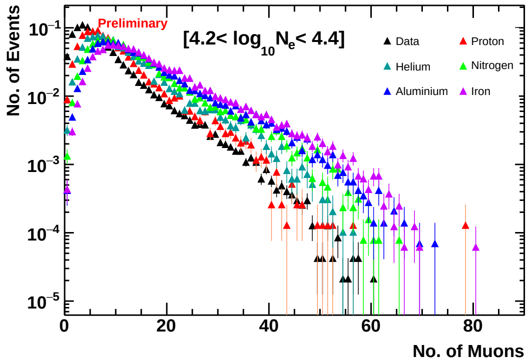

Figure 7: MMD in Shower Size bin 4.2 - 4.4

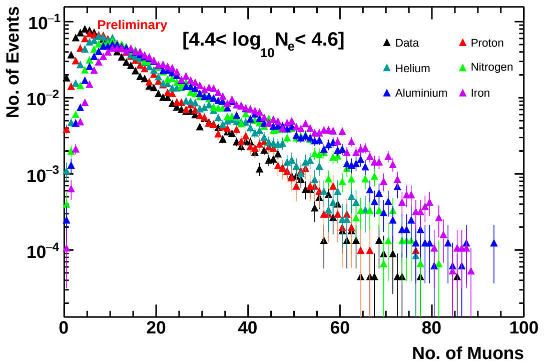

Figure 8: MMD in Shower Size bin 4.4 - 4.6

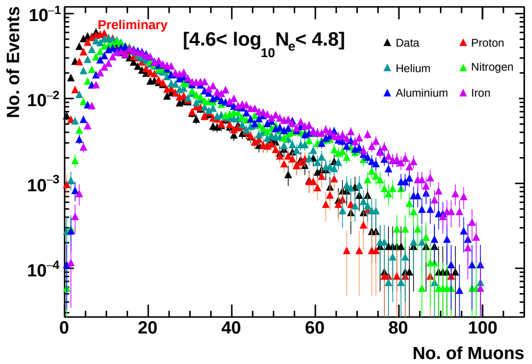

Figure 9: MMD in Shower Size bin 4.6 - 4.8

We also plotted a graph of mean muon multiplicity as a function of shower size $\log_{10}$ (3.0 - 6.0) in bins of 0.2 by considering real data. This is shown in Figure 10. From this plot we observe that the mean muon multiplicity increases with increasing shower size.

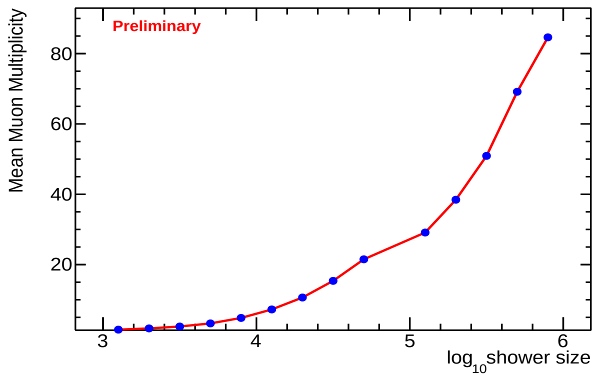

Figure 10: Mean muon multiplicity as a function of shower Size (3.0 - 6.0) in bins of 0.2 with real data.

5.1 Sensitivity of PCR Composition with the Expanded G3MT

In order to observe an enhanced sensitivity of PCR composition in the expanded G3MT, one approach is to compare the muon multiplicities in old G3MT with expanded G3MT. Given that the area of the expanded G3MT is nearly twice that of the original, an expected outcome is the observation of more muons in the expanded setup. We have graphically presented a comparison of MMDs in both old G3MT and expanded G3MT, using CORSIKA simulated data with Proton as the primary with two separate energy bins.

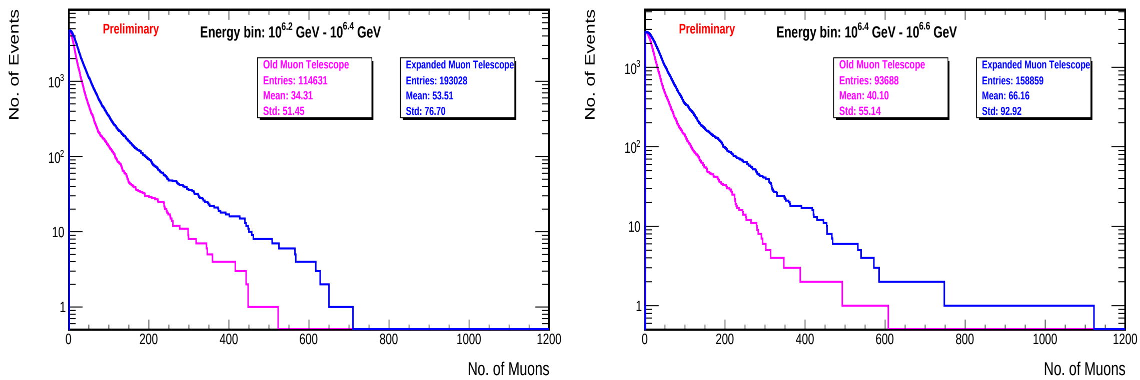

Figure 11: MMD comparisons for old and expanded G3MT in the energy bins of $10^{6.2}$ GeV - $10^{6.4}$ GeV (left) and $10^{6.4}$ GeV - $10^{6.6}$ GeV (right).

Figure 11 shows the comparison of muon multiplicities with the old and expanded G3MTs in the energy bins of $10^{6.2}$ GeV - $10^{6.4}$ GeV (left) and $10^{6.4}$ GeV - $10^{6.6}$ GeV (right). Within these plots, the statistics and the curves highlighted in magenta color correspond to the old G3MT, while those in blue color represent to the extended G3MT. From this investigation, we see an enhancement of number of muon multiplicity in expanded G3MT compared to old G3MT.

6. Conclusion

In this paper, we present a comprehensive comparative analysis of MMDs using both actual observed data and simulated data in bins of increasing shower sizes (N_e) to explore the relationships between these parameters. The data was collected from the 16 modules comprising the operational G3MT system in 2014, while the simulated data-sets were generated using CORSIKA for five primary particles: Proton, Helium, Nitrogen, Aluminium, and Iron. This investigation shows that MMDs cannot be explained solely by Proton or Iron primaries; instead, they necessitate the involvement of intermediate-mass primaries. We also performed a comparison of total muon multiplicities, using simulations (with Proton as primary), between the original G3MT and the extended G3MT configurations. We observe that there is an increase in the number of muon counts when considering the expanded G3MT configuration. Furthermore, once the new G3MT becomes fully operational, we will have the capability to compare real data with simulations and study the PCR composition more in depth.

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