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Search for gamma rays above 30 TeV from the Crab Nebula with the GRAPES-3 experiment

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The GRAPES-3 is a high-altitude, near-equator extensive air shower array at Ooty, India which is designed to observe cosmic and gamma-rays in TeV-PeV energy range. It consists of a dense array of 400 scintillator detectors operating in conjunction with a 560 m^2 area muon telescope. Due to recent improvements in the measurements of shower arrival time and corrections for shower front curvature based on shower size and age, the angular resolution of the array has been significantly improved. By leveraging the resultant improved angular resolution and an efficient rejection of the cosmic ray background using the muon content of the shower, a search for gamma-rays above 30 TeV from the Crab Nebula has been performed. The results will be presented during the conference.

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1. Introduction

Crab Nebula is a standard point source of γ-rays and the most studied astrophysical object in the sky. Detection of the γ-rays from the Crab Nebula is a challenge for the air shower array experiments because of the poor angular resolution. In order to detect the tiny flux of γ-rays out of the enormous background cosmic rays, the angular resolution of the array needs to be excellent.

GRAPES-3 (Gamma Ray Astronomy at PeV Energies Phase-3) experiment is an extensive air shower array located near the equator (11.4°N, 76.7°E, 2200 m a.s.l) at Ooty, India. It is designed to study cosmic ray sources in TeV-PeV energy range by detecting the primary γ-rays propagating directly from the sources [1]. It consists of an array of 400 scintillator detectors (1 m^2 area each) packed closely in a hexagonal geometry (see Figure 1) with a separation of 8 meters between two consecutive detectors. The densely populated detectors arrangement results in a very good angular resolution of the array. Along with the scintillator detectors, GRAPES-3 is also equipped with a large area muon telescope (560 m^2 area) that tracks the muons passing through it [2]. The muon content recorded in the muon detector plays a significant role to distinguish between the cosmic rays and γ-rays. This provides additional rejection of the background cosmic rays.

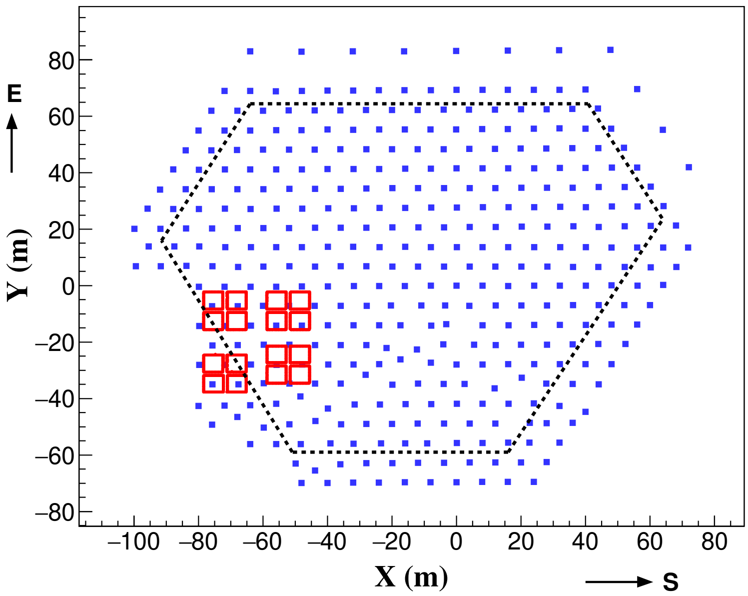

Figure 1: Schematic diagram of the GRAPES-3 array showing the scintillator detectors (■) and the muon telescope (□). The dashed line (- - -) represents the fiducial area of the array.

For each air shower trigger, the scintillator detectors record the particle densities and the arrival times with the help of charge sensing ADC (qADC) and high performance time-to-digital converter (HPTDC) respectively. These pieces of information are later used to reconstruct the shower properties as well as its arrival direction. The lateral densities of the air shower are fitted with the well-known Nishimura-Kamata-Greisen (NKG) function to determine various air shower properties, such as shower core, shower size and shower age [3, 4]. The timing information is used for the reconstruction of the arrival direction of the shower. Recently, after a detailed study on the shower front curvature, the angular resolution of the array has been improved further [5].

The muon telescope is also triggered by the air showers and tracks the muons passing through it. An energy threshold of 1 GeV ($E_{th} > 1\ GeV$ for vertical passing muons) has been kept with the help of concrete blocks to absorb the low energy radiations. Hence for each air shower, we could count the total number of muons passing through the muon telescope. Based on the muon content information, we could separate the cosmic rays from the γ-rays efficiently. The details will be discussed in the following sections.

2. Data selection

Three years for air shower data (January 01, 2014-December 31, 2016) are used for this analysis. The quality of the data is ensured by the following selection criteria.

- Successful NKG fit.
- Reconstructed shower cores should be within the fiducial area shown by the dashed line in Figure 1.
- Shower age parameter restricted within 0.2 to 1.8.
- Zenith angle below $45°$.
- The air shower event must have a valid muon event in the muon telescope.

3. Rejection of background cosmic rays

Since cosmic rays form an enormous background over the tiny flux of γ-rays, one needs to reject the background efficiently. In the GRAPES-3 experiment, the majority of the background has been reduced by improving the angular resolution. Further reduction in the background has been achieved by rejecting the muon-rich showers as cosmic ray showers.

3.1 Angular resolution

To detect the γ-rays from the point sources, the opening angle around the source has to be very small. If the angular resolution is poor, the background cosmic rays dominate over the γ-ray signals. The angular resolution of the GRAPES-3 array has been obtained by the Moon shadow analysis method at different energies, using three years of air shower data [6].

From Figure 2, it is clear that the angular resolution of the GRAPES-3 array gets better with an increase in energy (E). For E > 50 TeV, the angular resolution is ∼0.54° which improves to ∼0.35° for E > 100 TeV and ∼0.23° for E > 250 TeV. This result helped us to look at the Crab Nebula by opening a narrow angle comparable to the angular resolution obtained from the Moon shadow. Although a large fraction of background has been removed by restricting the opening angle, further background cosmic rays are rejected with the help of muon content.

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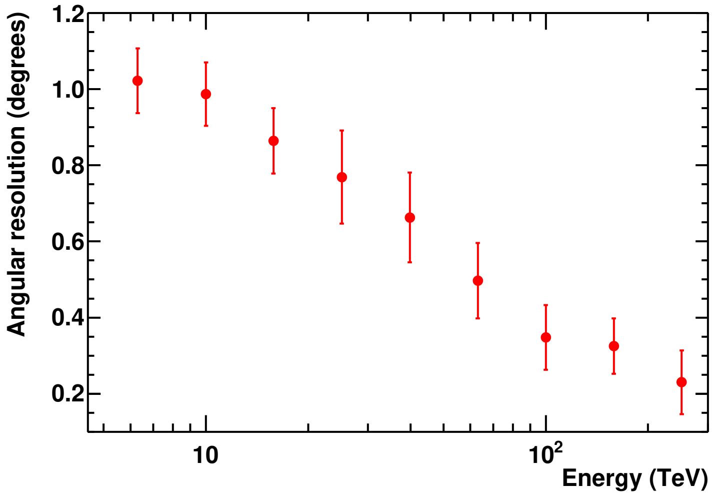


Figure 2: GRAPES-3 angular resolution obtained from the Moon shadow method as a function of energy

3.2 Distinction between cosmic rays and γ-rays

Cosmic rays produce a large number of muons in the air shower than the γ-rays. So one can treat the muon-poor showers as γ-ray like showers. In the GRAPES-3 experiment, we record the muon content in the muon telescope for each air shower. The air showers with zero muons ($N_{\mu=0}$) are considered to be γ-like showers, while the rest are treated as cosmic rays ($N_{\mu\geq1}$). The rejection efficiency is then given by,

$$Rejection\ efficiency\ (\%) = \frac{N_{\mu\geq1}}{N_{total}} \times 100$$

where N_{total} is the total number of air showers collected after the selection criteria.

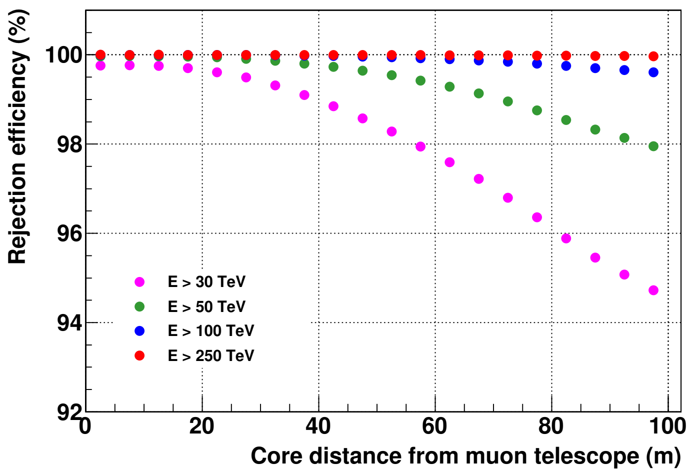


Figure 3: Cosmic ray rejection efficiency as a function of shower core distance from the center of the muon telescope at different energies.

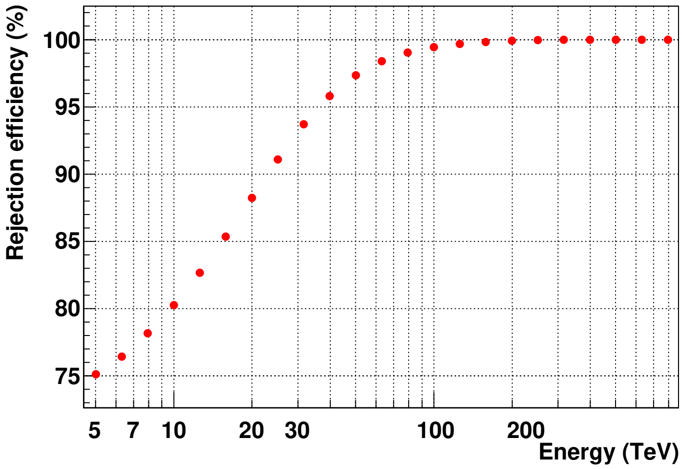


Figure 4: Cosmic ray rejection efficiency as a function of energy

The rejection efficiency of the muon telescope decreases as the distance of the shower core from the center of the muon telescope increases as shown in Figure 3. However, for higher energies, the rejection efficiency is large even though the showers are landing at a larger distance from the center of the muon telescope. The overall rejection efficiency increases with an increase in energy irrespective of their core locations (see Figure 4). For the showers above 50 TeV Energy (E), the rejection efficiency is ~97% while for showers above 100 TeV Energy, the rejection efficiency is more than 99%.

Better angular resolution and large rejection efficiency at higher energies makes the GRAPES-3 experiment more sensitive towards the γ-rays at higher energies.

4. Analysis method

The background plays a major role while searching for γ-rays from any point sources. In order to detect the tiny flux of γ-rays from the Crab Nebula, we first estimated the expected background at different energies.

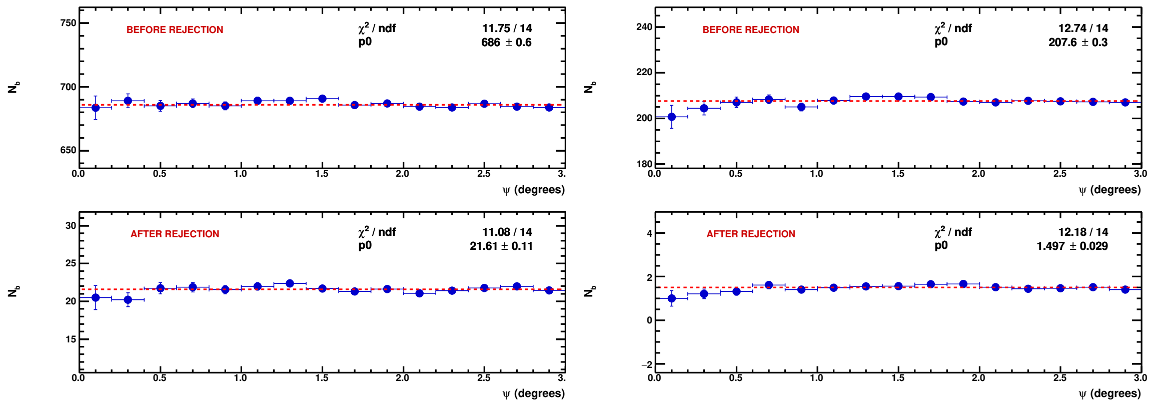
A total of 8 background (off-source) regions were selected with 10° successive shifts from the azimuthal angle of the Crab Nebula keeping the zenith angle fixed. Events were then binned with the equal incident angle (ψ) bins measured from the center of the off-source. Since the solid angle subtended by each incident angle bin increases gradually, the events in each bin were normalized appropriately with respect to the solid angle of the first bin. Hence, the background level (N_b) is defined by,

$$N_b = \frac{\langle N_i^{off} \rangle}{\Omega_i} \times \Omega_0 \tag{1}$$

Where,

$\langle N_i^{off} \rangle$ is the average number of events in i^{th} bin from the off-source direction,
$\Omega_i = \int_0^{2\pi} \int_{\psi_i}^{\psi_{i+1}} sin\psi d\psi d\phi \approx \pi(\psi_{i+1}^2 - \psi_i^2)$ and $\Omega_0 \approx \pi(\Delta\psi)^2 = \pi(\psi_{i+1} - \psi_i)^2$.

In order to understand the effectiveness of the background rejection based on the muon content, the background level was studied before and after the rejection of cosmic rays.



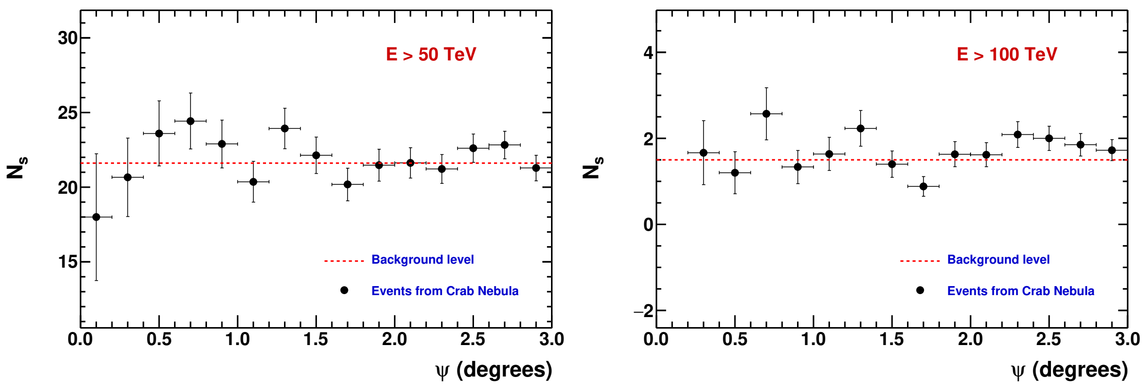
(a) Energy $>$ 50 TeV **(b)** Energy $>$ 100 TeV

Figure 5: Observed background level as a function of incident angle (ψ) measured from the direction of off-source, before and after the rejection of the cosmic rays based on the muon content. For (a) Energy > 50 TeV, $\sim$ 97% and (b) for Energy > 100 TeV, $\sim$99% of the background cosmic rays are rejected.

The average background level was obtained by fitting the distribution with a straight line for both before and after the rejection. For E > 50 TeV, the background level was reduced by $\sim$97% after rejecting the background cosmic rays based on the muon content and $\sim$99% for E > 100 TeV (see Figure 5). After the background estimation, muon-poor showers from the direction of the Crab Nebula were sampled to search for the γ-ray excess.

5. Results and Discussion

The air shower events with zero muons ($N_{\mu=0}$) arriving from the direction of Crab Nebula were distributed in the equal incident angle bins as we did for the off-source regions.



(a) Energy $>$ 50 TeV **(b)** Energy $>$ 100 TeV

Figure 6: Observed events from the direction of the Crab Nebula plotted with the average background level as a function of incident angle (ψ).

From the preliminary studies, we couldn't observe any significant excess in the γ-ray events from the direction of the Crab Nebula. However, this study helped us to understand the background rejection mechanism of the GRAPES-3 array. We are doing more systematic studies of the background and rejection mechanism to understand the performance of the instrument in more detail. After that, we will search for the excess in the γ-ray events from the Crab Nebula.

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