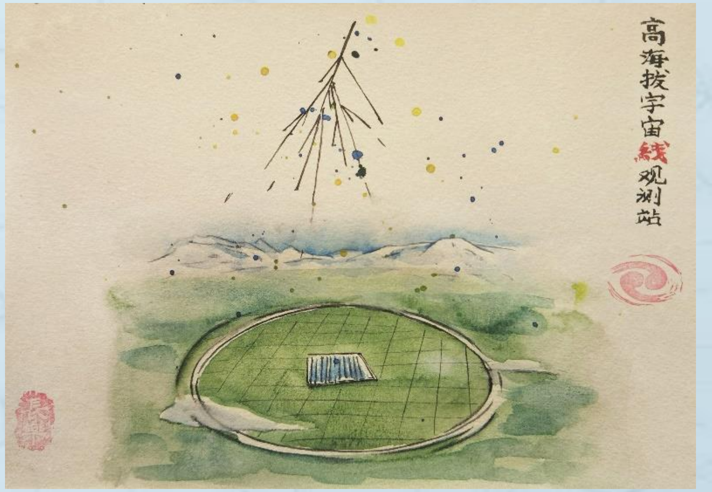
LHAASO
高海拔宇宙线观测站



LHAASO on Cosmic Ray Knees

Zhen Cao, IHEP
On behalf of LHAASO Collaboration

UHECR-2022, GSSI, L'Aquila, Italy, Oct. 2022

Outline

- LHAASO experiment
- Calibration
- CR spectrum measurements
- Summary

LHAASO Collaboration

275 members from
31 institutions in
5 countries

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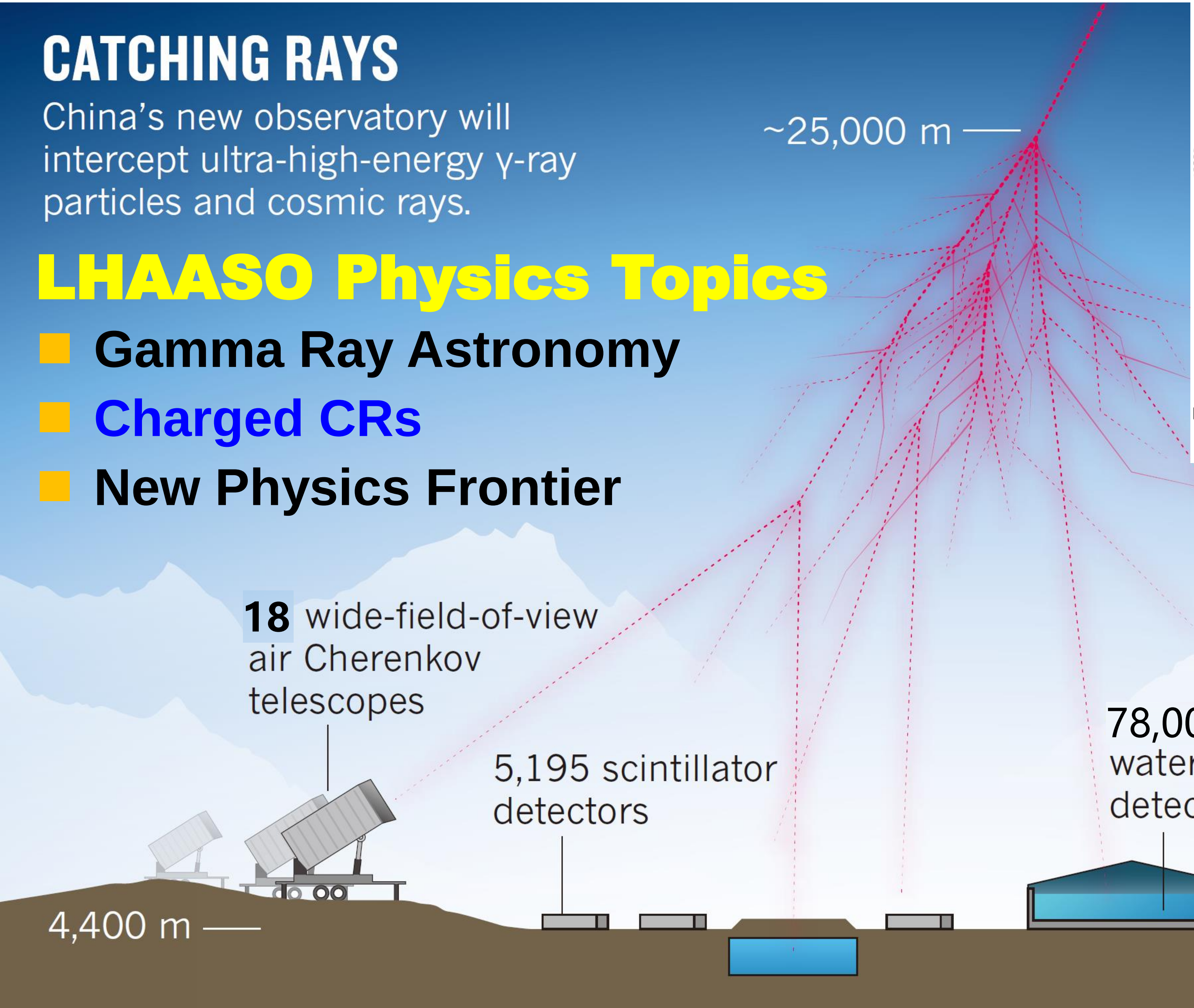
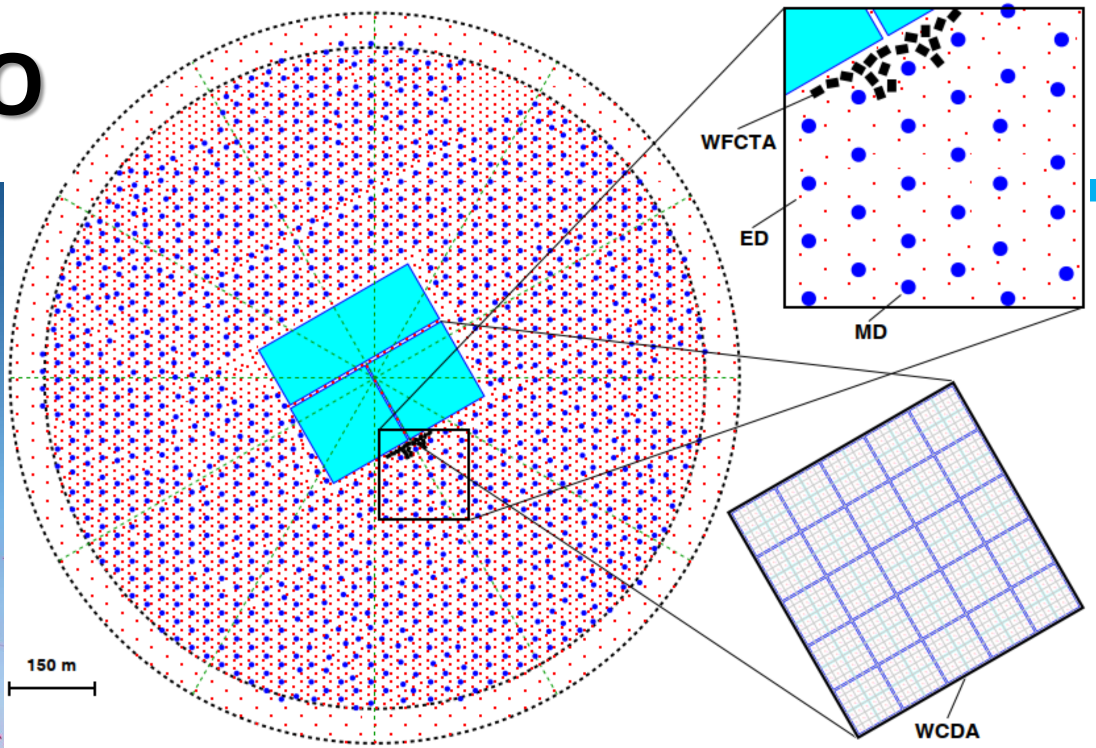
(LHAASO Collaboration)[*]

Hybrid Detection of EASs by LHAASO

LHAASO Physics Topics

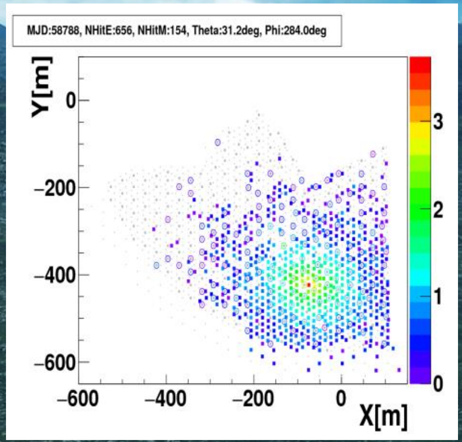
- Gamma Ray Astronomy
- Charged CRs
- New Physics Frontier





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



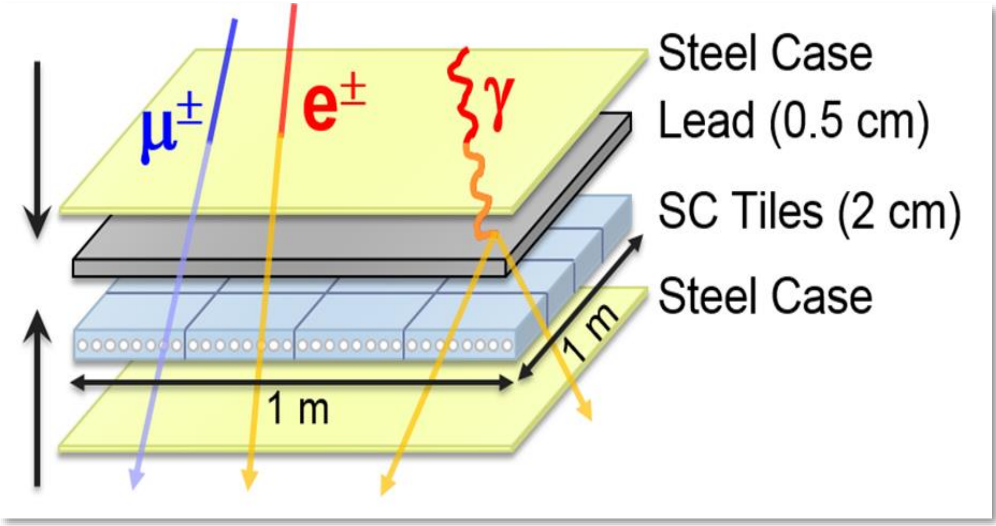
KM2A: 1.36 (km)^2

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

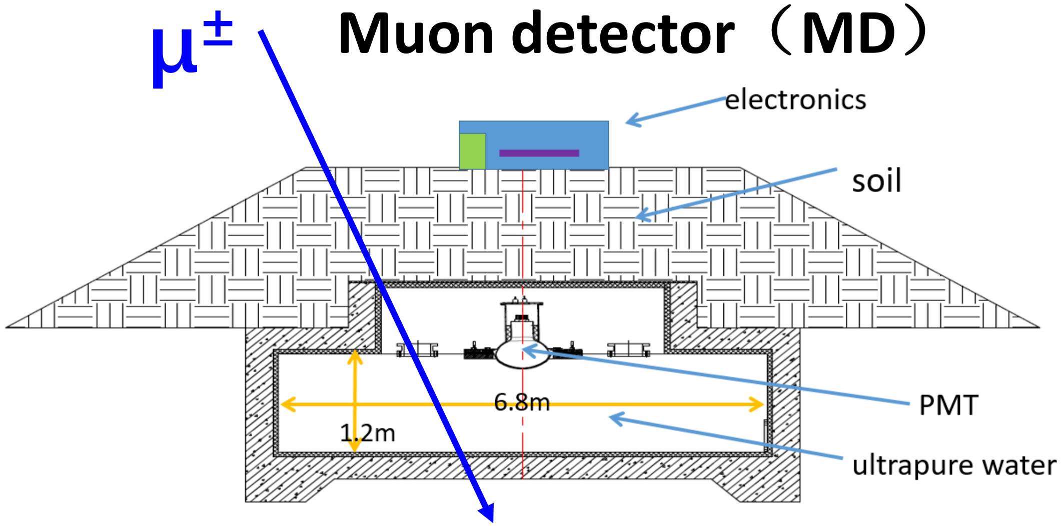
KM2A: 1.36 (km)^2

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

Scintillator Detectors （ED）

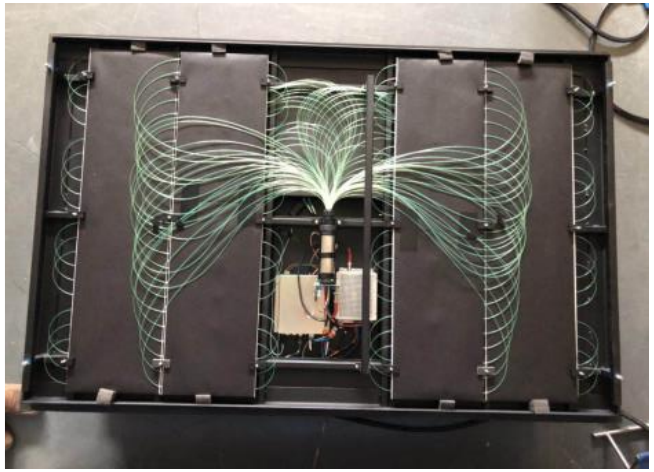


Muon detector（MD）

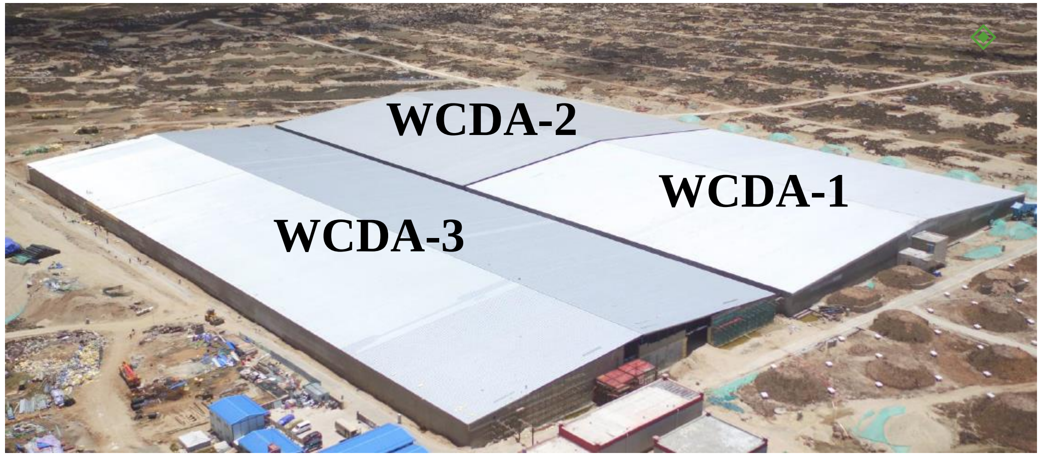


MD Bladder

Inner View of Scintillator Detector

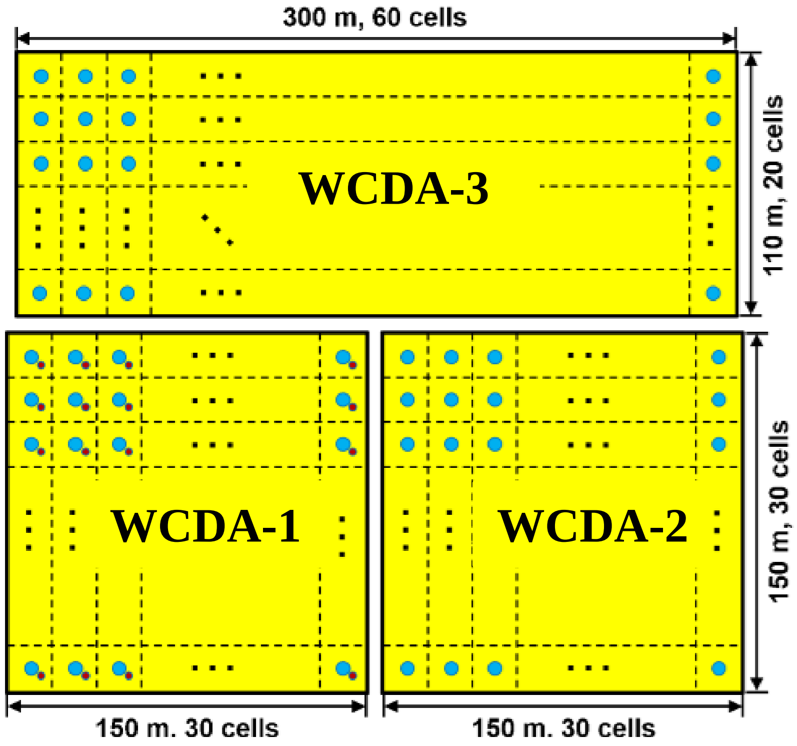


Water Cherenkov Detector Array (WCDA)

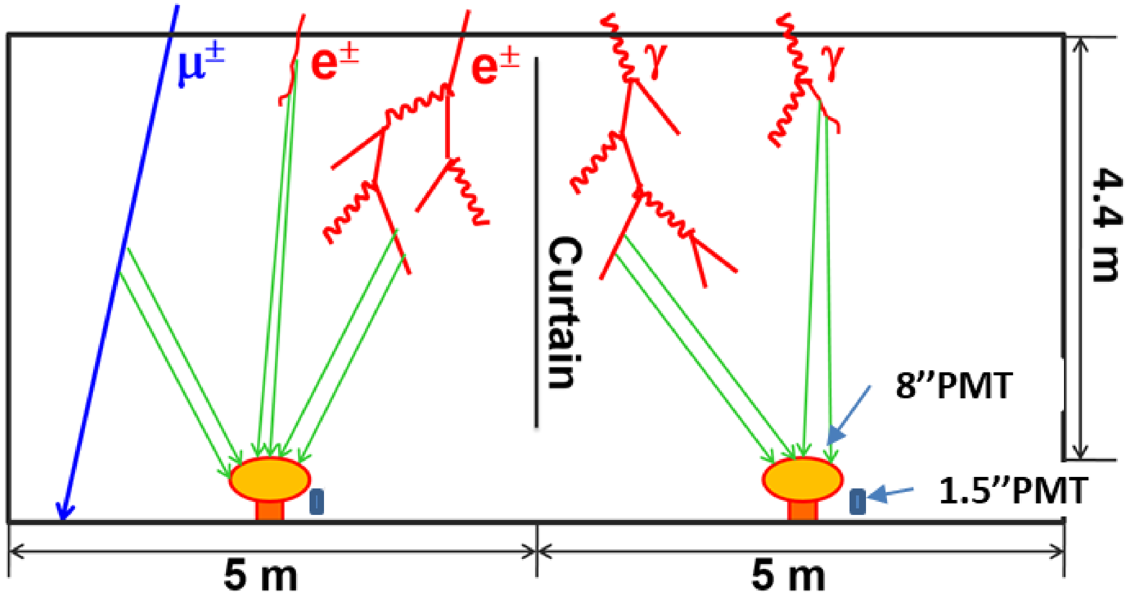


Energy rang

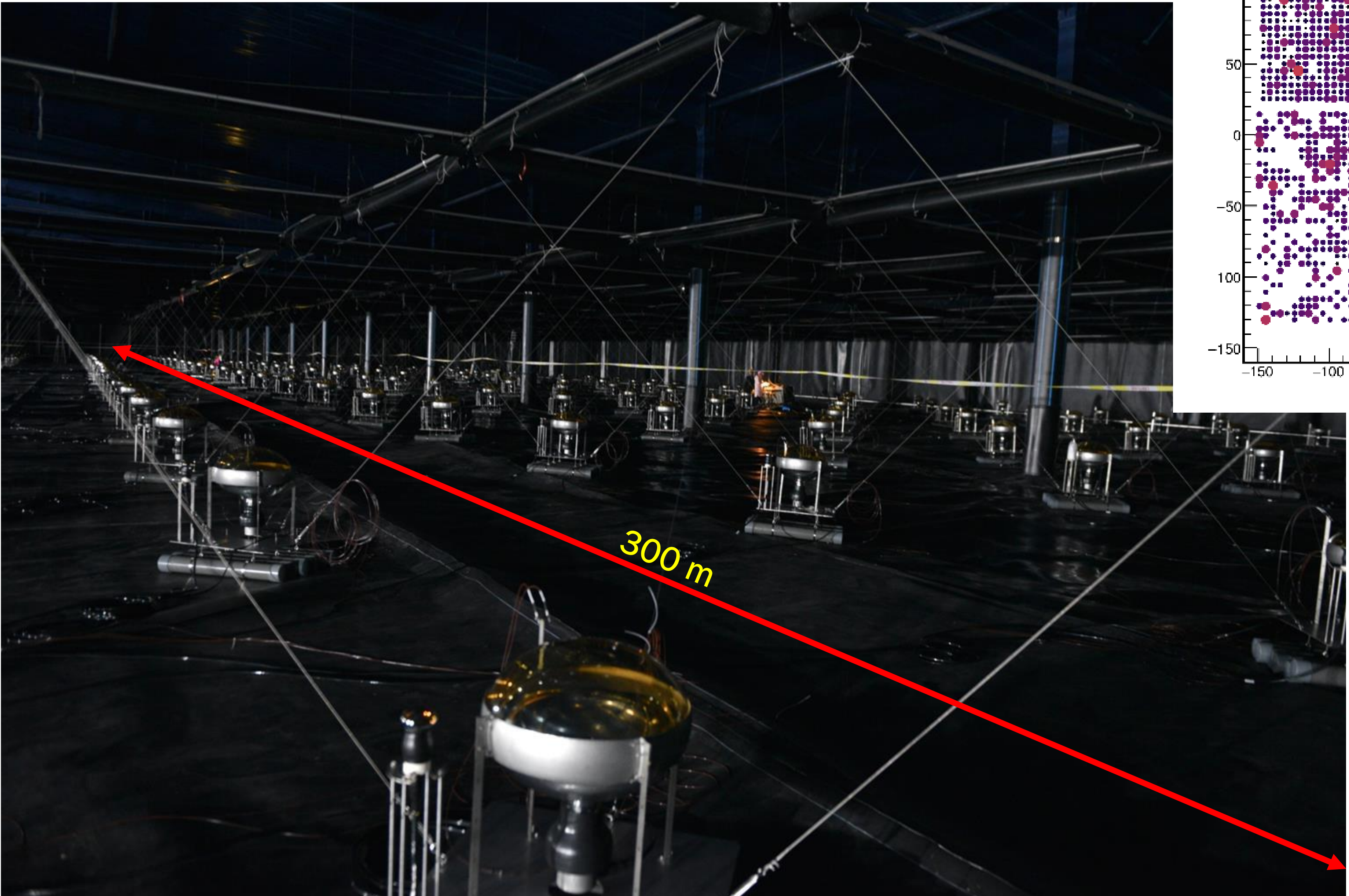
- WCDA-1
  - 0.3 – 10 PeV
- WCDA-2/3
  - 0.1 - 10 TeV

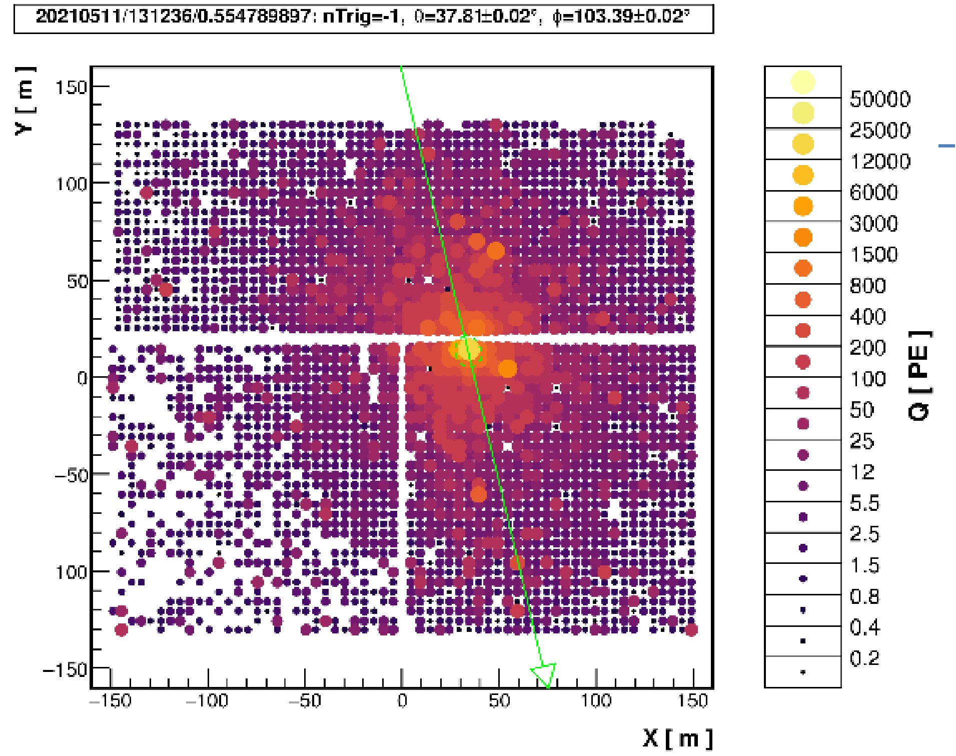


- Total area: $78,000m^2$
- Total units: 3,120
- Unit size: $5m \times 5m \times 4.4m$
- Two configurations:
  - 8” and 1.5” PMTs for WCDA-1 (900 ch)
  - 20” and 3” PMTs for WCDA-2/3 (2220 ch)



Inside of WCDA





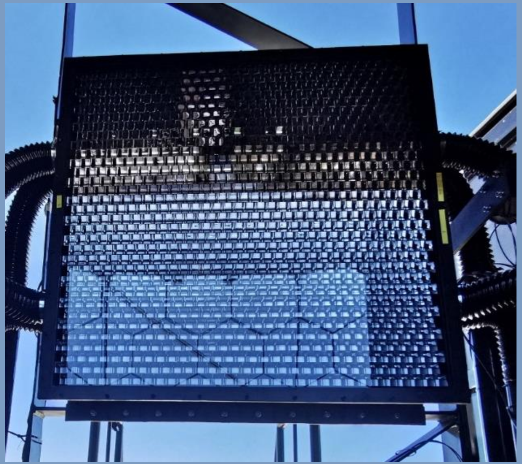
- WCDA-1 started operating on April 2019
- WCDA-2 started operating on January 2020
- WCDA-3 started operating on March 2021

Wide Field of View Cherenkov Telescope (WFCTA)

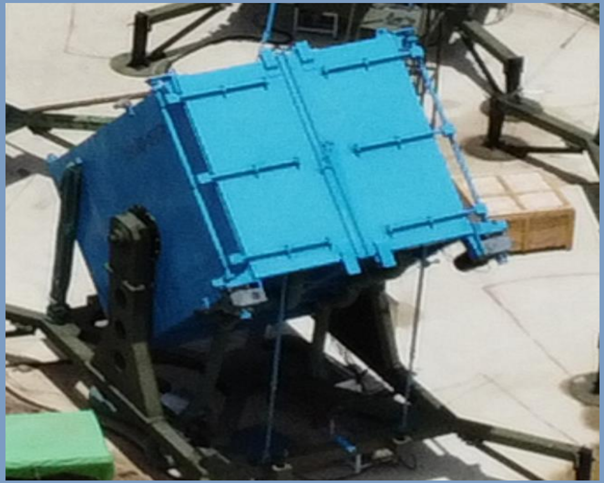
◆ Telescopes:

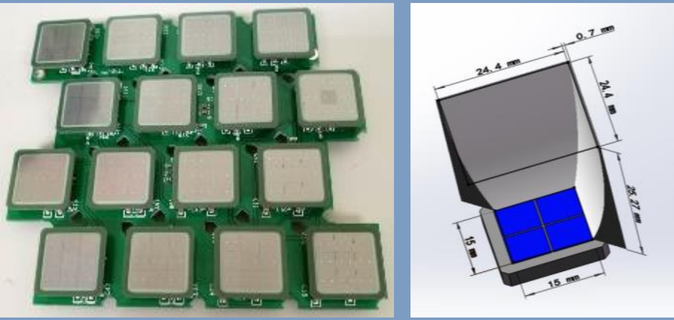
- ~5 m^2 spherical mirror
- Camera: 32×32 SiPMs array
- FOV: 16° × 16°
- Pixel size: 0.5°
- >30% duty cycle in winter

Mirror



SiPM camera

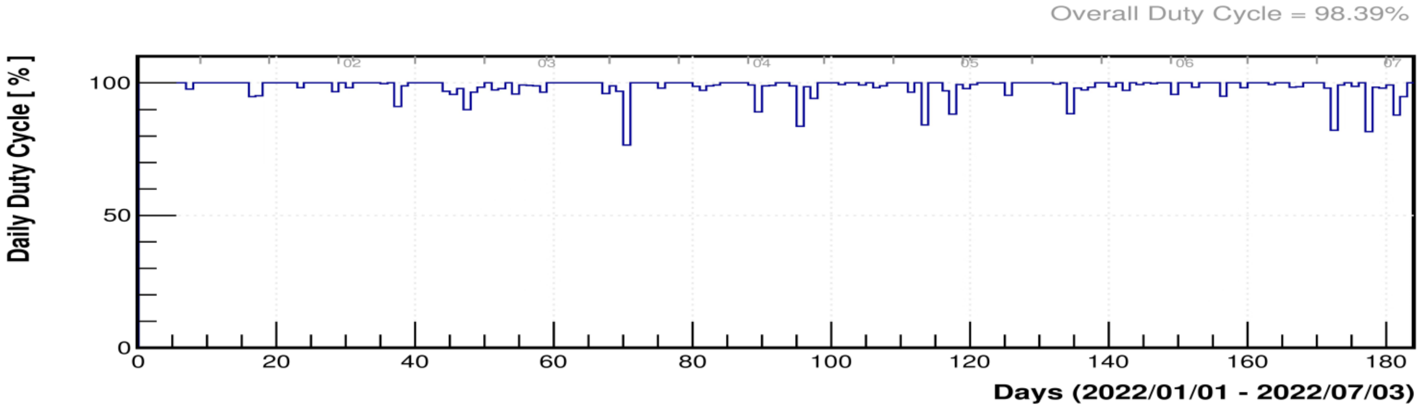


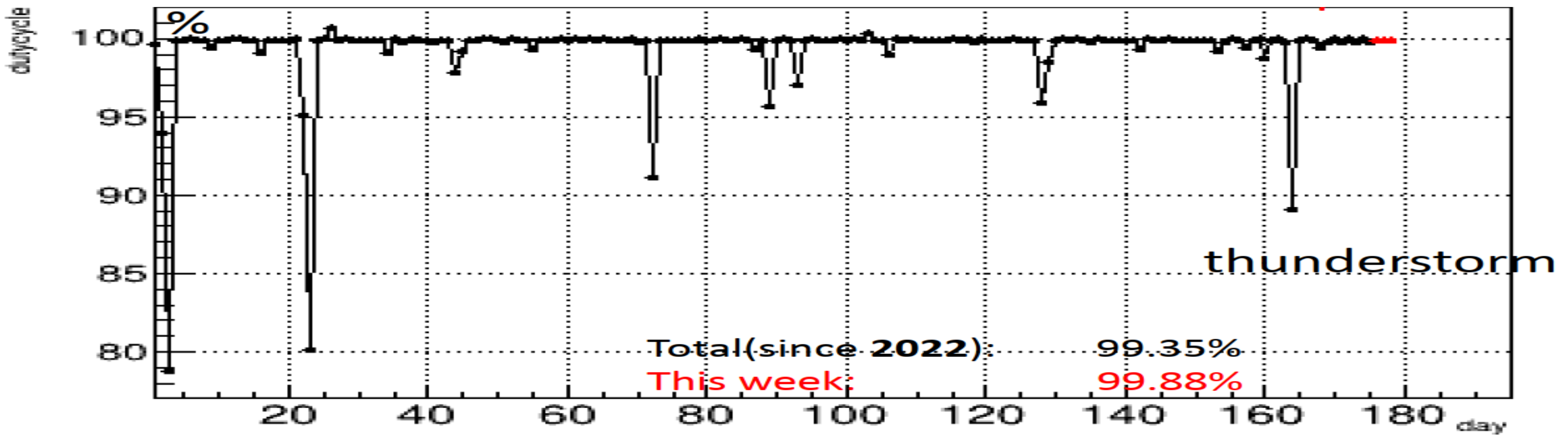


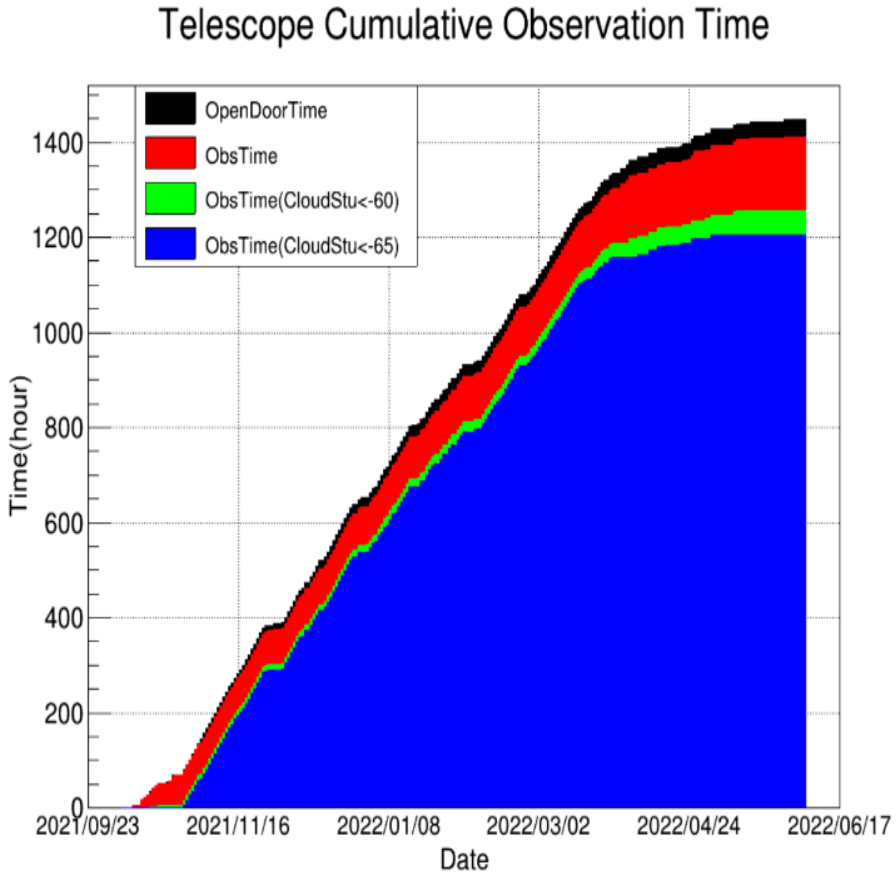
SiPM and Winston cone

Operation of LHAASO

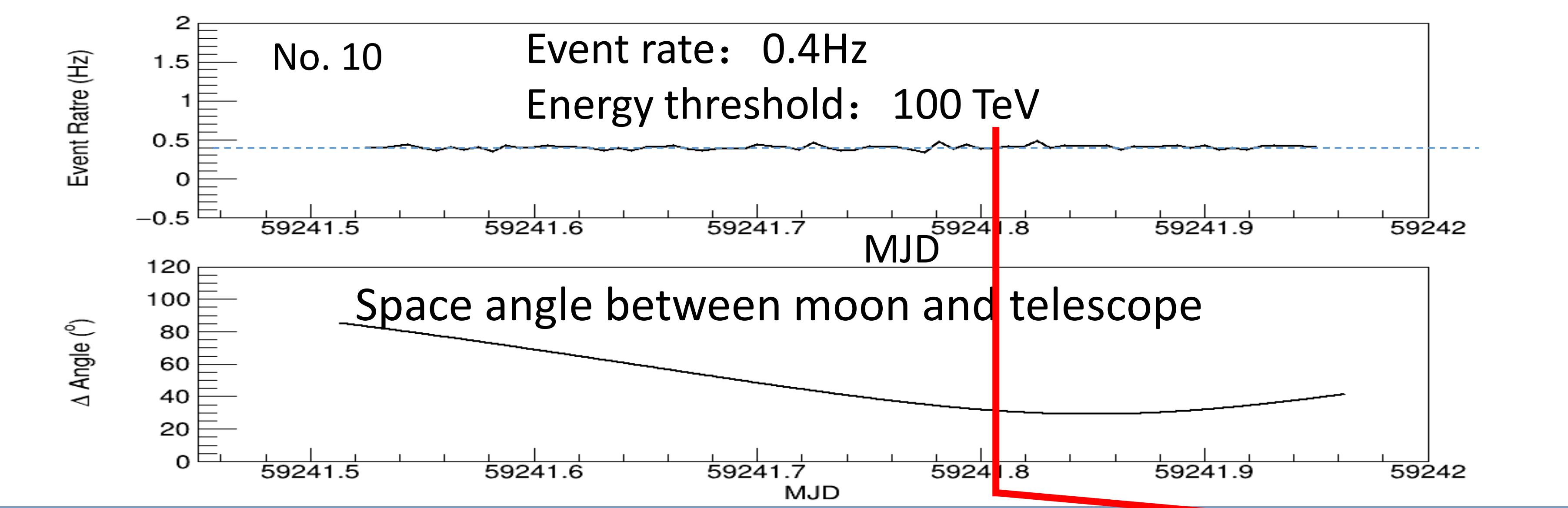
- **KM2A is operated with >99.4% duty cycle and event rate 2×10^8 /day**
- **WCDA is operated with 98.4% and event rate 3×10^9 /day**
- **Data acquisition time of WFCTA >1400 hrs and number of matched events ~70 million**

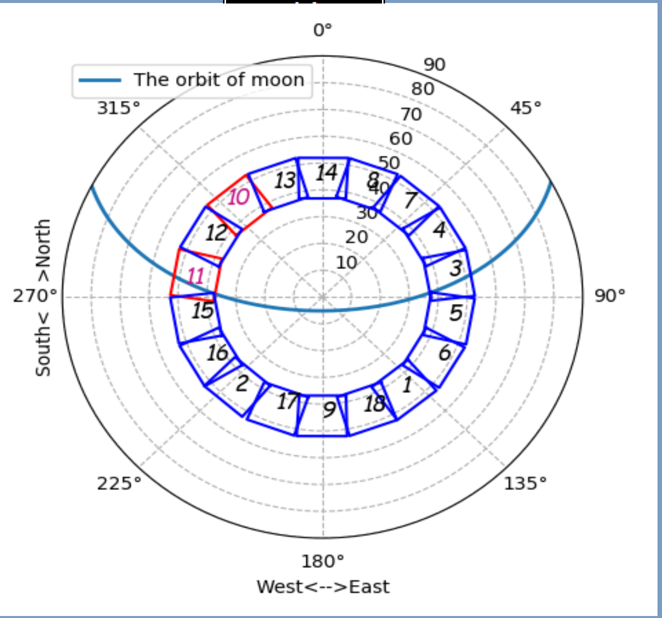




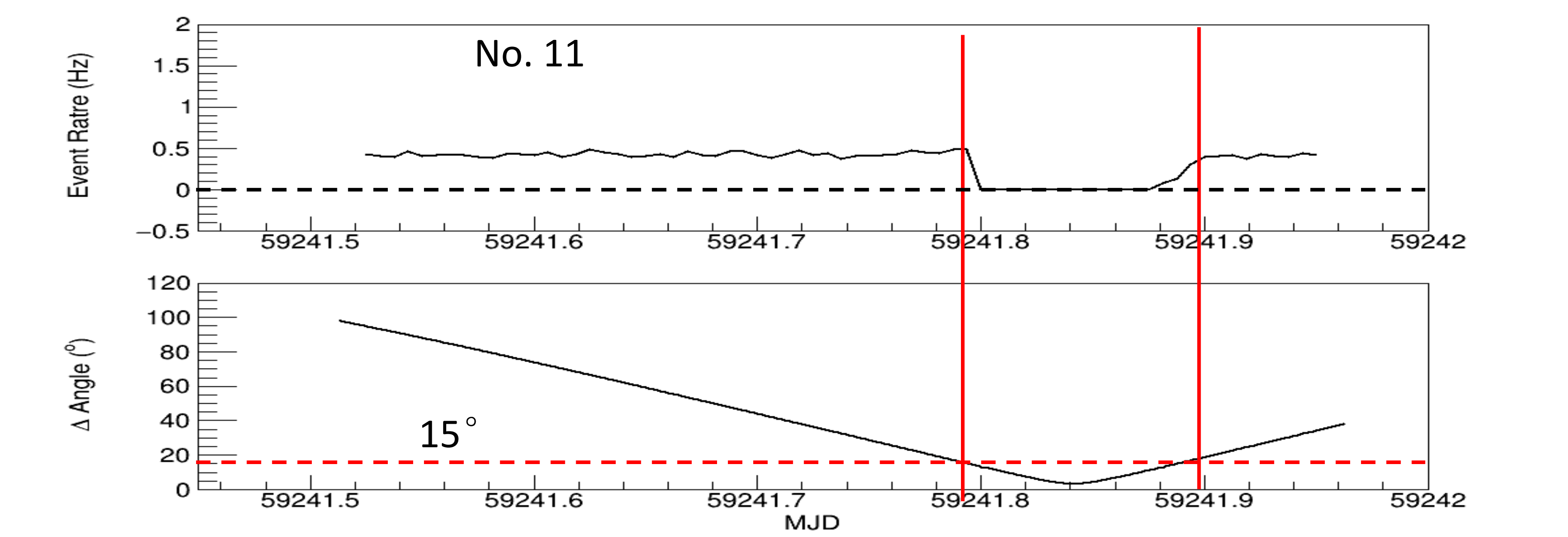


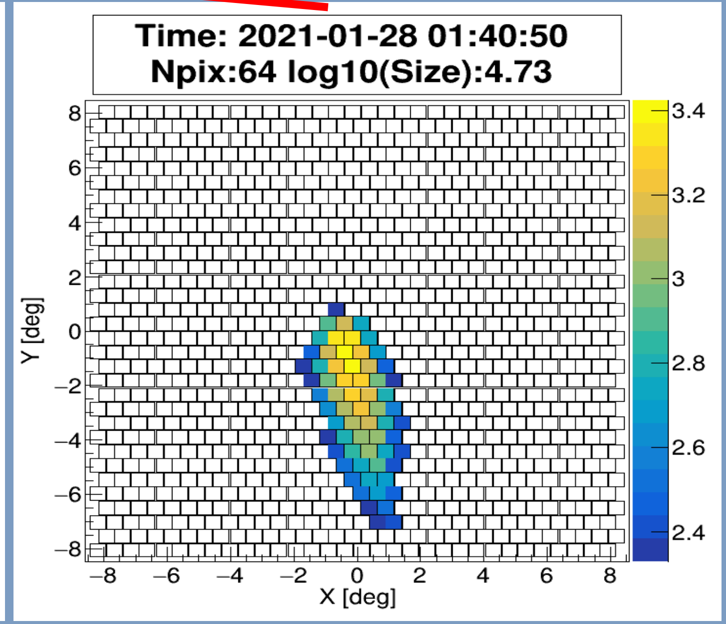
Telescope observation with the full moon

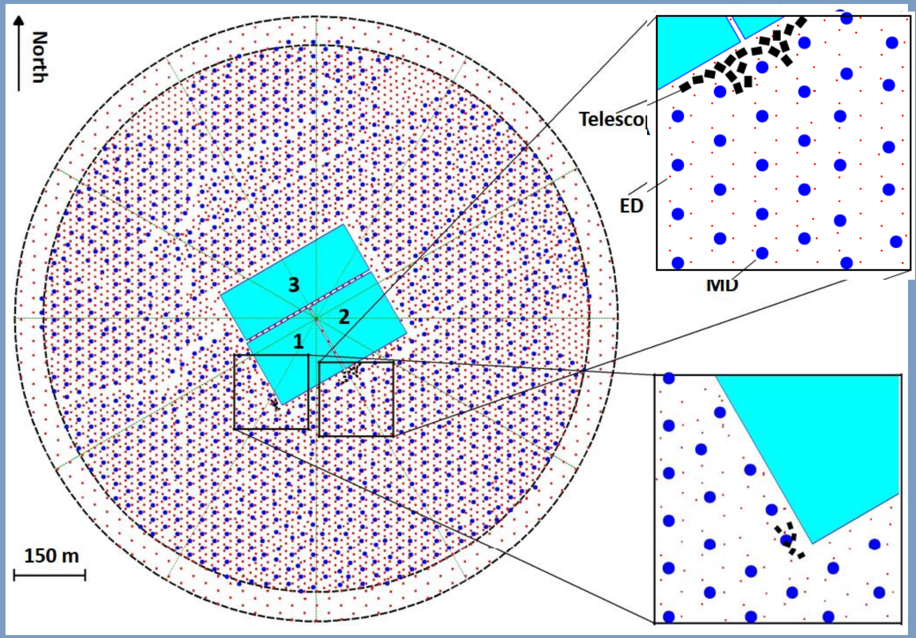




SiPM camera: LHAASO Coll., Eur. Phys. J. C (2021) 81:657

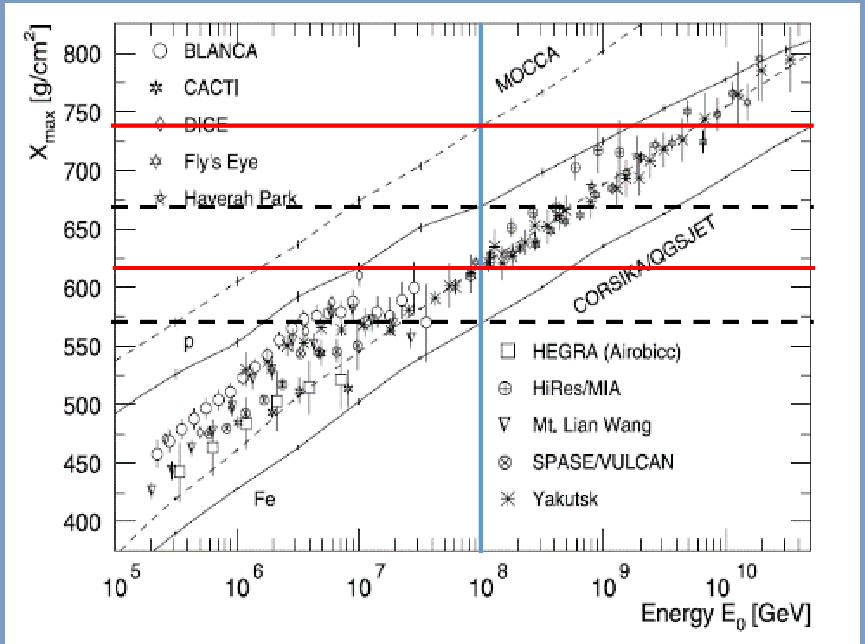


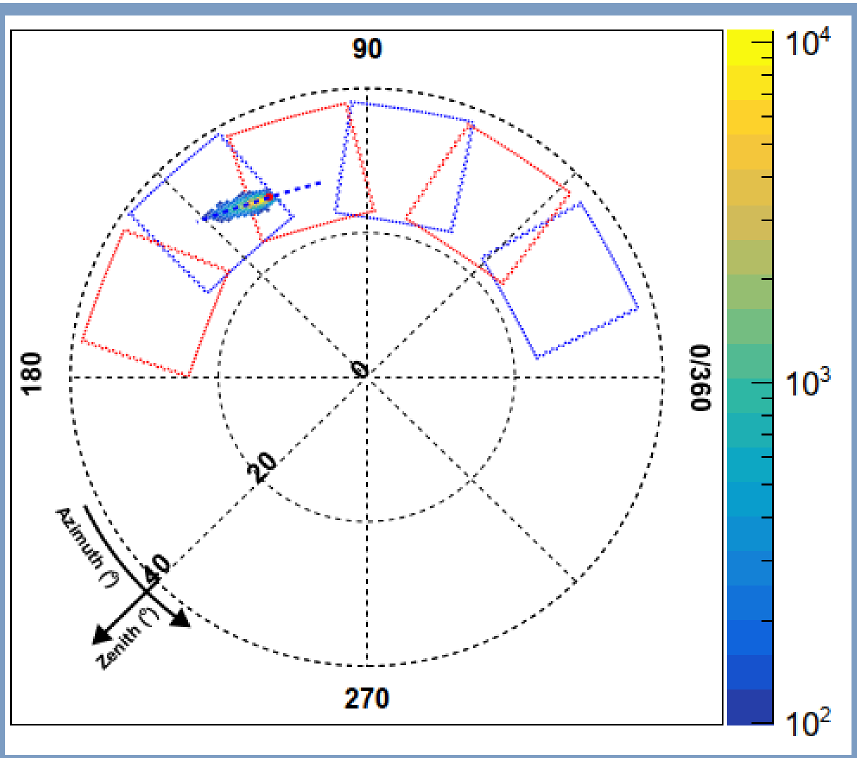




Observational Phases

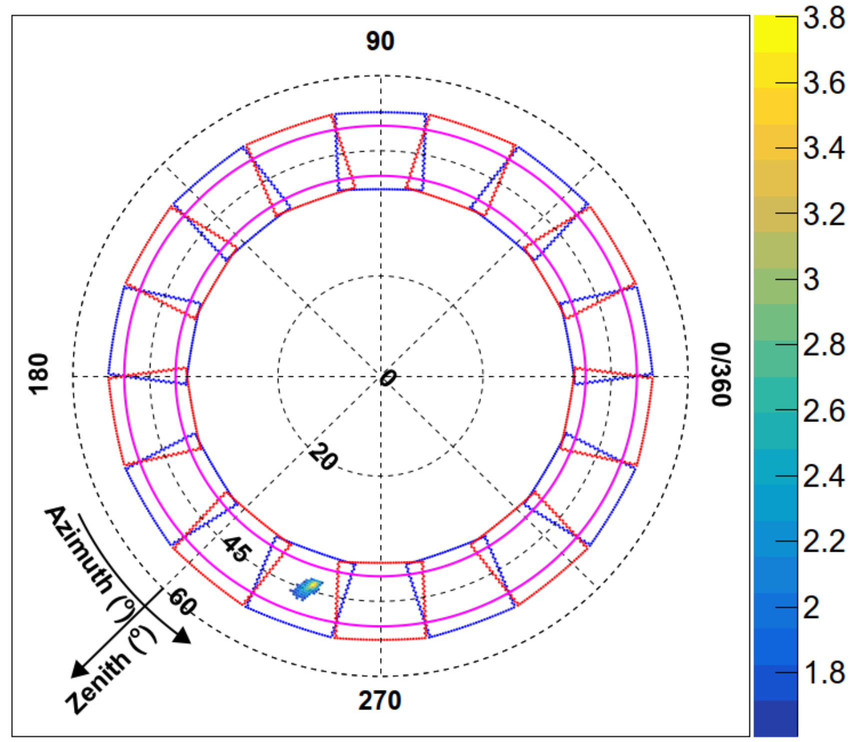
➢ Phase I: 6 telescopes
- 2019/10 – 2021/4
- Zenith angle: 30°
- Proton, H+He knees
- 100 TeV – 10 PeV





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
- 1 PeV – 200 PeV

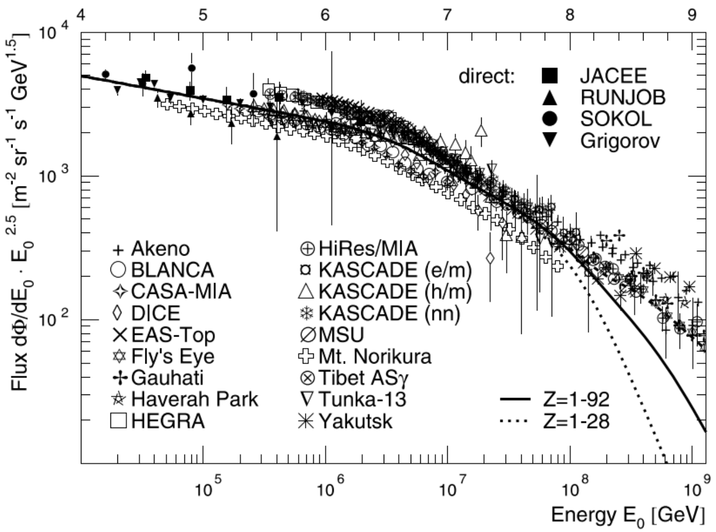


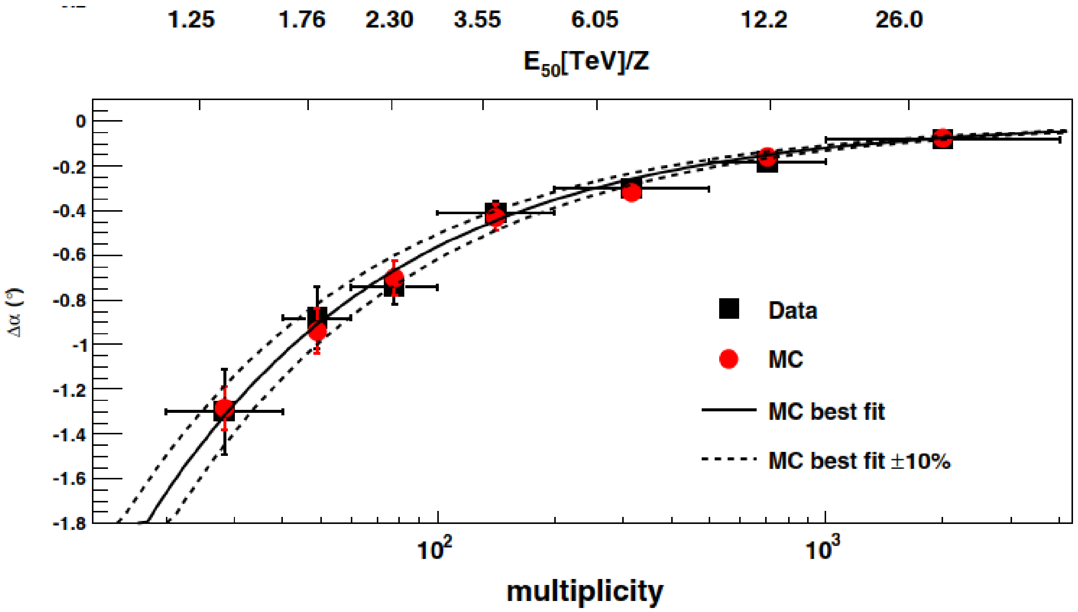
- LHAASO experiment
- Calibration
  - Absolute Energy Scale
  - Pointing Direction
  - Photometric calib.
- CR spectrum measurements
- Summary

Absolute energy scale obtained by LHAASO

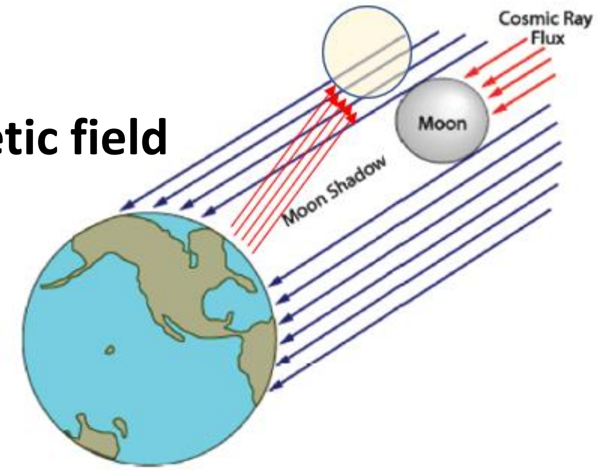
- In direct cosmic ray measurements: Detectors can be calibrated by the 350 GeV proton beam at CERN before launch.

- Ground-based detector array
  - It is impossible to generate an artificial test beam for the calibration
  - The test team from the CRs Moon shadow was first explored by ARGO-YBJ, which can be used to calibrate the ground-based experiment.





Geomagnetic field



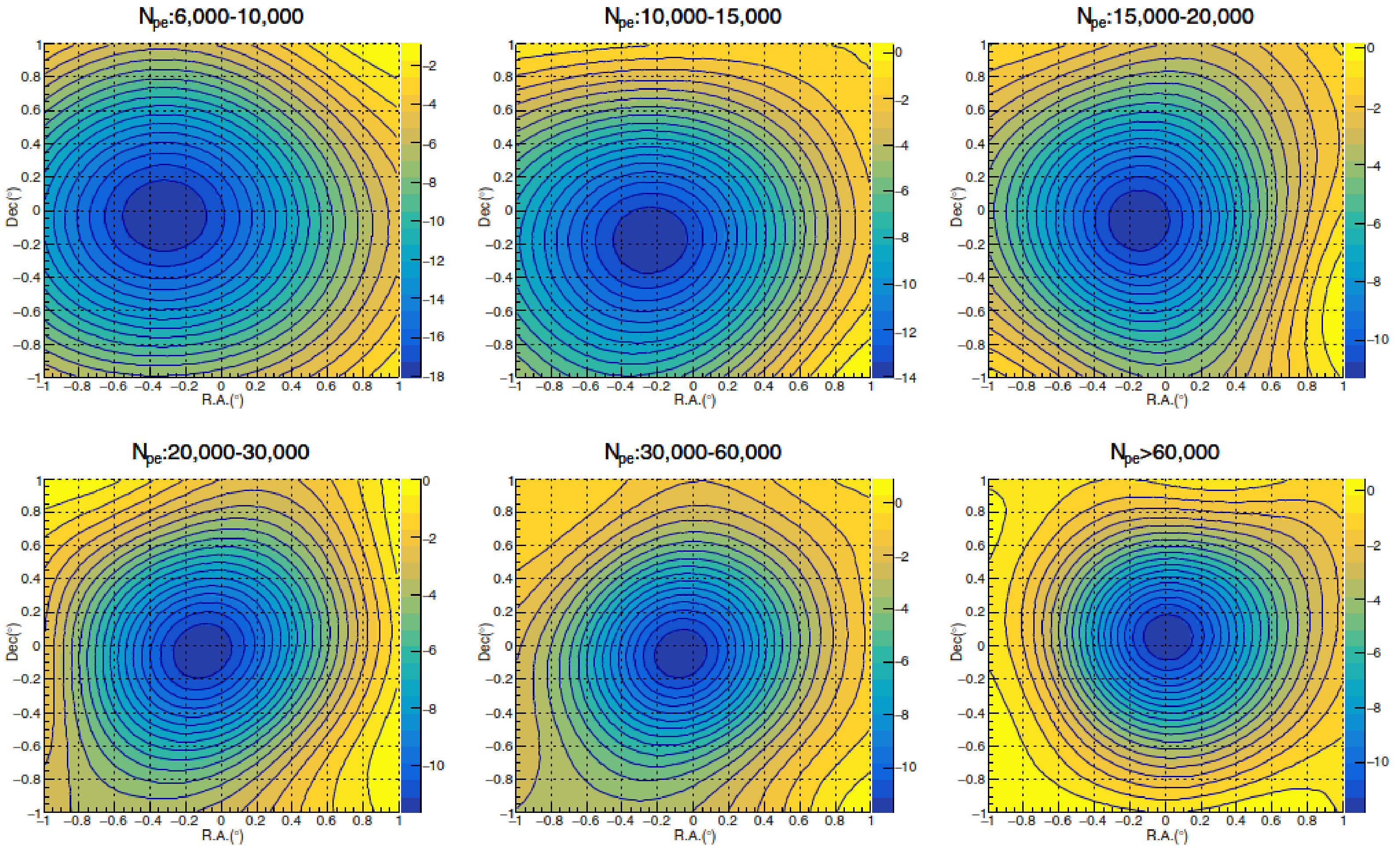
$$\Delta = z \times 1.59^{\circ}/E(\mathrm{TeV})$$

ARGO-YBJ Collaboration, PHYSICAL REVIEW D 84, 022003 (2011)

Moon Shadow measured by WCDA-1

Data:

- From 01/05/2019 to 31/01/2020 , 8 months, WCDA-1 ;
- Zenith angle < 45°;
- The data set are divided into 6 groups according to the energy estimator .



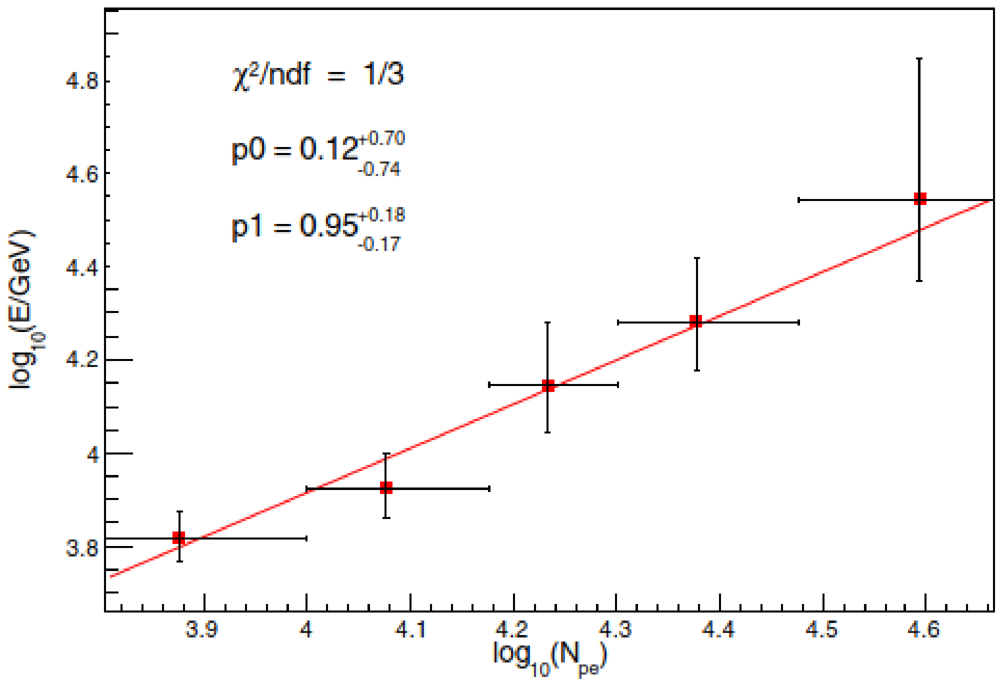
Range of N_{pe}	Shift of the Moon shadow (°)	Significance (σ)
6,000-10,000	-0.32±0.04	18.2
10,000-15,000	-0.25±0.04	14.0
15,000-20,000	-0.15±0.04	11.6
20,000-30,000	-0.11 ±0.03	11.9
30,000-60,000	-0.06 ±0.03	10.8
>60,000	-0.01±0.03	10.9

LHAASO Collaboration, PHYS. REV. D 104, 062007 (2021)

The absolute energy scale obtained by WCDA-1

- In the energy range from 1 TeV to 50 TeV, the cosmic rays are dominated by protons and helium nuclei.
- The ratio of protons and helium nuclei can be obtained from CREAM and DAMPE.
- The trigger efficiency of WCDA-1 for protons and helium is obtained from simulation.

$$\Delta = z \times 1.59^\circ / E(TeV) \rightarrow \Delta = 2.1^\circ / E(TeV)$$

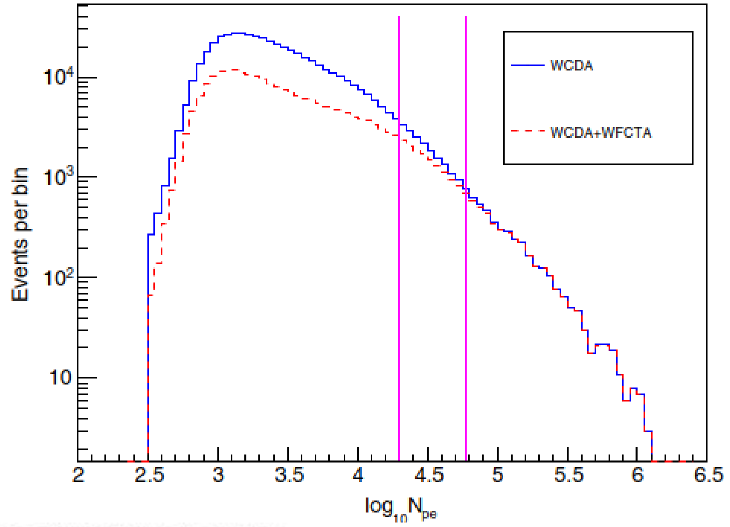


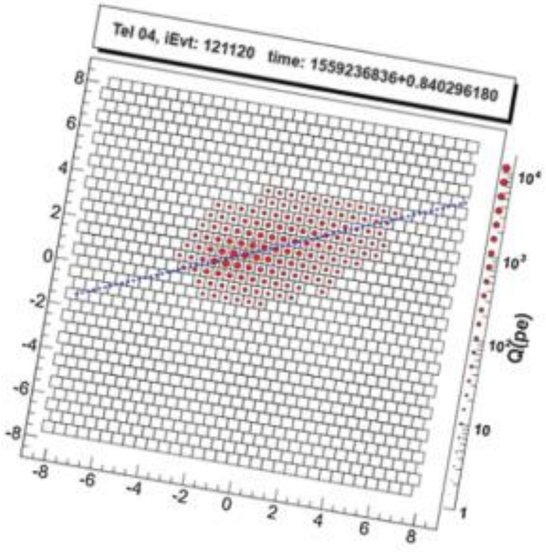
- System uncertainties:
  - Uncertainty caused by 10% changing of the ratio of protons and helium nuclei is about 3%.
  - Uncertainty from different hadronic models (EPOS-LHC vs. QGSJET-II04) is less than 2%.
  - An uncertainty of 4% is caused by the energy and angular resolution.

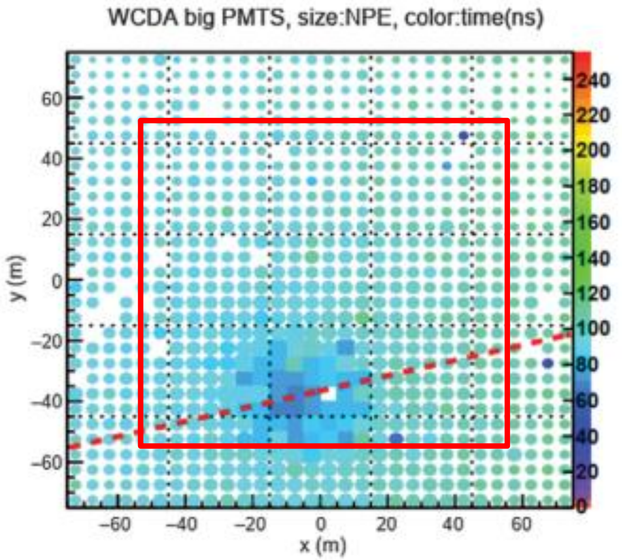
$$E(GeV) = aN_{pe}^{b}$$
$$a = 1.33^{+5.26}_{-1.06}$$
$$b = 0.95 \pm 0.17$$

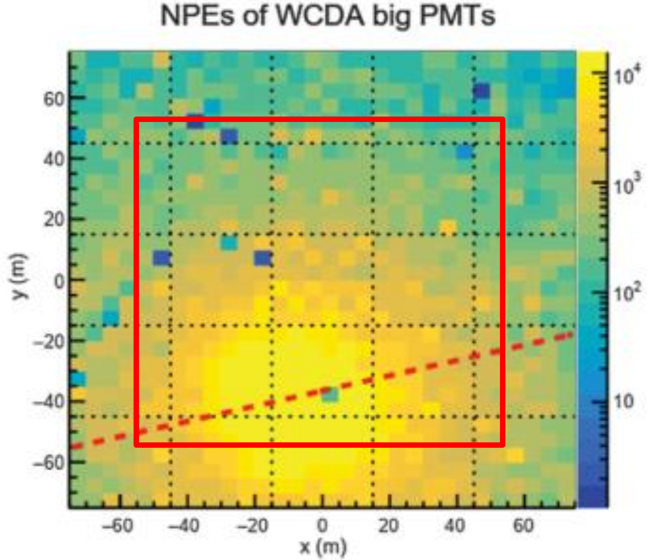
Absolute energy scale propagates from WCDA to C-telescopes

- The absolute energy scale is propagated to WFCTA by using the common trigger events together with WCDA
- Data Set of WCDA+WFCTA:
  - telescope FoV: 22° <Zenith angles <38°
  - Nhit>200
  - 20k<Npe<60k
  - shower cores fall inside WCDA: |corex|<55m, |corey|<55







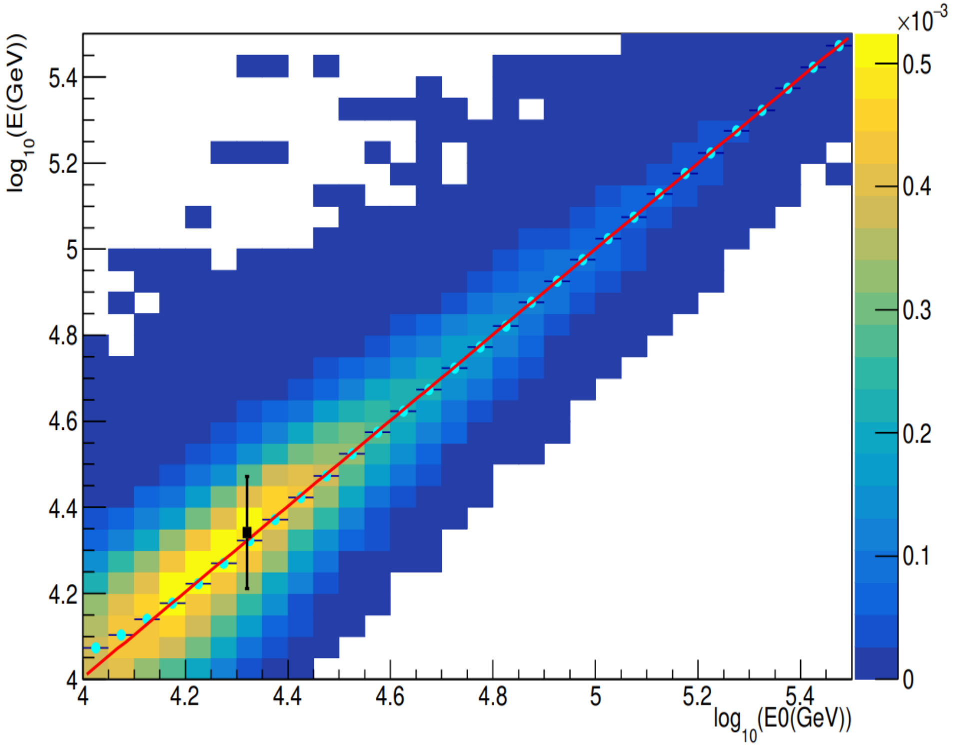


Absolute energy scale of WFCTA

➢ Propagation

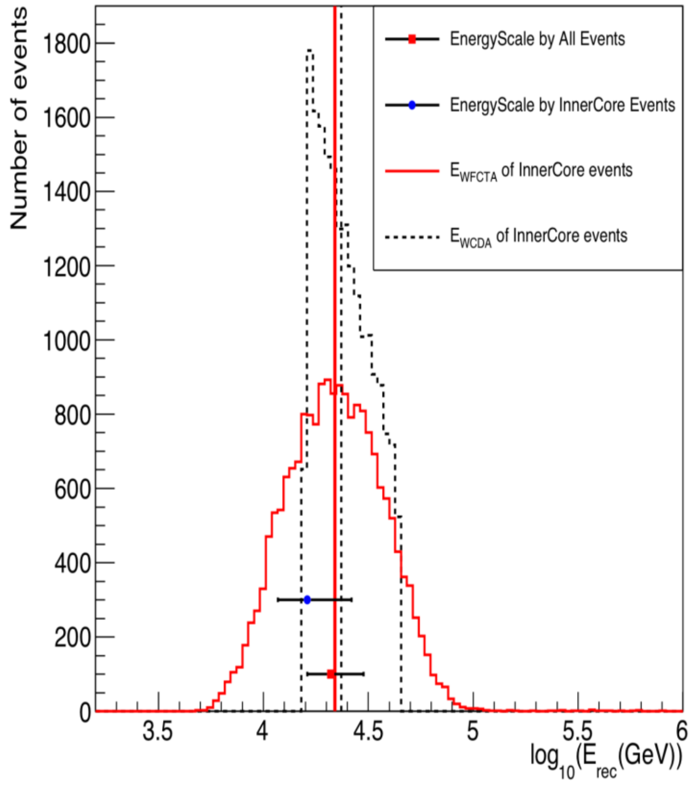
- The energy reconstructed by WFCTA is 21.9 ±0.1 TeV
- 23.4±0.1±1.3 TeV by the formula of the absolute energy scale

➢ The first time that the Cherenkov telescopes have an absolute energy scale

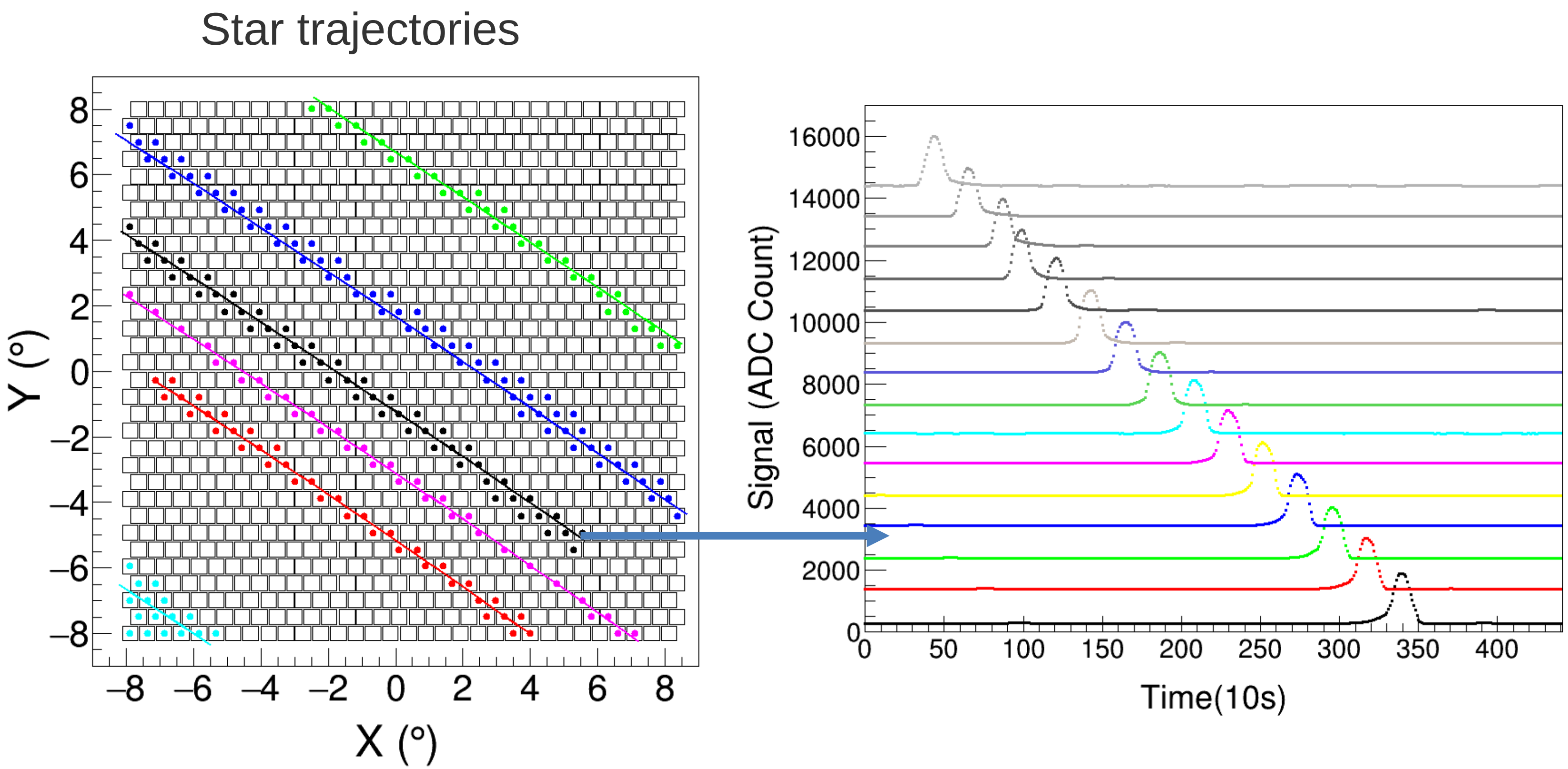


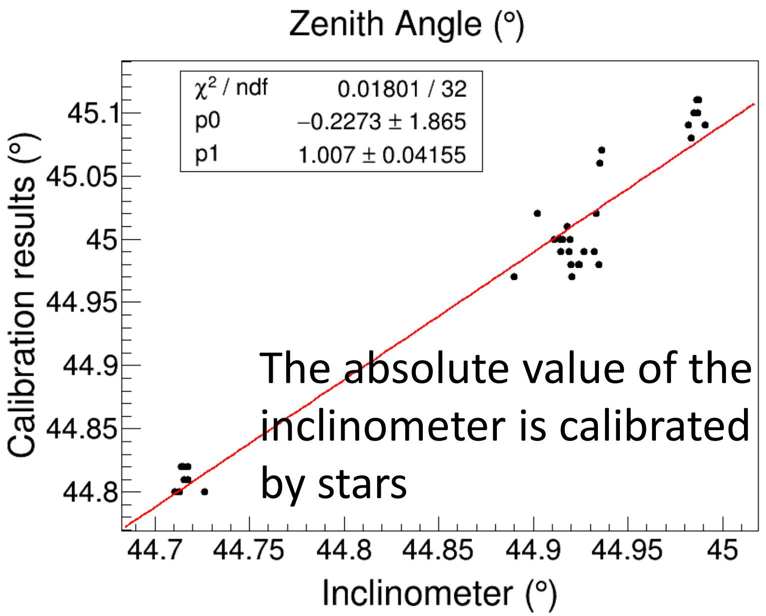
WCDA Calibration result (8 months, one pool):

- ✓ **21.0 ±6.5 TeV for all events**
- ✓ **The uncertainty dominated by statistics in moon position measurement**
- ✓ **the uncertainty < 10% in 4 years**

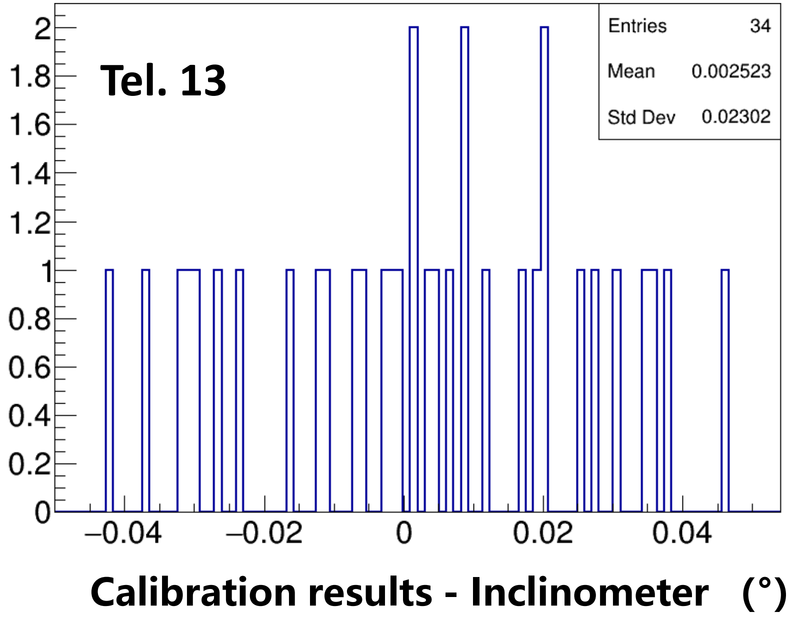


LHAASO Collaboration, PHYS. REV. D 104, 062007 (2021)





Trajectories of the stars (known) vs. signals on the camera

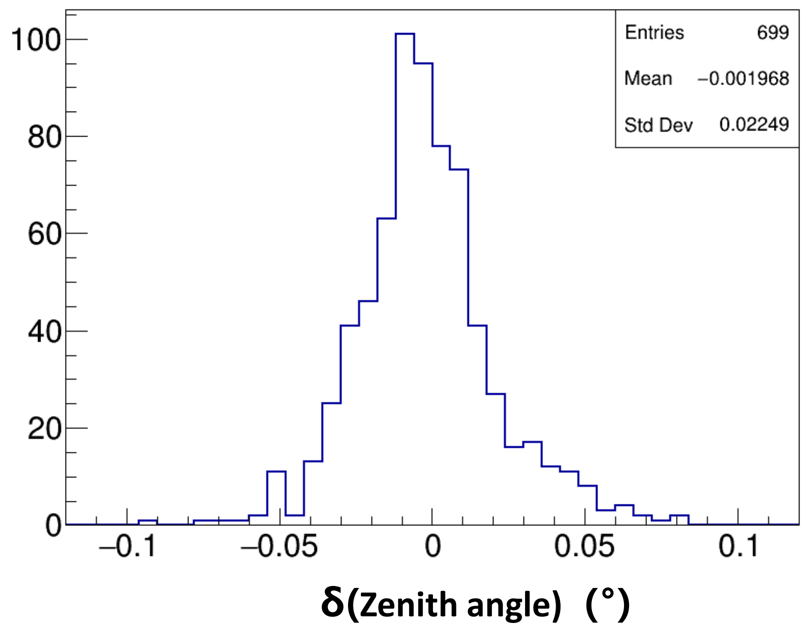


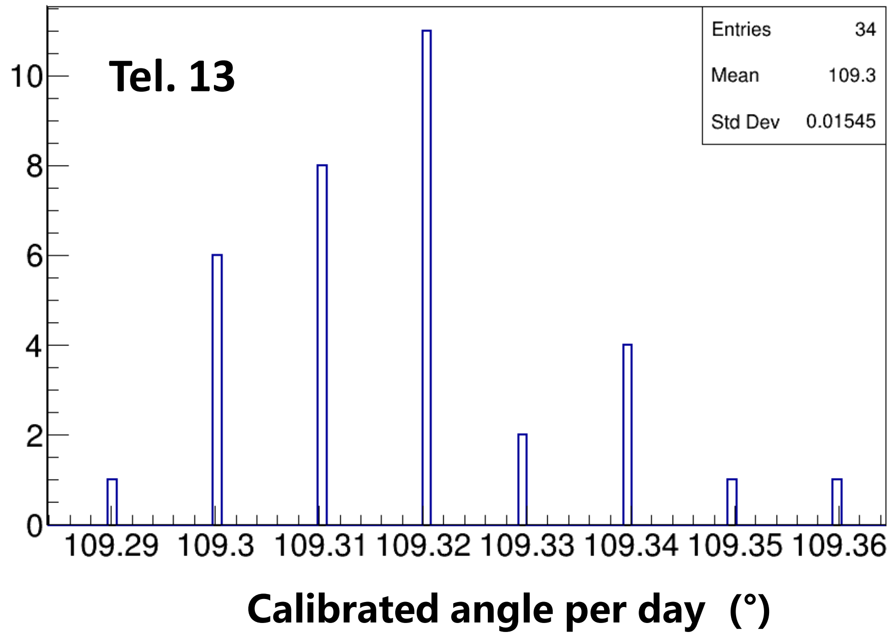
- **The telescope pointing is calibrated by stars in FOV**
- **The elevation angles are monitored by the inclinometer**

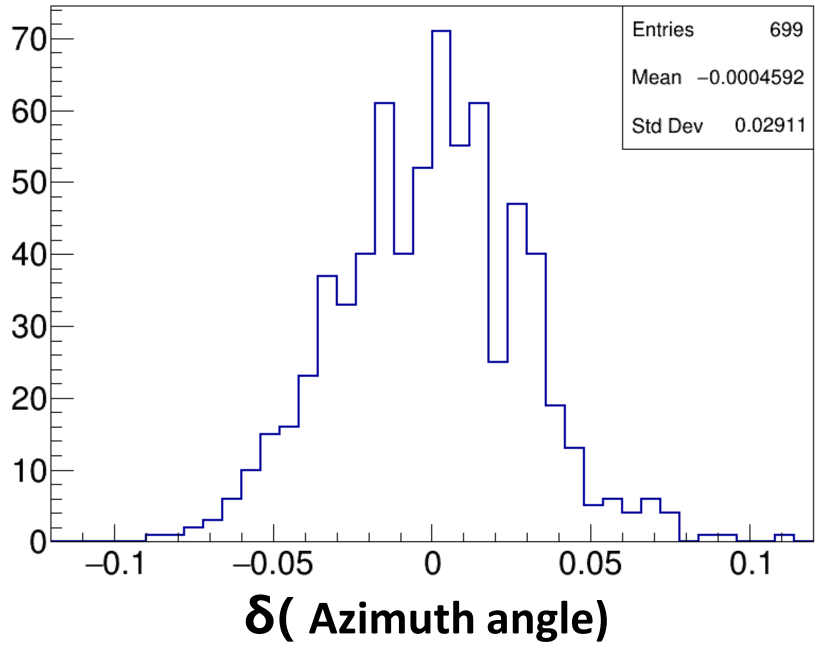
Daily calibration for 34 days

Calibration accuracy 0.022° in zenith

18 telescopes calibration results

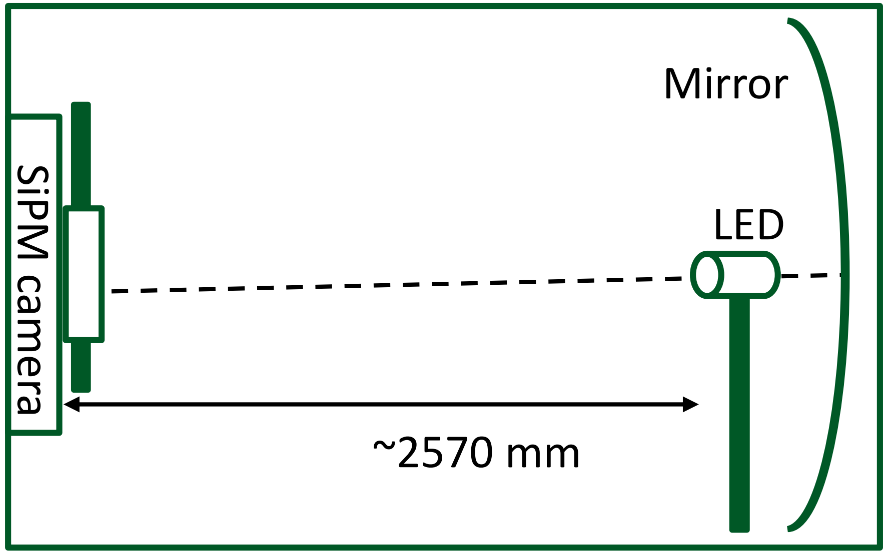


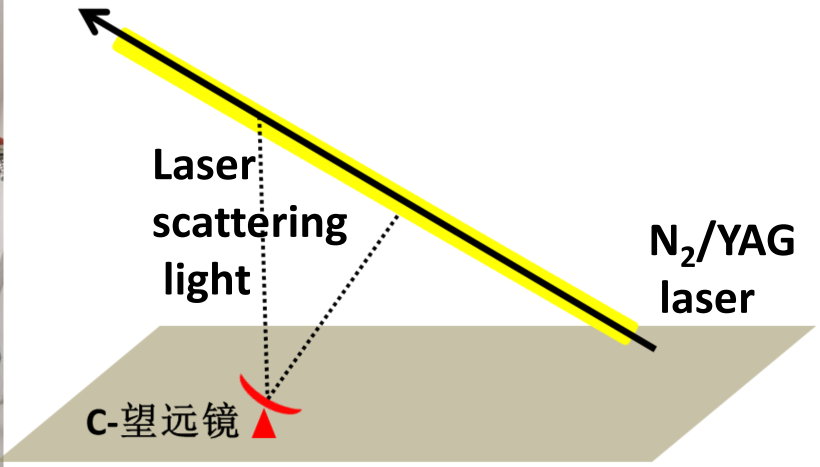




Calibration system

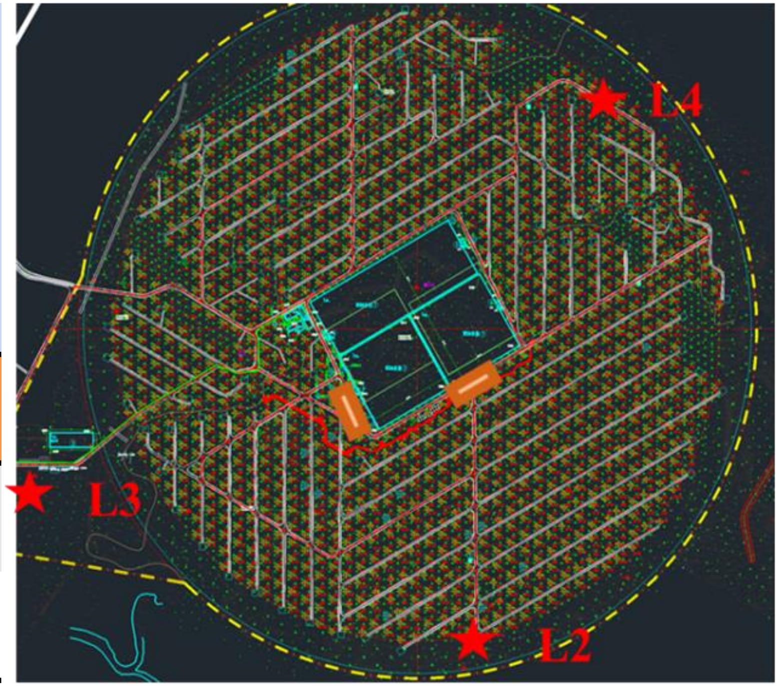
Probe





- SiPM camera is calibrated and monitored by LED
  - LED was calibrated by the probe and the probe is calibrated by National Institute of Metrology, China;
  - Calibration uncertainty is less than 2.6%.
  - LHAASO Coll., NIM, A 1021 (2022) 165824

Laser device	parameters	
N_2 laser	λ=337nm， E= ~ 145 μJ	2
YAG laser	λ==355nm， E= ~ 300 μJ	2



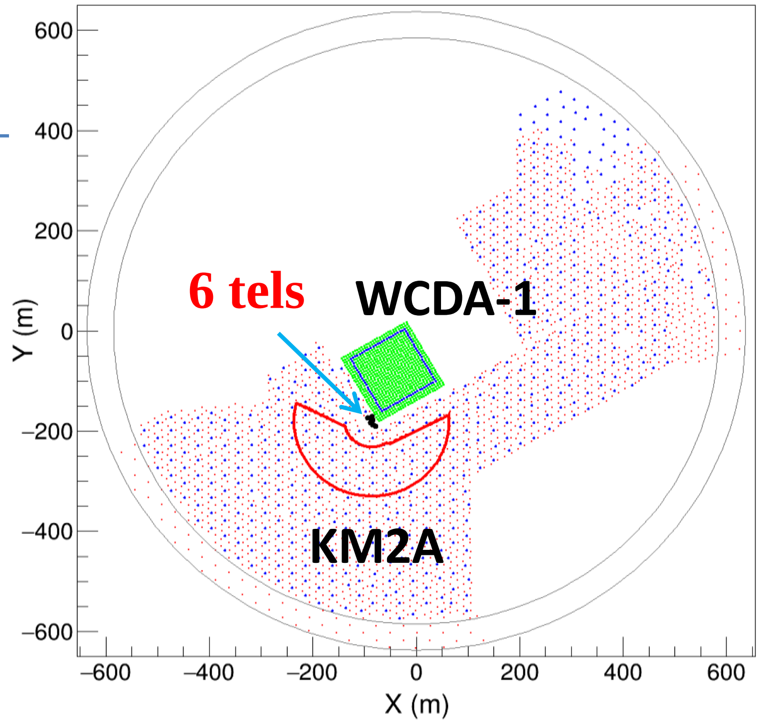
- LHAASO experiment
- Absolute energy scale
- CR spectrum measurements
  - 2 independent hybrid analyses
  - Primary particle identification (multi-parameter analysis)
  - Energy reconstruction (2 independent ways)
- Summary

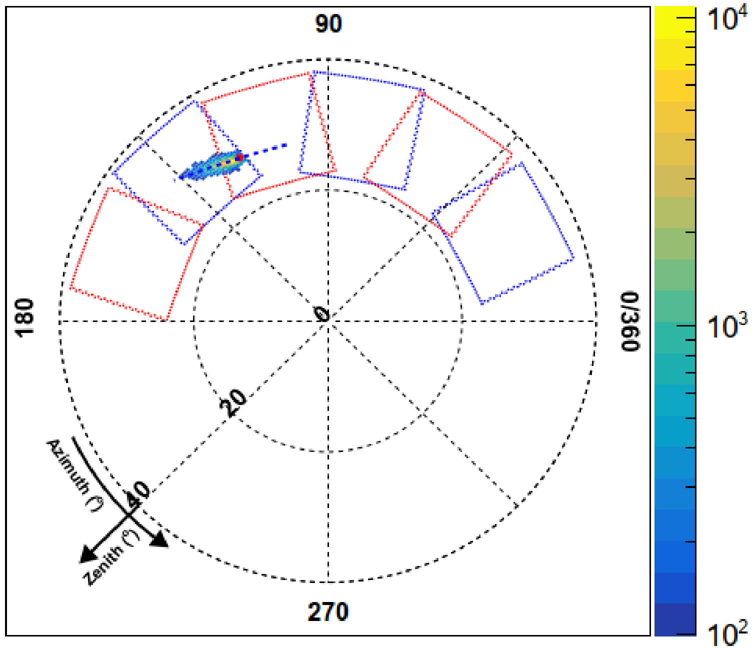
LHAASO data set for proton and H+He energy spectra

Phase I

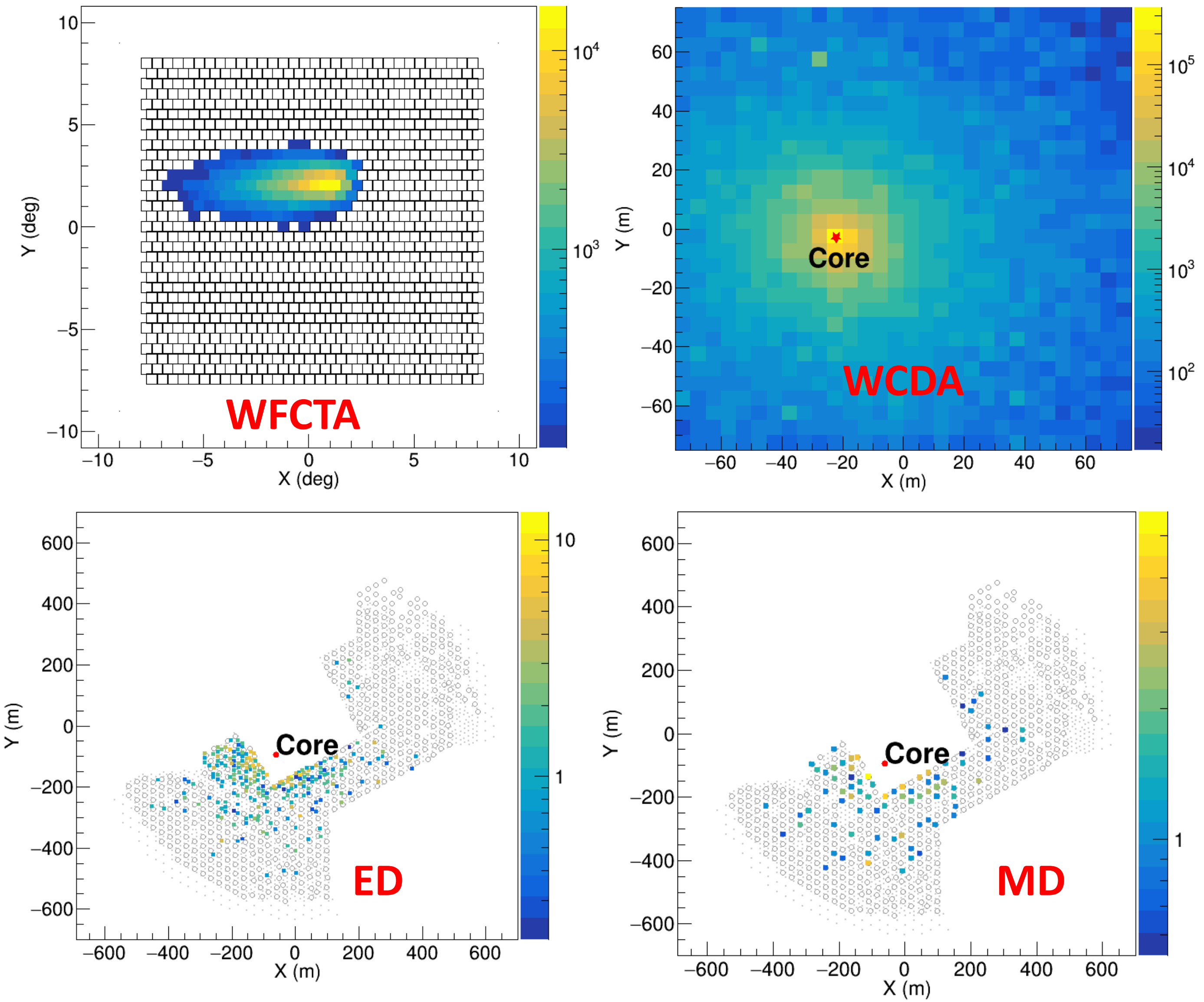
- **Period:** 2020.11 ~ 2021.04
- **WFCTA selection conditions:**
  - > 10 pixels in each Cherenkov image
  - Full image contained in FoV
- **Good weather (ST<-70°)**

- **Two independent measurements:**
  - **WFCTA(6 telescopes)+KM2A**
  - **WFCTA(6 telescopes)+WCDA-1+KM2A**
  - **750 hours, 0.7 million events (Core in WCDA)**



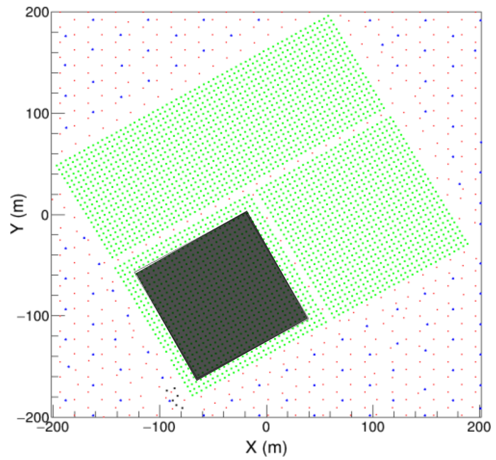


Hybrid measurement of LHAASO



- Shower geo-reconstructed
  - by WCDA/KM2A
    - **Core resolution: < 3 m**
    - **Angular resolution: < 0.2° @ >100 TeV**
- Shower energy reconstruction
  - Cherenkov size
- Mass sensitive parameters
  - X_{max} and Hillas parameters of Cherenkov image
  - Energy flux near shower core
  - Number of muons

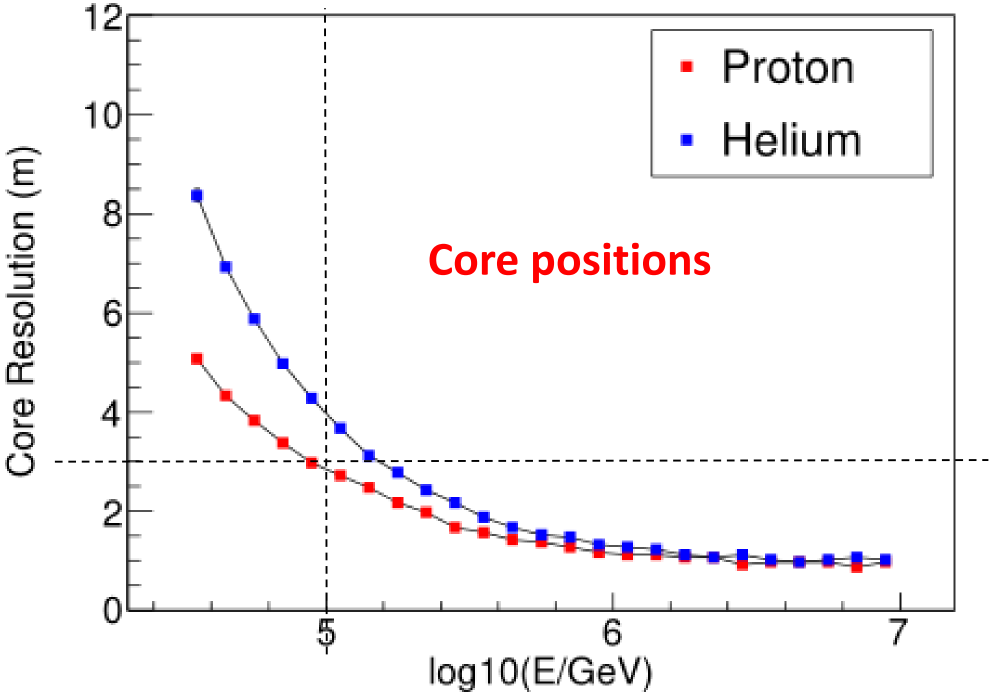
Hybrid measurement of LHAASO

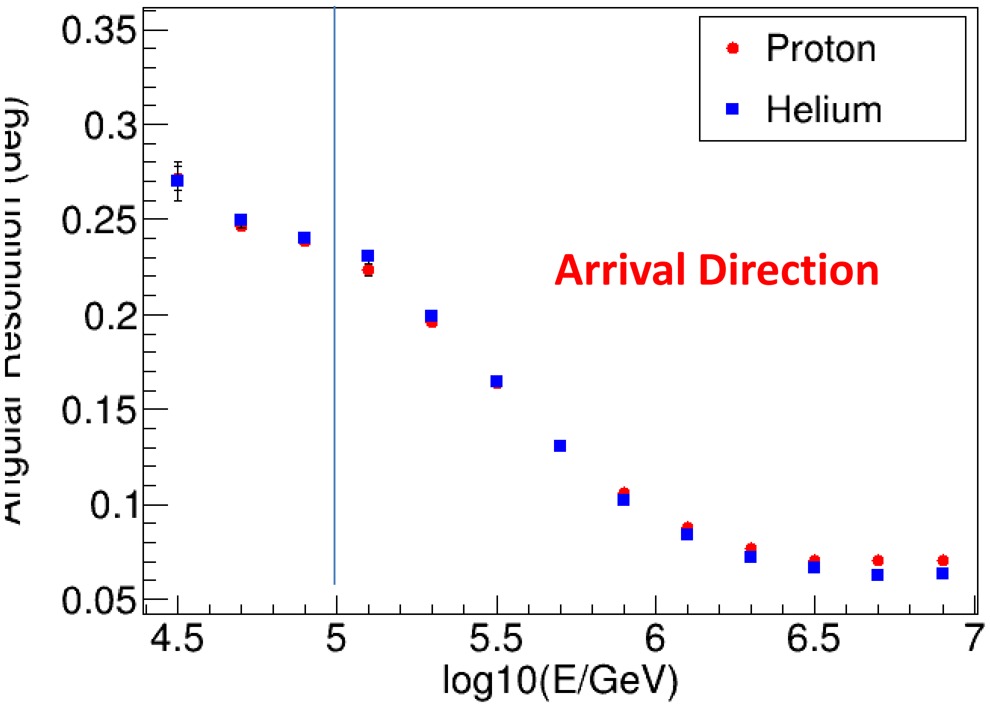


For pure protons：

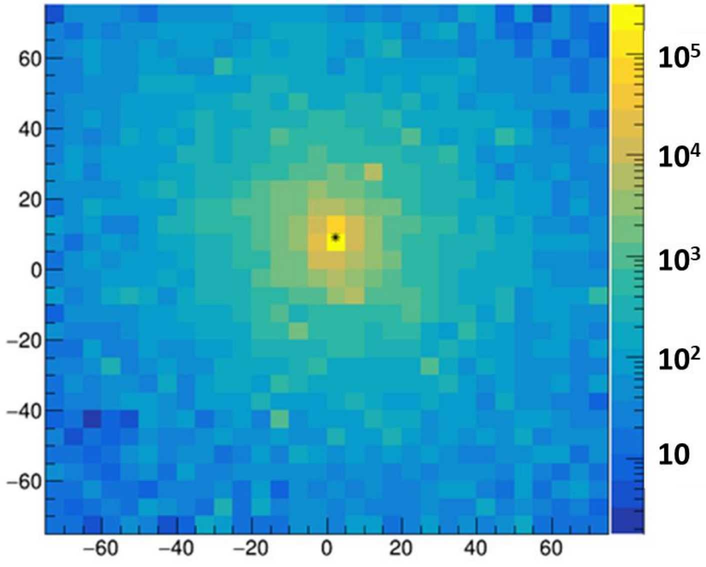
Core position errors： $< 3\ m$ $(> 100\ TeV)$

Arrive direction error： $< 0.3°$ $(> 100TeV)$

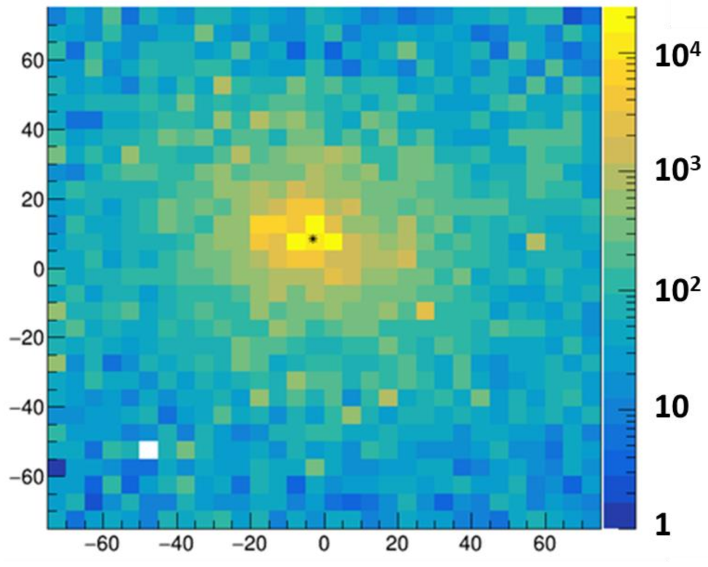




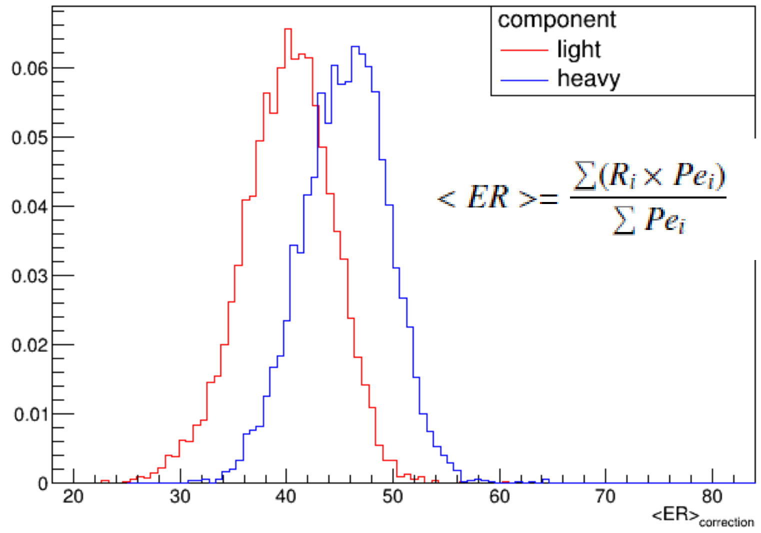
Mass sensitive parameters

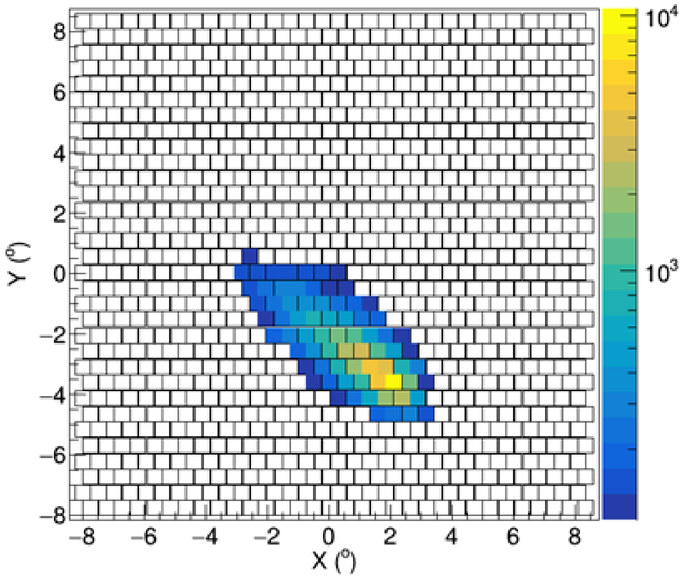


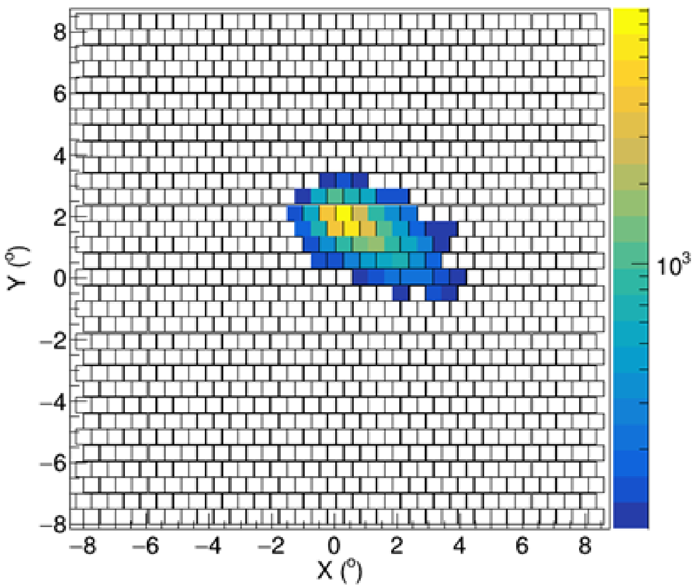
400 TeV proton

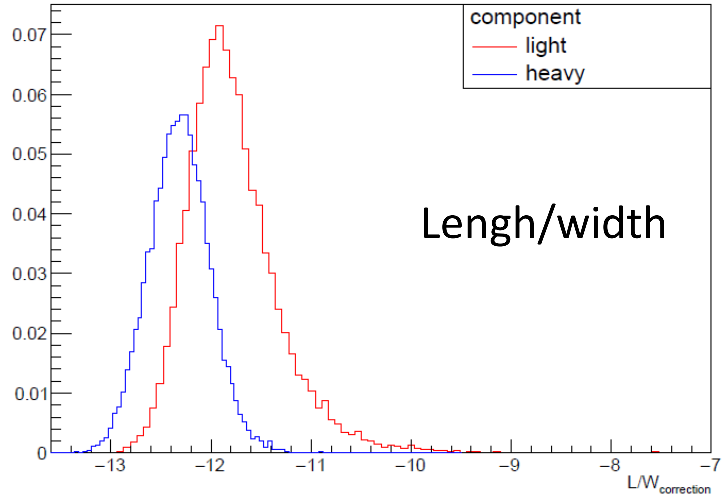


400 TeV iron

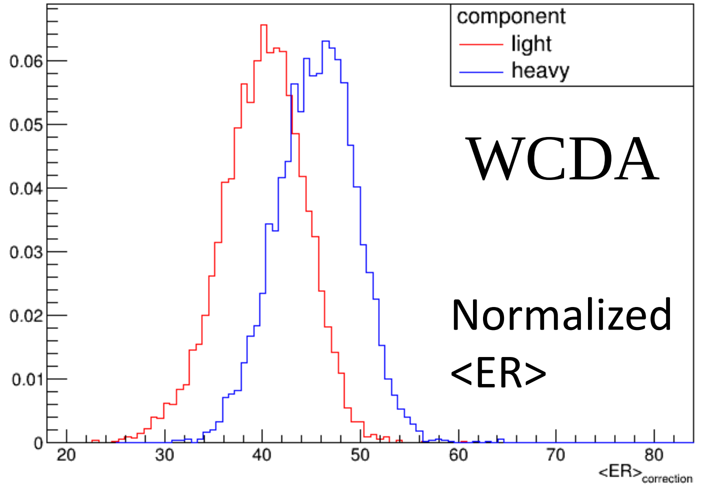




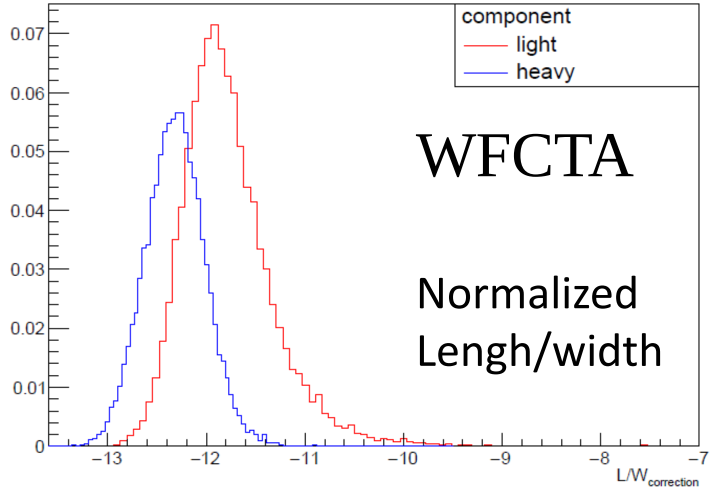




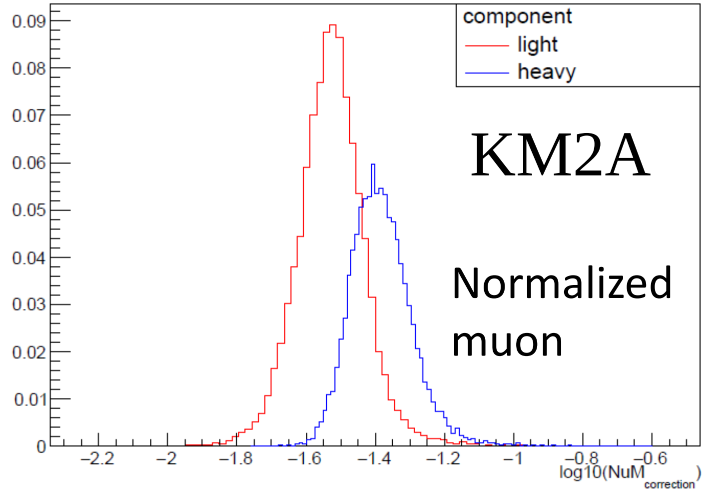
Composition Discrimination



P_F



P_C



P_μ

$$\log_{10} Size0 = \log_{10} Size + 0.00837 \times R_p$$

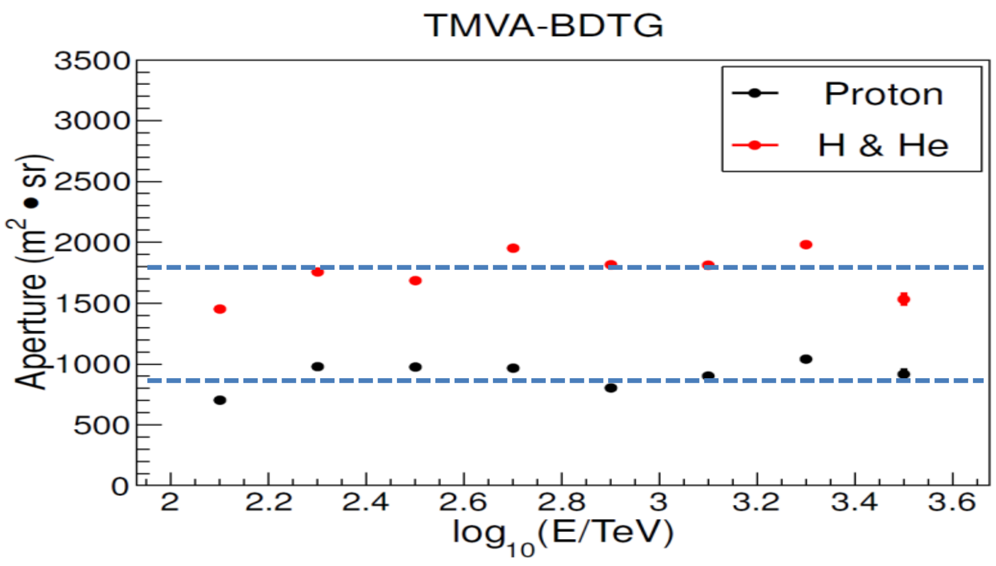
WCDA $$P_F = < ER > +4.844 \times \log_{10} Size0 \qquad < ER > = \frac{\sum (R_i \times Pe_i)}{\sum Pe_i}$$

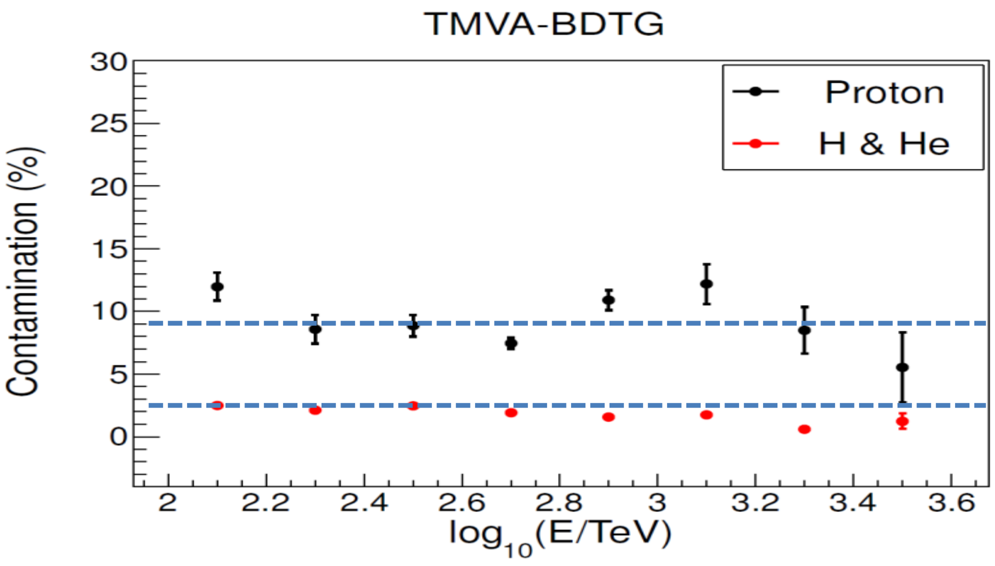
WFCTA $$P_C = \left(L/W - 0.0116 \times R_p\right) + 0.371 \times (\log_{10} Size0)^2 - 4.495 \times (\log_{10} Size0)$$

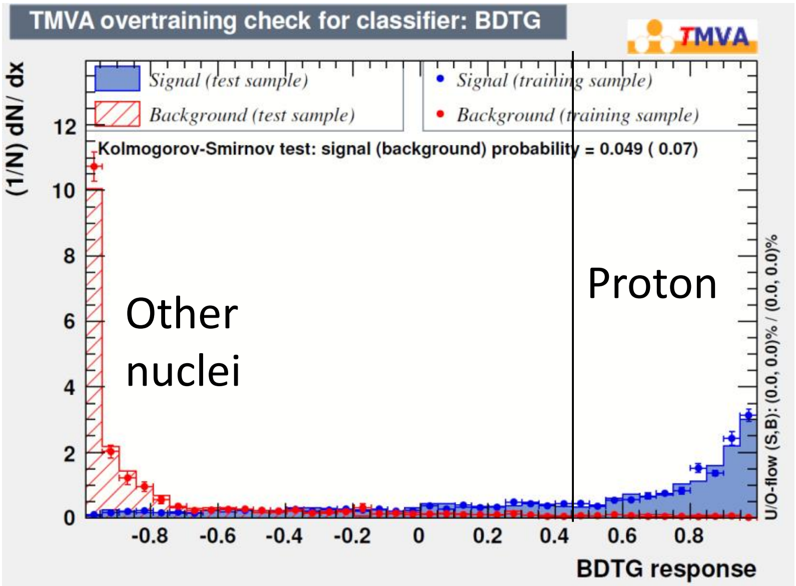
KM2A $$P_\mu = \log_{10}\left(N_{\mu|_{30-380}}\right) - 0.0916 \times (\log_{10} \sqrt{N_{e|_{40-100}} \times N_{\mu|_{40-200}}} + 3.44)$$

Multi-parameters analysis

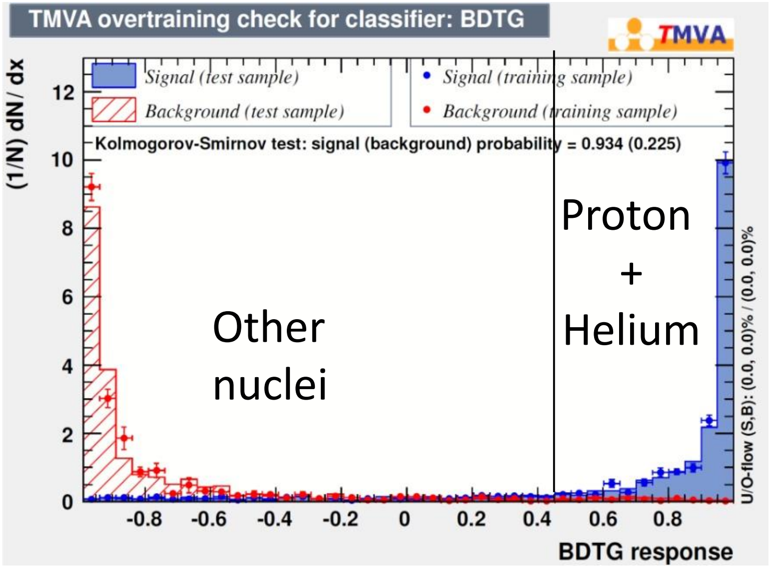
TMVA(Toolkit for Multivariate Data Analysis with ROOT)







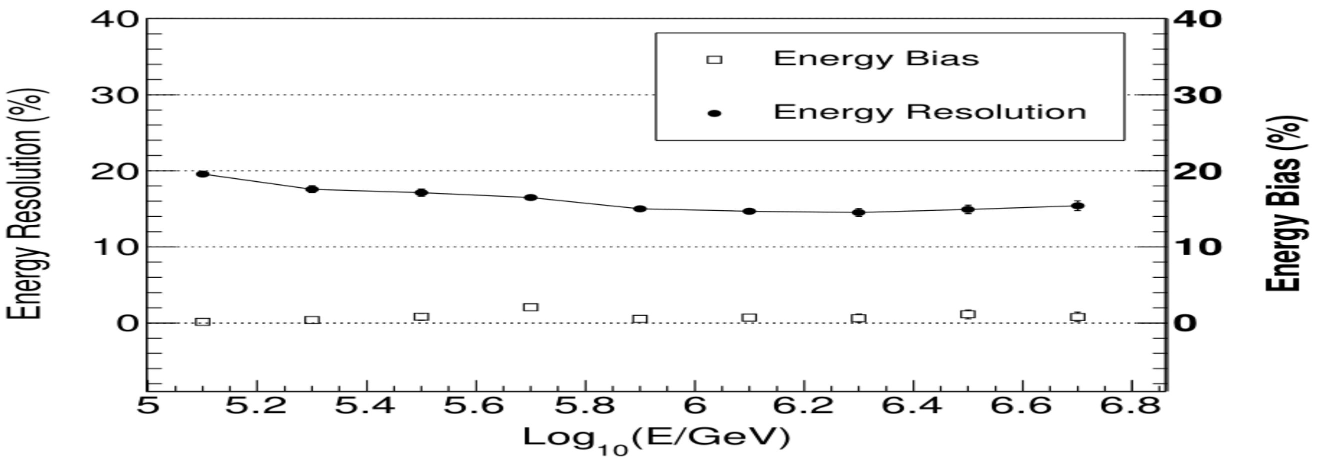
- **Aperture：**
  - **H: ~ 850 m^2Sr**
  - **H+He: ~1800 m^2Sr**
- **Contamination of heavy nuclei**
  - **H: ~ 10%**
  - **H+He: ~ 3%**



Energy reconstruction

For C-telescopes

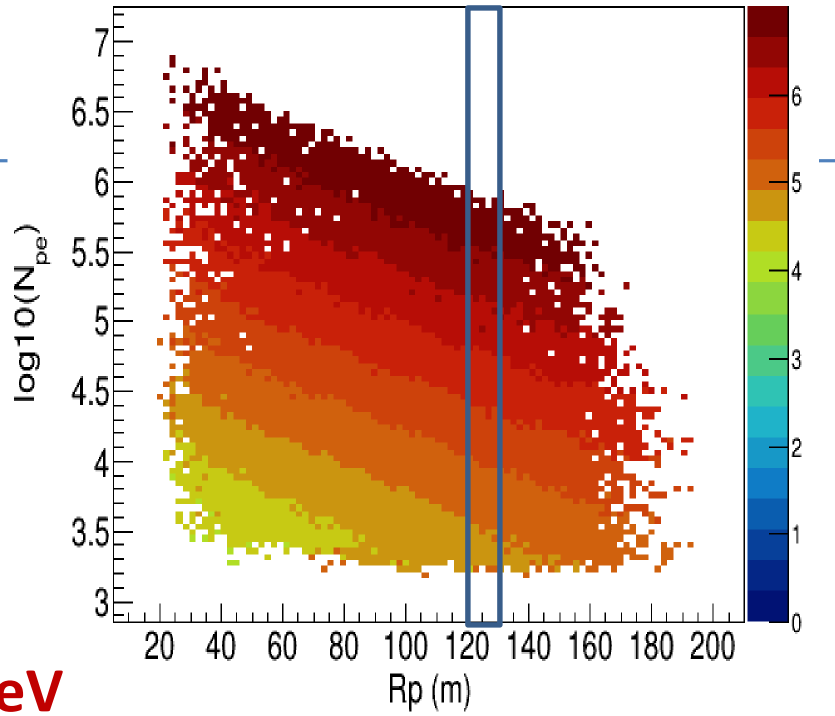
- ➤Energy estimator: total Charge in Cherenkov image (Npe)

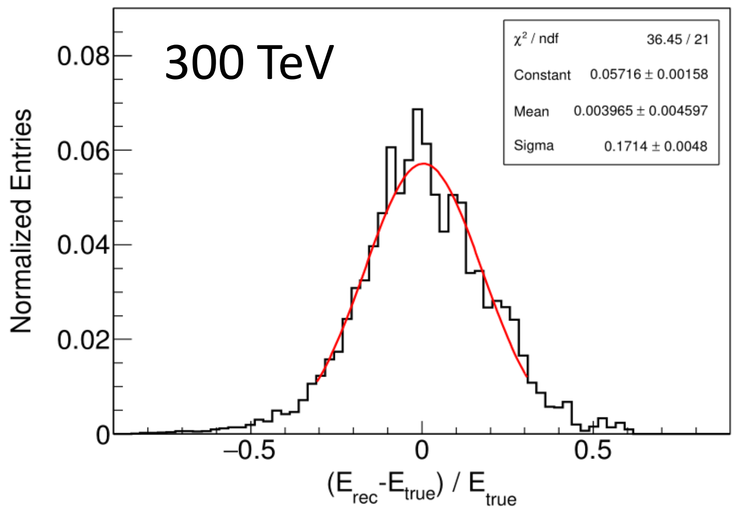


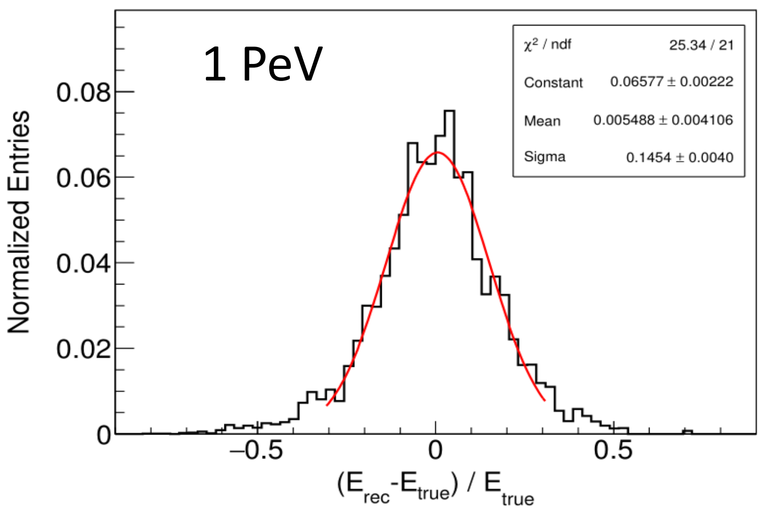
Bias < 2%

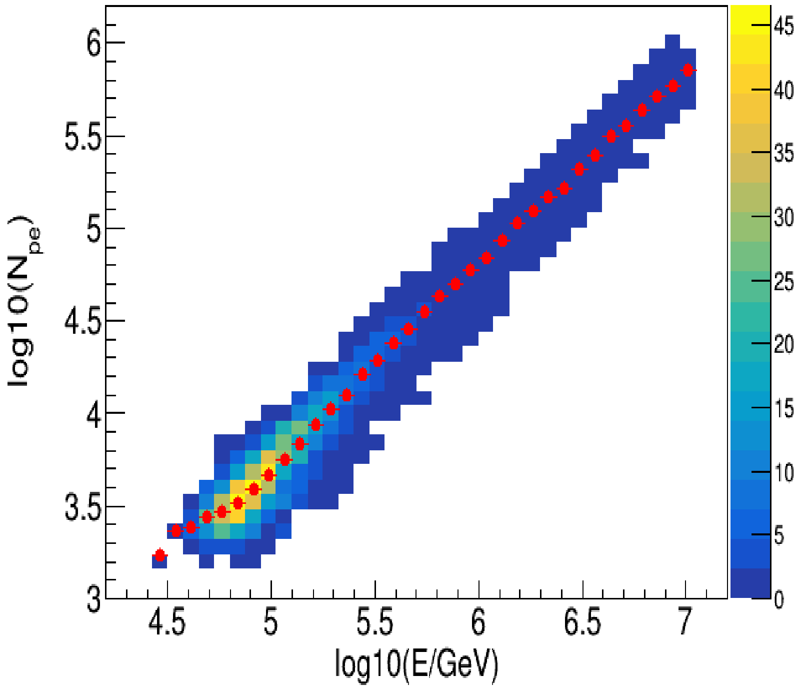
Resolution:

~16% @ 1PeV



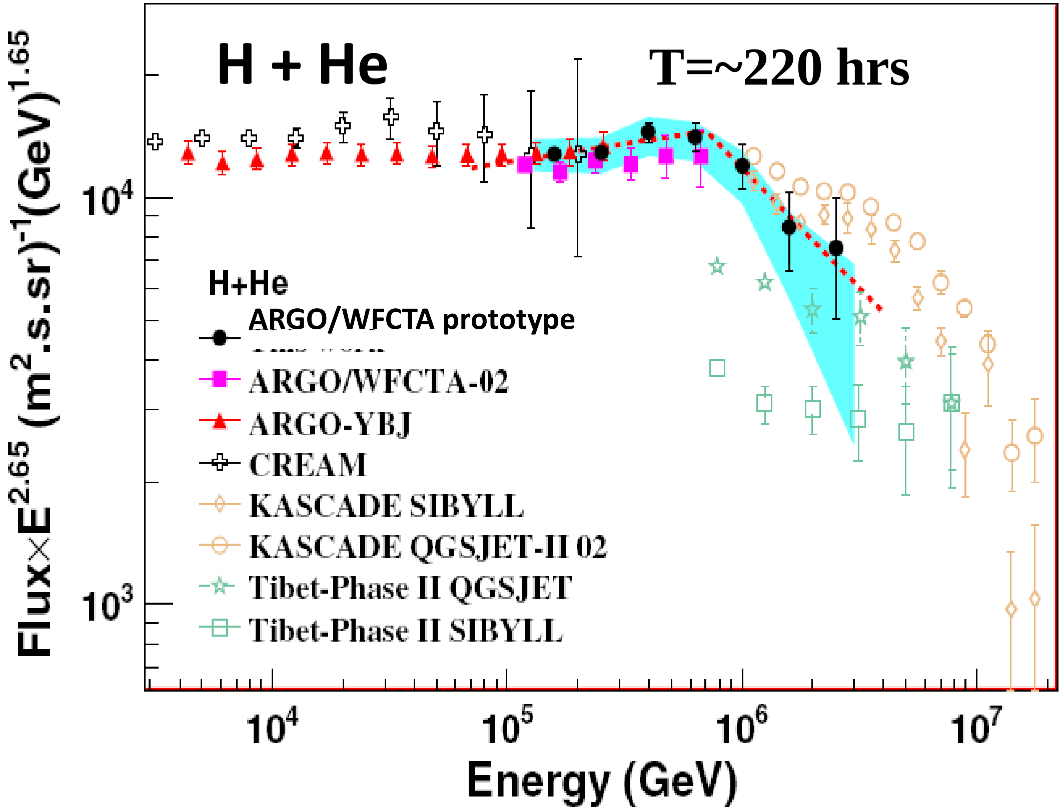






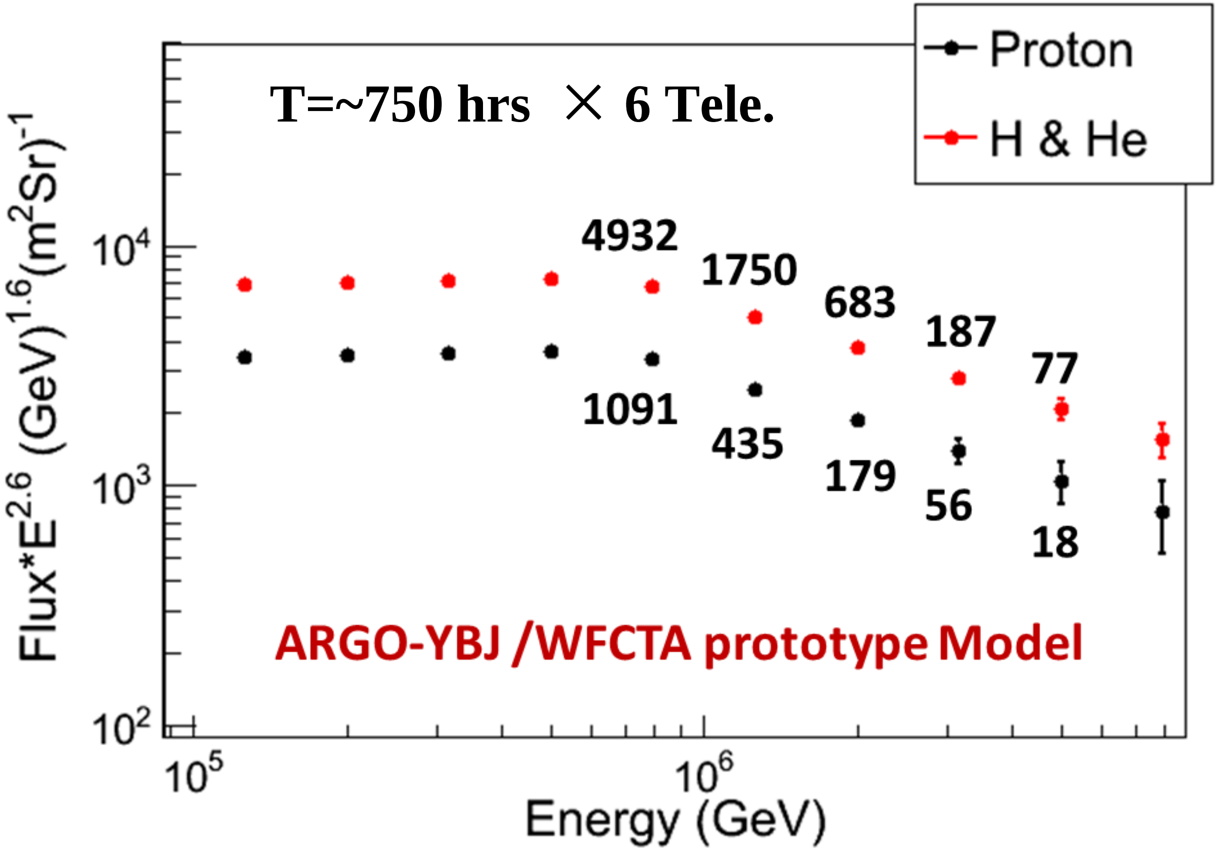
H and H+He spectra expectation by LHAASO

ARGO-YBJ + a Cherenkov prototype
The knee of H&He spectrum at
(700 ± 230) TeV is measured



PHYSICAL REVIEW D 92, 092005 (2015)

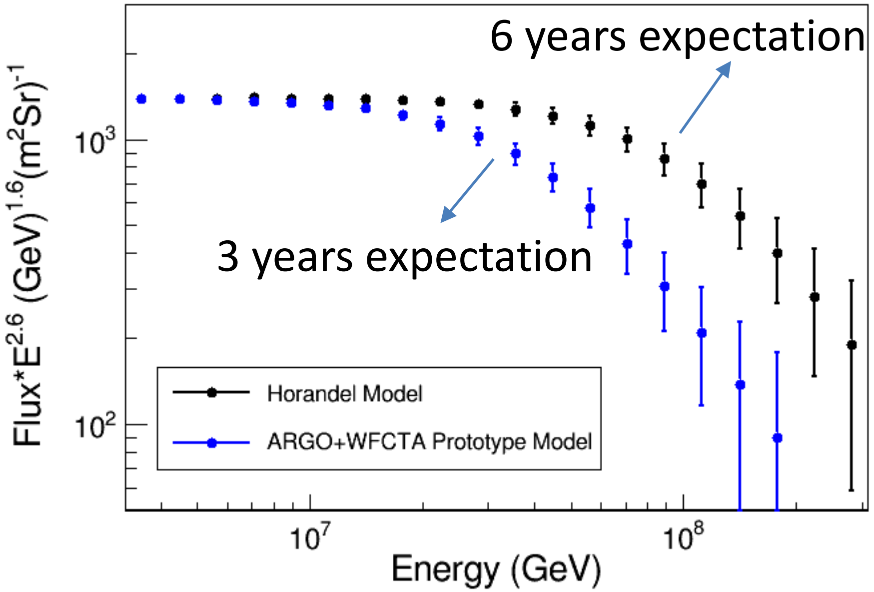
by six telescopes of LHAASO (zenith 60°)
during period of 2020.11 ~ 2021.04

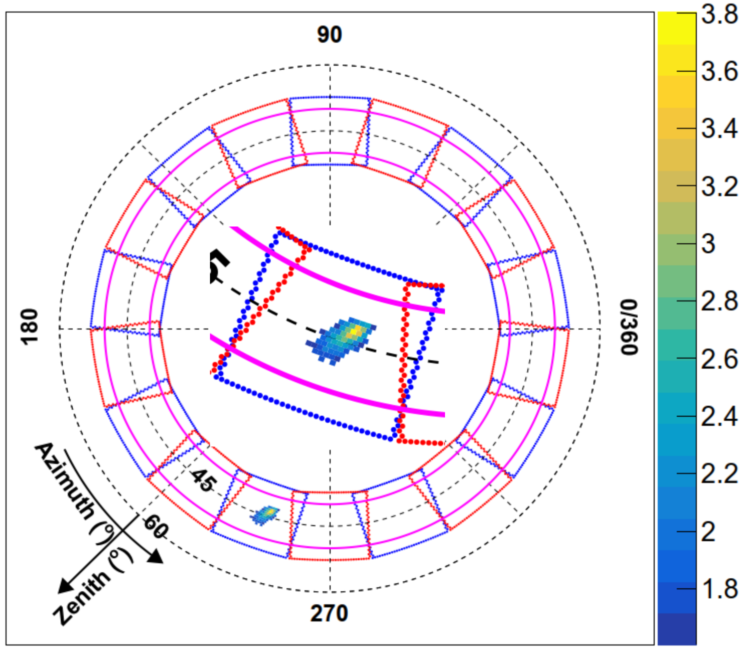


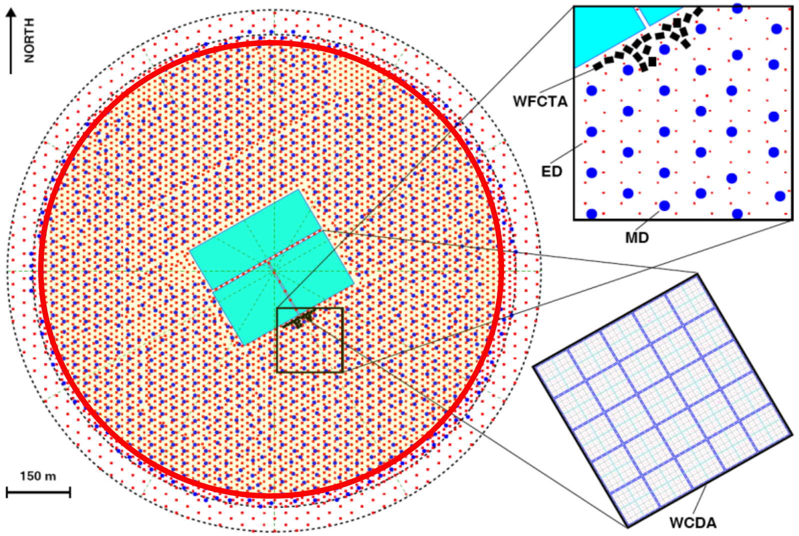
Iron knee expectation by LHAASO

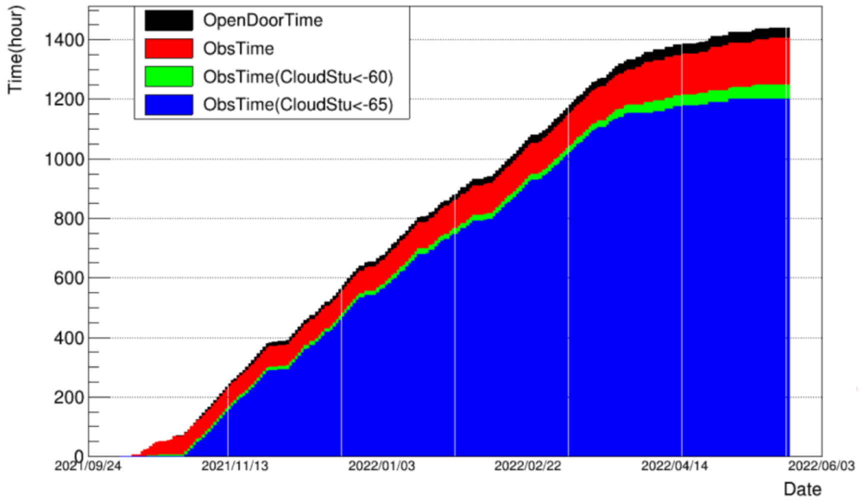
Phase II

- **Iron knee energy spectra observation:**
  - **18 telescopes point to zenith 45°, cover azimuth 0-360°**
  - **~1100 hours good data collected**
  - **WFCTA + KM2A (full array is used)**
  - **Energy range: several PeV - 200 PeV**





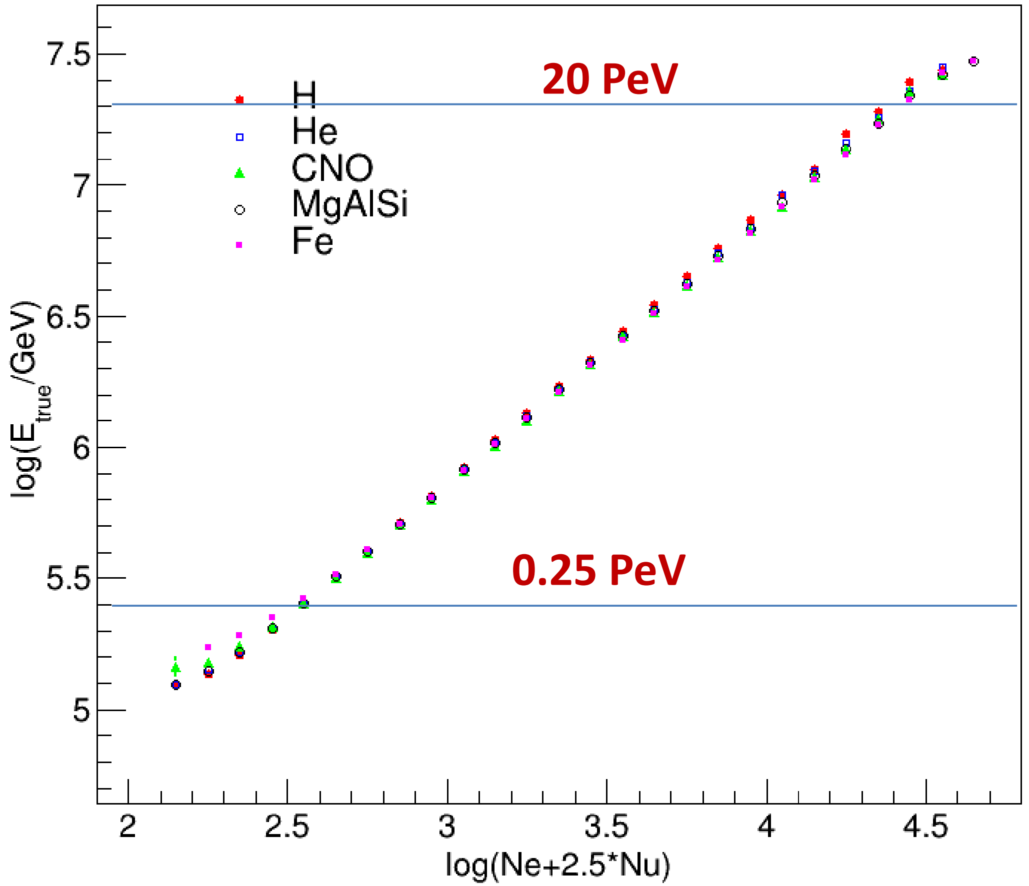


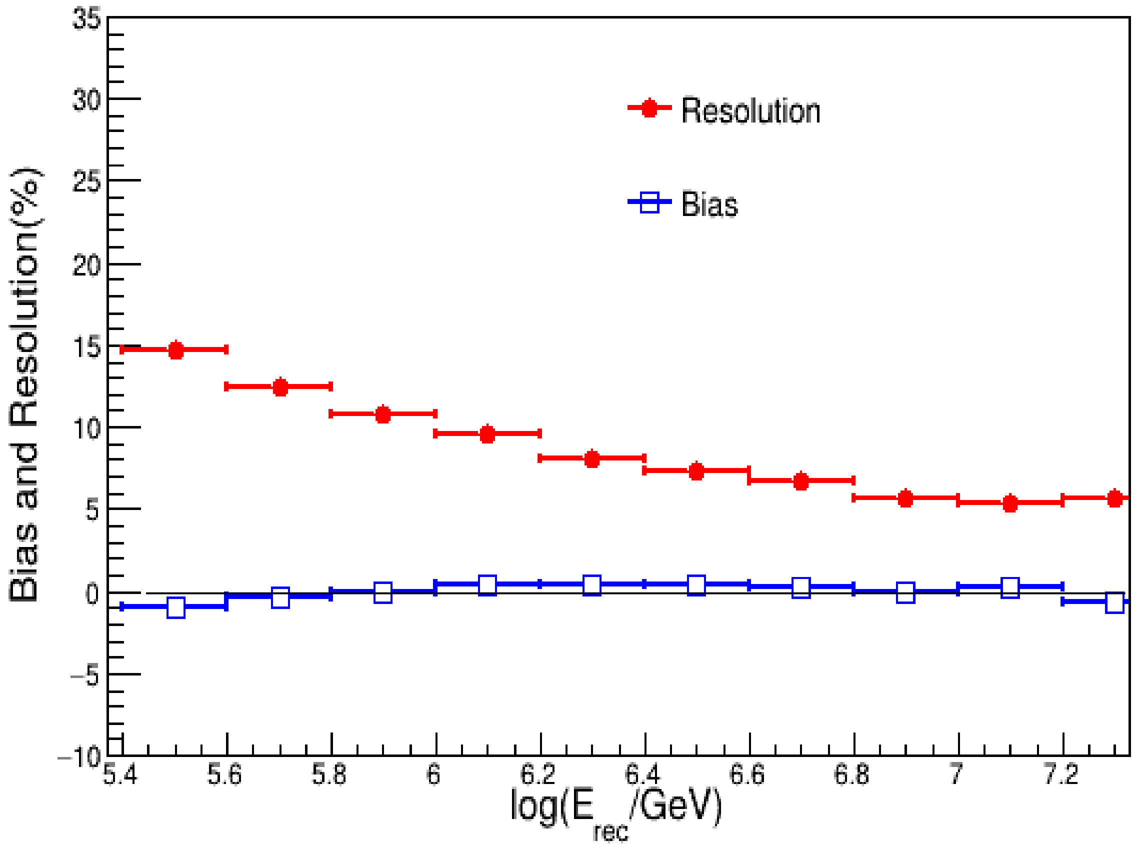


Progress of all particle spectrum by LHAASO

- Energy reconstruction independent of primary CRs components

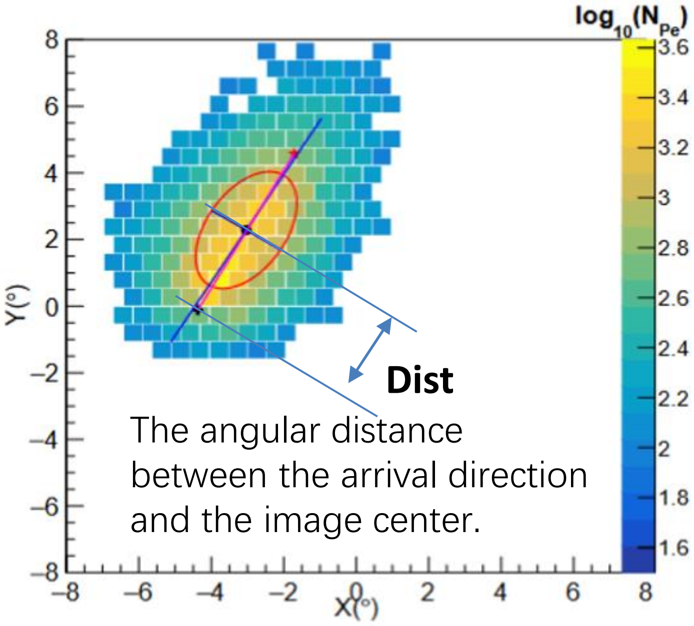
$$E_0 = E_e + E_h$$
$$N_{em} = N_e + 2.5 \cdot N_\mu$$
$$\log10(E) = a + b \cdot \log10(N_{em})$$



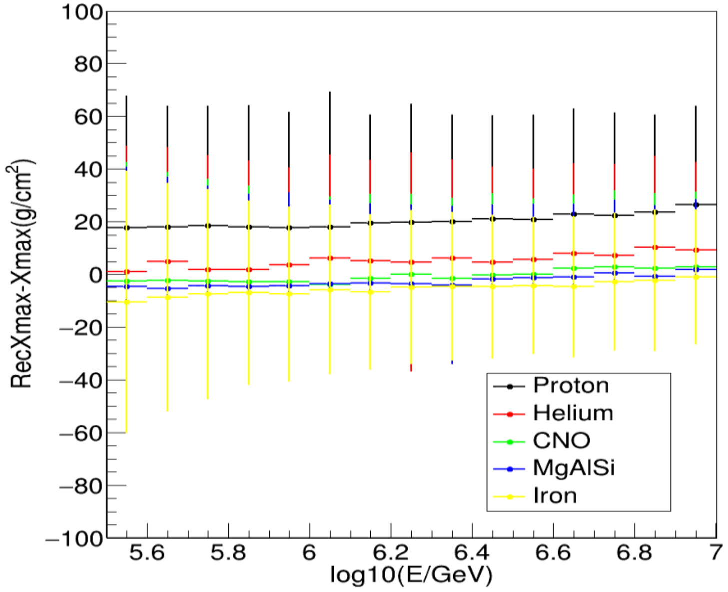


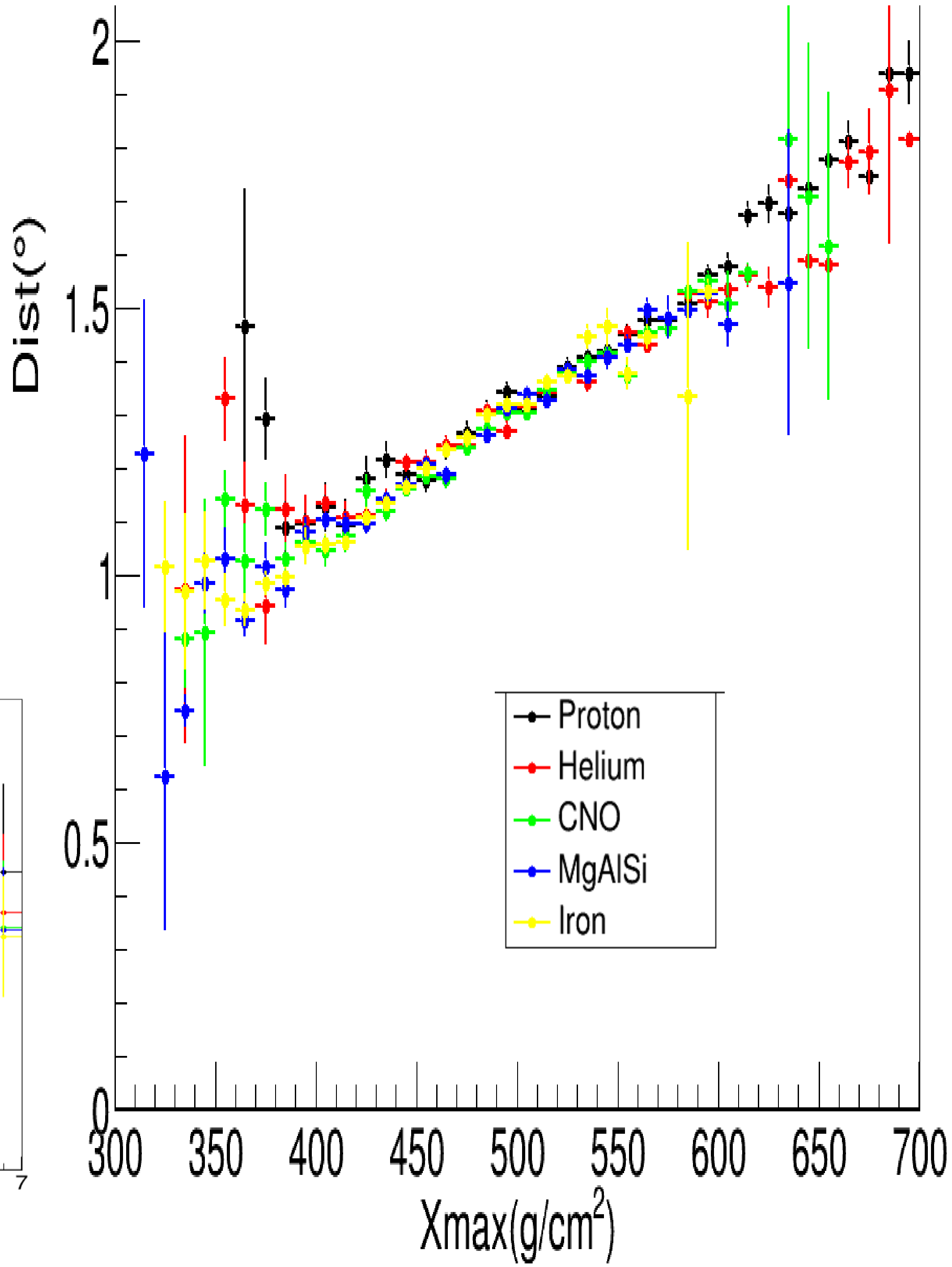
Xmax Measurement by WFCTA

- **Xmax is reconstructed by Dist**
- **Resolution**
  - **45g/cm² @ 1PeV for proton**
  - **34g/cm² @ 1PeV for iron**



Dist vs. Xmax
at a given Rp range



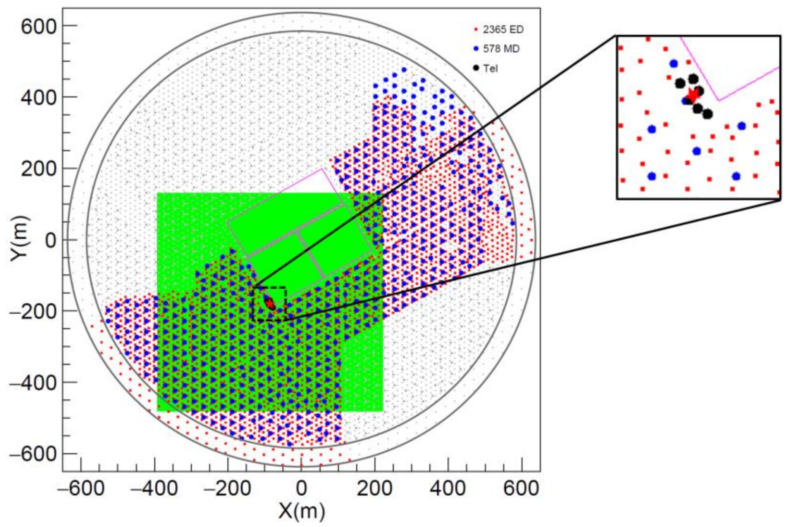


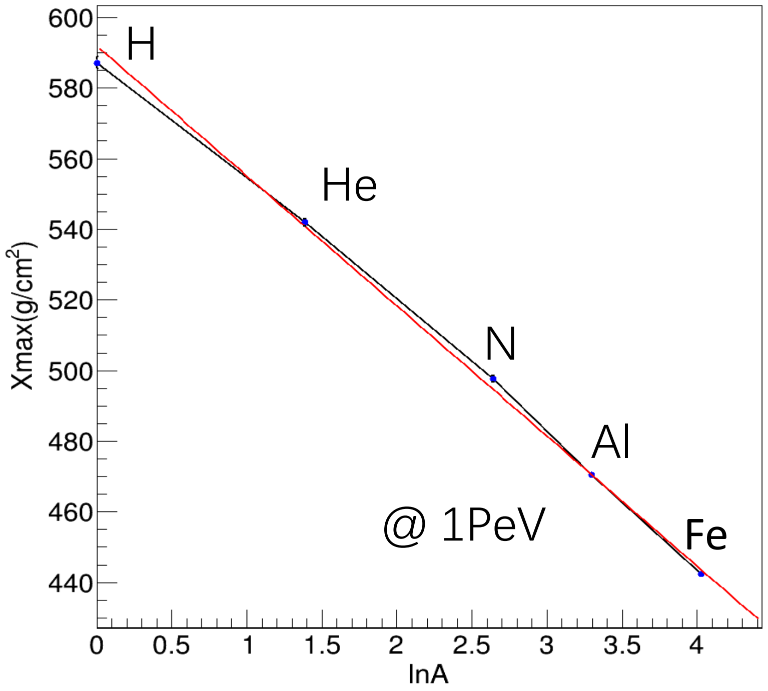
<lnA> Measured by Xmax of WFCTA

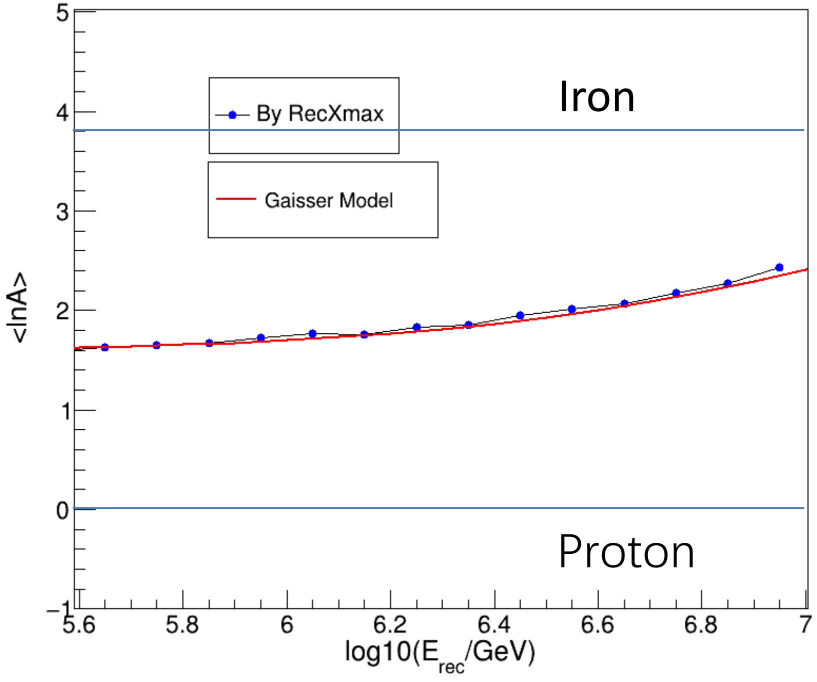
- Hybrid events with WFCTA and KM2A
  - 50 m<R_p<200 m, N_{pix}>20, (|X|<4˚ &|Y|<4˚)
  - 50+ hits and N_μ>5

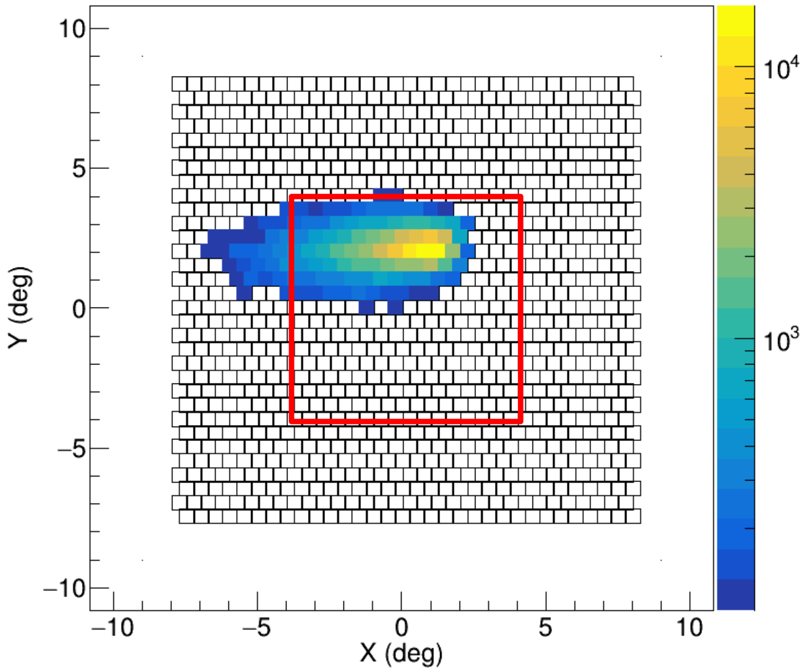
$$X^A_{max} = X^p_{max} - \lambda_r lnA$$

λ_r = 37g/cm² is radiation length

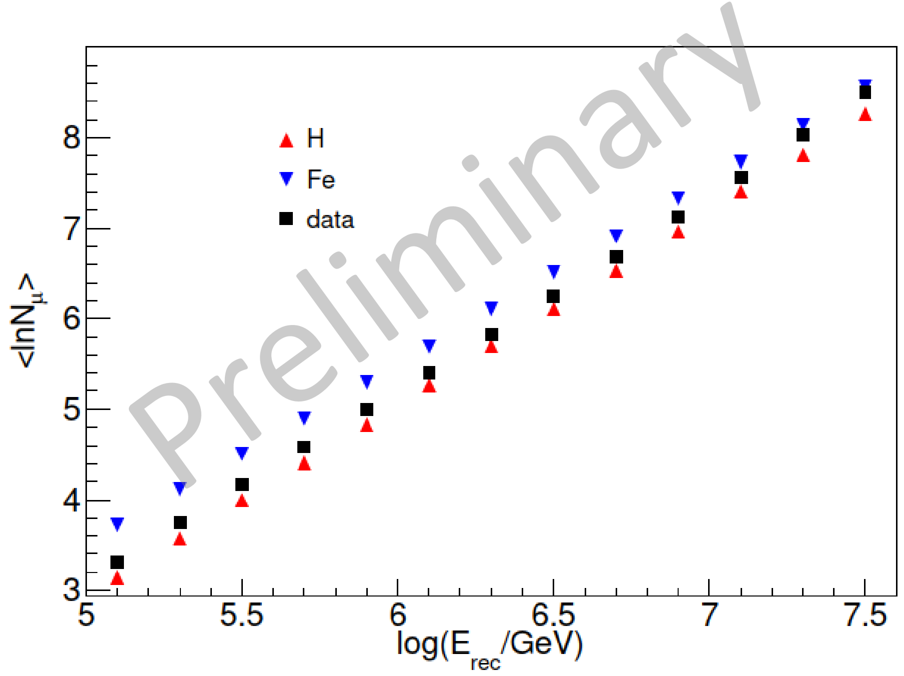








<lnA> reconstructed by muon in KM2A

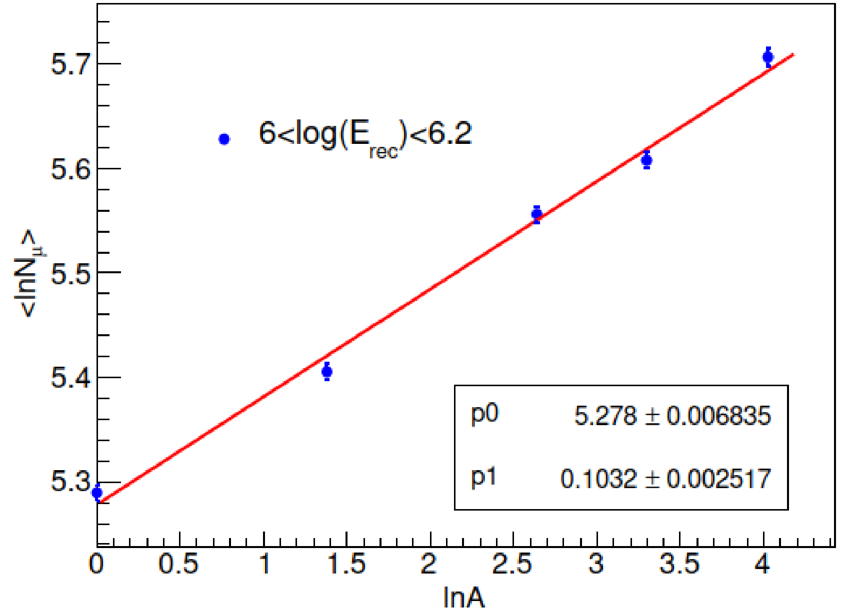


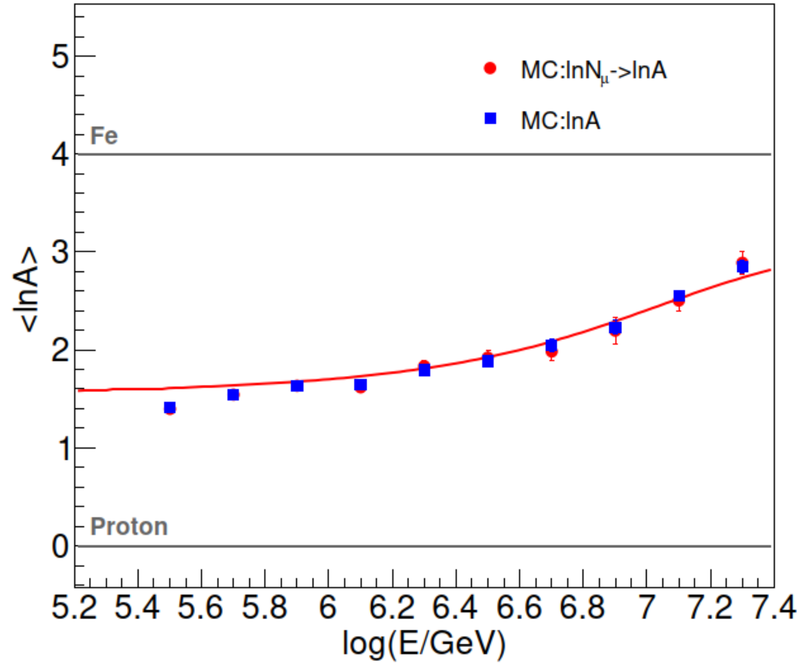
$$N_\mu = A \cdot \left(\frac{E}{A \cdot \varepsilon_c}\right)^\beta$$

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.

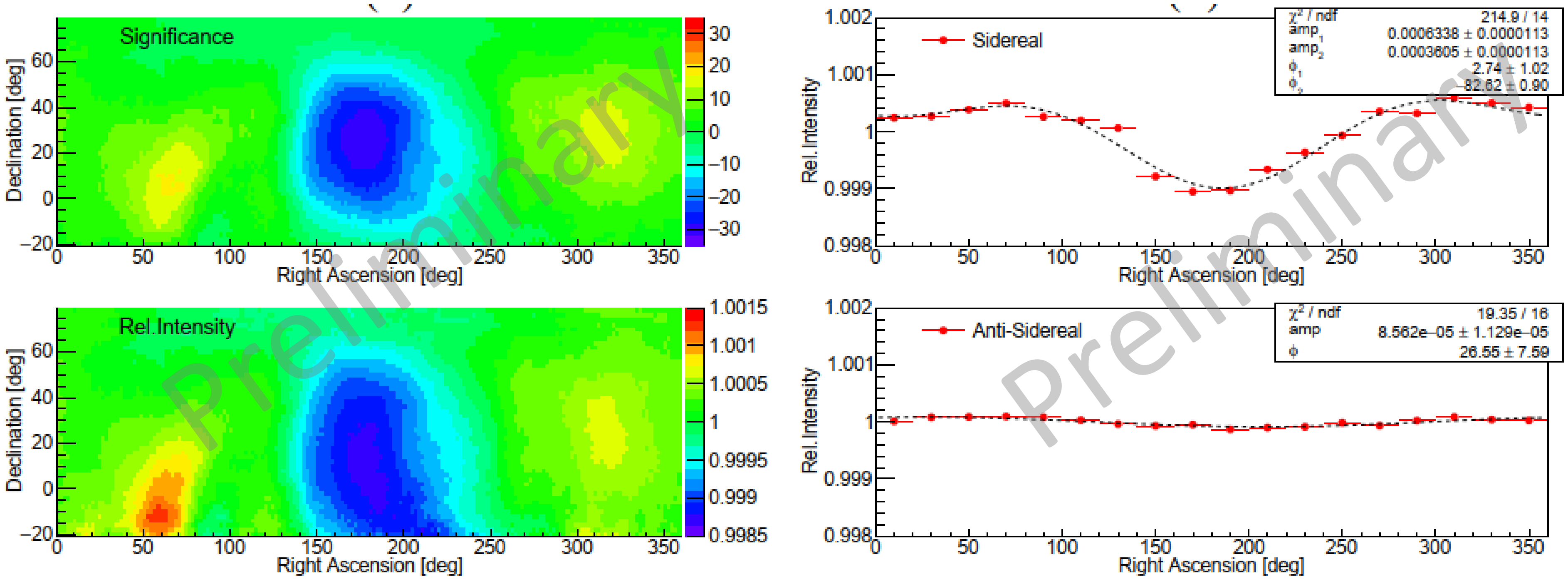
$$\ln N_\mu = p_0 + p_1 \cdot \ln A$$





Progress of large-scale CRs anisotropy observed by LHAASO

- **Data set:**
  - 1/2 KM2A array： 2020/01/01-2020/11/30
  - Core inside KM2A array
  - Number of fired EDs>20
- **The preliminary CRs all particle anisotropy was observed by 1/2 KM2A array**
- **Different component group of anisotropy analysis is in progress.**



Wei Gao et al., 37th International Cosmic Ray Conference (ICRC2021), 2021 Berlin, Germany

Summary

- LHAASO is built July 2021 and stably operating since then
- The absolute energy scale at 21 TeV was measured by using WCDA and propagated to WFCTA by using the common trigger events
  - the uncertainty will be less than 10% in 4 years with more statistics
- The knee of pure proton spectrum will be measured in the first phase
  - Analysis is in progress
- Since the last run, the second phase were started in last winter. The knee of the iron spectrum is the goal
- CR Composition, all-particle spectrum and anisotropy are under analysis

Thanks for you attention!