

The knee of the proton spectrum

Measured by using a hybrid experiment
at 4300 m a.s.l.

LHAASO for CRs

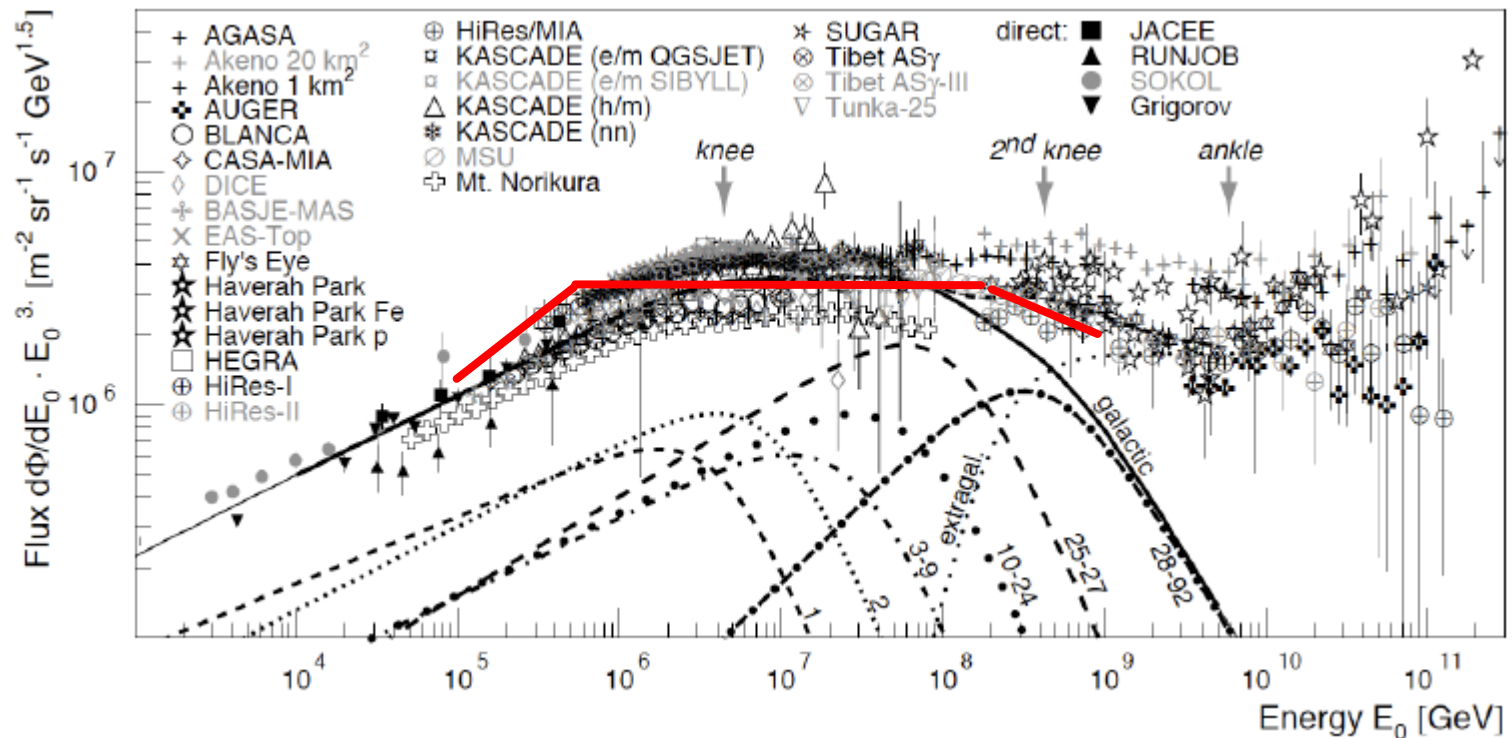
Zhen Cao, IHEP, Beijing
for the ARGO-YBJ Collaboration
& the LHAASO Collaboration

Outline

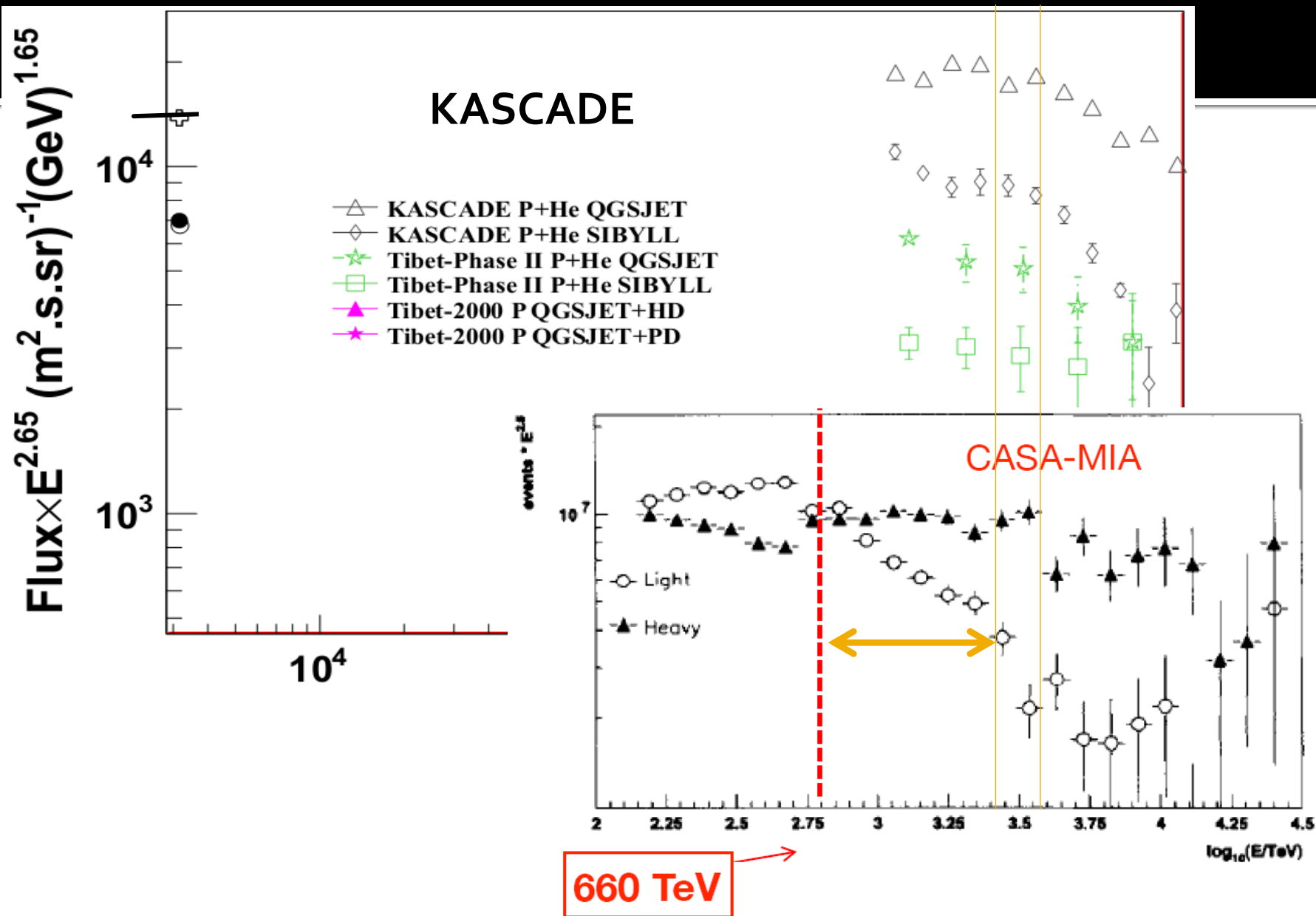
- ◆ The Motivation of the Hybrid Experiment with WFCTA Prototype and the ARGO-YBJ RPC Carpet
- ◆ Efficiency and the Observation
- ◆ The Performance of the Hybrid Experiment
 - ◆ Data vs. Simulation
 - ◆ Selection of H&He from All CR Showers
 - ◆ Aperture for H&He Detection and the Contamination
 - ◆ Energy reconstruction and its Resolution
- ◆ The H&He Spectrum
- ◆ **The knee of proton spectrum**
- ◆ **LHAASO on CRs and status**

Motivation

- Highly unknown “knee”-mechanism
- Too many assumptions, too many “measurements”!
- Major tension is between KASCADE and CASA/MIA



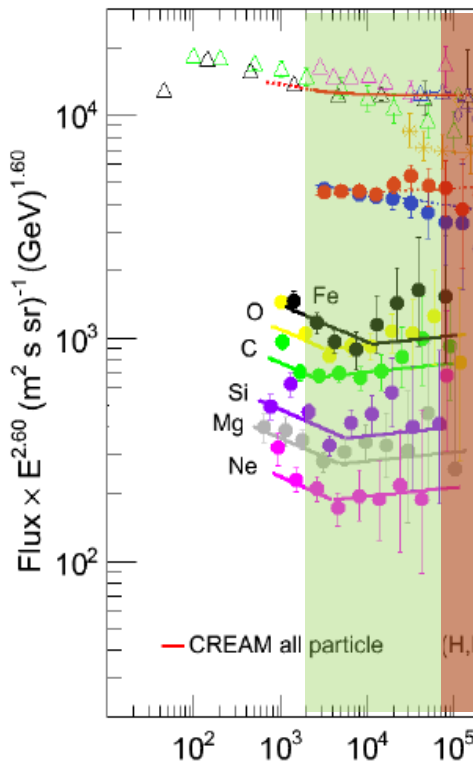
KASCADE vs. CASA-MIA



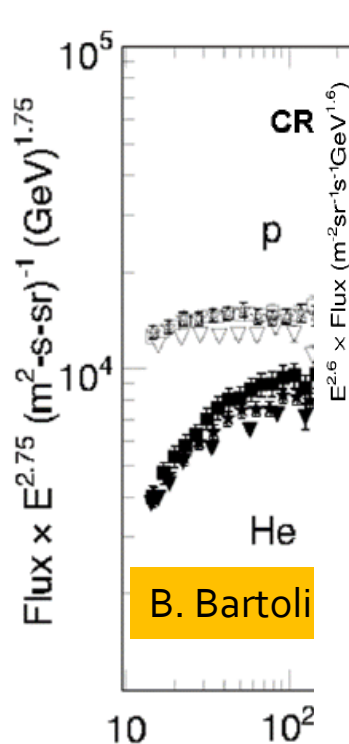
Motivation

- Aim: To bridge between balloon borne measurements and ground based experiments for *cross-calibration between the experiments.*

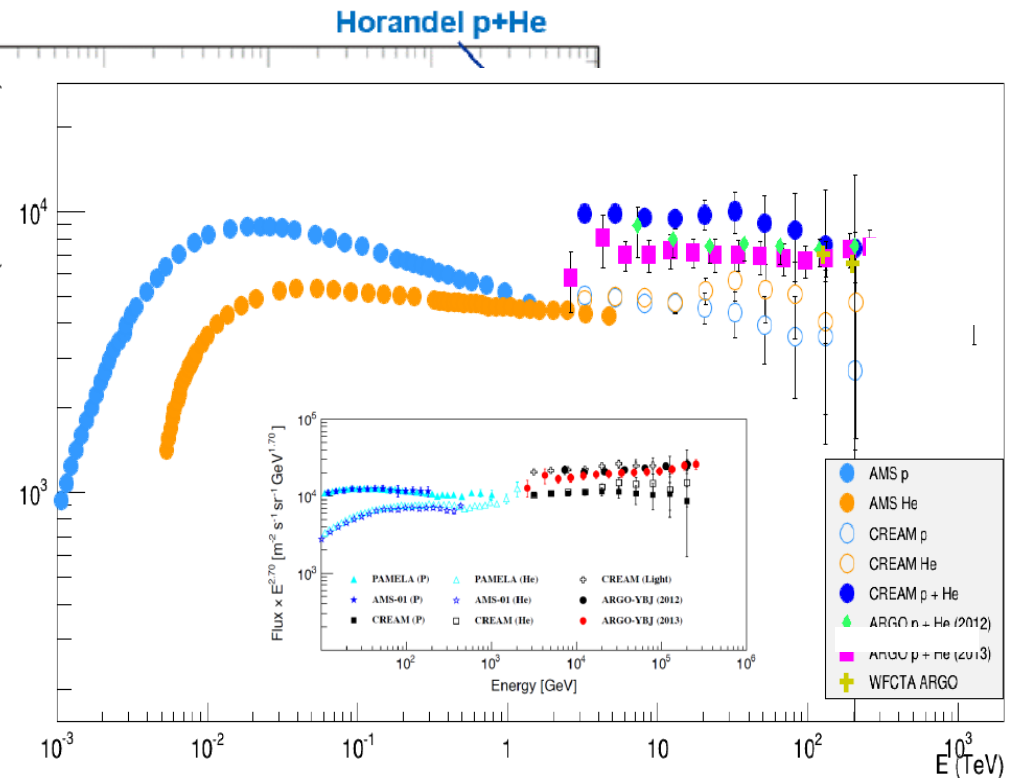
- CREAM: energy spectrum of single element up to 100TeV
- ARGO-YBJ (H&He): 7TeV-200TeV
- AMS02 further confirmed the energy scale
- **This work is to extend the ARGO-YBJ results to higher energies**



Y. S. Yoon et al., Ast



B. Bartoli



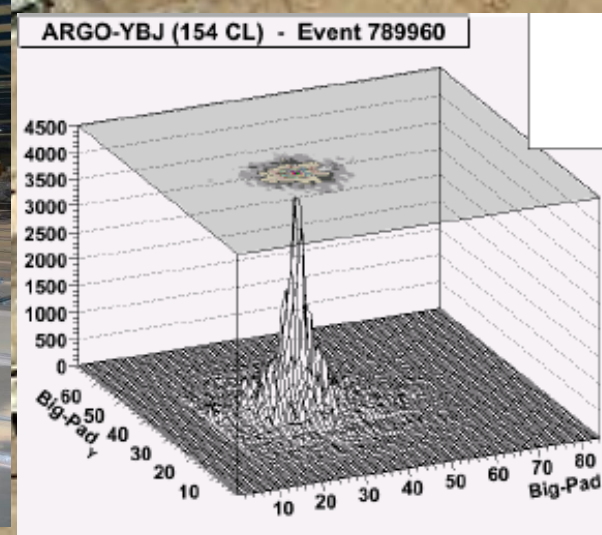
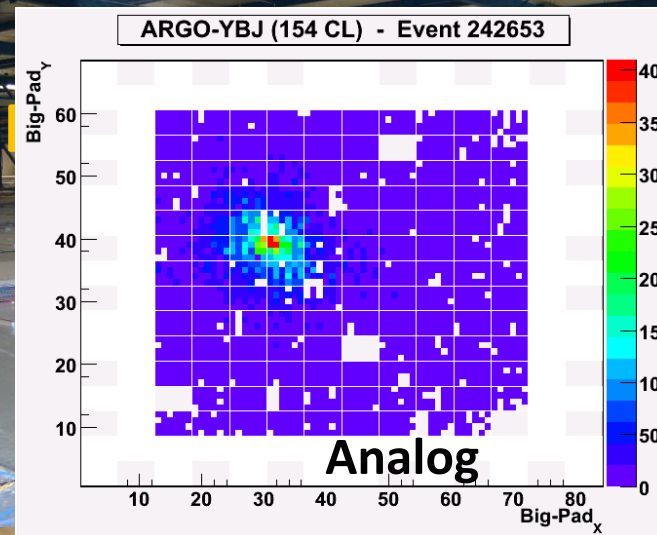
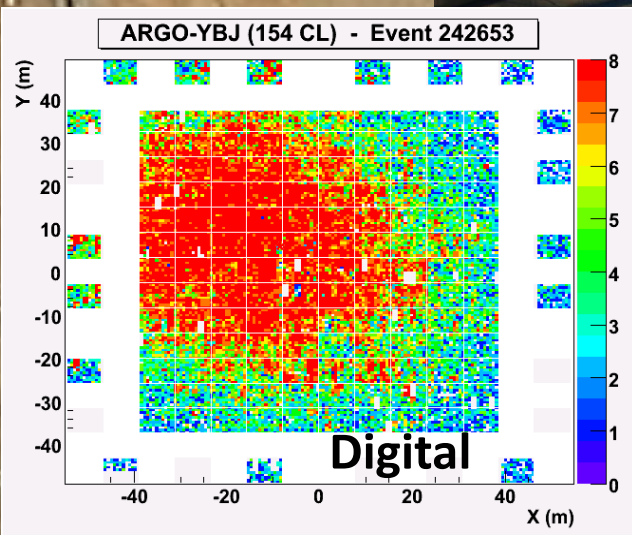
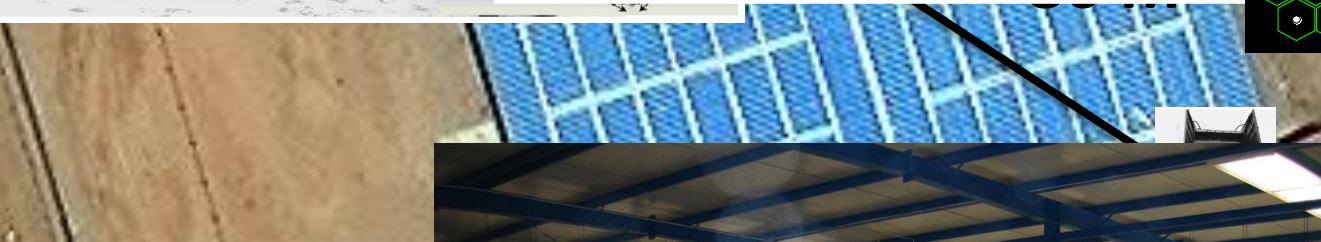
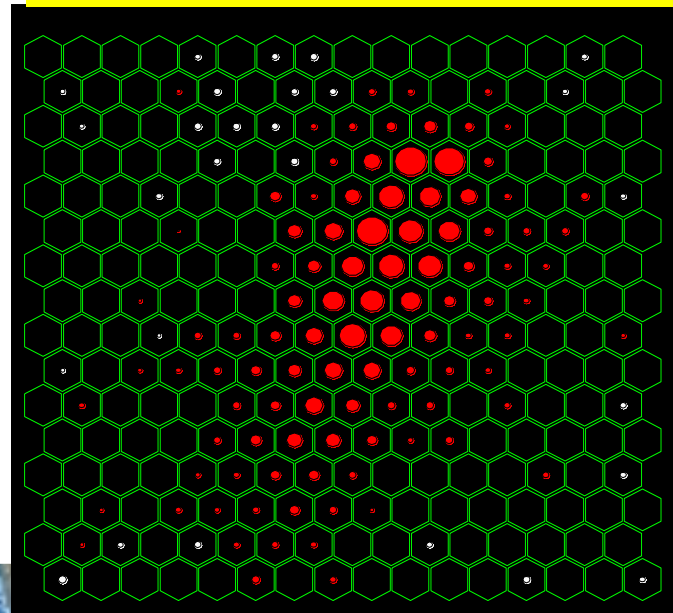
- AMS p
- AMS He
- CREAM p
- CREAM He
- CREAM p + He
- ▲ ARGO n + He (2012)
- ARGO p + He (2013)
- ✦ WFACTA ARGO



Wide Field of View Cherenkov Telescope (WFCTA)

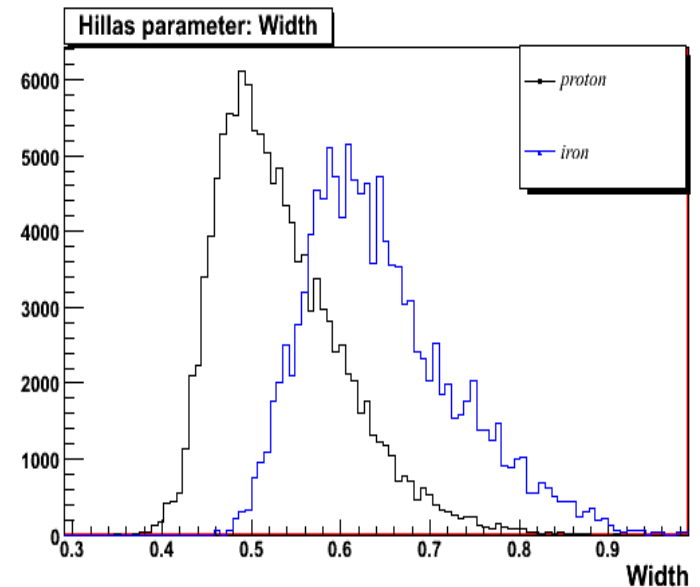
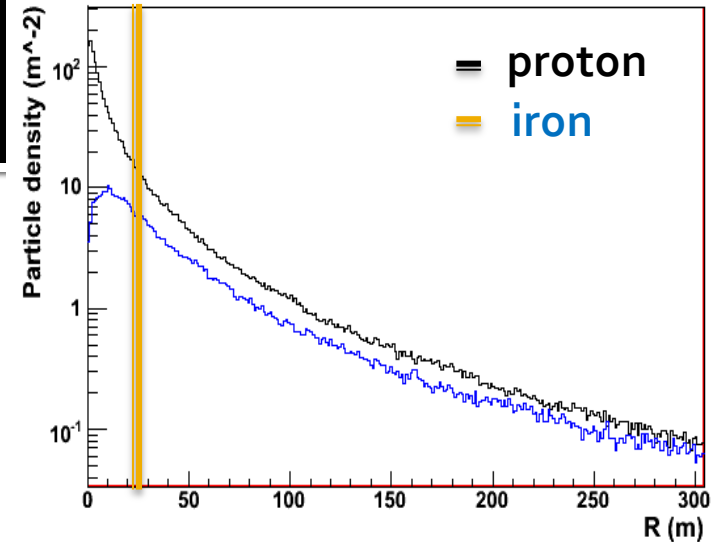
- 5m² spherical mirror;
- 16 × 16 PMT array
- Pixel size 1° ;
- FOV: 14° × 16° ;
- Elevation angle: 60° .

One of Cherenkov event



Hybrid Measurement

- **ARGO-YBJ:**
lateral distribution
 - In the core region → mass sensitive
- **Cherenkov Telescope:**
longitudinal information
 - Hillas parameter → mass sensitive
 - Good energy resolution



CR measurement of the hybrid experiment

➤ Extensive air showers

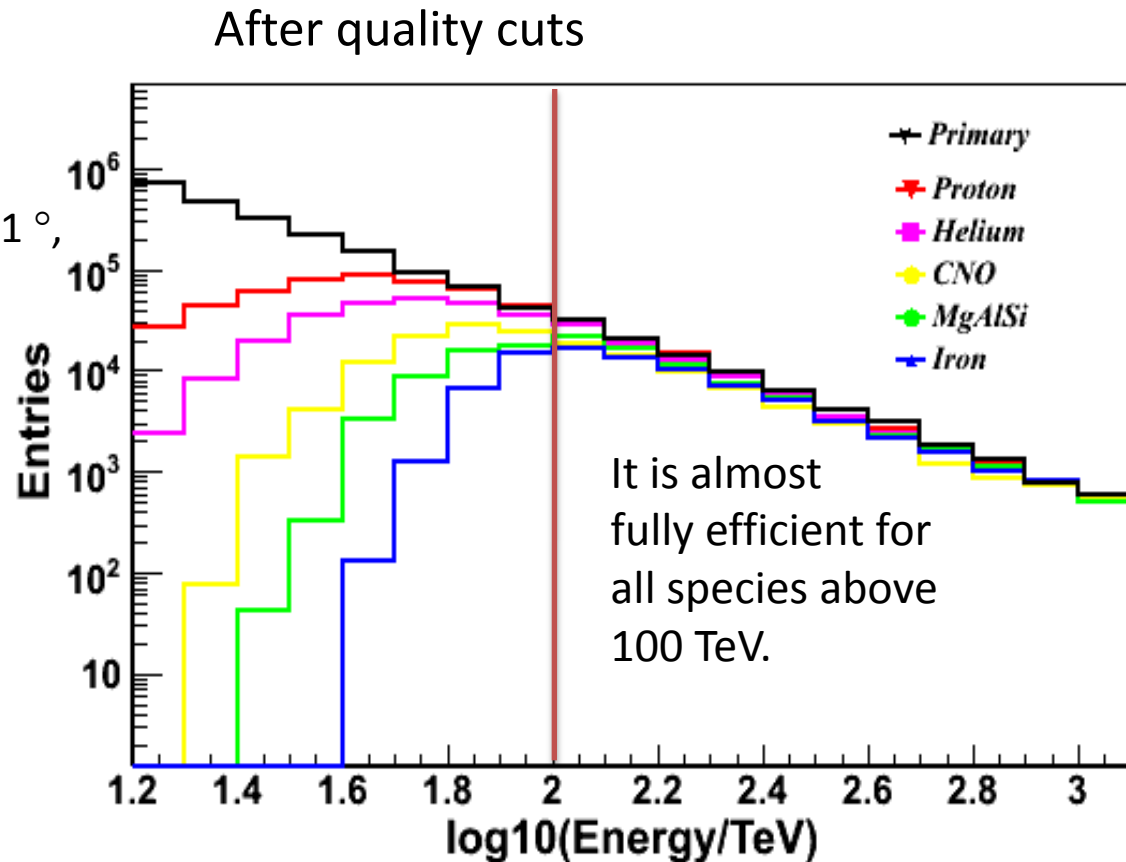
- Corsika6735: QGSJETII-03+GHEISHA
- All primary particles in 5 groups:
H, He, CNO, MgAlSi, Fe

1:1:1:1:1

- Energy range: 10 TeV – 10PeV
- Geometry: $\theta \sim 20^\circ - 42^\circ$, $\phi \sim 69^\circ - 111^\circ$,
Core: ± 150 m

➤ Detector simulation

- Cherenkov telescope:
Ray tracing for every photons
in shower images
- RPC-carpet: GEANT-4 based
program, G4argo



Hybrid Observation and Data Set

➤ Period:

- From 2010.12 ~ 2012.02: Coincidence events;
- Good weather: 728,000 sec

➤ *Criteria for reconstruction quality*

- Cores must be inside the ARGO carpet, cannot in the PRCs on the edges
- Cherenkov images must fully contained in the telescope, i.e.
space angle $< 6^\circ$ respect to the axis of the telescope
& the number of fired tubes ≥ 6

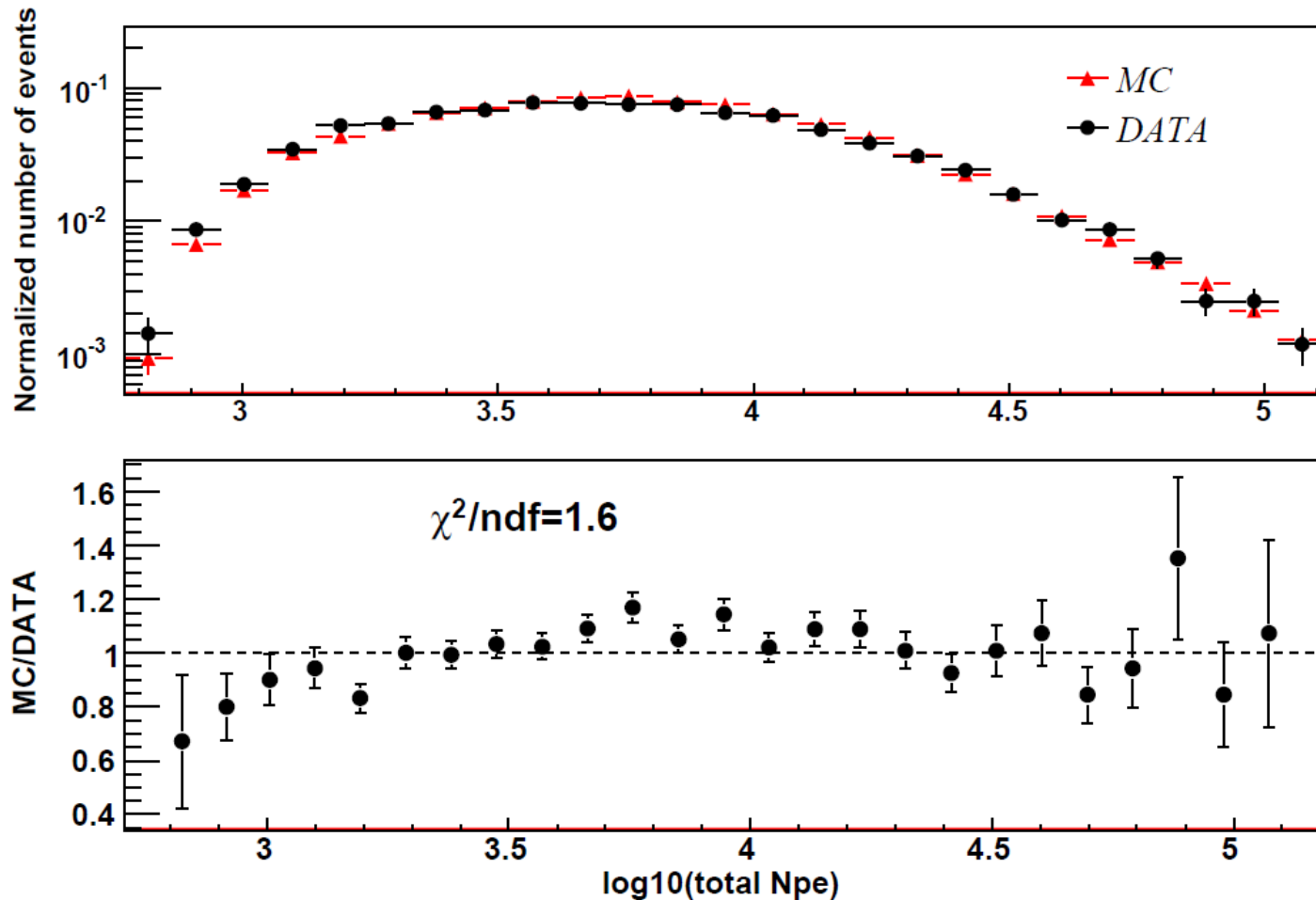
➤ Cherenkov image cleaning

- Single channel threshold: $S/N > 3.5$;
- Arrival time: all triggered pixel must be in a window of $\Delta t = 240$ ns;
- Isolated pixels must be rejected

8218 events are well reconstructed above 100 TeV

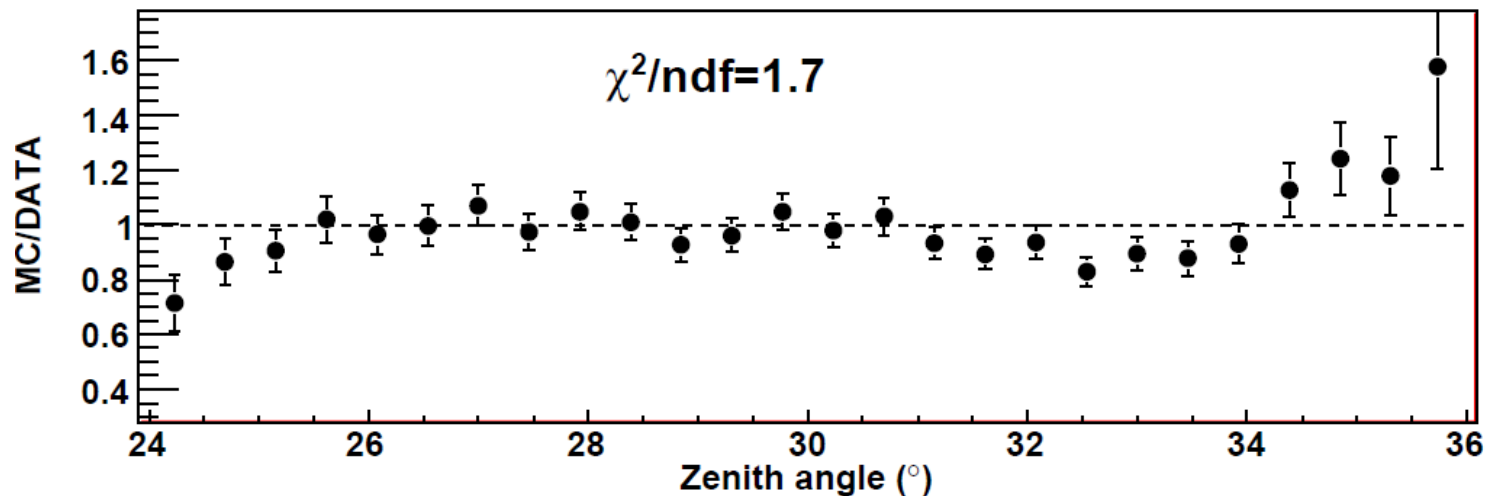
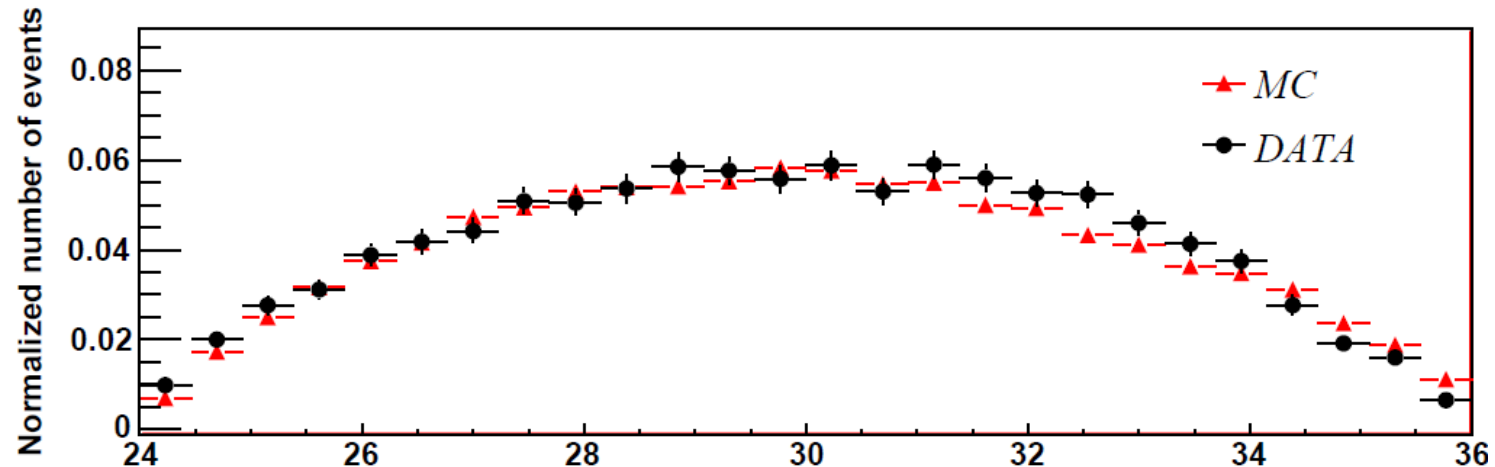
Comparison between Data and MC

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



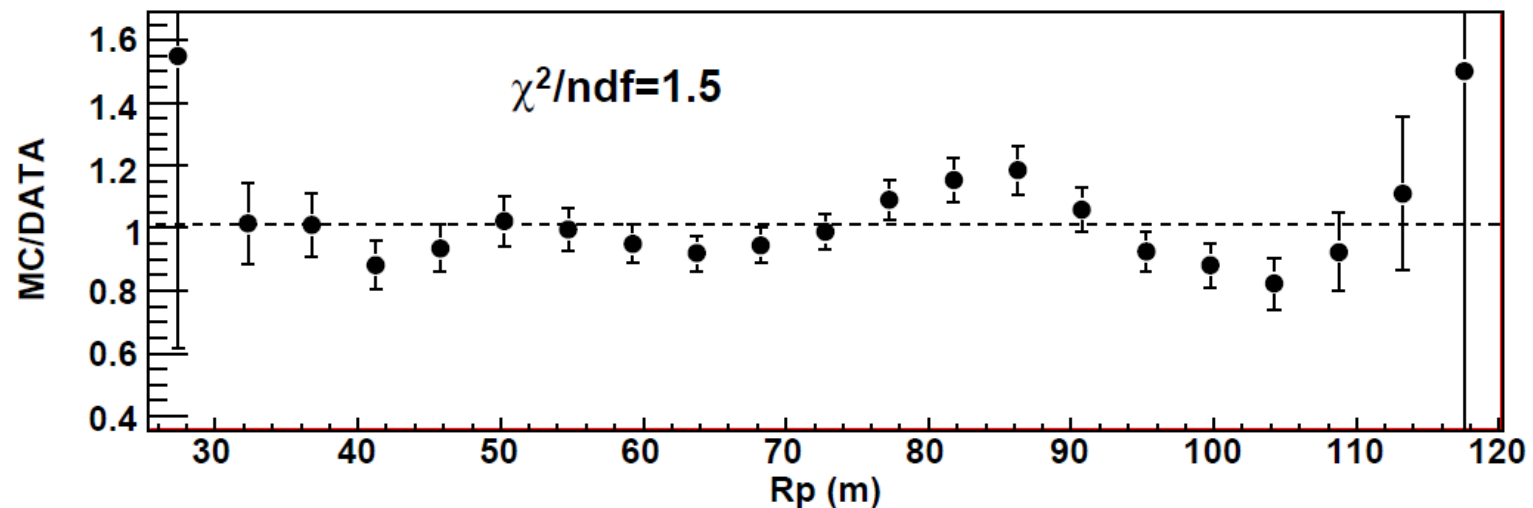
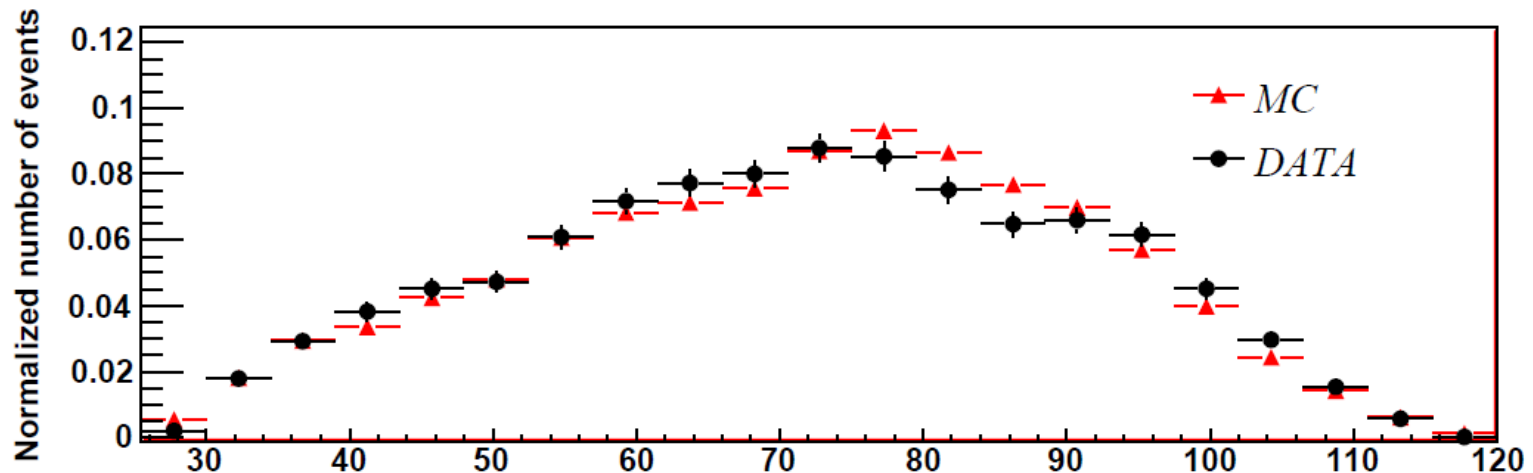
Comparison between Data and MC

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



Comparison between Data and MC

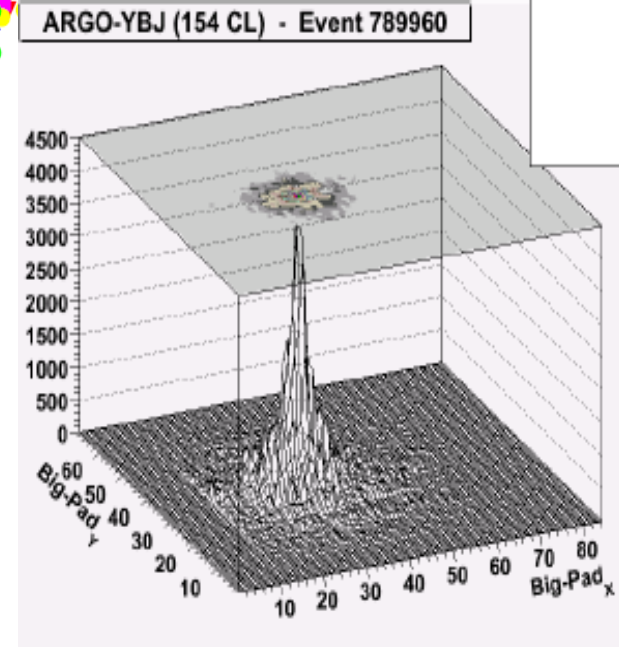
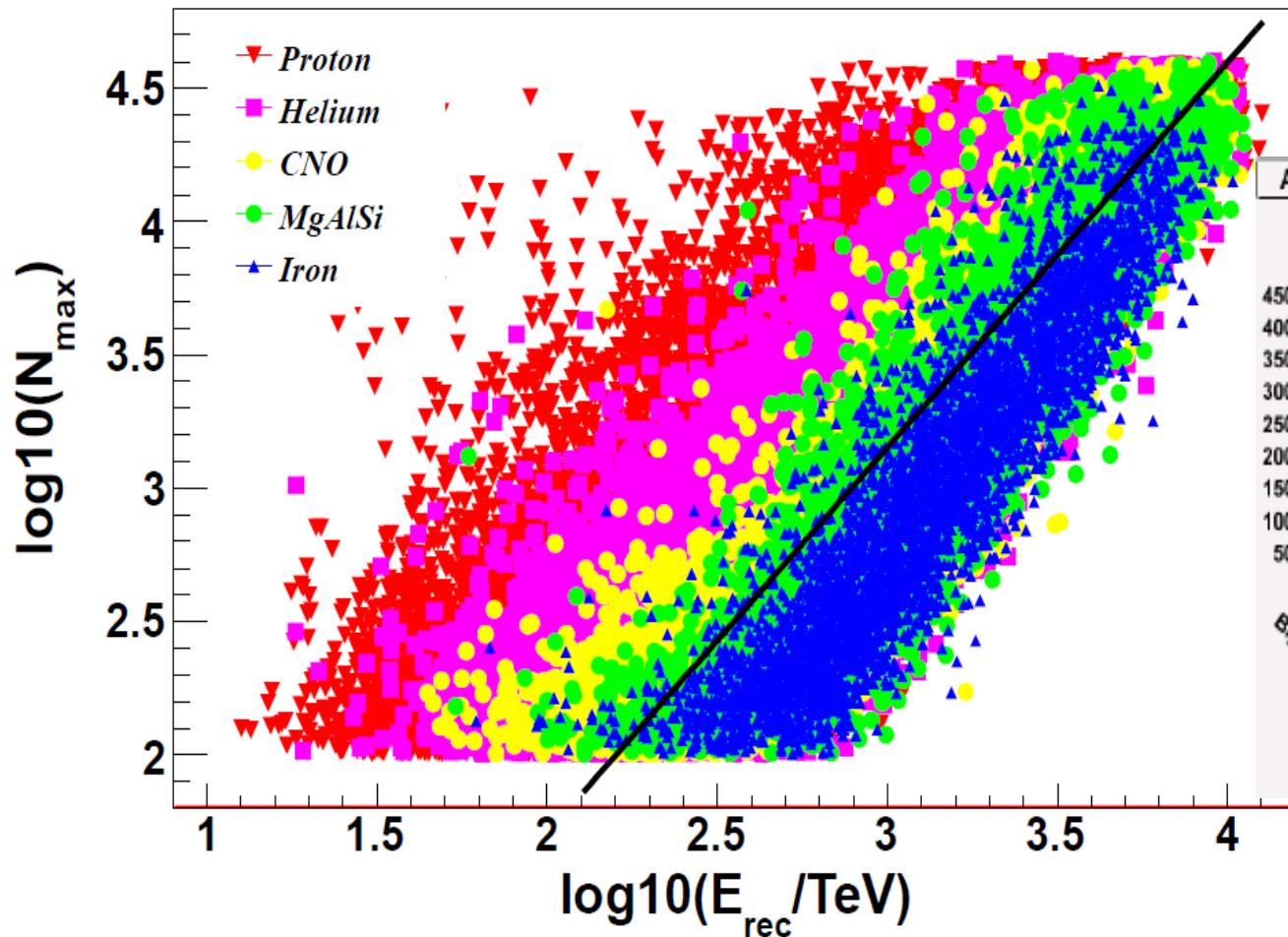
- The impact parameter of shower respect to the telescope
- The spatial resolution of the shower core position is 2 m



H&He Selection

- Most-hit-RPC at the core of a shower

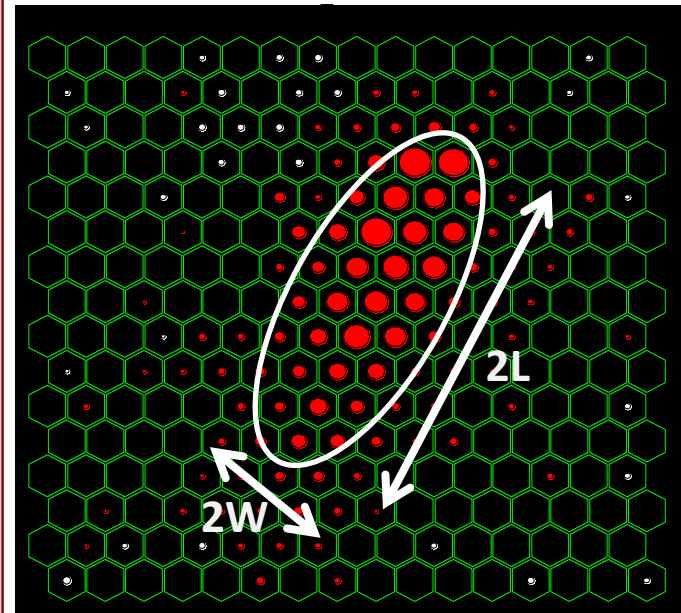
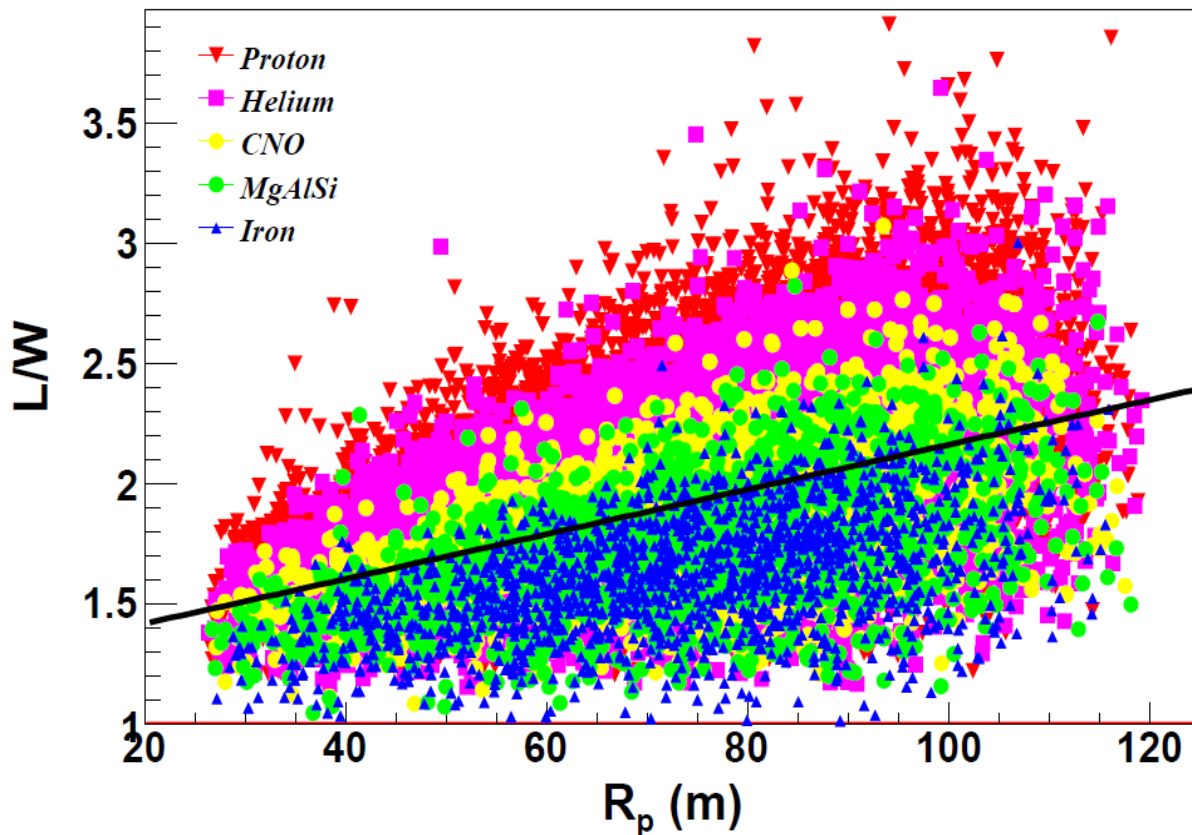
$$N_{\max} \sim 1.44 E_{\text{rec}}$$



H&He Selection

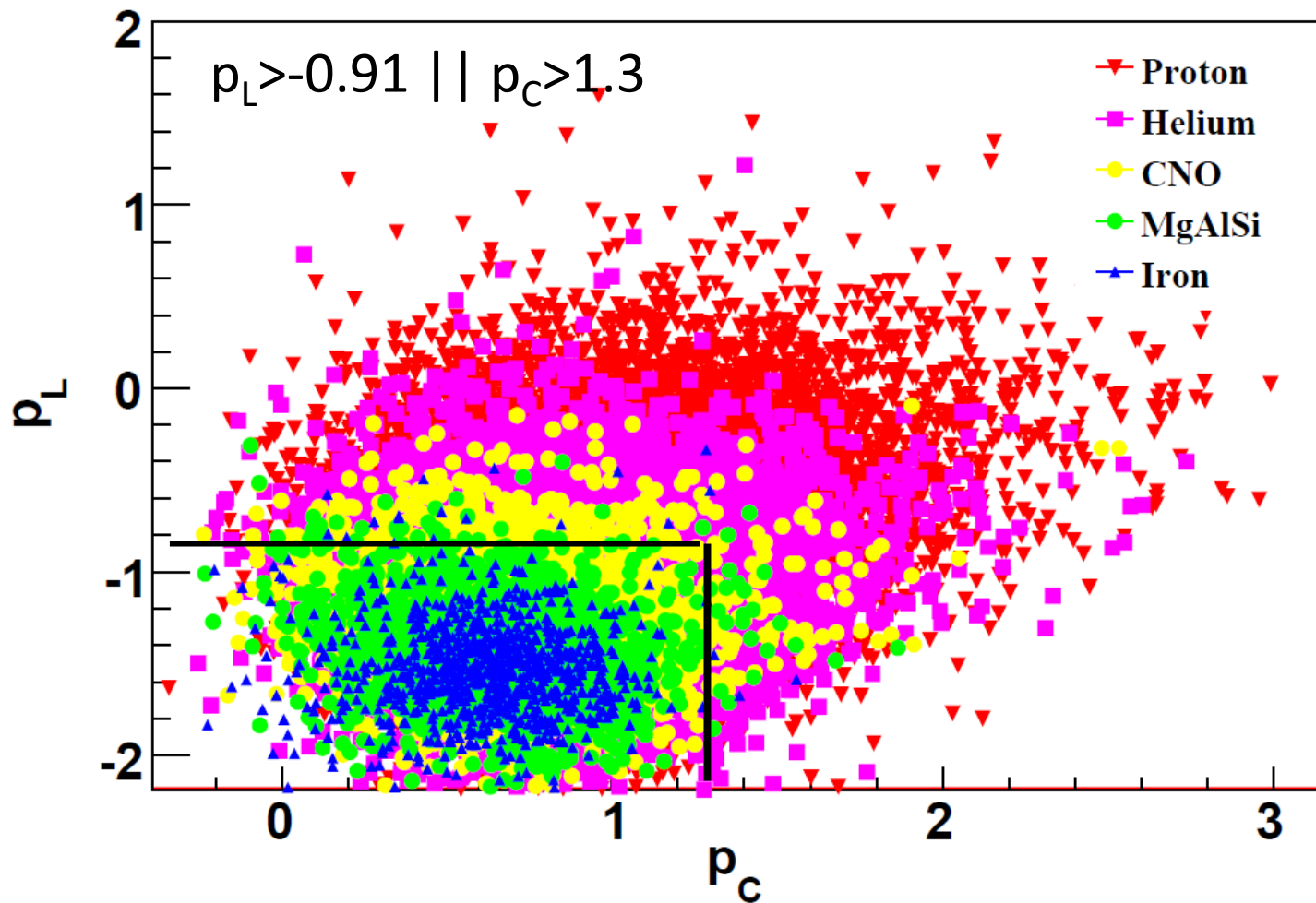
- Elongation of the shower image

$$L/W \sim 0.09(R_p/10\text{m})$$



Multi-parameter Analysis

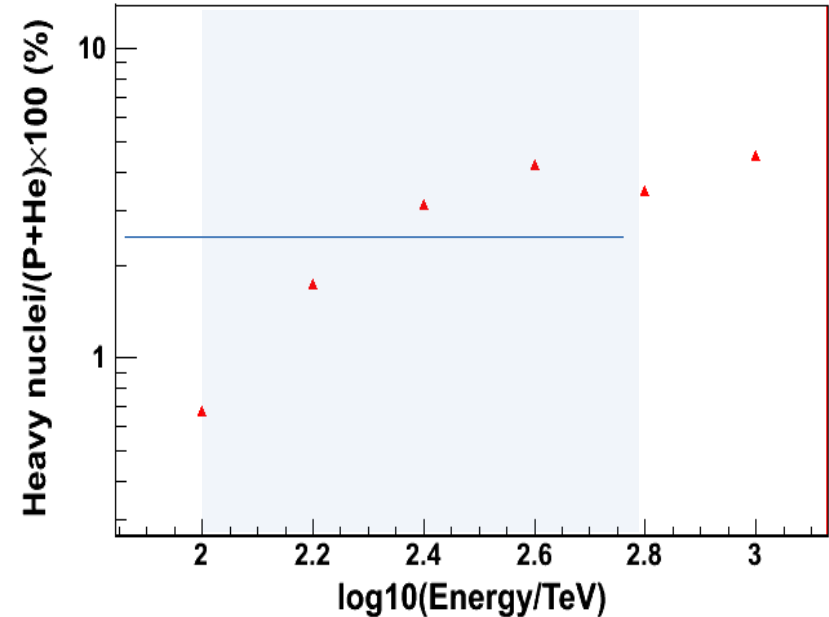
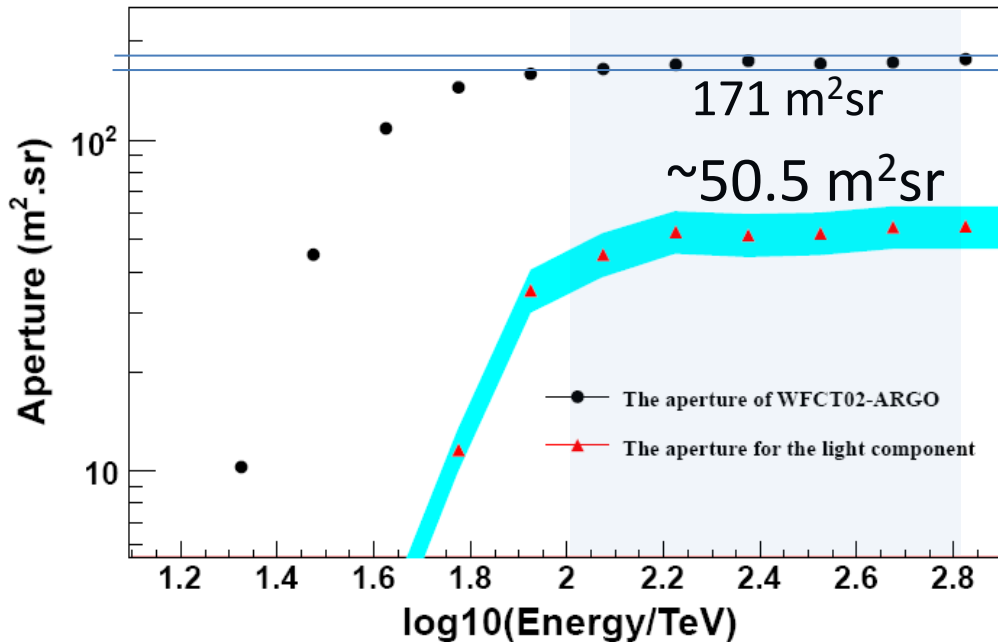
- $p_L = N_{\max} - 1.44 \log_{10}(E_{\text{rec}}/1\text{TeV})$
- $p_C = L/W - 0.091 \times (R_p/10m) - 0.14 \log_{10}(E_{\text{rec}}/1\text{TeV})$



Aperture and contamination

$$A=78 \times 68 \times \pi \times \sin^2 6^\circ = 181 \text{ m}^2 \text{sr}$$

$$\text{H:He}=1:0.39$$

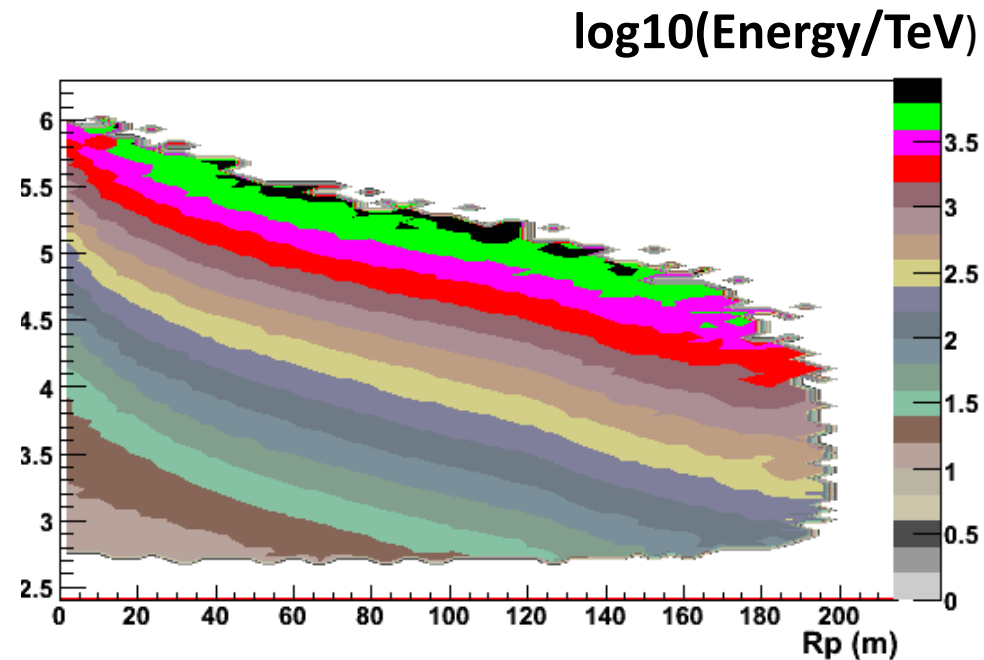
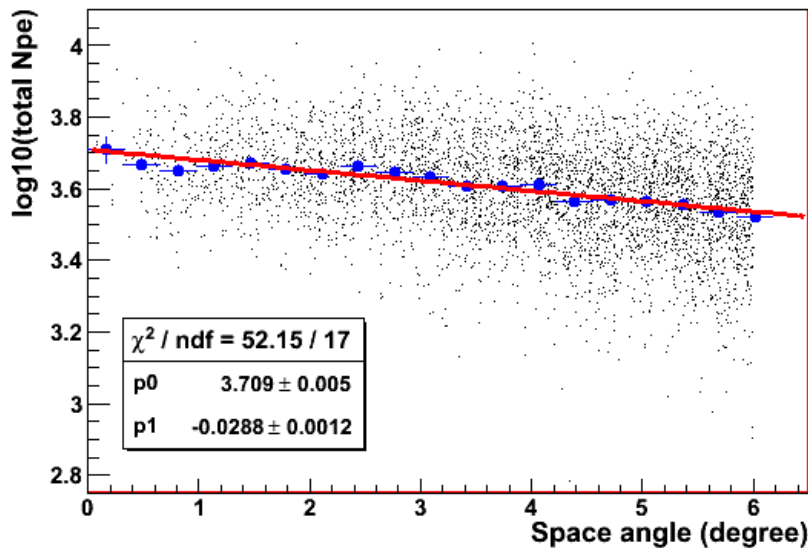
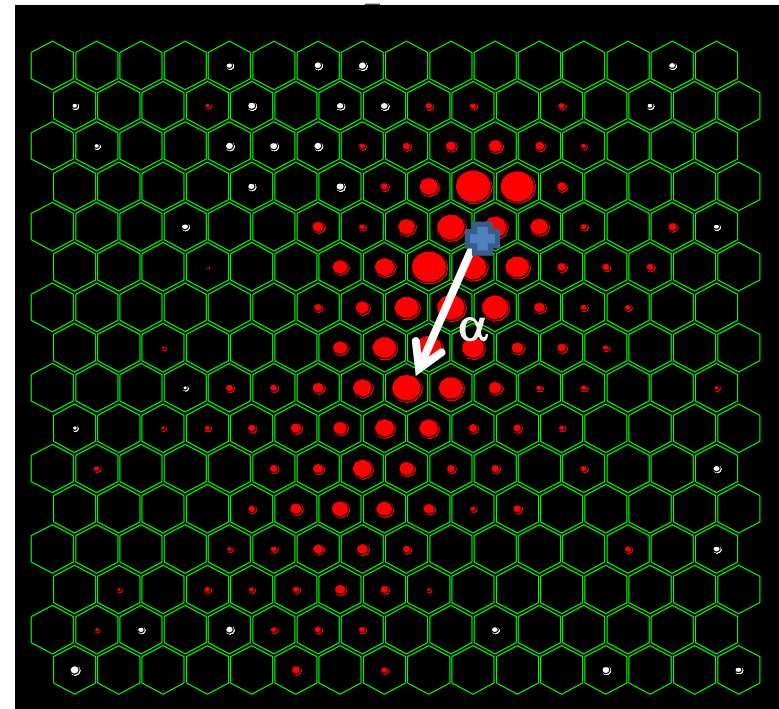


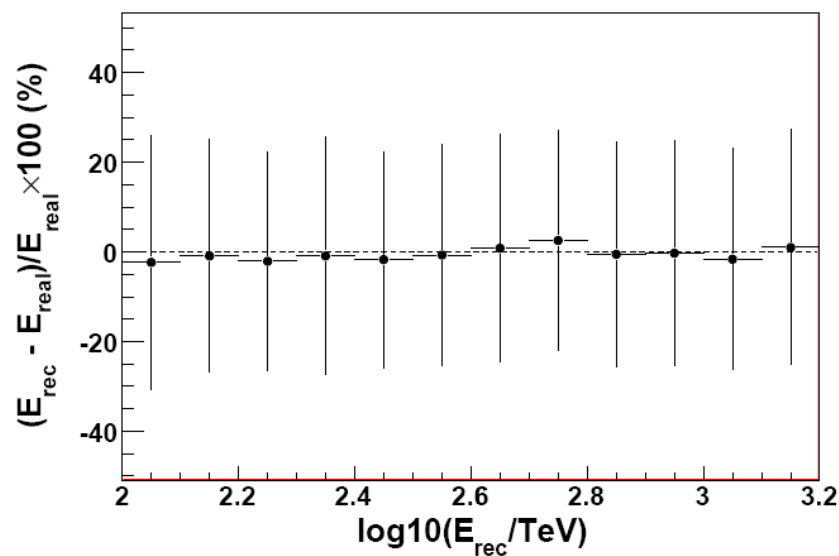
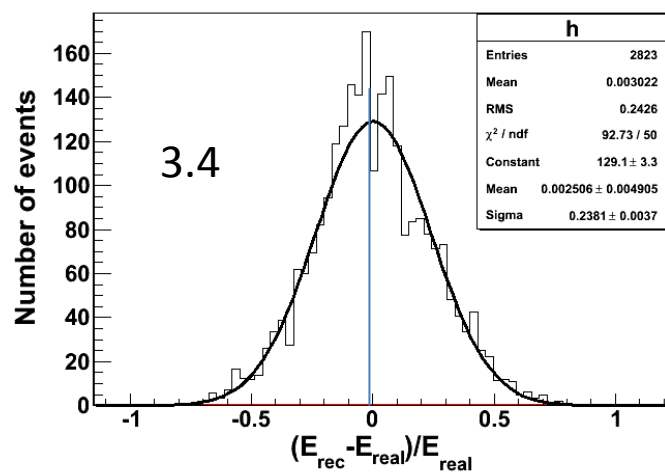
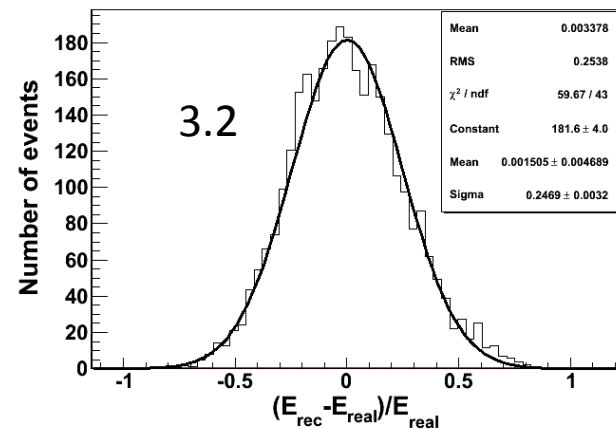
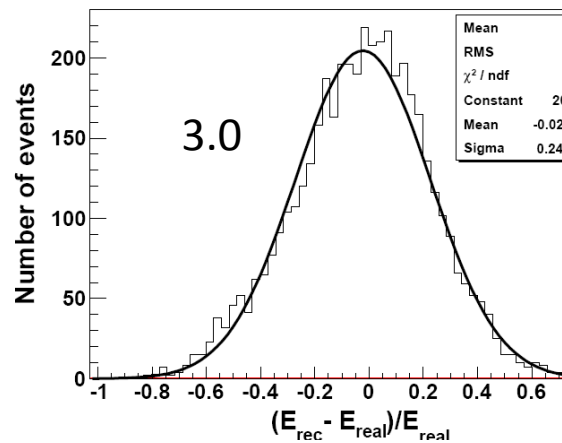
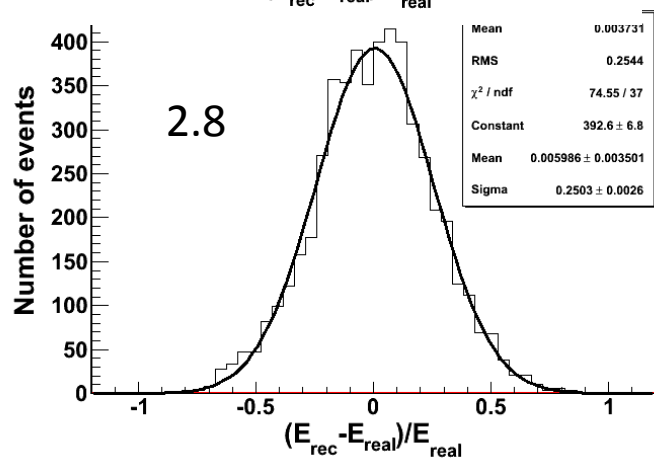
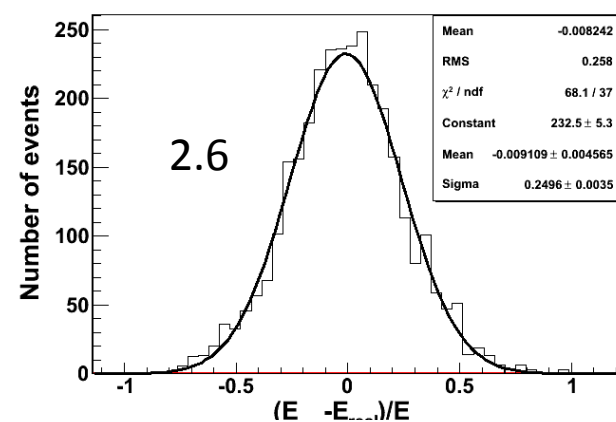
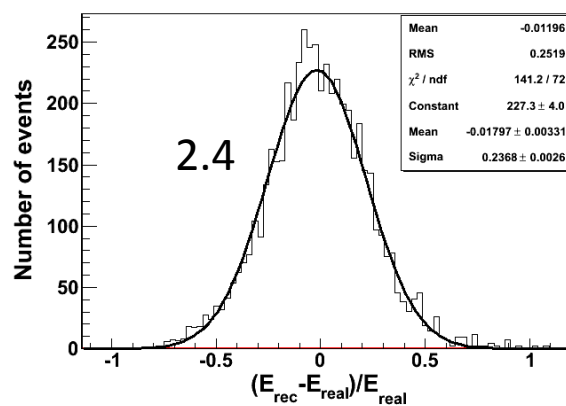
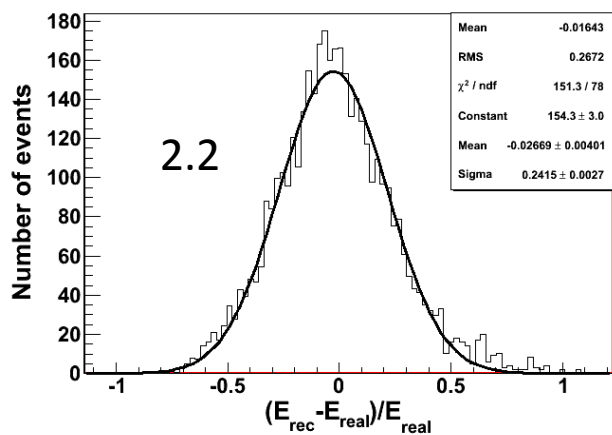
- The contamination of heavy nuclei is 2.3% below 700 TeV
- Selecting efficiency is $\sim 30\%$
- The ratio between H and He is 1:0.39

Energy reconstruction Using ΣN_{pe} in shower image

➤ Look-up table: light components only

- Impact parameter (R_p): 5m/bin
- $\text{Log}N_{pe}$: 0.1/bin
- R_p : linear interpolation between bins
- N_{pe} : Quadratic interpolation between bins





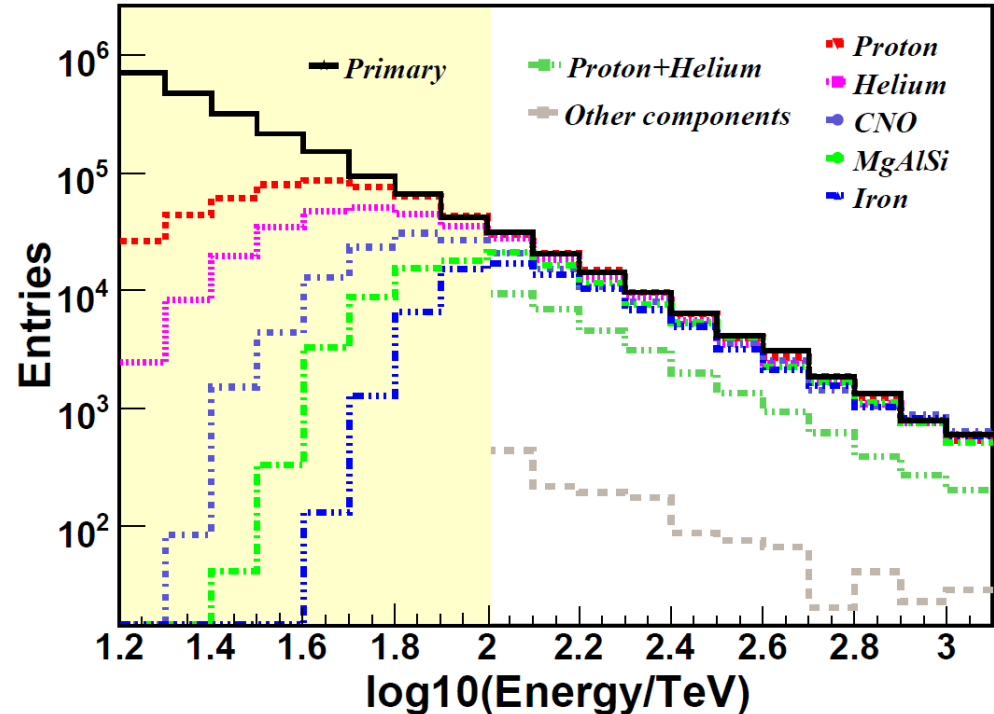
E-resolution:
~25%
constant with
energy
Bias: < 2%

Final H&He Data Set

827000 seconds good weather data,

$\log E_{min} - \log E_{max}$ (TeV)	2.00- 2.15	2.15- 2.30	2.30- 2.45	2.45- 2.60	2.60- 2.75	2.75- 2.90
# of events	565	371	227	121	69	39

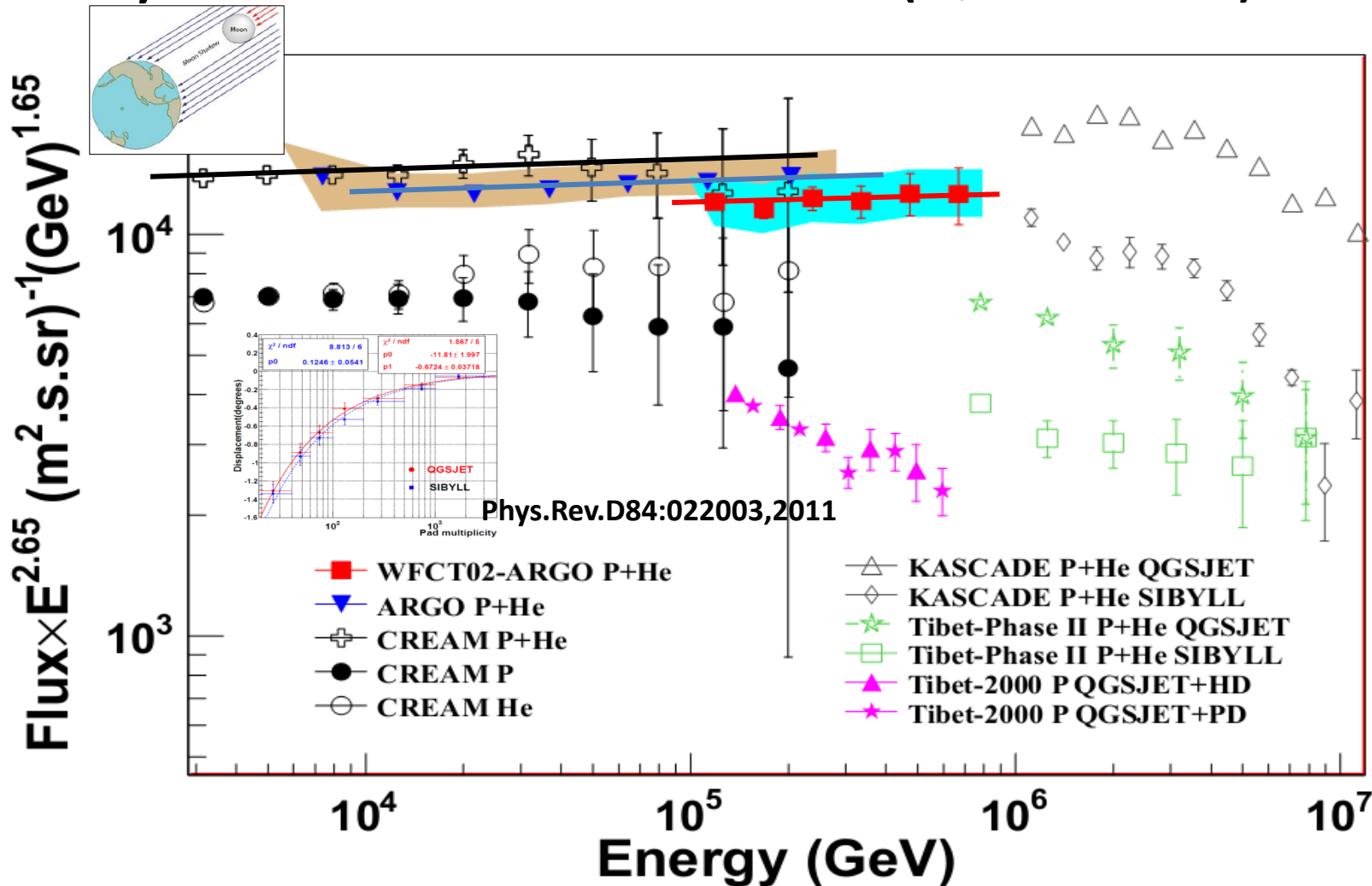
- The contamination of heavier nuclei is model dependent
 - 1:1:1:1:1, 5.1%
 - Horandel, 2.3%
 - H4A, <2%



CREAM: $1.09 \times 1.95 \times 10^{-11} (E/400 \text{ TeV})^{-2.62}$

ARGO-YBJ: $1.95 \times 10^{-11} (E/400 \text{ TeV})^{-2.61}$

Hybrid: $0.94 \times 1.95 \times 10^{-11} (E/400 \text{ TeV})^{-2.62}$

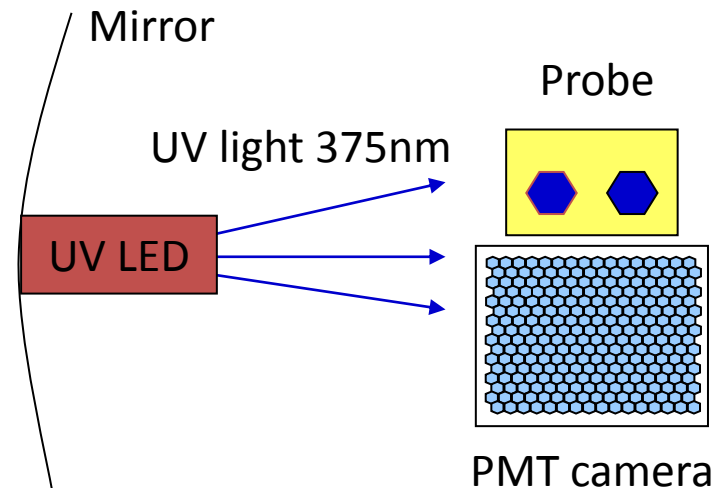
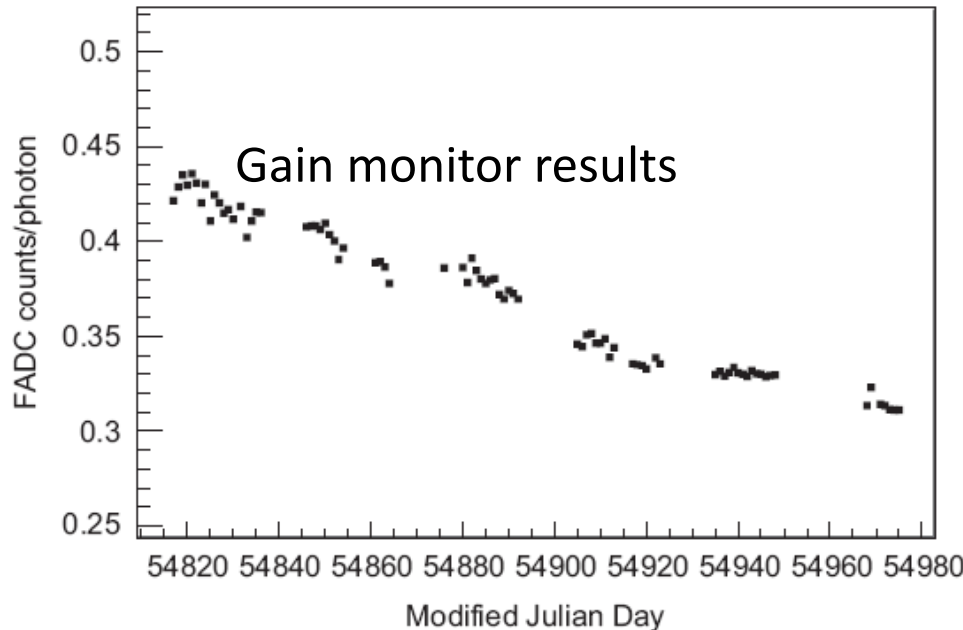
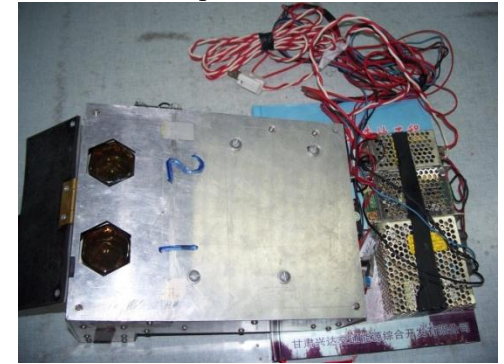


Photometric Calibration of the Cherenkov Telescopes

- A probe is calibrated by comparing with a HPD (calibrated by NIST) at the HiRes lab in Utah;
- An UV LED mounted at the center of the mirror is calibrated by the probe many times during the data taking;
- The PMT camera is calibrated by the UV LED every day.

➤ The systematic uncertainty of the calibration constant : $\sim 7\%$.

The probe



S.S. Zhang et al., Nucl. Instr. and Meth. A 629, 57 (2011)

Systematic Uncertainty (1)

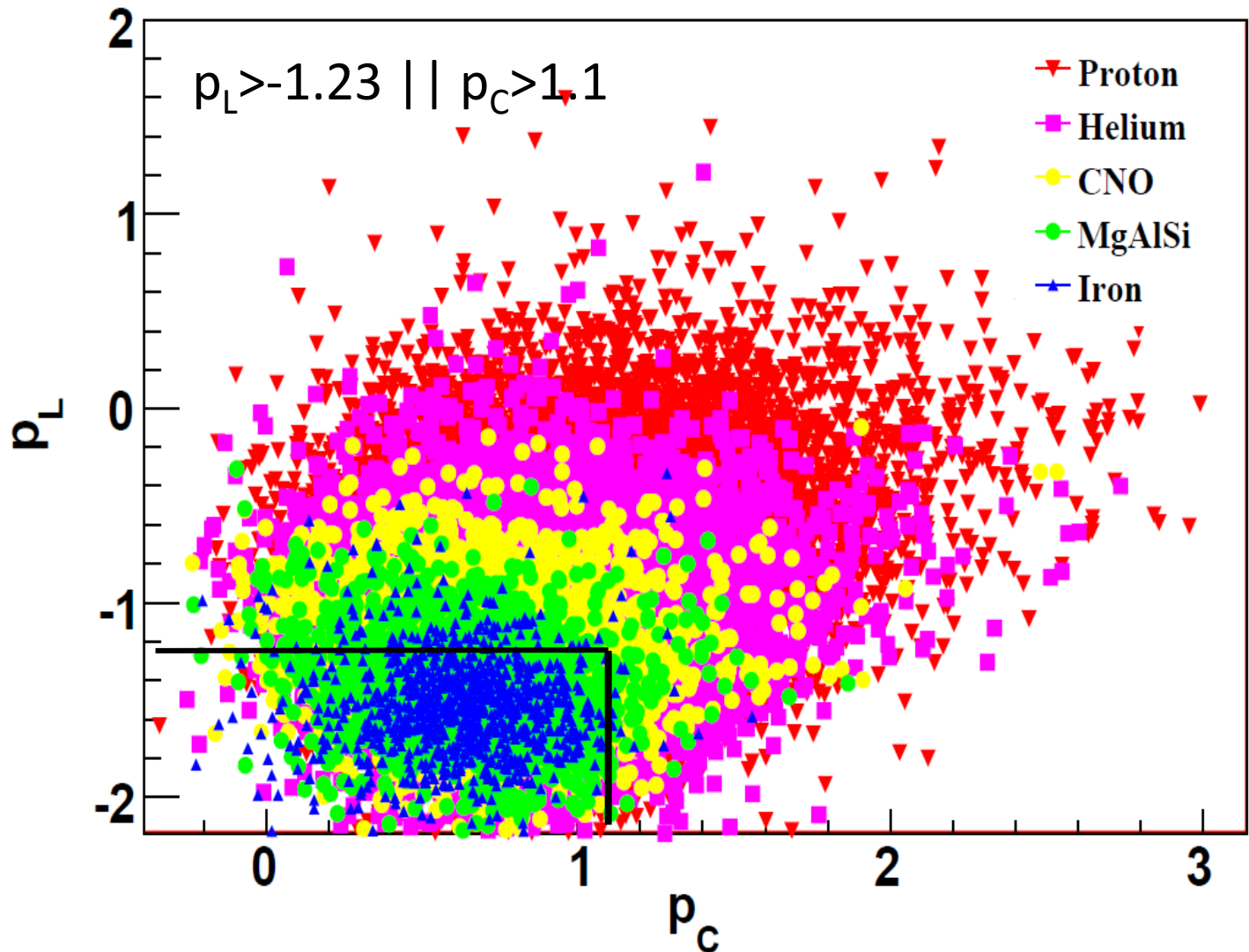
- **Energy determination uncertainty** **~9.7%**
 - Calibration 5.6%
 - Weather condition 7.6%
 - (include mirror reflectivity and
glass window transmission)
 - Method of energy reconstruction <1.2%
 - High energy hadronic interaction model <1.0%
(QGSJET II-03 vs. SIBYLL2.1)
 - Low energy hadronic interaction model <2.0%
(GHEISHA vs. FLUKA)

Systematic Uncertainty (2)

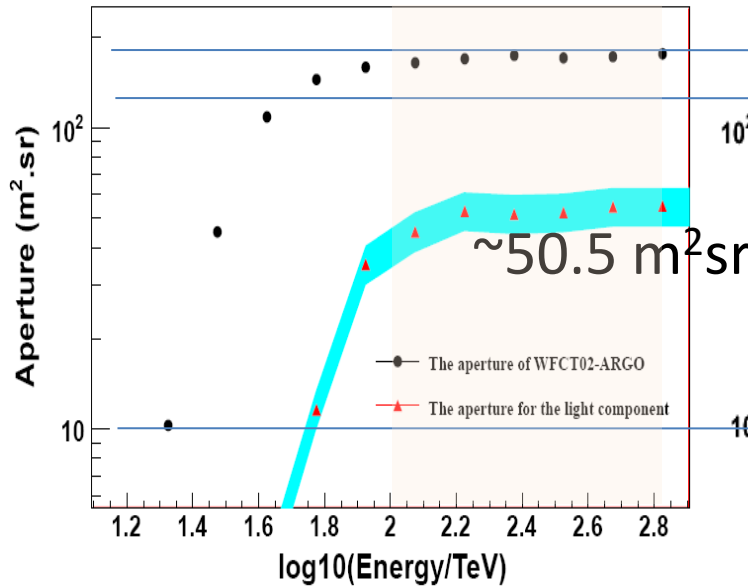
- **Selection efficiency uncertainty: 10.3 or 16.3%**
 - QGSJET II-03 vs. SIBYLL2.1 <1.0%
 - GHEISHA vs. FLUKA <3.5%
 - Reconstruction Quality Cuts <3.0%
 - Calib. of the analog read-out of RPC ~7.0%
 - The composition model by Horandel is compared with H4A by Gaisser or an extrapolation of CREAM data
 - The uncertainty due to composition model: ~ 6% on flux below 700 TeV. ~6.0%
 - If some extreme models are used, such as Proton dominant or Fe dominant, the uncertainty can be as large as 14% ~14.0%

Further Analysis:

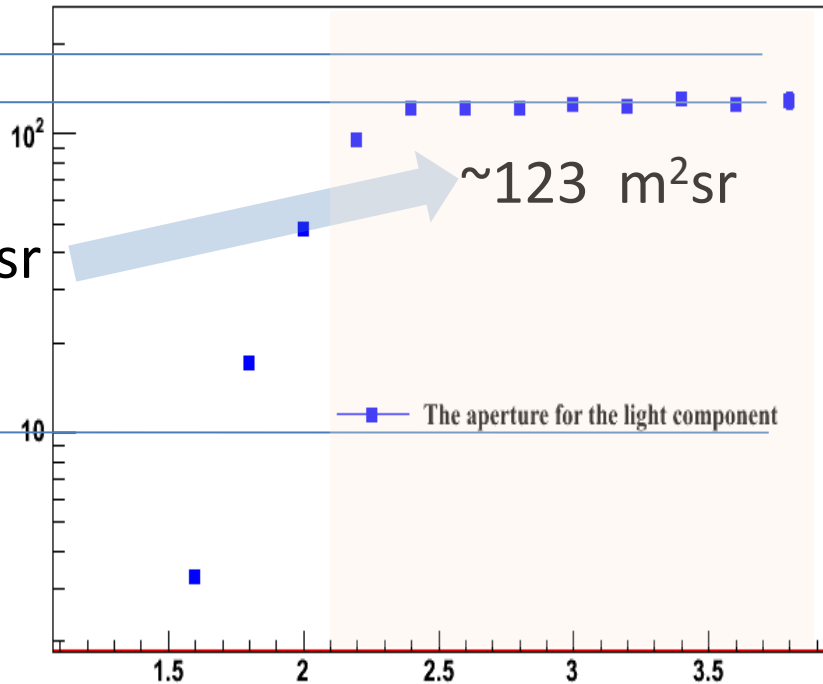
Optimizing for Statistics at High Energies



Surviving samples: H:He=1:0.39



H:He=1:0.8



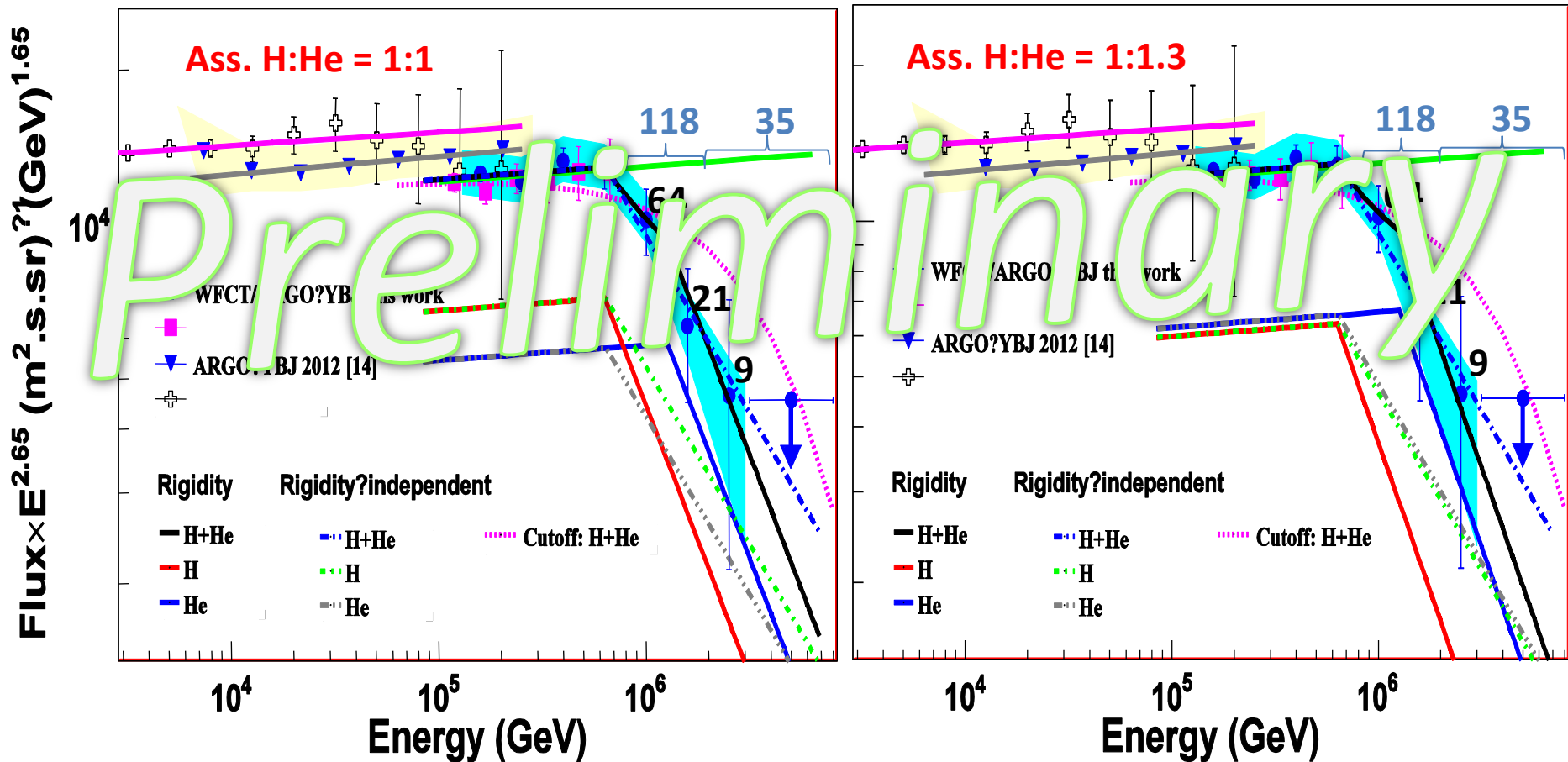
- **By loosening the criteria on H & He selection, the aperture is enlarged by a factor of 2.4, selecting efficiency $\sim 72\%$**
- **# of H & He events increases from 490 to 1231 above 200 TeV**
- **The contamination of heavy species increases from 2.3% to 7.2% below 700 TeV**
- **The ratio between H and He increases from 1:0.39 to 1:0.8**

Discover the “knee” of the Proton Spectrum below 1 PeV

~6 σ deviation from the single-index power law

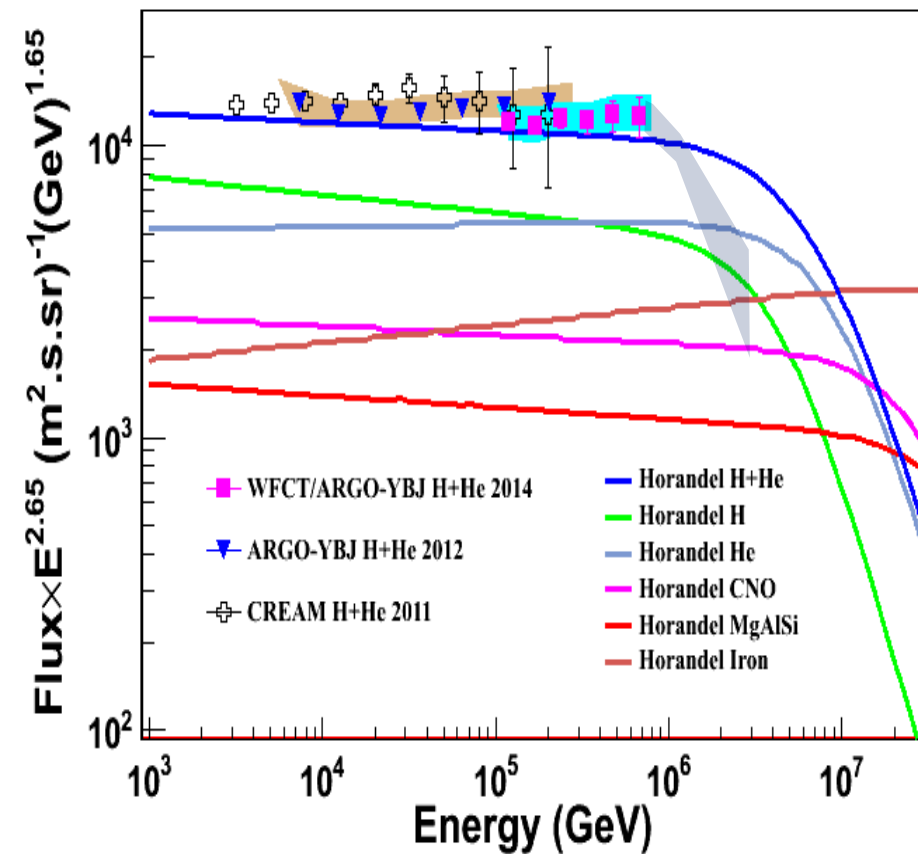
the knee is at (640 ± 87) TeV

spectral index is >3.3 above the knee

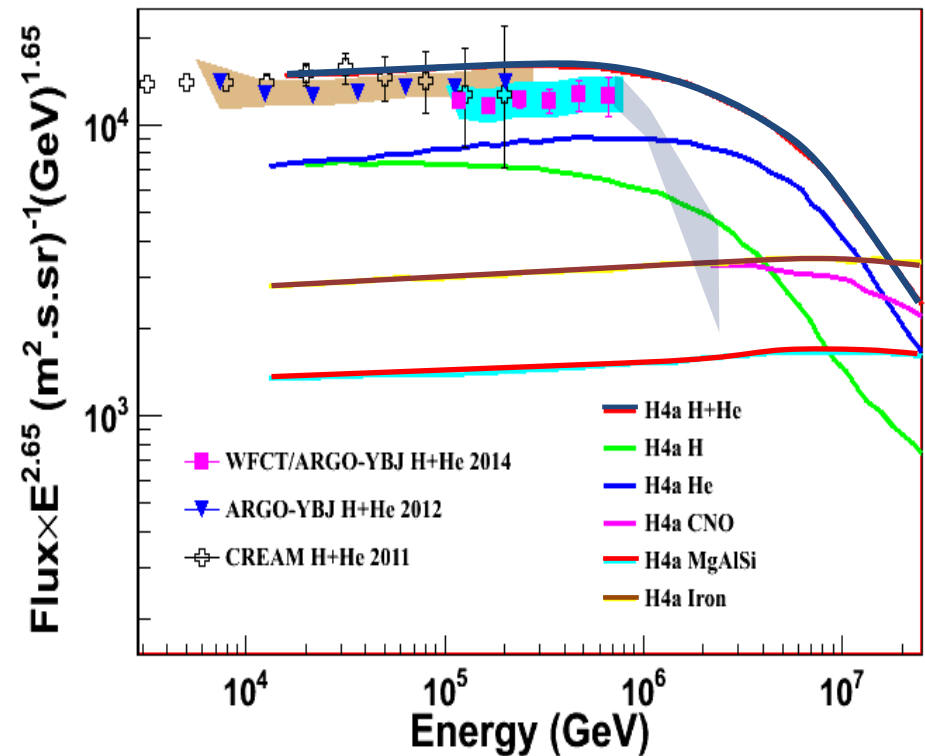


Most CR acceleration models have problems to produce the low energy knee of the proton spectrum!

- For instance, Horandel and H4A by Gaisser et. al



J.R. Horandel, APP, 21, 241 (2004)



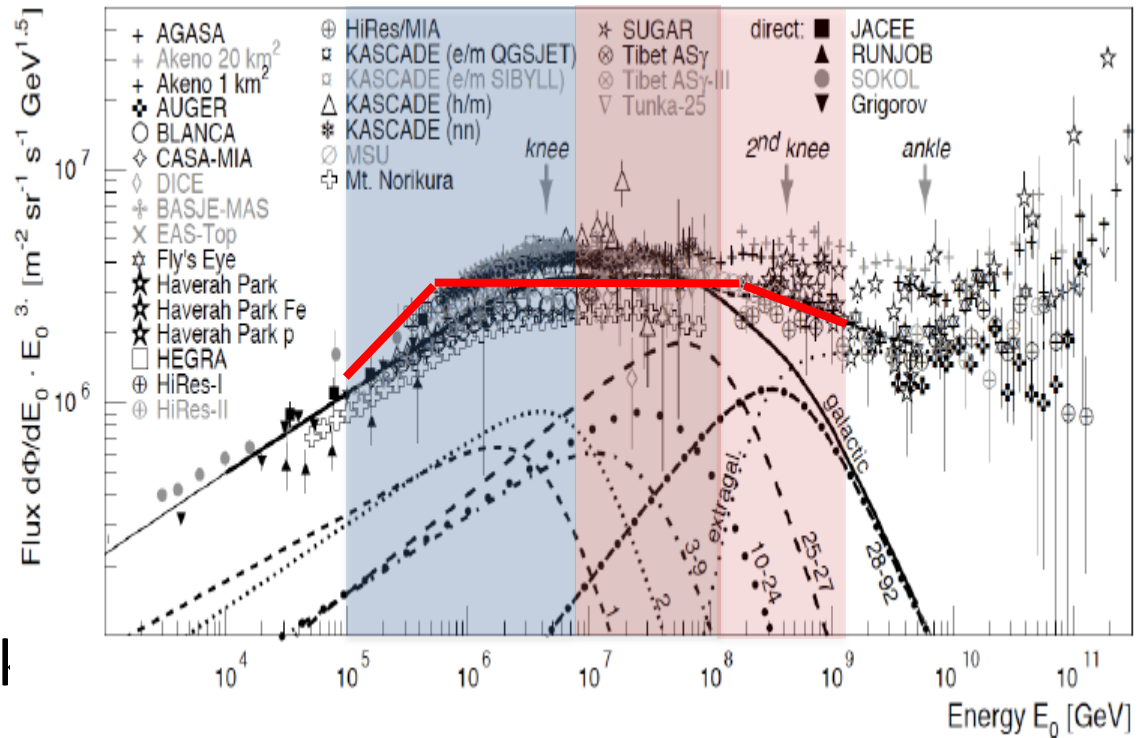
T.K. Gaisser et al., APP, 35, 801 (2012)

Summary

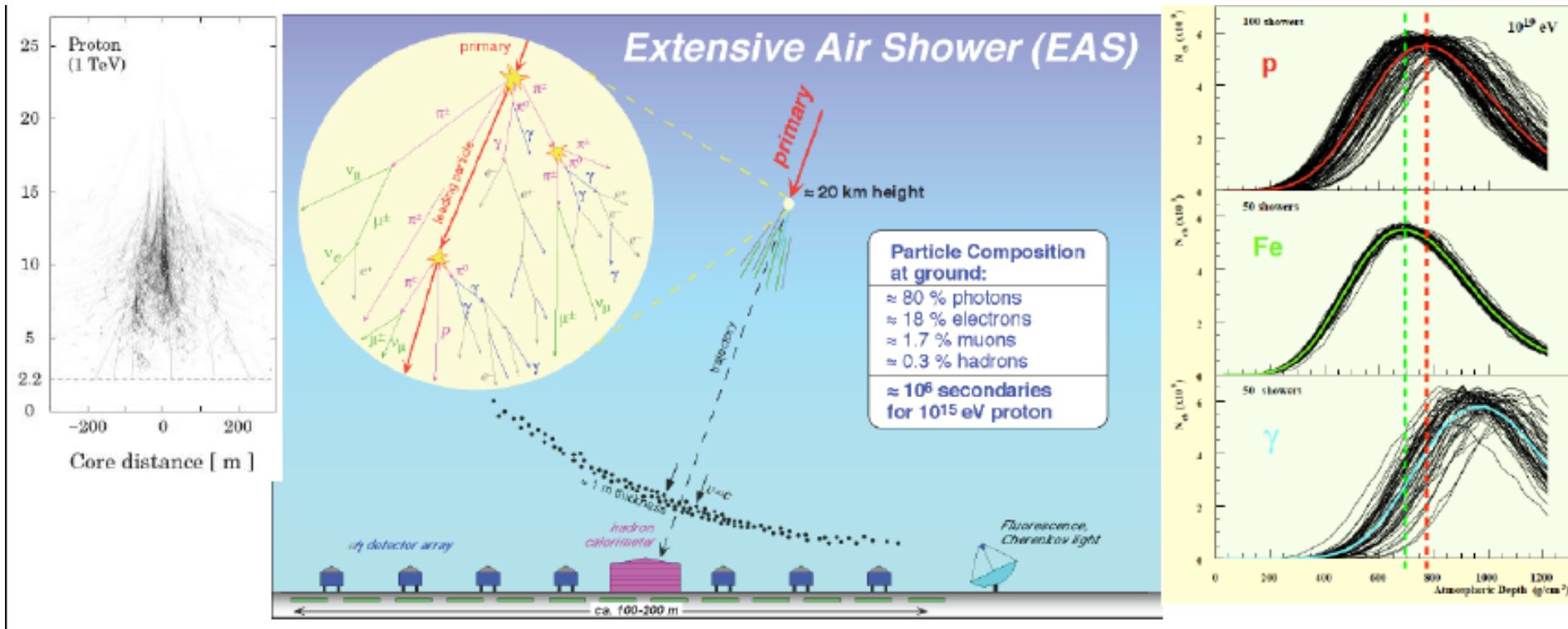
- From **2 TeV to ~700 TeV**, three measurements for the H&He spectrum by CREAM, ARGO-YBJ-digital and the Hybrid of ARGO-YBJ-analog and C-telescope agree well.
- They all fitted very well with single-index-power-law function form. The index is **2.62 ± 0.01** &
The flux is **$1.95 \times 10^{-11} \text{ } +9\% \text{ } -6\%$** ($\text{GeV}^{-1} \text{m}^{-2} \text{sr}^{-1} \text{s}^{-1}$) at 400 TeV
- The difference in flux can be interpreted due to a difference of **energy scale $\pm 3.5\%$** between experiments
- **The knee of the p-spectrum is discovered at $(640 \pm 87) \text{ TeV}$**
- **$\sim 6\sigma$ deviation from the single-index power law**
- **Spectral index is >3.3 above the knee**

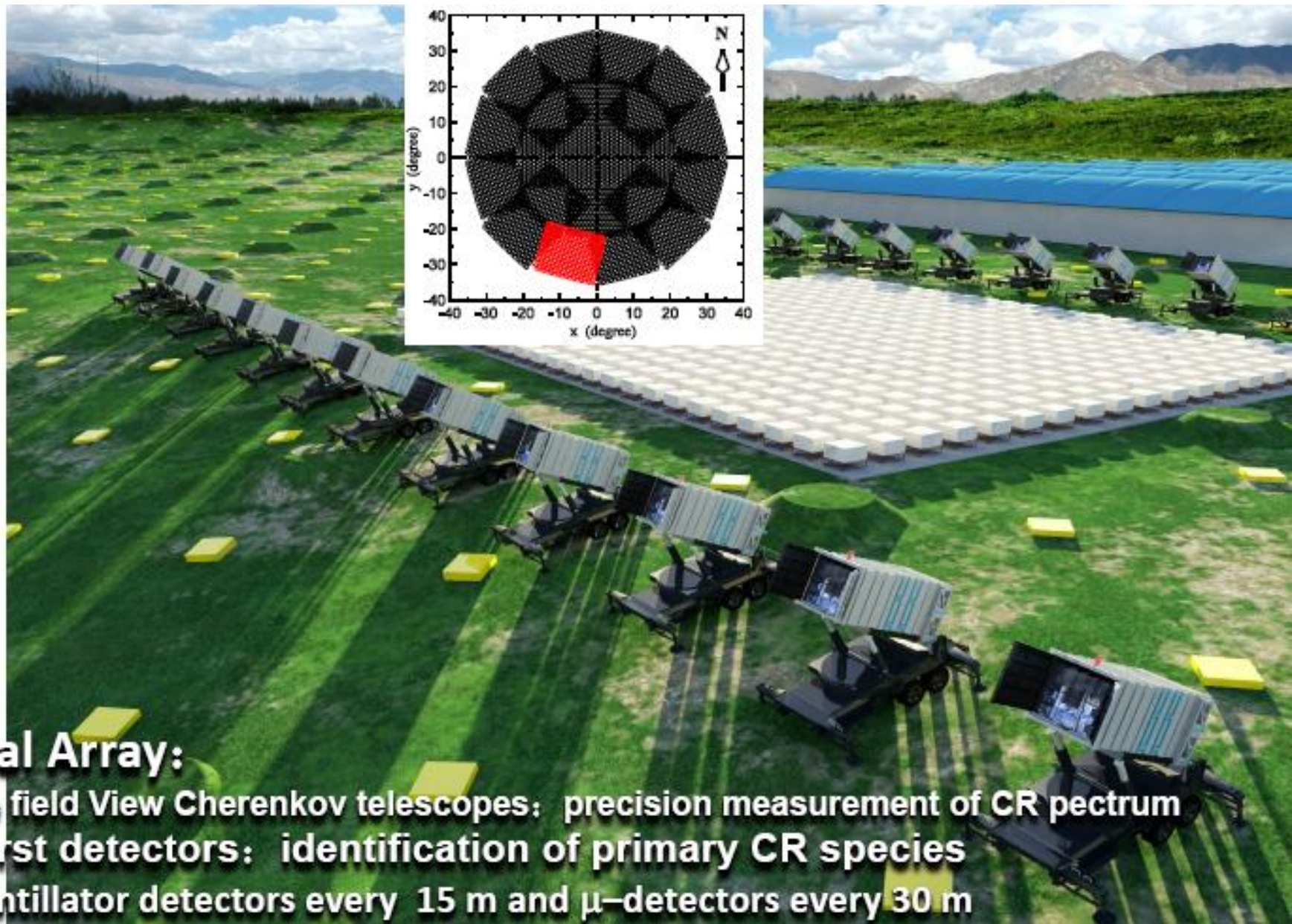
LHAASO: Prospects of CR Physics

- 30TeV-10PeV
 - Energy scale
 - Knees for H, He, \dots
 - Anisotropy
- 10PeV-100PeV
 - Composition
 - Energy spectrum: I
- 100PeV-2EeV
 - Spectrum bending and composition changing
 - Transition from galactic to extra-galactic



- The difficulty is to select individual species from air showers
- Event by event fluctuations and little recorded info
- **Solution: measuring more info about the showers**





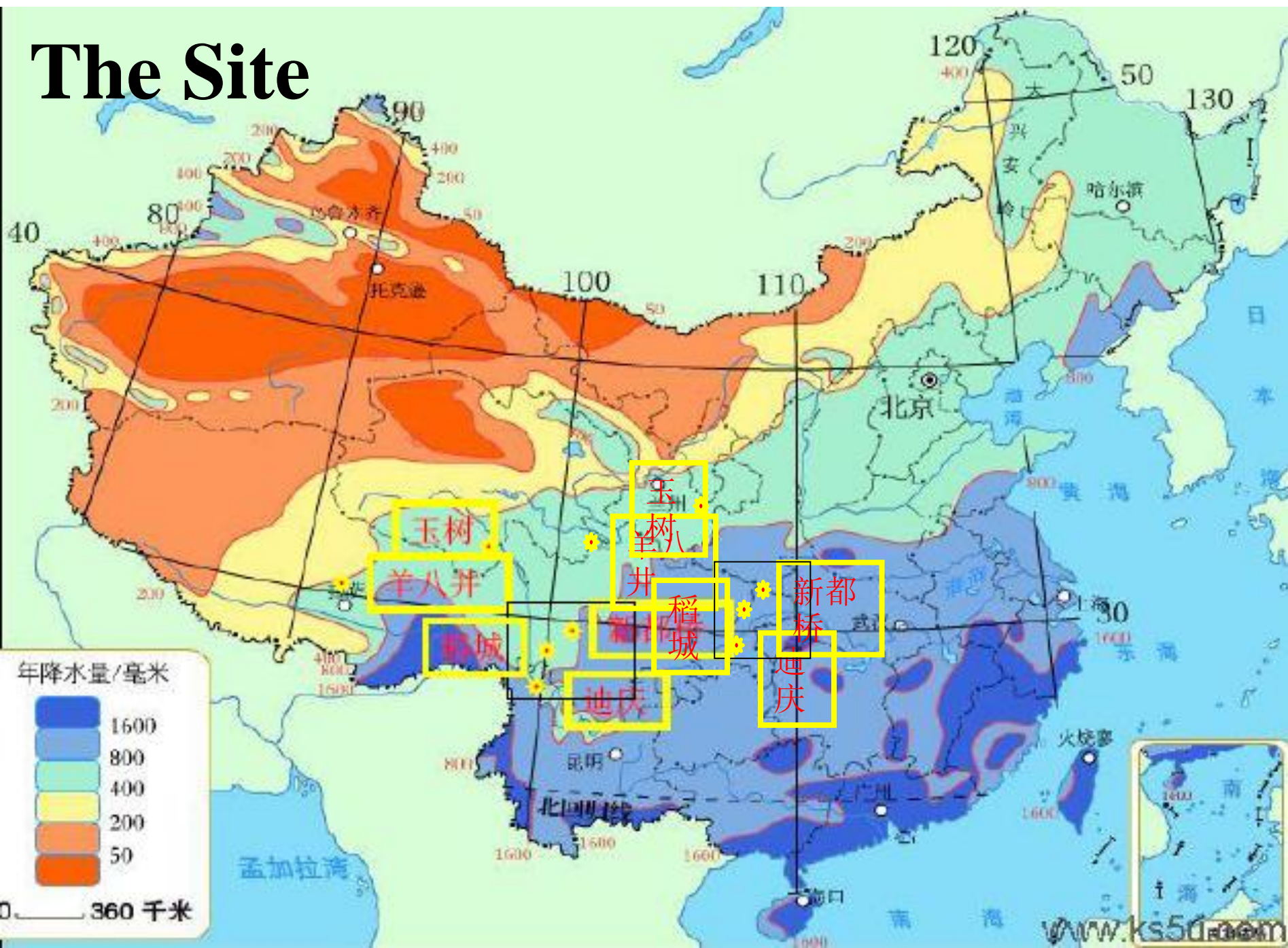
Central Array:

24 Wide field View Cherenkov telescopes: precision measurement of CR pectrum

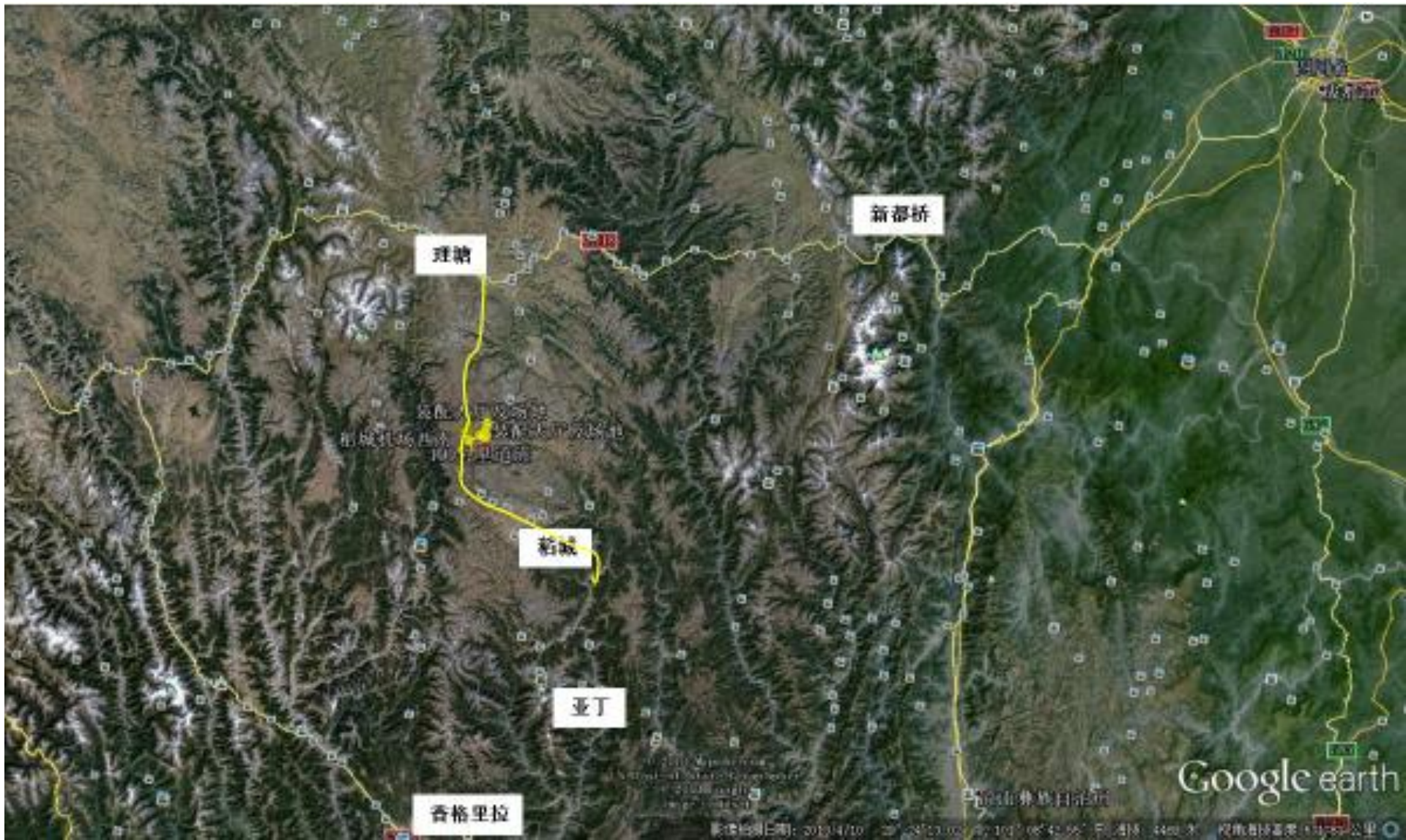
452 burst detectors: identification of primary CR species

Plus scintillator detectors every 15 m and μ -detectors every 30 m

The Site



地理位置：S217穿过海子山自然保护区中间地带
北纬29°21'30.7"，东经100°08'14.65"
海拔4400米



理塘 (3950m) 90公里

兴伊措
4426m

装备大厅及场地
装备大厅及场地
装备大厅及场地

稻城亚丁机场
4410m



~10公里



稻城 (3740m) 40公里

稻城海子山LHAASO站址

google earth

最后拍摄日期: 2020/05/28 10:03:30 东: 102.404 米 视向海拔高度: 10.00 公里



100公里道班北

450m

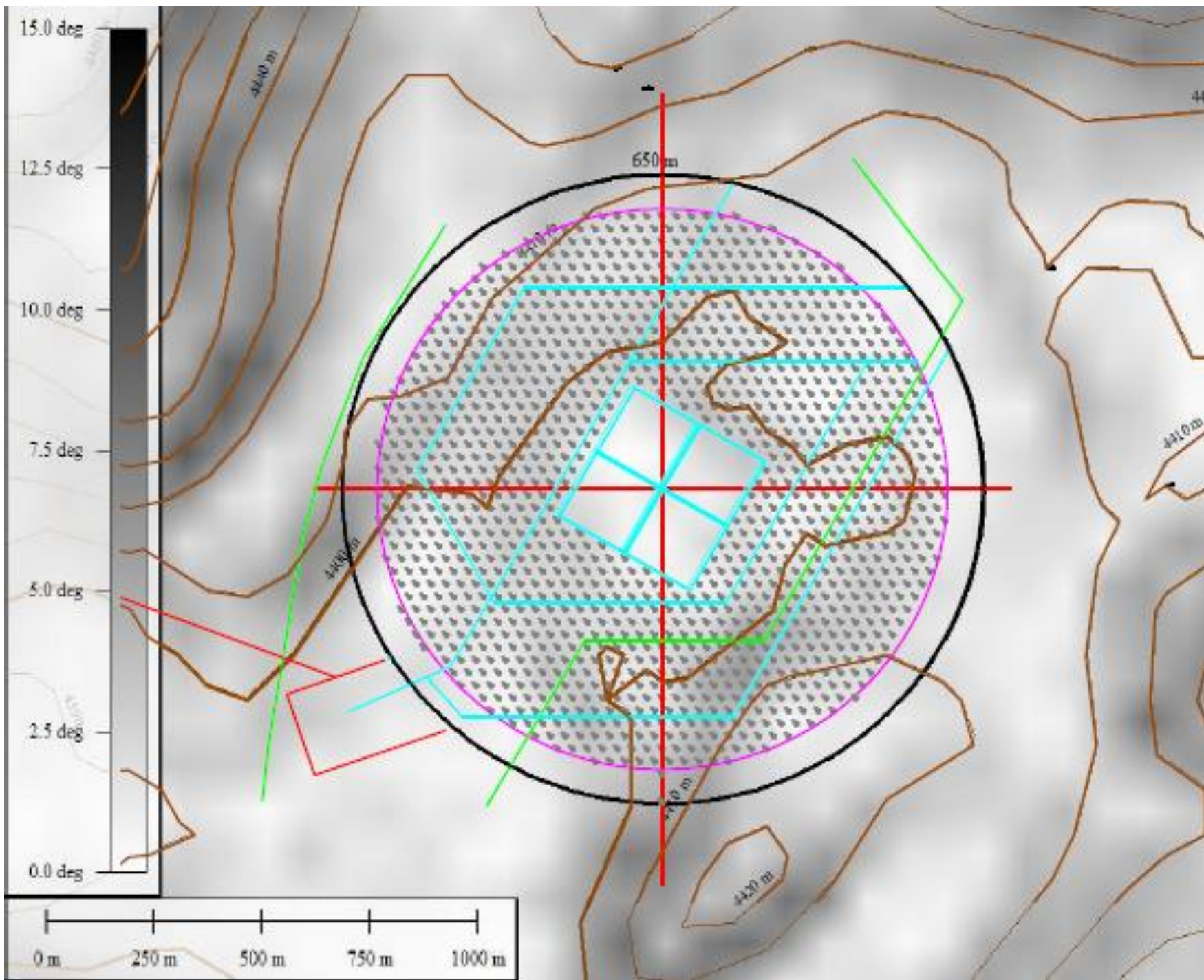
500米

© 2013 Mapabc.com

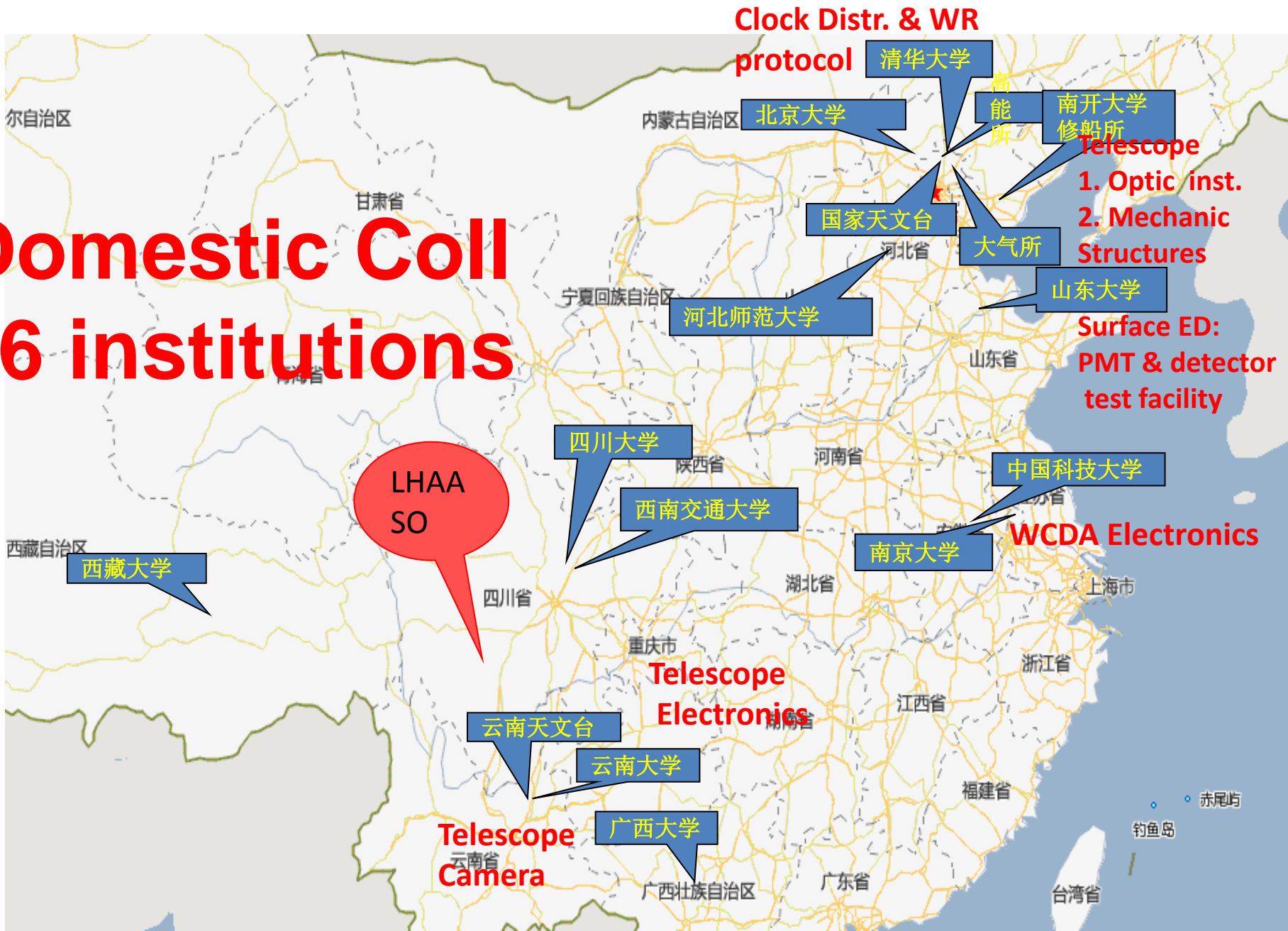
Image © 2013 DigitalGlobe

2012

影像拍摄日期: 2012/12/15 29° 21' 32.71" 北 100° 08' 20.85" 东 海拔 4405 米



Domestic Coll 16 institutions



International Collaboration

- **Physicists (IPN-Orsay)**
 - **Yingtao Chen (PhD student funded by CSC)**, Olivier Deligny, Isabelle Lhenry-Yvon, Tiina Suomijärvi, Francesco Salamida (post-doc)
 - New PhD student, Zizhao Zong, currently applying funds from CSC
- **Technical group**
 - Valérie Chambert, Bengyun Ky, Emmanuel Raully, Thi Nguyen Trung, Eric Wanlin (IPN-Orsay)
 - Gisèle Martin-Chassard, Frederic Dulucq, Christophe de la Taille (OMEGA)
- CAS Project for the China-France collaboration is approved (1.1 M CNY) this year
- **Proposing with Italian colleagues: G-astro, GRBs,DM,CRs (submitting to INFN)**
- Working group with Russian for neutron detectors
- Thailand solar CR group (working together)



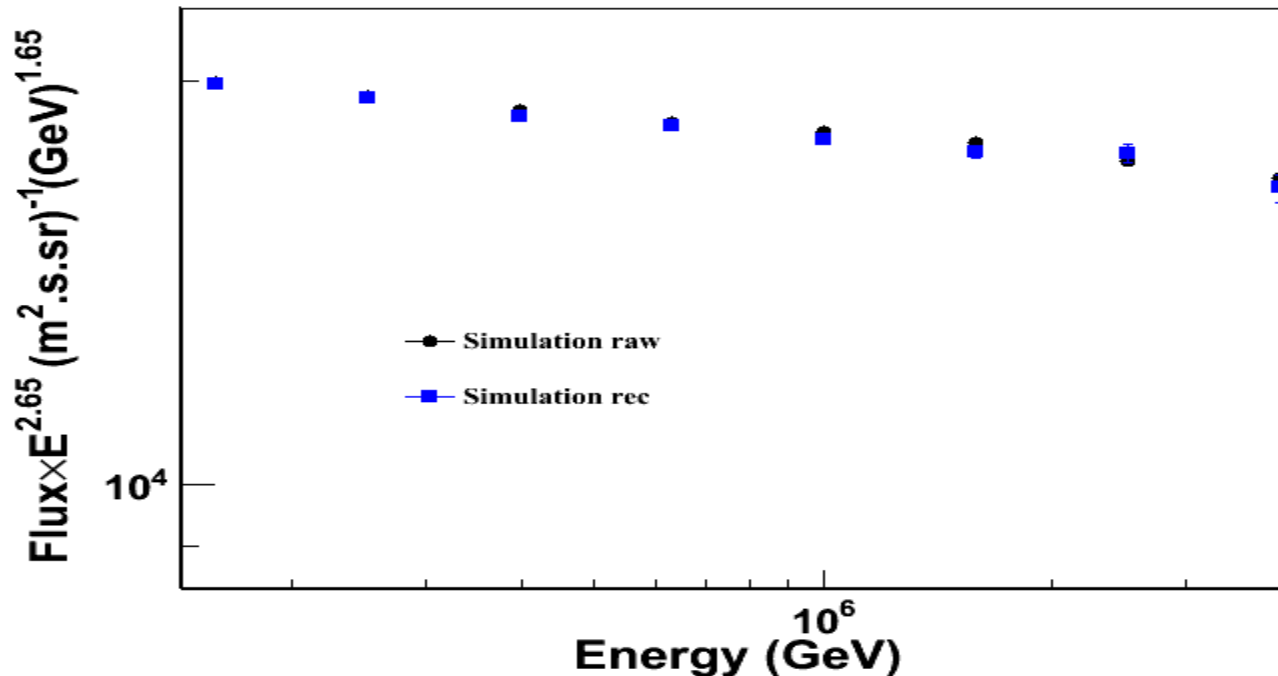
Conclusions

- LHAASO observatory
 - Provides also crucial CR data in the region of knees
- LHAASO has been selected for funding in China.
- Agreement with Sichuan province for site is scheduled to be signed on June 5th
- Domestic collaboration: for 25 sub-systems
- International Coll. is growing

Thanks for your attention!

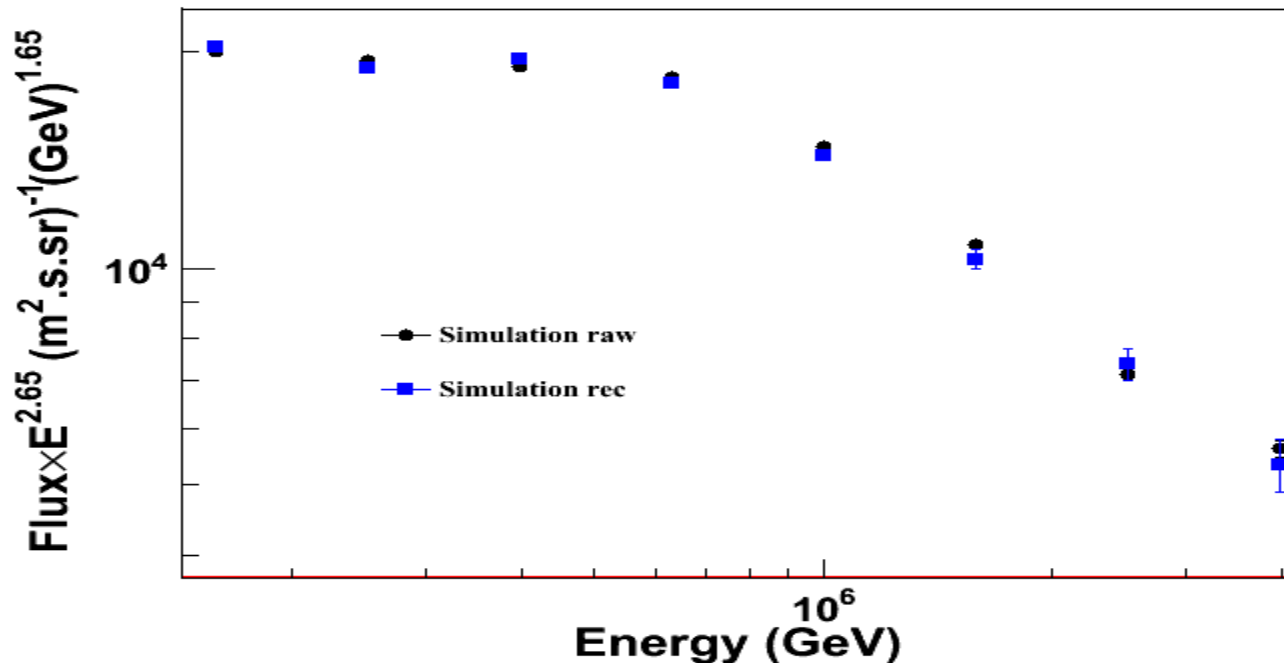
Generated H&He spectrum and its reconstruction

- Ivan required test on the generated H&He spectrum.
- Events are generated with a single-index-power-law ($\gamma=-2.7$) as represented by black dots. Spread over an area of 260mX260m, $22^\circ \times 21^\circ$ in the sky near $\theta=30^\circ$
- Corsika generates showers, G4ARGO generates RPC signals and ray-tracing procedure generates telescope images.
- Reconstruct and analyze them as what has been done on data. The “measured” spectrum is represented by the blue squares.



Generated H&He spectrum and its reconstruction

- Beyond Ivan required test on the generated H&He spectrum with bending.
- Events are generated with a double-index-power-law ($\gamma=-2.7/3.4$, $E_k=700\text{TeV}$) as represented by black dots. Spread over an area of $260\text{m}\times 260\text{m}$, $22^\circ\times 21^\circ$ in the sky near $\theta=30^\circ$
- Corsika generates showers, G4ARGO generates RPC signals and ray-tracing procedure generates telescope images.
- Reconstruct and analyze them as what has been done on data. The “measured” spectrum is represented by the blue squares.



Bayesian Unfolding

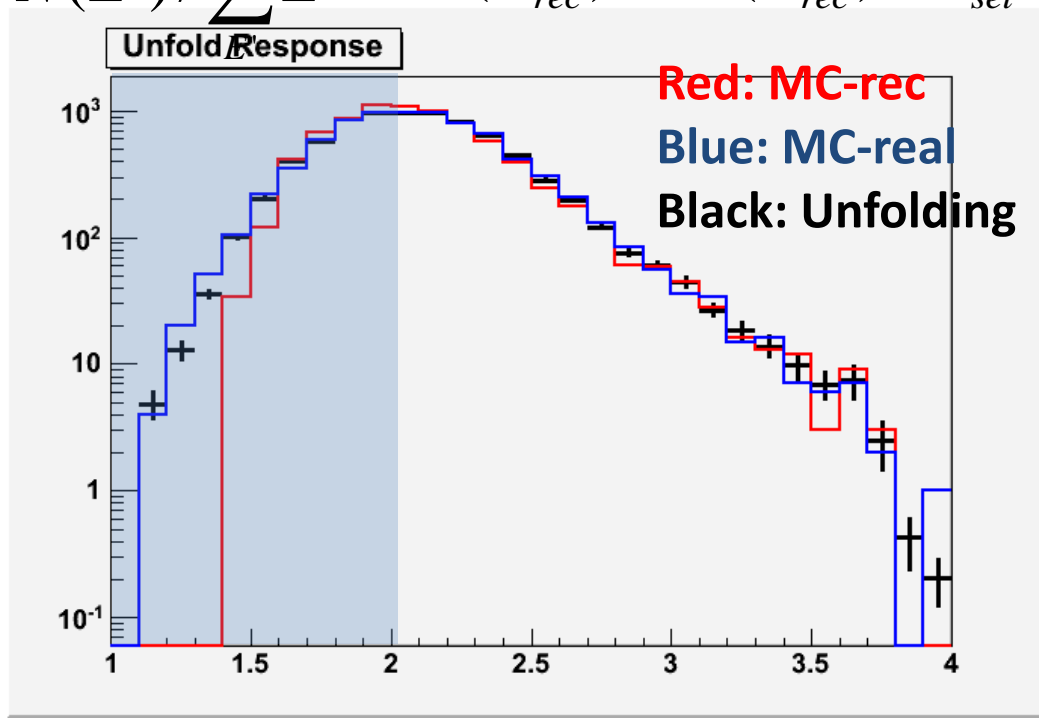
➤ To take into account any kind of smearing between bins due to the finite resolution of $\sim 25\%$, the Bayesian method is applied to the observed energy distribution $P(E_{rec})$.

$$P(E^i) = \sum_{j=1}^n \hat{P}(E^i | E_{rec}^j) \cdot P(E_{rec}^j)$$

$$P(E^i | E_{rec}^j) = P(E_{rec}^j | E^i) \cdot P(E^i) / \sum_{l=1}^m P(E_{rec}^j | E^l) \cdot P(E^l).$$

$P(E_{rec} | E)$ is from Monte Carlo simulation

$$P(E^i) = N(E^i) / \sum E' \quad P(E_{rec}^j) = N(E_{rec}^j) / N_{sel}$$



Energy scale: Moon Shadow displacement

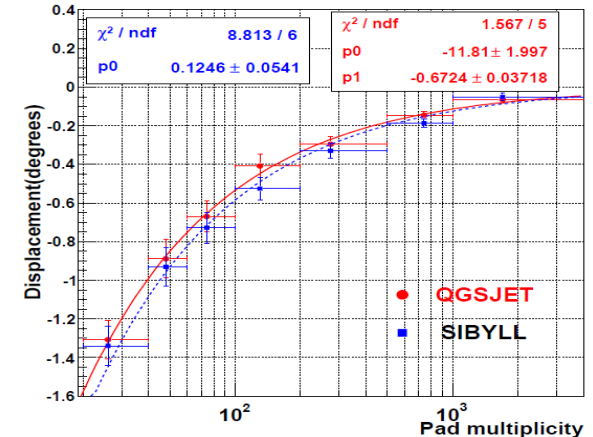
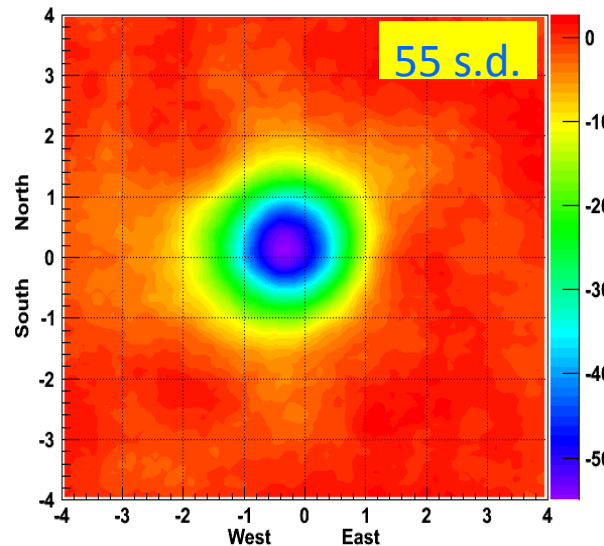
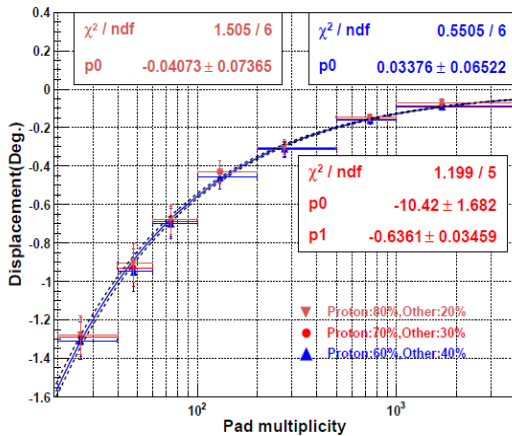


$$N \approx 21 \cdot (E_{\text{TeV}}/Z)^{1.5}$$

1 – 30 (TeV/Z)

Two systematic uncertainties may affect the Multiplicity-Energy relation:

- the assumed primary CR chemical composition (7%)
- the uncertainties of different hadronic models (6%)



The energy scale error is estimated to be smaller than 13% in the energy range 1 – 30 (TeV/Z).