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Calibration of the Air Shower Energy Scale of the Water and Air Cherenkov Techniques in the LHAASO experiment

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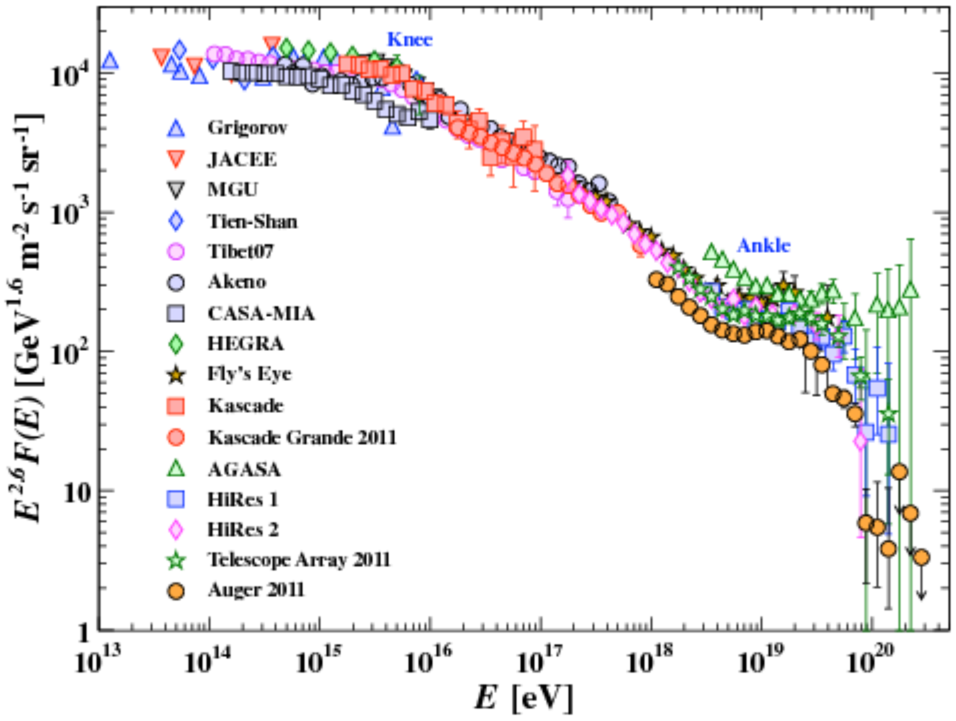
Outline

- Introduction
- LHAASO experiment
- Energy scale of WCDA-1
- Energy scale propagates to WFCTA
- Conclusion

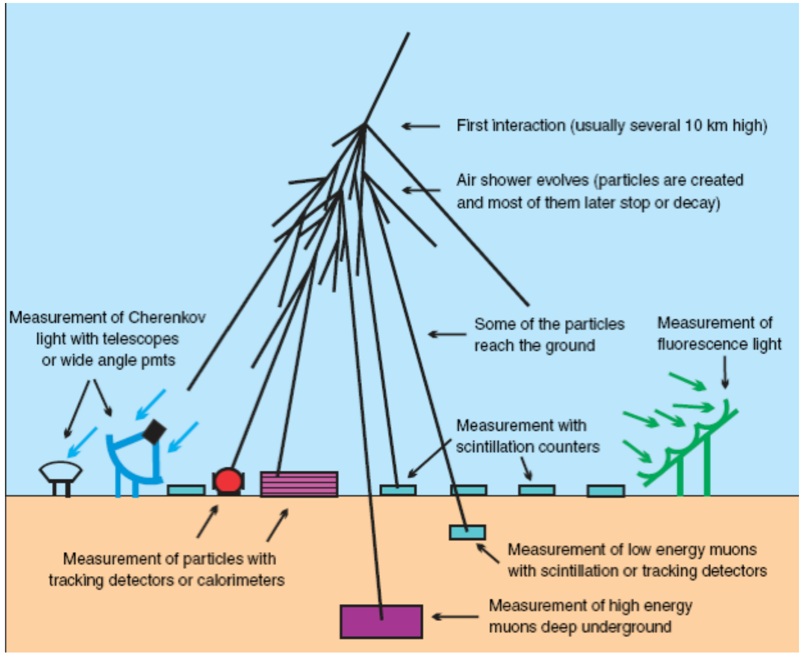
Introduction

Difficulties in energy spectrum measurement for cosmic rays with energies higher than 10TeV



Indirectly measurement

Ground-based experiments

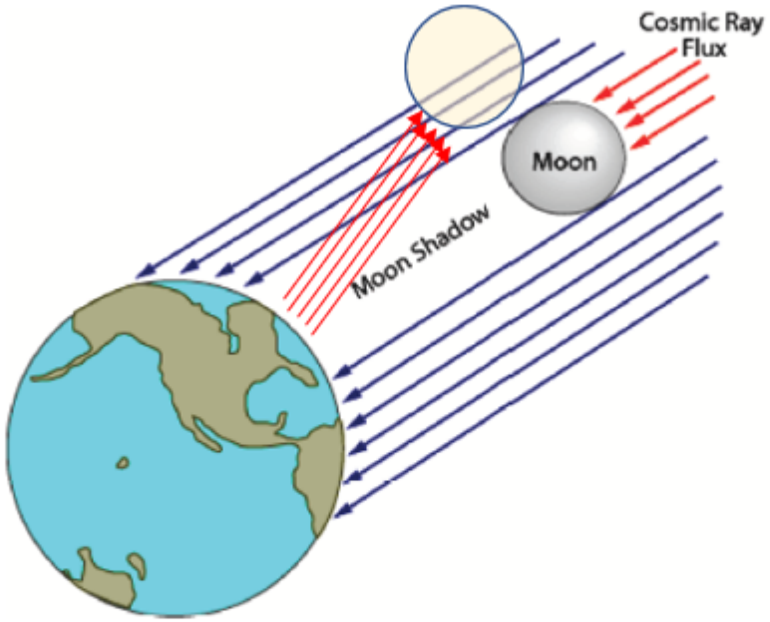


The energy scale of detectors can not be calibrated by beam experiment.

- ✓ **The results of different experiments are not very consistent.**
- ✓ **Mainly caused by uncertainty of the absolute energy scale.**

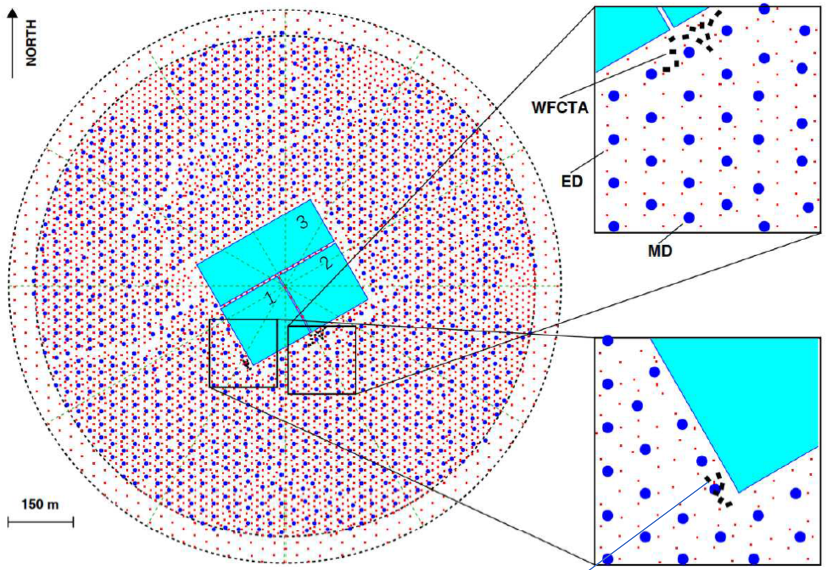
Earth-Moon magnetic spectrometer

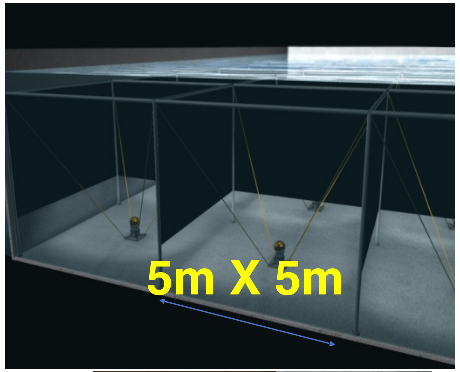
- ✓ Cosmic rays are blocked by Moon, a shadow of cosmic rays can be observed, we called that Moon shadow.
- ✓ Cosmic rays are deflected by the magnetic field between Moon and Earth.
- ✓ Moon shadow is deviated from Moon's Normal position.

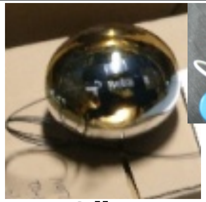


The LHAASO experiment

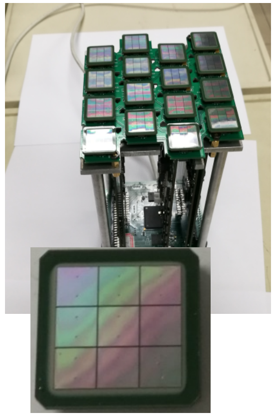
Water depth 4.4m






8”


1.5”



Water Cherenkov Detector Array (WCDA)

- ✓ Three water pools with 78,000m²
- ✓ Water depth: 4.4m
- ✓ Unit area: 5m x 5m
- ✓ Two PMTs (8” and 1.5”) to to cover a wide dynamic range spanning
- ✓ from 1 to 200,000 pe
- ✓ Angular resolution： 0.4° for showers with N_{hit} >200

Wide Field of view Cherenkov Telescope Array (WFCTA)

- ✓ FOV: 32 x 32 pixels with each pixel size 0.5° x 0.5°
- ✓ Reflector area：$5m^2$
- ✓ Dynamic range： 10-32,000pe
- ✓ Rotating from 0° to 90° in elevation

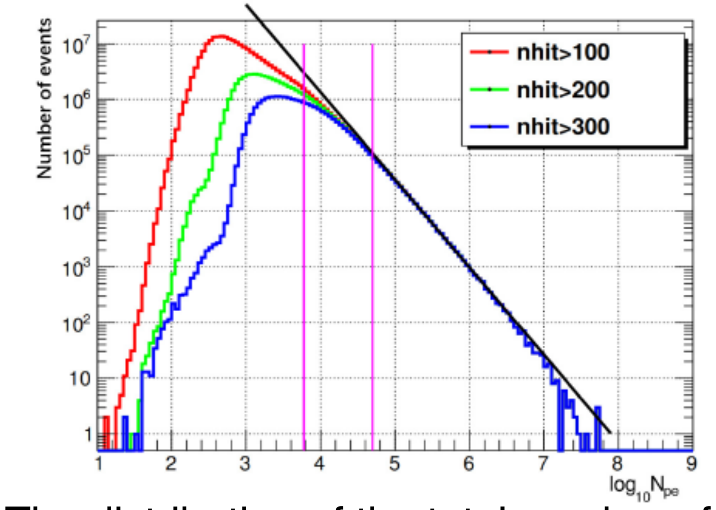
The energy scale of WCDA-1

Measurement of Moon Shadow

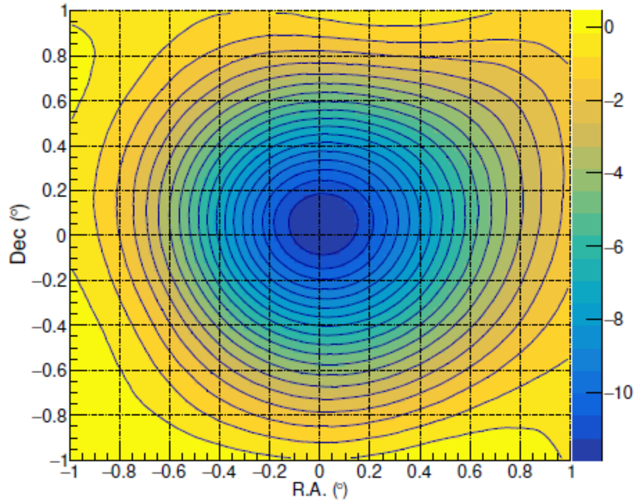
Data:

- ✓ From 01/05/2019 to 31/01/2020 , WCDA-1；
- ✓ Zenith angle < 45°, N_{hit} > 200；
- ✓ The data set are divided into 6 groups according to the energy estimator N_{pe}.

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



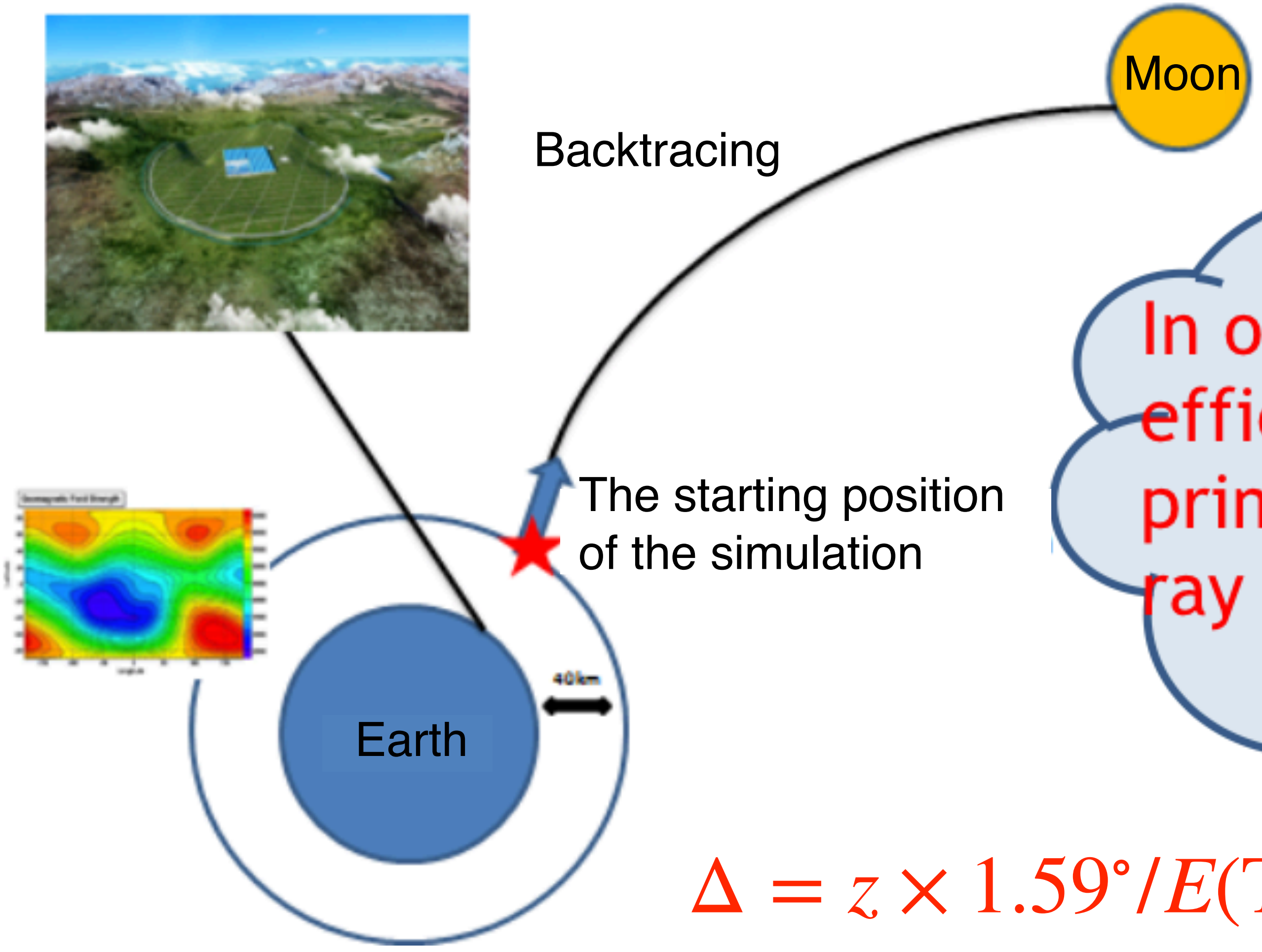
The distribution of the total number of photo-electrons, N_{pe} .



The significance map of the Moon shadow for shower events detected by WCDA-1 with N_{pe} > 60,000.

- ✓ The equal zenith method is used to estimate the background.
- ✓ Li-Ma formula is used to estimate the deficit significances.

Moon Shadow Simulation



In order to hit moon more efficiently, we extract primary direction of cosmic ray near to the moon .

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

Z can be determined by simulation

$$\Delta = z \times 1.59°/E(\text{TeV})$$

- ✓ In the energy range from 1 TeV to 50 TeV, the cosmic rays are dominated by proton and helium nuclei.
- ✓ The ratio of protons and helium nuclei is about 1:1.

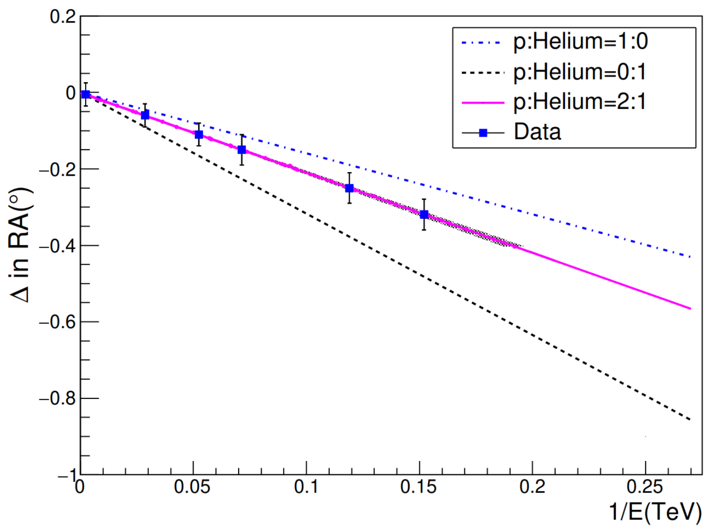
Range of N_{pe}	Shift of the Moon shadow (°)	Significance (σ)	Median E (TeV)
6,000-10,000	-0.32±0.04	18.2	$6.6^{+0.9}_{-0.7}$
10,000-15,000	-0.25±0.04	14.0	$8.4^{+1.6}_{-1.2}$
15,000-20,000	-0.15±0.04	11.6	$14.0^{+5.1}_{-2.9}$
20,000-30,000	-0.11 ±0.03	11.9	$19.1^{+7.2}_{-4.1}$
30,000-60,000	-0.06 ±0.03	10.8	$35.0^{+35}_{-11.6}$
>60,000	-0.01±0.03	10.9	>50.0

The trigger efficiency of WCDA-1 is different for protons and helium nuclei in a given N_{pe} range:

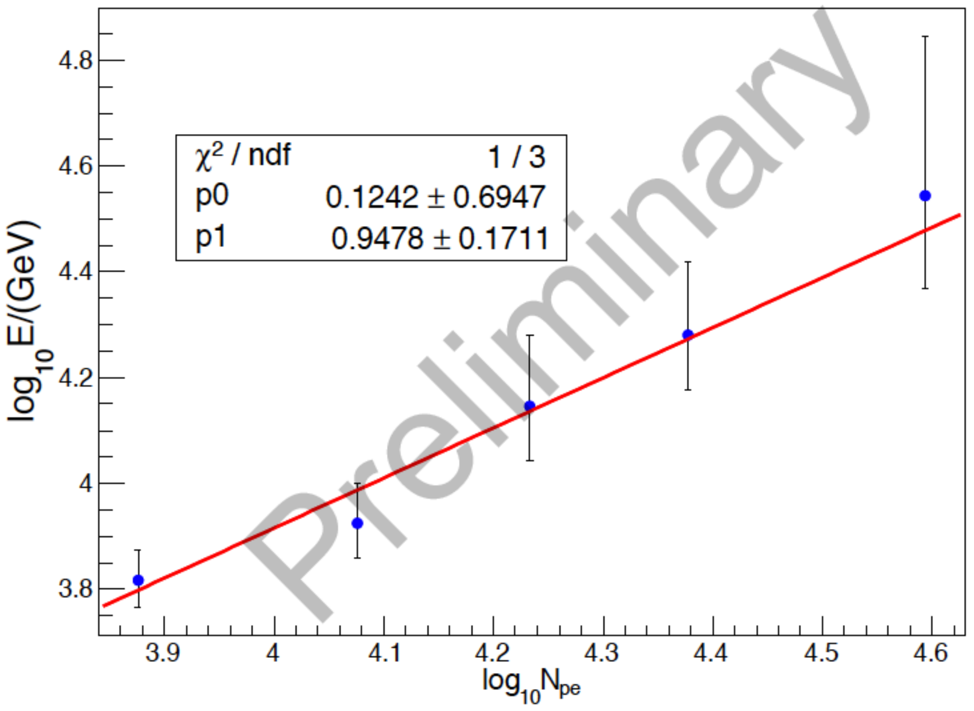
$$N_p : N_{he} = 2 : 1$$

$$E_p : E_{he} = 1 : 1.9$$

$$\Delta = 2.1°/E(\text{TeV})$$



Energy scale of WCDA-1 and uncertainties



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

The uncertainty of the energy scale is mainly due to the statistics.

- ✓ 12% at 6.6TeV
- ✓ 50% at 35 TeV

System uncertainties:

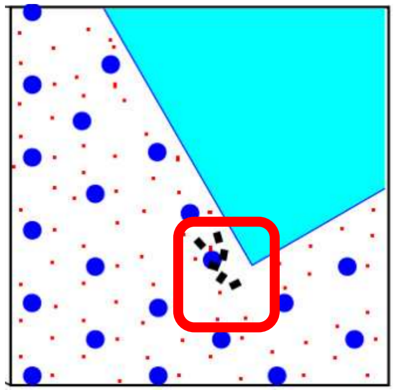
- ✓ Uncertainty caused by 10% changing of the ratio of protons and helium nuclei will be 3%.
- ✓ Uncertainty due to different hadronic models is less than 2%.
- ✓ An uncertainty of 4% is caused by the energy and angular resolution.

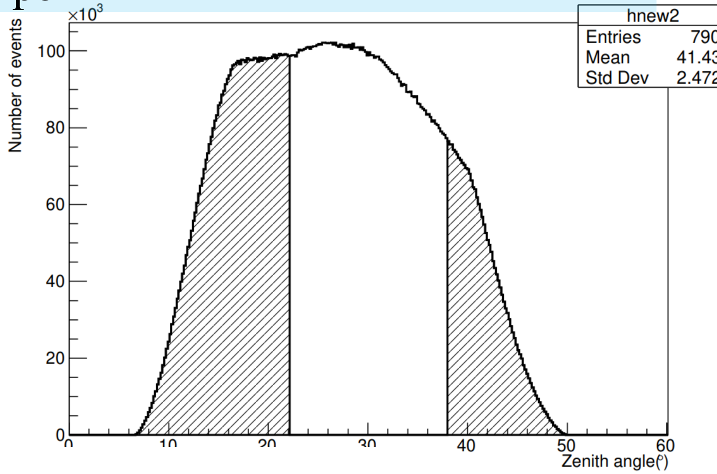
Energy scale propagates to WFCTA

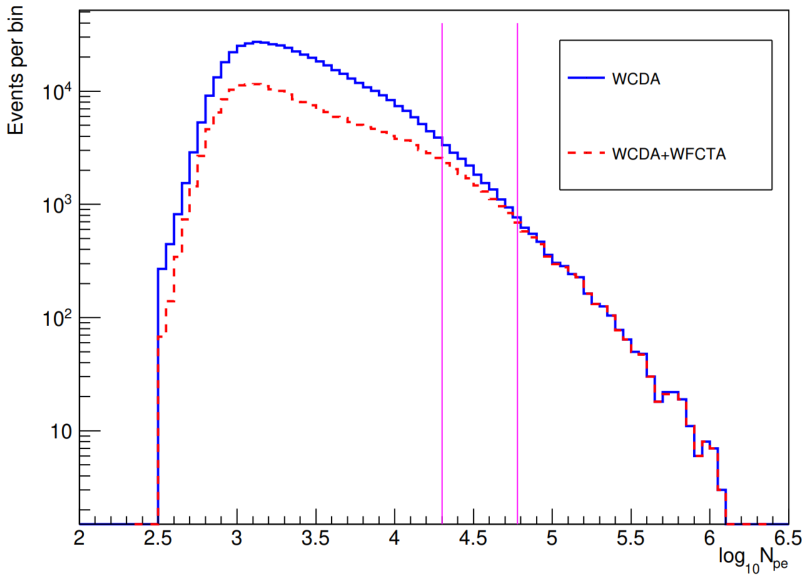
- ✓ WFCTA can only be operated on dark nights or at most with partial moonlight.
- ✓ WFCTA can not measure Moon shadow shifts.
- ✓ The commonly trigger of WCDA-1 and WFCTA can be achieved by offline.
- ✓ The energy scale of WCDA-1 can propagate to the WFCTA by the commonly triggered events.
- ✓ Due to the different energy threshold, the effective energy range is expected about 20 TeV of the commonly triggered events.

The commonly triggered events:

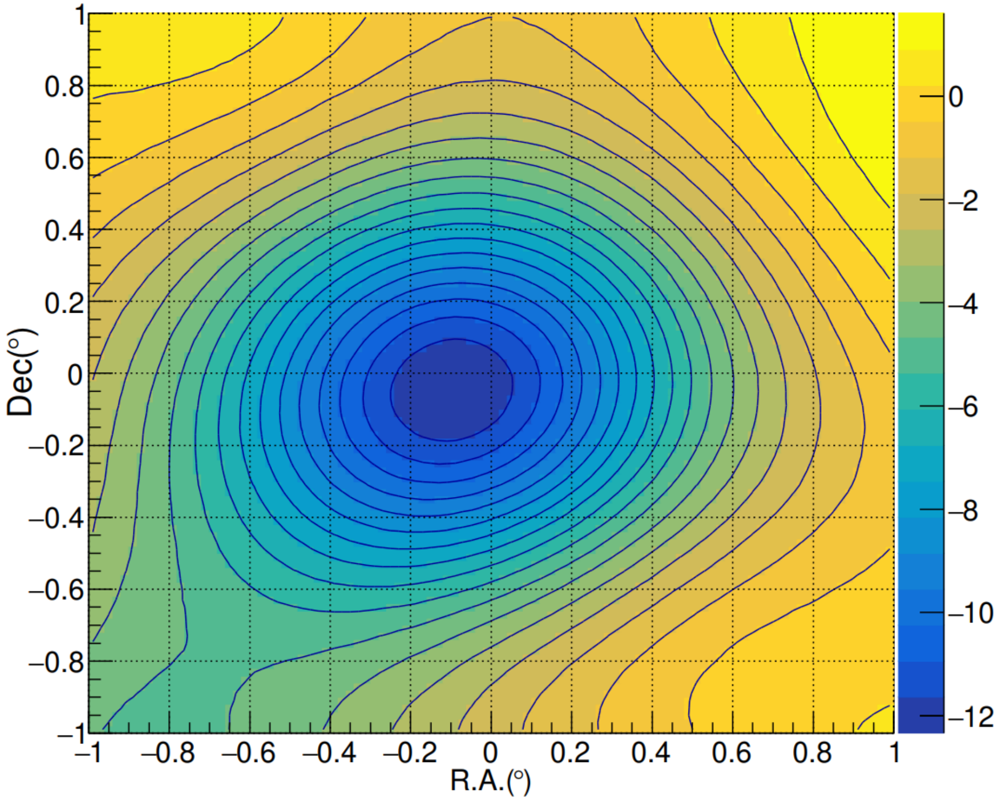
- 22°<Zenith angles <38°
- N_{hit} >200
- 20,000< N_{pe}<60,000







The moon shadow with the selection criteria of commonly triggered events



- ✓ 22°<Zenith angles <38°
- ✓ N_{hit} >200
- ✓ 20,000< N_{pe} <60,000

$$\Delta = \mathbf{0.1 \pm 0.03°}$$

$$\Delta = 2.1°/E(\mathrm{TeV})$$

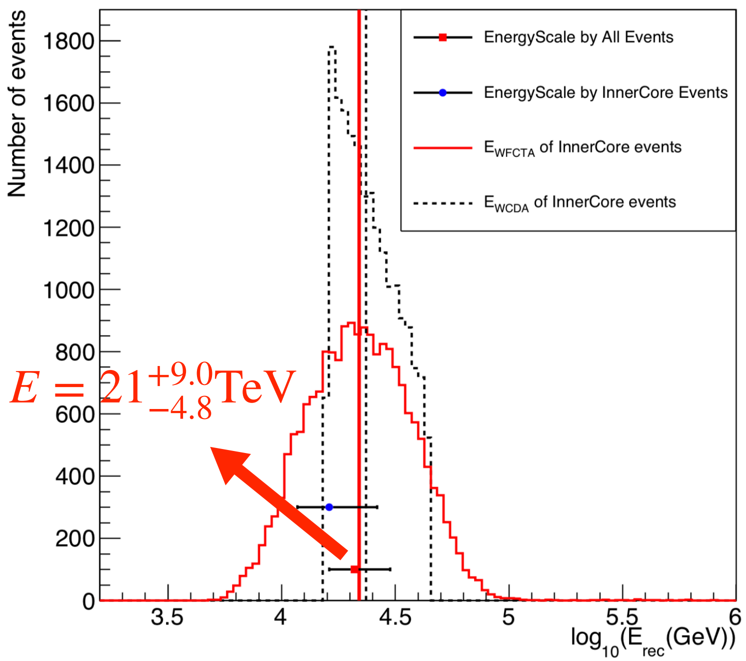
$$E = 21^{+9.0}_{-4.8}\mathrm{TeV}$$

The energy scale of WFCTA

Data Set of WCDA-1+WFCTA:

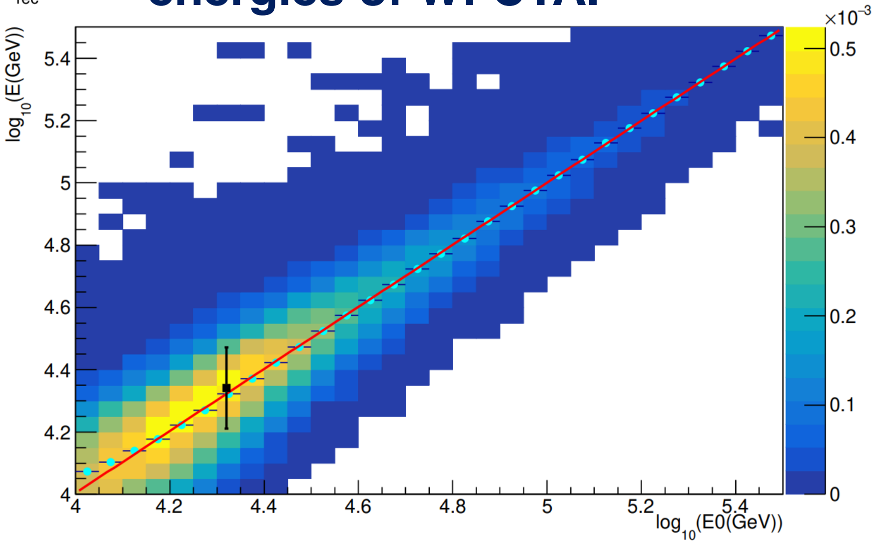
- ✓ 22°<Zenith angles <38°
- ✓ Nhit>200
- ✓ 20k<Npe<60k
- ✓ lcorexl<55m, lcoreyl<55
- ✓ **21.9 ±0.1TeV by WFCTA**
- ✓ **23.4±0.1±1.3TeV by the formula of the absolute energy scale**

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



The reconstructed energies distribution of commonly triggered events.

The relation between the reconstructed and simulated energies of WFCTA.



For air showers with greater energies, the energy reconstruction total relies on the simulations of the air showers and detectors.

Conclusion

- By the shifts of the moon shadows, the energy scale of WCDA-1 has been calibrated with uncertainty 12% at 6.6TeV 50% at 35 TeV dominated by statistical errors.
  - After accumulation of more data (4 years), the statistical errors will be reduced to 3% and 12%, respectively .
- With the selection criteria of the commonly triggered events, the shift of Moon shadow gives an energy scale $21^{+9.0}_{-4.8}$ TeV.
- The median energy reconstructed by WFCTA is found to be 21.9±0.1 TeV.