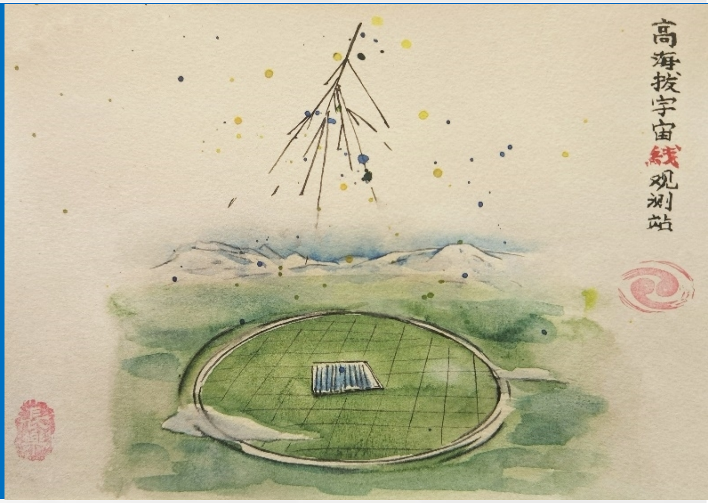
LHAASO
高海拔宇宙线观测站

Cosmic ray spectrum and Composition study with LHAASO



Shoushan Zhang for LHAASO collaboration

Institute of High Energy Physics

Cosmic Rays in the Multi-Messenger Era
Paris, France, 5-7 Dec. 2022

Outline

- ☐ LHAASO experiment
- ☐ Calibration
- ☐ CR spectrum measurements
- ☐ Summary

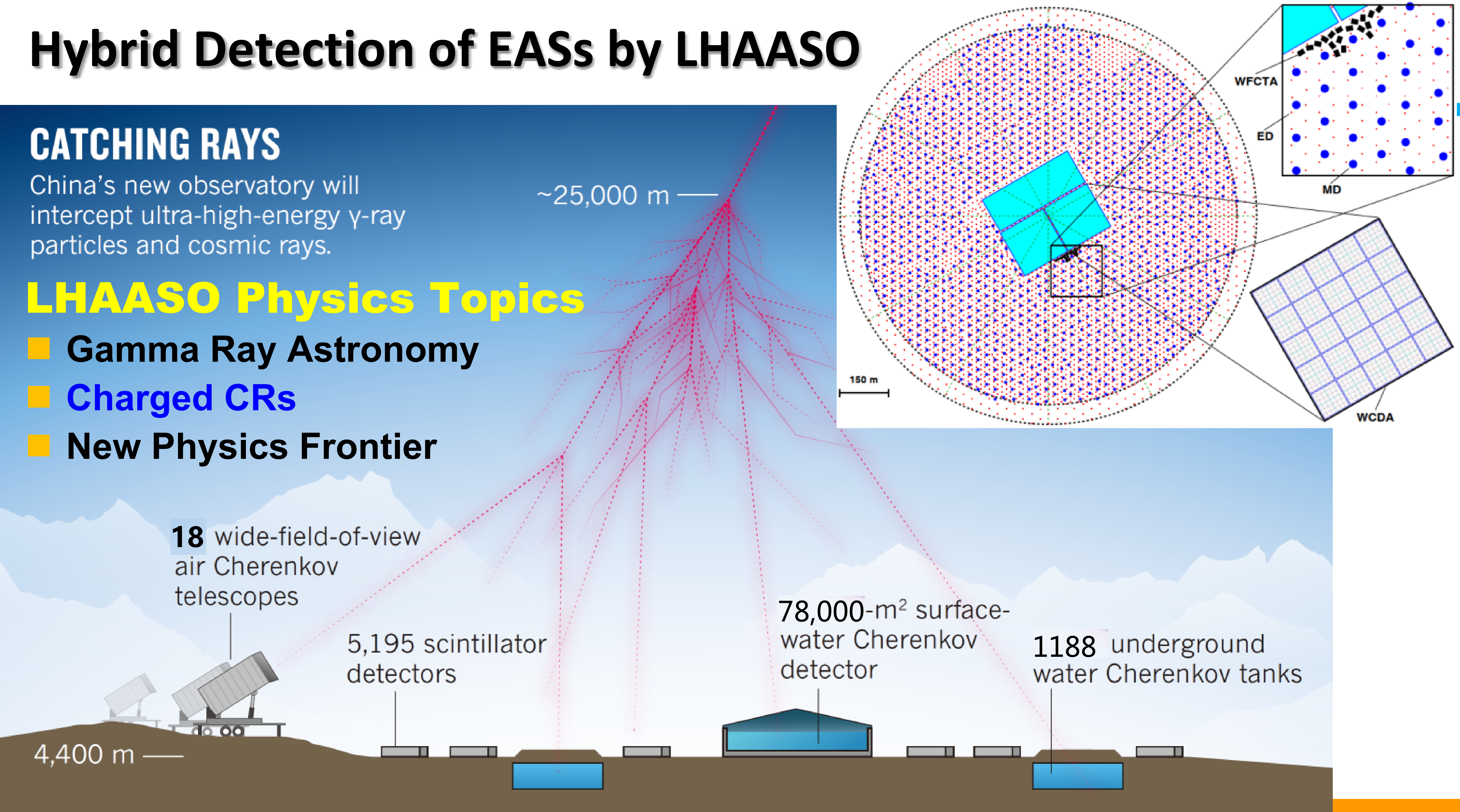
LHAASO Collaboration

275 members from
31 institutions in
5 countries

Zhen Cao,[1,2,3] F. Aharonian,[4,5] Q. An,[6,7] Axikegu,[8] L.X. Bai,[9] Y.X. Bai,[1,3] Y.W. Bao,[10] D. Bastieri,[11] X.J. Bi*,[1,2,3] Y.J. Bi,[1,3] H. Cai,[12] J.T. Cai,[11] Zhe Cao,[6,7] J. Chang,[13] J.F. Chang,[1,3,6] B.M. Chen,[14] E.S. Chen*,[1,2,3] J. Chen,[9] Liang Chen,[1,2,3] Liang Chen,[15] Long Chen,[8] M.J. Chen,[1,3] M.L. Chen,[1,3,6] Q.H. Chen,[8] S.H. Chen,[1,2,3] S.Z. Chen,[1,3] T.L. Chen,[16] X.L. Chen,[1,2,3] Y. Chen,[10] N. Cheng,[1,3] Y.D. Cheng,[1,3] S.W. Cui,[14] X.H. Cui,[17] Y.D. Cui,[18] B. D'Ettorre Piazzoli,[19] B.Z. Dai,[20] H.L. Dai,[1,3,6] Z.G. Dai,[7] Danzengluobu,[16] D. della Volpe,[21] X.J. Dong,[1,3] K.K. Duan,[13] J.H. Fan,[11] Y.Z. Fan,[13] Z.X. Fan,[1,3] J. Fang,[20] K. Fang,[1,3] C.F. Feng,[22] L. Feng,[13] S.H. Feng,[1,3] Y.L. Feng,[13] B. Gao,[1,3] C.D. Gao,[22] L.Q. Gao*,[1,2,3] Q. Gao,[16] W. Gao,[22] M.M. Ge,[20] L.S. Geng,[1,3] G.H. Gong,[23] Q.B. Gou,[1,3] M.H. Gu,[1,3,6] F.L. Guo,[15] J.G. Guo,[1,2,3] X.L. Guo,[8] Y.Q. Guo,[1,3] Y.Y. Guo,[1,2,3,13] Y.A. Han,[24] H.H. He,[1,2,3] H.N. He,[13] J.C. He,[1,2,3] S.L. He,[11] X.B. He,[18] Y. He,[8] M. Heller,[21] Y.K. Hor,[18] C. Hou,[1,3] X. Hou,[25] H.B. Hu,[1,2,3] S. Hu,[9] S.C. Hu,[1,2,3] X.J. Hu,[23] D.H. Huang,[8] Q.L. Huang,[1,3] W.H. Huang,[22] X.T. Huang,[22] X.Y. Huang,[13] Z.C. Huang,[8] F. Ji,[1,3] X.L. Ji,[1,3,6] H.Y. Jia,[8] K. Jiang,[6,7] Z.J. Jiang,[20] C. Jin,[1,2,3] T. Ke,[1,3] D. Kuleshov,[26] K. Levochkin,[26] B.B. Li,[14] Cheng Li,[6,7] Cong Li,[1,3] F. Li,[1,3,6] H.B. Li,[1,3] H.C. Li,[1,3] H.Y. Li,[7,13] Jian Li,[7] Jie Li,[1,3,6] K. Li,[1,3] W.L. Li,[22] X.R. Li,[1,3] Xin Li,[6,7] Xin Li,[8] Y. Li,[9] Y.Z. Li,[1,2,3] Zhe Li,[1,3] Zhuo Li,[27] E.W. Liang,[28] Y.F. Liang,[28] S.J. Lin,[18] B. Liu,[7] C. Liu,[1,3] D. Liu,[22] H. Liu,[8] H.D. Liu,[24] J. Liu,[1,3] J.L. Liu,[29] J.S. Liu,[18] J.Y. Liu,[1,3] M.Y. Liu,[16] R.Y. Liu,[10] S.M. Liu,[8] W. Liu,[1,3] Y. Liu,[11] Y.N. Liu,[23] Z.X. Liu,[9] W.J. Long,[8] R. Lu,[20] H.K. Lv,[1,3] B.Q. Ma,[27] L.L. Ma,[1,3] X.H. Ma,[1,3] J.R. Mao,[25] A. Masood,[8] Z. Min,[1,3] W. Mitthumsiri,[30] T. Montaruli,[21] Y.C. Nan,[22] B.Y. Pang,[8] P. Pattarakijwanich,[30] Z.Y. Pei,[11] M.Y. Qi,[1,3] Y.Q. Qi,[14] B.Q. Qiao,[1,3] J.J. Qin,[7] D. Ruffolo,[30] V. Rulev,[26] A. Sáiz,[30] L. Shao,[14] O. Shchegolev,[26,31] X.D. Sheng,[1,3] J.R. Shi,[1,3] H.C. Song,[27] Yu.V. Stenkin,[26,31] V. Stepanov,[26] Y. Su,[13] Q.N. Sun,[8] X.N. Sun,[28] Z.B. Sun,[32] P.H.T. Tam,[18] Z.B. Tang,[6,7] W.W. Tian,[2,17] B.D. Wang,[1,3] C. Wang,[32] H. Wang,[8] H.G. Wang,[11] J.C. Wang,[25] J.S. Wang,[29] L.P. Wang,[22] L.Y. Wang,[1,3] R.N. Wang,[8] W. Wang,[18] W. Wang,[12] X.G. Wang,[28] X.J. Wang,[1,3] X.Y. Wang,[10] Y. Wang,[8] Y.D. Wang,[1,3] Y.J. Wang,[1,3] Y.P. Wang,[1,2,3] Z.H. Wang,[9] Z.X. Wang,[20] Zhen Wang,[29] Zheng Wang,[1,3,6] D.M. Wei,[13] J.J. Wei,[13] Y.J. Wei,[1,2,3] T. Wen,[20] C.Y. Wu,[1,3] H.R. Wu,[1,3] S. Wu,[1,3] W.X. Wu,[8] X.F. Wu,[13] S.Q. Xi,[1,3] J. Xia,[7,13] J.J. Xia,[8] G.M. Xiang,[2,15] D.X. Xiao,[16] G. Xiao,[1,3] H.B. Xiao,[11] G.G. Xin,[12] Y.L. Xin,[8] Y. Xing,[15] D.L. Xu,[29] R.X. Xu,[27] L. Xue,[22] D.H. Yan,[25] J.Z. Yan,[13] C.W. Yang,[9] F.F. Yang,[1,3,6] J.Y. Yang,[18] L.L. Yang,[18] M.J. Yang,[1,3] R.Z. Yang,[7] S.B. Yang,[20] Y.H. Yao,[9] Z.G. Yao,[1,3] Y.M. Ye,[23] L.Q. Yin,[1,3] N. Yin,[22] X.H. You,[1,3] Z.Y. You,[1,2,3] Y.H. Yu,[22] Q. Yuan*,[13] H.D. Zeng,[13] T.X. Zeng,[1,3,6] W. Zeng,[20] Z.K. Zeng,[1,2,3] M. Zha,[1,3] X.X. Zhai,[1,3] B.B. Zhang,[10] H.M. Zhang,[10] H.Y. Zhang,[22] J.L. Zhang,[17] J.W. Zhang,[9] L.X. Zhang,[11] Li Zhang,[20] Lu Zhang,[14] P.F. Zhang,[20] P.P. Zhang,[14] R. Zhang,[7,13] S.R. Zhang,[14] S.S. Zhang,[1,3] X. Zhang,[10] X.P. Zhang,[1,3] Y.F. Zhang,[8] Y.L. Zhang,[1,3] Yi Zhang*,[1,13] Yong Zhang,[1,3] B. Zhao,[8] J. Zhao,[1,3] L. Zhao,[6,7] L.Z. Zhao,[14] S.P. Zhao*,[13,22] F. Zheng,[32] Y. Zheng,[8] B. Zhou,[1,3] H. Zhou,[29] J.N. Zhou,[15] P. Zhou,[10] R. Zhou,[9] X.X. Zhou,[8] C.G. Zhu,[22] F.R. Zhu,[8] H. Zhu,[17] K.J. Zhu,[1,2,3,6] and X. Zuo[1,3]

(LHAASO Collaboration)*

Hybrid Detection of EASs by LHAASO



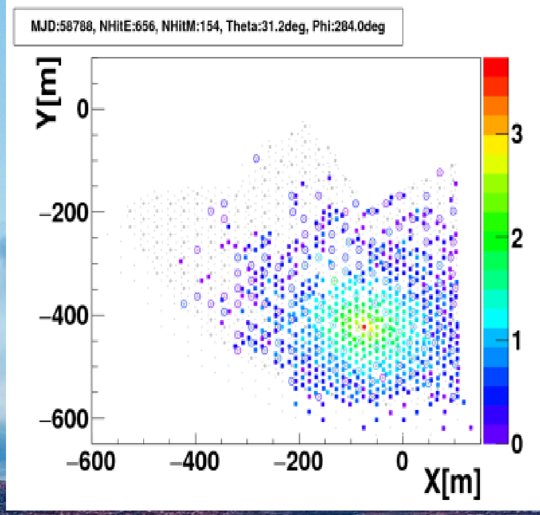
CATCHING RAYS

China's new observatory will intercept ultra-high-energy γ-ray particles and cosmic rays.

LHAASO Physics Topics

- Gamma Ray Astronomy
- Charged CRs
- New Physics Frontier

Bird's eye view of LHAASO (2021-12)



Location：Haizi Moutain, Daochen, Sichuan, China

Altitude: 4410 m

2021-07 completed built and in operation

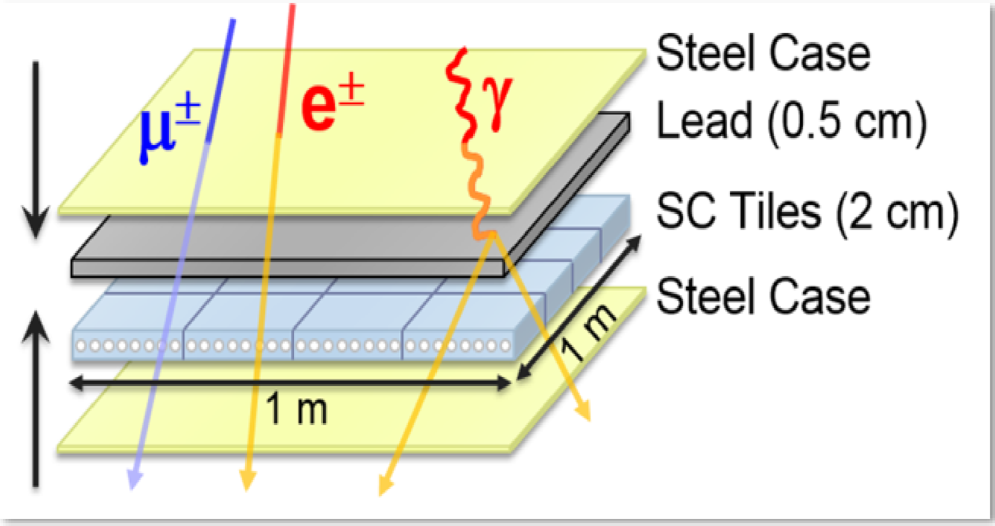
KM2A: 1.36 (km)^2

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

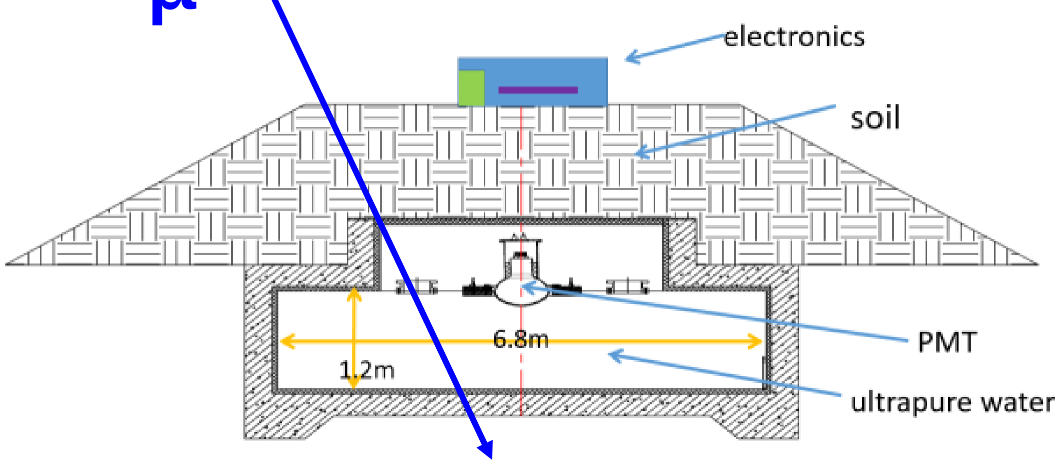
KM2A: 1.36 $(km)^2$

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

Scintillator Detectors （ED）

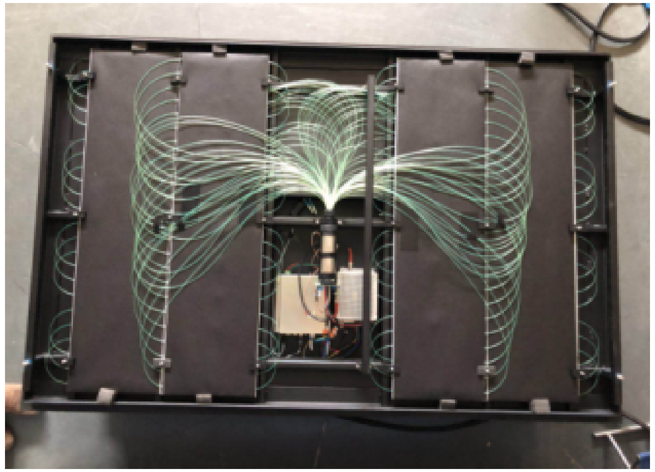


Muon detector（MD）

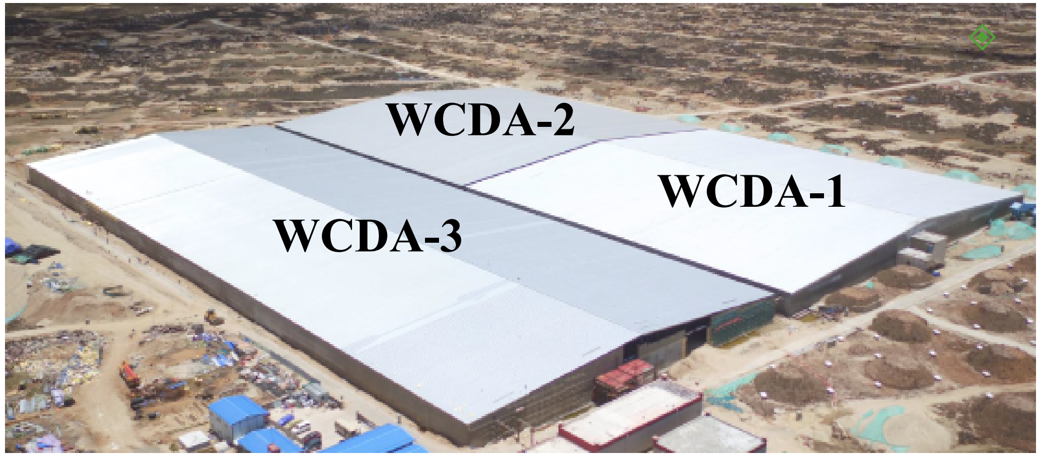


MD Bladder

Inner View of Scintillator Detector

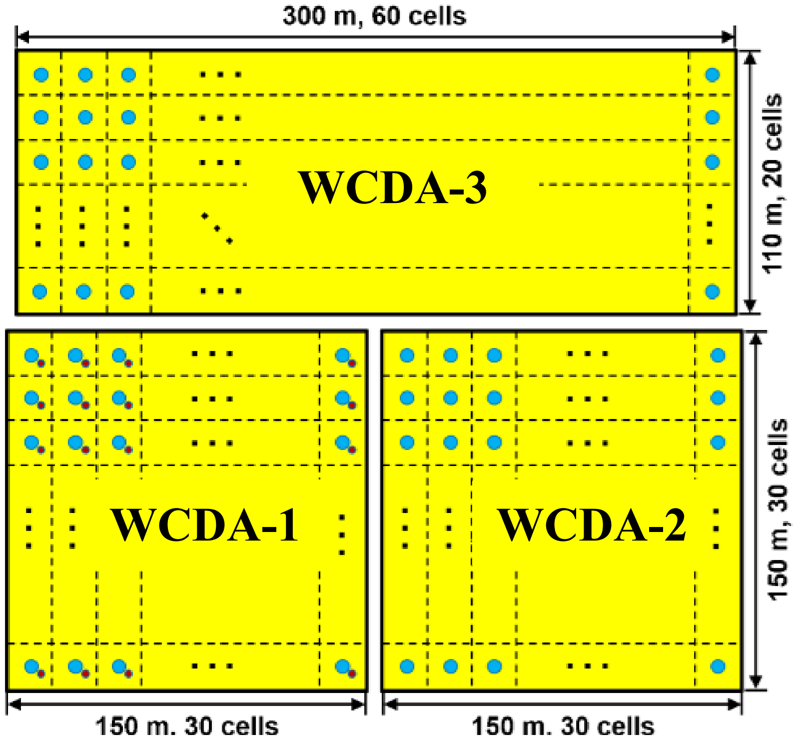


Water Cherenkov Detector Array (WCDA)

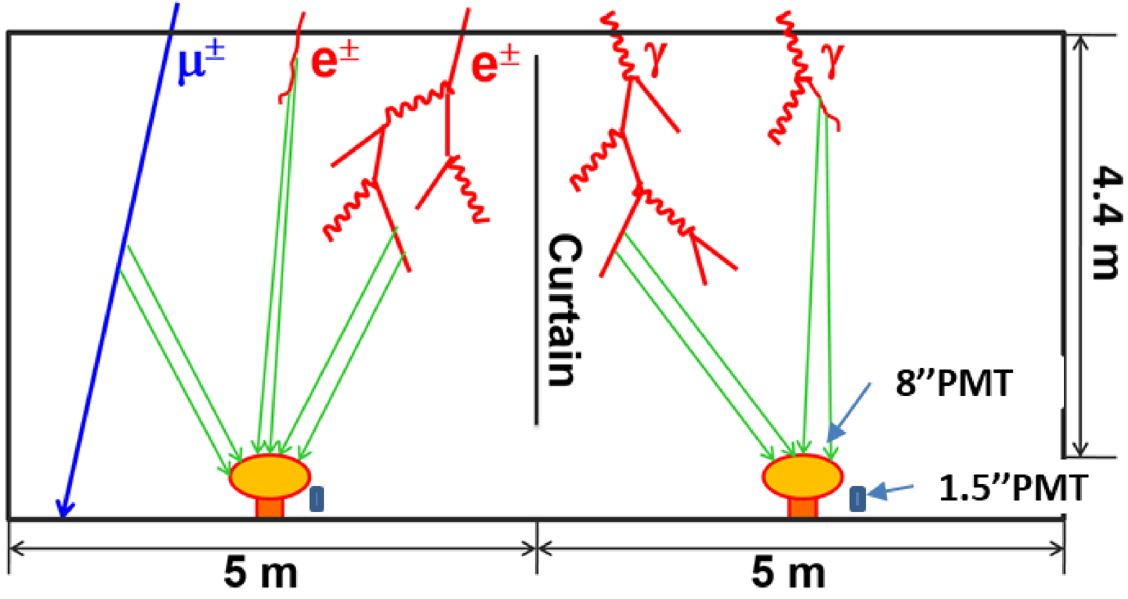


Energy rang

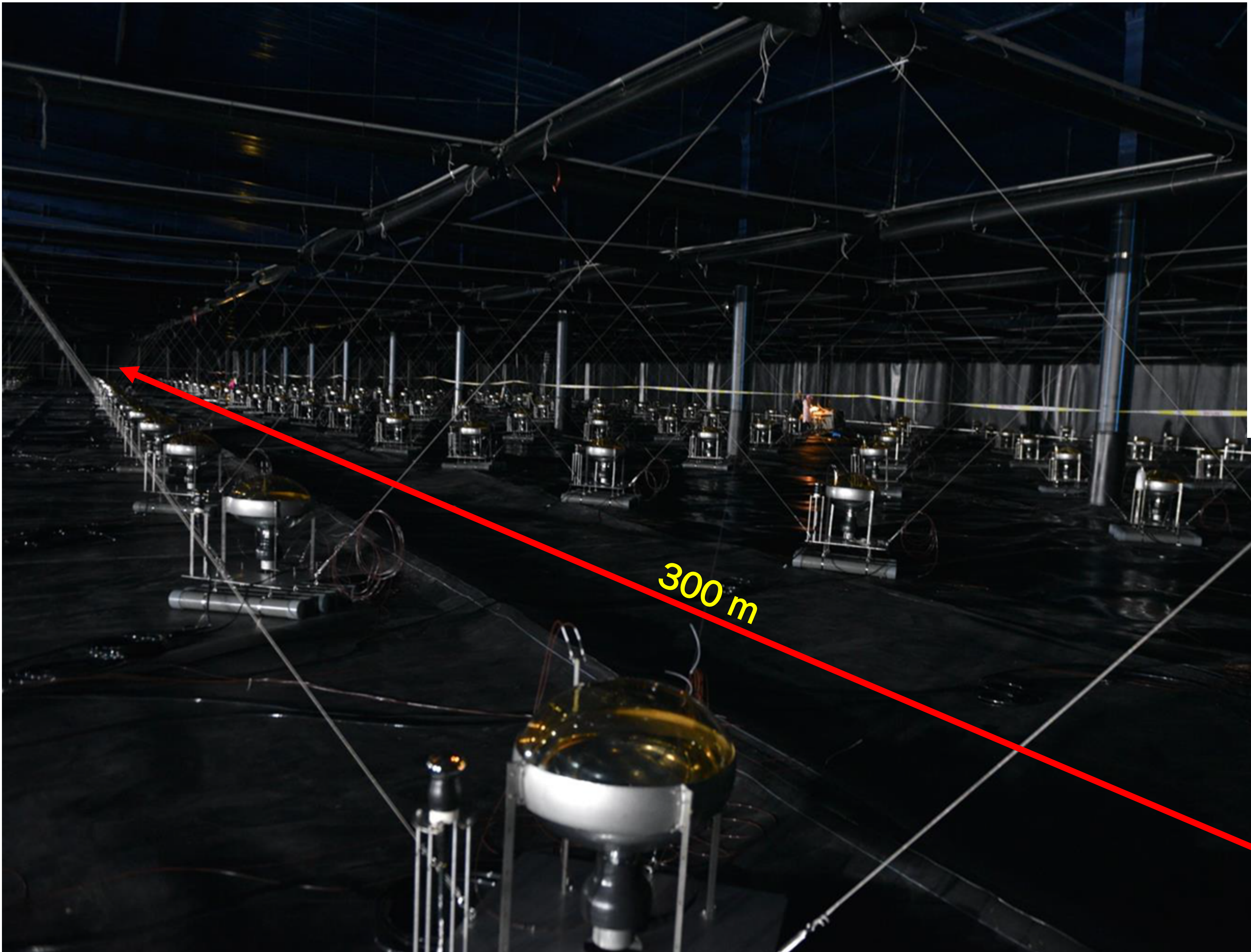
- **WCDA-1**
  - 0.3 – 10 PeV
- **WCDA-2/3**
  - 0.1 - 10 TeV

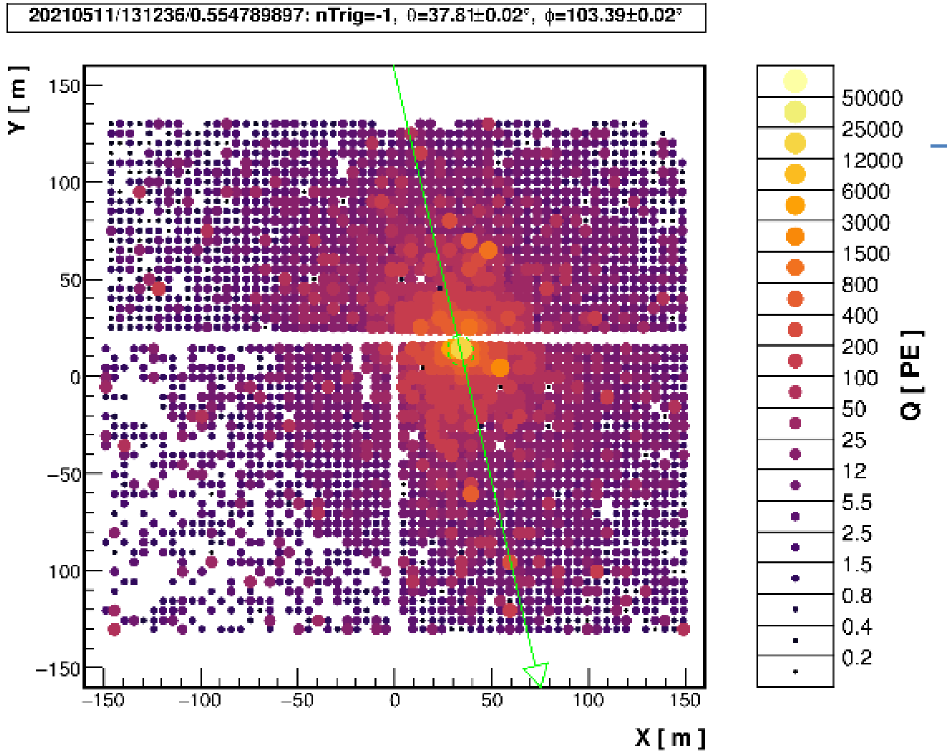


- Total area: $78,000m^2$
- Total units: 3,120
- Unit size: $5m \times 5m \times 4.4m$
- Two configurations:
  - 8” and 1.5” PMTs for WCDA-1 (900 ch)
  - 20” and 3” PMTs for WCDA-2/3 (2220 ch)



Inside of WCDA





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

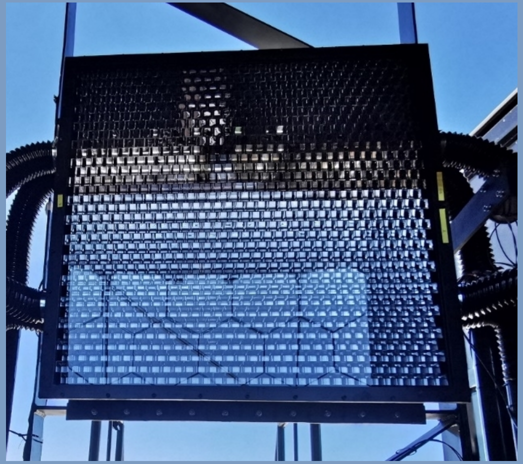
Wide Field of View Cherenkov Telescope (WFCTA)

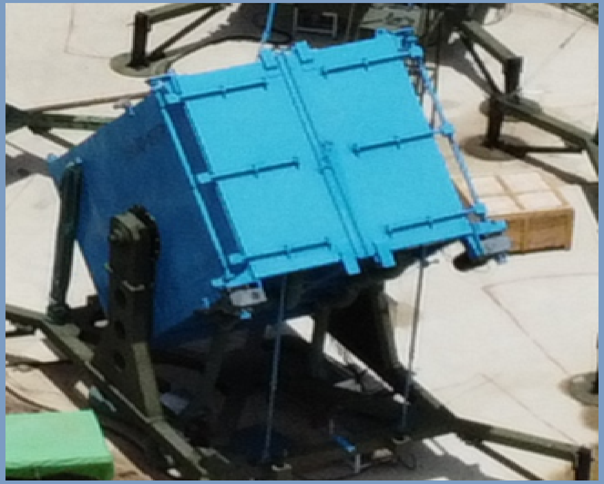
◆ Telescope parameters

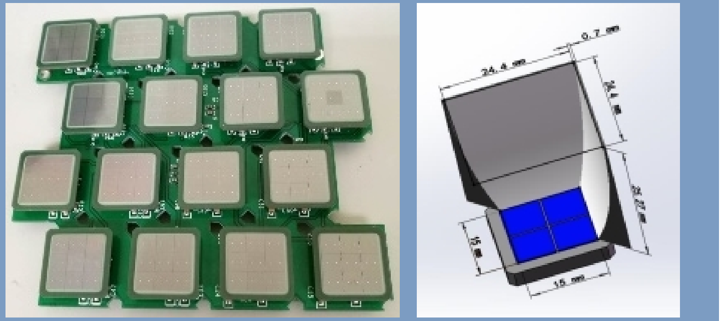
- ~5 m^2 spherical mirror
- Camera: 32×32 SiPMs array
- FOV: 16° × 16°
- Pixel size: 0.5°
- >30% duty cycle in winter


18 Telescopes

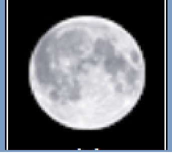

Mirror

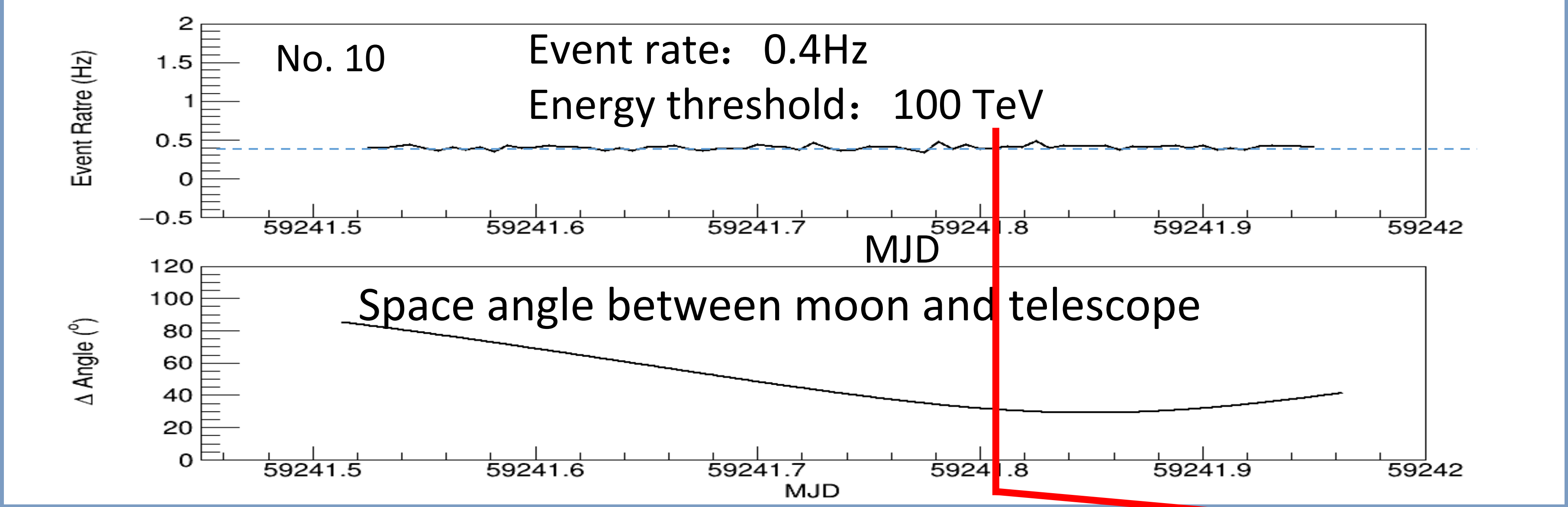

SiPM camera




SiPM and Winston cone

Telescope observation with the full moon

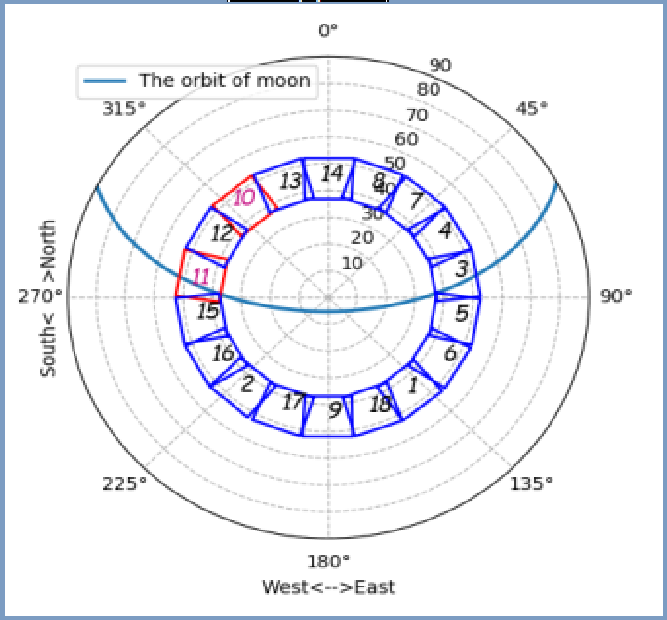



No. 10

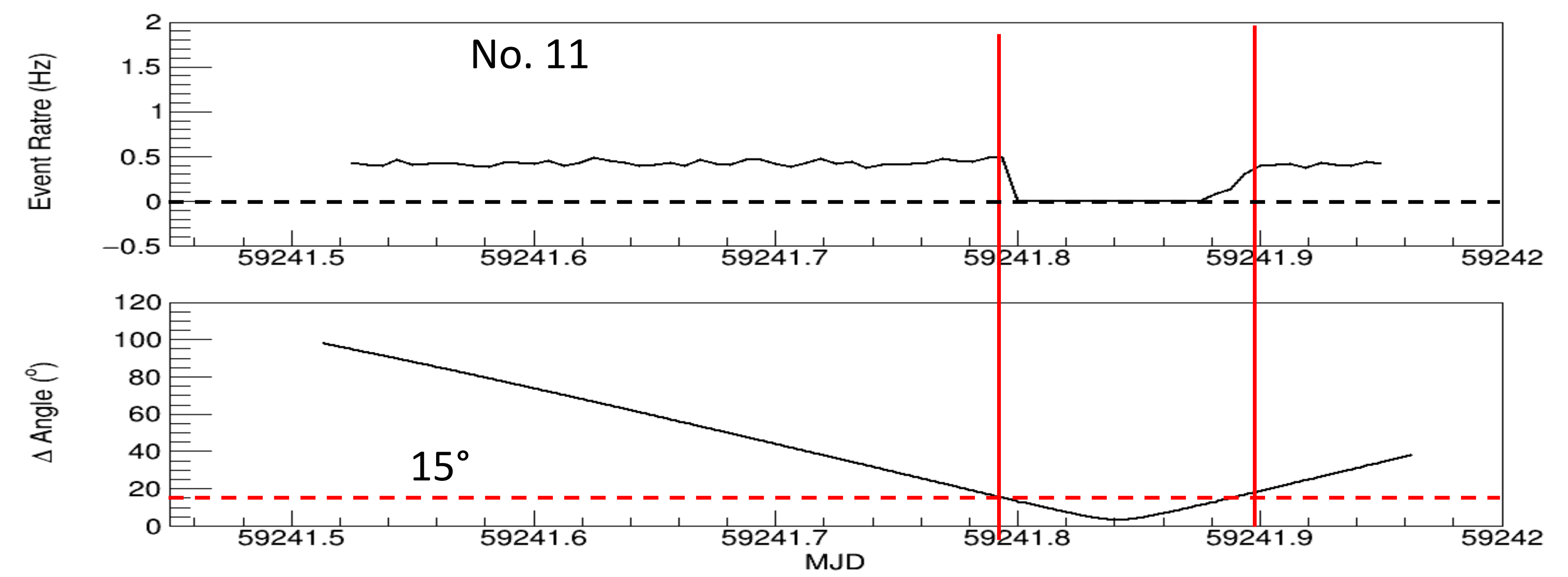
Event rate：0.4Hz

Energy threshold：100 TeV

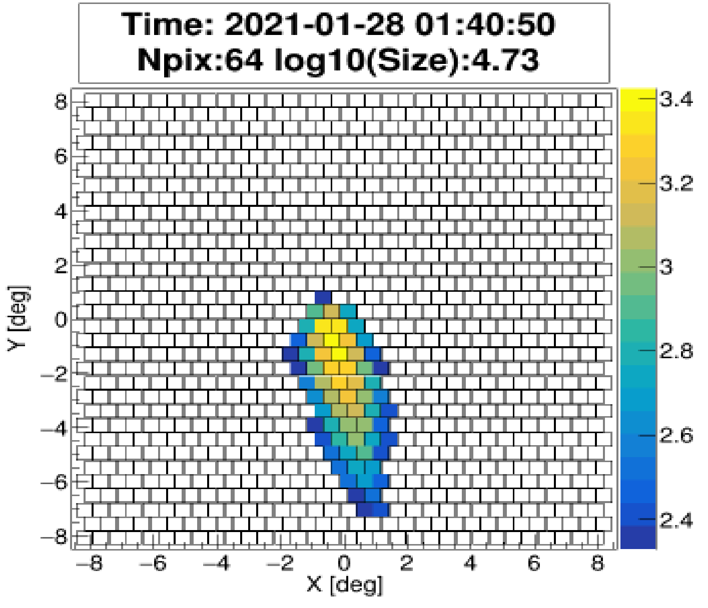
Space angle between moon and telescope



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


No. 11

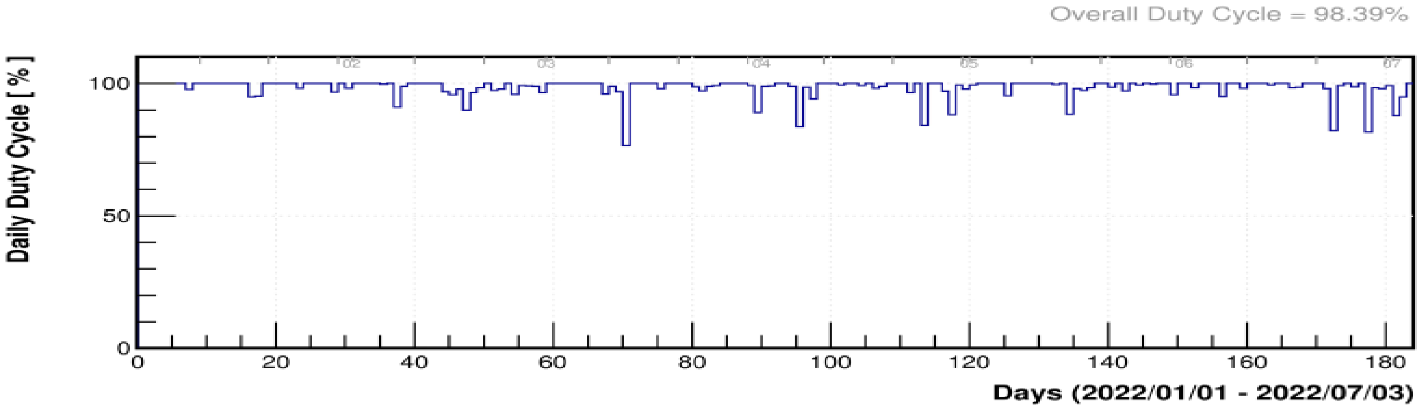
15°

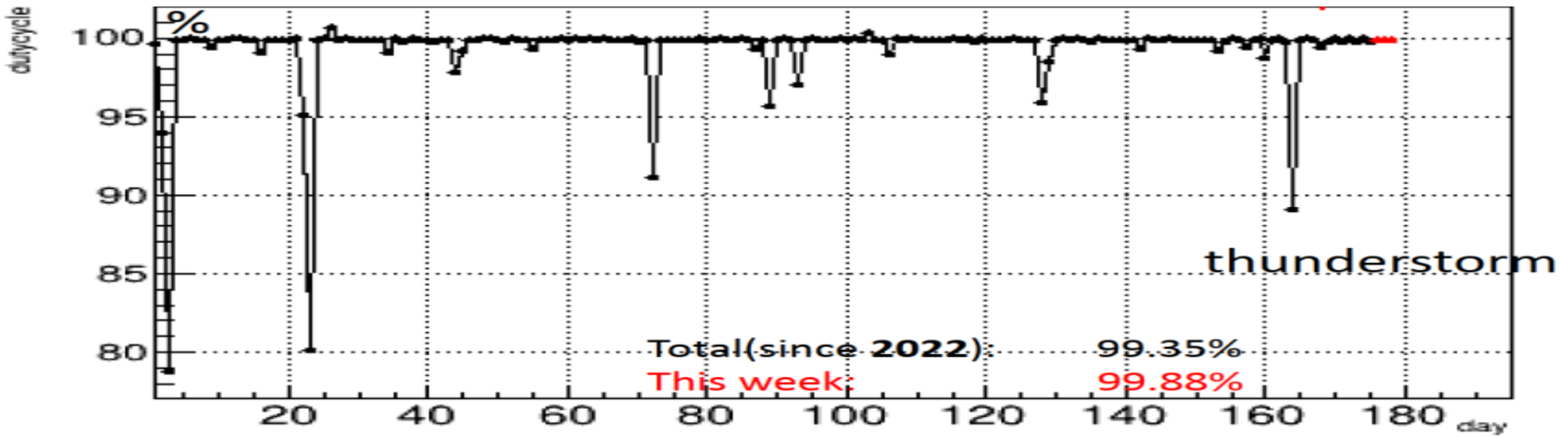

Time: 2021-01-28 01:40:50

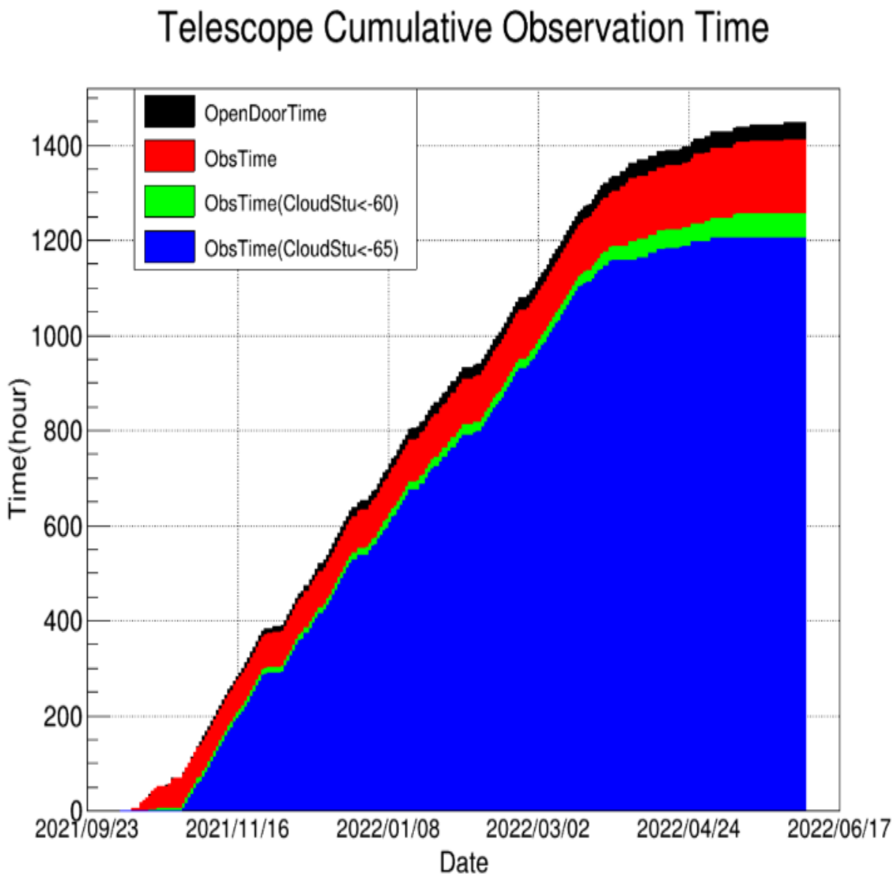
Npix:64 log10(Size):4.73

Operation of LHAASO

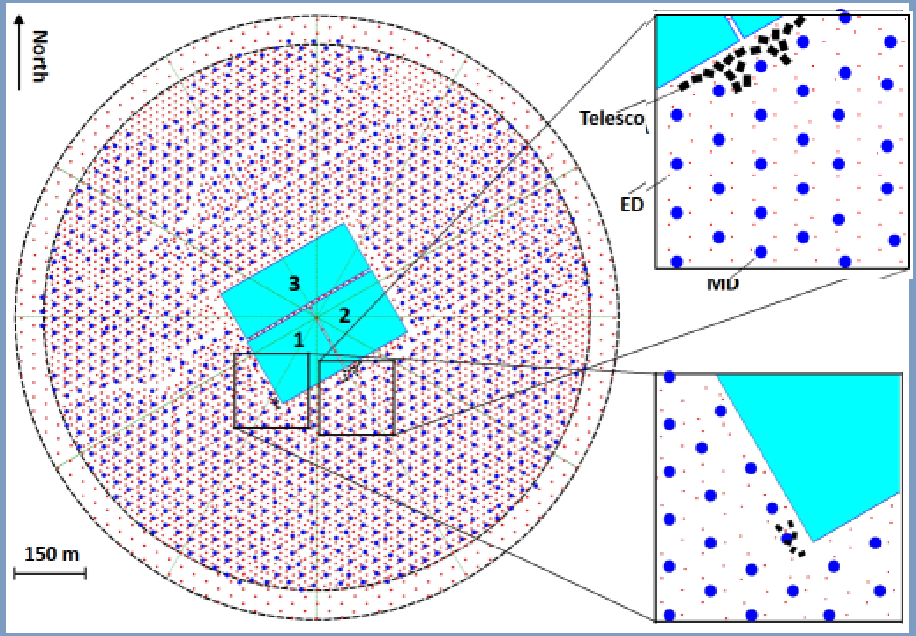
- KM2A is operated with >99.4% duty cycle and event rate 2x10⁸ /day
- WCDA is operated with 98.4% and event rate 3x10⁹ /day
- Data acquisition time of WFCTA >1400 hrs/year and number of matched events ~70 million

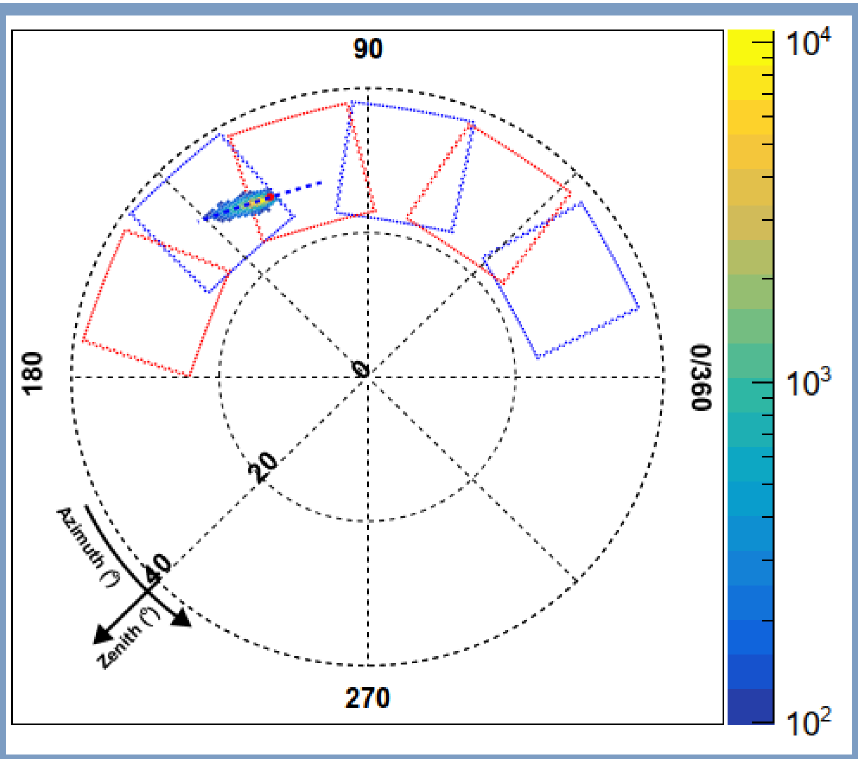






Observational Phases

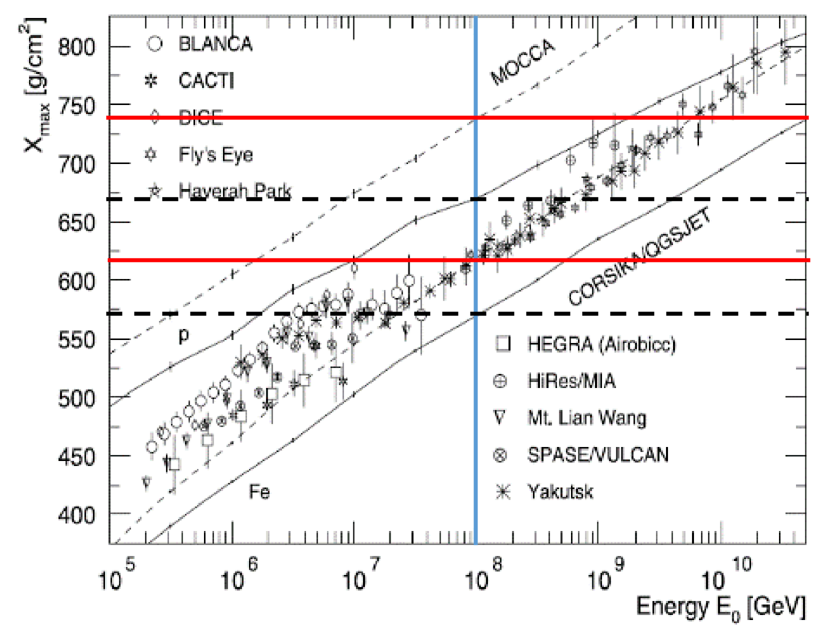


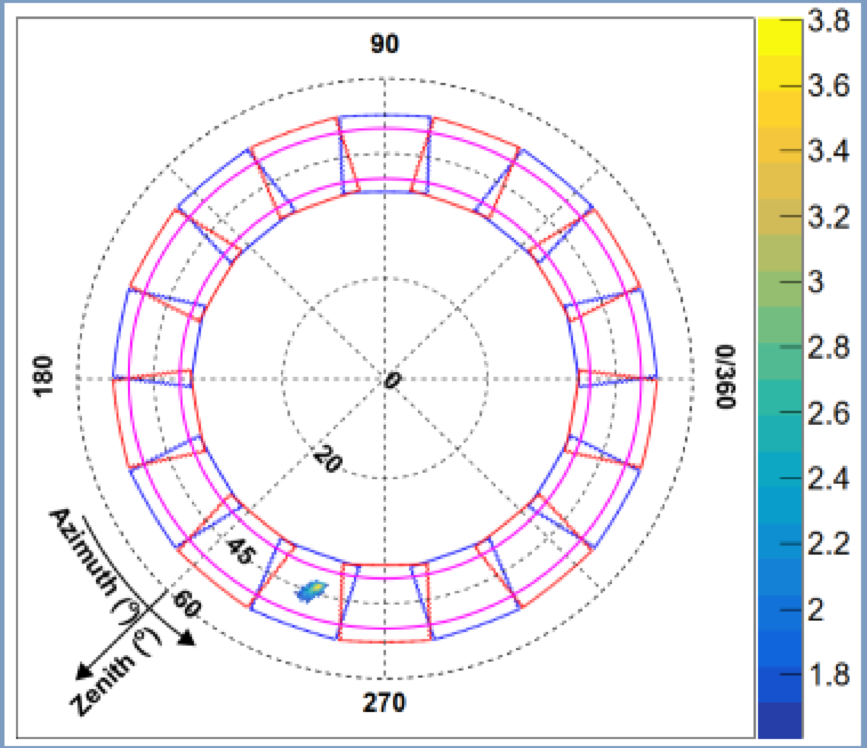


- Phase I: 6 telescopes
  - 2019/10 – 2021/4
  - Zenith angle: 30°
  - Proton, H+He knees
  - 100 TeV – 10 PeV

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



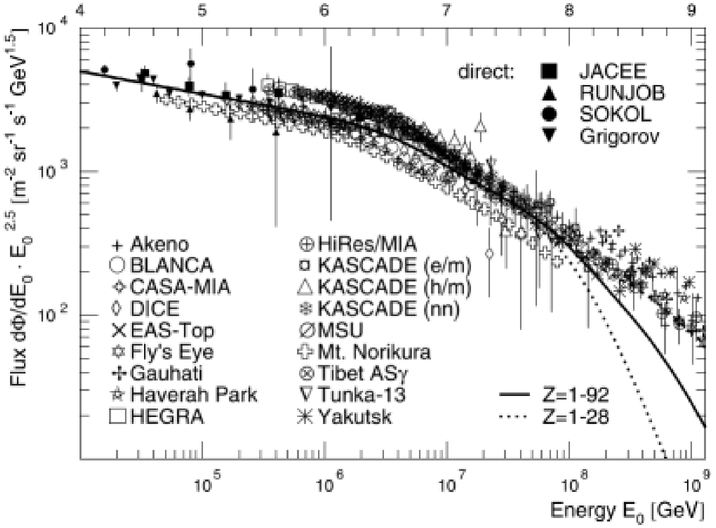


- ☐ LHAASO experiment
- ☐ Calibration
  - ☐ Absolute Energy Scale
  - ☐ Pointing Direction
  - ☐ Photometric calib.
- ☐ CR spectrum measurements
- ☐ Summary

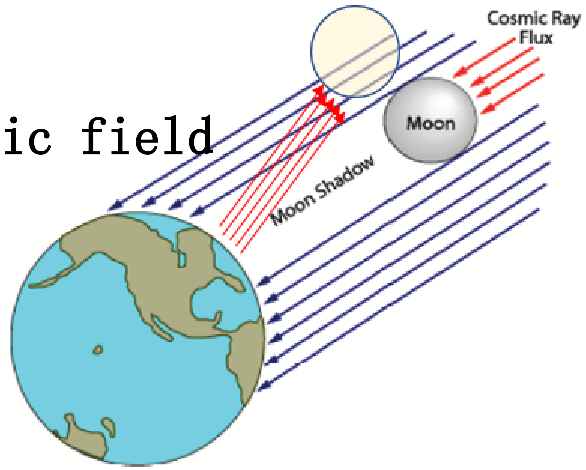
Absolute energy scale obtained by LHAASO

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

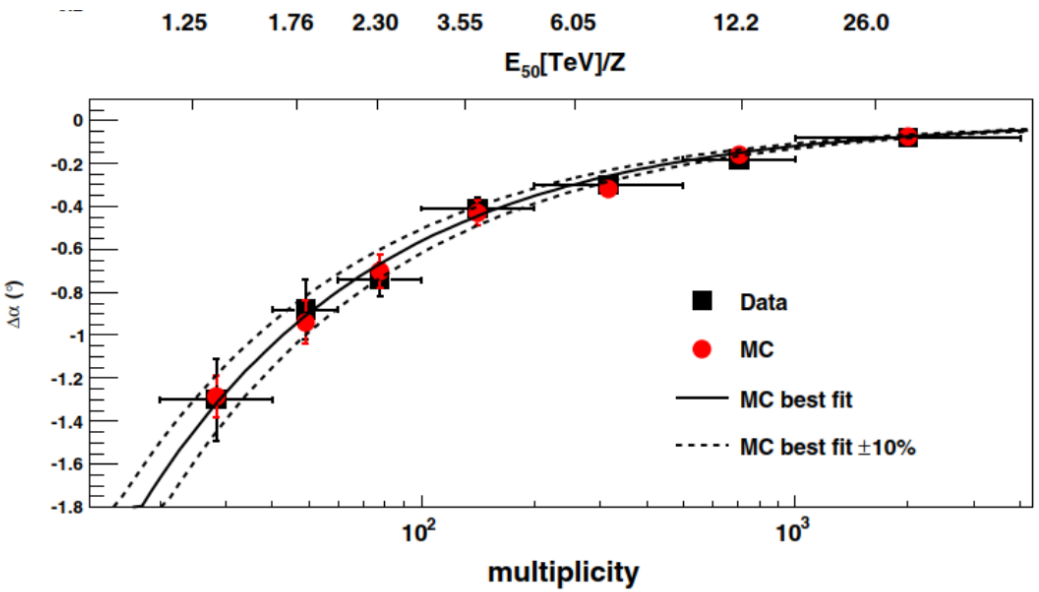
- Ground-based detector array
  - It is impossible to generate an artificial test beam for the calibration
  - The test team from the CRs Moon shadow was first explored by ARGO-YBJ, which can be used to calibrate the ground-based experiment



Geomagnetic field



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



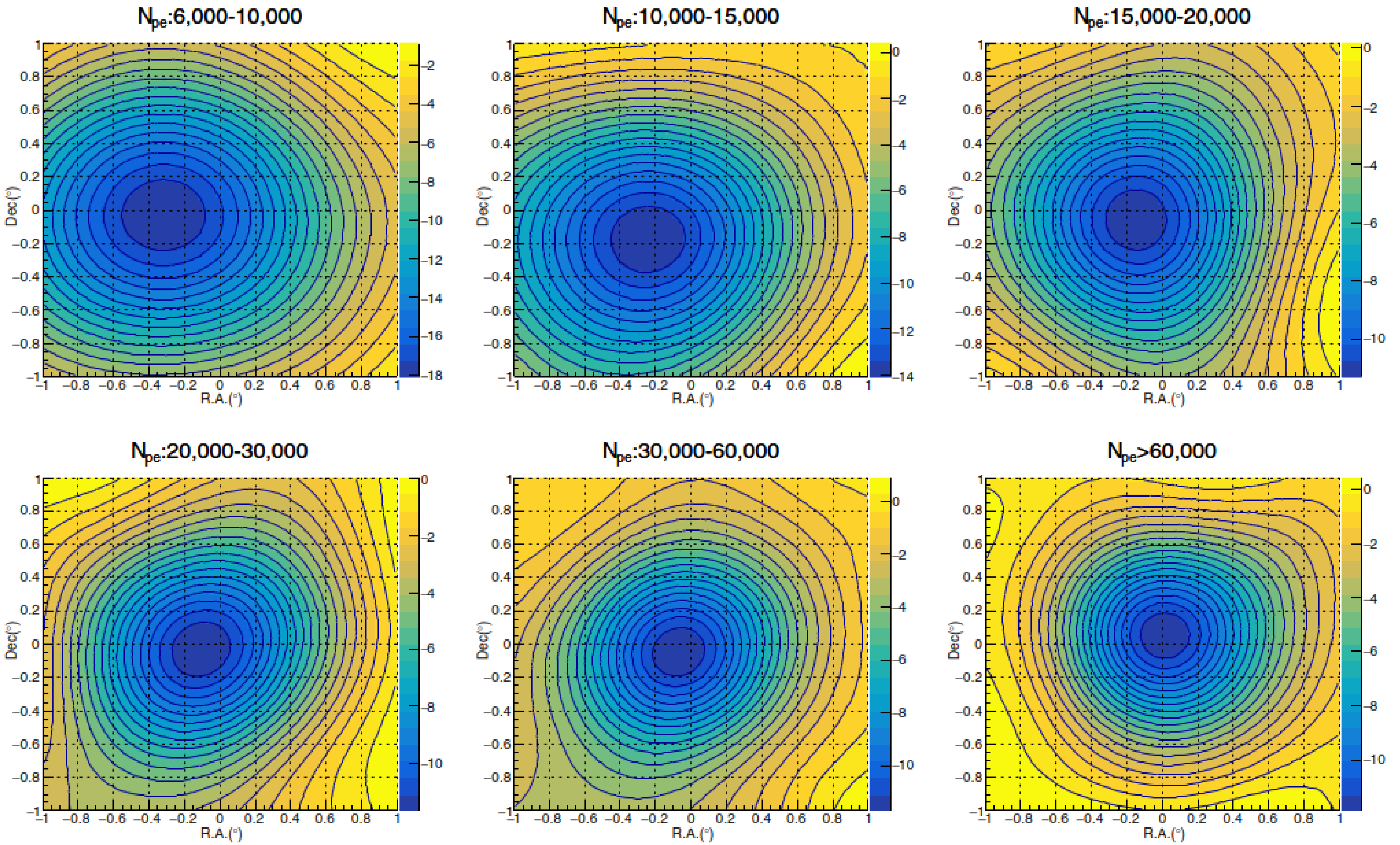
ARGO-YBJ Collaboration, PHYSICAL REVIEW D 84, 022003 (2011)

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

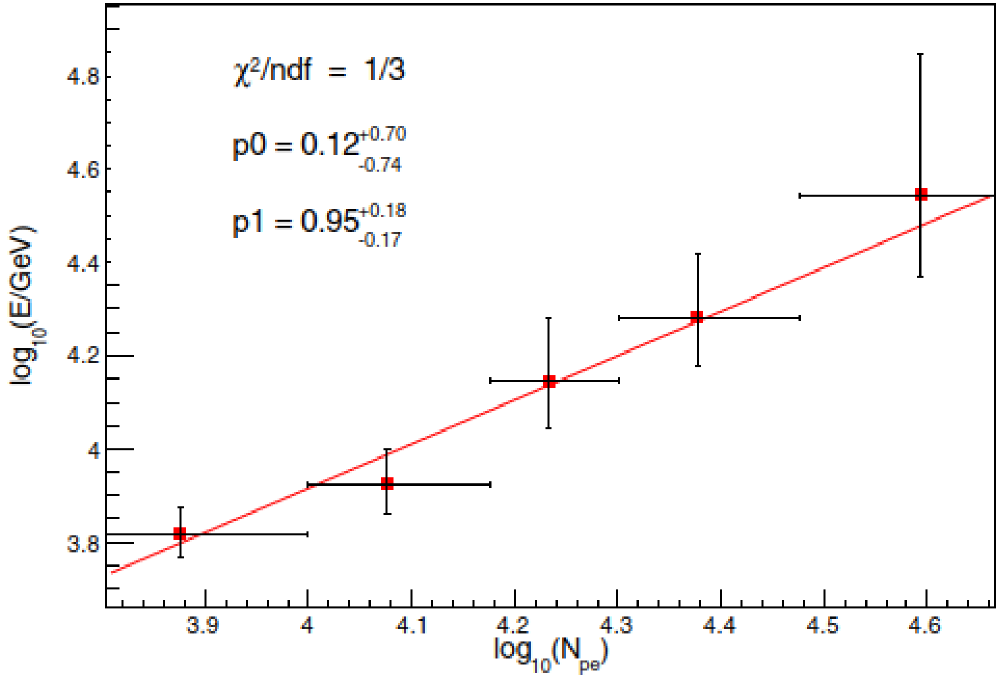


LHAASO Collaboration, PHYS. REV. D 104, 062007 (2021)

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.**

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



$$E(GeV) = aN_{pe}^{b}$$

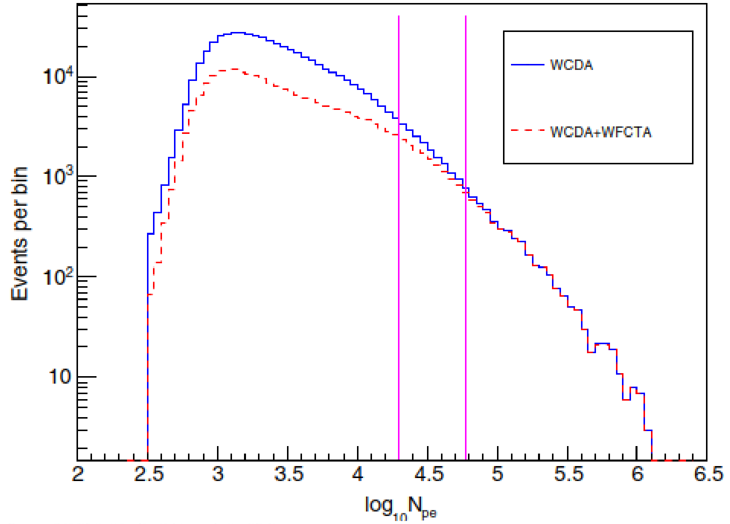
$$a = 1.33^{+5.26}_{-1.06}$$

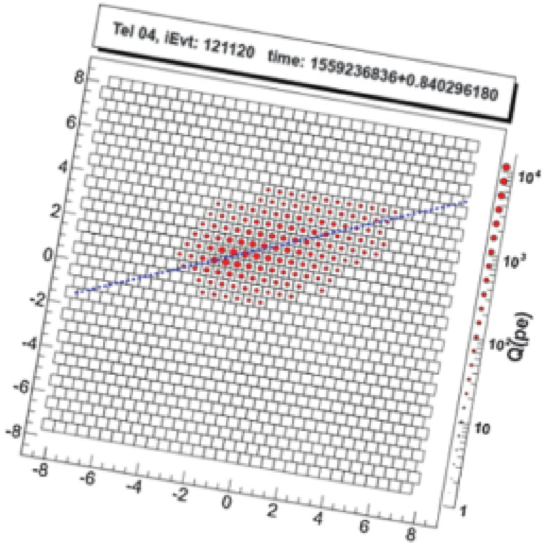
$$b = 0.95 \pm 0.17$$

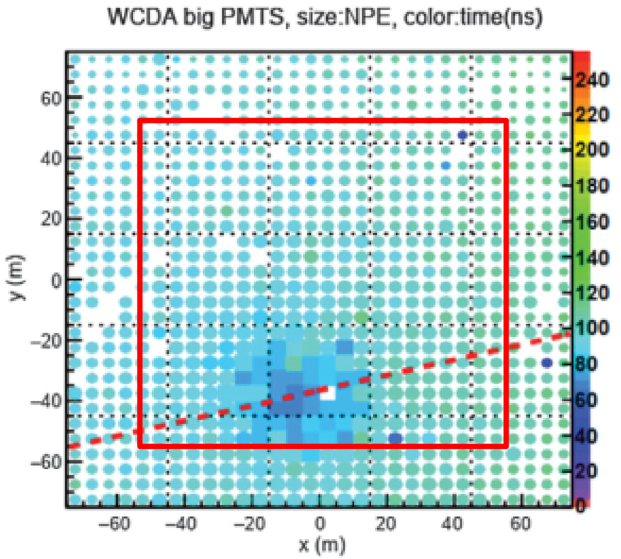
- **System uncertainties:**
  - **Uncertainty caused by 10% changing of the ratio of protons and helium nuclei is about 3%.**
  - **Uncertainty from different hadronic models (EPOS-LHC vs. QGSJET-II04) is less than 2%.**
  - **An uncertainty of 4% is caused by the energy and angular resolution.**

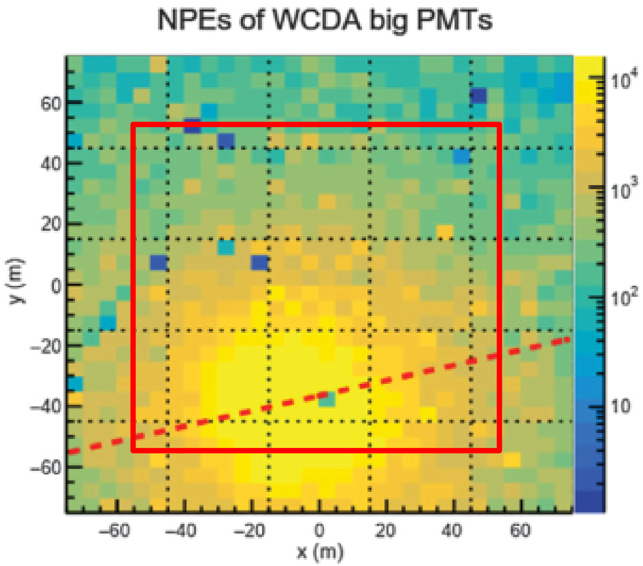
Absolute energy scale propagates from WCDA to C-telescopes

- 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



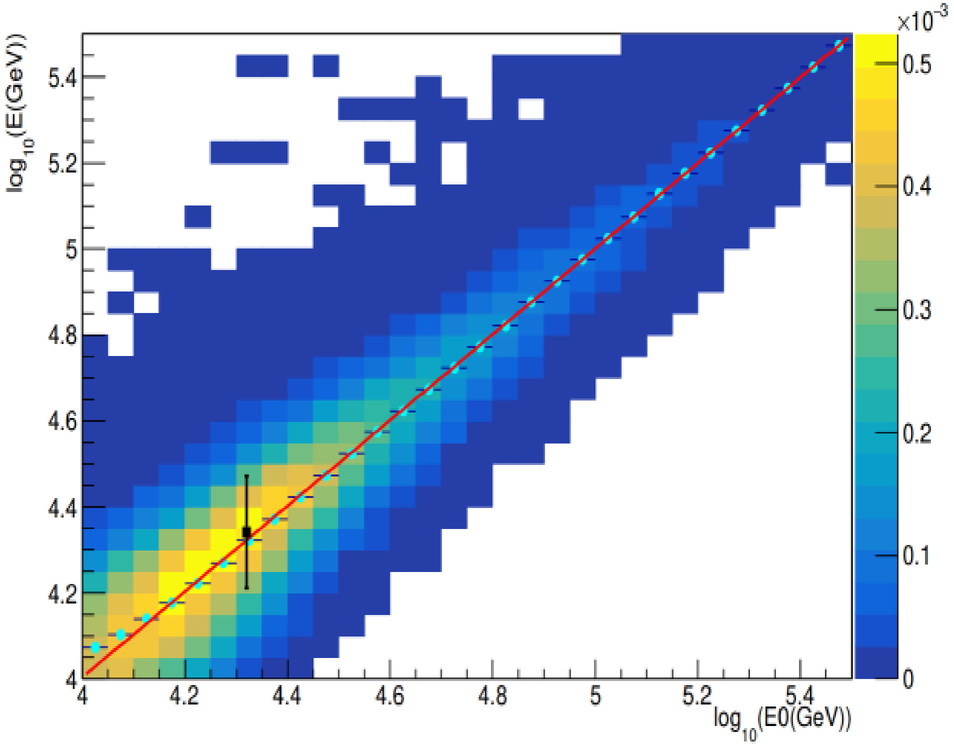






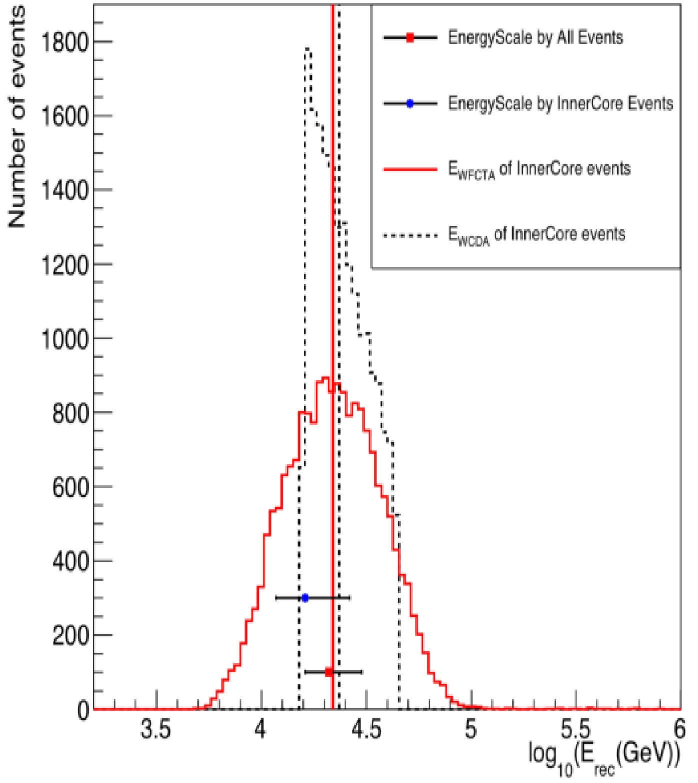
Absolute energy scale of WFCTA

- ➢ **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**



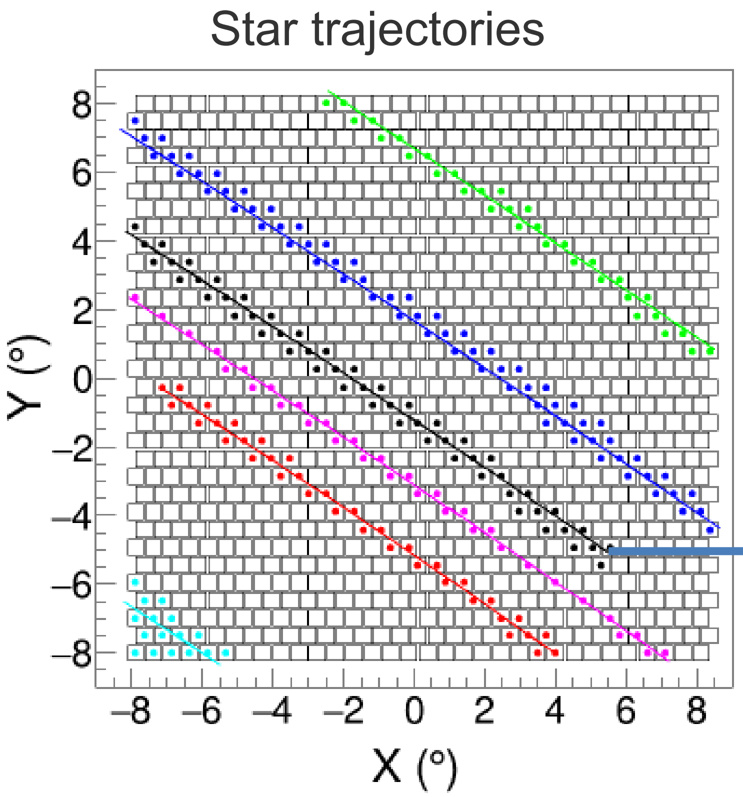
WCDA Calibration result (8 months, one pool):

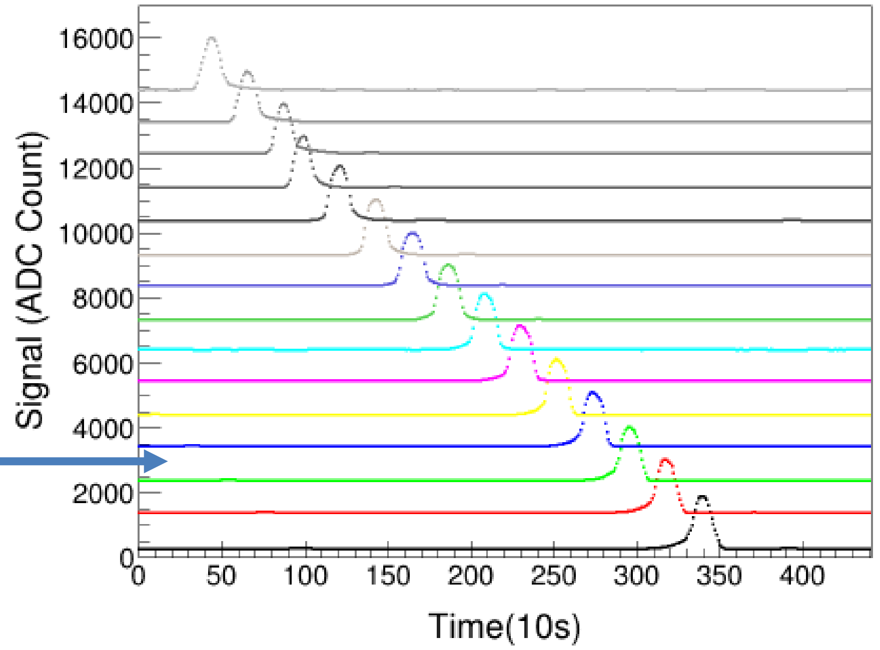
- ✓ **21.0 ±6.5 TeV for all events**
- ✓ **The uncertainty dominated by statistics in moon position measurement**
- ✓ **the uncertainty < 10% in 4 years**

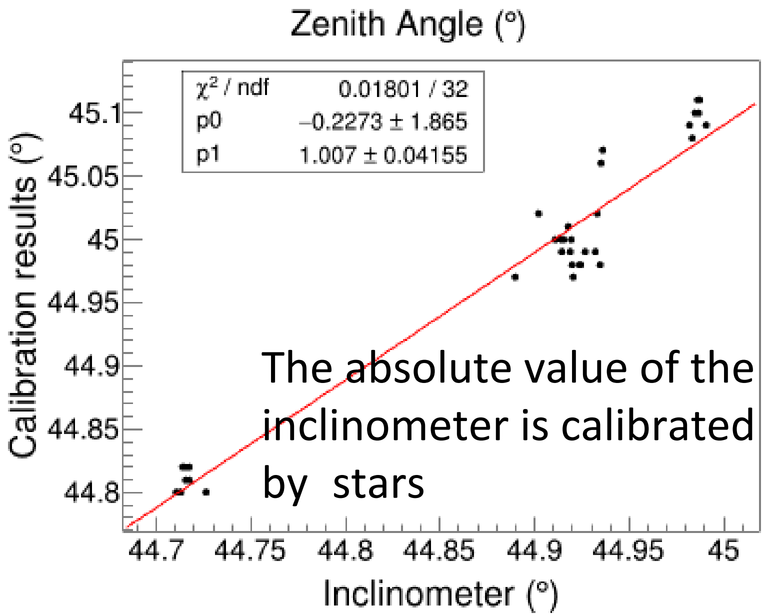


LHAASO Collaboration, PHYS. REV. D 104, 062007 (2021)

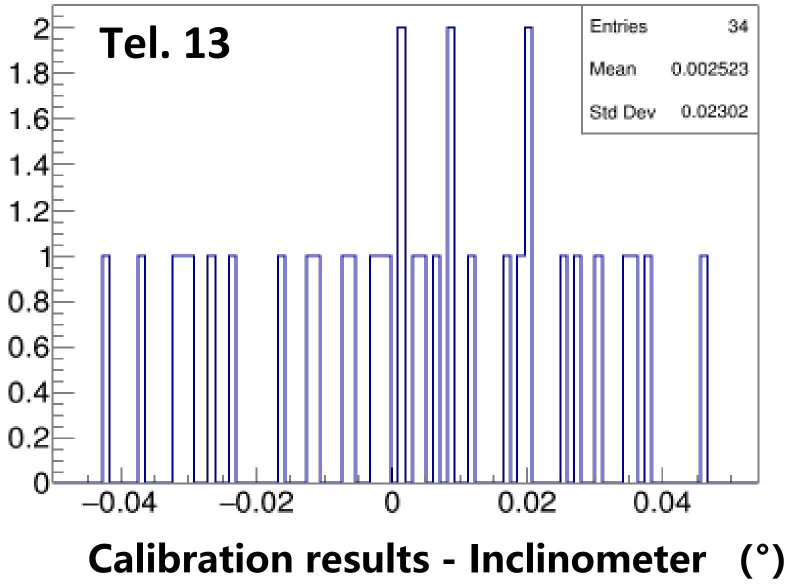
Telescope pointing calibration







The absolute value of the inclinometer is calibrated by stars



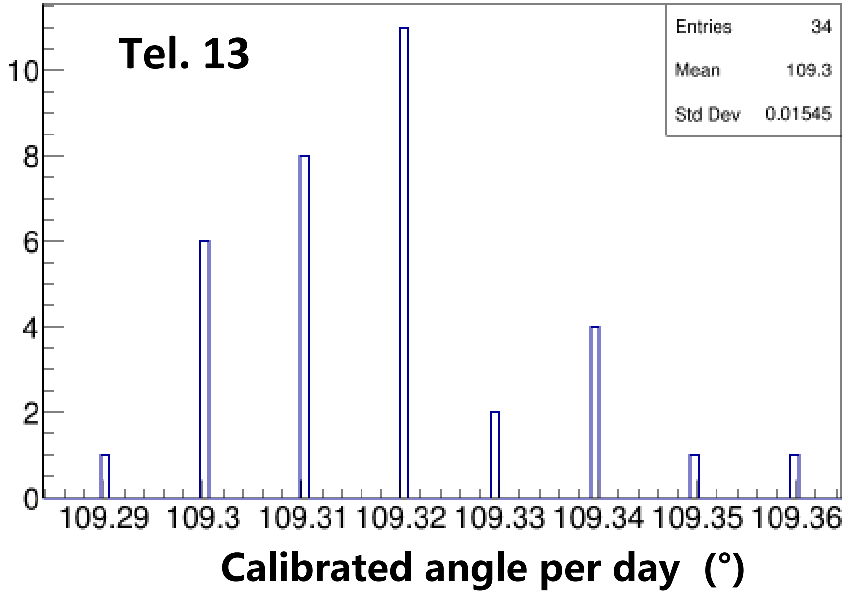
Trajectories of the stars (known)
vs. signals on the camera

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

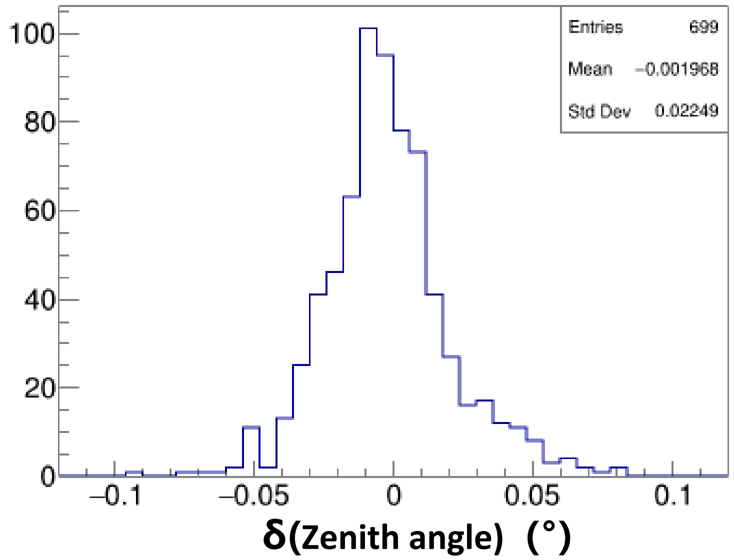
Telescope pointing calibration

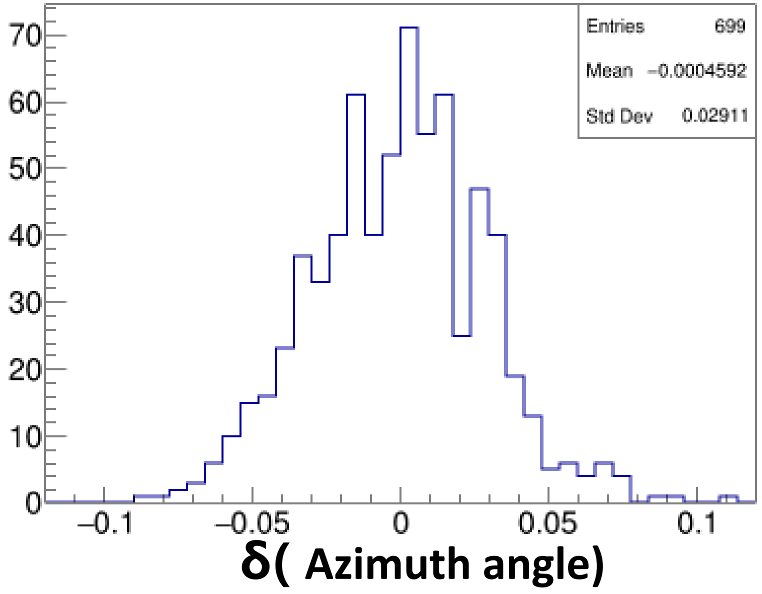
Daily calibration for 34 days

Calibration accuracy
~0.02° in zenith
~0.03° in azimuth

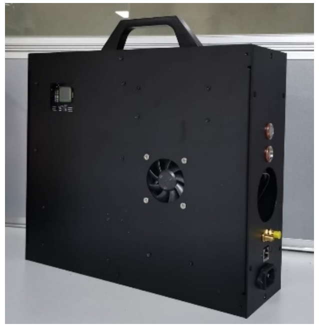


18 telescopes calibration results

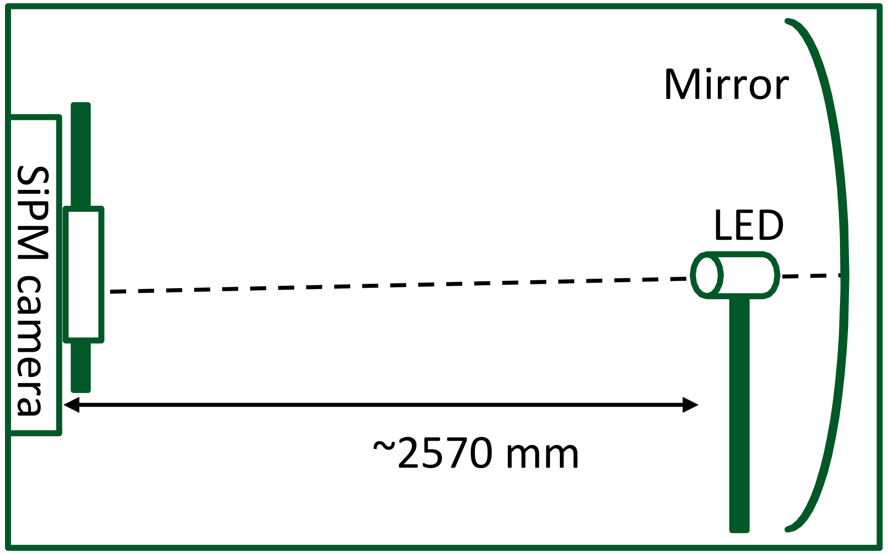


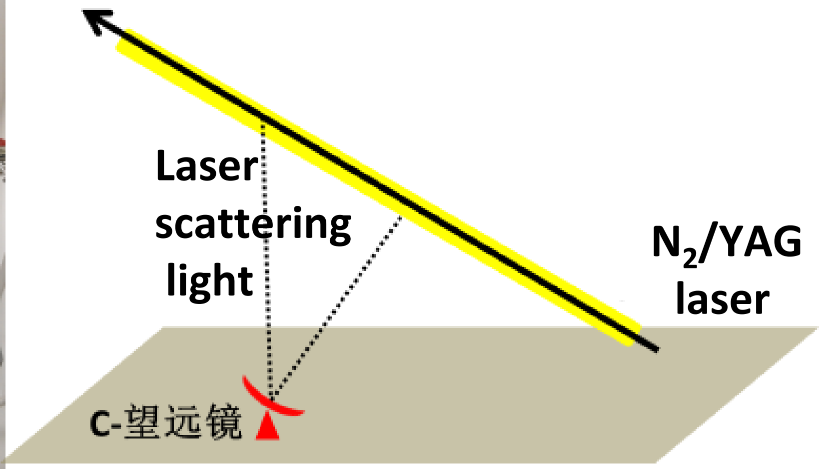


Photon response calibration system



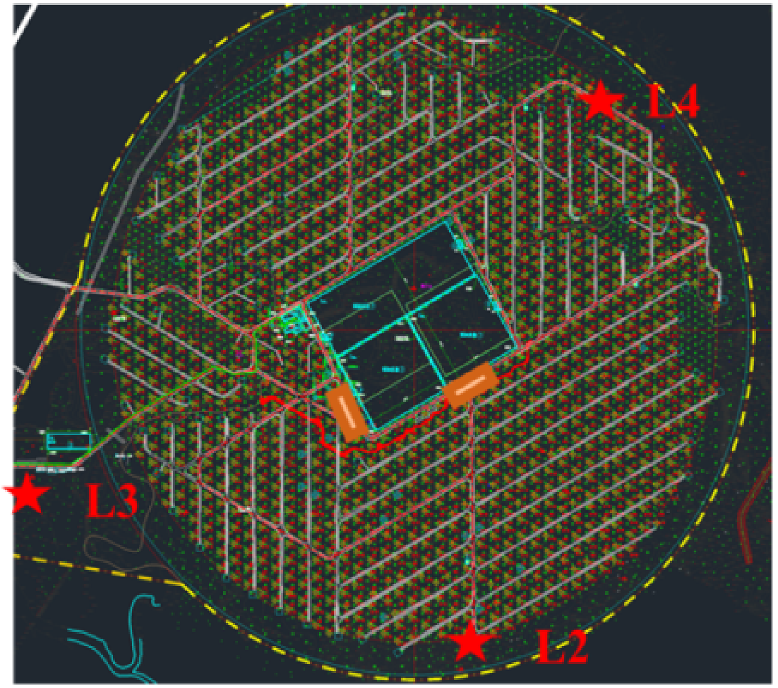
Probe





- ➢ 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

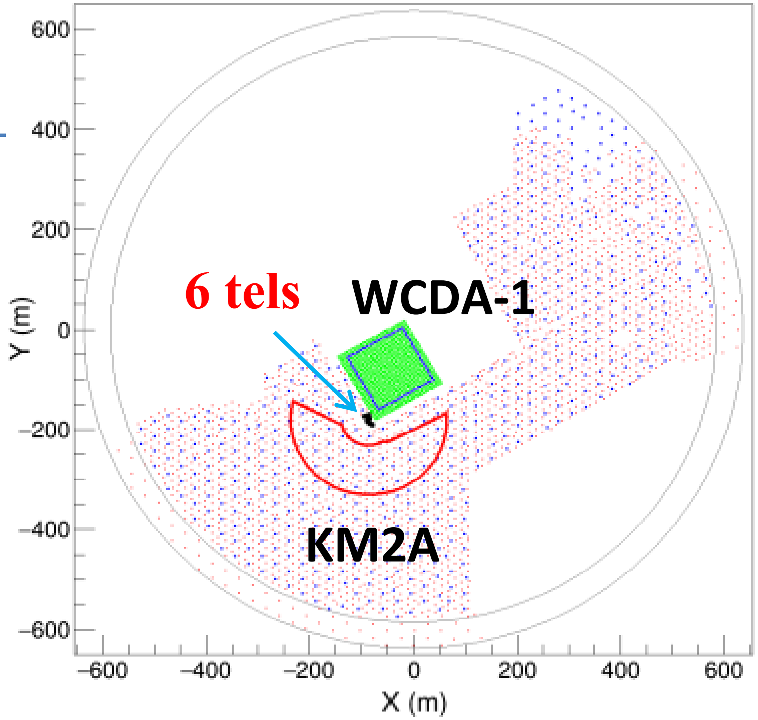


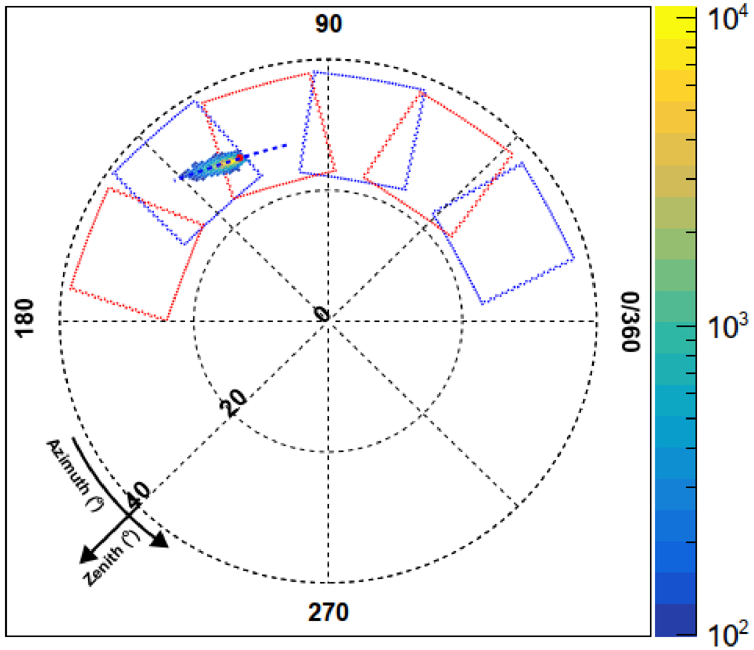
- ☐ LHAASO experiment
- ☐ Absolute energy scale
- ☐ CR spectrum measurements
  - ☐ 2 independent hybrid analyses
  - ☐ Primary particle identification (multi-parameter analysis)
  - ☐ Energy reconstruction (2 independent ways)
- ☐ Summary

LHAASO data set for proton and H+He energy spectra

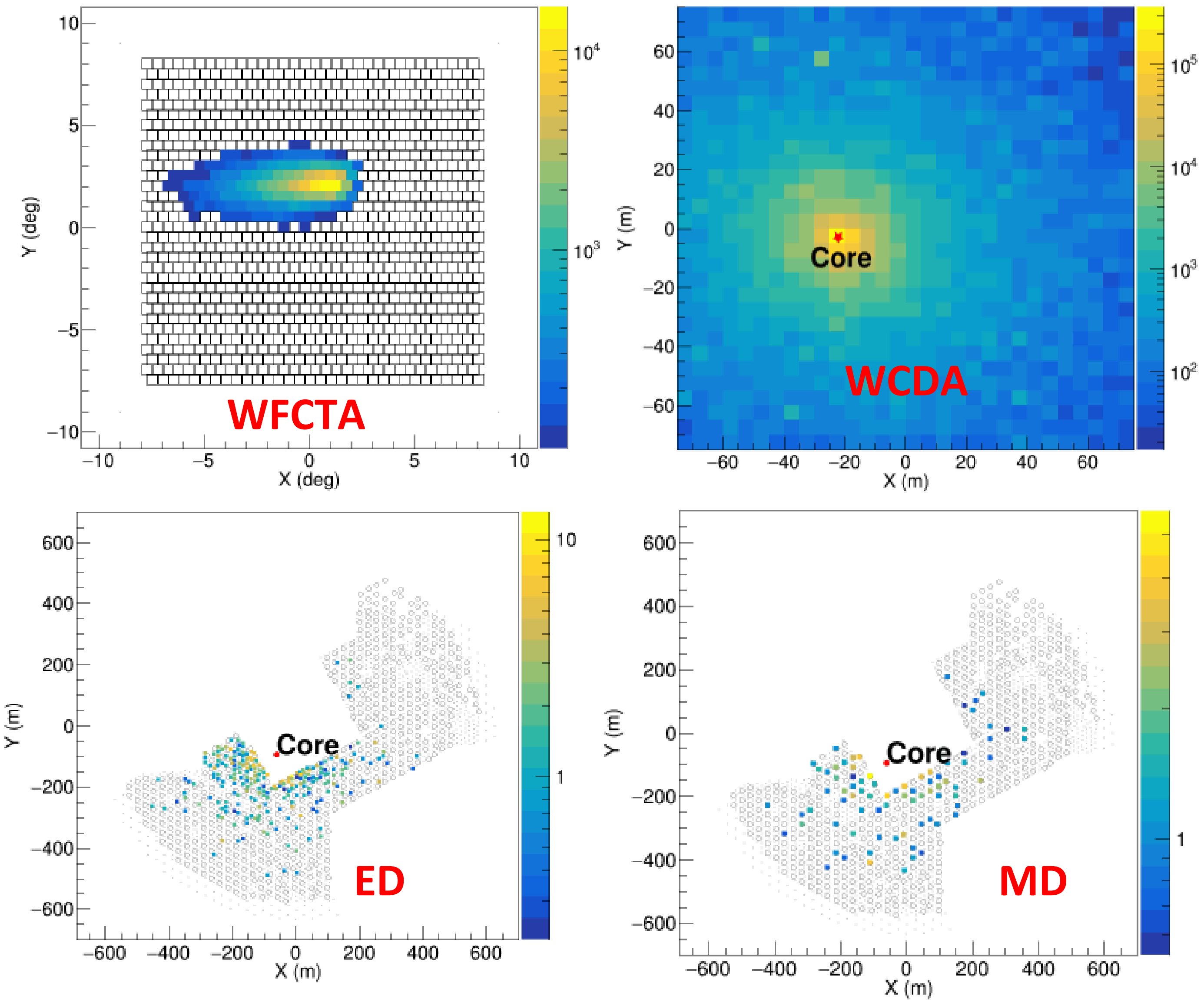
Phase I

- **Period:** 2020.11 ~ 2021.04
- **WFCTA selection conditions:**
  - > 10 pixels in each Cherenkov image
  - Full image contained in FoV
- **Good weather**
  - All-Sky Infrared Cloud Imager : T < -65°
- **Two independent measurements:**
  - **WFCTA(6 telescopes)+KM2A**
  - **WFCTA(6 telescopes)+WCDA-1+KM2A**
  - **750 hours, 0.7 million events (Core in WCDA)**



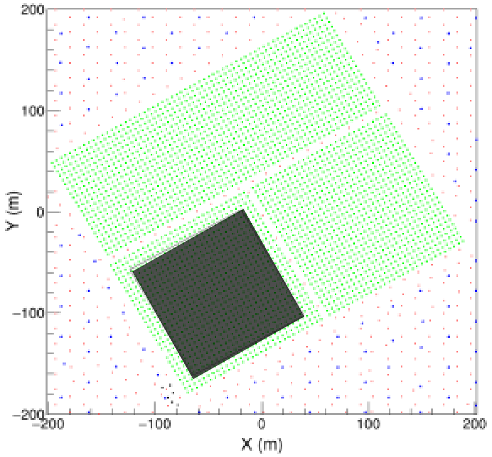


Hybrid measurement of LHAASO



- ➢ Shower geo-reconstructed
  - by WCDA/KM2A
    - **Core resolution: < 3 m**
    - **Angular resolution: < 0.3°**
- ➢ Shower energy reconstruction
  - Cherenkov size
- ➢ Mass sensitive parameters
  - X_{max} and Hillas parameters of Cherenkov image
  - Energy flux near shower core
  - Number of muons

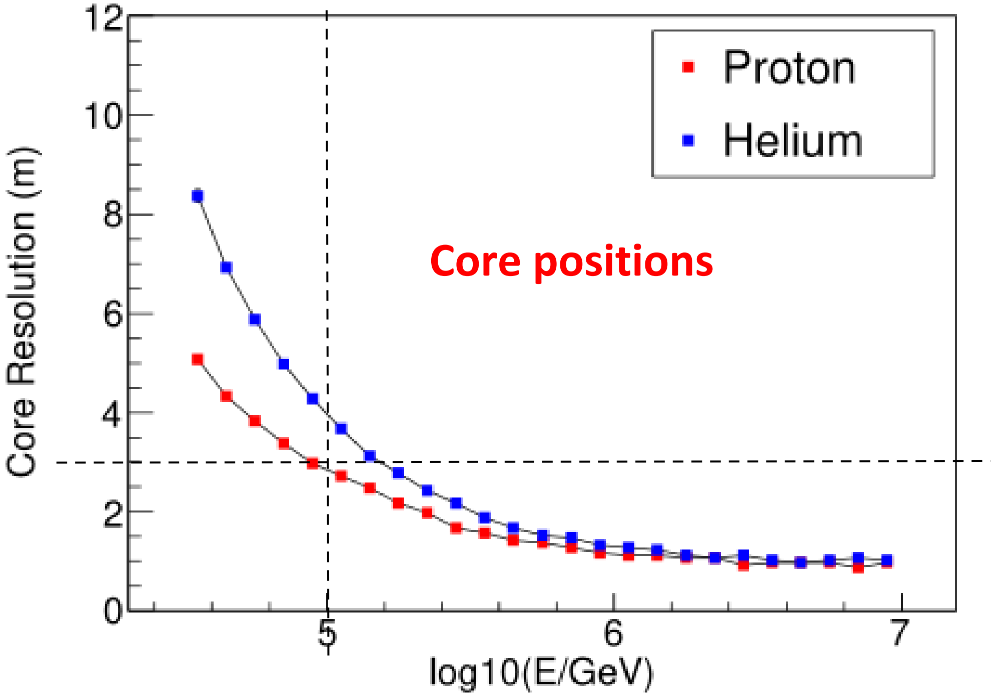
Hybrid measurement of LHAASO

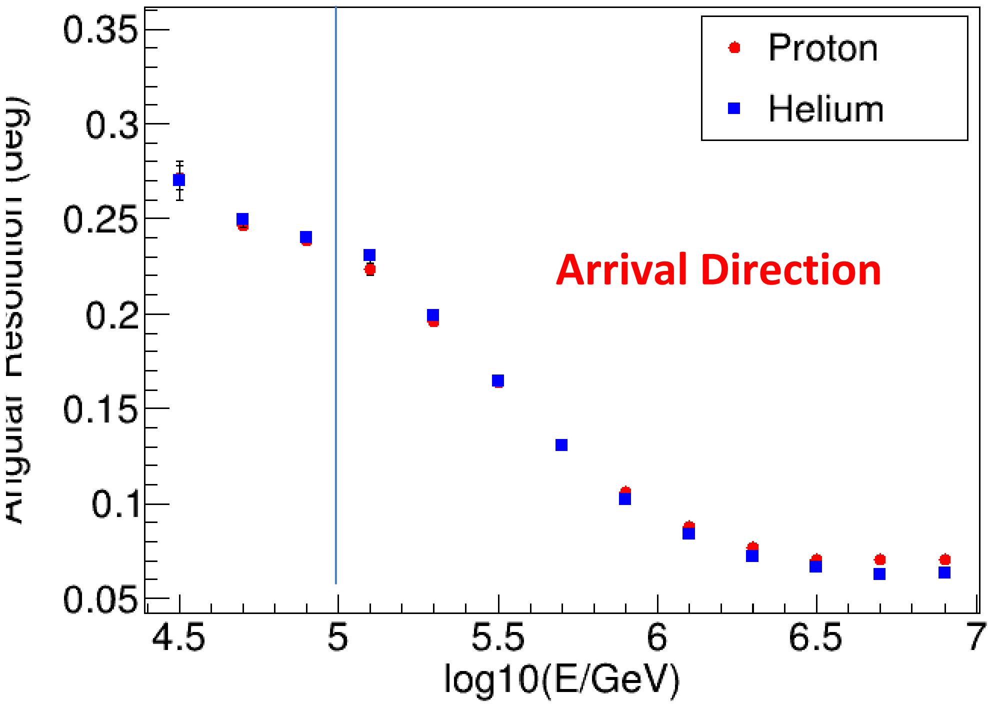


For pure protons：

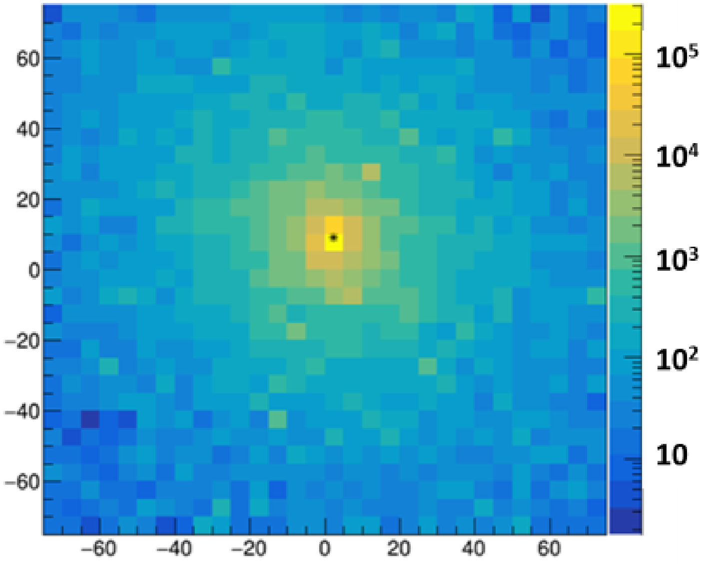
Core position errors： $< 3\ m$ $(> 100\ TeV)$

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

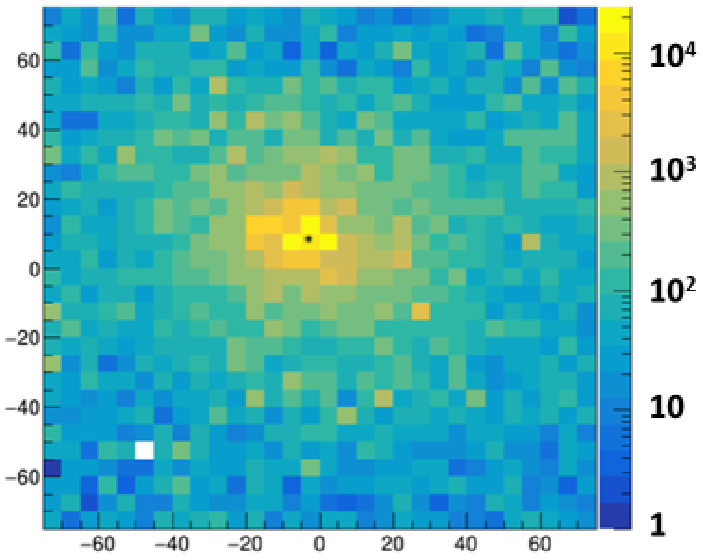




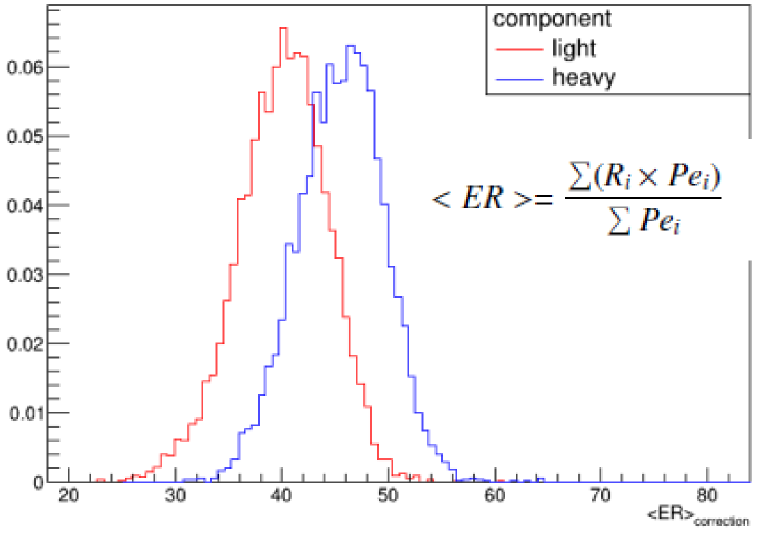
Mass sensitive parameters



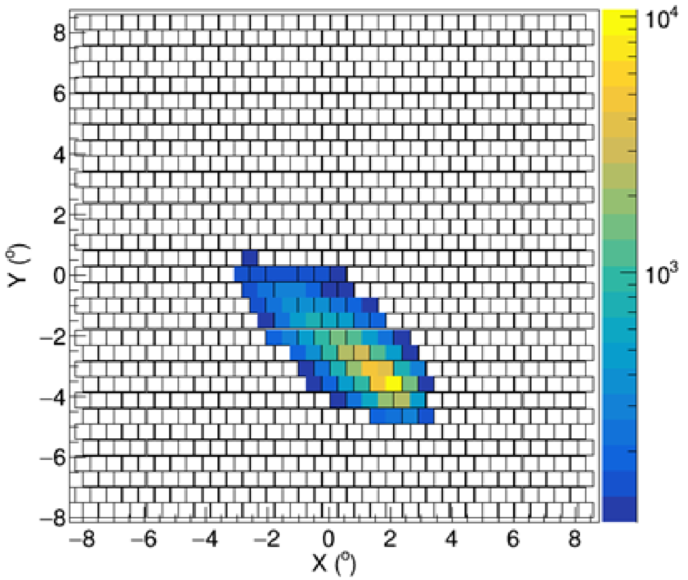
400 TeV proton

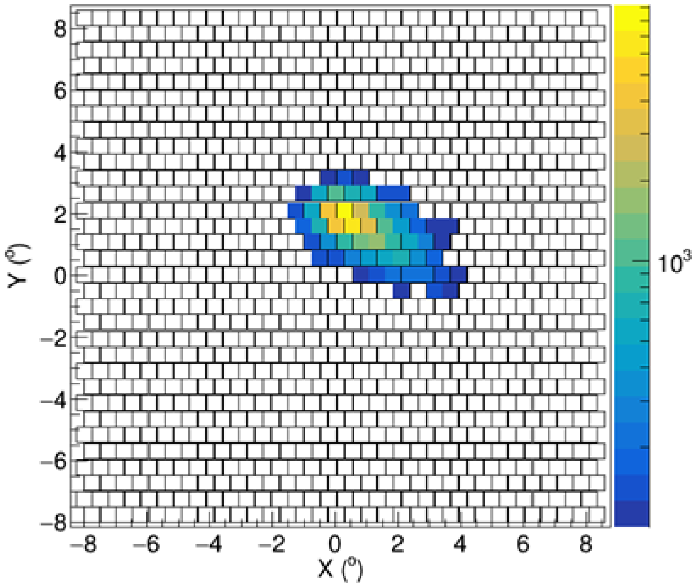


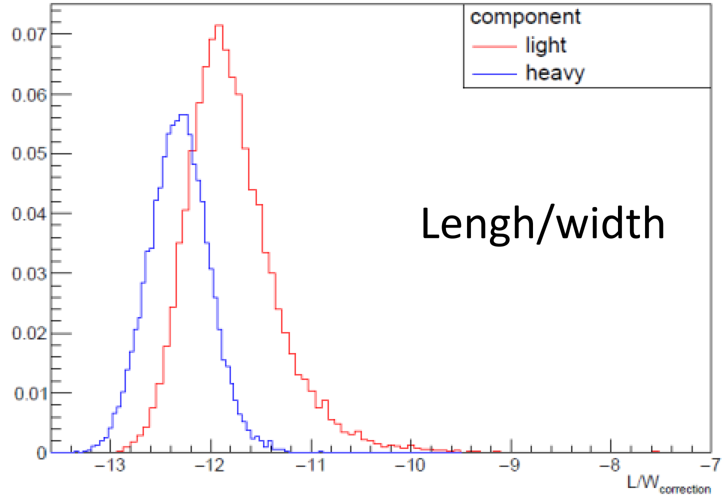
400 TeV iron



$$< ER >= \frac{\sum(R_i \times Pe_i)}{\sum Pe_i}$$

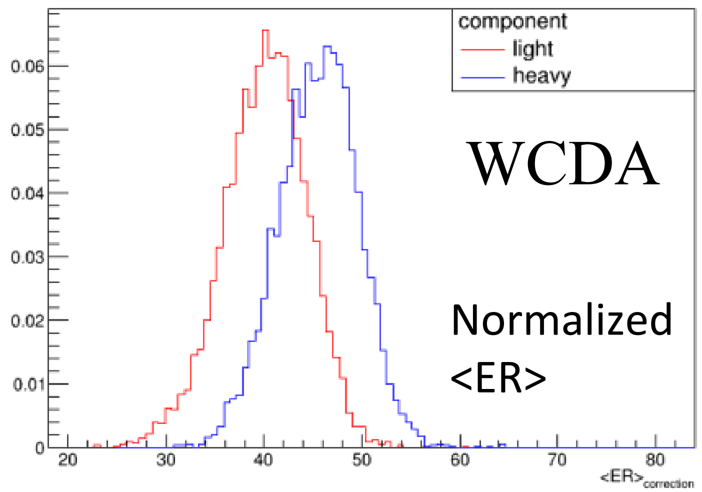




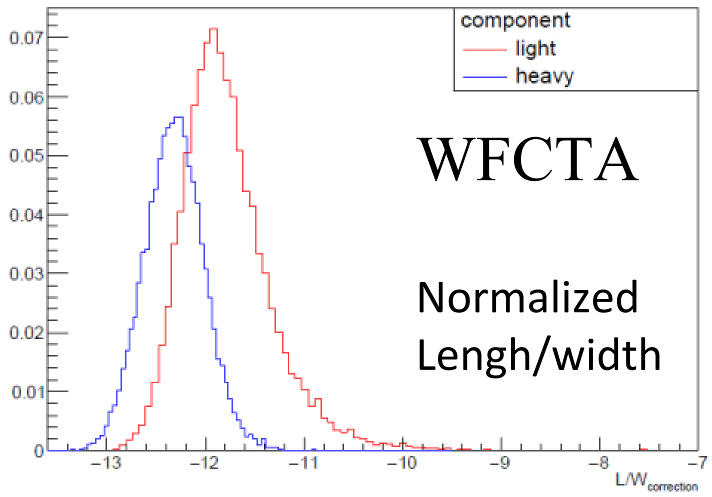


Lengh/width

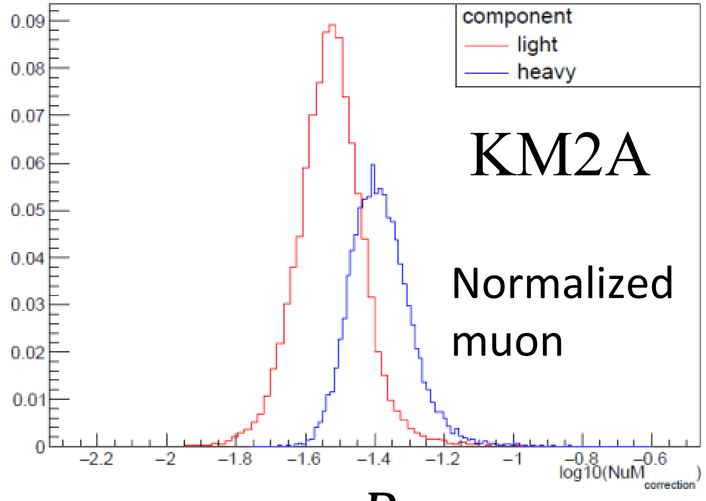
Composition Discrimination



P_F



P_C



P_μ

$$\log_{10} Size0 = \log_{10} Size + 0.0084 \times R_p$$

WCDA $P_F = < ER > +4.80 \times \log_{10} Size0$

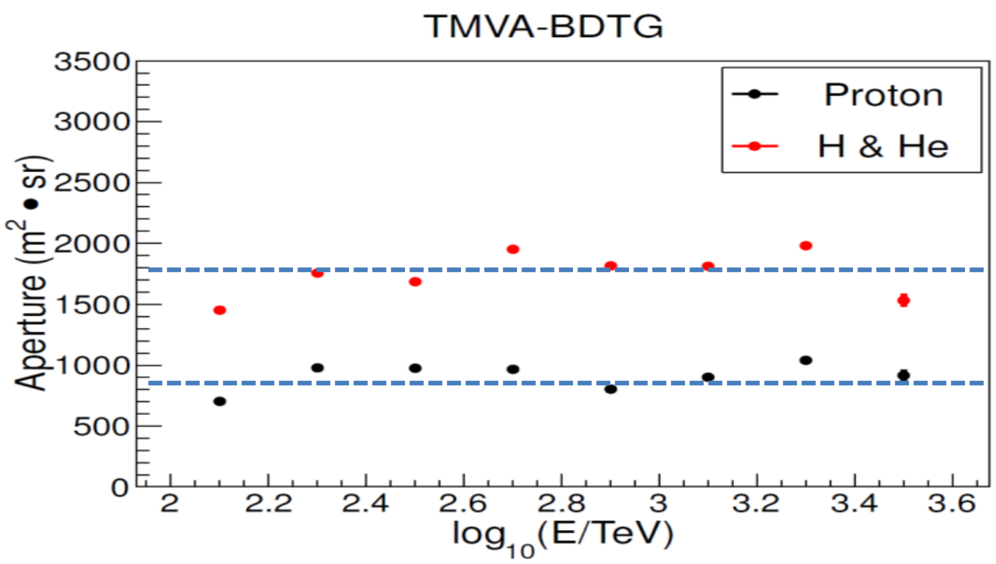
$$< ER >= \frac{\sum (R_i \times Pe_i)}{\sum Pe_i}$$

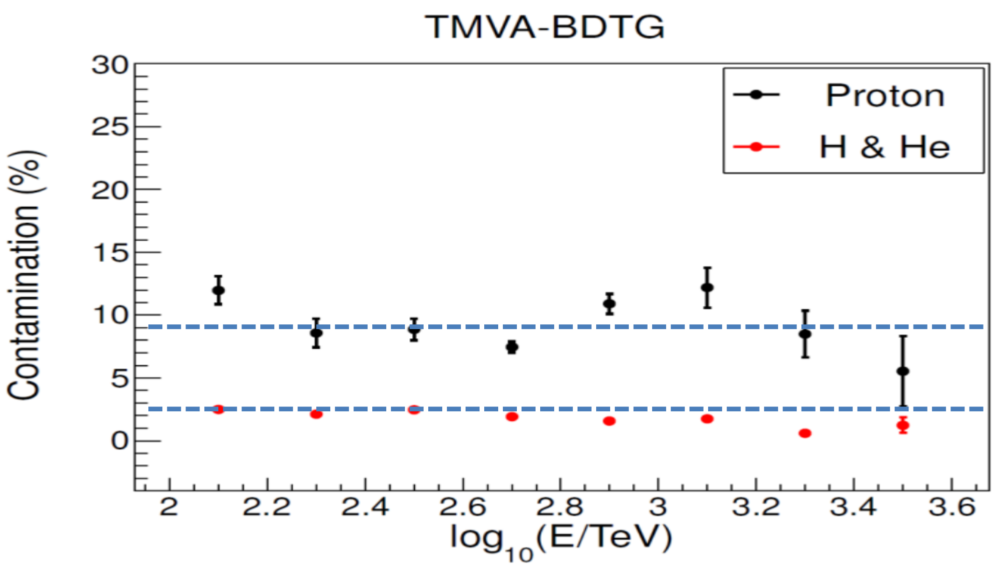
WFCTA $P_C = (L/W - 0.012 \times R_p) + 0.37 \times (\log_{10} Size0)^2 - 4.50 \times (\log_{10} Size0)$

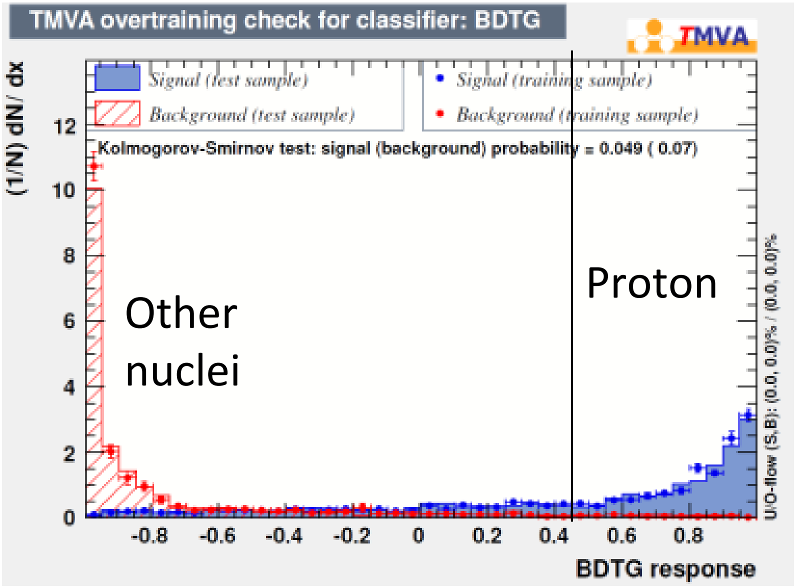
KM2A $P_\mu = \log_{10}(N_\mu|_{30-380}) - 0.092 \times (\log_{10} \sqrt{N_e|_{40-100} \times N_\mu|_{40-200}} + 3.44)$

Multi-parameters analysis

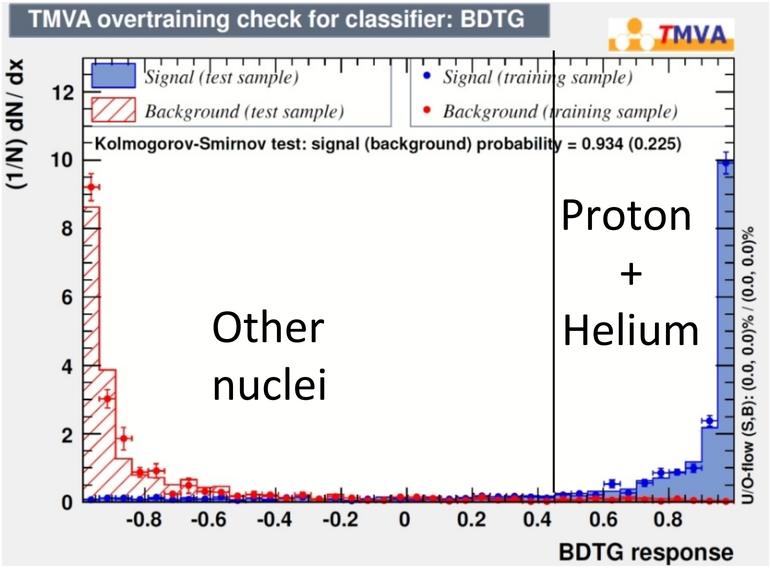
TMVA(Toolkit for Multivariate Data Analysis with ROOT)







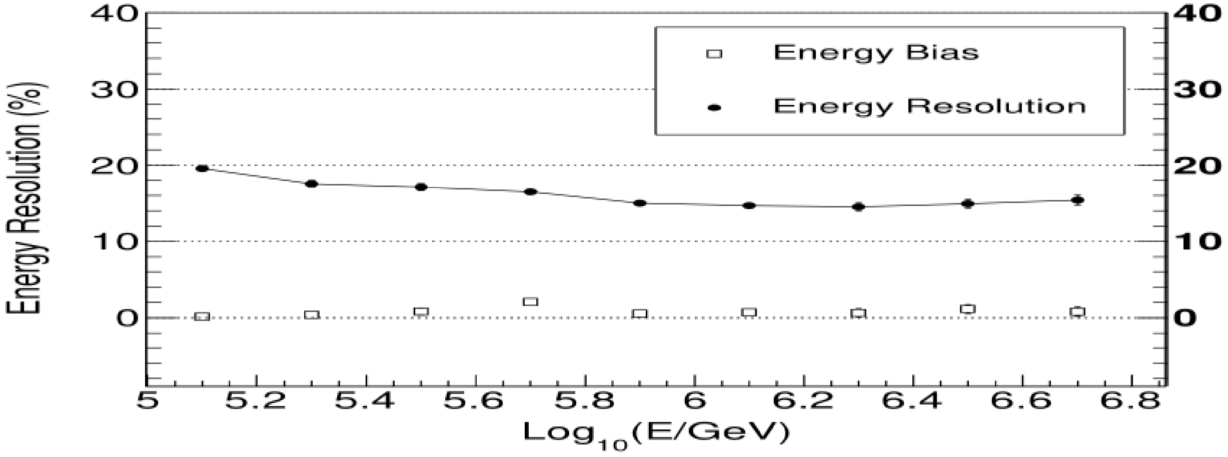
- **Aperture：**
  - **H: ~ 850 m^{2}Sr**
  - **H+He: ~1800 m^{2}Sr**
- **Contamination of heavy nuclei**
  - **H: ~ 10%**
  - **H+He: ~ 3%**



Energy reconstruction

For C-telescopes

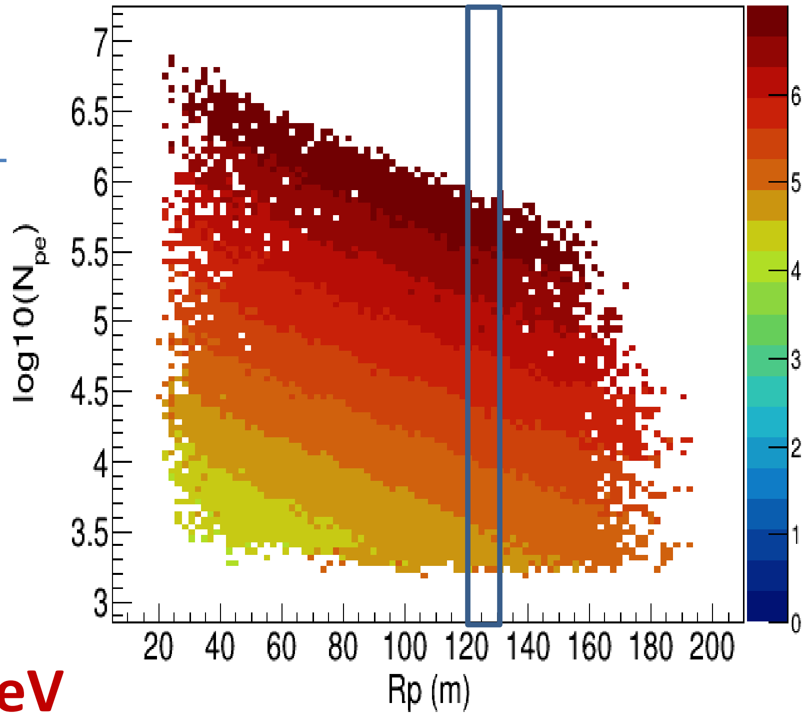
- Energy estimator: total Charge in Cherenkov image (Npe)

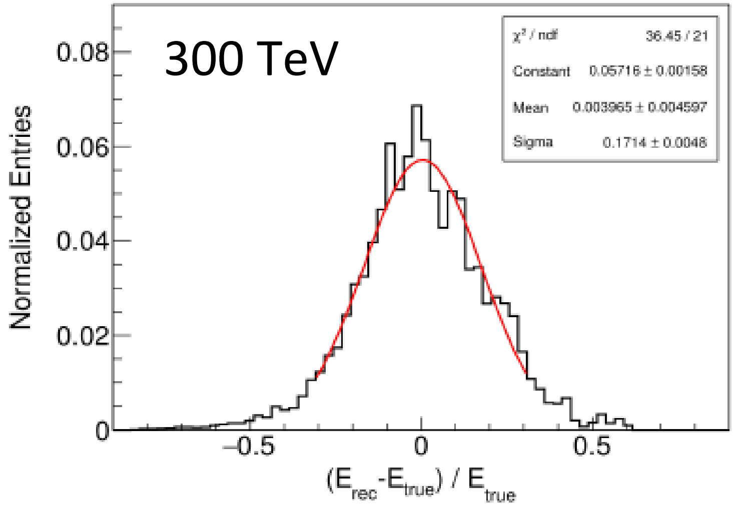


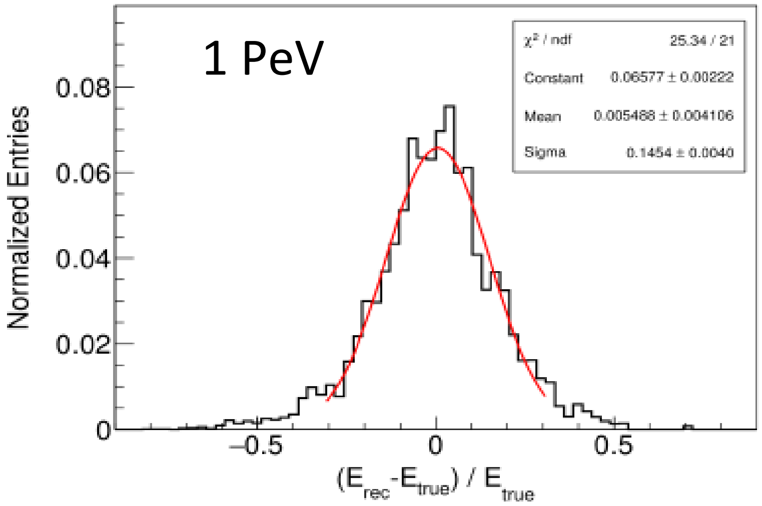
Bias < 2%

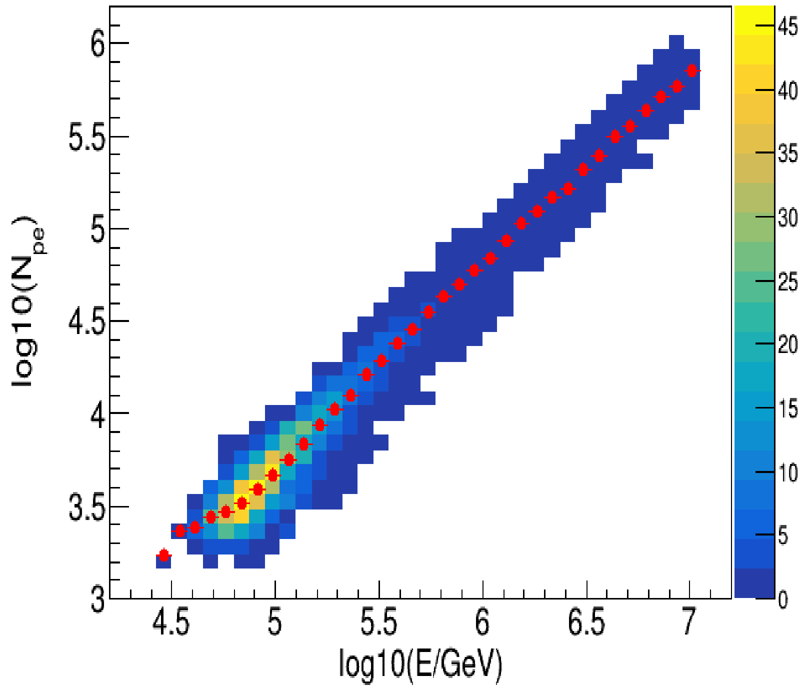
Resolution:

~16% @ 1PeV



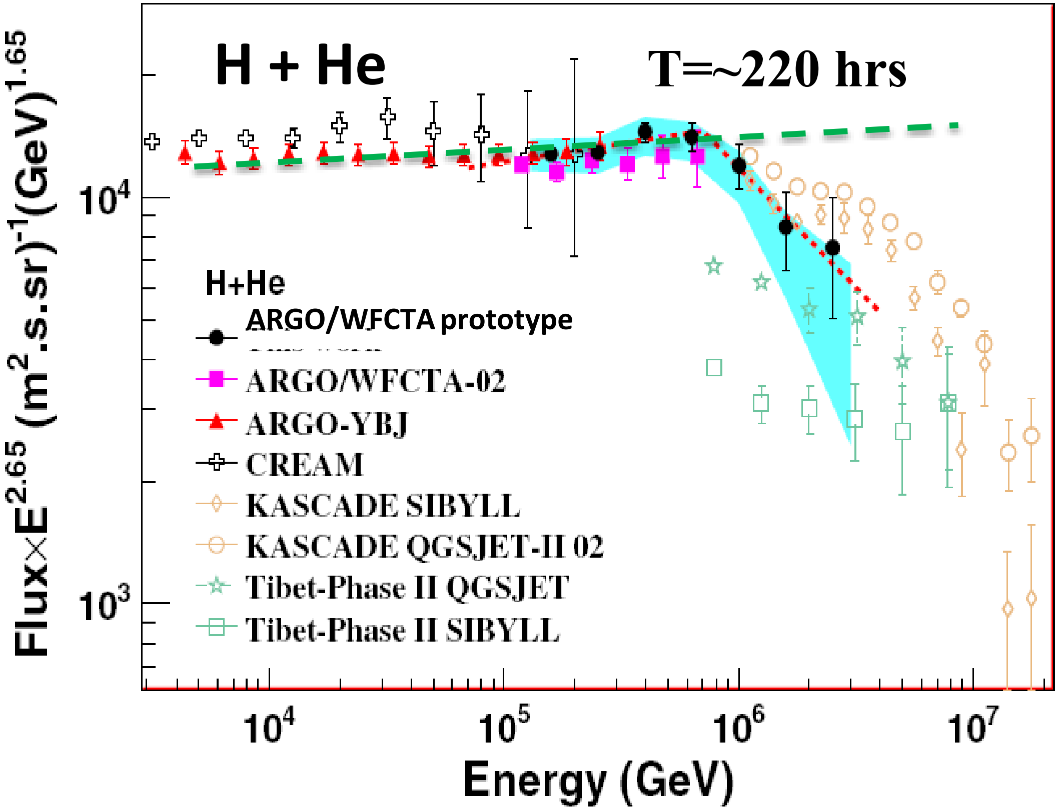






H and H+He spectra expectation by LHAASO

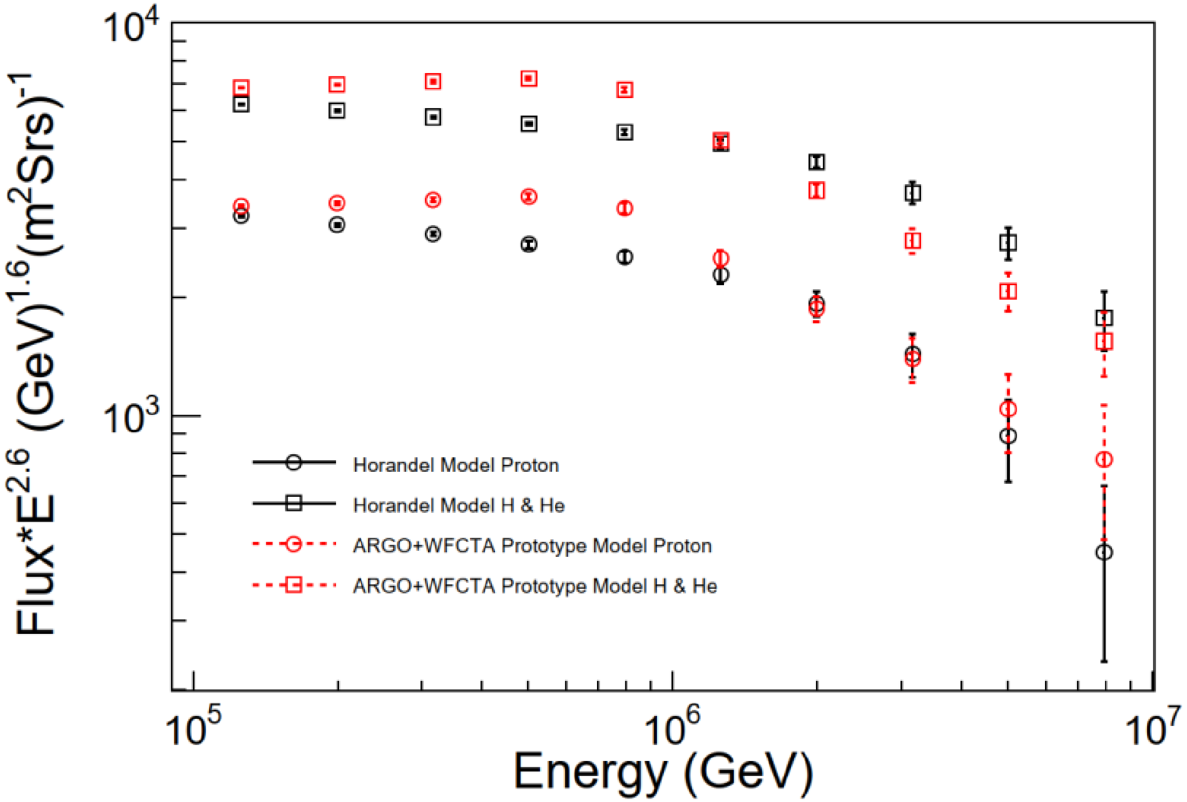
ARGO-YBJ + a Cherenkov prototype
The knee of H&He spectrum at
(700±230(stat.)±70(sys.)) TeV is measured



PHYSICAL REVIEW D 92, 092005 (2015)

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

T=~750 hrs × 6 Tele.

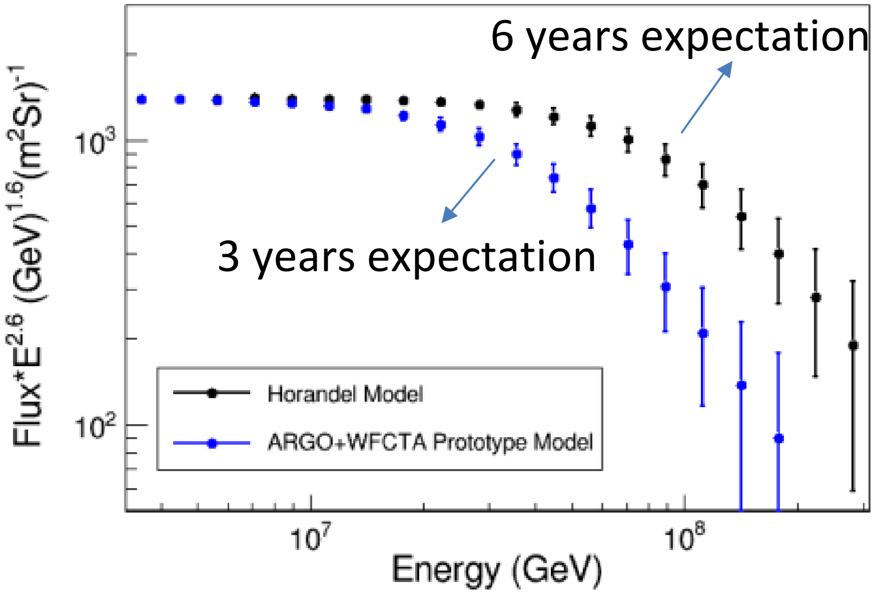


Iron knee expectation by LHAASO

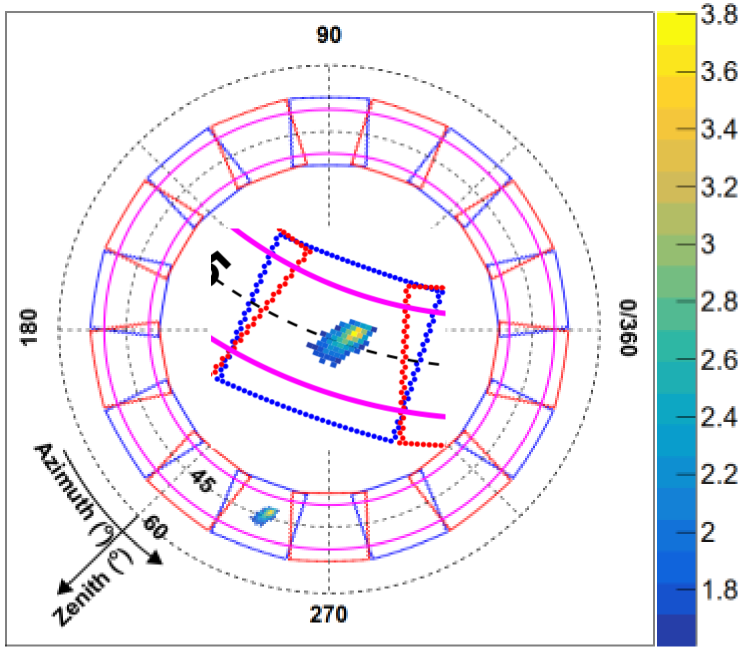
Phase II

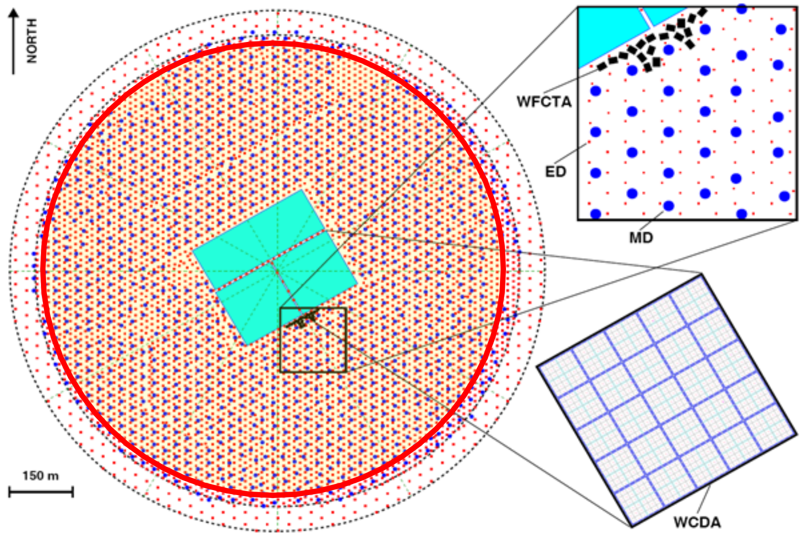
◈ **Iron knee energy spectra observation :**

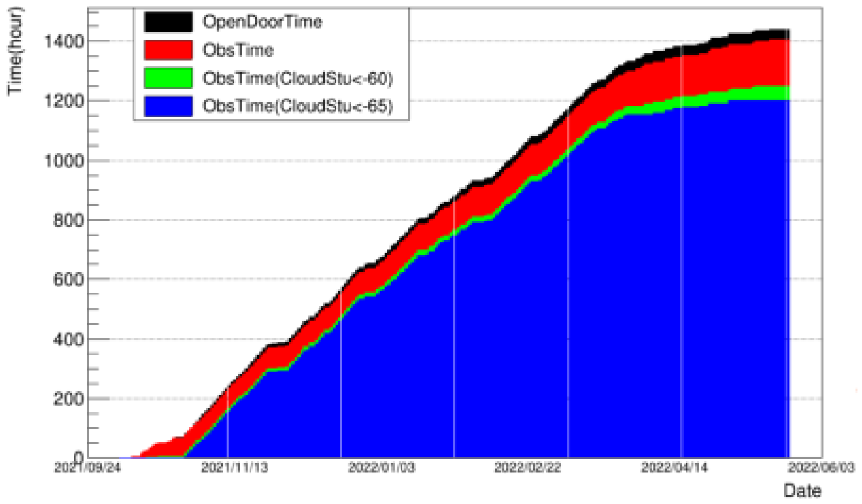
- 18 telescopes point to zenith 45°, cover azimuth 0-360°
- ~1100 hours good data collected
- WFCTA + KM2A (full array is used)
- Energy range : several PeV - 200 PeV


6 years expectation

3 years expectation





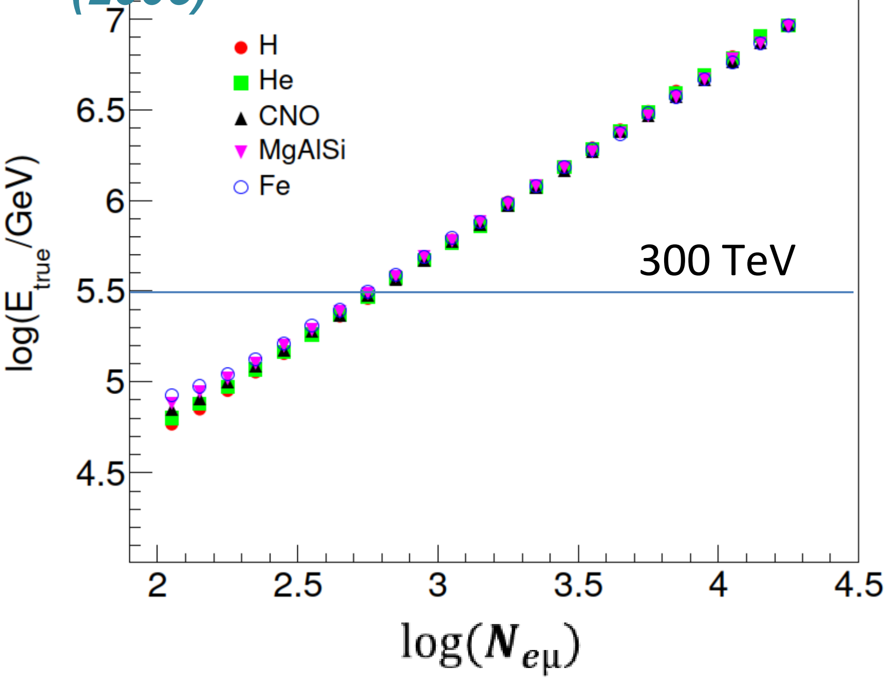


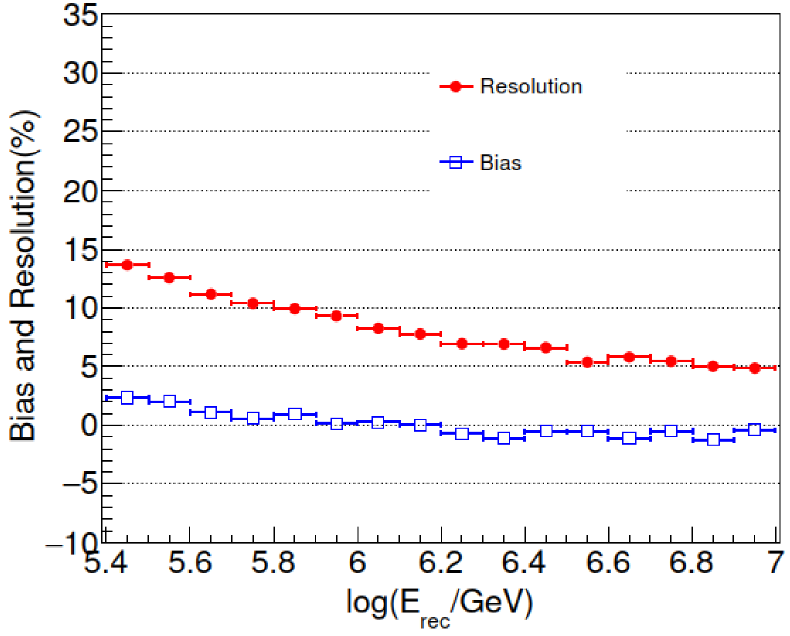
Progress of all particle spectrum by LHAASO

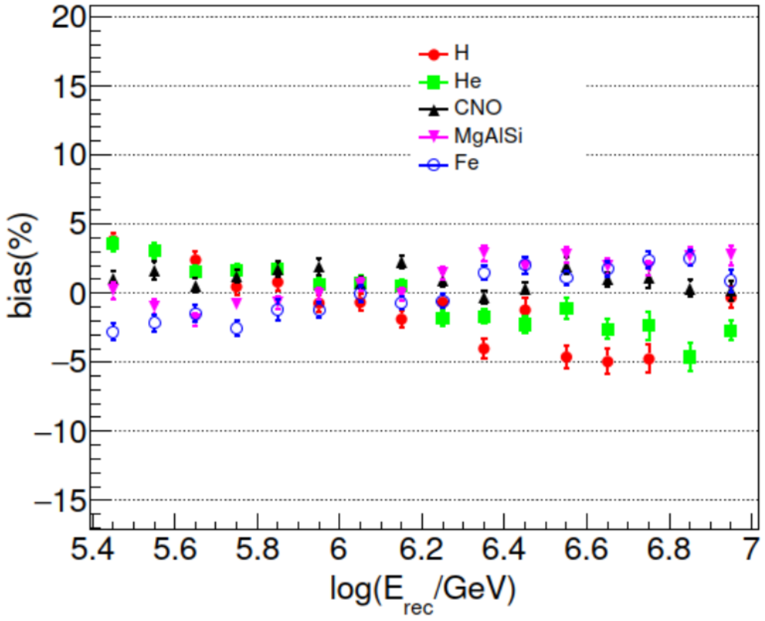
- ➢ **Energy reconstruction independent of primary CRs components**
- ➢ **Scintillator detector array（ED）： Electromagnetic component （E_e）**
- ➢ **Muon detector array （MD）： *hadron component* $\pi^0 \rightarrow \mu$ （N_μ）**

$$E_0 = E_e + E_\mu \approx N_e^{max} \times E_c^e + \alpha N_\mu \times E_c^\pi \qquad N_{e\mu} = N_e + 2.8 N_\mu \qquad E_{rec} = b \times N_{e\mu}$$

J. Matthews, Astropart. Phys. 22, 387 (2005)

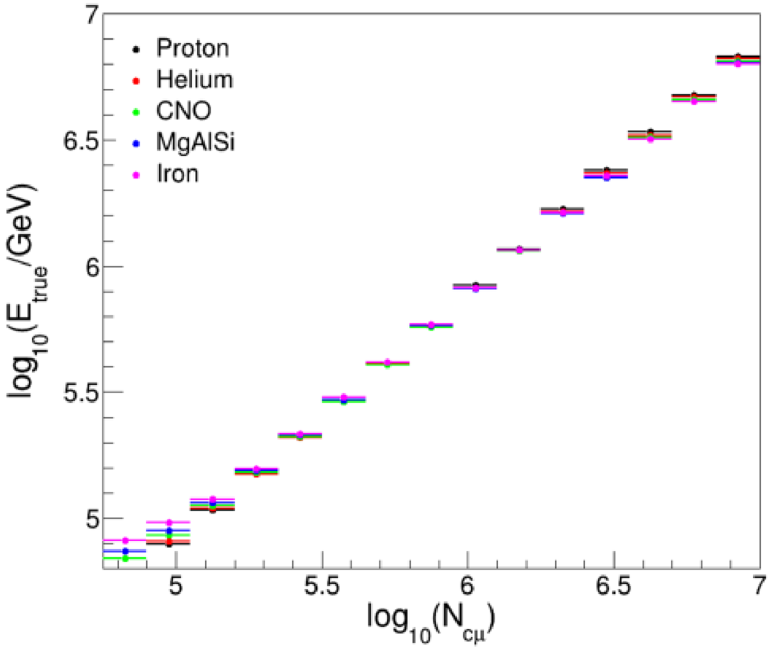




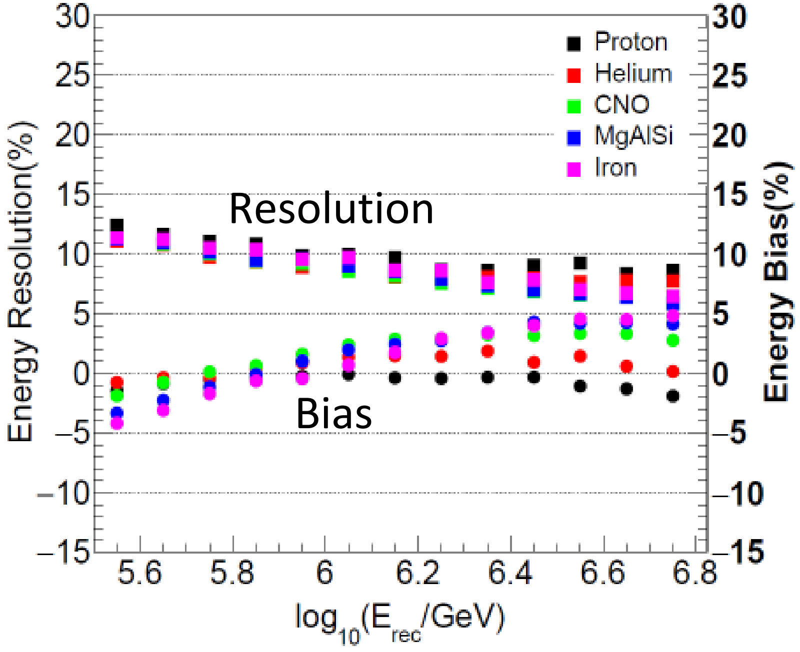


- **Energy reconstruction independent of primary CRs components**
- **Cherenkov telescopes（WFCTA）： Electromagnetic component （N_{pe}^0）**
- **Muon detector array （MD）：** ***hadron component*** **$\pi^0 \rightarrow \mu$ （N_μ）**

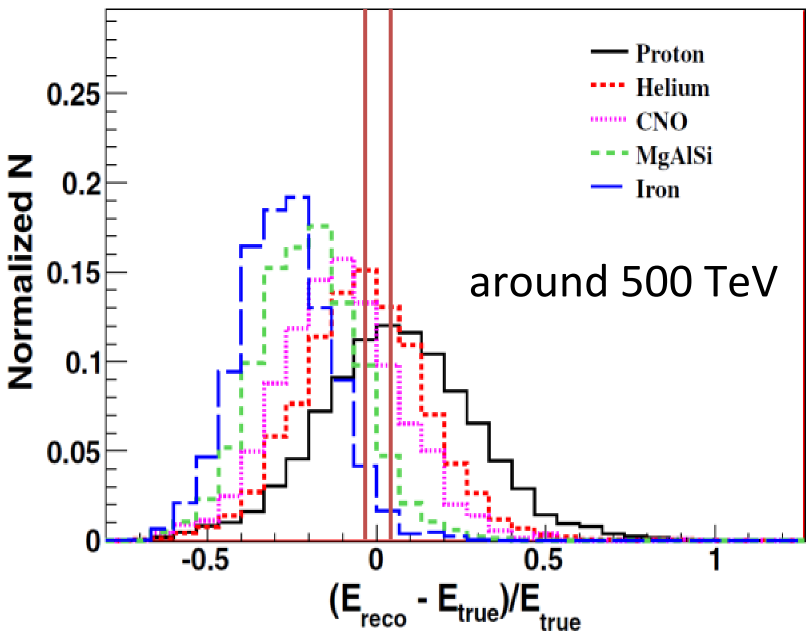
$$N_{c\mu} = N_{pe}^0 + CN_u' \quad (C = 140)$$
$$E_{rec} = kN_{c\mu}$$



Proton and helium: <2%



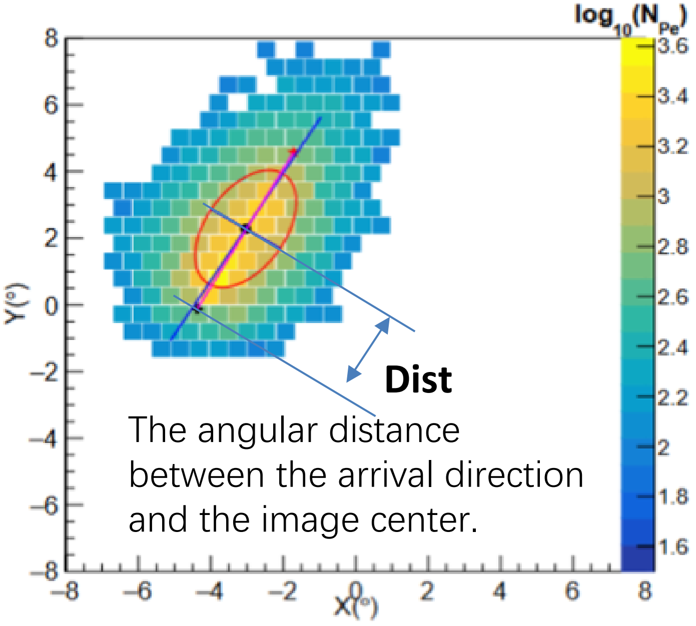
Proton and helium: ~7%



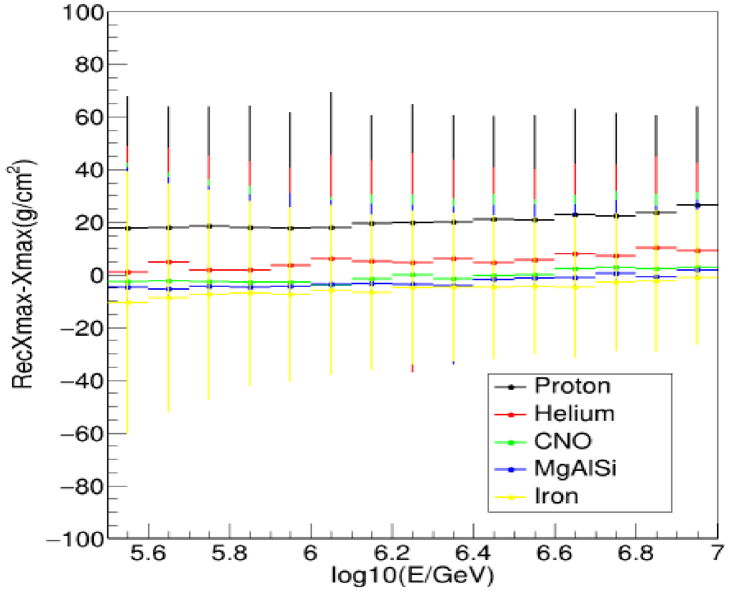
PHYSICAL REVIEW D 92, 092005 (2015)

Xmax Measurement by WFCTA

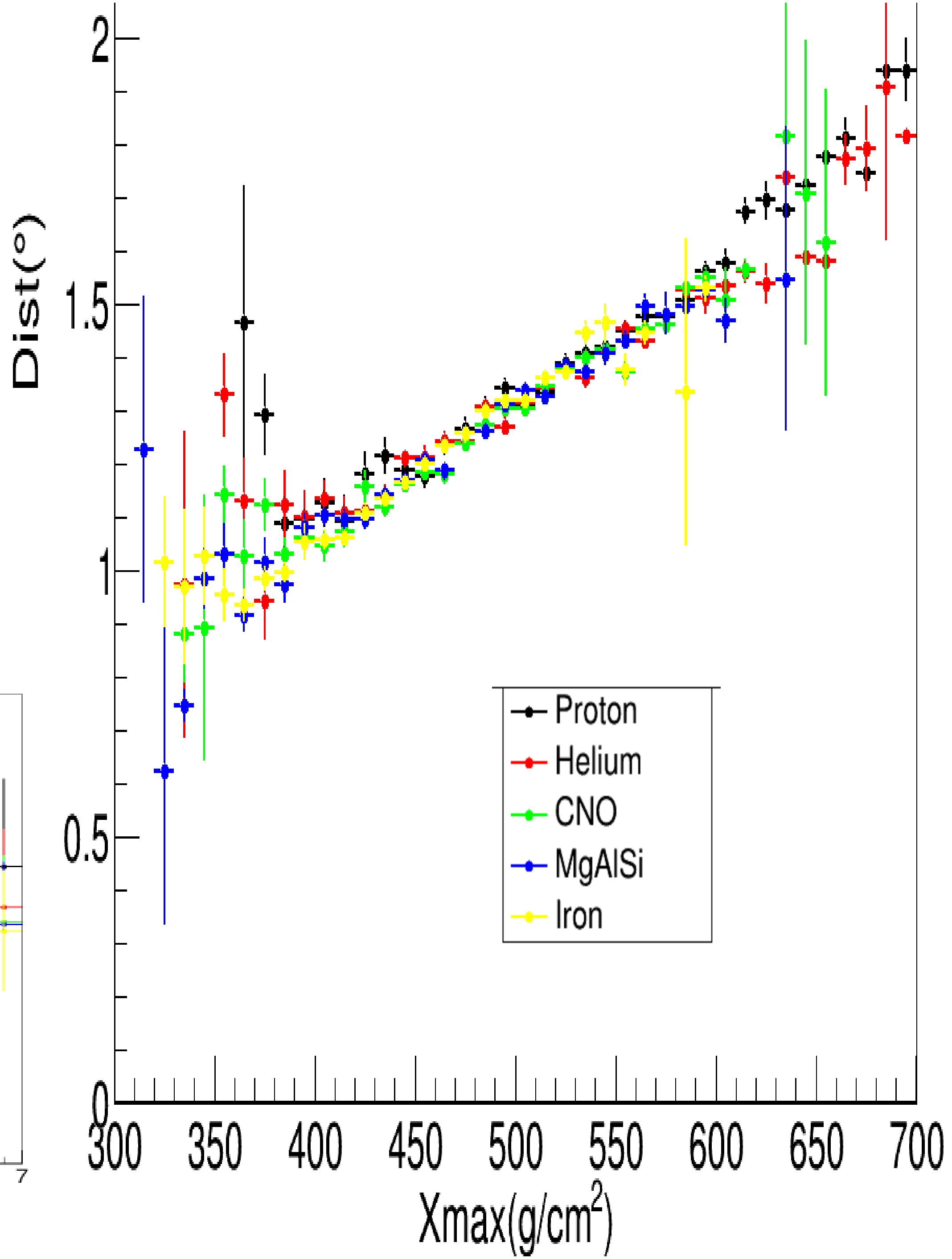
- Xmax is reconstructed by Dist
- Resolution
  - 45g/cm² @ 1PeV for proton
  - 34g/cm² @ 1PeV for iron



The angular distance between the arrival direction and the image center.



Dist vs. Xmax
at a given Rp range

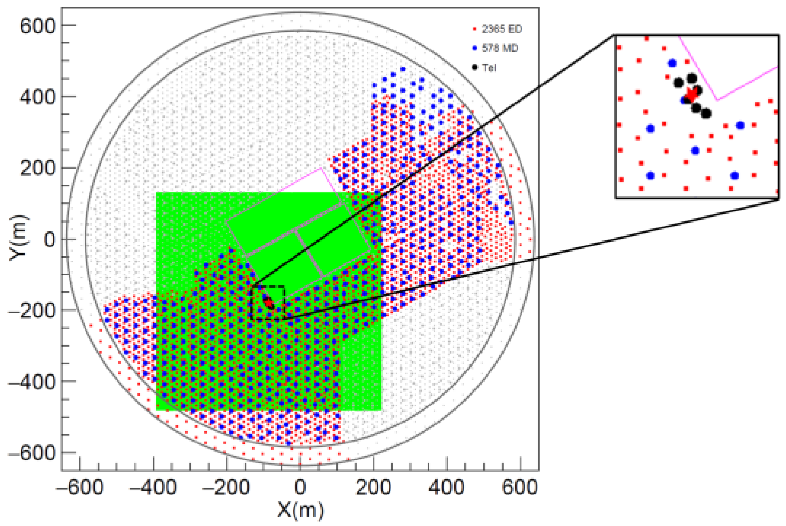


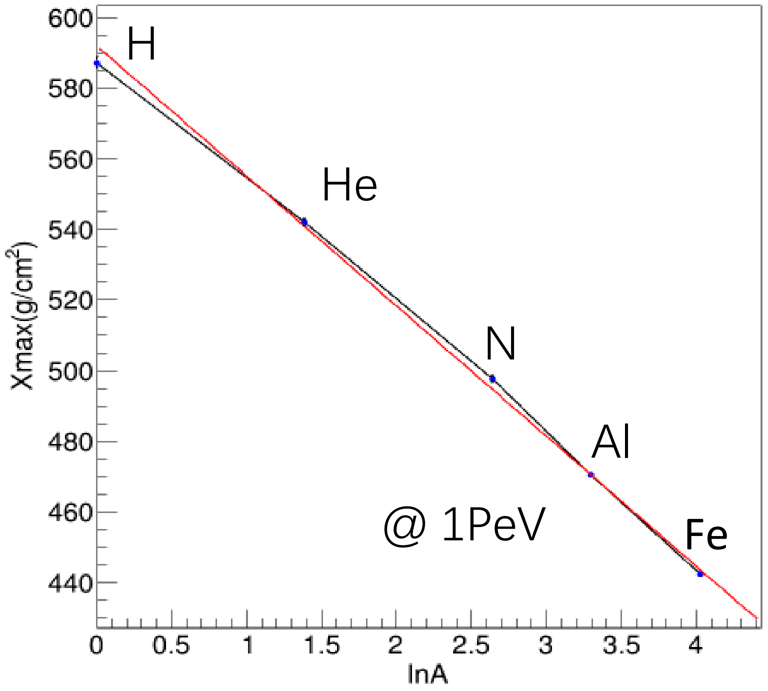
<lnA> Measured by Xmax of WFCTA

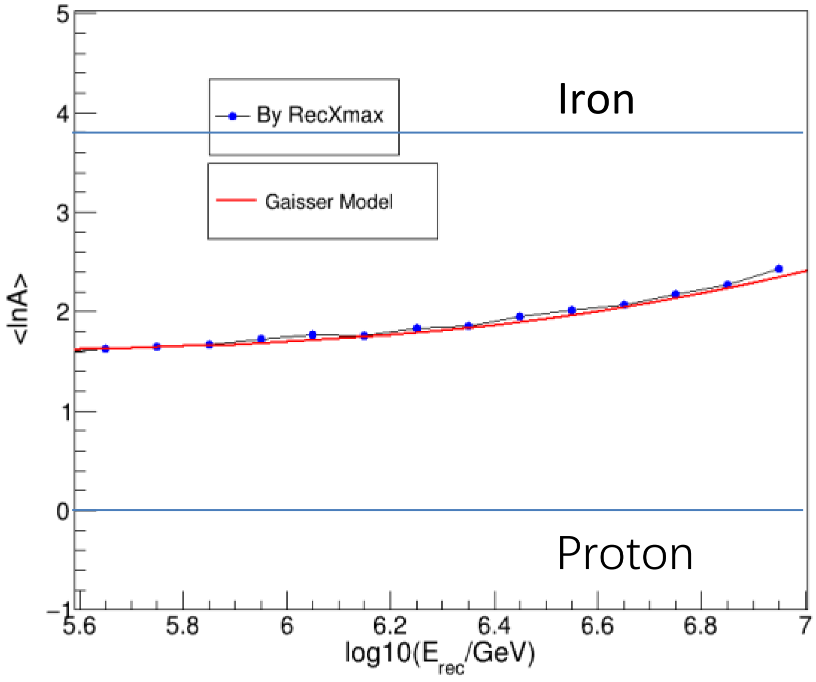
- Hybrid events with WFCTA and KM2A
  - 50 m<R_p<200 m, N_{pix}>20,   (|X|<4˚ &|Y|<4˚)
  - 50+ hits and N_μ>5

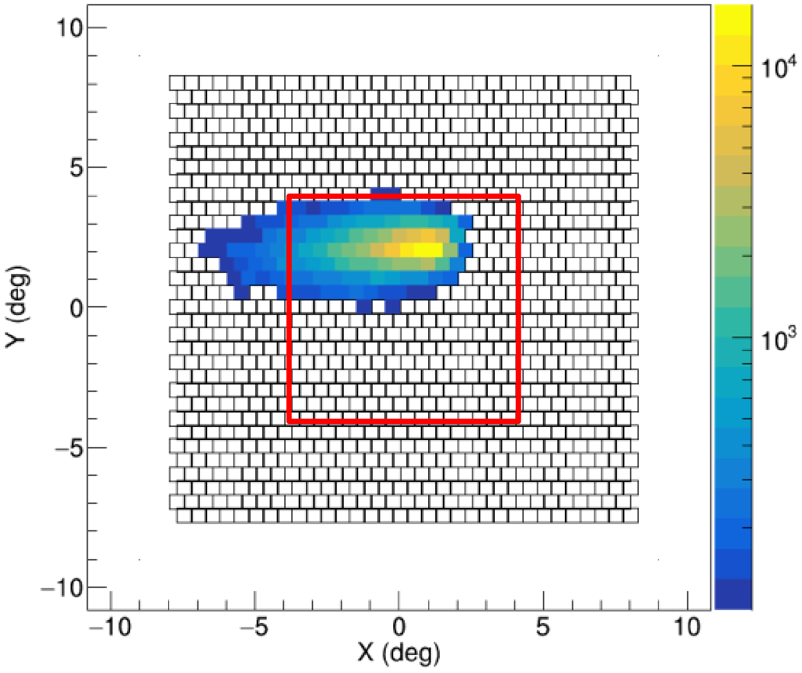
$$X_{max}^{A} = X_{max}^{p} - \lambda_r \ln A$$

λ_r = 37g/cm^2 is radiation length

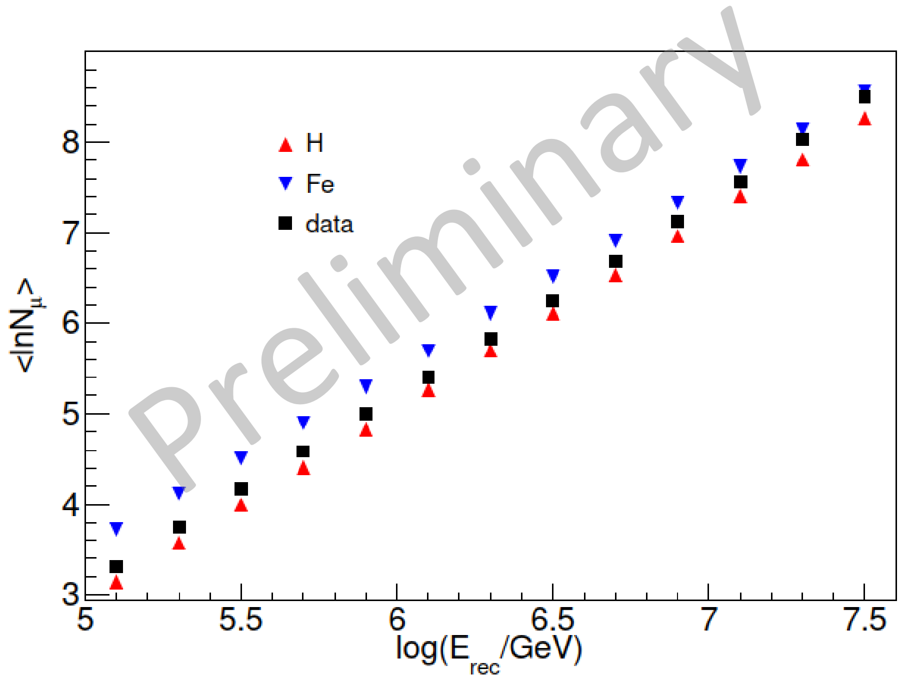








<lnA> reconstructed by muon in KM2A

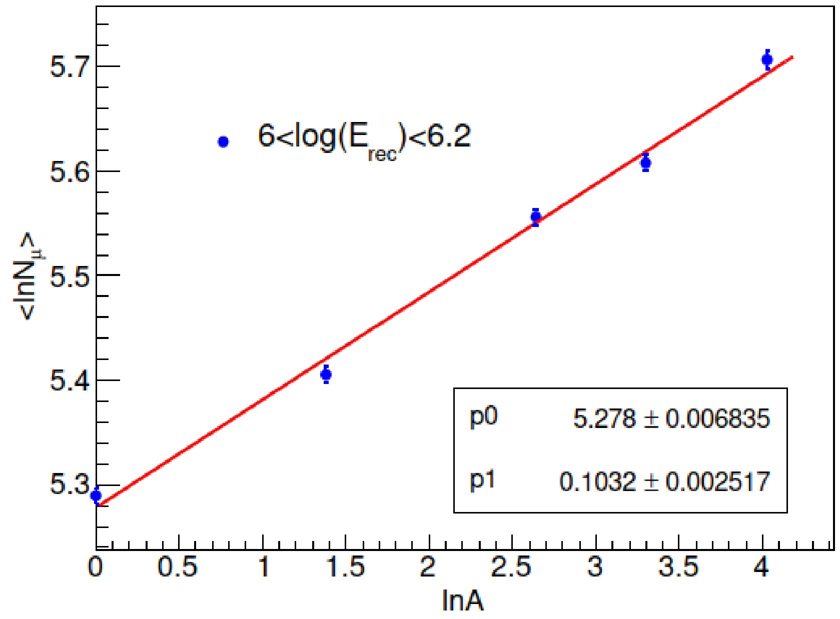


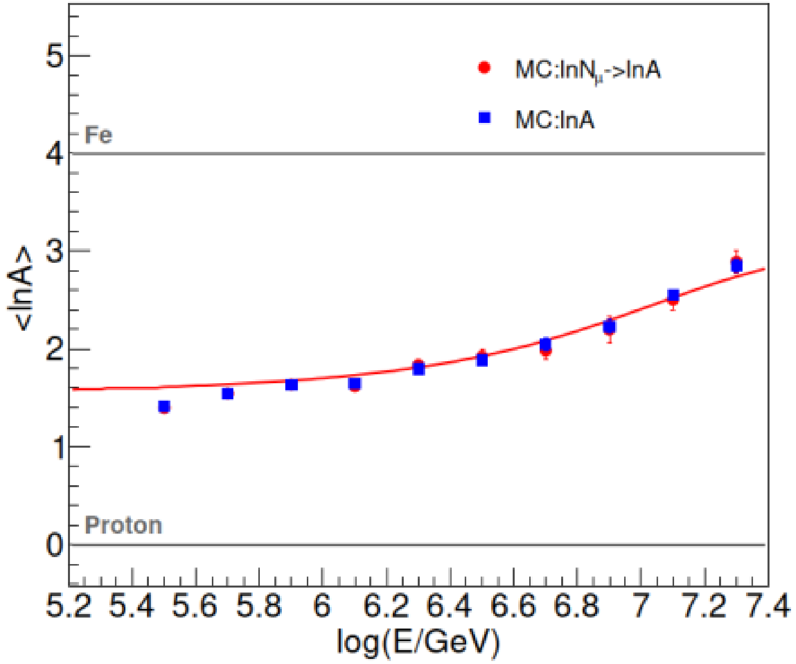
$$N_\mu = A \cdot \left(\frac{E}{A \cdot \varepsilon_c} \right)^\beta$$

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 β ≈ 0.9 varying with the primary energy.

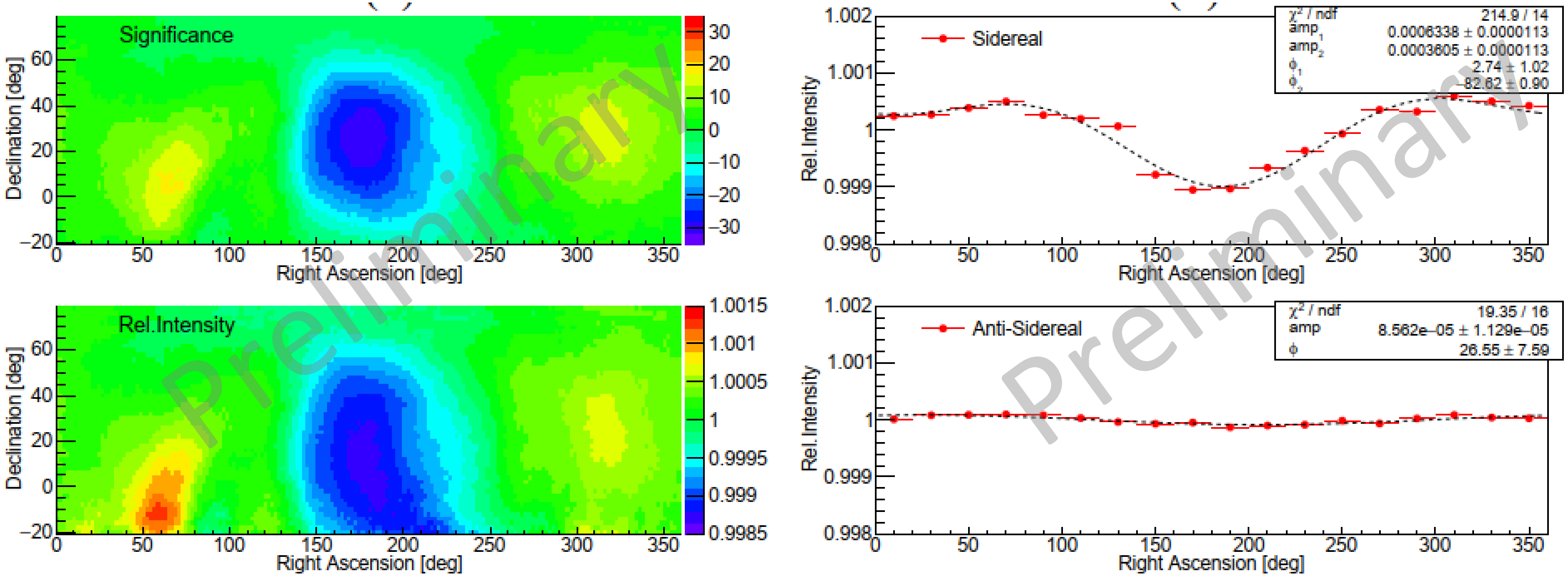
$$\ln N_\mu = p_0 + p_1 \cdot \ln A$$





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.**

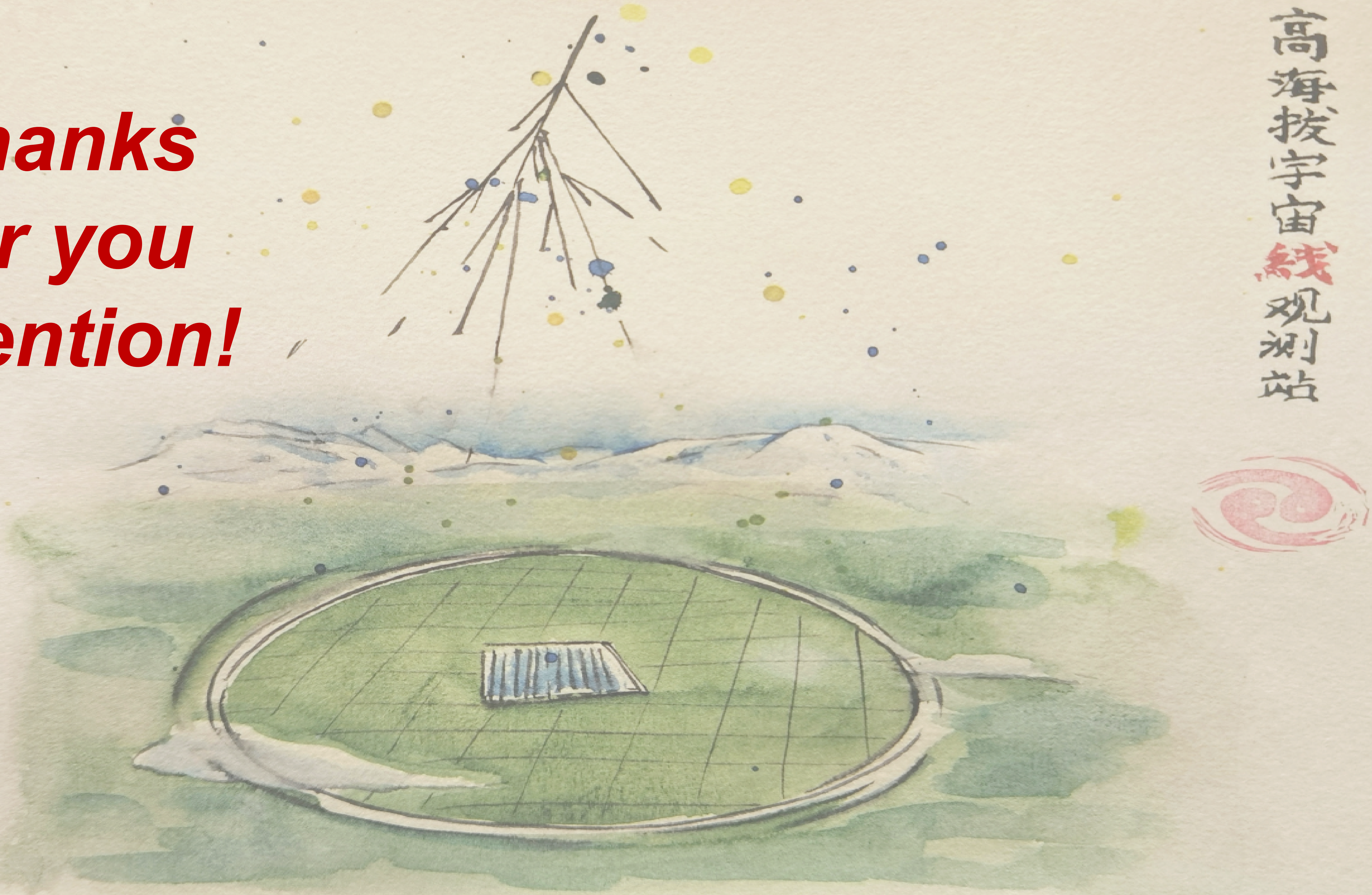


Wei Gao et al., 37th International Cosmic Ray Conference (ICRC2021), 2021 Berlin, Germany

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!

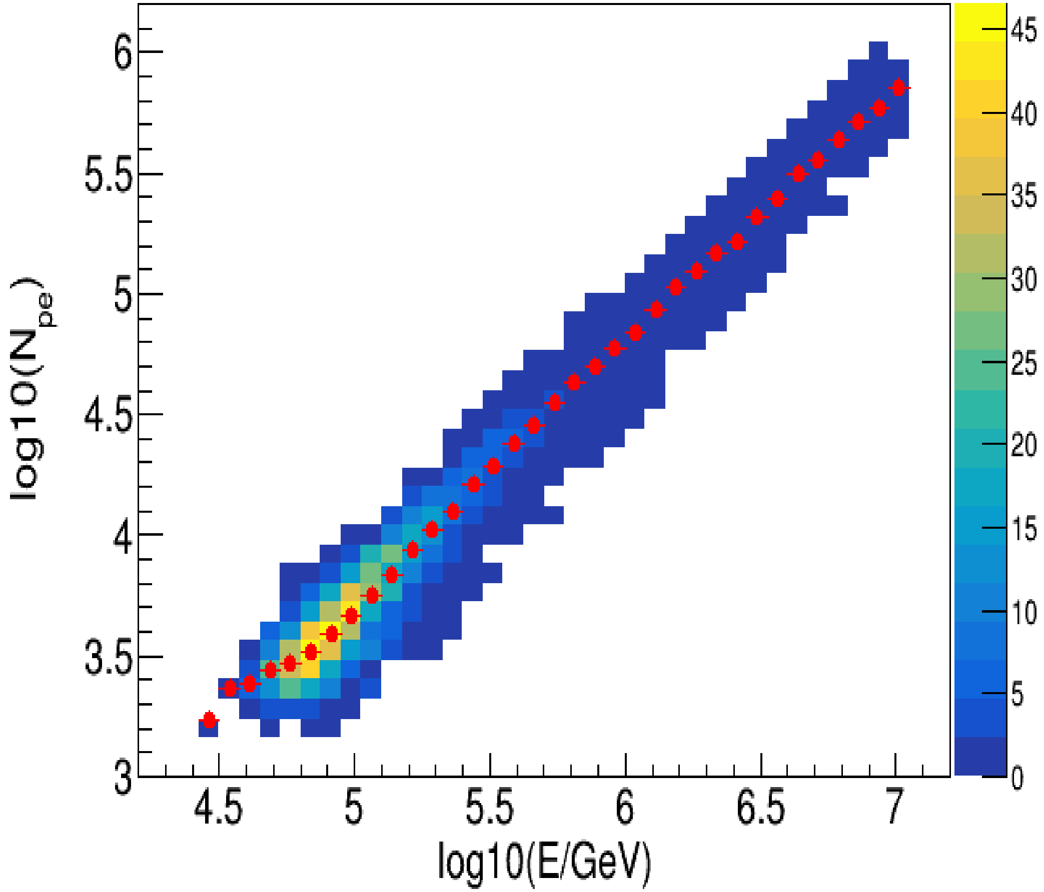


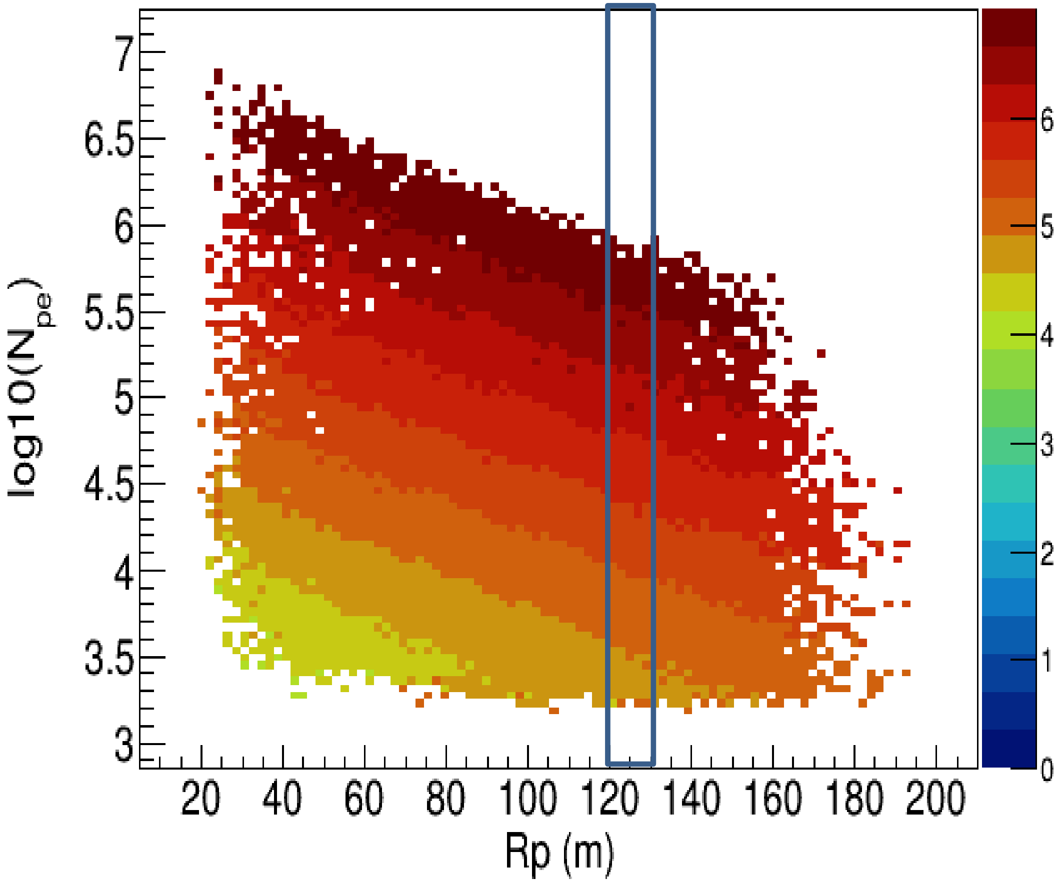
Thanks !

Energy reconstruction

For C-telescopes

For proton, energy response function for showers with Rp=$120m \sim 130m$





联合观测事例挑选条件

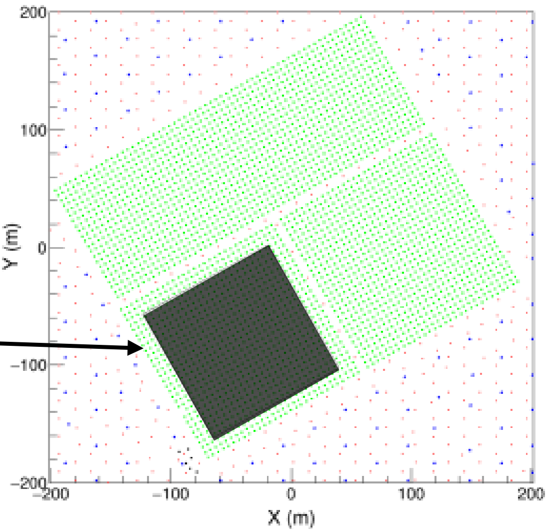
联合观测事例挑选

- **WCDA 挑选条件**
  1. 重建芯位 x 和 y 方向距离 1 号水池中心均小于 60 m
  2. 最亮的 cell 信号 Q_{max} 大于 3000 pe （簇射芯区能流密度大）
  3. $Q(10)/Q(30)$ 大于 0.3 （芯区能流密度变化快）

     $Q(10)$：距离簇射轴 10 米范围内的 Cell 信号和

     $Q(30)$：距离簇射轴 30 米范围内的 Cell 信号和

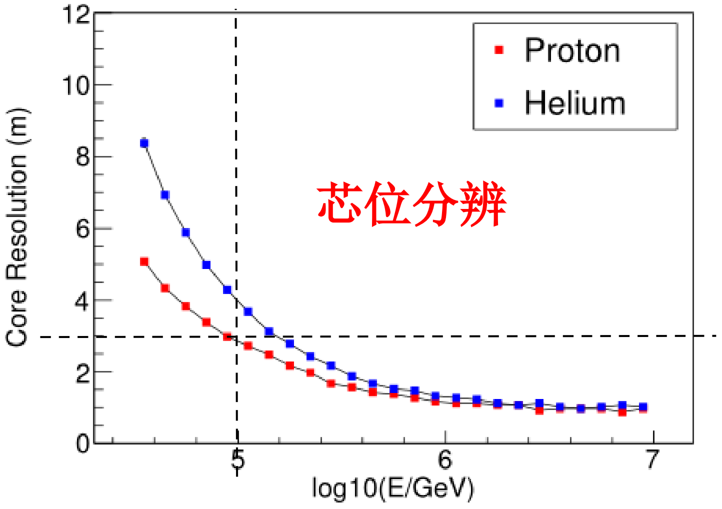
WCDA 芯位范围

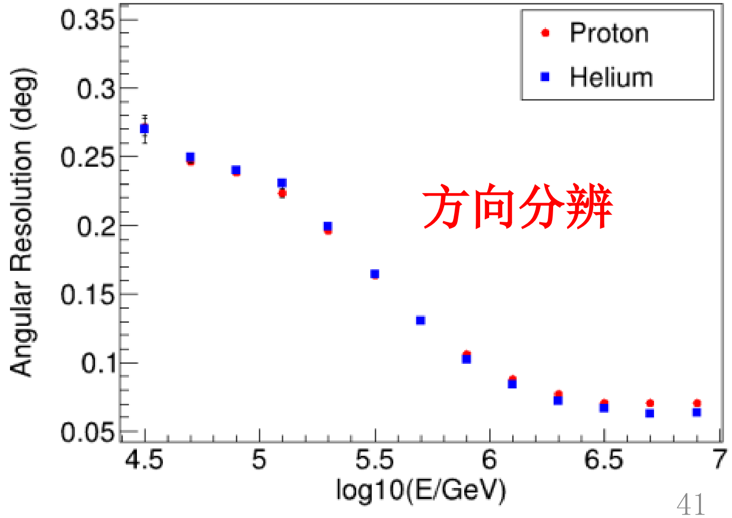


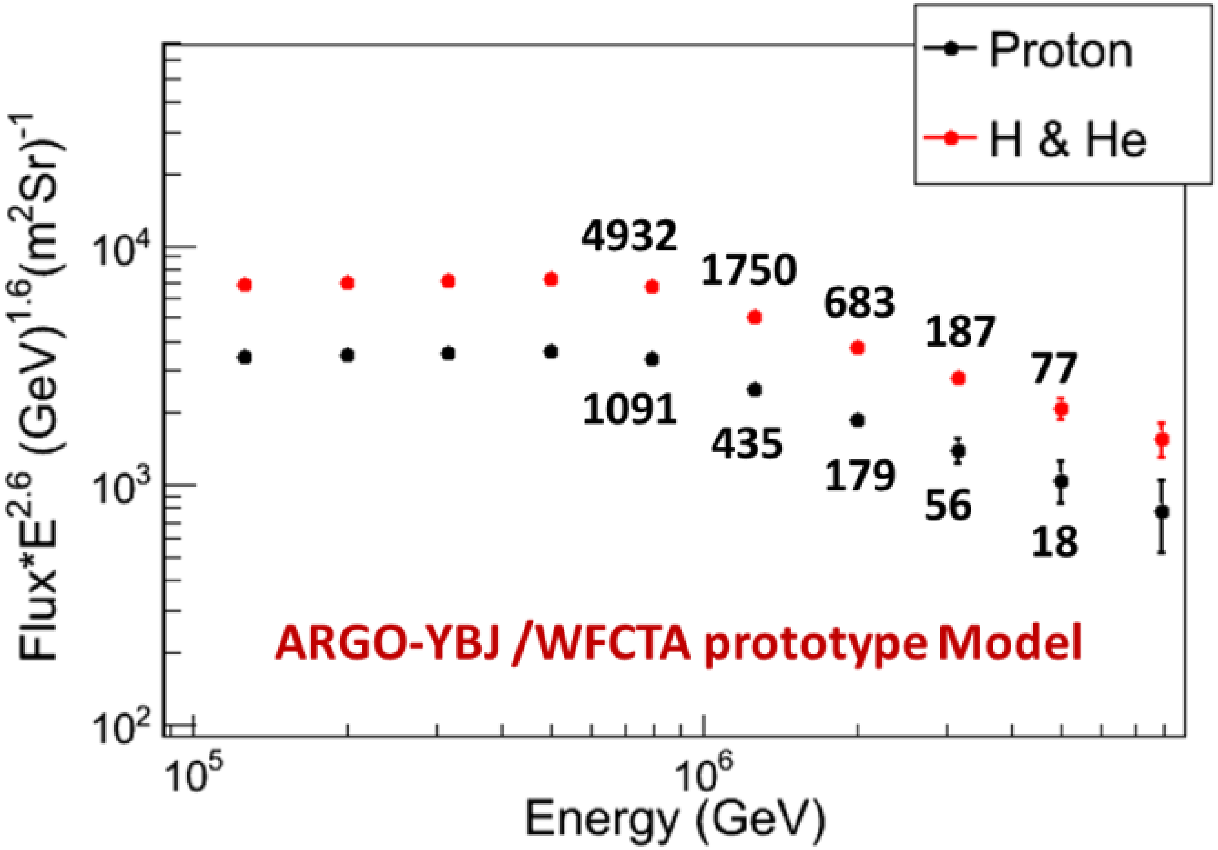
质子成分：

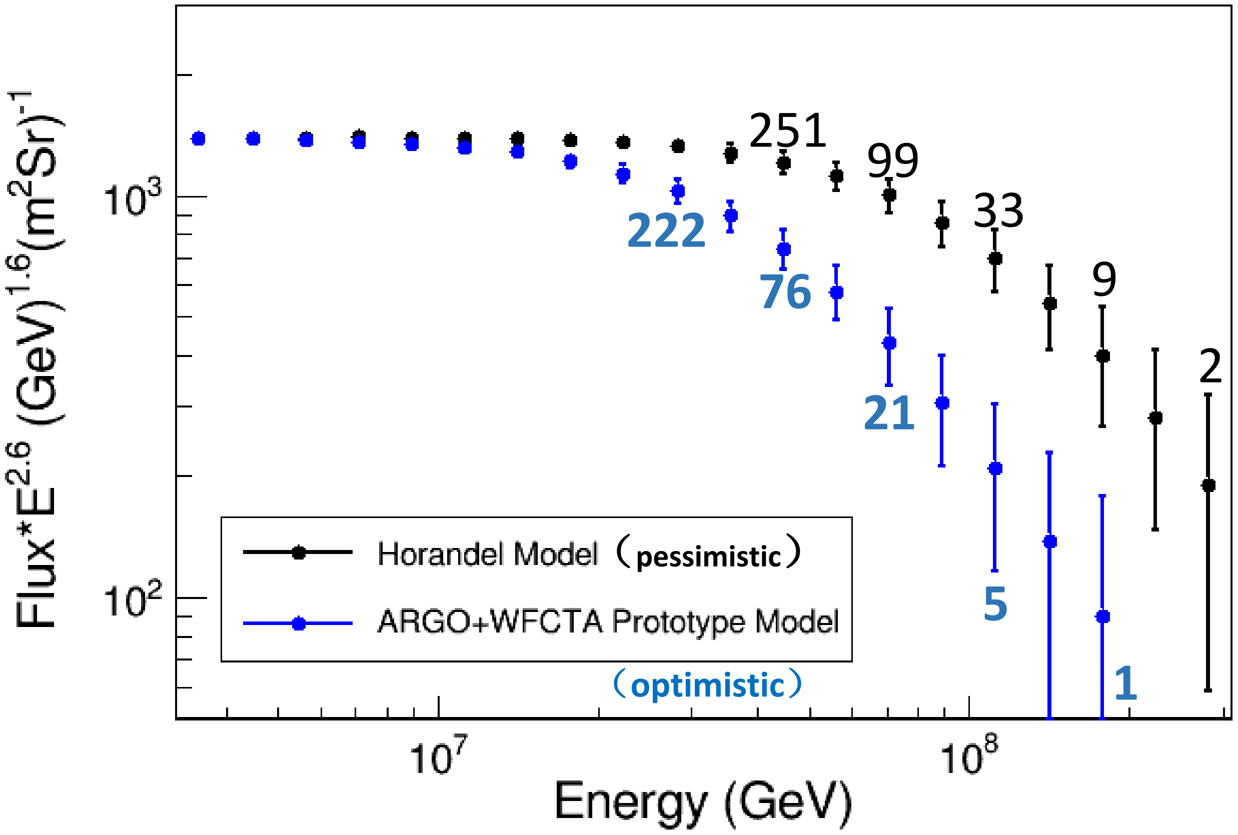
芯位分辨：$< 3m(above\ 100\ TeV)$

方向分辨：$< 0.3°(above\ 100TeV)$






Proton
H & He
4932
1750
683
187
77
1091
435
179
56
18
ARGO-YBJ /WFCTA prototype Model
10^4
10^3
10^2
10^5
10^6
Flux*$E^{2.6}$ (GeV)$^{1.6}$(m^{2}Sr)$^{-1}$
Energy (GeV)


251
99
33
9
2
222
76
21
5
1
Horandel Model（pessimistic）
ARGO+WFCTA Prototype Model
（optimistic）
10^3
10^2
10^7
10^8
Flux*$E^{2.6}$ (GeV)$^{1.6}$(m^{2}Sr)$^{-1}$
Energy (GeV)