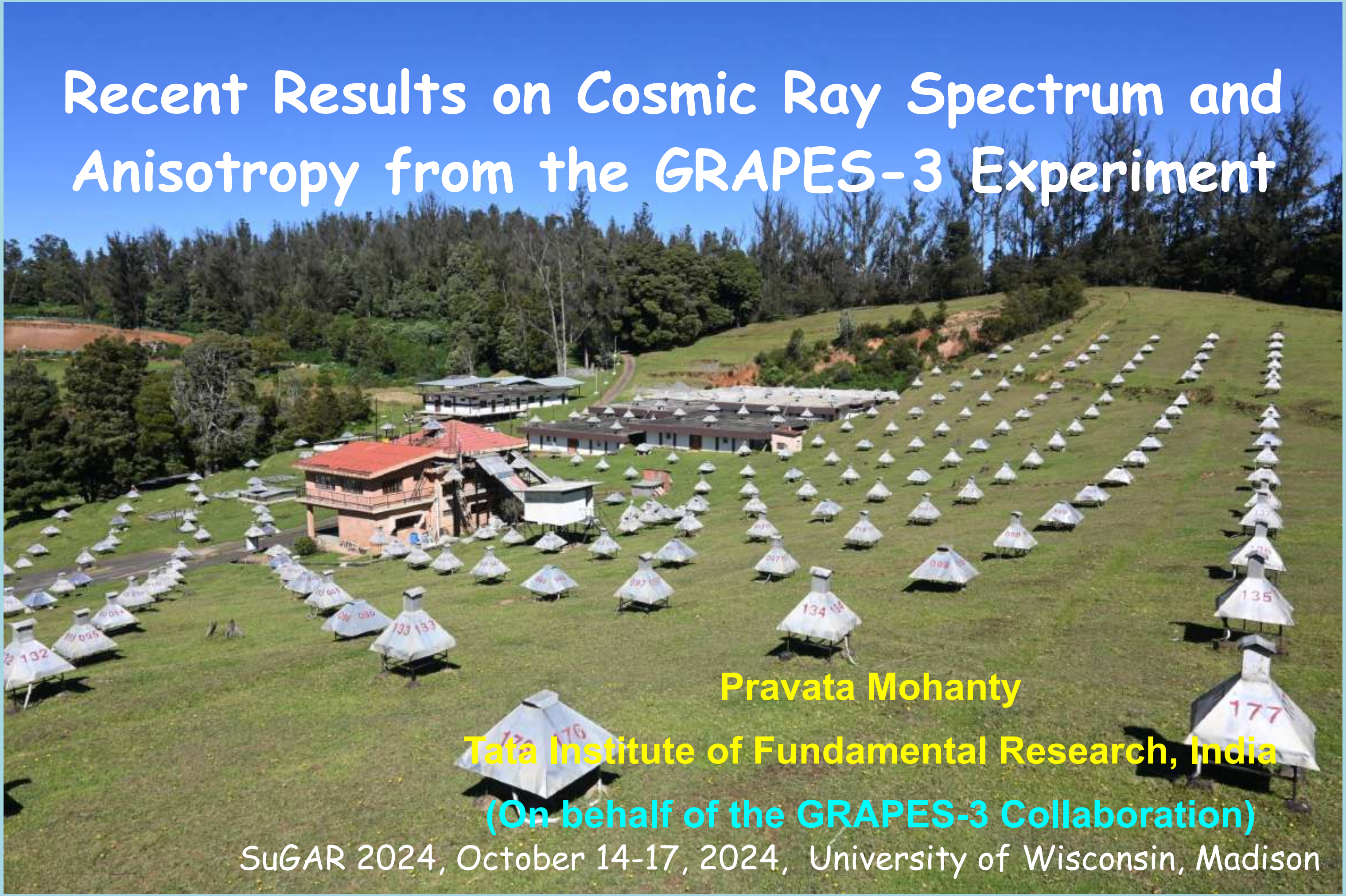
Recent Results on Cosmic Ray Spectrum and Anisotropy from the GRAPES-3 Experiment



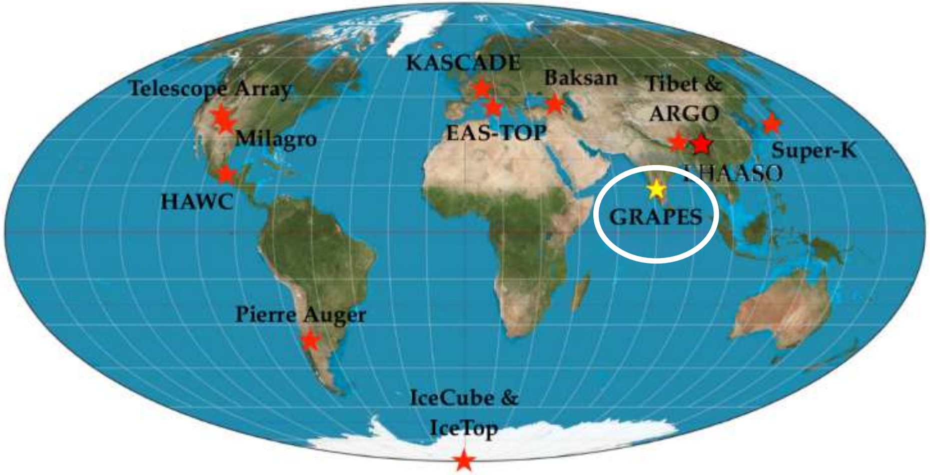
Pravata Mohanty

Tata Institute of Fundamental Research, India

(On behalf of the GRAPES-3 Collaboration)

SuGAR 2024, October 14-17, 2024, University of Wisconsin, Madison

The GRAPES-3 Collaboration



1. Tata Institute of Fundamental Research, Mumbai, India
2. Osaka City University, Osaka, Japan
3. Aichi Institute of Technology, Aichi, Japan
4. J.C. Bose Institute, Kolkata, India
5. Indian Institute of Science & Edu. Res. Pune, India
6. Chubu University, Kasugai, Aichi, Japan
7. Hiroshima City University, Hiroshima, Japan
8. Aligarh Muslim University, Aligarh, India
9. Indian Institute of Technology, Kanpur, India
10. North Bengal University, Siliguri, India
11. Vishwakarma Inst. of Information Tech., Pune, India
12. Kochi University, Kochi, Japan
13. Utkal University, Bhubaneswar, India
14. Dibrugarh University, Dibrugarh, India
15. Nagoya University, Nagoya, Japan
16. Tezpur Central University, Tezpur, India
17. Indian Institute of Technology, Jodhpur, India
18. Indian Institute of Technology, Indore, India
19. Institute for Cosmic Ray Research, Tokyo U., Japan
20. Amity University, Noida, India
21. Institute of physics, Bhubaneswar, India

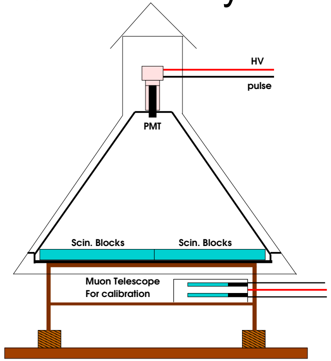
GRAPES-3 is located in Ooty, India

11.4° N lat., 76.7°E lon., 2200 m alt.

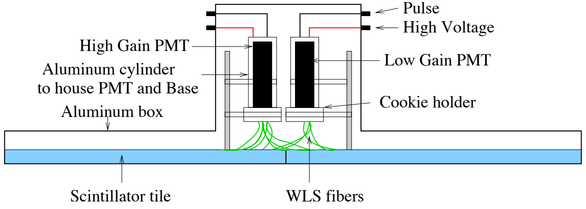
The GRAPES-3 Experiment

- 400 plastic scintillator detectors (1 m^2 area) with 8 m inter-separation spread over 25,000m^2
- 560 m^2 muon telescope consisting 3712 proportional counters (6m x 0.1m x 0.1m).

Single PMT conventional type
(photoelectron yield: 4-5)



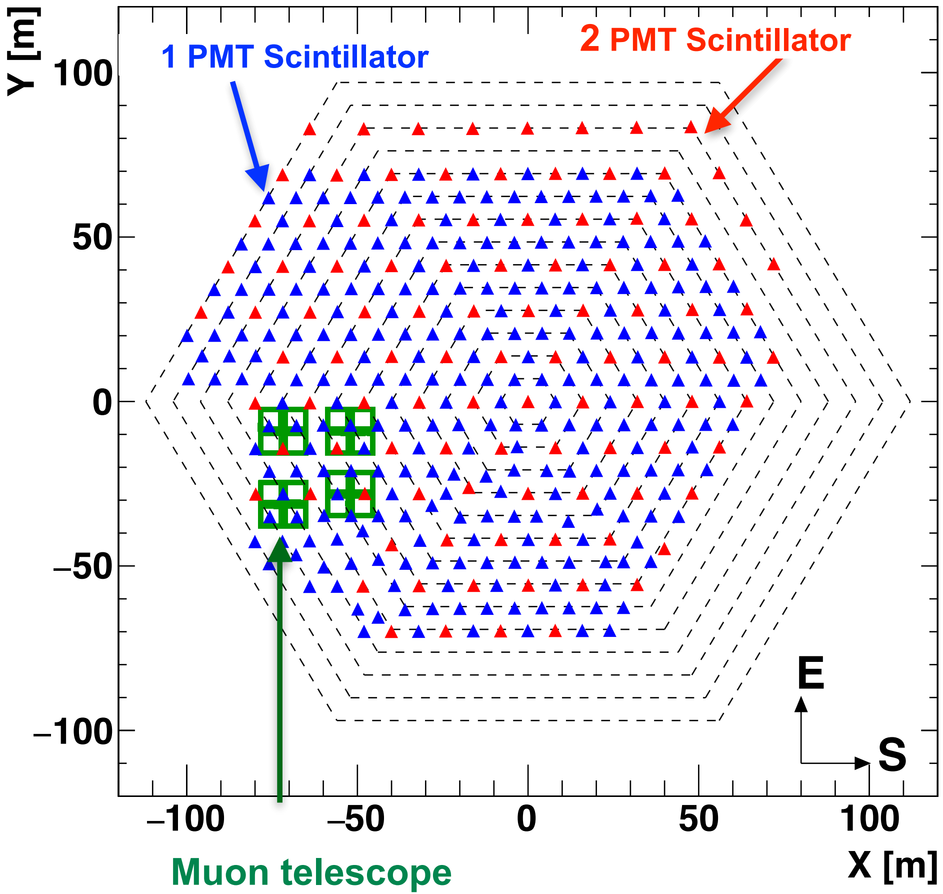
Two-PMT WLS fiber type
(photoelectron yield: 15-20)



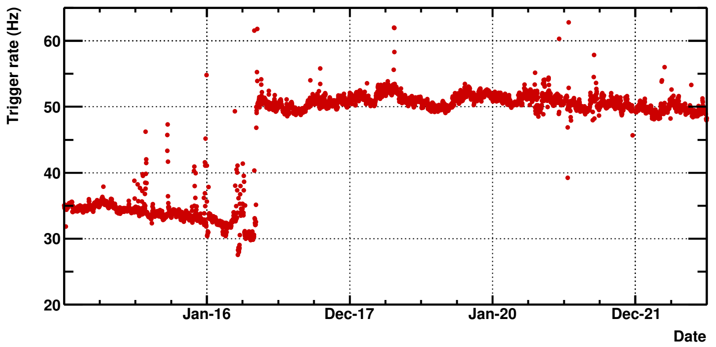
Each scintillator detector is designed to measure charged particle component and relative arrival times

25% of scintillators instrumented with 2 PMTs for extended density measurements (100 - 10,000 m^{-2})

GRAPES-3 Shower Data



- A shower trigger is generated when minimum 10 detectors observe above 0.5 equivalent minimum ionising particle.
- The array records 4 million shower events per day in the TeV-PeV energy range with median energy of 15 TeV
- Array has operated > 99% uptime. It has collected 15 billion showers since its operation in 2000



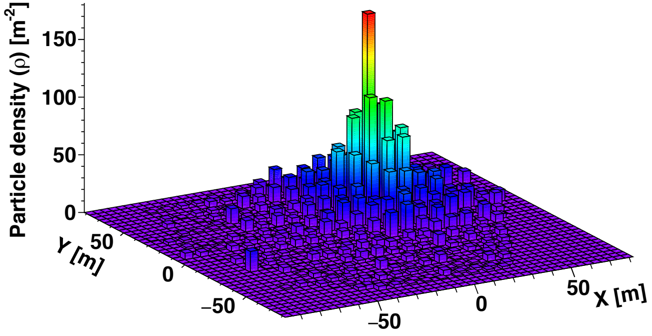
Jan 2014 to Dec 2022

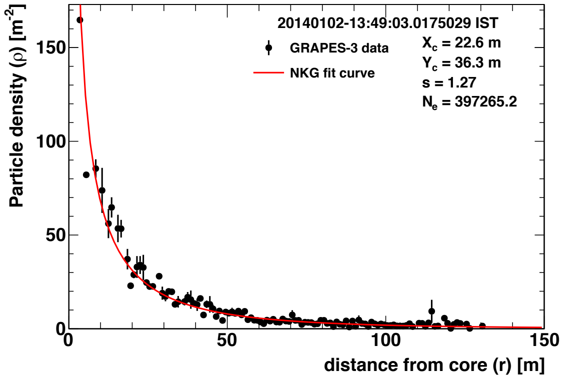
Shower Reconstruction

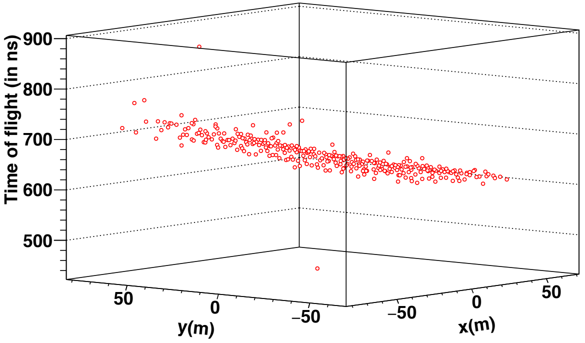
- Shower parameters such as core location (X_c, Y_c), size (N_e) and age (s) are obtained by fitting the observed lateral densities with NKG function
- Direction of the shower (zenith and azimuth) are obtained by fitting a plane front to the observed relative arrival times

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

20140102-13:49:03.0175029 IST

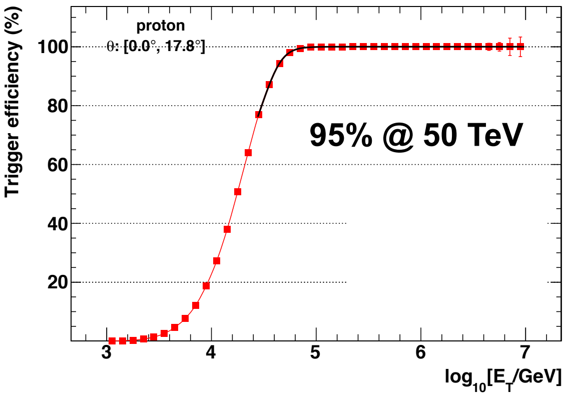




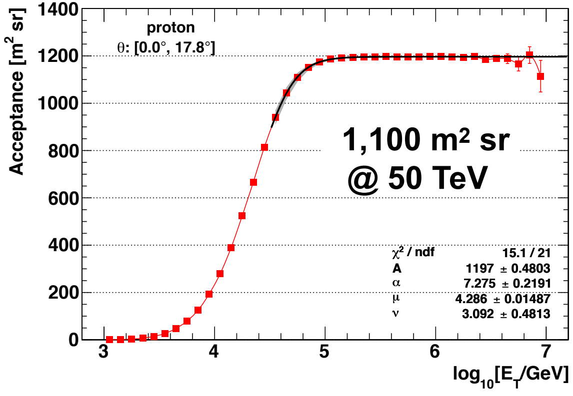


Performances of the scintillator array

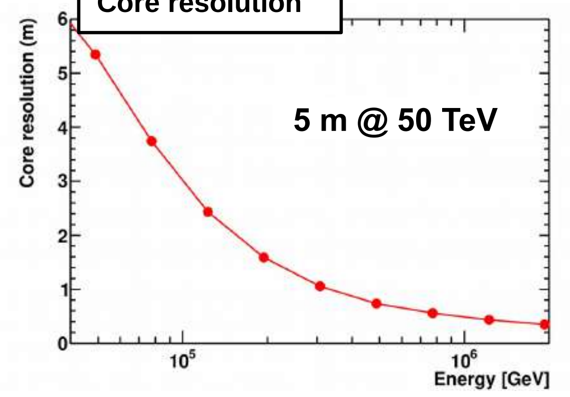
Trigger efficiency



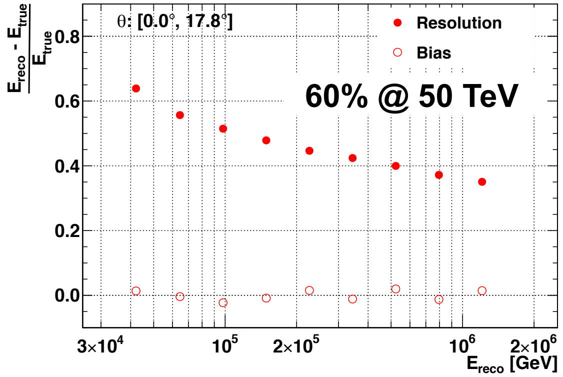
Acceptance



Core resolution

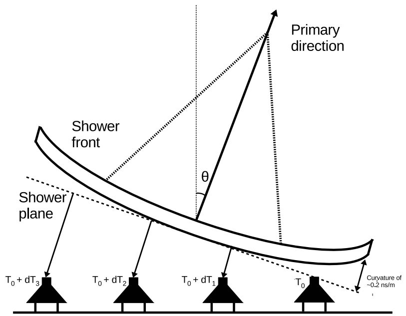


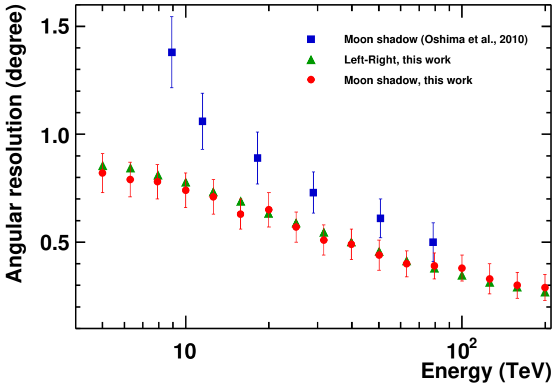
Energy resolution and bias



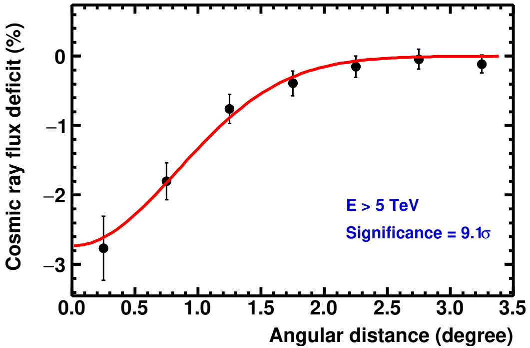
Performances of the scintillator array (angular resolution)

Shower front curvature

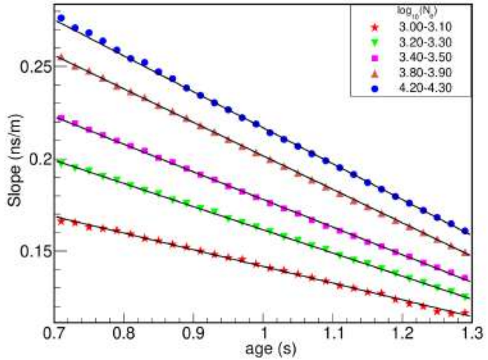




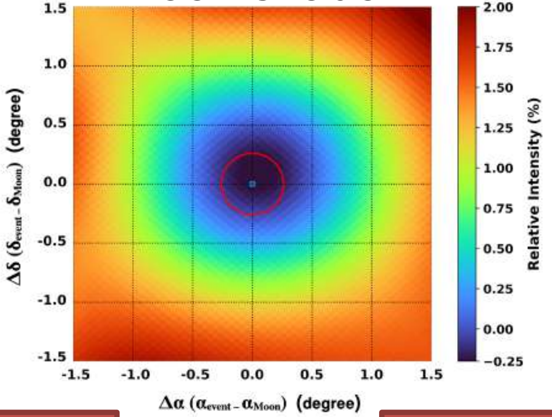
Moon shadow

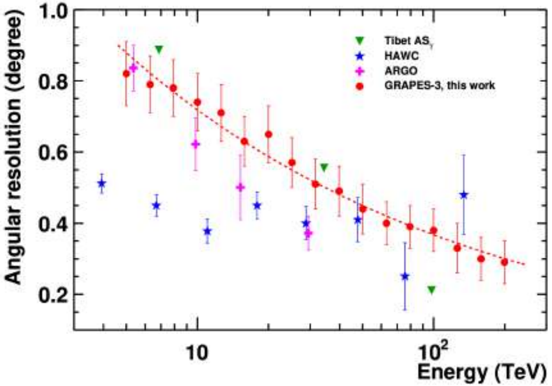


Dependence of slope on size and age:



Moon shadow





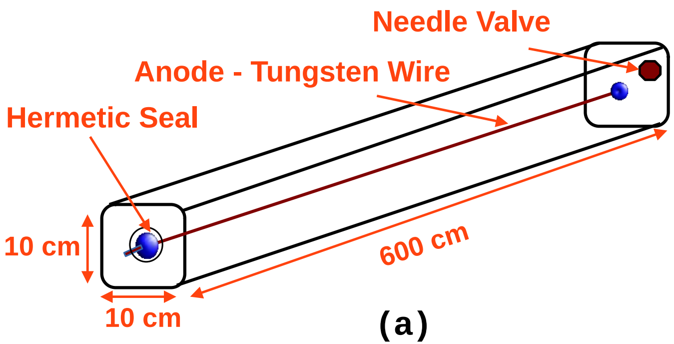
V.B. Jhansi et al., JCAP 07 (2020) 024

D. Pattanaik et al., PRD 106 (2022) 022009

GRAPES-3 muon telescope (560 m^2)

- Muon detector consists of 16 modules of 35 m^2 area each.
- Threshold of muons = 1 GeV
- Muons recorded associated with each EAS trigger
- Self triggered muons are recorded in 169 directional bins with 4^o resolution with a statistics of 4 billion muons per day

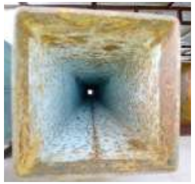
Proportional counter filled with P10 gas

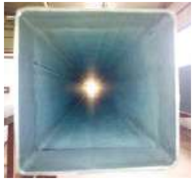


(a)

Proportional counter fabrication at GRAPES-3. ~4000 successfully made.

Rust removal





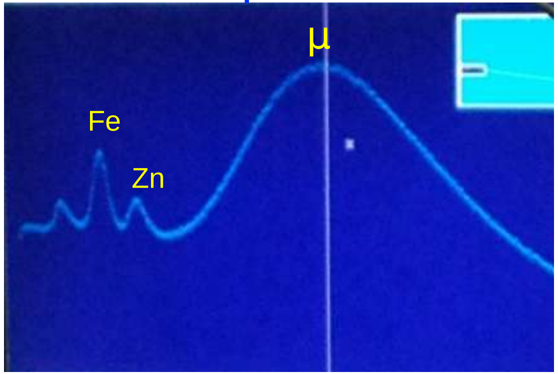
Hermetic seal fixing

Evacuation

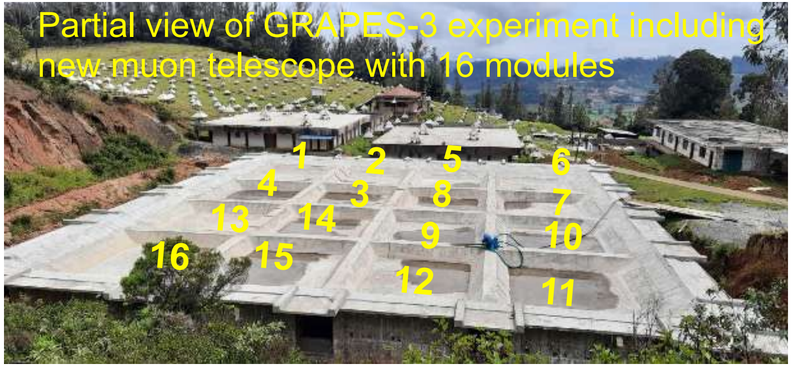
P10 gas filling

Long term test

PRC spectrum

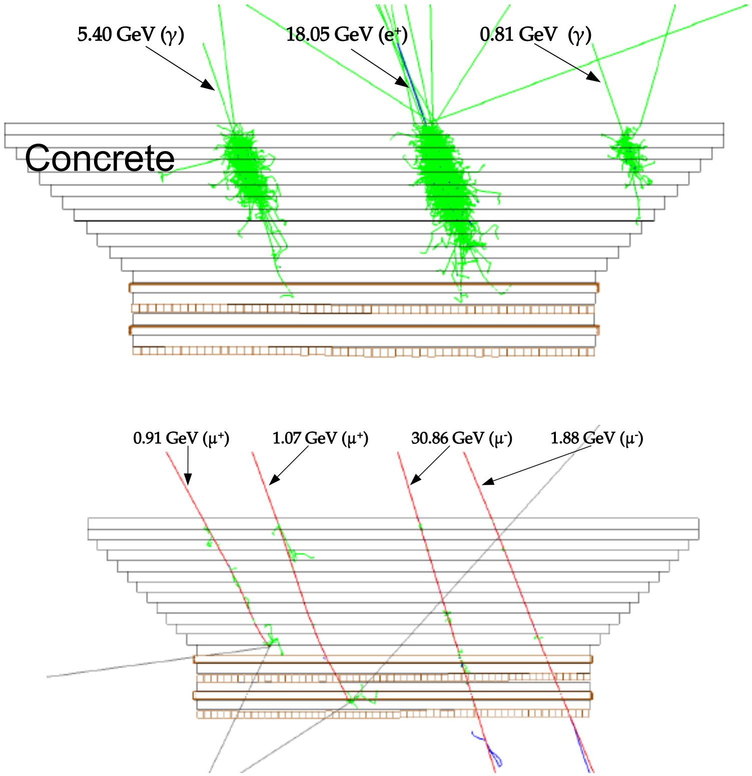


Muon telescope upgrade (560 m² to 1130 m²)

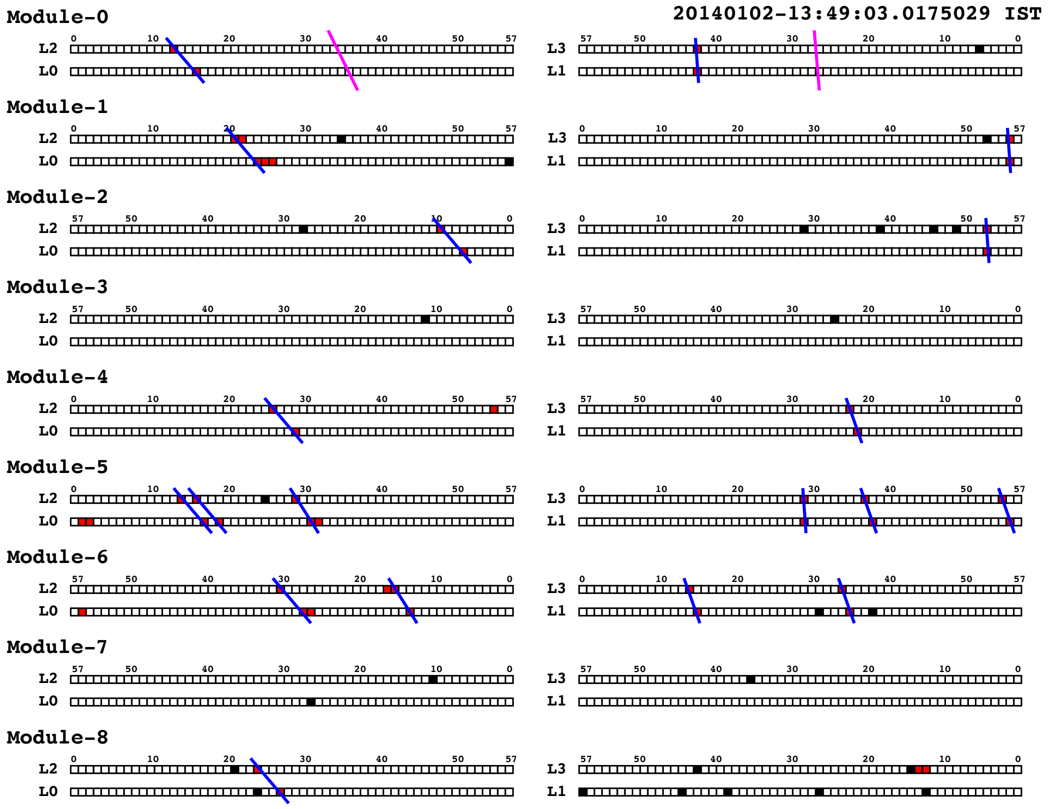


An operational module

Geant4 response of a muon module



Tracking of muons in a shower event

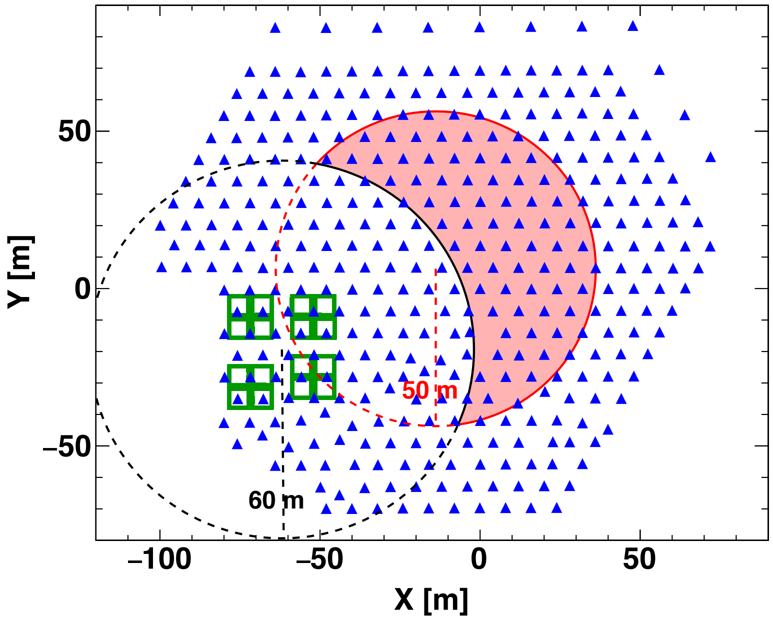


550 gm cm^{-2} of concrete absorber. Threshold for muons = 1 GeV x sec(theta).

Composition Analysis: Data selection and quality cuts

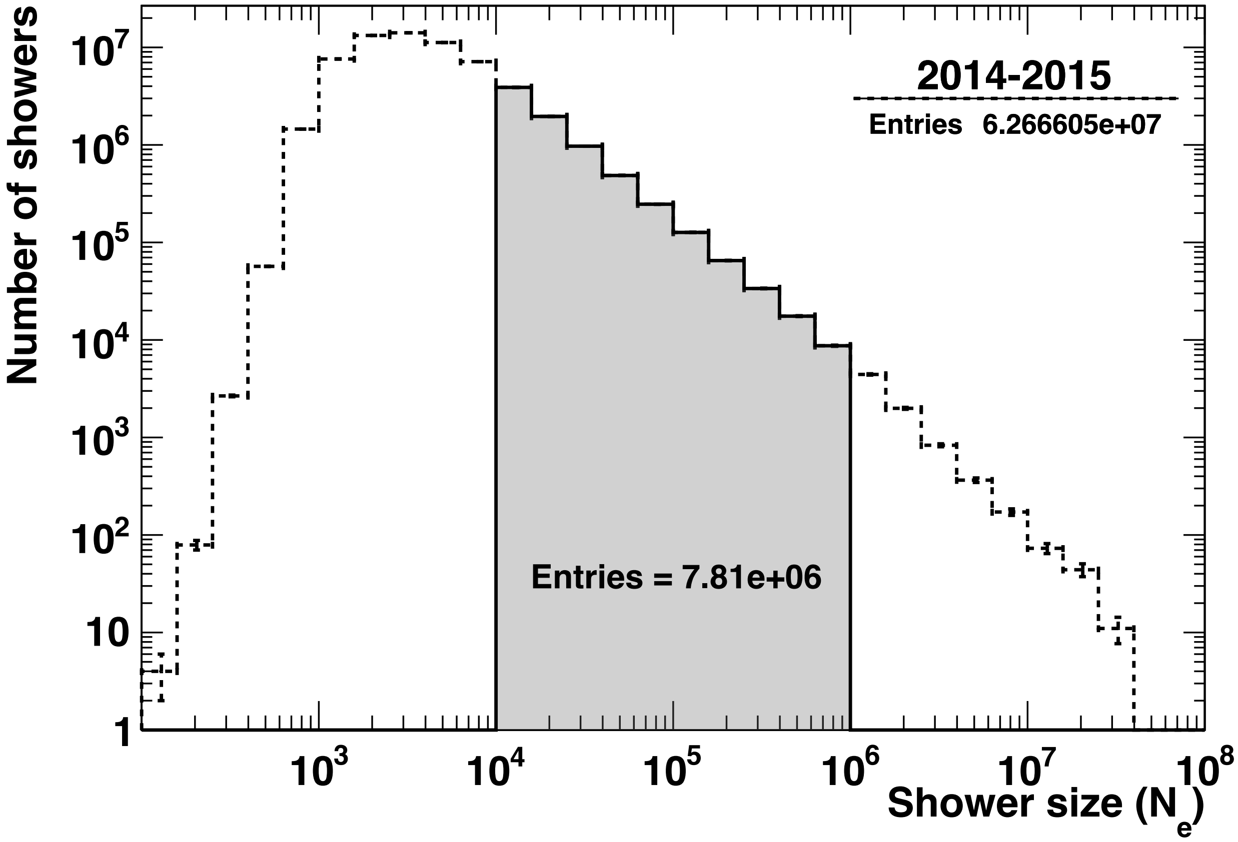
- GRAPES-3 data: 1 January 2014 to 26 October 2015.

Quality cut	Number of surviving EASs	% of surviving EASs
1. Triggered	1.75×10^{9}	100.0
2. Abnormal days based on N_e spectrum	1.58×10^{9}	90.0
3. Successful event matching & muon tracking	1.17×10^{9}	66.8
4. Angle and NKG reconstruction	8.47×10^{8}	48.3
5. Shower age (s) between 0.02 and 1.98	8.41×10^{8}	48.0
6. Circular area within 50 m radius	3.96×10^{8}	22.6
7. Zenith angle < 17.8°	1.33×10^{8}	7.5
8. Hadron punch-through < 2%	6.27×10^{7}	3.6
9. $10^{4.0} \le$ Shower size (N_e) $< 10^{6.0}$	7.81×10^{6}	0.4

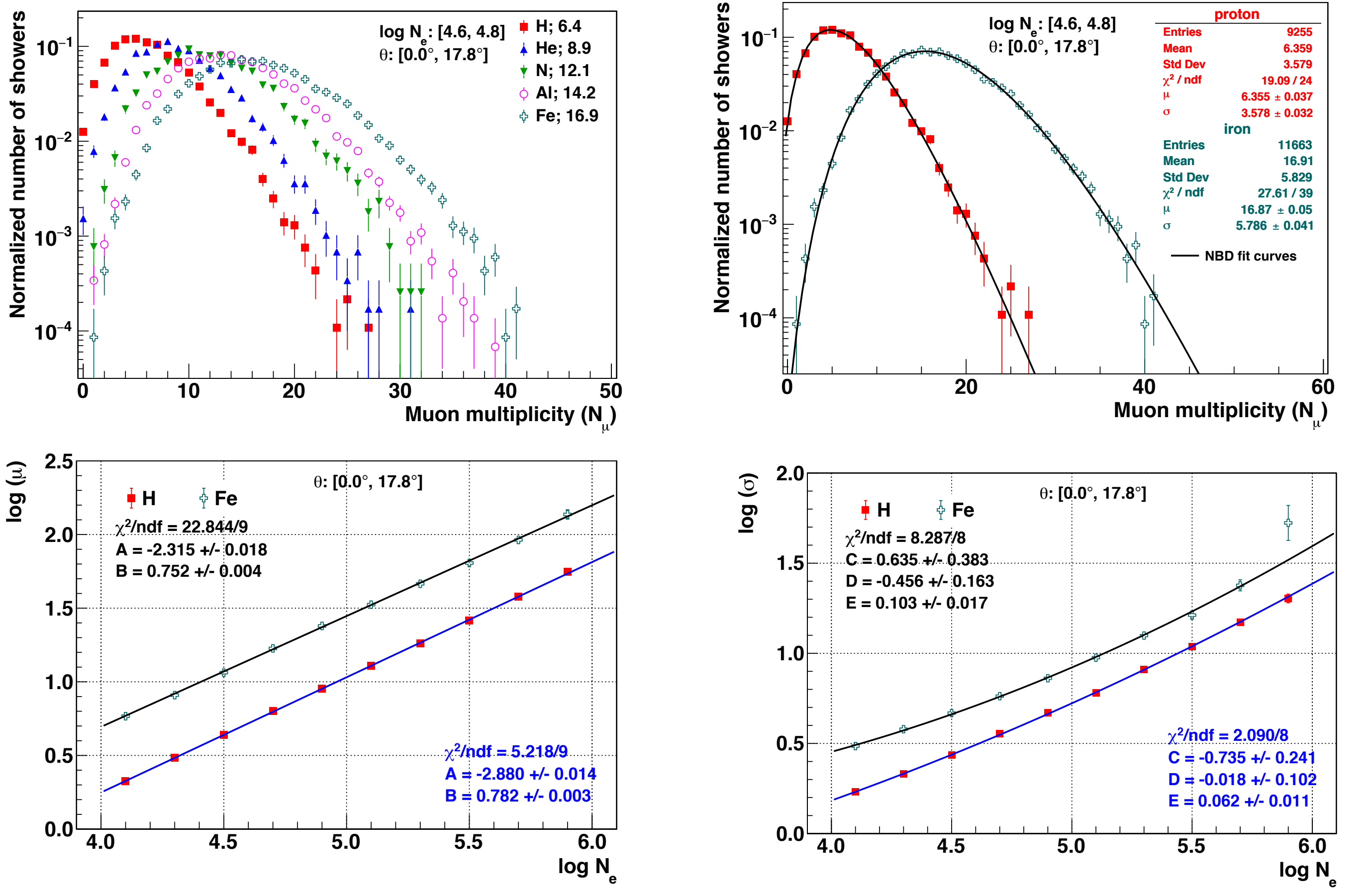


- Showers were selected within 50m from the centre of the array to exclude those landing outside the array while getting mis-reconstructed to be inside the array less than 1%.
- Showers were selected beyond 60 from the centre of the muon modules to restrict the hadron punch-through less than 2%.

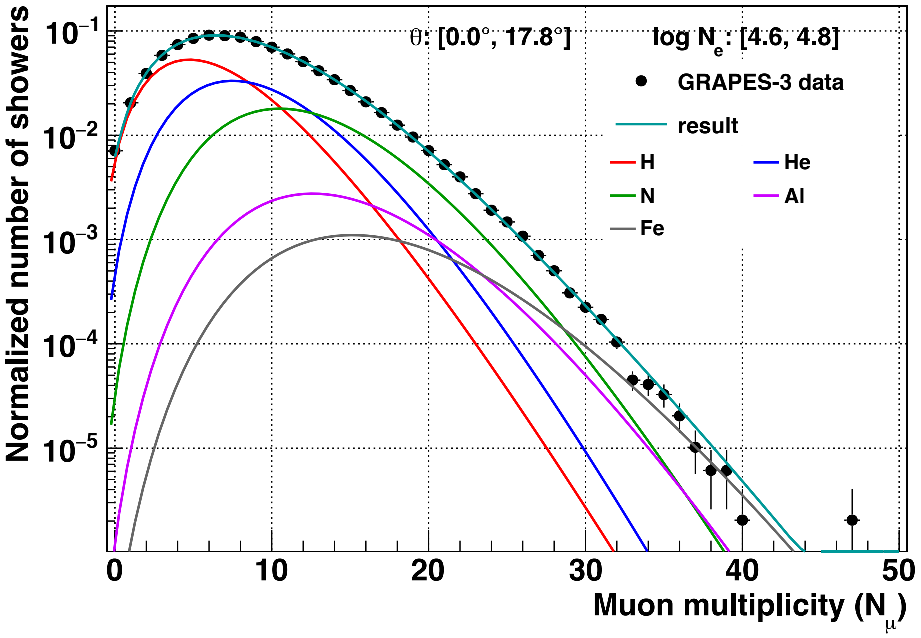
Showers selected for this analysis

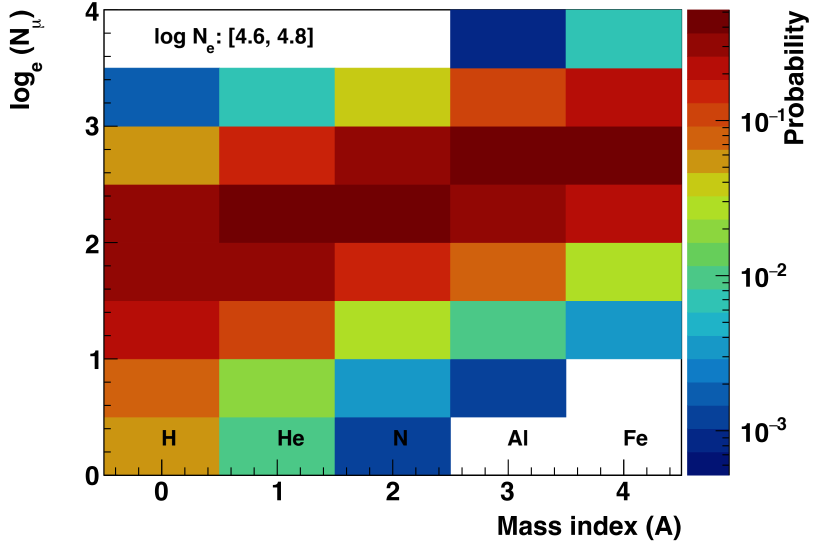


Muon multiplicity distribution (MMD): Monte Carlo



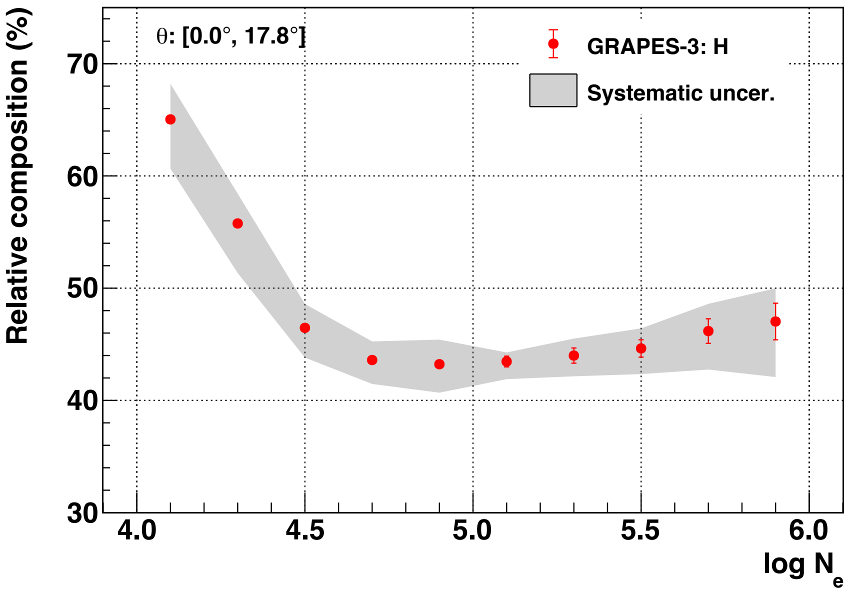
Fitting MMD and Extraction of Composition



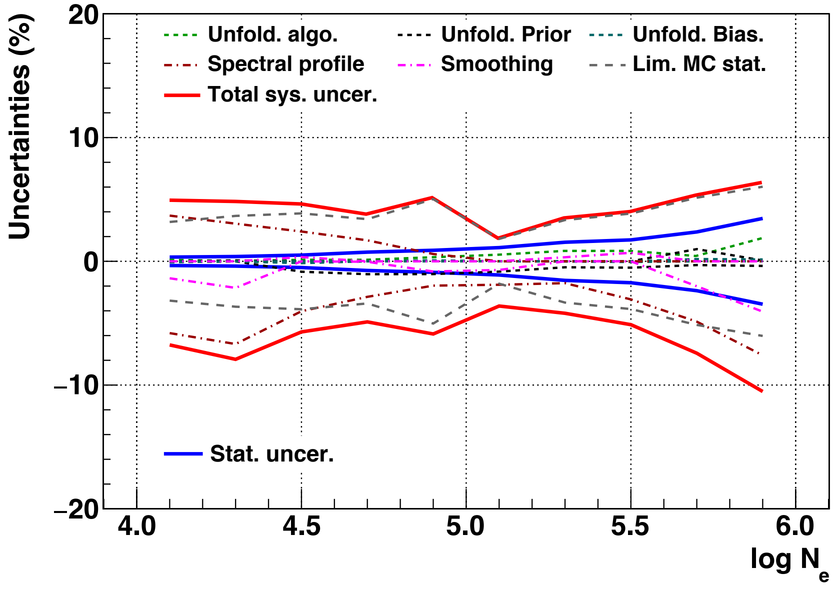


- Observed MMD cannot be described either H or Fe requiring intermediate masses.
- For a given N_e bin, response matrix is generated using MC simulation and Gold's unfolding algorithm is used for relative composition for the five mass groups.

Relative composition of proton primary

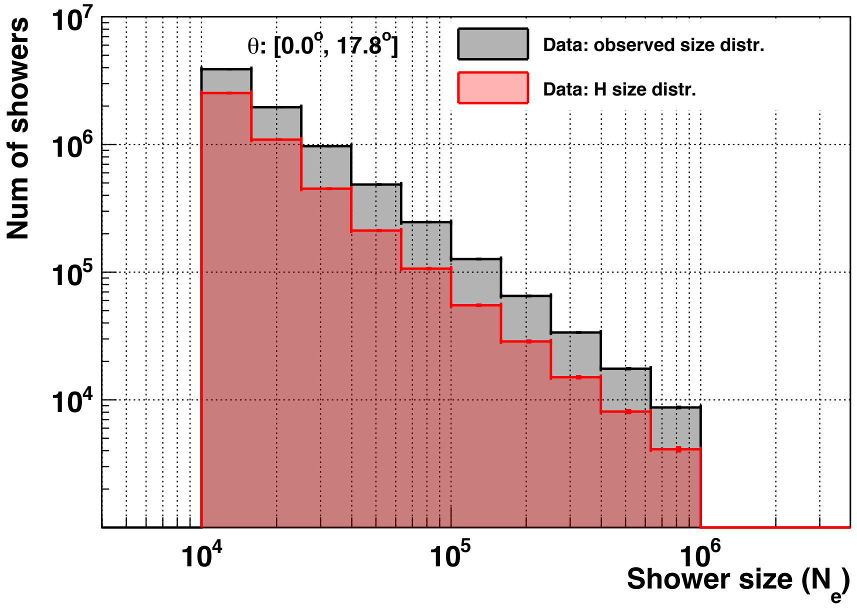


Relative composition for proton primary was obtained for each shower size (N_e) separately.

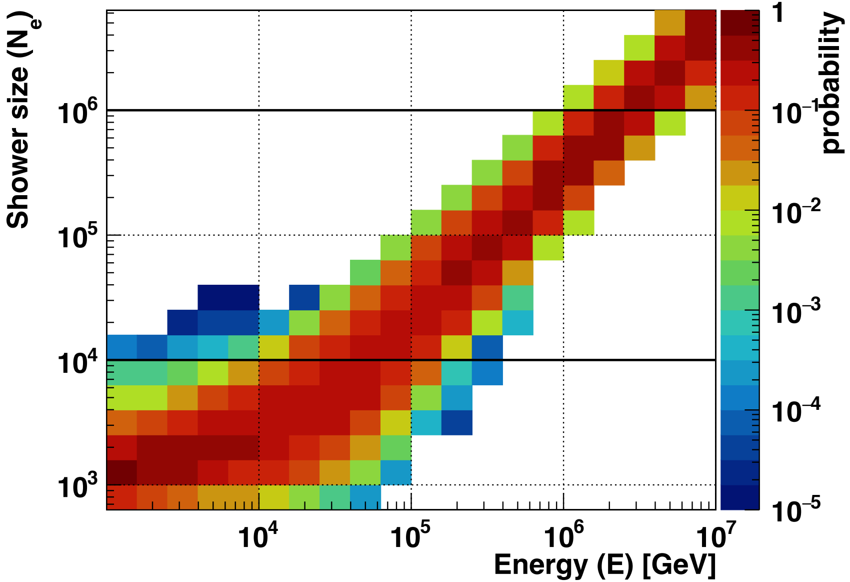


Systematics uncertainties from different sources. Limited MC statistics and differential spectral profiles are the dominant sources of uncertainties.

Shower size distribution for proton and unfolding



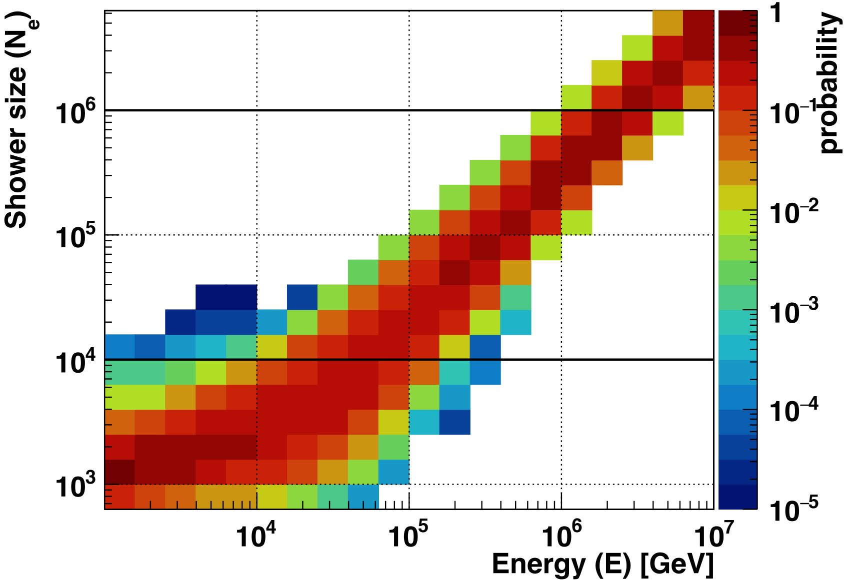
Response Matrix

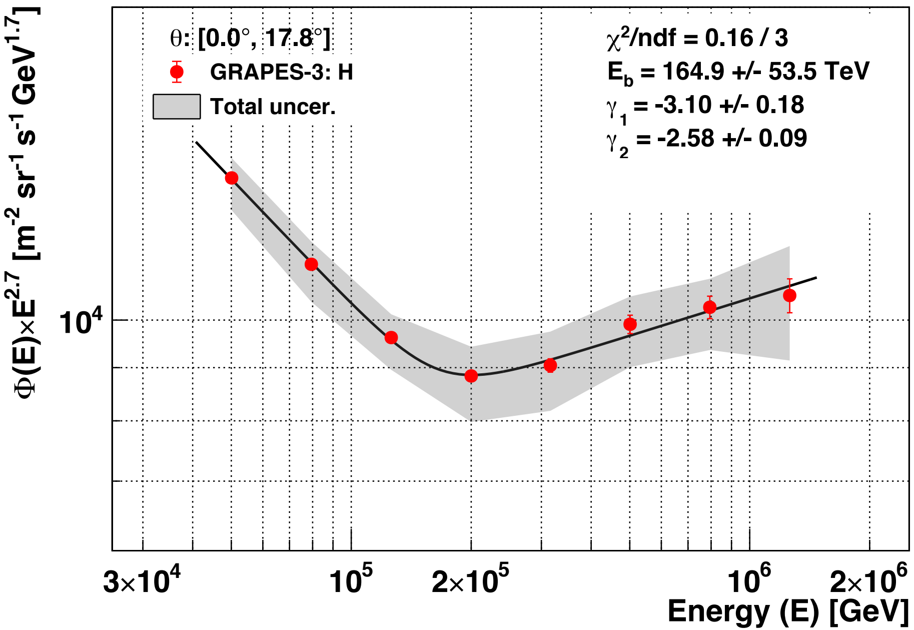


Shower size distribution for proton primary was obtained from all particle distribution using proton composition

Response matrix relating true energy and shower size was generated using Monte Carlo data

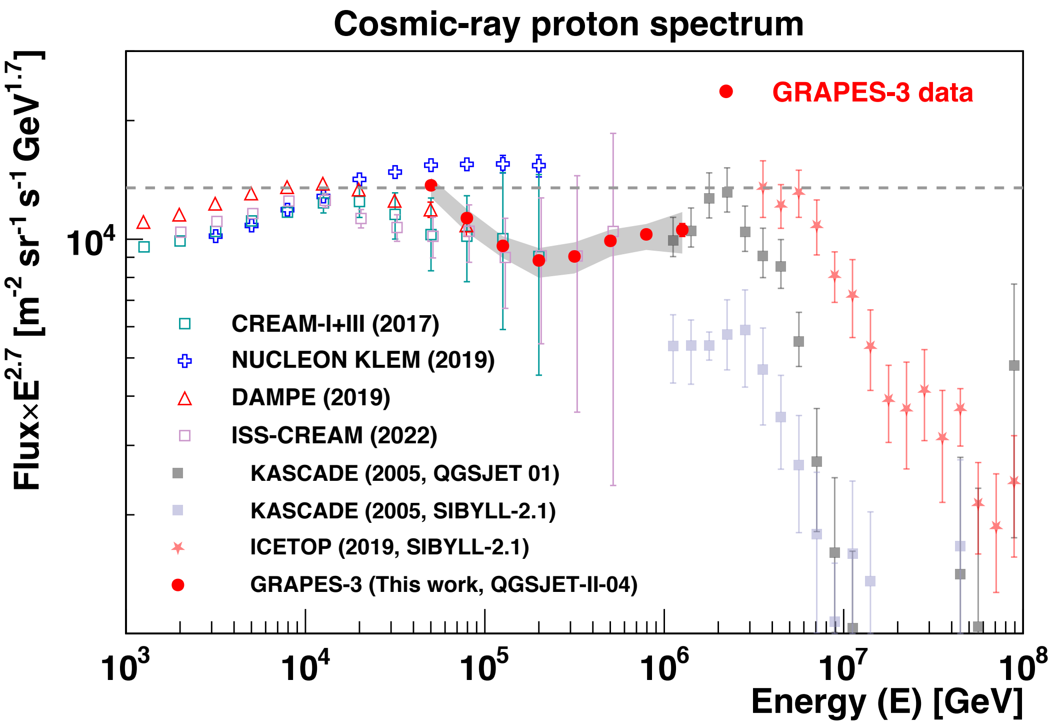
GRAPES-3 Proton Energy Spectrum from 50 TeV - 1.3 PeV





The observed spectral hardening by GRAPES-3 above165 TeV challenges the long-held belief that the spectrum is described by a simple power-law below the Knee.

Comparison with space and ground-based experiments



- Overlap with direct measurements with a flux agreement < 10%
- Observation of a spectral hardening above 165 TeV

F. Varsi et al., PRL 132, 051002 (2024)

PHYSICAL REVIEW LETTERS **132,** 051002 (2024)

Evidence of a Hardening in the Cosmic Ray Proton Spectrum at around 166 TeV Observed by the GRAPES-3 Experiment

F. Varsi,[1] S. Ahmad,[2] M. Chakraborty,[3] A. Chandra,[2] S. R. Dugad,[3] U. D. Goswami,[4] S. K. Gupta,[3] B. Hariharan,[3] Y. Hayashi,[5] P. Jagadeesan,[3] A. Jain,[3] P. Jain,[1] S. Kawakami,[5] H. Kojima,[6] P. Lipari,[7] S. Mahapatra,[8] P. K. Mohanty,[3,*] R. Moharana,[9] Y. Muraki,[10] P. K. Nayak,[3] T. Nonaka,[11] A. Oshima,[6] B. P. Pant,[9] D. Pattanaik,[3,8] S. Paul,[3] G. S. Pradhan,[12] M. Rameez,[3] K. Ramesh,[3] L. V. Reddy,[3] S. Saha,[1] R. Sahoo,[12] R. Scaria,[12] S. Shibata,[6] and M. Zuberi[3]

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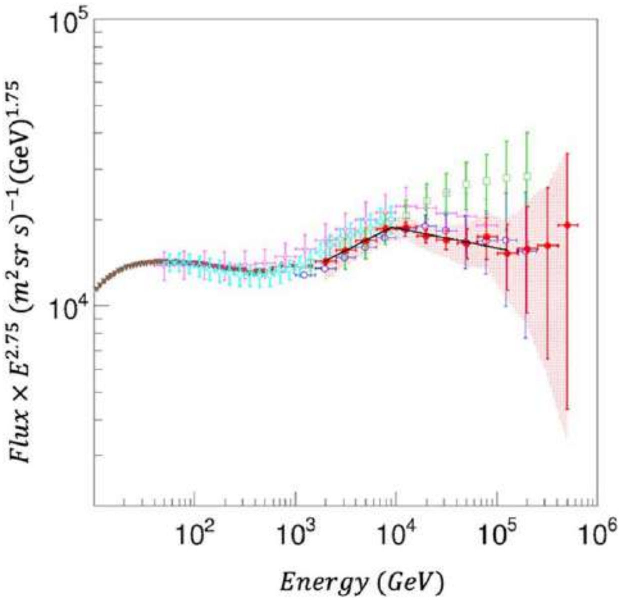
We present the measurement of the cosmic ray proton spectrum from 50 TeV to 1.3 PeV using 7.81×10^6 extensive air shower events recorded by the ground-based GRAPES-3 experiment between 1 January 2014 and 26 October 2015 with a live time of 460 day. Our measurements provide an overlap with direct observations by satellite and balloon-based experiments. The electromagnetic and muon components in the shower were measured by a dense array of plastic scintillator detectors and a tracking muon telescope, respectively. The relative composition of the proton primary from the air shower data containing all primary particles was extracted using the multiplicity distribution of muons which is a sensitive observable for mass composition. The observed proton spectrum suggests a spectral hardening at ~166 TeV and disfavors a single power law description of the spectrum up to the Knee energy (~3 PeV).

DOI: 10.1103/PhysRevLett.132.051002

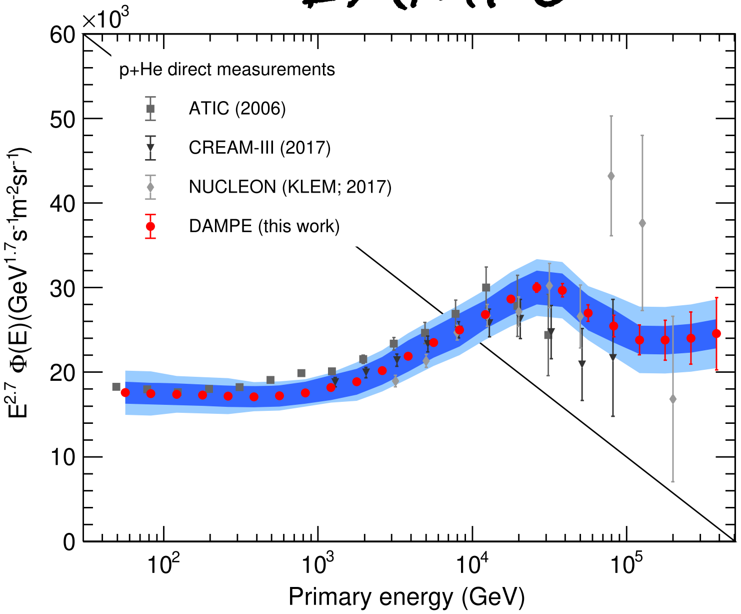
Indication of this feature by other experiments

ISS-CREAM



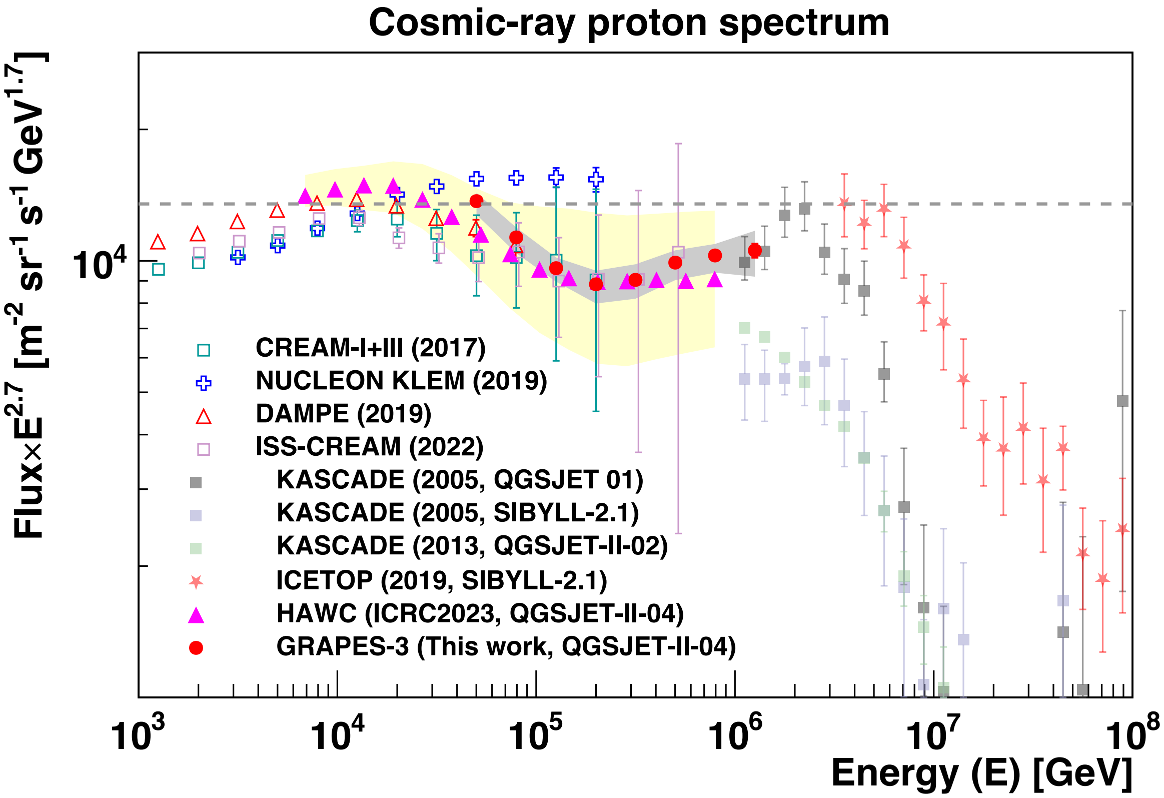
ISS-CREAM proton data suggest a spectral hardening above 164 TeV although the statistical errors are very large APJ 2022

DAMPE



DAMPE proton + helium data suggests a hardening above 150 TeV PRD 2024

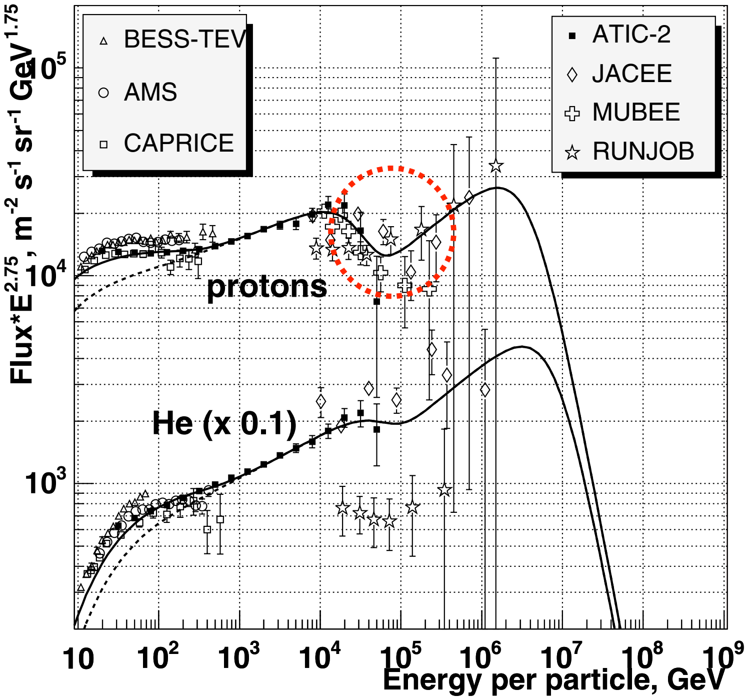
HAWC data (ICRC2023) shows a similar profile although systematic uncertainties are large.



Three component model of cosmic ray spectra from 10 GeV to 100 PeV

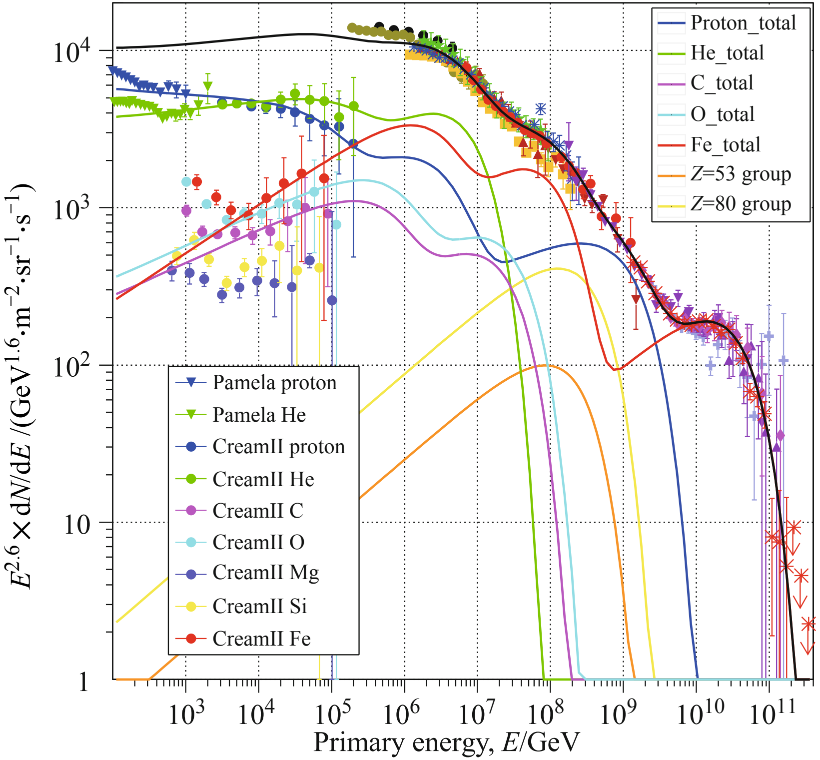
A&A 458, 1-5 (2006), V. I. Zatsepin and N. V. Sokolskaya

- The model assumed one class of sources (SNRs) terminates its effective acceleration at ~50 TeV
- The second source class, presumably supernovae within the local supper bubble accelerates cosmic rays up to rigidity of 4 PeV, producing the Knee.
- Assumed contribution of nova stars below ~300 GeV.



Gaisser-Stanev-Tilav (GST) model of cosmic ray composition

T.K. Gaisser, T. Stanev, S. Tilav, Front. Phys. 2013, 8(6):748-758



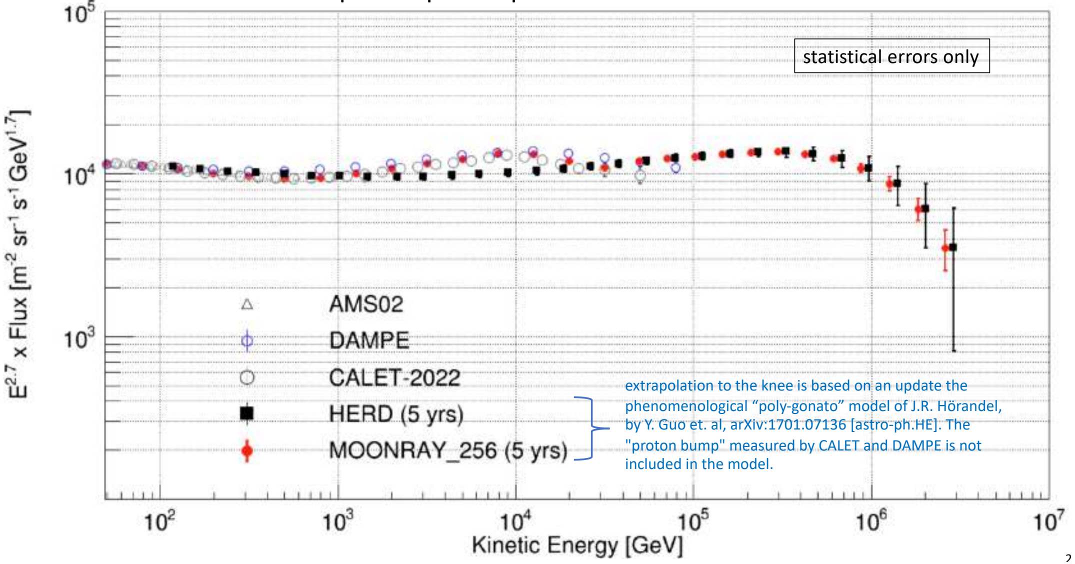
	p	He	C	O	Fe	$50 < Z < 56$	$78 < Z < 82$
Pop. 1:	7000	3200	100	130	60		
$R_c = 120$ TV	1.66 1	1.58	1.4	1.4	1.3		
Pop. 2:	150	65	6	7	2.3	0.1	0.4
$R_c = 4$ PV	1.4	1.3	1.3	1.3	1.2	1.2	1.2
Pop. 3:	14				0.025		
$R_c = 1.3$ EV	1.4				1.2		
Pop. 2*:	150	65	6	7	2.1	0.1	0.53
$R_c = 4$ PV	1.4	1.3	1.3	1.3	1.2	1.2	1.2
Pop. 3*:	12				0.011		
$R_c = 1.5$ EV	1.4				1.2		
Pop. 4*:	1.2						
$R_c = 40$ EV	1.4						

Population 1 has cutoff at 120 TV

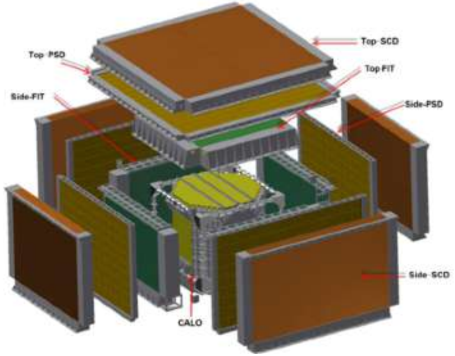
Population 2 has cut off at 4 PV

Future space-based experiments can reach up to Knee

An example: expected proton flux x $E^{2.7}$ at the knee



HERD

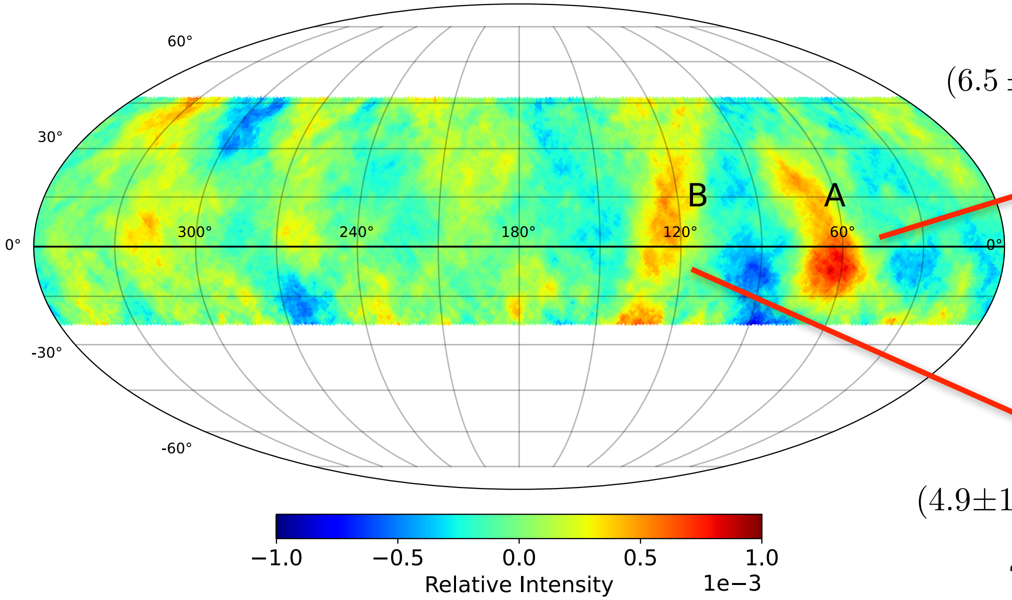


MOONRAY

Slide from Pier Simone's presentation at COSPAR 2024, Busan

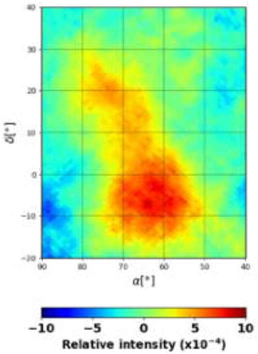
Cosmic ray anisotropy results from GRAPES-3

Analysis was performed using 3.7 billion cosmic ray events spanning 4 years at median energy of 16 TeV. Time scrambling method is used for background map generation.



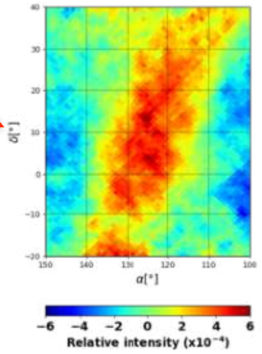
$(6.5 \pm 1.3) \times 10^{-4}$

6.8σ



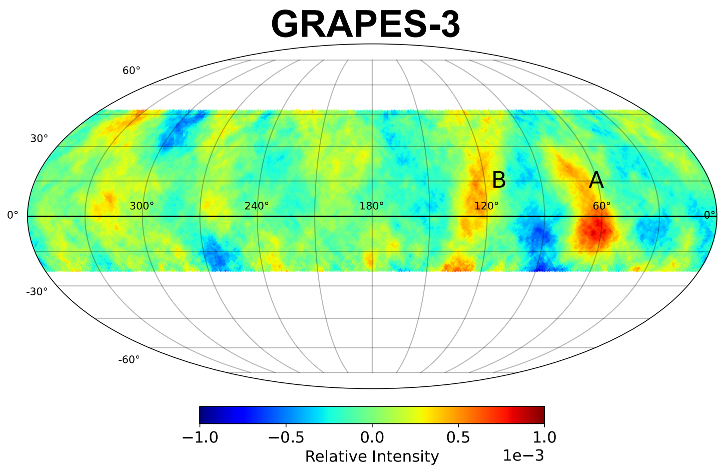
$(4.9 \pm 1.4) \times 10^{-4}$

4.7σ

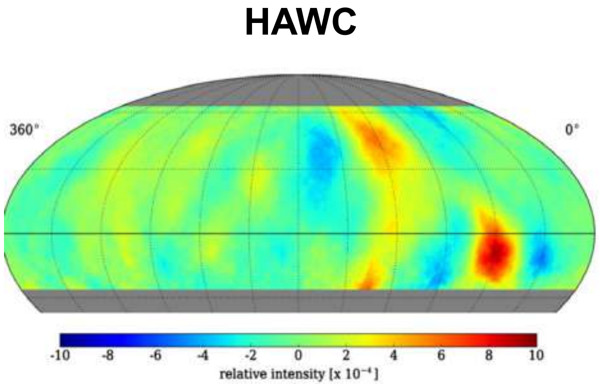


M. Chakraborty et al., ApJ, 961:87 (7pp) (2024)

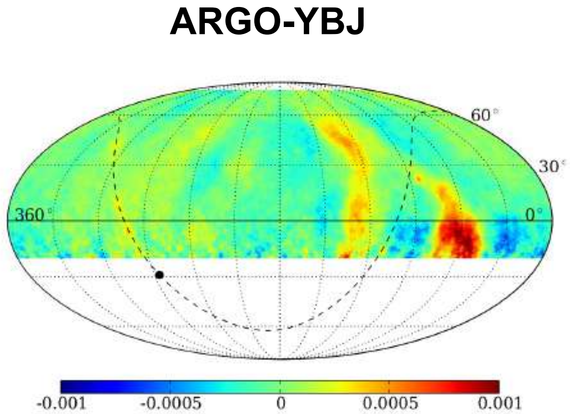
Comparison with other experiments



	Region A ($\times 10^{-4}$)	Region B ($\times 10^{-4}$)
ARGO-YBJ	10.0	5.0
HAWC	$(8.5 \pm 0.6 \pm 0.8)$	$(5.2 \pm 0.6 \pm 0.7)$
GRAPES-3	$(8.9 \pm 2.1 \pm 0.3)$	$(5.6 \pm 1.8 \pm 0.1)$



(a) HAWC

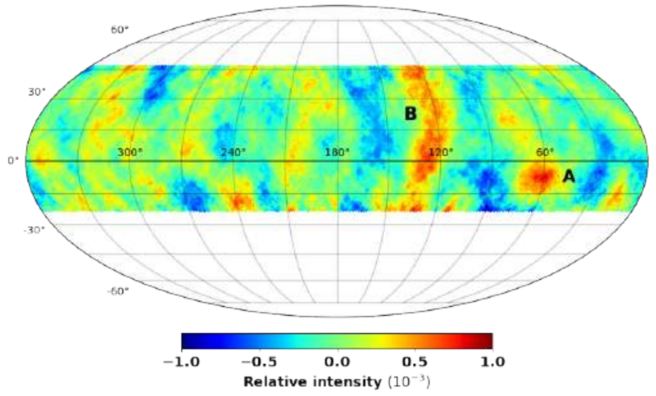


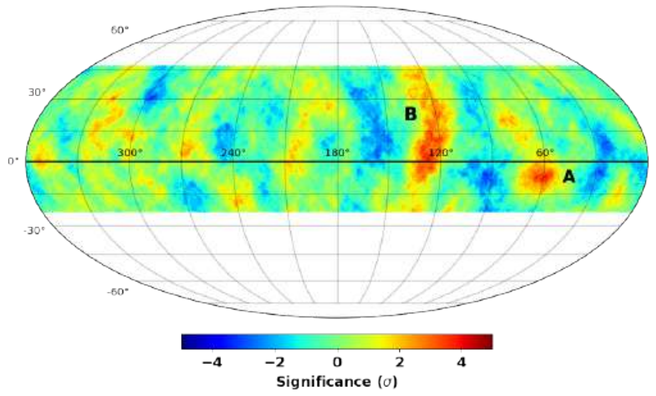
(b) ARGO-YBJ

Plan to perform joint analysis of GRAPES-3 and IceCube data

Results with Muon Cut

- Showers producing at least 2 tracks in the muon detector
- No of events: 1.9×10^9
- Change in strength of Region A : $(6.5 \pm 1.3) \times 10^{-4}$ to $(5.7 \pm 1.8) \times 10^{-4}$
- Change in strength of Region B : $(4.9 \pm 1.4) \times 10^{-4}$ to $(6.5 \pm 2.0) \times 10^{-4}$
- Change is within 1σ
- Primary contribution to these structures is hadronic.

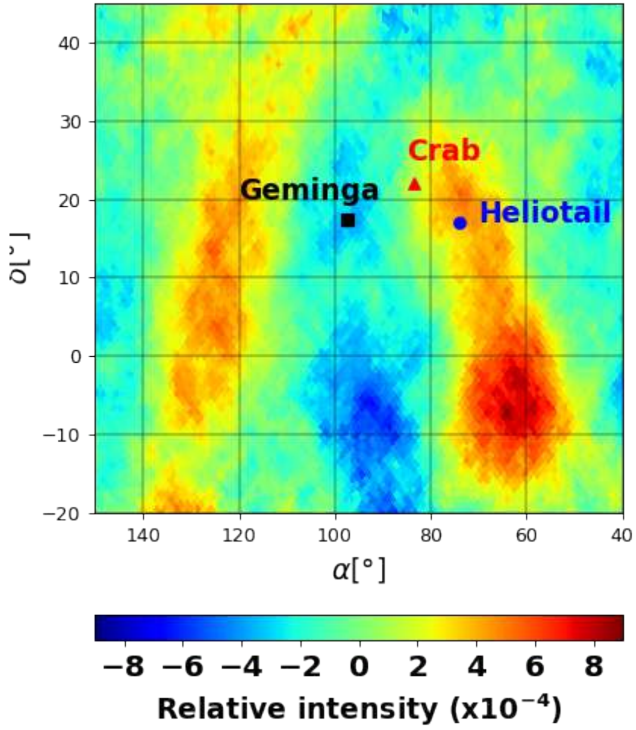




Physical origin of small-scale anisotropy?

UNSOLVED MYSTERY!!!

- Models suggest that the Supernova explosion giving rise to Geminga might give rise to the structures. Other models suggest this is unlikely (M. Salvati and B. Sacco: Cosmic rays from the Geminga supernova? A and A 485 (2008) 527)
- Nearby local sources of turbulence, Eg: The heliotail. (ApJ. 762 (2013) 44)
- Gamma ray source contribution Eg: Crab (Results by ARGO-YBJ, 2013, PRD, 88, 082001)



Summary and outlook

- We have measured cosmic ray proton spectrum below the Knee, providing a overlap with direct measurements.
- We have observed a spectral hardening in the proton spectrum above 165 TeV.
- We have observed two small-scale anisotropic structures from a near equatorial location.
- We are working to extract spectrum for other chemical groups below and above the knee
- We are working to extract large-scale anisotropy
- Upgrade of the muon telescope is in progress. Together with expansion of the scintillator array is expected to provide enhanced sensitivity for cosmic ray composition and gamma ray studies

Thank you for your attention

Backup slides

Monte Carlo (MC) simulations

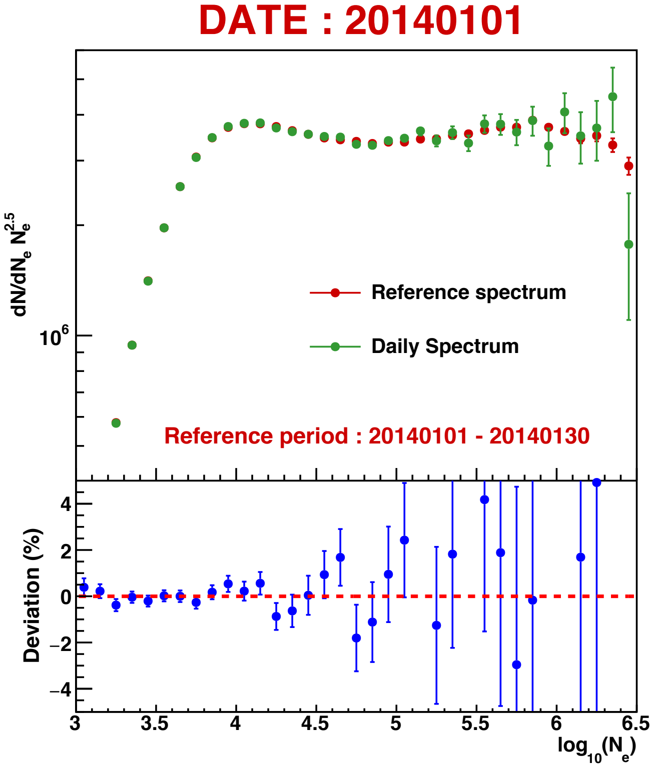
- Detailed MC simulation study is done, which broadly involves,
  1. EAS development simulation in Earth's atmosphere using the CORSIKA package.
  2. Simulation of the EAS particles in the SDs to estimate their corresponding ρ and t.
  3. Detailed simulation of the EAS particles response in the G3MT using the GEANT4 package.

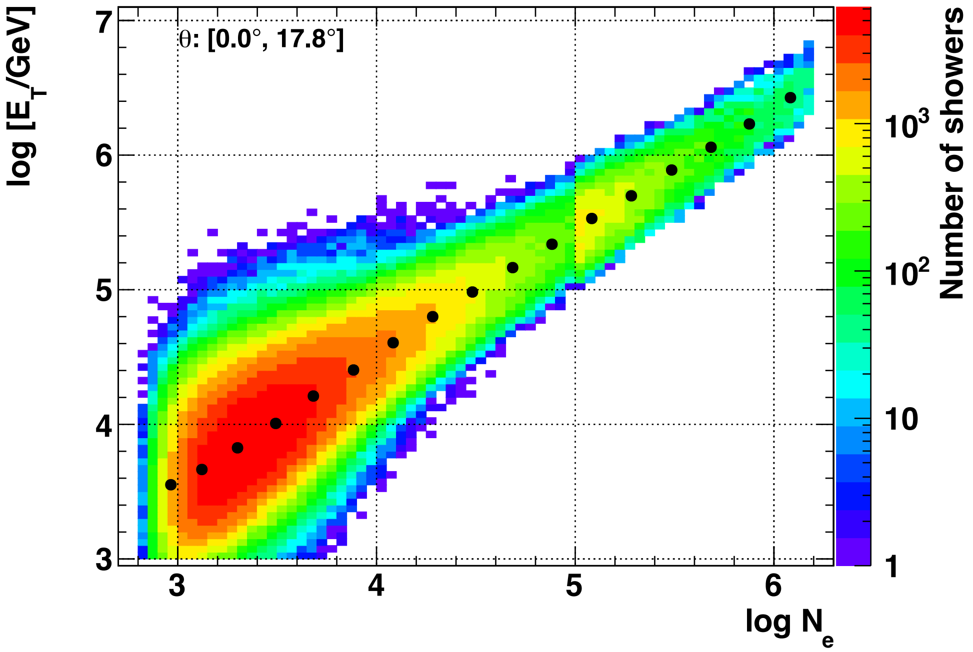
- EAS development simulation at GRAPES-3 site,
  - CORSIKA v7.6900 package.
  - QGSJET-II-04/FLUKA as high/low-energy hadronic interaction model.
  - H, He, N, Al and Fe.
  - E: 1 TeV to 10 PeV, with $E^{-2.5}$ spectral slope.
  - θ: 0° to 45°.
  - 6.1×10^7 EASs for each element.

- Simulation of the EAS particles in the SDs,
  - Analyzed with an in-house developed software framework.
  - Two datasets: dataset-1 with random core distributed within 150 m from array center for entire energy range, dataset-2 with 60 m from the center array for $E > 100$ TeV.
  - Each EAS used ten times with a random core location to improve statistics.
  - t $\leftarrow$ CORSIKA output.
  - ρ $\leftarrow$ GEANT-4 simulation of plastic SDs.
  - Generate EAS trigger and EAS parameters.

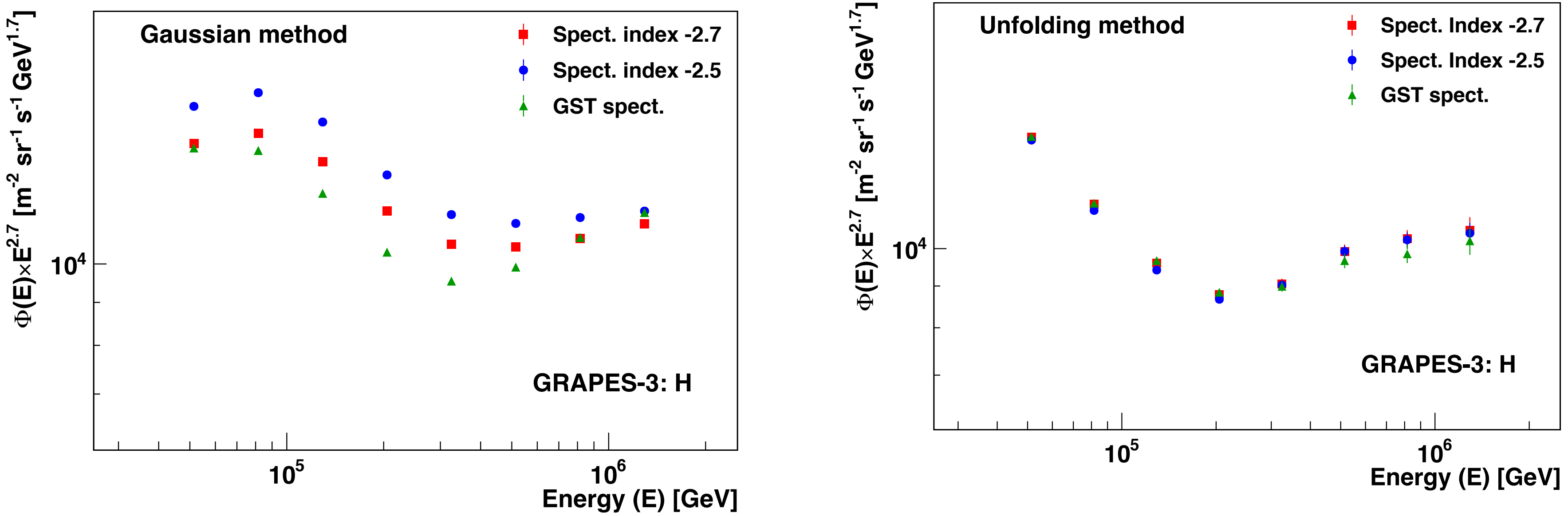
- Datasets with $E^{-2.7}$ spectral slope and proposed by GST and H4a composition models are derived.

Shower size (Ne)

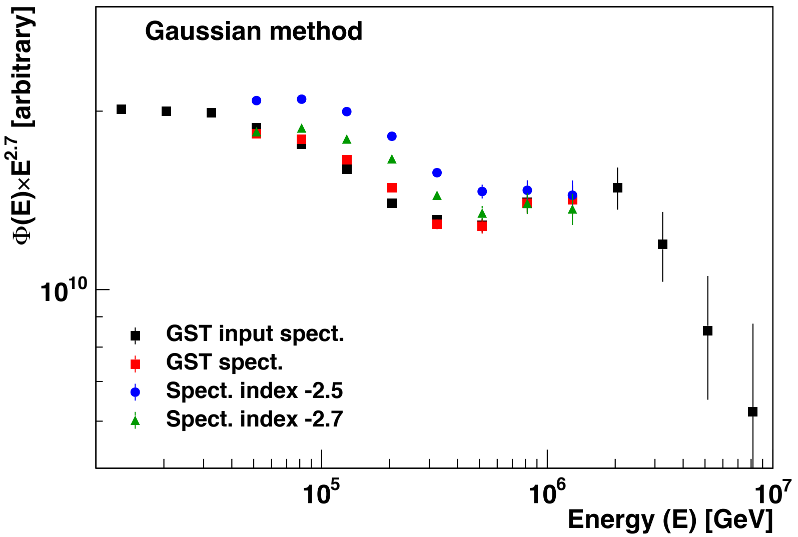


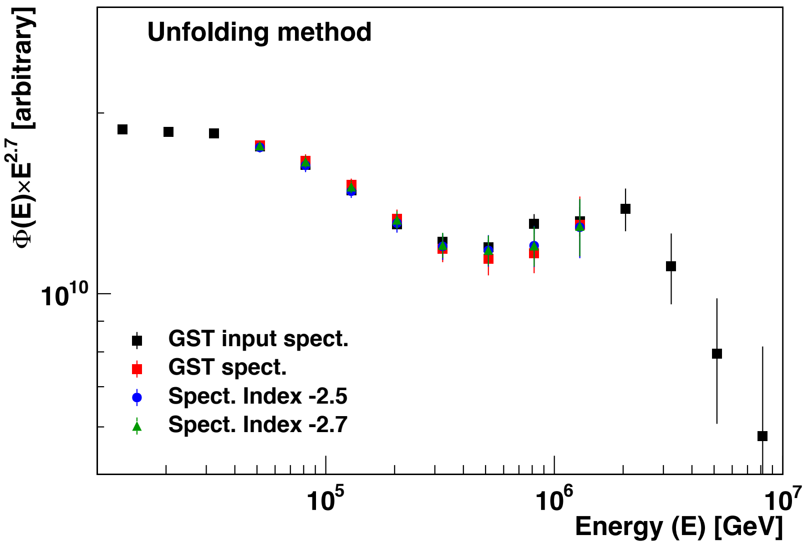


Gaussian and Unfolding Method



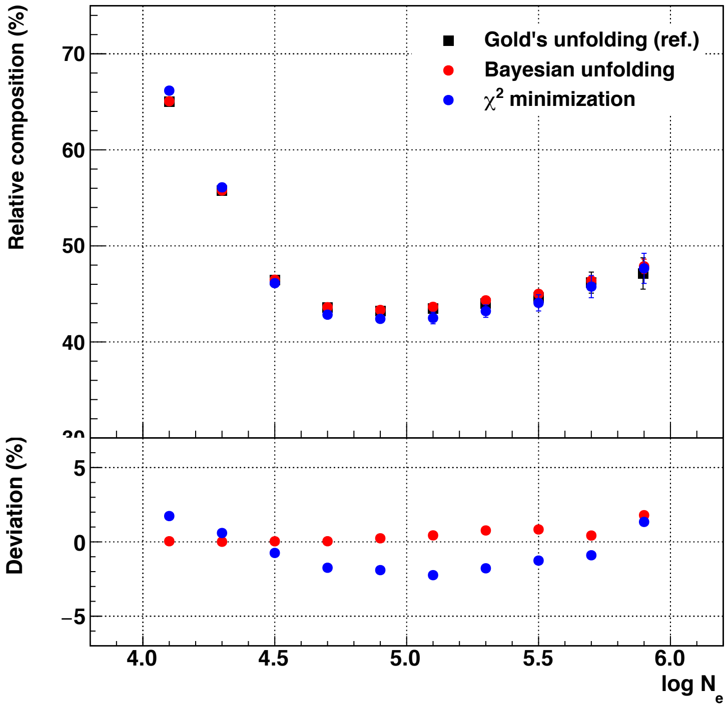
Gaussian and Unfolding Method for GST Composition model



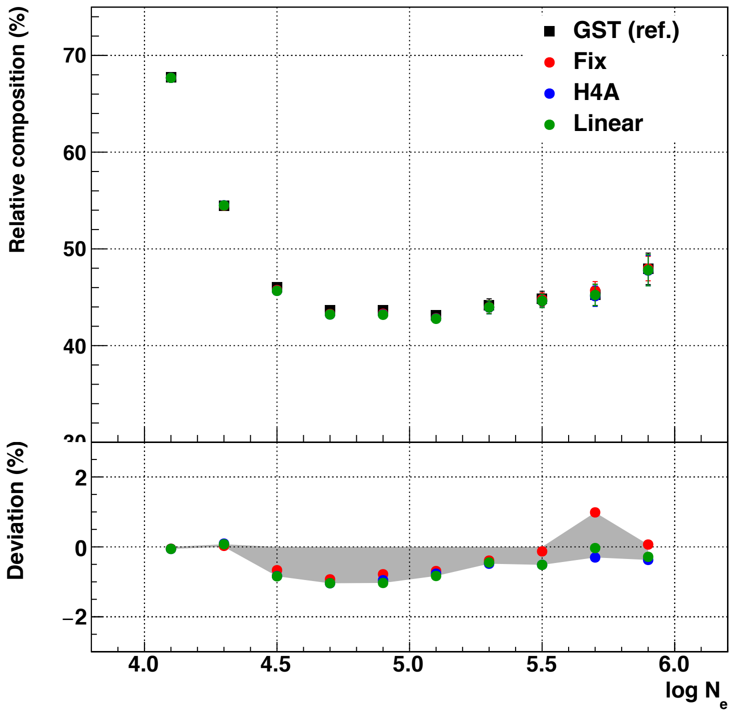


Systematic uncertainties

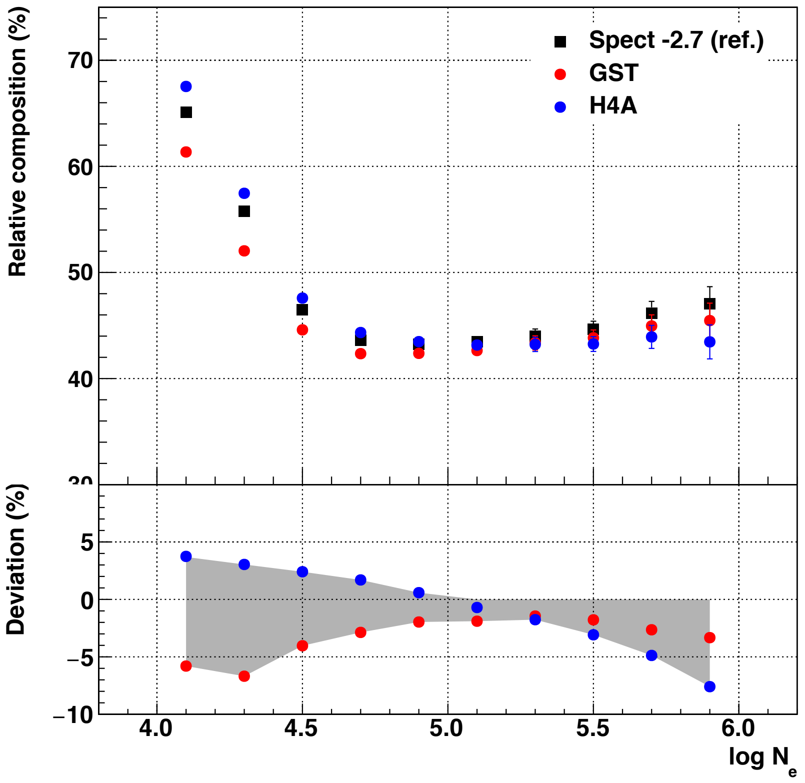
Due to unfolding procedure



Due to initial



Systematic uncertainties



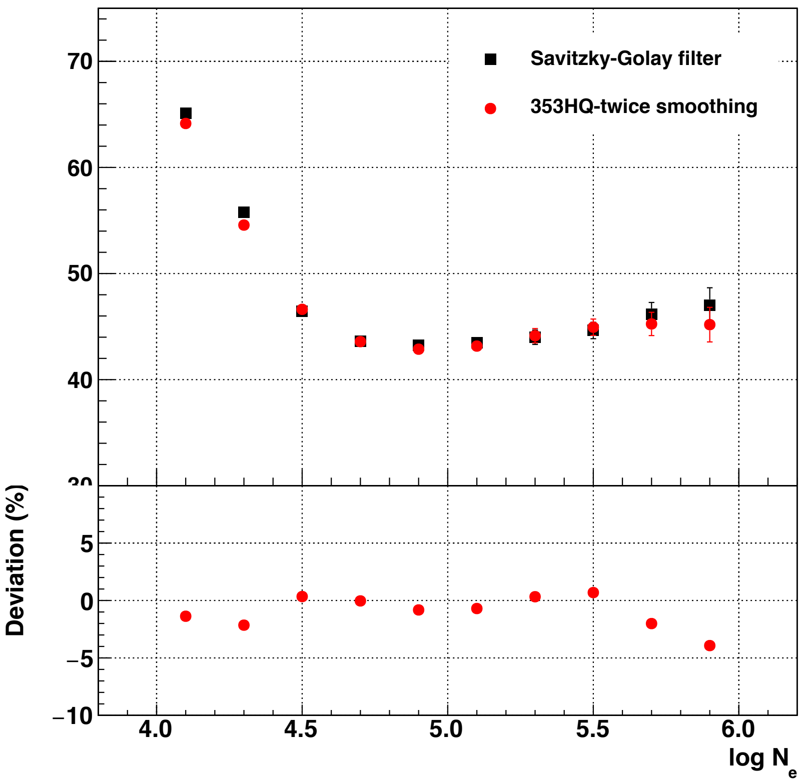


TABLE S3. Systematic uncertainties (%) in estimating the relative composition of proton primary from various sources. Here systematic uncertainty δ_{UA} due to unfolding algorithm, δ_P due to initial guess/prior, b_1 due to bias from unfolding, δ_{SP} due to differential spectral profiles, δ_S due to smoothing algorithm, and σ_1 due to limited Monte Carlo statistics. Please see the text in section S3 D for the description of each systematic uncertainty. The last column represents the total systematic uncertainty, which was calculated by adding the contribution of systematic uncertainty from different sources in quadrature.

N_e	$\delta_{UA}(\%)$	$\delta_P(\%)$	$b_1(\%)$	$\delta_{SP}(\%)$	$\delta_S(\%)$	$\sigma_1(\%)$	$\delta_{total}(\%)$
1.26×10^4	+0.04	+0.00/−0.06	−0.07	+3.69/−5.80	−1.37	±3.18	+4.87/−6.76
2.00×10^4	+0.01	+0.07/−0.00	−0.01	+3.04/−6.68	−2.15	±3.67	+4.77/−7.92
3.16×10^4	+0.04	+0.00/−0.84	−0.15	+2.41/−4.03	+0.34	±3.87	+4.57/−5.71
5.01×10^4	+0.04	+0.00/−1.04	+0.01	+1.70/−2.87	−0.04	±3.41	+3.80/−4.90
7.94×10^4	+0.24	+0.00/−1.03	+0.08	+0.60/−1.97	−0.82	±5.03	+5.07/−5.87
1.26×10^5	+0.44	+0.00/−0.83	+0.00	+0.00/−1.89	−0.70	±1.81	+1.86/−3.61
2.00×10^5	+0.77	+0.00/−0.48	−0.02	+0.00/−1.76	+0.33	±3.34	+3.44/−4.20
3.16×10^5	+0.84	+0.00/−0.51	−0.06	+0.00/−3.08	+0.69	±3.86	+4.01/−5.12
5.01×10^5	+0.43	+0.99/−0.30	+0.18	+0.00/−4.88	−2.01	±5.14	+5.25/−7.43
7.94×10^5	+1.80	+0.07/−0.37	+0.15	+0.00/−7.59	−4.07	±6.03	+6.29/−10.52

TABLE S2. Relative composition of proton primary estimated using Gold's unfolding procedure for the GRAPES-3 data. The statistical and systematic uncertainties are mentioned.

N_e	$a_1 \pm \delta_1^{stat} + \delta_1^{sys} - \delta_1^{sys}$
1.26×10^4	$0.650 \pm 0.002 + 0.032 - 0.044$
2.00×10^4	$0.558 \pm 0.002 + 0.027 - 0.044$
3.16×10^4	$0.465 \pm 0.002 + 0.021 - 0.027$
5.01×10^4	$0.436 \pm 0.003 + 0.017 - 0.021$
7.94×10^4	$0.432 \pm 0.004 + 0.022 - 0.025$
1.26×10^5	$0.435 \pm 0.005 + 0.008 - 0.016$
2.00×10^5	$0.440 \pm 0.007 + 0.015 - 0.018$
3.16×10^5	$0.446 \pm 0.008 + 0.018 - 0.023$
5.01×10^5	$0.462 \pm 0.011 + 0.024 - 0.034$
7.94×10^5	$0.470 \pm 0.016 + 0.030 - 0.049$

TABLE S4. The number of observed events by GRAPES-3 and corresponding proton events in different shower size bins. The statistical error in the estimation of proton events is listed in the last column.

N_e	$n(N_e^{obs})$	$n(N_{e1})$	$\delta N_{e1}(\%)$
1.26×10^4	3890720	2530350	0.34
2.00×10^4	1959300	1092590	0.39
3.16×10^4	970833	451097	0.51
5.01×10^4	486000	211886	0.76
7.94×10^4	246606	106595	0.91
1.26×10^5	126709	55074	1.14
2.00×10^5	65155	28664	1.59
3.16×10^5	33704	15043	1.81
5.01×10^5	17534	8097	2.49
7.94×10^5	8719	4100	3.63

TABLE S5. Summary of the unfolded number of events in the energy distribution of proton primaries for GRAPES-3 data estimated using Gold's unfolding algorithm. The values of differential flux ($\Phi(E)$) and the corresponding statistical and total systematic uncertainties are listed in the third column.

Energy [GeV]	Number of events	$\Phi \pm \delta\Phi_{stat.} + \delta\Phi_{sys.} - \delta\Phi_{sys.}$ $[m^{-2}\, sr^{-1}\, s^{-1}\, GeV^{-1}]$
5.01×10^4	2797488	$(2.80 \pm 0.01 + 0.13 - 0.19) \times 10^{-9}$
7.94×10^4	1139870	$(6.67 \pm 0.03 + 0.36 - 0.53) \times 10^{-10}$
1.26×10^5	450551	$(1.63 \pm 0.01 + 0.09 - 0.11) \times 10^{-10}$
2.00×10^5	189363	$(4.30 \pm 0.05 + 0.32 - 0.41) \times 10^{-11}$
3.16×10^5	89306	$(1.28 \pm 0.02 + 0.11 - 0.12) \times 10^{-11}$
5.01×10^5	44715	$(4.04 \pm 0.08 + 0.27 - 0.36) \times 10^{-12}$
7.94×10^5	21194	$(1.21 \pm 0.03 + 0.08 - 0.11) \times 10^{-12}$
1.26×10^6	9928	$(3.57 \pm 0.13 + 0.39 - 0.46) \times 10^{-13}$

Power spectrum analysis

$\delta \mathbf{I}(\alpha,\delta) = \Sigma_\ell \Sigma_m a_{\ell m} Y_{\ell m}(\alpha,\delta)$ $C_\ell = \frac{\Sigma_m |a_{\ell m}|^2}{2\ell+1}$, White noise $\sim 4\pi f_{sky}^2 / N_{tot}$