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Search for point sources of gamma-rays above 50 TeV with the GRAPES-3 experiment.

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The GRAPES-3 is an extensive air shower array located in Ooty (11.4° N, 76.7° E), designed to study cosmic rays and gamma rays at TeV-PeV energies. The compact array of scintillator detectors coupled with a mid-latitude location and shower front curvature corrections enable an angular resolution of ~0.5 degrees above 50 TeV energies, as verified using the Moon shadow method. Furthermore, GRAPES-3 is equipped with a large area (560 m^2) muon telescope (called G3MT) to determine the muon content of the recorded air showers. Since large muon content is a defining feature of cosmic ray initiated air showers, G3MT is useful in estimating the muon content and rejecting the overwhelming cosmic ray background. Using both the features of good angular resolution and gamma-hadron separation using the muon content, a search for very high energy (E > 50 TeV) gamma rays from the Crab Nebula is under progress. We have used ten years (2013-2022) of air shower data for this analysis. The detailed methodology, current status, and future plans for detecting point gamma ray sources will be discussed.

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1. Introduction

Ground-based air shower array experiments have the capability to detect gamma rays originating from cosmic ray sources at very-high (>50 TeV) and ultra-high energies (>300 TeV). Recent observations by the LHAASO collaboration have already demonstrated this ability, providing a new opportunity to study gamma ray astronomy at PeV energies [1, 2]. GRAPES-3 is a mid-altitude extensive air shower array consisting of densely populated scintillator detectors, which contribute to its excellent angular resolution at high energies [3]. Additionally, its large-area muon telescope effectively eliminates the enormous cosmic ray background, which is crucial for detecting the extremely low flux of the gamma rays. A nearly identical muon telescope, currently nearing completion within the array, will further enhance background rejection and improve sensitivity for gamma rays at energies above 50 TeV. In this study, we analysed ten years of air shower data spanning 2013-2022 to assess the consistency of recorded data by monitoring year-to-year variations in angular resolution. Moreover, we validated the rejection of cosmic rays on a daily basis to identify any instances of improper background rejection caused by maintenance breaks or data interruptions in the muon telescope. Later, we plan to search for gamma rays above 50 TeV from the Crab Nebula after optimizing the event selection area based on the rejection efficiency.

2. The GRAPES-3 experiment

GRAPES-3 stands for Gamma Ray Astronomy at PeV EnergieS phase-3. It is an extensive air shower array experiment, located at Ooty in India (11.4° N, 76.67° E, 2200 m a.s.l.), designed to study the cosmic rays and gamma rays in TeV-PeV range [4]. The equatorial location of the experiment enables to search for point sources in both southern and northern sky. The array consists of 400 plastic scintillator detectors arranged in a compact hexagonal arrangement with an inter-detector separation of 8 meters. This design facilitates better angular resolution at high energies. Recent results from the GRAPES-3 demonstrate that by applying corrections to the shower front curvature based on shower size and age, the angular resolution can be further enhanced [5]. The verification of these improved results was accomplished through the observation of the Moon's shadow [3]. Additionally, the GRAPES-3 experiment houses a large area (560 m^2) muon telescope within the array that determines the muon content of the associated air showers [6]. This capability is essential in distinguishing between air showers induced by cosmic rays and those initiated by gamma rays, since the latter tend to generate fewer muons.

3. Analysis

Ten years of air shower data spanning over 2013 to 2022 are concatenated to search for gamma rays coming from the Crab Nebula, which is considered as the standard candle for gamma rays. The air shower data were first reconstructed with the well known Nishimura-Kamata-Greisen (NKG) function [7, 8] to obtain the air shower parameters such as shower core, shower size (N_e) and age (s) [9]. The obtained shower size and age are then used for correcting the shower front curvature to find the arrival zenith (θ) and azimuthal (ϕ) direction. The events with adequate NKG and arrival direction reconstruction are used for the analysis. In addition, the age of showers was restricted

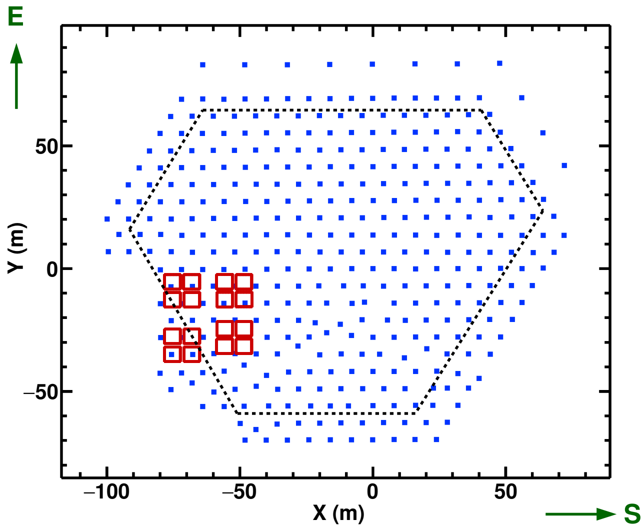

Figure 1: A schematic representation of the GRAPES-3 extensive air shower array showing the scintillator detectors in the blue markers and the muon telescope module in red squares. The dashed line represents the fiducial area (14500 m^2) of the array used for event selection.

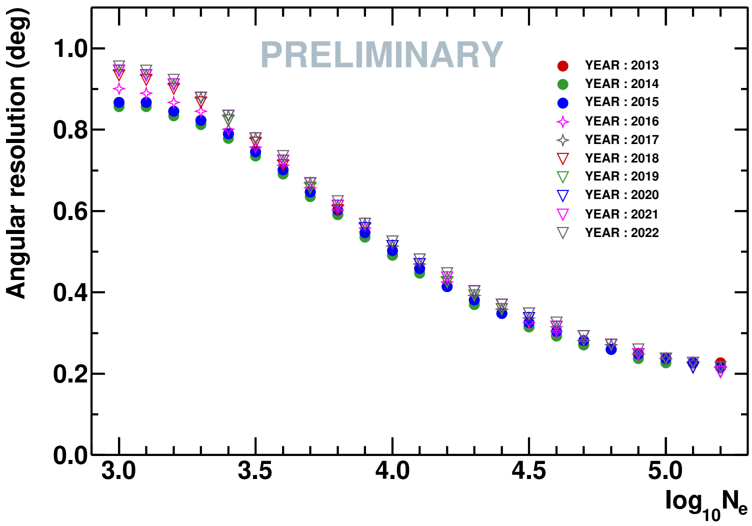

Figure 2: Angular resolution variations for ten years, estimated using the Left-Right method, (described in [5]) are shown as a function of shower size.

within a range of 0.2 to 1.8 while the zenith angle (θ) of the showers were restricted up to 45°. Furthermore, to reduce the contamination due to high energy showers arriving at a larger distance from the array, the showers with core outside the fiducial area (as shown in Fig.1) were removed from the analysis [10].

To assess the quality of data, the yearly angular resolution variations for all the ten years (2013-2022) data were plotted in Fig.2 as a function of shower size. The clear similarities in the angular resolution for all the years provide sufficient evidence of uniform air shower data quality.

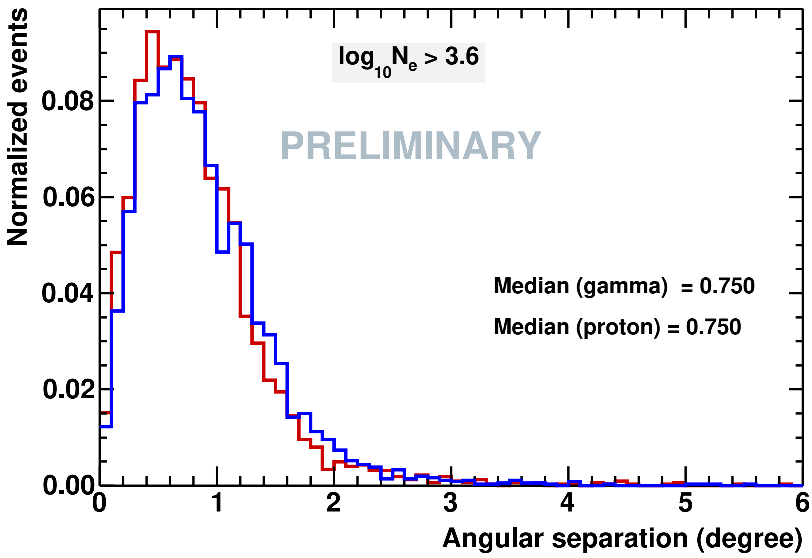

Figure 3: Comparison of angular separation between primary direction and reconstructed direction for proton and gamma rays. The median of the distribution provides a measure of the angular resolution. The angular resolution for both proton and gamma shows the same angular resolution of ~0.75° for events with shower size above $10^{3.5}$.

The angular resolution of the array for showers above 50 TeV energy is found to be ~0.47° which is in agreement with the angular resolution estimated from the Moon shadow method [3]. In addition, the GRAPES-3 array exhibits similar angular resolution for both gamma rays and cosmic rays, checked from a monte-carlo simulation using corsika v-76900. For the simulation, proton and gamma rays within an energy range of 10 TeV to 250 TeV are simulated using EPOS and FLUKA interaction model for high and low energies respectively. Then a detailed reconstruction of the events was carried out after considering the GEANT-4 response of the particles in the scintillator detectors. The angular separation between the primary direction and reconstructed direction provide the measure of the angular resolution of the array. Fig.3 shows a comparison of angular separation for both cosmic rays and gamma rays above shower size $10^{3.5}$, and the angular resolution for both gamma rays and cosmic rays was obtained to be 0.75°. The obtained angular resolution is in good agreement with the data (see Fig.2).

Once the angular resolution is estimated, then the cosmic rays are rejected based on the muon content recorded by the GRAPES-3 muon telescope. The muon telescope tracks muons within four orthogonally placed layers of proportional counters [11]. Air showers without any recorded muons in the muon telescope are categorized as gamma ray-like showers, while the remaining showers are treated as cosmic rays and excluded from the analysis. The efficiency of cosmic ray rejection, defined as the percentage of cosmic ray showers rejected out of the total events considered, is calculated on a daily basis throughout the entire duration. Figure 4 illustrates the distribution of daily rejection efficiency for showers above 50 TeV energy in the year 2014. The mean of the rejection efficiency after fitting with a Gaussian function is estimated to be 94.6% with a standard deviation of 0.1%. For the analysis, only days with a daily rejection efficiency within a range of

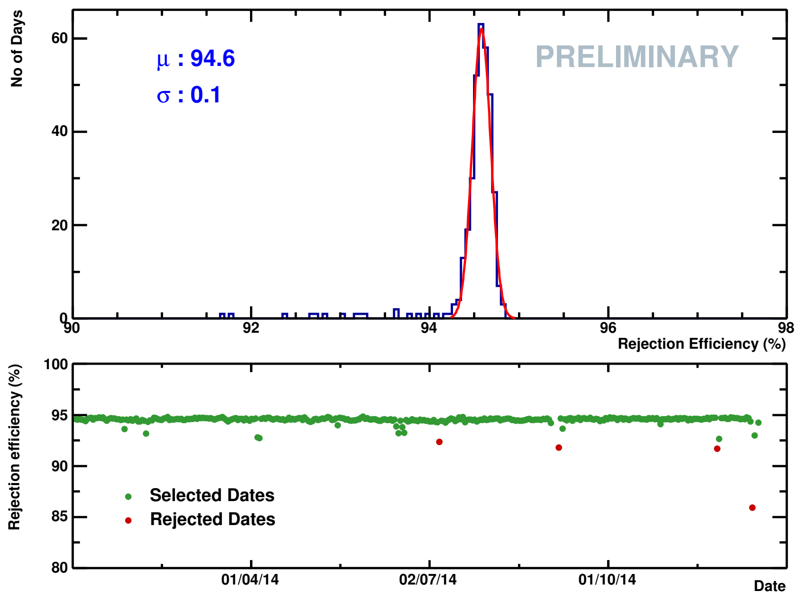

Figure 4: In this figure, the upper panel shows the distribution of daily rejection efficiency for the year 2014. The mean of the rejection efficiency after a Gaussian fitting was obtained to be 94.6% with a standard deviation of 0.1%. The green markers on the lower panel shows the rejection efficiency of the days selected for the analysis as they are within 20 standard deviation from the mean, while the red markers represents the rejected dates.

20 standard deviations from the mean are considered. Lower rejection efficiencies typically occur when at least one of the 16 modules of the muon telescope is not operational due to maintenance breaks or technical issues. Since these days with lower rejection efficiencies can result in a higher contamination of cosmic rays, they are excluded from the analysis. In addition, the peripheral location of the muon telescope results in decreasing rejection efficiency with increasing distance from the Muon telescope. Hence, it is essential to optimise the core distance and the work is under progress to find the optimal core distance for each shower size bins.

4. Conclusion

A comprehensive analysis of ten years of GRAPES-3 data (2013-2022) has been conducted, revealing consistent angular resolution throughout all the years. Additionally, a study was conducted to evaluate the rejection efficiency of the muon telescope on a daily basis by examining the number of muons recorded. This analysis helped identify periods of improper data, characterized by poor rejection efficiency, which could result in contamination of the cosmic ray background in the gamma ray signals. Currently, an ongoing detailed investigation aims to determine core selection criteria to optimize the signal-to-background ratio. Once the core selection is optimized, a search for gamma rays from the Crab Nebula will be conducted using GRAPES-3 air shower data spanning ten years, specifically targeting energies above 50 TeV.

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