Using LHAASO to test high-energy hadron interaction models

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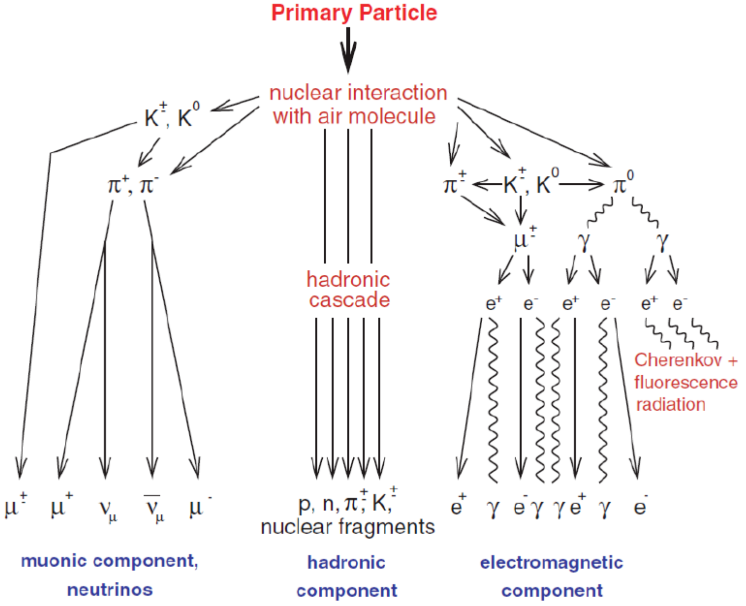
- Extensive air shower
- LHAASO experiment
- Parameters measured by LHAASO
- Hadronic interaction model test
- Summary

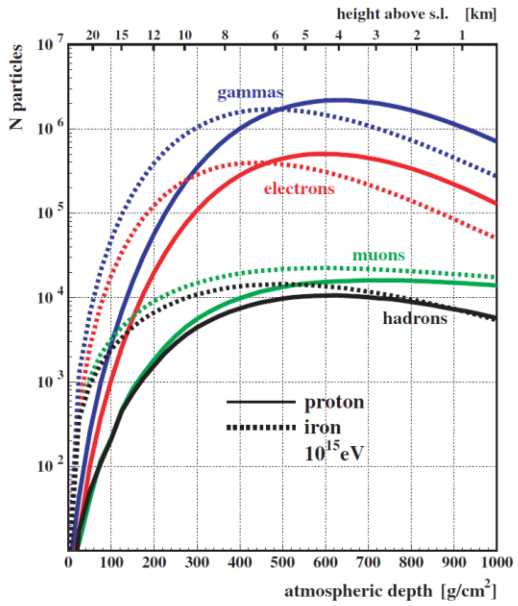
Extensive air shower (EAS)

$$N_\mu \propto A^{1-\beta}\left(\frac{E_0}{1\ PeV}\right)^{\beta}, N_e \propto A^{1-\alpha}\left(\frac{E_0}{1\ PeV}\right)^{\alpha}$$

$$\beta = 0.9, \alpha = 1.046$$

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)



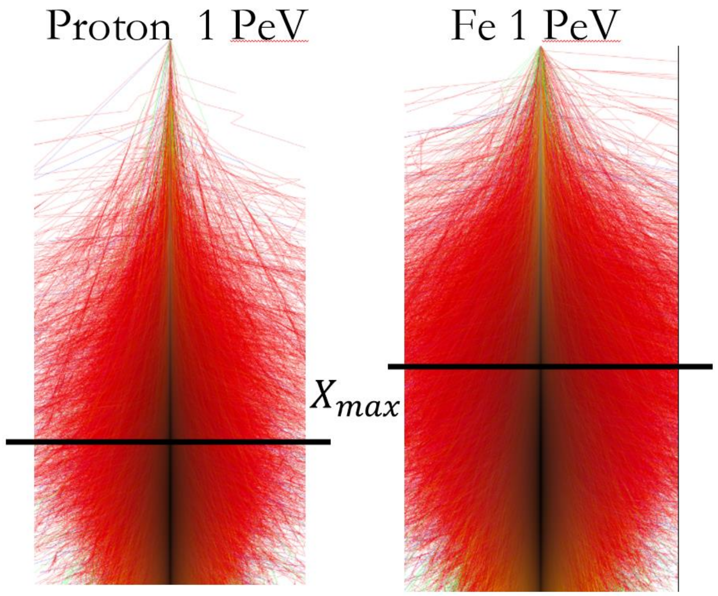


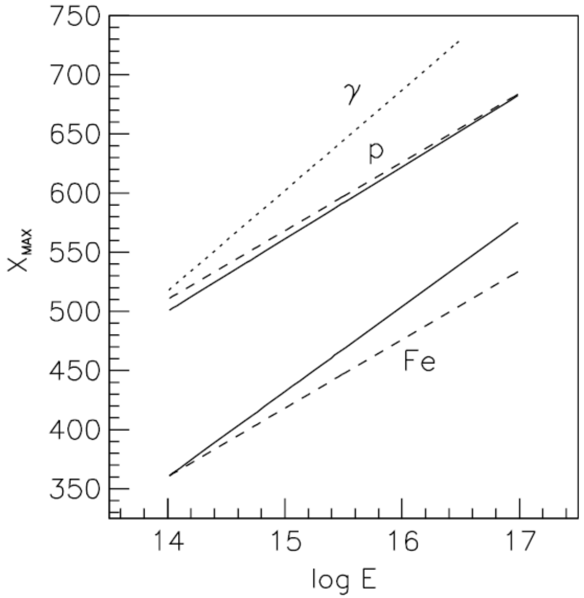
$$X_{max}^{A} = X_{max}^{P} - \lambda_r \ln A$$

Elongation rate :

$$\Lambda \equiv \frac{dX_{max}}{d\log_{10}E} \approx 58\mathrm{g}\cdot\mathrm{cm}^{-2}/\mathrm{decade}$$

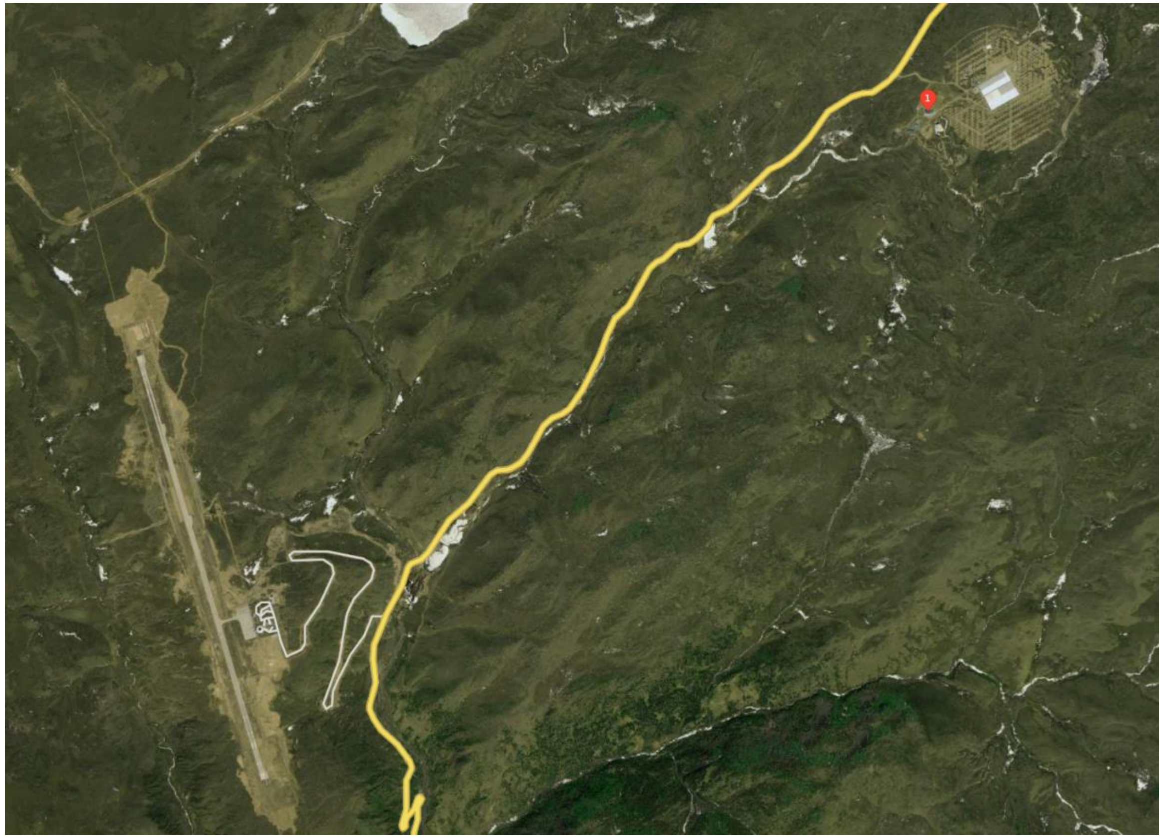
J. Matthews, A Heitler model of extensive air showers, Astropart. Phys. 22, 387 (2005)





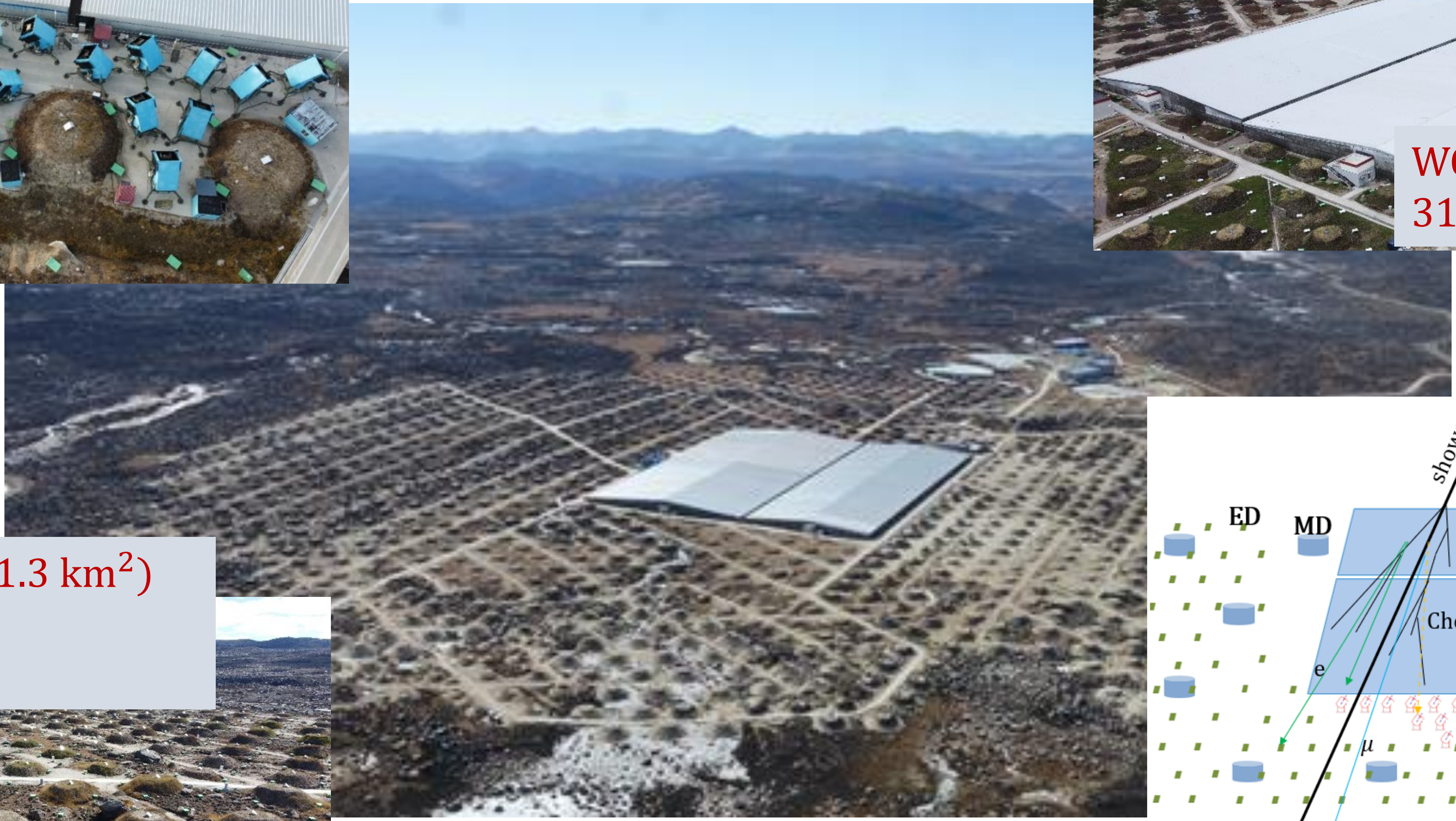
LHAASO experiment

Lacation: Mountain Haizi, Sichuan Province, China
29^{o}21’ N, 100^{o}08’E
4410m a.s.l.
Air depth: 600 g/cm



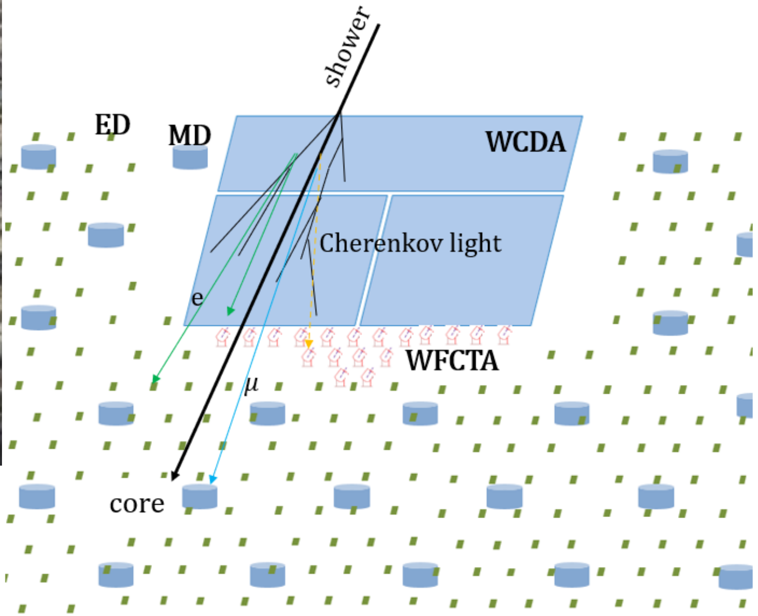
LHAASO experiment

WFCTA: 18 telescopes



WCDA: (78000m^2)
3120 Cells

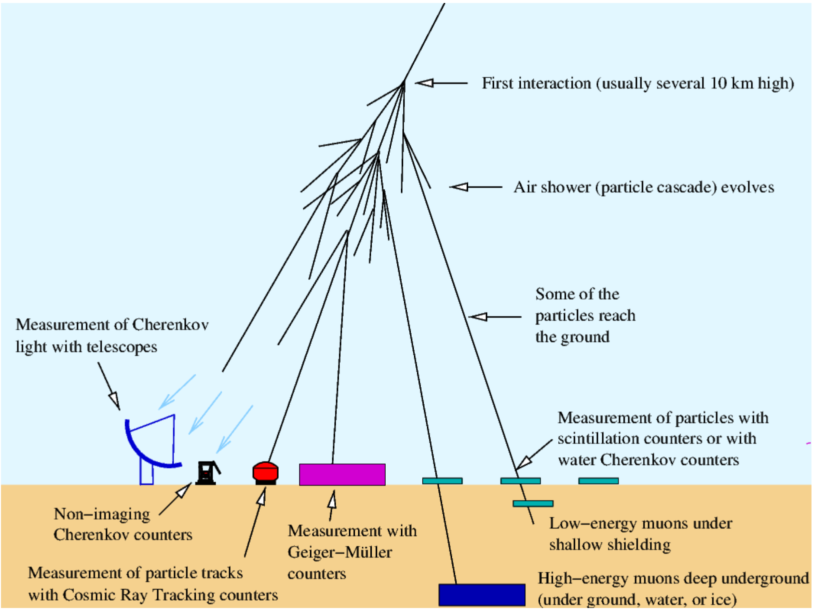
KM2A: (ED, MD, 1.3 km^2)
ED: 5216
MD: 1188

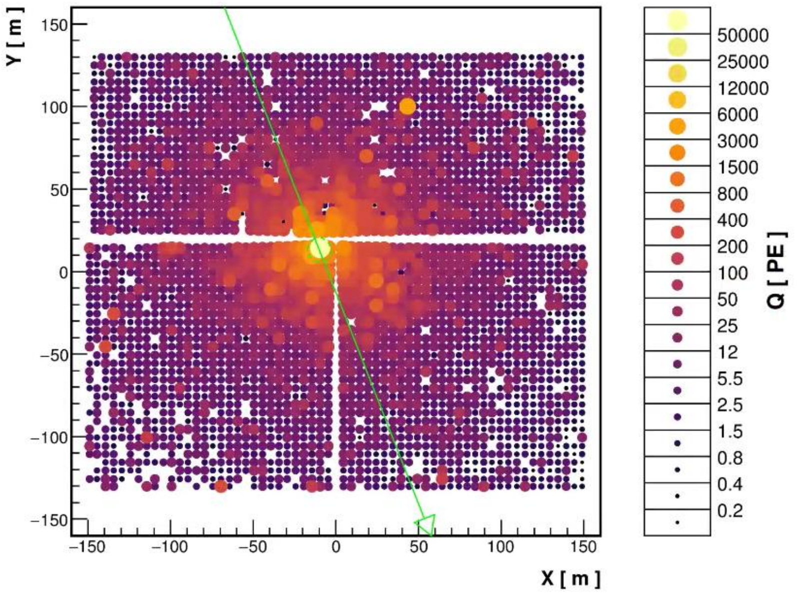


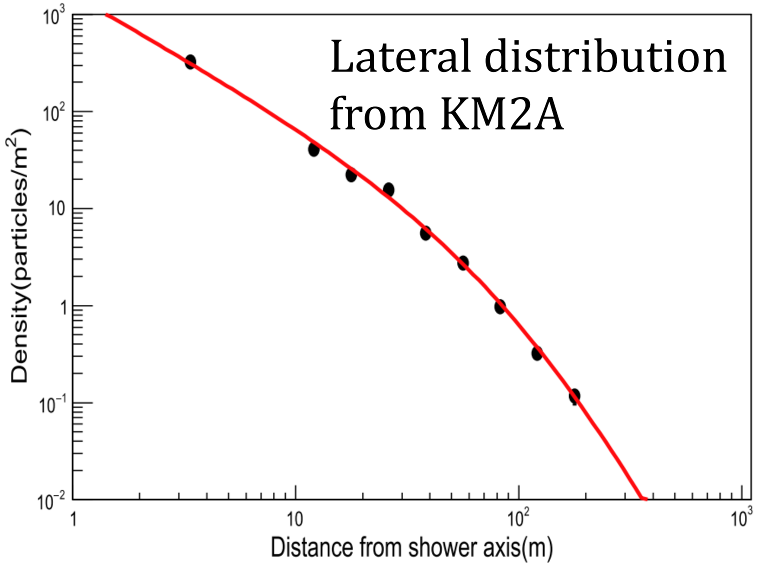
EAS measured by WCDA and KM2A

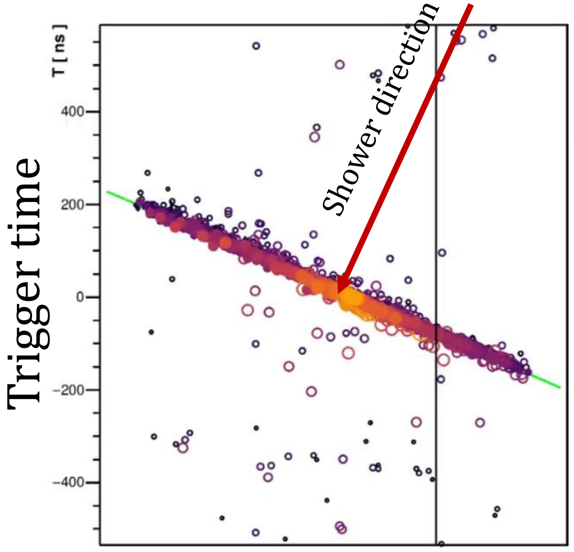
- Core reconstruction:
  1. Calculating the charge-weighted averages of the detector positions
  2. Fit the lateral distribution: Nishimura-Kamata-Greisen (NKG) function
- Direction reconstruction:

  Fit the shower front, conical shape function

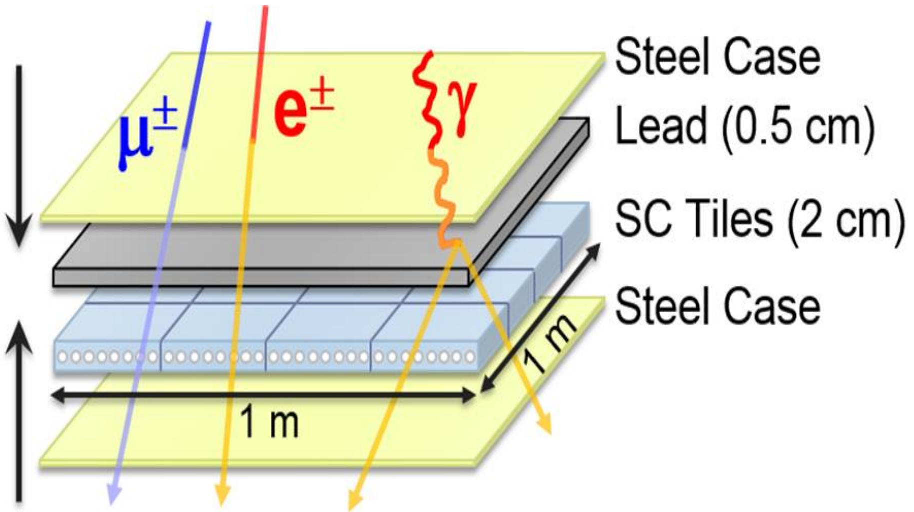




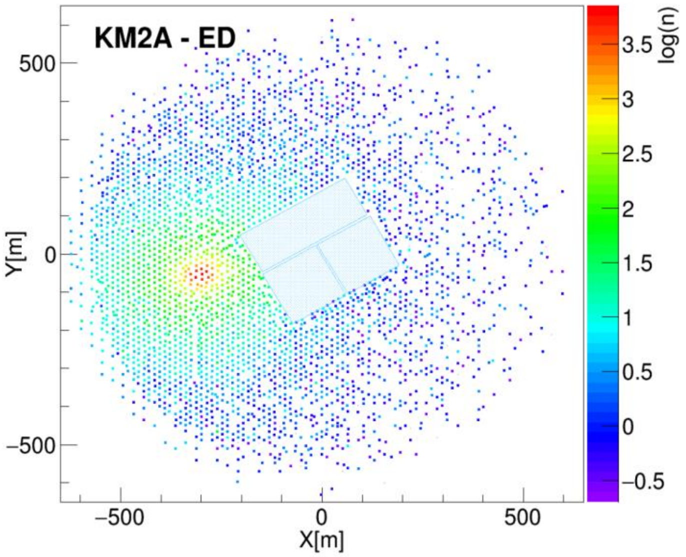


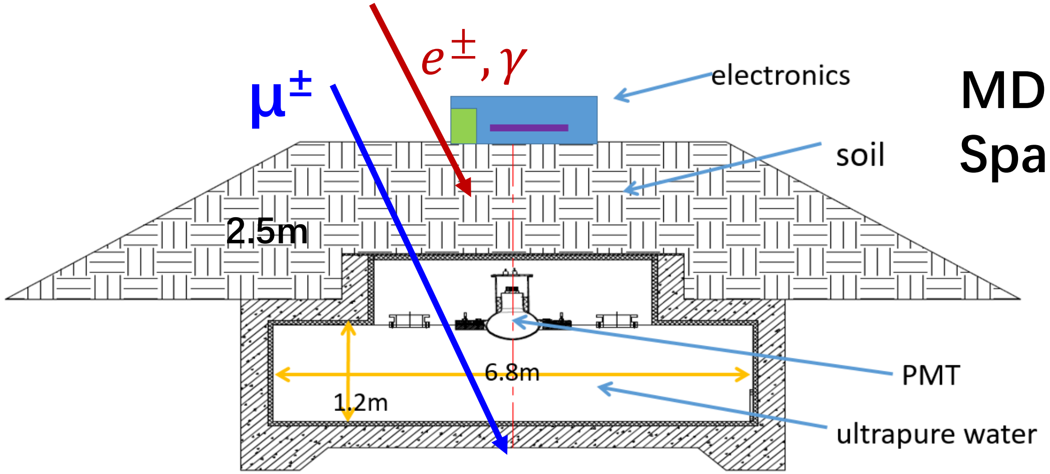


Precise measurements of N_e and N_μ

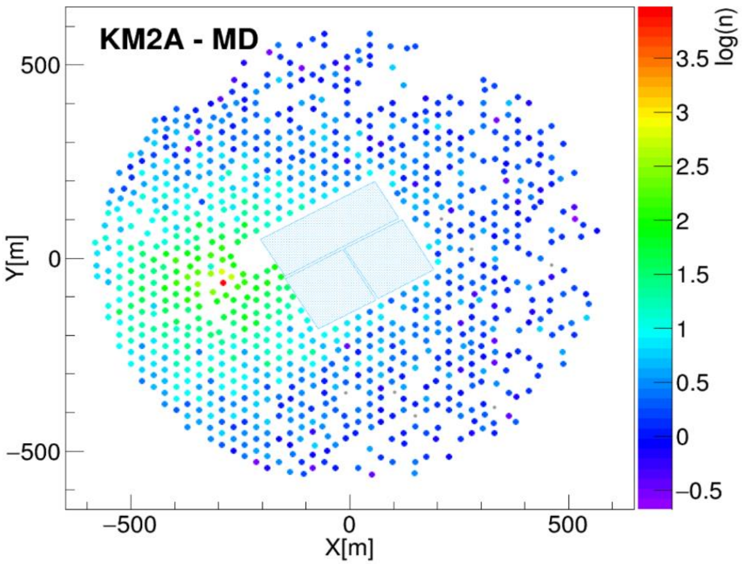


ED: 5216
Spacing: 15m

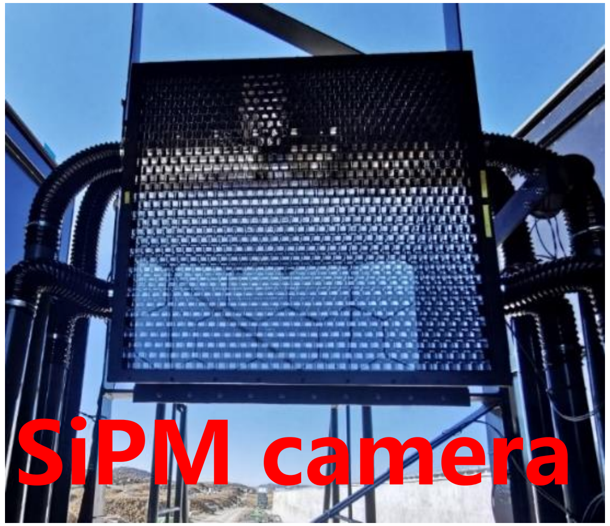


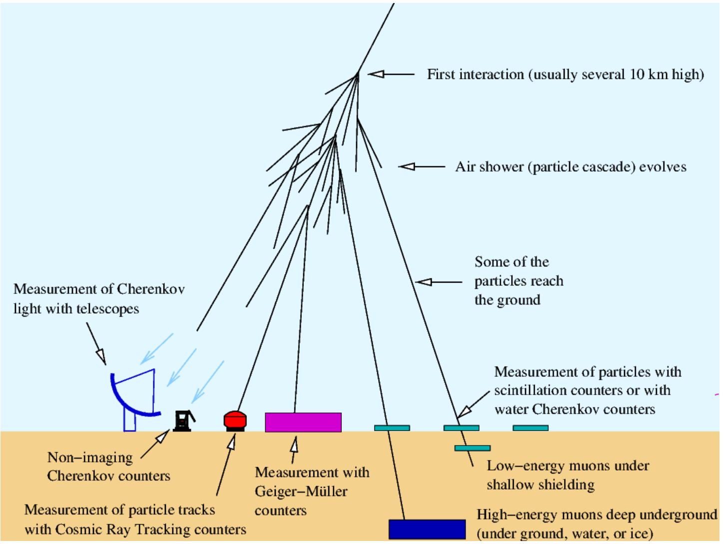


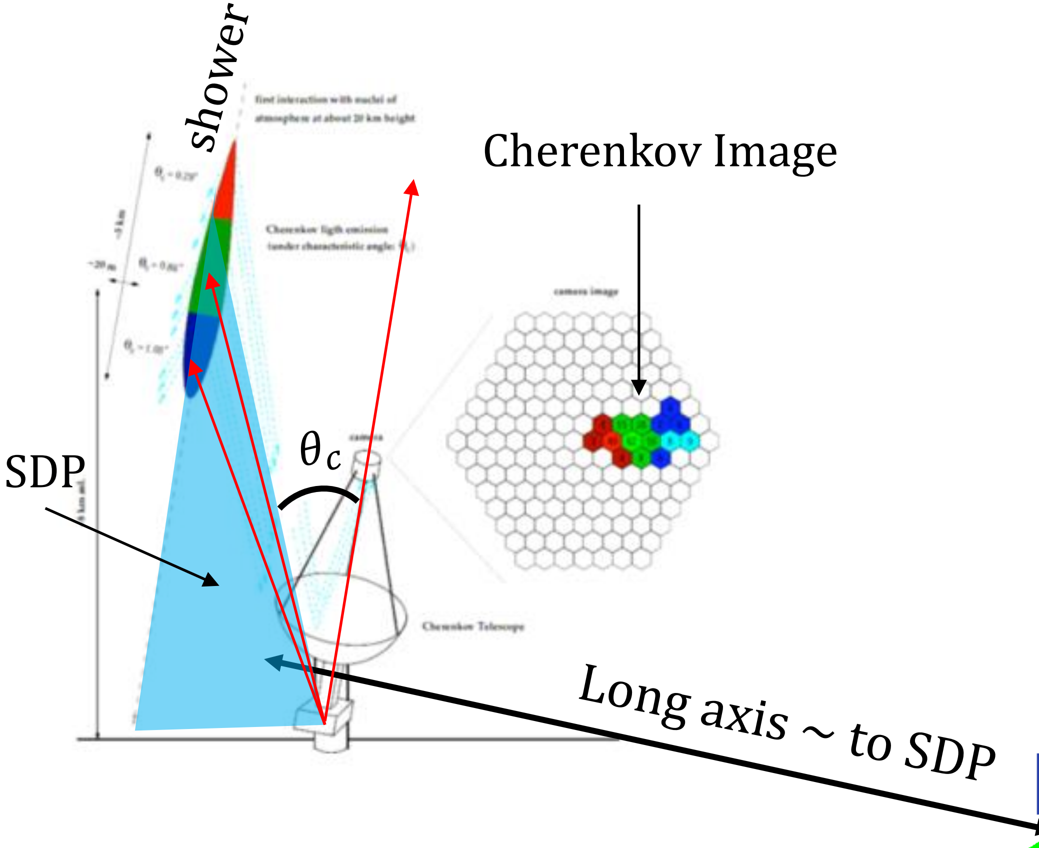
MD: 1188
Spacing: 30m

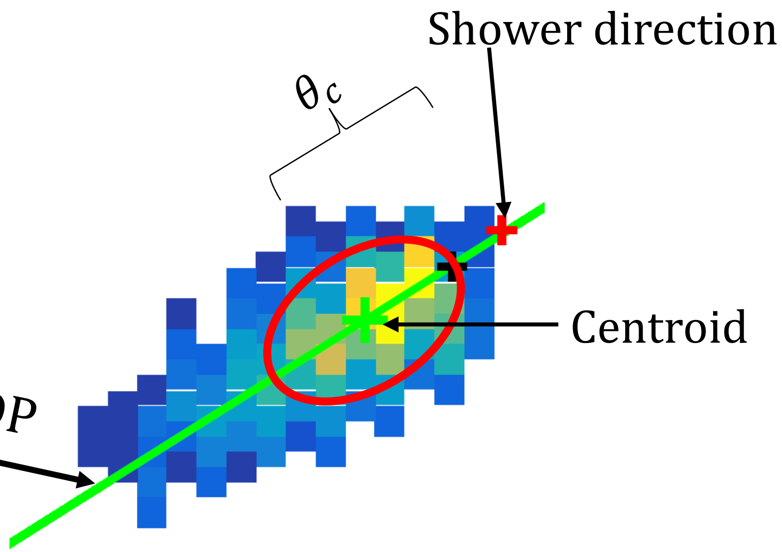


Cherenkov Image measured by WFCTA







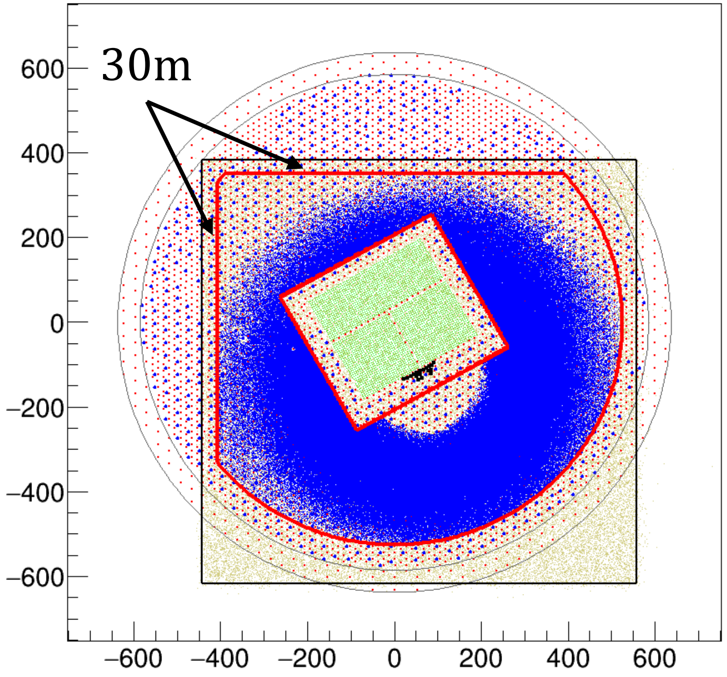


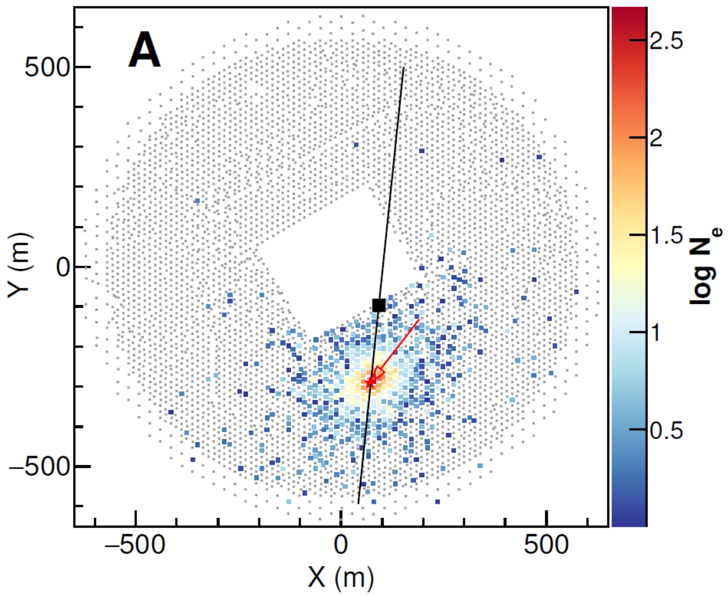
Data set

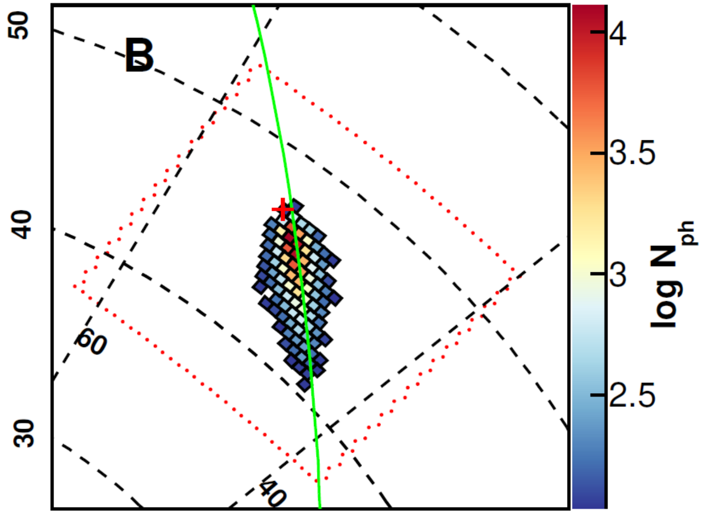
- **KM2A:**
  1. Core selection (Red line region)
  2. Number of fired EDs： NtrigE>20
  3. Rp: 180m~310m

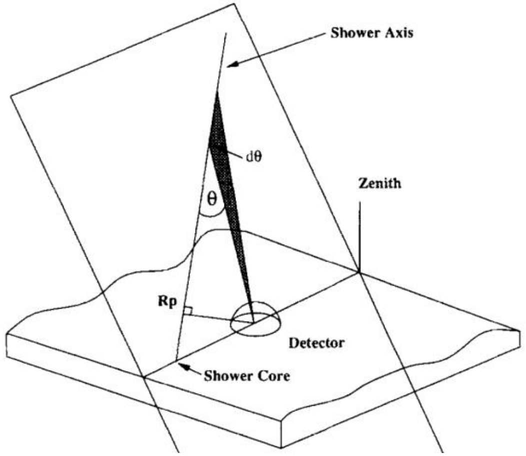
“Rp” is the perpendicular distance from the shower axis to the telescope

- **WFCTA:**
  1. Number of SiPMs： Npix>6
  2. Centroid of Cherenkov Image： $|X_I| < 5° \&\& |Y_I| < 5°$
     (field of view of camera is $8° \times 8°$)









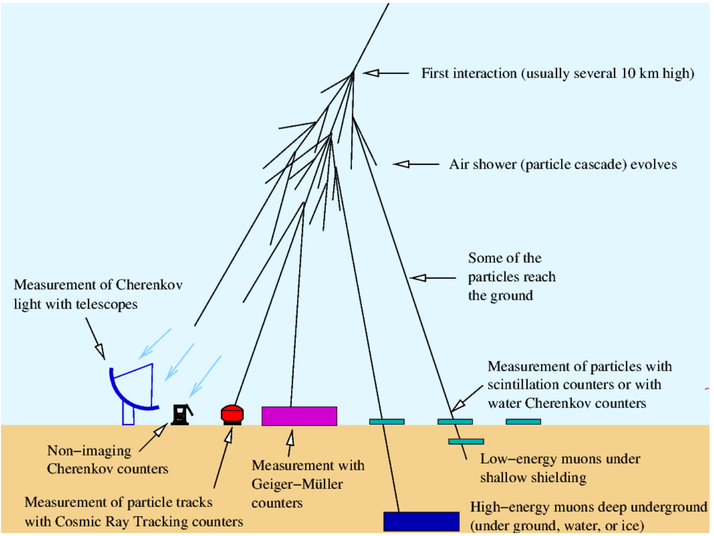
Energy reconstruction

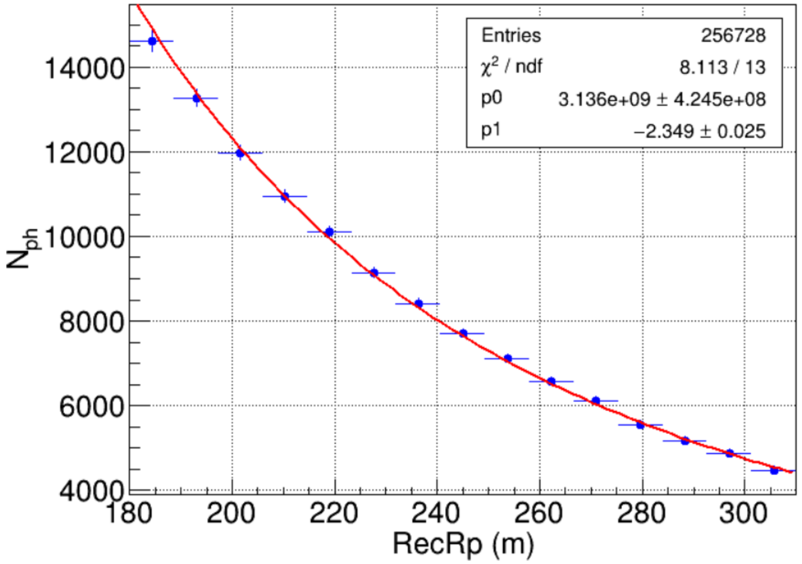
1. Energy estimator: $N_{C\mu} = N_{ph}^{250} + 3.0 \cdot N_{\mu}$

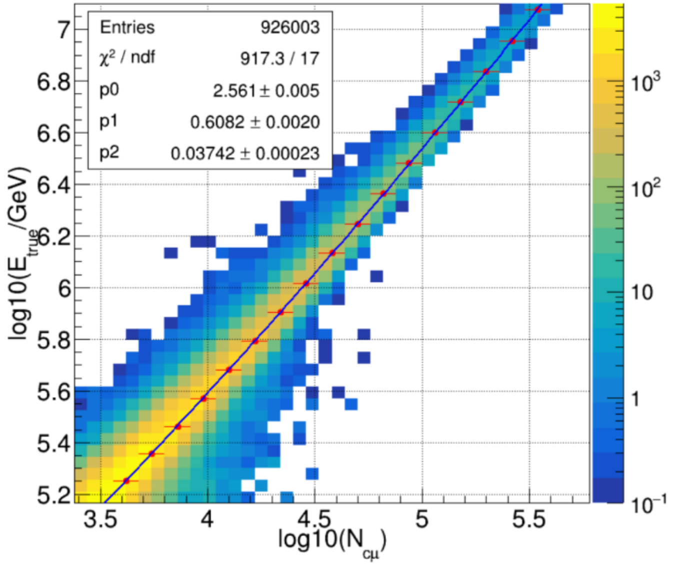
2. Energy reconstruction: $\log_{10} E_{rec} = p_2 \times \log_{10}^2 N_{C\mu} + p_1 \times \log_{10} N_{C\mu} + p_0$

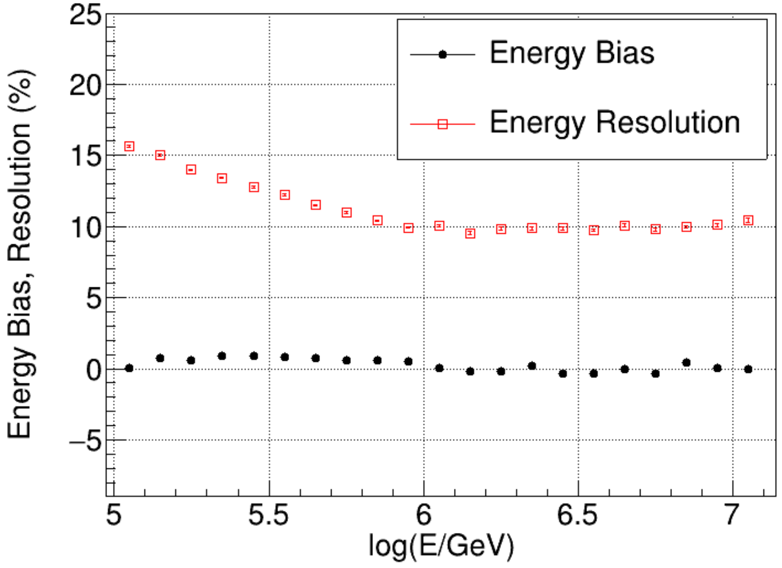
Liping Wang, et al. Phys. Rev. D 107, 043036 (2023)

- $N_{ph} \sim R_p$ relationship: $N_{ph}(R_p) = C_0 \cdot R_p^{\alpha}$
- Normalized N_{ph}: $N_{ph}^{250} = N_{ph} \cdot \left(\frac{250}{R_p}\right)^{\alpha}$
- N_{μ}: Number of muons in the ring of range from 40 to 200m







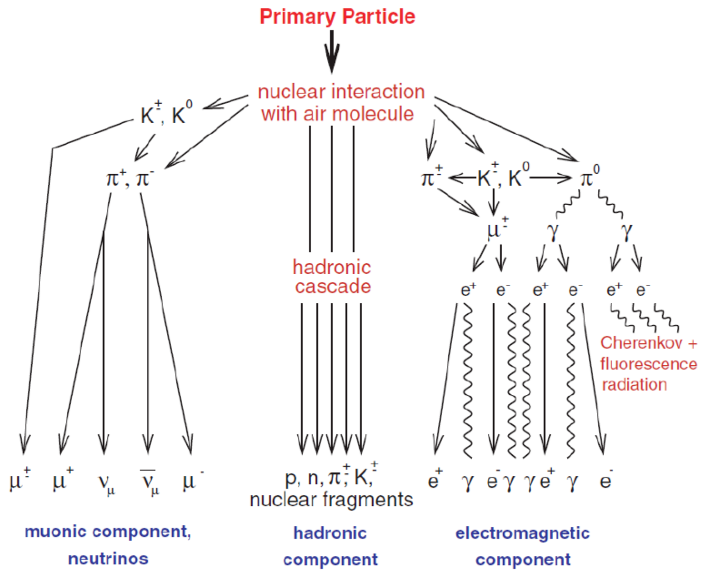


Muons and electromagnetic particles in EAS

$$N_\mu \propto A^{1-\beta}\left(\frac{E_0}{1\ \mathrm{PeV}}\right)^\beta$$

$$N_e \propto A^{1-\alpha}\left(\frac{E_0}{1\ \mathrm{PeV}}\right)^\alpha$$

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)

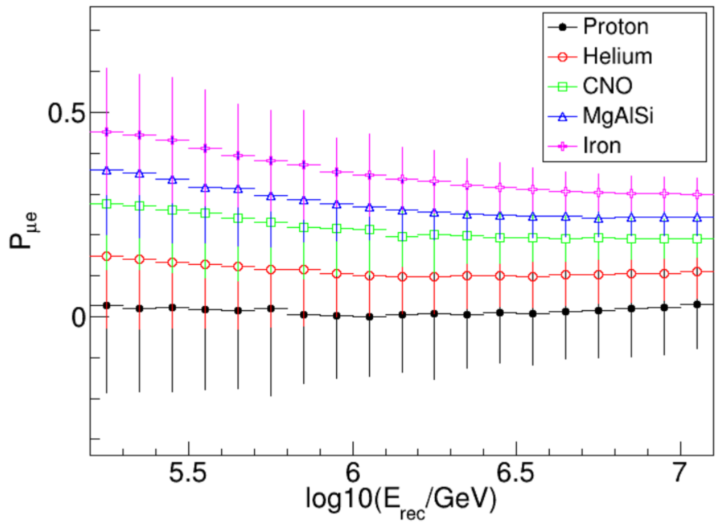


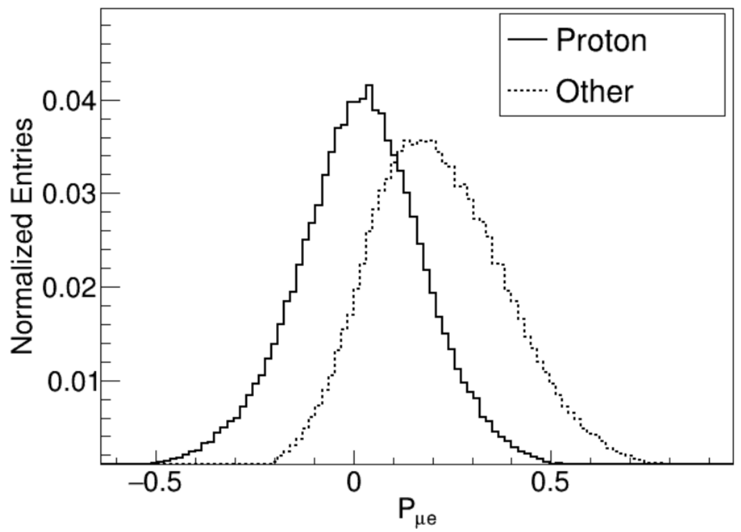
$$\log A = \frac{\alpha}{\alpha-\beta}\log\left(\frac{N_\mu}{N_e^{\beta/\alpha}}\right) - \frac{\alpha}{\alpha-\beta}\log\left(\frac{K_\mu}{K_e^{\beta/\alpha}}\right)$$

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

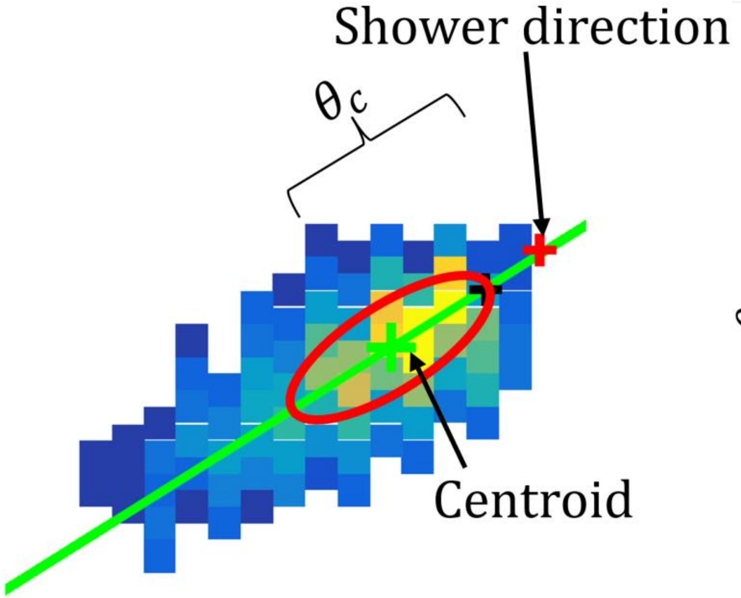
$$P_{\mu e} = \log_{10}\frac{N_\mu}{N_e^{0.82}}$$

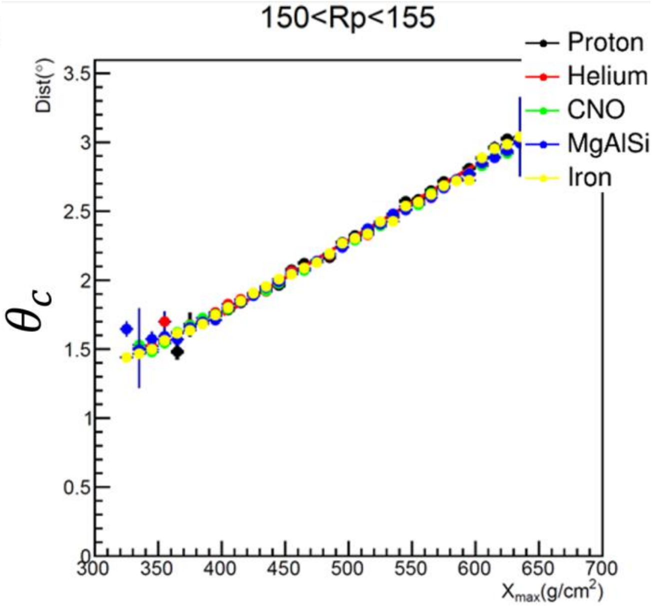
- N_μ : 40~200 m
- N_e : 40~200 m





X_{max} in EAS





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

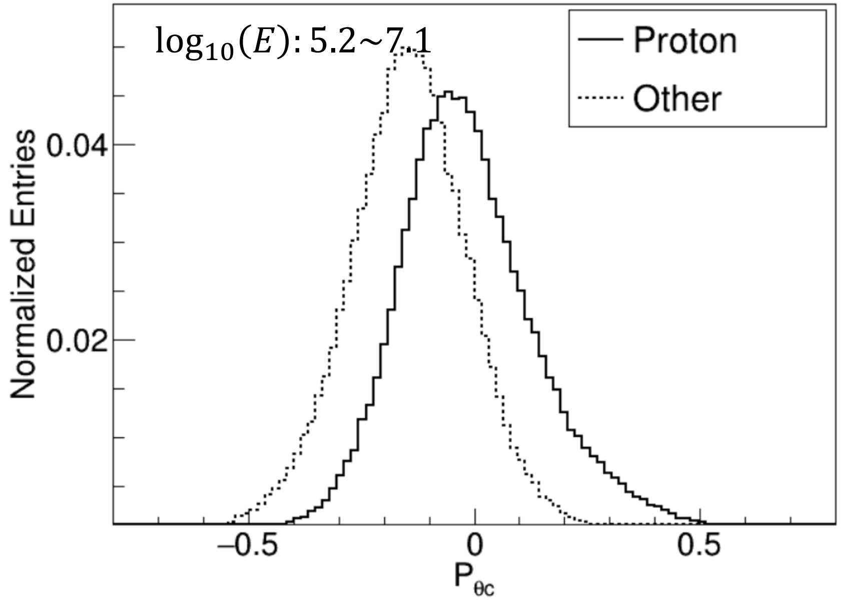
- Remove geometric dependence:

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

- Remove energy dependence:

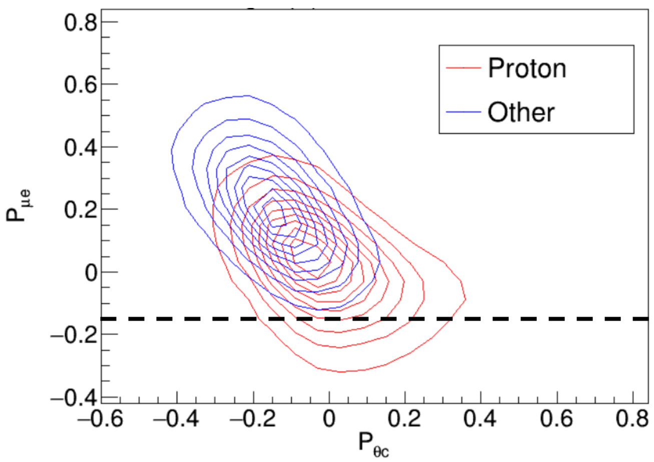
$$\langle\theta_c^{250}\rangle = p_0 + p_1 \cdot \log_{10} E + p_2 \cdot \log_{10}^2 E$$

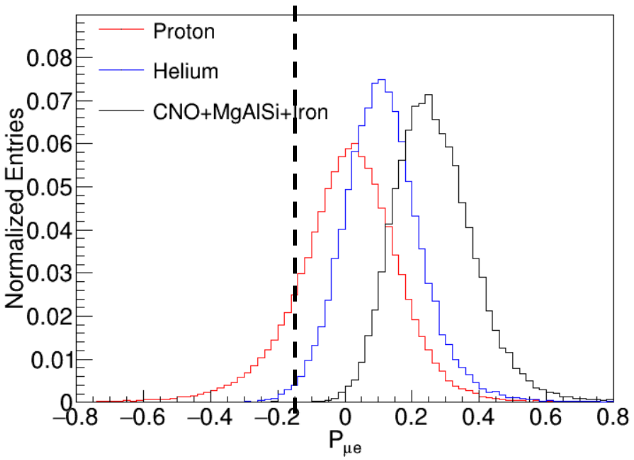
- $\langle\theta_c^{250}\rangle|_{PeV}$: The average value of θ_c for proton events near R_p at 250 m and 1 PeV



For selected events

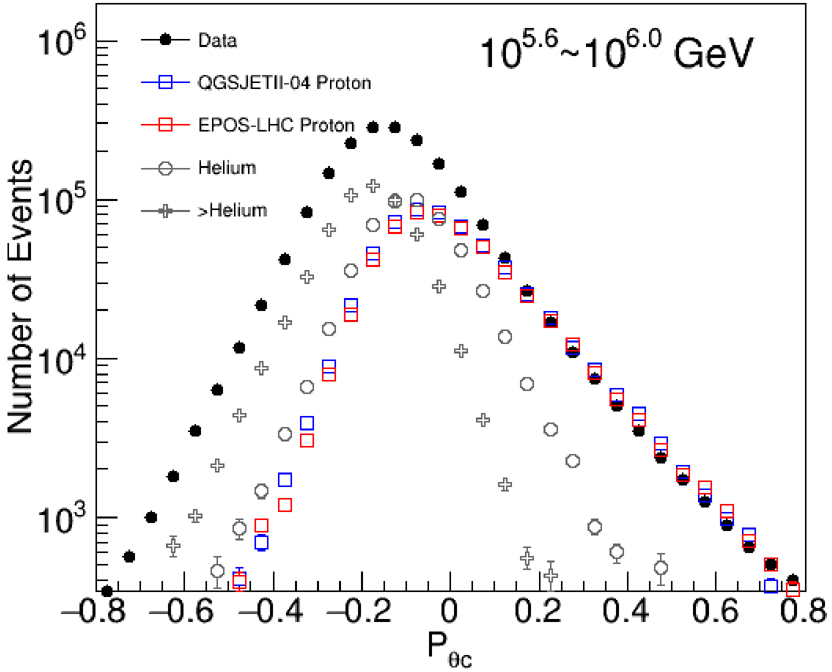
By selecting events using $P_{\mu e}$, proton events with purity of 95% can be obtained.

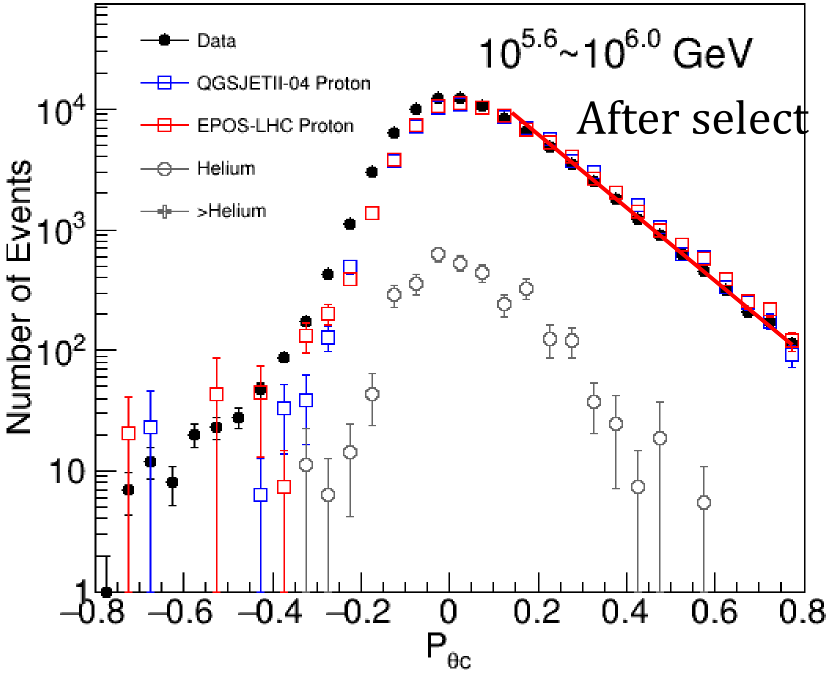




First interaction depth in the air for proton events

Before select

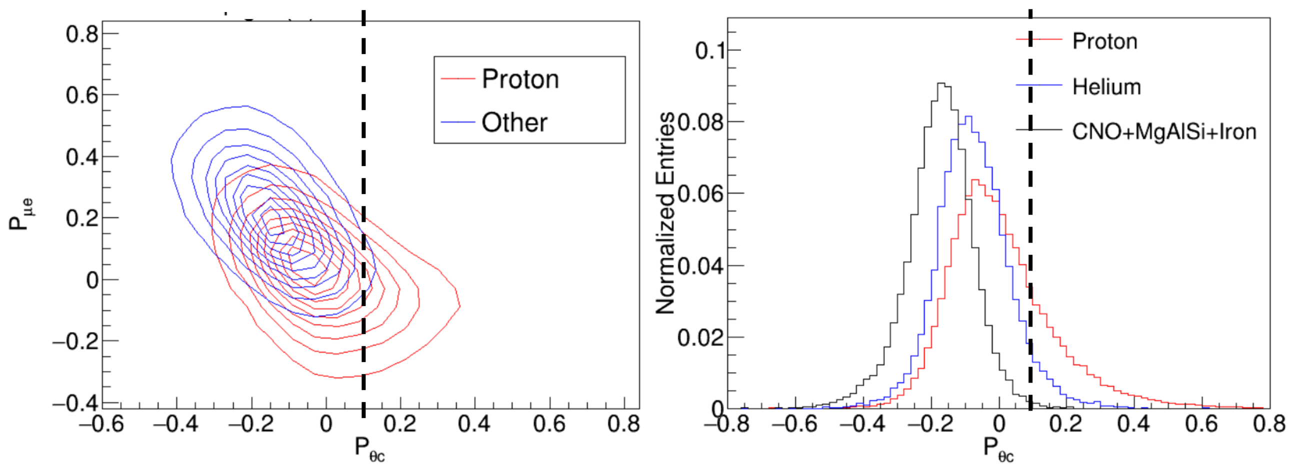




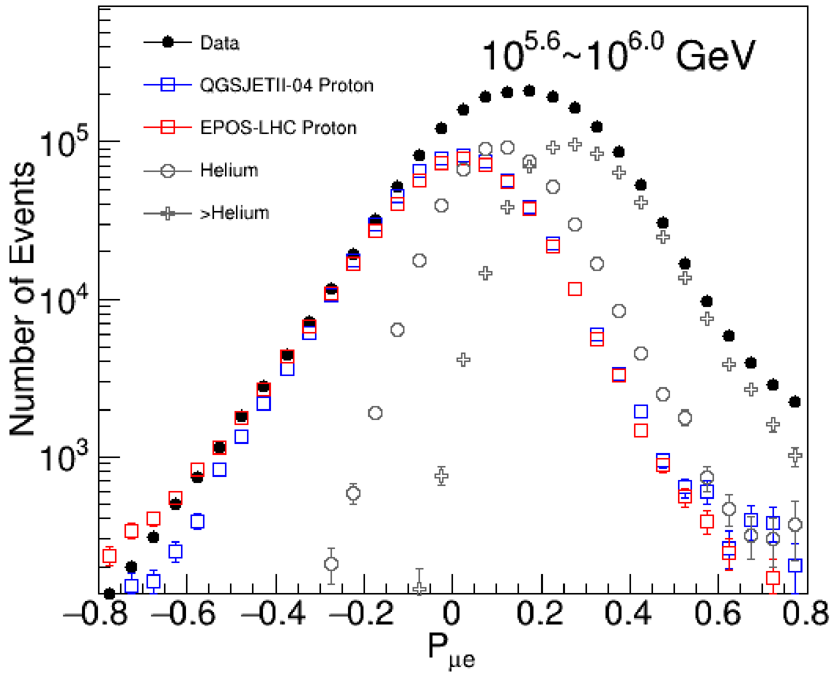
Test of $P_{\mu e}$

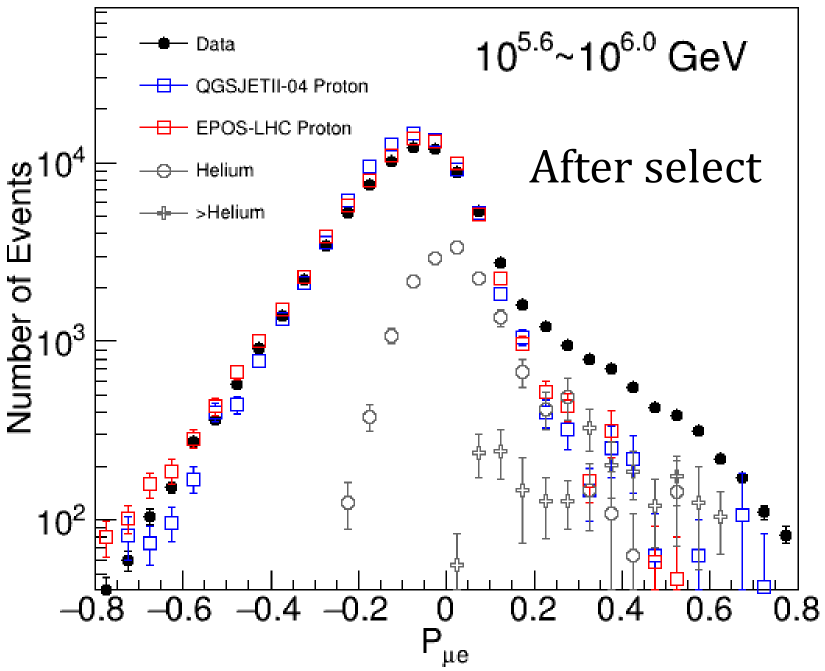
For selected events

By selecting events using $P_{\theta c}$, proton events with 80% purity can be obtained.



Before select





Summary

- LHAASO can simultaneously measure muons and parameters related to X_{max}
- By using a single parameter for selection, high-purity proton events can be obtained. The selected events can be used to test the hadronic interaction models by comparing the distribution of other parameters