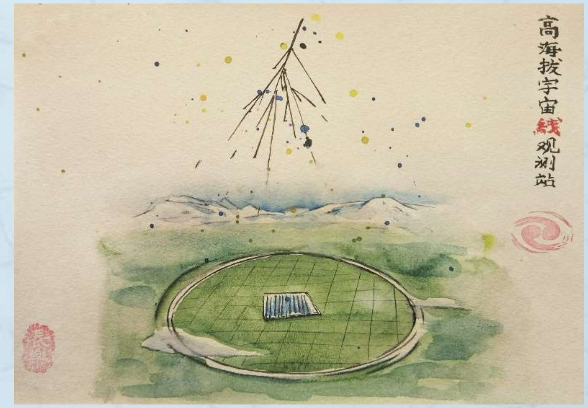
LHAASO
高海拔宇宙线观测站



Cosmic Rays @ LHAASO

Zhen Cao, **IHEP**
On behalf of LHAASO Collaboration

CRIS-MAT Workshop, Italy, Oct. 2024

LHAASO

Outline

- LHAASO experiment
- Pure Proton Sample
- Light Component (H + He) Sample
- All Particle Spectrum and Composition

LHAASO Collaboration

275 members from
31 institutions in
5 countries

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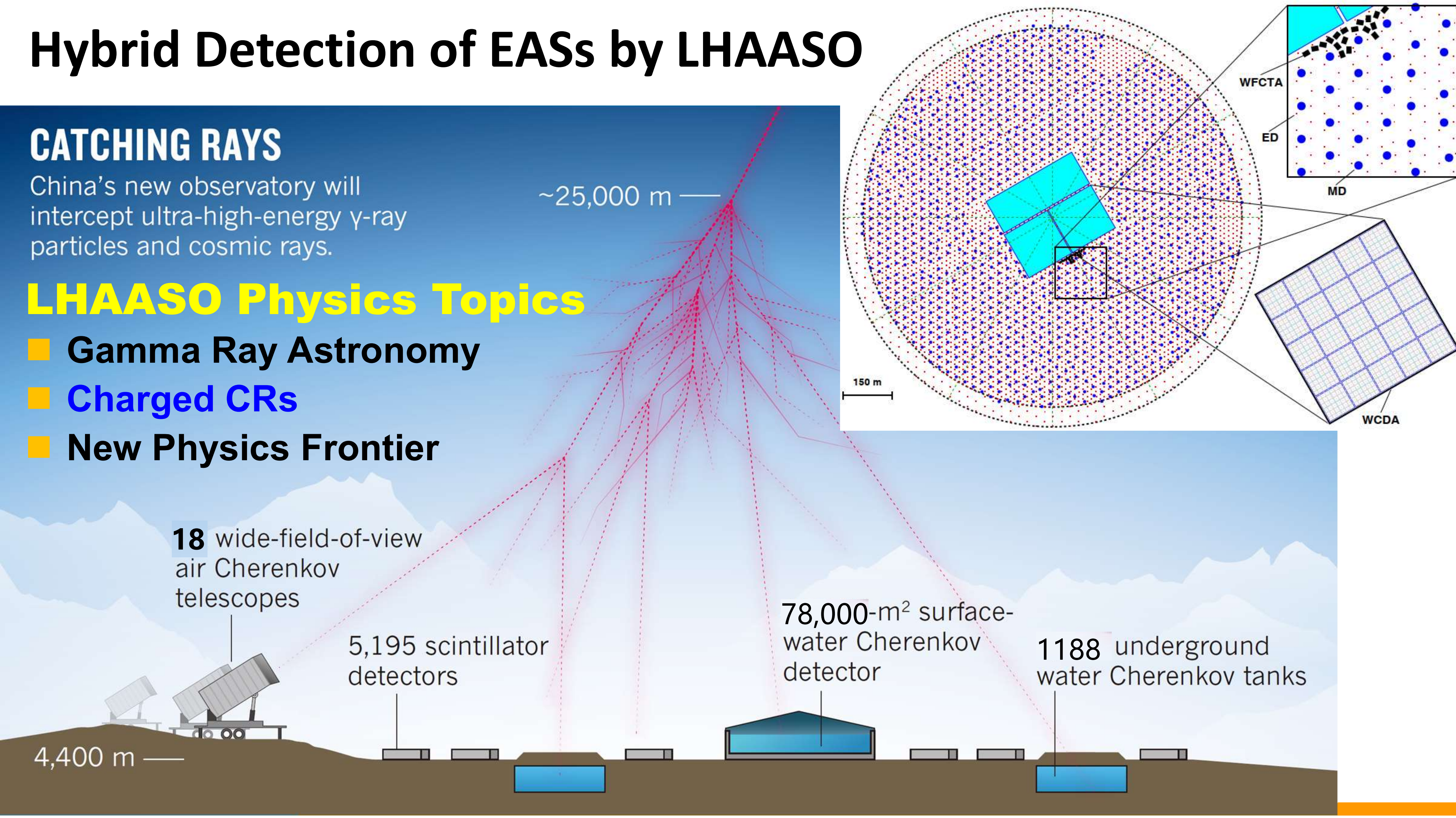
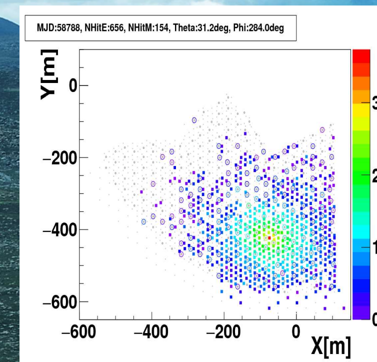
(LHAASO Collaboration)[*]

Hybrid Detection of EASs by LHAASO



LHAASO bird view on August 2021

- Location: Haizi Moutain, Daochen, Sichuan, China
  - Altitude: 4410 m a.s.l.
  - 2021-07: The full array was complete and in operation



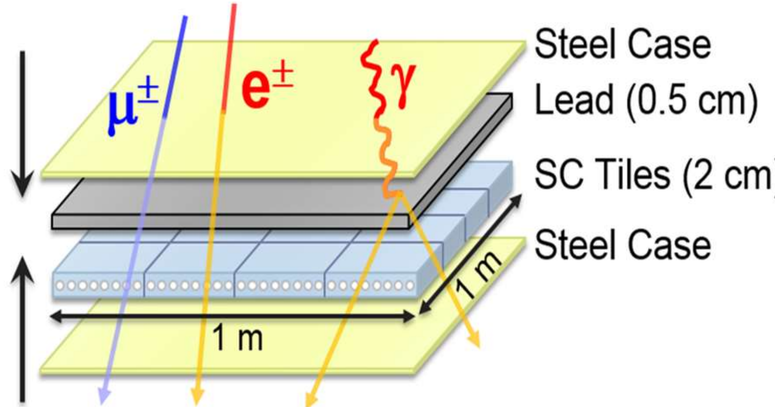
KM2A: 1.36 $(km)^2$

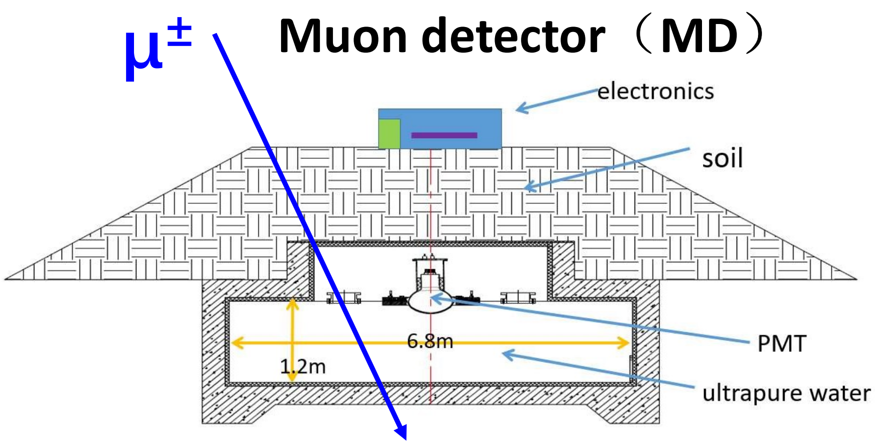
- ¼ array operation: 2019/09
- ½ array operation: 2020/01
- ¾ array operation: 2020/12
- Full array operation: 2021/7

KM2A: 1.36 $(km)^2$

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

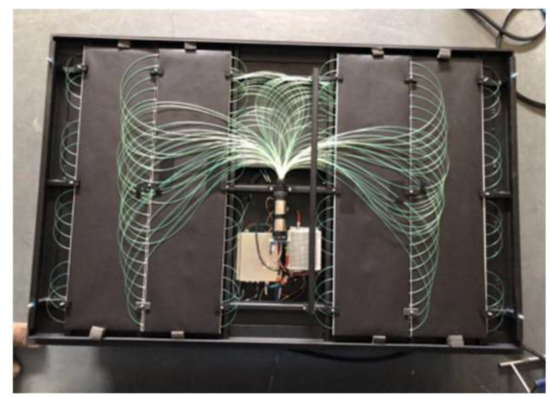
Scintillator Detectors （ED）





MD Bladder

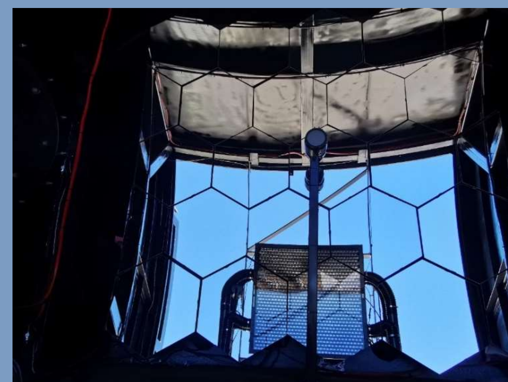
Inner View of Scintillator Detector



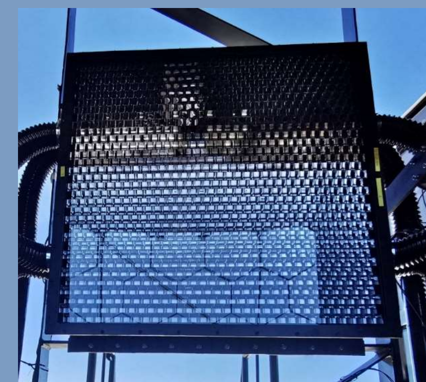
Wide Field of View Cherenkov Telescope (WFCTA)

◆ **Telescopes:**

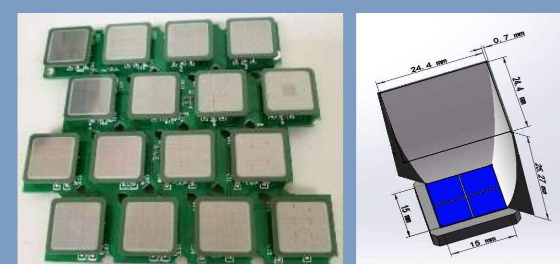
- ~5 m^2 spherical mirror
- Camera: 32×32 SiPMs array
- FOV: 16° × 16°
- Pixel size: 0.5°
- >30% duty cycle in winter



Mirror



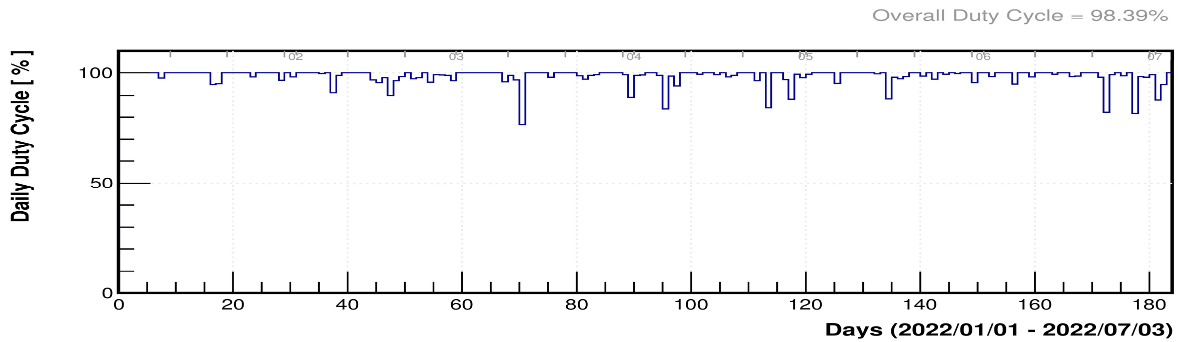
SiPM camera

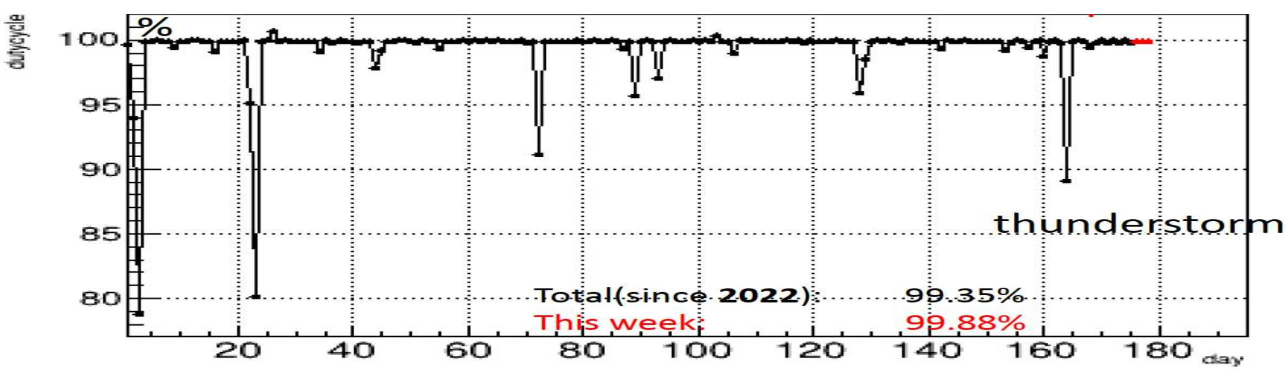


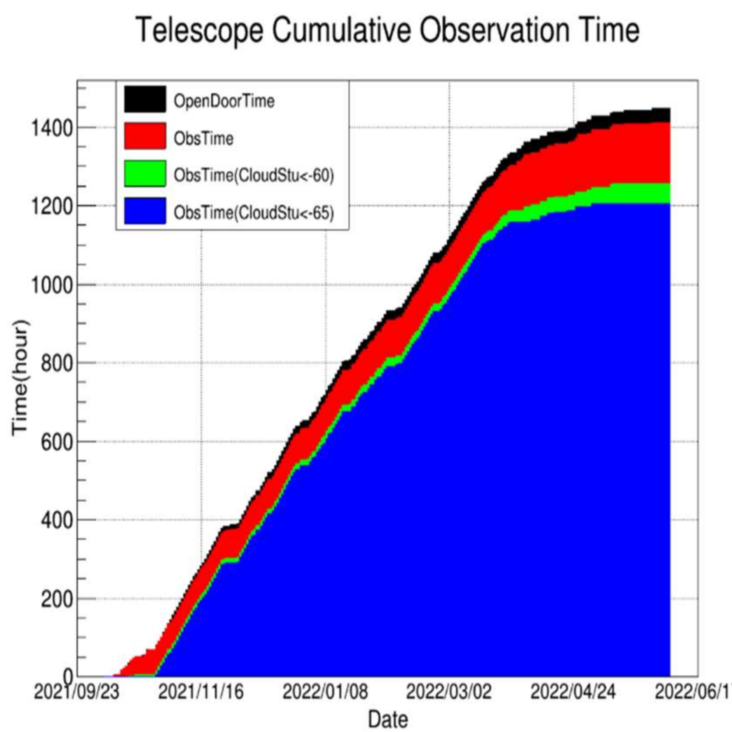
SiPM and Winston cone

Operation of LHAASO

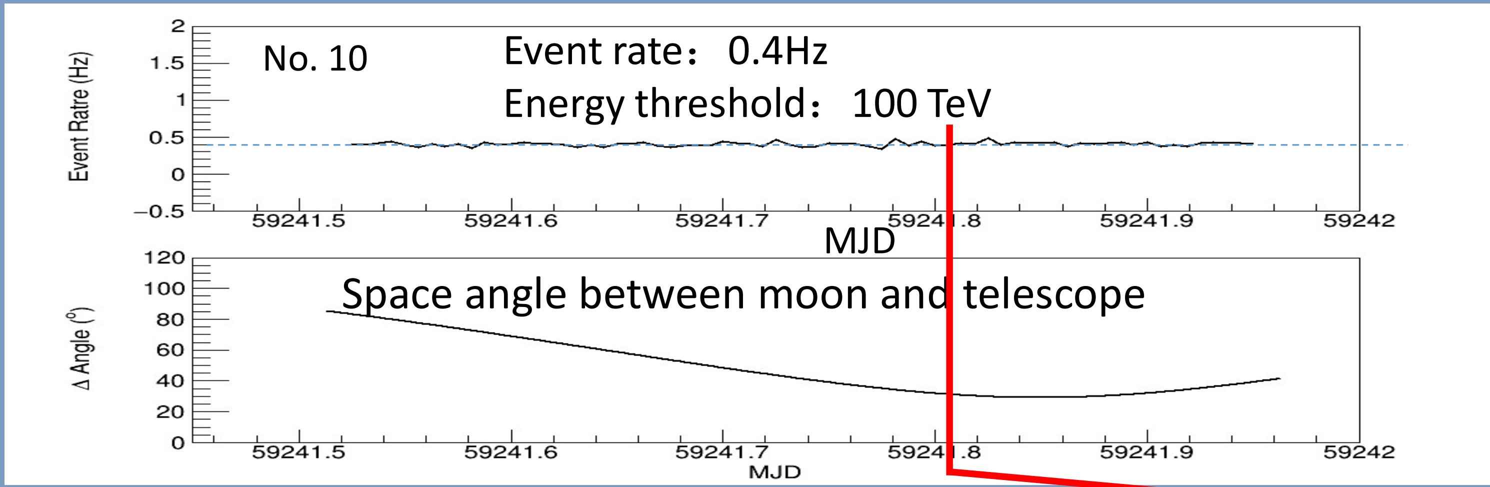
- KM2A is operated with >99.4% duty cycle and event rate $2x10^8$ /day
- WCDA is operated with 98.4% and event rate $3x10^9$ /day
- Data acquisition time of WFCTA >1400 hrs and number of matched events ~70 million

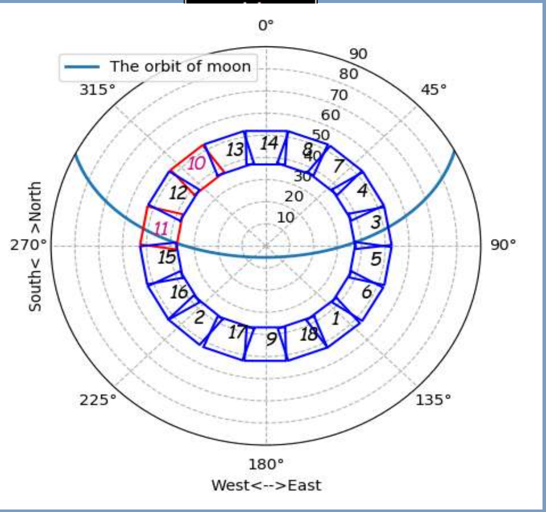




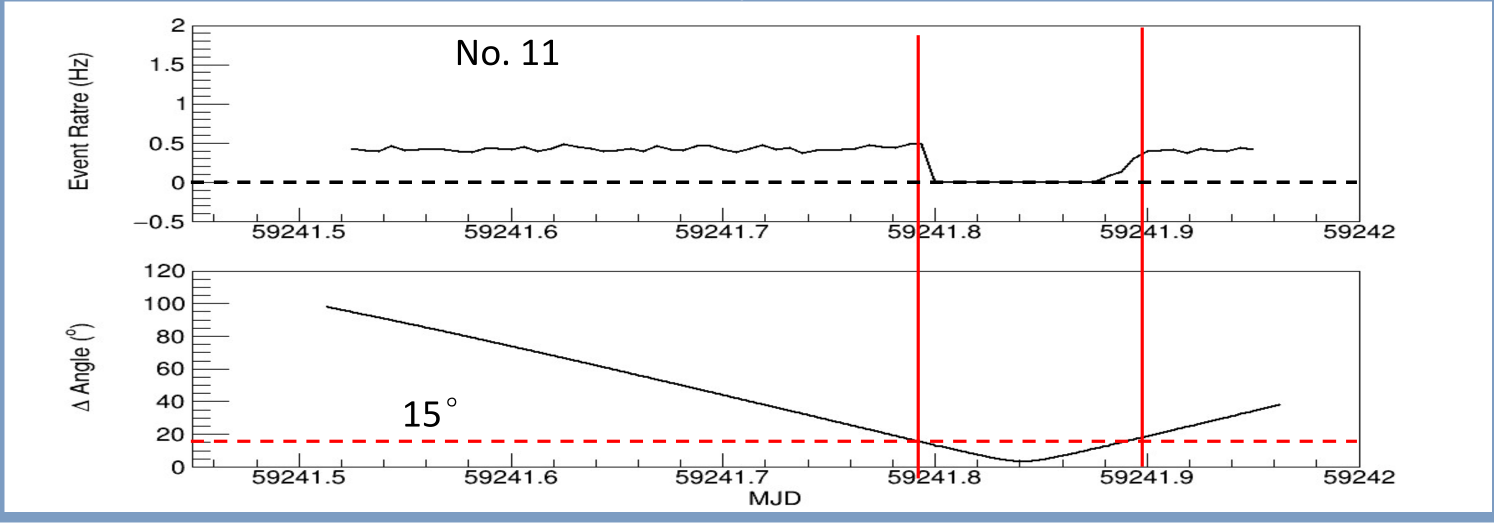


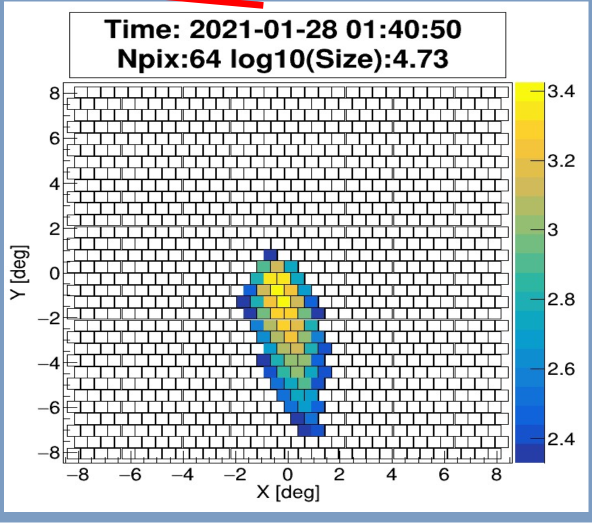
Telescope observation with the full moon



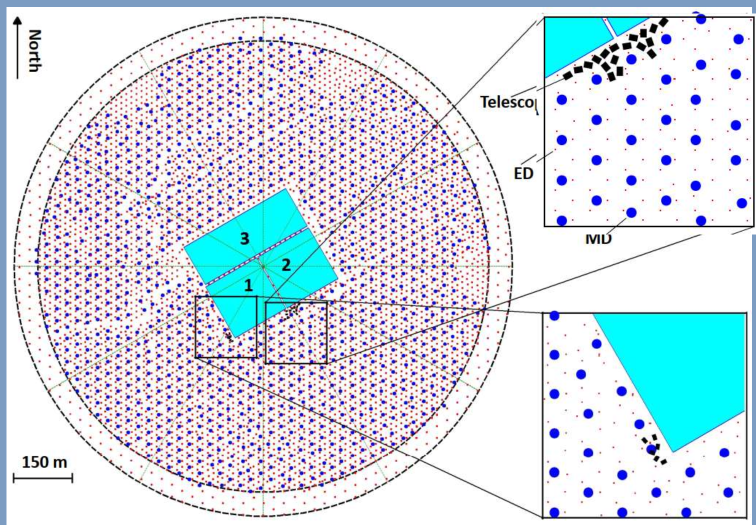


SiPM camera: LHAASO Coll., Eur. Phys. J. C (2021) 81:657

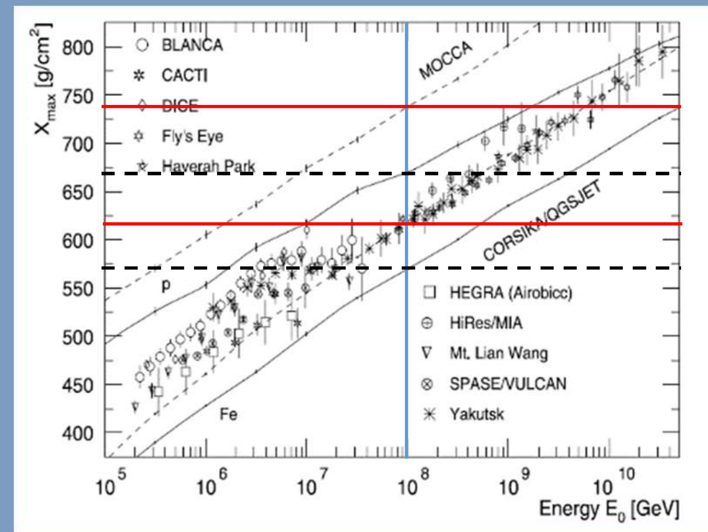


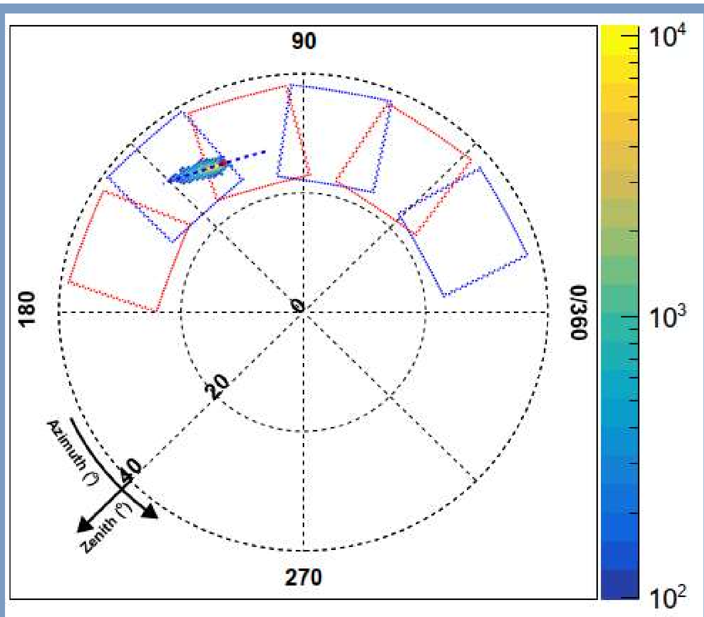


Observational Phases



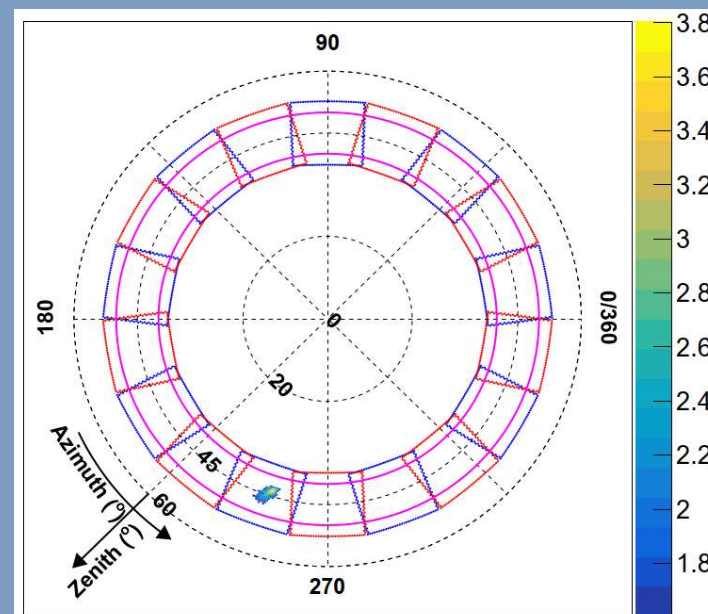
- Phase I: 6 telescopes
  - 2019/10 – 2021/4
  - Zenith angle: 30°
  - Proton, H+He knees
  - 100 TeV – 10 PeV



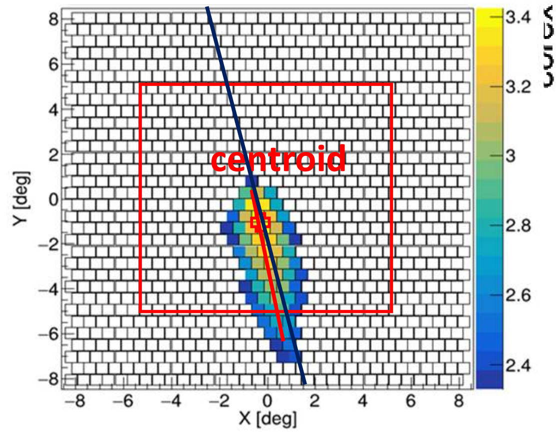


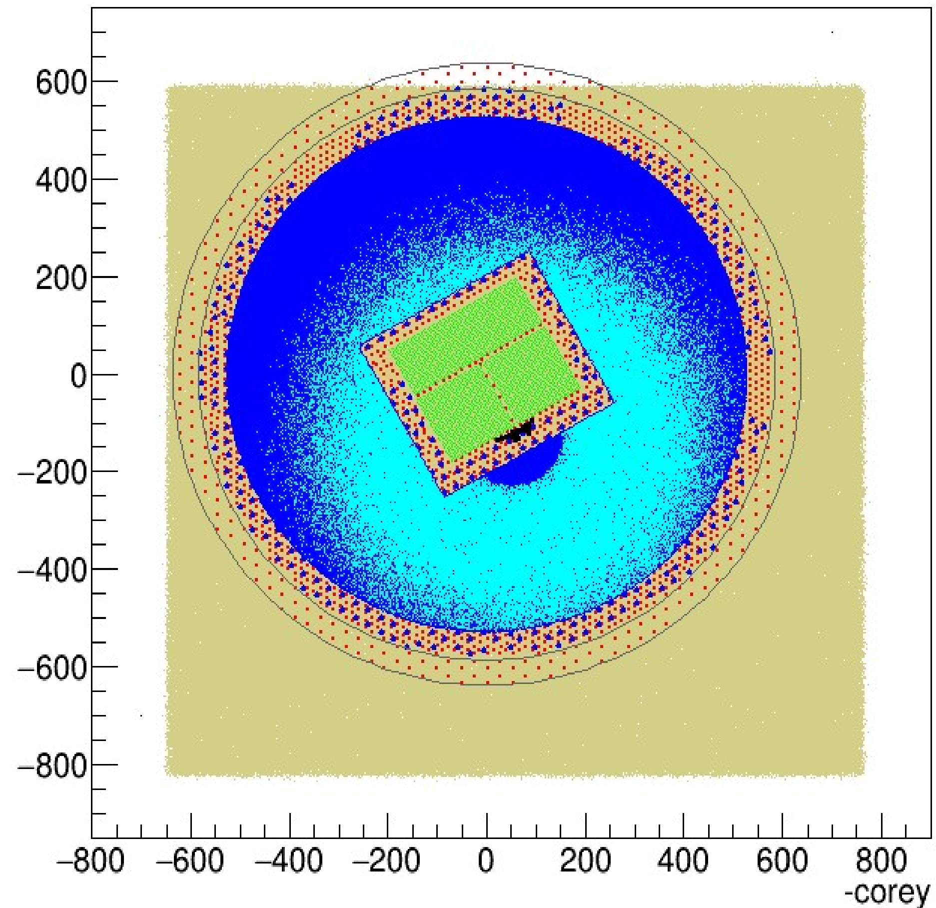
6 Tele's were moved in 2021/5 to form a full ring

- Phase II: 18 telescopes
  - Operation: 2021/5
  - Zenith angle: 45°
  - Iron knee, proton
  - 1 PeV – 200 PeV



Measurements using KM2A+WFCTA



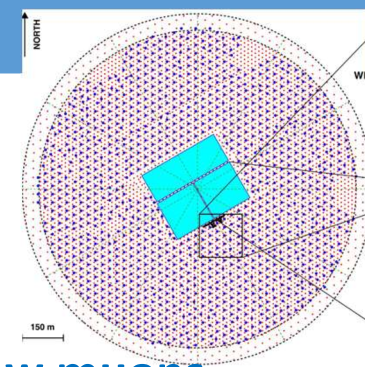


1. WFCTA image has >10 pixels and the centroid must be in the central window 10° ×10°
2. The angle between long axis and STP <15°
3. From shower axis to the Telescope, 100 m<R_p<300 m
4. KM2A footprint:
   1. The core must be inside the array but not in WCDA (the edge of ~60 m is excluded)
   2. The number of scintillator detector >20

- LHAASO experiment
- Pure Proton Sample
- Light Component (H + He) Sample
- All Particle Spectrum and Composition

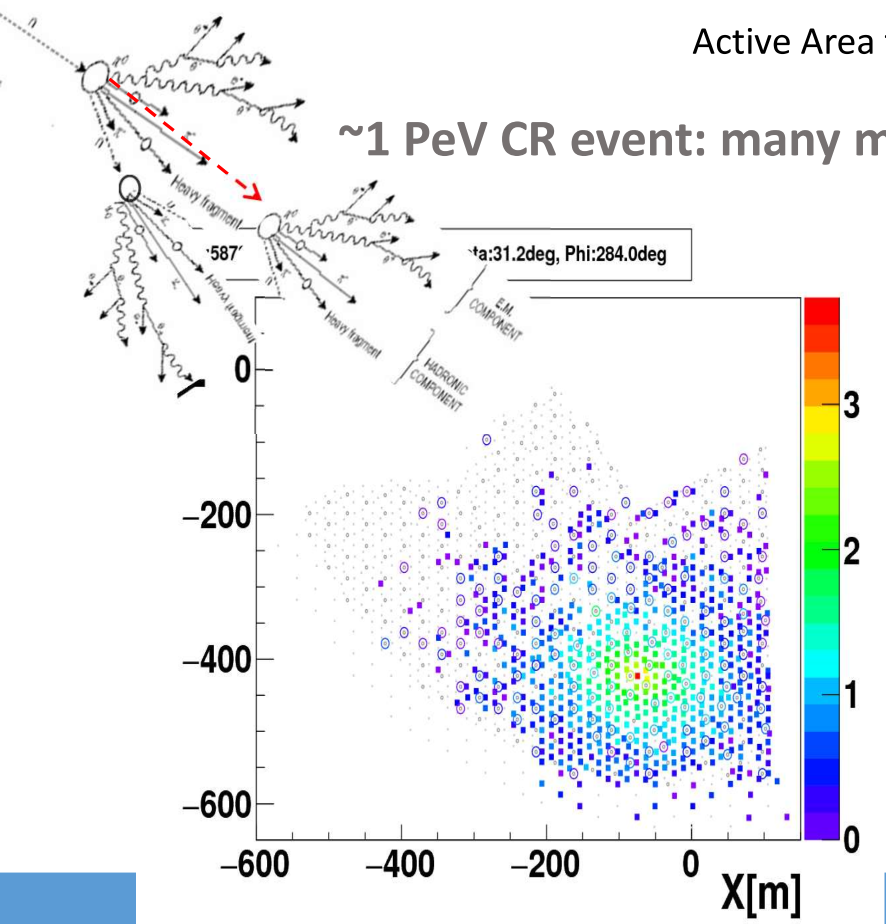
LHAASO-KM2A

Selection of γ–rays out of CR background



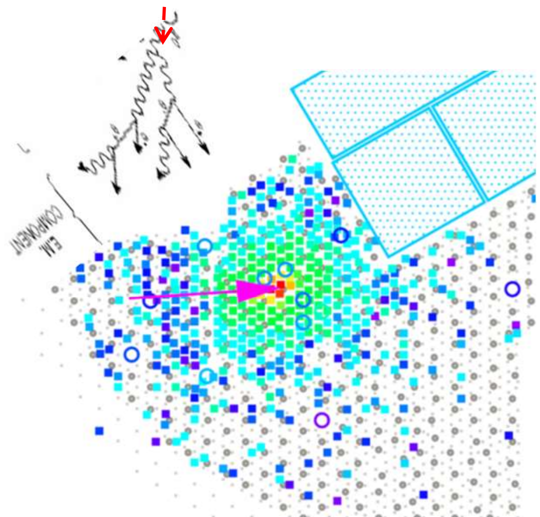
Active Area for Muons vs. Array Area: 4%

~1 PeV CR event: many muons



~ 1 PeV γ–ray event： very few muons

from the Crab



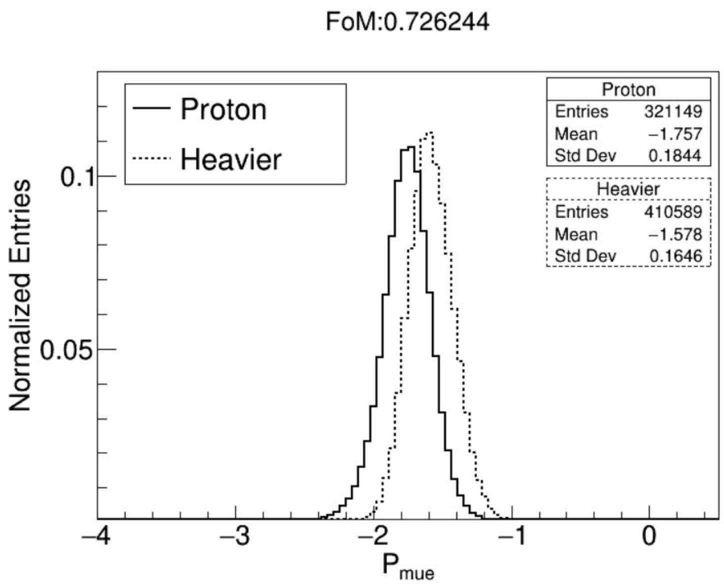
- **Area：**
  1.3 km^2
- **Detectors：**
  5216 ED
  1188 MD
- **Energy Range：**
  0.01-10 PeV

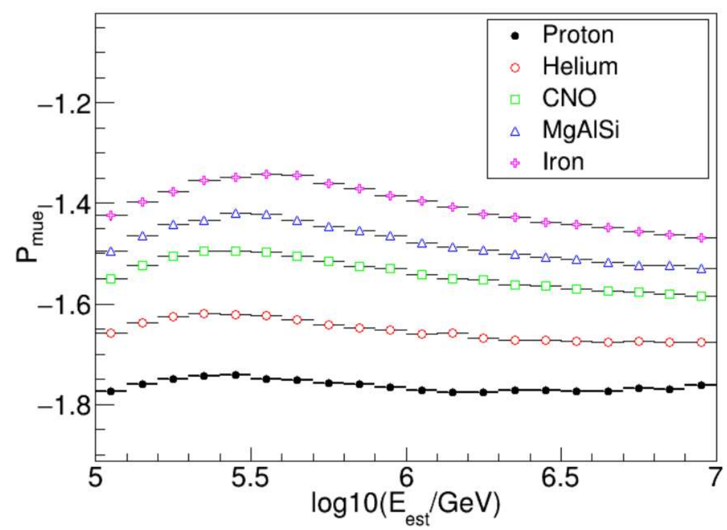
Muon Content in Showers

$$P_{\mu} = \log_{10}\frac{\rho_{\mu}}{\rho_e^{0.83}}$$

ρ_{μ}: *muon density in the ring between* 40*m and* 200*m* from the core

ρ_e: *EM − particle density in the ring between* 40*m and* 200*m*

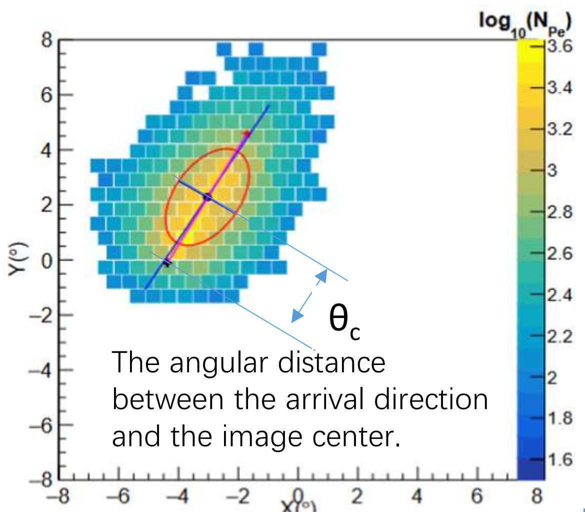


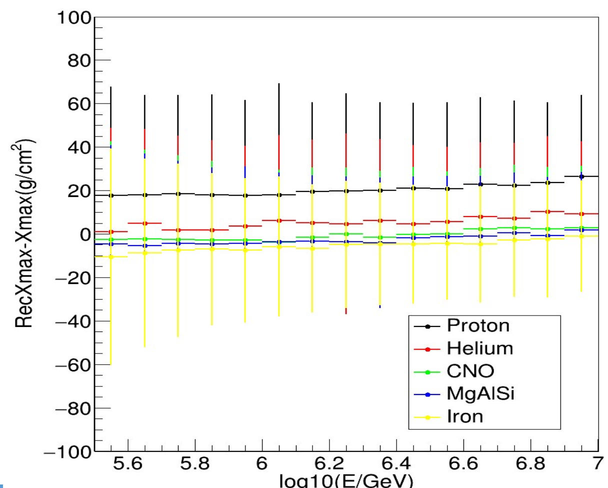


Shower Maximum Depth

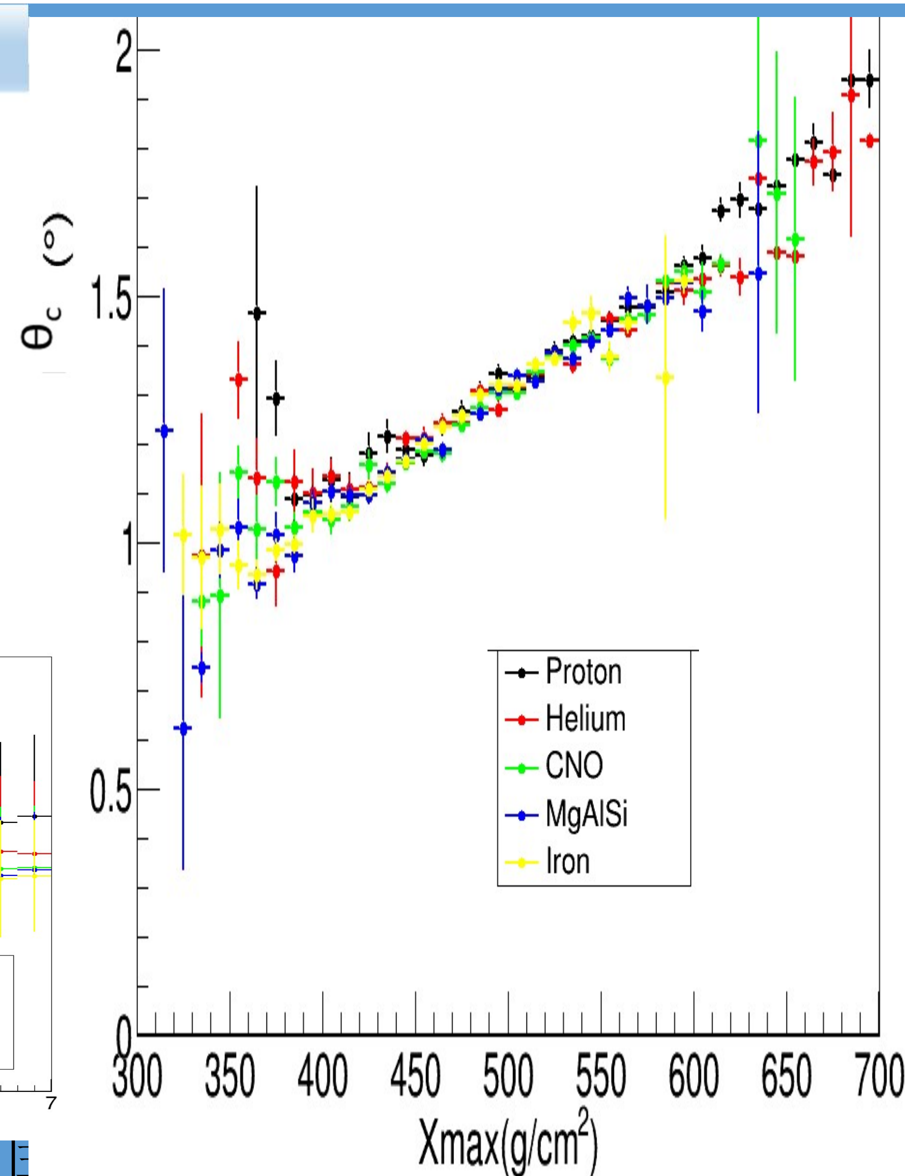
Xmax Measurement by WFCTA

- **Xmax is reconstructed by Dist**
- **Resolution**
  - **45 g/cm^2 @ 1PeV for proton**
  - **34 g/cm^2 @ 1PeV for iron**





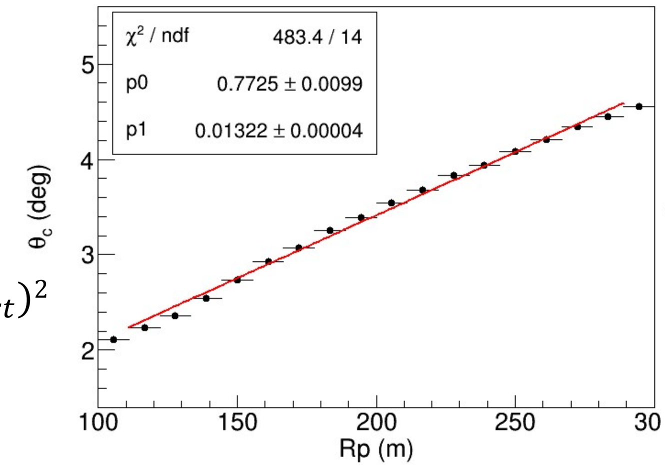
Θ_c vs. X_{max} at a given R_p range

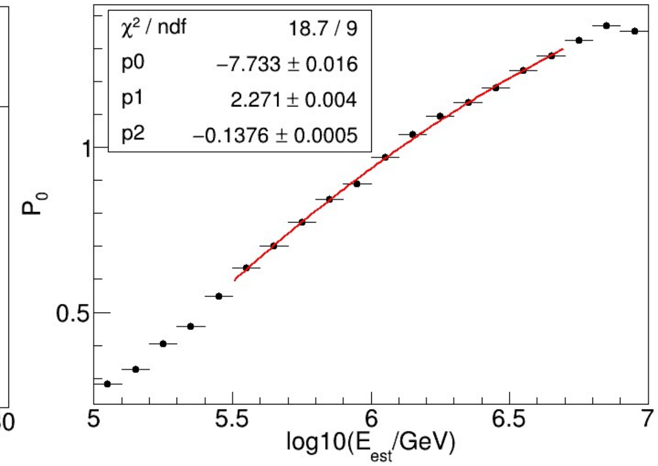


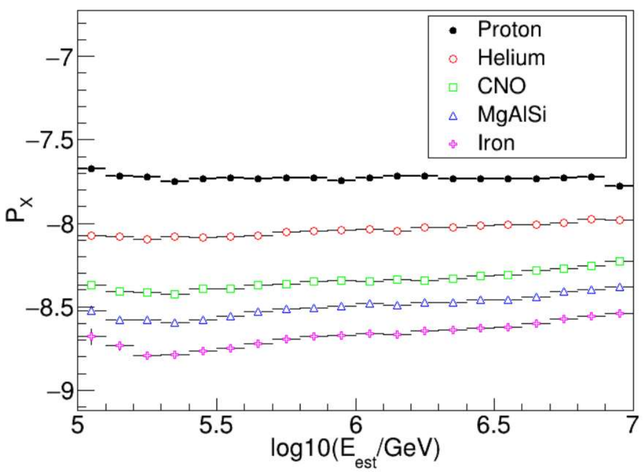
Shower Maximum Depth

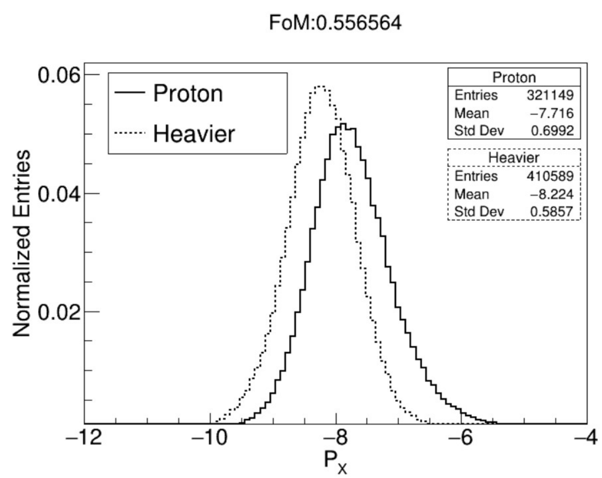
$$P_0 = \theta_c/\cos\theta - 1.322\times10^{-2}R_p$$

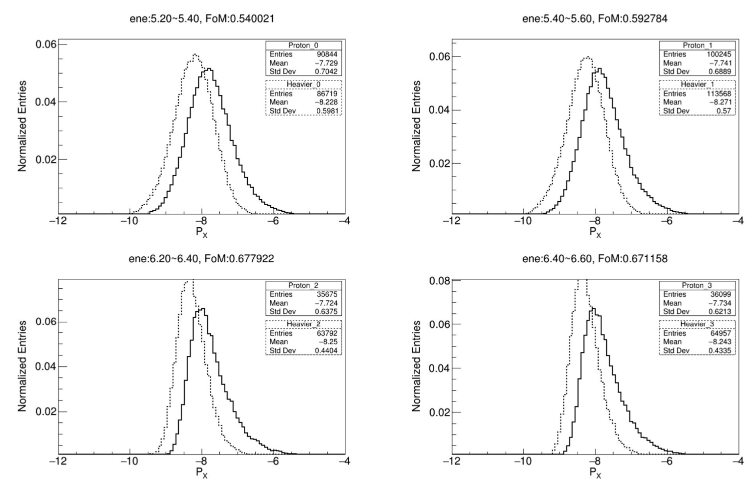
$$P_x = P_0 + 0.1376\times\lg E_{\text{est}} - 2.271\times(\lg E_{est})^2$$



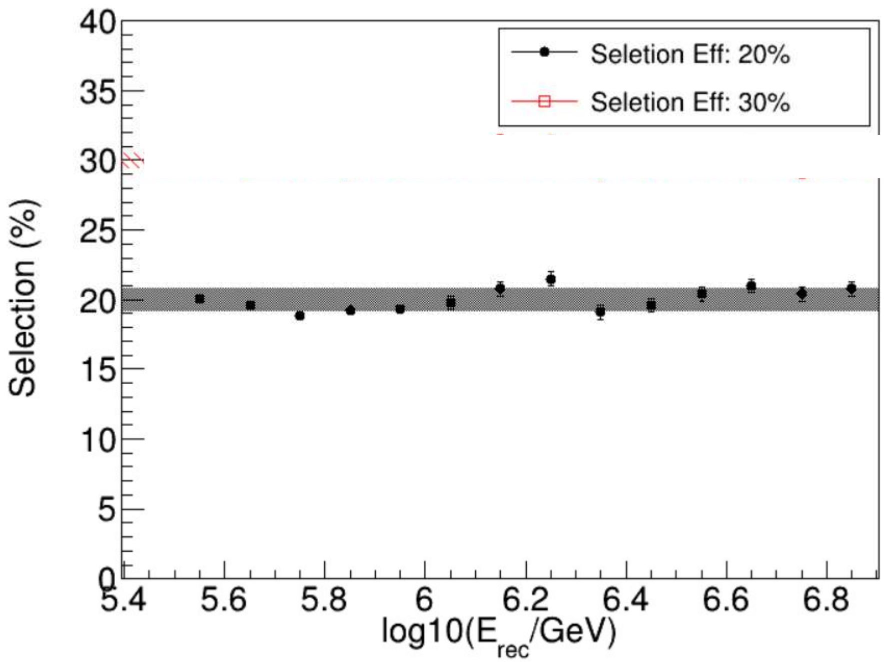


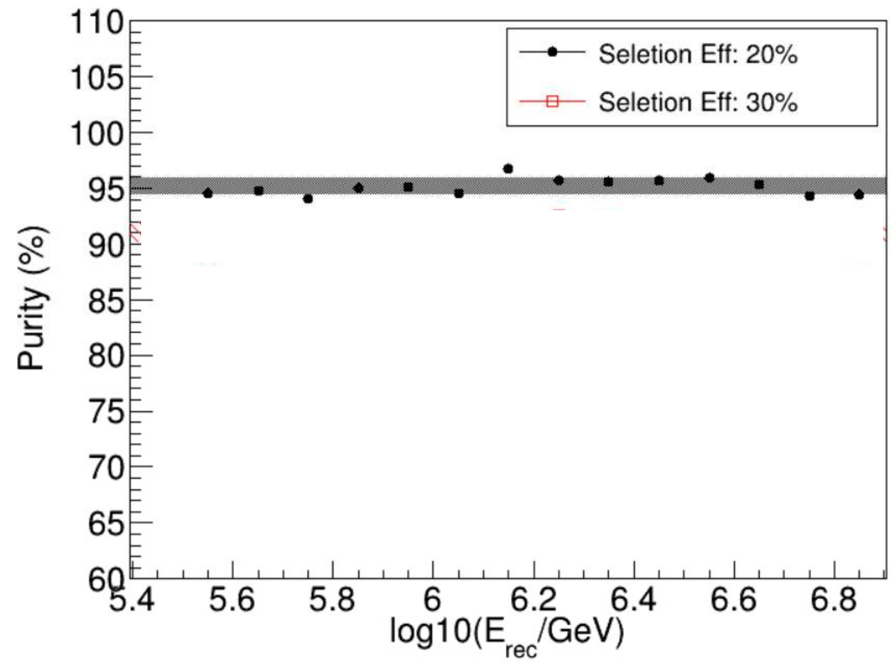






Selection Efficiency versus Purity of the Proton Sample





Systematic uncertainty Estimates

1. Loosened criteria for proton selection

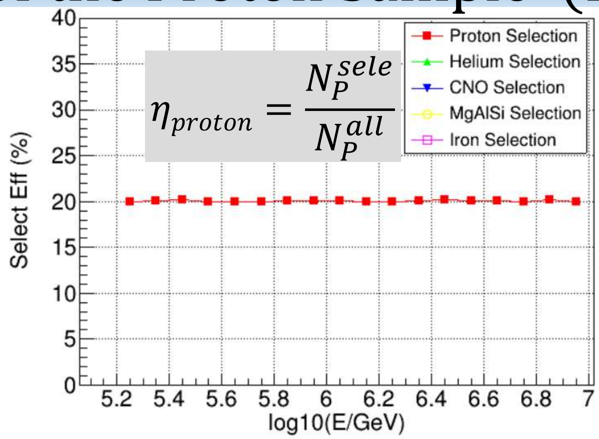
1. More events selected: better statistics
2. but contamination from Helium hurts the energy resolution at low energies

Selection Efficiency versus Purity of the Proton Sample (20%)

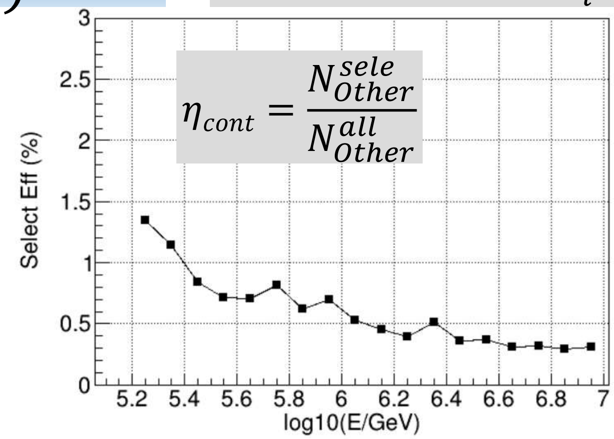
$$N * \frac{purity}{\eta} = N * \frac{N_P^{sele}}{\Sigma N_i^{sele}} / \frac{N_P^{sele}}{N_P^{all}}$$

高海拔宇宙线观测站
LHAASO Large High Altitude Air Shower Observatory

$$\eta_{proton} = \frac{N_P^{sele}}{N_P^{all}}$$

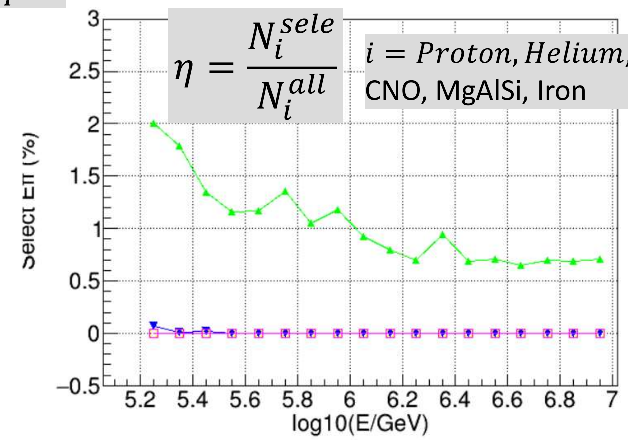


$$\eta_{cont} = \frac{N_{Other}^{sele}}{N_{Other}^{all}}$$

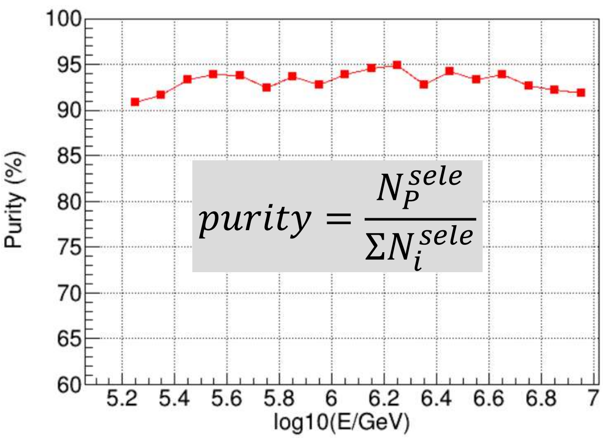


$$\eta = \frac{N_i^{sele}}{N_i^{all}}$$

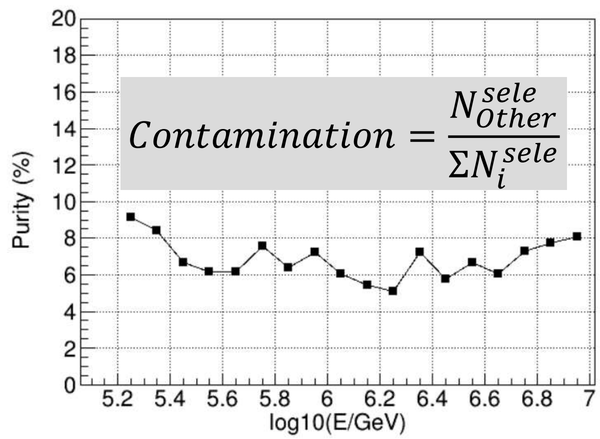
$i = Proton, Helium,$ CNO, MgAlSi, Iron



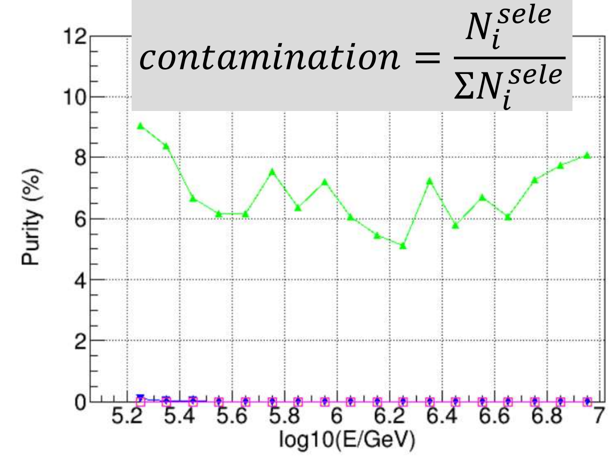
$$purity = \frac{N_P^{sele}}{\Sigma N_i^{sele}}$$



$$Contamination = \frac{N_{Other}^{sele}}{\Sigma N_i^{sele}}$$

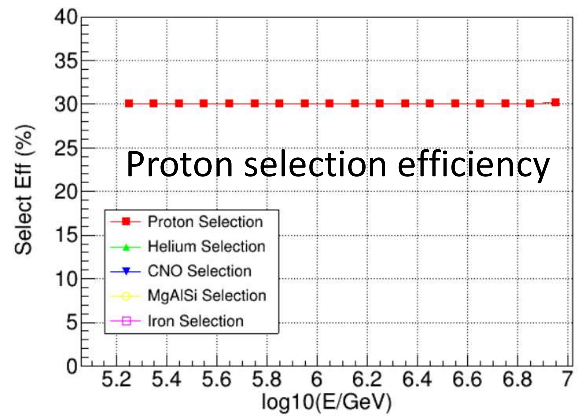


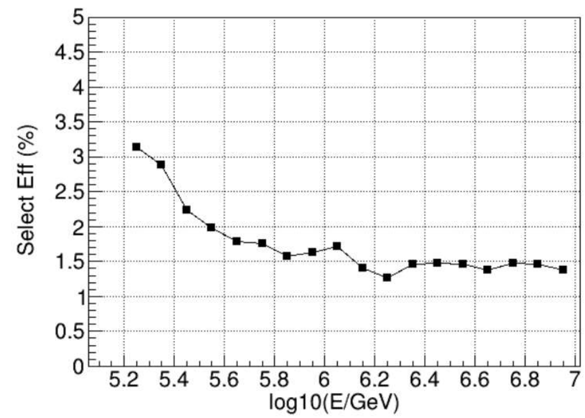
$$contamination = \frac{N_i^{sele}}{\Sigma N_i^{sele}}$$

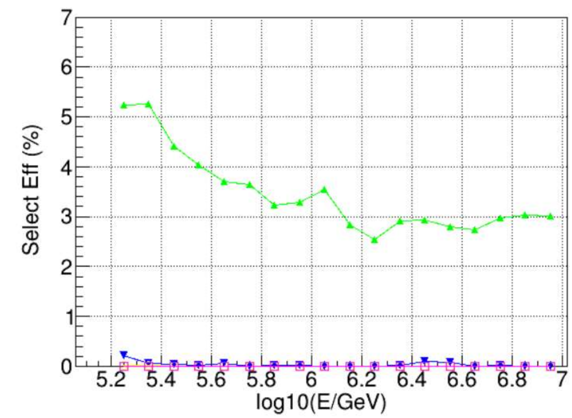


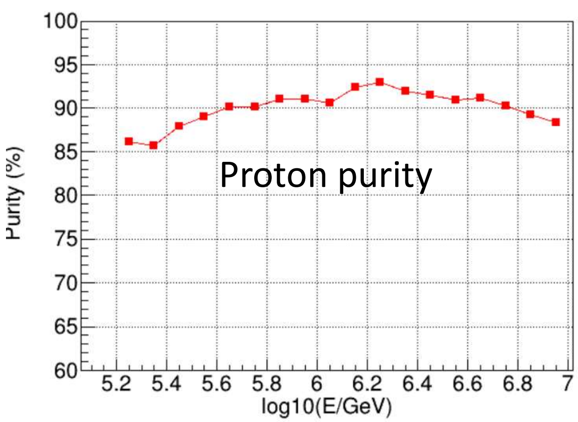
Efficiency versus Purity (30%)

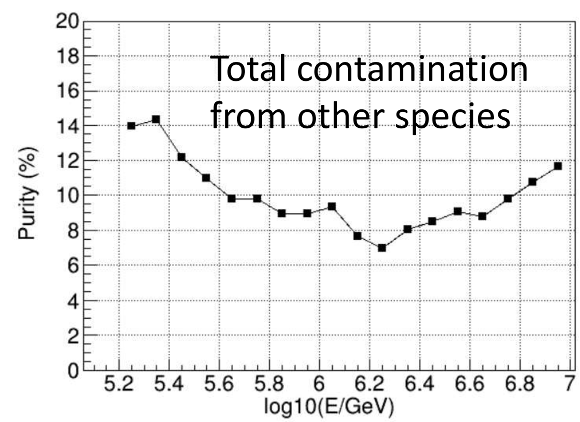
高海拔宇宙线观测站 LHAASO Large High Altitude Air Shower Observatory

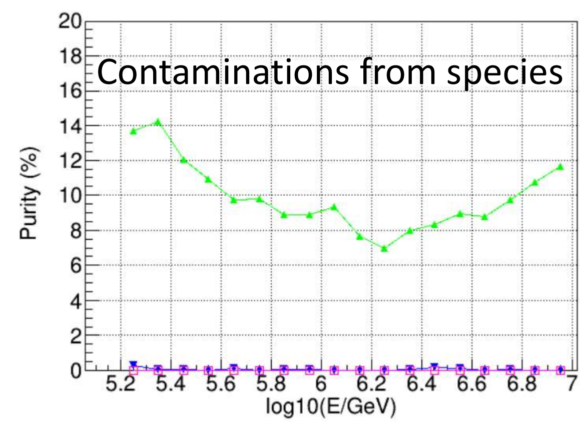




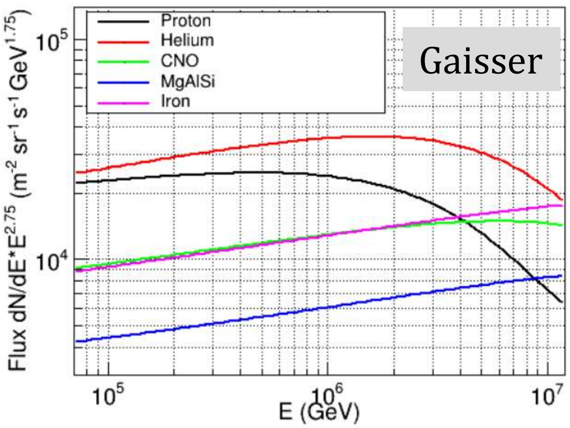


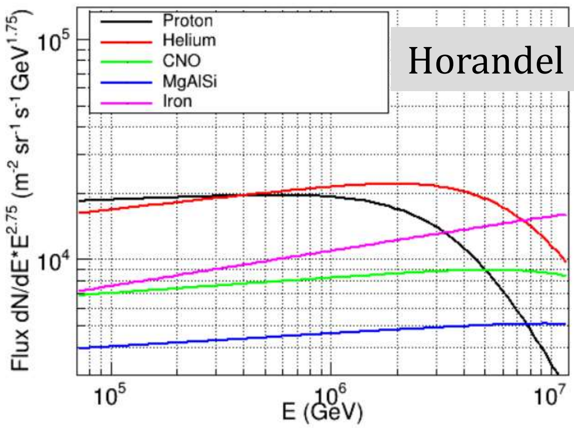


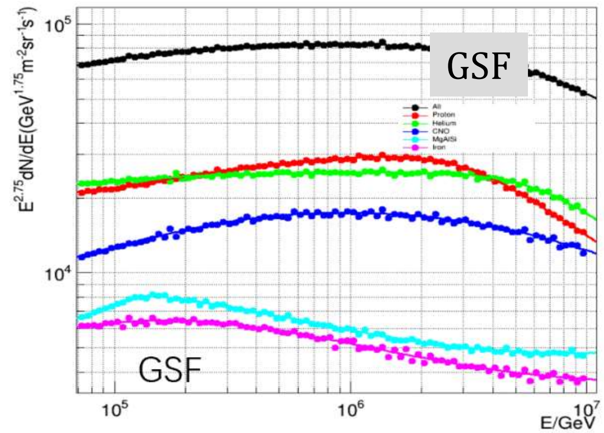


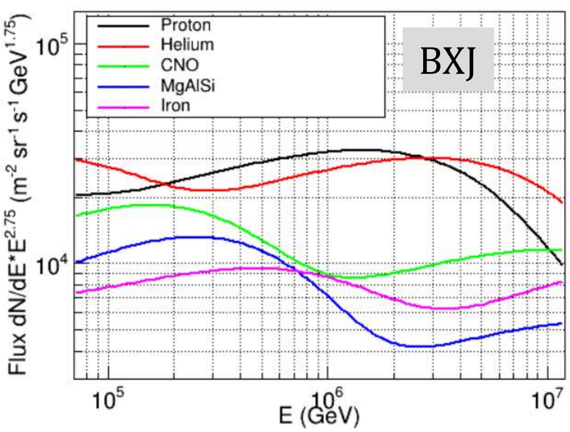


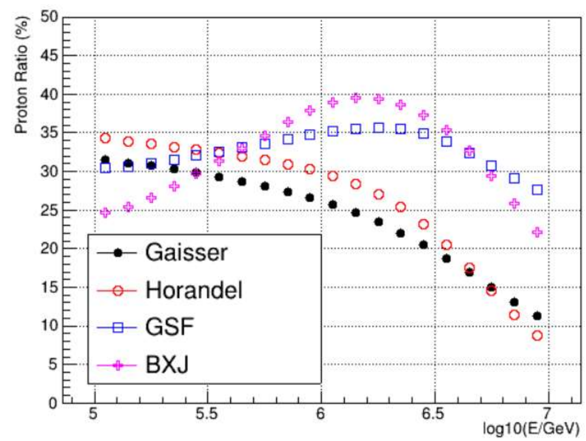
2. Difference between Composition Assumptions



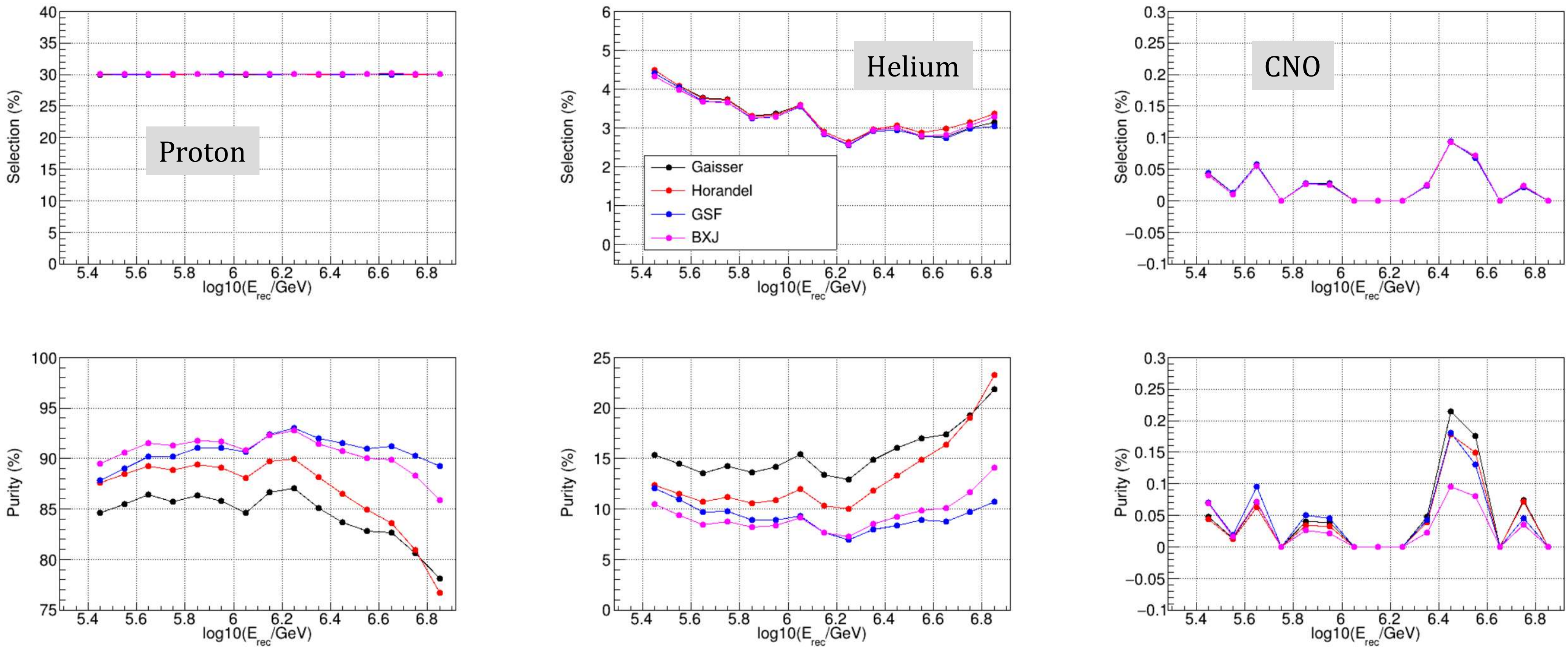








Selection efficiency 30% vs. 20%



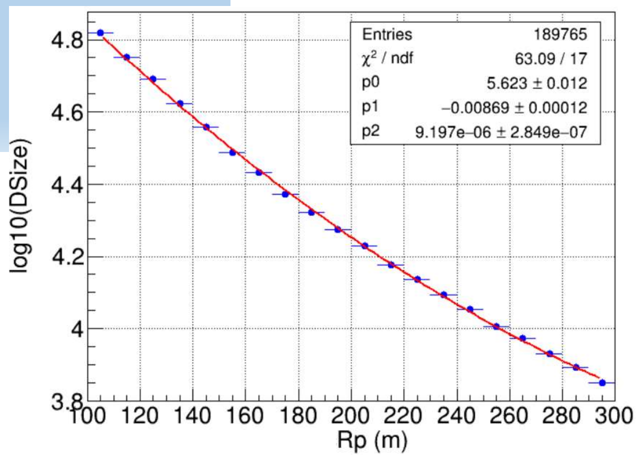
Shower Energy Reconstruction

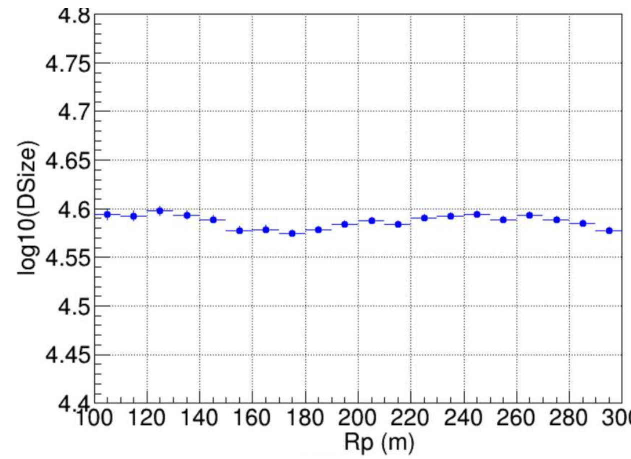
using WFCTA measured total number Cherenkov photons N_{pe} and MD measured N_μ

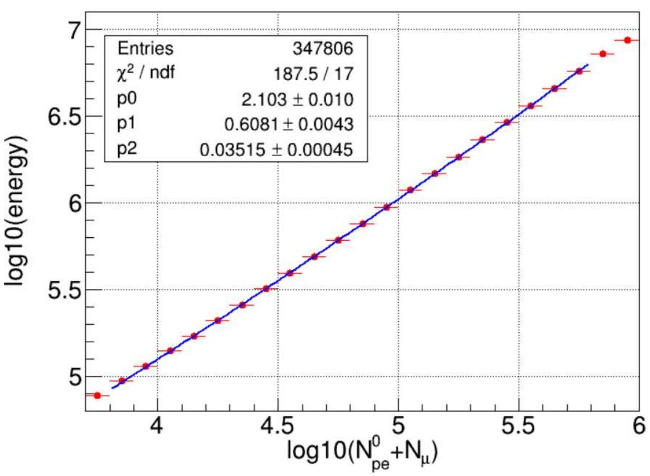
$$N_{pe}^{140} = N_{pe} - a \times (R_p - 140m)^2 - b \times (Rp - 140m)$$

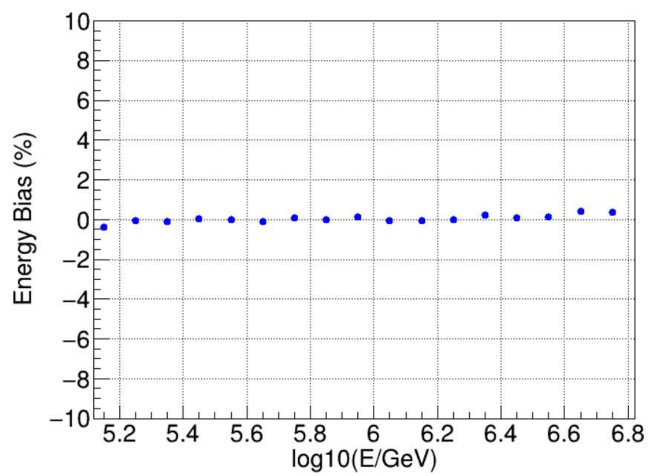
$$N_{C\mu} = N_{pe}^{140} + 10N_\mu$$

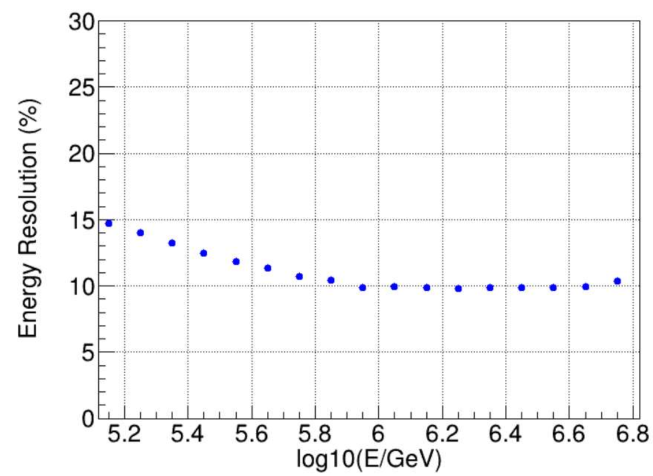
$$\lg E_{rec} = A \times \lg^2 N_{C\mu} + B \times \lg N_{C\mu} + C$$











Systematic biases due to the primary composition

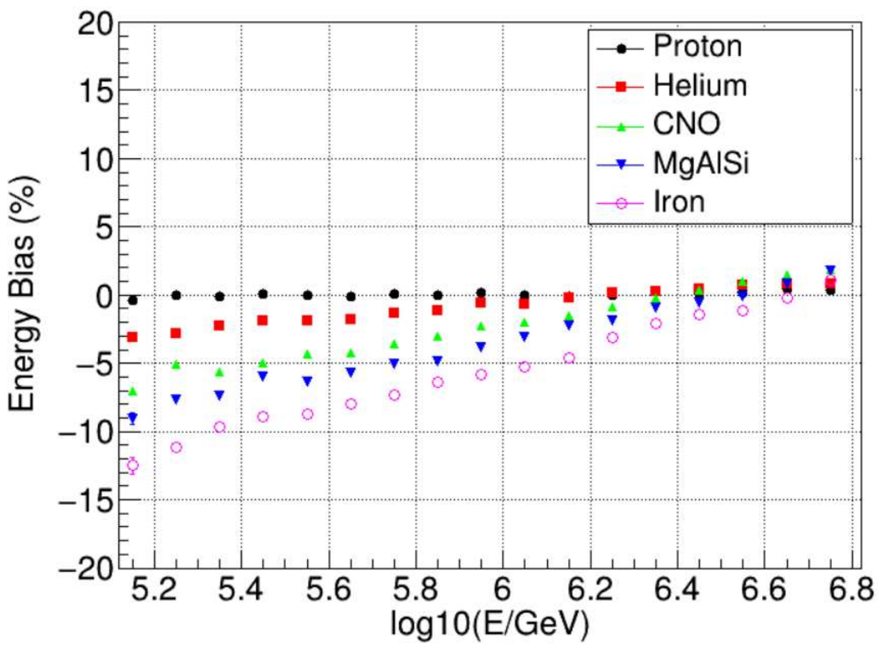
Large High Altitude Air Shower Observatory

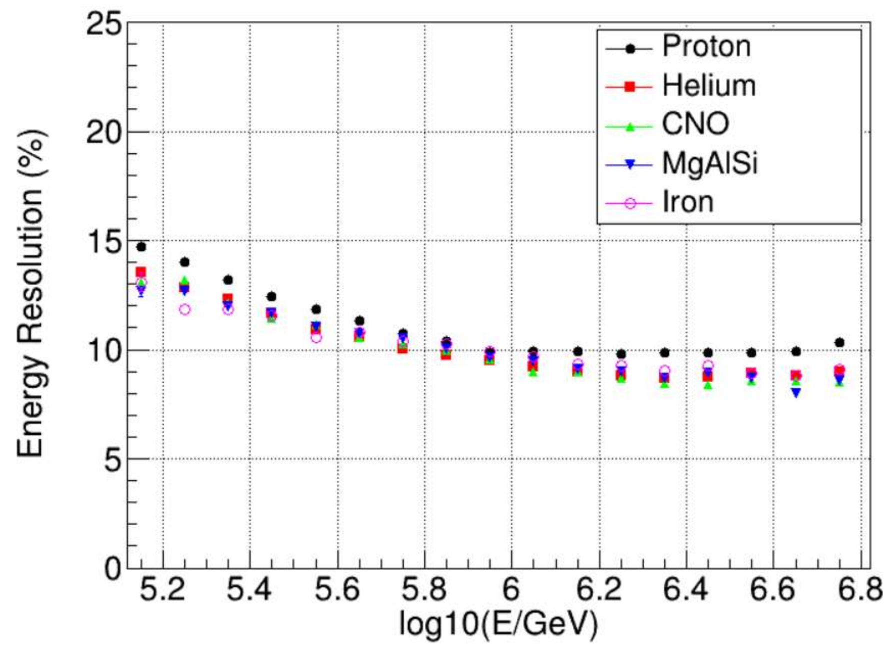
Bias is minimized for Proton sample, i.e. <1%
The energy is clearly underestimated for showers induced by heavier species

Note: This has advantages in proton selection due to steep spectra of heavier species

The resolution is slightly worse than other species due to the shower-to-shower fluctuations, quite stable between 10% and 12% above 300 TeV

Note: This is a good feature for identifying any spectral structure like the knee





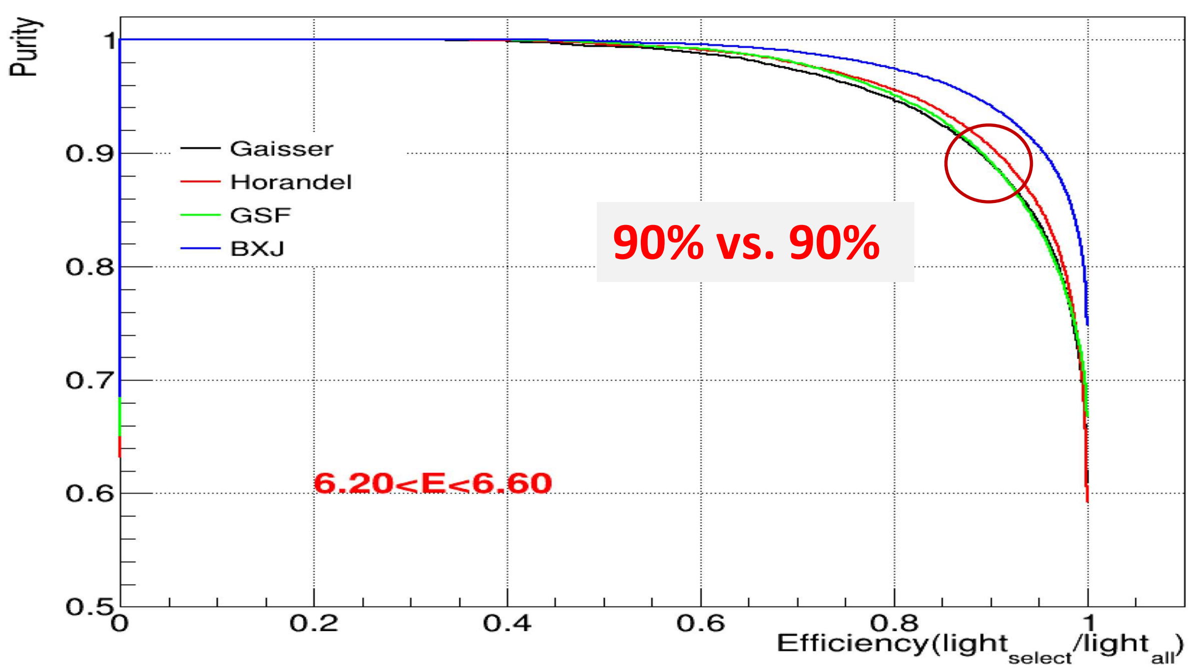
- LHAASO experiment
- Pure Proton Sample
- **Light Component (H + He) Sample**
- All Particle Spectrum and Composition

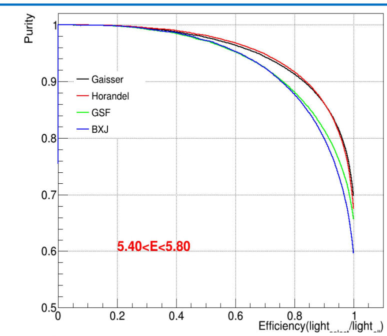
Muon Content in Showers

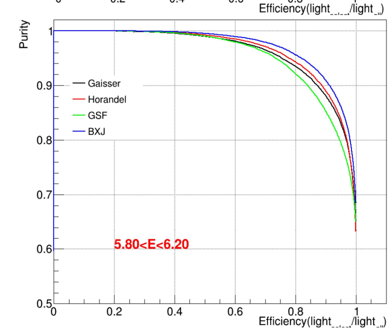
$$P_{\mu} = \log_{10}\frac{\rho_{\mu}}{\rho_e^{0.83}}$$

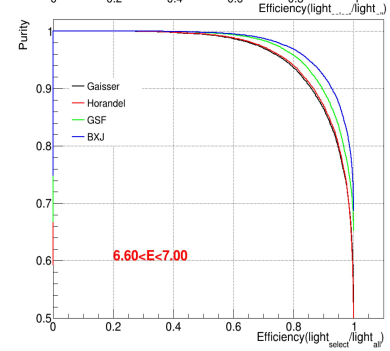
ρ_{μ}: *muon density in the ring between* 40*m and* 200*m* from the core

ρ_e: *EM* − *particle density in the ring between* 40*m and* 200*m*

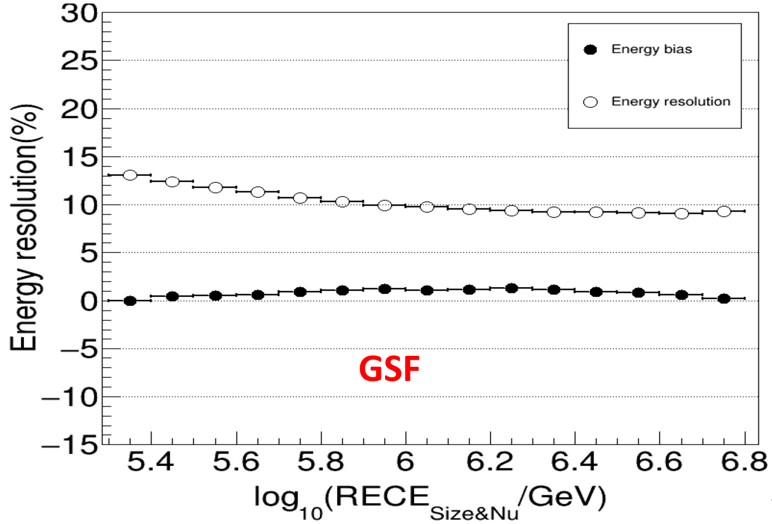


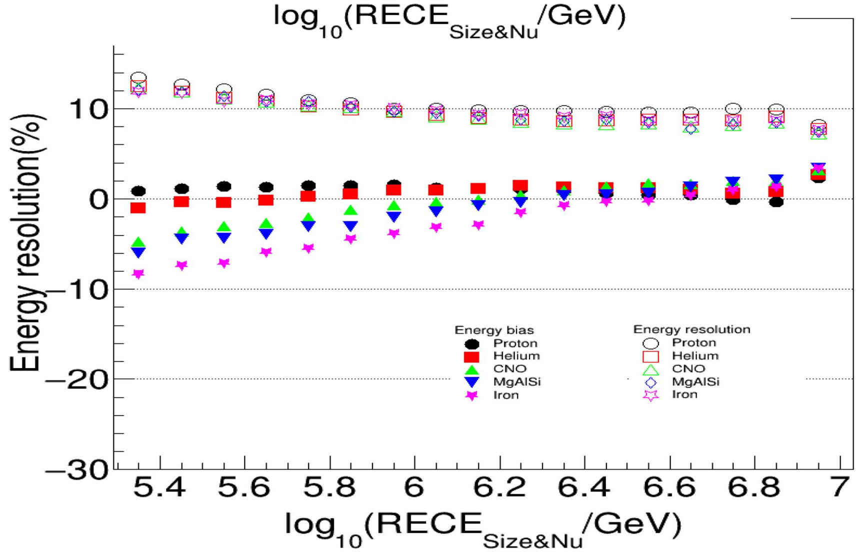


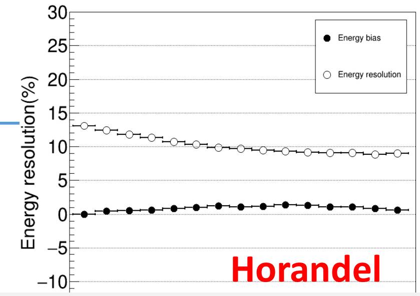


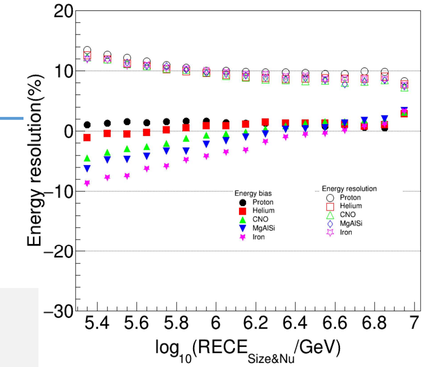


Energy Reconstruction





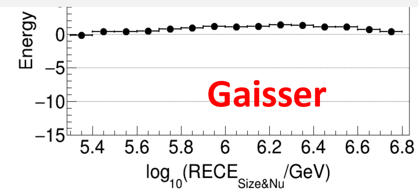


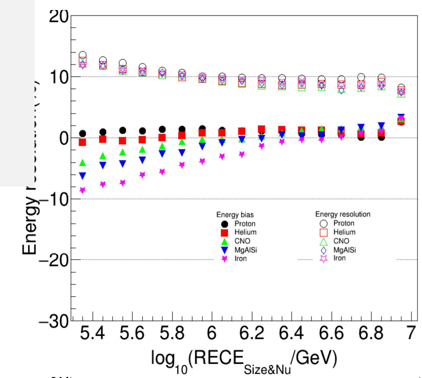


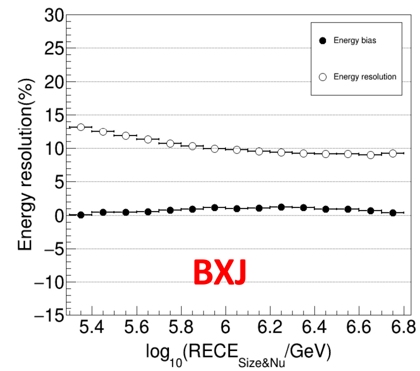
Invisible difference between composition assumptions

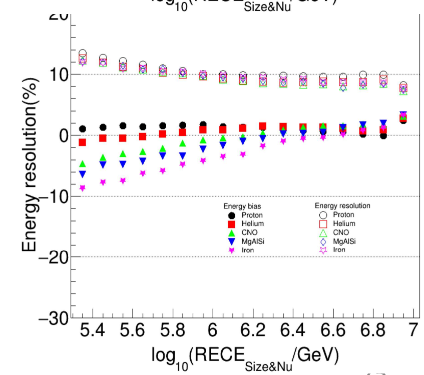
Bias: <±1%

resolution: 13% to 9%







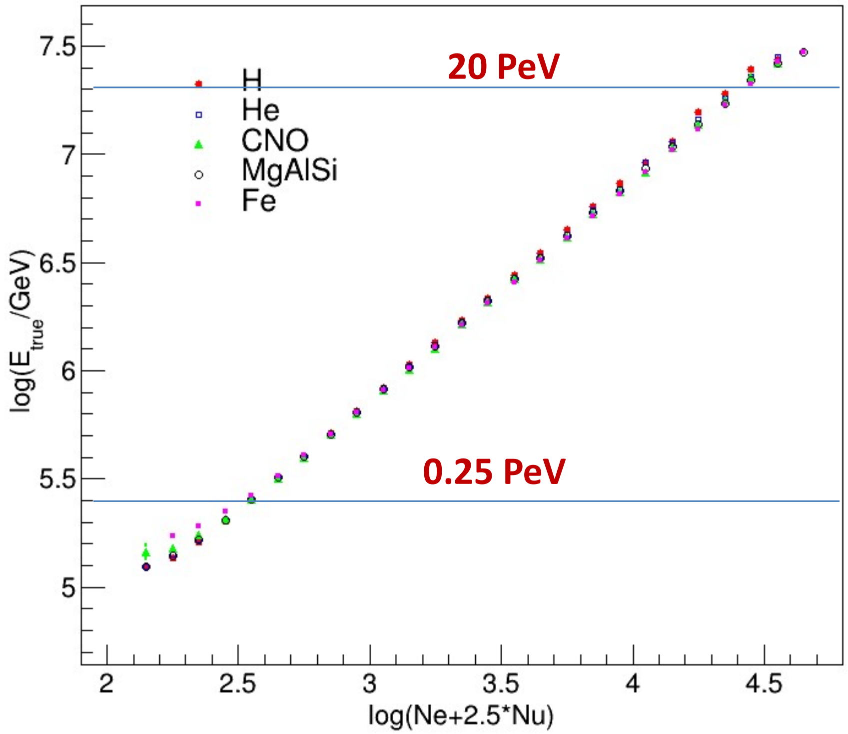


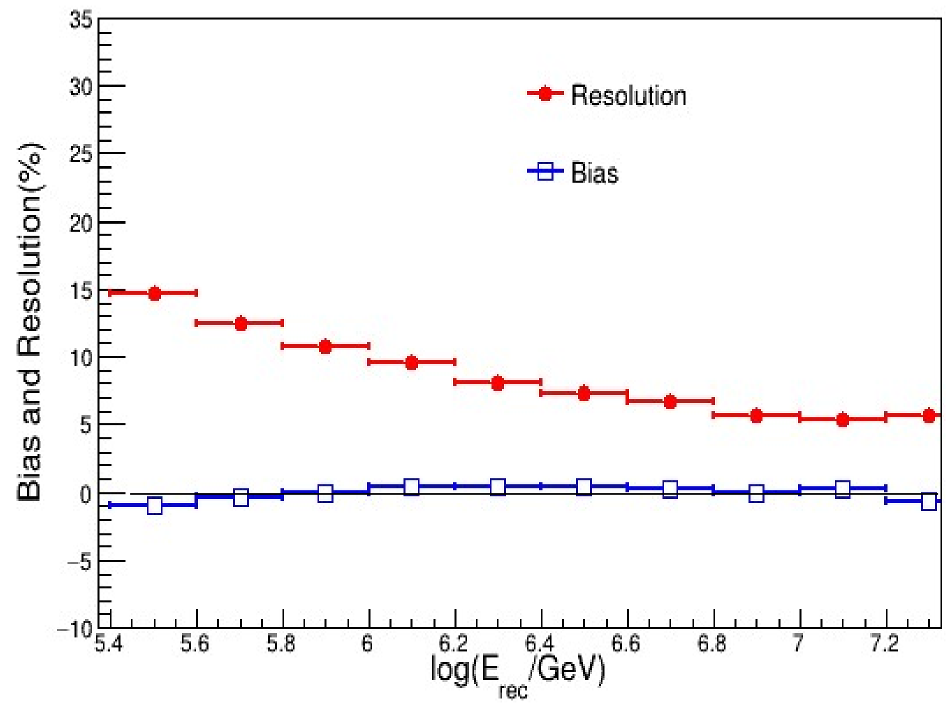
- LHAASO experiment
- Pure Proton Sample
- Light Component (H + He) Sample
- All Particle Spectrum and Composition

All particle spectrum by LHAASO

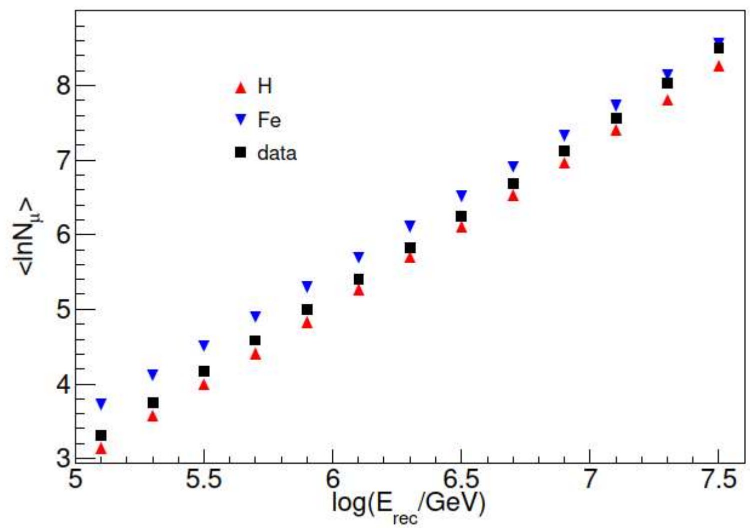
- Energy reconstruction independent of primary CRs components

$$E_0 = E_e + E_h$$
$$N_{em} = N_e + 2.5 \cdot N_\mu$$
$$\log 10(E) = a + b \cdot \log 10(N_{em})$$





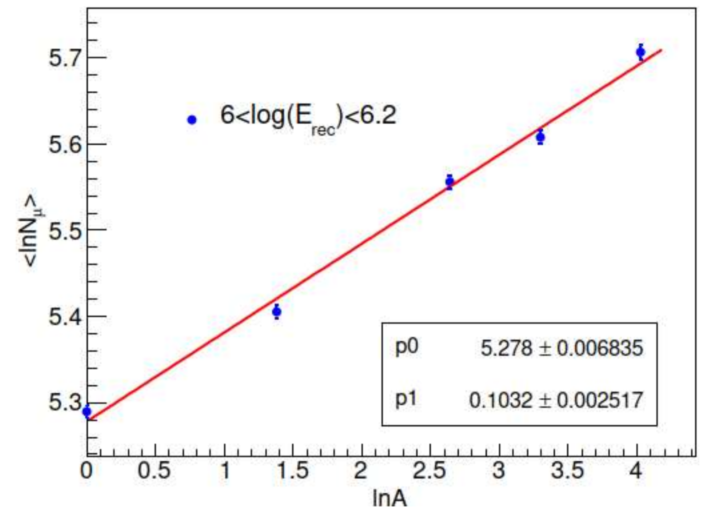
<lnA> reconstructed by muon in KM2A

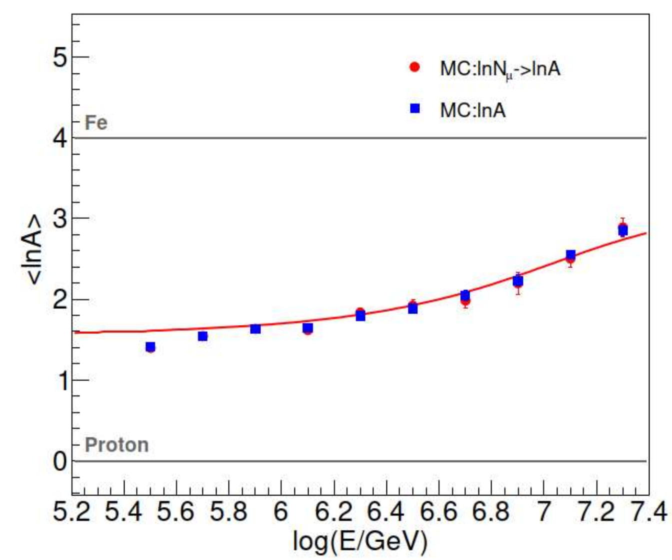


$$N_\mu = A \cdot \left(\frac{E}{A \cdot \varepsilon_c}\right)^\beta$$ Matthews-Heitler model

A is the mass of the cosmic ray, ε_c is the critical energy where charge pions blow it then are all assumed to decay (yielding muons), and $\beta \approx 0.9$ varying with the primary energy.

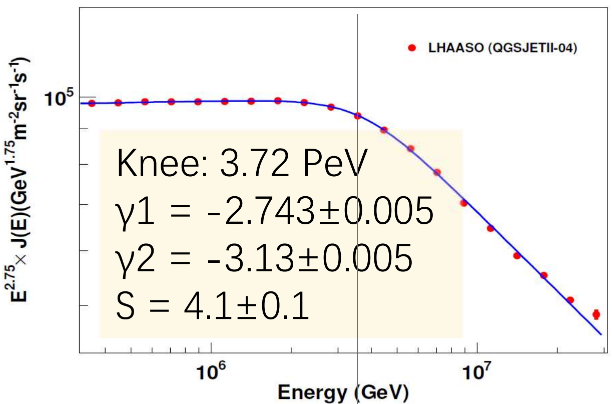
$$\ln N_\mu = p_0 + p_1 \cdot \ln A$$

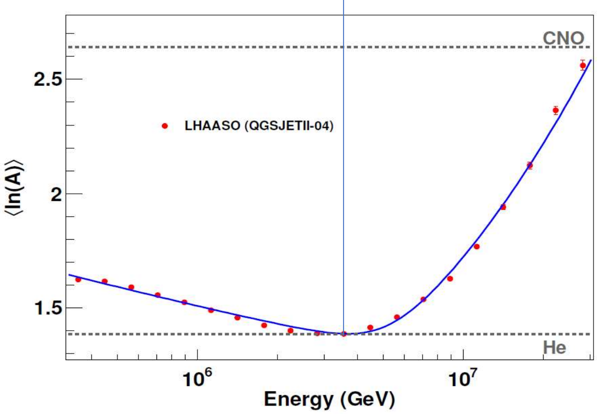


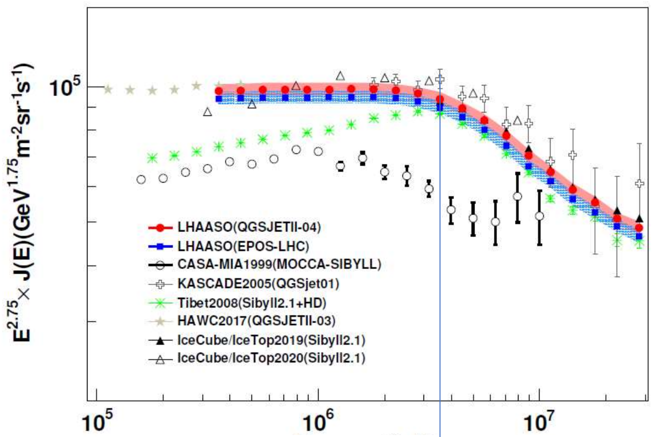


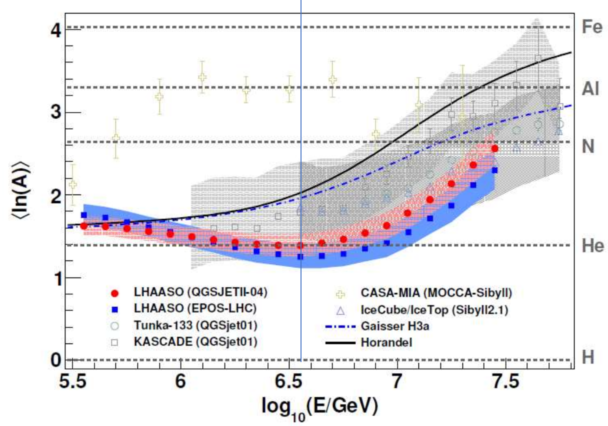
All-particle energy spectrum & composition by LHAASO

(from 0.3 to 30 PeV)





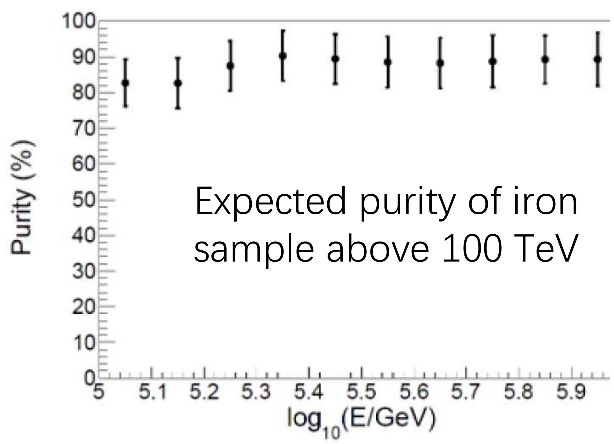


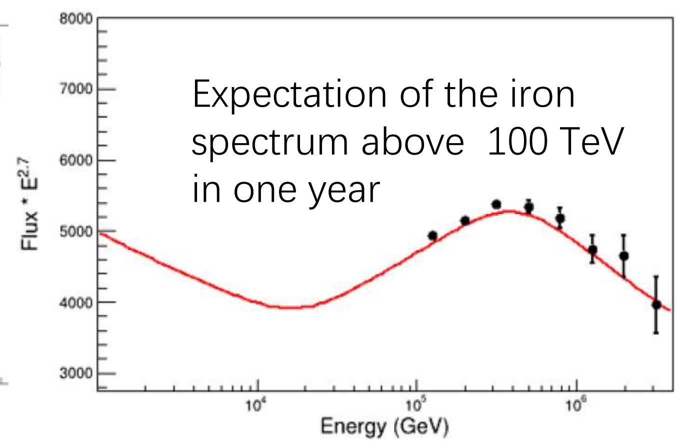


- Systematic uncertainties are sufficiently small
- This unveils a clear correlation between the flux and the composition at the knee

Discussion

- The composition is getting lighter towards the knee
- Iron may bump up around 400 TeV (hinted by the proton at 13 TeV and Helium at 34 TeV)
- LHAASO is trying hard to measure the Iron spectrum around 400 TeV by lowering the threshold energy





Summary

- LHAASO is designed to dedicate on the measurements of knees of CR species
- The knee of pure proton spectrum
  - Criteria for selection are developed
  - Systematic uncertainty analysis
- H + He mixed sample is also ready
  - Helium spectrum will be resolved
- All-particle spectrum
  - The knee has been confirmed
  - CR Composition is measured by using <lnA> showing correlation with the spectrum
- The iron spectrum around 400 TeV is crucial and will be measured
- The knee of the iron spectrum is the goal for many years