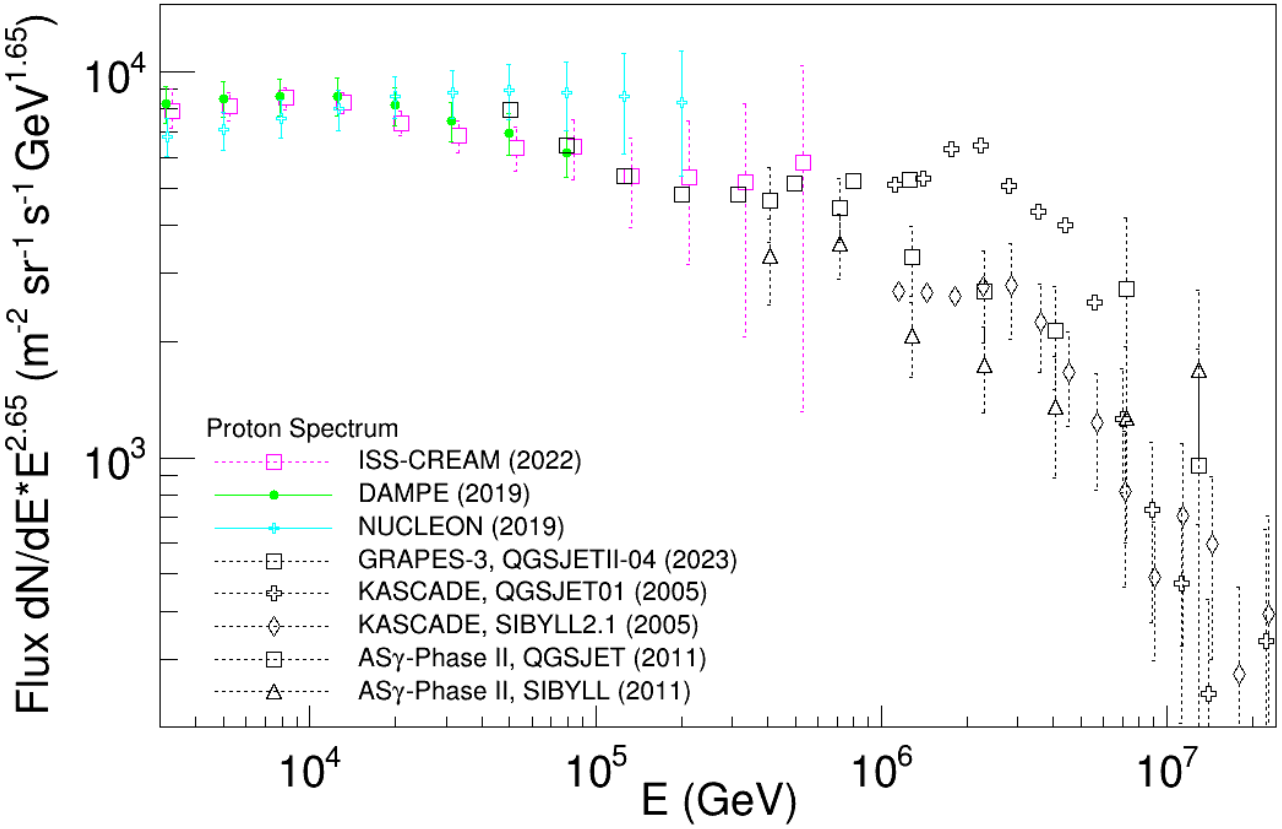
Measurement of the cosmic ray proton spectrum around the knee region with LHAASO

Zhiyong You
Institute of High Energy Physics, CAS

2024.06
Erice · Italy

Proton spectrum instruction

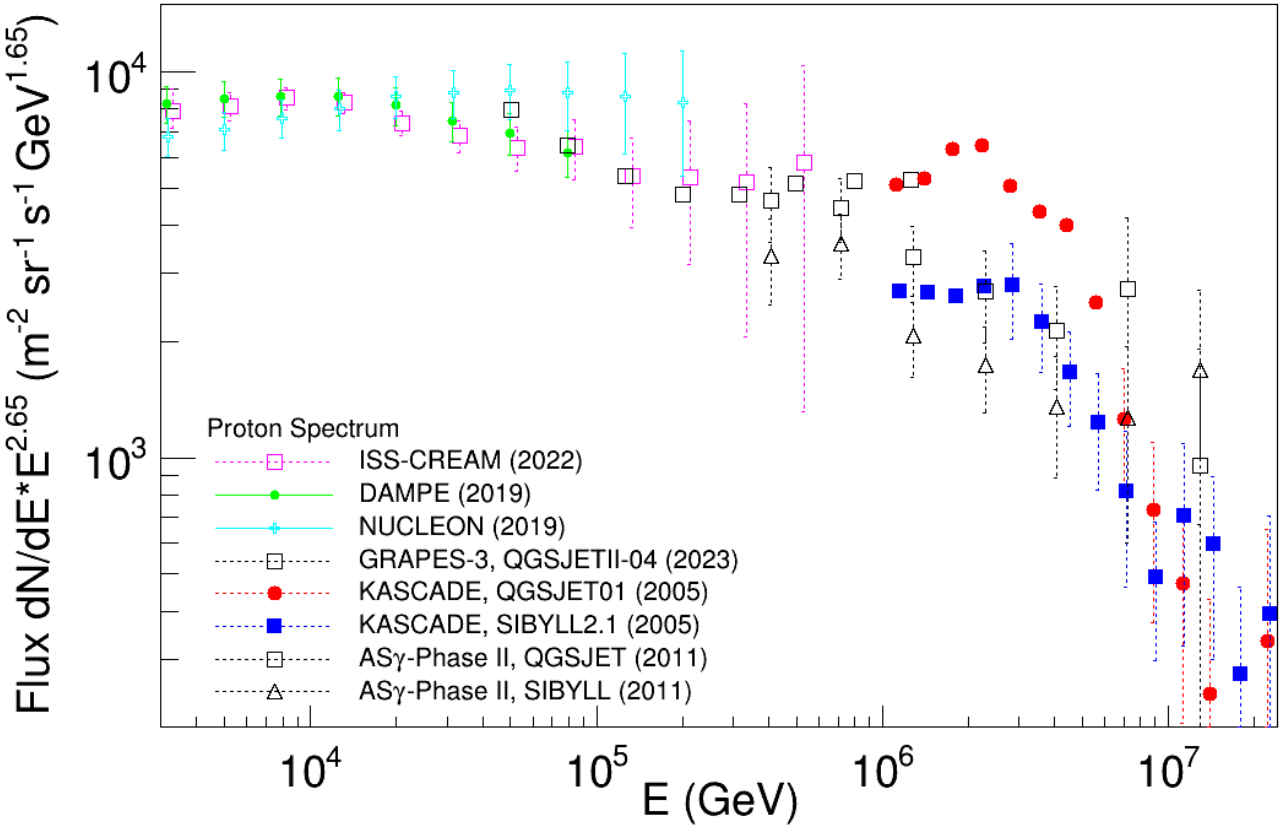
- Space-borne experiment: large statistical uncertainties
  - ISS-CREAM
  - DAMPE
  - NUCLEON
- Ground-based experiment: large systematic uncertainties
  - KASCADE
  - ASγ
  - GRAPES-3



Key to measure proton spectrum: Good energy resolution. High proton purity. Large statistics.

Proton spectrum instruction

- Space-borne experiment: large statistical uncertainties
  - ISS-CREAM
  - DAMPE
  - NUCLEON
- Ground-based experiment: large systematic uncertainties
  - KASCADE
  - ASγ
  - GRAPES-3



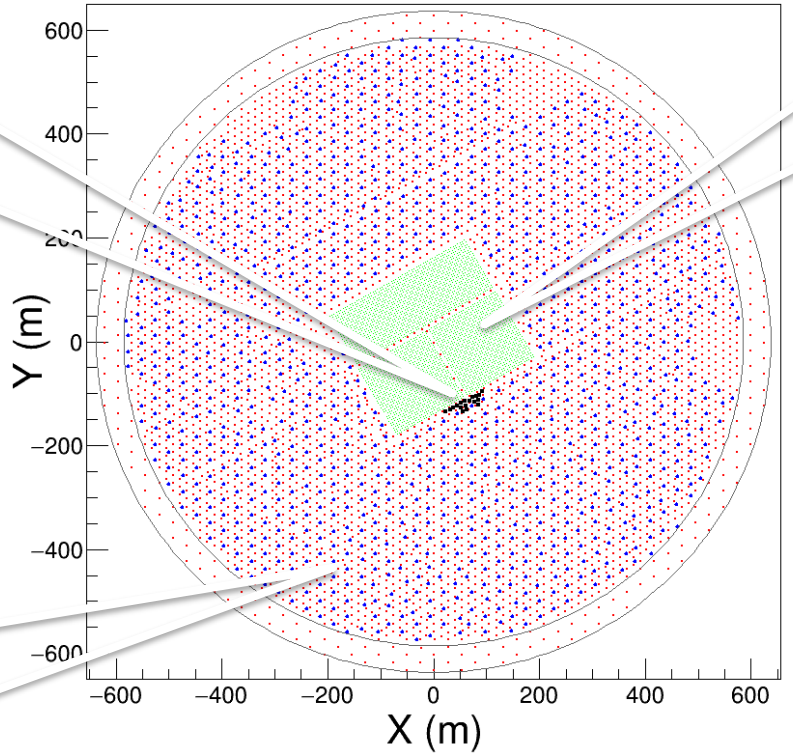
Key to measure proton spectrum: Good energy resolution. High proton purity. Large statistics.

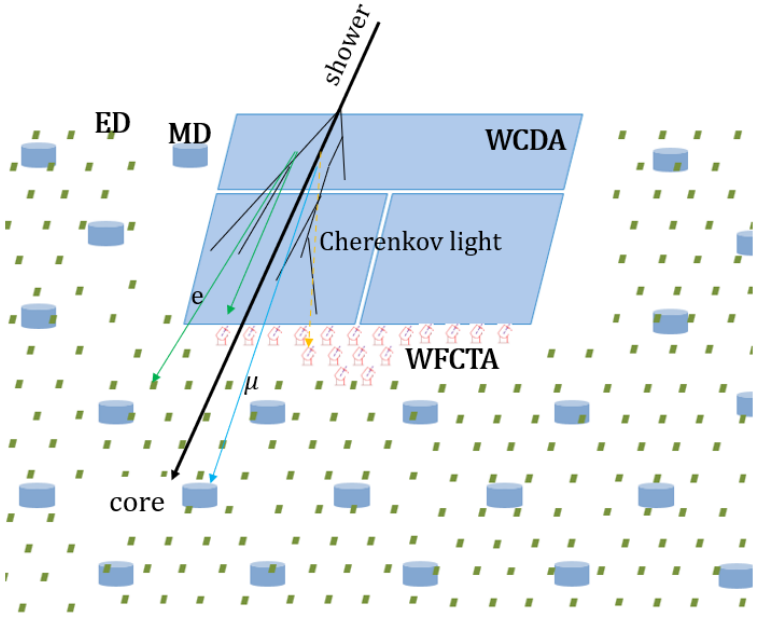
LHAASO experiment

WFCTA: 18 Telescopes

WCDA: (78000m^2) 3120 detector units.

KM2A: (ED, MD, 1.3 km^2) ED: 5195 MD: 1188 (4% coverage rate)

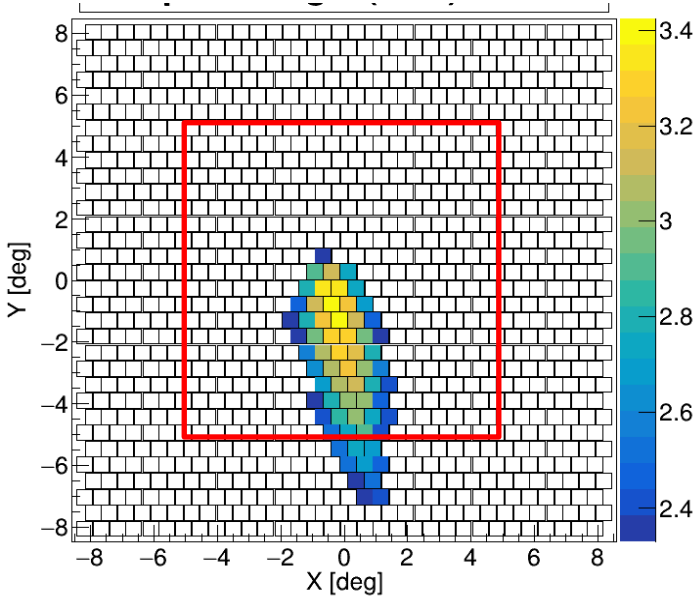


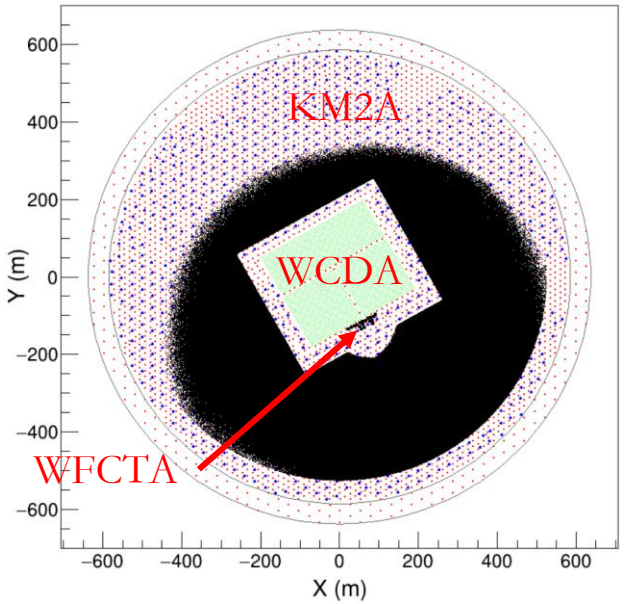


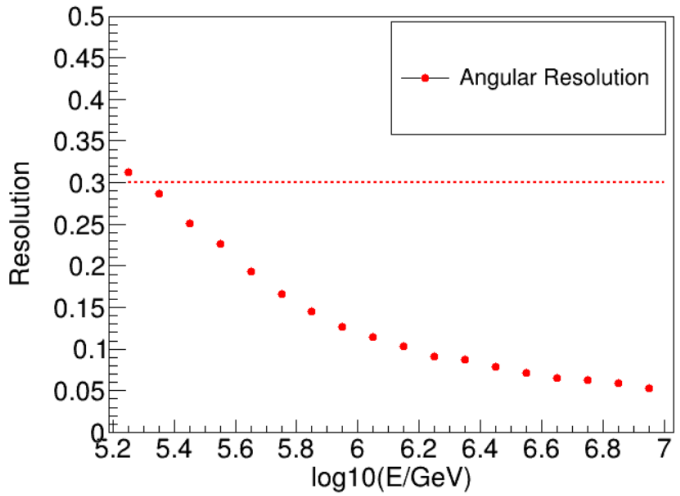
Data set

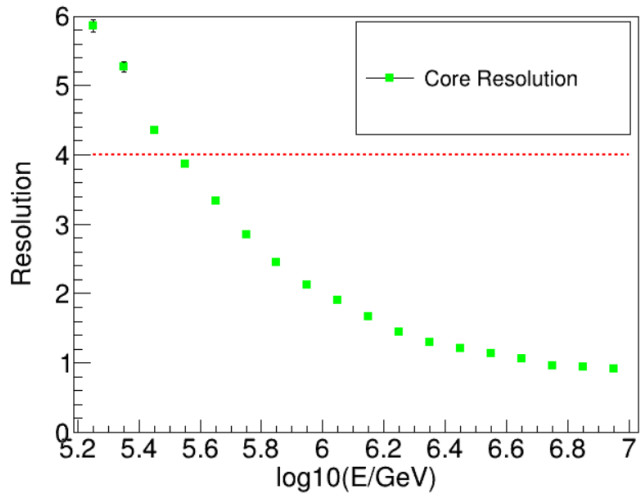
- Data selection
  - **WFCTA:**
  - $N_{tube}>10$
  - Centroid of the Cherenkov image limited in $\pm 5^{\circ}$
  - **KM2A:**
  - shower core located in KM2A
  - More than 20 EDs fired
  - Perpendicular distance from shower axis to telescopes (Rp): 100m~300m

- Geometry reconstruction (>300TeV)
  - Angular resolution: < 0.3˚
  - Core resolution: < 4 m









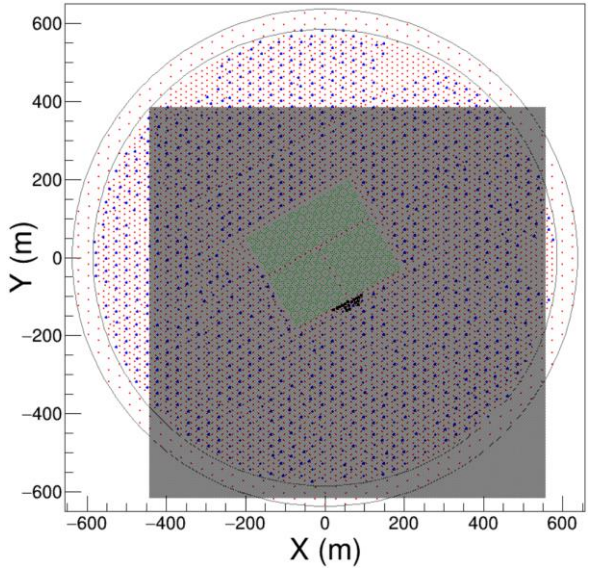
Simulation

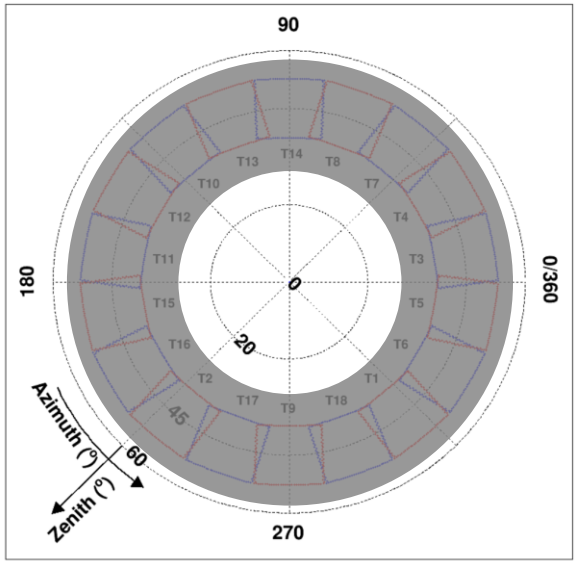
EAS simulation

- EAS simulation package: CORSIKA 7.4005
- Hadronic model: QGSJETII04 + FLUKA, EPOS-LHC+FLUKA

Event sample

- Primary particles: proton, helium, CNO, MgAlSi, iron
- Energy range: 10TeV~10PeV
- Spectrum index: -1
- Core range: ±500 m (Taking the center of the telescope array as the zero point)
- Direction range: zenith: 30~50 deg, azimuth: 0~360 deg





Energy reconstruction

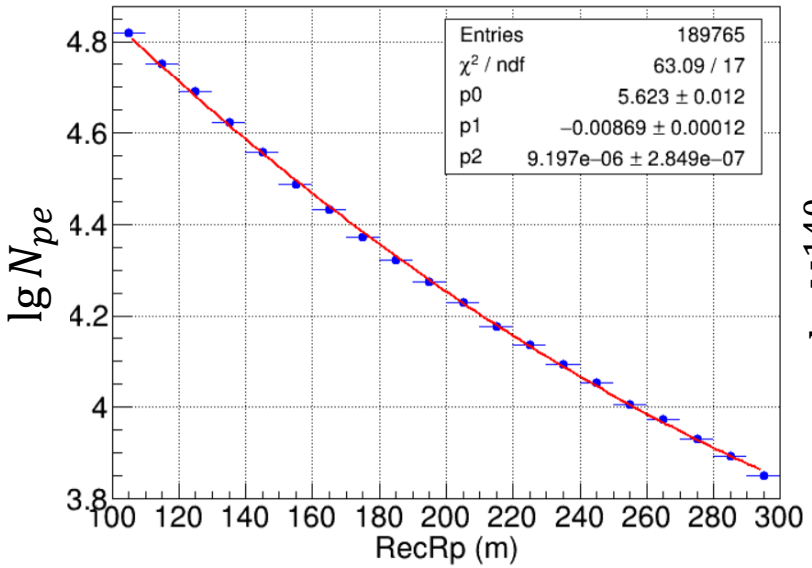
$$N_{pe}^{140} = N_{pe} - a \times (R_p - 140m)^2 - b \times (Rp - 140m)$$

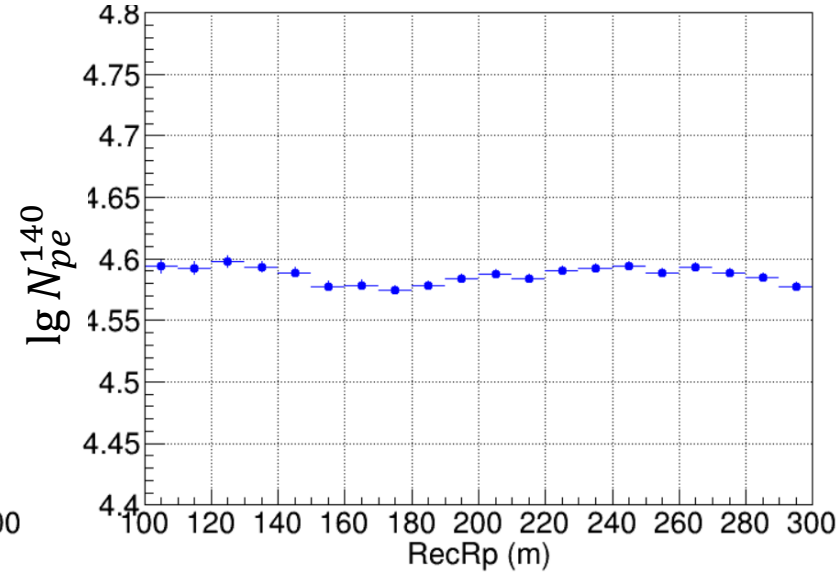
$$\lg E_{rec} = A \times \lg^2 N_{pe}^{140} + B \times \lg N_{pe}^{140} + C$$

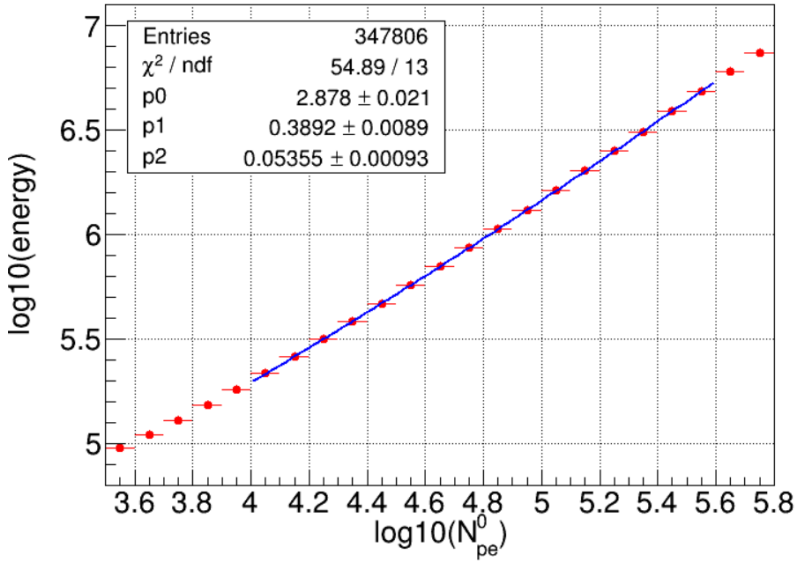
N_{pe}: number of photon-electrons in the Cherenkov image

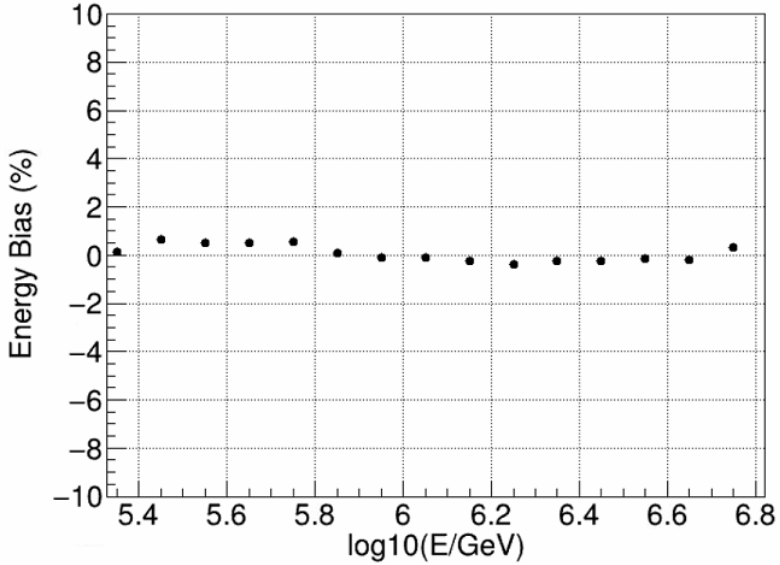
Rp: Perpendicular distance from telescope to shower axis

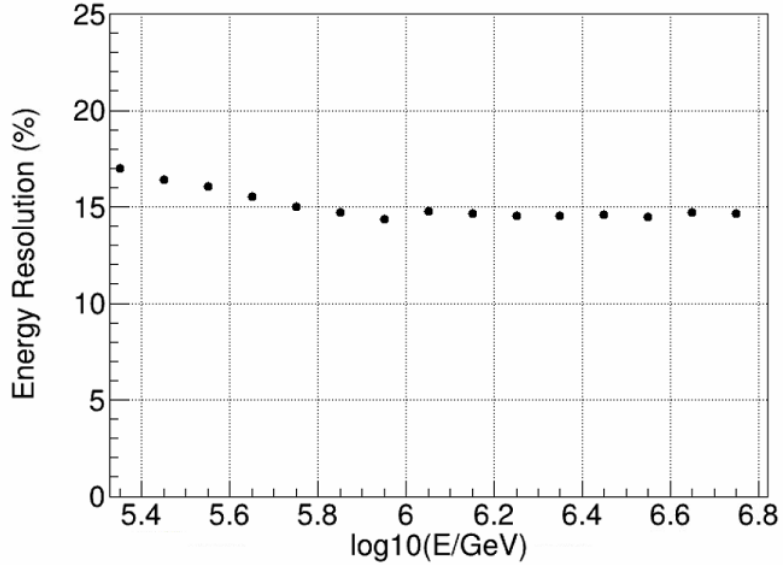
- Systematic bias: <2%
- Energy resolution: ~15%









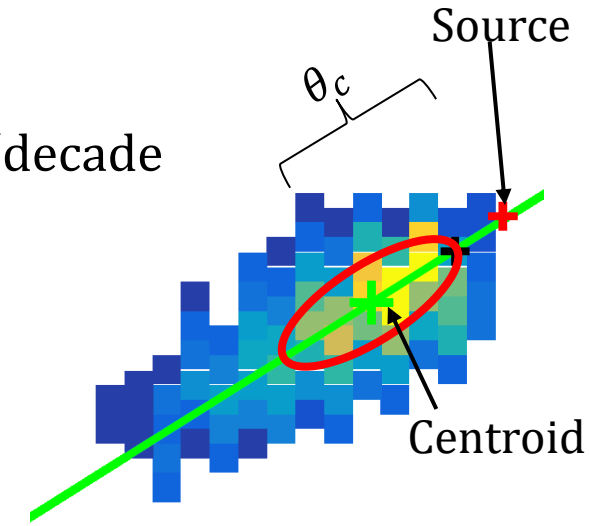


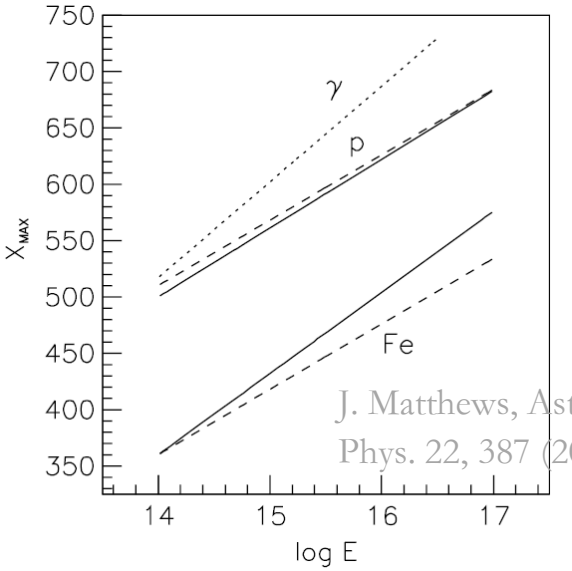
Proton select

X_{max} for different nuclei: $X_{max}^{A} = X_{max}^{P} - \lambda_r \ln A$

Elongation rate : $\Lambda \equiv \frac{dX_{max}}{d\log_{10}E} \approx 58\mathrm{g}\cdot\mathrm{cm}^{-2}/\mathrm{decade}$

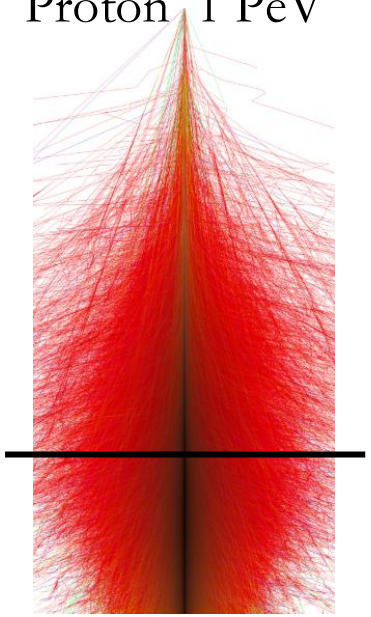
- $P_0 = \theta_c/\cos zenith - 1.322\times10^{-2}R_p$
- $P_X = P_0 + 0.1376\times\lg^2 E_{rec} - 2.271\times\lg E_{rec}$





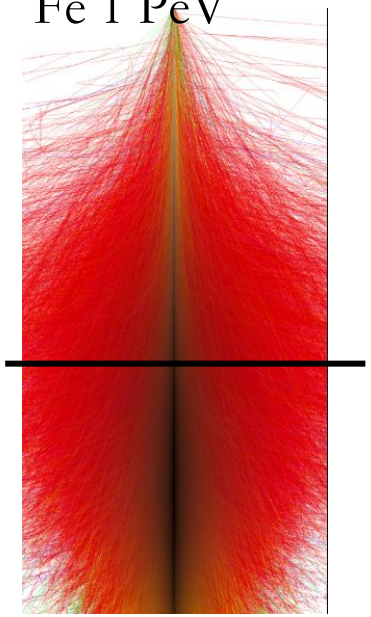
J. Matthews, Astropart. Phys. 22, 387 (2005)

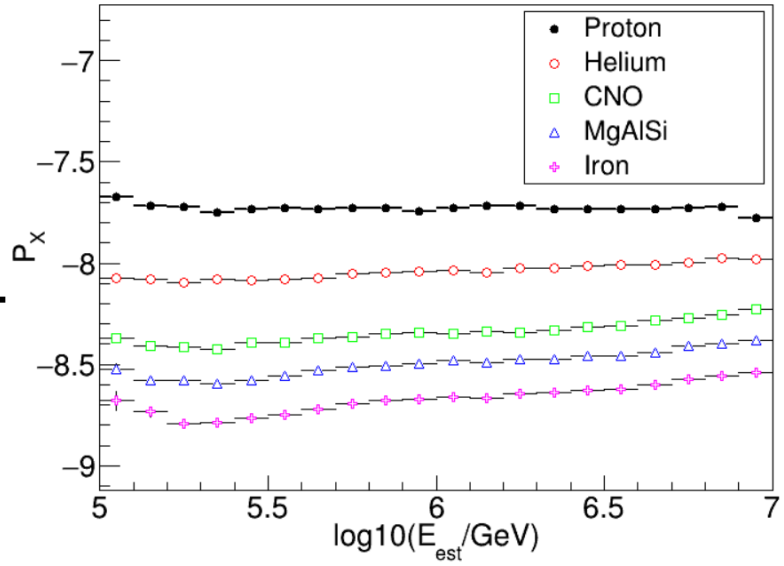
Proton 1 PeV

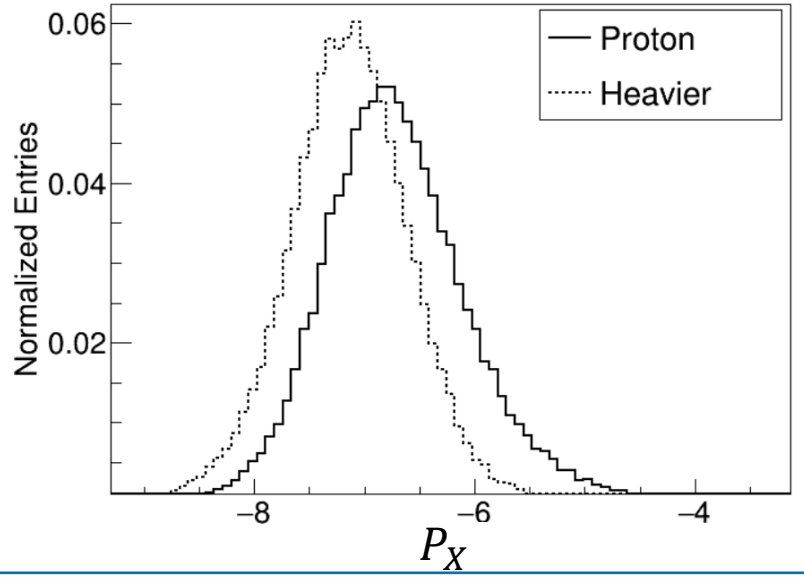


X_{max}

Fe 1 PeV





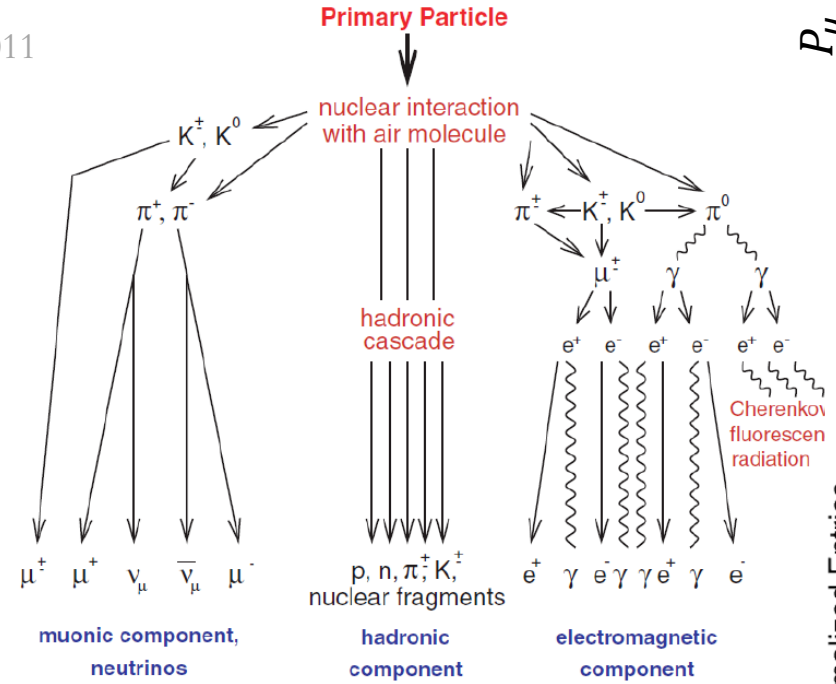


Proton select

Muons in EAS

$N_\mu^A = A^{1-\alpha} N_\mu^P$ J. Matthews, Astropart. Phys. 22, 387 (2005)

α: 0.85~0.92 Phys. Rev. D, 2002, 66: 033011



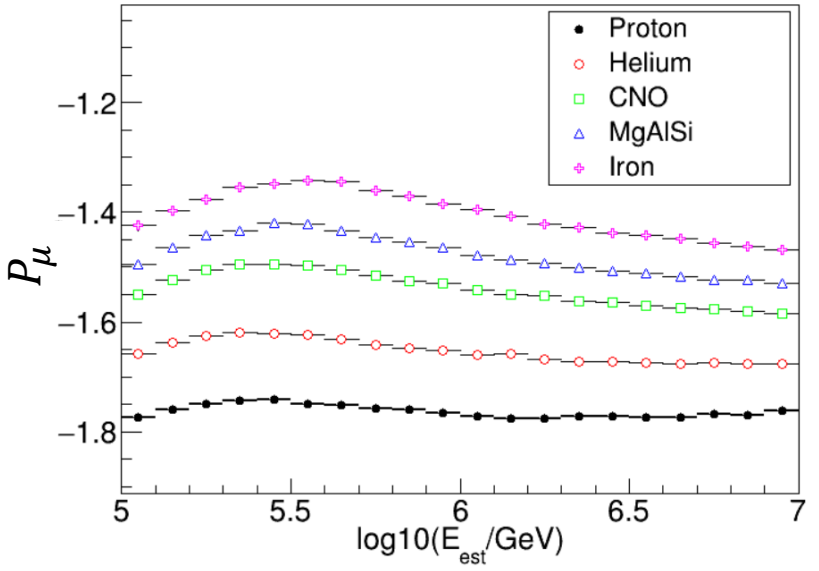
HAUNGS A, REBEL H, ROTH M. Reports on Progress in Physics, 2003, 66(7) : 1145 – 1206.

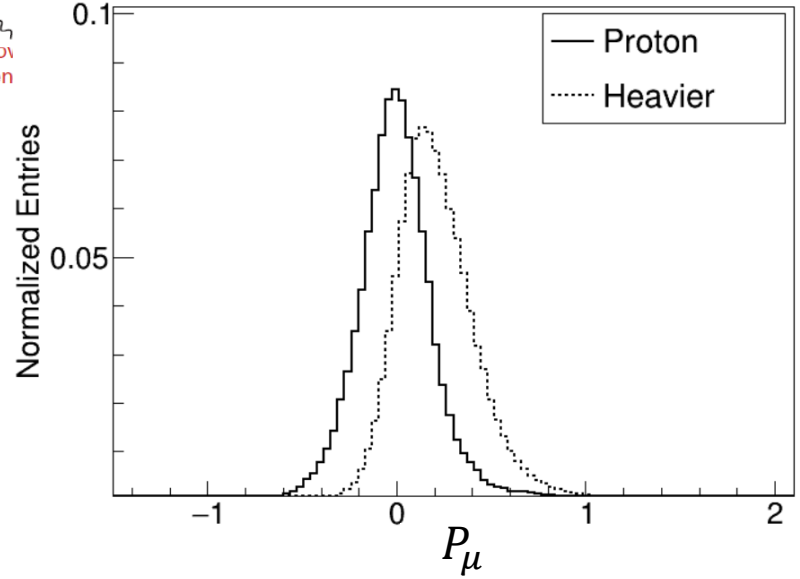
Mass-sensitive parameters

- $P_\mu = \lg \frac{\rho_\mu}{\rho_e^{0.83}}$

ρ_μ: muon density in a ring of 40~200 m from shower axis

ρ_e: electromagnetic particle density in a ring of 40~100 m from shower axis



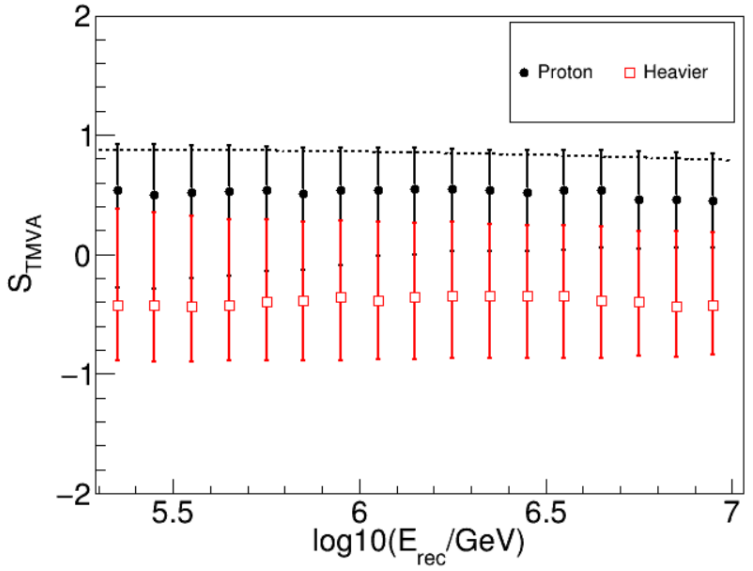


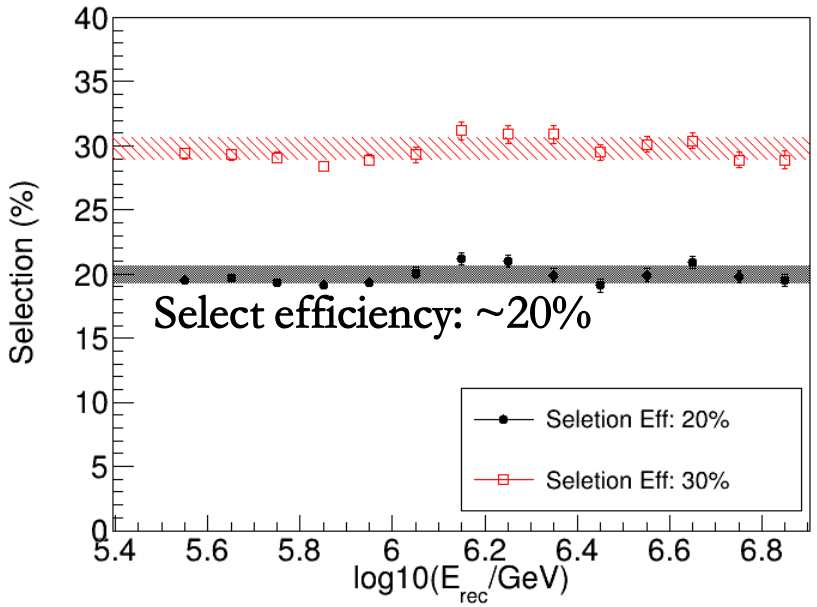
Proton select

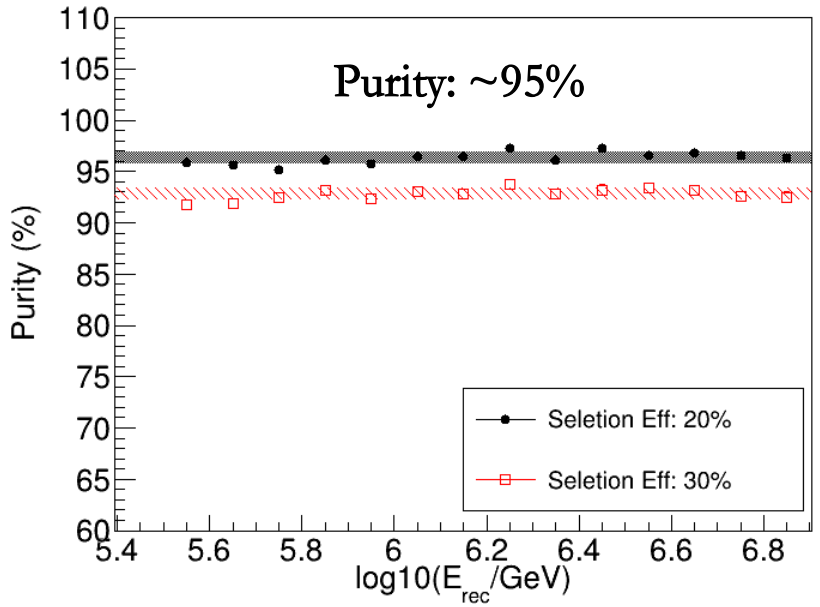
Multi-parameter analysis

ROOT-TMVA package

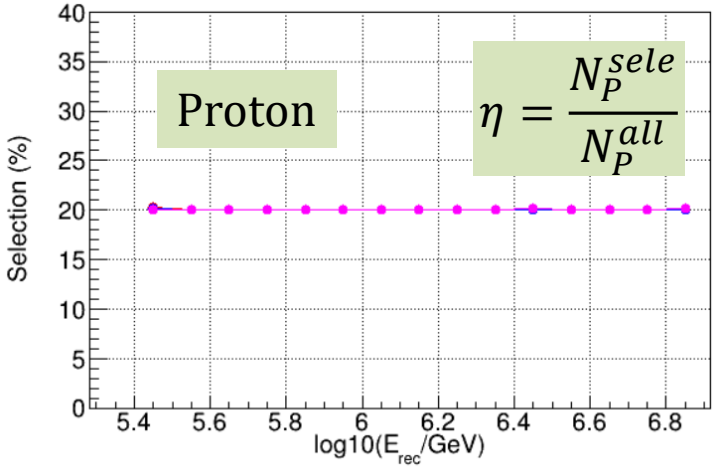
- Parameters: P_X, P_μ
- Signal: Proton
- Background: Helium+CNO+MgAlSi+Iron

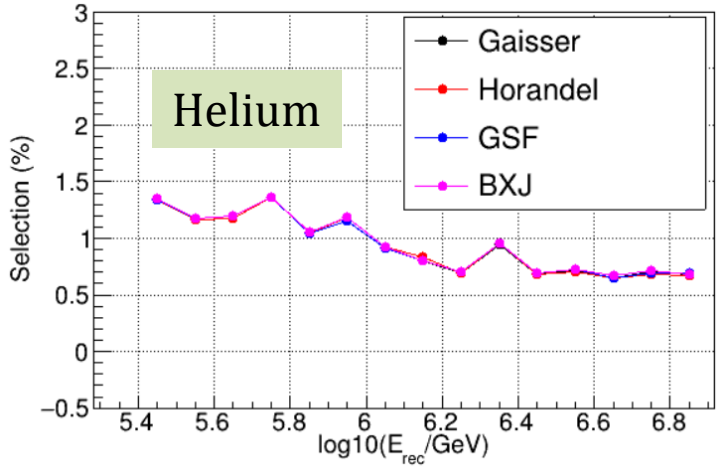


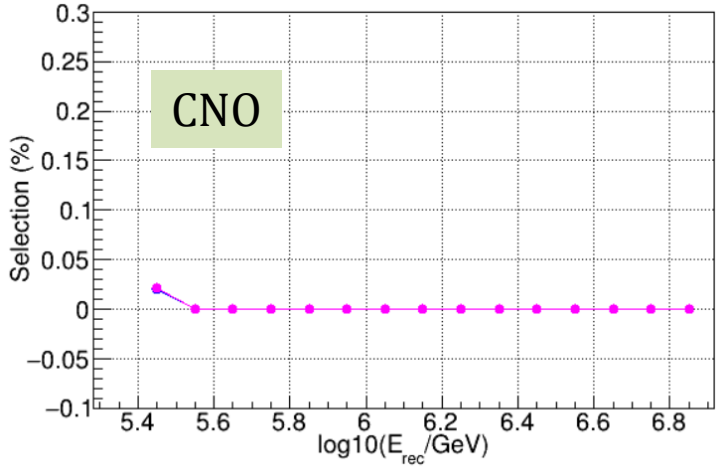


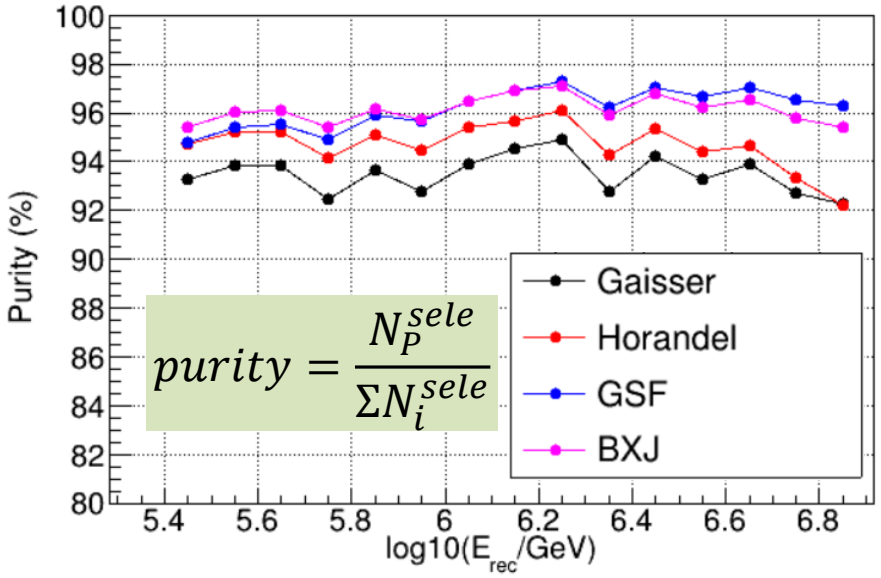


Proton purity









Gaisser Model: Gaisser, T.K., Stanev, T. & Tilav, S. Front. Phys. 8, 748–758 (2013)

Horandel Model: Horandel J R. Astroparticle Physics, 2003, 19(2):193–220

GSF Model: H. P. Dembinski, R. Engel, A. Fedynitch, T. Gaisser, F. Riehn, and T. Stanev, PoS ICRC2017, 533 (2018)

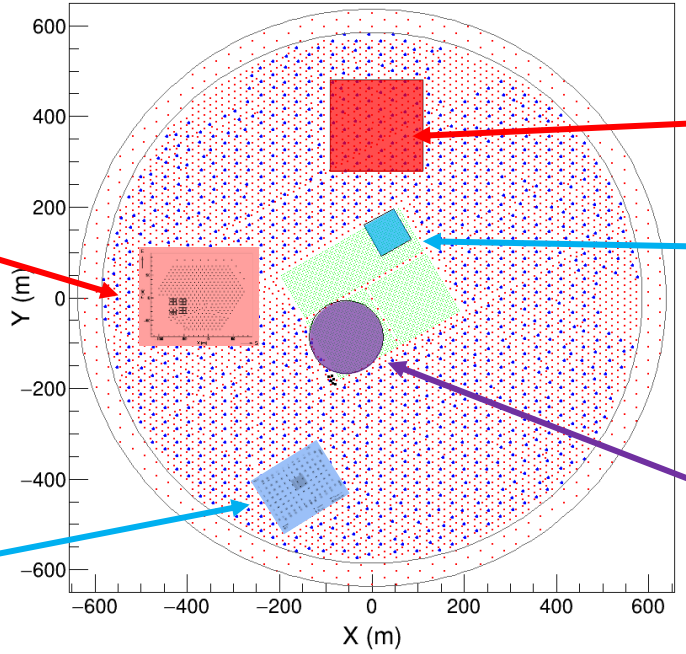
BXJ Model: Lv X.-J., Bi X.-J., Fang K., et al. , arXiv:2403.11832. (2024)

Summary

- Energy resolution:
  - Reconstructed energy bias is less than 2%, and energy resolution is about 15%
- Component discrimination capability:
  - Purity of proton in selected events is higher than 90%
  - The differences of proton purity among different composition model assumptions are less than 3%
- Large statistics:

GRAPES
Area: 25000 m²

ASγ
165m × 120m

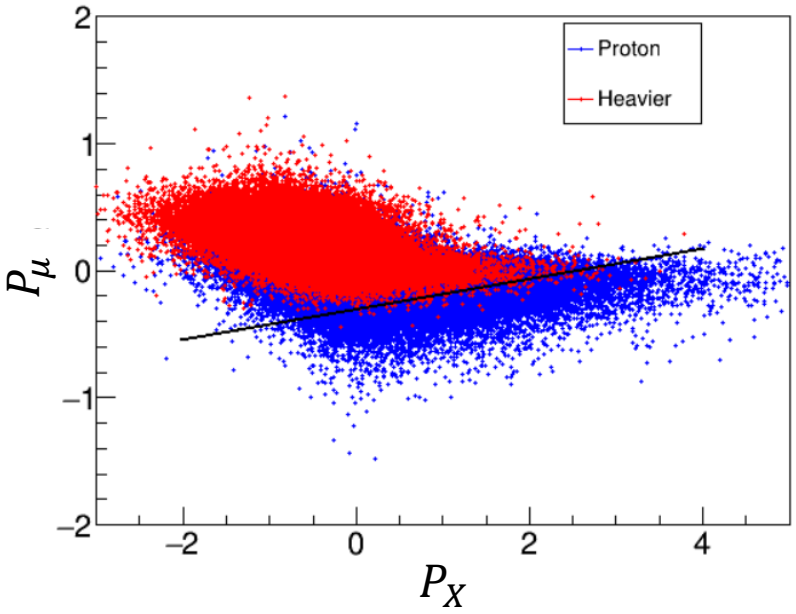


KASCADE
200m × 200m

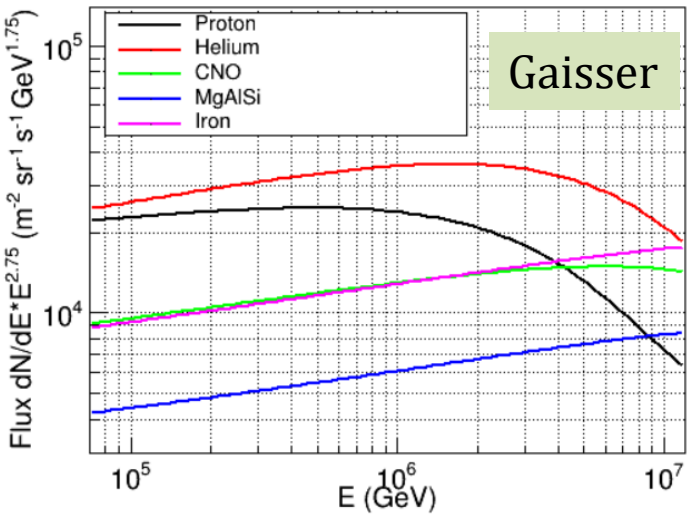
ARGO
74m × 78m

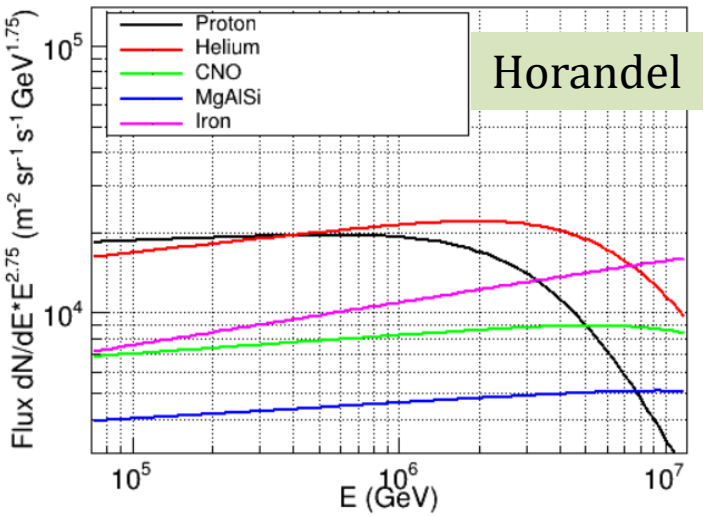
HAWC
Area: 22000 m²

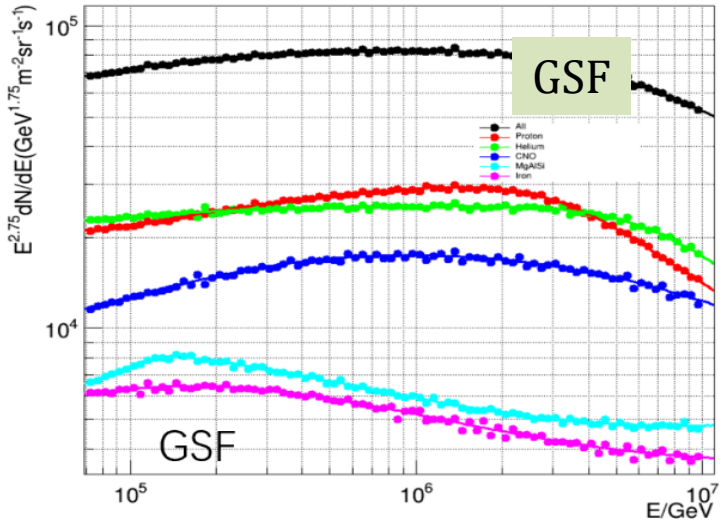
- Identification Parameters (<5%)

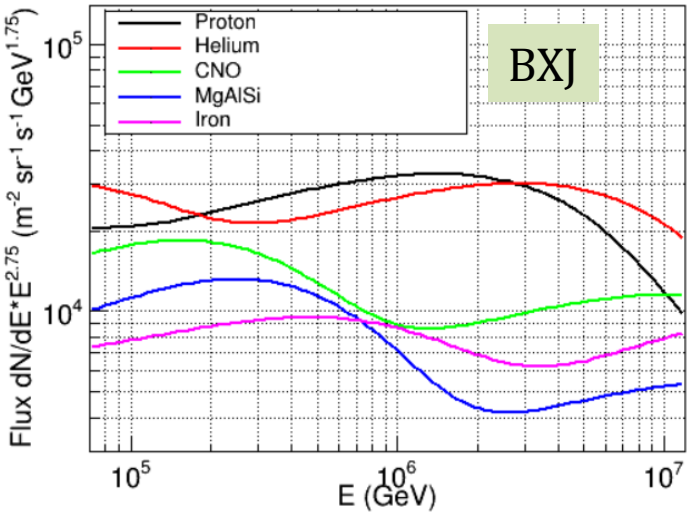


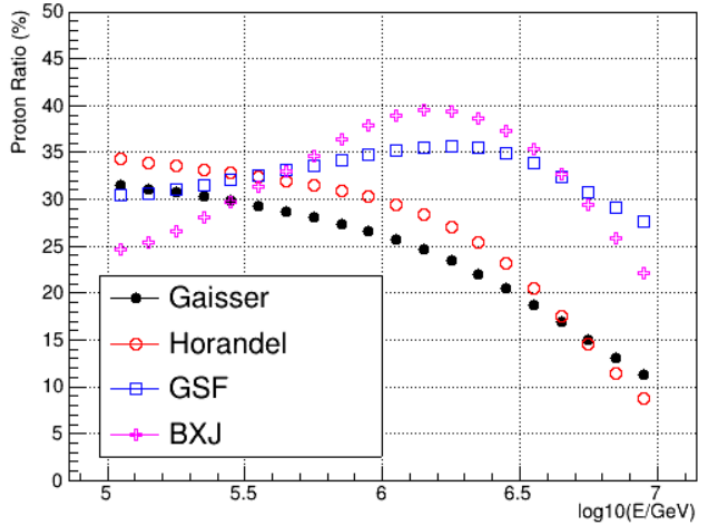
Black line: $P_{combine} = P_\mu + A \times P_X$


Gaisser
Proton
Helium
CNO
MgAlSi
Iron
Flux dN/dE*E^2.75 (m^-2 sr^-1 s^-1 GeV^1.75)
E (GeV)


Horandel
Proton
Helium
CNO
MgAlSi
Iron
Flux dN/dE*E^2.75 (m^-2 sr^-1 s^-1 GeV^1.75)
E (GeV)

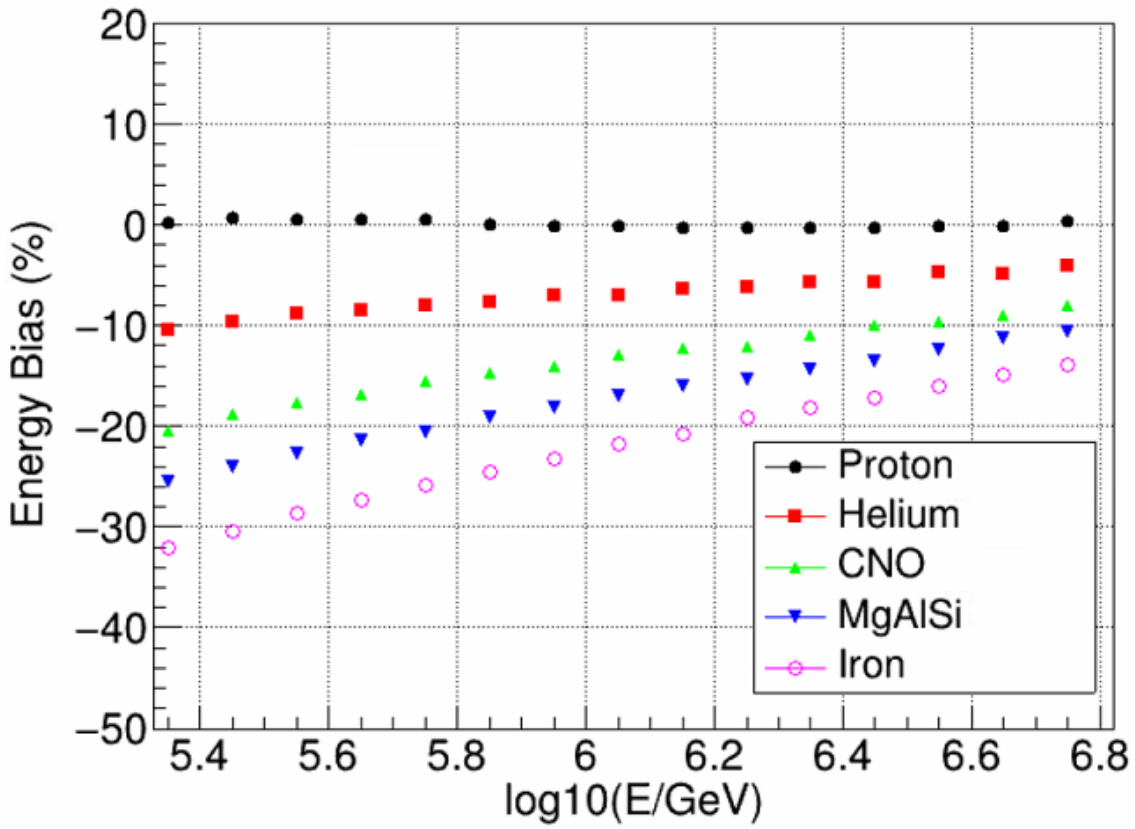

GSF
E^2.75dN/dE(GeV^1.75m^-2sr^-1s^-1)
E/GeV

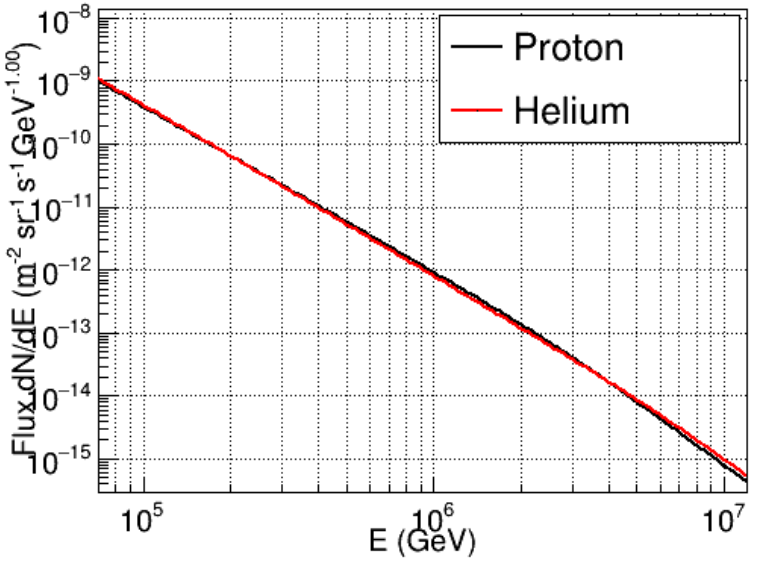

BXJ
Proton
Helium
CNO
MgAlSi
Iron
Flux dN/dE*E^2.75 (m^-2 sr^-1 s^-1 GeV^1.75)
E (GeV)

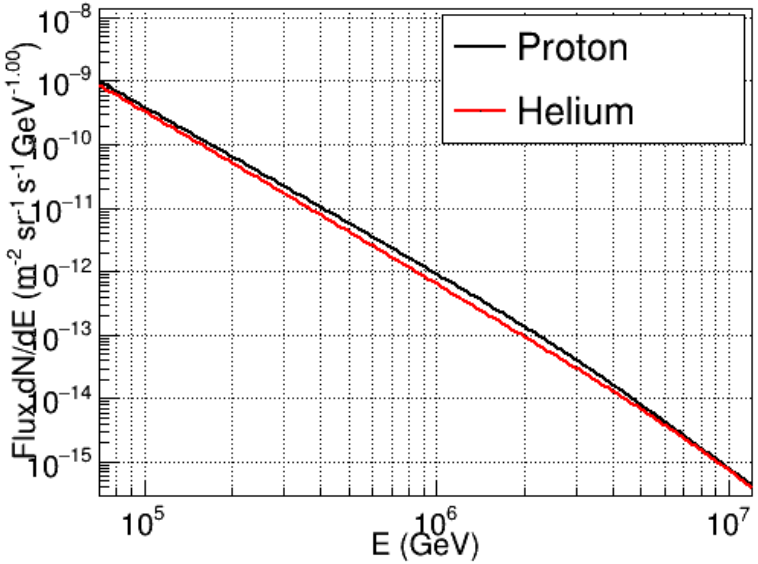

Proton Ratio (%)
Gaisser
Horandel
GSF
BXJ
log10(E/GeV)

Energy reconstruction

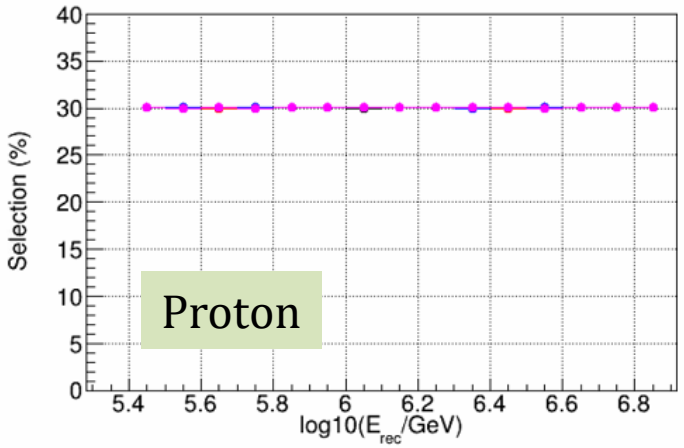
Influence of energy bias to select proton events

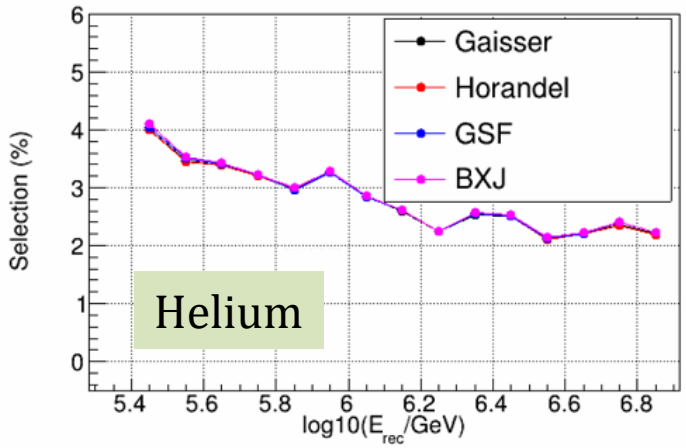


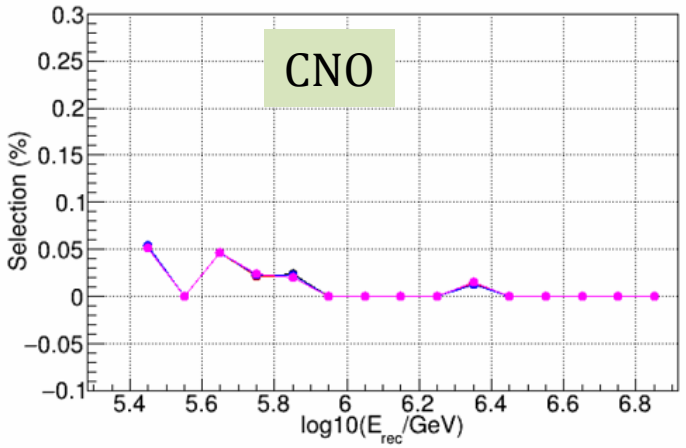


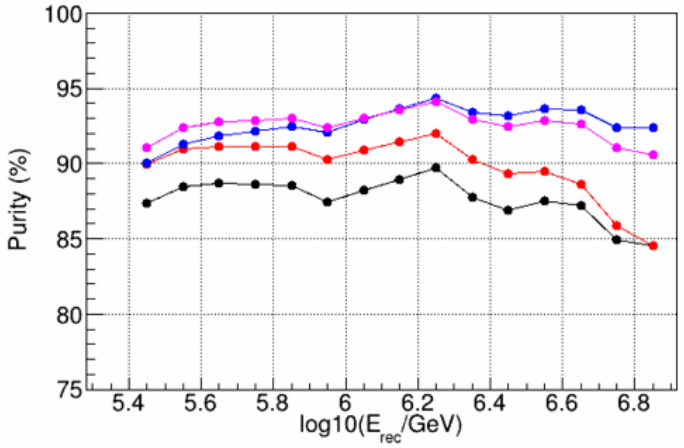


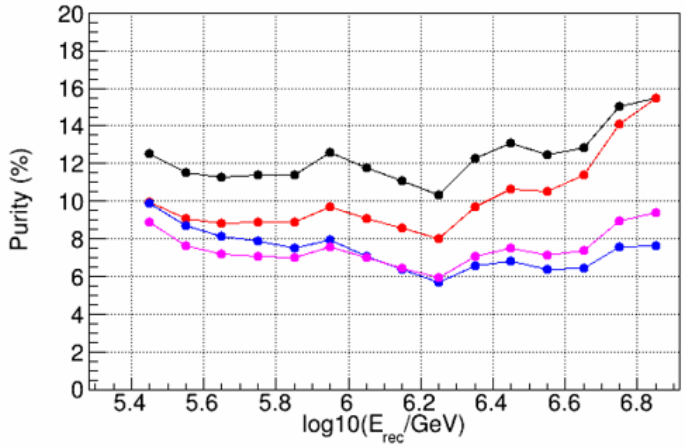
Proton Purity

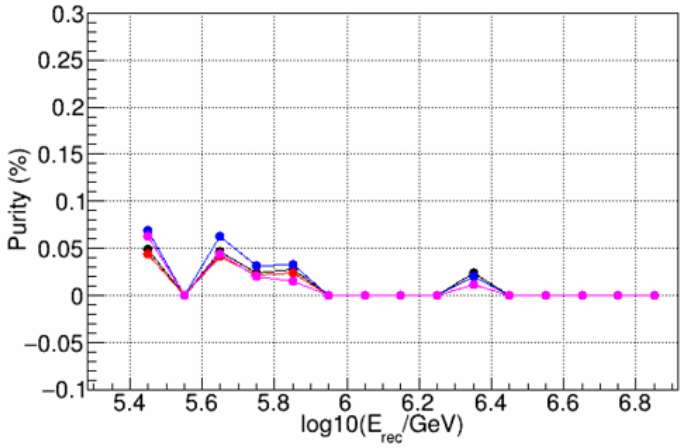








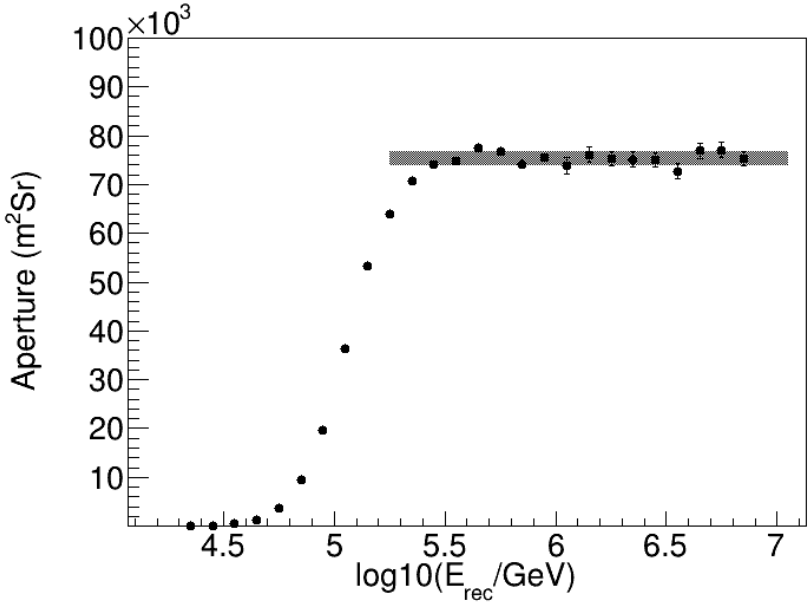




Proton Spectrum

$$f(E) = \frac{N(E) \cdot p}{A \cdot \eta \cdot T \cdot \Delta E}$$

$N(E)$	Number of events in energy bin
T	Observation time
A	Effective aperture
p	Purity of proton events
η	Select efficiency of proton events

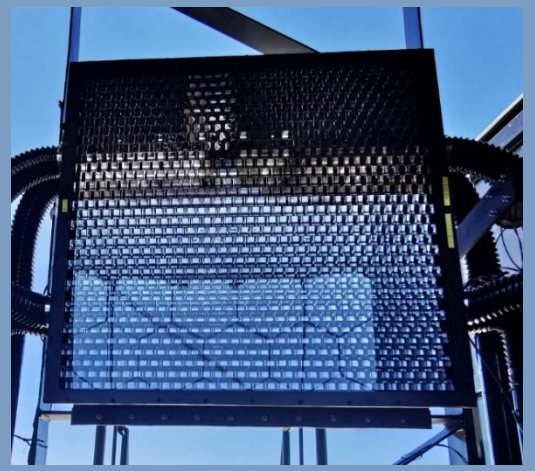


LHAASO WFCTA

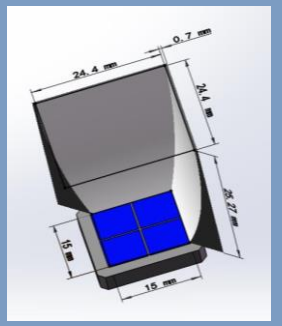
Telescopes:

- ~5 m^2 spherical mirror
- Camera: 32×32 SiPMs array
- FOV: 16° × 16°
- Pixel size: 0.5°
- >30% duty cycle in winter

Mirror

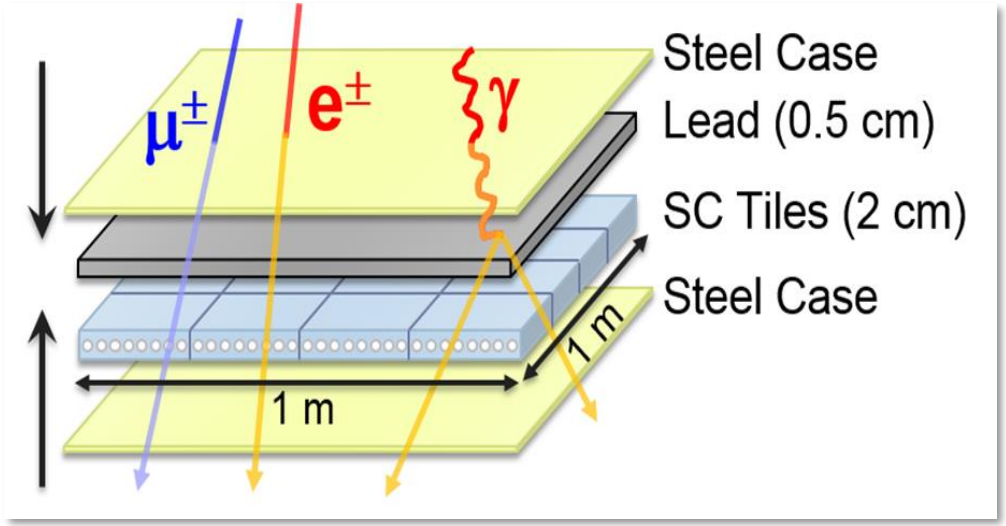


SiPM camera

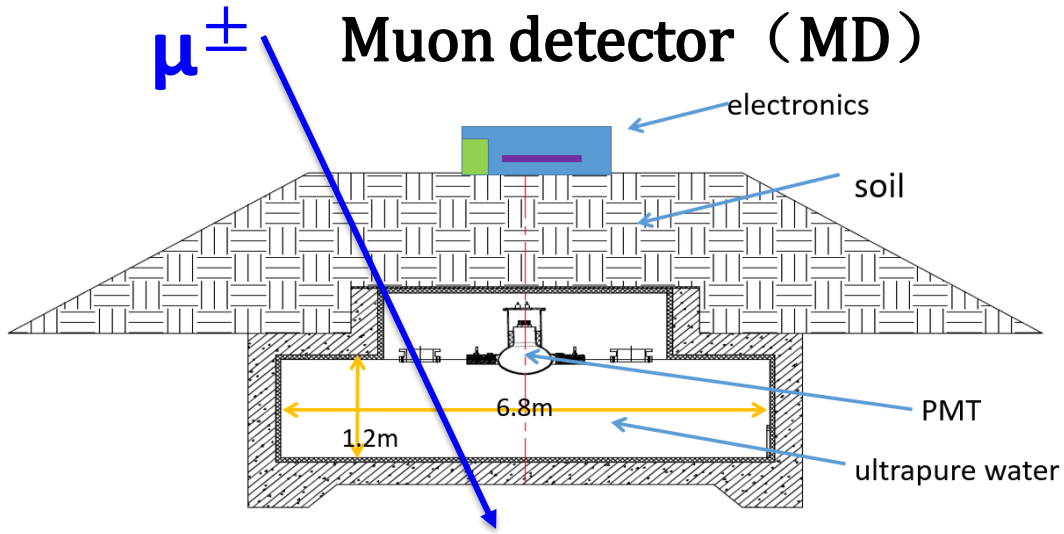


SiPM and Winston cone

LHAASO KM2A （1.36 km^2）



- 5195 EDs
  - A: 1 m^2
  - S: 15 m
- 1188 MDs
  - A: 36 m^2
  - S: 30 m



Outline

- Proton spectrum instruction
- Hybrid experiment
- Data selection and simulation
- Energy reconstruction
- Proton select