PROCEEDINGS OF SCIENCE

A new approach to determine muon multiplicity at the GRAPES-3 experiment

R. Scaria,[a,*] M. Chakraborty,[b] S.R. Dugad,[b] S.K. Gupta,[b] B. Hariharan,[b] Y. Hayashi,[c] P. Jagadeesan,[b] A. Jain,[b] P. Jain,[d] S. Kawakami,[c] H. Kojima,[e] S. Mahapatra,[f] P.K. Mohanty,[b] Y. Muraki,[g] P.K. Nayak,[b] T. Nonaka,[h] A. Oshima,[e] D. Pattanaik,[b,f] G.S. Pradhan,[a] M. Rameez,[b] K. Ramesh,[b] L.V. Reddy,[b] R. Sahoo,[a] S. Shibata,[e] F. Varsi[d] and M. Zuberi[b] [The GRAPES-3 collaboration]

[a] *Indian Institute of Technology Indore, Indore 453552, India*
[b] *Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India*
[c] *Graduate School of Science, Osaka City University, Osaka 558-8585, Japan*
[d] *Indian Institute of Technology Kanpur, Kanpur 208016, India*
[e] *College of Engineering, Chubu University, Kasugai, Aichi 487-8501, Japan*
[f] *Utkal University, Bhubaneshwar 751004, India*
[g] *Institute for Space-Earth Environmental Research, Nagoya University, Nagoya 464-8601, Japan*
[h] *Institute for Cosmic Ray Research, Tokyo University, Kashiwa, Chiba 277-8582, Japan*

E-mail: ronaldscaria.rony@gmail.com, pkm@tifr.res.in

The muon content in extensive air showers (EAS) is a sensitive observable for measuring the primary cosmic ray composition. An accurate determination of the muon multiplicity in an EAS is thus imperative for composition studies. The GRAPES-3 experiment, located in Ooty, India, contains a dense scintillator array to measure the electromagnetic components and a large area muon telescope to measure the muonic component in the EAS by counting the reconstructed muon tracks based on the proportional counter hit information. However, due to the large dimension of the proportional counters (6m $\times$ 0.1m $\times$ 0.1m), saturation of tracks in a given module (35 m^2 area) occurs below about 20 muons. Here, we present a new method to calculate the number of muons in an EAS based on the pulse height information recorded in the proportional counters in addition to the hit information. The pulse height is proportional to the energy deposited by the muons. The preliminary results of the analysis show that the dynamic range of detecting muons has increased by more than a factor of two. This is an important development for reliable measurement of PCRs' composition beyond the Knee region ($\sim$ 3 PeV) of the cosmic ray spectrum when the the density of muons is higher than the saturation limit with the current method.

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

*Speaker

1. Introduction

The GRAPES-3 (Gamma Ray Astronomy at PeV Energies Phase-3) experiment, located at Ooty in India (11.4 ° N, 76.7 ° E, 2200 m a.s.l), is designated to detect Extensive Air Showers (EAS) produced by cosmic rays and γ-rays. The GRAPES-3 experiment consist of an EAS array of 400 plastic scintillator detectors [1], each of 1 m^2 area, and a large area tracking muon telescope [2]. A schematic of the array is given in Fig.1. The scintillator array is spread over an area of 25,000 m^2. The detectors are arranged in a hexagonal array with an inter-detector spacing of 8 m to allow a very dense packing (~ 2% scintillator area). Being highly dense, with an atmospheric overburden of 800 g cm^{-2}, the GRAPES-3 array can detect primary cosmic rays (PCRs) with energies ranging from a few TeV to about 10 PeV giving substantial overlap with direct experiments. The 560 m^2 tracking muon telescope consist of 16 muon modules each having 232 proportional counters (PRCs). Each PRC has a length of 6 m and cross sectional area of 10 cm×10 cm. Each module has 4 orthogonal layers consisting 58 PRCs each [2]. The muon telescope has a concrete shielding of 550 g cm^{-2} which gives an energy threshold of $sec(\theta)$ GeV for incident muons having zenith angle θ. The muon content detected by the muon telescope plays an important role in distinguishing cosmic ray and γ-ray initiated showers and also in determining the PCR composition.

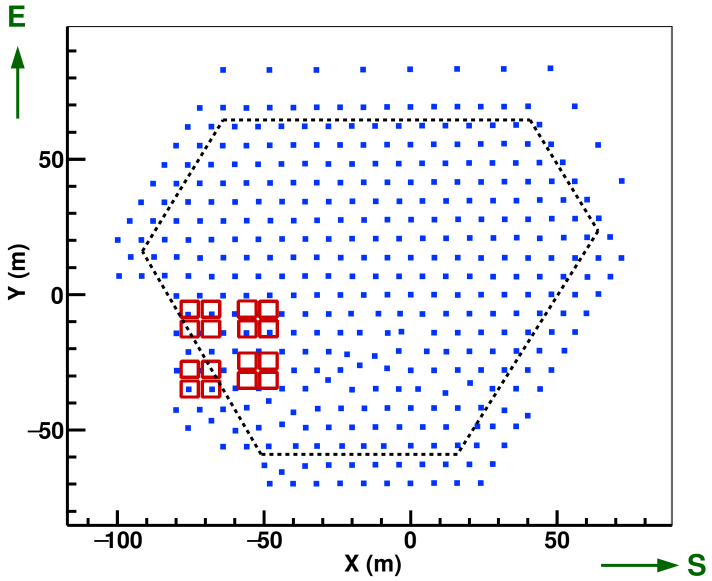

Figure 1: Schematic representation of the GRAPES-3 EAS array. The blue filled squares are scintillator detectors while the red open squares represent muon modules. The fiducial area of the array is enclosed by the black dashed line.

GRAPES-3 uses a two-level trigger for shower detection: a simple 3-line coincidence in 100 ns time window (level-0 trigger) and at least 10 detectors hit in 1 μs time window (level-1 trigger). The scintillator array detect the density and the relative arrival time of secondary particles in each triggered shower. This information is used to reconstruct the shower parameters such as core (X_c, Y_c), size (N_e), age (s) by fitting the observed particle densities with Nishimura-Kamata-Greisen

(NKG) function given by [3, 4]

$$\rho(r_i) = \frac{N_e}{2\pi r_0^2}\frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-2s)}\left(\frac{r_i}{r_0}\right)^{(s-2)}\left(1+\frac{r_i}{r_0}\right)^{(s-4.5)} \tag{1}$$

where r_i is the lateral distance of the ith detector from the shower core (X$_c$, Y$_c$) and r_0 is the Moliére radius which is 103 m for GRAPES-3. The shower direction is reconstructed by fitting the relative arrival time with a plane front followed by applying a shower-front curvature correction which is shown to increase the angular resolution of the array [5].

The determination of PCR composition is dependent on the ability of the muon telescope to successfully reconstruct muon tracks within the muon module. Due to the geometry and low granularity of the module, using the hit information alone leads to underestimation of tracks as number of incident muons increases [6]. This saturation effect becomes more prominent at high PCR energies. In this analysis, we employ an alternate method using the energy deposition in a counter to develop a new muon counting algorithm to overcome the saturation effects.

2. Methodology

The GRAPES-3 muon telescope records the energy deposited in a PRC through the pulse width information which is stored along with the hit information. The pulse width is recorded with a resolution of 333 ns and can be converted to the equivalent number of muons passing through the PRC using the formula [2]

$$N_{eq} = exp\left(\frac{T_i - T_s}{\tau}\right) = \frac{E_i}{E_s} \tag{2}$$

where T_i is the pulse width observed for the event, T_s is the pulse width for a minimum ionizing particle (MIP) and τ is the decay time constant maintained at 7 μs. E_i and E_s are the energies deposited in the PRC during the event and by a MIP, respectively. Thus, knowing the MIP pulse width of all the counters one can easily determine the equivalent number of particles passing through a layer. This information can thus be used to find the number of particles in an event as detailed below.

A (58 × 58) two dimensional grid of adjacent layers is constructed and the equivalent particle number is filled along rows and columns which gives a two-dimensional map of the counters being hit. All the filled cells in the 2-D map are reduced by one so that only those cells which lie at the intersection points of triggered PRCs remain. In the case of $N_{eq} > 1$ in a PRC, this operation leaves behind a fully filled row or column corresponding to that PRC. Further a simple counting of the number of intersections along rows and columns is performed. In the event of a fully filled row or column, the corresponding number of intersections is raised by the minimum along that row or column. Further, the equivalent number of particles along a projection is given by taking the lower value of the number of intersections to reduce the effect of landau tail. The same exercise is performed for all the three possible X-Y projections (L0-L1, L1-L2 and L2-L3 where L represents the layer) in a module. The minimum among the three layer combinations gives the number of particles within the module in an event. Further, the same exercise is performed for all the 16 muon modules to obtain the number of particles in an EAS event. Fig. 2 shows a schematic representation of this process showing the 2-D map of one of the 16 modules during an event followed by the final 2-D map from which the equivalent number of particles is determined.

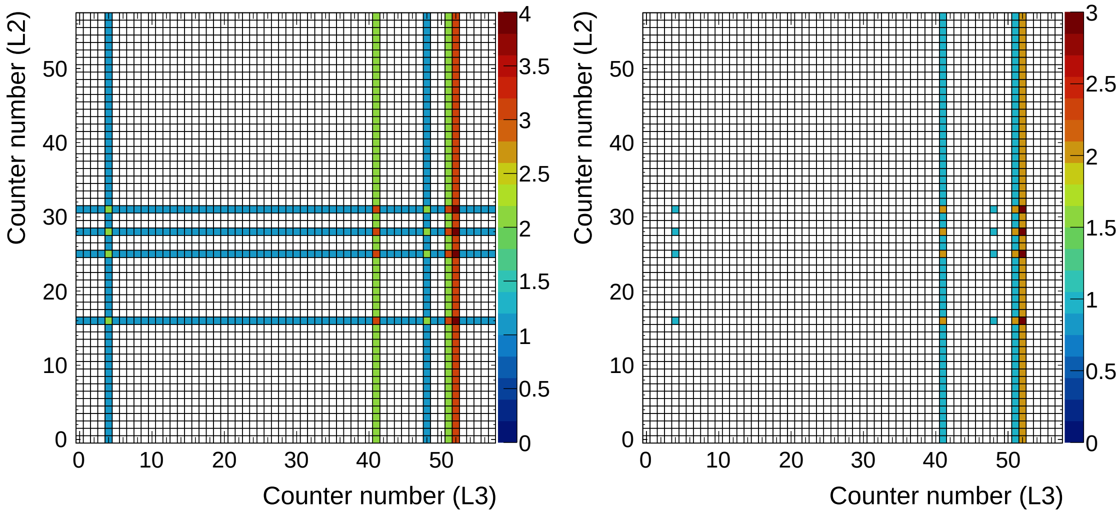

Figure 2: (Left Panel) The 2-D map combining layers L3 and L2 obtained by directly filling the corresponding counters with the equivalent particle numbers. (Right Panel) The 2-D map showing only the intersecting points. The fully filled columns indicate $N_{eq} > 1$ in the corresponding PRC.

3. Quality selection cuts and experimental data

The quality of data used is ensured by using the following event selection criteria:

- Only events with successful shower parameter and angle reconstructions are used.
- The shower core should lie within the fiducial area to ensure improper reconstruction due to core landing near the edges or beyond the array is avoided.
- The shower core should lie beyond 60 m from the muon telescope to reduce hadron contamination.
- The recontructed shower age is limited to between 0.12 and 1.96
- Shower size (N_e) should be greater than 10^4 to keep trigger efficiency greater than 90%.

4. Simulations

A detailed simulation study of the muon telescope response based on the GEANT-4 package [6] for the GRAPES-3 muon telescope (further referred to as G3MT package) is performed. Proton initiated showers generated using the CORSIKA package (version 7.69) using QGSJET-II-04 and FLUKA as high and low energy interaction models, respectively, are used for this study. Data is generated in the energy range 1 TeV - 10 PeV in 20 logarithmic bins of bin width $10^{0.2}$ and zenith angle range 0 - 45°, following a power law spectral index of -2.5. The generated showers are thrown randomly in a circular area of radius 150 m from the centre of the array (-13.85 m, 6.29 m). Each shower is reused 10 times to increase statistics. The scintillator response is modelled using the GEANT-4 package. The G3MT package is used to obtain a detailed response of the muon telescope

N_μ	MPV	Lower Limit	Upper Limit
1	0.94	0.2	1.605
2	2.07	1.605	2.778
3	3.29	2.778	4.026
4	4.57	4.026	5.327
5	5.89	5.327	6.670

Table 1: The limits to the equivalent numbers for increasing incident muons passing through the PRC obtained from the GEANT-4 simulation. Since more than 5 muons have largely overlapping energy deposition curves, this is considered as the upper limit of the PRC to properly detect multiple muons.

to to the muons and hadrons in terms of PRC hits and energy deposition. These PRC hit information are used to find the number of muons in the muon telescope.

In addition, the GEANT-4 response of a single counter to multiple muons is also studied to obtain limits to the equivalent numbers for corresponding number of incident muons determined by Eq.2.

5. Results

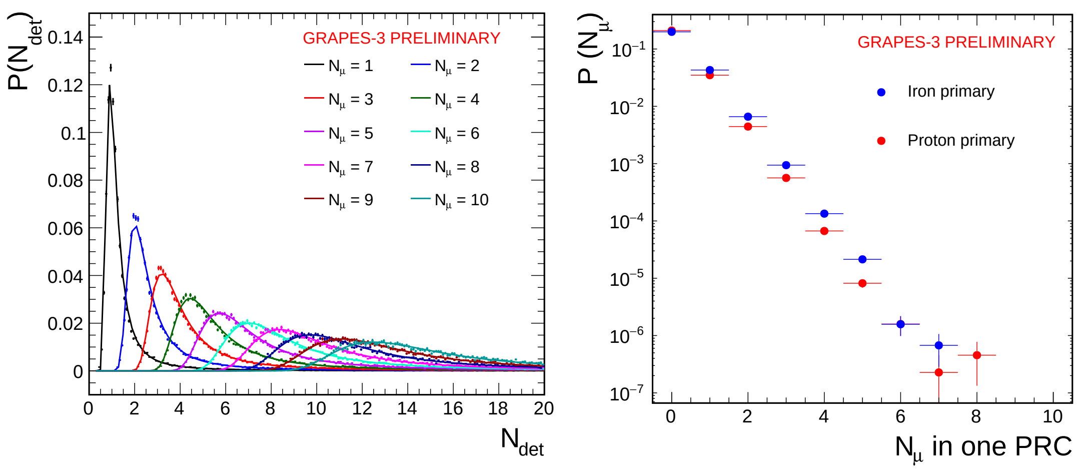

Figure 3: (Left Panel) The energy deposition obtained from the GEANT-4 simulation for a single counter for increasing incident muons is shown in equivalent number. (Right Panel) Probability for increasing muon numbers in a single PRC during an EAS.

The left panel of Fig. 3 shows the response of a single muon to different number of incident muons on a single PRC determined from the GEANT-4 simulation which is used to determine the limits on equivalent particle number provided in Table.1. Since the the curves for energy deposition significantly overlaps for more than 5 incident muons, it is assumed that energy deposition cannot be used to distinguish more than 5 muons in a PRC. The right panel of Fig.3 shows the probability of obtaining more than one muon inside a PRC during an event considering proton and Iron primaries at the highest energy bin.

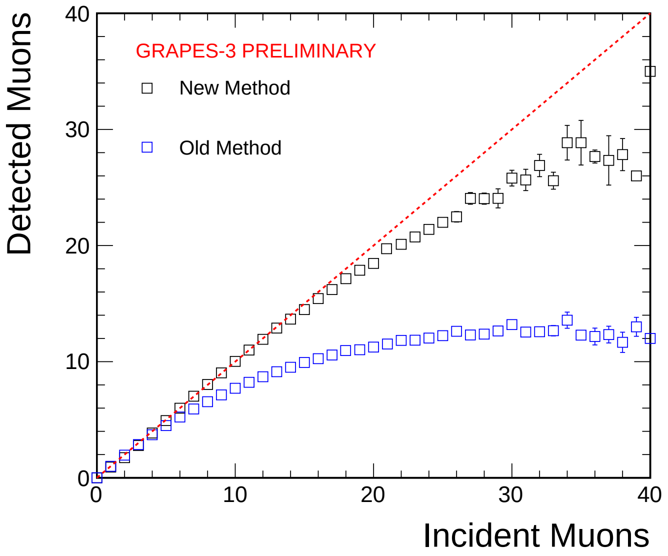

Figure 4: Comparison of the new muon counting method with the previously used tracking method. The red dashed line is shown to aid the eye and show linearity between incident and detected muons.

By using the muon counting method explained earlier, we have estimated the response of a muon module and studied its ability do determine the muon multiplicity in an event. It was observed that the tracking algorithm and the 2-D grid method gave better for $N_\mu \leq 3$ and $N_\mu > 3$, respectively. Thus the tracking and 2-D grid counting methods were combined in these respective ranges and is referred to further as the "new method" while the tracking method alone is referred as "old method". Fig. 4 shows the response of a muon module to increasing number of incident muons. It is seen that the newly developed algorithm is able to reconstruct muons correctly up to 13 incident muons beyond which saturation effects begin to be visible. This effect can be corrected by using a third order polynomial function for detected muons $N_{det} \geq 13$. The estimated coefficients of the polynomial function can now be used to correct the saturation effect for both data and simulations. The corrected estimate for the detected muon number is given by

$$N_\mu^c = \begin{cases} N_{det} & \text{if} \quad N_{det} \leq 13 \\ \\ -21.74 + 4.86N_{det} - 0.23N_{det}^2 + 0.0048N_{det}^3 & \text{if} \quad N_{det} > 13 \end{cases} \tag{3}$$

In the left panel of Fig. 5, the muon multiplicity estimated in data for a single module by using the previously used method is compared with the results from the new method. The number of detected muons in the module is seen to be extended up to nearly 40 as compared to 16 by using the tracking method. In the absence of the shower size cuts mentioned earlier it is seen that the new method estimates is extended up to 65 as seen in the right panel of Fig.5.

Finally, the left panel of Fig.6 gives the comparison of the total multiplicity detected by the muon telescope (obtained by adding the detected muons of all 16 modules for an event). The corrected numbers using Eq.3 is computed and the corrected muon multiplicity obtained is shown

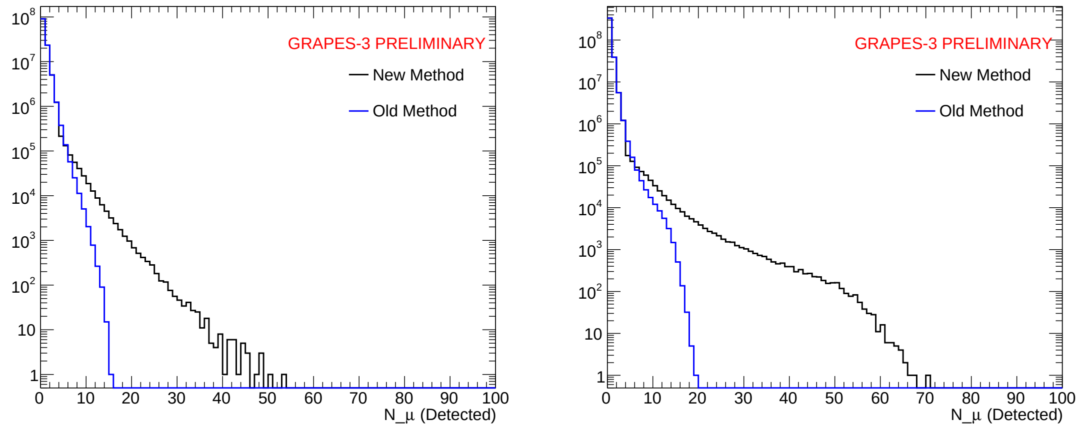

Figure 5: (Left Panel) Comparison of detected muon multiplicities in a single module using the new method and the tracking algorithm for $4.0 < log(N_e) < 6.0$. The dynamic range is seen to be extended in the new method proposed. (Right Panel) The maximum possible muon multiplicities ($\sim$ 65) possible is explored by removing the shower size cut.

in the right panel of Fig.6. It is observed that the new method improves the dynamic range of the GRAPES-3 muon telescope allowing composition studies at higher energies.

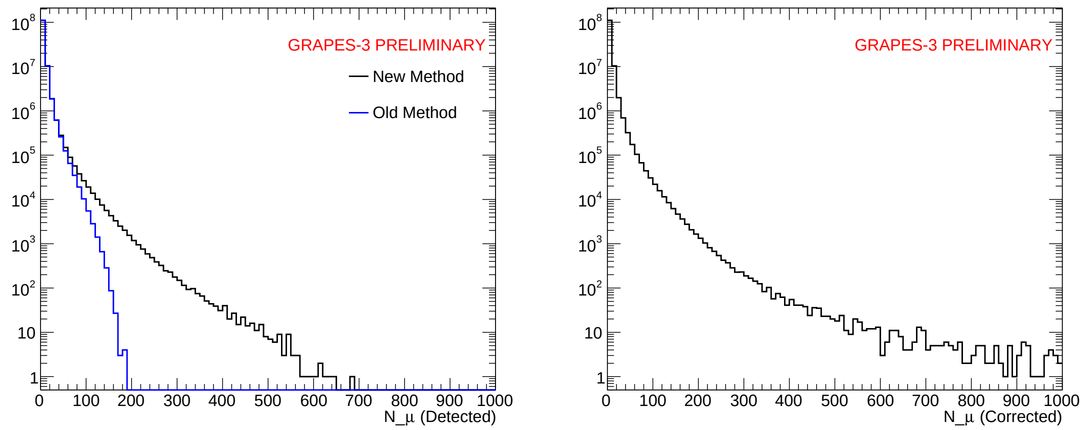

Figure 6: (Left Panel) Total muon multiplicity obtained by combining all the 16 muon modules. (Right Panel) Corrected muon multiplicity obtained from the new method.

6. Conclusion

An updated method for the detection of muon multiplicity in an event using the energy deposited in the GRAPES-3 muon telescope is presented. A detailed simulation of the single PRC response and that of the entire telescope is performed using GEANT-4. It is observed that the observed muon multiplicities is more than doubled on application of the new method thus increasing the dynamic range and aiding composition studies at high PCR energies.

Acknowledgement

We thank 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 the efficient running of the experiment. We acknowledge the 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. R. Scaria acknowledges financial support from Council for Scientific and Industrial Research (CSIR), India.

References

[1] S. K. Gupta *et al.* [GRAPES-3], Nucl. Instrum. Meth. A **540**, 311 (2005).

[2] Y. Hayashi *et al.* [GRAPES-3], Nucl. Instrum. Meth. A **545**, 643 (2005).

[3] K. Kamata and J. Nishimura, Progr. Theoret. Phys. **6**, 93 (1958).

[4] K. Greisen, Ann. Rev. Nucl. Part. Sci. **10**, 63 (1960).

[5] V. B. Jhansi *et al.* JCAP **07**, 024 (2020).

[6] F. Varsi *et al.* JINST **18**, P03046 (2023).