# Highlights of LHAASO Cosmic Ray Energy Spectrum and Composition Measurements

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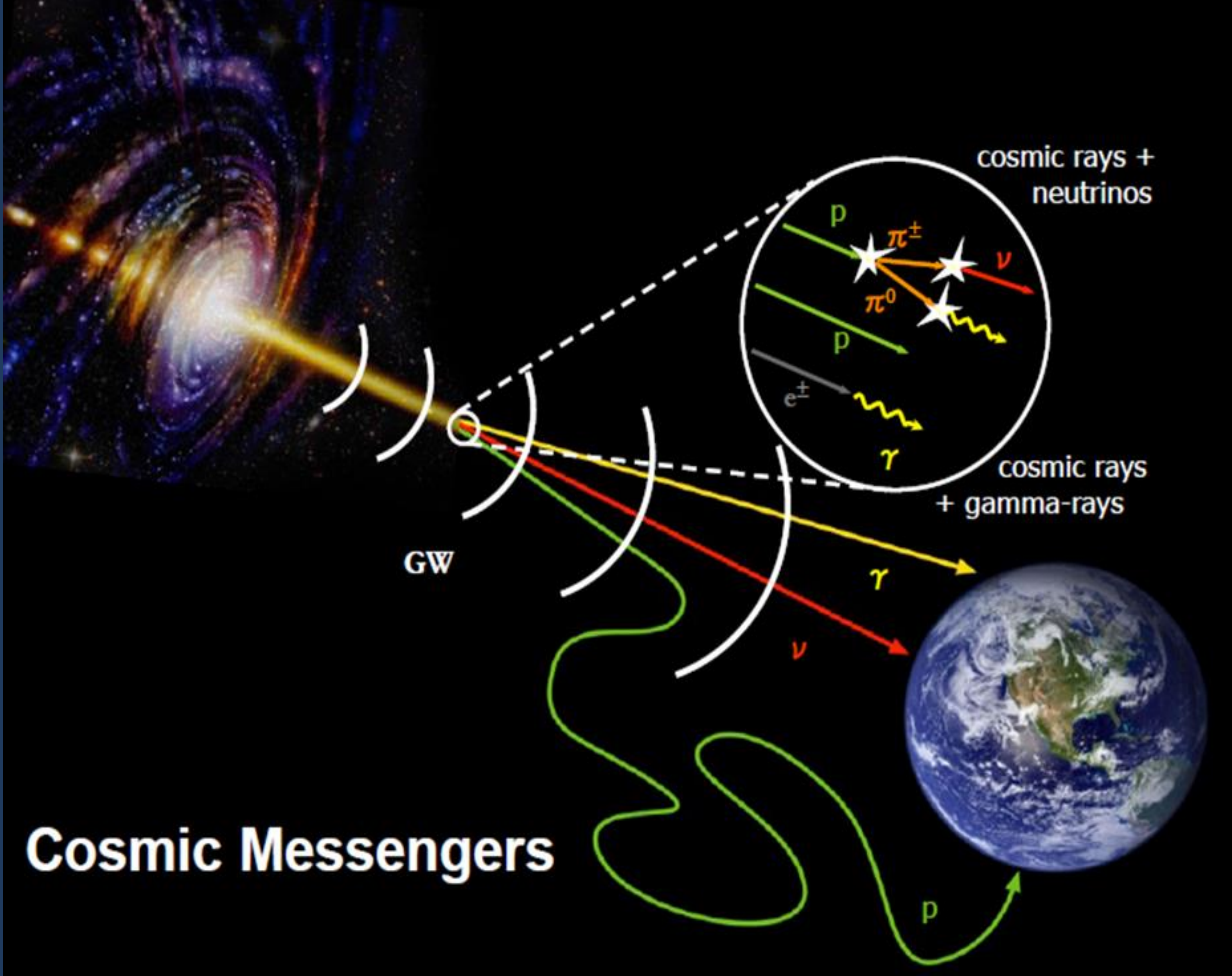
XiChang 20250826

# Outline

- Status and challenges in the measurements of energy spectrum and compositions
- Measurements of all-particle energy spectrum and <lnA> around the knee
- Measurements of proton spectrum around the knee
- Progress in the light component and helium energy spectrum measurements
- Summary and outlook

It is hard to trace cosmic rays back by their arriving directions



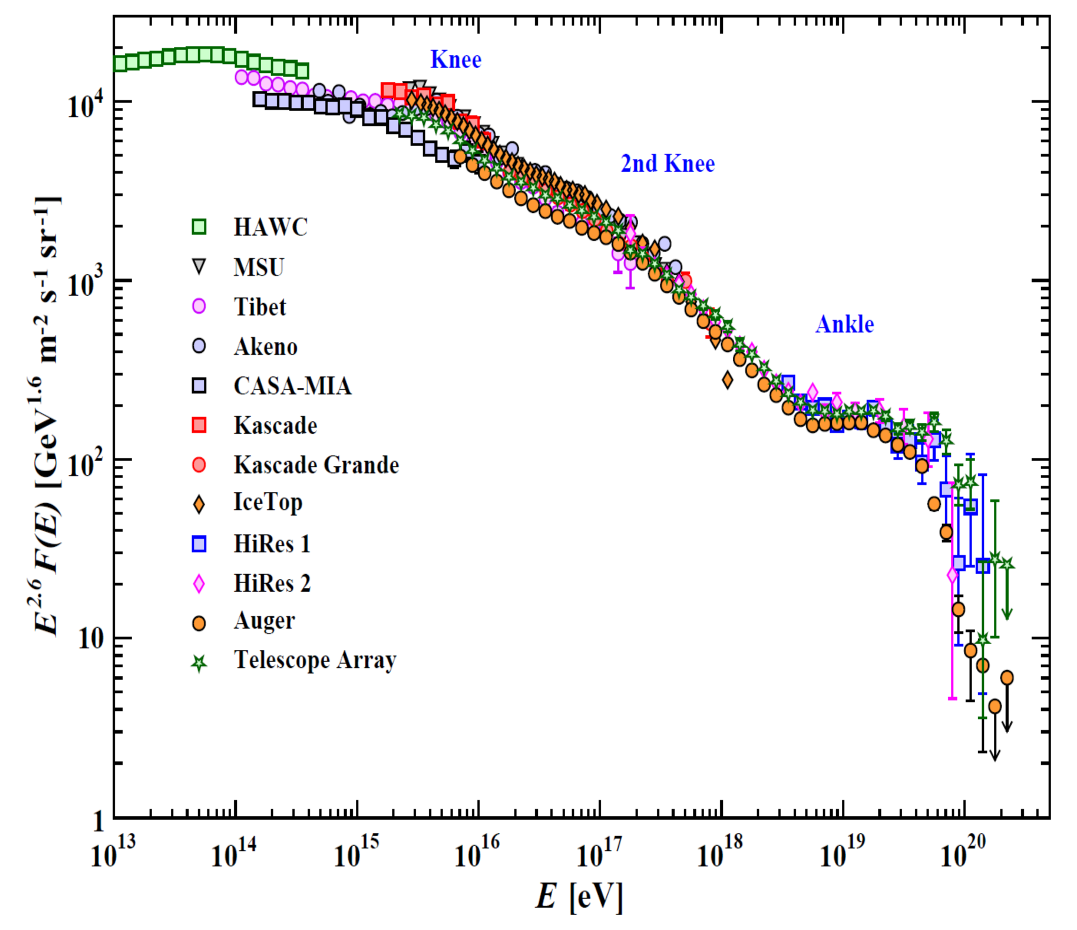
# Knee: a 65 years old puzzle

- The most striking features in the energy spectrum, whose origin remains enigmatic.
  - Index: -2.7->-3.1
  - Position: around 4PeV

- A key to the origin, acceleration and propagation
  - Acceleration upper limits of Galactic cosmic ray sources can be achieved

    **Z dependent Ec = ZEp**
  - New physics：

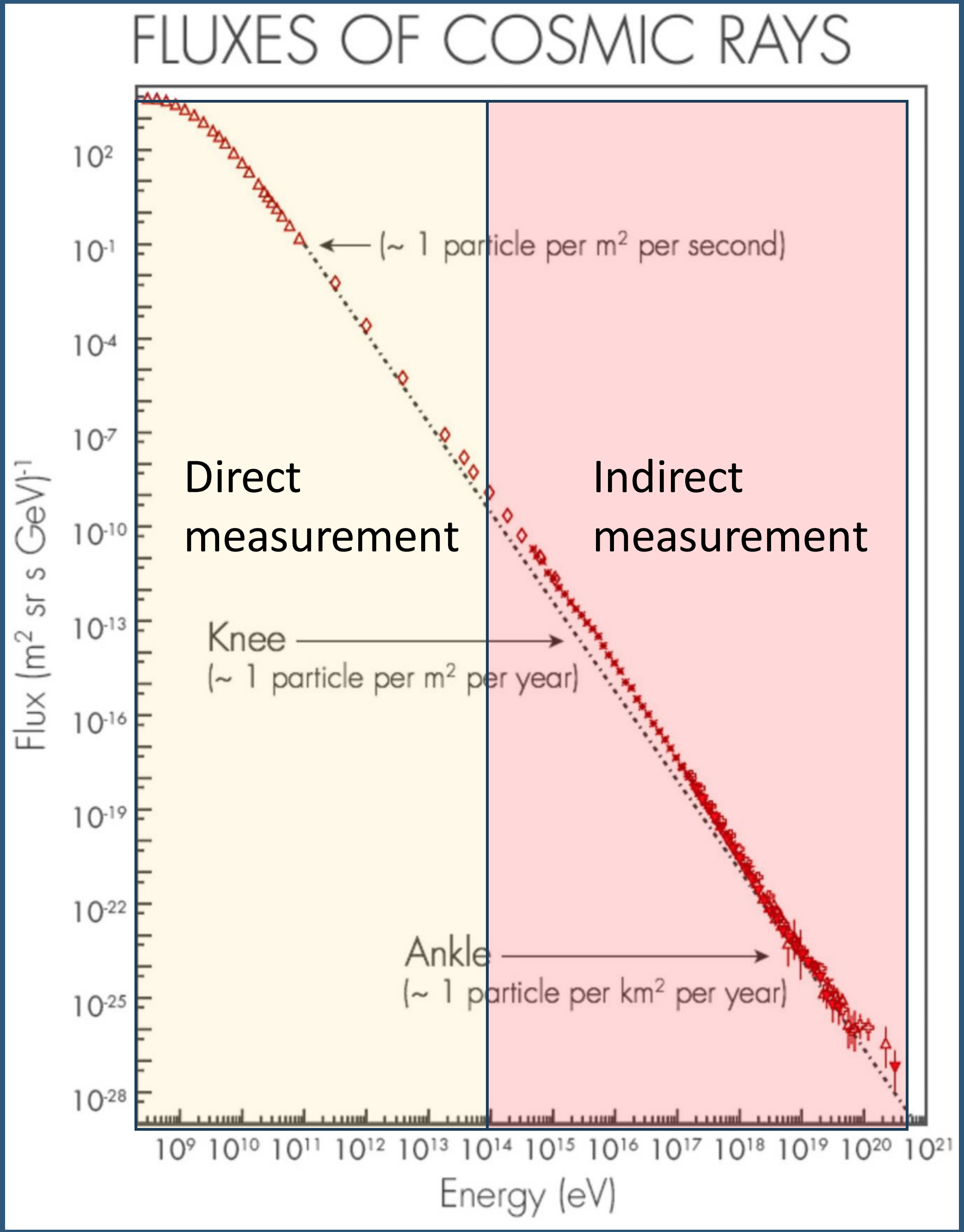
    **A dependent Ec = AEp**



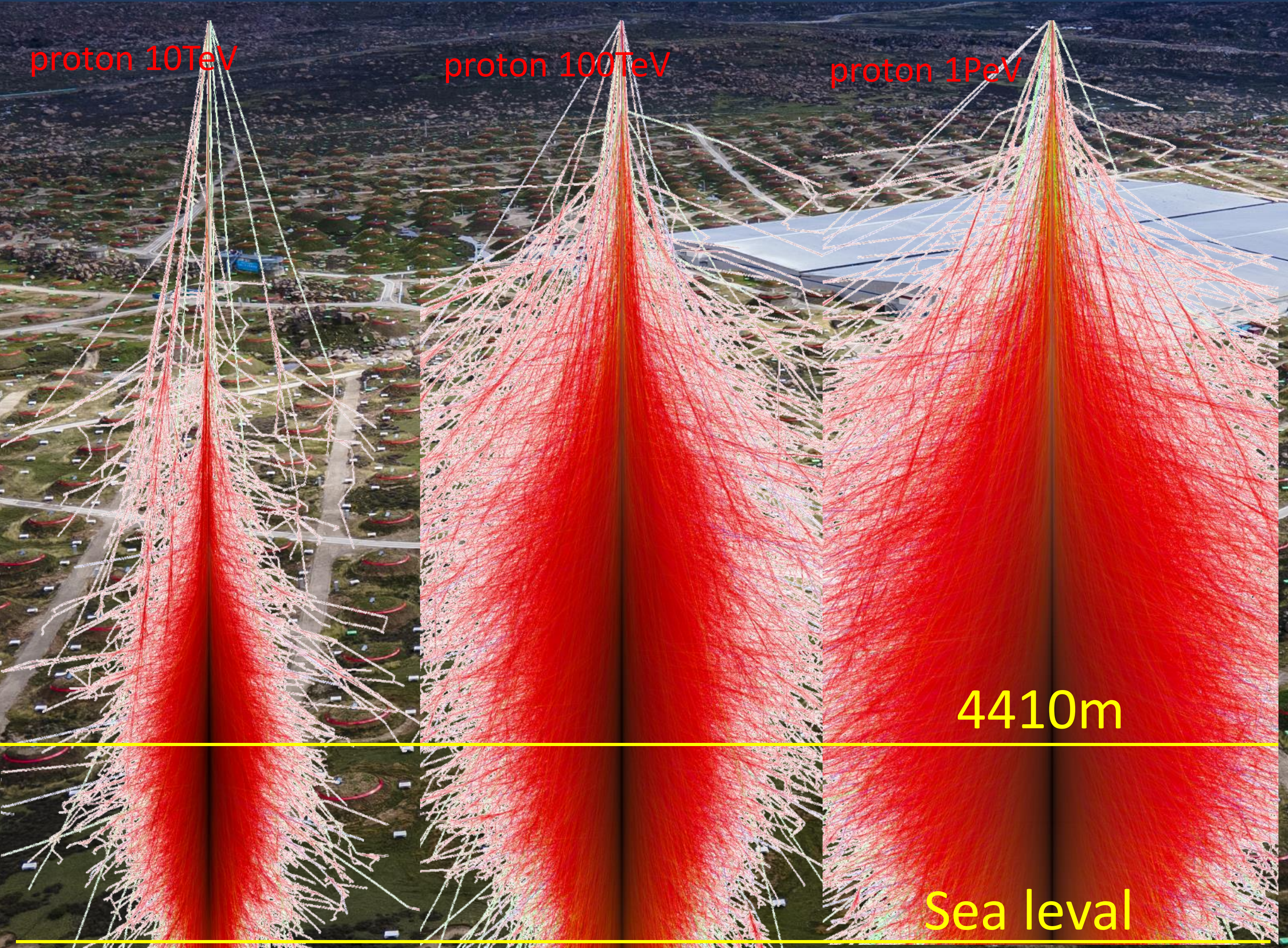
The measurements of the energy spectrum and compositions are crucial to unveil the nature of the knee

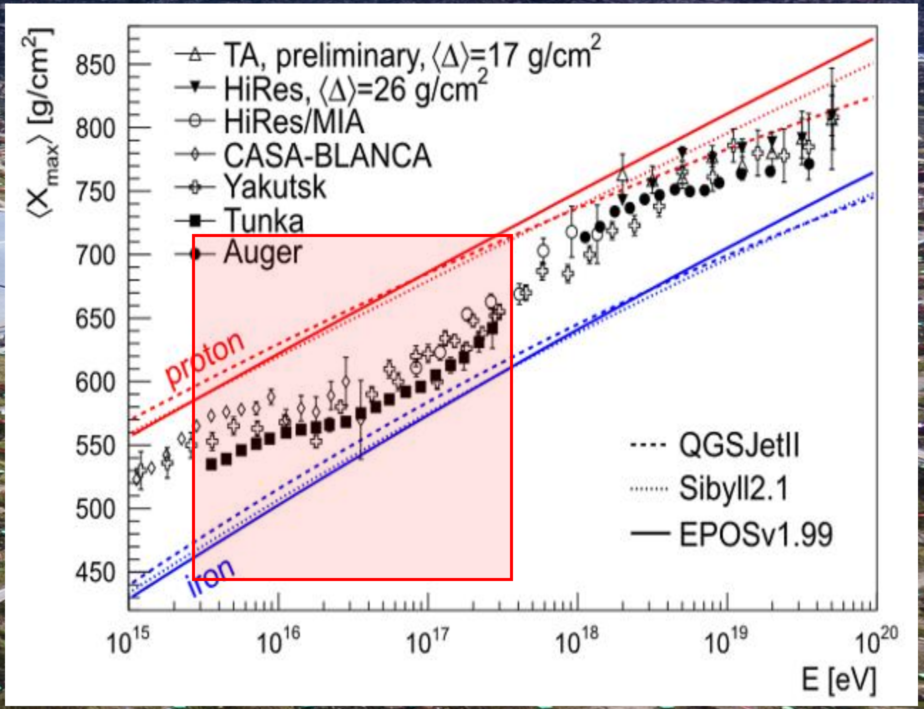
The flux of CRs is too low to observed by the space experiments directly, and can only be carried out by the ground-based experiments by detecting the Extensive Air Showers(EAS)

- Huge effective aperture
- Long observation time
- Large fluctuations from shower to shower
- The reconstructions of energy and composition dependent on each other
- The absolute energy scale is absent
- Effected by the high energy hadronic interaction models



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





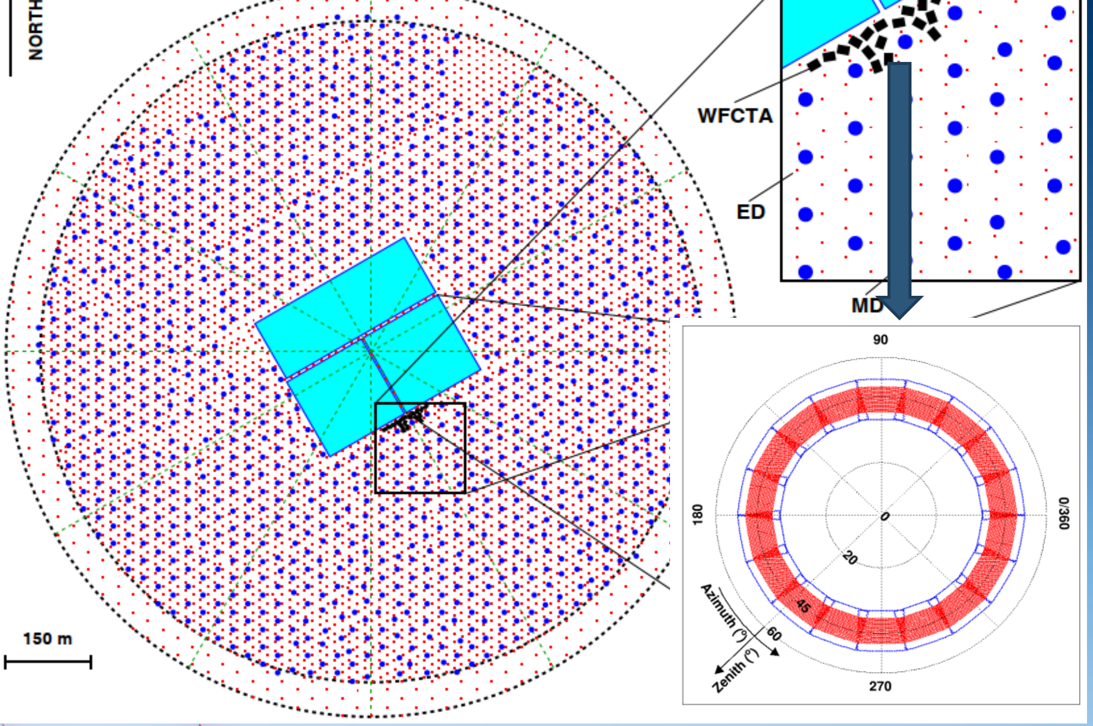
**Vertical Air depth of LHAASO site: 600g/cm²**

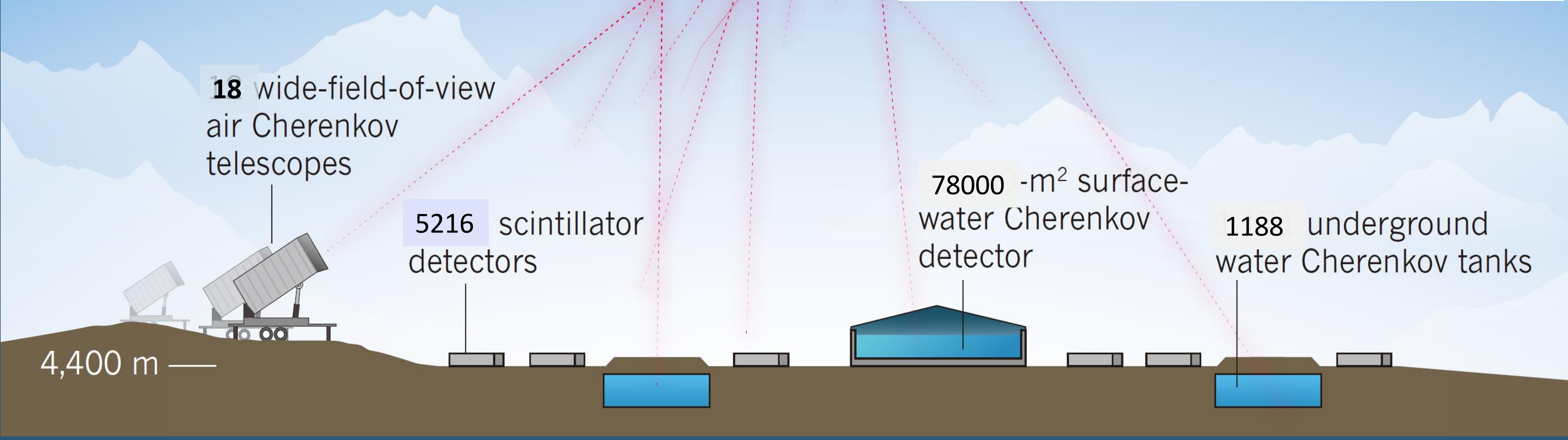
**The best altitude for cosmic rays around the knee region**

# Multi-type detectors

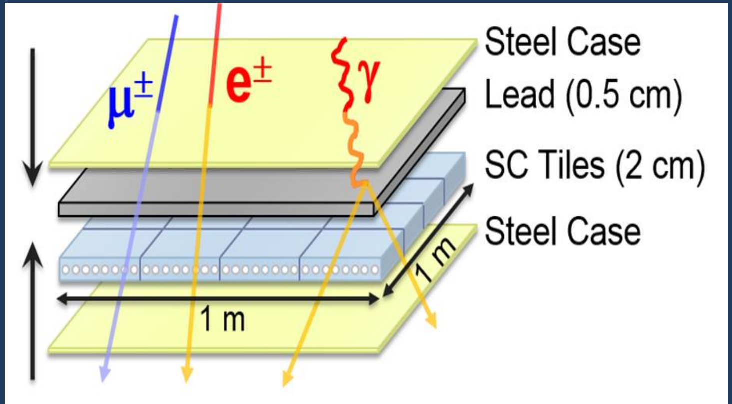
- 1188 muon detector (KM2A-MD)
- 5216 electromagnetic detector(KM2A-ED)
- 18 Widefield of view Cherenkov telescope array (WFCTA)
- 78000m$^2$water Cherenkov detector array (WCDA)

- To improve the composition discriminative capabilities
- To reduce the effects of high energy hadronic interaction models

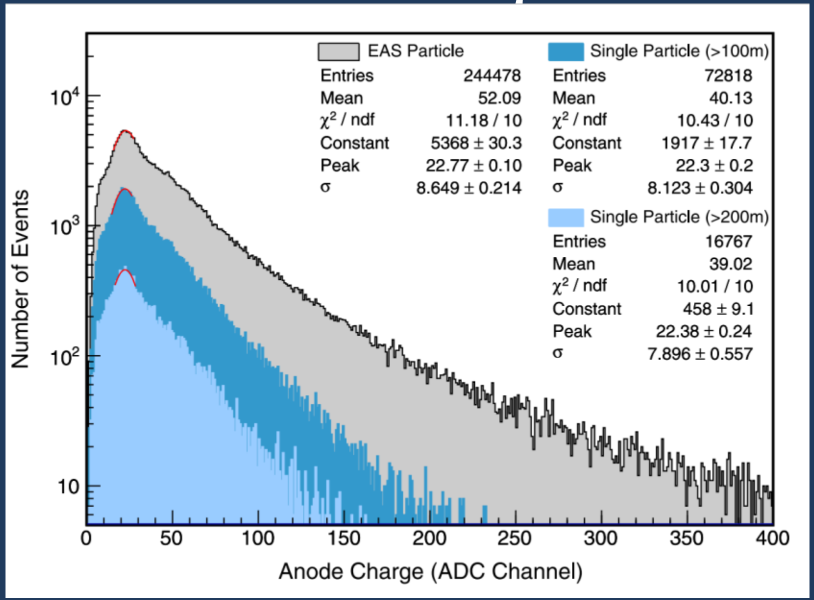


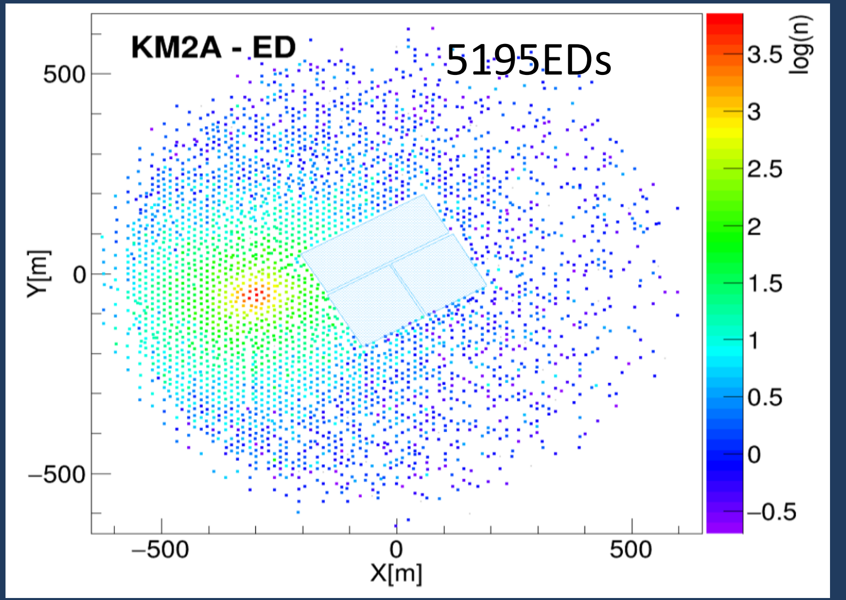


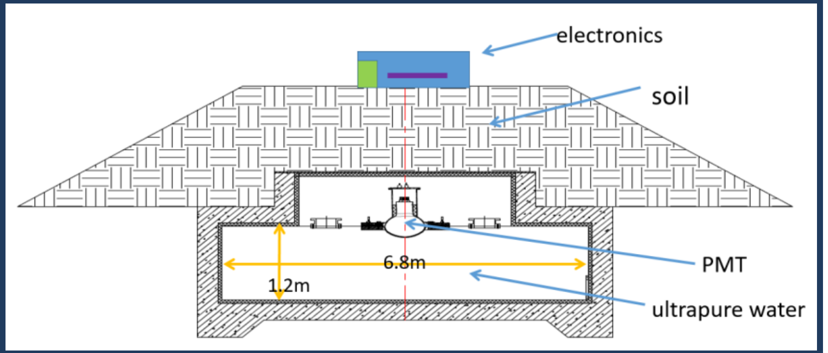
# Precise measurements of number of electromagnetic particles and muons （$N_e$ and $N_\mu$）



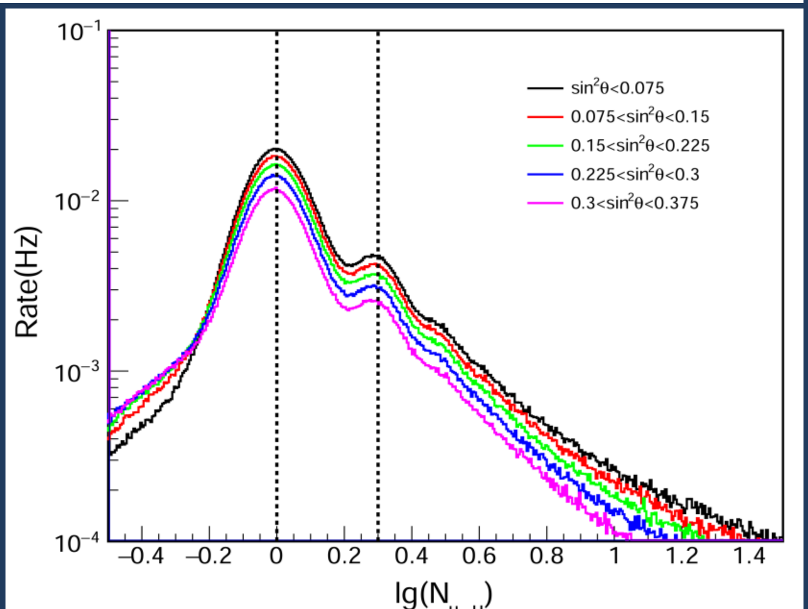
Area: $1m^2$
Spacing: 15m

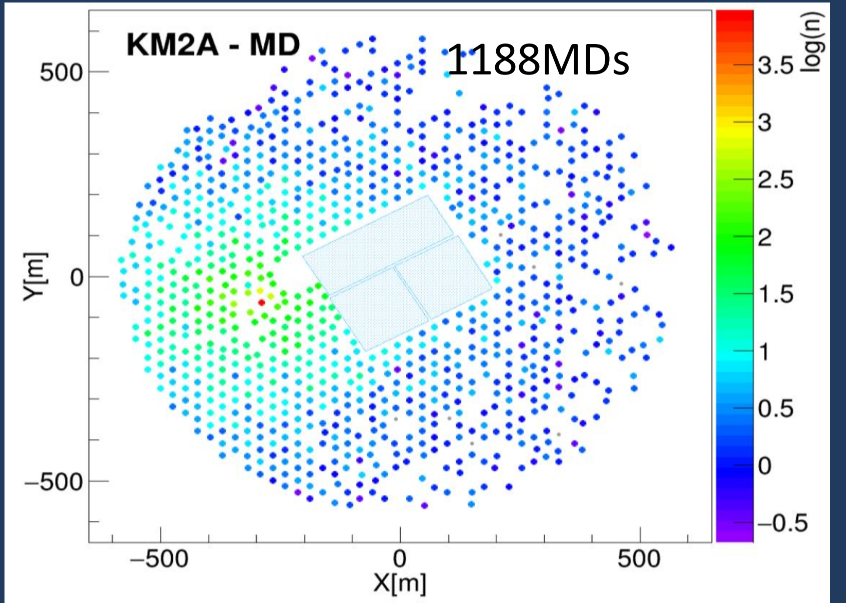






Area: $36m^2$
Spacing: 30m



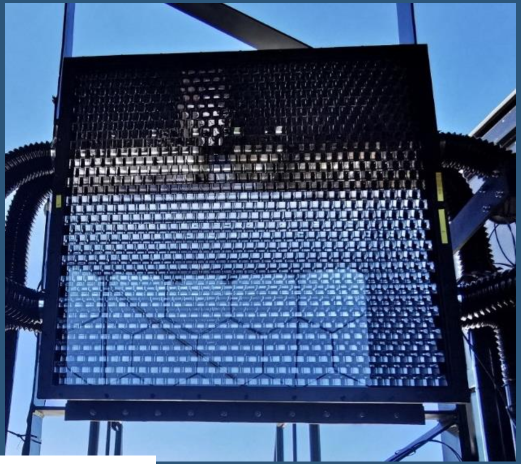


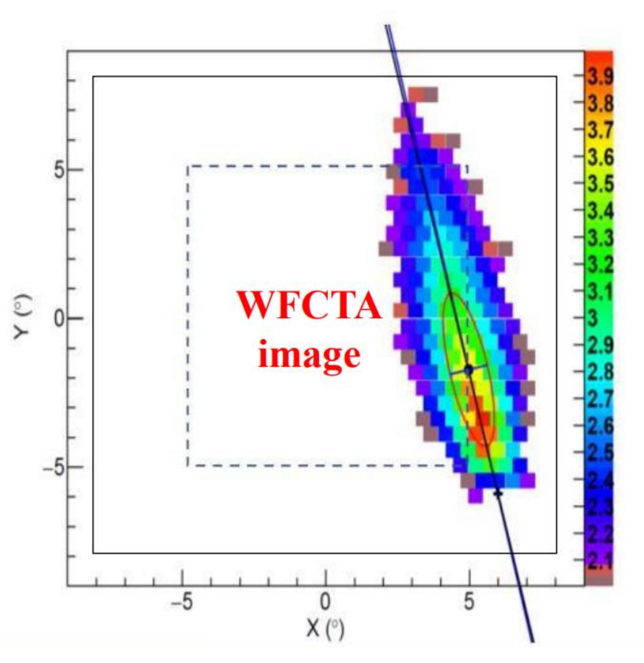
# Measurements of Cherenkov size in the shower $N_c$

18 Wide Field Cherenkov telescopes

$5m^2$ spherical mirror

$32 \times 32$ pixels
$16^\circ \times 16^\circ$ FoV
$0.5^\circ \times 0.5^\circ$ pixel size



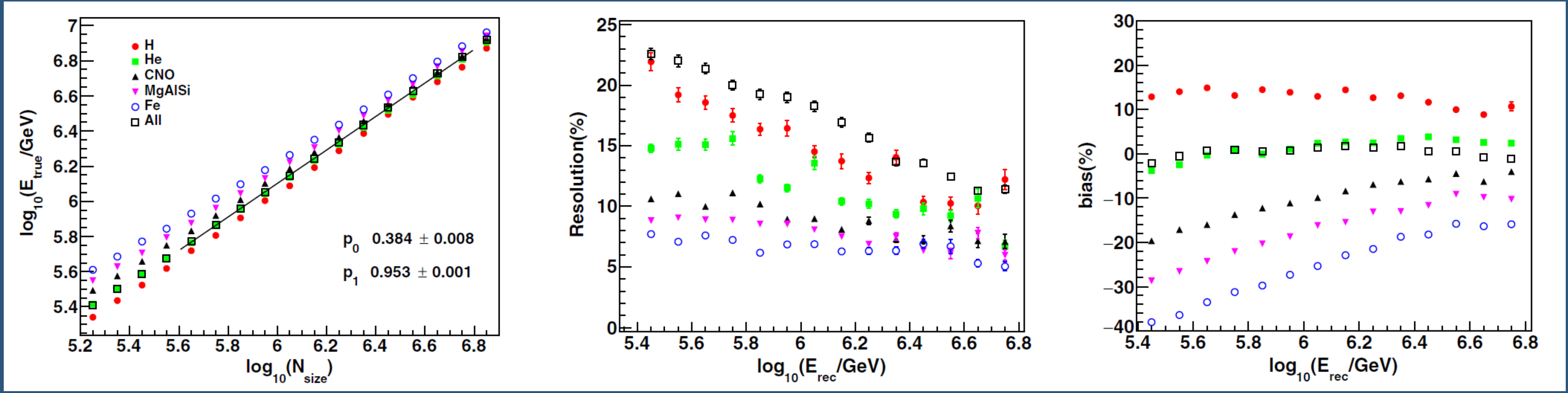


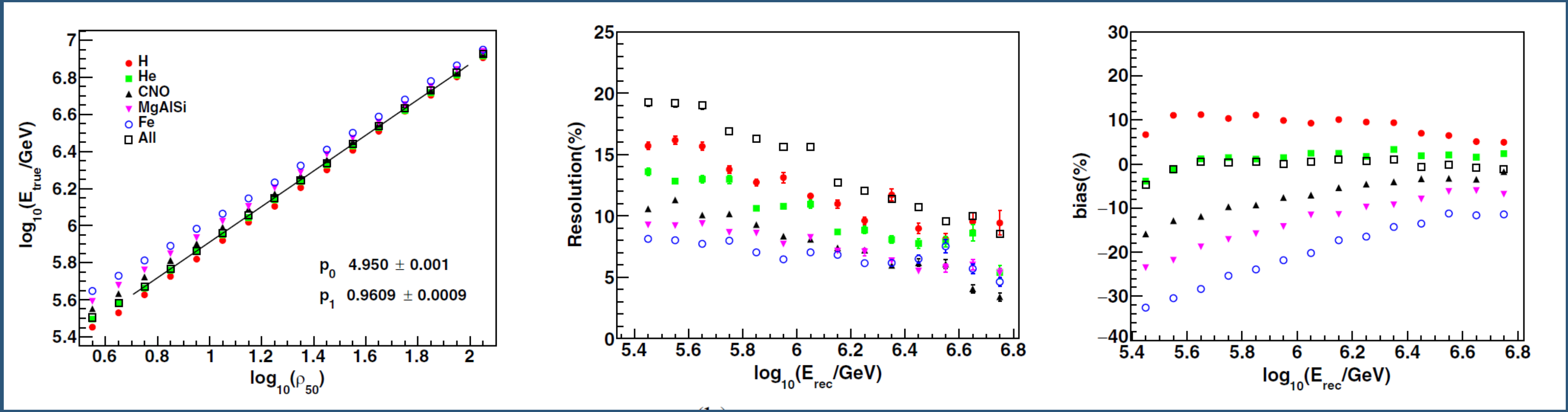
# Measurement of all-particle energy spectrum and <lnA>

# Problems in traditional energy estimators

$N_{size}$ or Density of electromagnetic particles

Strong dependence on composition





# calorimetric energy estimator based one heitler-matthews model

$$E_\circ = \xi_c^e N_{\max} + \xi_c^\pi N_\mu$$

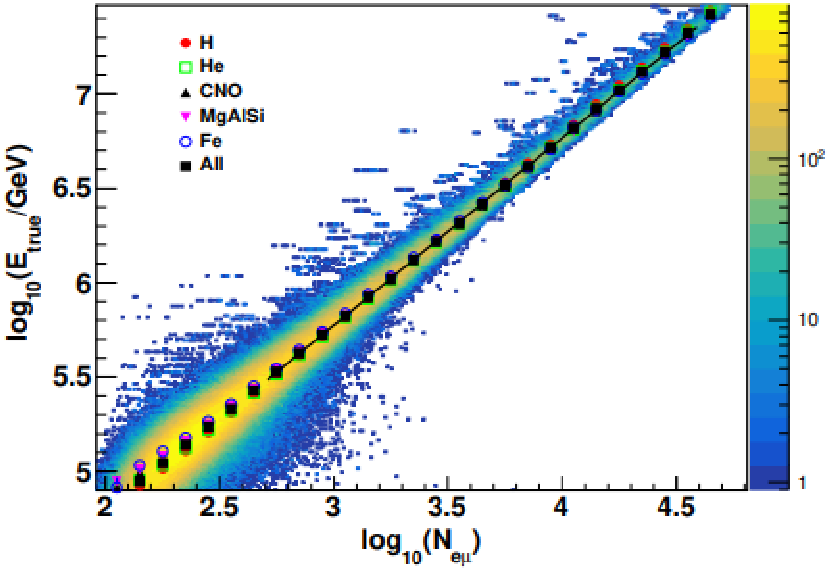
$$E_0 = \boxed{E_e} + \boxed{E_h}$$

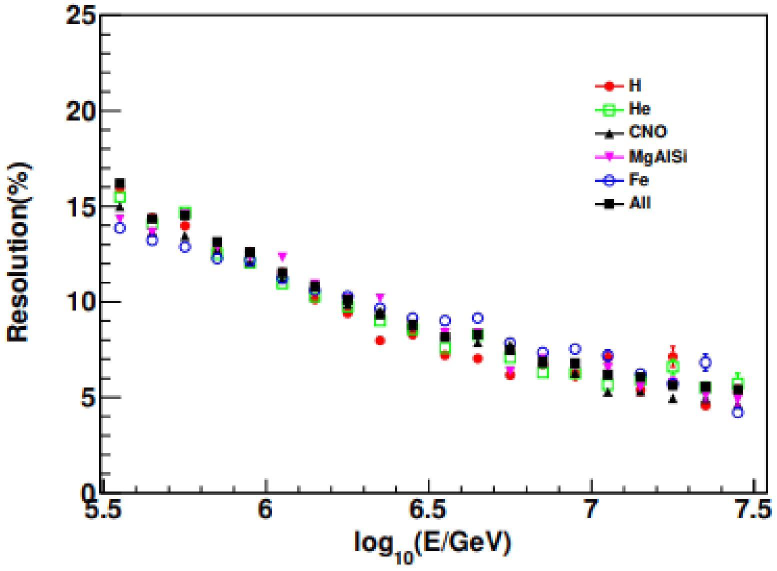
$$N_{e\mu} = \underset{\substack{\uparrow \\ \text{ED}}}{N_e} + \underset{\substack{\uparrow \\ \text{MD}}}{2.8N_\mu}$$

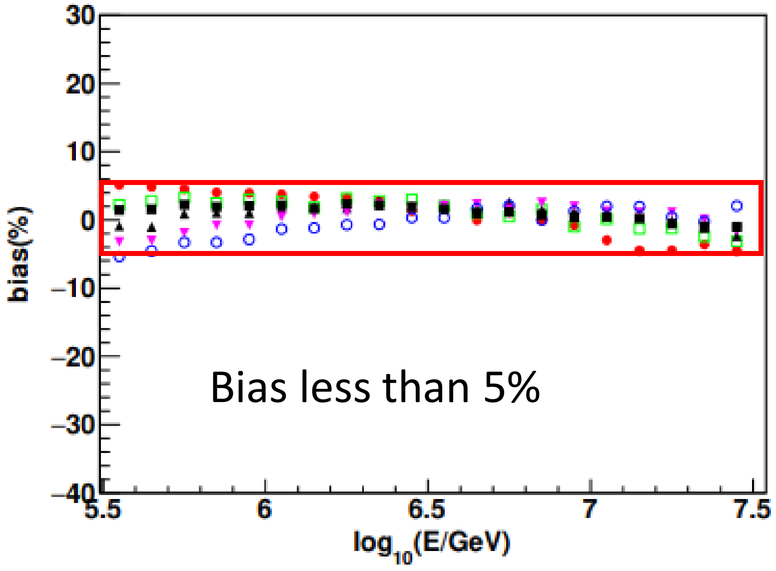
$N_e, N_\mu$ :

number of electromagnetic particles and muon recorded by EDs and MDs located from 40 m to 200 m to the shower core.

Works only at shower maximum



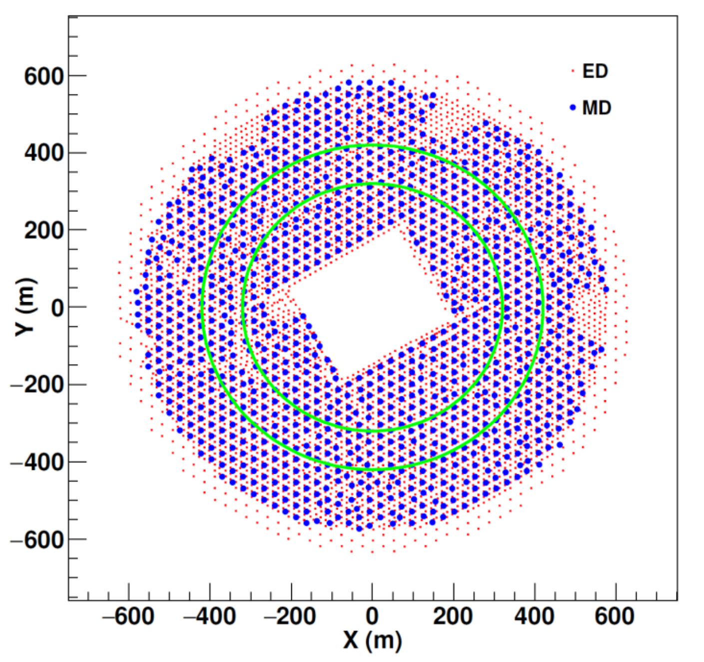


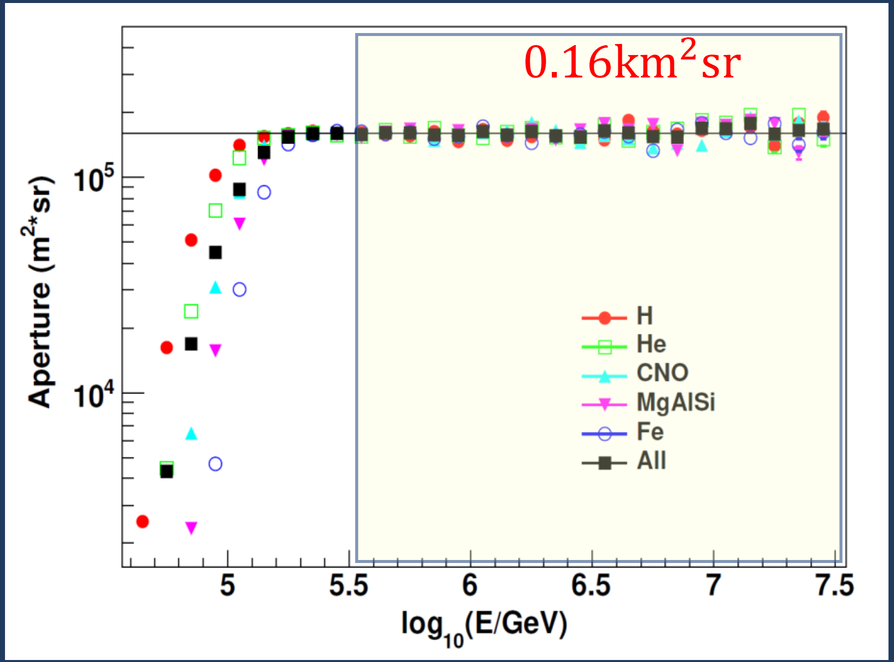


Bias less than 5%

# Measurement of all-particle energy spectrum and <lnA>

- ➢KM2A data
- ➢Zenith angle: $10° < \theta < 30°$
  - slant air depth: $610 g/cm^2 < X < 692 g/cm^2$
  - Near the Xmax of the cosmic rays around the knee
- ➢Core position: $320m < r < 420m$
  - Keep the observation of showers completely



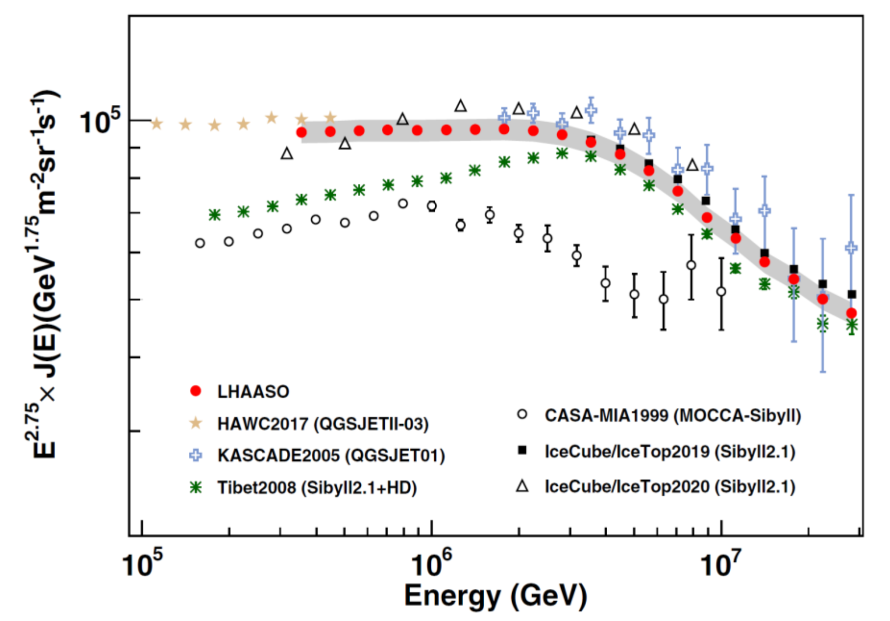


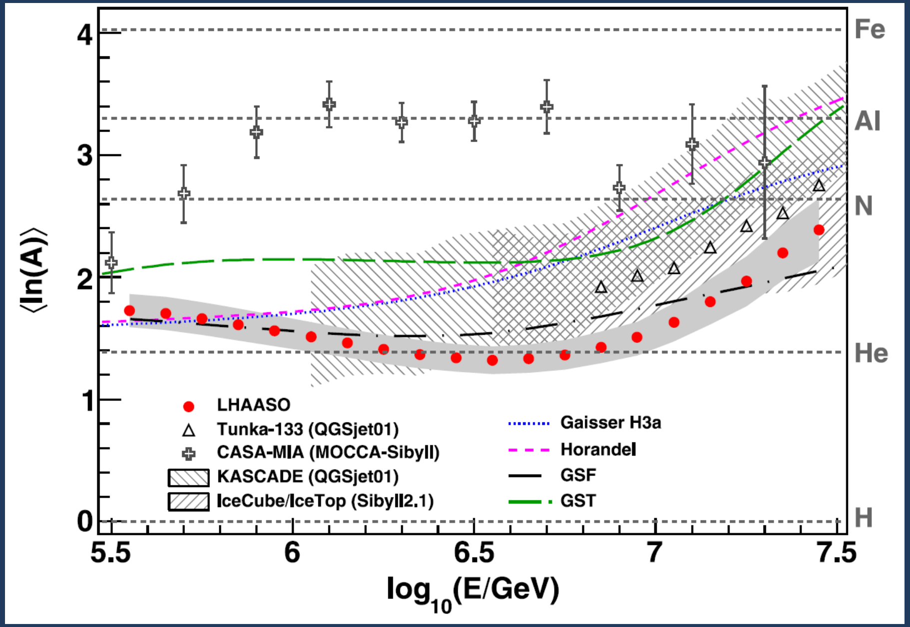
Full efficiency is achieved above 300TeV

Geometric aperture:

$$\pi\left(R_1^2 - R_2^2\right) \int_{10°}^{30°} \sin\theta\cos\theta d\theta \int_0^{2\pi} d\varphi = 0.16\mathrm{km}^2\mathrm{sr}$$

# The most precise measurements of all-particle energy spectrum and <lnA> from 0.3PeV to 30PeV





| | Flux | <lnA> |
|---|---|---|
| Air pressure | ±3% | ±4% |
| Composition models | ±1.5% | ±3% |
| Interaction models | ±2.5% | ±6% |

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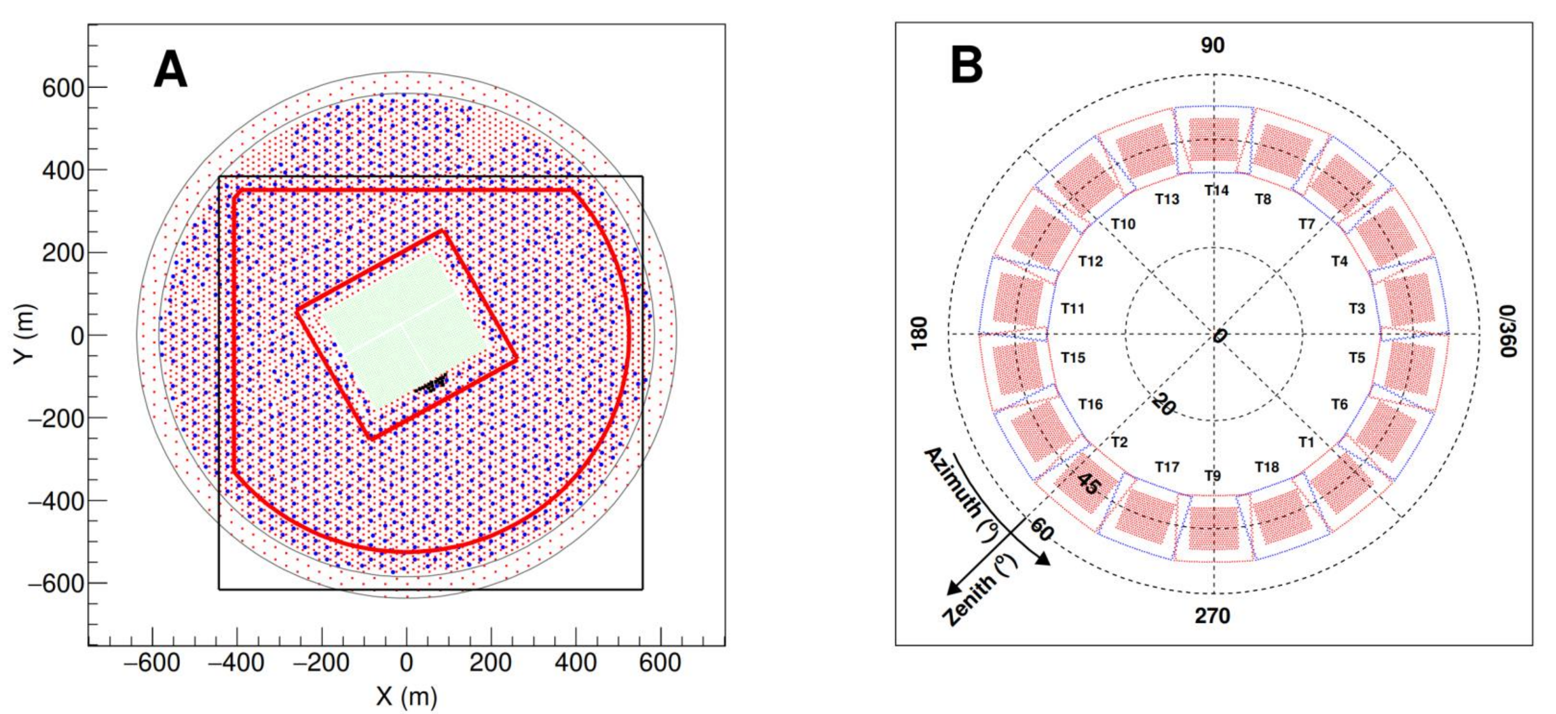
# measurement of the proton energy spectrum around the knee

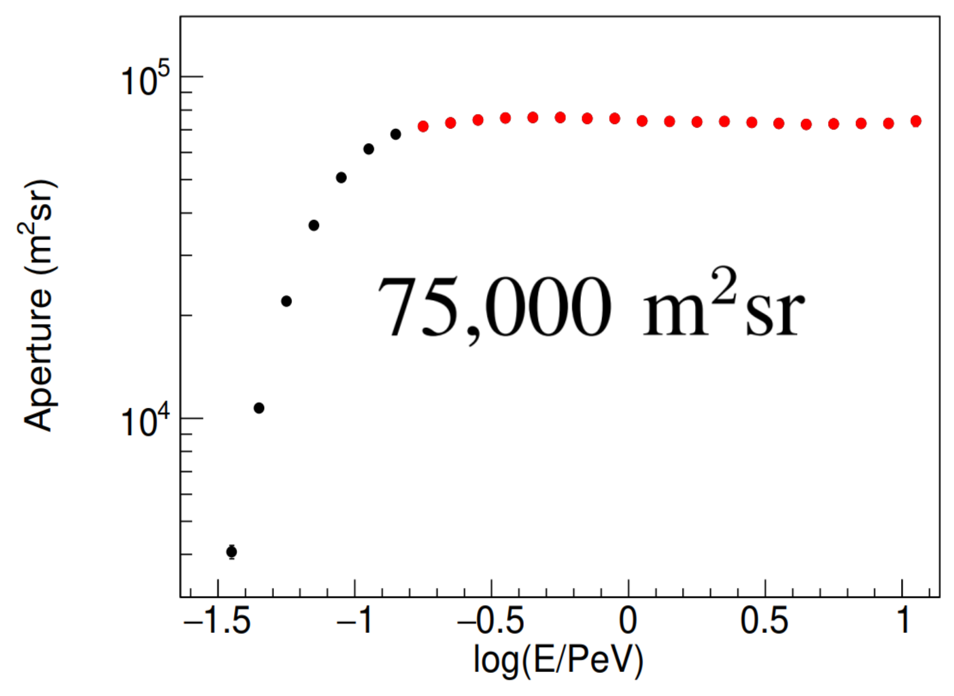
# Data introduction

## Hybrid observation of WFCTA + KM2A

- **WFCTA: Cherenkov telescopes**
  1. **Number of pixels: Npix≥6**
  2. **FoV: 10° × 10° out of 16° × 16° for the centroid of the image**
  3. **$R_p$: 180 – 310 m**

- **KM2A:**
  1. **Core (x,y)**
     - $\sqrt{x^2 + y^2} < 470\ m$
     - !|x’|<200m & !|x’|<160m
  2. **Number of fired EDs > 20**

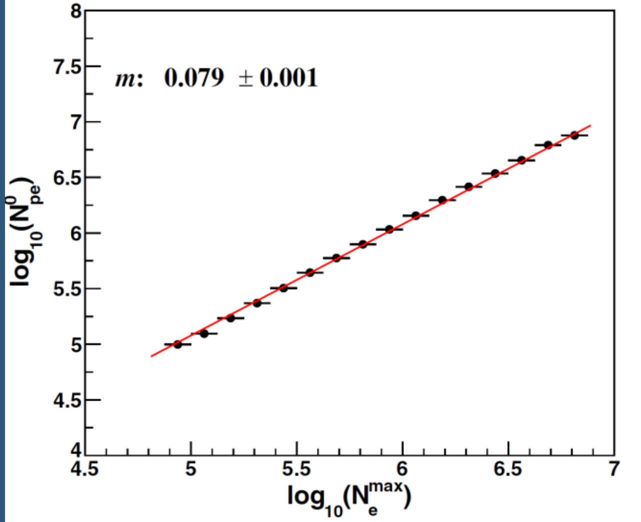


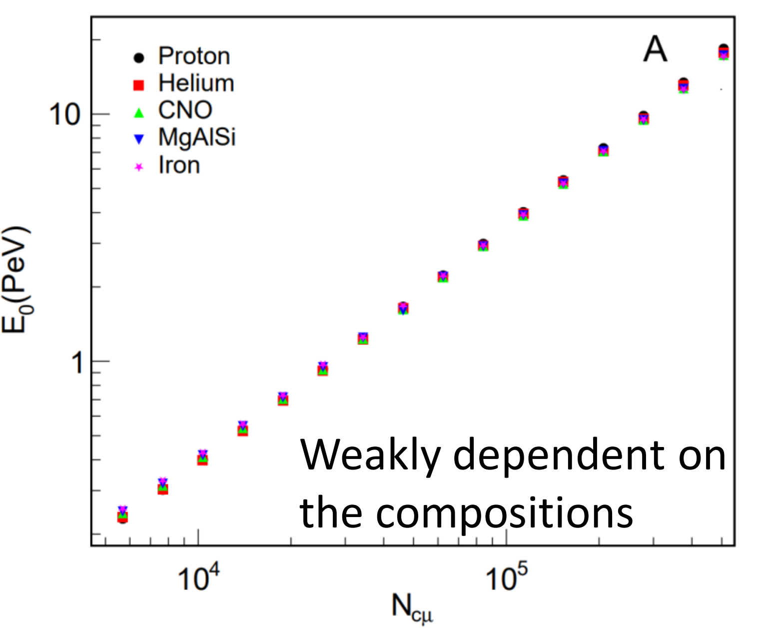


# Calorimetric energy estimator

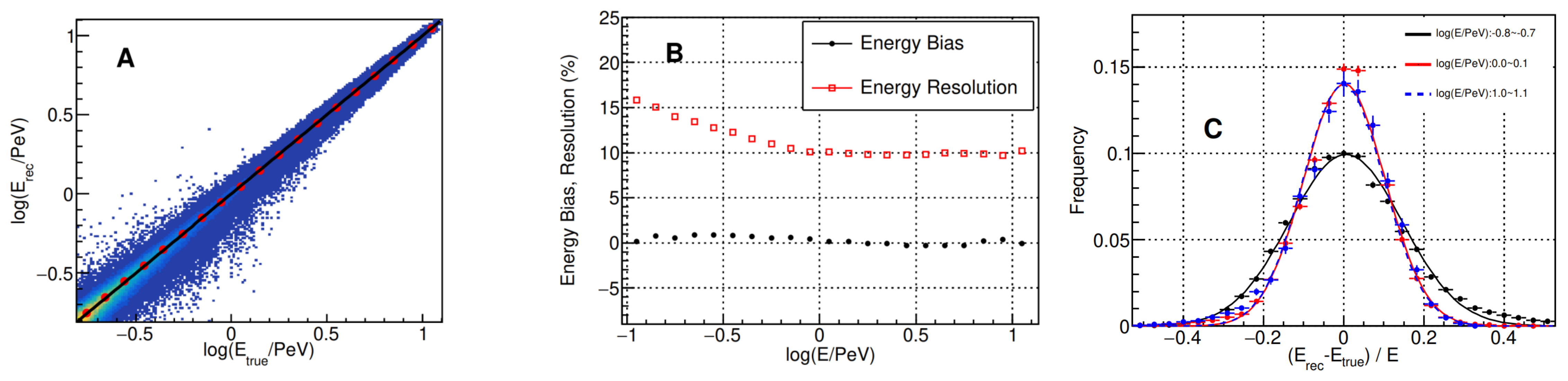
$$E_\circ = \xi_c^e N_{\max} + \xi_c^\pi N_\mu$$

$$N_{c\mu} = N_c + kN_\mu$$





Weakly dependent on the compositions

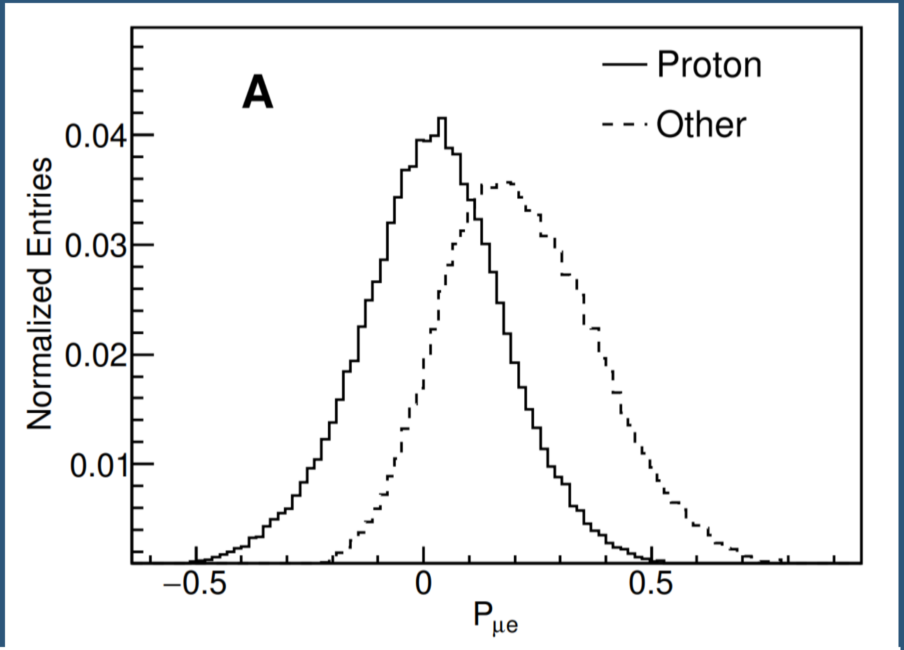


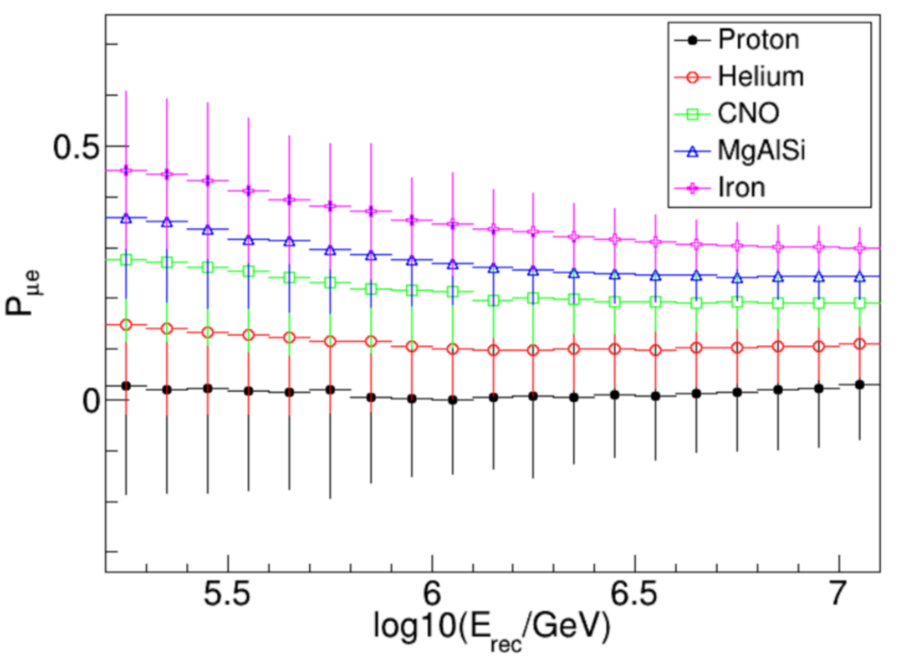
# Proton selection based on multi-parameters

$$\left.\begin{aligned} N_\mu^A &= A\left(\frac{E}{A}\right)^\beta \\ N_e^A &= A\left(\frac{E}{A}\right)^\alpha \end{aligned}\right\} \Rightarrow \boldsymbol{P_{\mu e} = \frac{N_\mu^A}{N_e^{0.82}} \sim A^{0.15}}$$

$N_e$ $N_\mu$ :

number of electromagnetic particles and muon recorded by EDs and MDs located from 40 m to 200 m to the shower core.



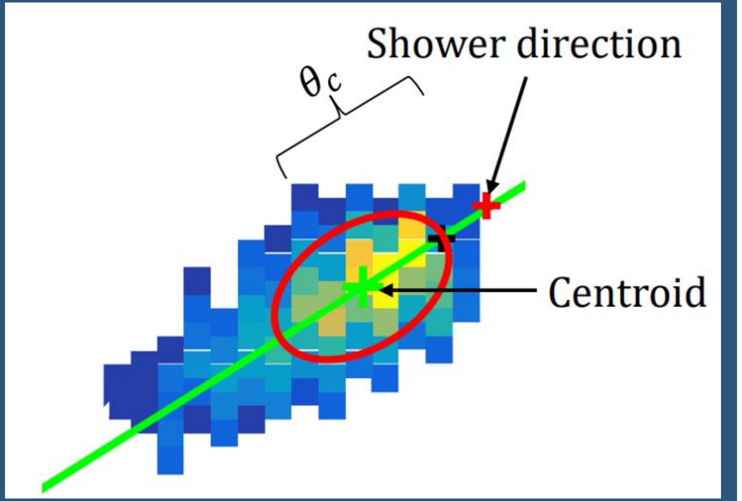


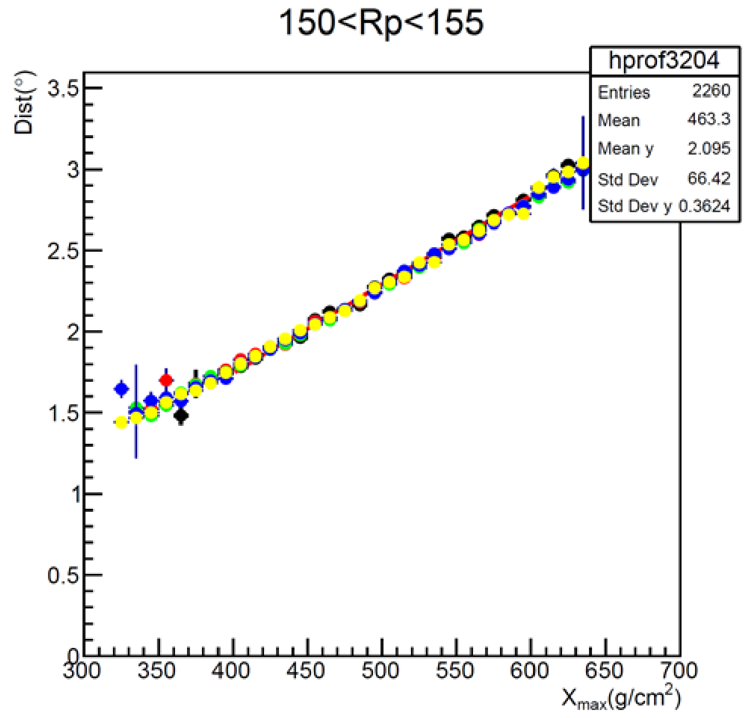
# Proton selection based on multi-parameters

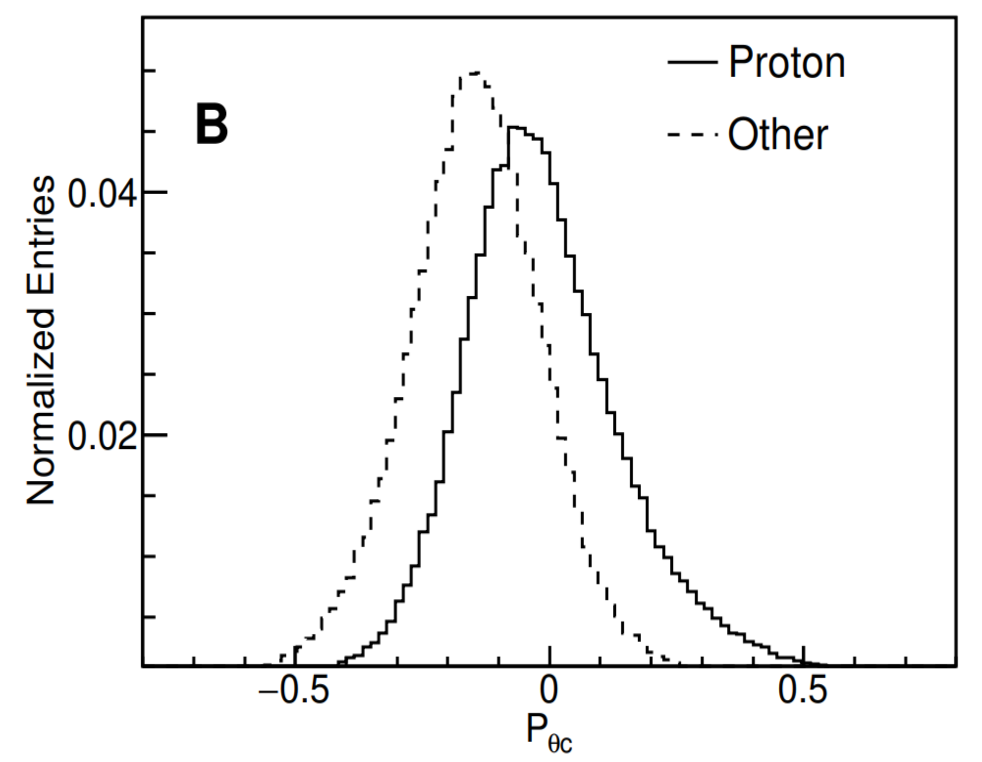
$$\theta_c^{250} = \frac{\theta_c}{\cos\theta} - 0.011 \times (R_p - 250).$$

$$P_{\theta_c} = \frac{\theta_c^{250} - \langle \theta_c^{250}|_p(E)\rangle}{\langle \theta_c^{250}|_p(E = 1PeV)\rangle}$$

$$X_{max}^{A} = X_{max}^{p} - \lambda_r \ln A \Longrightarrow \theta_c$$

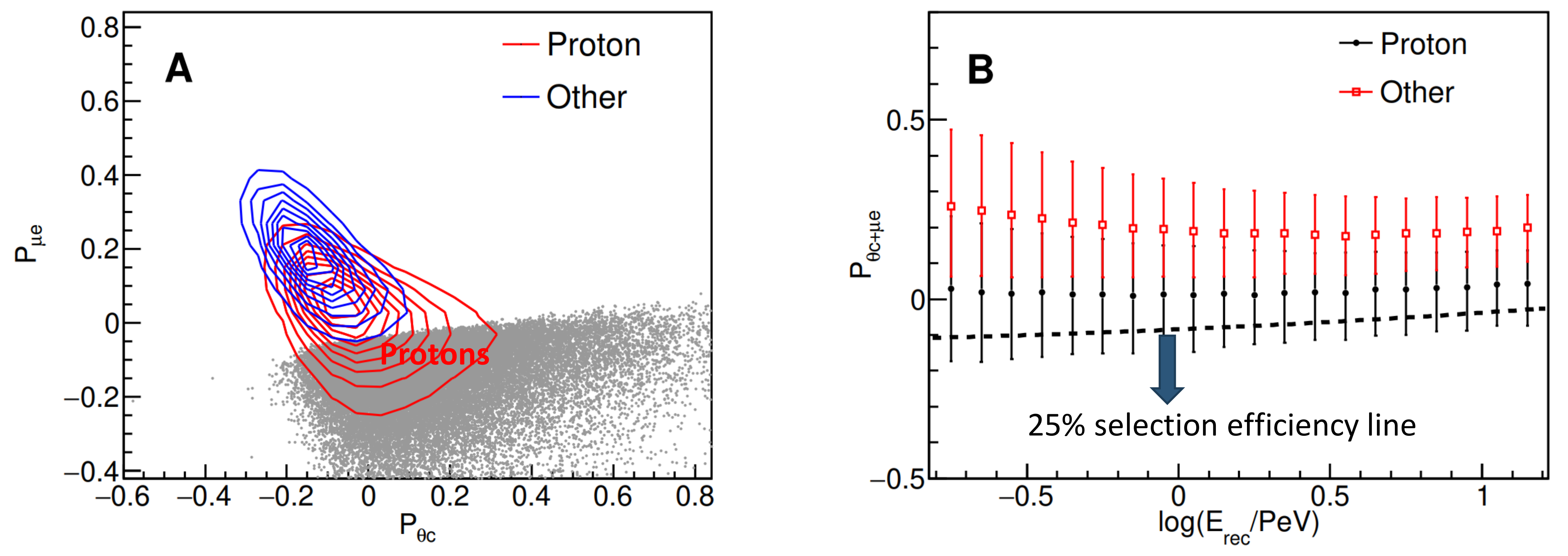




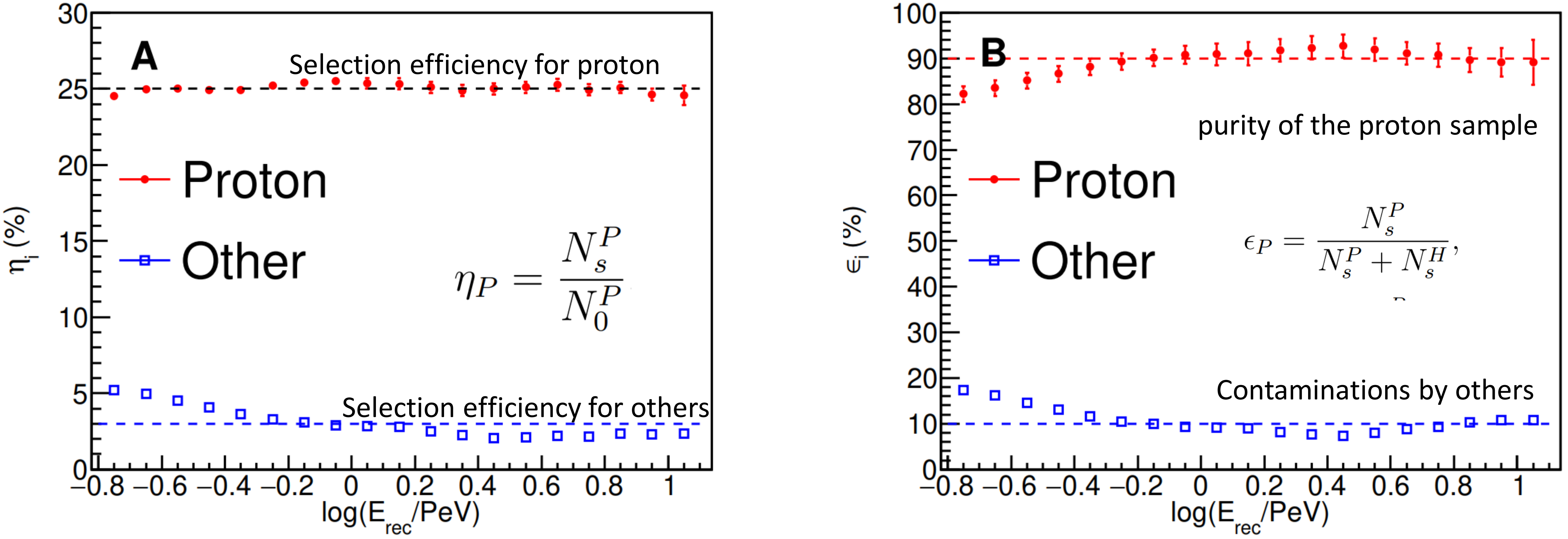


# Combing the two discriminative parameters

$$P_{\theta c+\mu e} = -\sin(\delta) \cdot P_{\theta c} + \cos(\delta) \cdot P_{\mu e}$$

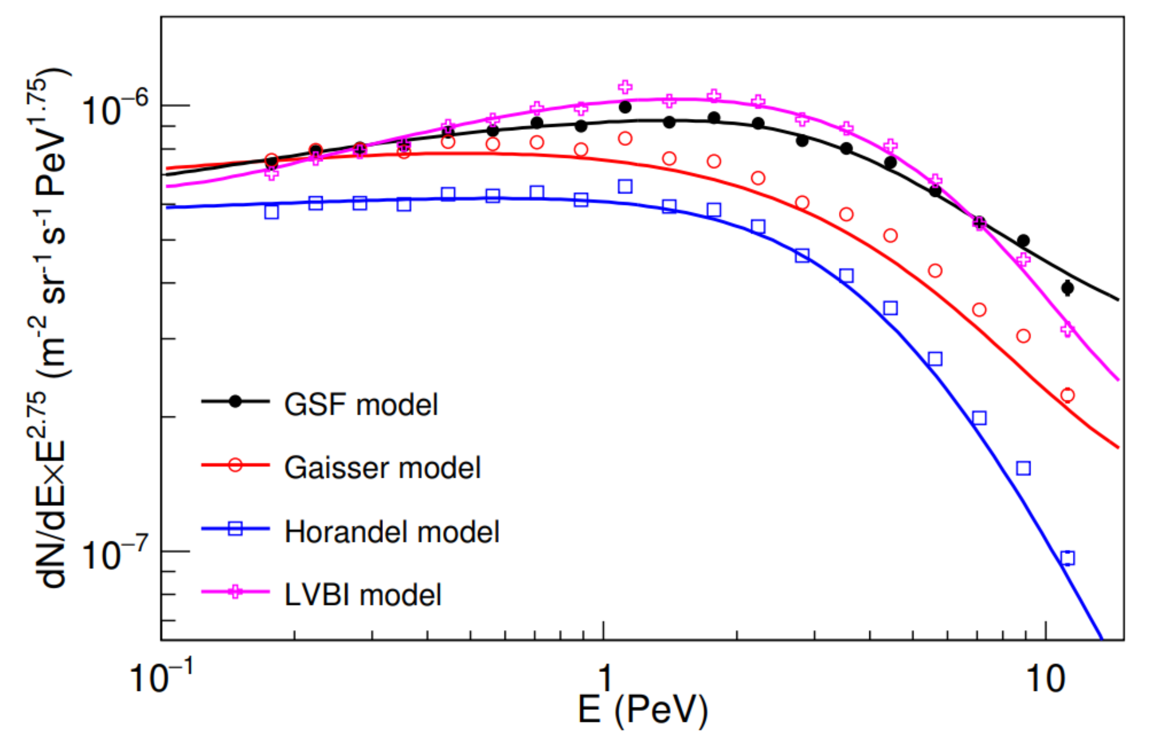


25% selection efficiency line



Based on GSF composition model

# Method validity test
# Reconstruct the proton energy spectrum for different composition models



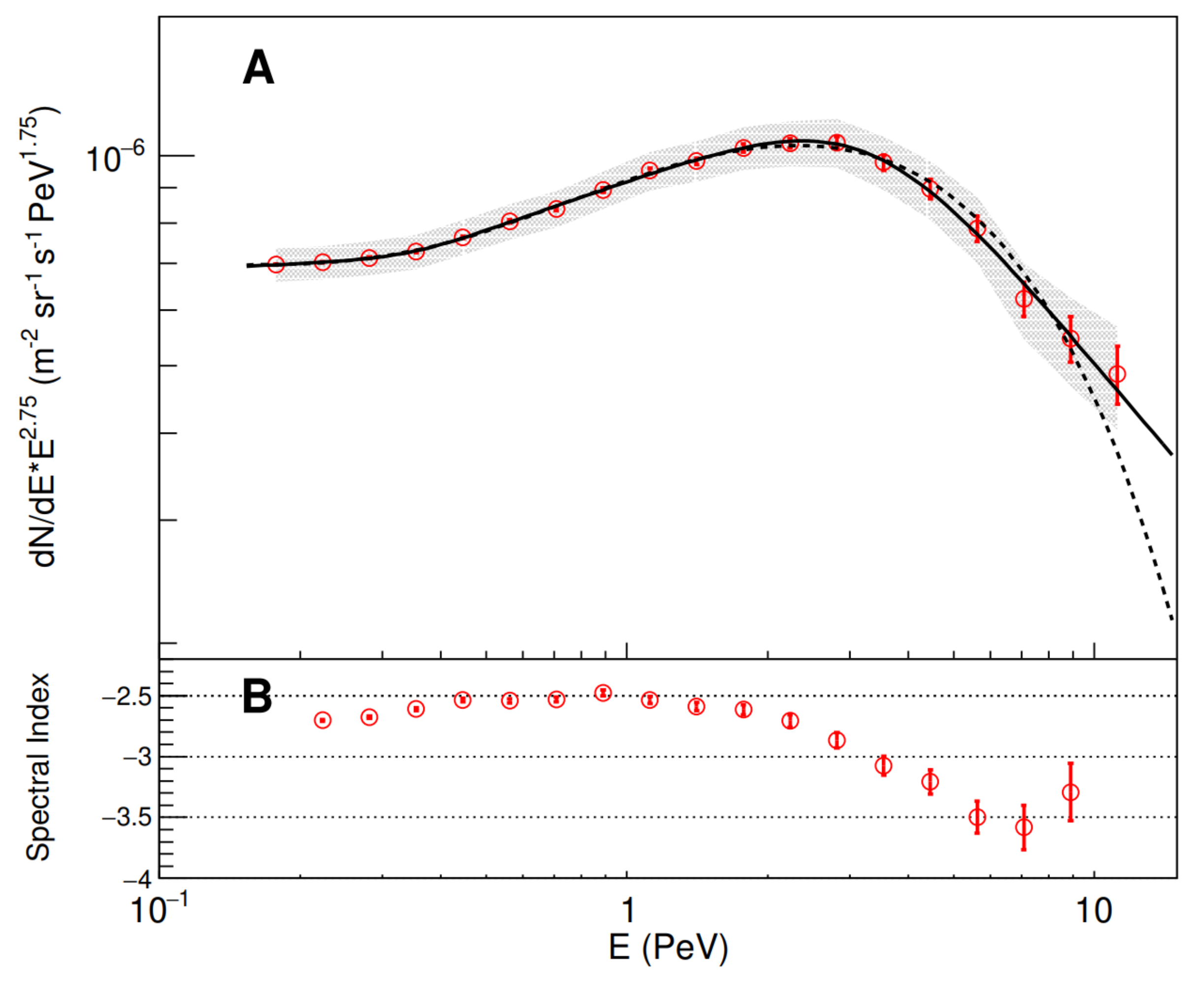
Discrepancies：

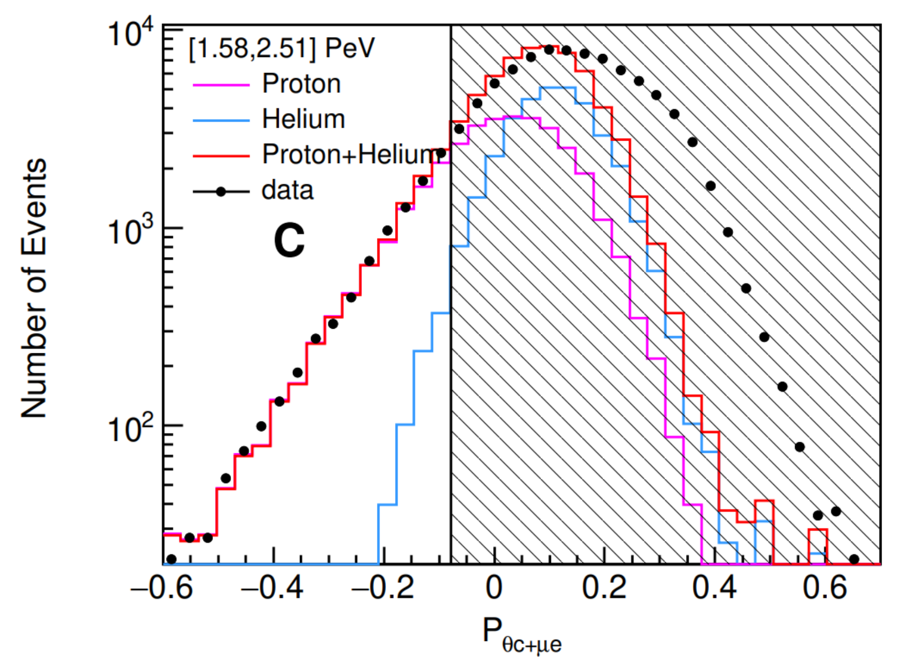
<1PeV: 3-5%
3PeV: 7%
10PeV： 15%

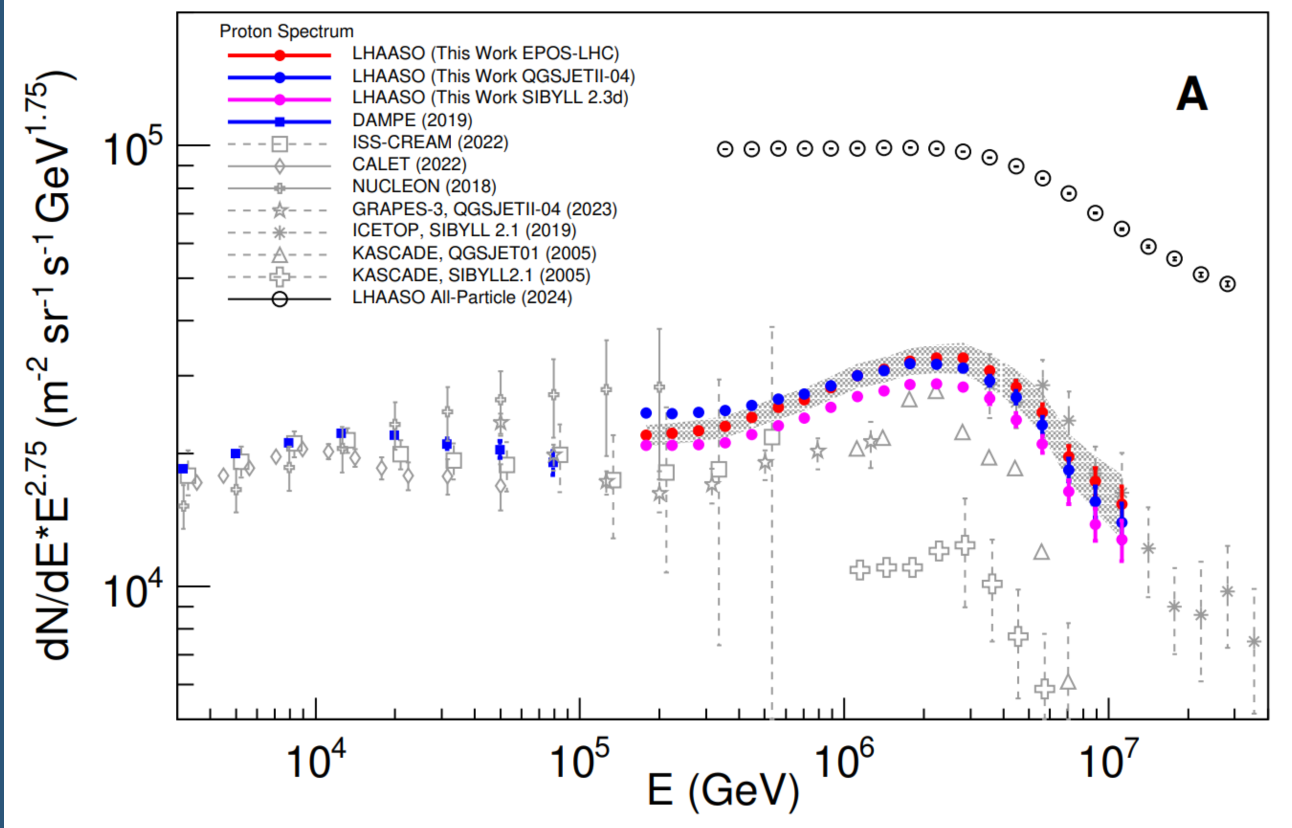
# Proton energy spectrum measured by LHAASO in the knee region

arXiV:2504.1444v1

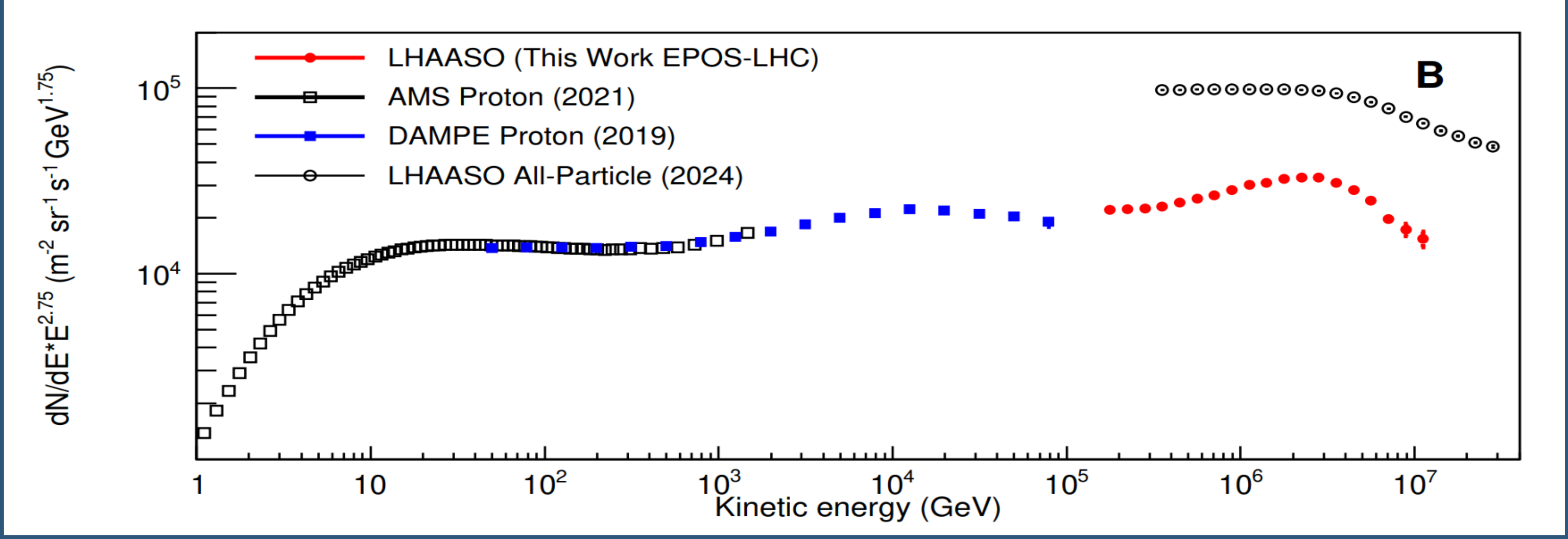
- Data set： 2021.10-2022.4
- Total time after good weather selection: ~900 hours
- The proton energy spectra from 158TeV to 12.5 PeV







- ➢ CR protons around the knee have been selected with high purity for the first time
- ➢ HAASO purity: ~90%, above 100TeV
- ➢ Direct measurement (e.g. DAMPE) purity: 99% - 95%, below 100TeV
- ➢ KASCADE and ICETOP: Unfolding method, no purity provided.



- ➢ Hardening: ~340 TeV, with index change Δγ=~0.2
- ➢ Softening (knee): ~3.3 PeV, with index change Δγ=~−1

# Systematic uncertainties

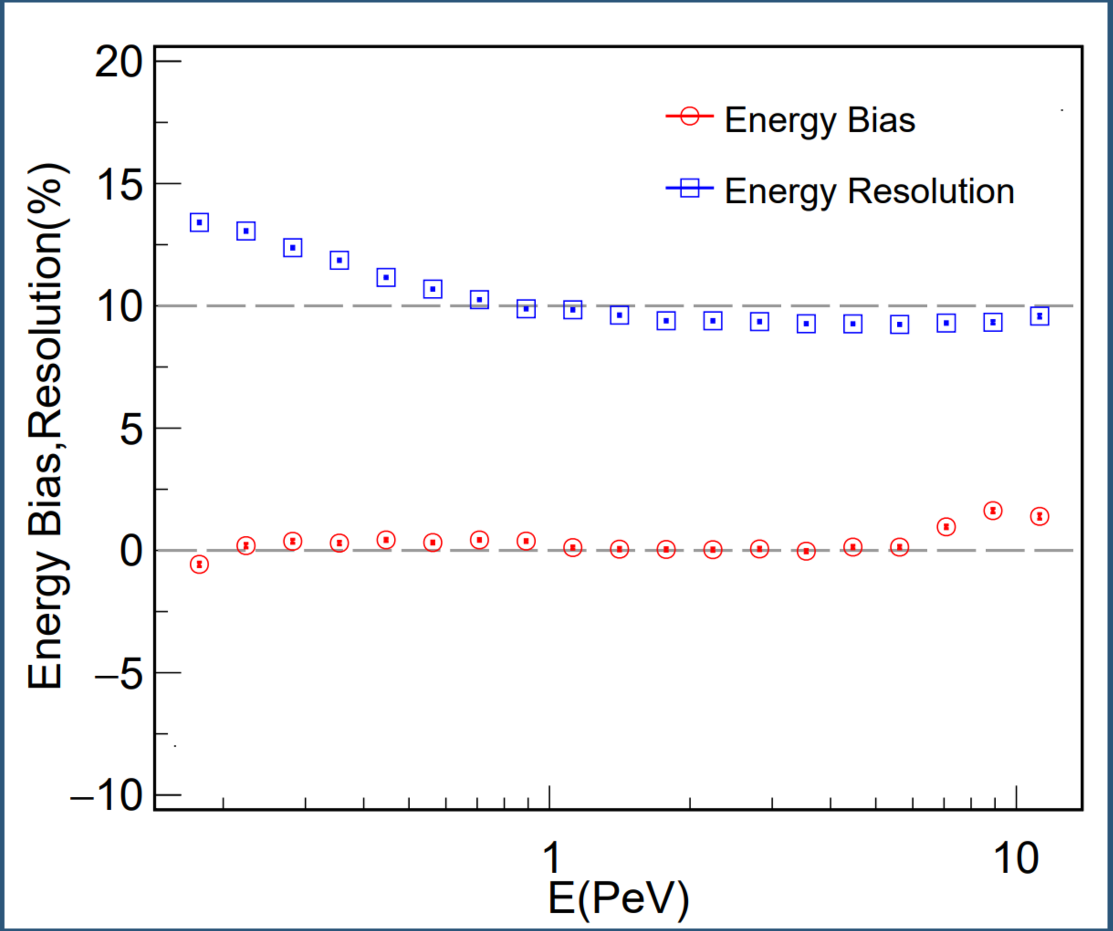
| Systematic uncertainties on flux | |
|---|---|
| Hadronic model | ≤ 15% |
| Composition model | ~7%@3PeV |
| Different purity | ≤ 2% |
| SiPM camera calibration | ≤ 2% |
| Background light | ≤ 2% |
| Absolute Humidity | ≤ 1% |
| Air pressure | ≤ 1% |
| Total | ~17 % |

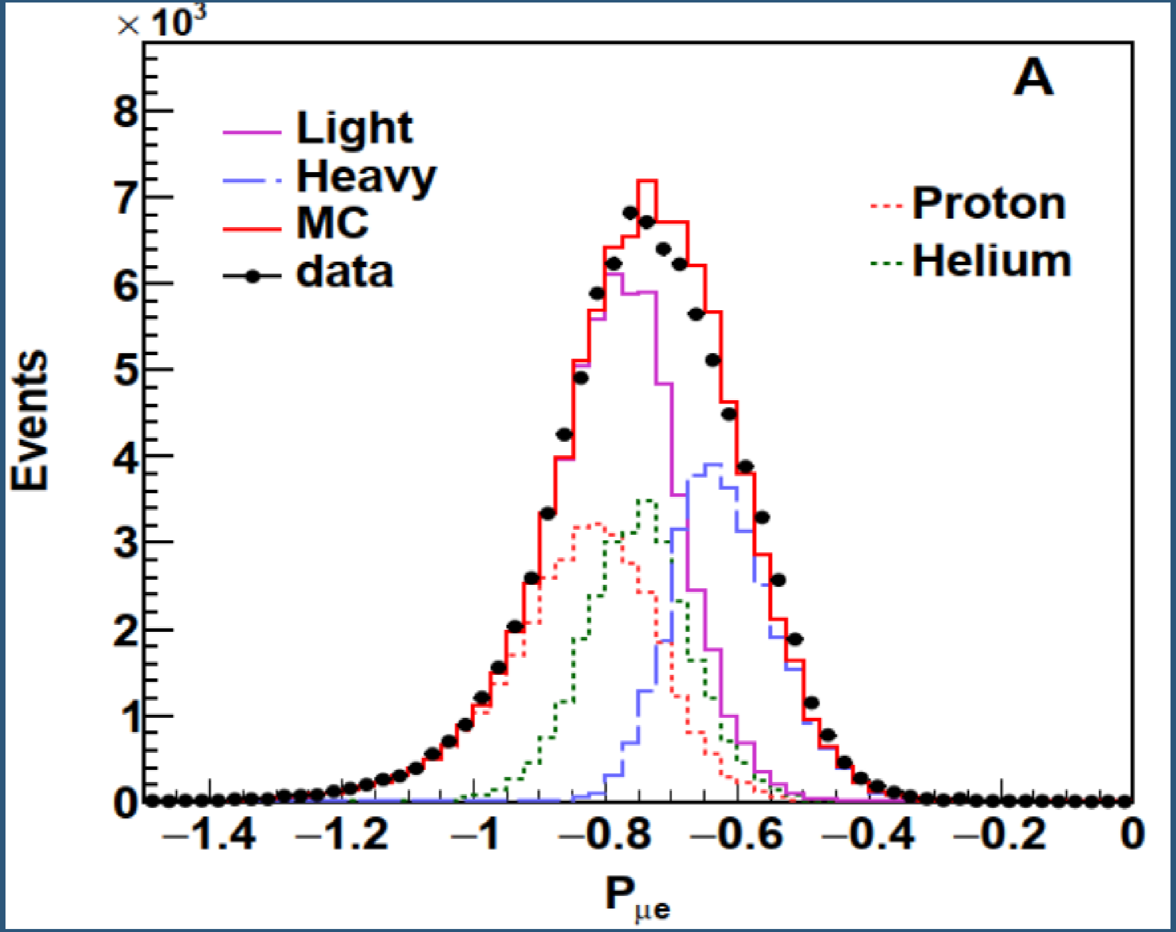
| Systematic uncertainties on Energy Scale | |
|---|---|
| SiPM camera calibration | ~1.5% |
| Mirror reflectivity Calibration | ~1% |
| Nμ Calibration | ~1% |
| Absolute Humidity (water vapor) | ~1% |
| Aerosol | ~2% |
| Air pressure | ~0.5% |
| Hadronic model | ~1.4% |
| Total | ~4% |

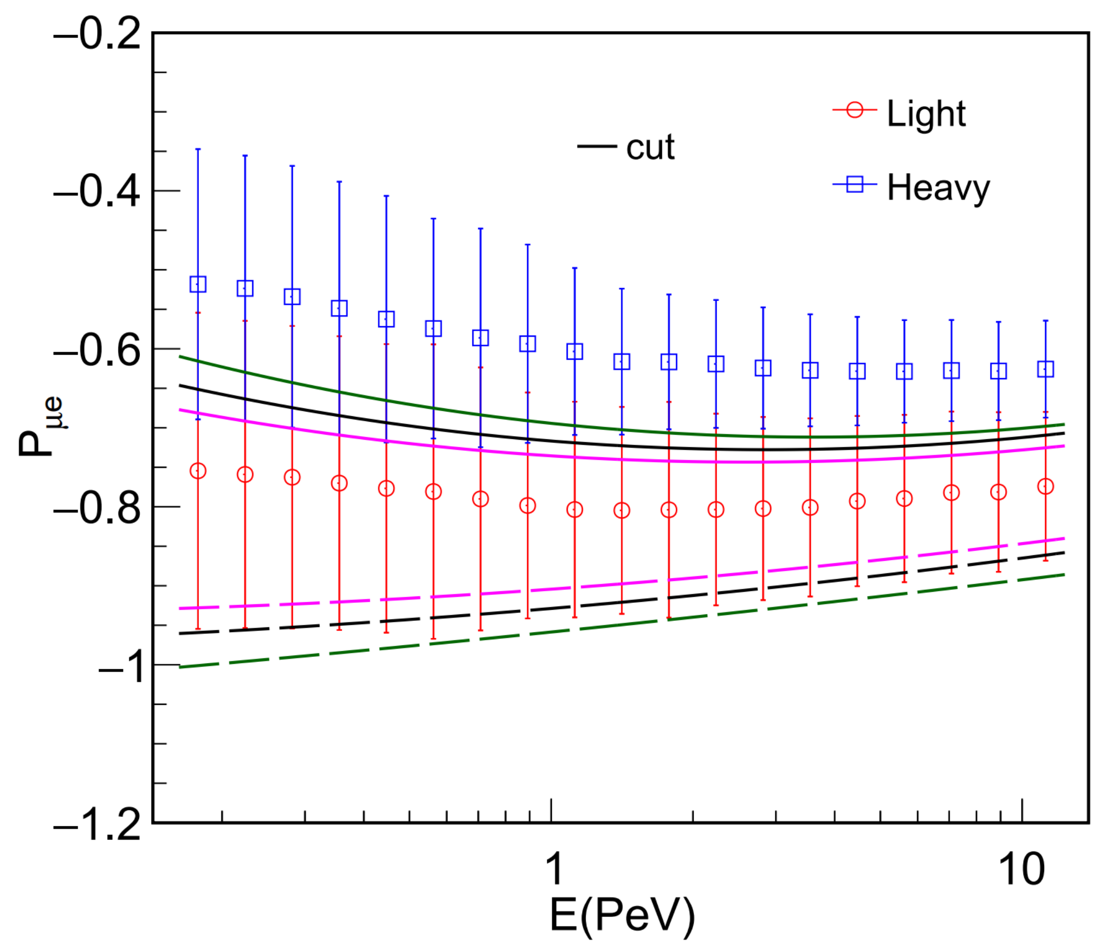
# Progress in the light component and helium energy spectrum

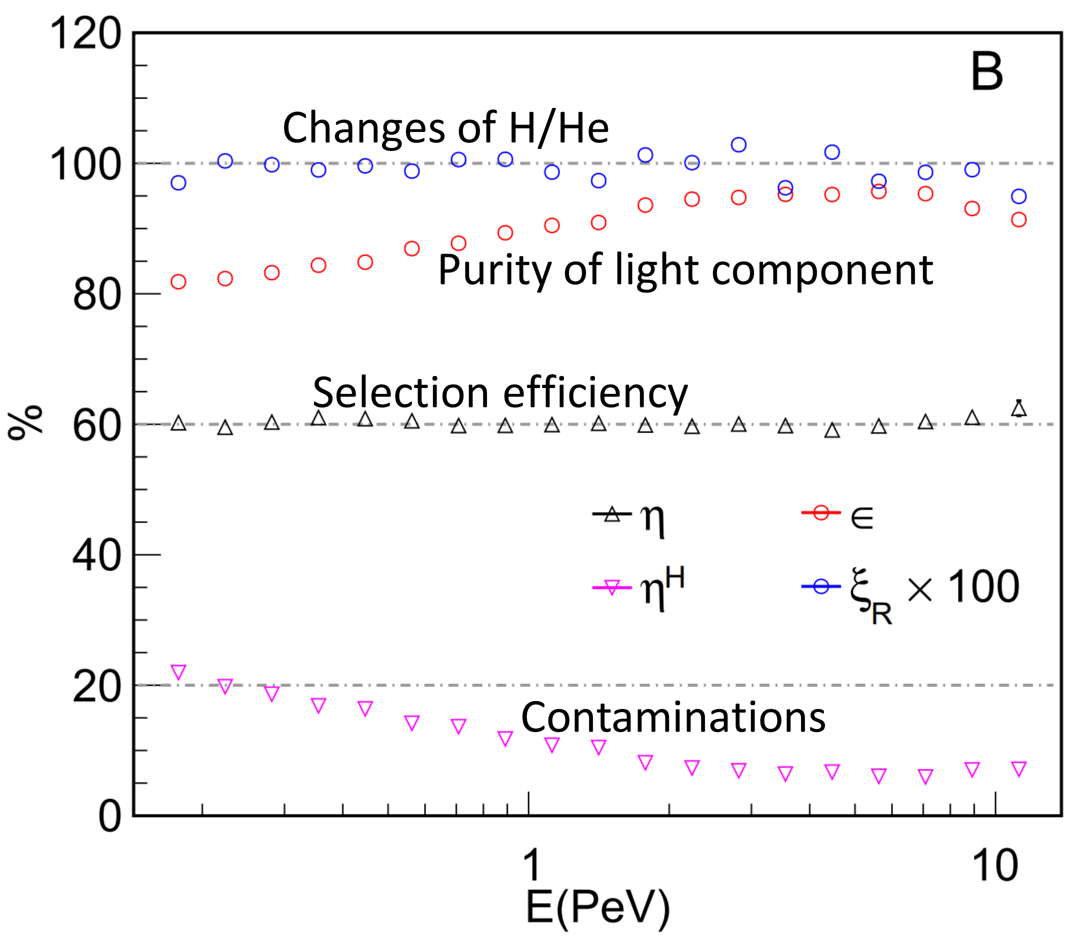
The same data selection criteria and energy reconstruction formula with the proton

$P_{e\mu}$ is used to select light component



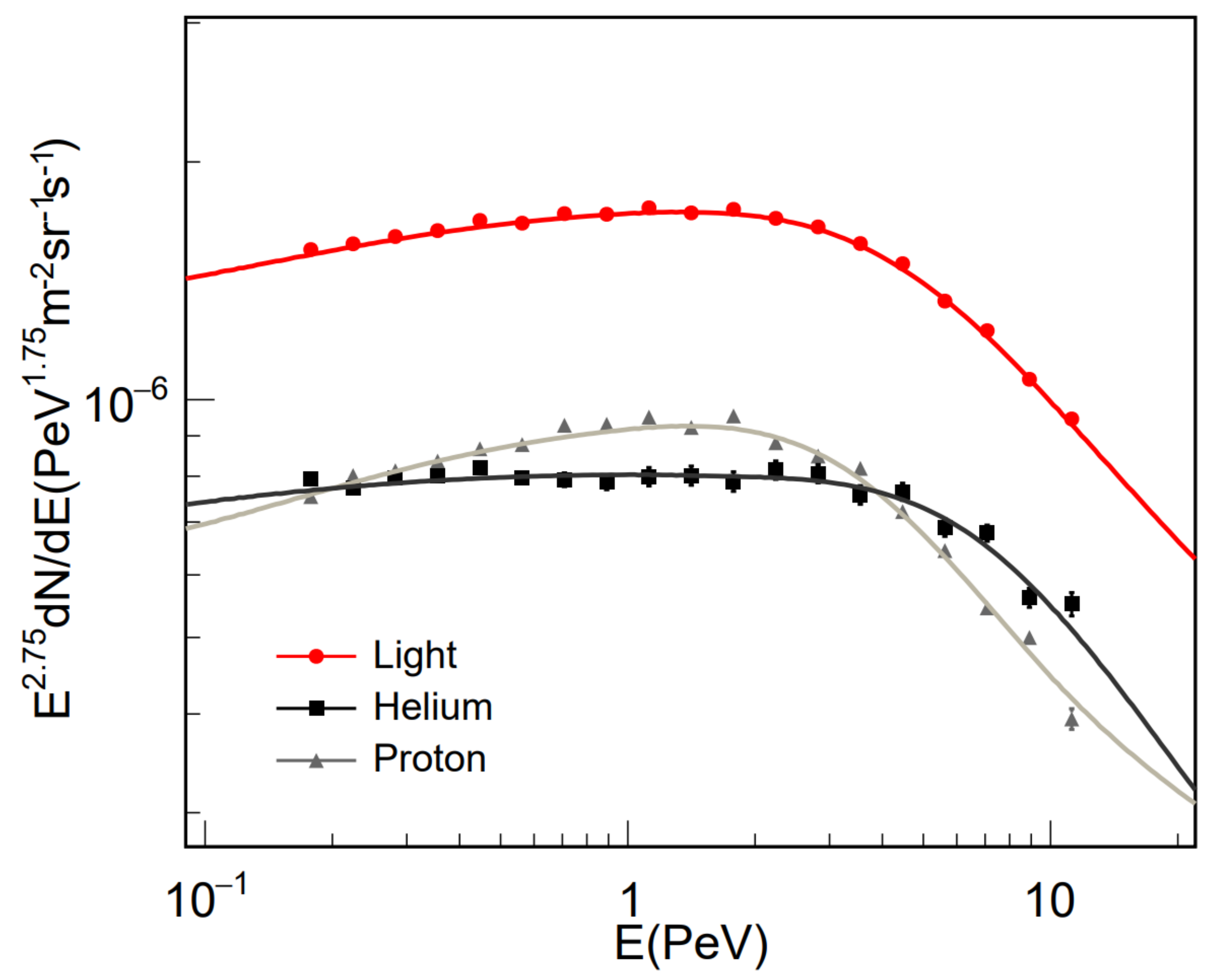






Two sides cut is used to keep the ratio of H/He is not changed before and after the light component selection

# Method validity test
Reconstruct the light component energy spectrum and the helium energy spectrum based on the measured proton spectrum



Take GSF as an example

# Summary and outlook

- With the calorimetric energy estimator, the most precise all-particle energy spectrum and <lnA> around the knee are measured

- With the multi-discriminative parameter the most purity proton sample is obtained, and proton energy spectrum around the knee is measured

- All of them are big steps to understand the features and origin of the knee

- The paper of light component is under review in LHAASO group.
- To understand more clear about the knee
  - The all-particle energy spectrum and <lnA> around the second knee is under analysis
  - The iron nuclei energy spectrum especially it's knee is under analysis

# Thank you for your attention

# <lnA>

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

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