Angular resolution of the GRAPES-3 array obtained from the Moon shadow

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On behalf of the **GRAPES-3** collaboration

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The GRAPES-3 experiment

- Location: Ooty, India (11.4°N, 76.7°E, 2200 m asl).
- 400 scintillator detectors (1 m^2 area each).
- 8 m inter-detector separation.
- A large area (560 m^2) muon telescope.
- 14500 m^2 fiducial area bounded by the dashed line.

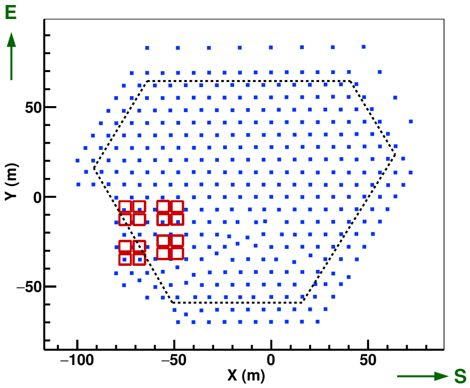
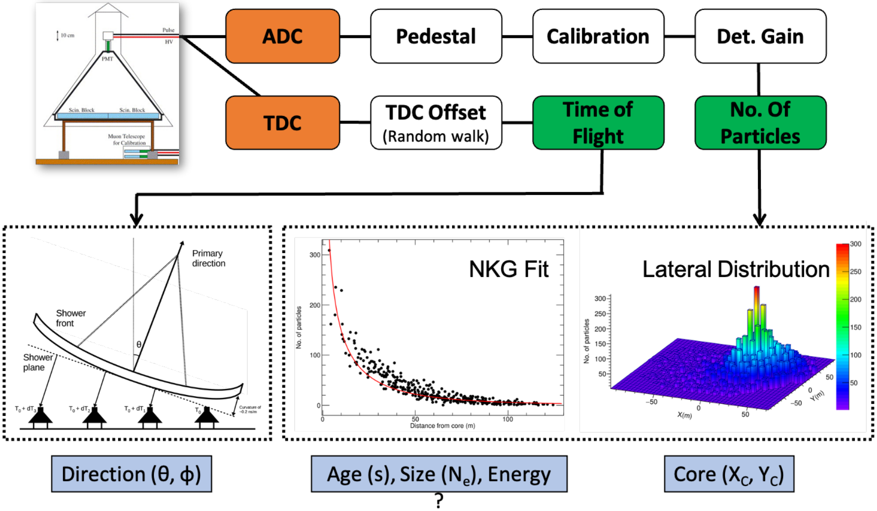


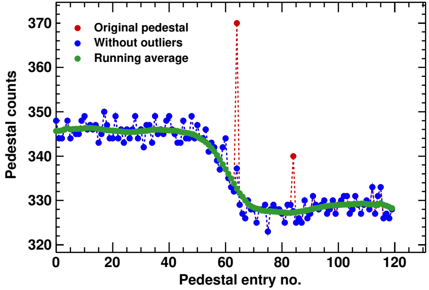
Figure: GRAPES-3 array

⇒ GRAPES-3 records about $\sim 3\times10^6$ air showers/day in TeV-PeV energy range.

Air shower reconstruction

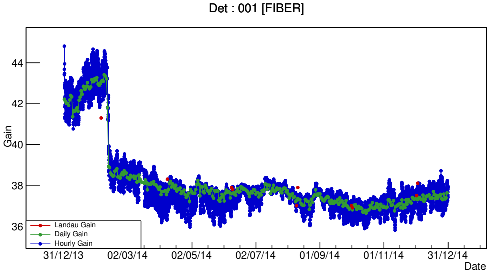


Pedestal measurements:



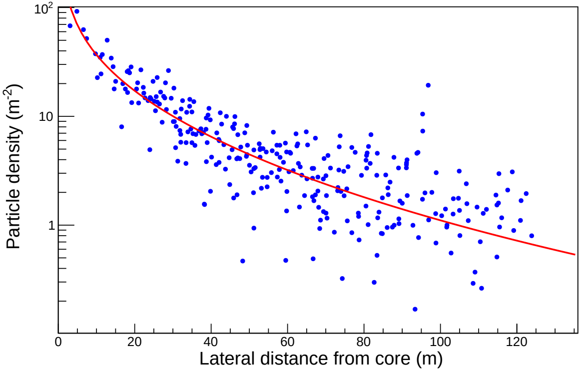
- Pedestal measurement improved with a robust technique.

Hourly gain:



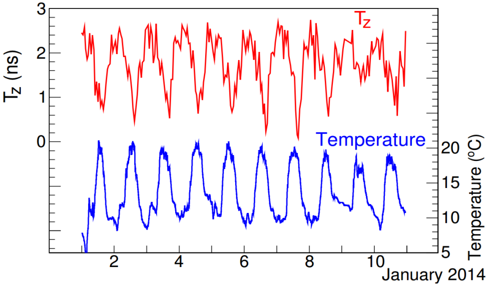
- Gain of detectors calculated hourly basis.

Measurement of air shower properties



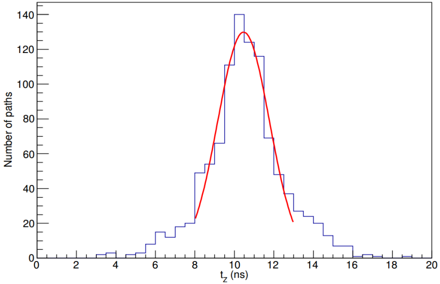
- Lateral particle density distribution fitted with Nishimura-Kamata-Greisen (NKG) function.
- Obtained parameters: **Shower core, Size** (N_e) **and age (s)**.

Measurement of time offset



- Time offset (T_Z) of each detector shows temperature dependance.
- Using air shower data itself, the time offset was calculated on hourly basis.

- Time offset (T_Z) for each detector was calculated using a random walk method.



Shower front curvature

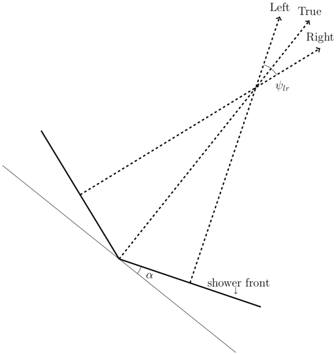
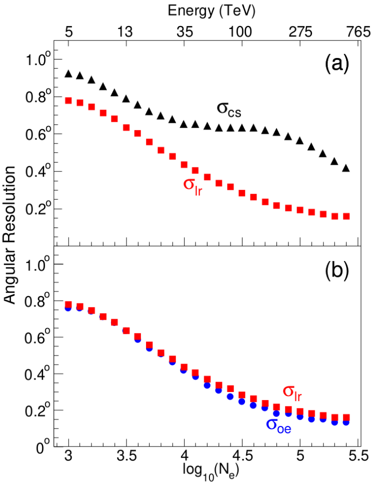


Figure: Shower front curvature

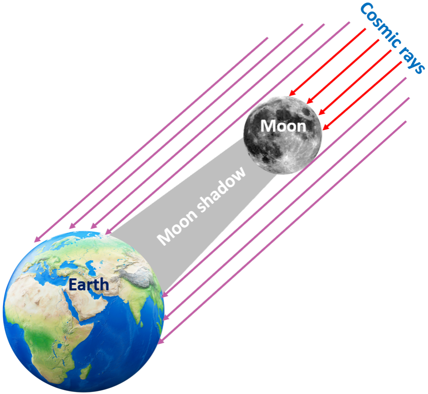


- Shower front curvature depends on shower size and age.
- Correction to the shower front, improves the angular resolution.

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

Moon shadow

- Moon blocks the isotropic cosmic rays, hence creates a deficit in their flux; known as the ***Moon shadow***.
- Air shower experiments calibrate the angular resolution by Moon shadow method.
- Moon shadow also determines the pointing accuracy.



- The improvement in angular resolution needs to be verified by observing the Moon shadow.

Data selection

⇒ 2.98×10^9 air shower events recorded during January 1, 2014 to December 31, 2016 were used for this analysis.

Quality cuts:

- Events with good quality NKG fit.
- Showers with core inside the fiducial area.
- Shower age between [0.2, 1.8].
- Zenith angle (θ) below 40°.

⇒ 1.65×10^9 events remained after the quality cuts.

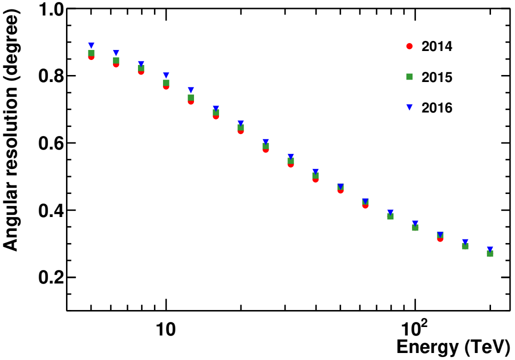


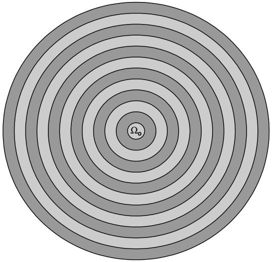
Figure: The angular resolution using Left-Right method for 2014, 2015 and 2016.

Analysis method

Background selection:

- 10 different background regions were selected.
- Each with 6° successive shift in azimuthal angle (ϕ).
- Shift in background ϕ_B, $(\pm 6^\circ, \pm 12^\circ, \pm 18^\circ, \pm 24^\circ, \pm 30^\circ)$.
- The zenith (θ) of the background regions were same as of the Moon.

$\Rightarrow$ Average number of events from the 10 background regions was calculated for further analysis.



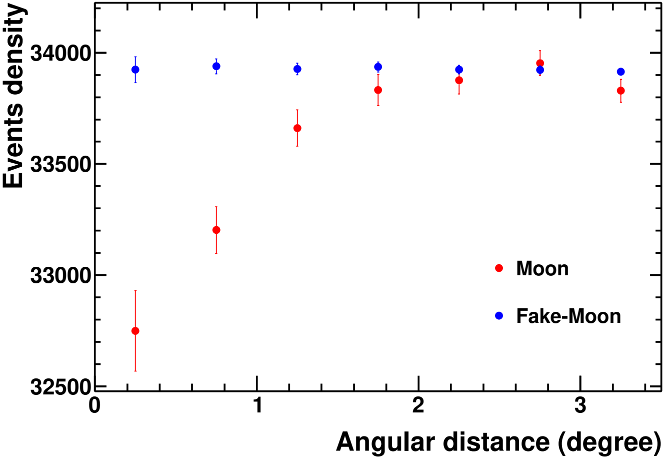
- A circular region of angular radius 3.5° from the center of the Moon was selected.
- The region was then divided into 14 annular bins of equal bin width i.e. 0.25°.
- The central bin is comparable to the size of the Moon (angular radius = ∼0.26°).

Analysis method

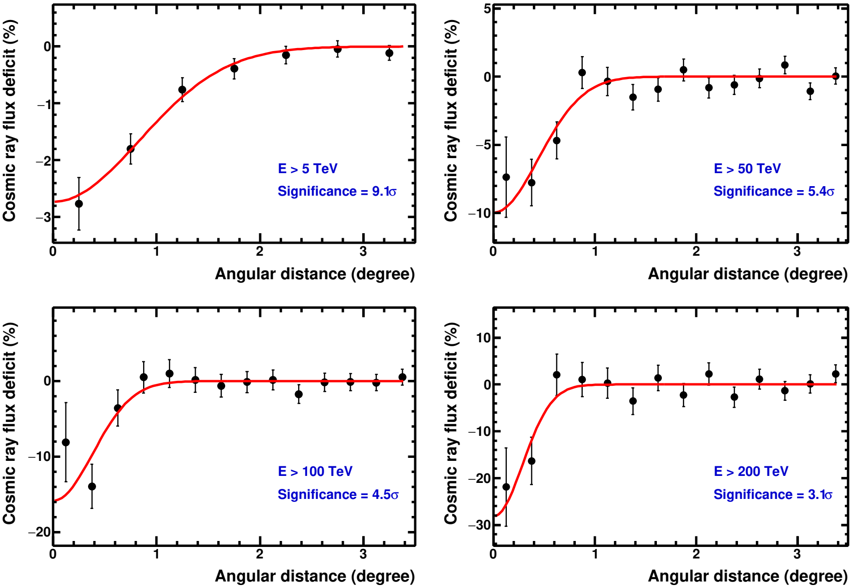
- Event density in each annuar bin is given by,

$$Event\ density\ (N_{\Omega_i}) = \frac{N_i}{\Omega_i} \times \Omega_\circ$$

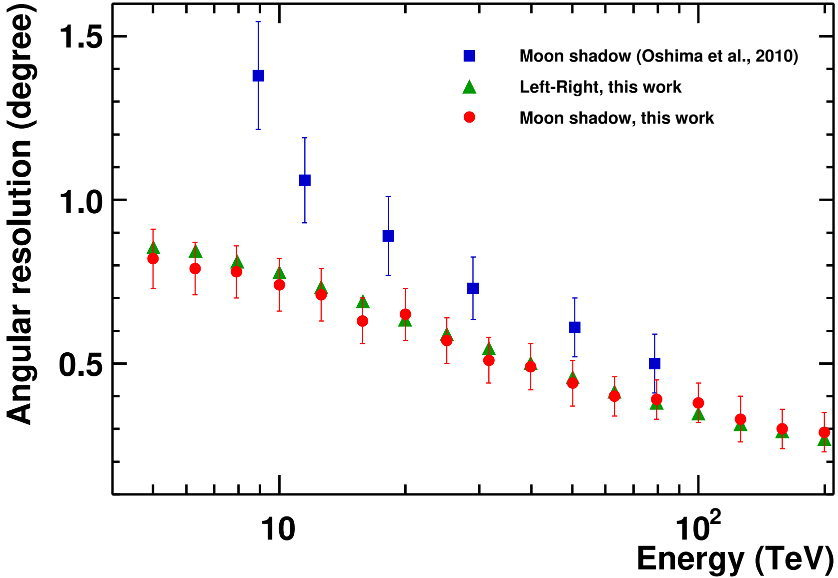
N_i = Observed events in i^{th} annular bin.
Ω_i = Solid angle of the i^{th} annular bin.
$\Omega_\circ$ = Solid angle of the central bin



Results : Cosmic ray flux deficit

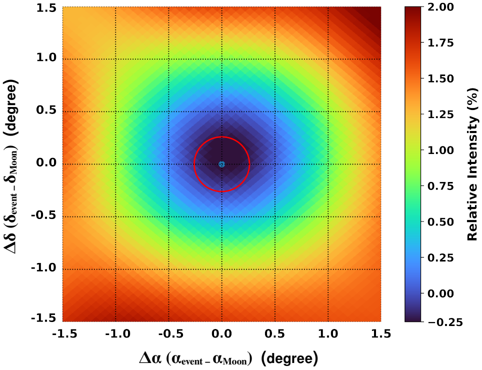


Results: Angular resolution



Results : Pointing accuracy

- Local co-ordinates of the observed events (θ, ϕ) were transformed into equatorial co-ordinates i.e. Right ascension (α) and Declination(δ).

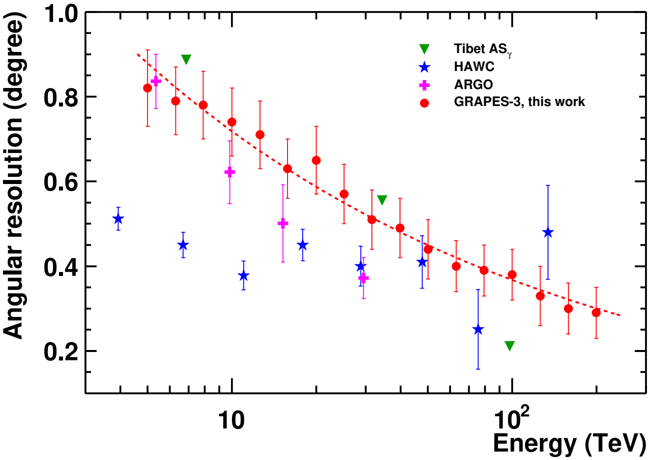


- $\Delta\delta = \delta_{event} - \delta_{Moon}$
  $\Delta\alpha = \alpha_{event} - \alpha_{Moon}$
- HEALPix map between $\Delta\delta$ and $\Delta\alpha$ generated.
- Location of the maximum deficit determines the pointng accuracy.

Pointing accuracy

- Pointing accuracy along $\alpha = 0.032^\circ \pm 0.004^\circ$
- Pointing accuracy along $\delta = 0.09^\circ \pm 0.003^\circ$

Summary



- Despite being located at 2200 meter, GRAPES-3 angular resolution is comparable to other experiments located at twice the altitude.

Future: Multi-TeV gamma ray astronomy

- ✓ Excellent angular resolution at multi-TeV energies.
- ✓ Pointing accuracy is better than the uncertainity in the angular resolution.
- ✓ Muon telescope helps to distinguish between cosmic rays and gamma rays.

Excellent angular resolution combined with the muon telescope, reject the large background cosmic rays over the tiny flux of gamma rays.

- GRAPES-3 is suitable for multi-TeV gamma ray astronomy.
- Equatorial location gives advantage to search in both southern as well as northern sky for cosmic ray sources.