New results from GRAPES-3 spanning over a large energy range

Pravata Mohanty

On behalf of GRAPES-3 group

DHEP annual meeting, 8-9 May 2018

Outline

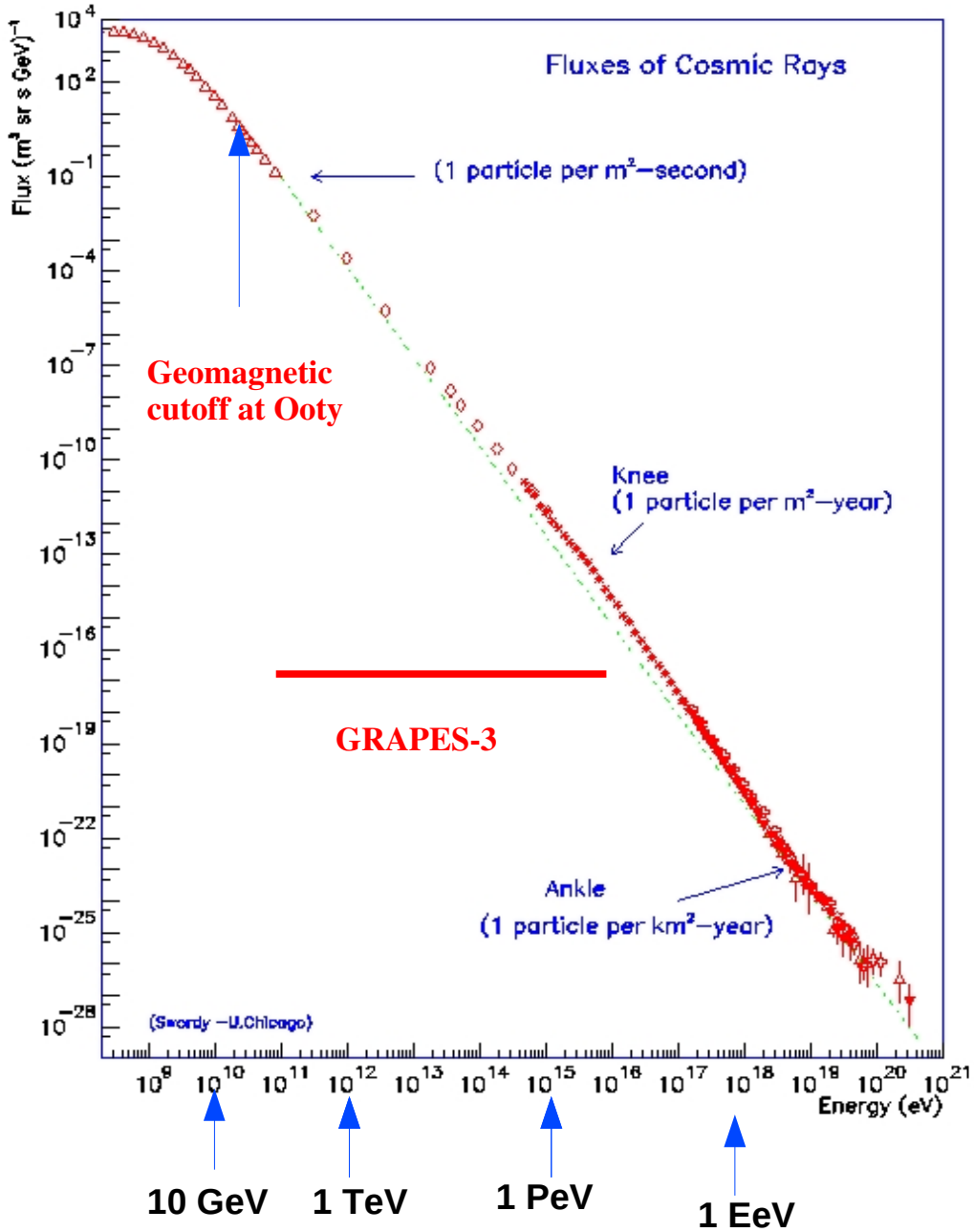
Muon flux measurement (100 GeV)

- Muon burst event
- Transient weakening of Earth's magnetic field
- Further work

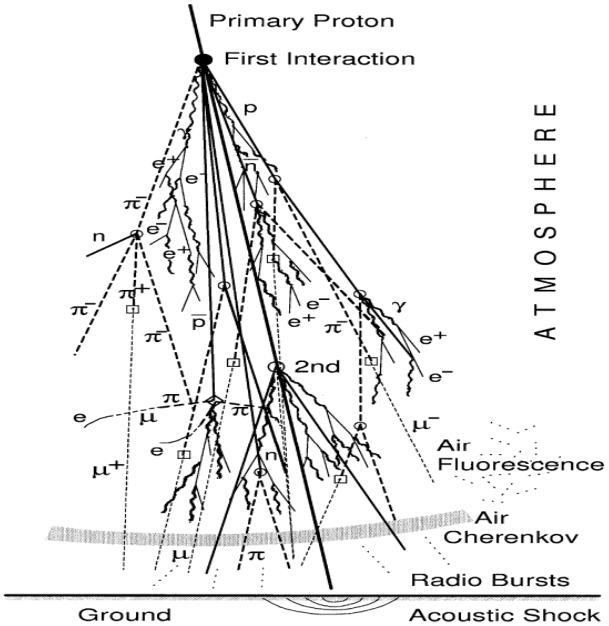
EAS measurement (TeV – PeV)

- Understanding of calibrations
- EAS reconstruction
- Monte Carlo Simulations

Cosmic ray energy spectrum



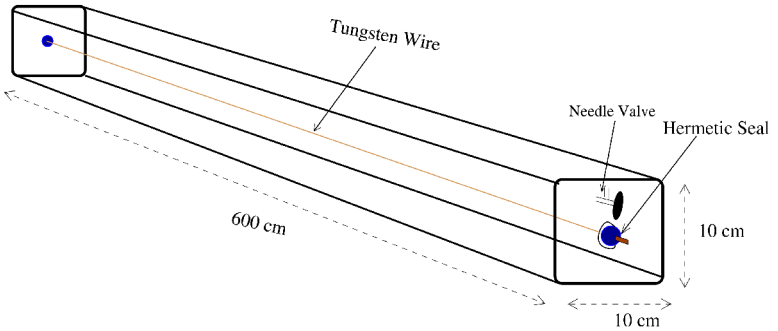
Extensive Air Shower

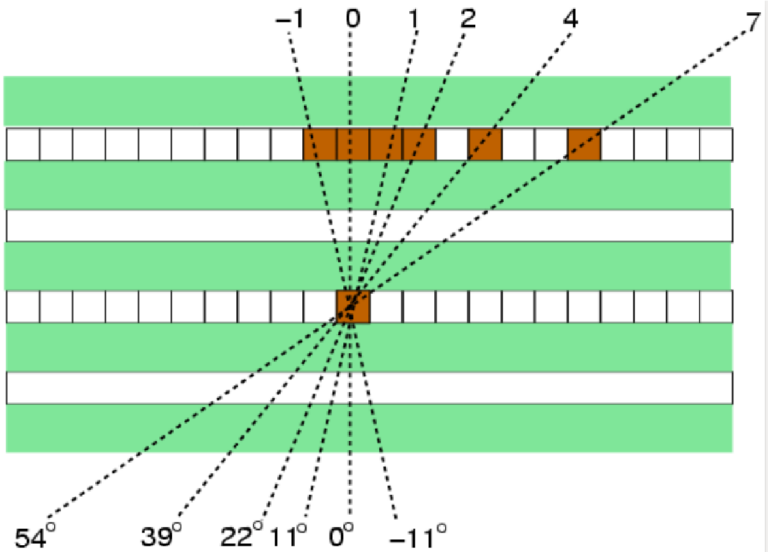


- Cosmic rays below ~10 GeV do not reach Ooty atmosphere due to geomagnetic cut off
- Below TeV, cosmic rays do not produce enough secondary particles that can survive till the ground
- Muons being penetrating survive to the ground
- Muon flux serves as a good proxy to cosmic ray intensity.

GRAPES-3 Muon Telescope (Ooty, India, 11.4°N, 76.7°E, Rc = 17 GV)

Modules	16 (35 m^2 each)
Directions	13 x 13 (169)
Sky coverage	up to 60° zenith
Total Area	560 m^2
Muon Rate	5 x 10^4 / sec
Sensitivity	0.1% / minute

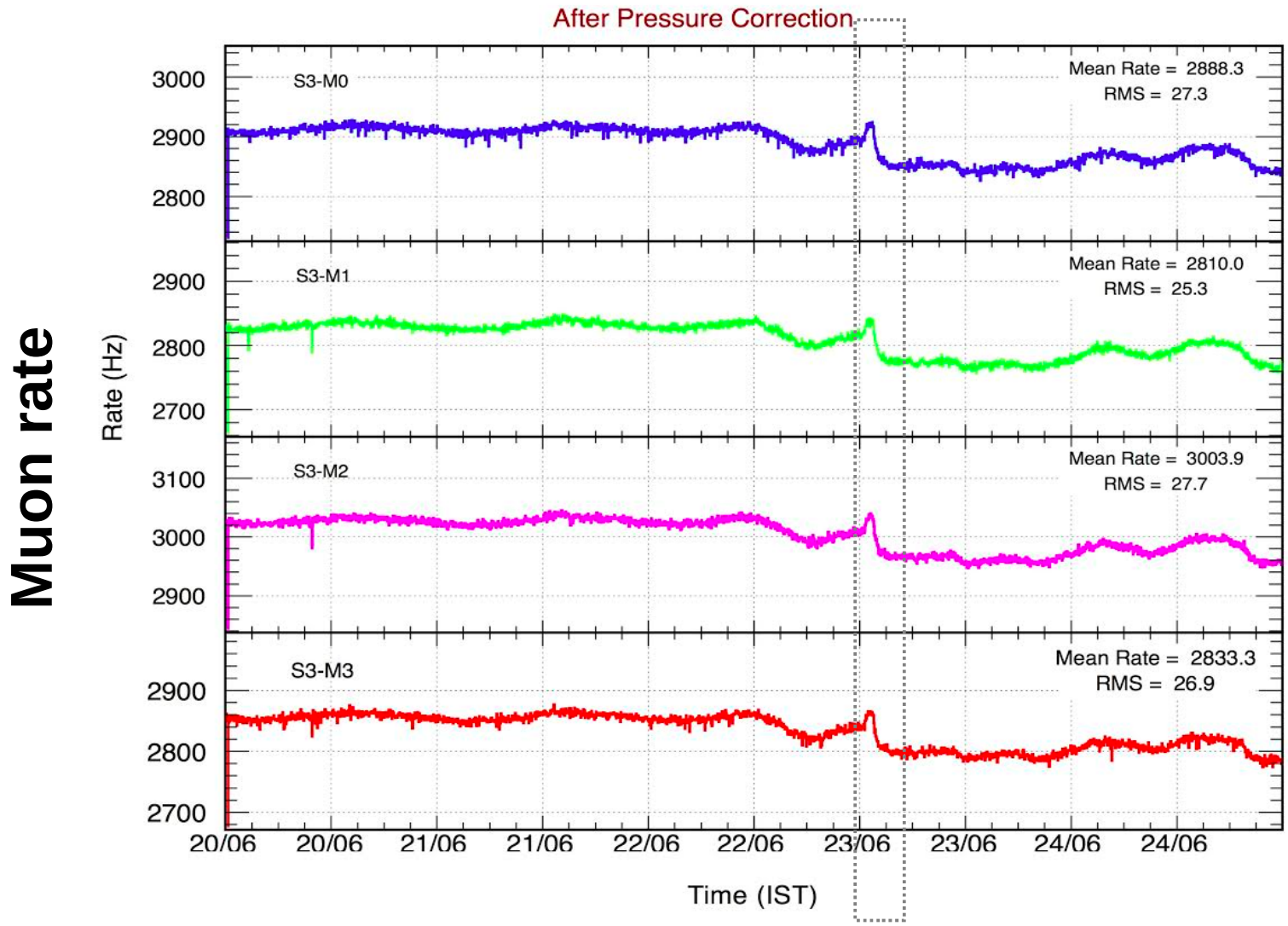




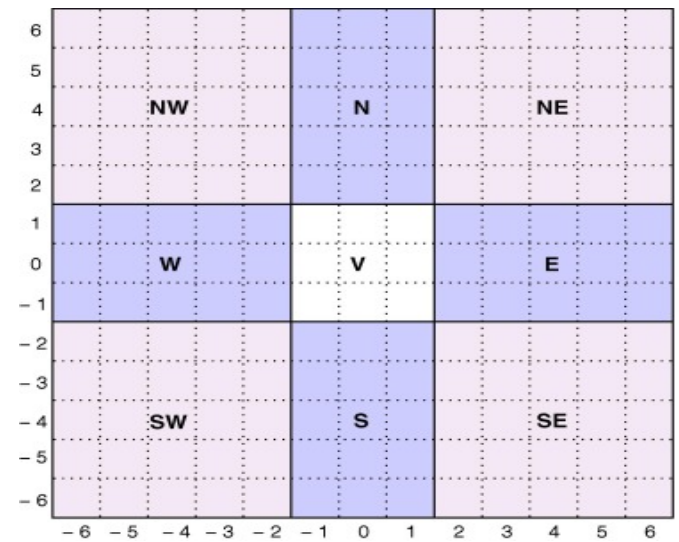
Each module : 58 x 4 PRCs

PRC dimension: 6 m x 10 cm x 10cm

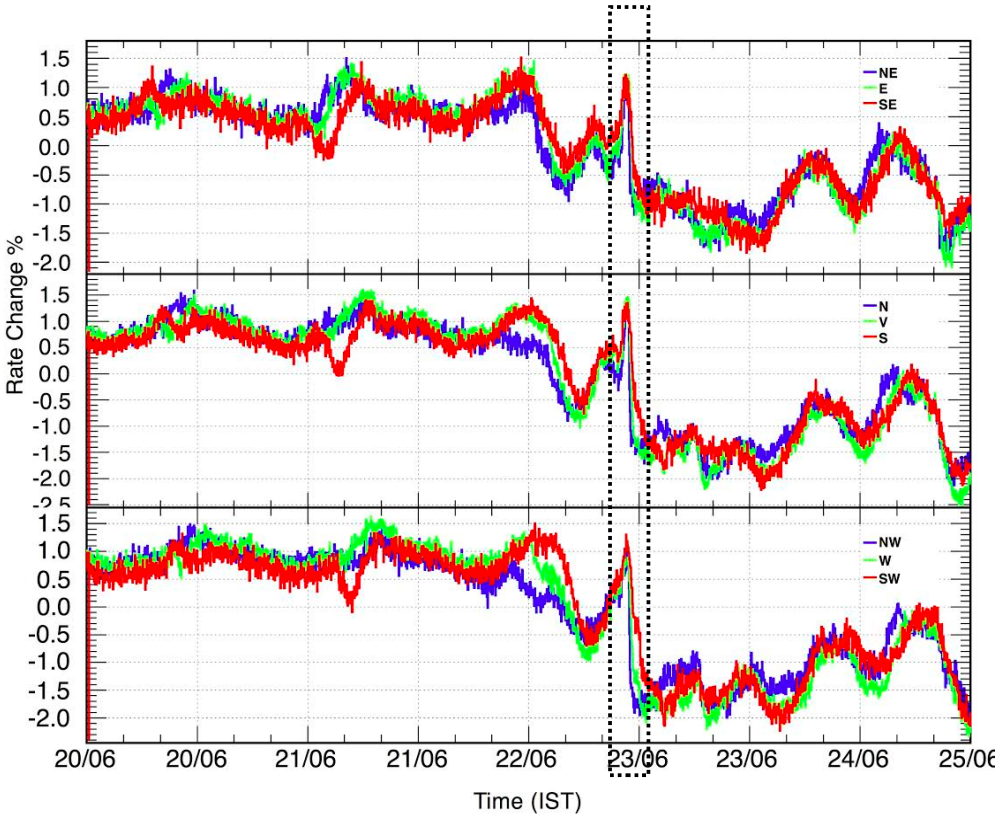
Muon burst on 22 June 2015 midnight



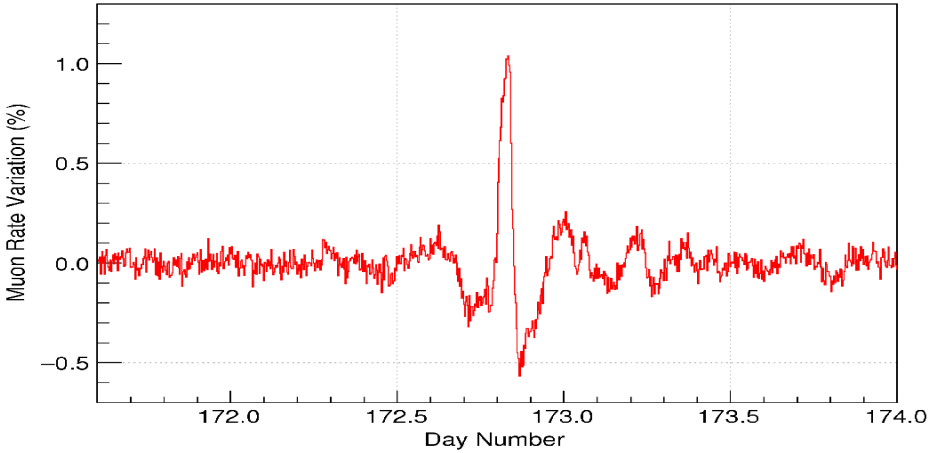
Muon telescope field of view

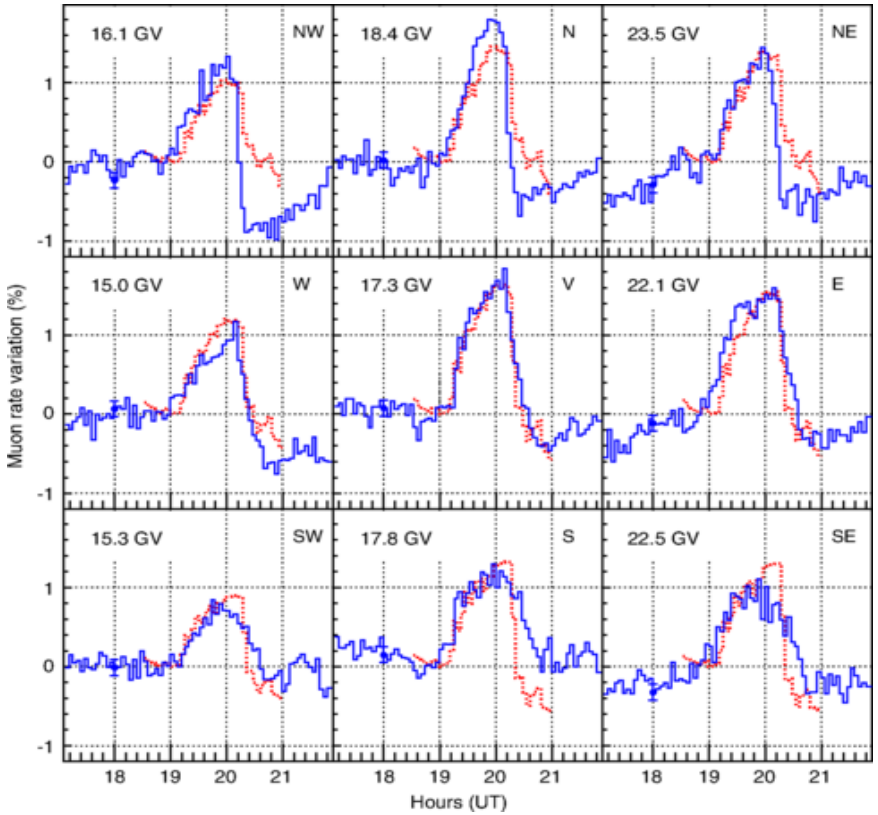


Simultaneous occurrence of the burst

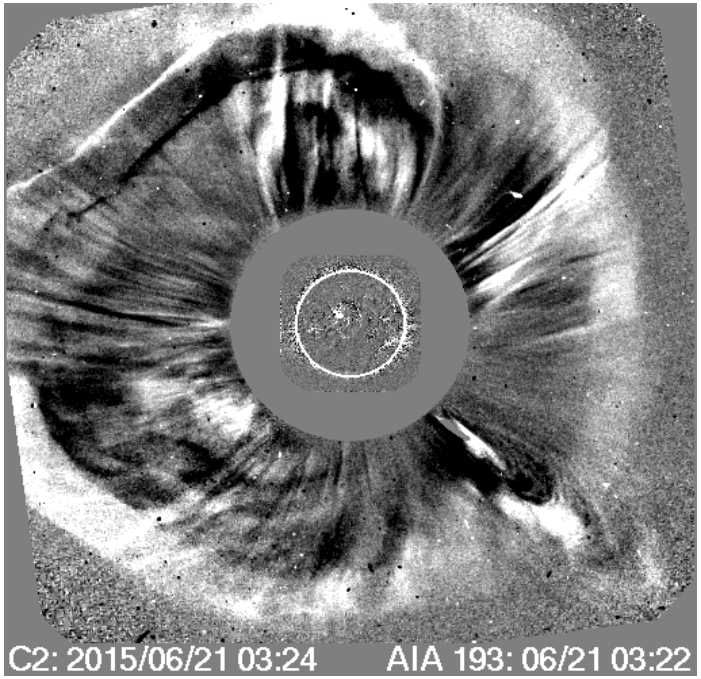


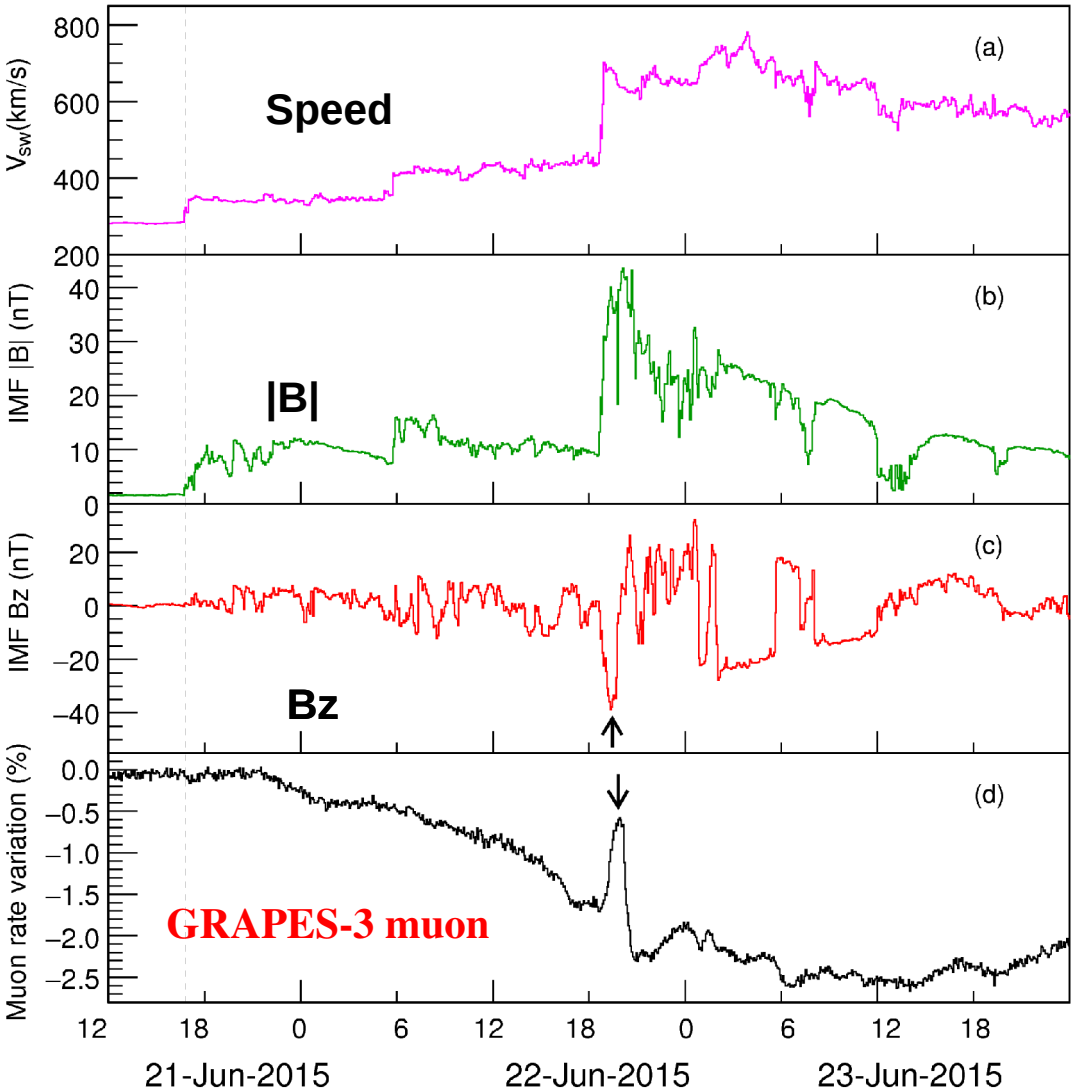
FFT to remove frequency < 3.5 cycles/day





Muon burst associated with coronal mass ejection (CME)





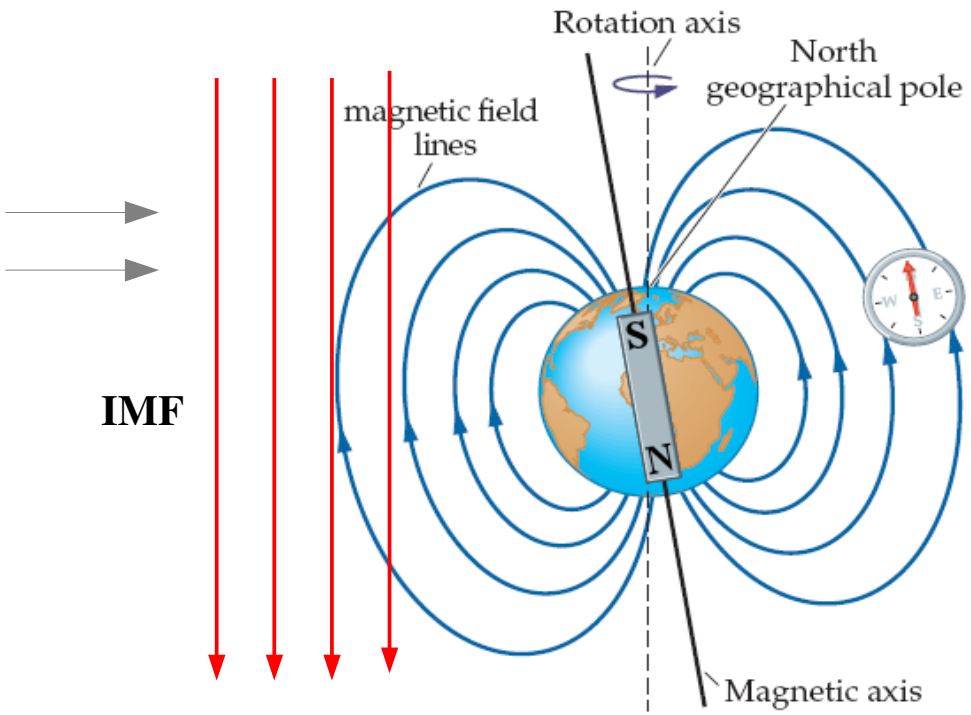
Wind spacecraft measurement at L1

A coronal ejection struck Earth on 22 June 2015 at 18:40 hour triggered a severe G4 class storm

IMF data from NASA OMNIWeb measured by WIND spacecraft at L1

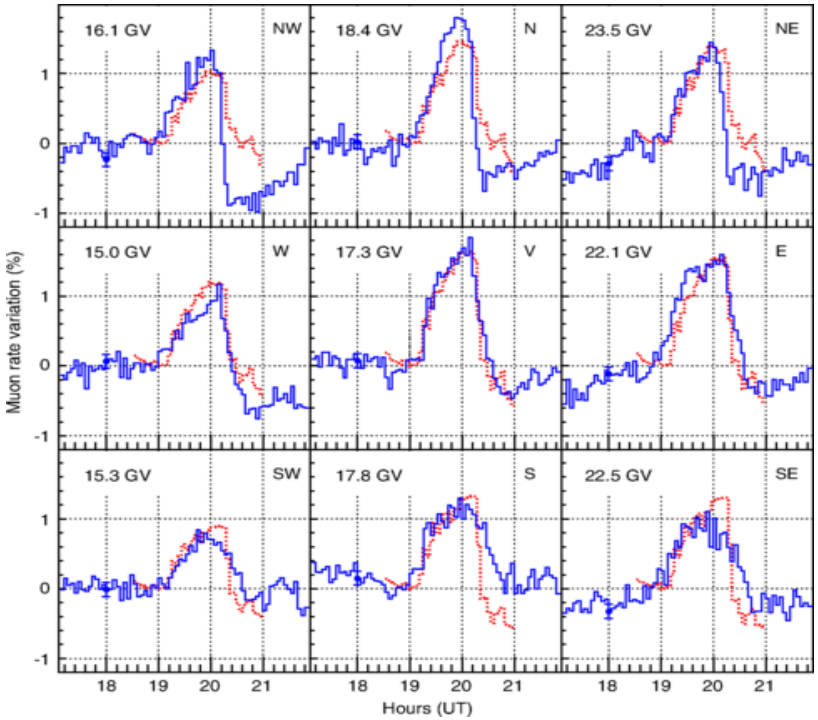
94% correlation between IMF Bz and muon burst

Magnetic reconnection simulation



IMF was superposed on dipolar geomagnetic field and cosmic ray trajectory calculation performed in the new field.

50 days simulation using GRAPES-3 1280 core computing cluster



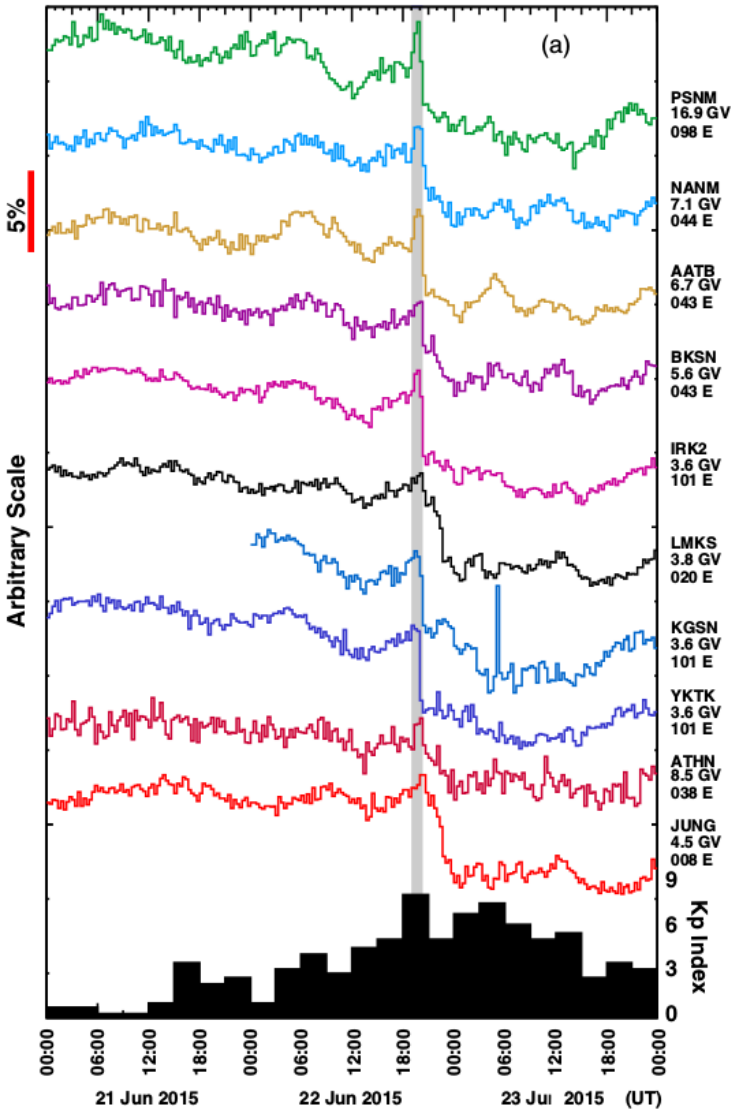
Transient weakening of Earth's magnetic field of 700 nT allowed entry of low energy cosmic rays

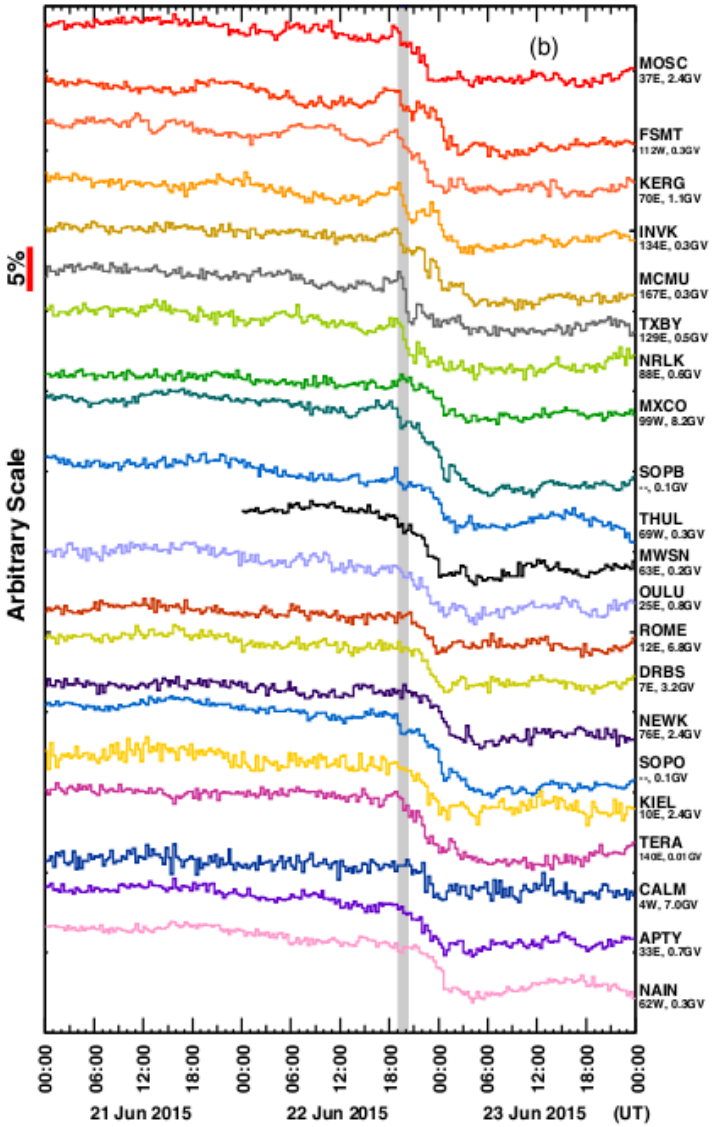
P.K. Mohanty et al., Physical Review Letters (2016)

Post PRL publication

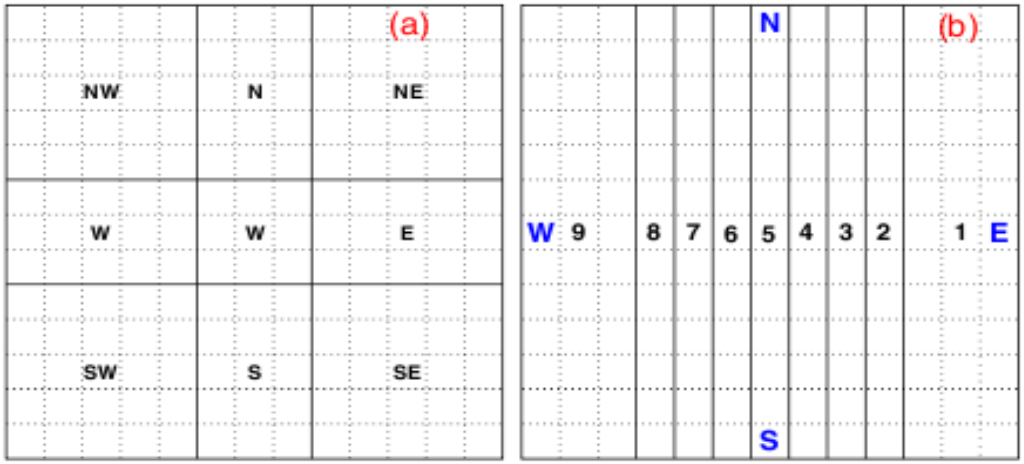
A group including IceCube observed the GRAPES-3 burst in 10 out of 31 neutron monitors spread across the world

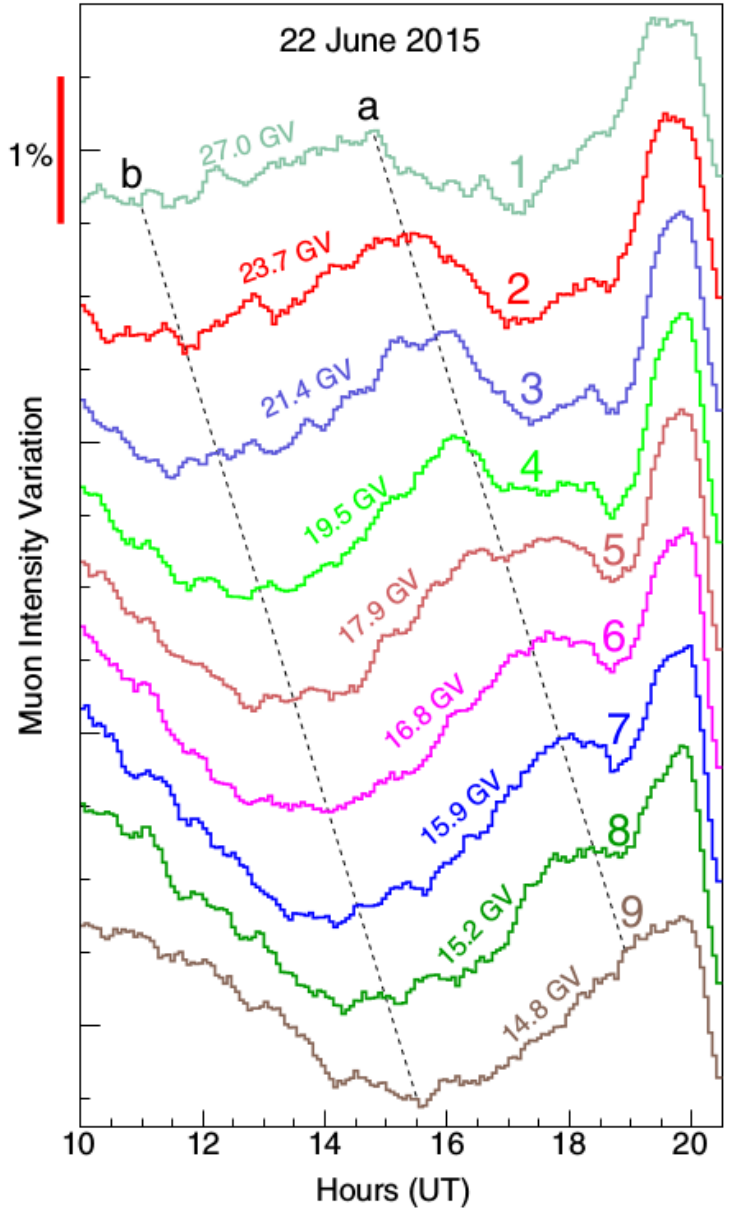
They speculated the burst due to an anisotropy and not due to transient weakening





A new analysis





P.K. Mohanty et al., Physical Review D, 17 April 2018

Extract from referees comment

The analysis of Mohanty et al. separates out the cutoff-change effects from the effects due to interplanetary cosmic-ray anisotropy. It shows that the magnitude of the bursts decrease in size at lower rigidity. This is exactly what would be expected

The analysis of GRAPES-3 data in this paper suggests that muon measurements may provide a complimentary and possibly improved forecast of the onset of geomagnetic storms than does the extrapolation of real-time solar wind and CME data from L1

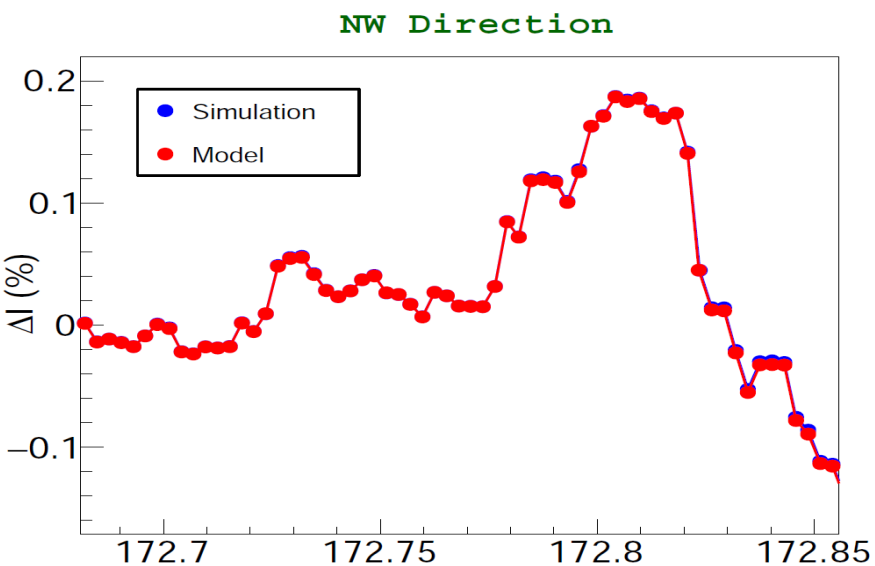
Further work

Search for more burst events with the existing 18 years of data.

Understanding with CME speed, burst amplitude and delay for more accurate prediction of geomagnetic storms.

In last 18 years more than 100 G3, G4 class geomagnetic storms

A full simulation takes lot of computing resources (time and storage) to simulate a single event as a billion cosmic ray event have to tracked in the time dependent modeled field at interval of 4 minutes



A faster method have developed that does the job in a fraction of a second

Poster by Meeran Zuberi

GRAPES-3 EAS measurement (TeV - PeV)

- **Scintillator array (400 of 1 m^2 each), designed to measure electron components in EAS**

- **The high density configuration (8 m inter-detector separation) enabled energy measurement over a large range (1 TeV – 10 PeV) giving a good over with satellite and balloon measurements**

- **560 m^2 muon detector gives an excellent measurement of muon contents in EAS for nuclear composition and gamma-hadron separation**

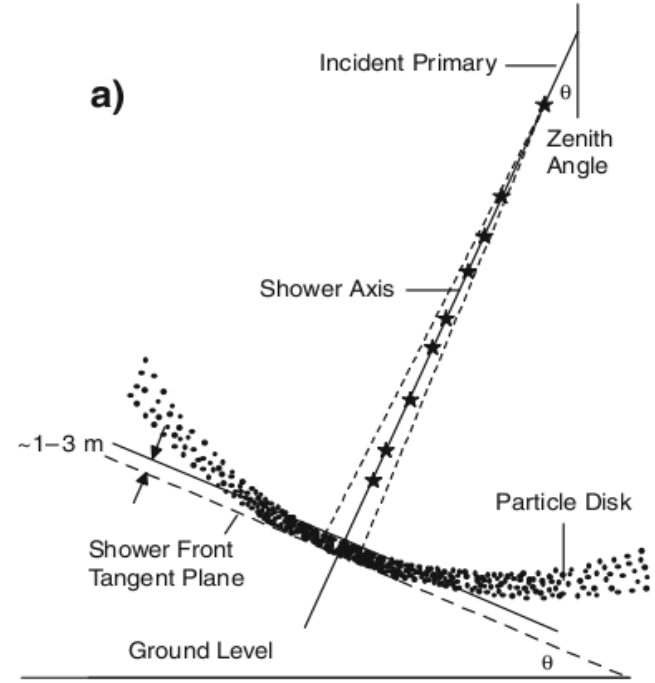
EAS measurement method

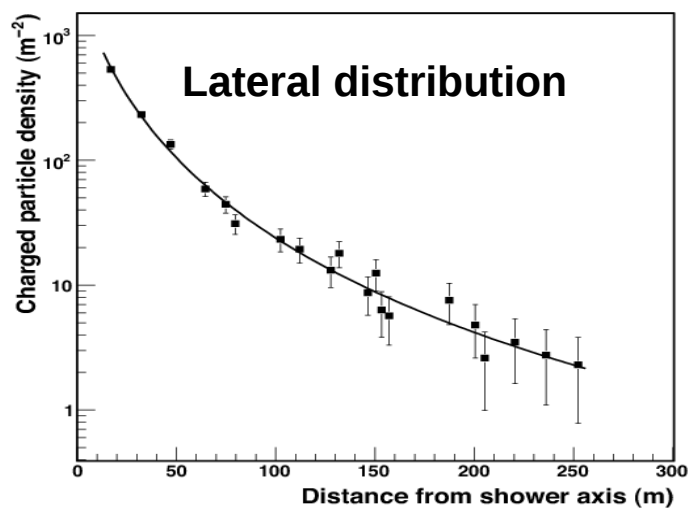
ADC → **Particle density**

TDC → **Calibration** → **Arrival Times (ns)**

EAS Reconstruction
core (x,y), angle (θ,ϕ)
shower size (Ne), Age (s)

Primary Energy
CORSIKA, Geant4

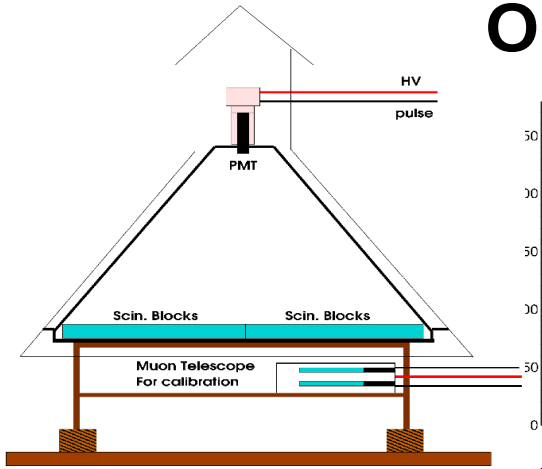


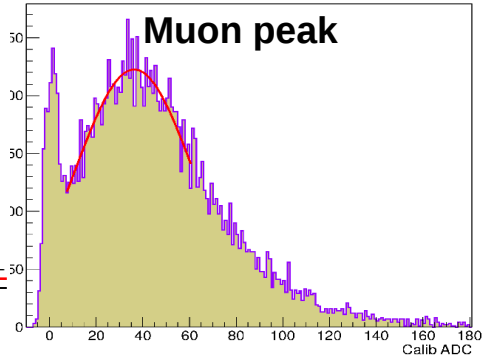


NKG function: $\rho(r) = c(s)(N_e/r_0^2)(r/r_0)^{(s-2)}(1 + r/r_0)^{(s-4.5)}$,

Single muon response (MIP calibration)

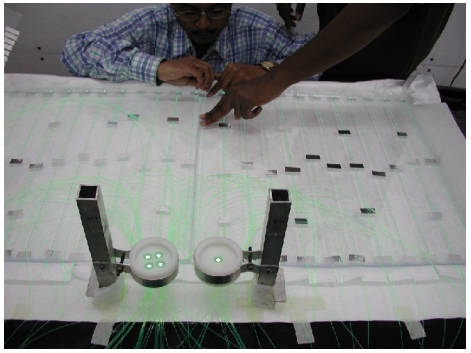
Old

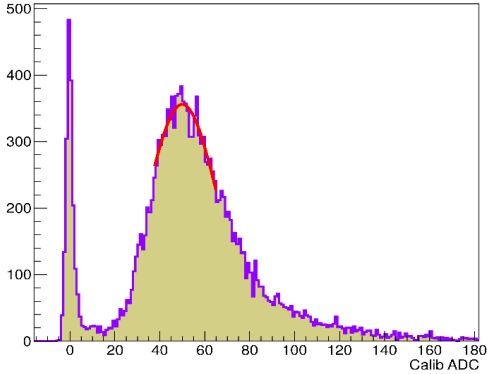




Charge (adc counts)

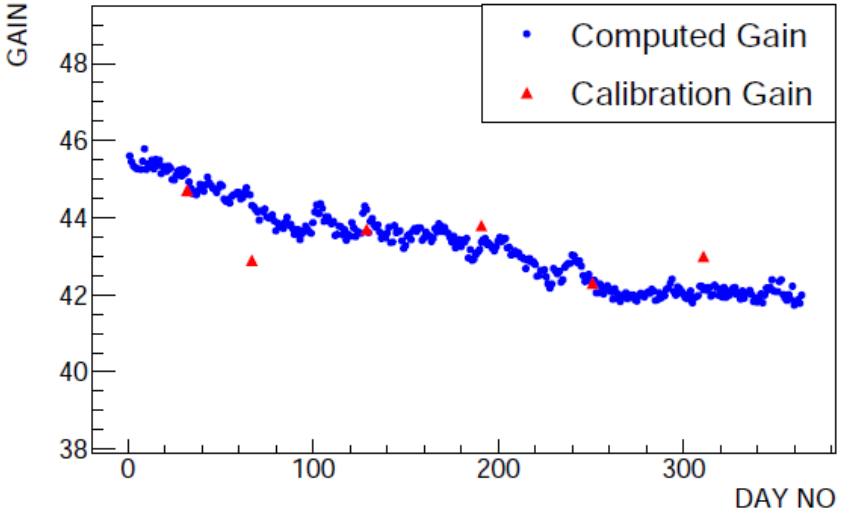
New



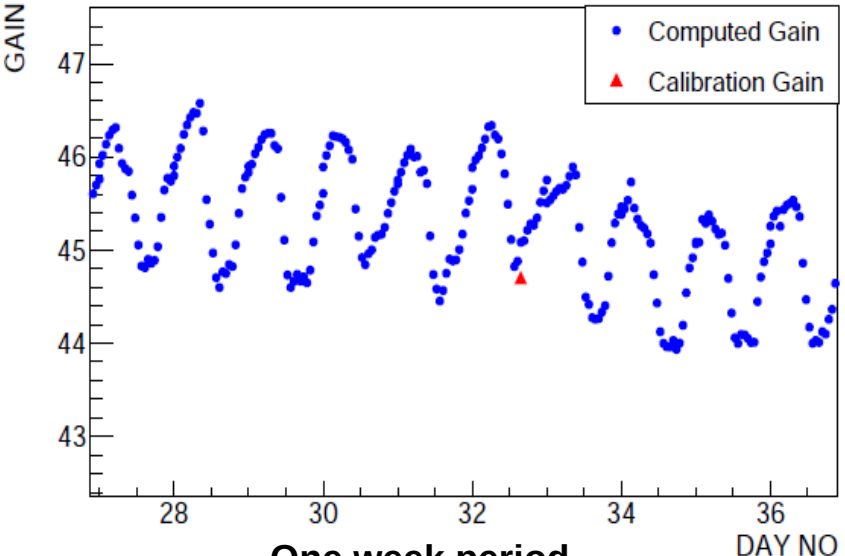


Charge (adc counts)

P.K. Mohanty et al. Astropart. Phys. 31 (2009) 24



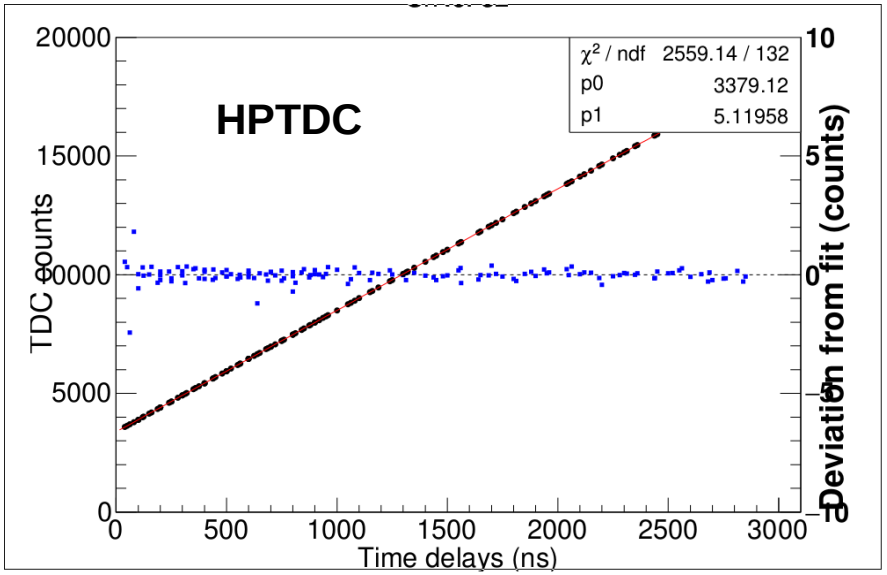
1 January to 31 December 2014



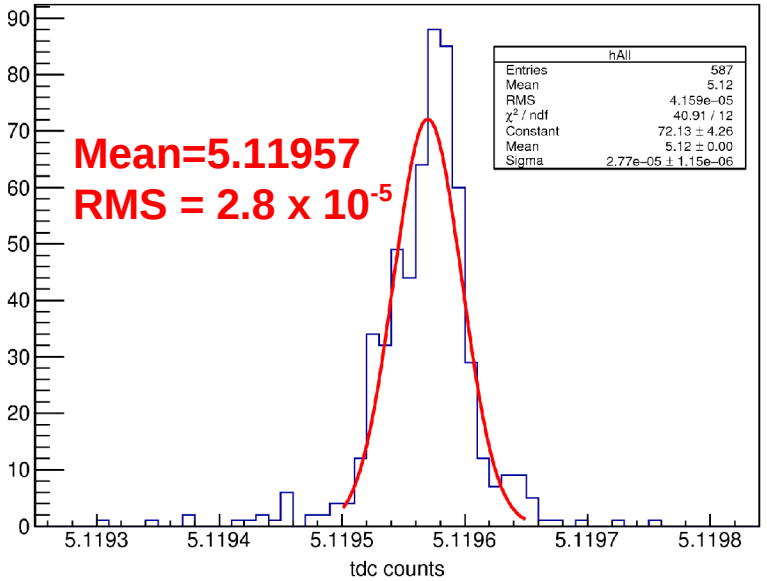
One week period

V.B. Jhansi et al, Pos(ICRC2017) 356

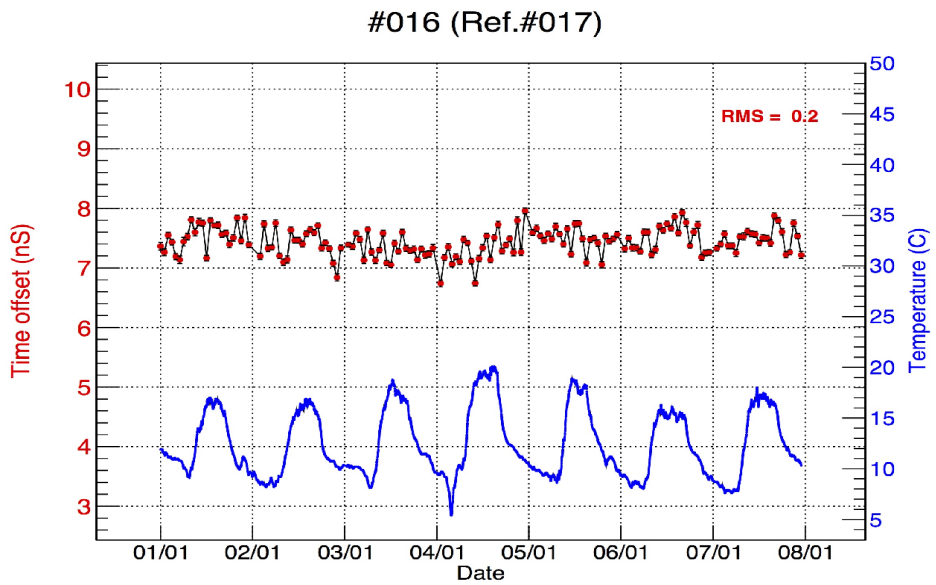
TDC Calibration



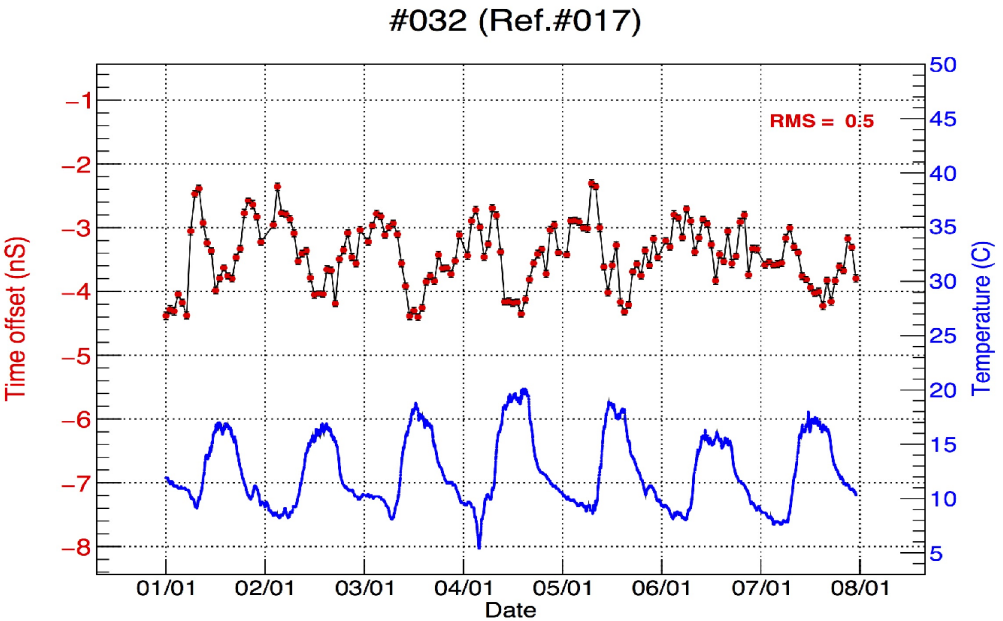
Distribution of 587 channels



Propagation delay (Time offset)

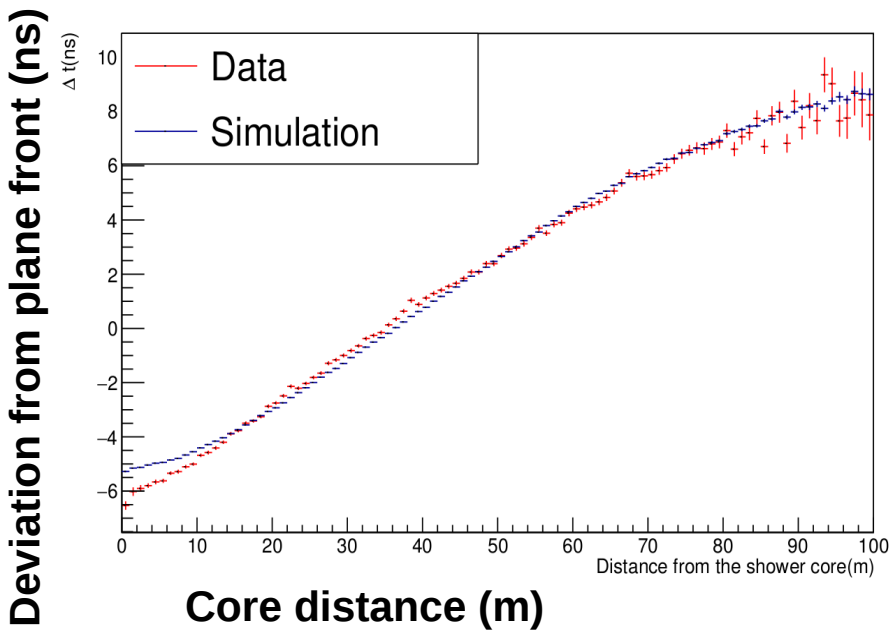


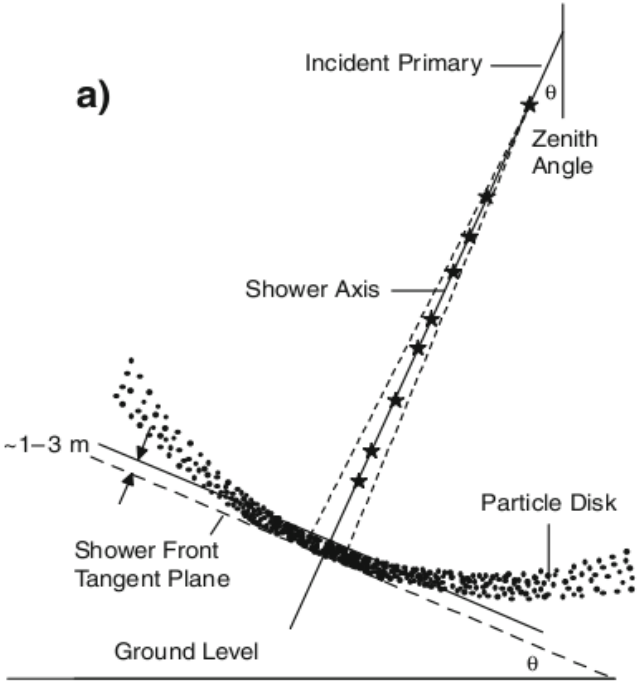
One week period



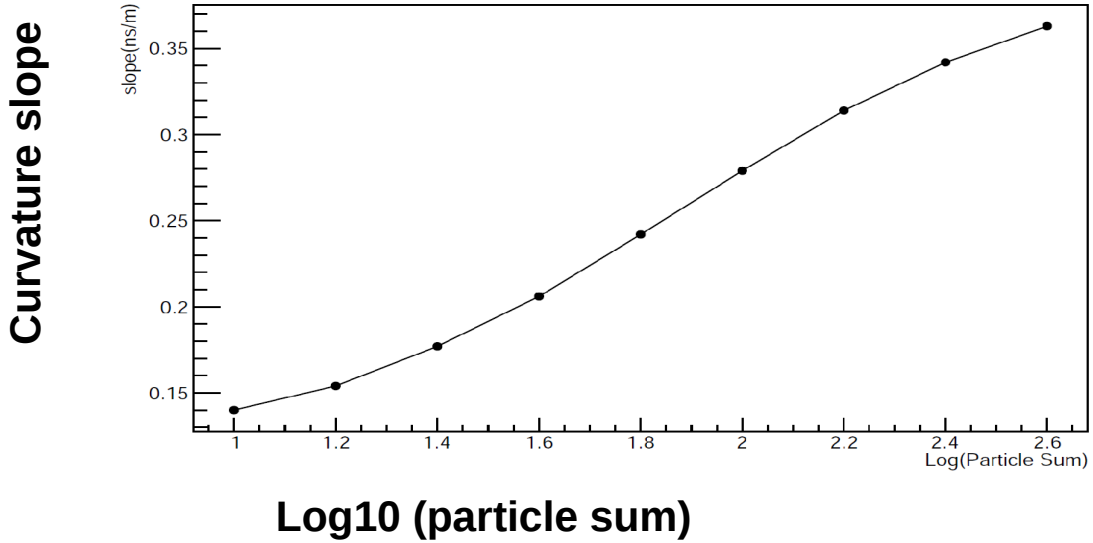
V.B. Jhansi et al, Pos(ICRC2017) 354

Shower front curvature





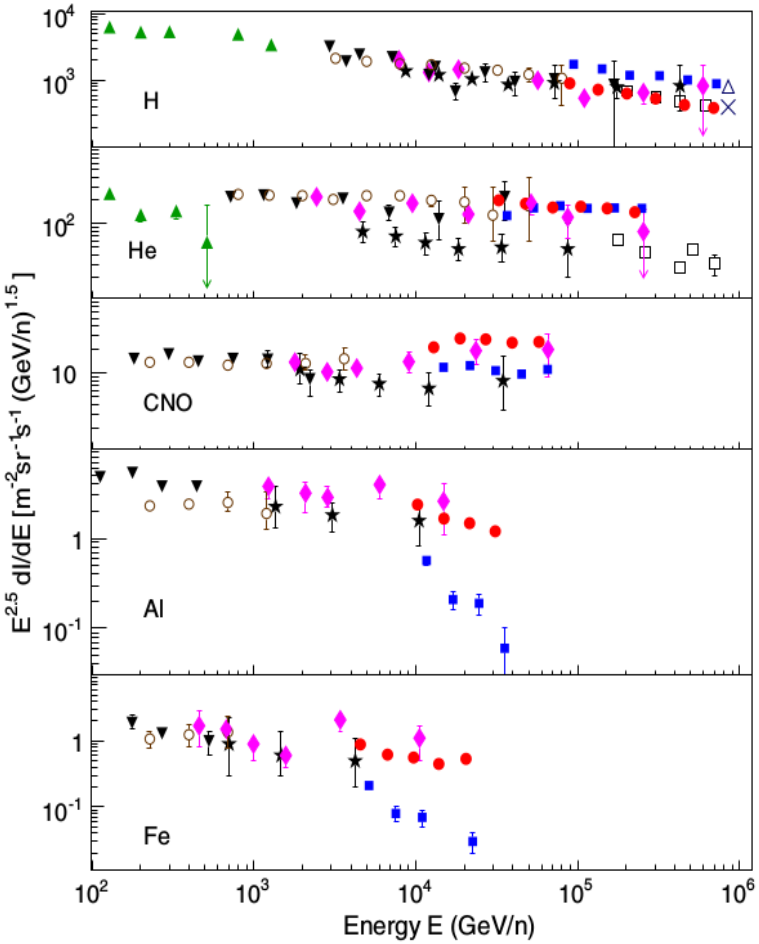
Energy dependence of curvature



Mean curvature = 0.2 ns/m

Poster by Jhansi Bhavani
DHEP seminar on 11 May

GRAPES-3 composition below knee



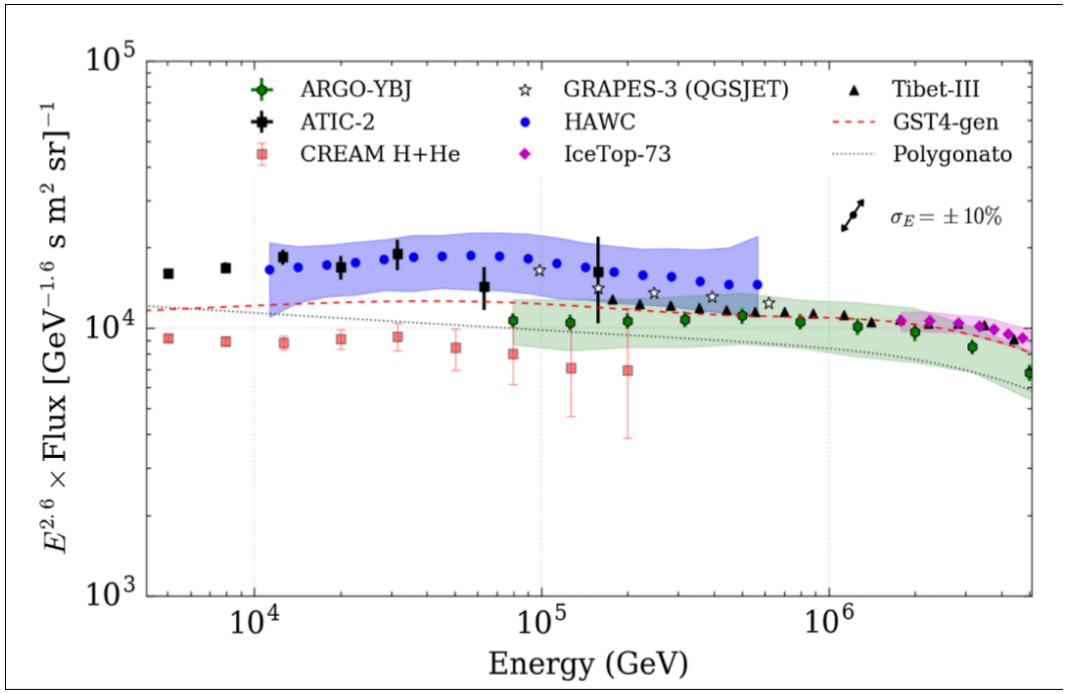
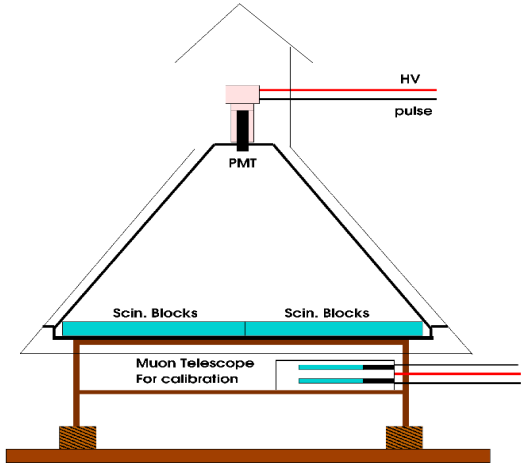
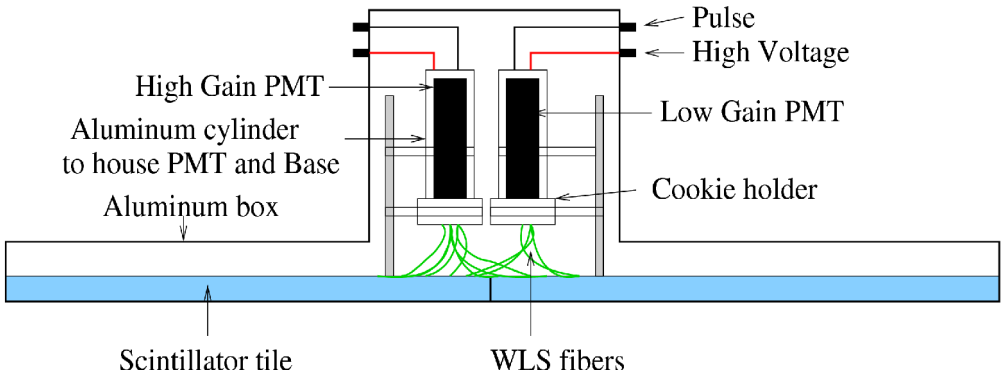


Figure 12. H, He, CNO, Al, Fe spectra from direct experiments: ▲ Ryan [29], ▼ SOKOL [30], ♦ JACEE [2], ★ RUNJOB [3], ○ CREAM [4], □ TIBET [7], KASCADE [11] × SIBYLL, △ QGSJet and GRAPES-3 ● SIBYLL, ■ QGSJET.

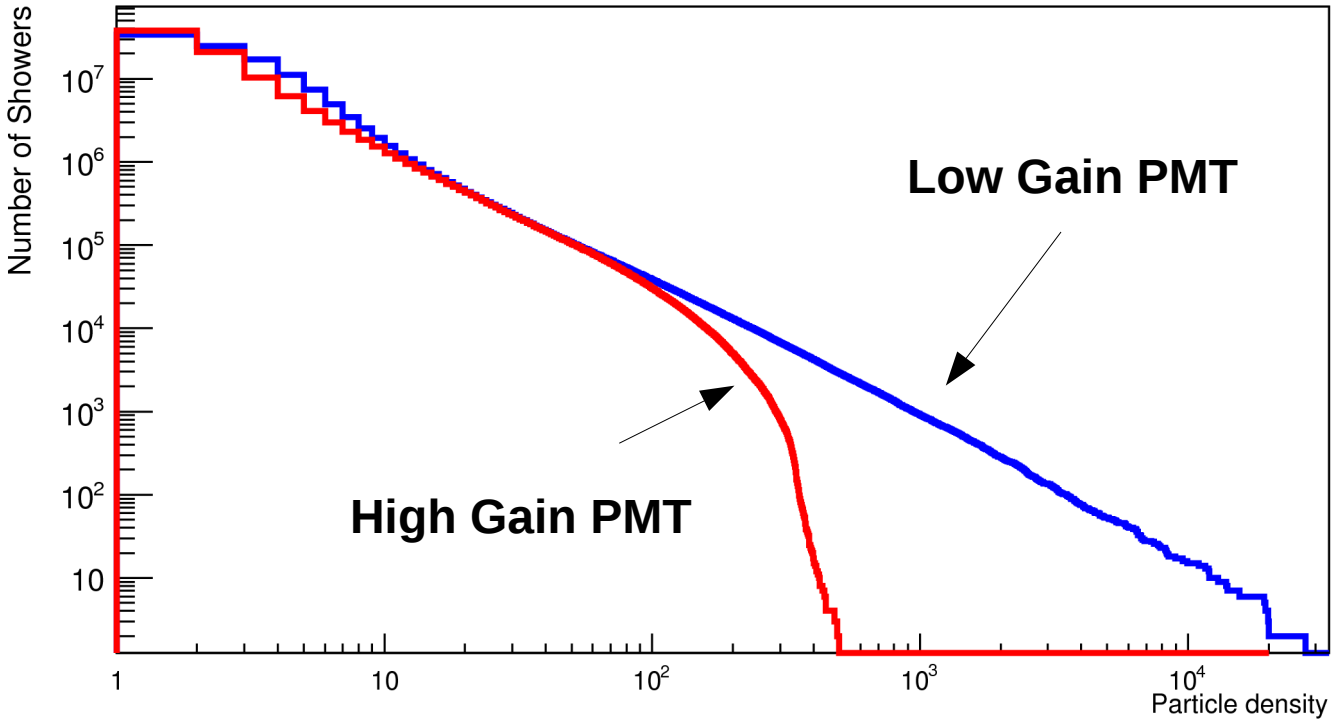
H. Tanaka, et al., J. Phys. G: Nucl. Part. Phys. 39 (2012).

Extending density measurement with two PMT design



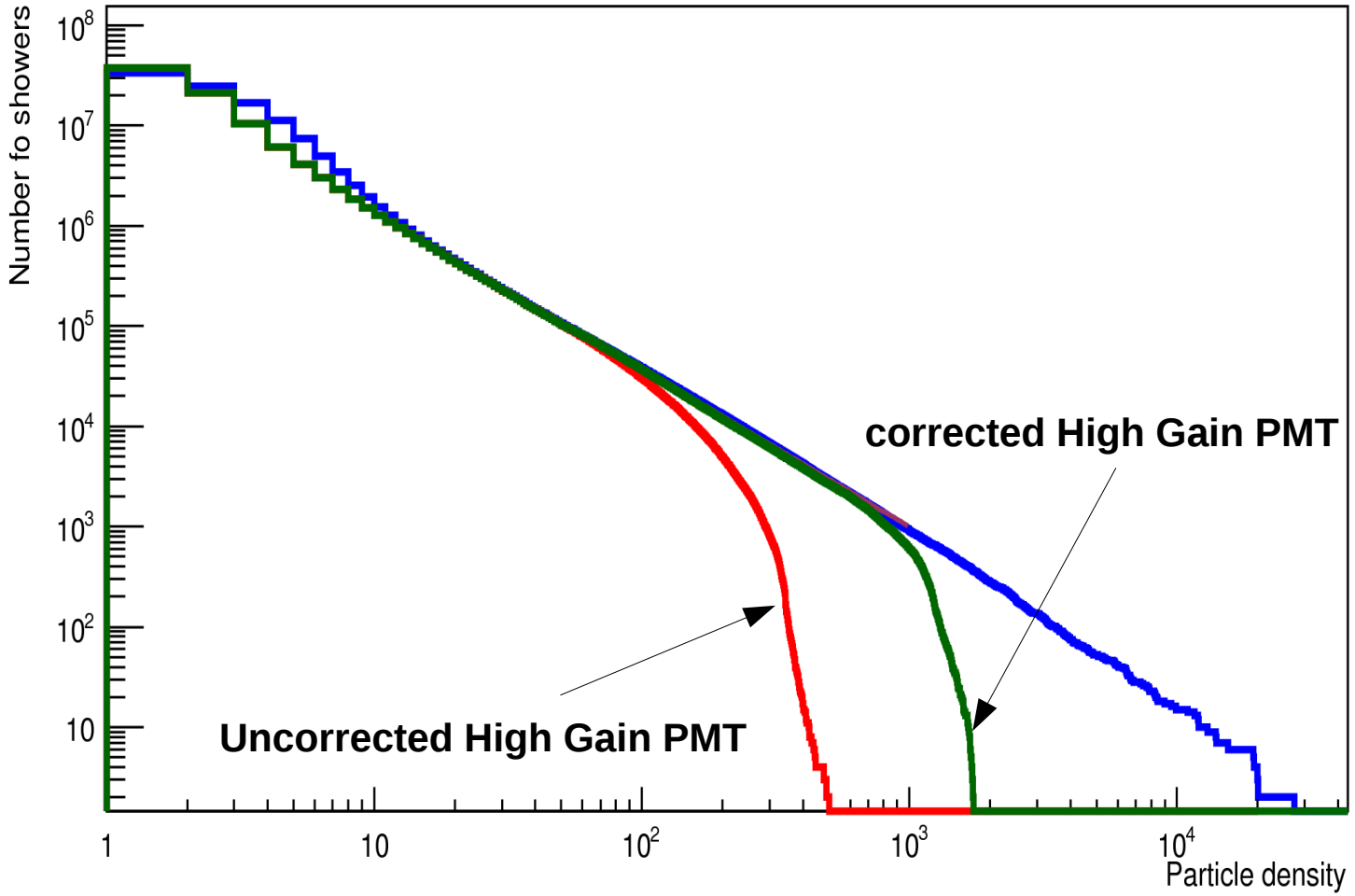


105 two PMT detectors



Work of Anuj Chandra

Effective use of single PMT data (non-linearity correction)

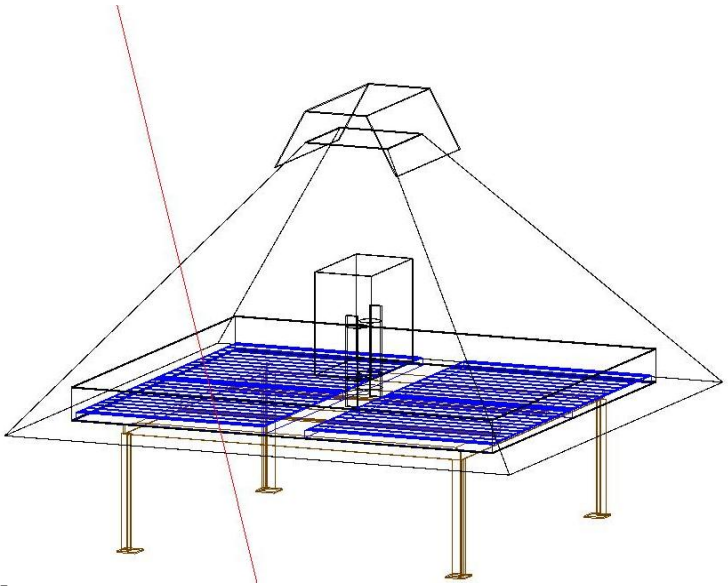


Work of Anuj Chandra

Geant4 Simulation

Atmospheric simulation using CORSIKA
10^8 proton primaries
1 TeV – 3 PeV
Full simulation with EGS option
Tracked till 1 MeV for gamma, electron, 5 MeV muon

2cm, 3cm, 5cm scintillator thickness and zenith angle 0 to 60 deg



Secondary particle composition in EAS
γ (85%), e (13%), μ (1%) and 1% (n, p)

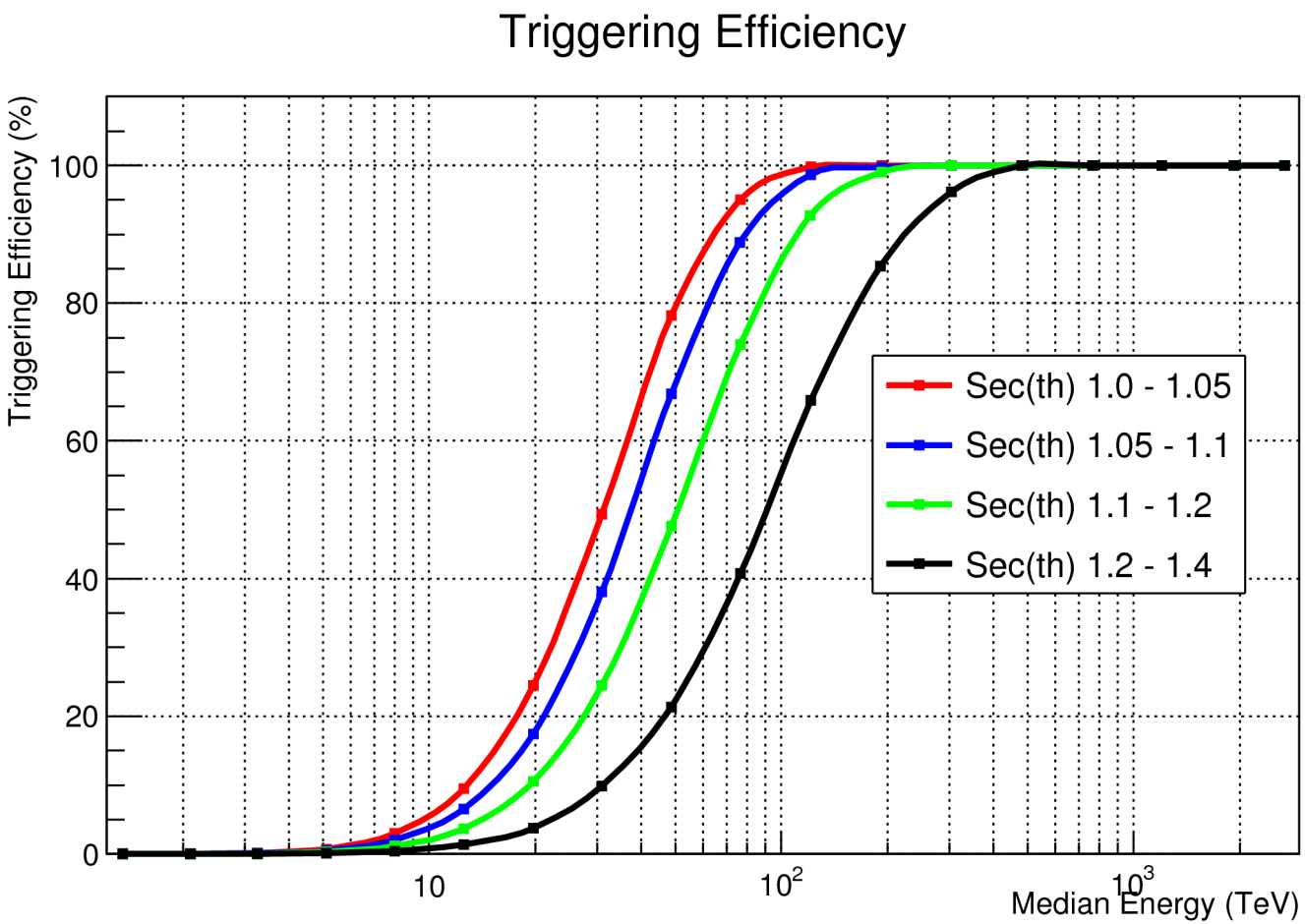
Scintillator response to γ: 4%

It is still 20% of the total detected particles.
Underestimation of size if we ignore this

Simulation shows 2 cm thick scintillator detects 10% more particles than 5 cm. An independent work by Jhansi Bhavani with experimental data shows similar result

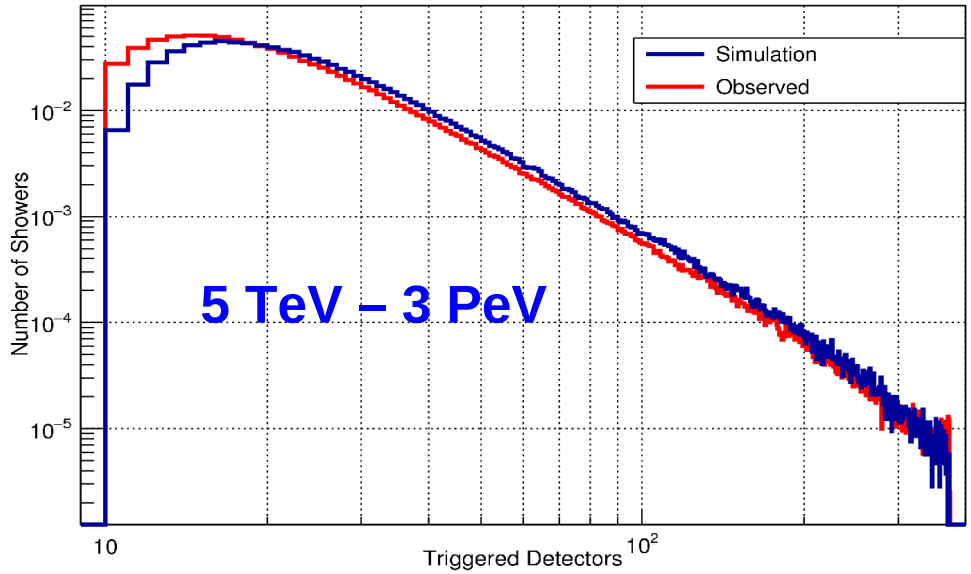
Poster by Saswat Mishra

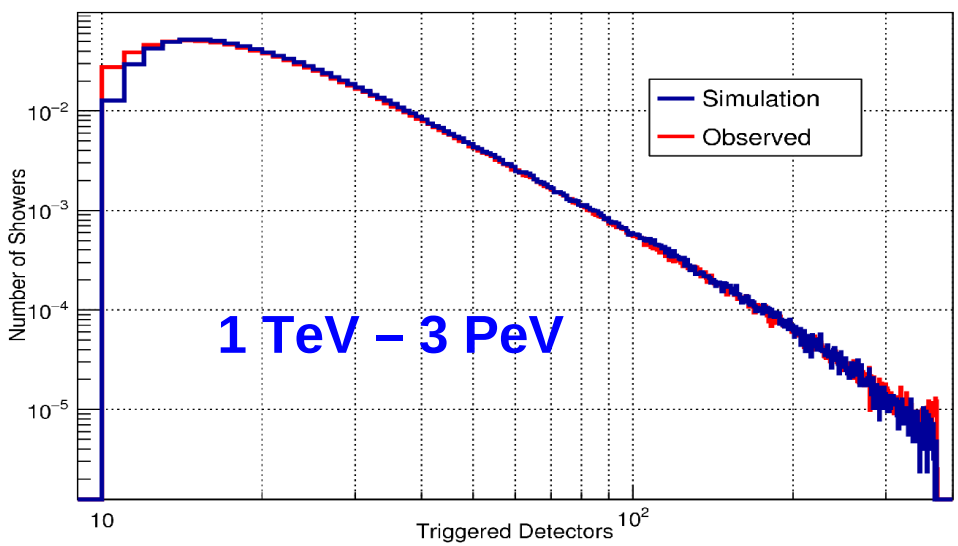
Trigger efficiency



50% events below 10 TeV

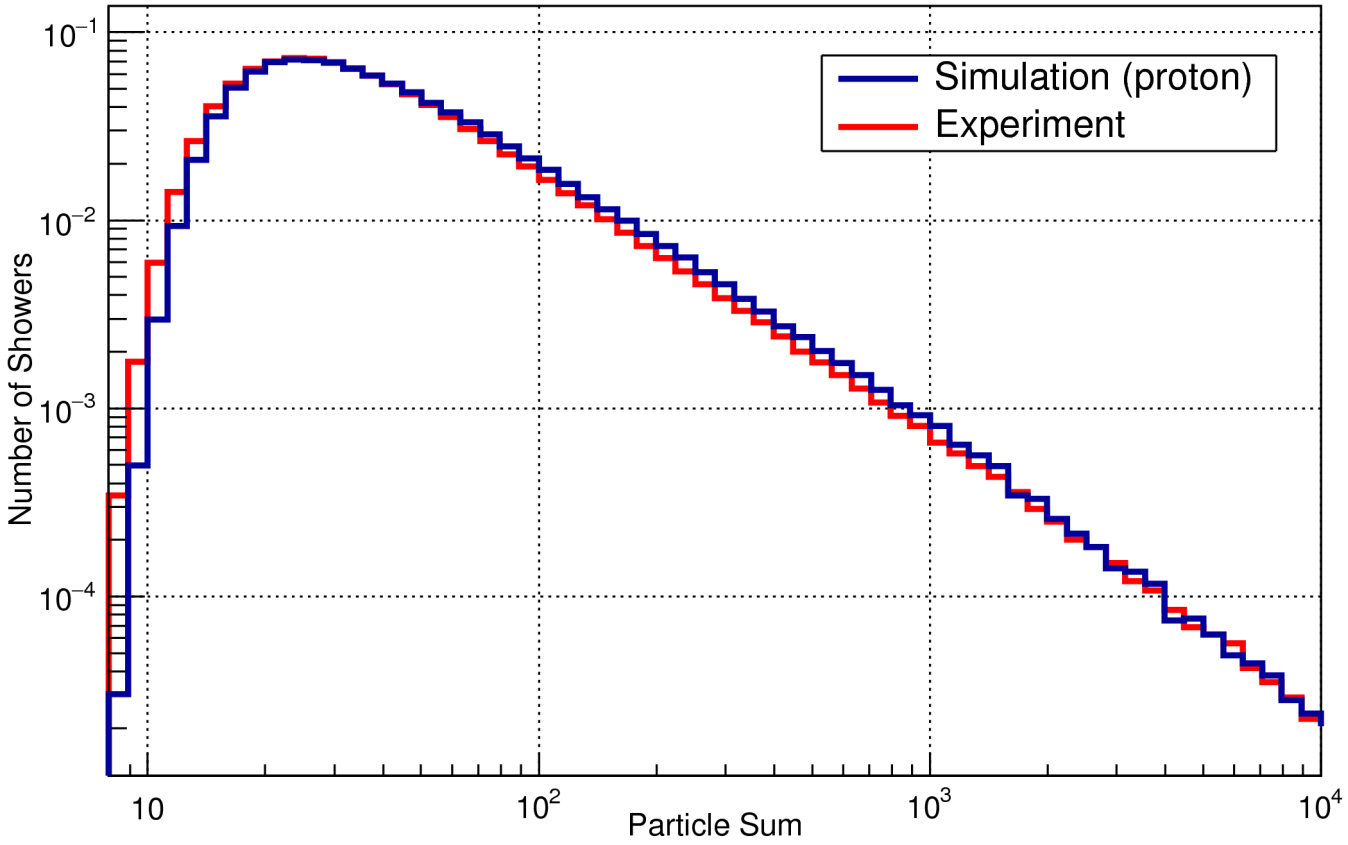
Triggered detectors



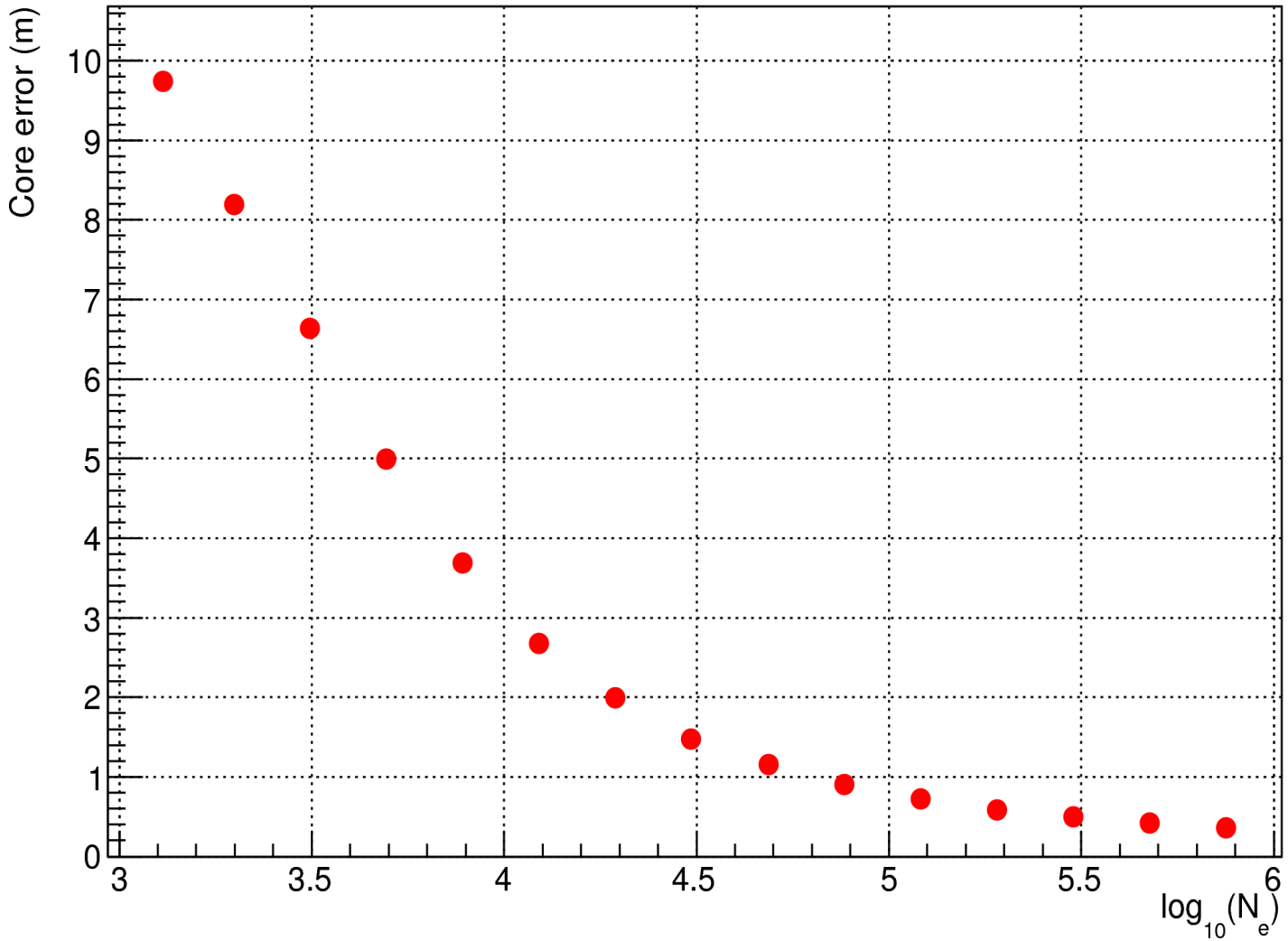


Poster by Saswat Mishra

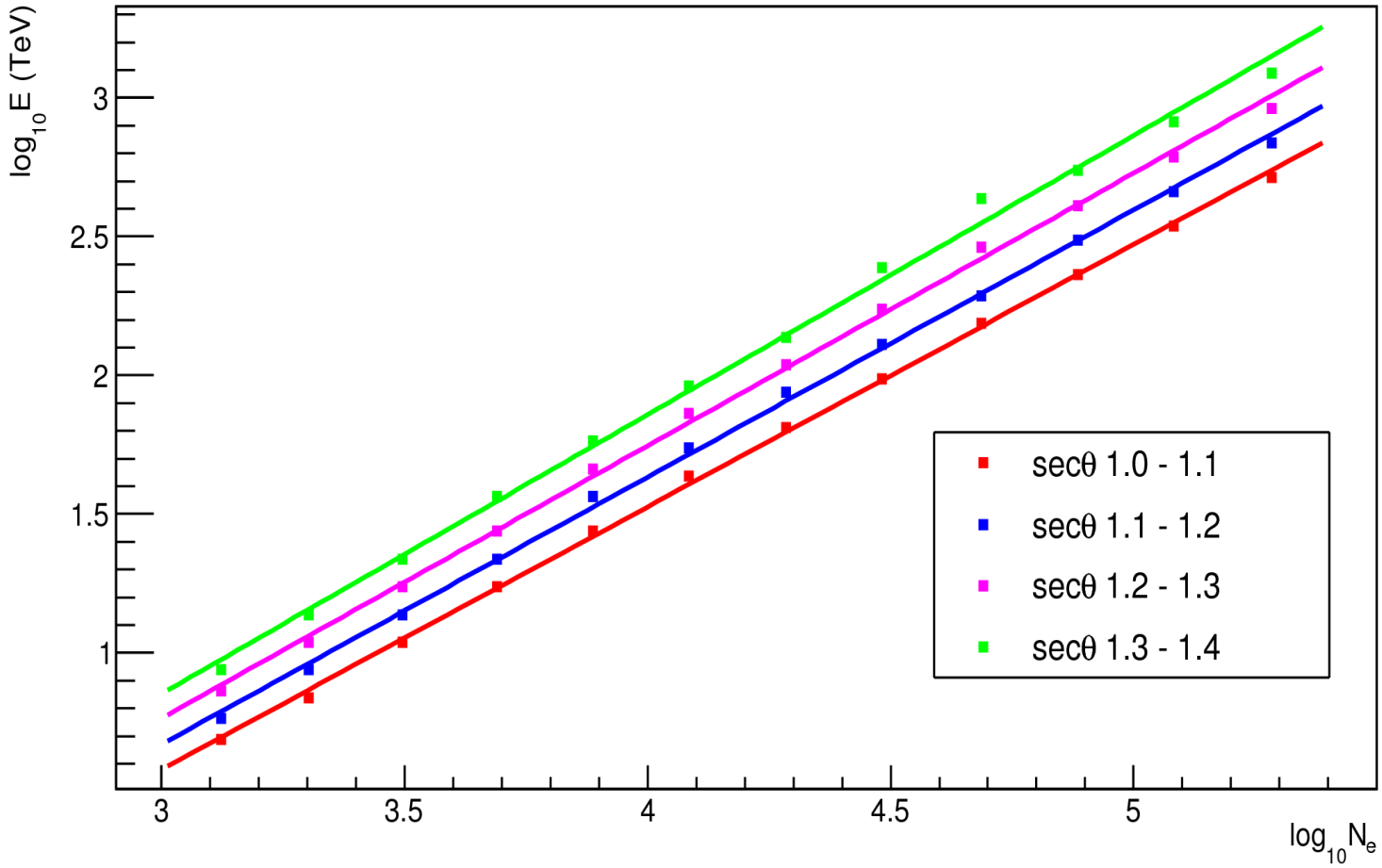
Total detected particles

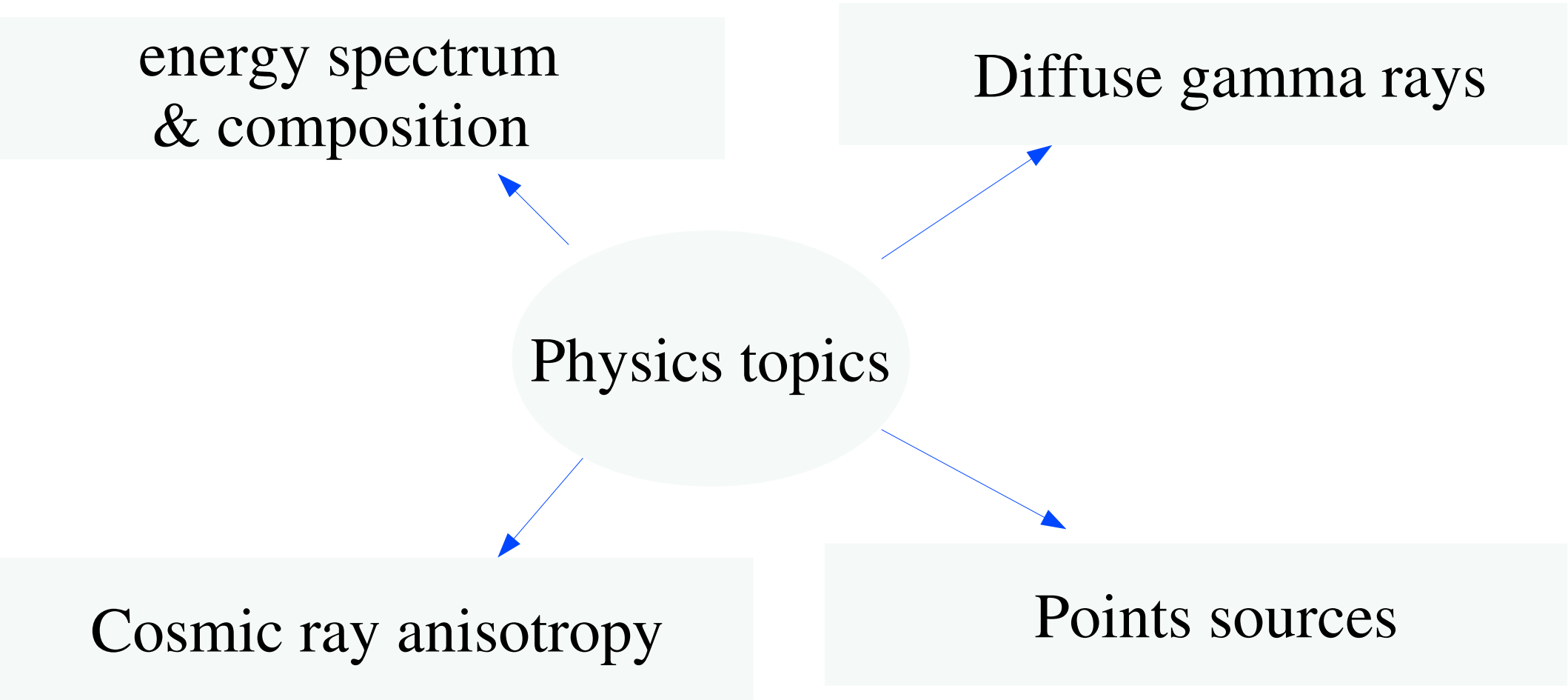


core reconstruction error



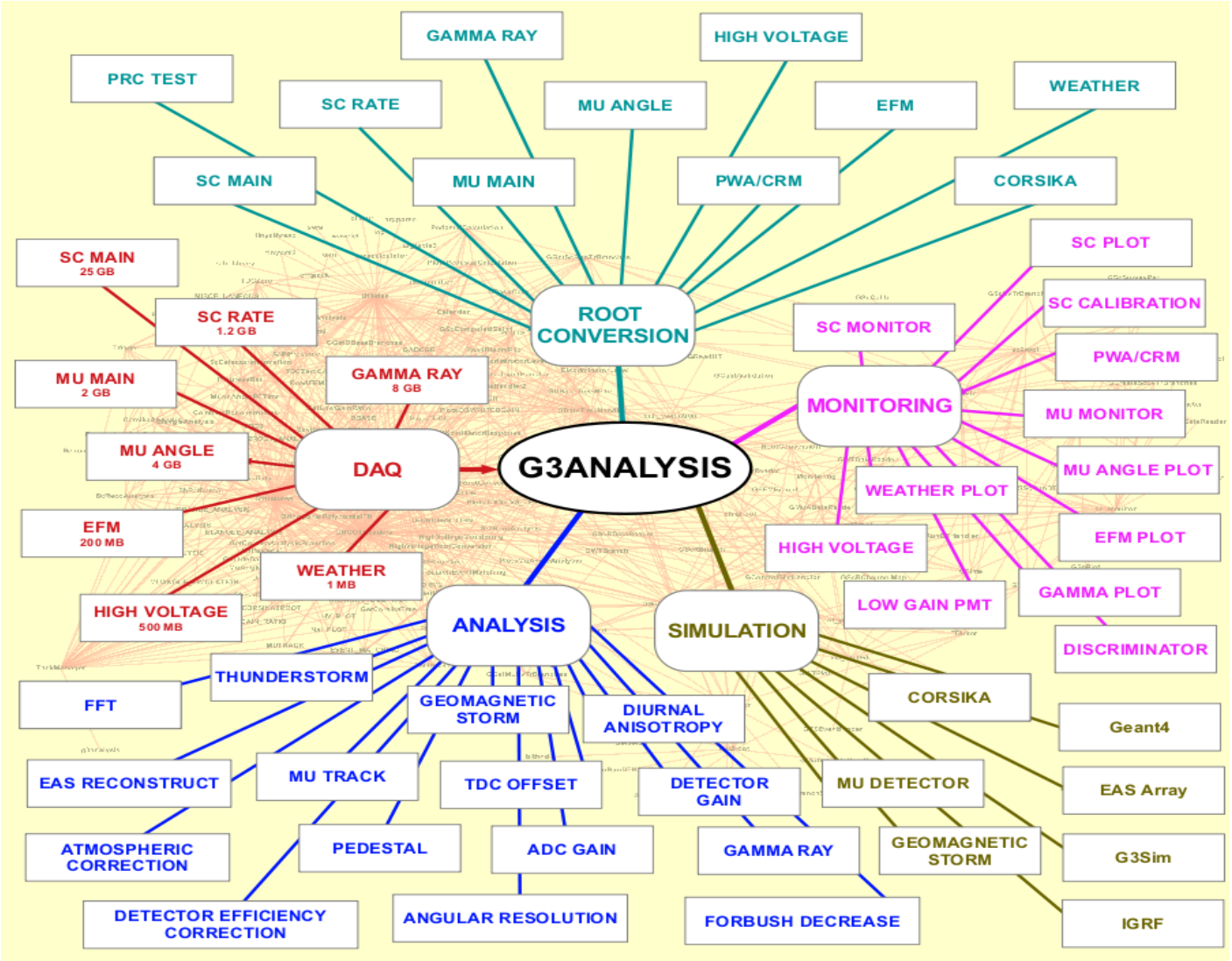
Shower Size – Energy relation




energy spectrum
& composition
Diffuse gamma rays
Physics topics
Cosmic ray anisotropy
Points sources

GRAPES-3 analysis framework

200 classes, 300K lines of code



Poster by B Hariharan

GRAPES-3 Physics Analysis Team

THANK YOU