Cosmic Ray Proton Spectrum by LHAASO

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(on behalf of LHAASO Coll.)

22nd Lomonosov Conference, Moscow, Aug., 2025

The Site

Bird's eye view of LHAASO， 2021-08

- **Location： 29o21' 27.6" N , 100o08'19.6" E**
- **Altitude: 4410 m**
- **2021-07 completed built and in operation**

LHAASO, *Nature Astronomy* *5:849 (2021)*

(Aug. 2018, at 4410 m a.s.l.)

LHAASO: Multi-Messenger Collaboration Network

ANTARES (NT)

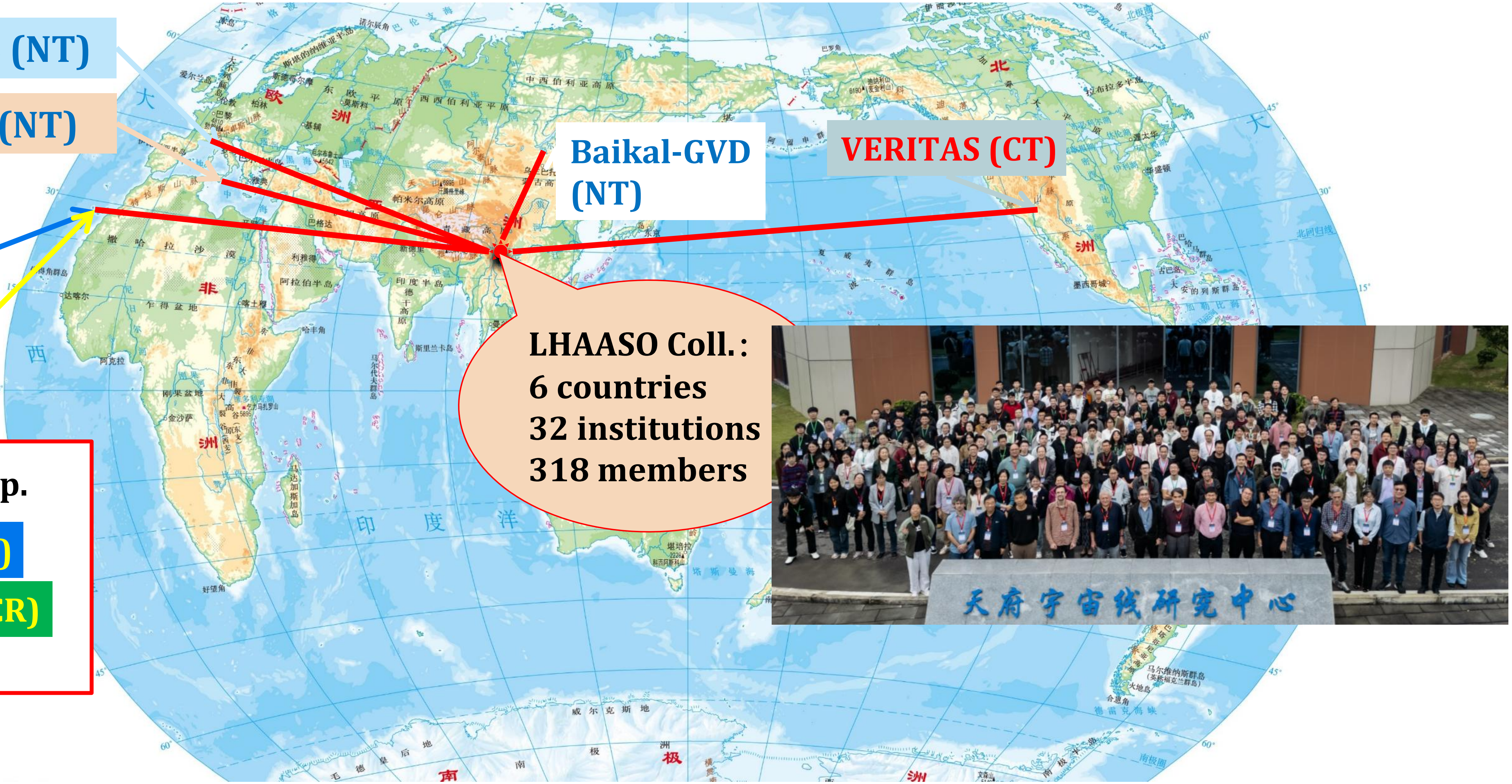
KM3Net (NT)

LST/CTA-N (CT)

MAGIC(CT)

Baikal-GVD (NT)

VERITAS (CT)



Space borne Exp.

eROSITA(X-ray)

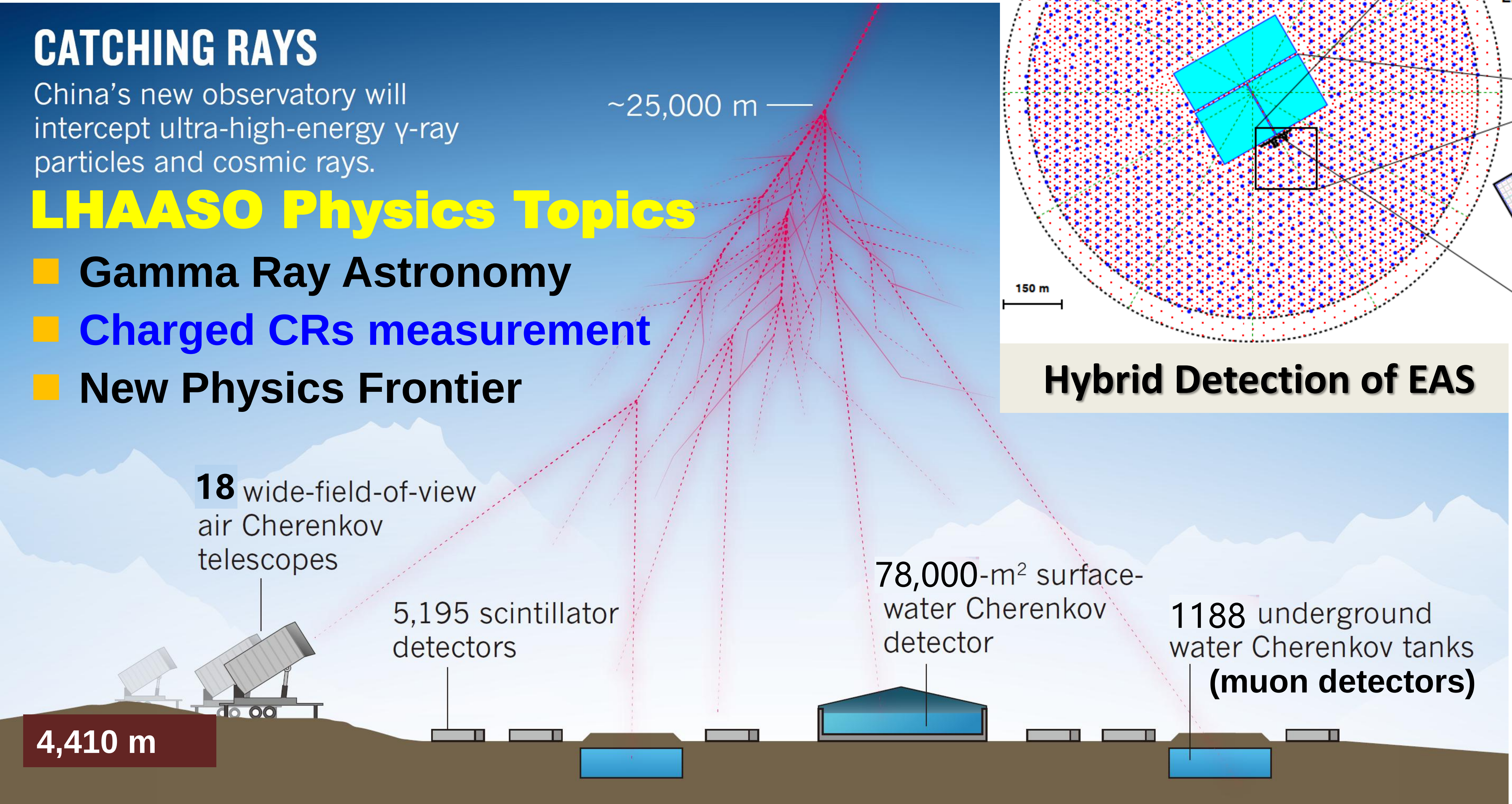
DAMPE(γ-ray, CR)

LHAASO Coll.:
6 countries
32 institutions
318 members

The LHAASO collaboration has signed MOUs with 8 international collaborations

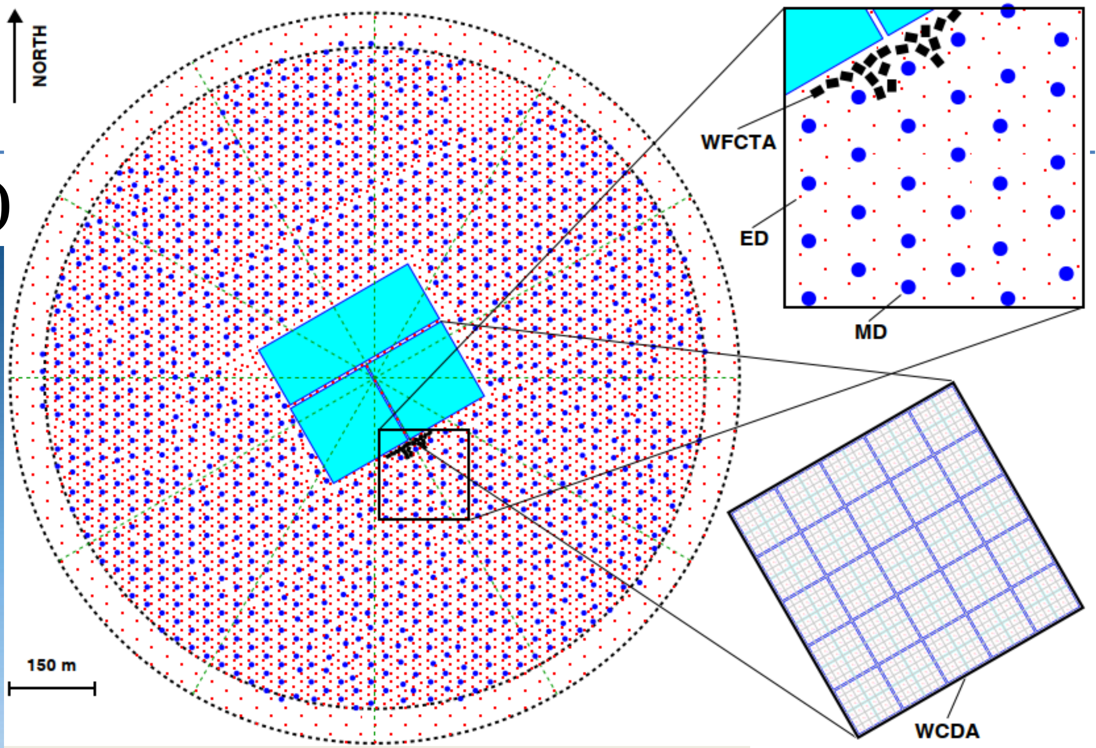
High Energy Cosmic Rays

Large High Altitude Air Shower Observatory (LHAASO)



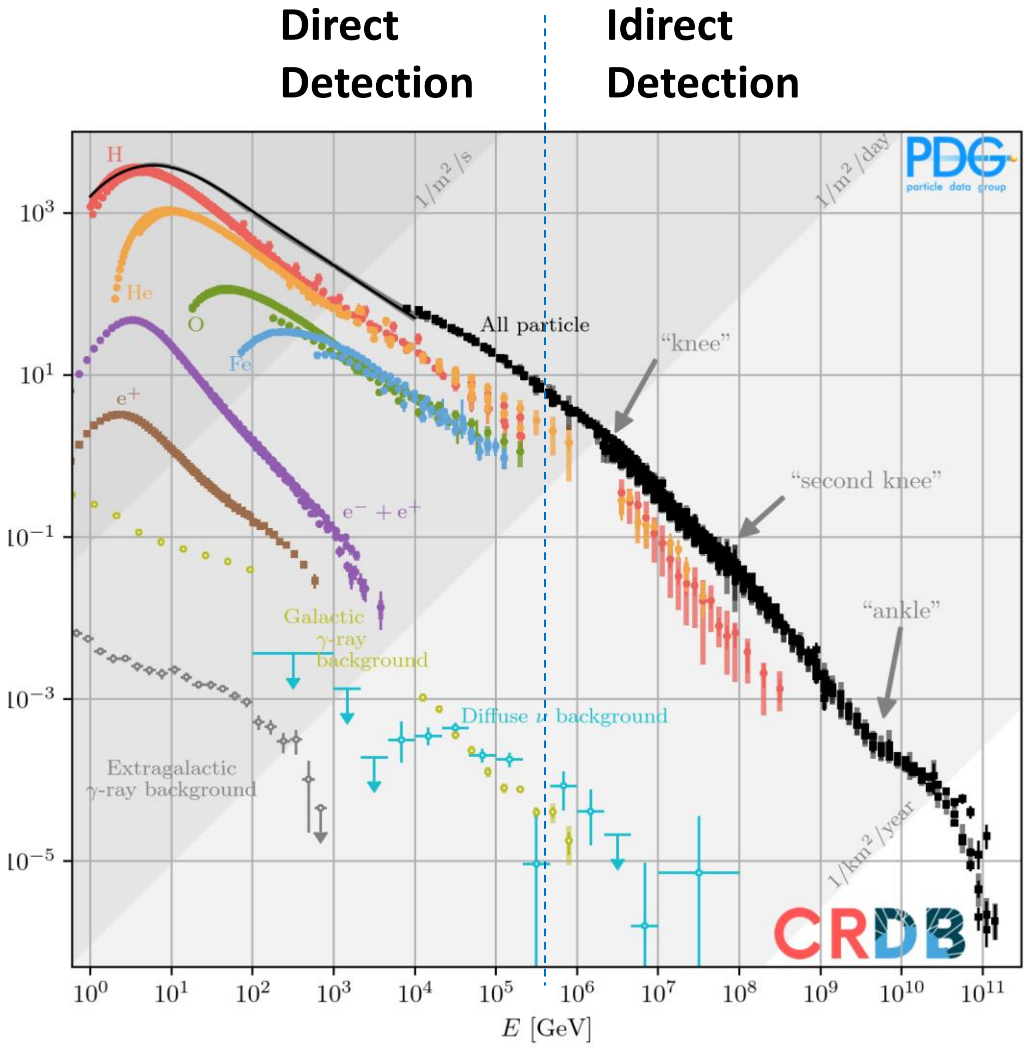
LHAASO Physics Topics

- Gamma Ray Astronomy
- Charged CRs measurement
- New Physics Frontier



Hybrid Detection of EAS

Cosmic rays

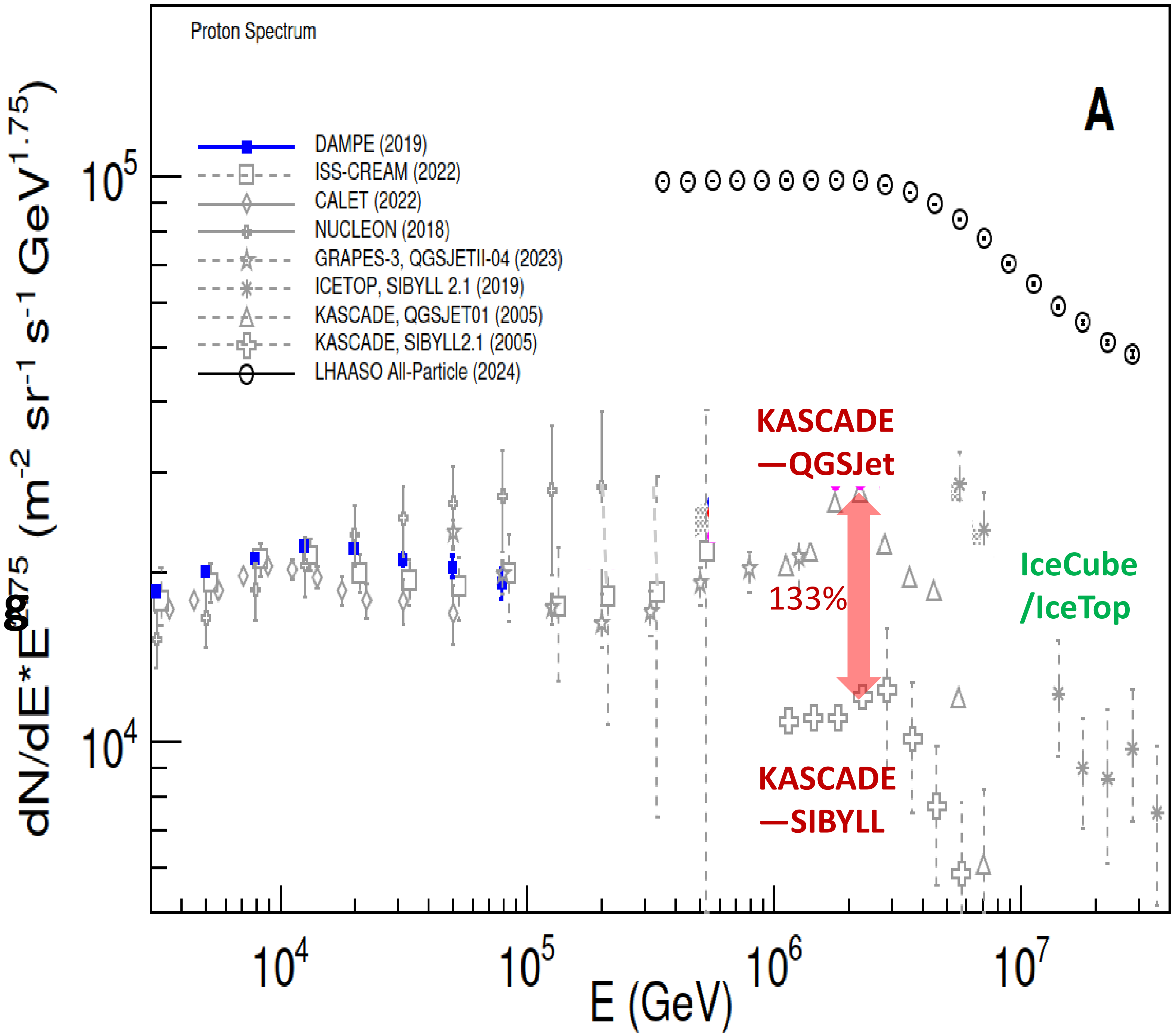


PDG 2025，

- Proton, helium nuclei and heavier nuclei , all the way to uranium
- Discovered in 1912, many things (e.g. source, acceleration mechanism) about cosmic rays remain a mystery more than a century later
- Individual energy spectra play am important role to solve the mystery
  - Proton knee, helium knee, iron knee …
  - Knees may indicate the energy limit for cosmic ray acceleration by astrophysical sources

The Proton Spectrum around the knee

- ➢ Energy is too high to be detected in direct measurement
- ➢ KASCADE gives confusing results due to the large uncertainty
- ➢ IceCube has too high threshold



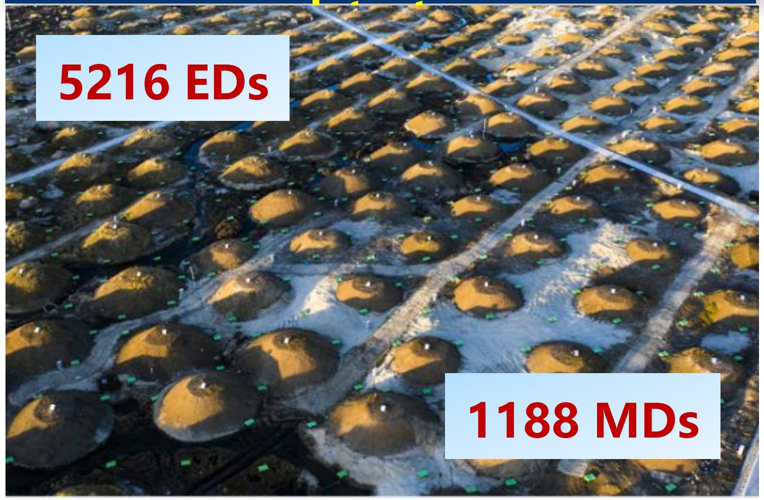
Hybrid Detection of EAS

LHAASO, Daocheng, China

- at 4410 m above sea level
- Construction finished in 2021
- Operation for 4 years
- Discovery of many PeVatrons and the brightest GRBs

KM2A of scintillators and μ-D

The most sensitive UHE



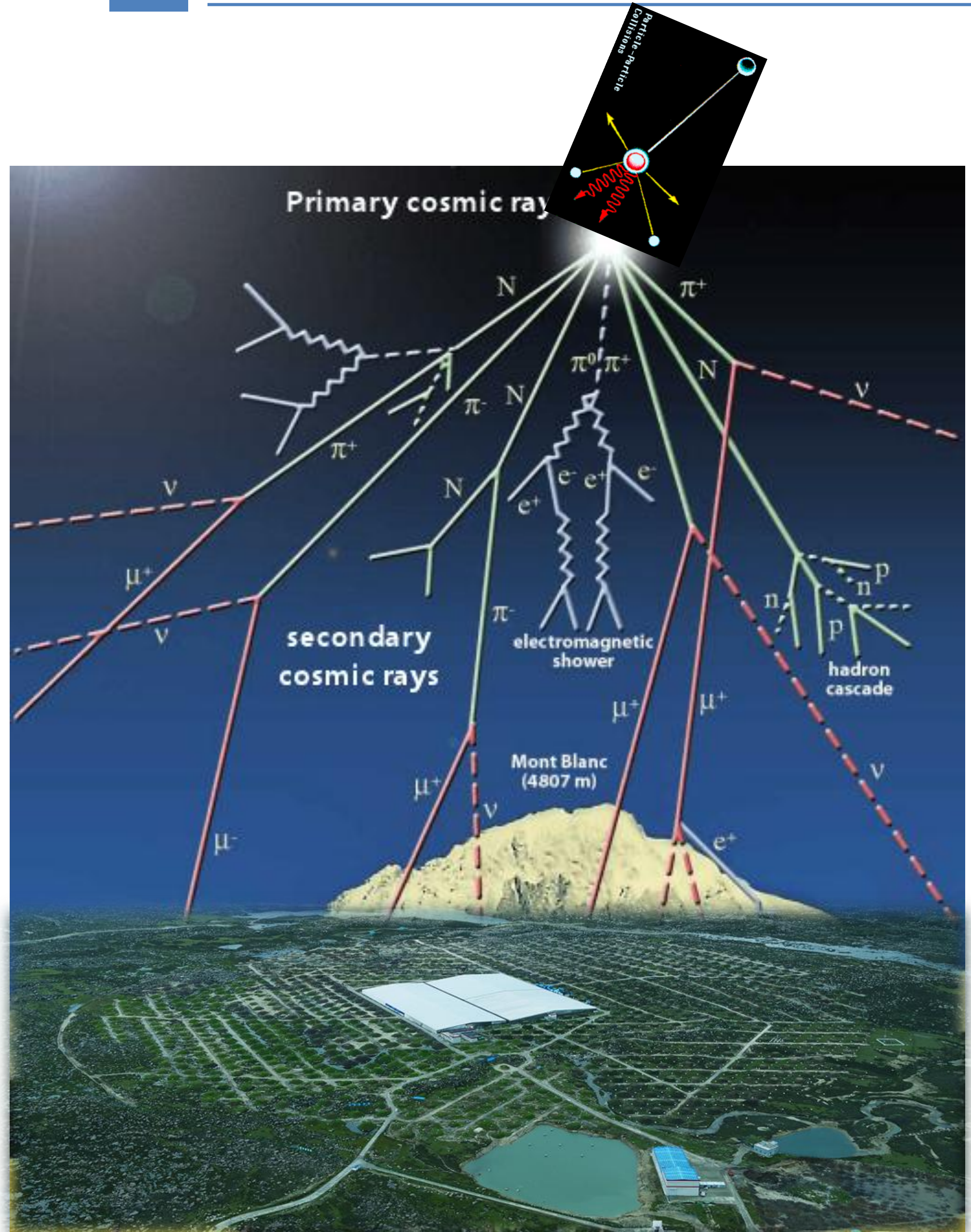
Water C-Detector Array

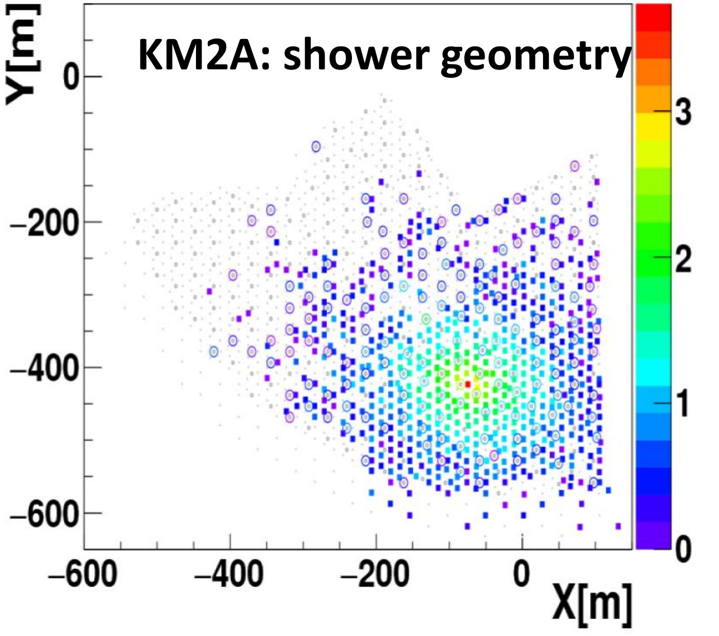
The most sensitive γ-survey

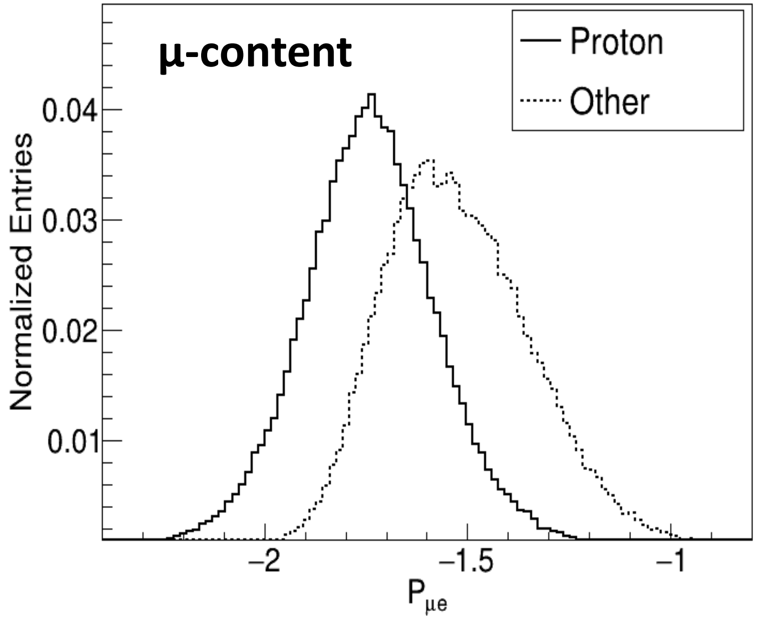
Wide FoV C-Telescope Array

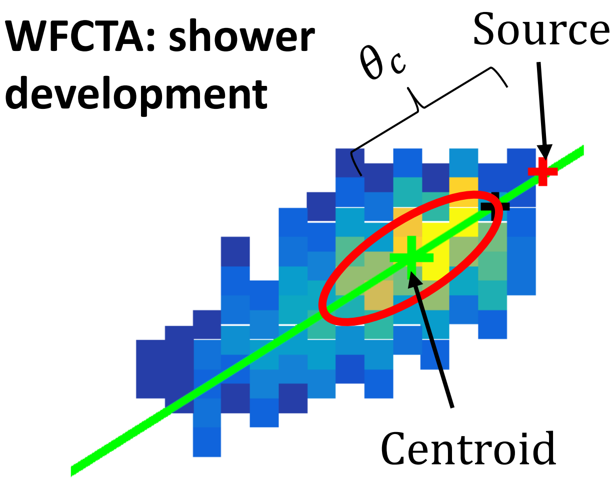
Stereoscopic measurement of CR

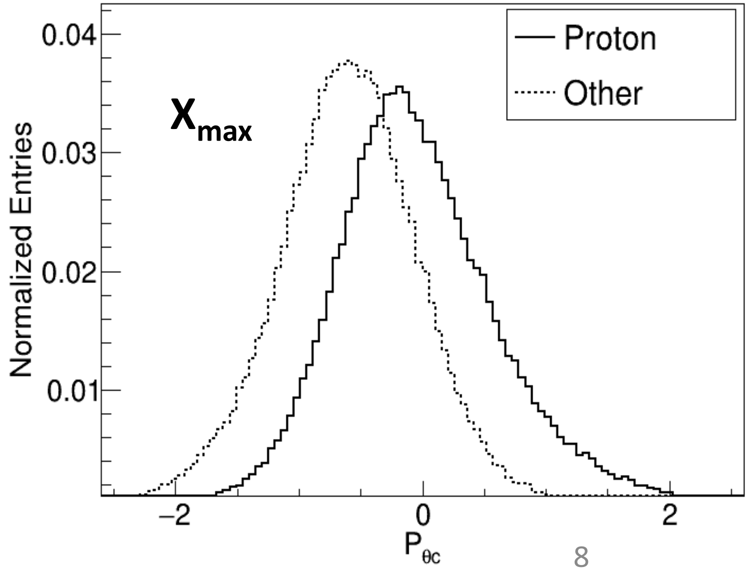
Hybrid Detection of EAS

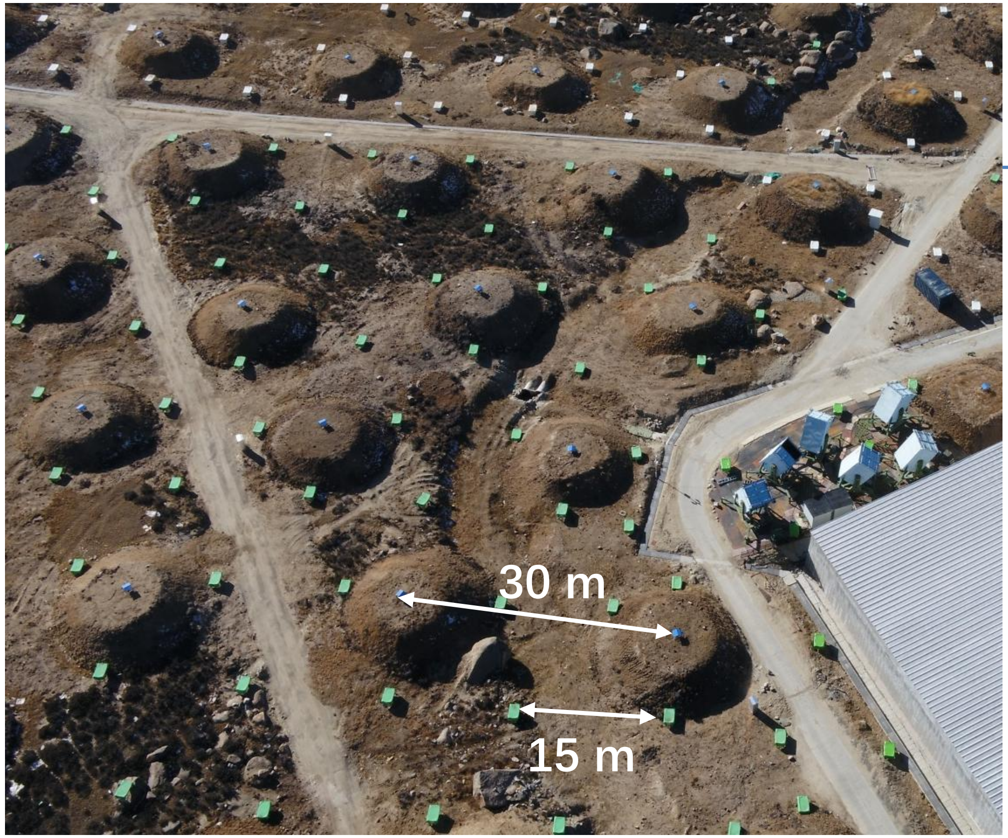






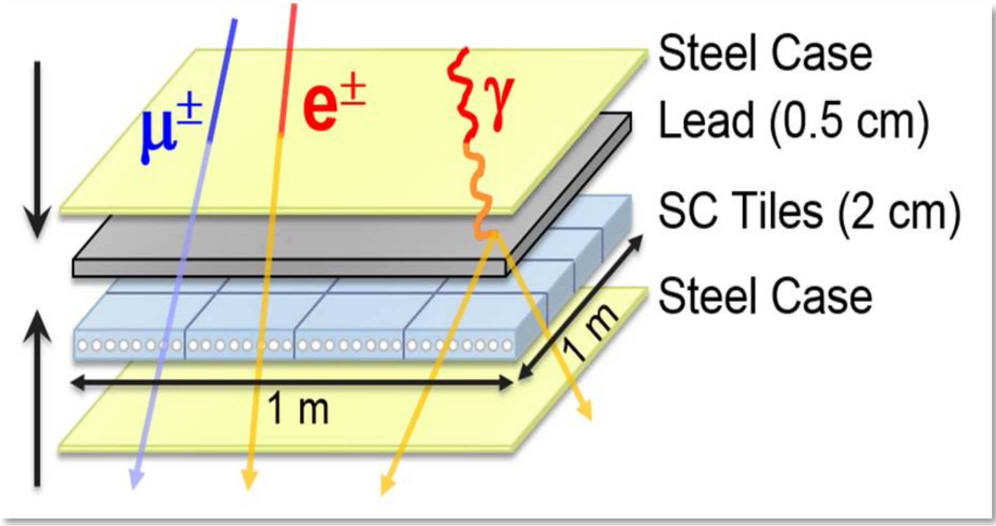




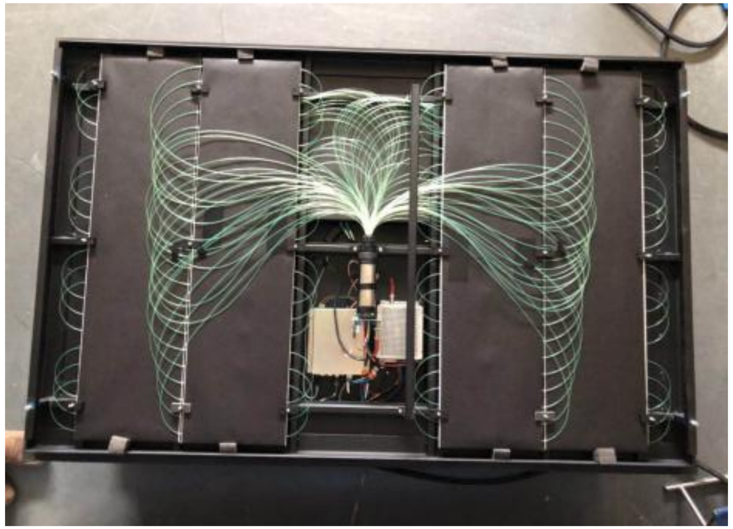


KM2A: 1.36 (km)^2

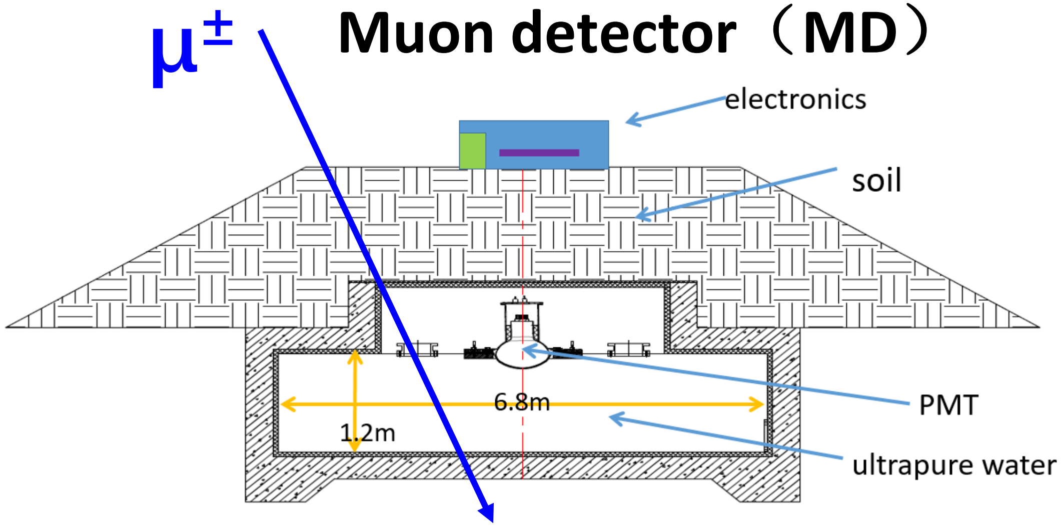
- 5195 EDs
  - 1 m^2 each
  - 15 m spacing
- 1188 MDs
  - 36 m^2 each
  - 30 m spacing



Inner View of one ED



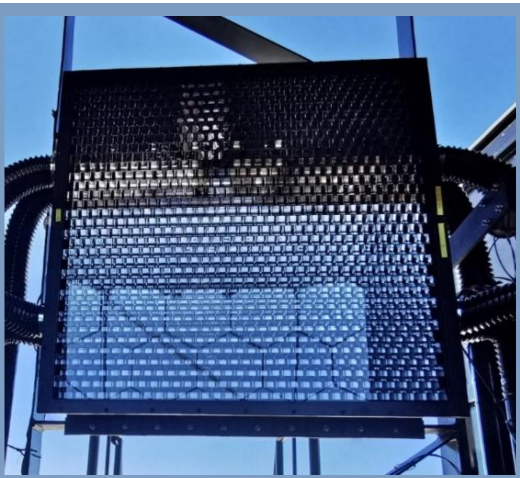
Muon detector（MD）



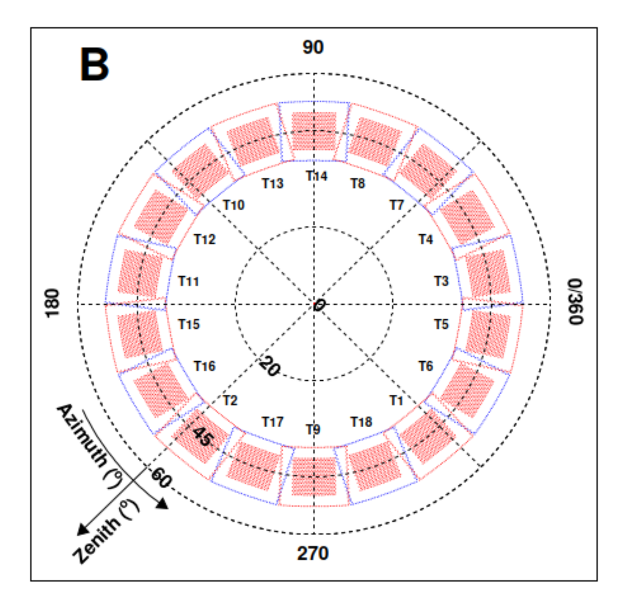
Wide Field of View Cherenkov Telescope (WFCTA)

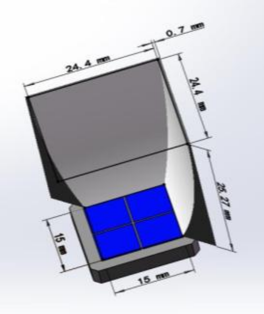
- **Telescope parameters:**
  - ~5 m^2 spherical mirror
  - Camera: 32×32 SiPMs array
  - FOV: 16° × 16°
  - Pixel size: 0.5°
- **18 tels are pointed at a zenith angle of 45° cover azimuth angle from 0° to 360°**

Mirror



SiPM camera

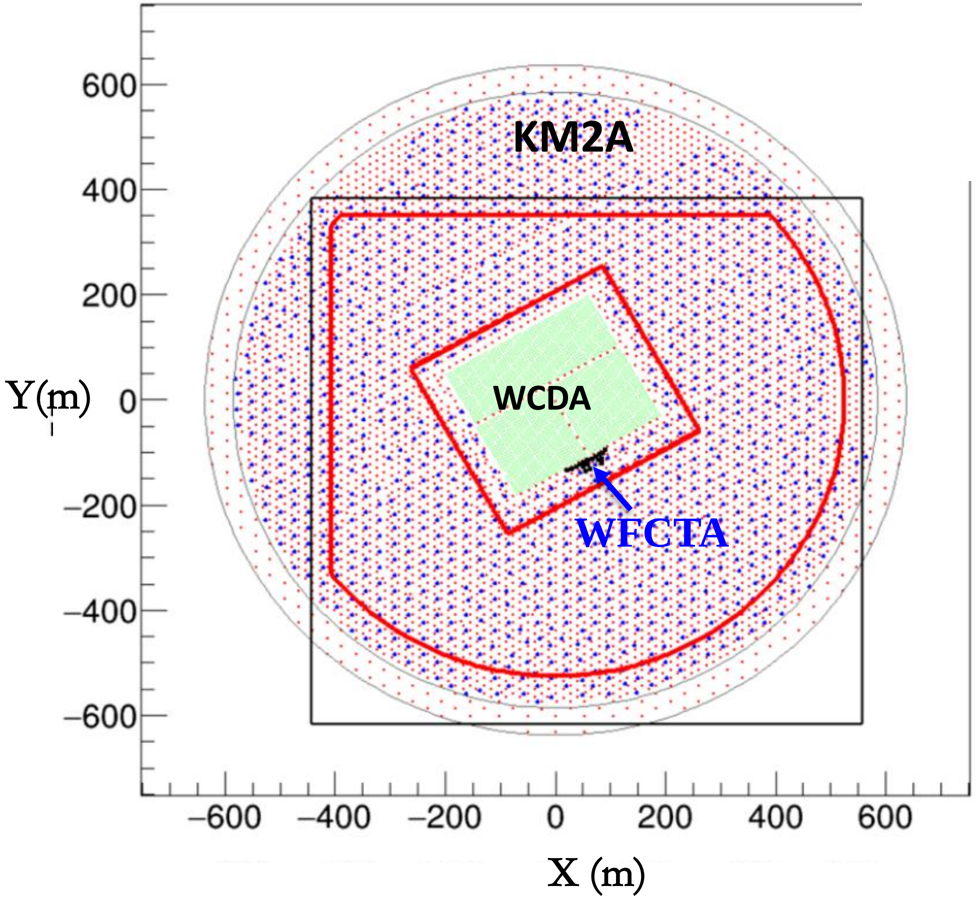




SiPM and Winstone cone

Hybrid Measurement of CR Showers around the Knee

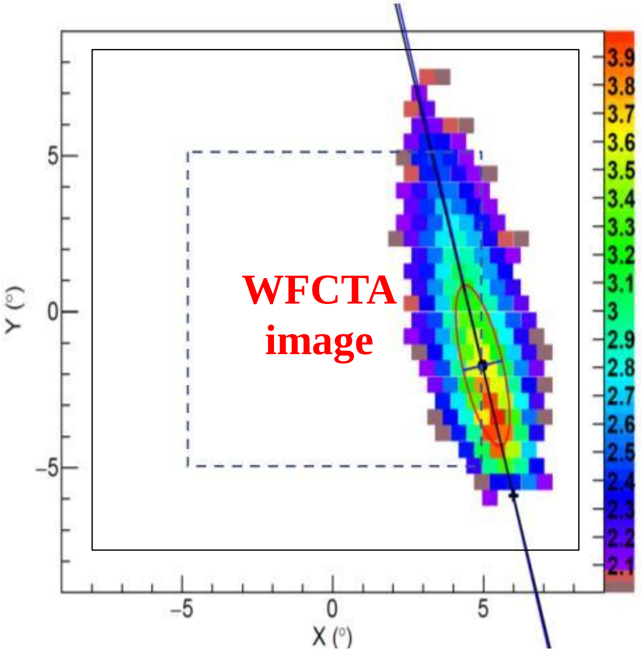
- **KM2A:**
  1. **Core (x,y)**
     - $\sqrt{x^2 + y^2} < 470\ m$
     - !|x'|<200m & !|x'|<160m
  2. **Number of fired EDs > 20**

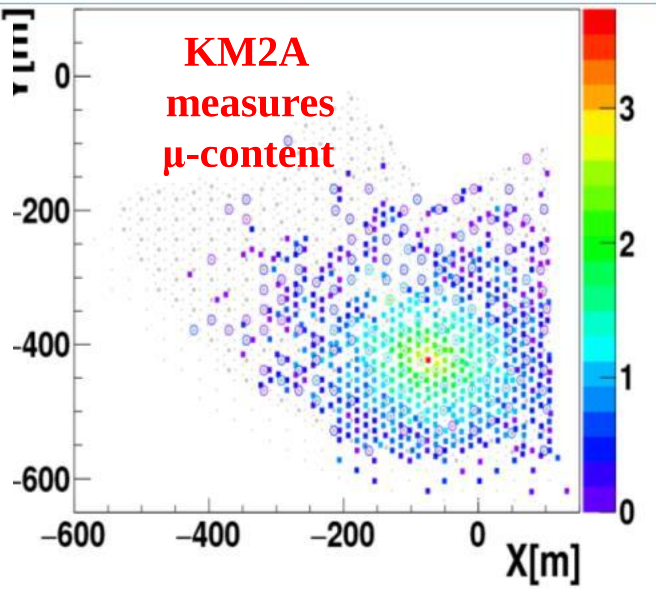


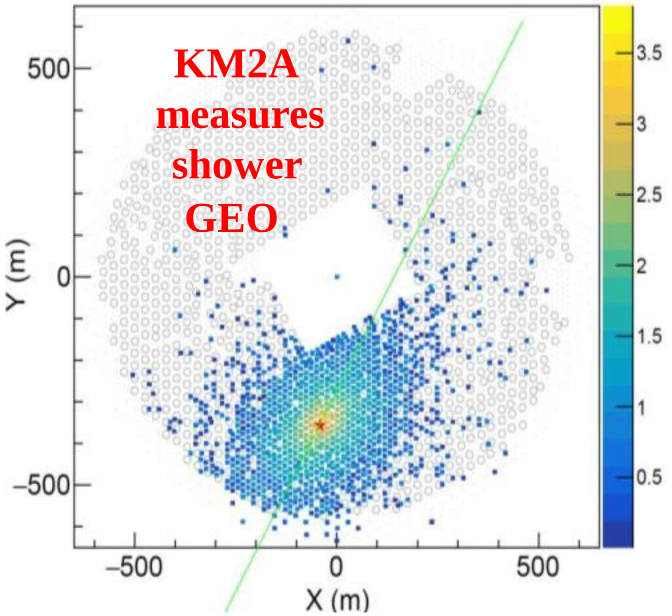
- **WFCTA: Cherenkov telescopes**
  1. **Number of pixels: $N_{pixel} \geq 6$**
  2. **FoV: 10° ×10° out of 16° ×16°**
  3. **R_p: 180 – 310 m**

—— **Core resolution 2.5 m**

—— **Angular resolution 0.1°**

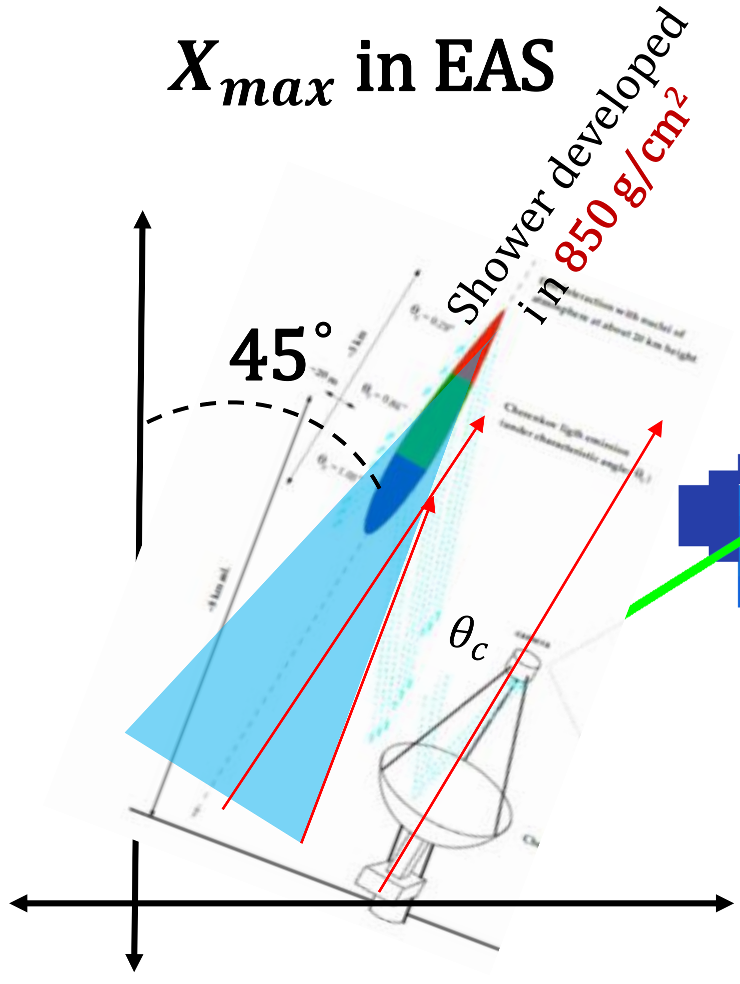






Well Contained !

Component sensitive parameters: $P_{\theta c}$



$$P_{\theta c} = \frac{\theta_c^{250} - \langle \theta_c^{250} \rangle}{\langle \theta_c^{250} \rangle|_{PeV}}$$

- Normalization in the impact parameter R_p:

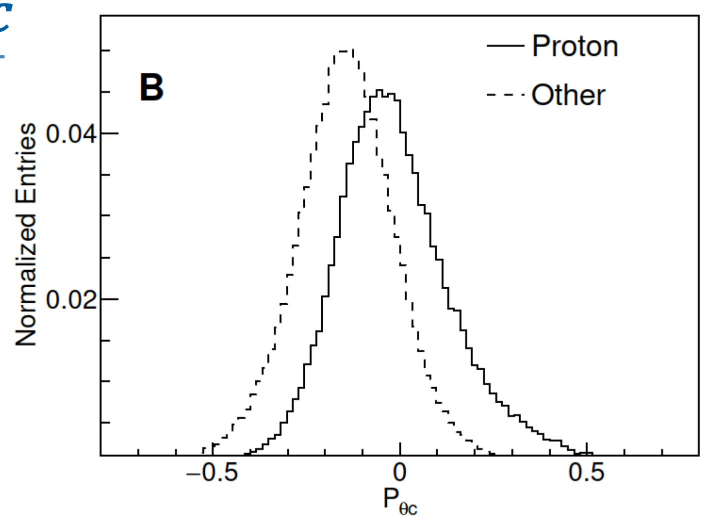
$$\theta_c^{250} = \frac{\theta_c}{\cos(\theta)} + 0.011 \times (R_p - 250)$$

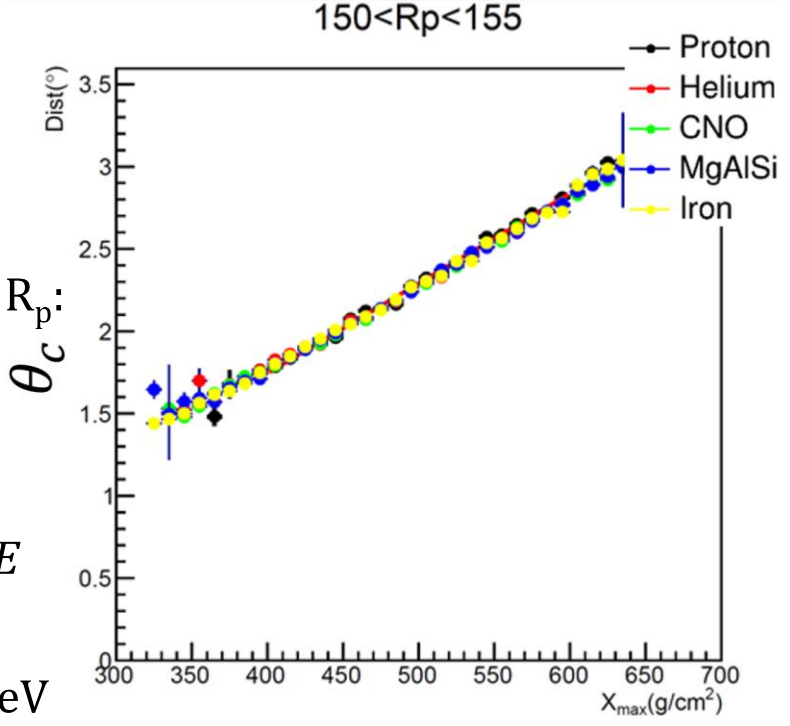
- Normalization in energy:

$$\langle \theta_c^{250} \rangle = p_0 + p_1 \cdot \log_{10} E + p_2 \cdot \log_{10}^2 E$$

- $\langle \theta_c^{250} \rangle|_{PeV}$: the average value of θ_c for proton events at R_p =250 m and E=1 PeV

Well Contained !





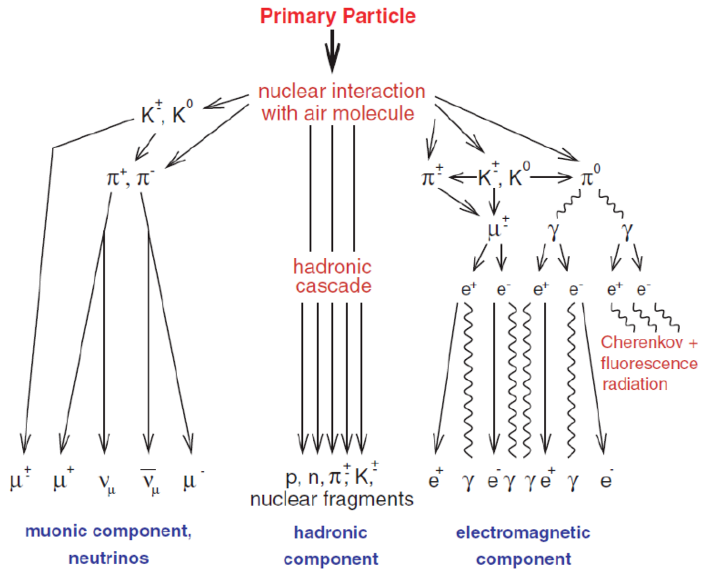
Component sensitive parameters: $P_{\mu e}$

Muons and electromagnetic particles in EAS

$$N_\mu \propto A^{1-\beta}\left(\frac{E_0}{1\ \mathrm{PeV}}\right)^{\beta} \approx 1.69\times10^4\cdot A^{0.10}\left(\frac{E_0}{1\ \mathrm{PeV}}\right)^{0.90}$$

$$N_e \propto A^{1-\alpha}\left(\frac{E_0}{1\ \mathrm{PeV}}\right)^{\alpha} \approx 5.95\times10^5\cdot A^{-0.046}\left(\frac{E_0}{1\ \mathrm{PeV}}\right)^{1.046}$$

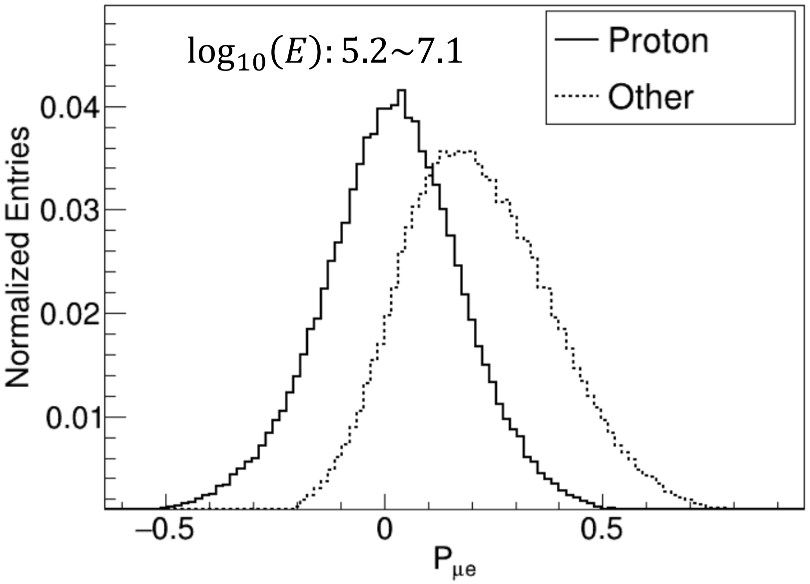
J. R. Hörandel, Cosmic rays from the knee to the second knee: 10^{14} to 10^{18} eV, Mod. Phys. Lett. A 22, 1533 (2007)

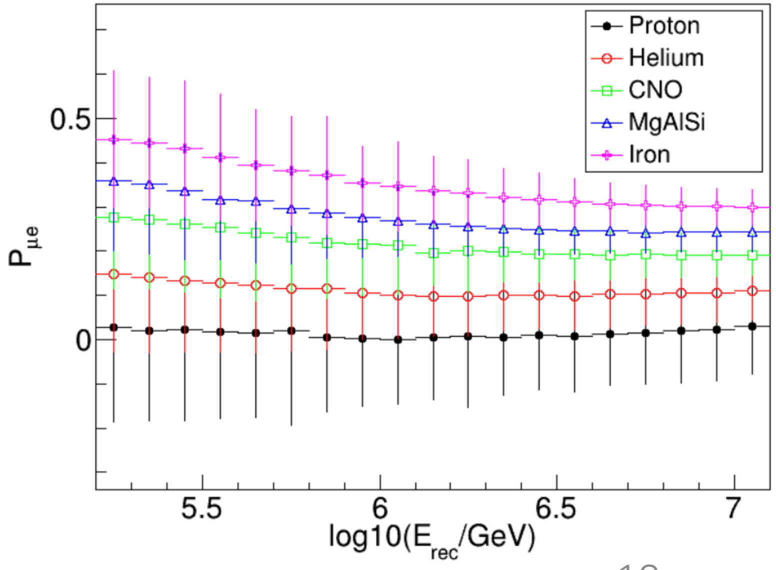


$$\Rightarrow \log A = \frac{\alpha}{\alpha-\beta}\log\left(\frac{N_\mu}{N_e^{\beta/\alpha}}\right) + \mathrm{const}$$

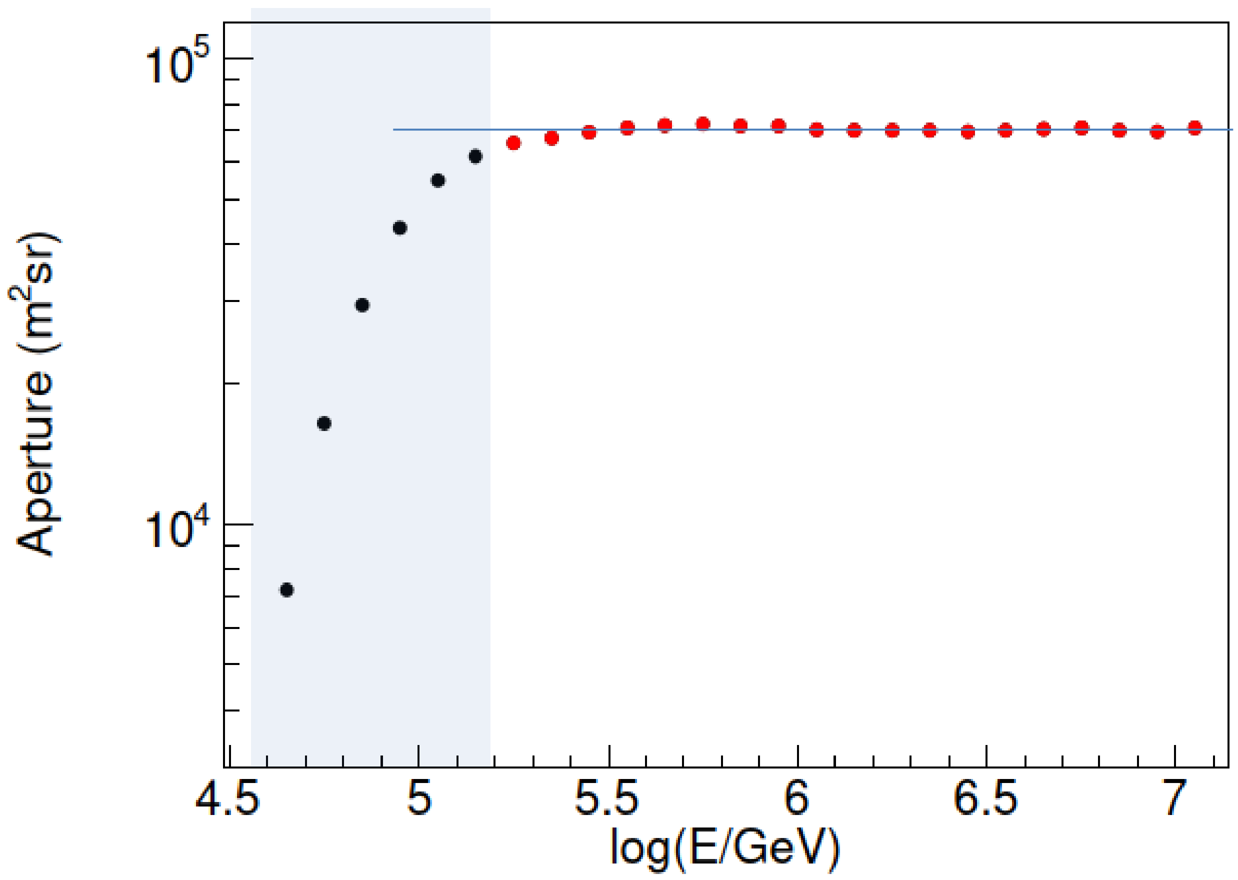
$$P_{\mu e} = \log_{10}\frac{N_\mu}{N_e^{0.82}}$$

- N_μ : 40~200 m
- N_e : 40~200 m



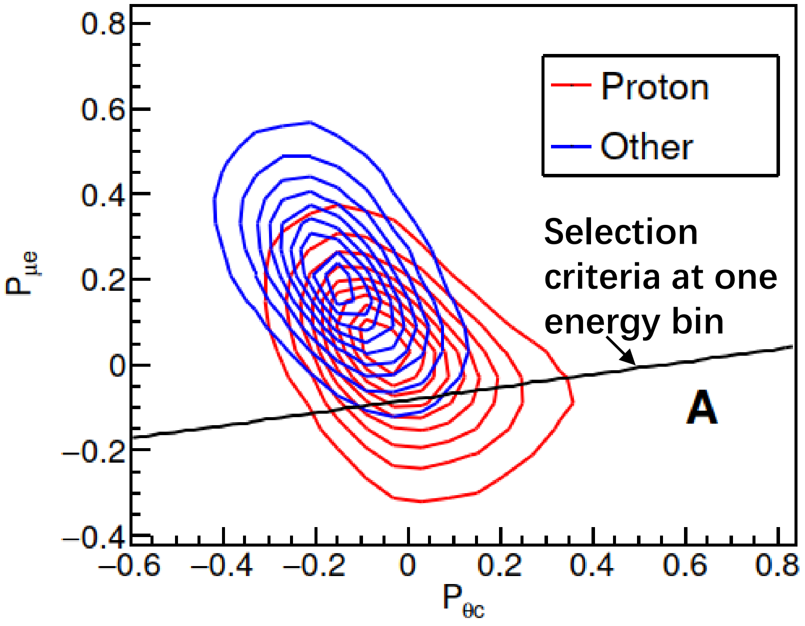


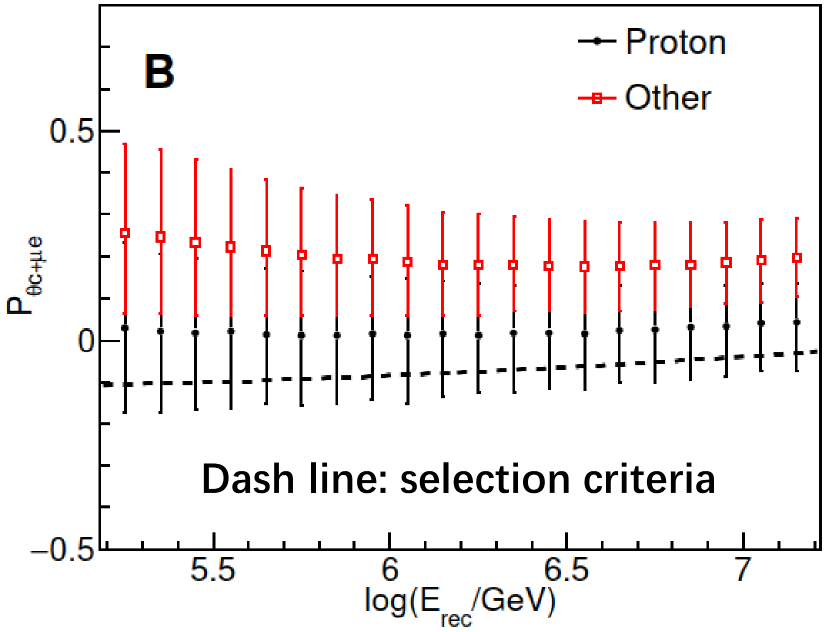
Effective Area and Efficiency, and Data Set

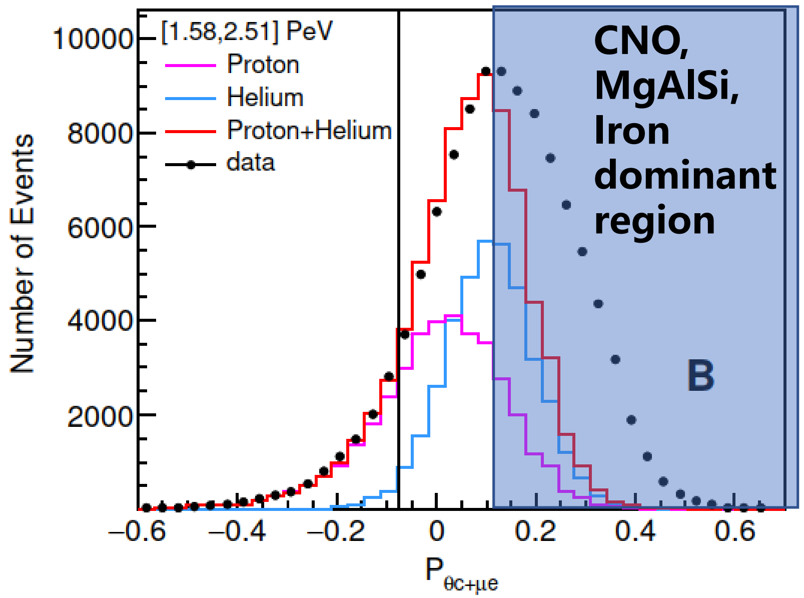


- **Data set： 2021.10-2022.4**
- **Total time after good weather selection: ~1,000 hour**
- **Aperture: ~70,000 m^2sr**
- **The proton energy spectra from 0.158 to 12.5 PeV**
- **Fully efficient detection**

Proton Selection: multi-parameter analysis

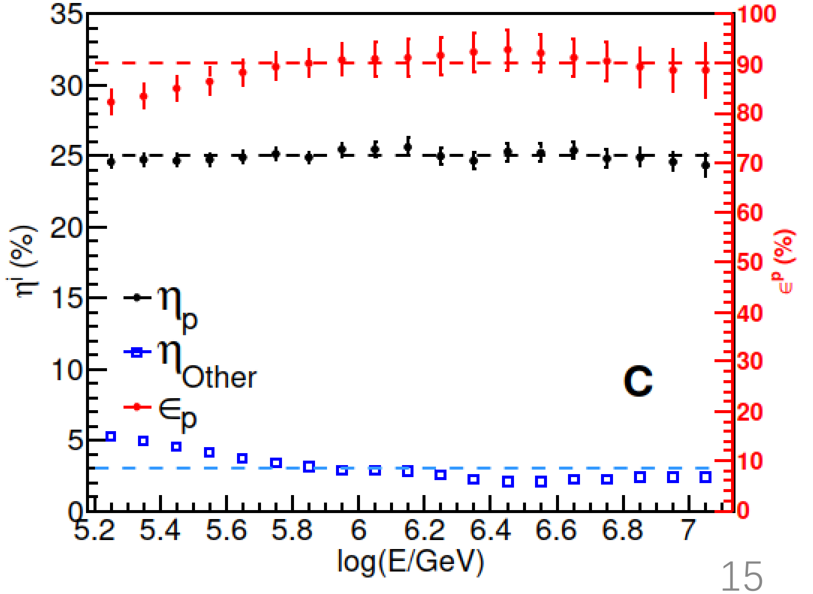






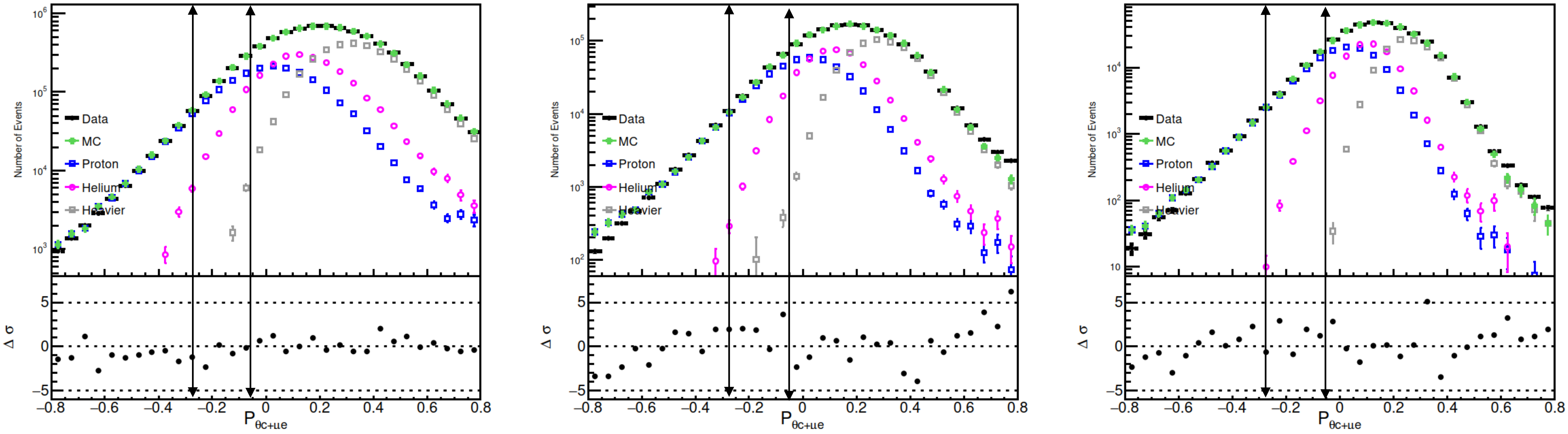
$$P_{\theta c+\mu e} = -\sin(\delta) \cdot P_{\theta c} + \cos(\delta) \cdot P_{\mu e} \quad (\delta = 8.5^\circ)$$

- Purity ($\epsilon^l = \frac{N^L_{select}}{N^L_{select}+N^H_{select}}$) : ~90% @ 1PeV
  - Most of the contaminations come from Helium
- Selection efficiency ($\eta^l = \frac{N^L_{select}}{N^L_{all}}$) : 25%.



Simulation vs. Data

- EPOS-LHC: P-distributions for species
- Normalizing the proton distribution below -0.3
- Assuming p/He ratio following GSF model, normalizing the distribution below -0.05
- Matching the heavier species at large values: bin by bin, agree with each other in **±2σ**

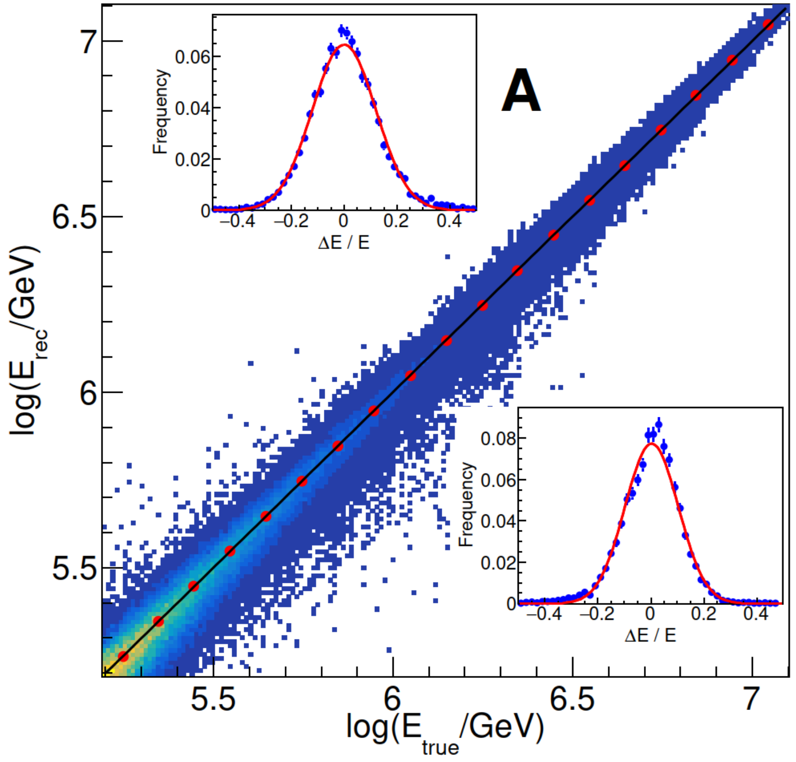


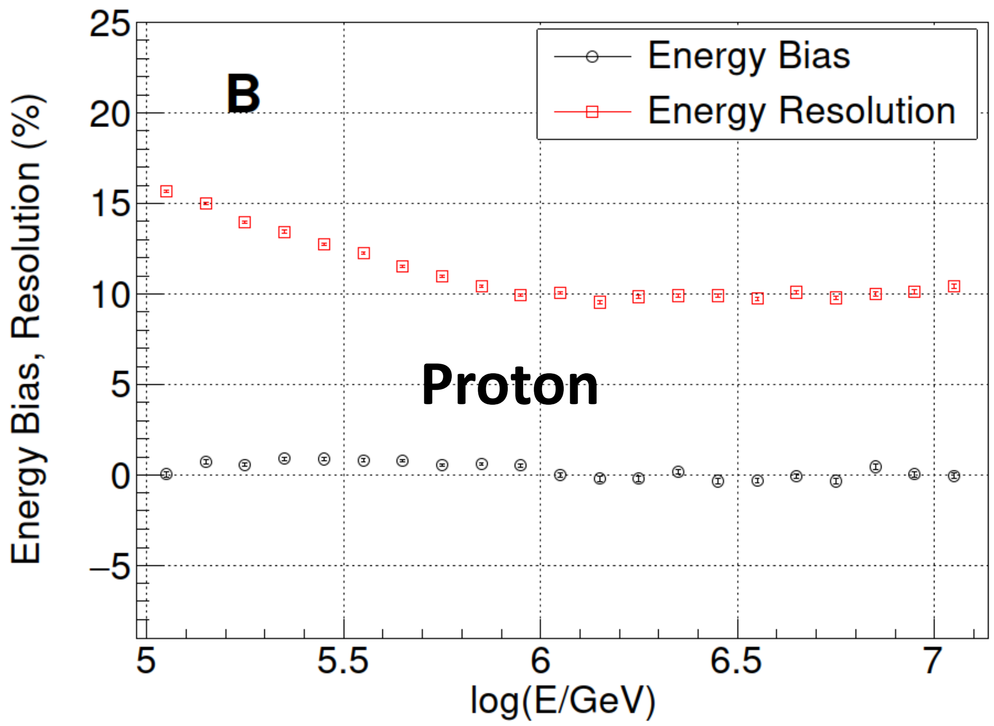
Energy Reconstruction

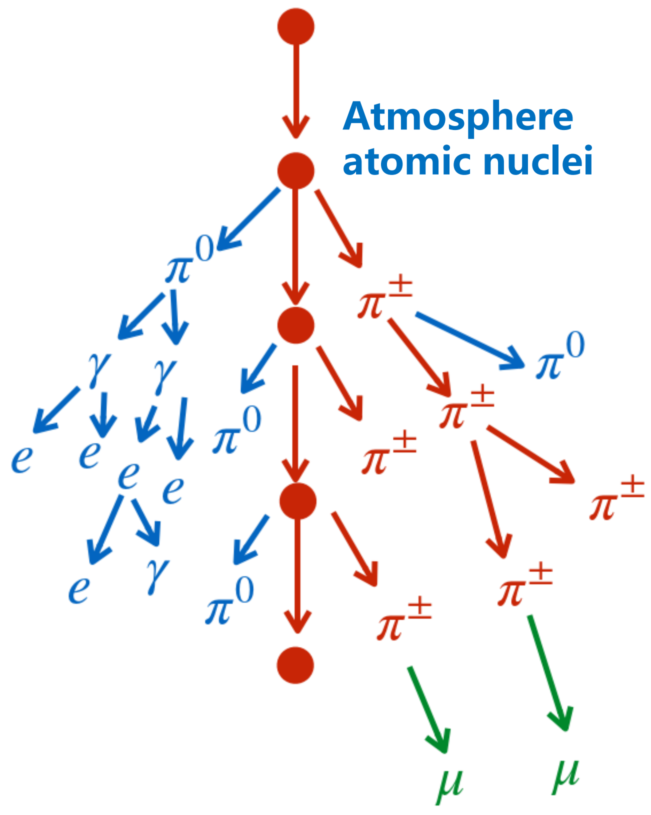
- **Shower energy: $E_0 \sim E_{em} + E_h$**
  - Electromagnetic component (E_{em}): Cherenkov photons (N_{ph}) or electrons + gamma rays (N_e)
  - *Hadronic component*(E_h): $\pi^{\pm} \rightarrow \mu$ （N_μ）

$$N_{c\mu} = N_{ph} + CN_{\mu}$$
$$E_{rec} = kN_{c\mu}$$

- Energy Resolution： <15%
- Systematic Bias： <2%

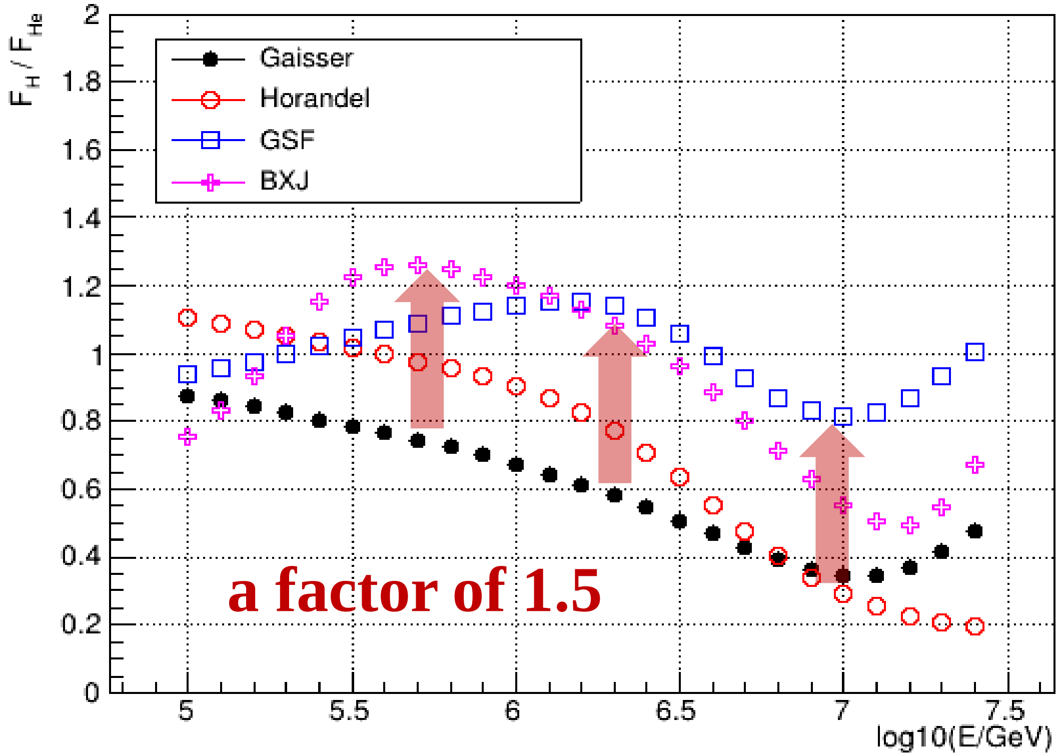




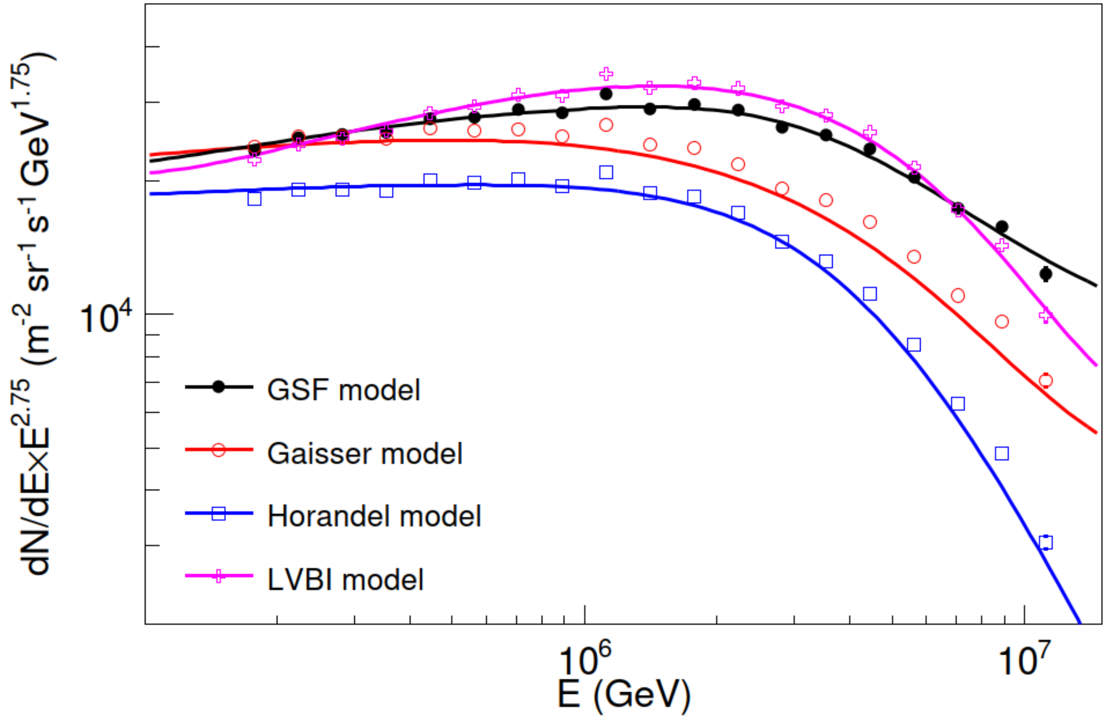


Contamination from Helium Nuclei

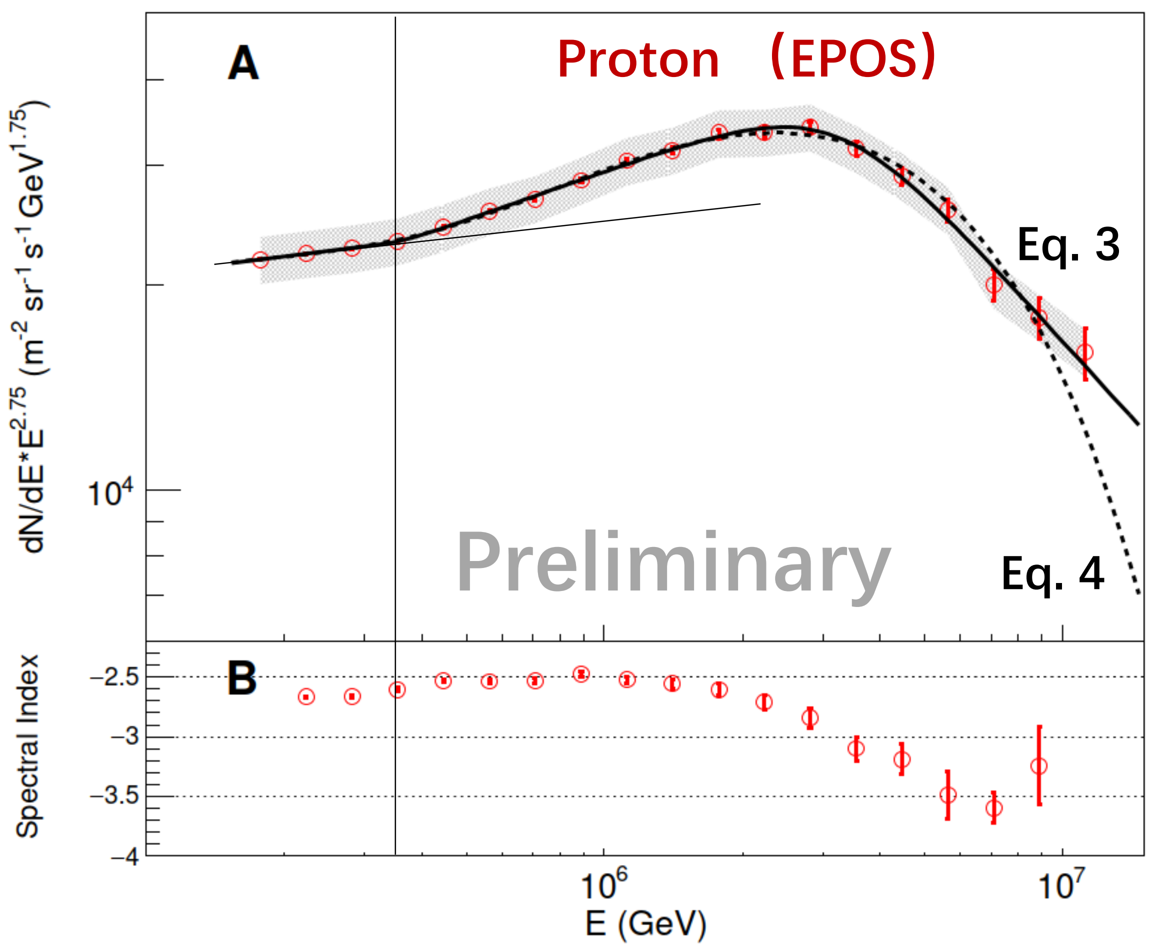
Ratio of proton vs Helium nuclei in composition assumptions



Re-produced pure-proton spectra under 4 assumption of composition mixtures



- **The discrepancies between the expected spectra and reconstructed results of different component models: 3-5% for energies below 1 PeV, about 7% for 3 PeV and ~15% for 10 PeV.**



Eq. 3: $F(E) = F_0 \left(\frac{E}{100TeV}\right)^{\gamma_1} \left(1 + \left(\frac{E}{E_h}\right)^{1/w_1}\right)^{(\gamma_2-\gamma_1)w_1} \left(1 + \left(\frac{E}{E_k}\right)^{1/w_2}\right)^{(\gamma_3-\gamma_2)w_2}$

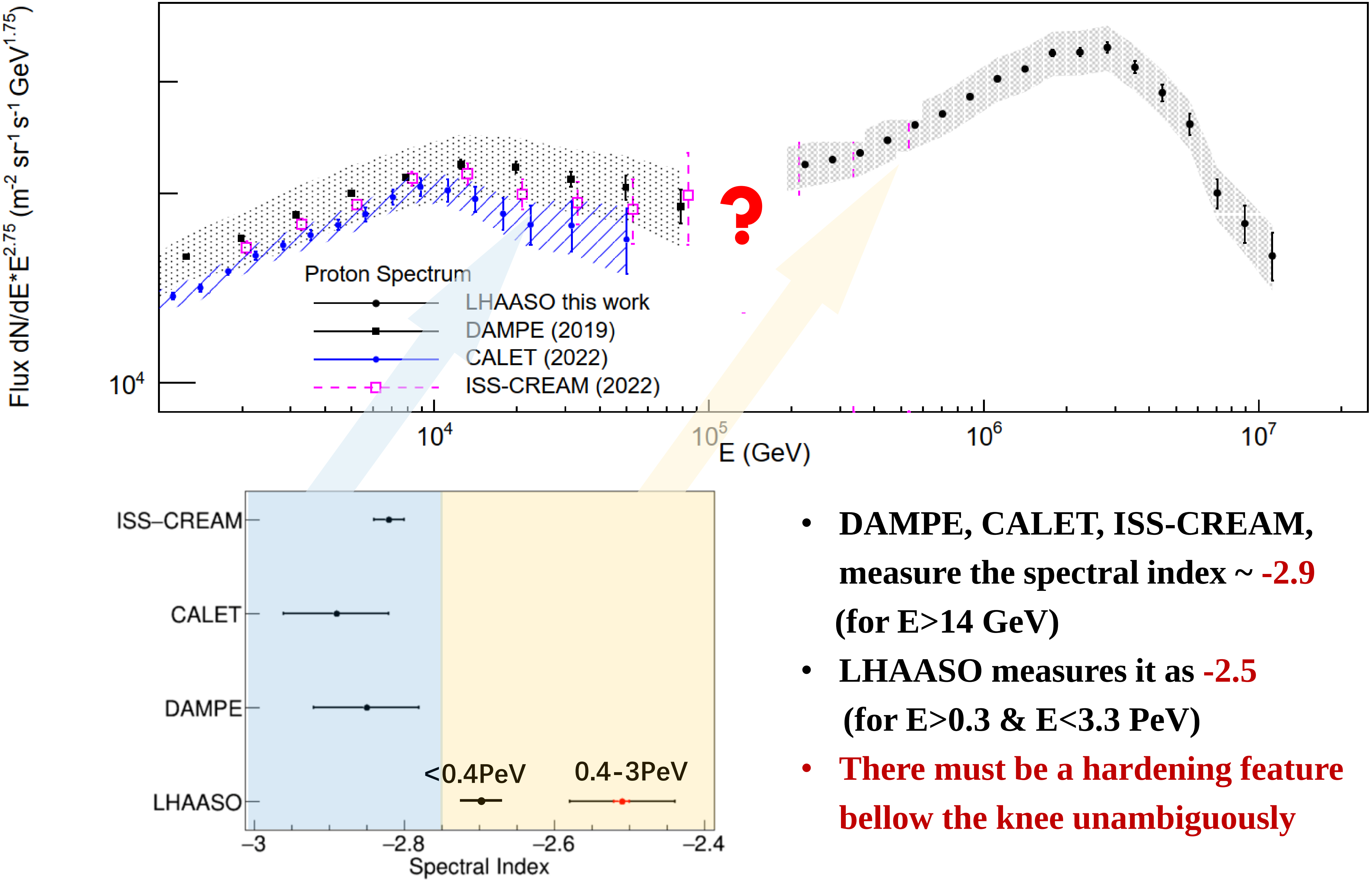
Eq. 4: $F(E) = F_0 \left(\frac{E}{100TeV}\right)^{\gamma_1} \left(1 + \left(\frac{E}{E_h}\right)^{1/w}\right)^{(\gamma_2-\gamma_1)w} e^{-\frac{E}{E_{cut}}}$

- Eq. 3: Three broken power laws

  $E_h = 365 \pm 20$
  $E_k = 3.2 \pm 0.3$
  $\gamma 1 = -2.67 \pm 0.01$
  $\gamma 2 = -2.51 \pm 0.02$
  $\gamma 3 = -3.5 \pm 0.1$
  $\chi^2/n.d.f. = 9.9/11$

- Eq. 4: Two broken power law + an exponential cutoff

  $E_h = 436 \pm 22$
  $E_{cut} = 5.1 \pm 0.3$
  $\gamma 1 = -2.66 \pm 0.02$
  $\gamma 2 = -2.29 \pm 0.05$
  $\chi^2/n.d.f. = 27.1/13$



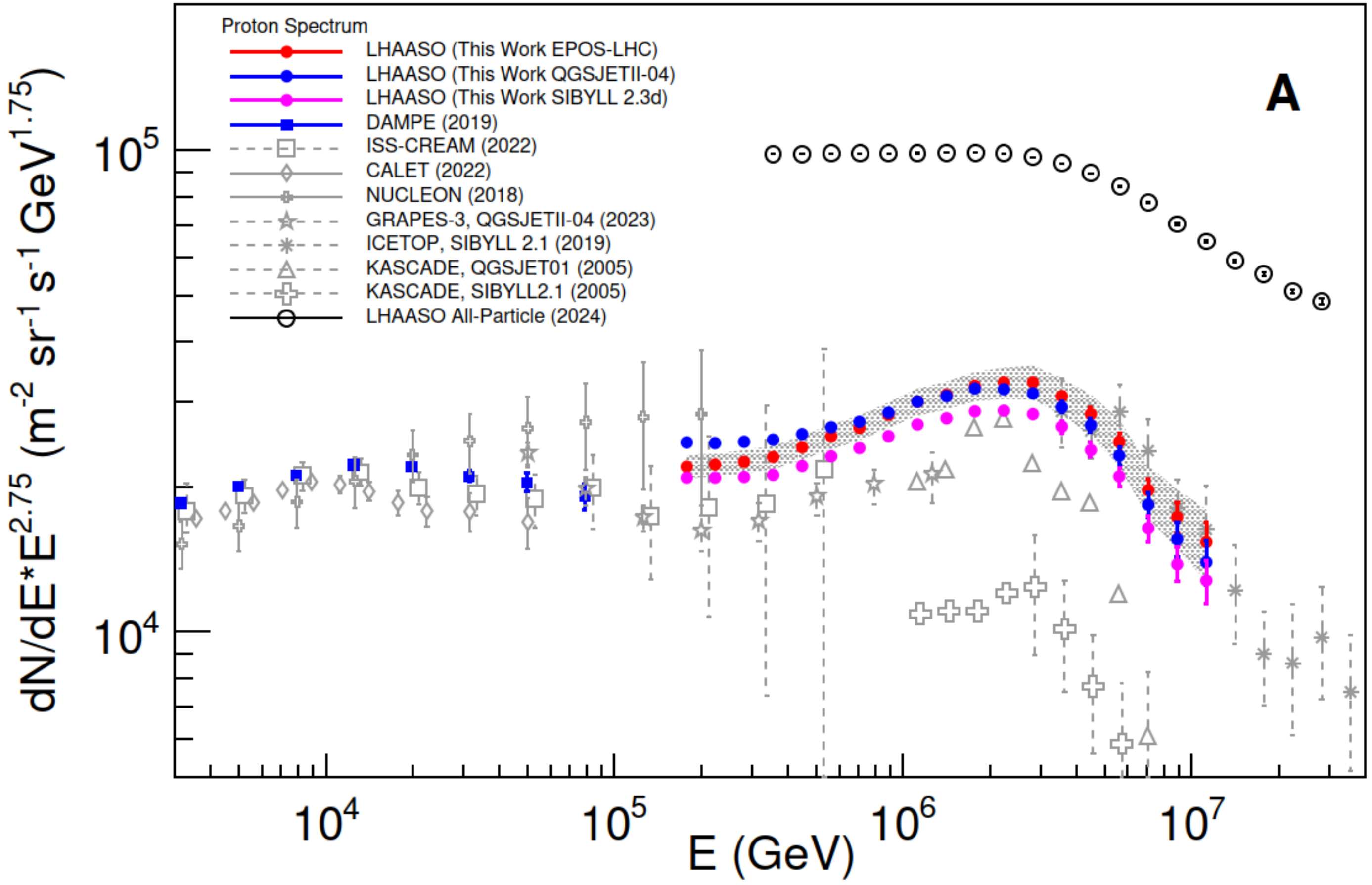
- **DAMPE, CALET, ISS-CREAM, measure the spectral index ~ -2.9 (for E>14 GeV)**
- **LHAASO measures it as -2.5 (for E>0.3 & E<3.3 PeV)**
- **There must be a hardening feature bellow the knee unambiguously**

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%

Proton energy spectrum measured by LHAASO in the knee region



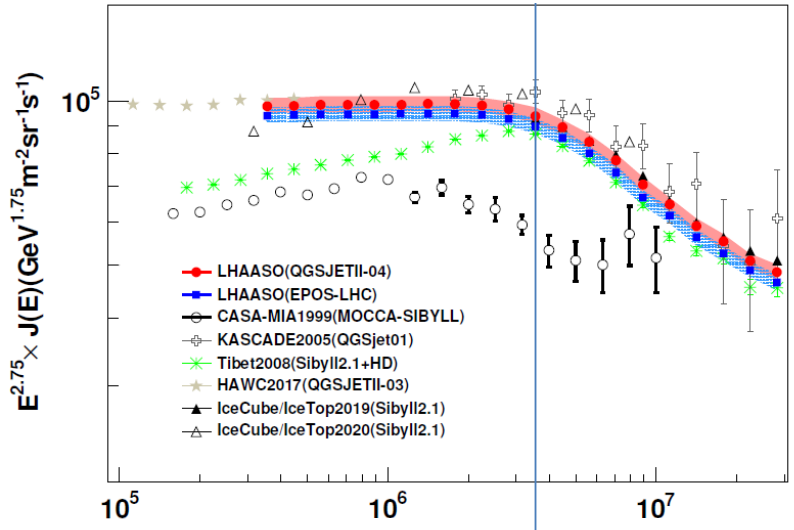
LHAASO Coll., arXiv:2505.14447

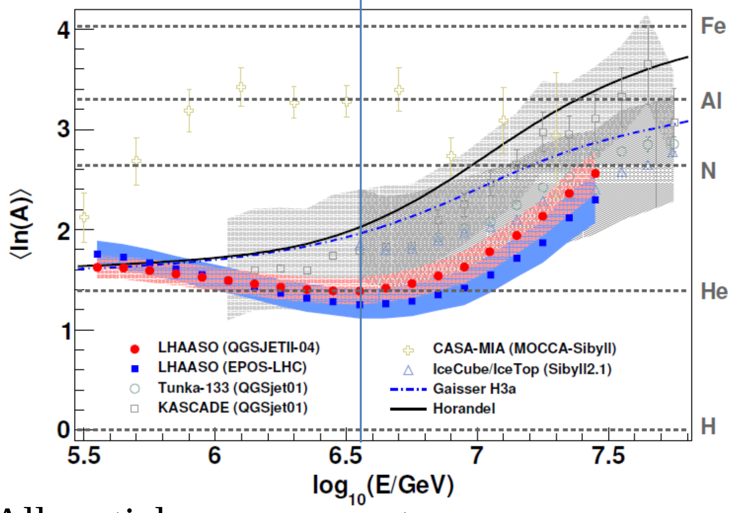
- CR protons around the knee have been identified from 0.15 to 12 PeV by LHAASO.
  - LHAASO purity: ~90%, above 100TeV
  - Direct measurement (e.g. DAMPE) purity: 99% - 95%, below 100TeV
  - KASCADE and ICETOP: Unfolding method, no purity provided.
- **Hardening:** >300 TeV, with index change $\Delta\gamma$=~0.4 respect to the space-borne measurement
- **Softening (knee):** ~3.3 PeV, with index change $\Delta\gamma = -1$

Compatible precision with the space borne direct measurement !

Proton knee vs. all particle knee

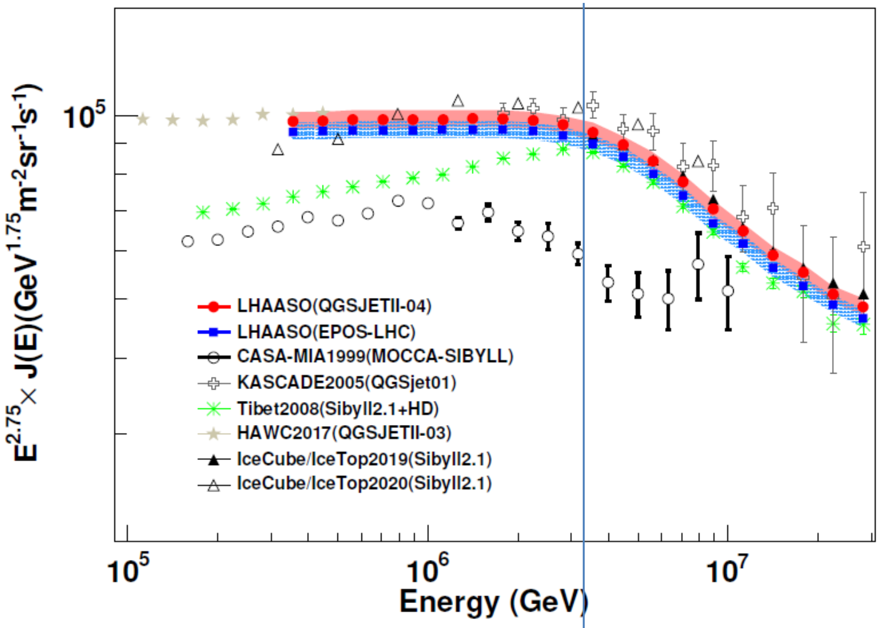
LHAASO Collaboration, PRL, 132, 131002 (2024)



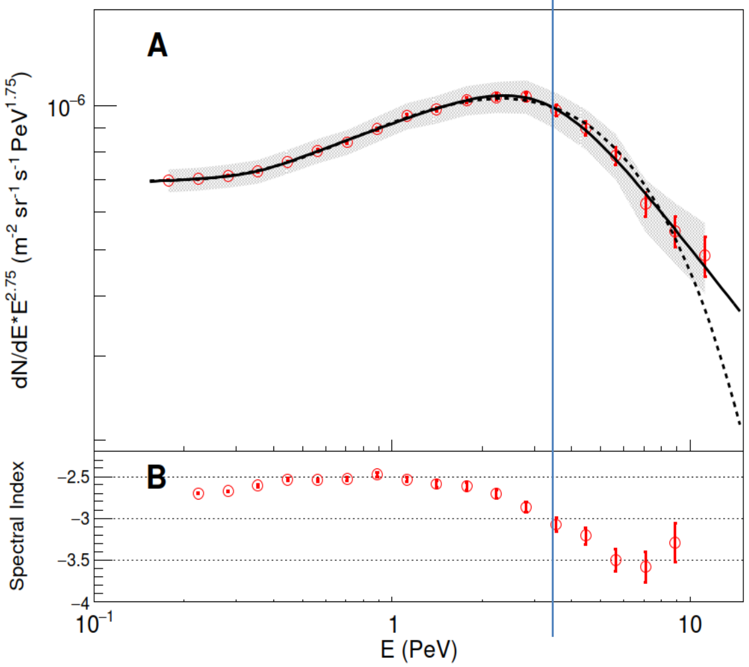


All particle energy spectrum: see Hengying Zhang talk for more details.

Knee: ~3.67 PeV
γ1 = -2.74±0.005
γ2 = -3.13±0.005

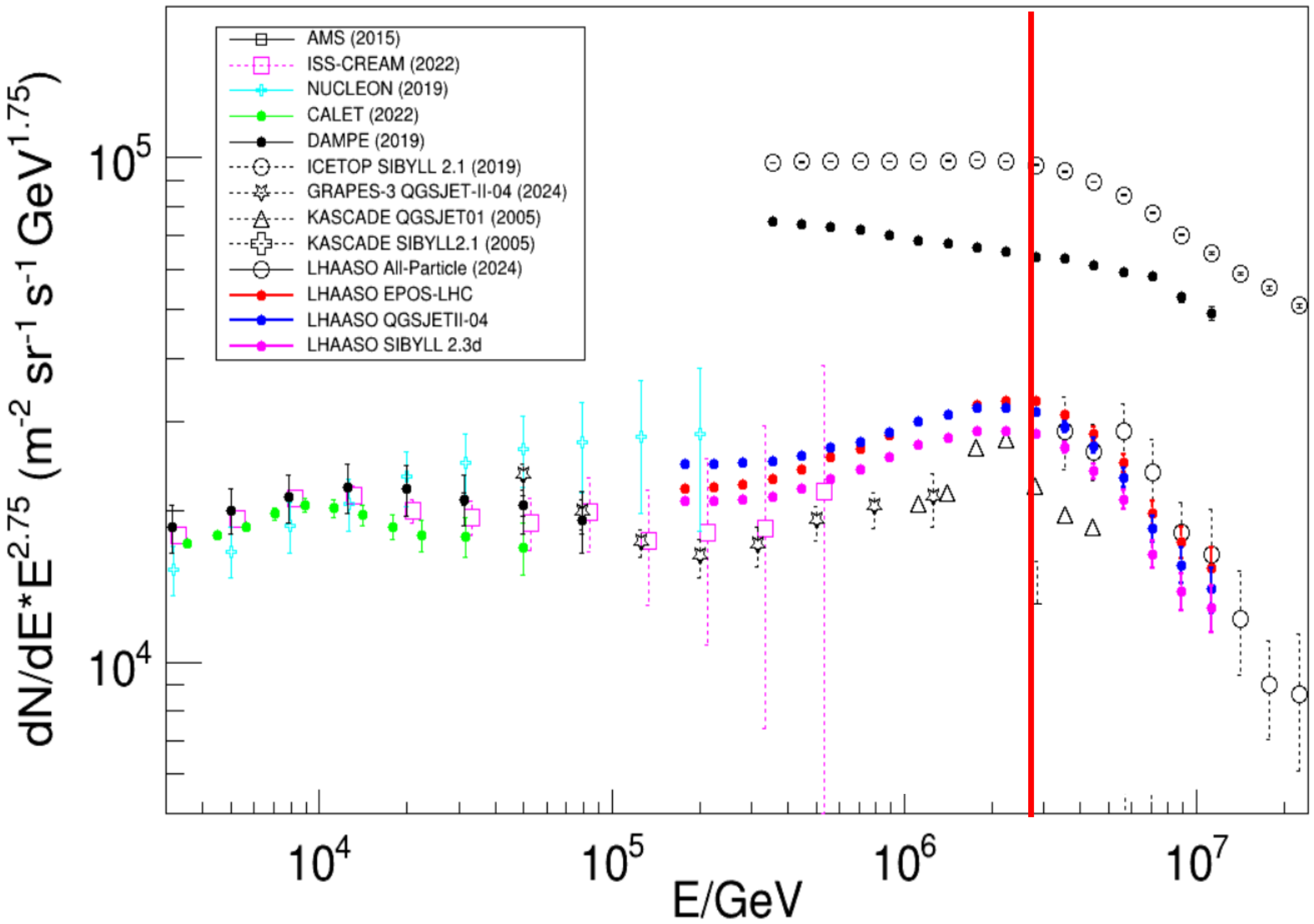


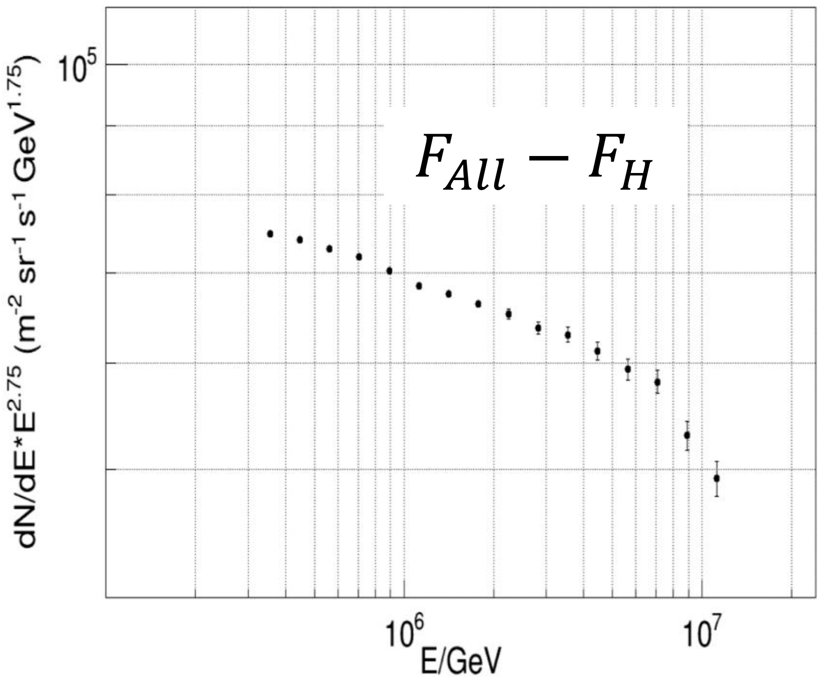
Knee: ~3.3 PeV
γ1 = −2.71 ± 0.02
γ2 = −2.51 ± 0.03
γ3 = −3.5 ± 0.2



The all-particle knee is likely dominated by the proton knee

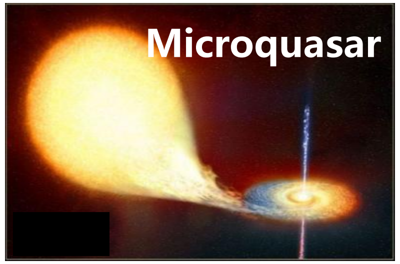
- Protons dominating the Knee over other species

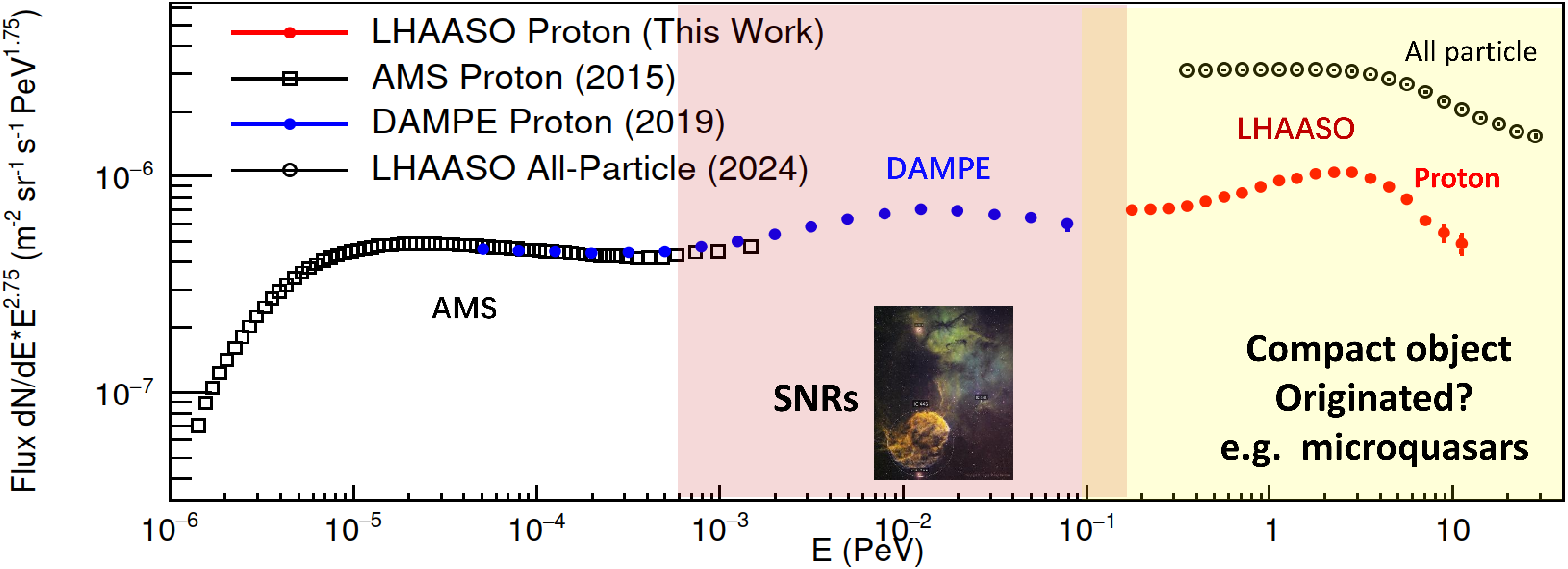




Wideband spectrum of protons

- A potential explanation could be the existence of multiple groups of cosmic ray sources with varying acceleration limits, as indicated by their maximal cosmic ray energies.

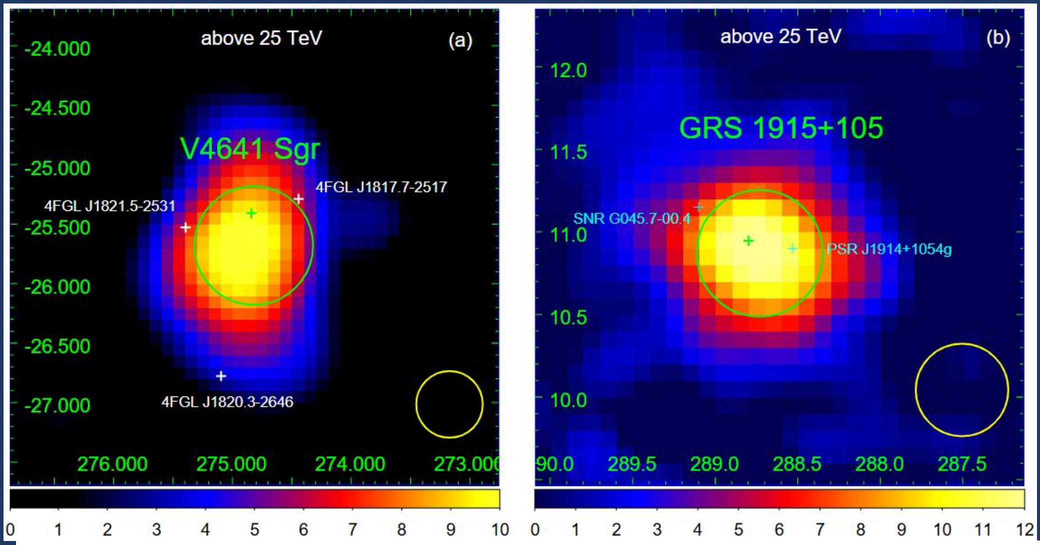


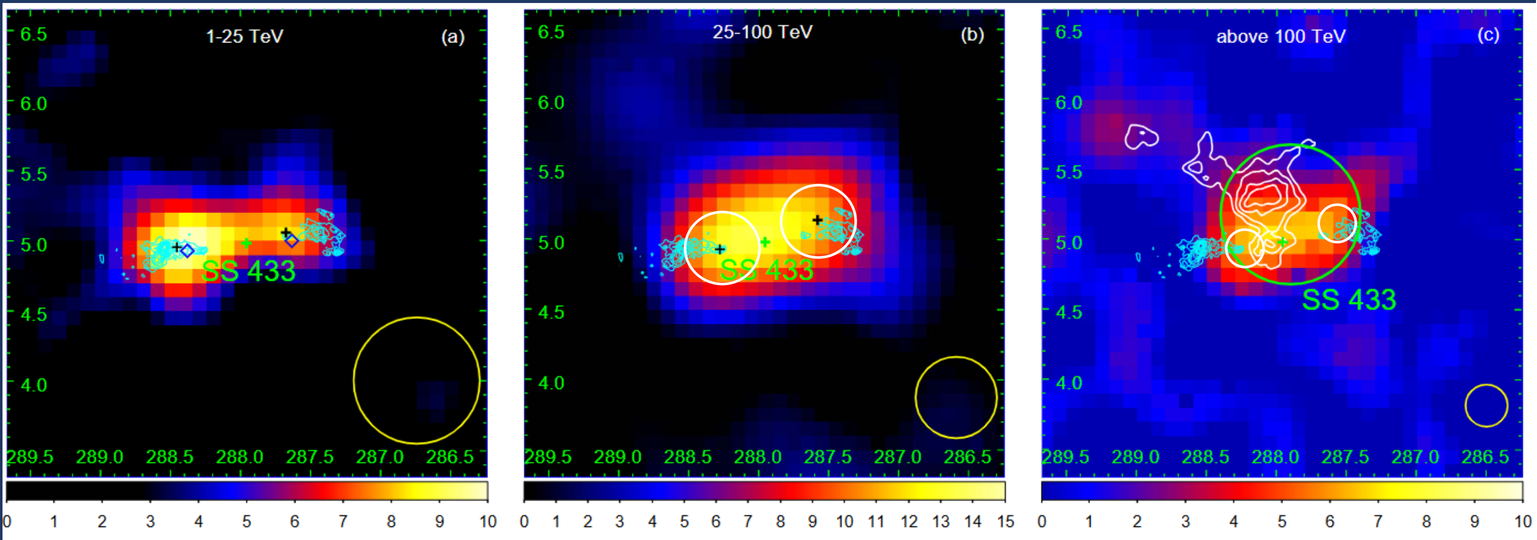


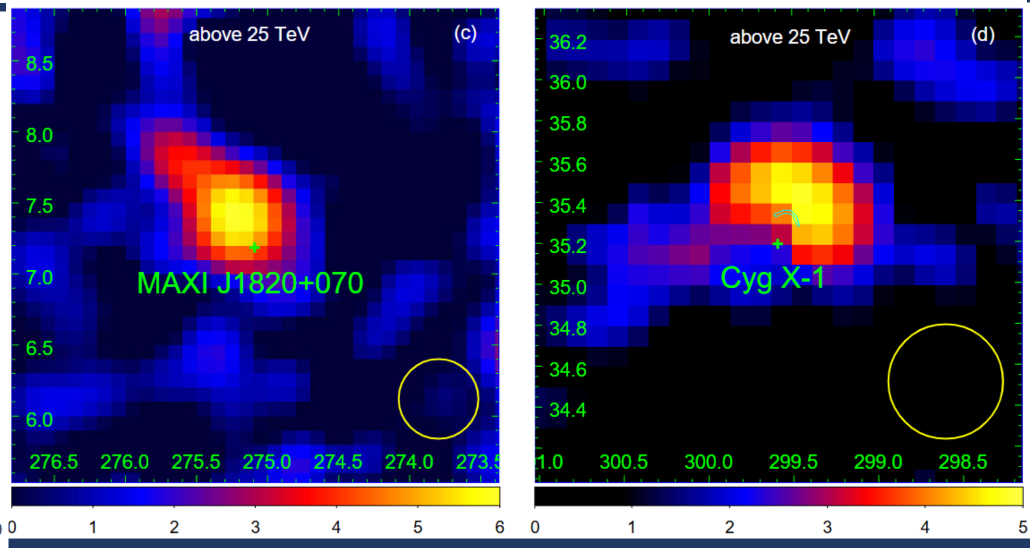
LHAASO Coll., arXiv:2505.14447

Black Holes and Jets: μQs

- Very important !!
- New CR source population particularly at energy E >3 PeV

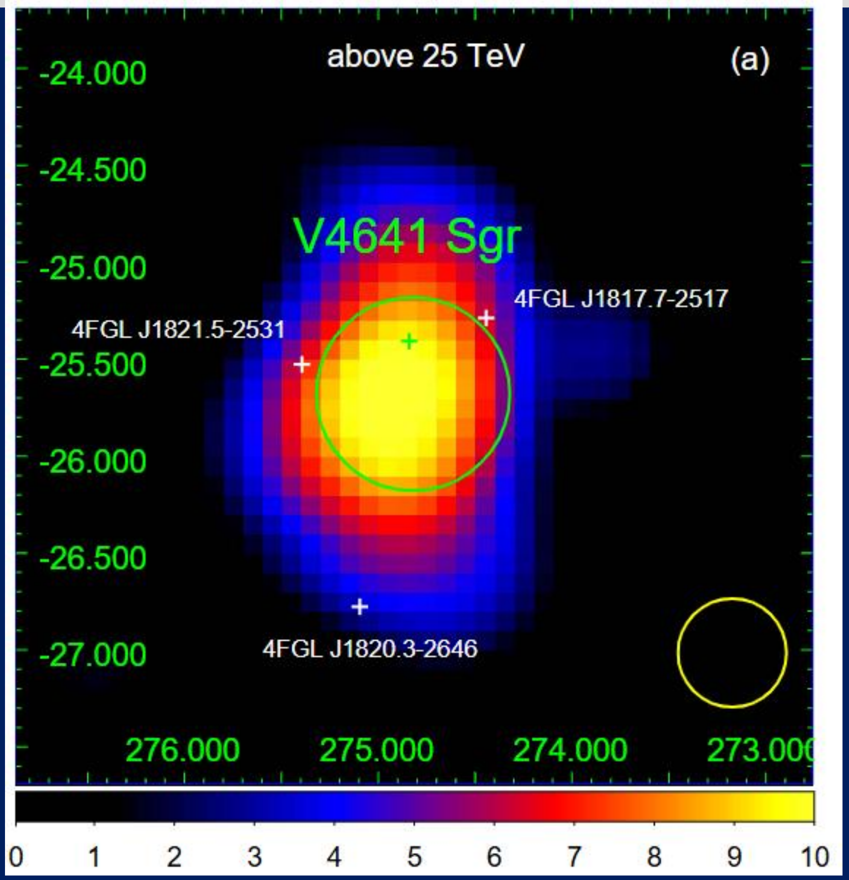


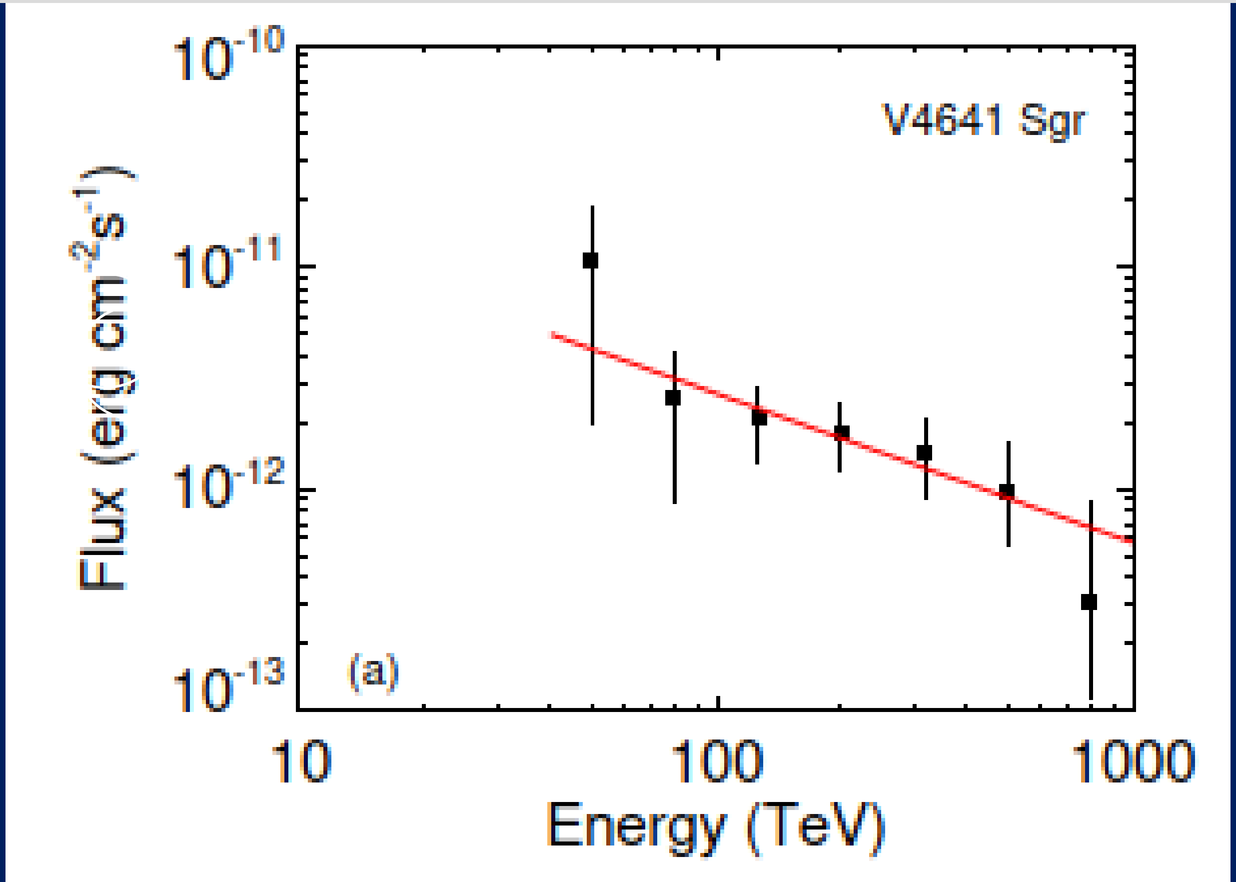


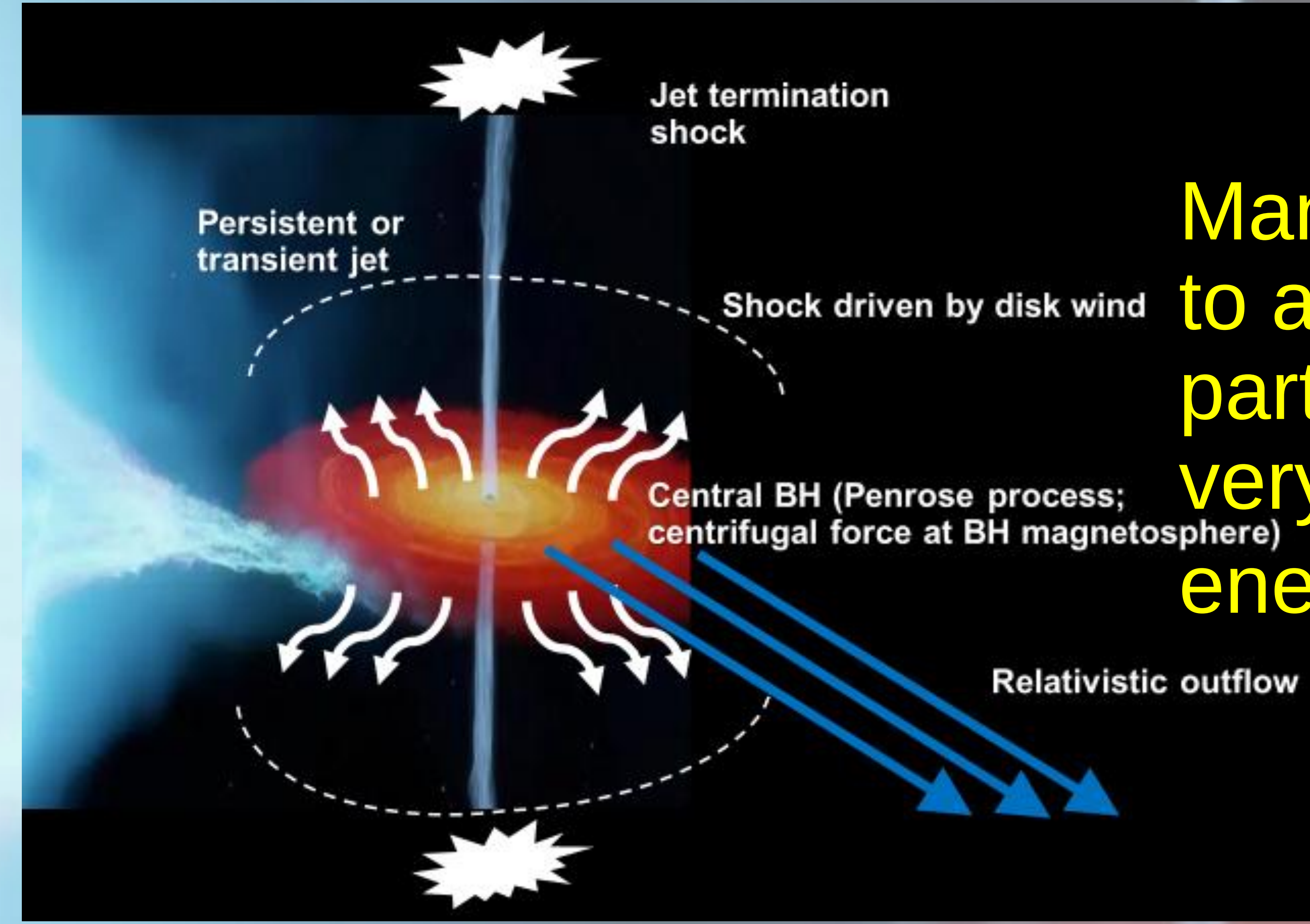


Black Hole as a super-PeVatron?

Very difficult to detect: not only due to the distant: ~20,000 light-year !
But also out of main field of view of LHAASO: a source in southern hemisphere
Powerful accelerator generating particle at E >10 PeV !!





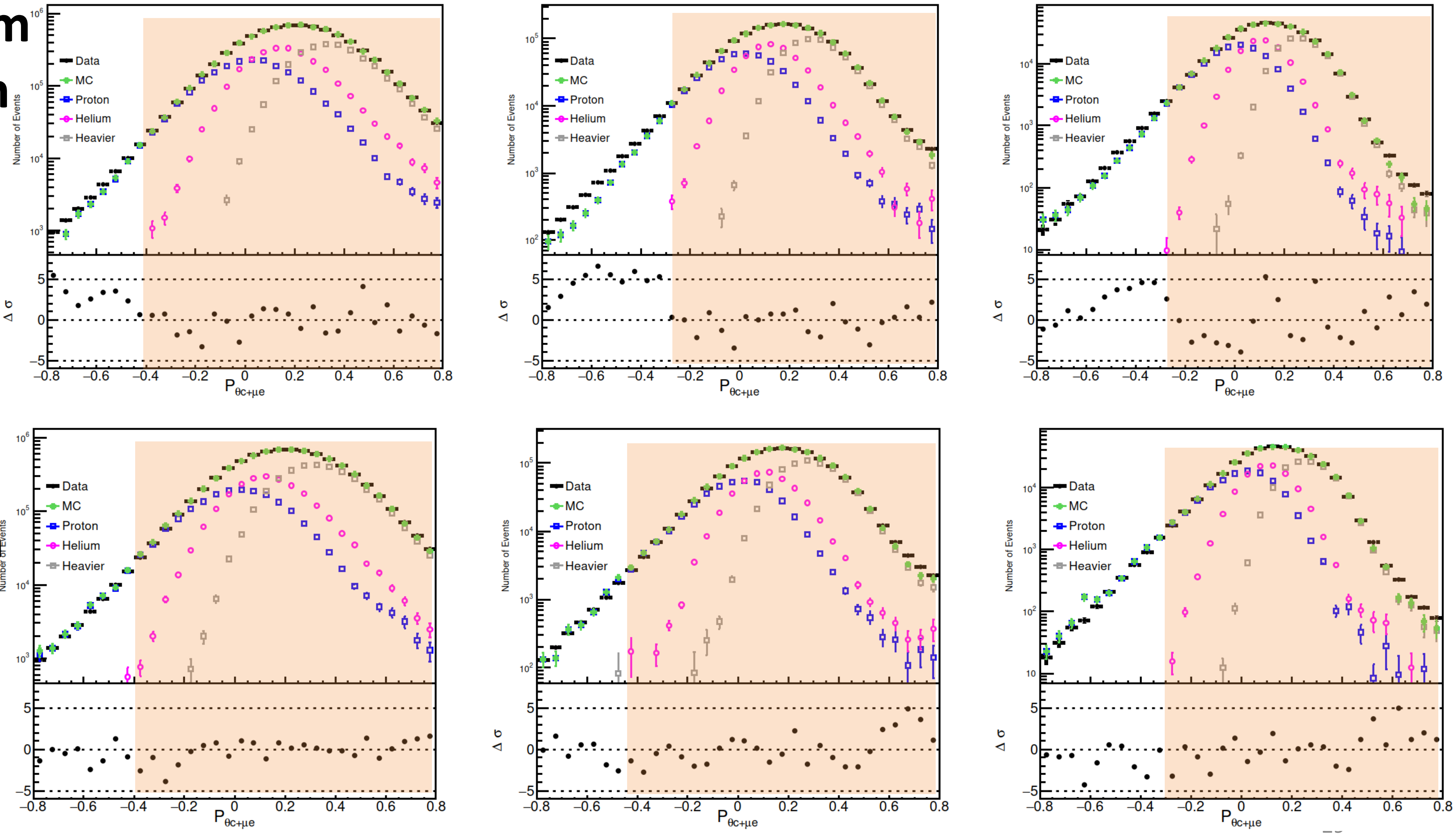


Many ways to accelerate particles to very high energy

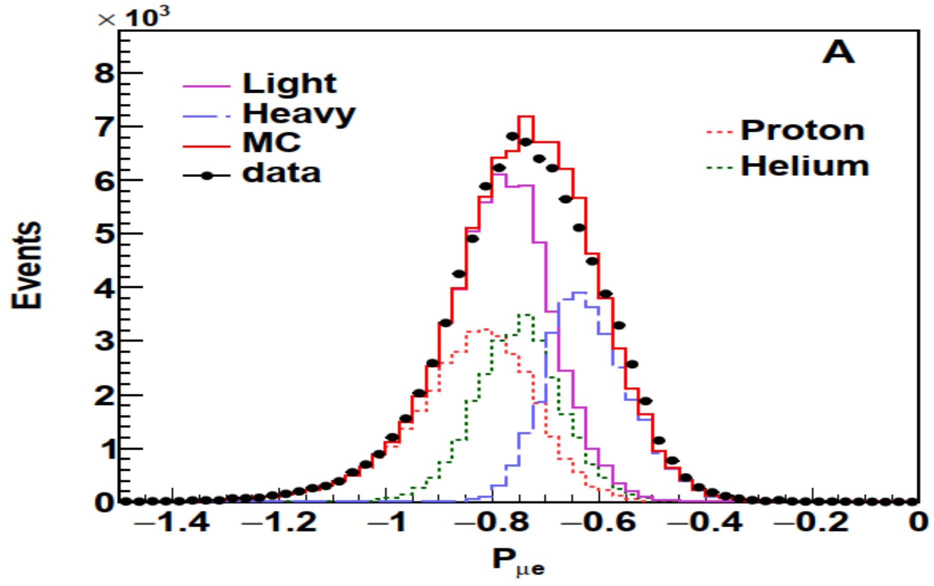
Testing on Hadronic Interaction Models

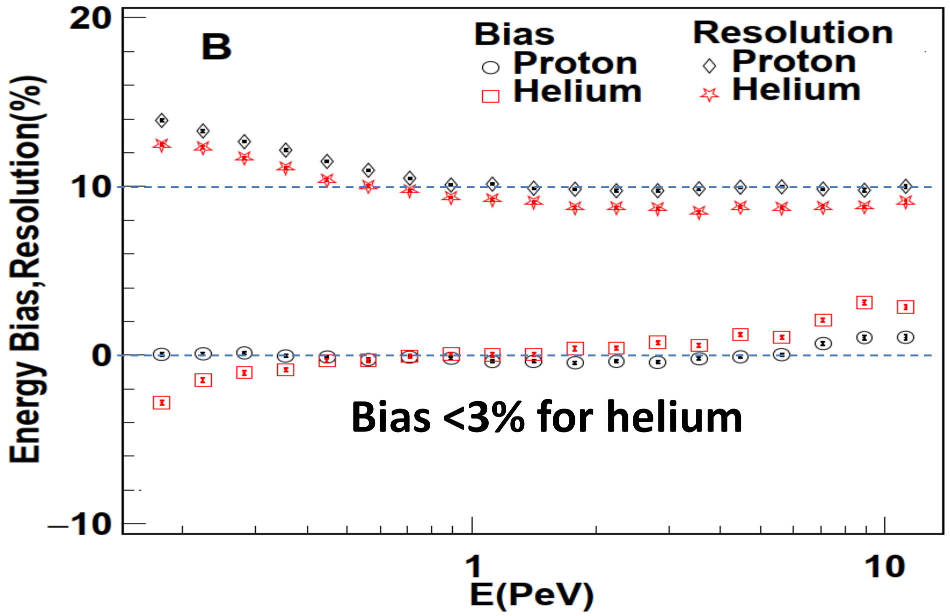
Disentangle from the composition assumption

- ➢ **QGSJet seems systematically shifted over 5σ**
- ➢ **SIBYLL is good in ±2σ**



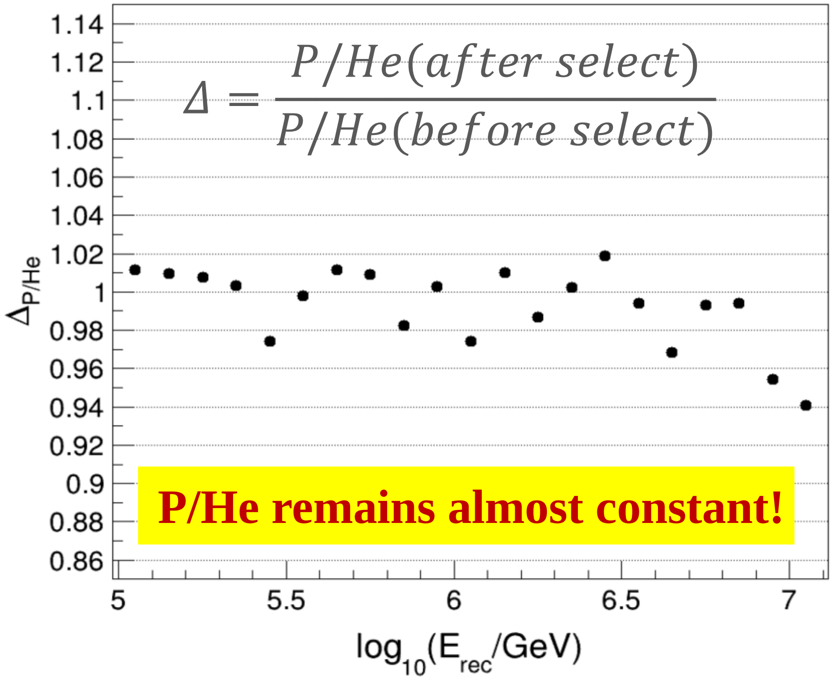
Light component (H+He) Selection

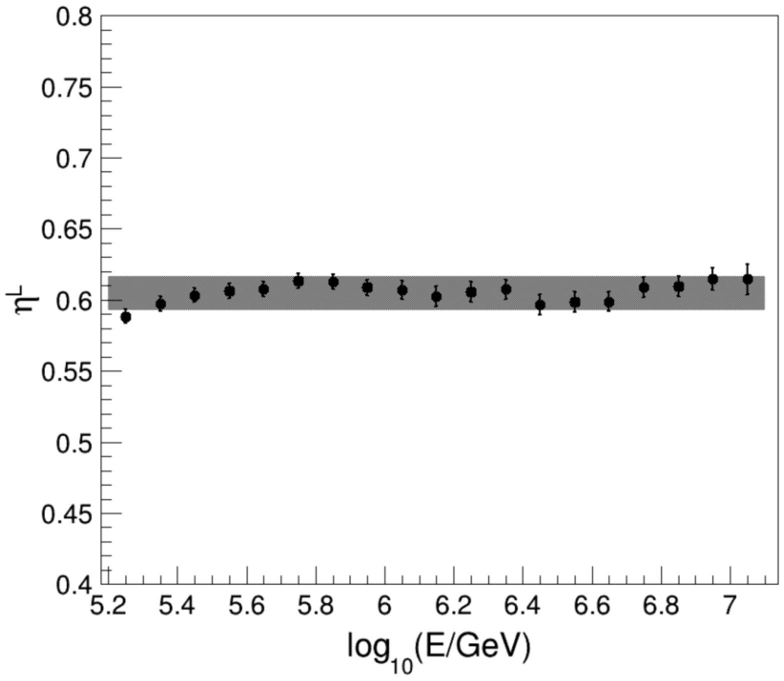


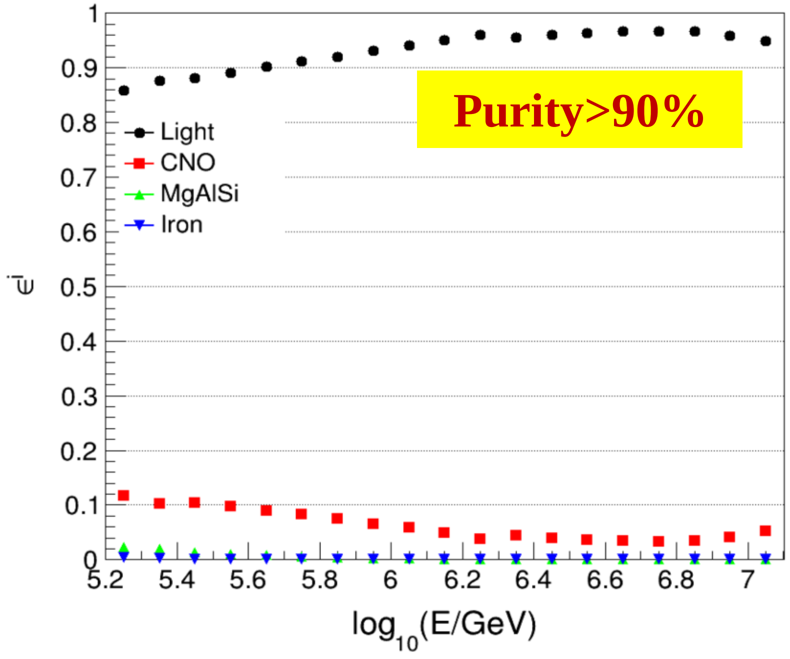


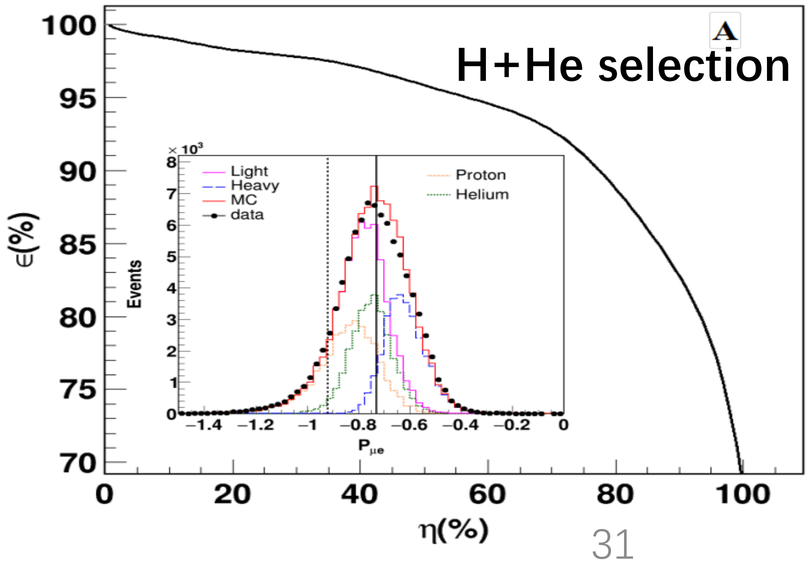
- Helium showers are very similar with proton showers
- it is impossible to separate helium from all other particles event by event
- Methodology:
  - Helium spectrum = $F_{P+He} - F_{proton}$
  - The same dataset and the same energy reconstruction as used in the proton energy spectrum
- High efficiency in selection for light showers

Light component (H+He) Selection









- Dual cutting is applied to keep the same ratio of Proton and Helium before and after the composition selection;
- Purity ($\epsilon^l = \frac{N^L_{select}}{N^L_{select}+N^H_{select}}$) : ~90% @ 1PeV,
  Most of the contaminations come from CNO
- Selection efficiency ($\eta^l = \frac{N^L_{select}}{N^L_{all}}$) : 60%.

Conclusion

- LHAASO measures showers at 4410m above sea level
- Multi shower parameters are well measured with a full containing both longitudinally and laterally
- Enable separation of proton showers from other species event by event, with a purity of ~90%
- Hardening and Knee features is revealed with sufficiently small uncertainties
- The knee is dominated by protons
- Three components in the wideband proton spectrum indicate different source population groups
- Stay tuned, the Helium spectrum coming soon ……