PROCEEDINGS OF SCIENCE

Muon Flux Measurements and their angular distribution with the new muon telescope at GRAPES-3 experiment

R. Kataria,[a,*] B. Parida,[a] M. Chakraborty,[b] S R Dugad,[b] U D Gowswami,[c] S K Gupta,[b] B Hariharan,[b] Y Hayashi,[d] P Jagadeesan,[b] A Jain,[b] P Jain,[e] S Kawakami,[d] H Kojima,[f] S Mahapatra,[g] P K Mohanty,[b] R Moharana,[h] Y Muraki,[i] P K Nayak,[b] T Nonaka,[j] A Oshima,[f] B P Pant,[h] D. Pattanaik,[b,g] M Rameez,[b] K Ramesh,[b] L V Reddy,[b] S Shibata,[f] F Varsi[e] and M Zuberi[b]

[a]*Amity University, Noida, 201301, India*
[b]*Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India*
[c]*Dibrugarh University, Dibrugarh 786004, India*
[d]*Graduate School of Science, Osaka City University, Osaka 558-8585, Japan*
[e]*Indian Institute of Technology Kanpur, Kanpur 208016, India*
[f]*College of Engineering, Chubu University, Kasugai, Aichi 487-8501, Japan*
[g]*Utkal University, Bhubaneshwar 751004, India*
[h]*Indian Institute of Technology Jodhpur, Jodhpur 342037, India*
[i]*Institute for Space-Earth Environmental Research, Nagoya University, Nagoya 464-8601, Japan*
[j]*Institute for Cosmic Ray Research, Tokyo University, Kashiwa, Chiba 277-8582, Japan*
[a]*Amity University,*
Sector 125, Noida, India

E-mail: ria.kataria@s.amity.edu, bparida@amity.edu

The GRAPES-3 experiment consists of a large area ($560m^2$) muon telescope consisting of 3712 proportional counters of each dimension of 6m x 0.1m x 0.1m. A similar muon telescope next to the existing one is under construction. The new muon telescope is designed to have a 70% larger field of view (2.3 sr to 3.9 sr) as compared to the existing one. One of the 16 modules of the new muon telescope has been made operational. The energy threshold is 0.5 GeV for vertically incident muons. We present the measurements of integrated muon flux and the angular distributions and compare with the prediction from simulations.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)1361

1. Introduction

Cosmic Rays are high energetic radiations originating from outer space and extra galactic sources. Their energy ranges from 10^8 eV to 10^{20} eV [1, 2]. The energy spectrum measurements of Primary Cosmic Rays (PCRs) has been measured in the energy range 10^8 eV to 10^{14} eV [3]. Since Cosmic Rays travel at high energies, they interact and get deflected by interstellar radiation fields and matter, which makes it incredibly difficult to determine their sources and by the time they reach our Solar System, they have lost all information about their origins. This makes studying the various parameters like their energy spectrum, flux, angular distributions and chemical compositions all the more important. They provide us with valuable information required to understand Cosmic Rays and fundamentally, the universe itself.

Primary Cosmic Rays consisting mainly of protons, upon entering the Earth's atmosphere undergo interaction with charged nuclei present in the atmosphere and decay further into energetic hadrons. These unstable hadrons decay further, this process of subsequent decays is known as the Extensive Air Shower (EAS). One of the daughter particles of this cascade are muons. Muons travelling at relativistic speeds cover long distances to reach the Earth's surface despite their incredibly small lifetime of $\sim 2\mu s$, being a direct example of the Special Theory of Relativity. Accompanying muons, other hadronic particles, gamma rays and electrons are also produced. The atmosphere has more than 10 interaction lengths, which is sufficient for these particles to lose most of their energy by the time they reach sea level.

It has been observed that PCRs are directional dependent and come mostly from the West. The positively charged particles coming from the West, bend towards the Earth, and the ones coming from East, bend away. This asymmetry is known as the East-West effect. [4]

The heliospheric magnetic field also plays a role in deflecting the Galactic Cosmic Rays. Facing the turbulent solar winds leads to change in their intensity and energies with respect to their positions in the heliosphere. This process, known as Solar Modulation takes part in the low energy spectrum of the radiation [5].

2. GRAPES-3 Muon Telescope

The GRAPES-3 (**G**amma **R**ay **A**stronomy at **P**eV **E**nergie**S** phase - 3) experiment is a large area ($560m^2$) ground based experiment, located in Ooty, Tamil Nadu, India. The GRAPES-3 Muon Telescope (G3MT) investigates the muon component of PCRs using a large array of gaseous Proportional Counters (PRC). One of the 16 modules of the new muon telescope has been made operational. The new muon telescope is similar to the old muon telescope but with a larger field of view (2.3 sr to 3.9 sr), 70% more than that of the old muon telescope. It has a threshold energy of 0.5 GeV $\times$ sec θ for muons at θ angles.

The 16 independent modules house a total of 3,776 PRCs, each module containing 4 layers of 59 PRCs. The bottom most layer is termed as layer 0 and the topmost as layer 3. These layers are placed orthogonal to each other in order to maximise the detection of the Cosmic Muons. Between each layer of the PRCs, a 15 cm thick layer of concrete is placed and 13 other layers of concrete are placed on top of layer 3 in an inverted pyramid shape, with an angle of 45°. These 13 layers of concrete are termed as the absorber. The role of this absorber is to shield other electromagnetic components and muons with less than the above mentioned threshold energy. Hadrons passing through the absorber interact with concrete leading to a hadronic EAS depending on the hadron's energy. These hadrons leave their signature in the form of a cluster hit inside the PRC [6].

One PRC is a galavnised mild steel tube of the dimensions 600cm × 10cm × 10cm, containing a 600cm long Tungsten wire with a diameter of 100 microns and P10 gas (90% Argon, 10% Methane). The gas is kept at 1.09 bar and 295K with a density of 1.67 kgm^{-3}. A hermetic seal is also used to separate the anode and the cathode.

3. GEANT4 Simulation of one module of the G3MT

GEANT4, **GE**ometry **AN**d **T**racking is the simulation toolkit version (v-4.10.07) [8–10] is used to prepare the detector geometry of the G3MT starting with creating one PRC of the above mentioned parameters in the GEANT4 framework. Each of the 600cm × 10cm × 10cm PRC has a 0.23 cm thick Iron coating, within it lies the P10 gas and the Tungsten wire along the axis of the tube. The desired geometry is achieved using G4Box and G4Tubs classes, and the materials are defined using the G4NistManager class. The geometry of one PRC can be seen in Figure 1.

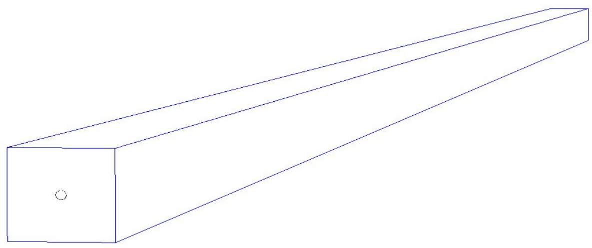

Figure 1: Geometry of one PRC; blue body represents the PRC tube and the black circle represents the Tungsten wire.

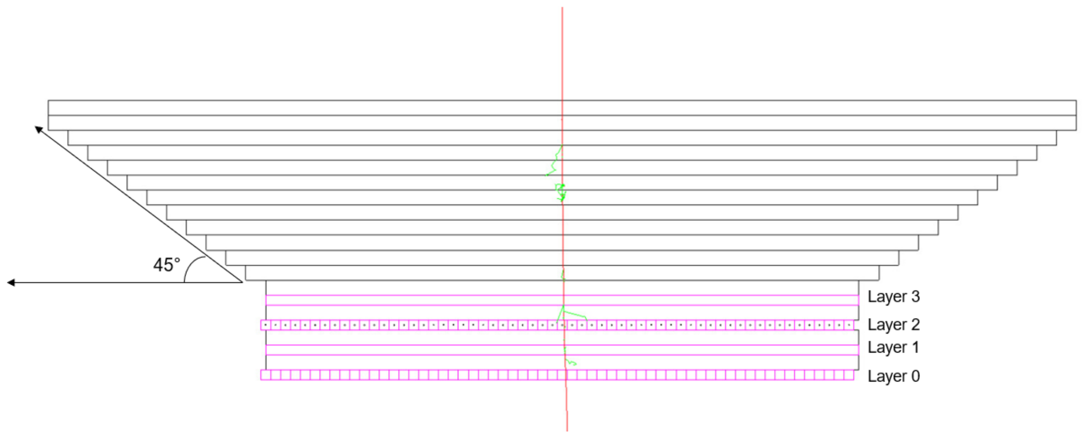

Figure 2: One G3M3 module with a muon of 10 GeV injected vertically.

The 4 layer of PRCs consisting of 59 counters are then constructed, placed orthogonal to each other. Then the concrete layers between each PRC layer and the absorber were constructed, as seen in Figure 2. The muons are injected vertically on the individual counter and also the module to study its energy deposition. The hits stored in the counters is done by defining a Scoring Volume which makes the volume sensitive to information about the incident particles like their deposited energy, track length, momentum direction etc and is able to store this information. The desired parameters can then be extracted as per use case for analysis. The energy deposited was extracted by making a user defined stepping action inherited from the class G4UserSteppingAction.

Particles other than muons have also been injected on the module to study their deposited energy. These particles were defined using the G4ParticleGun class. The particle gun was placed 3m above the module and the material surrounding the module and the particle gun was set to Air, using the G4NistManager class to define air. In each case 100K particles have been fired.

Energy deposited by muons of 4 GeV in one PRC was simulated to peak at 24.02 keV, Figure 3. Experimentally, at GRAPES-3, the peak was observed at 20.7 keV [6].

Energy deposition by other particles such as electrons, protons and anti muons are also studied under the same conditions of vertically incident particles of 4 GeV on one PRC. Protons deposited 20.26 keV, while anti muons deposited 24.07 keV, almost the same as muons. The energy deposited by electrons was simulated to peak at 28.96 keV as shown in Figure 3. This is as expected, since electrons lose more energy than muons.

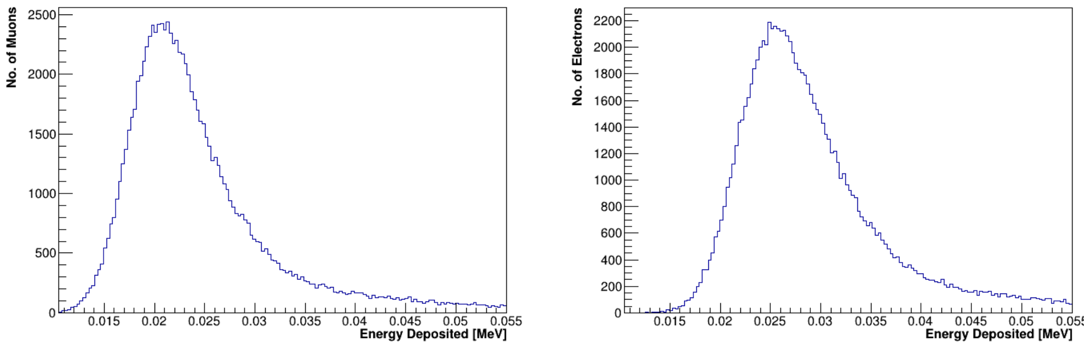

Figure 3: Energy deposited by muons (24.07 keV) and electrons (28.96 keV) of incident 4 GeV energy on one PRC

4. Flux and Angular Distributions

Cosmic Ray Muon flux is subject to changes, depending in their energies and the radiation fields they interact with. Low energy rays are effected by the solar winds as mentioned in 1 along with the Earth's magnetic field causing a change in their intensities and flux [11, 12]. The flux of cosmic rays is measured in $m^{-2}sr^{-1}s^{-1}$ and has a cos^2 dependence.

The differential flux is calculated as: $\frac{dN}{dAdtd\Omega} = I_{\circ}cos^2\theta$, where θ is the zenith angle and $I_{\circ}$ is the intensity when $\theta = 0$. The integral flux is calculated by taking the integral of the cosine distribution. The flux for muons > $1GeV$ is observed to be ~ $70m^{-2}sr^{-1}s^{-1}$[12, 13]

The GEANT4 study of angular distributions of muons is done using the G4GeneralParticleSource. Where muons were fired vertically from above the module of energy 10 GeV with a cosine law distribution. Their zenith angle (θ) and azimuthal angle (ϕ) were then plotted. We only gather information about the muons that make it through the entire module. For this purpose, Layer 0 2 has been made the Scoring Volume. We have observed that the zenith angle peaks at 1.596 rad (~ 91°) and azimuthal angle peaks at 3.13 rad (~ 179.4°).

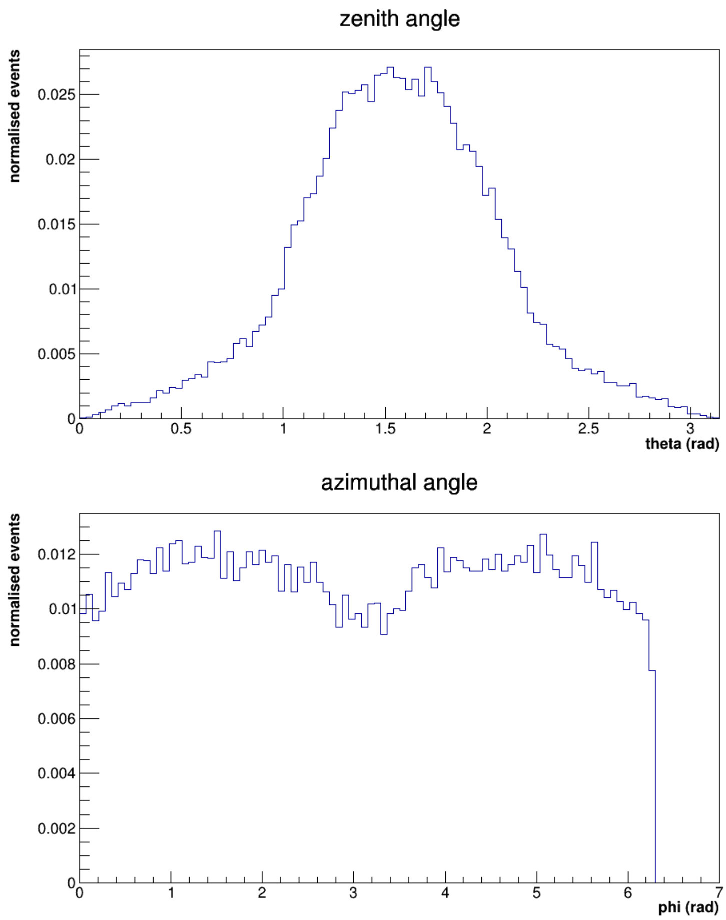

Figure 4: The zenith angle (θ) and azimuthal angle (ϕ) distributions for the vertically incident muons.

5. CORSIKA and GRAPES-3 Data Analysis

For simulation of the Air Shower, CORSIKA is being used [14] and we are using the low energy interaction model, FLUKA [15, 16] for this study. We use the secondary particles produced from CORSIKA to inject on the muon module, then study the angular distributions with respect to the flux of the muons. After getting the desired plots, we compare with the data collected at GRAPES-3.

The data collected by GRAPES-3 is done by reconstruction of muon tracks in two planes, the X-Z plane and the Y-Z plane. Where the projection of secondaries calculated in the planes, considering the θ and ϕ angles. The details of this can be found in Ref. [6, 7]

The angular distribution of the Cosmic Ray Muons using the GRAPES-3 data has been plotted using 4 modules. The preliminary graph can be found here 5

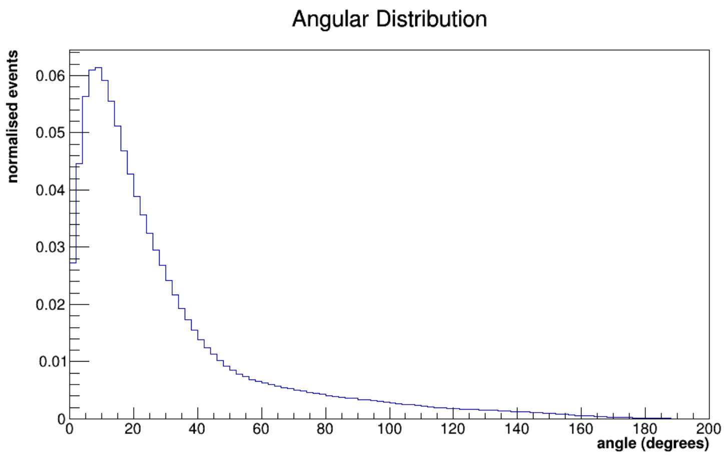

Figure 5: The angular distribution of Cosmic Muons as observed by GRAPES-3

This part of the work is still under progress and these are just the preliminary results and will be updated soon.

6. Summary and Discussions

We construct one module of the new muon telescope at GRAPES-3 using GEANT4 [8–10]. We inject the secondary particles produced in the Air Shower, simulated by CORSIKA [14] using the FLUKA model [15, 16] and plot the angular distributions with respect to the flux.

This section will be updated soon.

7. Acknowledgements

We acknowledge support of the Department of Atomic Energy, Government of India, under Project Identification No. RTI4002. This work was partially supported by grants from Chubu University, Japan.

We are grateful to D.B. Arjunan, A.S. Bosco, V. Jeyakumar, S. Kingston, N.K. Lokre, K. Manjunath, S. Murugapandian, S. Pandurangan, B. Rajesh, R. Ravi, V. Santhoshkumar, S. Sathyaraj, M.S. Shareef, C. Shobana, and R. Sureshkumar for their role in efficient running of the experiment.

References

[1] D.J. Bird et al., Phys. Rev. Lett., 71 (1993) 3401

[2] AMS and Alcaraz, J Cosmic Protons, Physics Letters B, 490 (2000)

[3] DAMPE Collaboration et al., Measurement of the cosmic ray proton spectrum from 40 GeV to 100 TeV with the DAMPE satellite.Sci. Adv.5,eaax3793(2019).DOI:10.1126/sciadv.aax3793

[4] Johnson, T. H. (1941). The East-West Asymmetry of the Cosmic Radiation in High Latitudes and the Excess of Positive Mesotrons. Physical Review, 59(1), 11–15. doi:10.1103/physrev.59.11

[5] Potgieter, M.S. Solar Modulation of Cosmic Rays. Living Rev. Sol. Phys. 10, 3 (2013). https://doi.org/10.12942/lrsp-2013-3

[6] F. Varsi et al, A GEANT4 based simulation framework for the large area muon telescope of the GRAPES-3 experiment, 2023 JINST 18 P03046 DOI 10.1088/1748-0221/18/03/P03046

[7] GRAPES-3 Collaboration, B. Hariharan et al., Measurement of large angle muon flux in GRAPES-3 experiment using triggerless DAQ system, PoS ICRC2021 (2021), 379, DOI: 10.22323/1.395.0379

[8] J. Allison et al., Recent Developments in GEANT4, Nucl. Instrum. Meth. A 835 (2016) 186-225

[9] J. Allison et al., GEANT4 Developments and Applications, IEEE Trans. Nucl. Sci. 53 (2006) 270-278

[10] S. Agostinelli et al., GEANT4 - A Simulation Toolkit, Nucl. Instrum. Meth. A 506 (2003) 250-303

[11] Cosmic Rays, revised August 2011 by J.J Beatty and J .Mathews, https://pdg.lbl.gov/2019/reviews/rpp2019-rev-cosmic-rays.pdf

[12] P.K. Mohanty et al., Fast Fourier transform to measure pressure coefficient of muons in the GRAPES-3 experiment, Astroparticle Physics, 79, 2016, https://doi.org/10.1016/j.astropartphys.2016.02.006

[13] Measuring the Angular Distribution of Muons, Inna Shteinbuk, https://www.s.u-tokyo.ac.jp/en/utrip/archive/2011/pdf/17Inna.pdf

[14] D. Heck et al., CORSIKA: A Monte Carlo code to simulate extensive air showers, FZKA-6019, Forschungszentrum Karlsruhe GmbH, Karlsruhe, Germany (1998)

[15] G. Battistoni et al., "Overview of the FLUKA code", Annals of Nuclear Energy 82, 10-18 (2015)

[16] C. Ahdida et al.,"New Capabilities of the FLUKA Multi-Purpose Code", Frontiers in Physics 9, 788253 (2022)