The knee of the proton spectrum

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

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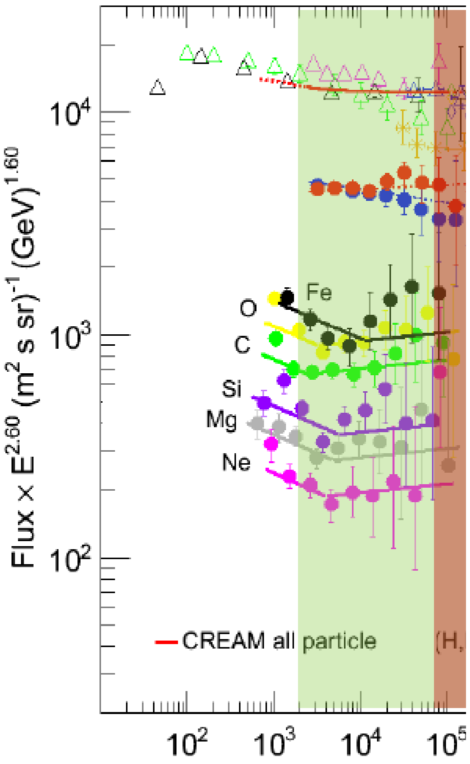
Outline

- 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**

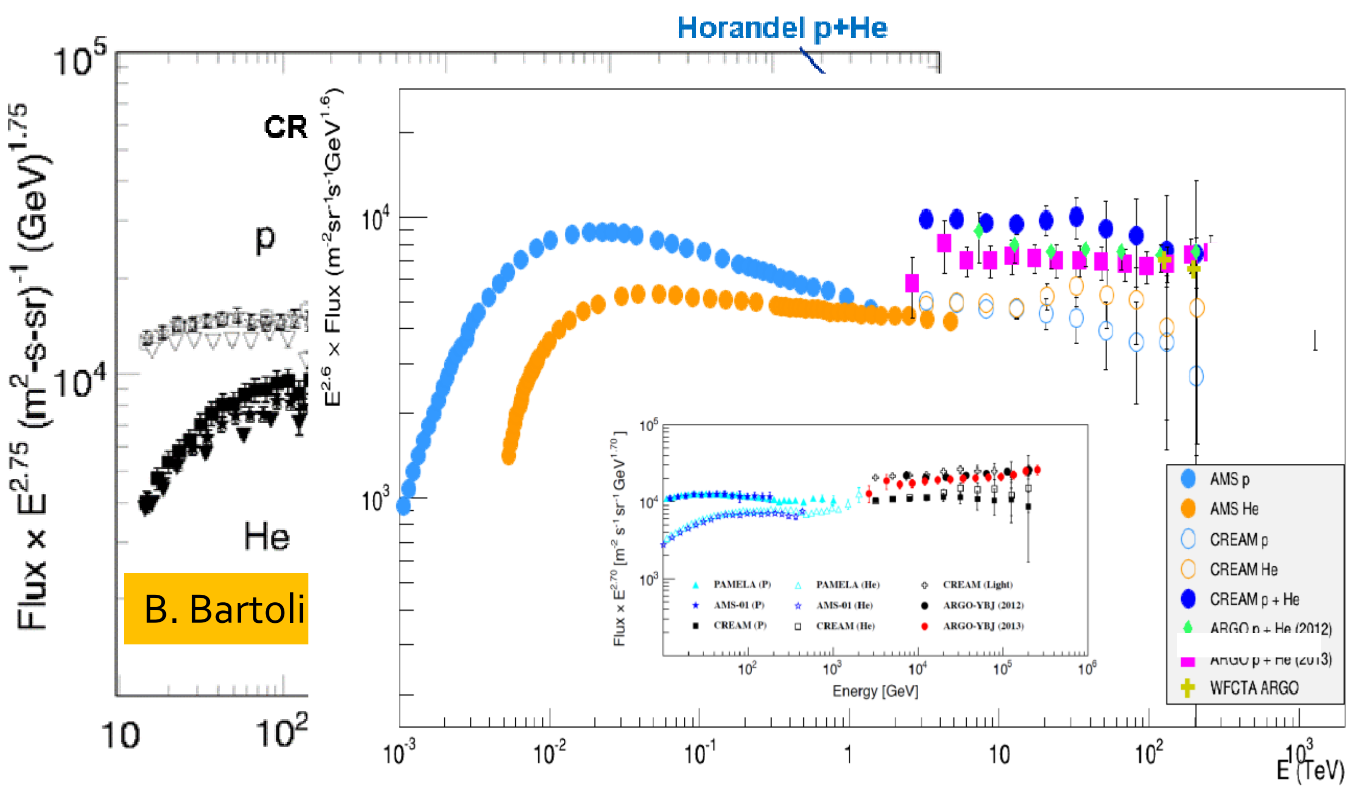
Motivation

- **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**



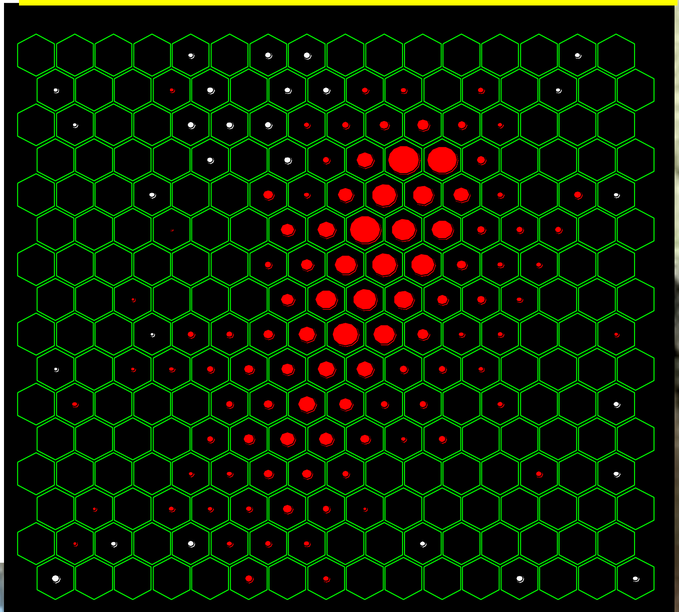
Y. S. Yoon et al., Ast

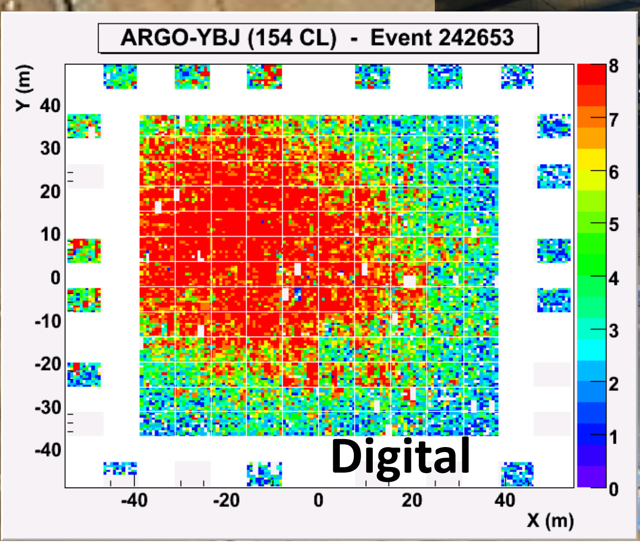


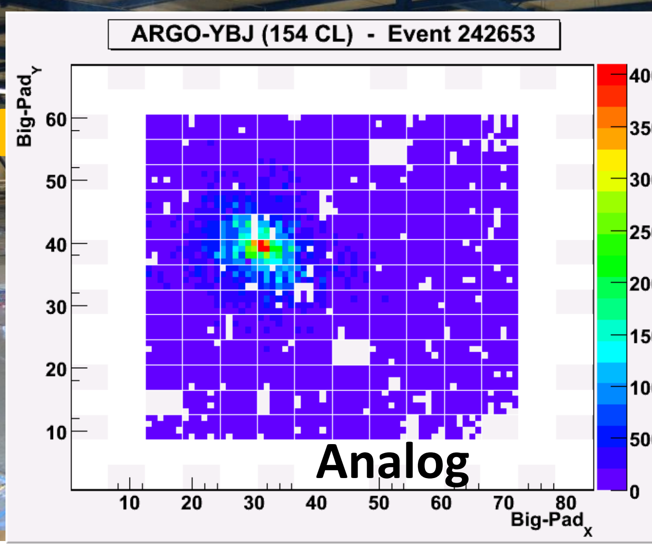
Wide Field of View Cherenkov Telescope (WFCTA)

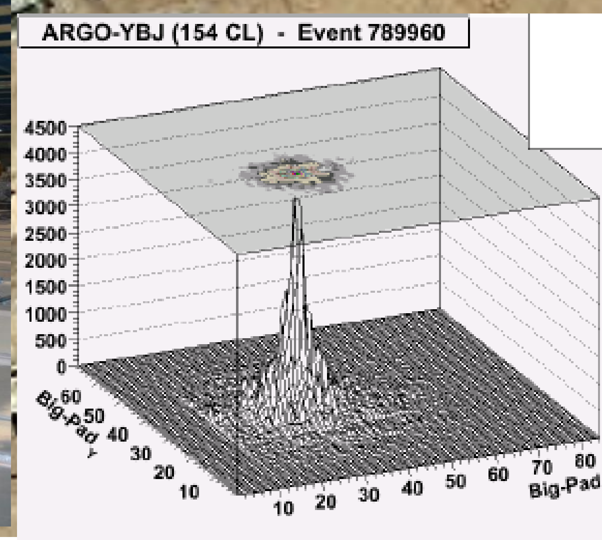
- ➢ $5m^2$ spherical mirror;
- ➢ 16×16 PMT array
- ➢ Pixel size 1° ;
- ➢ FOV: 14° × 16° ;
- ➢ Elevation angle: 60° .

One of Cherenkov event



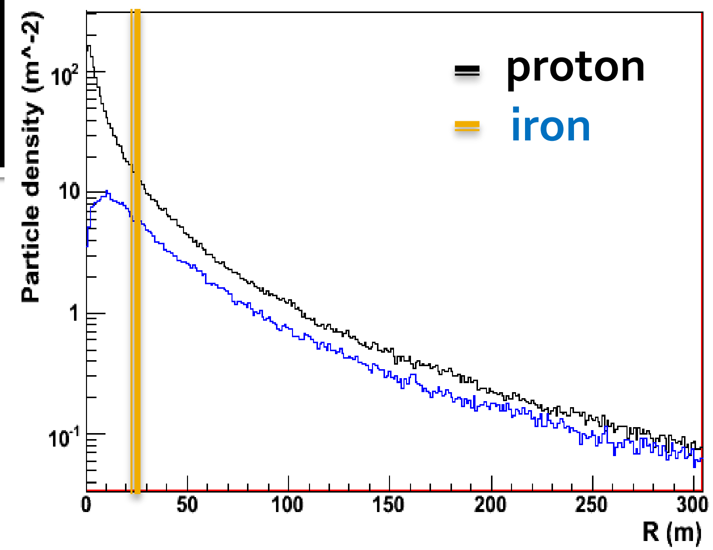


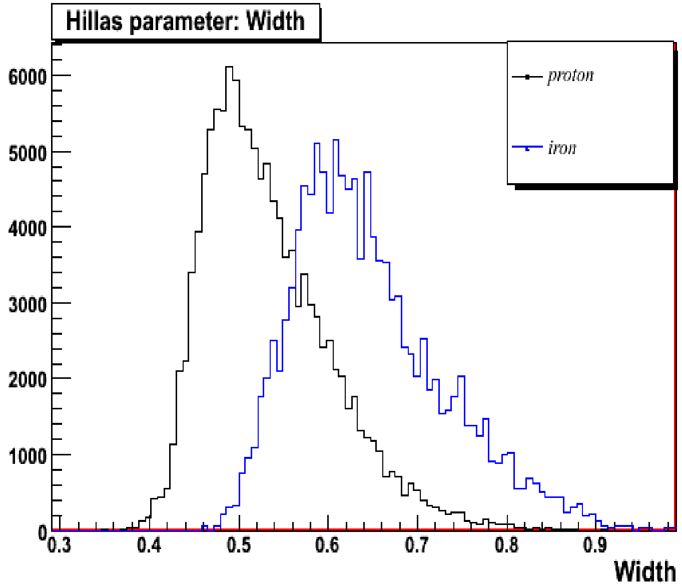




Hybrid Measurement

- **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

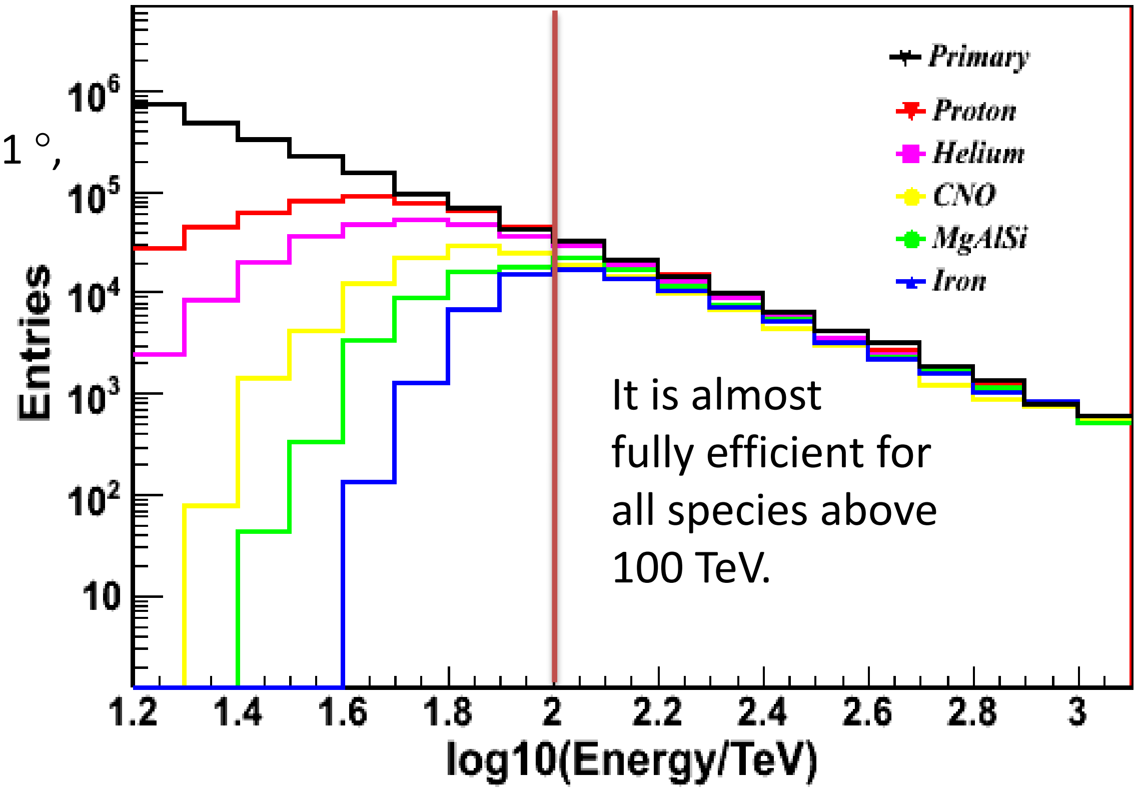
➢ Extensive air showers

- 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: θ~20° – 42 °, ϕ~69 ° -111 °,
  Core: $\pm$150 m

➢ Detector simulation

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

After quality cuts



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° respect to the axis of the telescope
  & the number of fired tubes >= 6

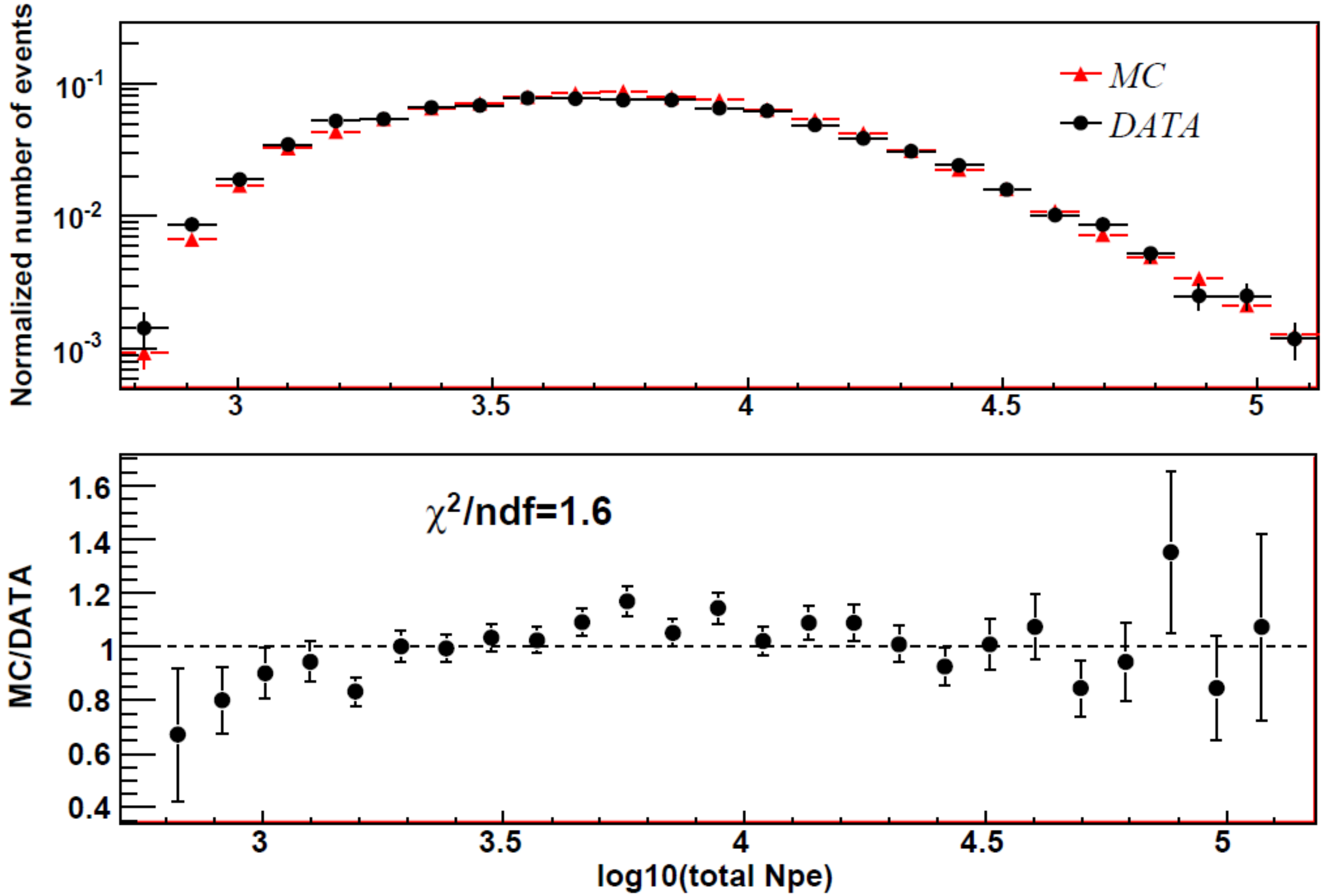
➢ Cherenkov image cleaning

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

8218 events are well reconstructed above 100 TeV

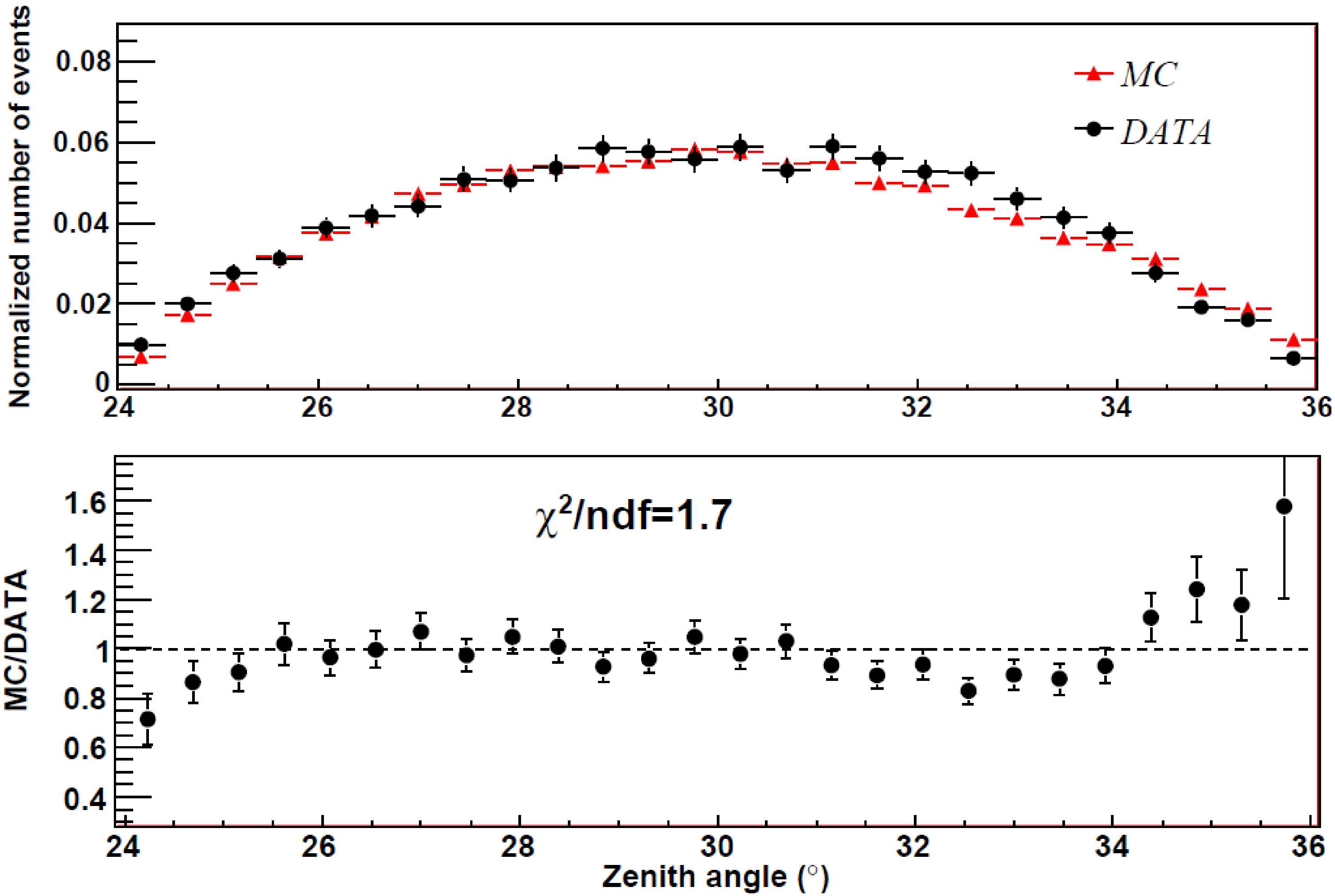
Comparison between Data and MC

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



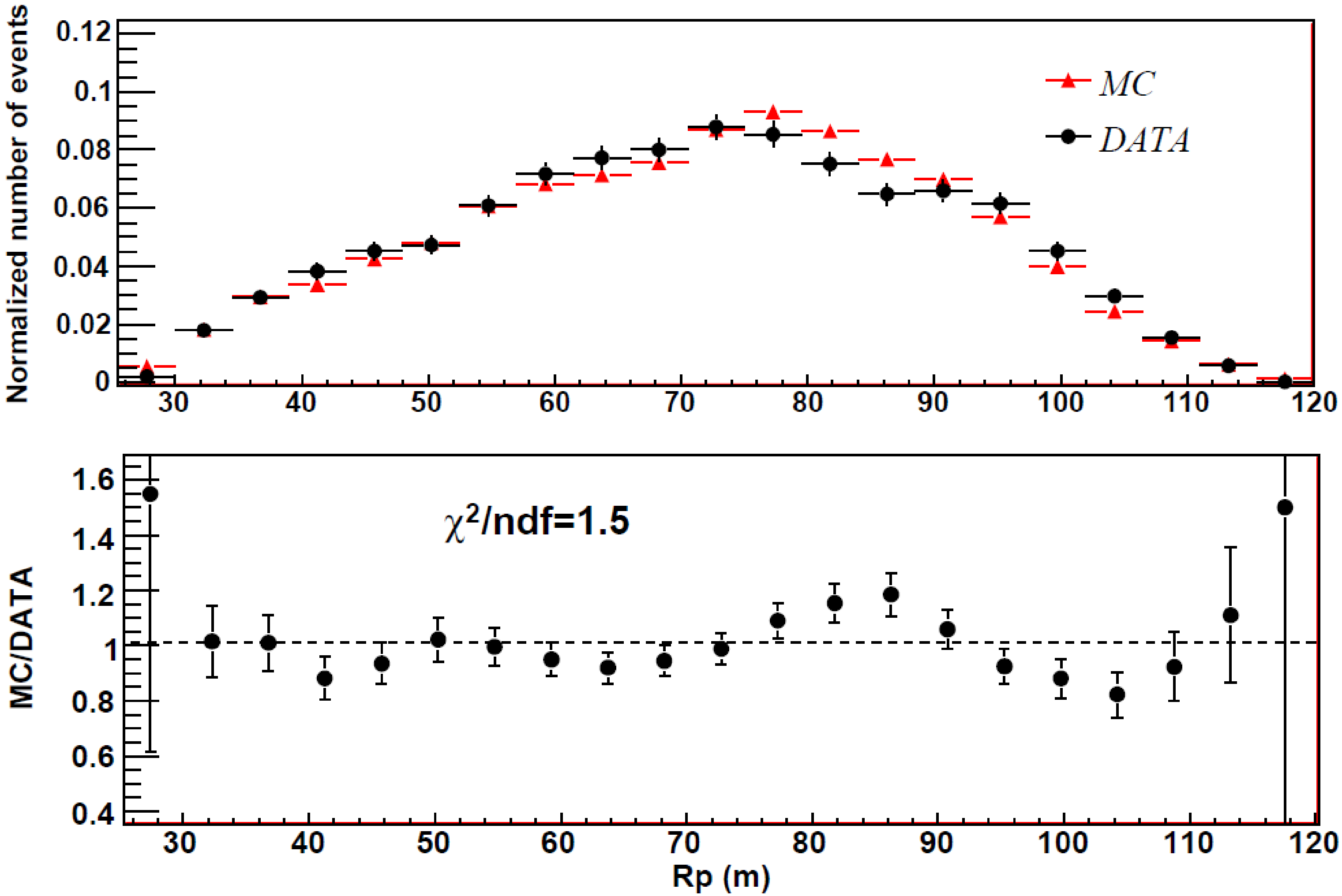
Comparison between Data and MC

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



Comparison between Data and MC

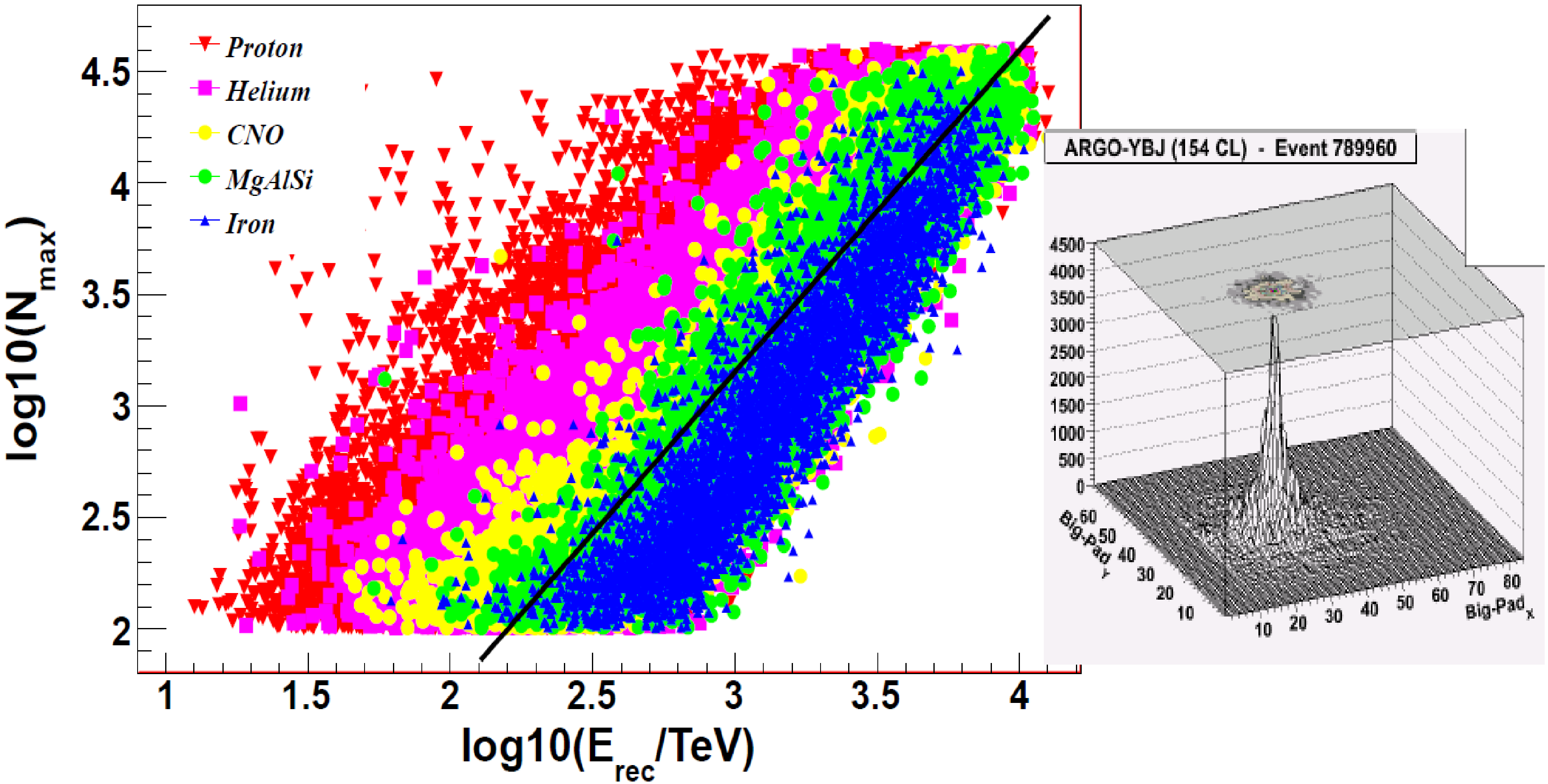
- The impact parameter of shower respect to the telescope
- The spatial resolution of the shower core position is 2 m



H&He Selection

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

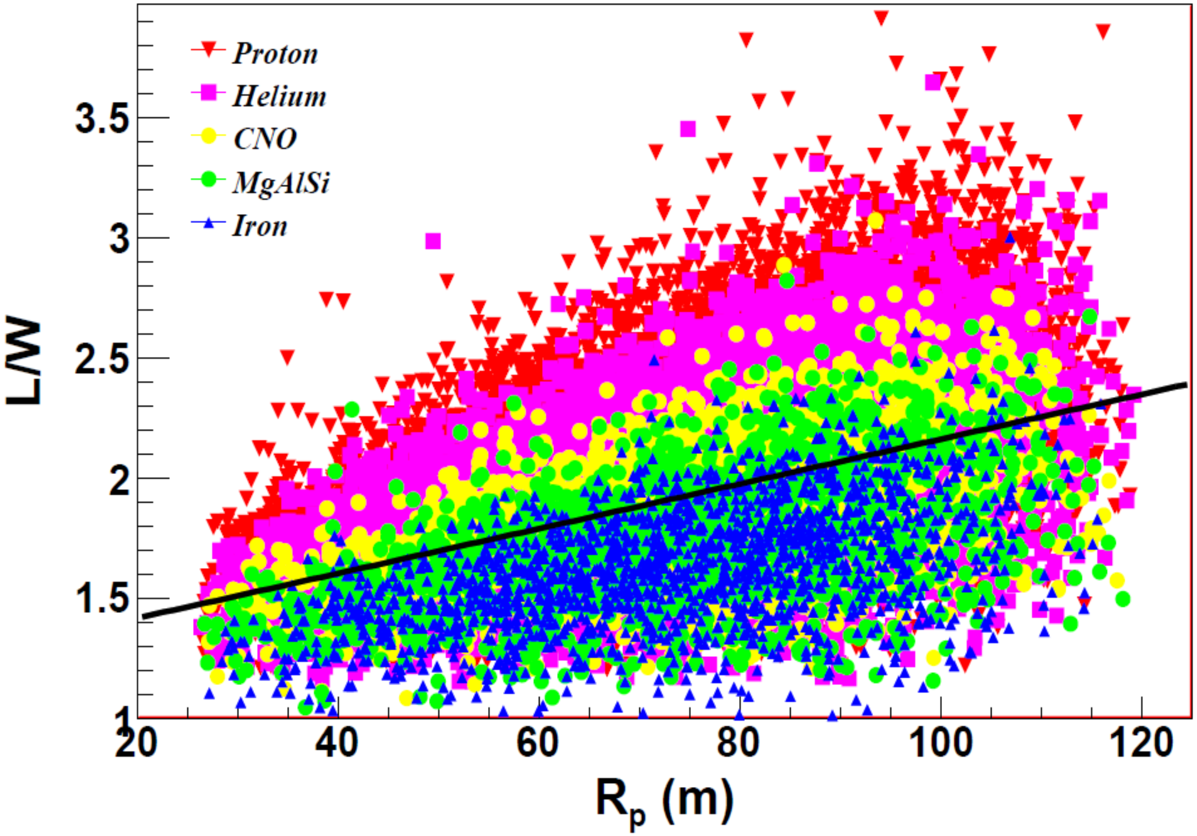
$N_{max} \sim 1.44E_{rec}$

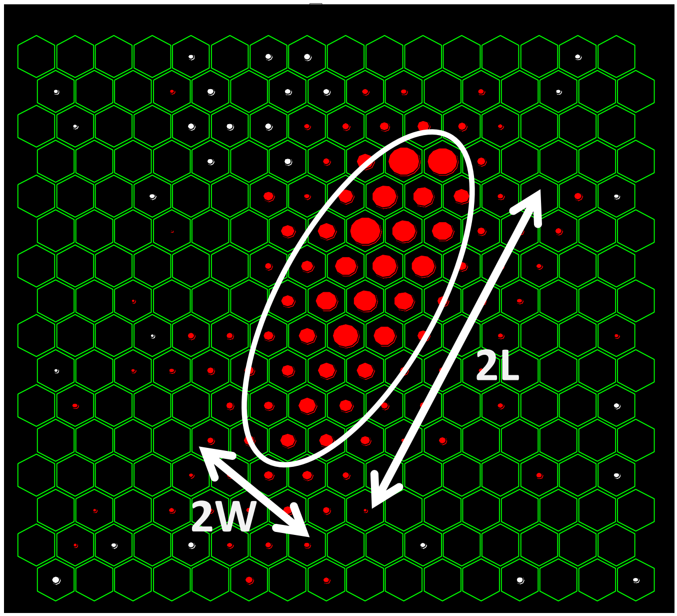


H&He Selection

- Elongation of the shower image

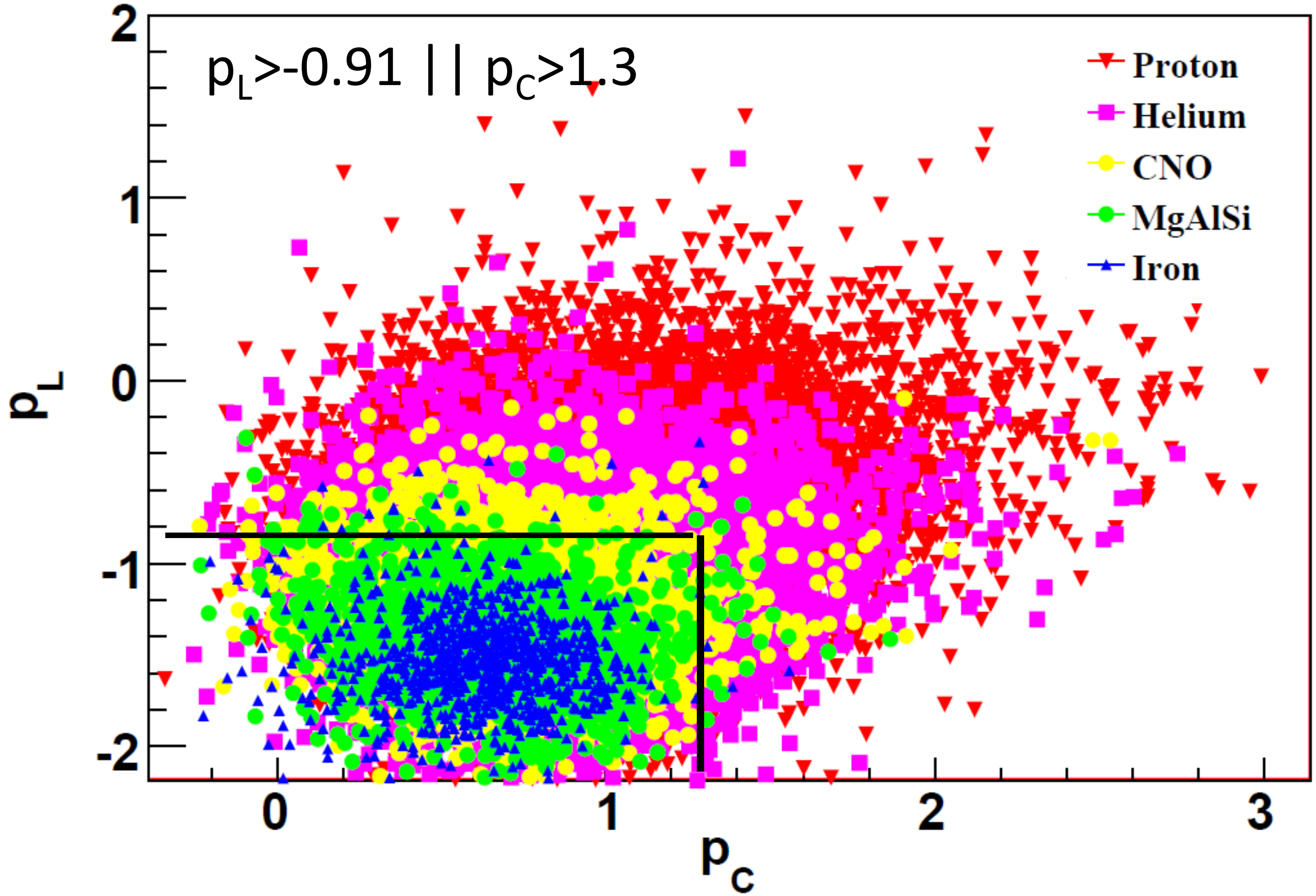
$$L/W \sim 0.09(R_p/10m)$$





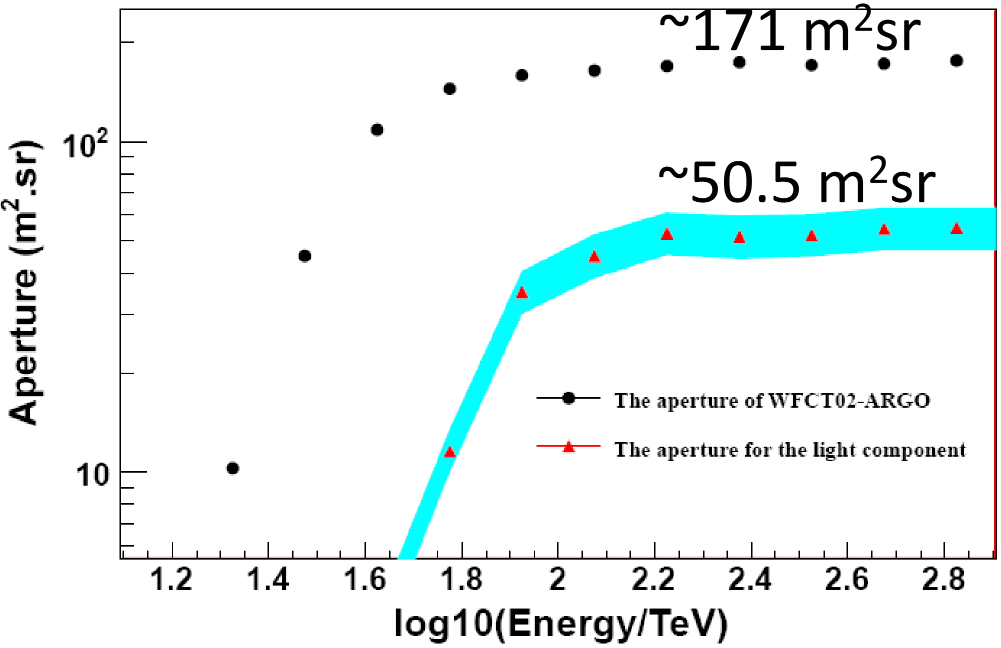
Multi-parameter Analysis

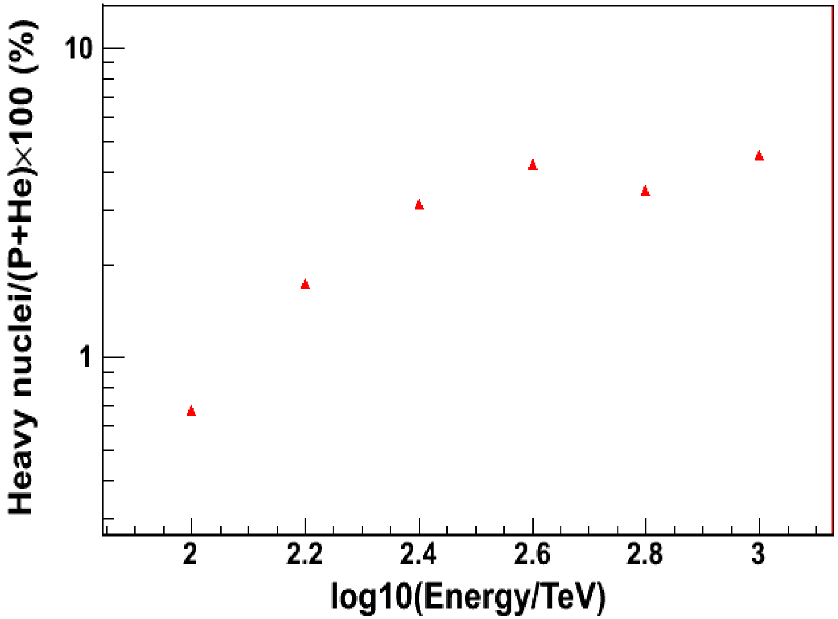
- $p_L = N_{\max} - 1.44 log_{10}(E_{\text{rec}}/1TeV)$
- $p_C = L/W - 0.091 \times (R_{\text{p}}/10m) - 0.14 log_{10}(E_{\text{rec}}/1TeV)$



Aperture and contamination

H:He=1:0.39





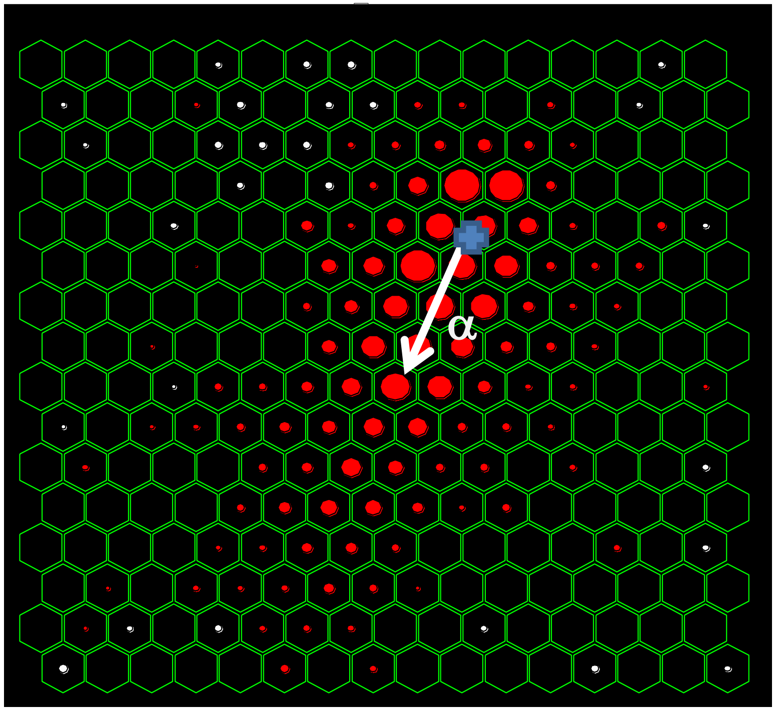
- **The contamination of heavy nuclei is 2.3% below 700 TeV**
- **Selecting efficiency is ~ 30%**
- **The ratio between H and He is 1:0.39**

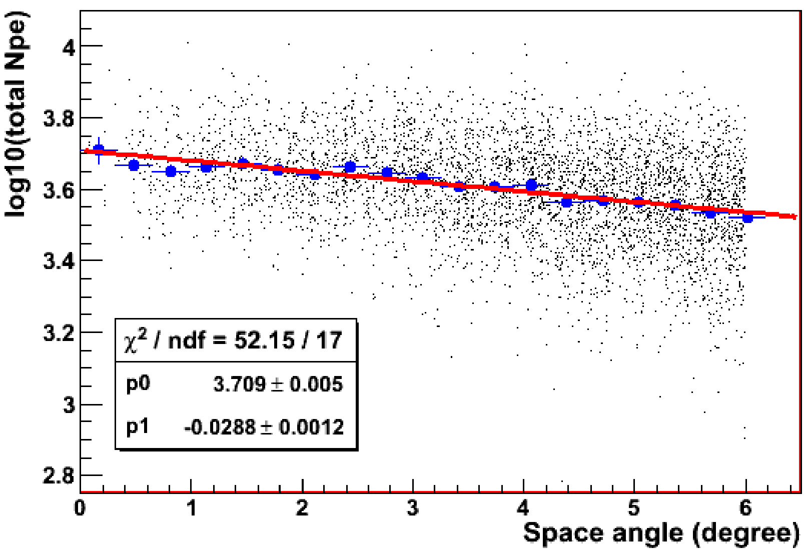
Energy reconstruction
Using ΣN_{pe} in shower image

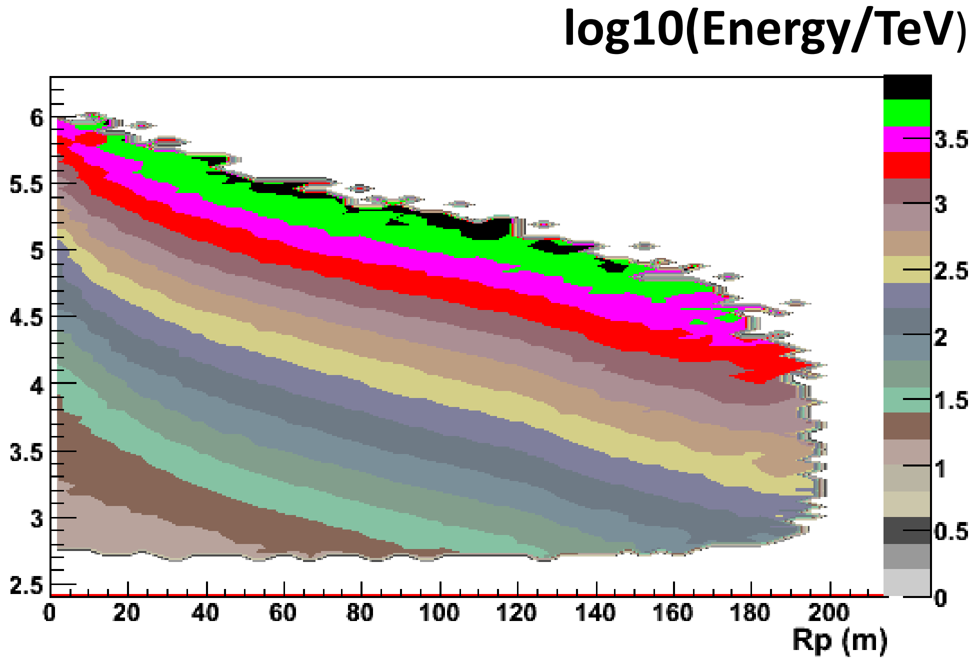
- **Look-up table: light components only**

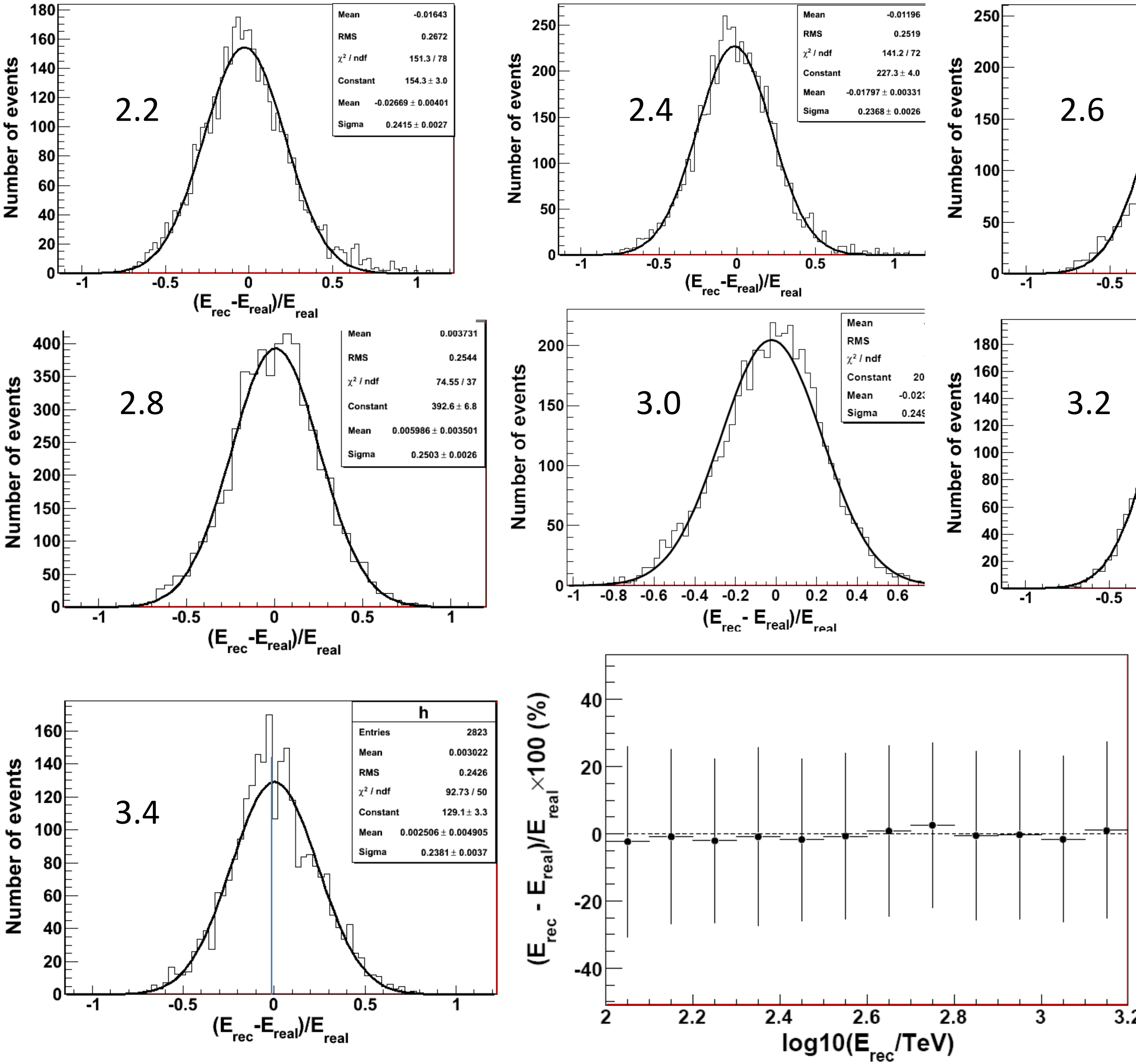
- Impact parameter (R_p): 5m/bin
- $\log N_{pe}$: 0.1/bin

- R_p : linear interpolation between bins
- N_{pe} : Quadratic interpolation between bins









E-resolution: ~25% constant with energy

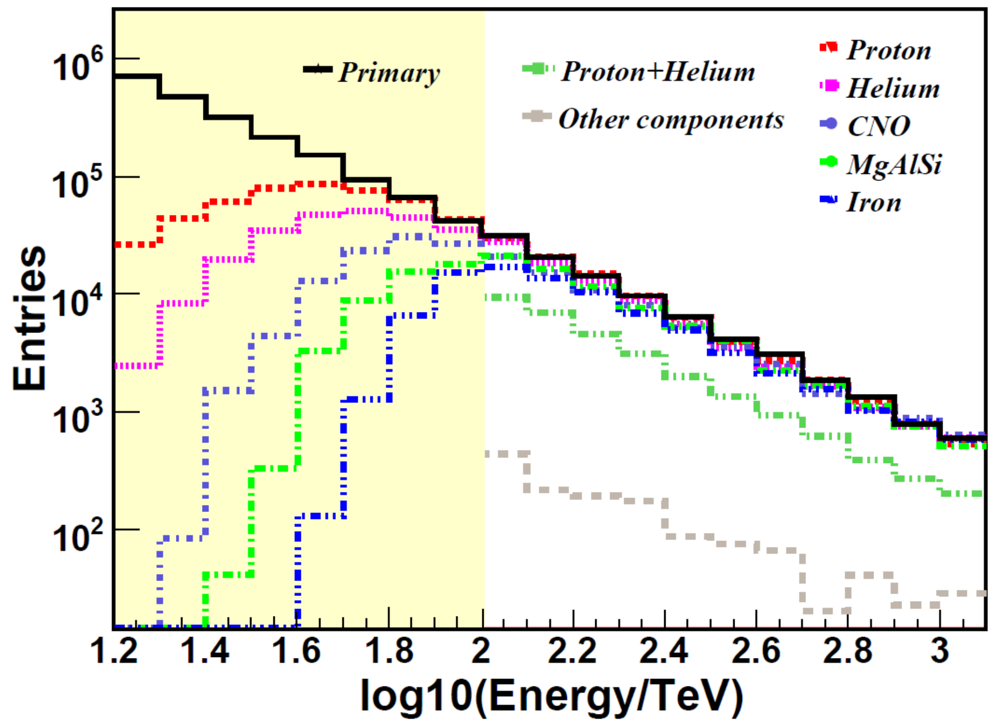
Bias: < 2%

Final H&He Data Set

827000 seconds good weather data,

$logE_{min}$-$logE_{max}$ (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

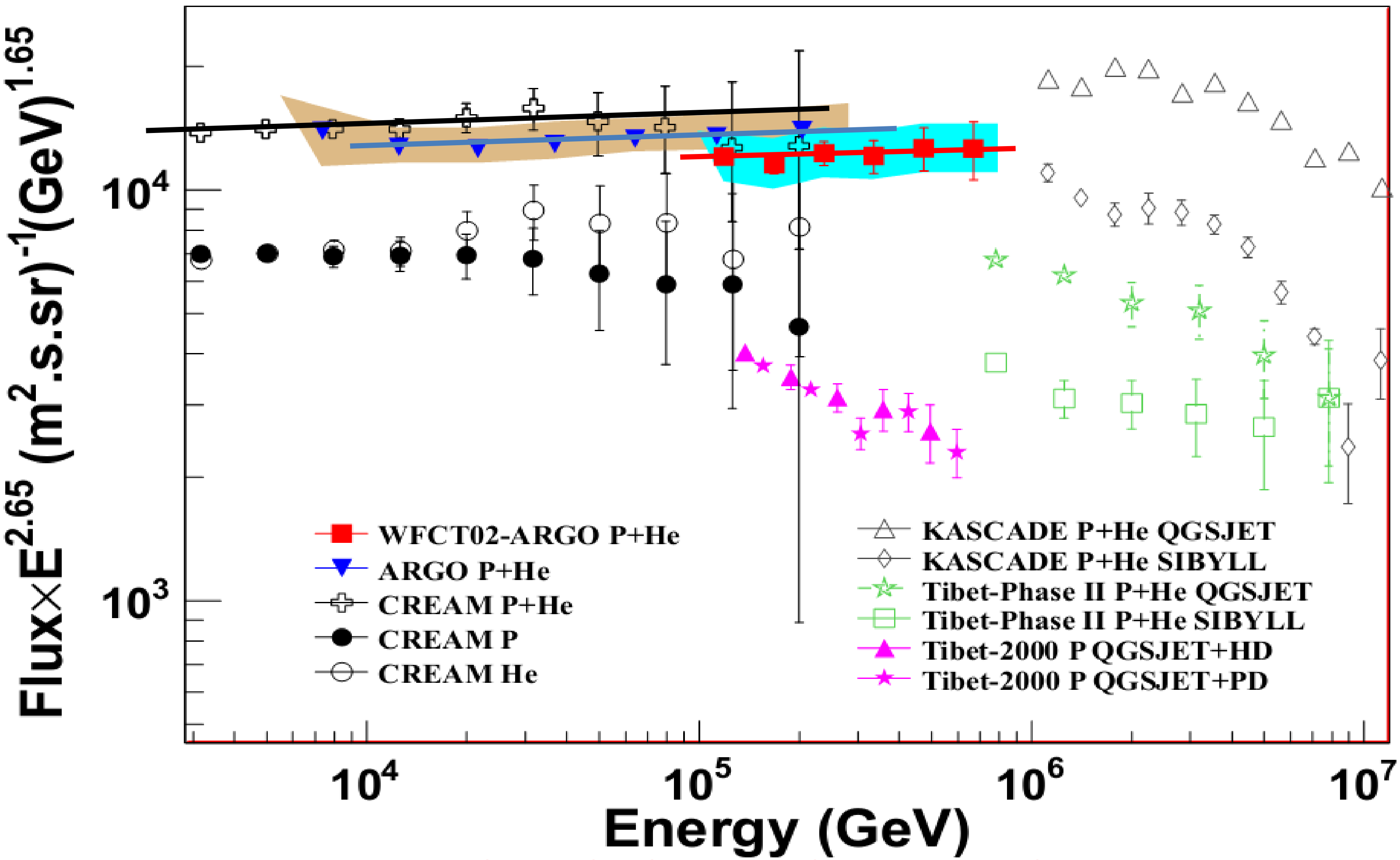
- The contamination of heavier nuclei is model dependent
  - 1:1:1:1:1, 5.1%
  - Horandel, 2.3%
  - H4A, <2%



CREAM: 1.09x1.95x10^{-11}(E/400TeV)$^{-2.62}$

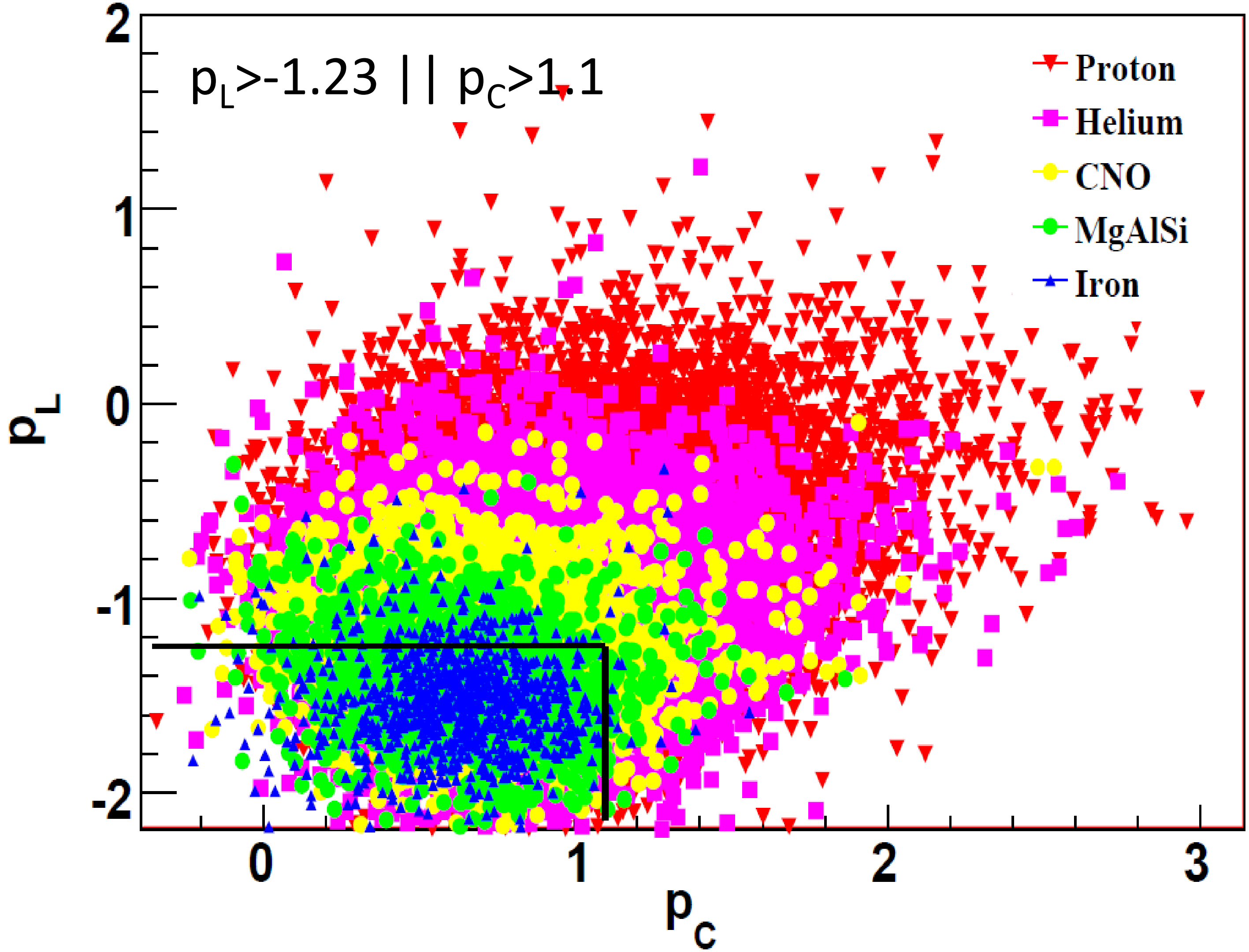
ARGO-YBJ: 1.95x10^{-11}(E/400TeV)$^{-2.61}$

Hybrid: 0.94x1.95x10^{-11}(E/400TeV)$^{-2.62}$

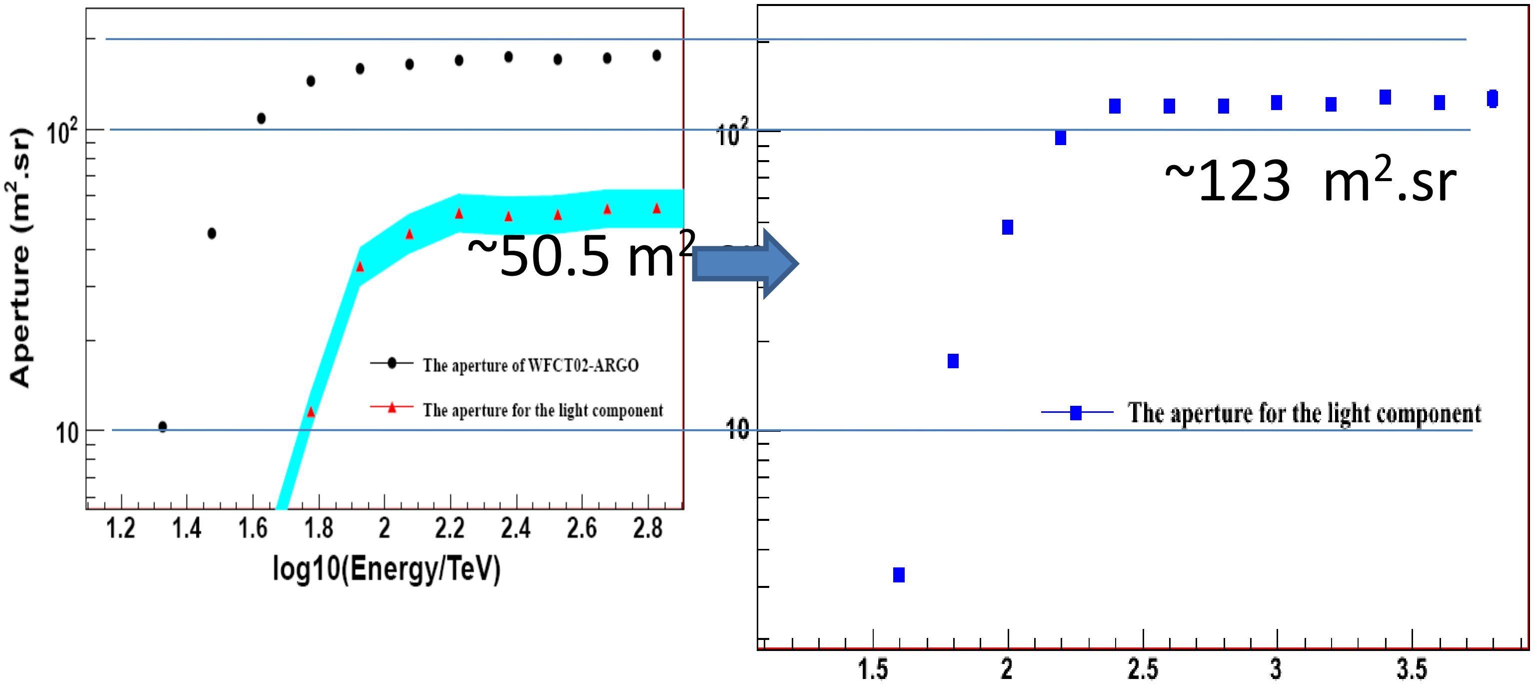


B. Bartoli et al, Chinese Physics C, Vol. 38, No. 4, 045001 (2014)

Further Analysis:
Optimizing for Statistics at High Energies



Surviving samples: H:He=1:0.39 H:He=1:0.8



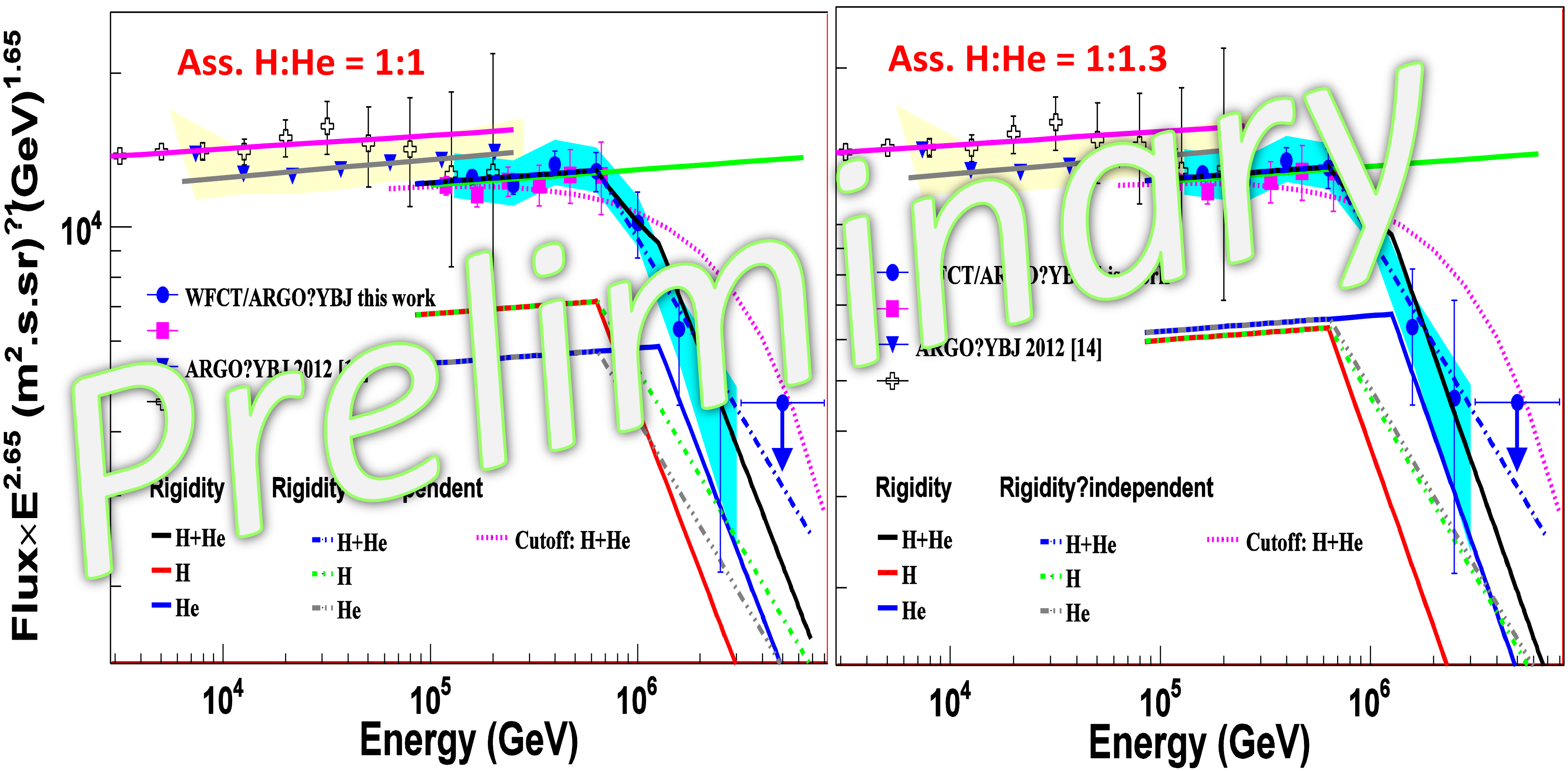
- **By loosening the criteria on H & He selection, the aperture is enlarged by a factor of 2.4, selecting efficiency ~ 72%**
- **# of H & He events increases from 490 to 1231 above 200 TeV**
- **The contamination of heavy species increases from 2.3% to 7.2% below 700 TeV**
- **The ratio between H and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

Discover the "knee" of the Proton Spectrum below 1 PeV

~6σ deviation from the single-index power law

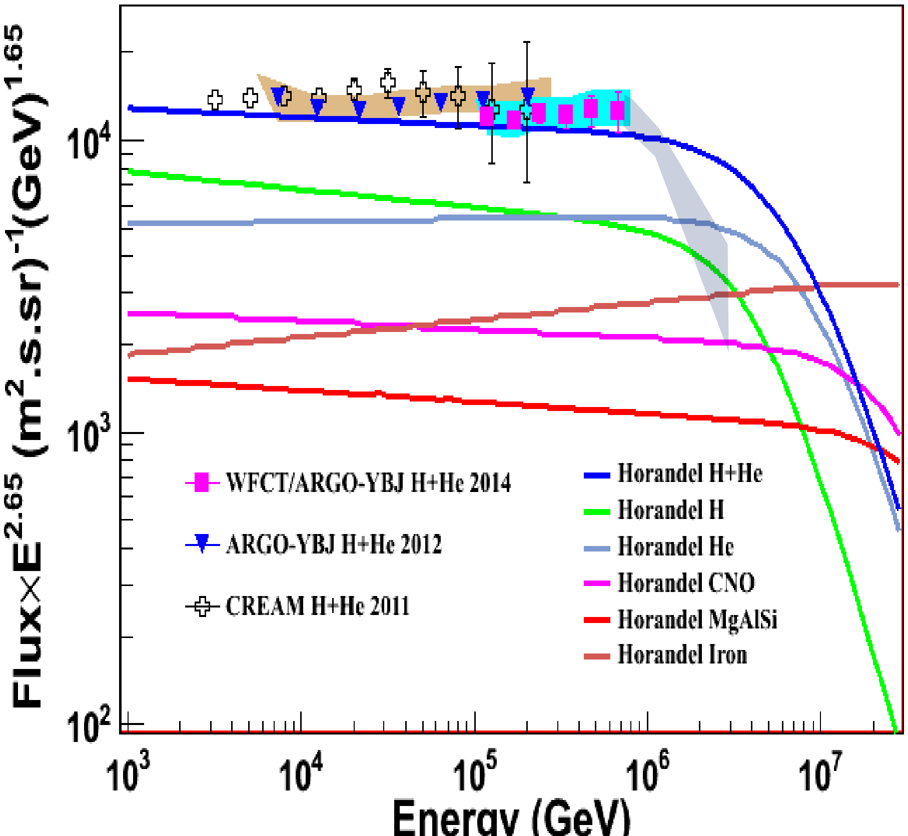
the knee is at (640 ±87) TeV

spectral index is >3.3 above the knee

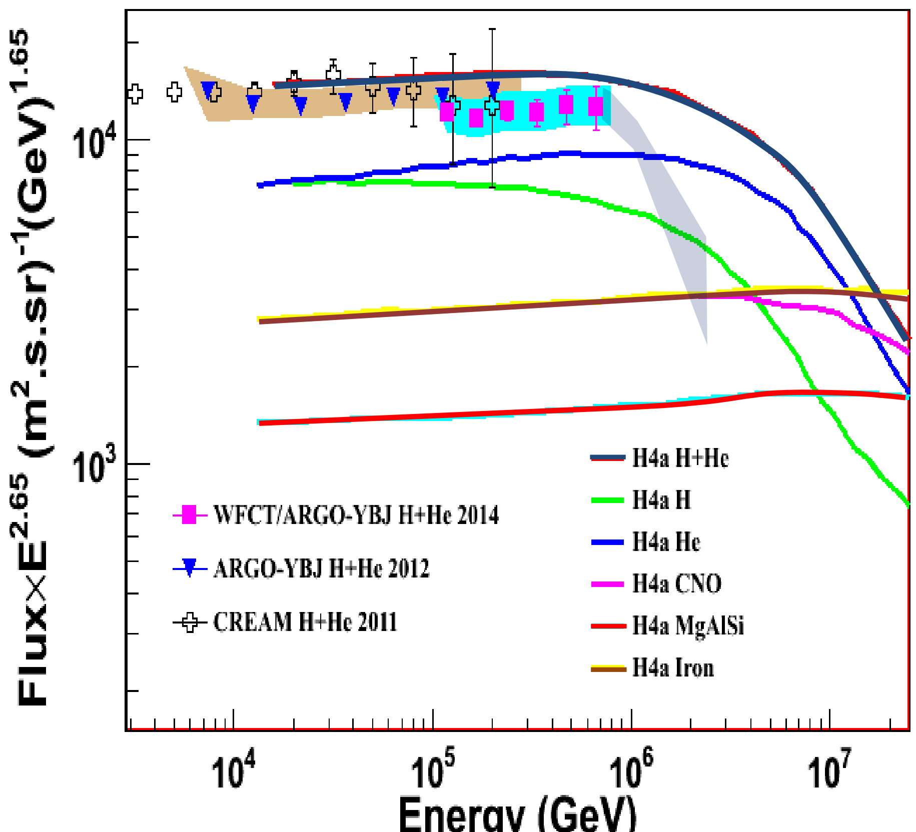


Most CR acceleration models have problems to produce the low energy knee of the proton spectrum!

- 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)

Conclusion

- 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** &

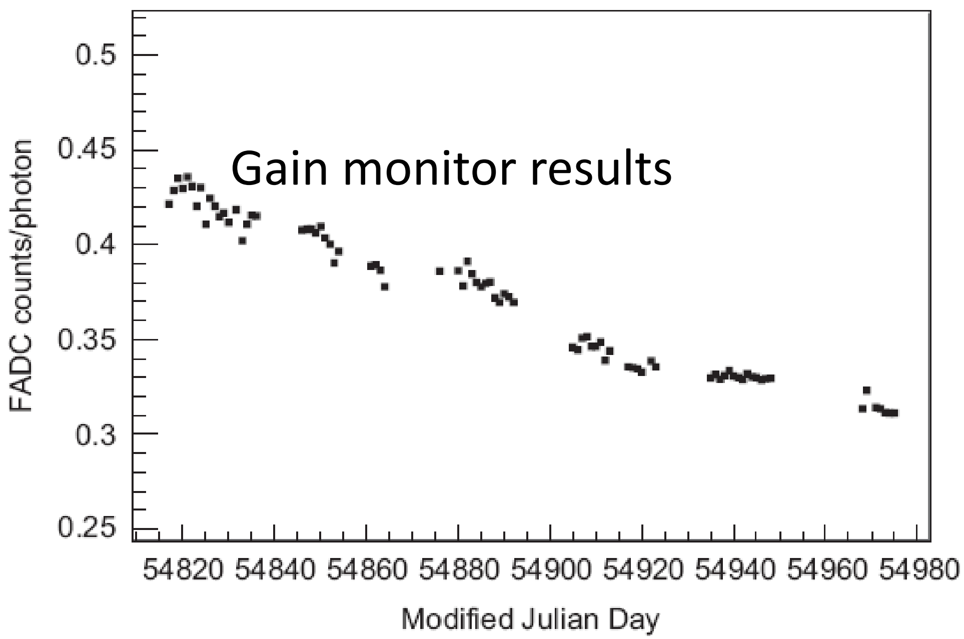
  The flux is **1.95×10^{-11} +9%\-6%** (GeV^{-1}m^{-2}sr^{-1} s^{-1})at 400TeV
- The difference in flux can be interpreted due to a difference of **energy scale ±3.5%** between experiments
- **The knee of the p-spectrum is discovered at (640±87) TeV**
- **~6σ deviation from the single-index power law**
- **Spectral index is >3.3 above the knee**

Thanks for your attention!

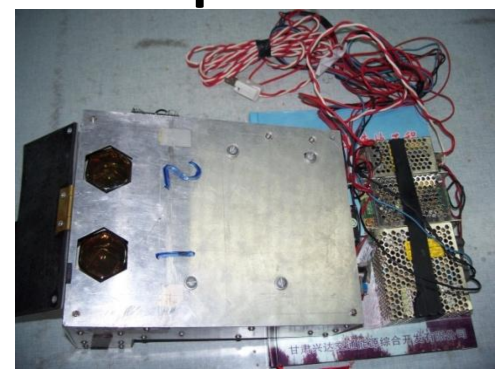
Photometric Calibration of the Cherenkov Telescopes

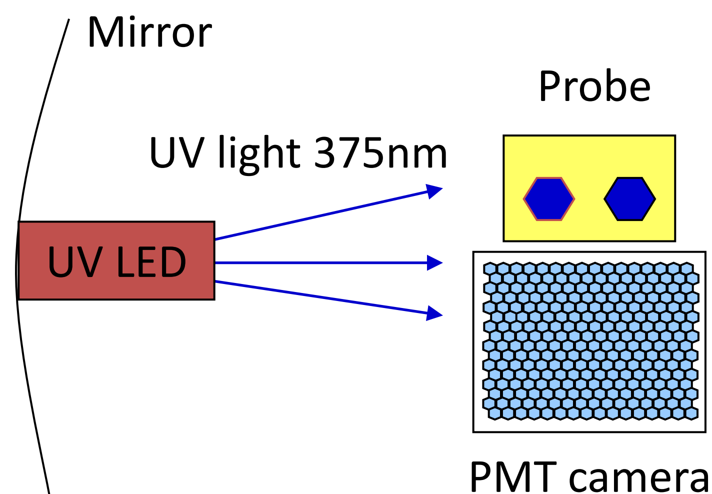
- A probe is calibrated by comparing with a HPD (calibrated by NIST) at the HiRes lab in Utah;
- An UV LED mounted at the center of the mirror is calibrated by the probe many times during the data taking;
- The PMT camera is calibrated by the UV LED every day.

➢ The systematic uncertainty of the calibration constant : ~ 7%.



The probe





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

Systematic Uncertainty (1)

- **Energy determination uncertainty ~9.7%**

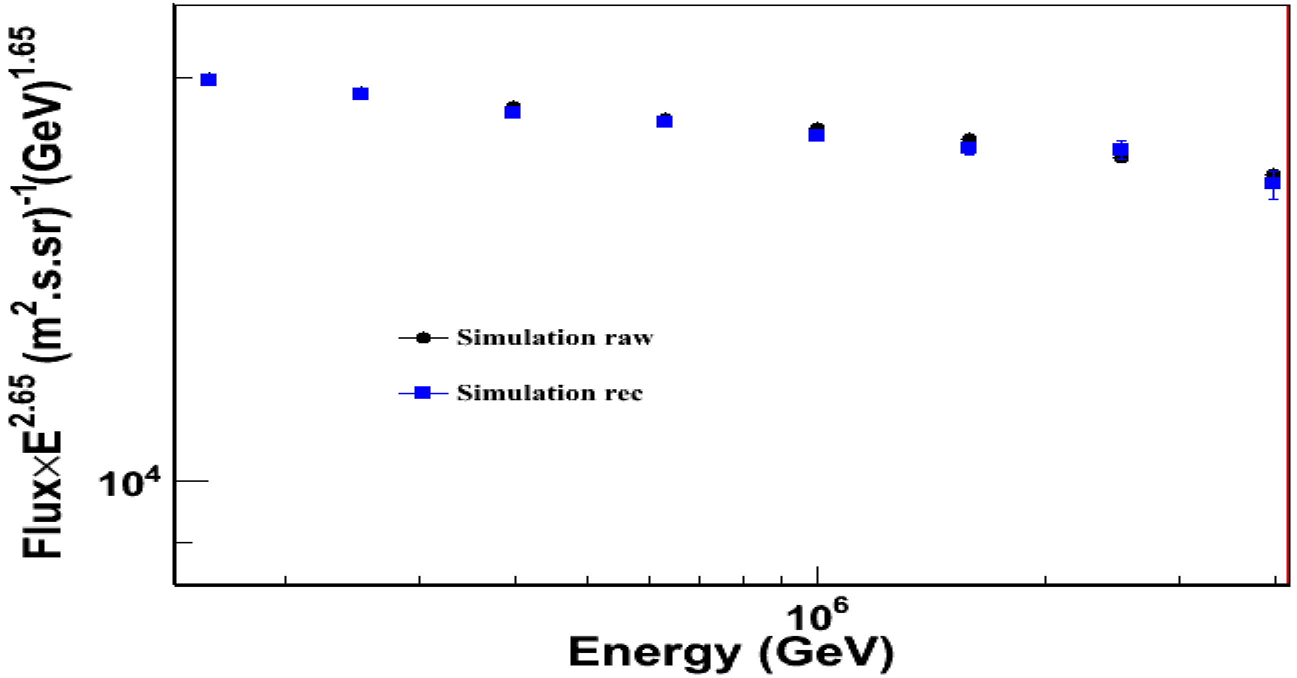
• Calibration	5.6%
• Weather condition （include mirror reflectivity and glass window transmission）	7.6%
• Method of energy reconstruction	<1.2%
• High energy hadronic interaction model （QGSJET II-03 vs. SIBYLL2.1）	<1.0%
• Low energy hadronic interaction model (GHEISHA vs. FLUKA)	<2.0%

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%

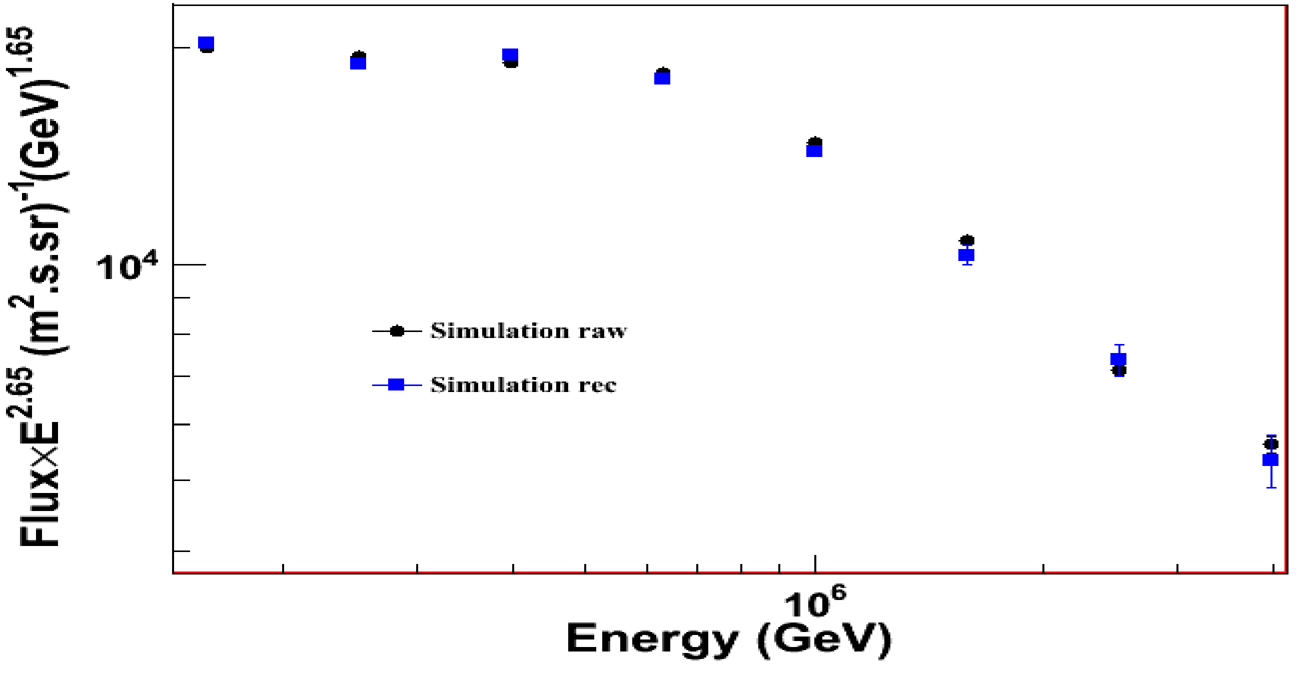
Generated H&He spectrum and its reconstruction

- Ivan required test on the generated H&He spectrum.
- Events are generated with a single-index-power-law (γ=-2.7) as represented by black dots. Spread over an area of 260mX260m, 22°X21° in the sky near θ=30°
- 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 (γ=-2.7/3.4, E_k=700TeV) as represented by black dots. Spread over an area of 260mX260m, 22°X21° in the sky near θ=30°
- 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

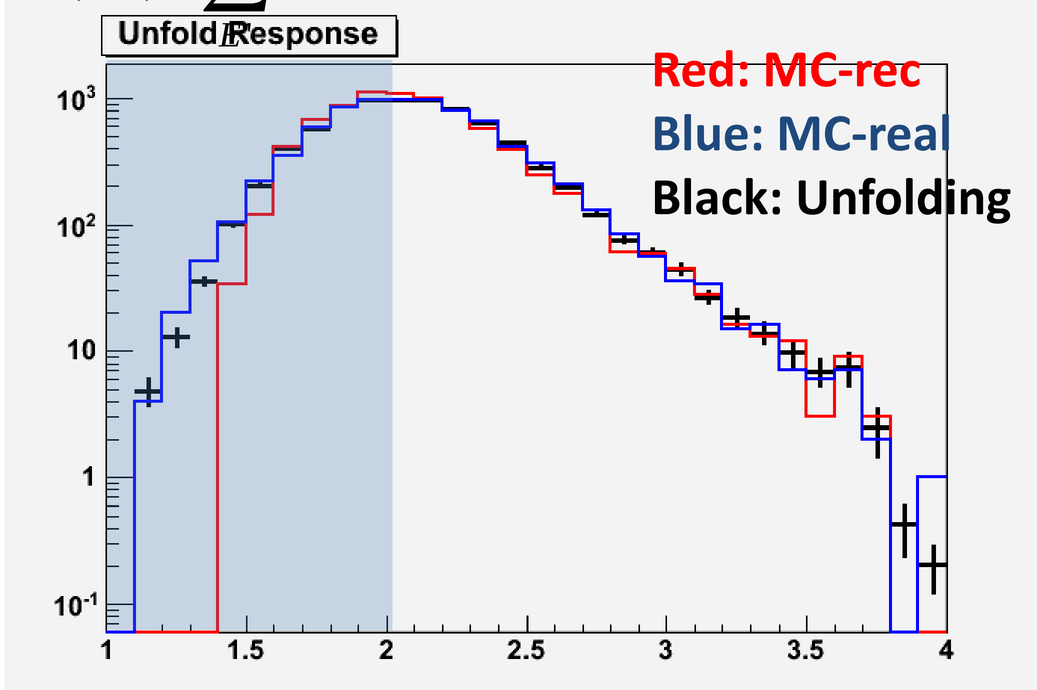
➢ To take into account any kind of smearing between bins due to the finite resolution of ~25%, the Bayesian method is applied to the observed energy distribution P(E_{rec}).

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

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

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

$$P(E^i) = N(E^i) / \sum E' \qquad P(E^j_{rec}) = N(E^j_{rec}) / N_{sel}$$



Criterion on N_{max}

- All real CR events well reconstructed in hybrid analysis in the upper figure. The black line indicates the cut of p_L>-1.23. In the lower figure, the remained events after the cut of p_C>1.1 is shown. The black line is the same cut on p_L.