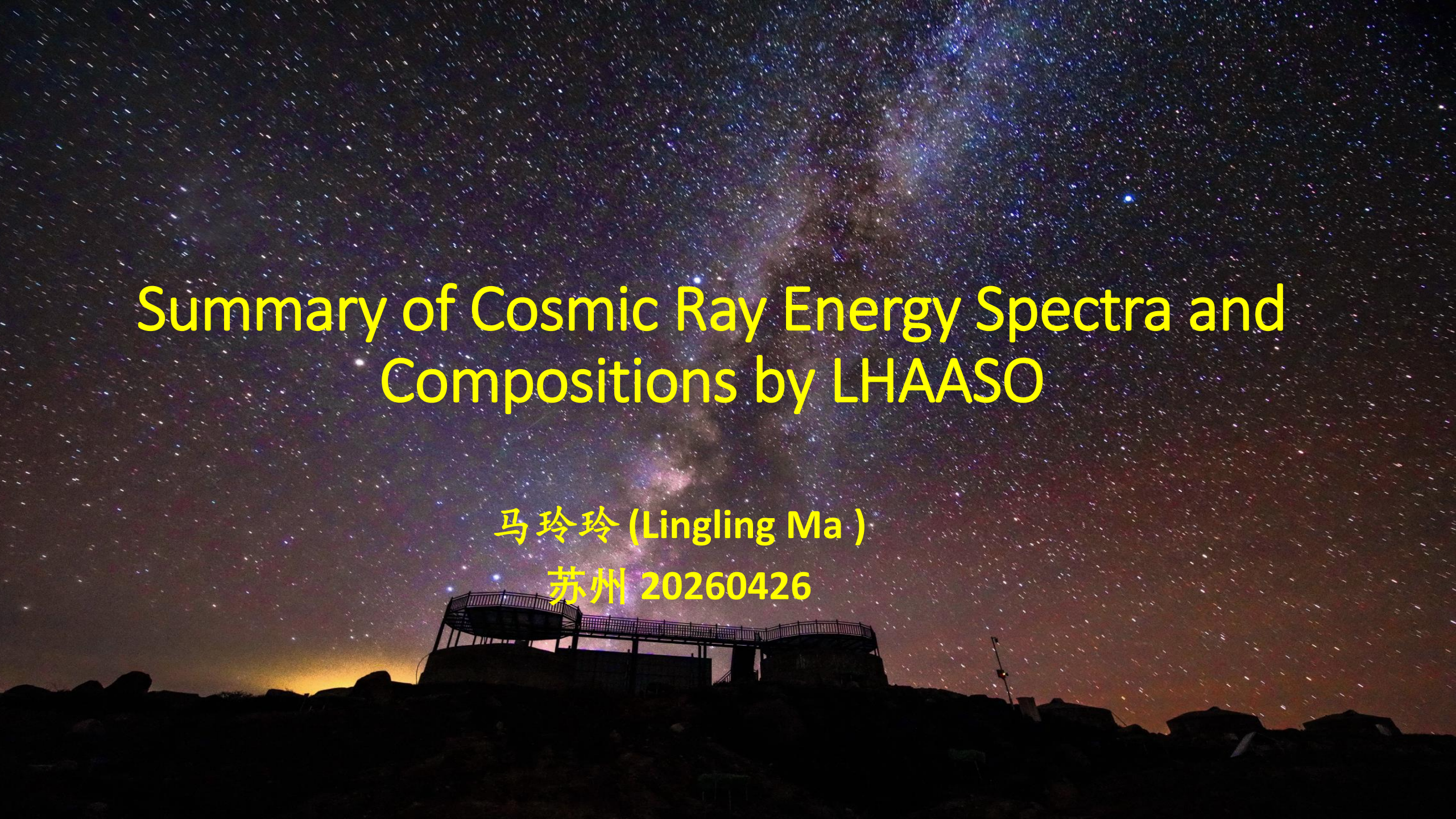

Summary of Cosmic Ray Energy Spectra and Compositions by LHAASO

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Outline

- Summary of Works of pcc in Cosmic Ray Physics
- Results of LHAASO measurements
  - All-particle energy spectrum and <lnA>
  - Proton spectrum
  - Helium spectrum

Summary of Works in Cosmic Ray Physics

Works for Collaborations

- Published
  - The precision measurements of all-particle spectrum and mean logarithmic mass of cosmic rays in the knee region with LHAASO-KM2A detector (PRL 2024))
  - Measurement of attenuation length of the muon content in extensive air showers from 0.3 to 30 PeV with LHAASO (PRD 2024)
  - Energy calibration of LHAASO-KM2A using the cosmic ray Moon shadow(PRD 2025)
  - Constraints on the cosmic-ray electron spectrum above 25 TeV from the LHAASO experiment (PRD 2025)
  - Precise measurements of the cosmic ray proton energy spectrum in the ‘‘knee” region (Science Bulletin 2025)
  - Precise Measurement of the Cosmic Ray Helium Spectrum above 0.1 PeV(PRL 2026)
- Under EB review
  - Calibration of Energy Scale by using Cosmic Ray Moon shadow for LHAASO-WCDA
- Under PCC discussion
  - Constraining the TeV cosmic ray anti-proton/proton ratio with LHAASO-WCDA moon shadow observation

Works for group （9 papers）

- Approaches to composition independent energy reconstruction of cosmic rays based on the LHAASO-KM2A detector
- Cosmic ray mass independent energy reconstruction method using Cherenkov light and muon content in LHAASO
- Fast Simulation of Muon Detectors in High Energy Cosmic Ray Air Showers
- WCDA DETECTOR OF THE LHAASO EXPERIMENT AS A PAIR-METER TO MEASURE ATMOSPHERIC MUON SPECTRUM
- A Method to Investigate the Variance of Cosmic Ray Logarithmic Mass in the Knee Region with LHAASO-KM2A Simulation Data
- A new approach to measure cosmic ray composition via muon and electromagnetic particles detected by LHAASO-KM2A
- Study of energy and composition reconstruction for Nuclei with LHAASO-KM2A Direction
- Reconstruction of 10–100 TeV Iron-Induced Showers with Graph Neural Networks in LHAASO-KM2A
- Simulation Study of Reconstruction of Cosmic Ray Extensive Air Shower with Thermal Neutron, Electron and Muon Detected by ENDA and LHAASO-KM2A

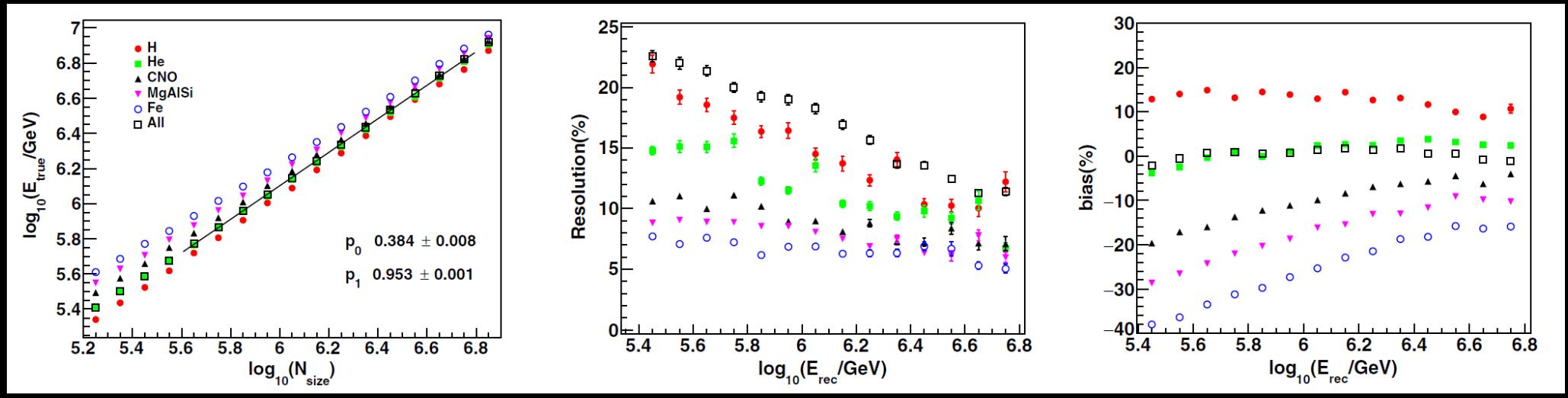
Results of LHAASO measurements

Energy reconstruction

Traditional estimator

Ne only

Strong dependence on composition

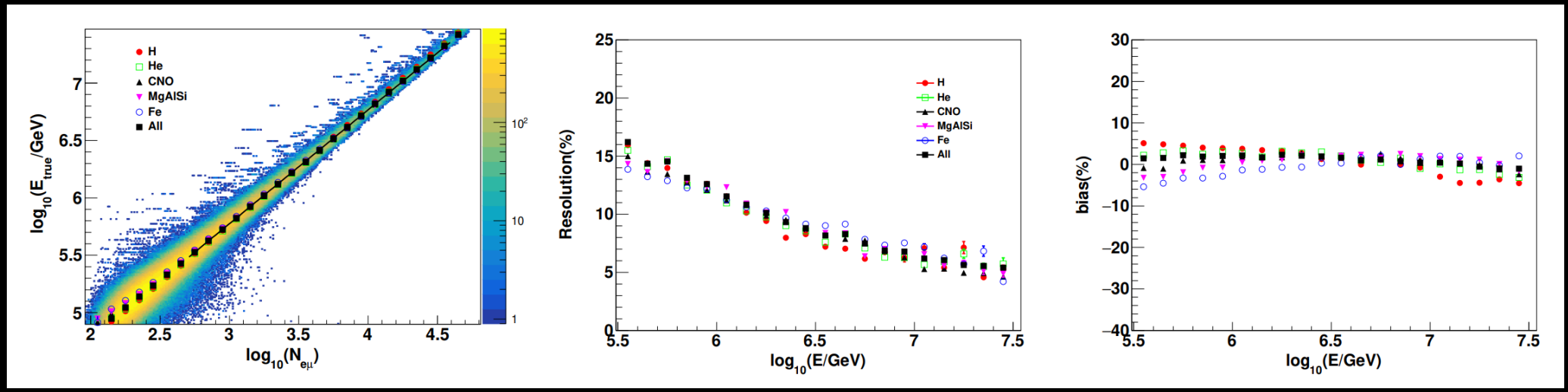


LHAASO estimator

$N_{e\mu} = N_e + \alpha N_\mu$

Resolution is improved

Bias is reduced



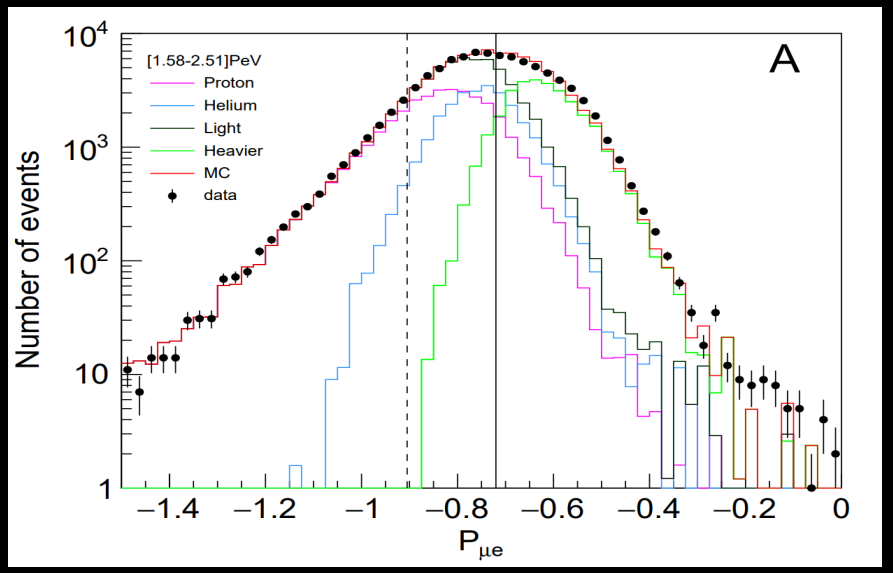
Composition separation

- Muon content:

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

$$N_e^A = A\left(\frac{E}{A}\right)^\alpha$$

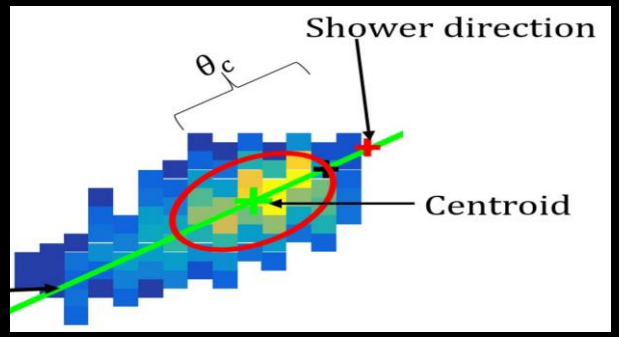
$$\boldsymbol{P_{\mu e} = \frac{N_\mu}{N_e^{0.82}} \sim A^{0.15}}$$

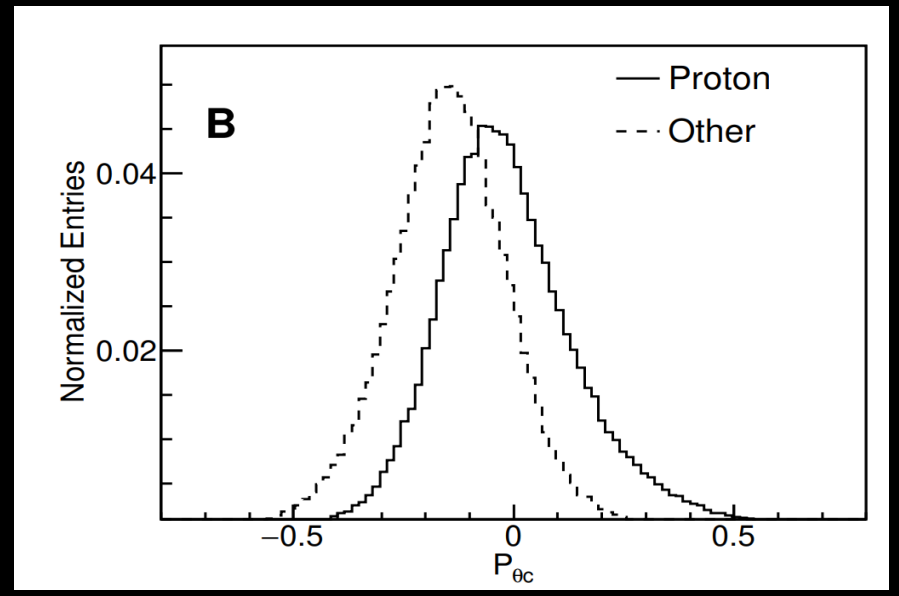


N_μ is the number of muons in the shower

N_e is the number of EM particles in the shower

- X_{max} measurements:





θ_c is the angular distance between the shower direction and the image center

All particle Energy Spectrum and <lnA>measured by LHAASO

HIGHLIGHTED ARTICLES

FEATURED IN PHYSICS EDITORS' SUGGESTION

Measurements of All-Particle Energy Spectrum and Mean Logarithmic Mass of Cosmic Rays from 0.3 to 30 PeV with LHAASO-KM2A

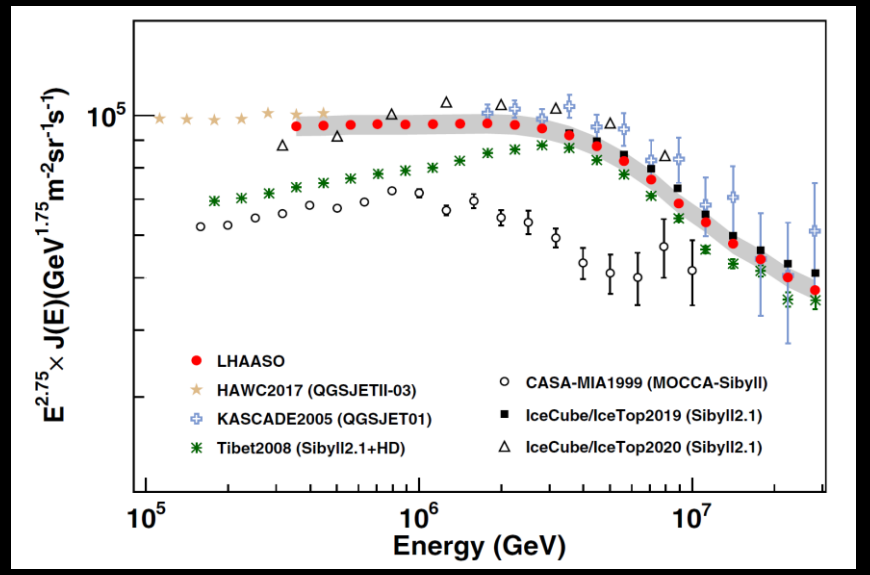
Zhen Cao *et al.* (LHAASO Collaboration)

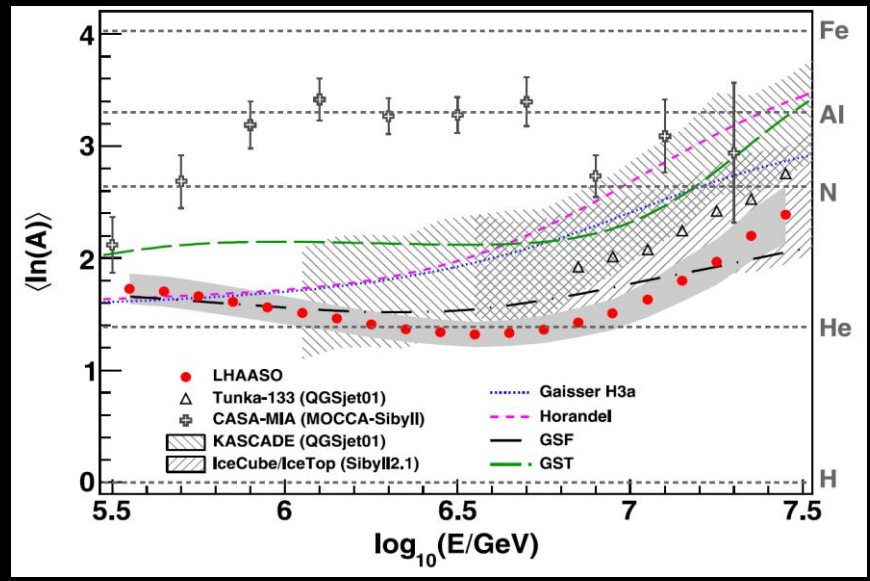
Phys. Rev. Lett. **132**, 131002 (2024) - Published 26 March, 2024

Using observations made with an array of thousands of particle detectors, researchers have uncovered an important clue about cosmic rays that originate from outside of our Galaxy.

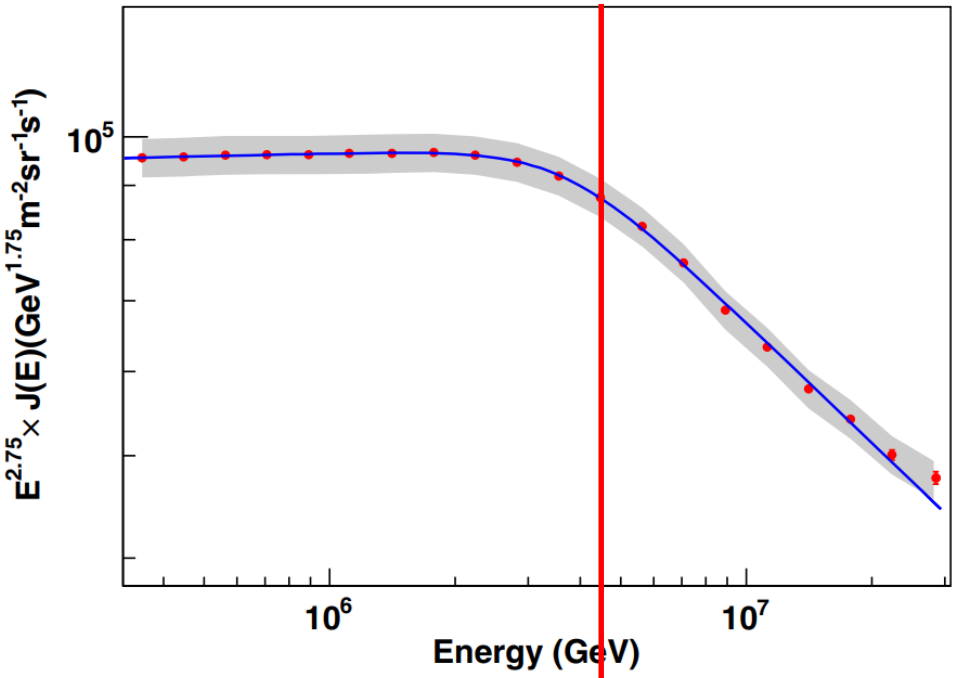
The most precise measurements of all-particle energy spectrum and <lnA> from 0.3PeV to 30PeV

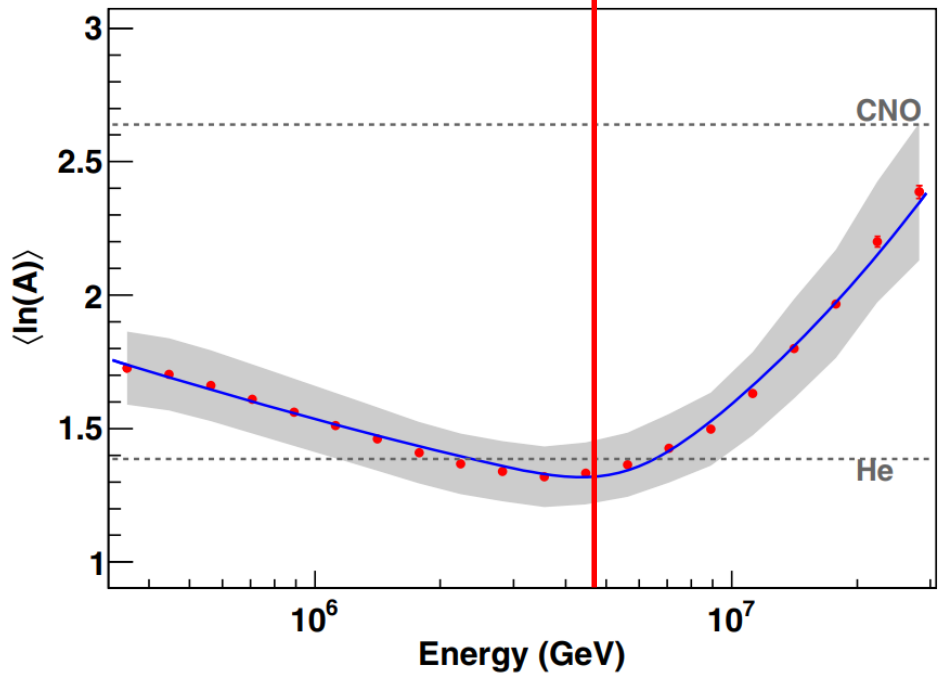
- Energy spectrum
  - The AS gamma underestimate the flux below the knee.
  - The CASA-MIA's measurements is about 50% lower than other measurements
- <lnA>
  - Above the knee: a clear increasing
  - Below the knee: a decrease with energy, which is missed by other experiments





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





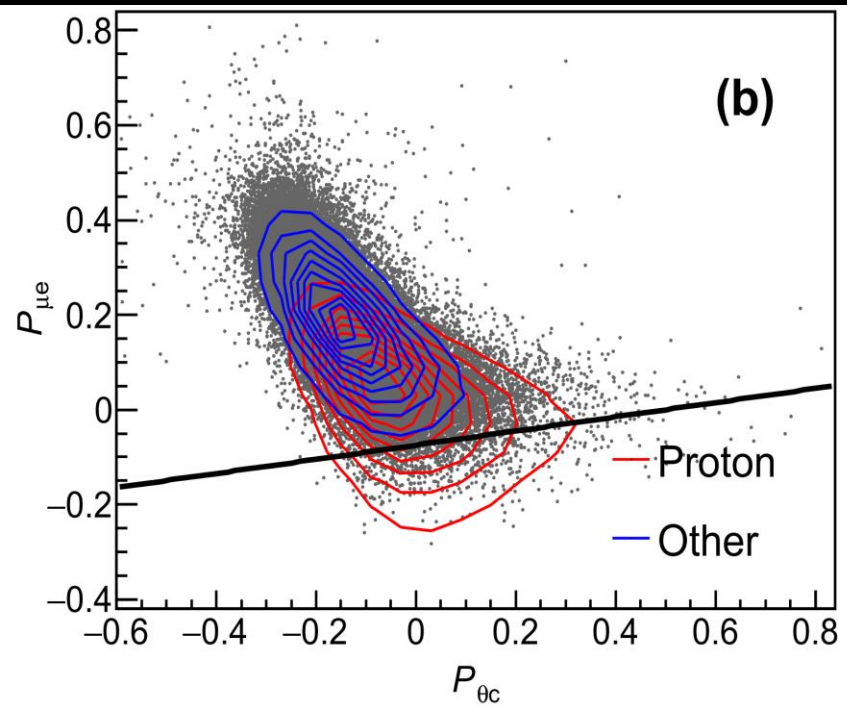
A correction between the flux and composition at the knee.

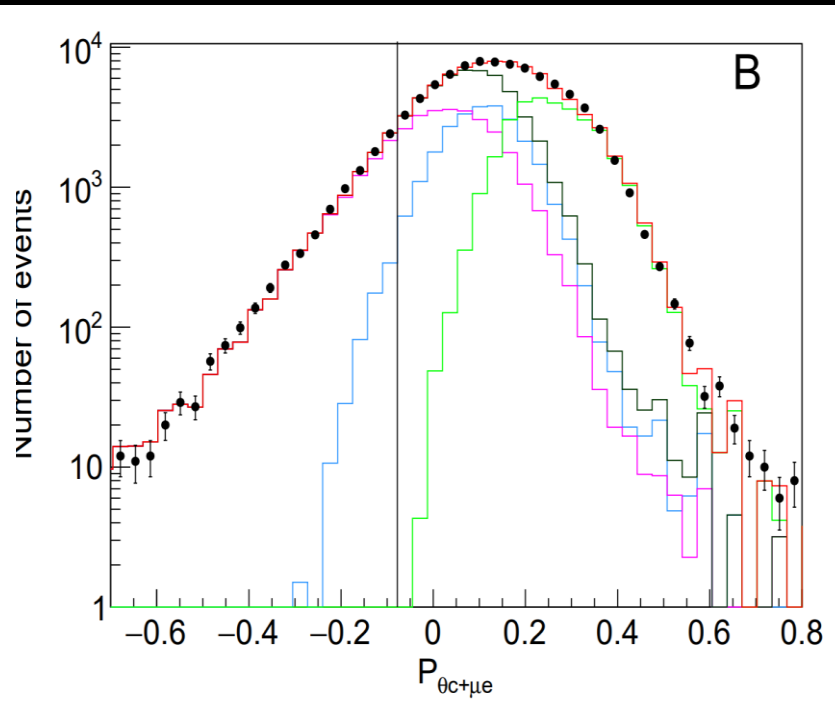
- Both the flux and lnA can be fitted by smooth broken power law.
- Precise knee position: 3.65± 0.05 ±0.15 PeV

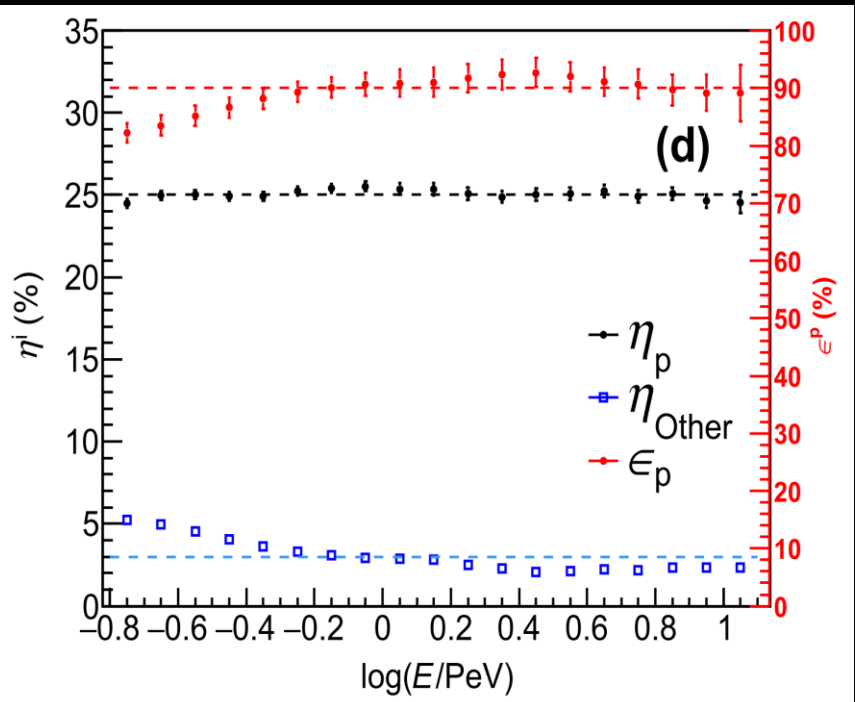
proton energy spectrum in the “knee” region

Proton selection efficiency and purity

- $P_{\mu e}$ and θ_c are used to sperate the compositions
- 90% purity can be achieved with 25% selection efficiency

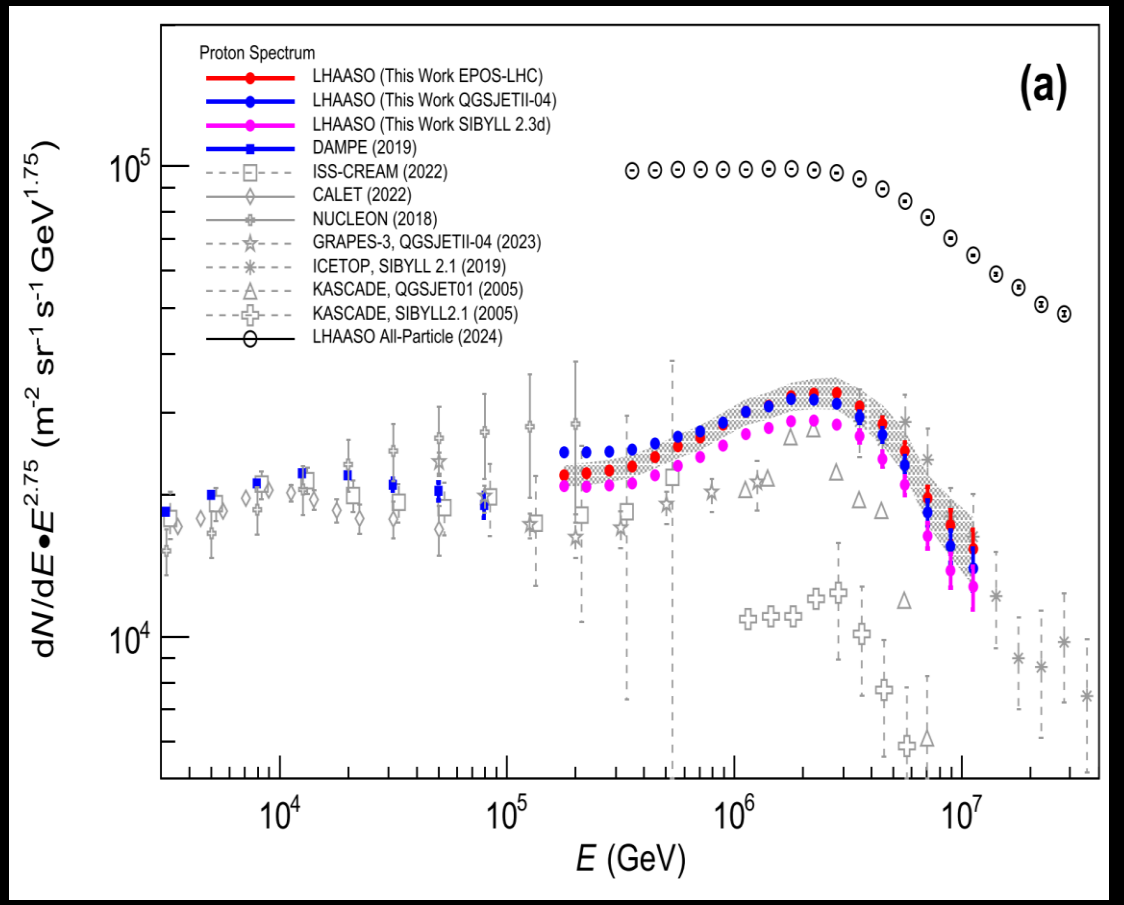






Proton energy spectrum from 0.15 PeV to 10 PeV

- $F = \frac{dN}{dE \times A \times T} \times \frac{\epsilon_p}{\eta_p}$
- The systematic uncertainty caused by hadronic models is about 12% @ 3PeV
- The knee @ knee of all-particle energy spectrum
- Before the knee, the proton energy spectrum is harder than all-particle energy spectrum
- After the knee, the spectrum is steeper than all-particle energy spectrum



Helium energy spectrum above 0.1PeV

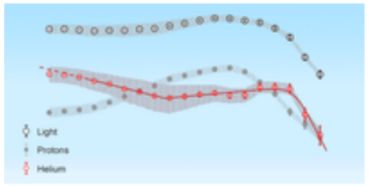
HIGHLIGHTED ARTICLES

FEATURED IN PHYSICS EDITORS' SUGGESTION

Precise Measurement of the Cosmic Ray Helium Spectrum above 0.1 PeV

Zhen Cao *et al.* (LHAASO Collaboration)

Phys. Rev. Lett. **136**, 121001 (2026) - Published 26 March, 2026

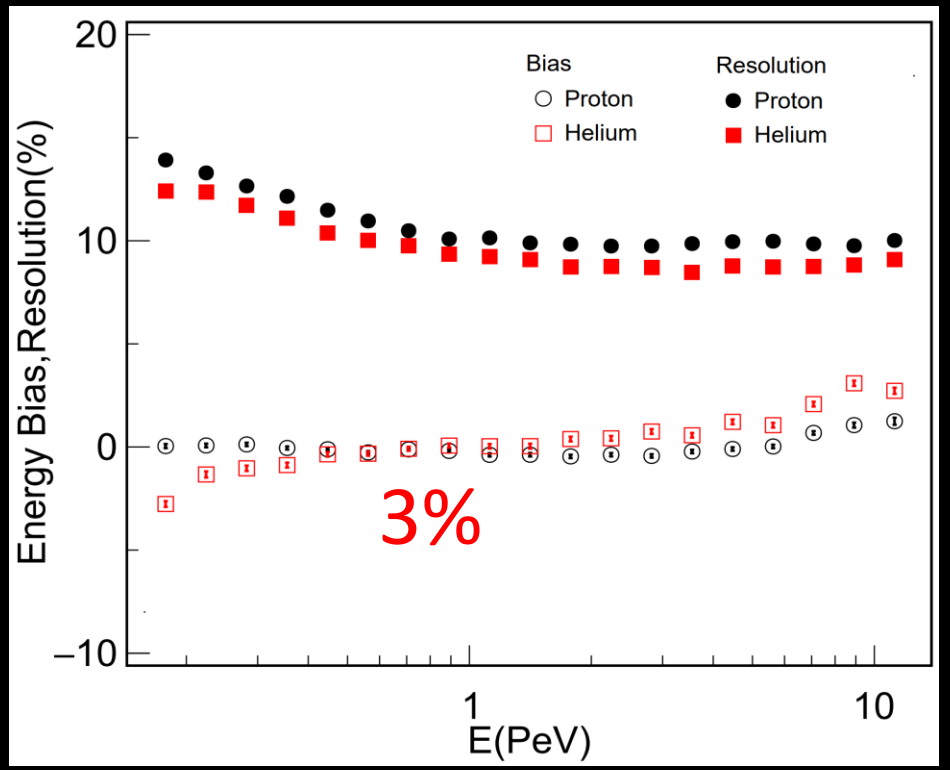


New observations of cosmic rays that distinguish between hydrogen and helium find unexpected complexity in a long-observed spectral feature.

Light composition (proton+helium) selection

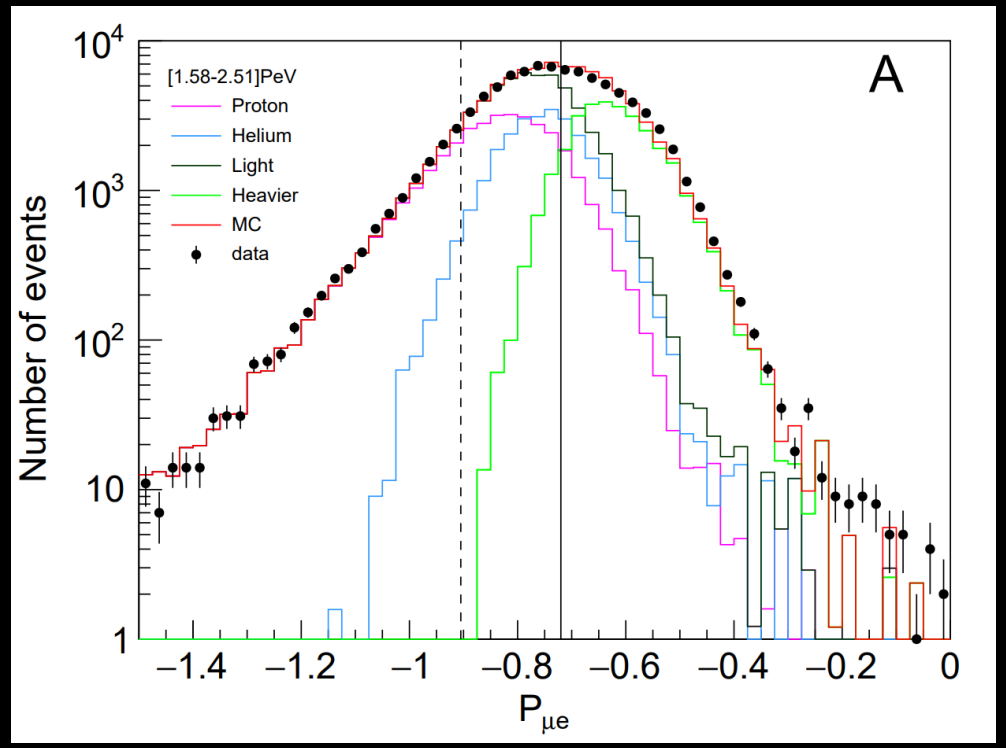
- Helium showers faces contamination from proton and other heavier compositions
- It is impossible to separate helium from all other particles event by event

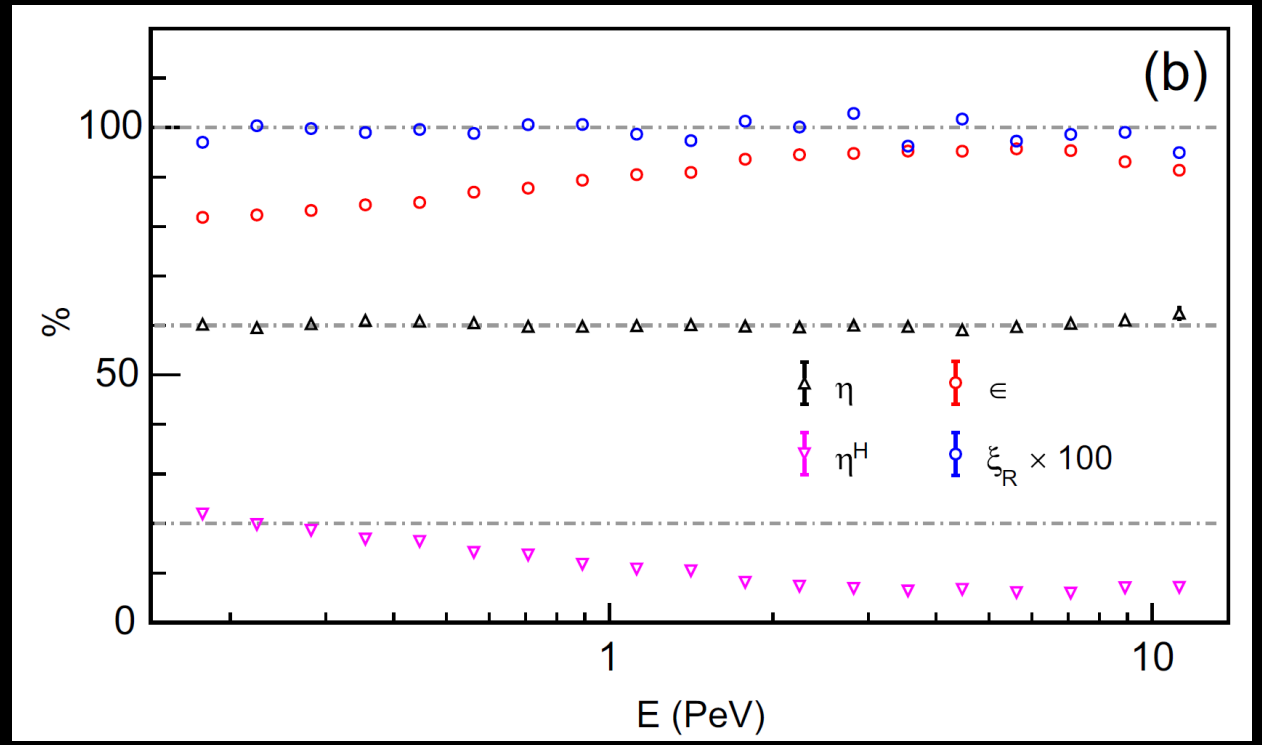
- $F_{He} = F_{p+He} - F_p$
  - The same dataset and the same energy reconstruction as used in the proton energy spectrum



Light composition (proton+helium) selection

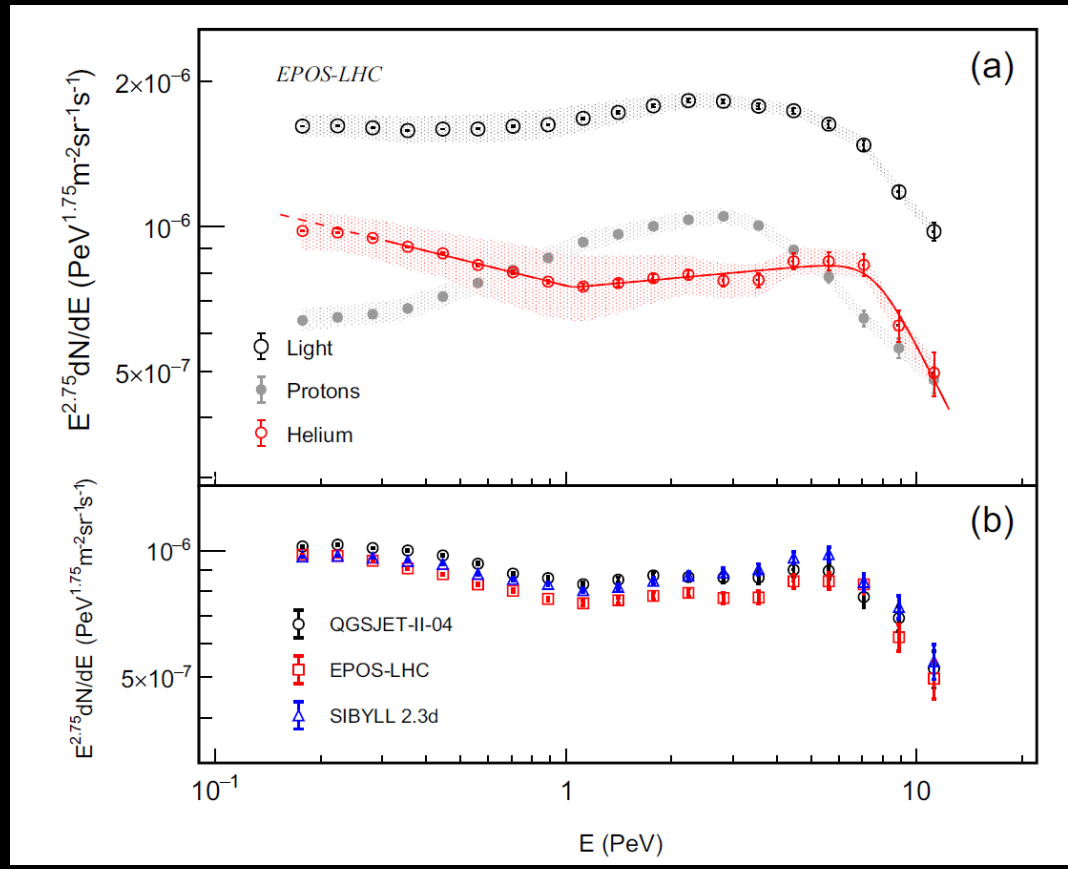
- $P_{\mu e}$ is used to select light composition.
- Two cuts is used to make sure the same selection efficiency of proton and helium
- Purity can reach 90% for energies above 1 PeV.



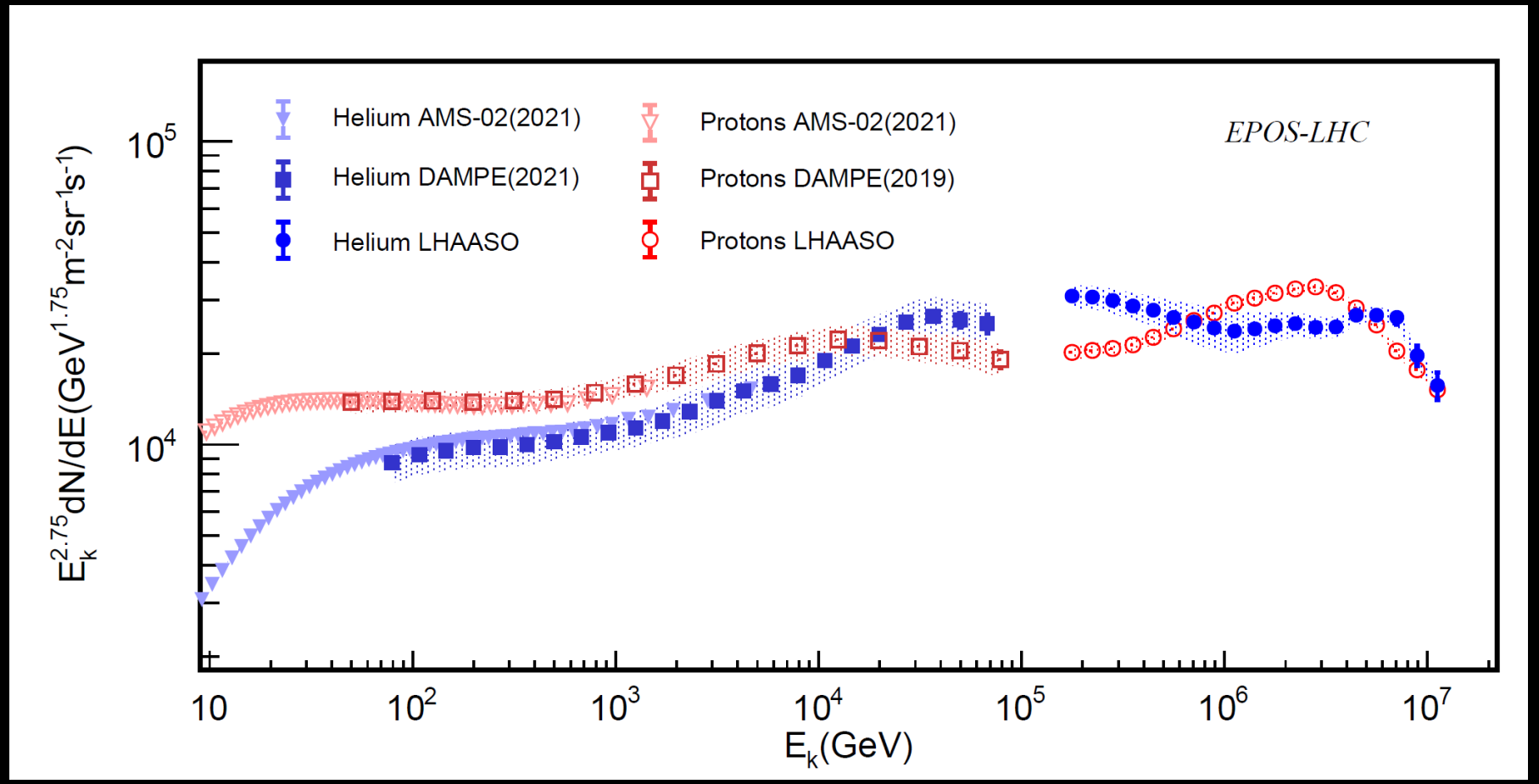


Spectra of Light composition and helium nuclei

- $F_{He} = F_{p+He}$-F_p
- High precision measurement of light composition energy spectrum
- The hadronic uncertainty is 15% at 6PeV
- Systematic errors: same sources as proton spectrum
  - Clear hardening at 1.05 PeV： >10 σ
  - Knee at 7 PeV: 6 σ
  - Strong deviation from the single index power-law spectrum below 0.3 PeV: > 10 σ

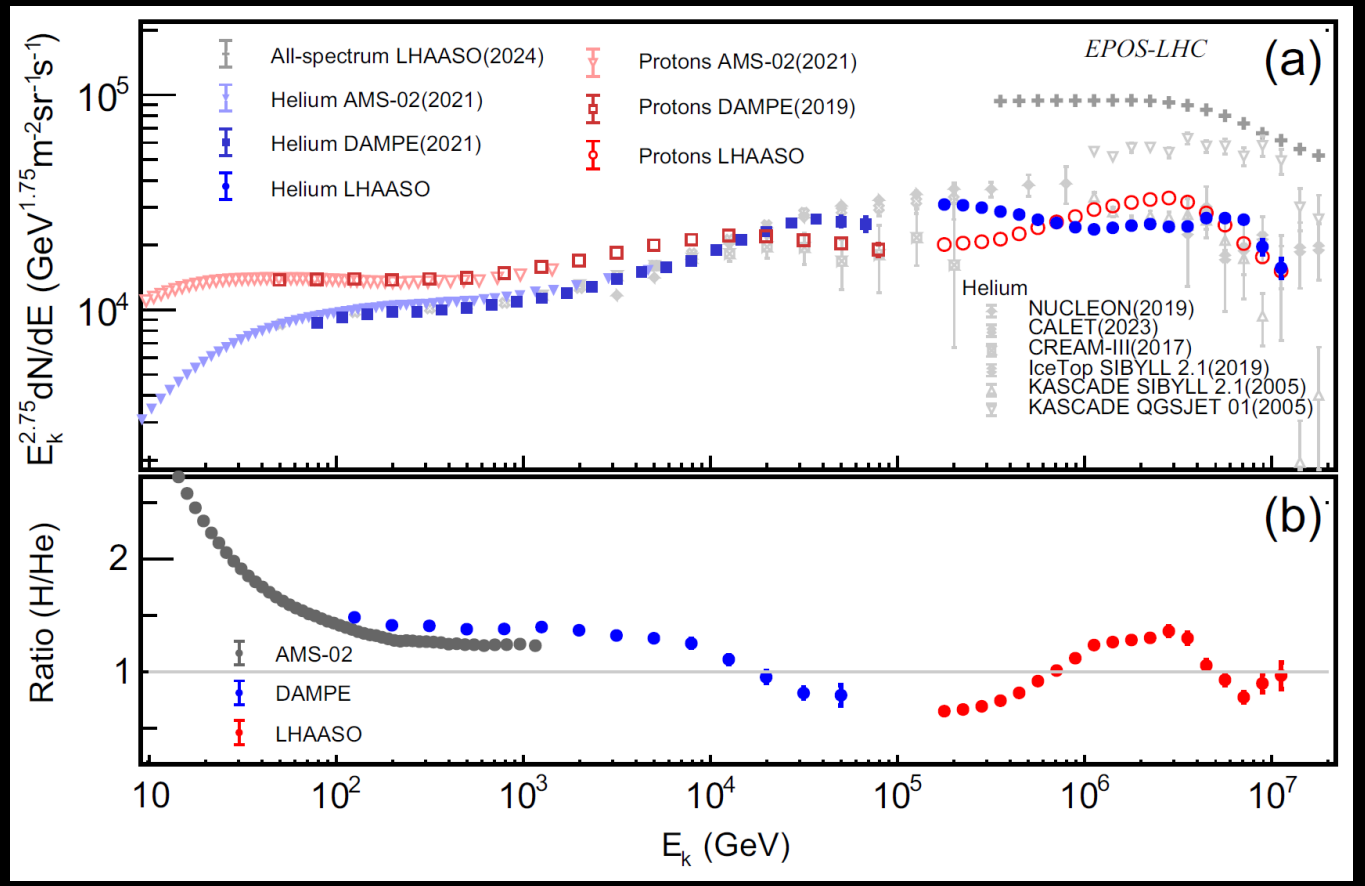


Ground-Based Measurement Precision Reaching Space Level



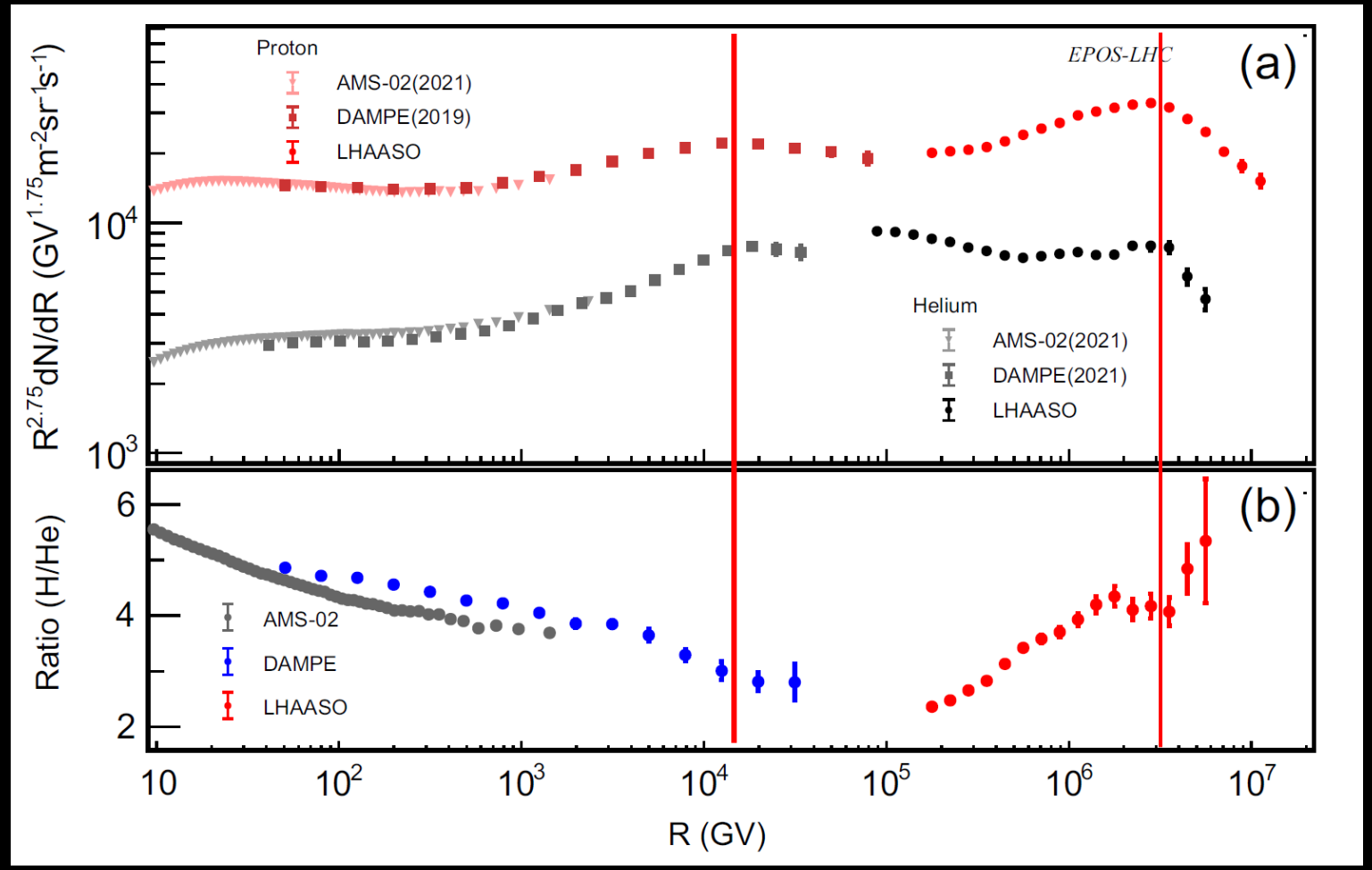
LHAASO results with other measurements

- Two bumps in the energy spectrum
- Hardening-Softening structure
  - The softening position is almost rigidity dependent
  - The hardening position is not show the rigidity dependent
- The proton spectrum is harder than helium spectrum before the knee,
  - which leads to the H/He increasing with energy from 0.7@0.2PeV to 1.4@0.7PeV.
  - The proton is the dominate composition above 0.7PeV again



Spectra of Rigidity of protons and helium nuclei

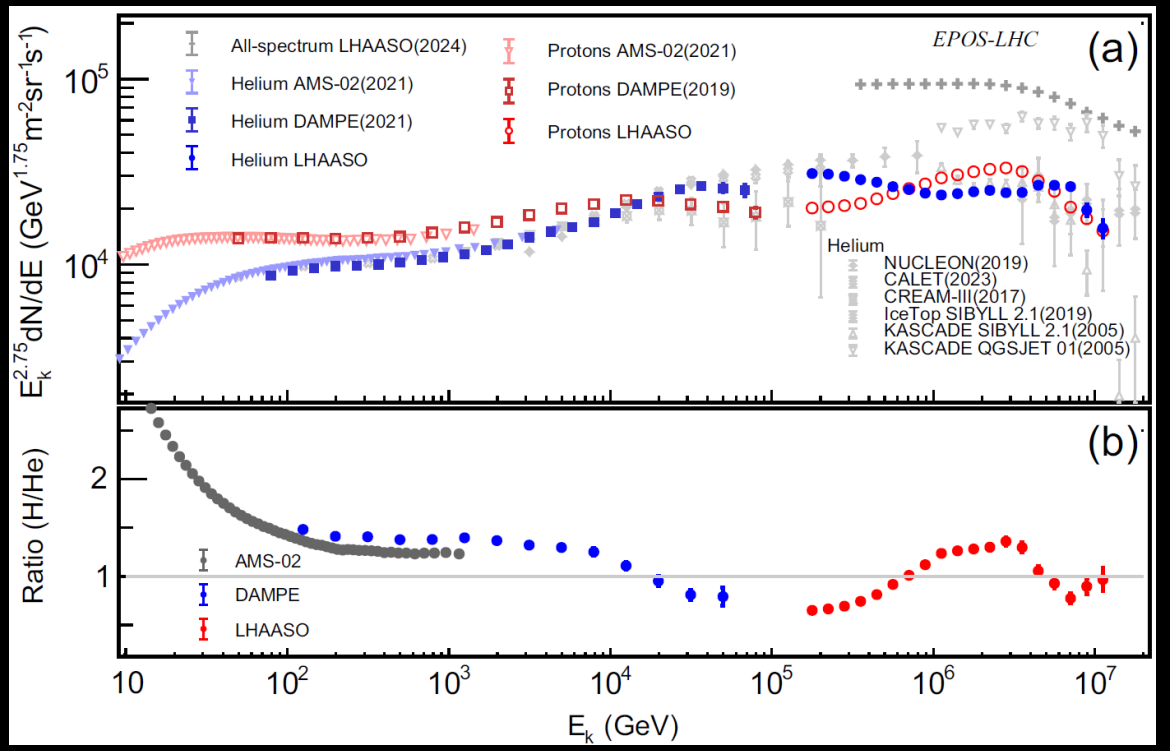
- Both proton and helium exhibit a softening structure at almost the same rigidity around 15 TV and 3 PV
- The spectral indices of proton and helium before and after the softening are not consistent
  - ✓ Leads to the H/He changes with energy



Summary

LHAASO has measured three energy spectra in the knee region

Spectrum	Energy region	Knee position	Hardening
All-particle	0.3~30 PeV	~3.67 PeV	
Proton	0.16~12.6 PeV	~3.3 PeV	0.1~0.3 PeV
Helium	0.16~12.6 PeV	~7 PeV	~1.1 PeV



Cosmic rays around several tens of TeV and a few PeV may be contributed by different sources, and these two types of sources may have different elemental abundances.

Thanks for your attention