PROCEEDINGS OF SCIENCE

Acceptance of the GRAPES-3 experiment towards gamma-ray showers

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Compared to satellites and balloon-borne experiments, ground based air shower detectors enjoy larger fields-of-view and higher effective areas, making them ideal for studies of gamma rays above TeV energies. The Gamma Ray Astronomy at PeV EnergieS Phase-3 (GRAPES-3) experiment is an extensive air shower (EAS) array located in Ooty, India, with ~400 densely packed scintillator detectors accompanied by a 560 m^2 muon telescope. With the recent improvement in the angular resolution and an effective background rejection efficiency, the GRAPES-3 experiment has an excellent ability to study gamma-ray sources in the ultra-high energy (UHE) regime. In this work, we will present the acceptance of the GRAPES-3 towards gamma-ray-initiated showers, studied using CORSIKA simulated data.

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1. The GRAPES-3 experiment

The GRAPES-3 (**G**amma **R**ay **A**stronomy at **P**eV **E**nergie**S** – phase **3**) is an extensive air shower (EAS) array located at Ooty (11.4° N, 76.7° E, 2200 m a.s.l.), Tamil Nadu, India. It consists of 400 plastic scintillators, each 1 m^2 in area, and arranged in a hexagonal configuration. The scintillators are spread over a physical area of 25,000 m^2 with 8 m of inter-detector separation [1, 2]. The EAS array records about 3×10^6 events per day in the energy range 10^{12}–10^{16} eV.

The other major component is a large area tracking muon telescope (560 m^2) which comprises 3712 proportional counters (PRCs) housed in 4 stations [3]. Each station consists of 4 modules where in each module, the PRCs are arranged in 4 layers. Each layer consists of 58 PRCs of length 6 m having a square cross-sectional area of 0.1 m × 0.1 m. The alternating PRCs layers are orthogonally placed each separated by 15 cm thick concrete layer. The orthogonal configuration permits a two-dimensional reconstruction of muon tracks in two vertically orthogonal planes. Above each module, there is a mass overburden of 550 $g.cm^{-2}$ in the form of concrete blocks stacked in an inverted pyramidal shape. The concrete absorber provides an energy threshold of $\sec\theta$ GeV for muons incident at zenith angle θ.

GRAPES-3 uses two-level trigger, namely, level-0 and level-1. The level-0 trigger is a simple 3-line coincidence with 100 ns time window and the level-1 trigger requires hit in atleast 10 detectors in 1 μs time window. A schematic view of the GRAPES-3 array is shown in Fig. 1.

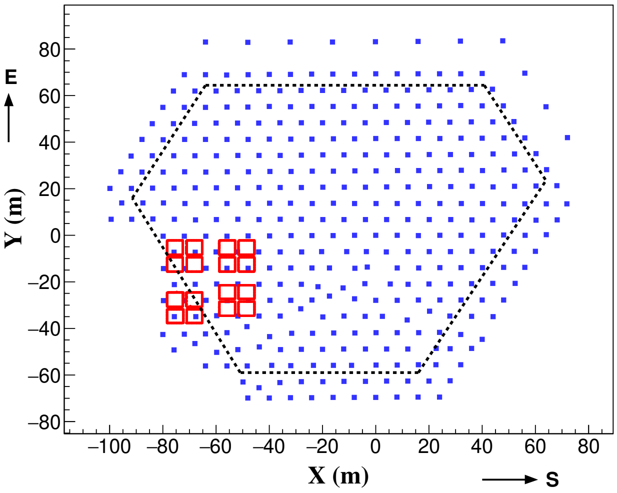


Figure 1: Schematic of the GRAPES-3 EAS array. The blue filled squares represent scintillator detectors and the red squares represent muon telescope modules. The dotted line represents the fiducial area.

2. Gamma-ray simulation & shower reconstruction

We performed a detailed Monte-Carlo simulation of an EAS development using CORSIKA (v7.6900)[4] for primary gamma-rays. The hadronic interaction models used are QGSJET-II [5, 6] and FLUKA-CERN [7, 8], for high and low energies, respectively. The showers are generated in

Parameter	**Value**
Primary Particle (Id)	Gamma (1)
Primary Energy	$10^3 - 10^6$ GeV
Energy Slope	-2.0
Zenith Angle	0° – 60°
Observation Level	2200 m

Table 1: Summary of CORSIKA parameters used for the simulation

the energy range 1 TeV to 1 PeV for zenith angle less than 60° with a differential energy spectrum of $E^{-2.0}$. Table 1 summarizes the values of some CORSIKA parameters used in the simulation.

Each CORSIKA simulated shower is then passed through an in-house developed analysis framework to generate the triggers and record the GEANT4 [9] response of each scintillator detector. The shower cores are randomly thrown, with each core reused 10 times, in a uniform circular area of radius 150 m from the array center. The relative arrival time is used to reconstruct the arrival direction of an EAS by fitting it with a plane EAS front. The shower parameters like core location, age, and shower size are obtained by fitting observed particle densities with a lateral density distribution function called Nishimura-Kamata-Greisen (NKG) formula [10, 11]:

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

where N_e is the shower size, s is the shower age, r_i is the lateral distance of the i^{th} detector from the shower core, and r_M is the Moliére radius which is 103 m for the GRAPES-3.

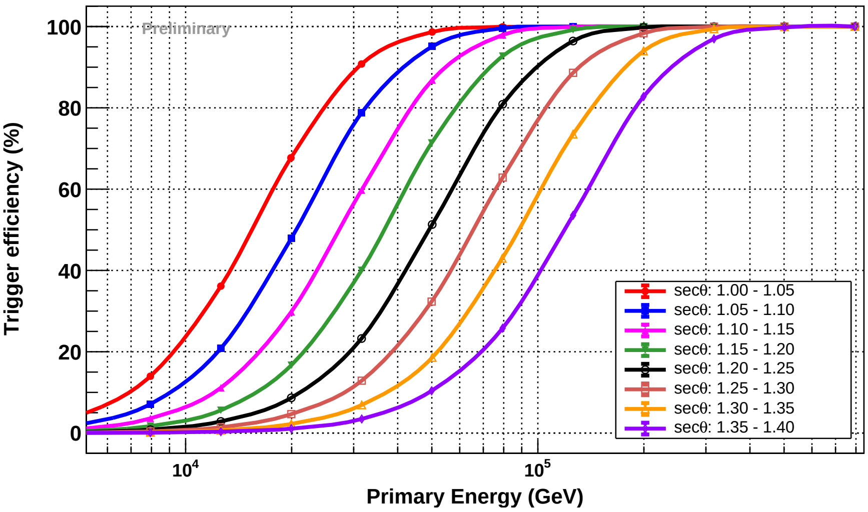
After the reconstruction of shower parameters, a GEANT4 simulation of the muon telescope is performed. Using the hit information of the PRCs, the muon track is identified with any three-layer coincidence out of four. The muon number is counted from the observed muon tracks in the detector for those showers whose direction matches the air shower direction. The muon tracks counting rate unrelated to air shower triggers is 3000 Hz per module. Therefore, the average number of muons due to chance coincidence is estimated to be very small, about 0.07 per event [12].

3. Efficiency and Acceptance

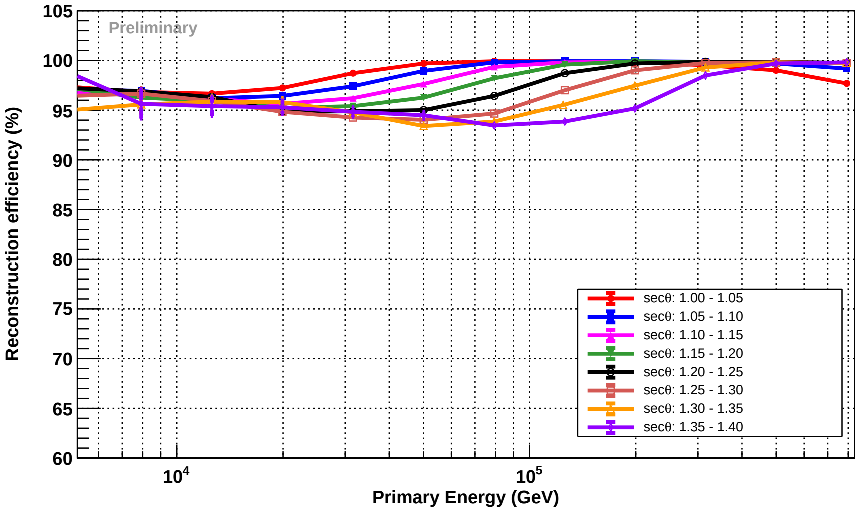
3.1 Trigger and reconstruction efficiency

The reconstructed showers are divided into eight angular (secθ) bins ranging from 1.00 to 1.40 with a bin-width of 0.05, and 15 logarithmic energy bins ranging from 1 TeV to 1 PeV. For each energy and secθ bin, we calculate the trigger efficiency (ε_{tri}) by the fraction of EAS having the shower core within the fiducial area that passes the level-0 and level-1 trigger conditions. In a similar fashion, we calculate the reconstruction efficiency (ε_{rec}) by the fraction of triggered EAS that passes the below reconstruction quality cuts:

- Successful reconstruction of shower parameters.
- Shower age (s) lies between 0.12 to 1.8.



(a) Trigger efficiency



(b) Reconstruction efficiency

Figure 2: Trigger efficiency (top) and reconstruction efficiency (bottom) of GRAPES-3 for gamma-ray initiated showers.

The total efficiency (ε_{tot}) is determined by the product of trigger and reconstruction efficiency. Due to limitations of the poissonian and binomial error calculation, we calculate the error in total efficiency as [13]:

$$\sigma_i = \sqrt{\frac{(k_i+1)(k_i+2)}{(n_i+2)(n_i+3)} - \frac{(k_i+1)^2}{(n_i+2)^2}}, \tag{2}$$

where, for a given angular bin, n_i and k_i are the number of EAS having the shower core within the fiducial area, and the number of EAS that pass both the trigger conditions and reconstruction quality cut, respectively, in the ith energy bin.

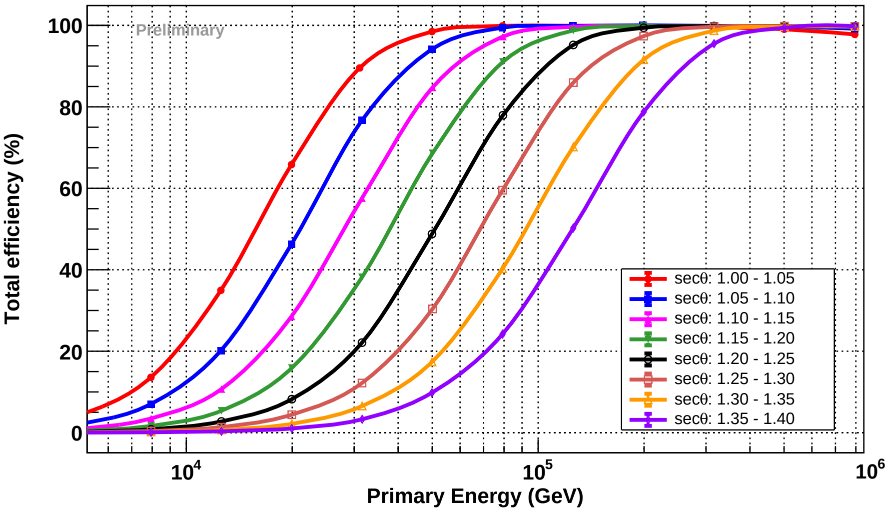


Figure 3: Total efficiency of GRAPES-3 for gamma-ray showers.

The trigger efficiency and the reconstruction efficiency for all angular bins are shown in Fig.2. The total efficiency is shown in Fig.3. The trigger efficiency increases with energy of the primary gamma-rays because at higher energies large number of secondary particles will be produced with relatively higher energy. Hence, the probability of triggering the EAS array will increase as can be seen for the first angular bin ($1.0 \leq \sec\theta < 1.05$), where the trigger efficiency increases from 14.0% at 8.0 TeV to 99.9% at 80.0 TeV. Also, it is to be noted that the trigger efficiency at a given energy decreases with increase in the zenith angle since the effective length travelled by the EAS increases and causes more attenuation of the EAS. Hence, the probabilty of the trigger decreases.

3.2 Gamma-ray Acceptance

The acceptance is defined as the product of effective area of the detector and the effective viewing angle with the inclusion of total efficiency. It is also a function of zenith angle and energy.

$$\delta_{tot}(E_t) = \frac{\pi A}{2} \sum_{k=1}^{n} \varepsilon_{tot}(E_t, \theta_k)(cos2\theta_k - cos2\theta_{k+1}), \tag{3}$$

where A is the fiducial area, n is the total number of angular intervals, θ_k and θ_{k+1} is the lower and upper edge of each angular bin, and E_t is the energy of the primary gamma rays.

In Table 2, we tabulate the total acceptance of GRAPES-3 for gamma-ray initiated showers and are also plotted in Fig.4.

4. Summary

In this work, we perform a detailed MC simulation for primary gamma-rays to estimate various efficiencies in the energy range 1 TeV – 1 PeV. We find the total efficiency for near vertical showers to be < 0.1% for 1 TeV increasing to > 99% above 50 TeV.

Similarly, we estimate the total acceptance of the EAS array to be ~3.32 m^2 sr at 1.58 TeV reaching a maximum of ~ 22226.6 at 794 TeV.

Bin	Mean Energy (TeV)	δ_{tot} (m^2 sr)
1	1.58	3.32
2	1.99	17.27
3	3.16	79.37
4	5.01	306.54
5	7.94	1021.69
6	12.59	2835.67
7	19.95	6226.81
8	31.62	10556.1
9	50.12	14708.3
10	79.43	18070.5
11	125.89	20449.8
12	199.53	21765.1
13	316.23	22246.0
14	501.19	22303.7
15	794.33	22226.6

Table 2: Summary of total acceptance of GRAPES-3 for gamma-ray showers.

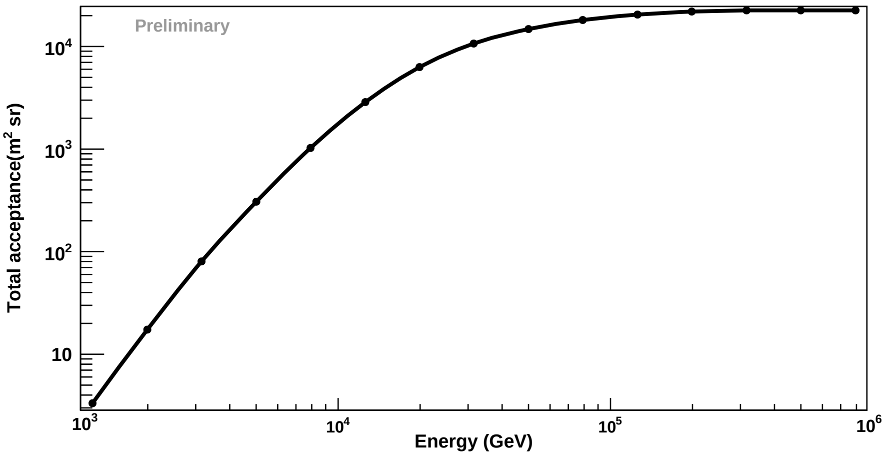


Figure 4: Total acceptance of GRAPES-3 array.

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