利用WFCTA样机和ARGO实验多参数测量宇宙线质子+氦核能谱

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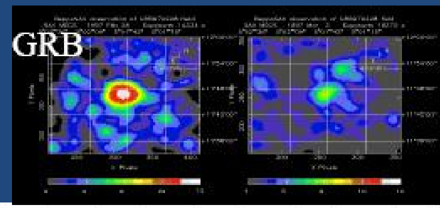
报告内容

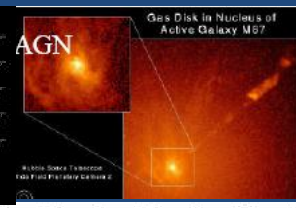
- 引言
- WFCTA样机和ARGO-YBJ实验介绍
- 多参数分析和质子+氦核能谱结果
- 总结和展望

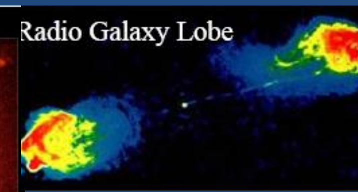
高能宇宙线的起源和加速机制仍然是迷

$$E_{max} = \beta Z e B L$$

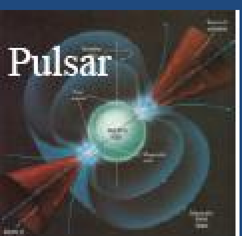
河外宇宙线：

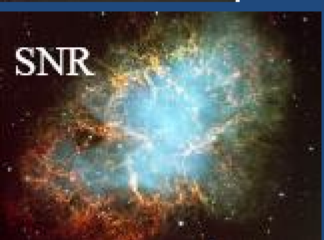


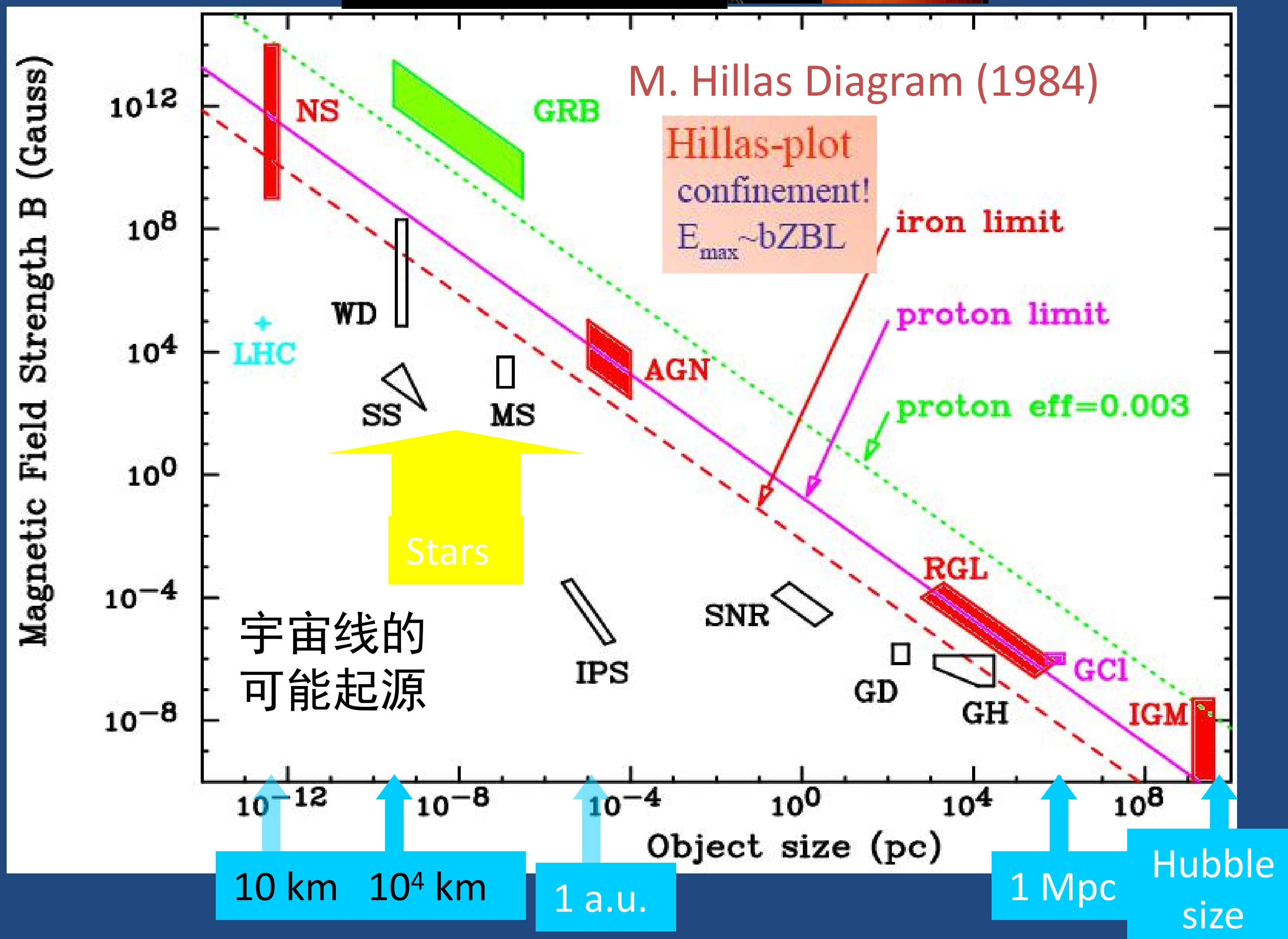




银河宇宙线：



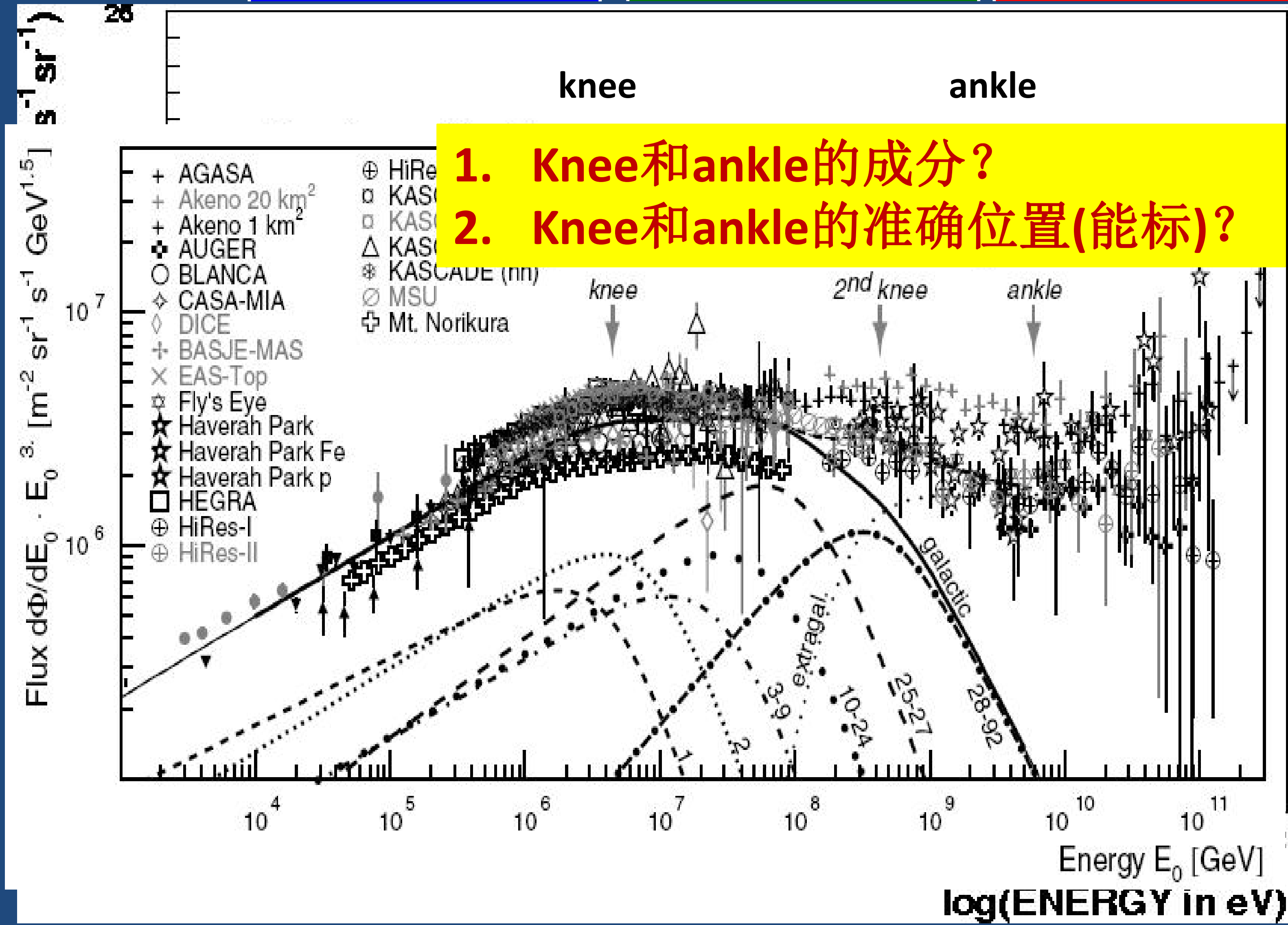




宇宙线的可能起源

$$E_{max} = \beta Z e B L$$

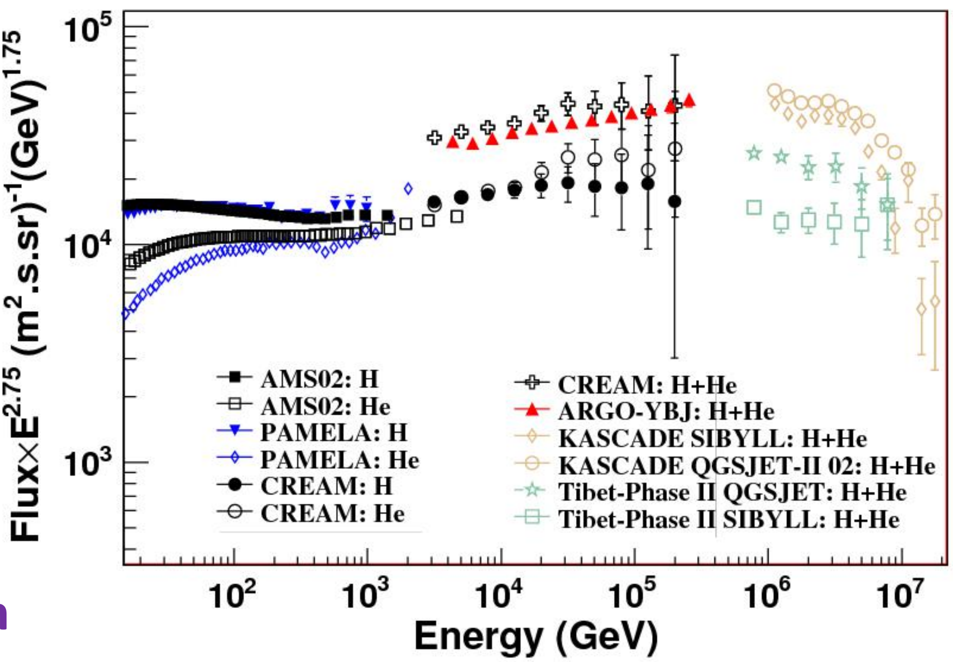
SNRs　　pulsars, galactic wind　　AGN, top-down ??



1. Knee和ankle的成分？
2. Knee和ankle的准确位置(能标)？

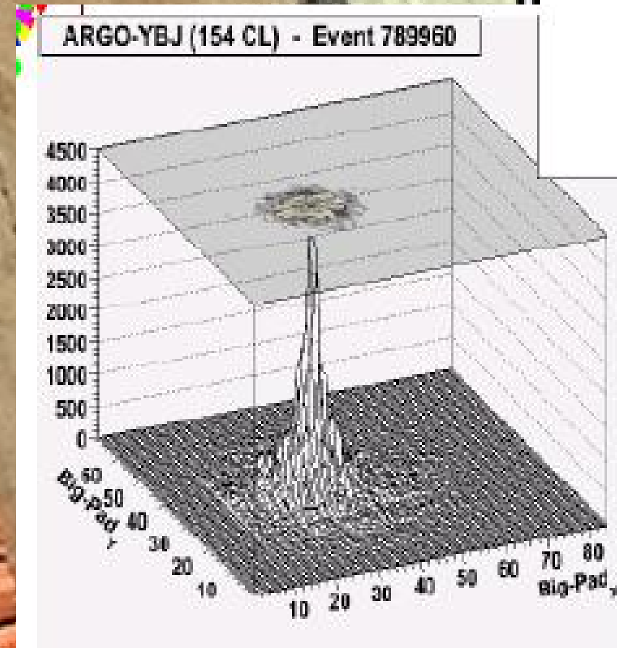
Introduction

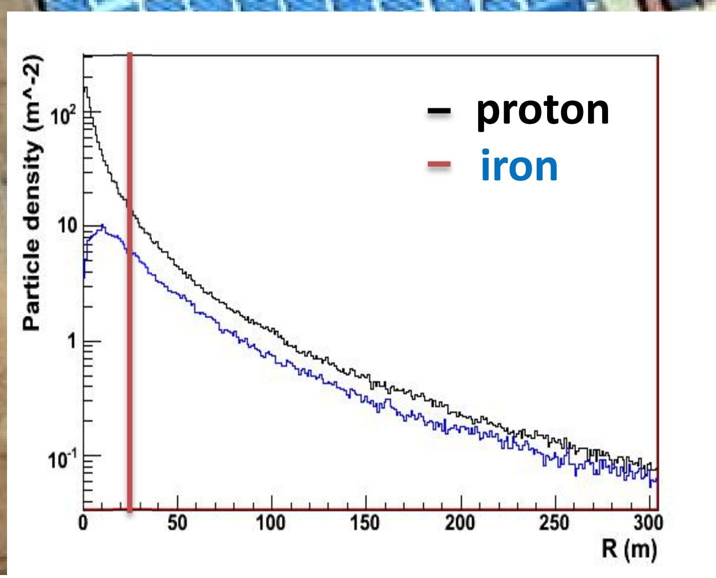
- **CREAM results: energy spectrum of single element up to 100TeV;**
- **It is very difficult to discriminate single element from showers by ground based experiment.**
- **ARGO-YBJ（H+He）： 3TeV-300TeV;**
- **Hybrid analysis (ARGO-YBJ + one Cherenkov telescope)**
  - **to extend the ARGO-YBJ results to higher energy;**
  - **To fill the gap between the balloon based measurements and ground based experiment for *cross-calibration of the experiments.***



ARGO-YBJ array and a Cherenkov telescope

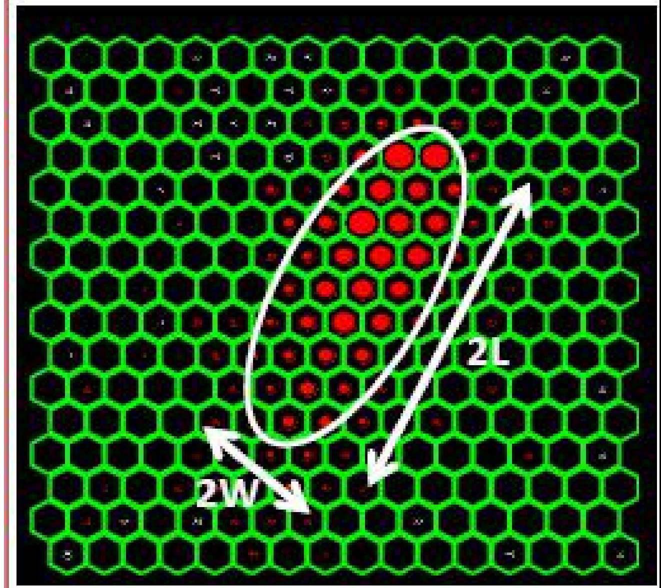
ARGO-YBJ experiment @ 4300 m a.s.l.

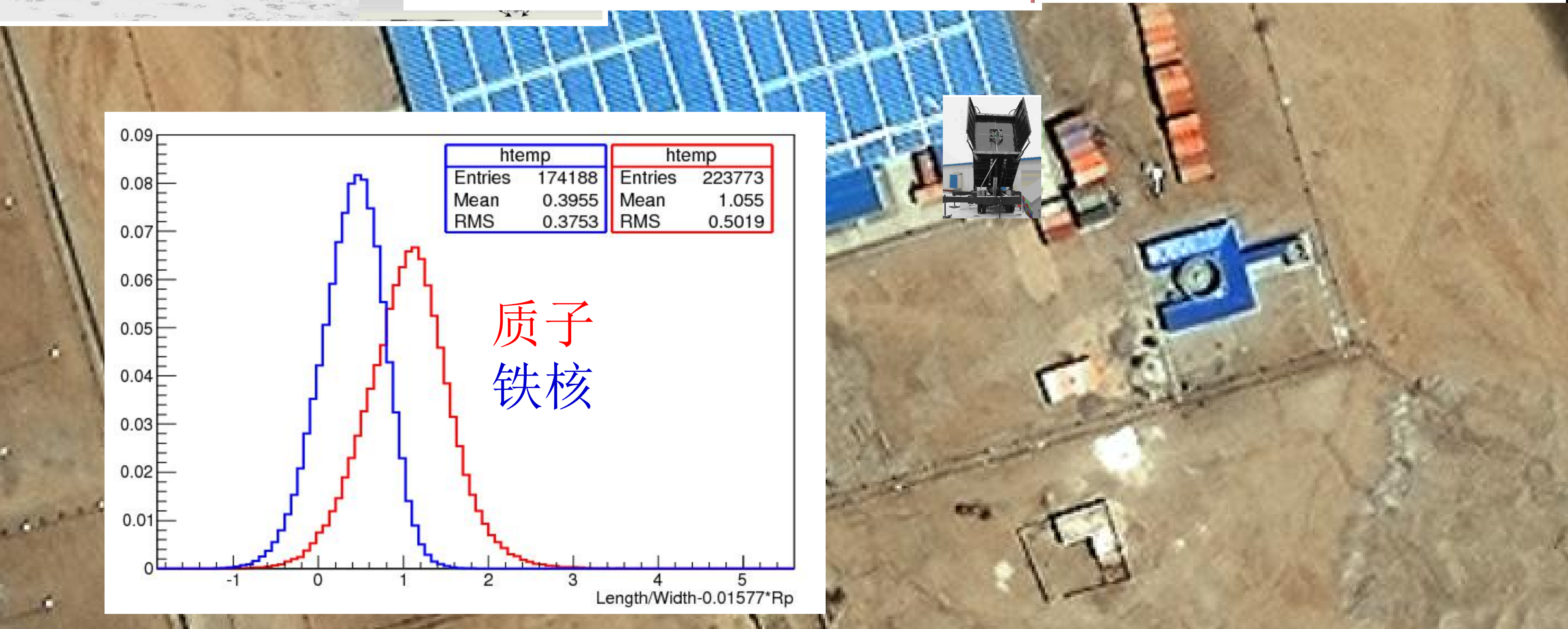




Wide Field of View Cherenkov Telescope (WFCTA)

- 5m² spherical mirror;
- 16×16 PMT array
- Pixel size 1°;
- FOV: 14°× 16°;
- Elevation angle: 60°.





Hybrid Observation and Data Set

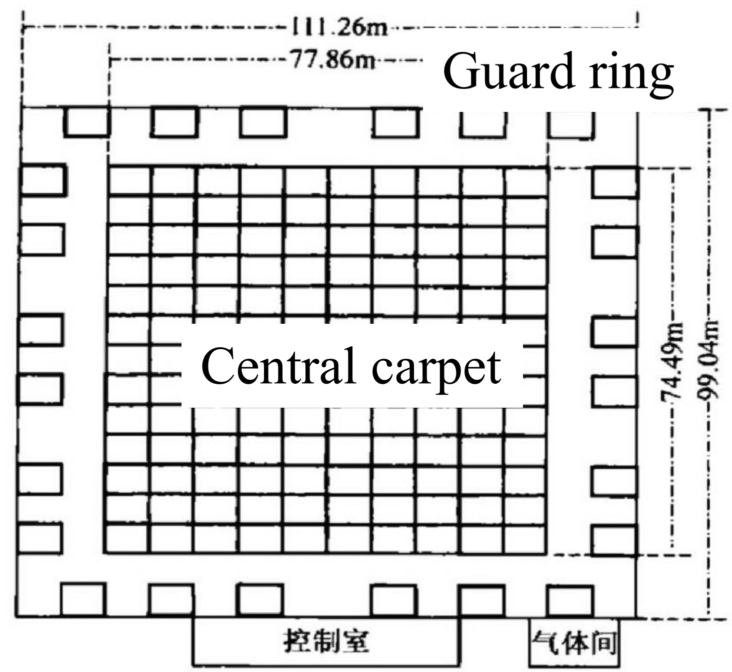
➢ Period:

- From 2010.12 ~ 2012.02: Coincidence events;
- Good weather selection: 7.28×10^5 sec.

➢ *Criteria for well measured events*

- Shower core contained in the ARGO central carpet, excluding an outer region by 1 meter;
- More than 1000 fired pads on the ARGO-YBJ central carpet;
- Cherenkov image must be fully contained in the telescope, i.e. space angle < 6 respect to the axis of the telescope;
- The number of fired tubes >= 6.

RPC detector array



~8200 events are well reconstructed above 100 TeV

Simulation information

➢ Extensive air showers simulation

- Tool: Corsika6735 + QGSJETII-03 + GHEISHA
- Primary particles: proton, helium, CNO, MgAlSi, iron
- Energy range: 10 TeV – 50PeV
- Geometry: θ : 20° – 42°, Φ: 69°- 111°,
- Core: +/- 150 m

➢ Detector simulation

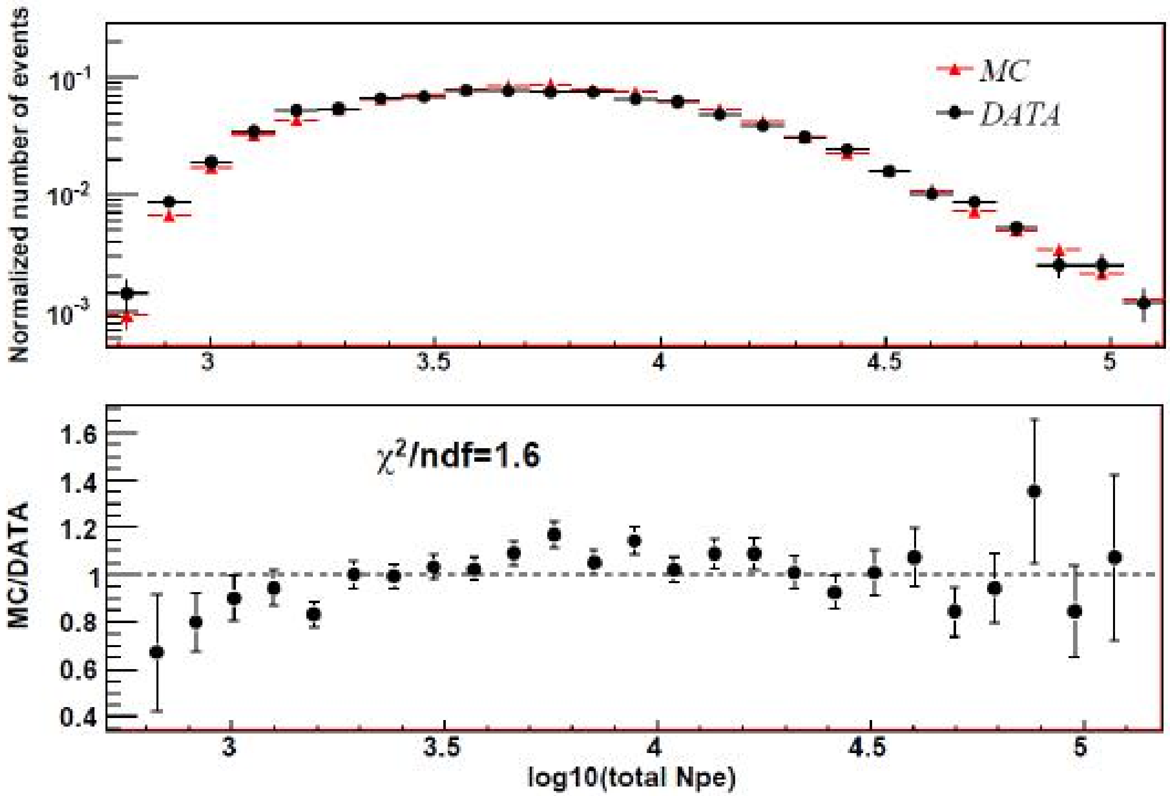
- Cherenkov simulation : Ray tracing package
- RPC carpet: G4argo (GEANT4 based program)

➢ Geometry reconstruction: From ARGO-YBJ

- **Core resolution: < 2 m**
- **Angular resolution: < 0.3°**

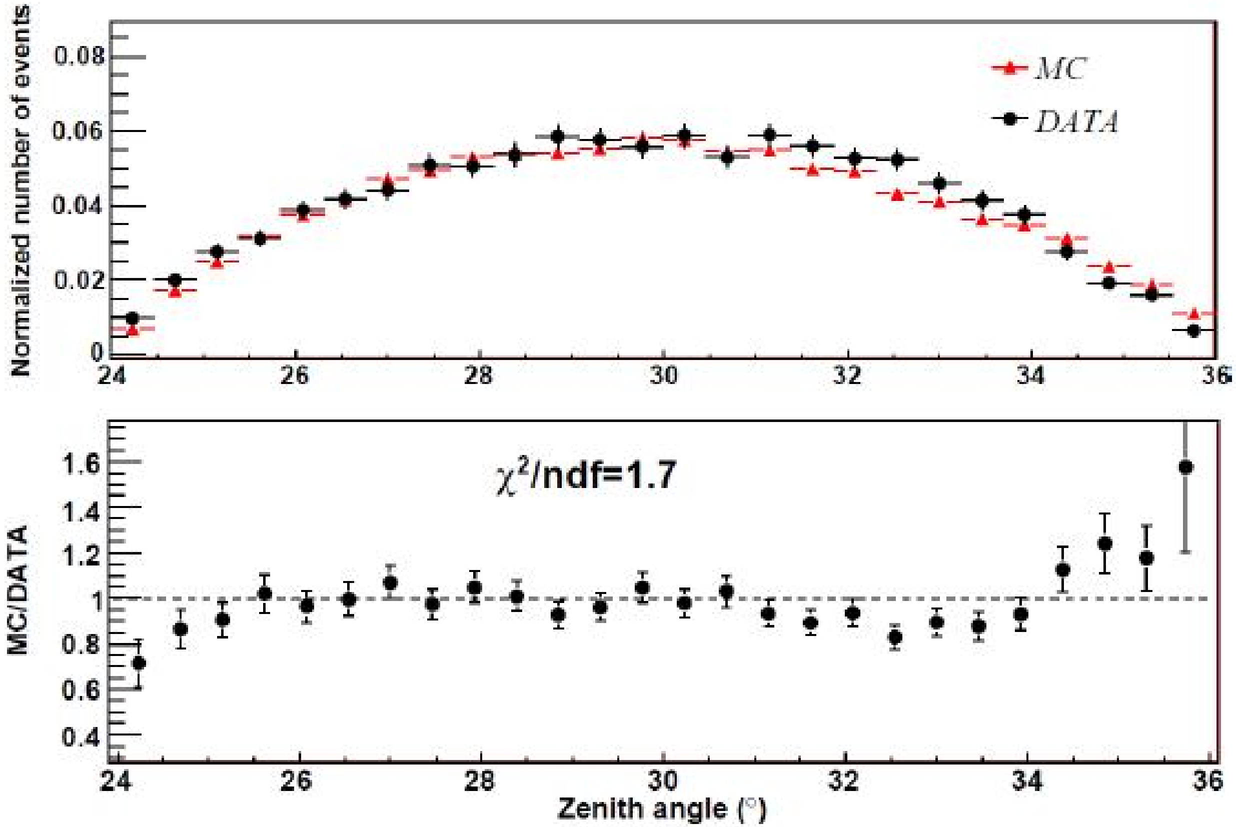
Comparison between Data and MC

- Total number photo-electrons in shower images for shower energy measurement



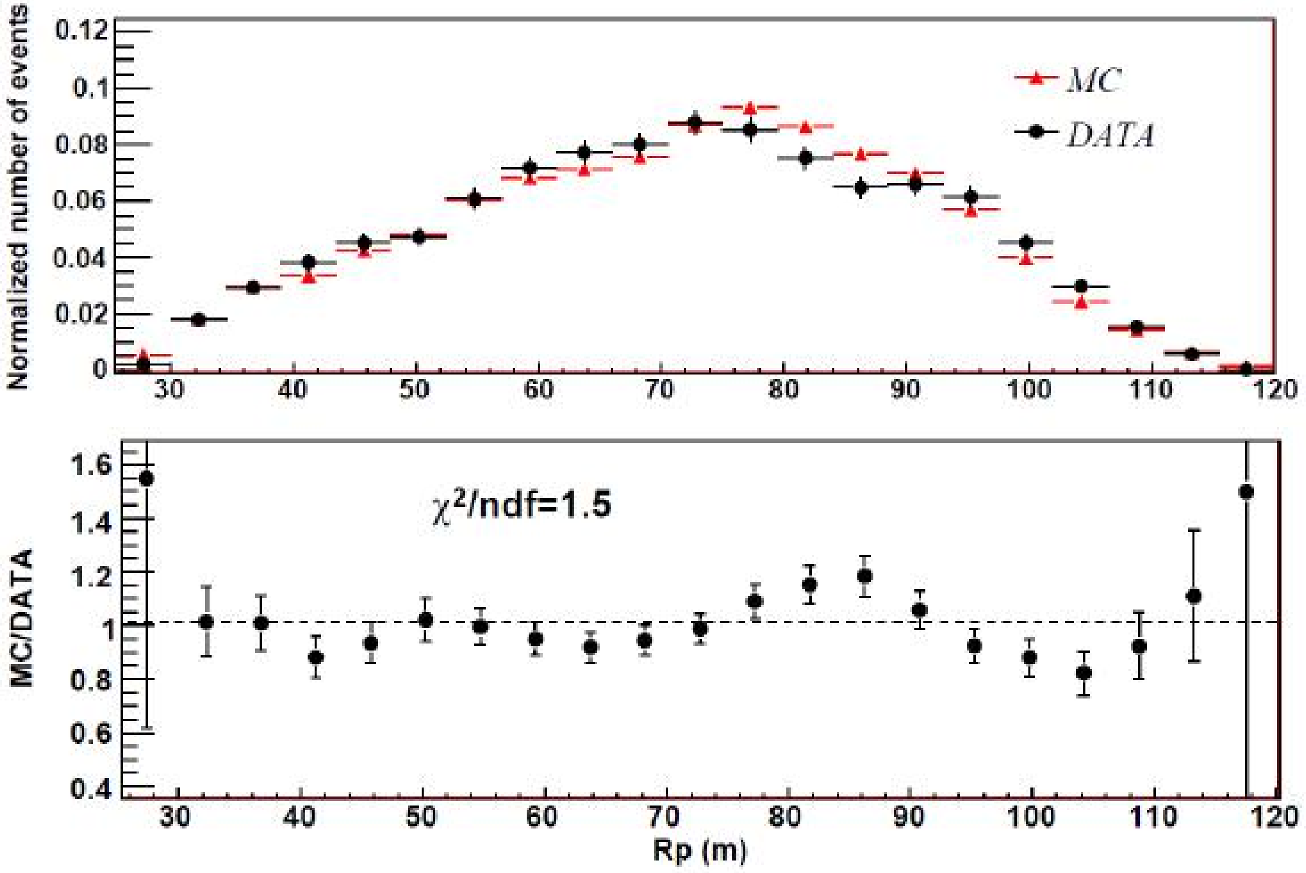
Comparison between Data and MC

- Zenith angle of the shower arrival direction
- The angular resolution of the arrival direction is 0.3°



Comparison between Data and MC

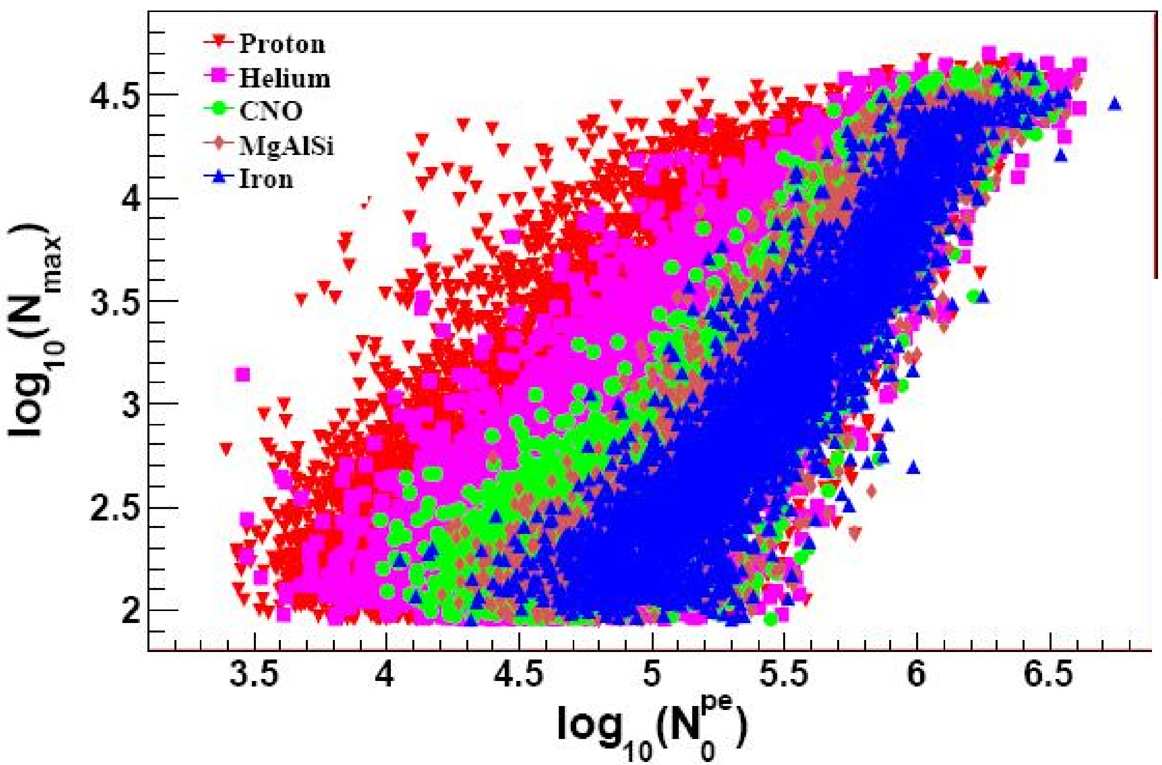
- The impact parameter of shower respect to the telescope
- The spatial resolution of the shower core position is 2 m

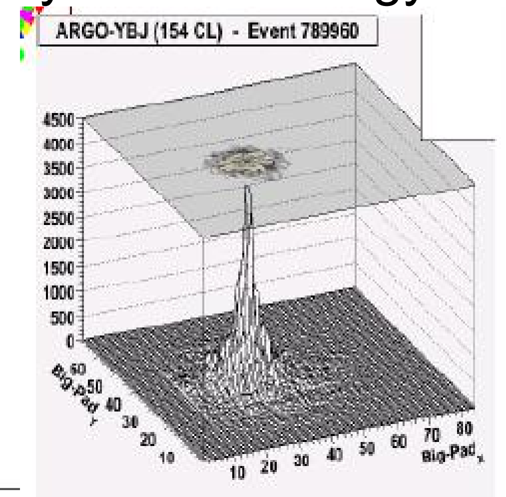


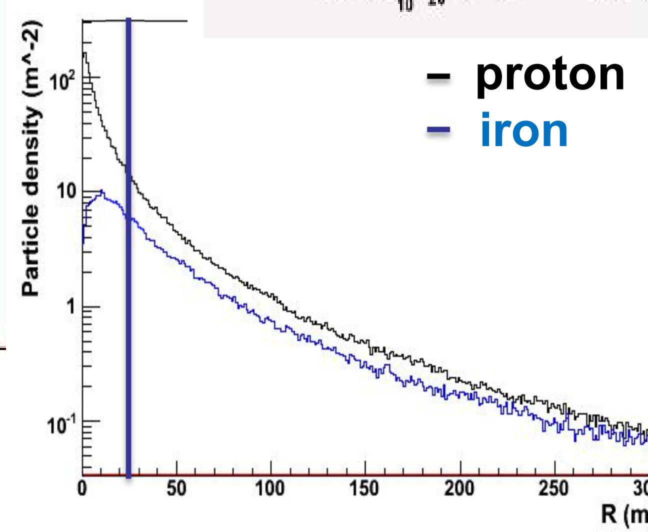
1. Mass-sensitive Parameter in the Shower Lateral Distribution

Most-hit-RPC at the core of a shower : $N_{max} \sim (N_0^{pe})^{1.44}$

N_0^{pe} is the normalized total number of photo-electrons measured by Cherenkov telescope, which is proportion to primary shower energy.



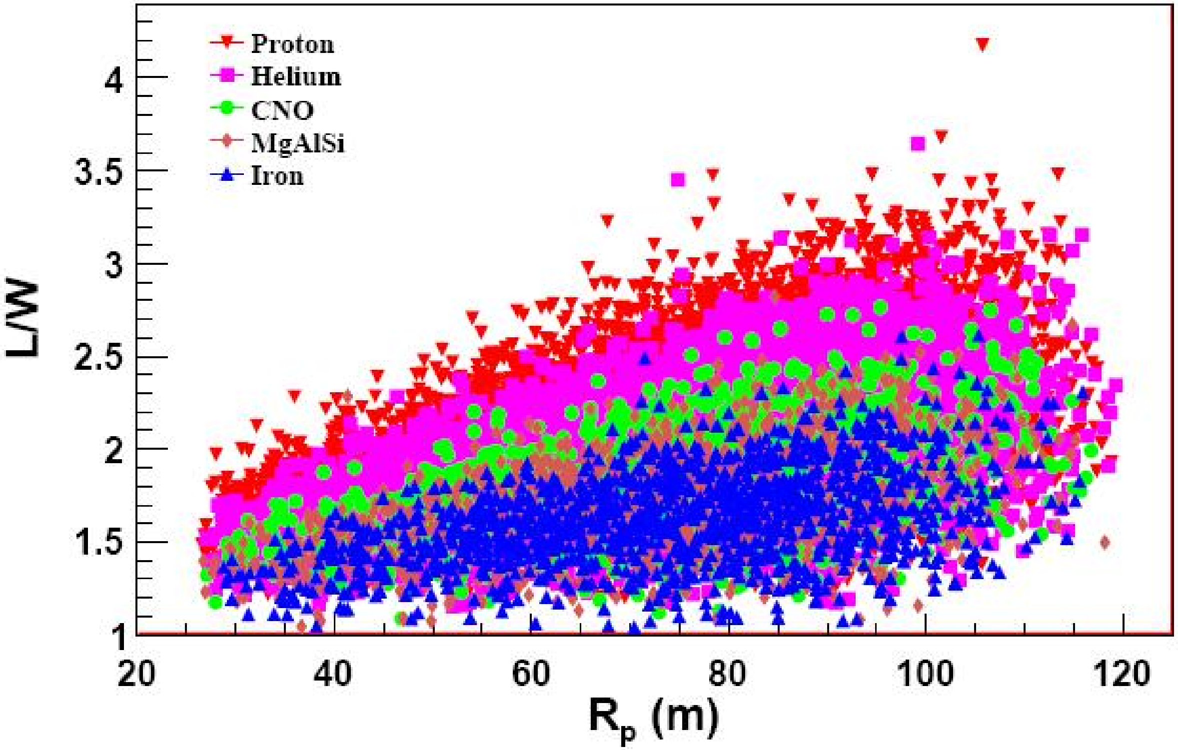




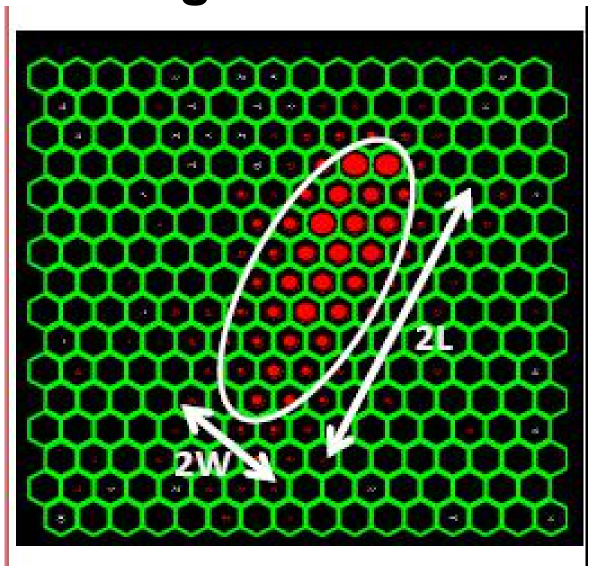
2. Mass-sensitive Parameter in the Cherenkov Image

Elongation of the shower image : L/W ~ R_p/109.9m

L/W is sensitive to the depth of shower maximum.



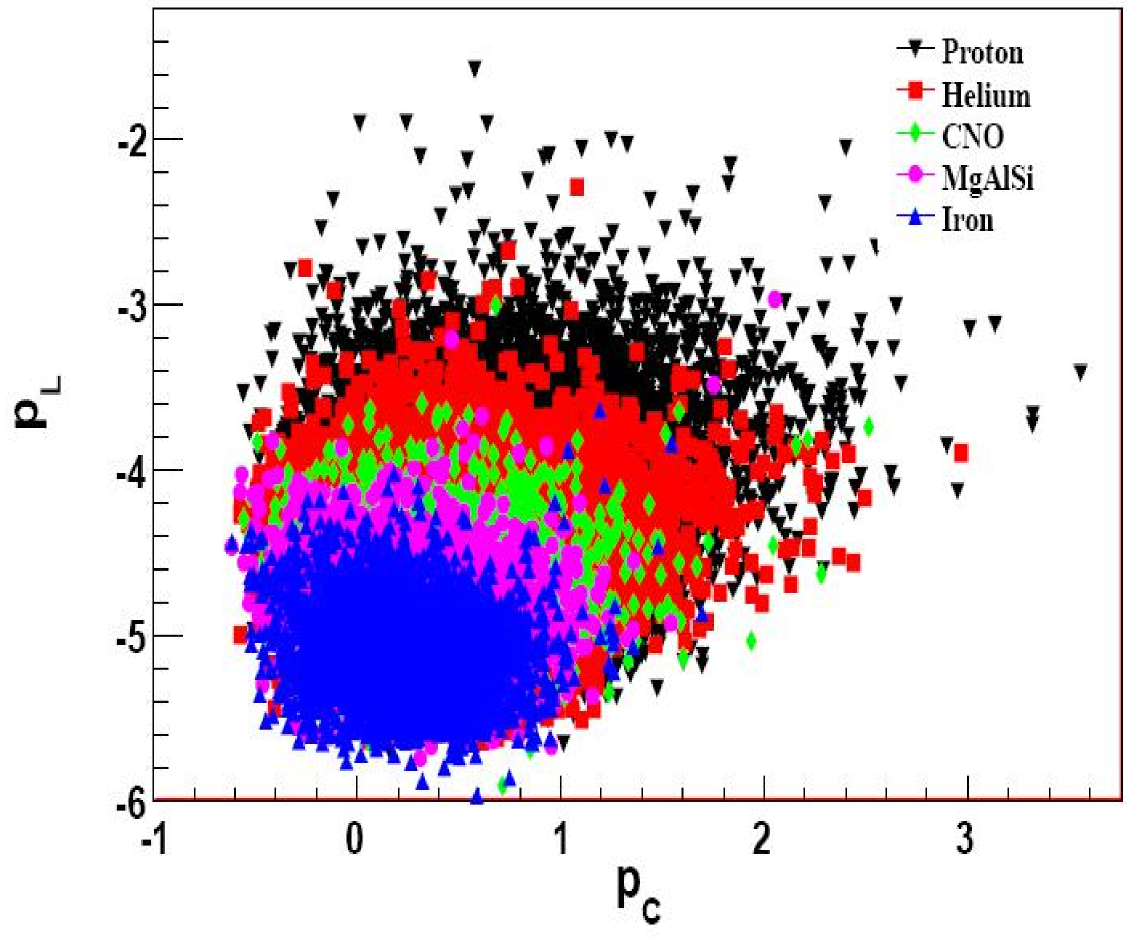
Hillas parameters: Length and Width



Multi-parameter Analysis

$$p_L = log_{10}N_{max} - 1.44log_{10}N_0^{pe}$$

$$p_C = L/W - R_p/109.9m - 0.1log_{10}N_0^{pe}$$



Multi-parameter Analysis

$$p_L = log_{10}N_{max} - 1.44log_{10}N_0^{pe}$$

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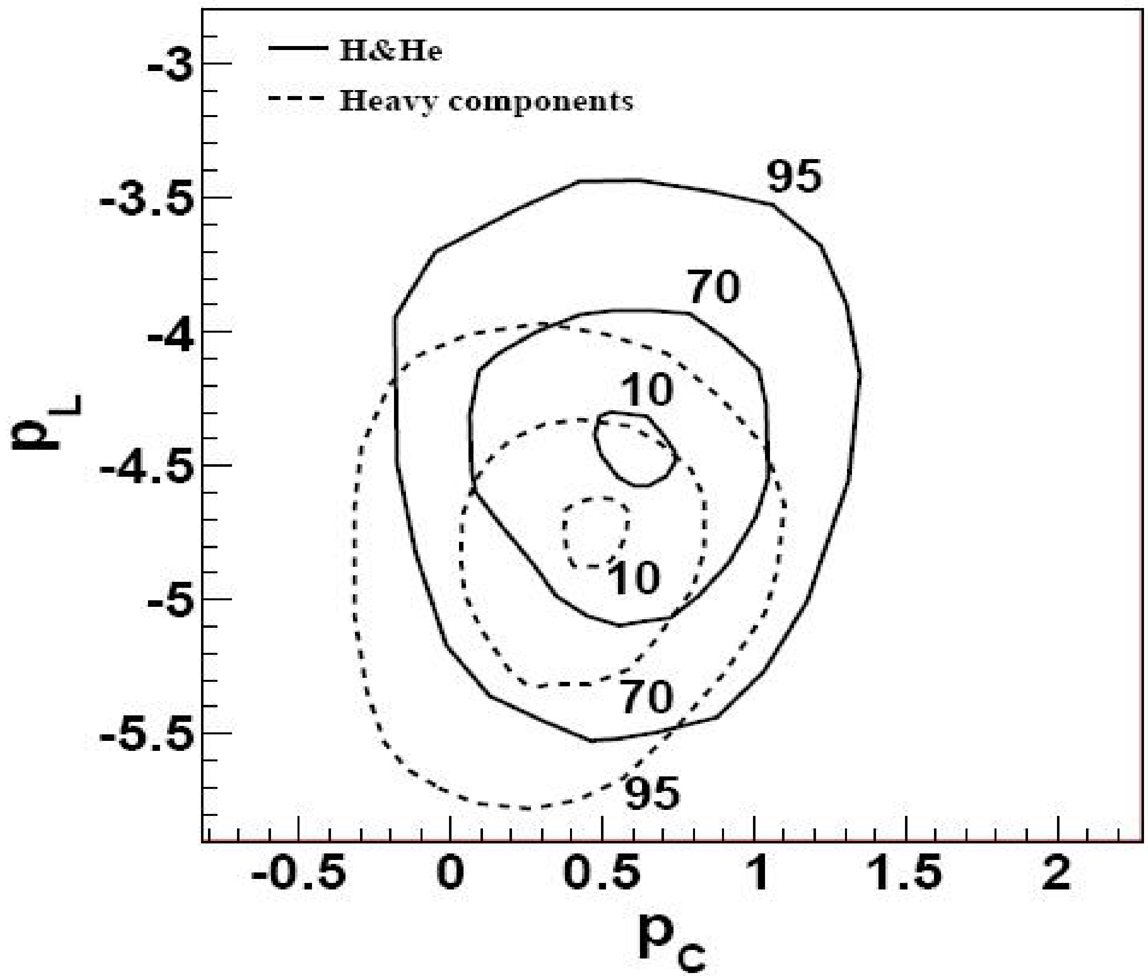
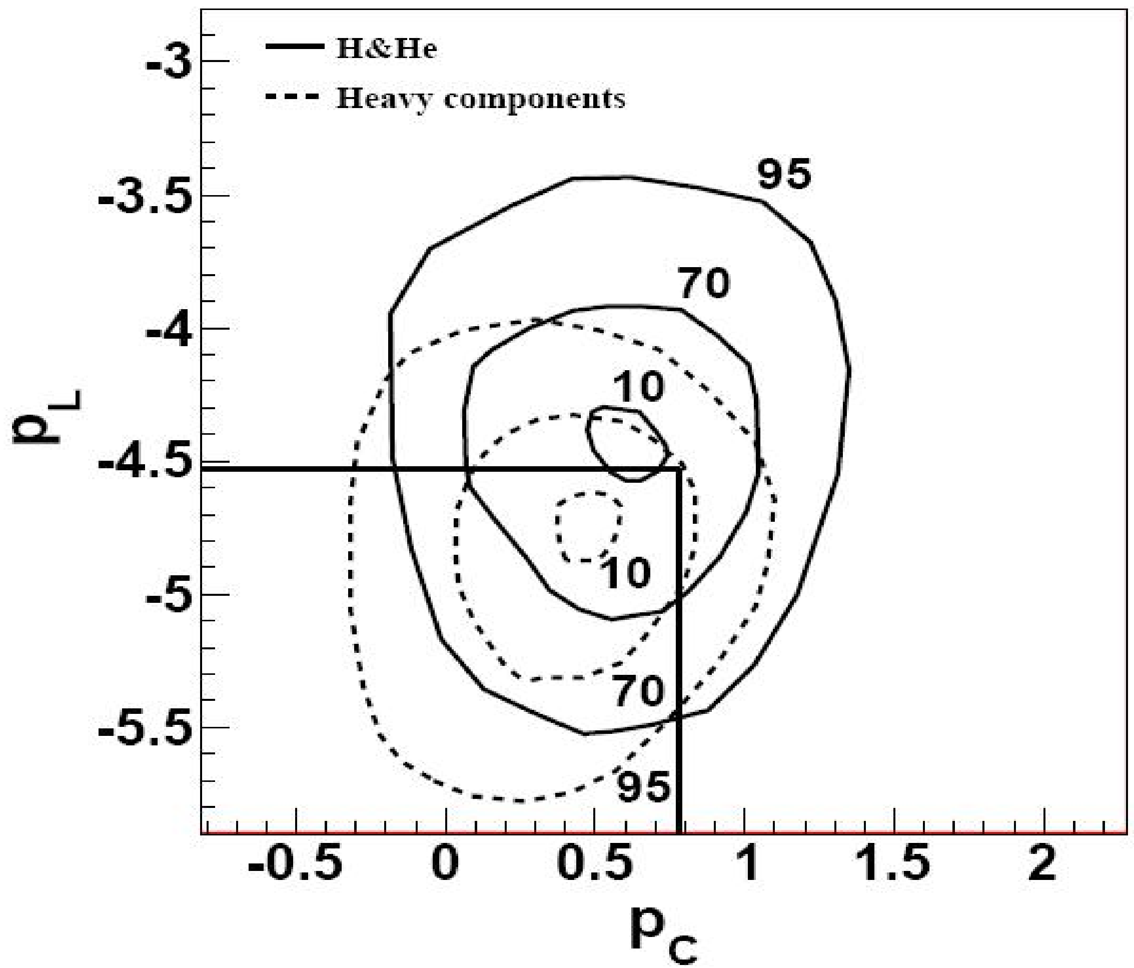
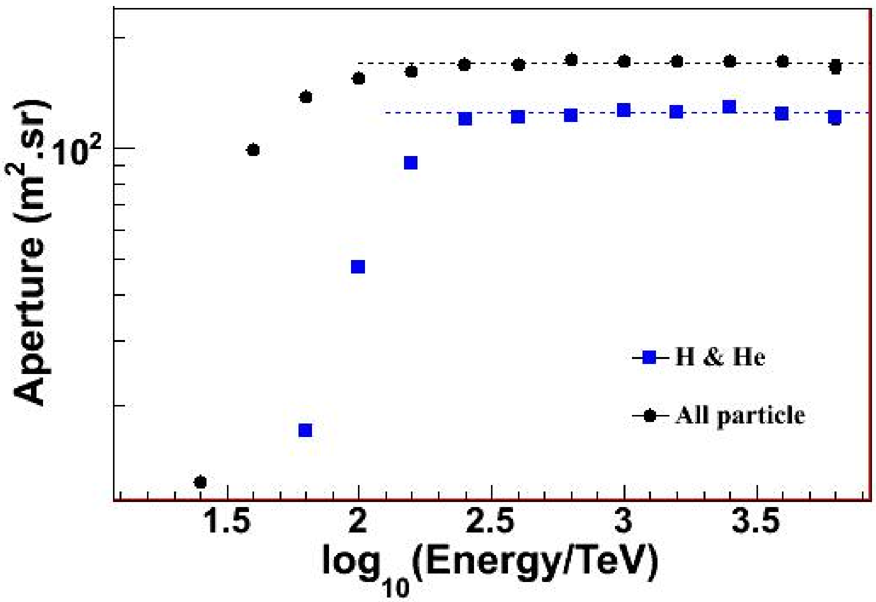


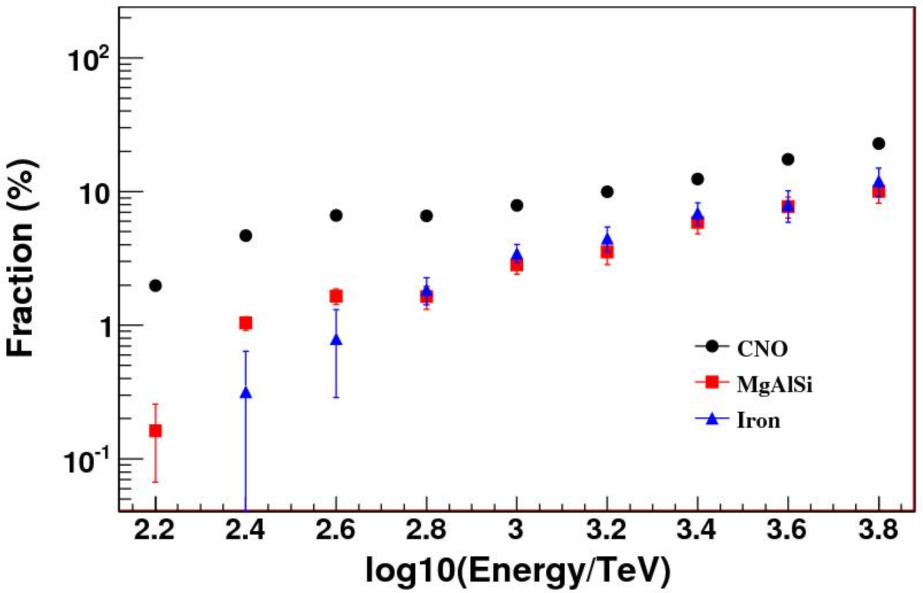
Multi-parameter Analysis

H&He selection critiea : p_L>-4.53 or p_C>0.78





J.R. Hörandel, Modern Physics Letter A, 22, 1533 (2007)



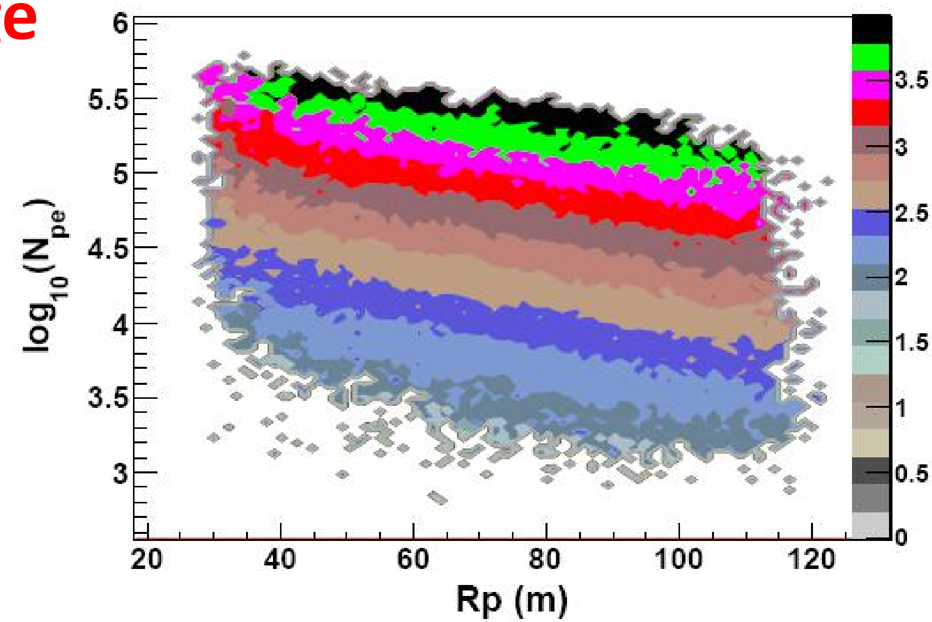
- A simple geometrical calculation gives a aperture of 163 m^2 sr
- The aperture of H&He: ~120 m^2 sr above 300 TeV;
- The purity of H&He showers: ~93% below 700 TeV;
- The contamination of heavy nuclei increases with energy: 13% @ 1 PeV, gradually increases to 27% @ 3 PeV;
- The contamination of heavy nuclei is model dependent

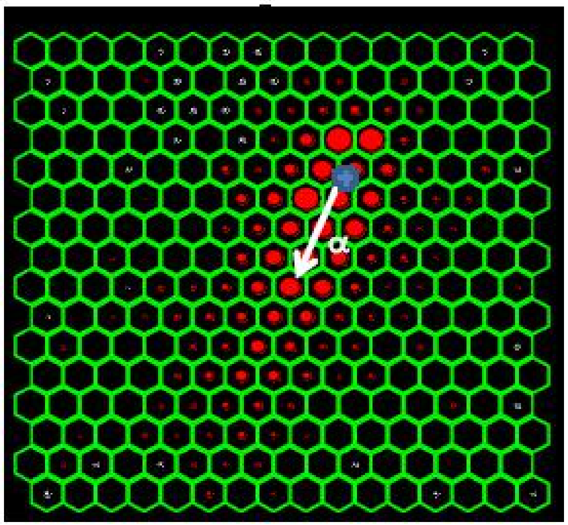
Energy reconstruction

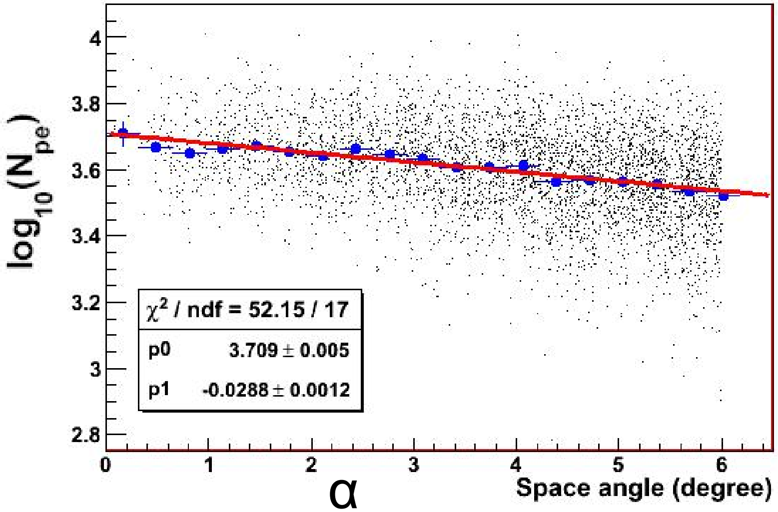
Using $\sum N_{pe}$ in Cherenkov image

➢ **Look-up table:**
light component only

- Impact parameter (R_p): 5m/bin
- Log(total N_{pe}) bin: 0.1/bin
- R_p bin： linear interpolation
- α bin: linear interpolation
- Total N_{pe} bin： quadratic curve interpolation

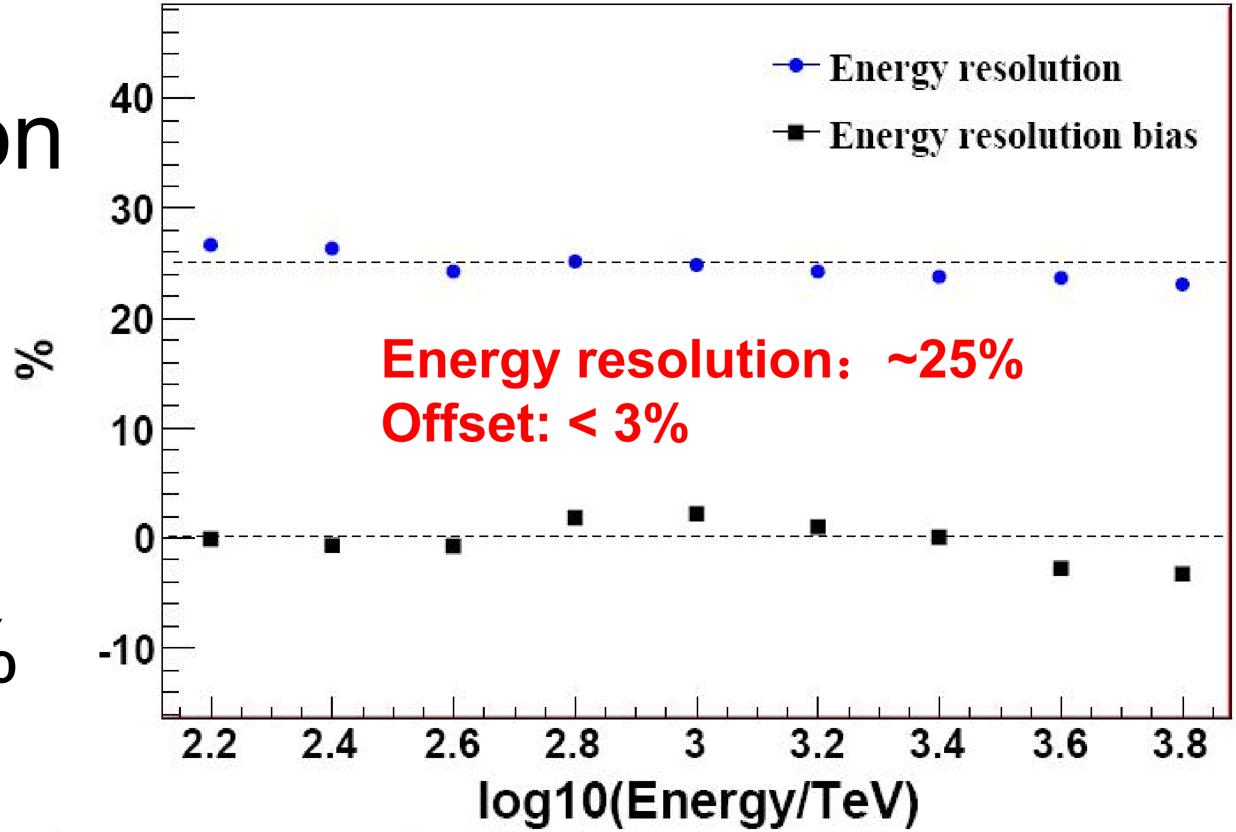


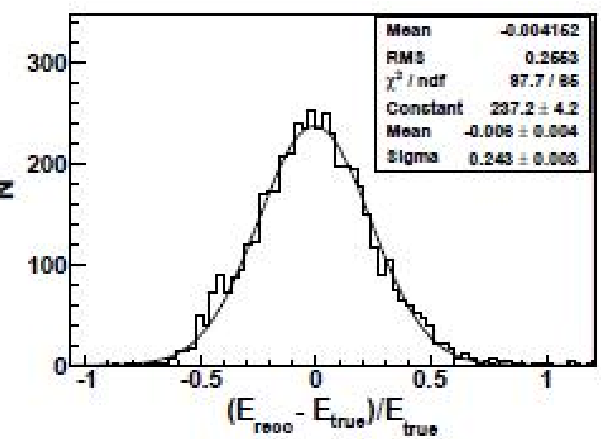




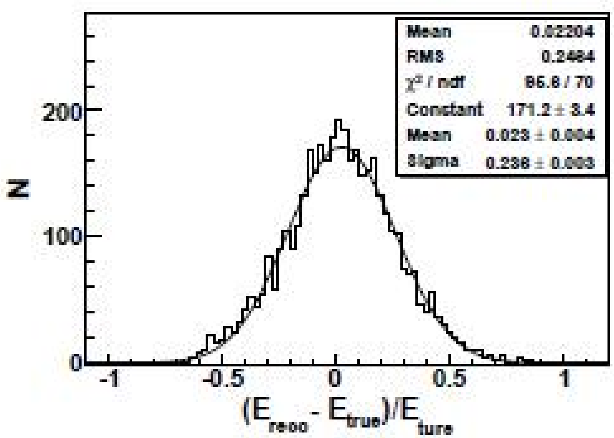
E-reconstruction

- Systematic bias: <3%
- Constant resolution: 25%
- Gaussian

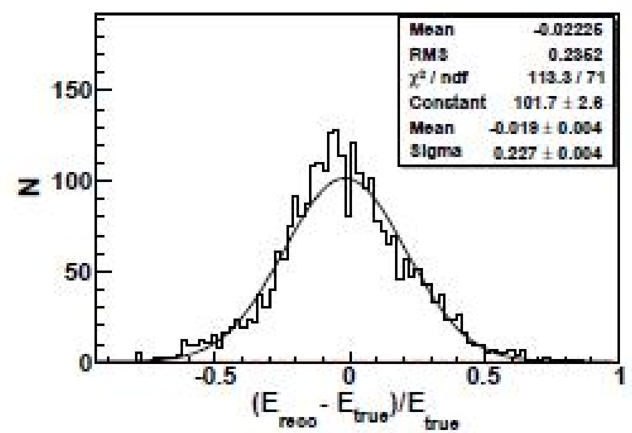




300 TeV

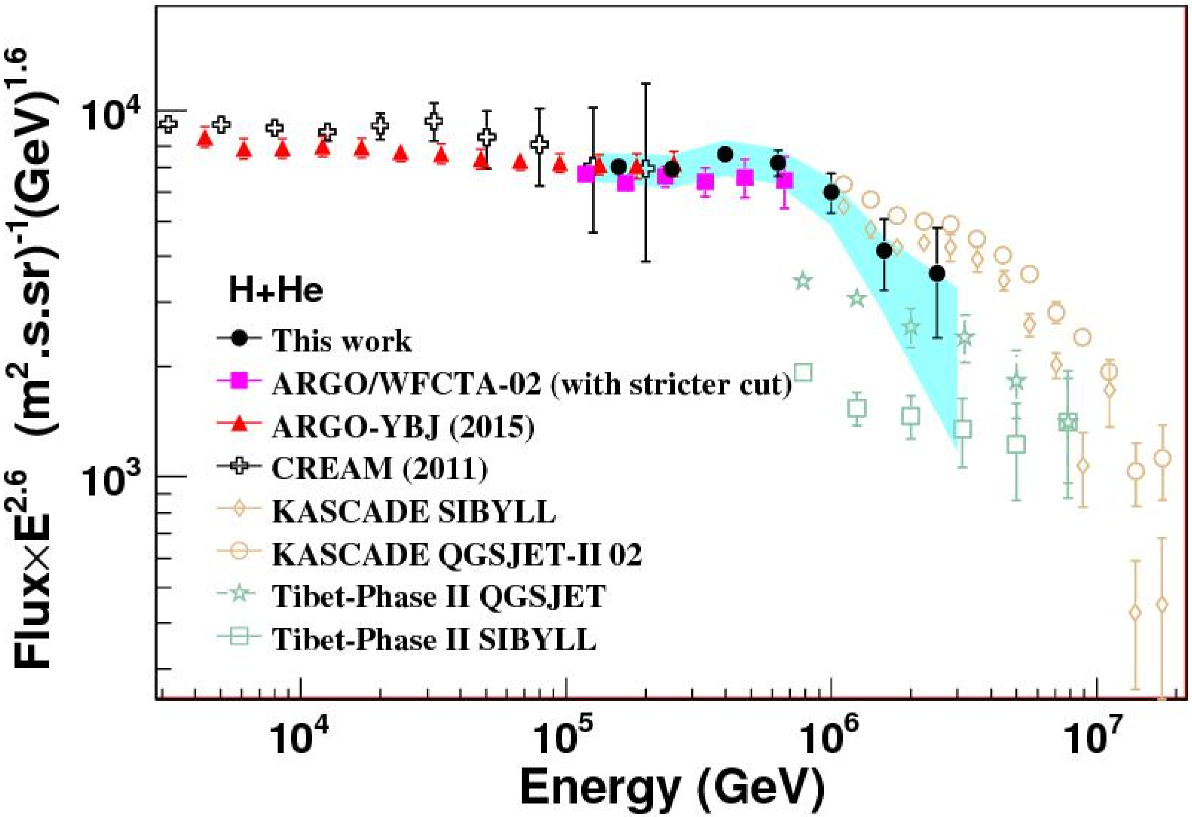


1 PeV



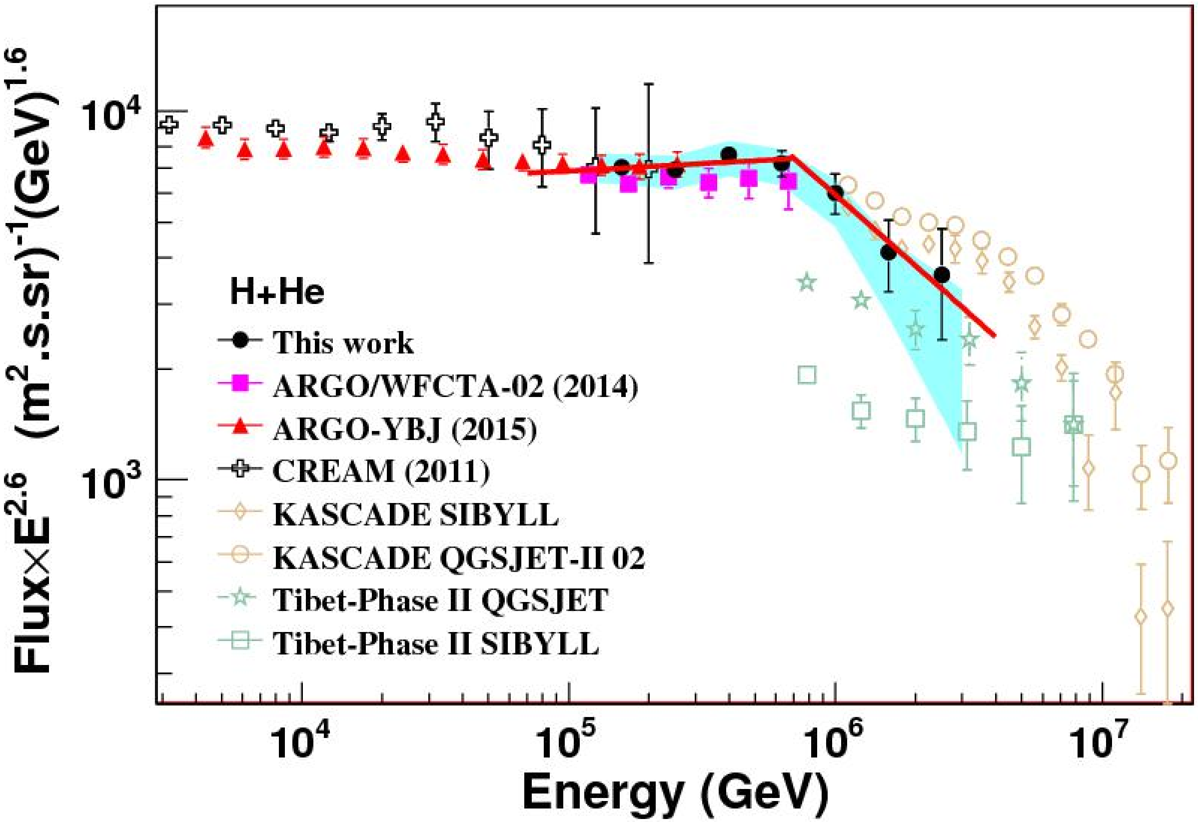
3 PeV

The spectrum of H & He with its knee below 1PeV



- ➢ Light component energy spectrum of 125 TeV - 3 PeV is measured;
- ➢ The knee of H&He spectrum at **~700** TeV is clearly measured.

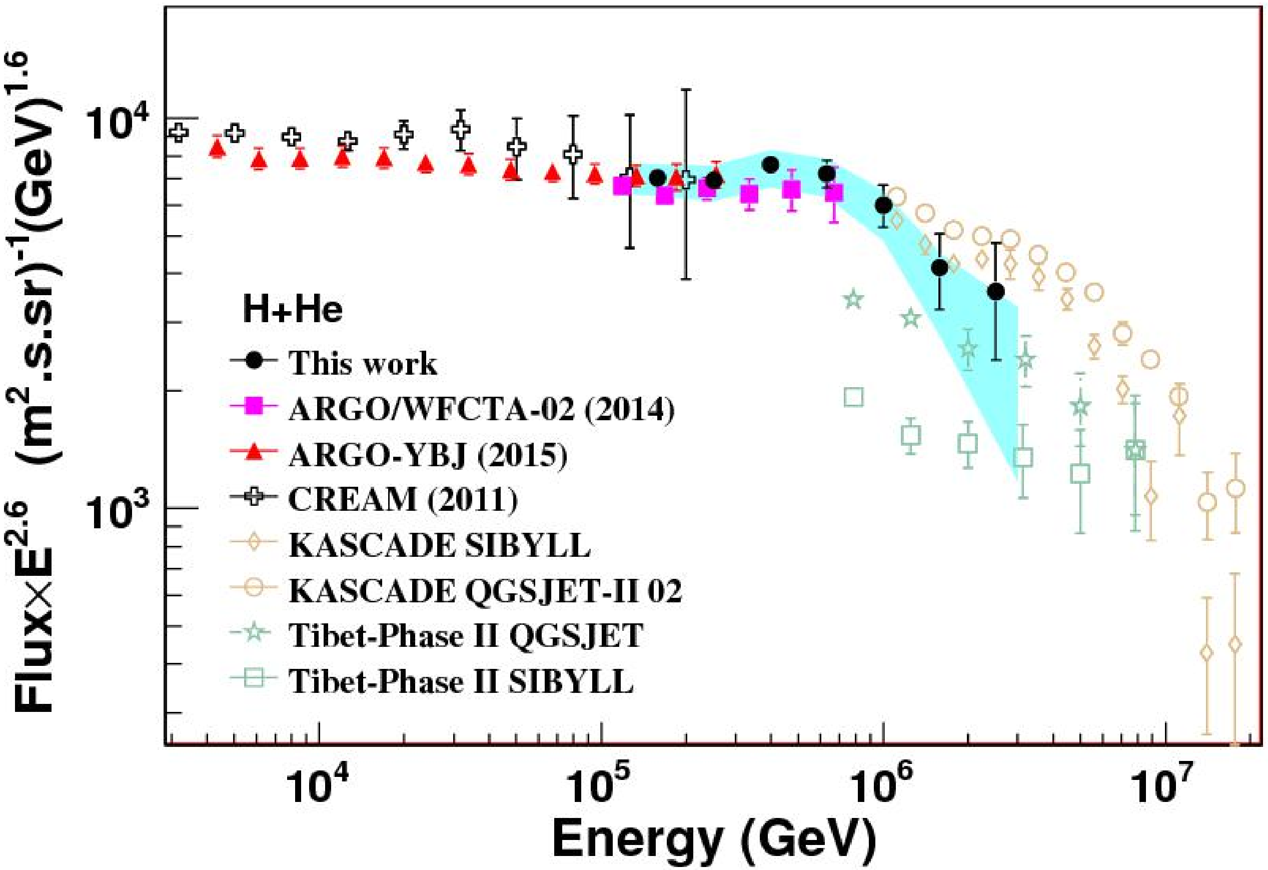
The spectrum of H & He with its knee below 1PeV



- Spectra index: β1=-2.56 ± 0.05 below knee; β2=-3.24 ± 0.36 above knee; The H&He knee of (700±230) TeV is found. The relatively large error on knee position is due to the limited statistics and the energy resolution.

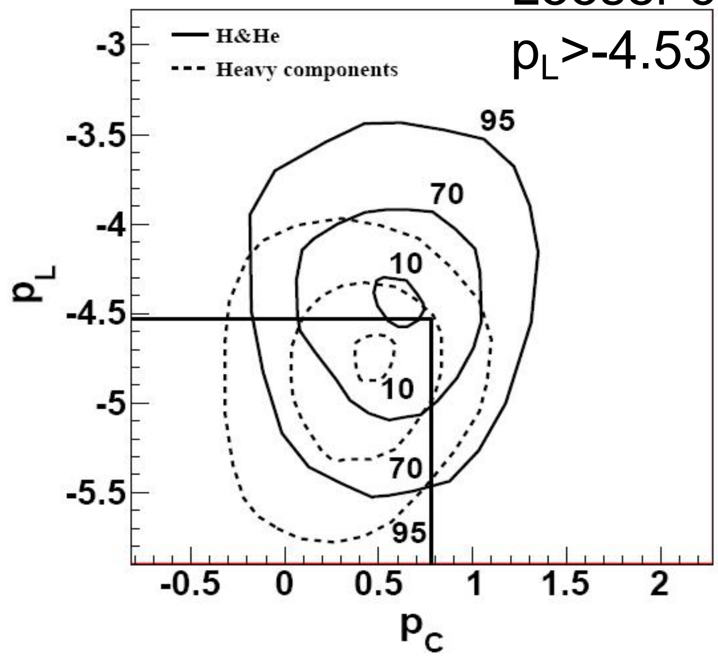
Systematic Uncertainties

- **Uncertainties in the energy scale: ~9.7 %**
  - Photometric calibration: 5.6%;
  - Weather/atmosphere conditions：7.6%;
  - QGSJET II-03 vs. SIBYLL2.1：<1.0%;
  - GHEISHA vs. FLUKA：<2.0%;
  - Composition model: 1%.
- **Systematic uncertainties on the H&He flux:**
  - ARGO-YBJ RPC calibration: 7%;
  - Composition models: the uncertainty is dependent on primary energy.
    - -(1.5~2.5)% @ 158 TeV,
    - -(29~51)% @ 2.5 PeV;
  - QGSJET II-03 vs. SIBYLL2.1: <1.0%;
  - GHEISHA vs. FLUKA：<3.5 %;
  - Boundary effects in the hybrid detector aperture calculation: <3%;
  - The difference between proton and Helium selection efficiencies: 3%;
  - Saturation of RPCs: <0.03%.

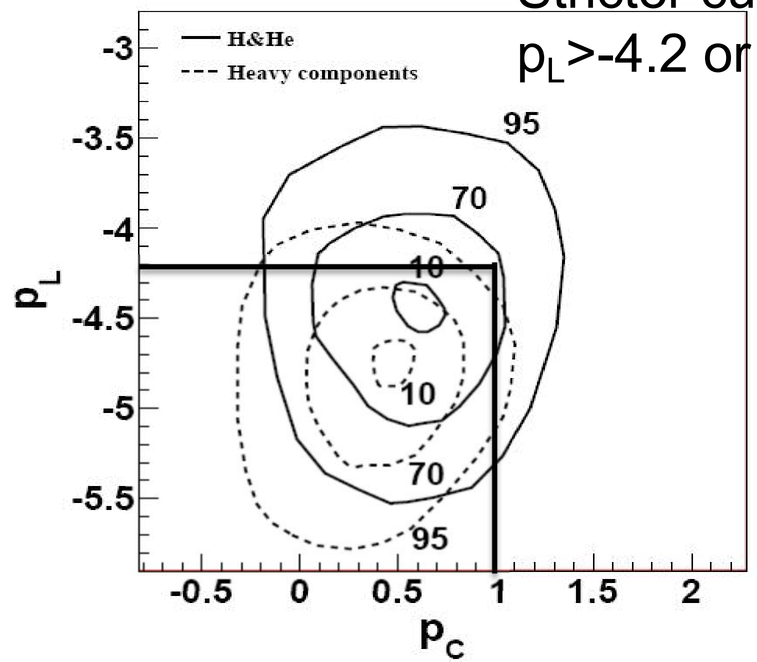


- The total systematic uncertainty on the flux is plotted as the shaded area in figure.

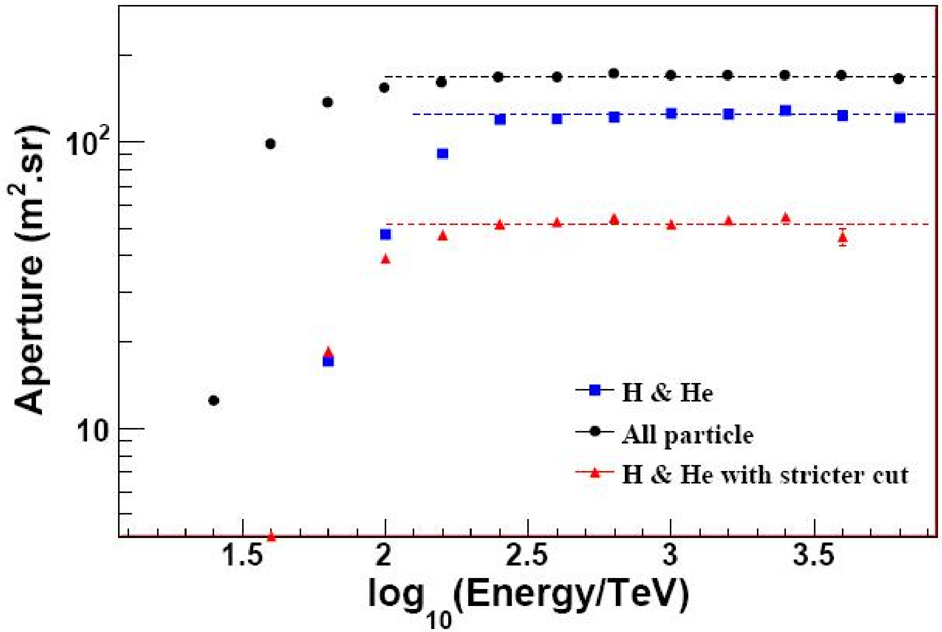
Looser cut:
$p_L > -4.53$ or $p_C > 0.78$



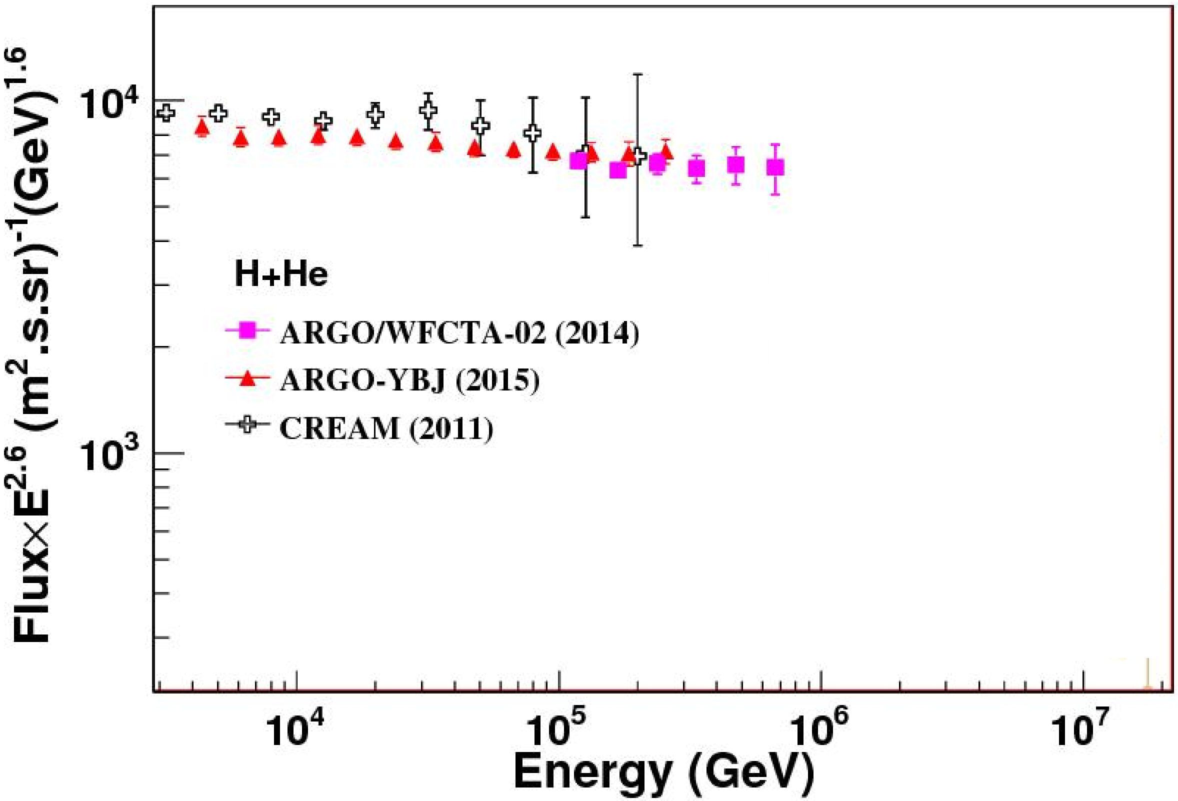
Stricter cut:
$p_L > -4.2$ or $p_C > 1.0$



- With stricter cut criteria
  - The purity of H&He showers: ~98% below 700 TeV;
  - The aperture of H&He: ~50 m^2.sr above 300 TeV;



H & He energy spectrum (with stricter cut)



- The *H&He spectrum (100 TeV- 700TeV) is* consistent with a single-index power law, in good agreement with CREAM and ARGO-YBJ results.

  -- Spectra index: ARGO-YBJ/WFCTA-02:-2.63 ± 0.06

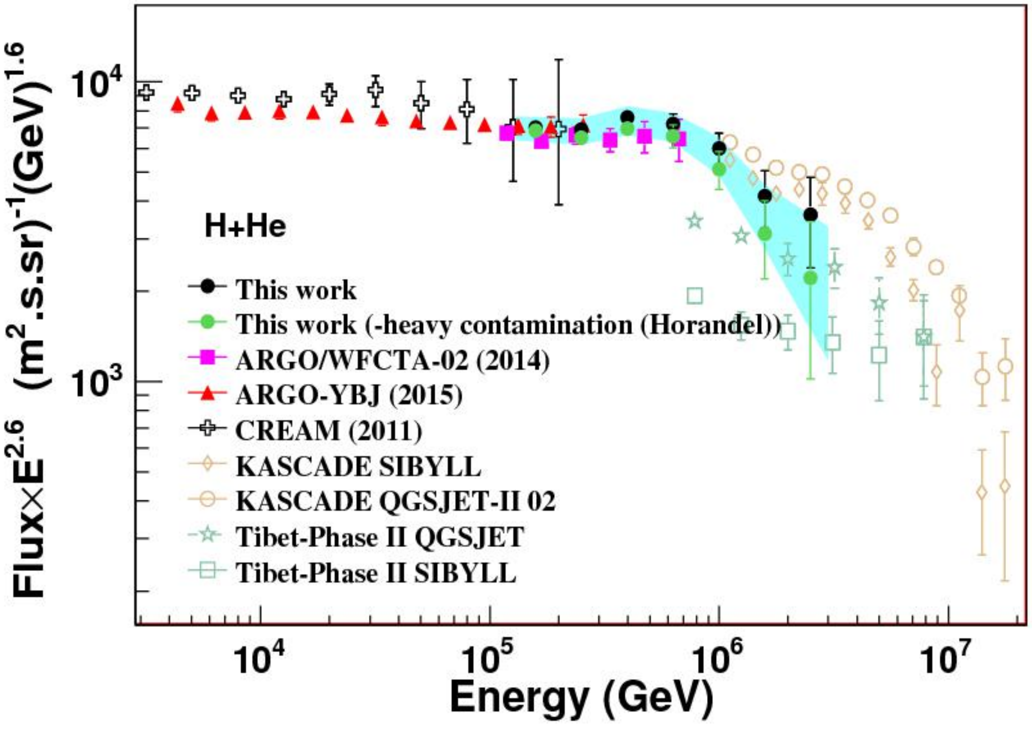
  ARGO： -2.61 ± 0.04

  CREAM (H+He): -2.62 ± 0.02

  -- The overall difference between three measurements: ±9%;

- This makes us confident on the hybrid observation and the analysis techniques

H & He energy spectrum

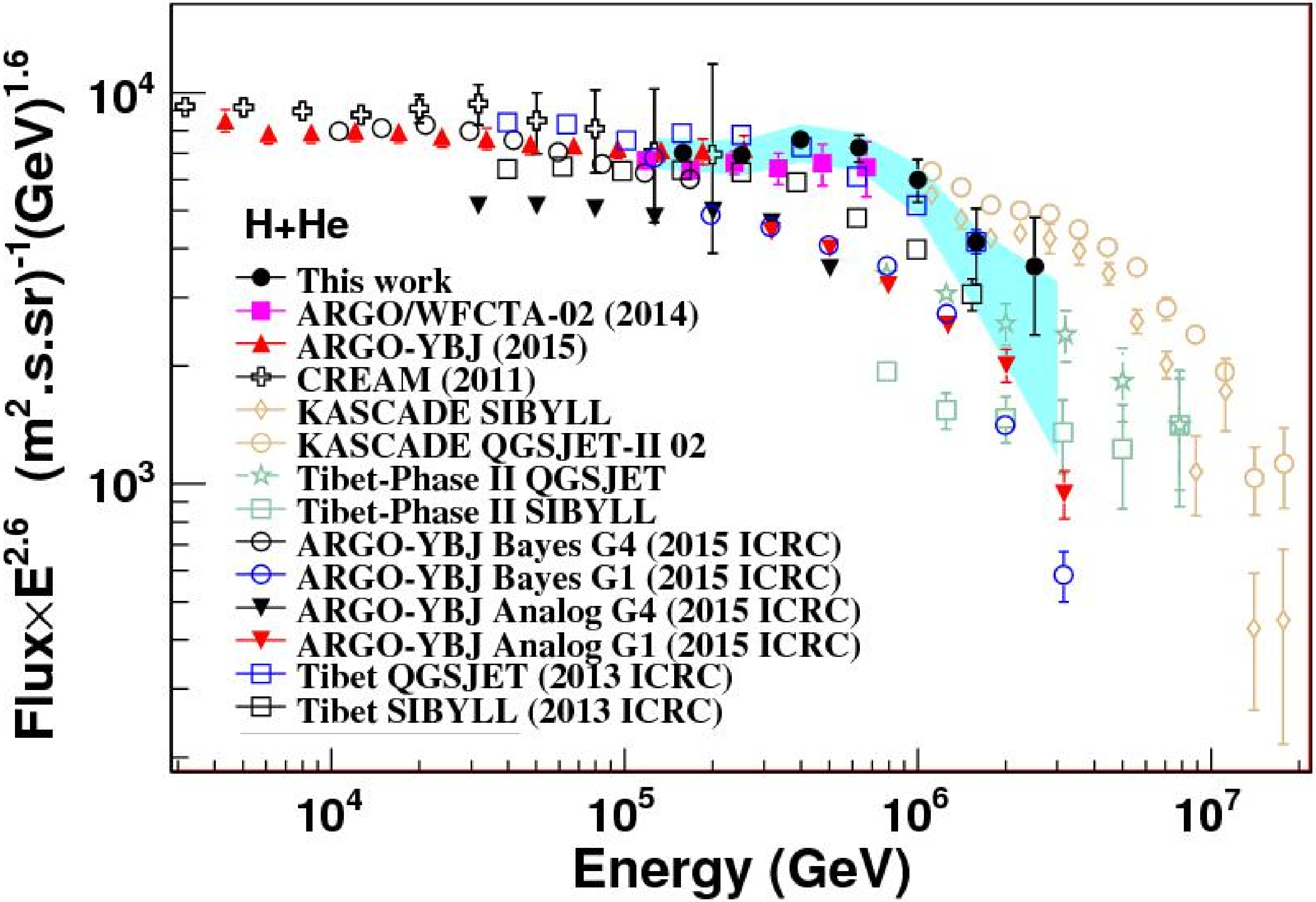


- To subtract the contamination of heavy nuclei from the H&He spectrum by using the composition model given in Horandel (green full circles):
  - Spectra index: β1=-2.62 ± 0.05 below the knee; β2=-3.58 ± 0.50 above the knee;
  - β_1=-2.62 is agreement with the spectral index -2.63 with stricter cut, correspondingly consistent with the spectral indexes reported by CREAM and ARGO-YBJ.
- The knee of H&He spectrum at ~700 TeV is clearly measured.

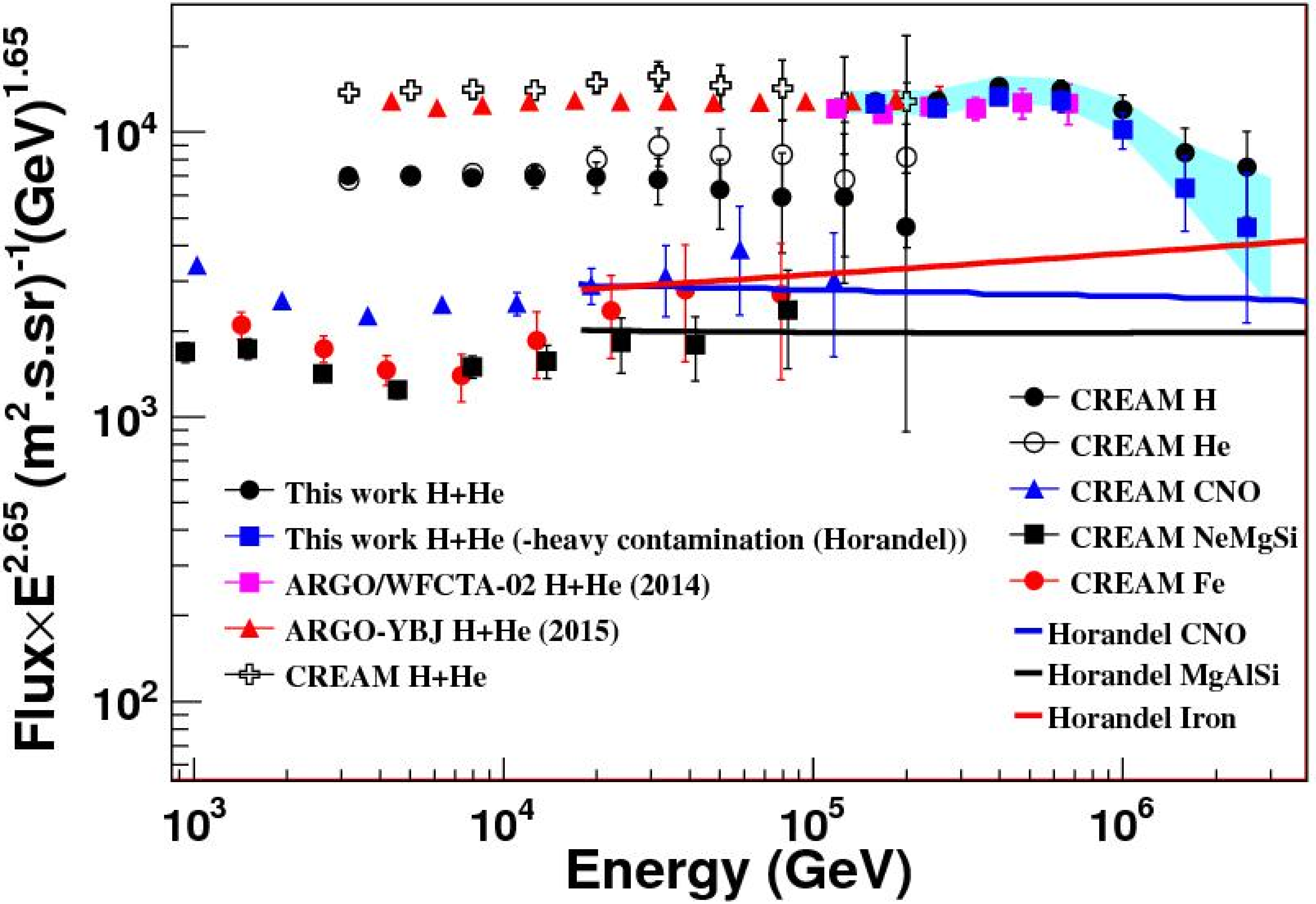
Conclusion

- 利用ARGO-YBJ实验和一台广角契伦科夫望远镜样机测量了100TeV-3PeV的质子+氦核能谱；
  - The knee of $(700\pm230_{stat.}\pm70_{sys.})$ TeV is found
  - Spectra index: β_1=-2.56 ± 0.05 below the knee; β_2=-3.24 ± 0.36 above the knee;
  - Energy resolution: ~25% with offset <3%；
  - filling the gap between the direct observations of CREAM and the EAS experiment, such as KASCADE
  - The observation of the knee of the primary light component at such a low energy gives fundamental inputs to galactic cosmic ray acceleration models.
- **LHAASO：WFCTA+WCDA+KM2A测量宇宙线分成分能谱展望**（马玲玲、刘加丽、毕白洋、尹丽巧）
  - Single element spectrum will be measured in the LHAASO project: muon detector, Cherenkov telescope, shower core detector, water Cherenkov detector
  - Energy range: 10TeV-1EeV.

Thanks!

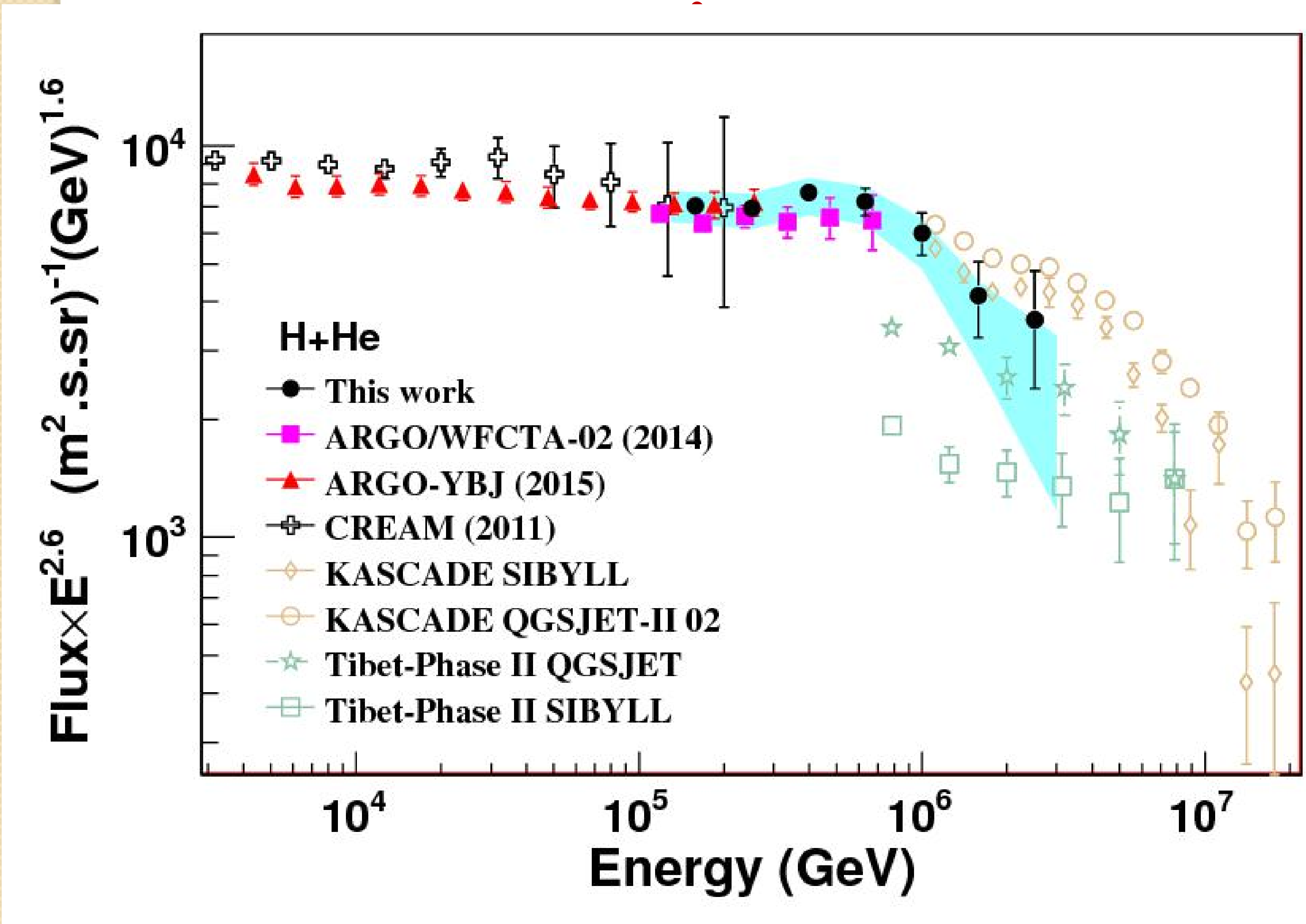


- The knee below 1 PeV is also consistent with two independent analyses of ARGO-YBJ data by using the RPC charge readout only (presented by Paolo).
  - -- Event by event reconstruction method.
  - -- Bayes method.



Flux×E^2.65 (m^2.s.sr)^-1(GeV)^1.65
Energy (GeV)
10^2
10^3
10^4
10^5
10^6
This work H+He
This work H+He (-heavy contamination (Horandel))
ARGO/WFCTA-02 H+He (2014)
ARGO-YBJ H+He (2015)
CREAM H+He
CREAM H
CREAM He
CREAM CNO
CREAM NeMgSi
CREAM Fe
Horandel CNO
Horandel MgAlSi
Horandel Iron

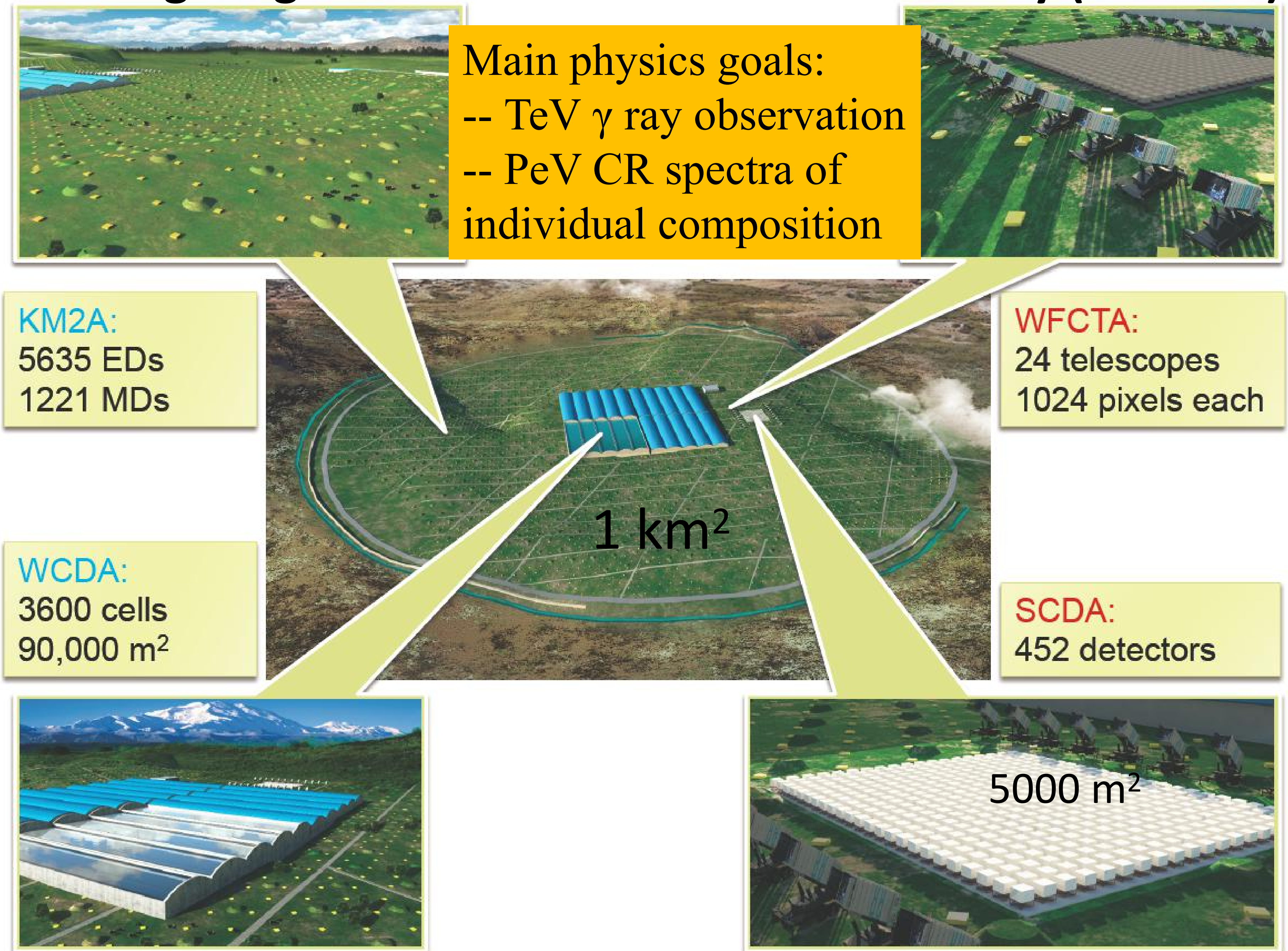
The H & He spectrum : comparison with other



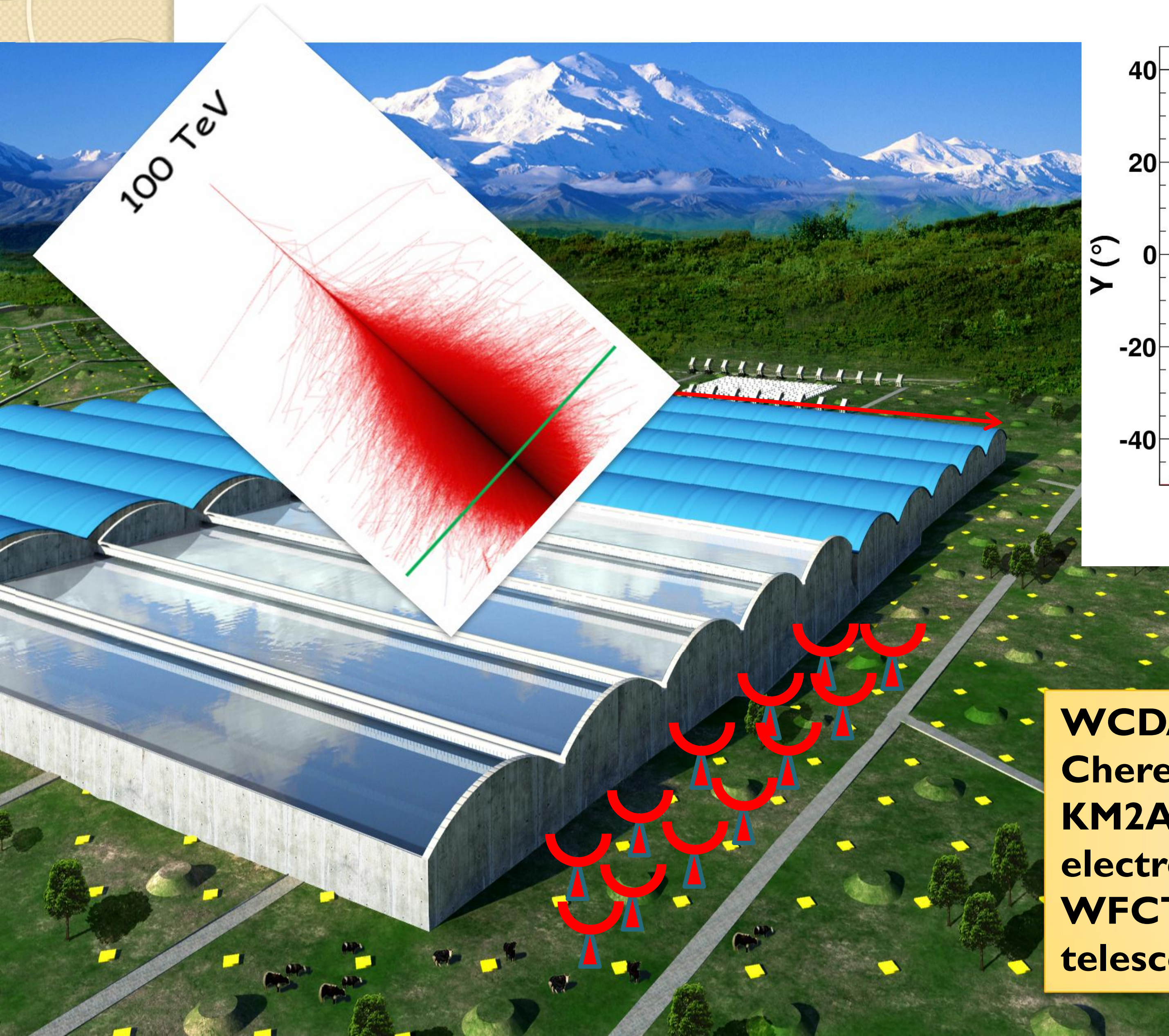
Outline

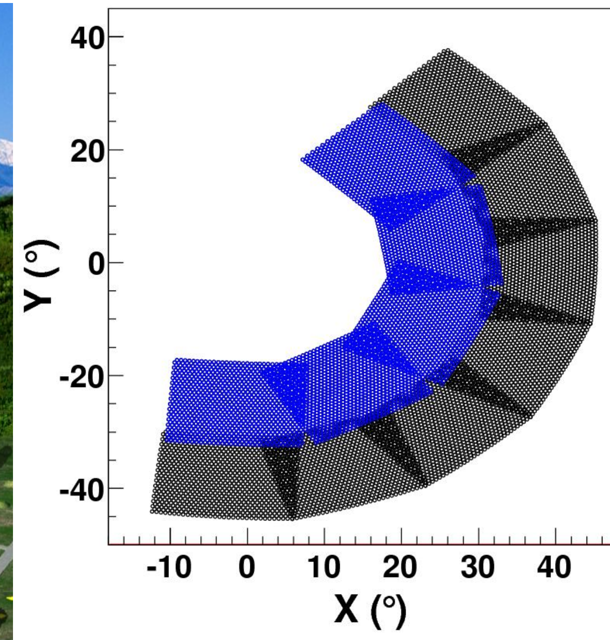
- Motivation
- Hybrid experiment introduction
- Data analysis
- Result and discussion
- Conclusion

Large High Altitude Air Shower Observatory (LHAASO)



LHAASO project: CR spectrum

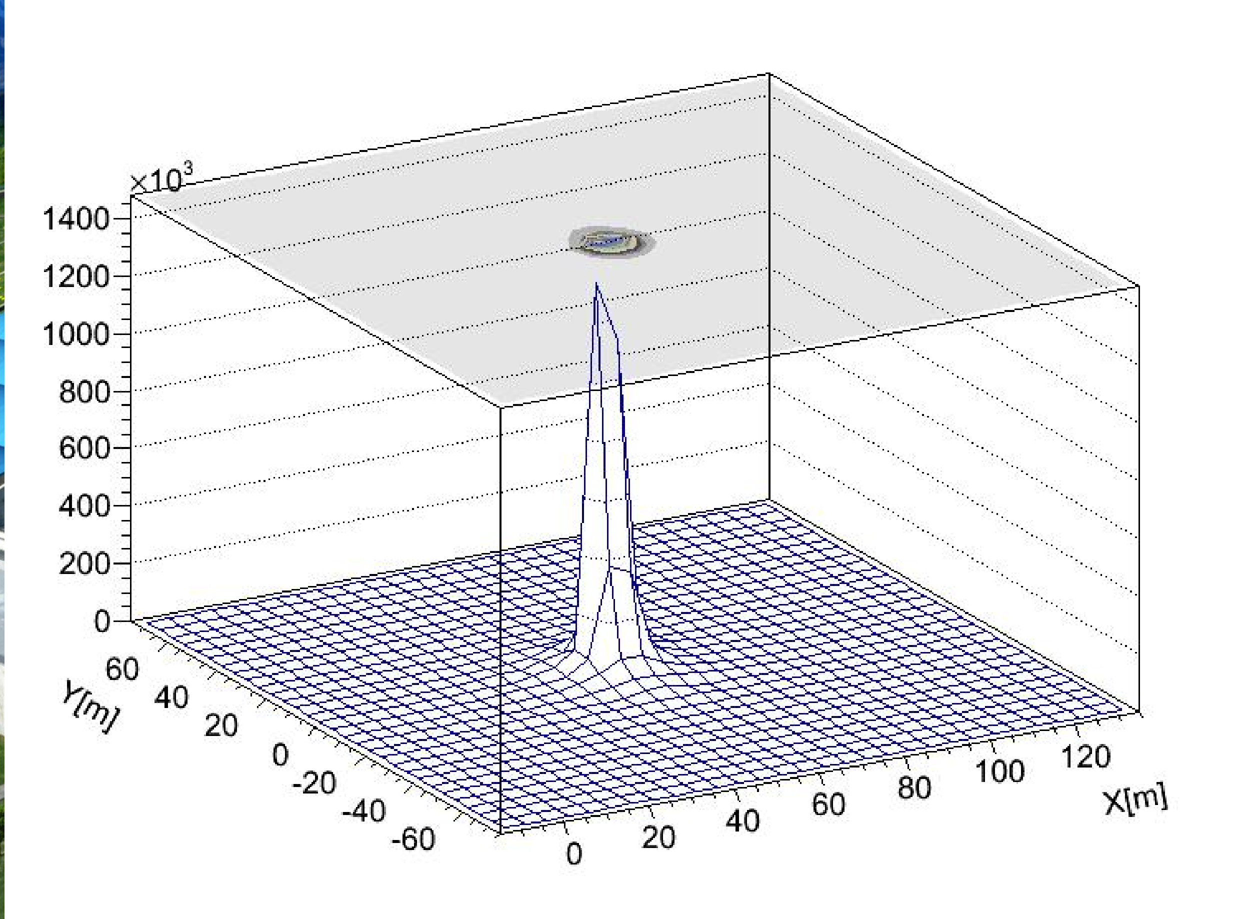


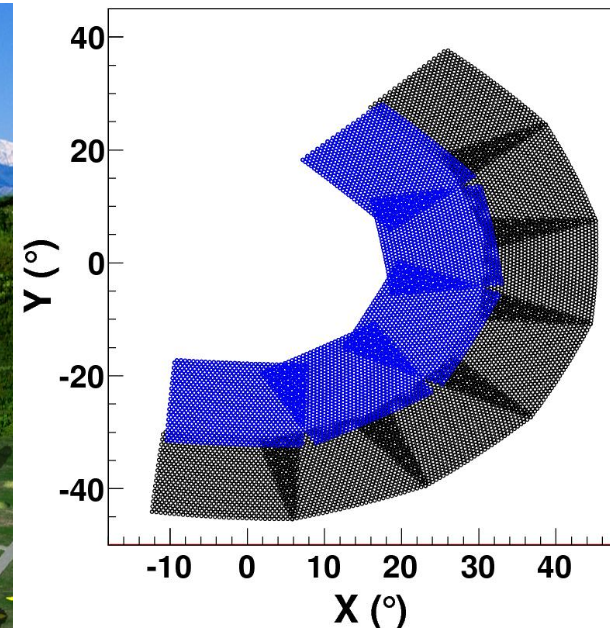


WCDA: Water Cherenkov detector array
KM2A: 1 km² muon and electron detector array
WFCTA: 12 Cherenkov telescope

LHAASO project: CR spectrum

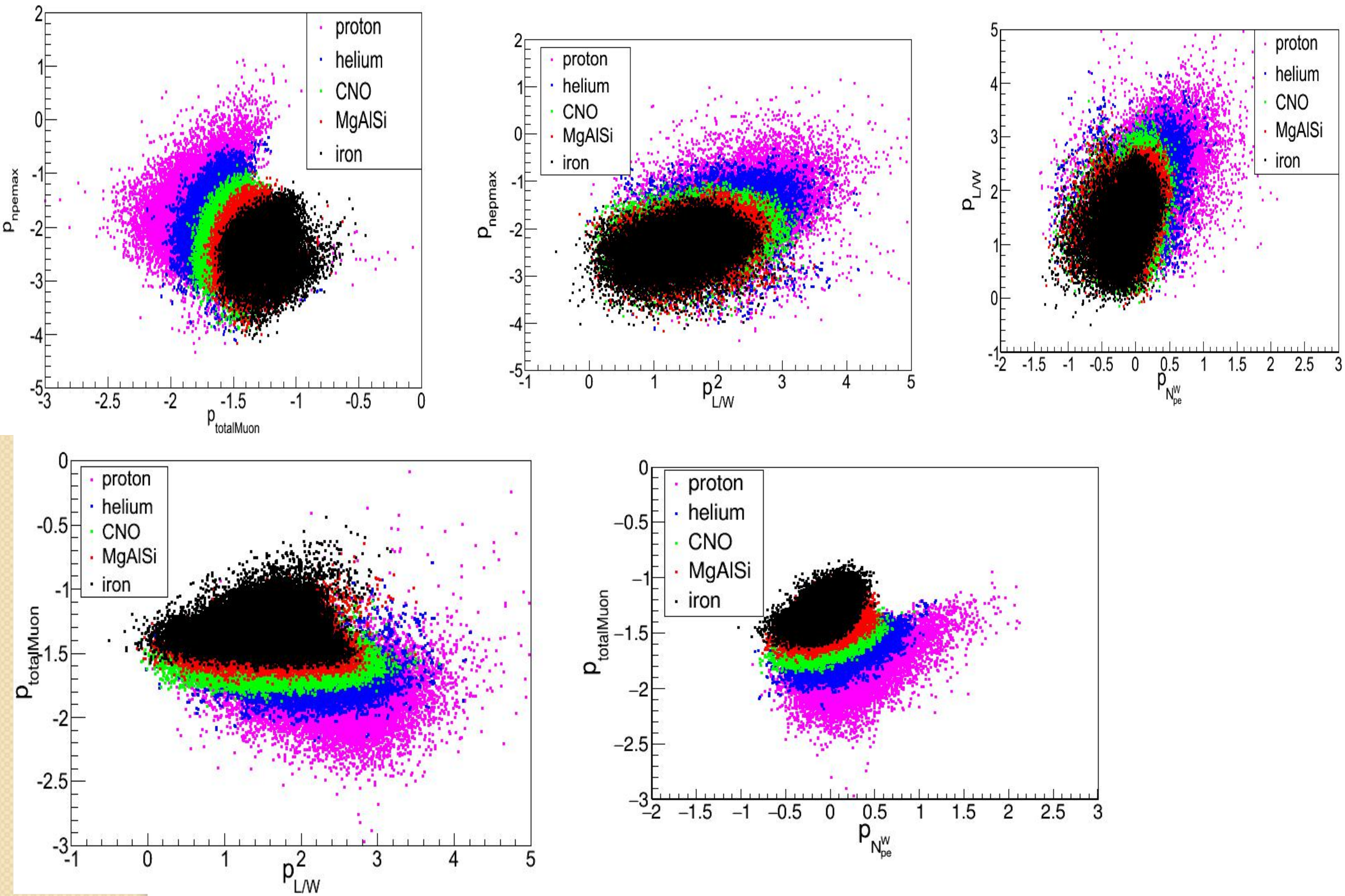
An event in WCDA

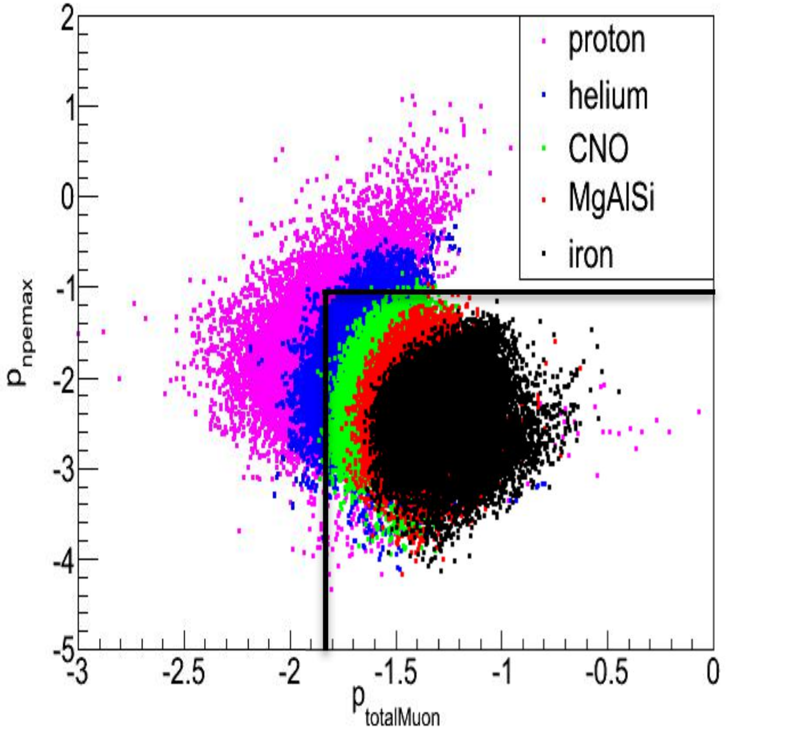


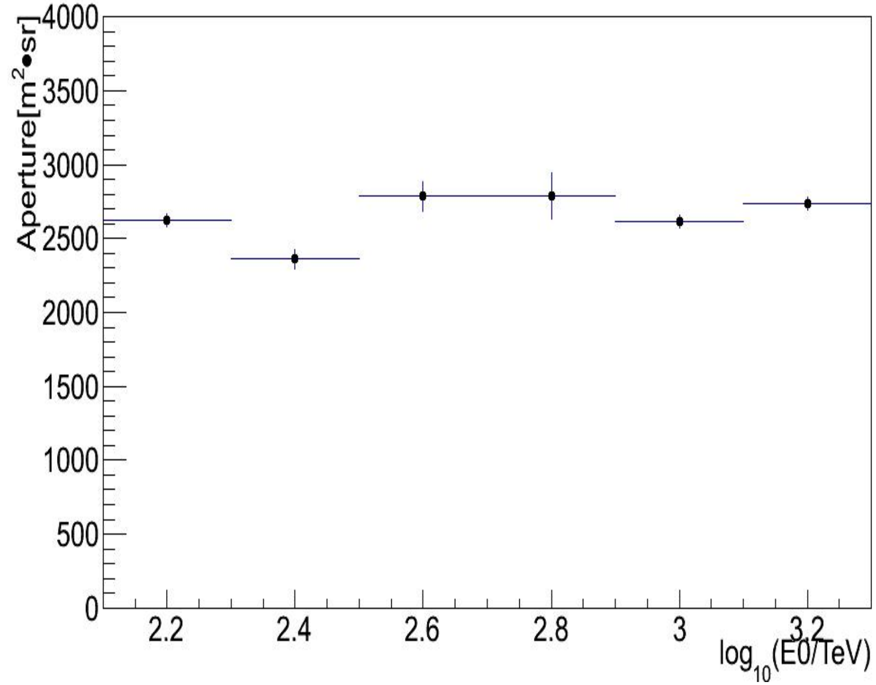


WCDA: Water Cherenkov detector array
KM2A: 1 km² muon and electron detector array
WFCTA: 12 Cherenkov telescope

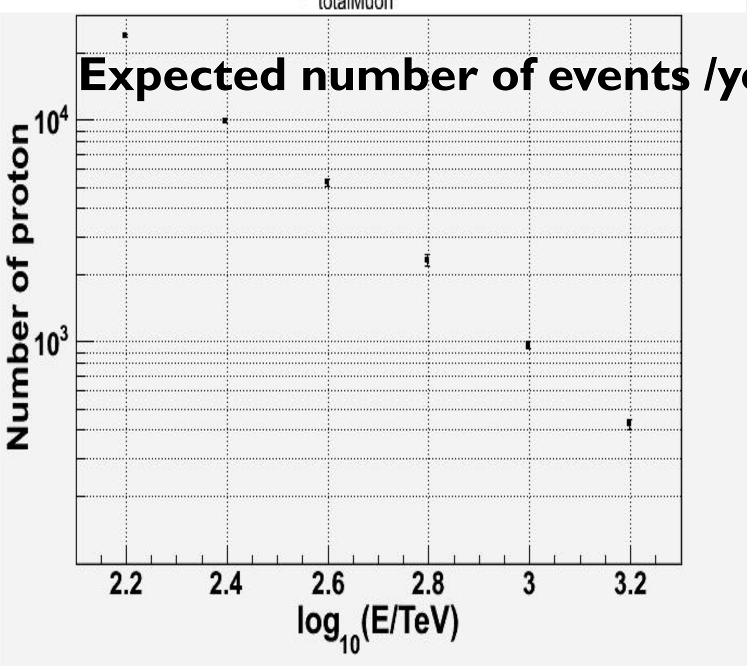
Mass sensitive parameters

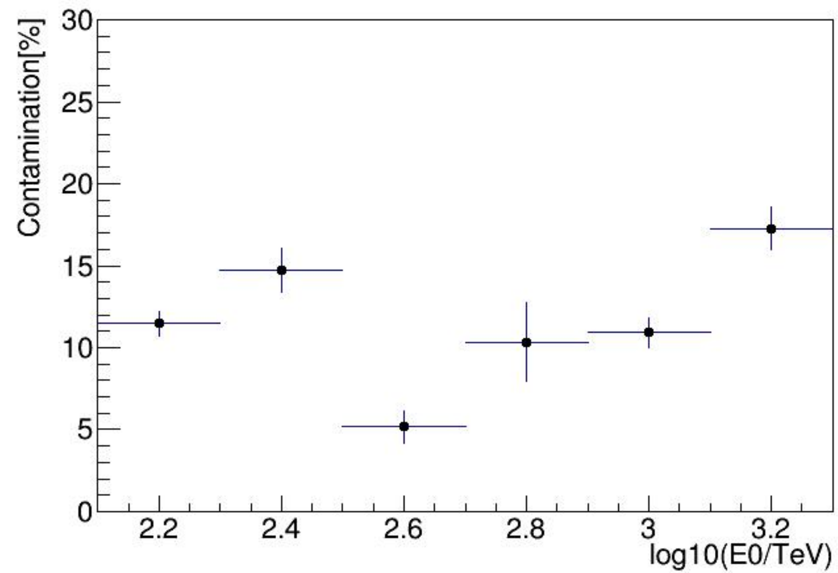






Expected number of events /year





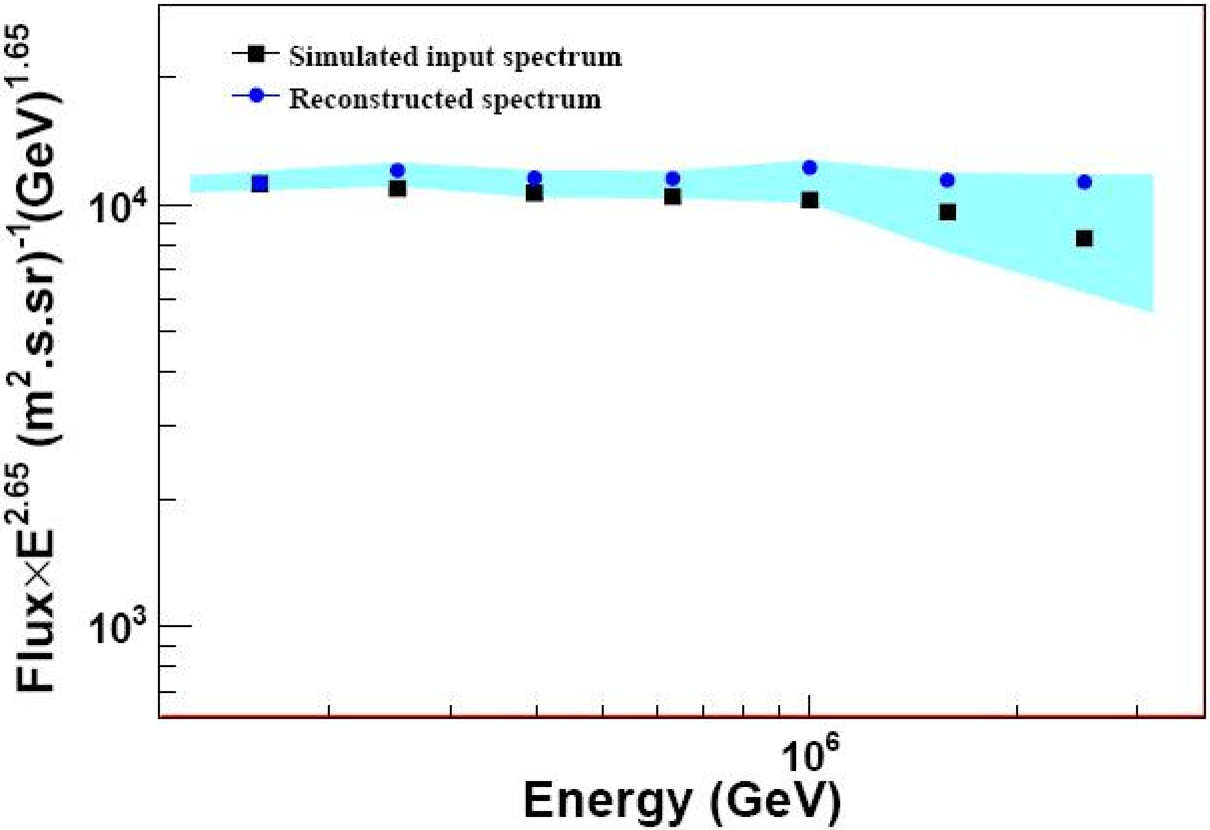
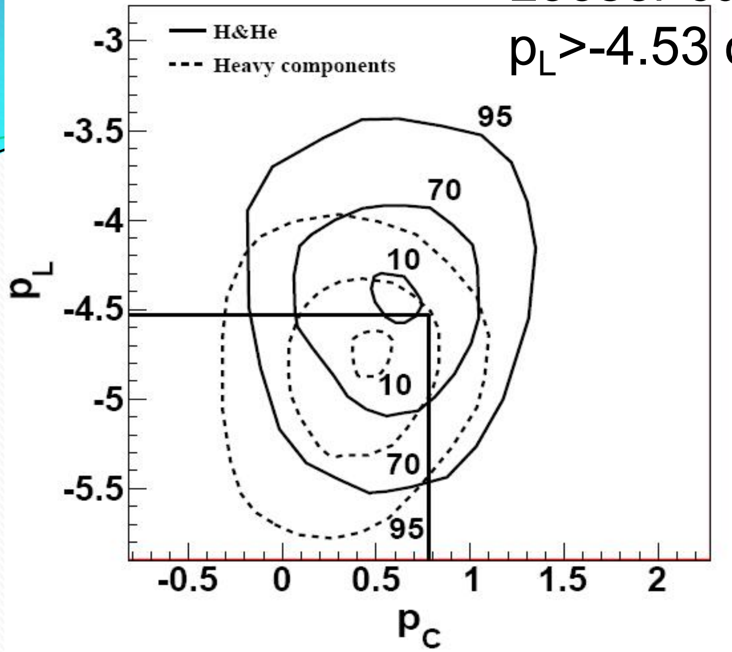
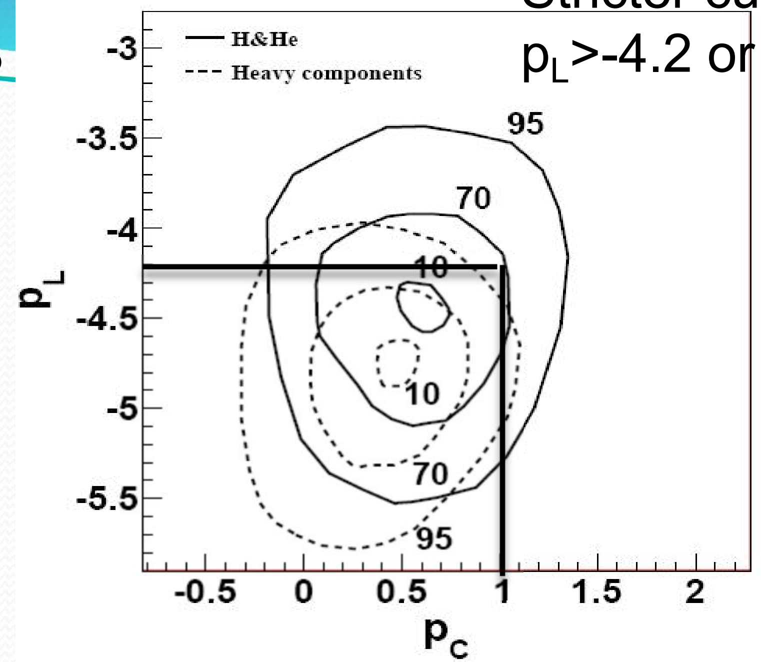


FIG. 11. Comparison between the input $H\&He$ spectrum according to ref. [35] and the reconstructed one. The slightly harder reconstructed spectrum shape is consistent with the contamination from heavier components shown in FIG. 8. The shaded area represents the systematic uncertainty caused by the contamination of heavy nuclei and boundary selection.

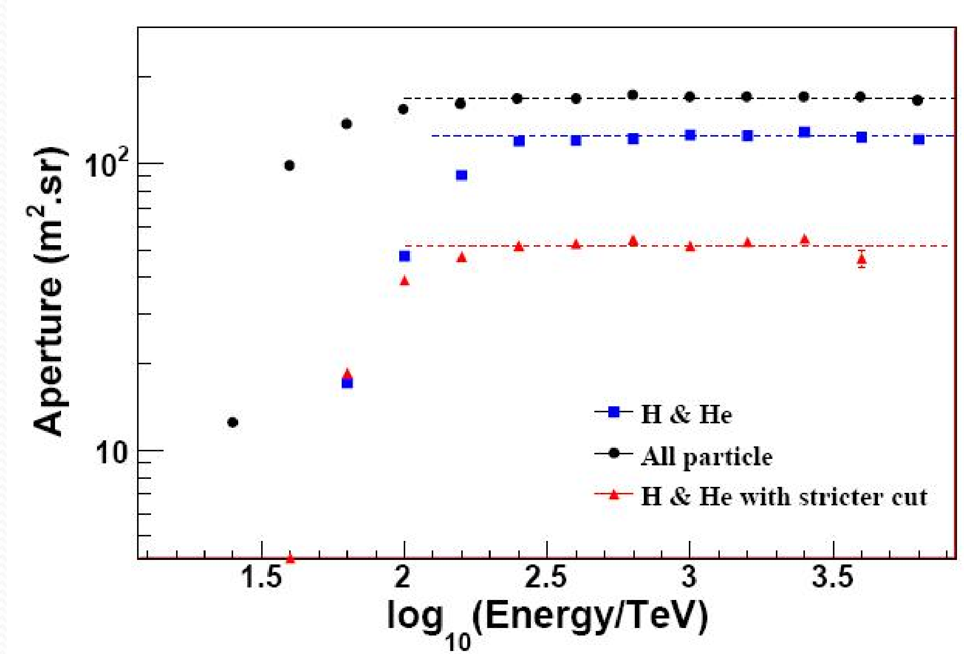
Looser cut:
$p_L > -4.53$ or $p_C > 0.78$



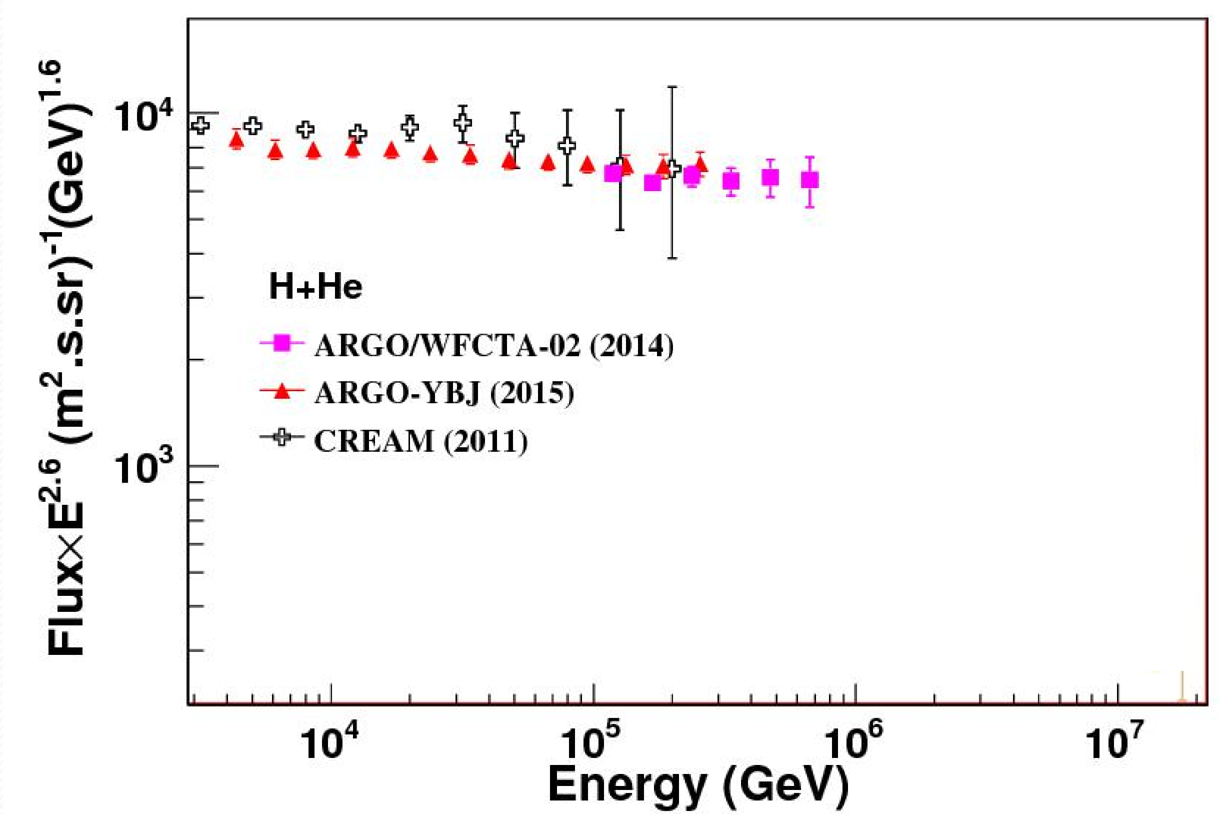
Stricter cut:
$p_L > -4.2$ or $p_C > 1.0$



- With stricter cut criteria
  - The purity of H&He showers: ~98% below 700 TeV;
  - The aperture of H&He: ~50 $m^2.sr$ above 300 TeV;



H & He energy spectrum (with stricter cut)



➤ The *H&He spectrum (100 TeV- 700TeV) is* consistent with a single-index power law, in good agreement with CREAM and ARGO-YBJ results.

-- Spectra index: ARGO-YBJ/WFCTA-02:-2.63 ± 0.06

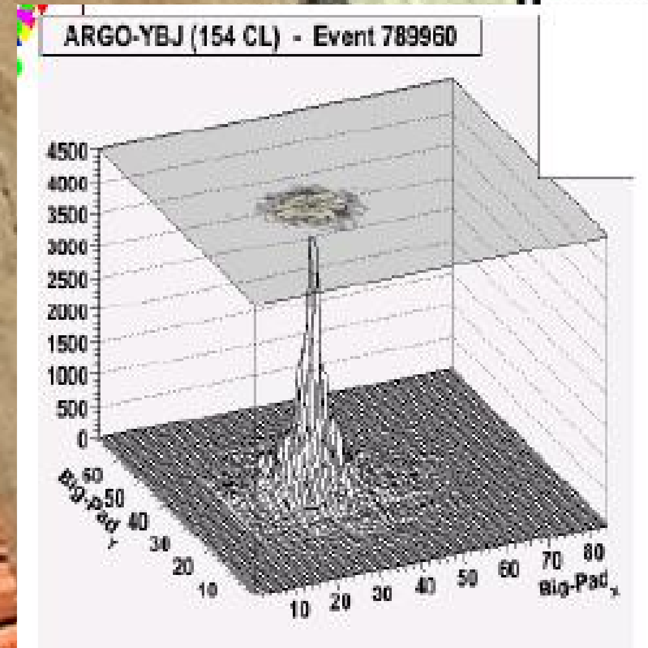
ARGO： -2.61 ± 0.04

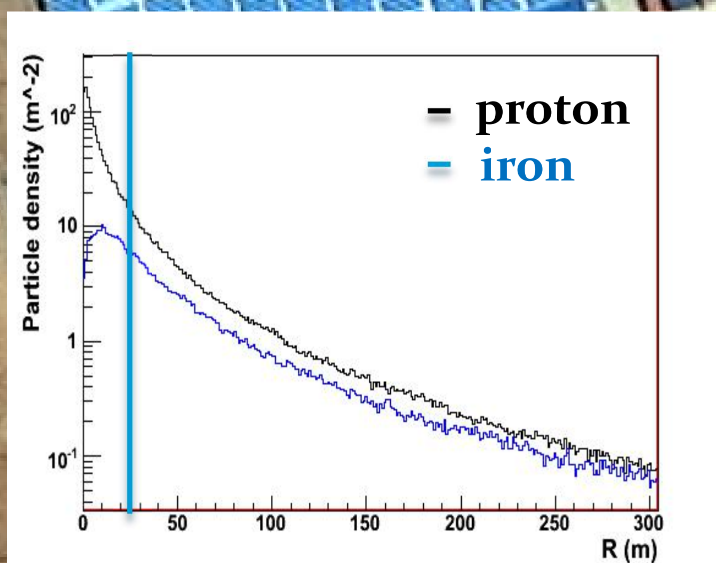
CREAM (H+He): -2.62 ± 0.02

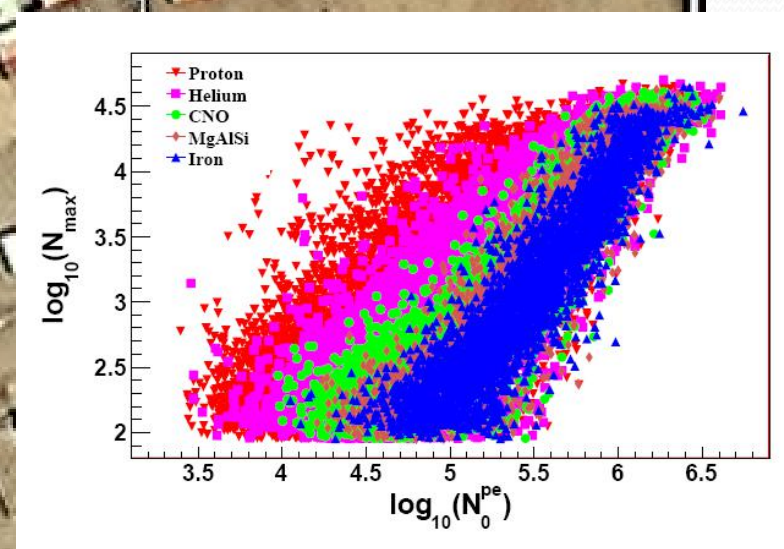
-- The overall difference between three measurements: ±9%;

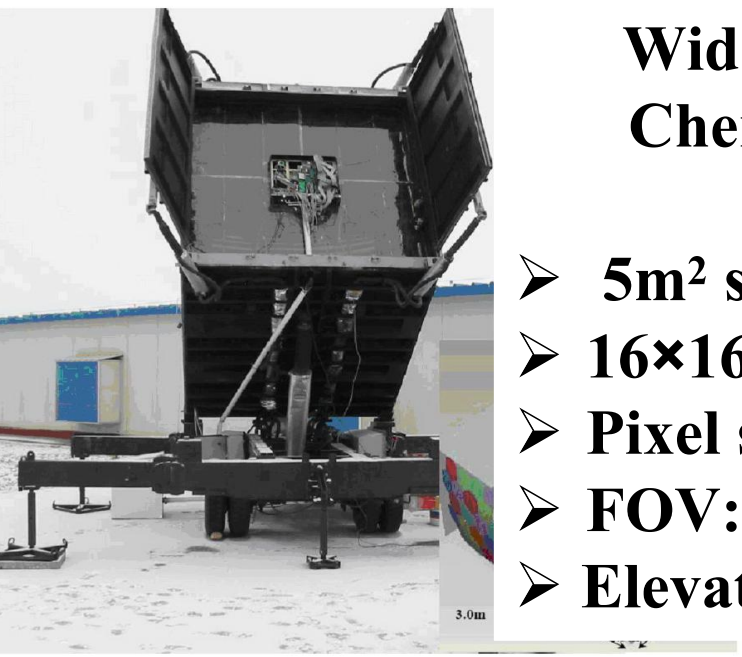
➤ This makes us confident on the hybrid observation and the analysis

ARGO-YBJ experiment @ 4300 m a.s.l.









Wide Field of View Cherenkov Telescope (WFCTA)

- 5m^2 spherical mirror;
- 16×16 PMT array
- Pixel size 1°;
- FOV: 14°× 16°;
- Elevation angle: 60°.