Precision Simulation of Muon Flux for GRAPES-3

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GRAPES-3 Experiment
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GRAPES-3
(Gamma Ray Astronomy at PeV EnergieS Phase-3)

- Scintillator detector ~ 400 x 1m^2 each with 8m inter detector separation

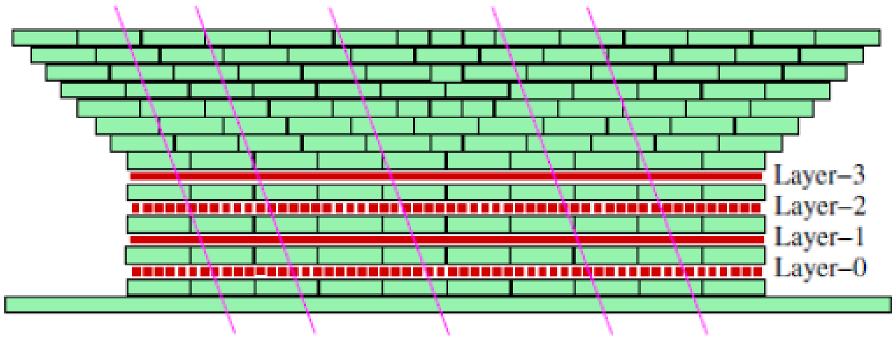
- Measure particle densities and relative arrival times in EAS to estimate primary energy and direction.

- Muon detector 35m^2 x 16 modules, 560 m^2 area. Consists of 58 counters x 4 layer x 16 modules = 3712 proportional counters.

- Detection of muons associated with EAS trigger (35Hz)
- Continuous record of muon flux in 225 direction bins (10s interval)

GRAPES-3 Muon Telescope

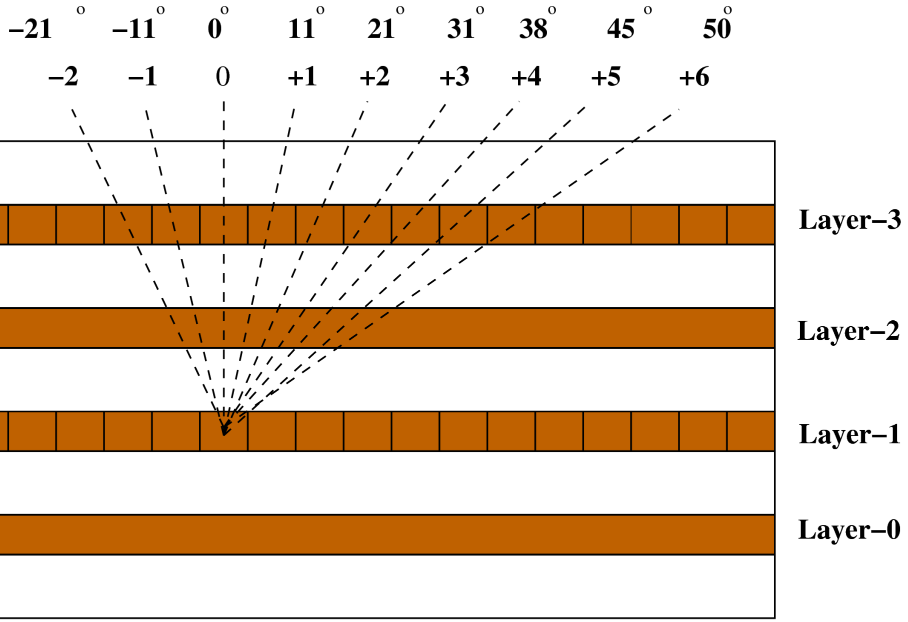
A Muon Module



Detect muons of E_μ >= 1 GeV

Trigger:
4-layer coincidence trigger
Clean Muon events

Angular Reconstruction



Directional measurements: 13 x 13 = 169

Muon Rate

Muon rate for each module ~ 3000 Hz.

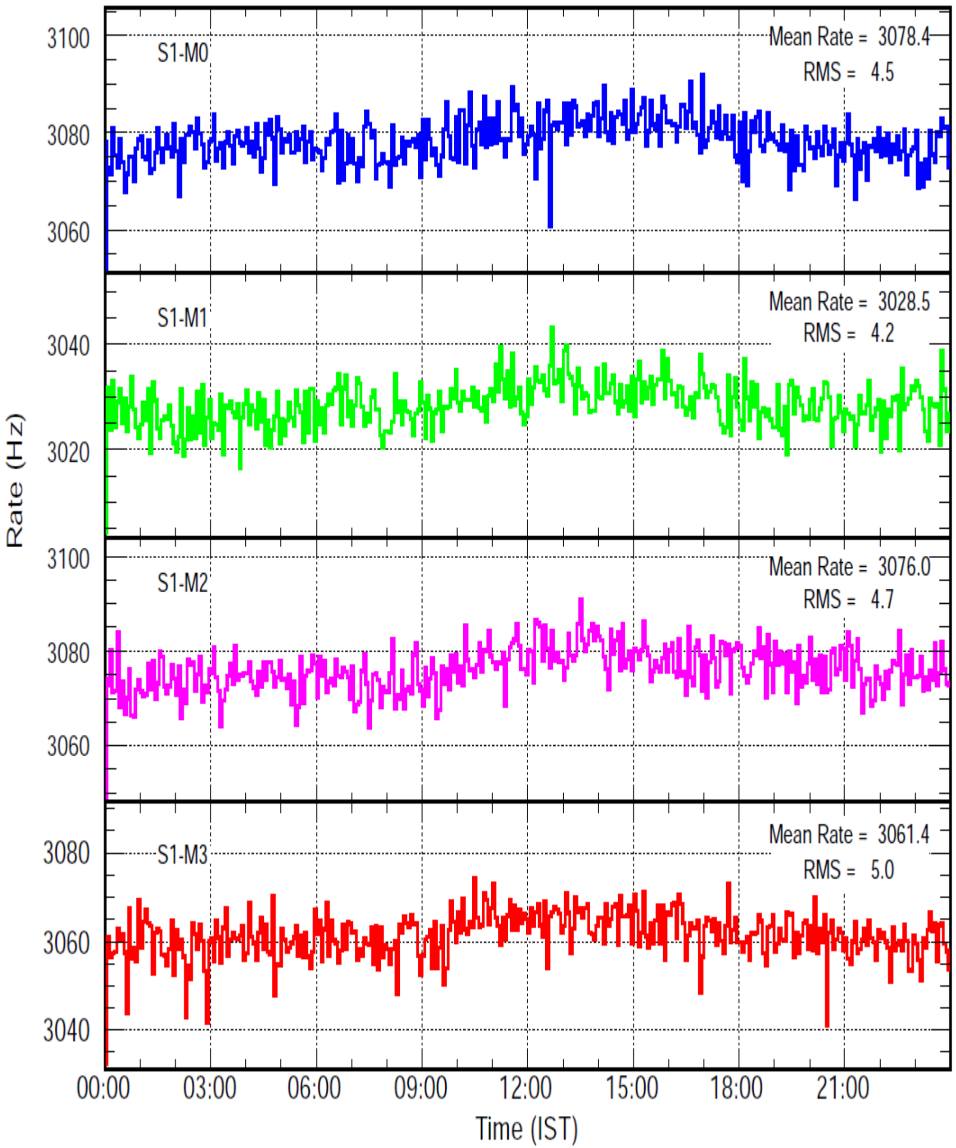
The number of muons being measured in a day counted by 560m^2 muon station is:

~ 4 billion in a day

Within 0.002% of statistical variations

Good statistics of muon data.

Most sensitive muon detector to measure tiny variation in cosmic ray flux



We propose to exploit this high statistics of muons measured by GRAPES-3, to identify appropriate hadronic interaction models.

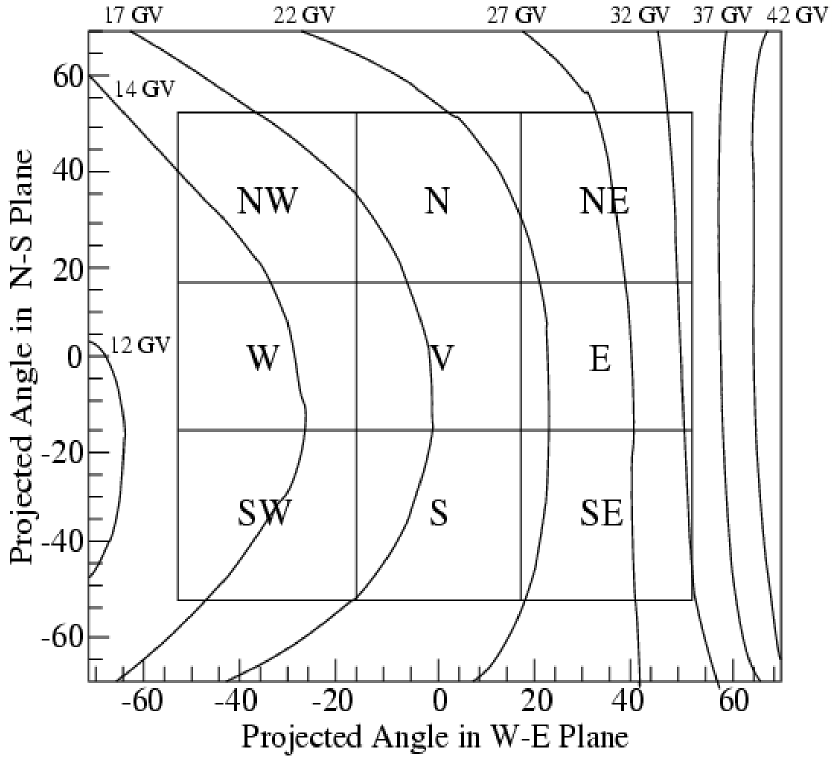
The 169 directional measurement of muon telescope demands a detailed simulation study of equally good statistical precision.

The geomagnetic rigidity cutoff for the GRAPES-3 muon telescope Field Of View (FOV) varies significantly.

GRAPES-3 cutoff rigidity measured using IGRF-11 and simulations varies from 14 to 32 GV.

10 GeV - 10 TeV for proton primaries
20 GeV – 20TeV for Helium primaries

Expect enough statistics for the simulation of secondary cosmic particles.



Spectral Index

For a precise determination of primary spectrum of H and He, the following direct measurements have been used

1) CREAM (Proton & Helium) Balloon Borne Experiment

Proton Energy Range: 2.5 TeV – 250.0 TeV, $\gamma_p = 2.66 \pm 0.02$,

Helium Energy Range: 0.63 TeV/n – 63.0 TeV/n, $\gamma_{he} = 2.58 \pm 0.02$

2) CAPRICE (Proton & Helium) Balloon Borne Experiment

Proton Energy Range: 20 GeV – 350GeV, $\gamma_p = 2.776 \pm 0.002$,

Helium Energy Range: 15 GeV/n – 150 GeV/n, $\gamma_{he} = 2.753 \pm 0.014$

3) BESS (Proton & Helium) Balloon Borne Experiment

Proton Energy Range: 30 GeV – 540GeV, $\gamma_p = 2.732 \pm 0.011$,

Helium Energy Range: 20 GeV/n – 250 GeV/n, $\gamma_{he} = 2.699 \pm 0.010$

4) PAMELA (Proton & Helium) Satellite Based Experiment

Proton Energy Range: 30 GeV – 1000GeV, $\gamma_p = 2.782 \pm 0.003$,

Helium Energy Range: 15 GeV/n – 600 GeV/n, $\gamma_{he} = 2.712 \pm 0.01$

5) AMS (Helium) Satellite Based Experiment

Helium Rigidity Range: 20 GV – 200 GV, $\gamma_{he} = 2.740 \pm 0.010$

PAMELA and AMS measured Proton & Helium flux in terms of rigidity while CREAM, CAPRICE and BESS have observed in terms of kinetic energy per nucleon.

Therefore, in order to generate cosmic rays showers by using CORSIKA-Simulator, which needs total energy of the primary particles as input, hence, we need to transform units of flux from:

$$(m^2 \text{ sr sec GeV-n}^{-1})^{-1} \text{ -->> } (m^2 \text{ sr sec GeV})^{-1}$$

$$(m^2 \text{ sr sec GV})^{-1} \text{ -->> } (m^2 \text{ sr sec GeV})^{-1}$$

K.E (GeV/n) ←→ Total Energy (GeV)

(m² sr sec GeV-n⁻¹)⁻¹ ←→ (m² sr sec GeV)⁻¹

$$\frac{dN}{dE_T} = K(E_T)^{-\gamma} \ (\text{m2 sr sec GeV-n}^{-1})^{-1}$$

$$\frac{dN}{dE_T} = K(E - mc^2)^{-\gamma}$$

$$\frac{dN}{dE_T} = KE^{-\gamma}\left(1 - \frac{mc^2}{E}\right)^{-\gamma}$$

$$\frac{dN}{dE_T} = \frac{dN}{dE}\left(\frac{E_T}{E}\right)^{-\gamma}$$

$$\frac{dN}{dE} = \left(\frac{E_T}{E}\right)^{\gamma}\frac{dN}{dE_T}$$

$(\text{m}^2 \text{ sr sec GeV-n}^{-1})^{-1}$

$$\frac{dN}{dE} = \frac{1}{n}\left(\frac{E_T}{E}\right)^{\gamma}\frac{dN}{dE_T} \ (\text{m}^2 \text{ sr sec GeV})^{-1}$$

Rigidity ←→ Total Energy (GeV) ←→ K.E (GeV/n)

$(m^2\ sr\ sec\ GV)^{-1}$ ←→ $(m^2\ sr\ sec\ GeV)^{-1}$ ←→ $(m^2\ sr\ sec\ GeV/n)^{-1}$

$$\frac{dN}{dR} = KR^{-\gamma}\ (m^2\ sr\ sec\ GV)^{-1}$$

$$\frac{dN}{dE} = \frac{dN}{dR}\frac{dR}{dE}$$

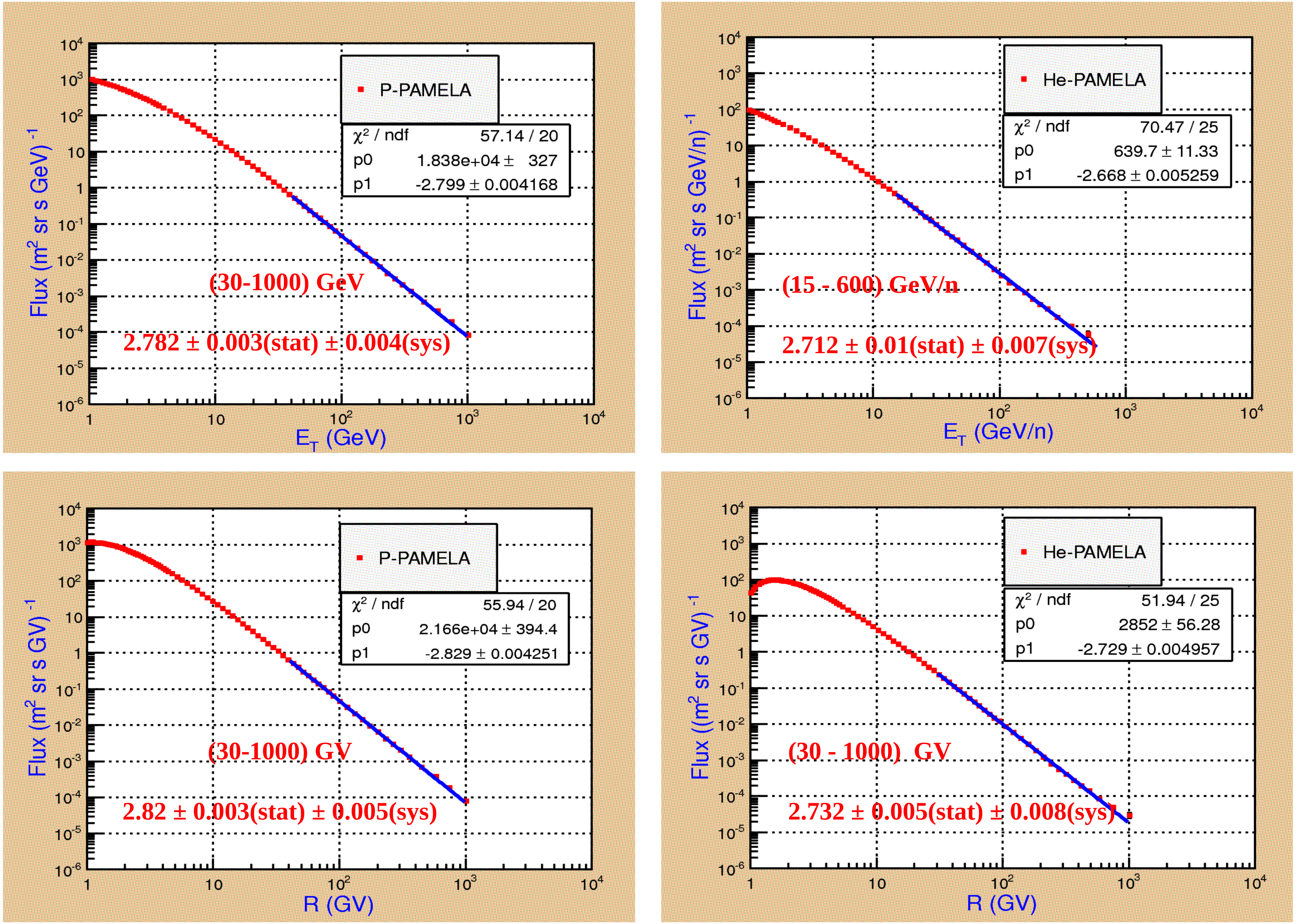
$$R = \frac{pc}{|z|e}$$

$$R = \frac{\sqrt{E^2 - m^2c^4}}{|z|e} = \frac{\sqrt{E_T(E_T + 2*mc^2)}}{|z|e}$$

$$\frac{dN}{dE} = \frac{E}{z^2}\frac{(dN/dR)}{R}\ (m^2\ sr\ sec\ GeV)^{-1}$$

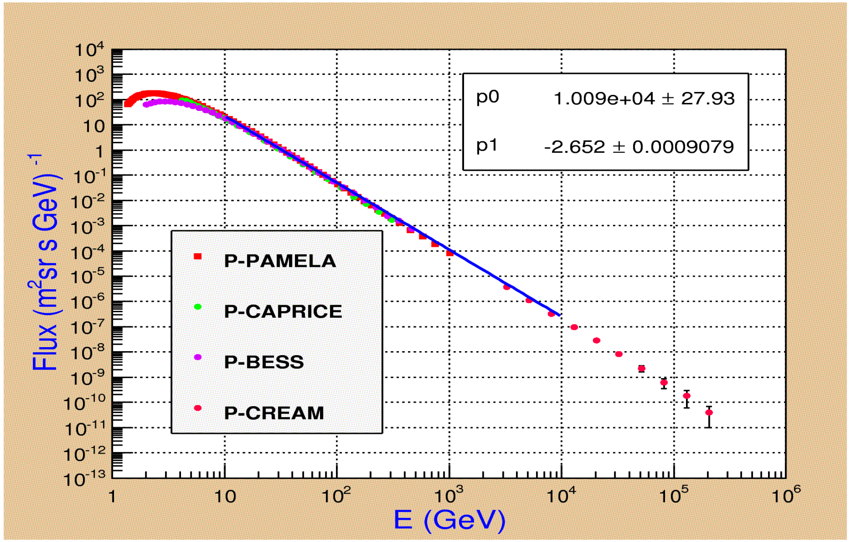
$$\frac{dN}{dE_T} = \frac{n*(E_T + mc^2)}{Z*\sqrt{E_T*(E_T + 2*mc^2)}}\left(\frac{dN}{dR}\right)\ (m^2\ sr\ sec\ GeV/n)^{-1}$$

PAMELA



P-PAMELA
χ^2 / ndf 57.14 / 20
p0 1.838e+04 ± 327
p1 -2.799 ± 0.004168
(30-1000) GeV
2.782 ± 0.003(stat) ± 0.004(sys)
Flux (m² sr s GeV) -1
E_T (GeV)
He-PAMELA
χ^2 / ndf 70.47 / 25
p0 639.7 ± 11.33
p1 -2.668 ± 0.005259
(15 - 600) GeV/n
2.712 ± 0.01(stat) ± 0.007(sys)
Flux (m² sr s GeV/n) -1
E_T (GeV/n)
P-PAMELA
χ^2 / ndf 55.94 / 20
p0 2.166e+04 ± 394.4
p1 -2.829 ± 0.004251
(30-1000) GV
2.82 ± 0.003(stat) ± 0.005(sys)
Flux (m² sr s GV) -1
R (GV)
He-PAMELA
χ^2 / ndf 51.94 / 25
p0 2852 ± 56.28
p1 -2.729 ± 0.004957
(30 - 1000) GV
2.732 ± 0.005(stat) ± 0.008(sys)
Flux ((m² sr s GV) -1
R (GV)

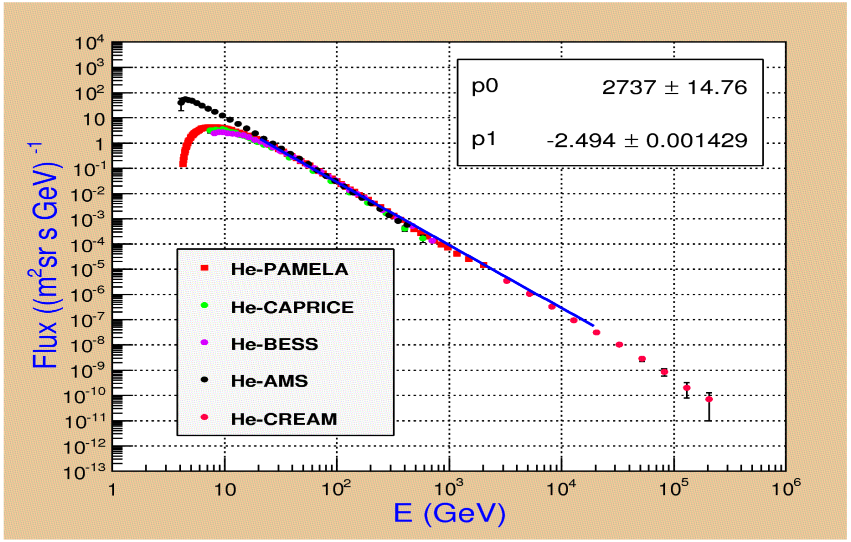
Since geomagnetic rigidity cutoff for GRAPES-3 FOV is 14 GV, we are fitting the all experimental points from 10GeV - 10TeV for Proton and 20GeV - 20TeV for Helium.



For Protons: 10GeV - 10TeV

$\gamma_p = 2.652 \pm 0.001$

$K_p = 1.009 \pm 0.0028 \times 10^4$



For Helium : 20GeV - 20TeV

$\gamma_{he} = 2.494 \pm 0.001$

$K_{he} = 2.740 \pm 0.0148 \times 10^3$

Shower Generation

Interaction of primary CRs with atmosphere by using CORSIKA-73700.

Precise study of simulation requires precise values of input parameters: spectral index in the selected energy range, zenith and azimuthal angle range, site location parameters, etc.

Input parameters for event generation:

Number of events to be produced about ~ 10^9.

Particle ID: Proton=14, Helium = 402 (A x 100 + Z)

Energy Slope: For proton = 2.652 ± 0.001 & Helium: 2.494 ± 0.001

Energy range: Proton: 10GeV – 10TeV & Helium: 20GeV – 20TeV.

Range of Zenith angle (in degrees): 0^0 - 60^0 & Azimuthal angle: 0^0 – 360^0.

Observation level at Ooty: 2200 x 10^2 cm

Computation for the generation of similar number of muons takes several months on a conventional computer of high performance(Dual Core processor).

We have cluster of 200 nodes each of 2.8TB memory, which is capable to complete multiple jobs in few days.

While generating billions of showers, modification in corsika.F has been done on the basis of the geomagnetic rigidity cutoff by using standard geomagnetic rigidity field model (IGRF-11).

Primaries are rejected before generation if their rigidity is smaller than the geomagnetic rigidity cutoff for that direction bin.

This modification improves the computing time and storage space.

In CORSIKA:

High Energy	**Low Energy**
SIBYLL 2.1	FLUKA
QGSJETII-04	GHEISHA 2002d
EPOS LHC	UrQMD 1.3cr

Before and after modified generation time and file size comparison

Generation Time (minutes)		
Models	**Before Modification**	**After Modification**
Sibyll_Gheisha	19	11
Sibyll_Fluka	52	28
Sibyll_Urqmd	116	64

Time has reduced by a factor of two after performing the modification

Data Size (GB)		
Models	**Before Modification**	**After Modification**
Sibyll_Gheisha	2.2	1.1
Sibyll_Fluka	2.2	1.1
Sibyll_Urqmd	2.2	1.1

Output file size has also reduced by a factor of two.

Same behavior was observed for other combinations of high and low energy models.

Computing time details for the 10^6 Proton primaries generation on the individual node of the cluster by using modified corsika.F

Computation Time (minutes)			
Models	**SIBYLL 2.1**	**QGSJET-II 04**	**EPOS**
GHEISHA	11	12	26
FLUKA 2002d	28	30	44
UrQMD 1.3cr	64	66	80

For each low energy model: EPOS takes longer time to generate same number of showers when compared to SIBYLL 2.1 and QGSJET-II 04.

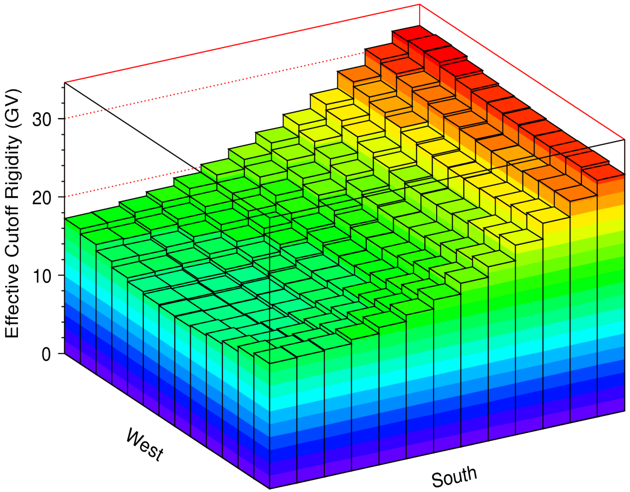
For each high energy model: UrQMD 1.3cr takes longer time than GHEISHA and FLUKA 2002d

SIBYLL 2.1 and QGSJET-II 04 take almost same amount of time irrespective of the low energy model used.

The three low energy models are used up to an energy of ~ 80GeV and afterwards the high energy hadronic interaction models are used.

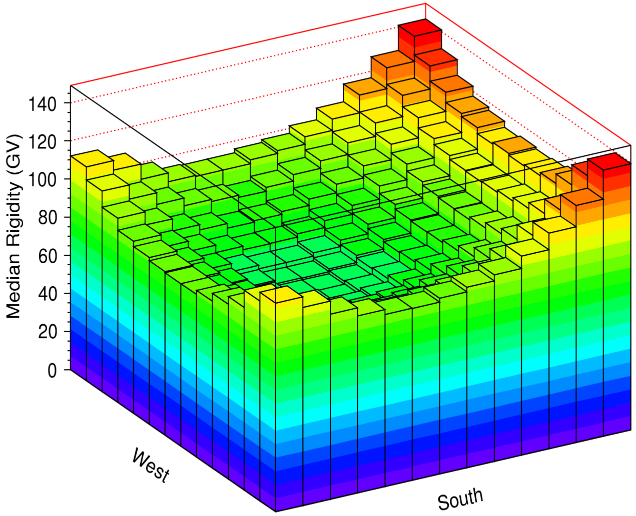
The median rigidity for GRAPES-3 is ~ 77GV, therefore, sensitivity to the low and high energy models can be tested.

Rigidity Cutoff Map



Range 14 - 32 GV

Median Rigidity Map



Range 64 - 141 GV

Summary

By combining different direct measurements of cosmic ray spectrum and after proper transformation we get the appropriate spectrum for proton and helium.

Spectral index values:
10GeV – 10TeV proton primaries γ_p = 2.652 ± 0.001
20GeV – 20TeV Helium primaries γ_{he} = 2.494 ± 0.001.

A comparative study of simulated data from various combinations of high and low energy interaction models is in progress.

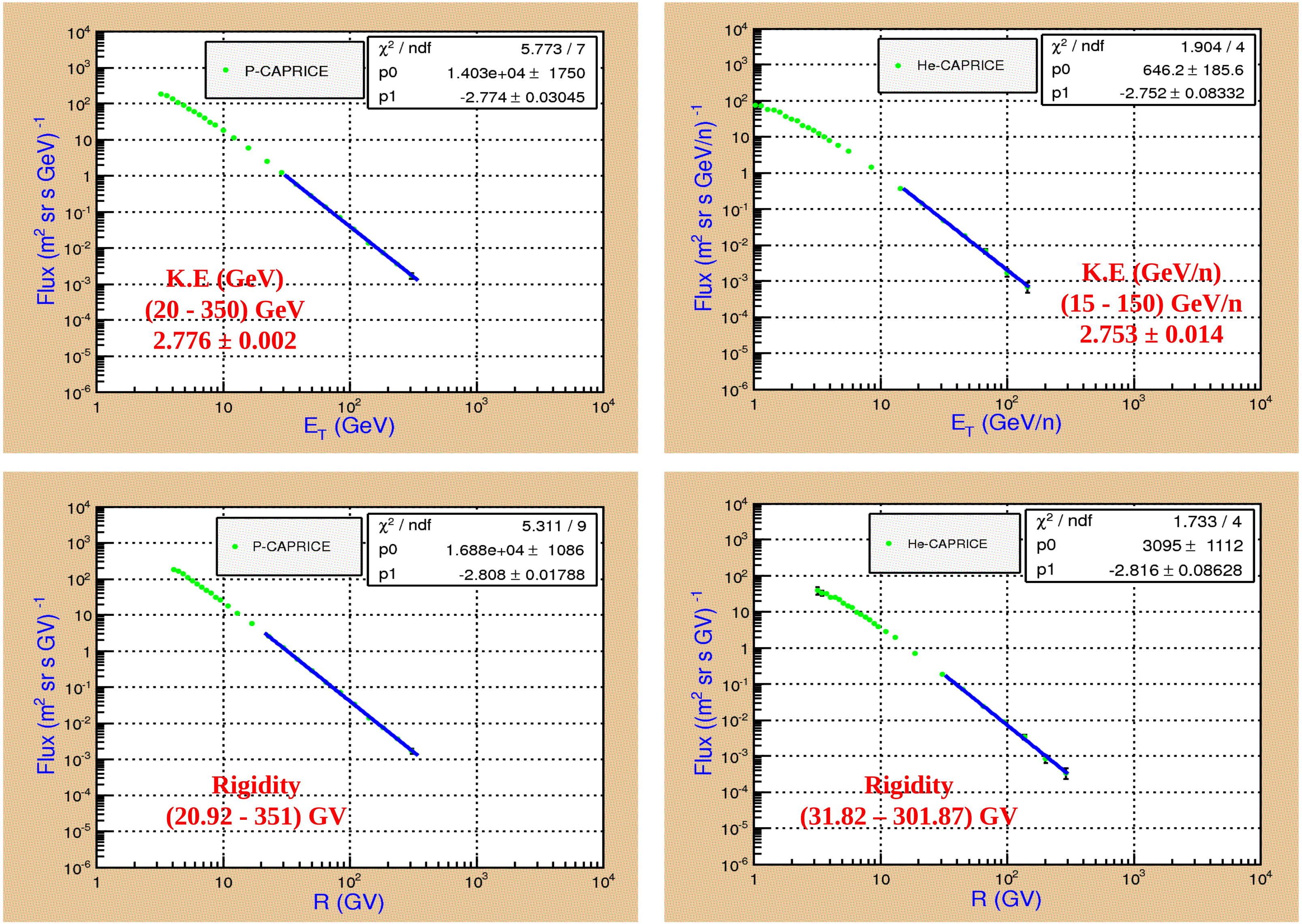
The results of simulated data will be compared with the GRAPES-3 muon data for identifying appropriate high and low energy hadronic interaction models.

So far 10^9 proton showers and 150×10^6 helium showers have been generated by using nine combination of high and low energy models.

Further analysis is under progress.

THANK YOU

CAPRICE

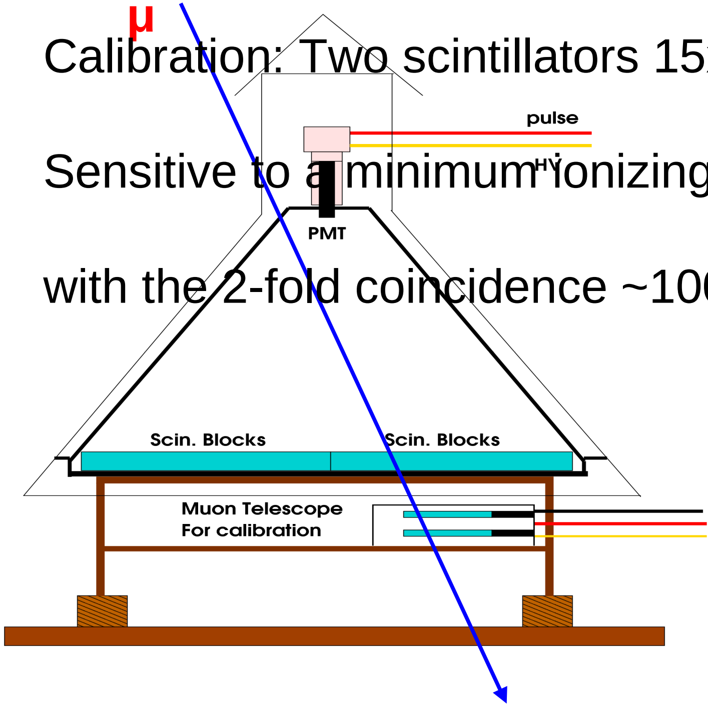


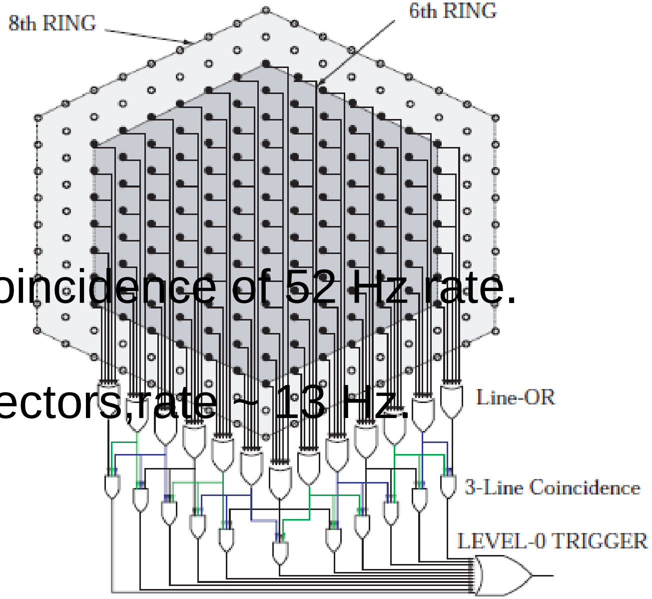
P-CAPRICE
χ² / ndf 5.773 / 7
p0 1.403e+04 ± 1750
p1 -2.774 ± 0.03045
Flux (m² sr s GeV)⁻¹
E_T (GeV)
K.E (GeV)
(20 - 350) GeV
2.776 ± 0.002
He-CAPRICE
χ² / ndf 1.904 / 4
p0 646.2 ± 185.6
p1 -2.752 ± 0.08332
Flux (m² sr s GeV/n)⁻¹
E_T (GeV/n)
K.E (GeV/n)
(15 - 150) GeV/n
2.753 ± 0.014
P-CAPRICE
χ² / ndf 5.311 / 9
p0 1.688e+04 ± 1086
p1 -2.808 ± 0.01788
Flux (m² sr s GV)⁻¹
R (GV)
Rigidity
(20.92 - 351) GV
He-CAPRICE
χ² / ndf 1.733 / 4
p0 3095 ± 1112
p1 -2.816 ± 0.08628
Flux ((m² sr s GV)⁻¹
R (GV)
Rigidity
(31.82 – 301.87) GV

Calibration: Two scintillators 15x15 cm2 area of 5 cm thickness with the 5 cm separation

Sensitive to a minimum ionizing particles.

with the 2-fold coincidence ~100 ns selects almost all muons of zenith angle θ ≤ 500.

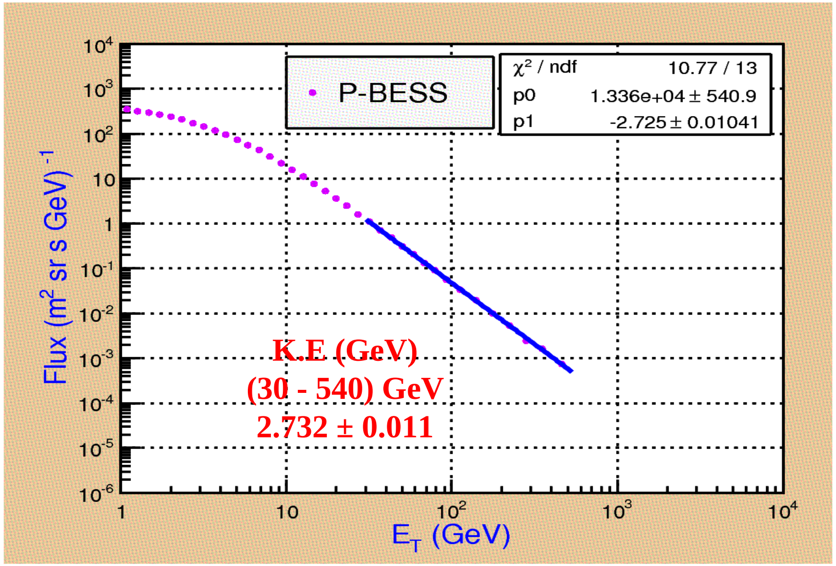


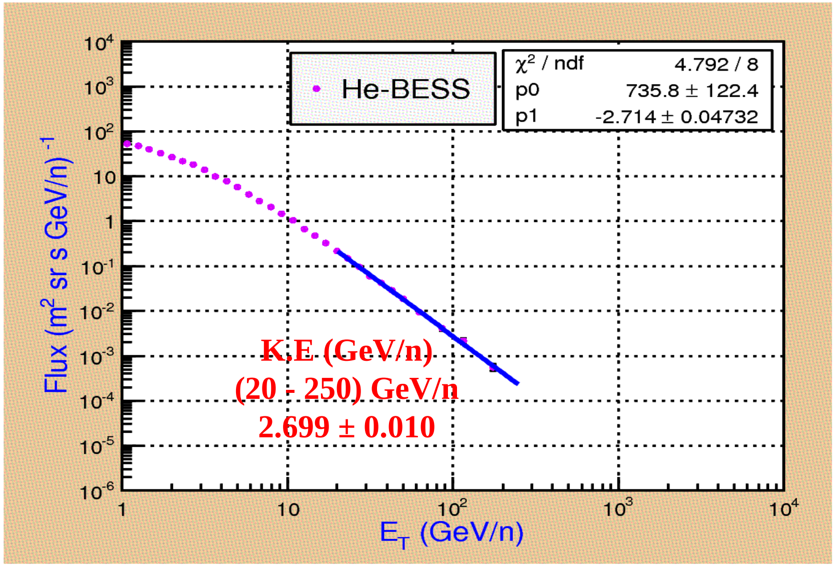


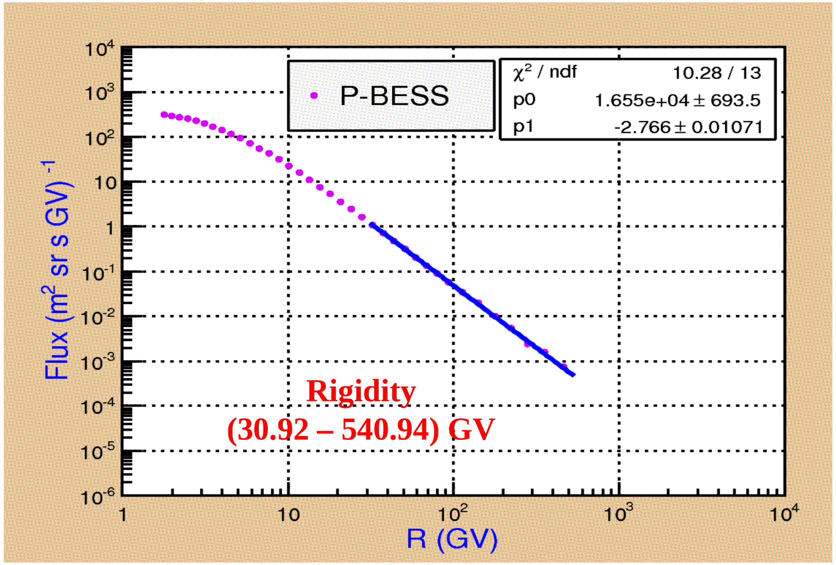
s level - 0 trigger: To achieve a low energy threshold 3 line coincidence of 52 Hz rate.

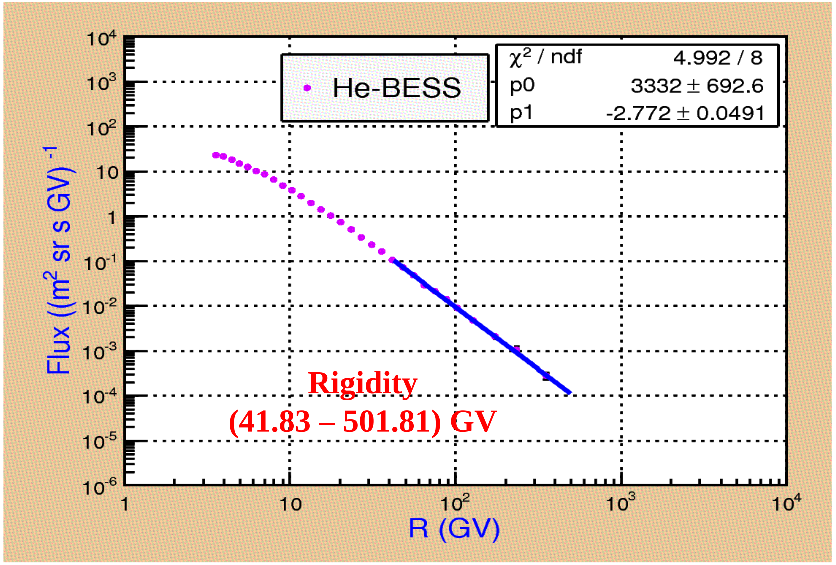
vel – 1 trigger: At least 10 detectors should hit out of 127 detectors,rate ~ 13 Hz.

BESS

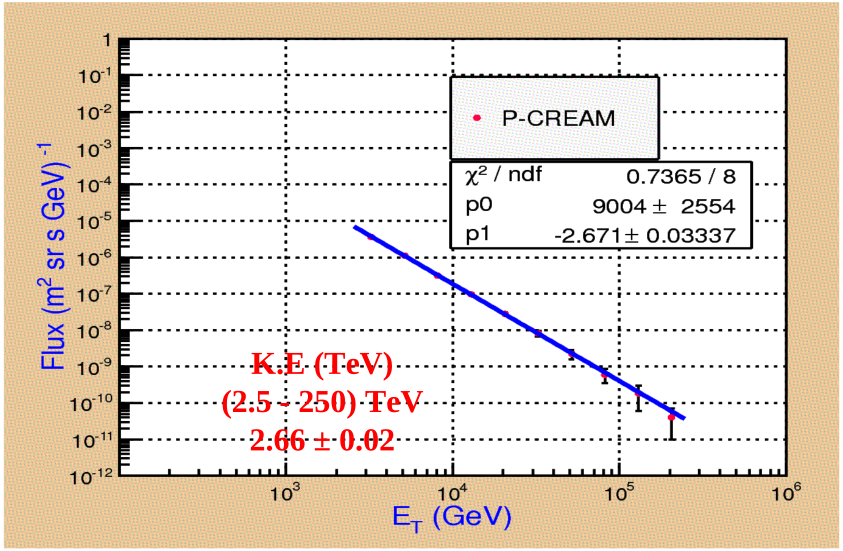

P-BESS
χ^2 / ndf 10.77 / 13
p0 1.336e+04 ± 540.9
p1 -2.725 ± 0.01041
K.E (GeV)
(30 - 540) GeV
2.732 ± 0.011
Flux (m² sr s GeV)⁻¹
E_T (GeV)


He-BESS
χ^2 / ndf 4.792 / 8
p0 735.8 ± 122.4
p1 -2.714 ± 0.04732
K.E (GeV/n)
(20 - 250) GeV/n
2.699 ± 0.010
Flux (m² sr s GeV/n)⁻¹
E_T (GeV/n)

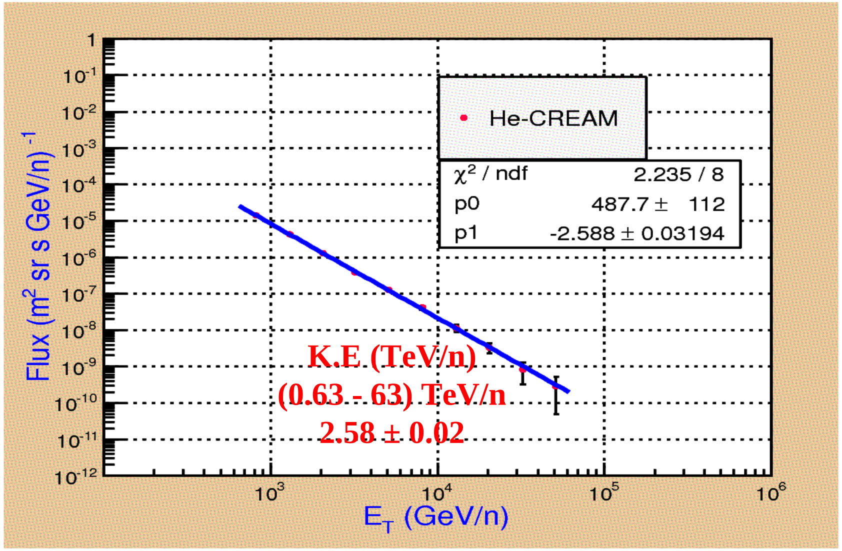

P-BESS
χ^2 / ndf 10.28 / 13
p0 1.655e+04 ± 693.5
p1 -2.766 ± 0.01071
Rigidity
(30.92 – 540.94) GV
Flux (m² sr s GV)⁻¹
R (GV)


He-BESS
χ^2 / ndf 4.992 / 8
p0 3332 ± 692.6
p1 -2.772 ± 0.0491
Rigidity
(41.83 – 501.81) GV
Flux ((m² sr s GV)⁻¹
R (GV)

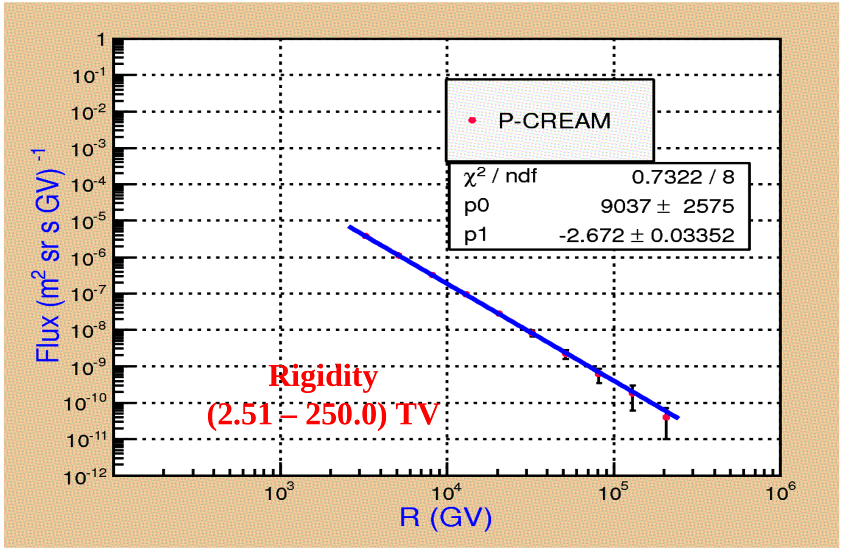
CREAM



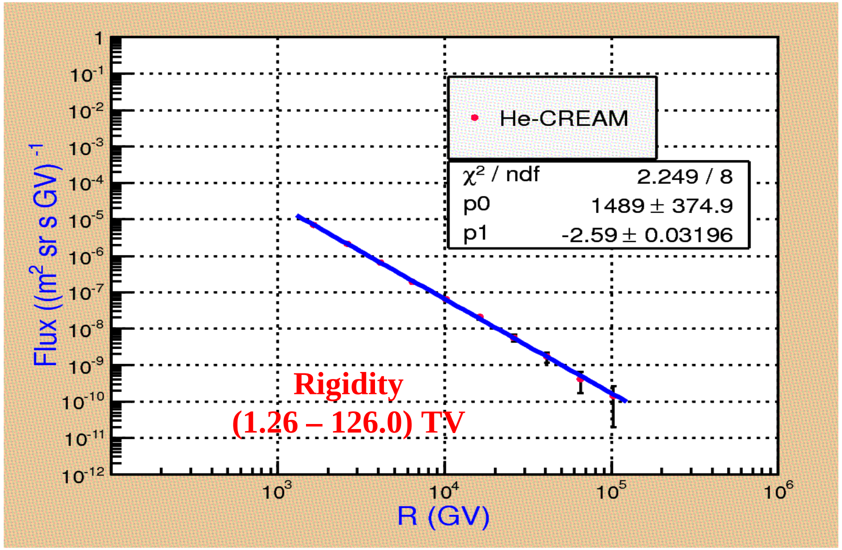
P-CREAM
χ^2 / ndf 0.7365 / 8
p0 9004 ± 2554
p1 -2.671 ± 0.03337
K.E (TeV)
(2.5 - 250) TeV
2.66 ± 0.02
Flux (m² sr s GeV)⁻¹
E_T (GeV)



He-CREAM
χ^2 / ndf 2.235 / 8
p0 487.7 ± 112
p1 -2.588 ± 0.03194
K.E (TeV/n)
(0.63 - 63) TeV/n
2.58 ± 0.02
Flux (m² sr s GeV/n)⁻¹
E_T (GeV/n)

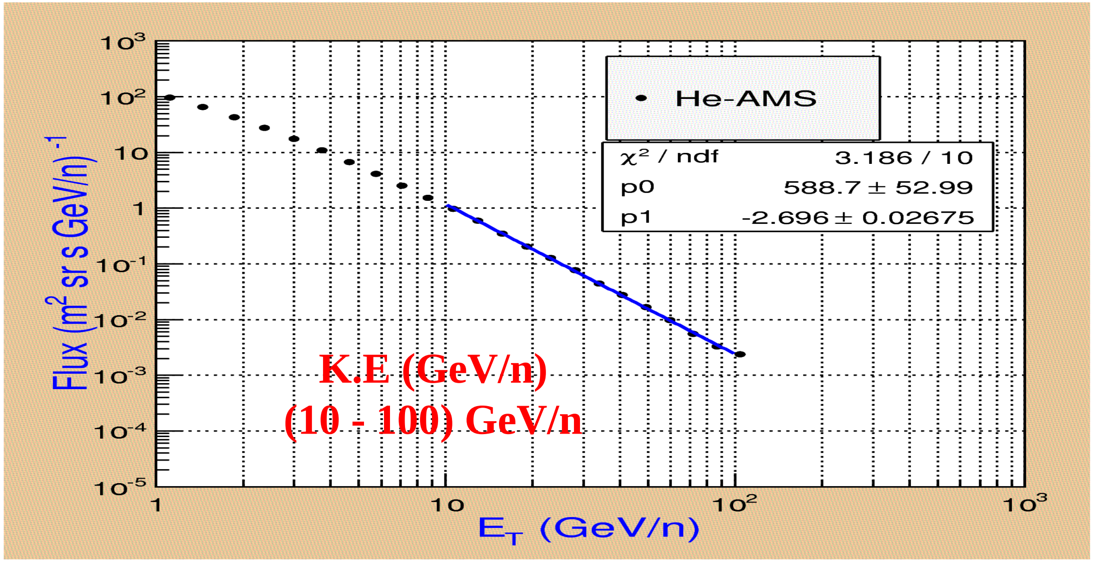


P-CREAM
χ^2 / ndf 0.7322 / 8
p0 9037 ± 2575
p1 -2.672 ± 0.03352
Rigidity
(2.51 – 250.0) TV
Flux (m² sr s GV)⁻¹
R (GV)

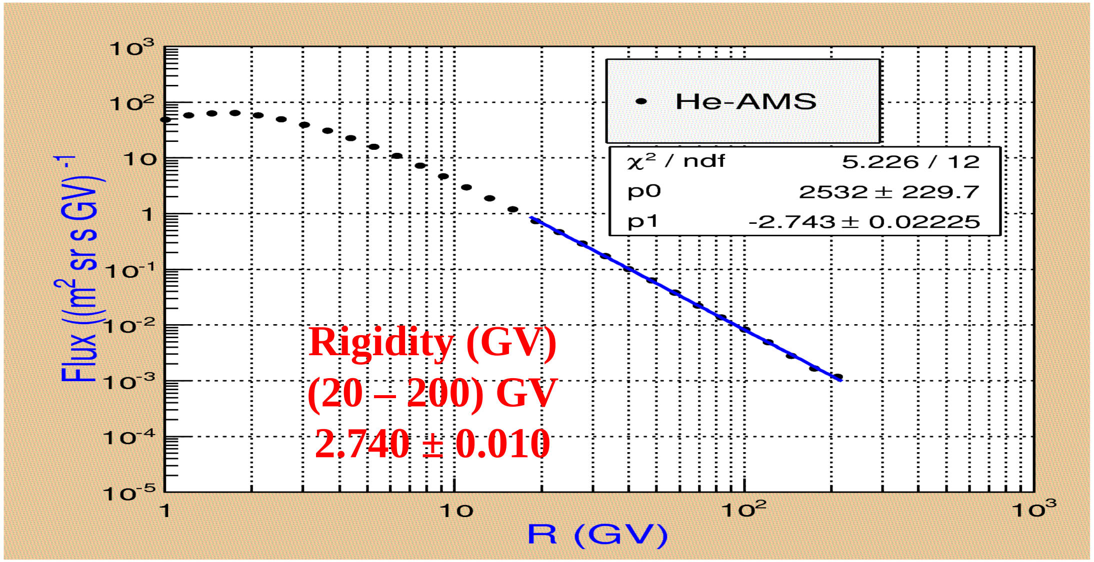


He-CREAM
χ^2 / ndf 2.249 / 8
p0 1489 ± 374.9
p1 -2.59 ± 0.03196
Rigidity
(1.26 – 126.0) TV
Flux ((m² sr s GV)⁻¹
R (GV)

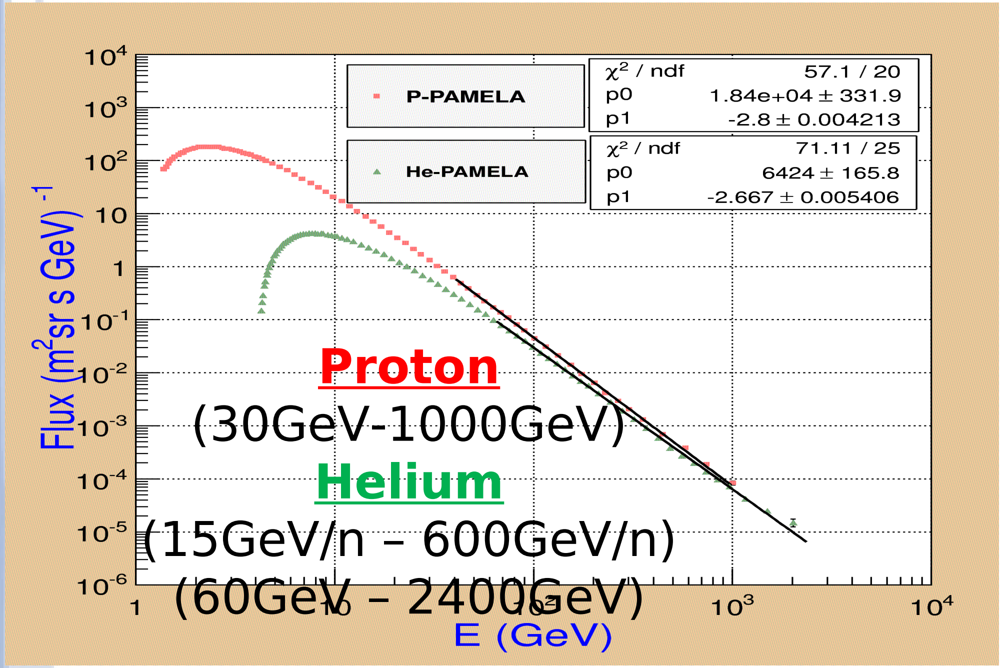
AMS



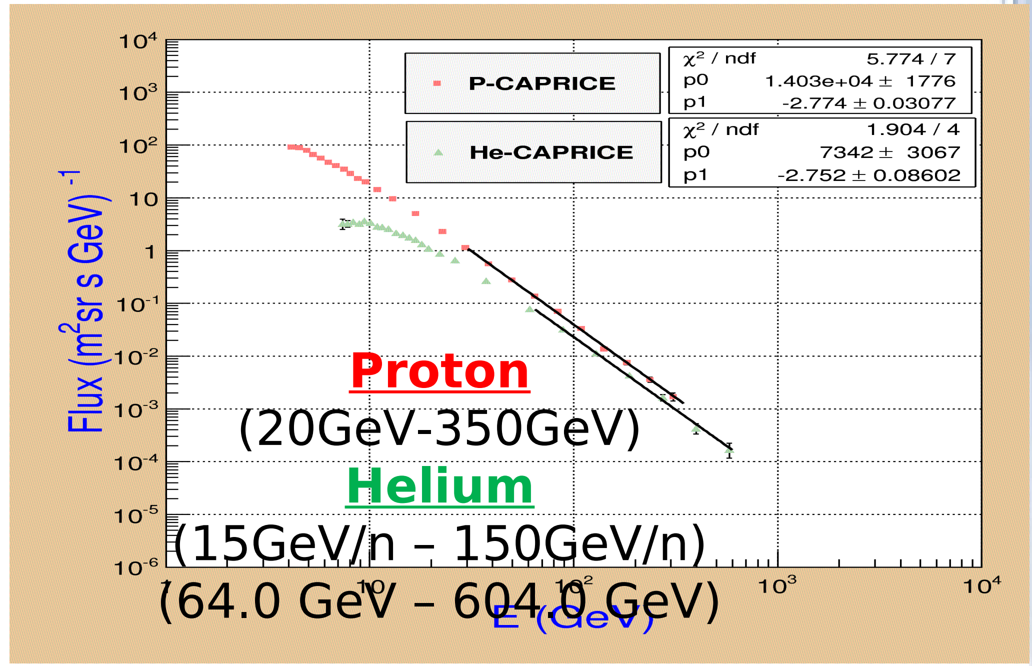
He-AMS
χ² / ndf 3.186 / 10
p0 588.7 ± 52.99
p1 -2.696 ± 0.02675
K.E (GeV/n)
(10 - 100) GeV/n
Flux (m² sr s GeV/n)⁻¹
E_T (GeV/n)



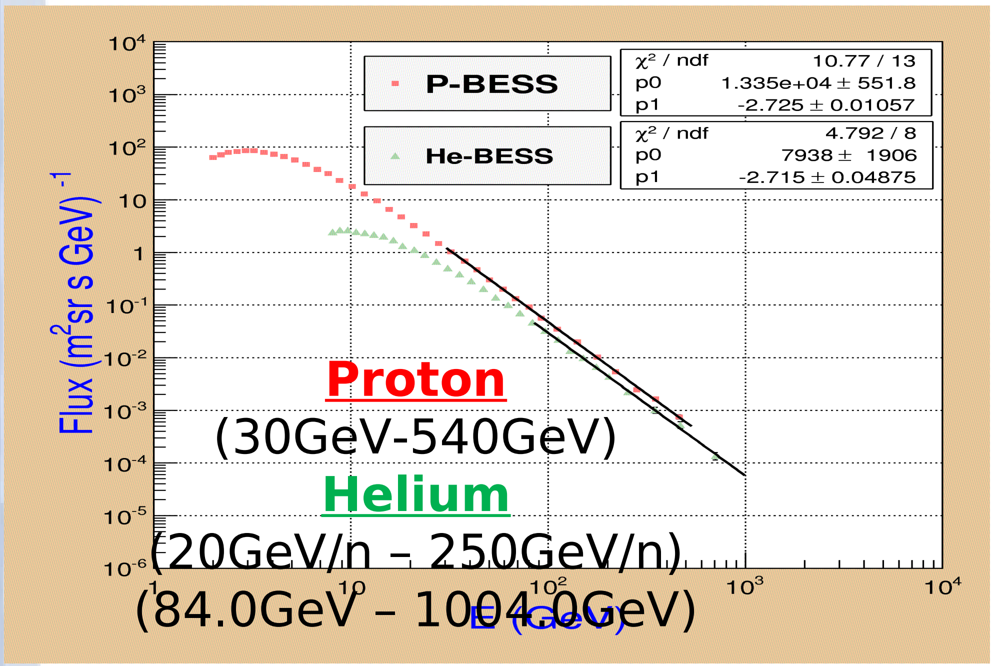
He-AMS
χ² / ndf 5.226 / 12
p0 2532 ± 229.7
p1 -2.743 ± 0.02225
Rigidity (GV)
(20 – 200) GV
2.740 ± 0.010
Flux ((m² sr s GV)⁻¹
R (GV)



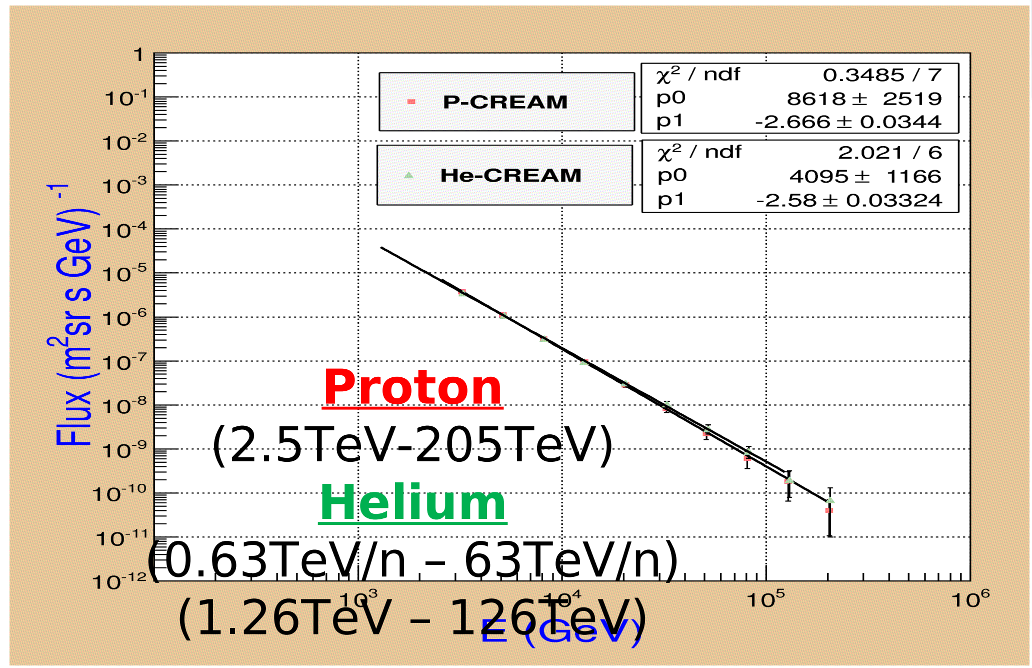
P-PAMELA
He-PAMELA
χ² / ndf 57.1 / 20
p0 1.84e+04 ± 331.9
p1 -2.8 ± 0.004213
χ² / ndf 71.11 / 25
p0 6424 ± 165.8
p1 -2.667 ± 0.005406
Flux (m²sr s GeV)⁻¹
E (GeV)
Proton
(30GeV-1000GeV)
Helium
(15GeV/n – 600GeV/n)
(60GeV – 2400GeV)



P-CAPRICE
He-CAPRICE
χ² / ndf 5.774 / 7
p0 1.403e+04 ± 1776
p1 -2.774 ± 0.03077
χ² / ndf 1.904 / 4
p0 7342 ± 3067
p1 -2.752 ± 0.08602
Flux (m²sr s GeV)⁻¹
E (GeV)
Proton
(20GeV-350GeV)
Helium
(15GeV/n – 150GeV/n)
(64.0 GeV – 604.0 GeV)

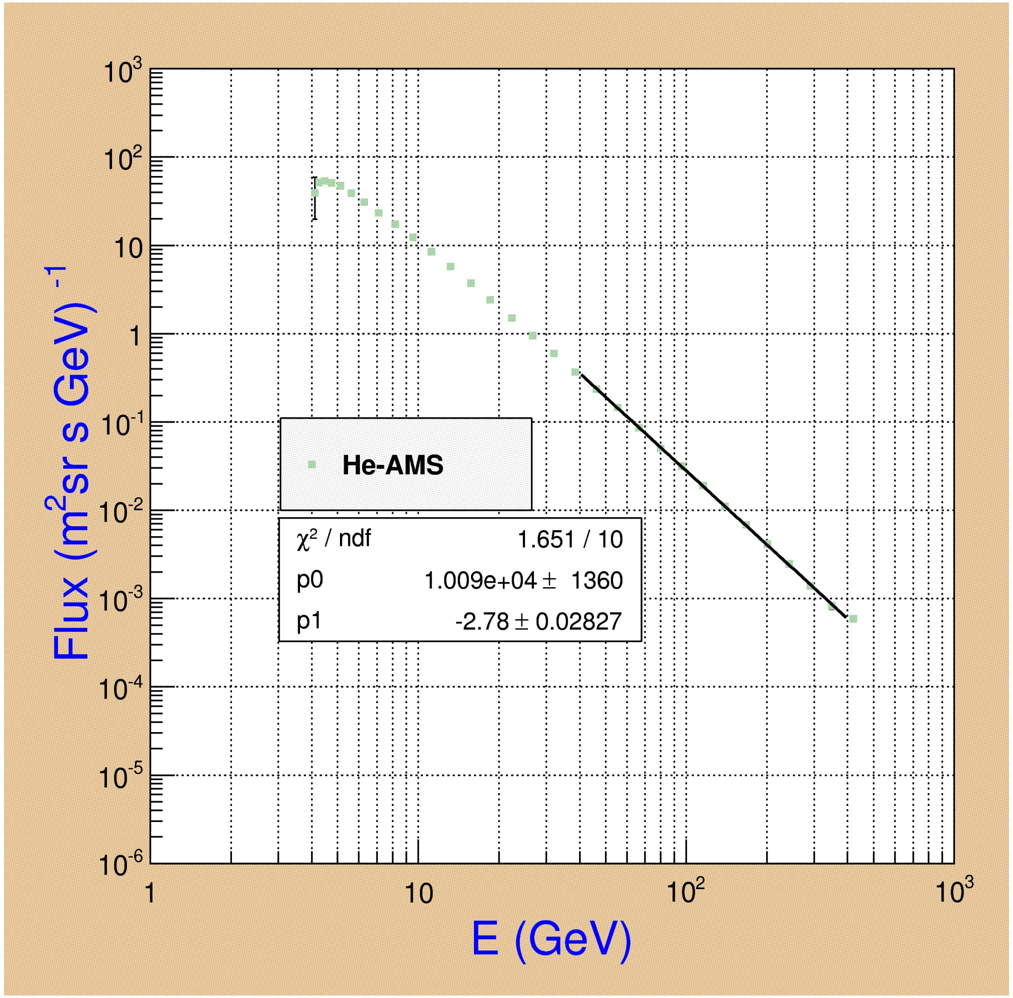


P-BESS
He-BESS
χ² / ndf 10.77 / 13
p0 1.335e+04 ± 551.8
p1 -2.725 ± 0.01057
χ² / ndf 4.792 / 8
p0 7938 ± 1906
p1 -2.715 ± 0.04875
Flux (m²sr s GeV)⁻¹
E (GeV)
Proton
(30GeV-540GeV)
Helium
(20GeV/n – 250GeV/n)
(84.0GeV – 1004.0GeV)



P-CREAM
He-CREAM
χ² / ndf 0.3485 / 7
p0 8618 ± 2519
p1 -2.666 ± 0.0344
χ² / ndf 2.021 / 6
p0 4095 ± 1166
p1 -2.58 ± 0.03324
Flux (m²sr s GeV)⁻¹
E (GeV)
Proton
(2.5TeV-205TeV)
Helium
(0.63TeV/n – 63TeV/n)
(1.26TeV – 126TeV)

AMS



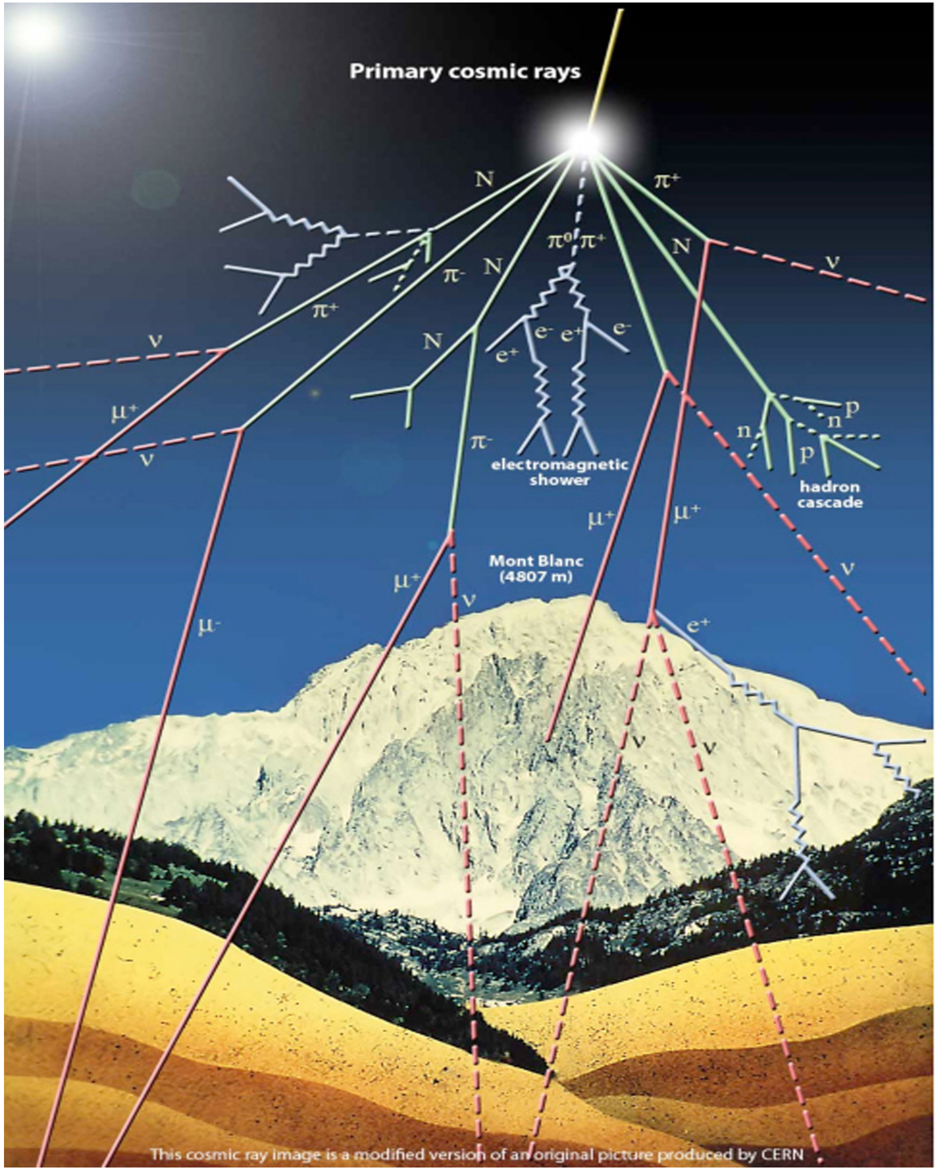
Helium

R ⬛ (20GV – 200GV)

E ⬛ (40GeV – 400GeV)

Cosmic Rays

- These are the charged particles or <u>atomic nuclei</u> zooming through space
  - Called “primary” CRs
  - Mostly protons or α (He) nuclei (other elements too, in much shorter supply)
  - There are more coming in at lower than higher energies
- When these hit another nucleus in the atmosphere and stop, more particles are knocked downward, causing a cascading effect called a “shower”
  - Particles in the shower are called “secondary” Crs
  - E.M and Hadronic components



mic Ray Spectrum:

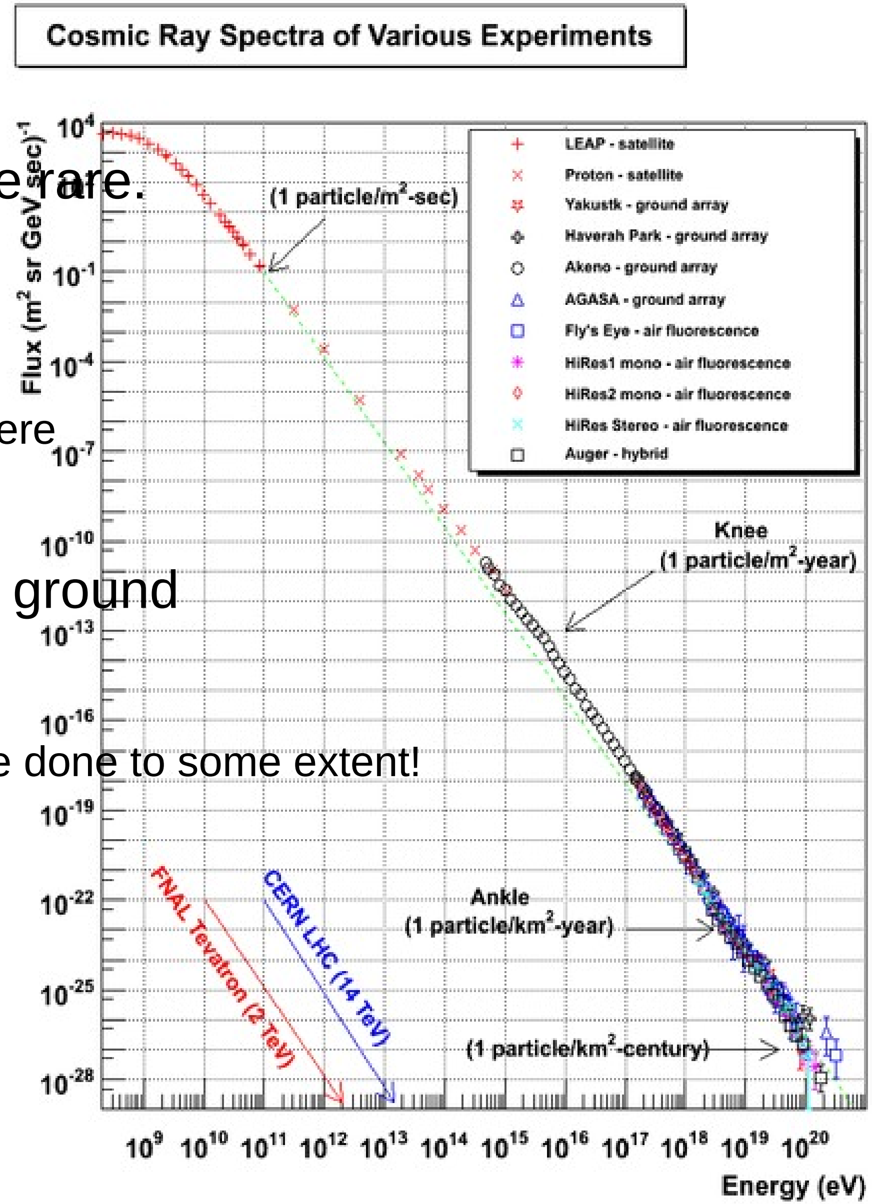
y CRs are common, while high-energy CRs are rare.

naries, observatories are put in space

he original cosmic ray w/o interference from the atmosphere
ensive detector that is too small to “catch” a lot of Crs.

ondary showers, observatories are put on the ground

heaper, bigger, and detect a lot more!
ne work to figure out what the primary is like. But it can be done to some extent!



- BIGGER = BETTER

nerate one kind of primaries in some fraction of other.

with in the selected energy ranges for proton and helium primaries for the same solid angle and e

e K and γ values from the spectrum for all the experimental data sets used earlier.

.5 x 107 helium primaries for 20GeV - 20TeV energy ranges.

in the CORSIKA program, which caused the unwanted primaries to be rejected have their rigidity

nost 50% of the unmodified CORSIKA generation.

are produced when pion decay, whereas pion is being produced in the shower developed in the a

mic rays that reach the Earth's surface. We look for them to detect that a primary cosmic ray has