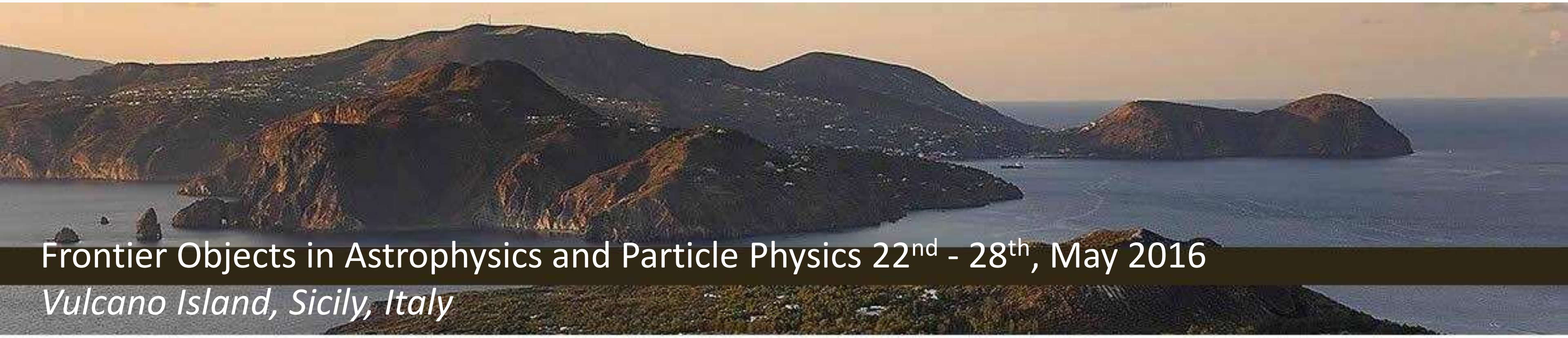


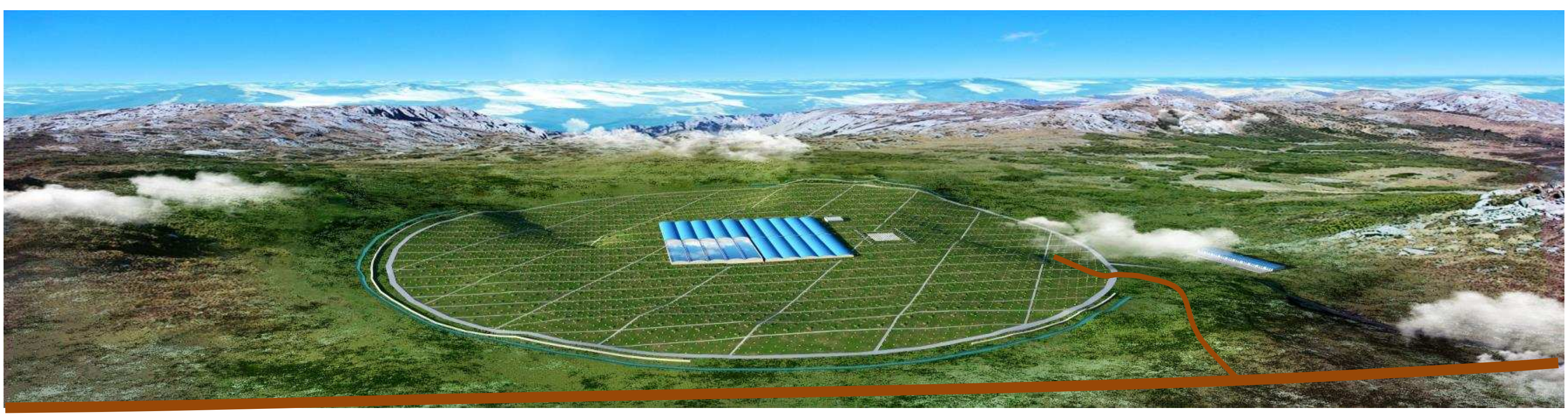
LHAASO Prospects: Spectra of Cosmic Ray Species

Zhen Cao
IHEP, Beijing, China

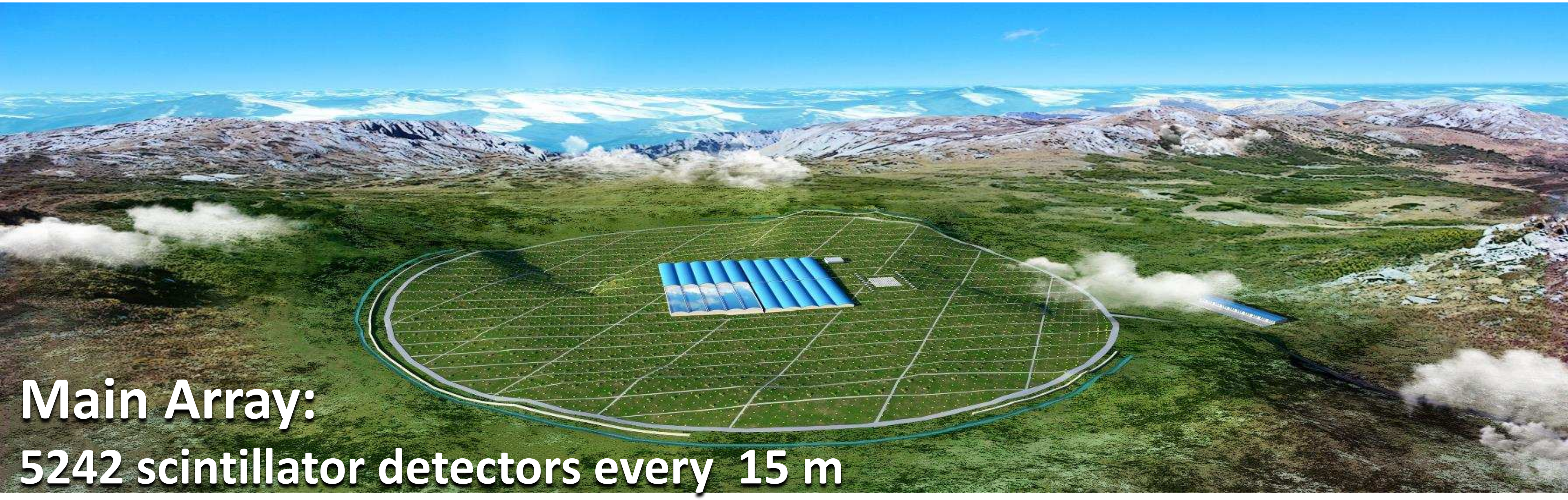
VULCANO Workshop 2016

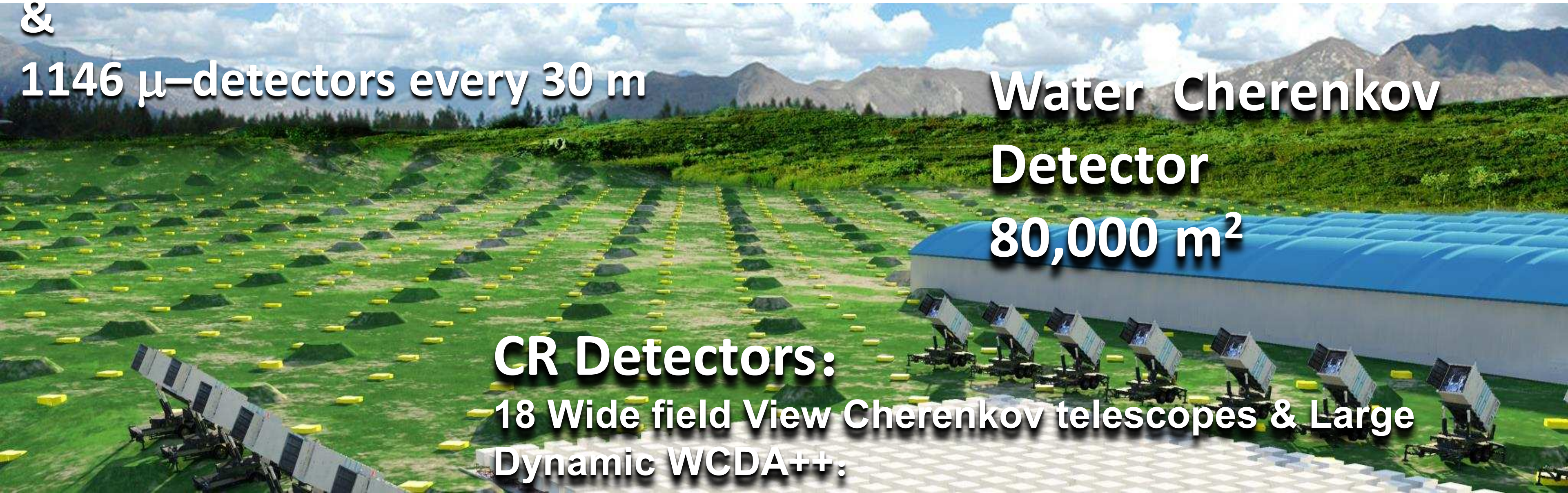
LHAASO at Mt. Haizi, Sichuan, China

N29°21’27.6”, E100 ° 08’19.6”, 4400 m a.s.l.



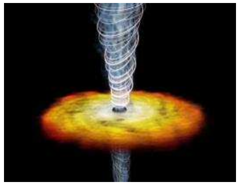
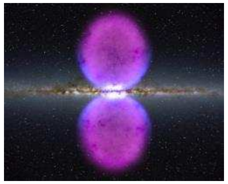
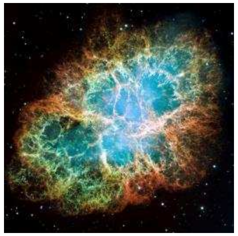
LHAASO Layout



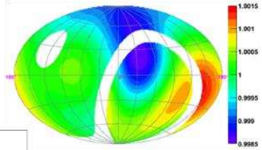
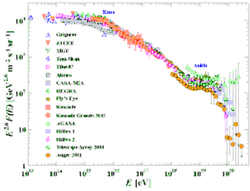
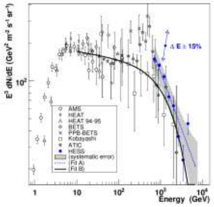


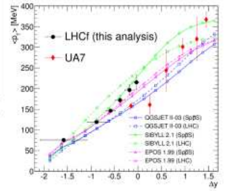
Physics of LHAASO

- VHE gamma sky survey (100 GeV-1 PeV):
  - Galactic sources;
  - Extragalactic sources & flares;
  - VHE emission from Gamma Ray Bursts;
  - Diffused Gamma rays.

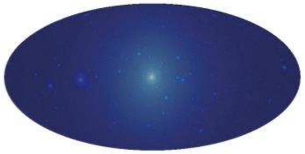
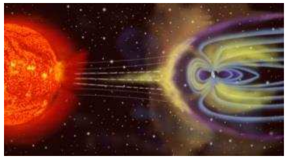





- Spectrum measurement at the high end:
  - Nature of the acceleration: leptonic or hadronic;
  - Origin of cosmic rays – 100 years' mystery.
- Cosmic rays
  - Spectra of CR Species;
  - Anisotropy of VHE cosmic rays;
  - Cosmic electrons / positrons;



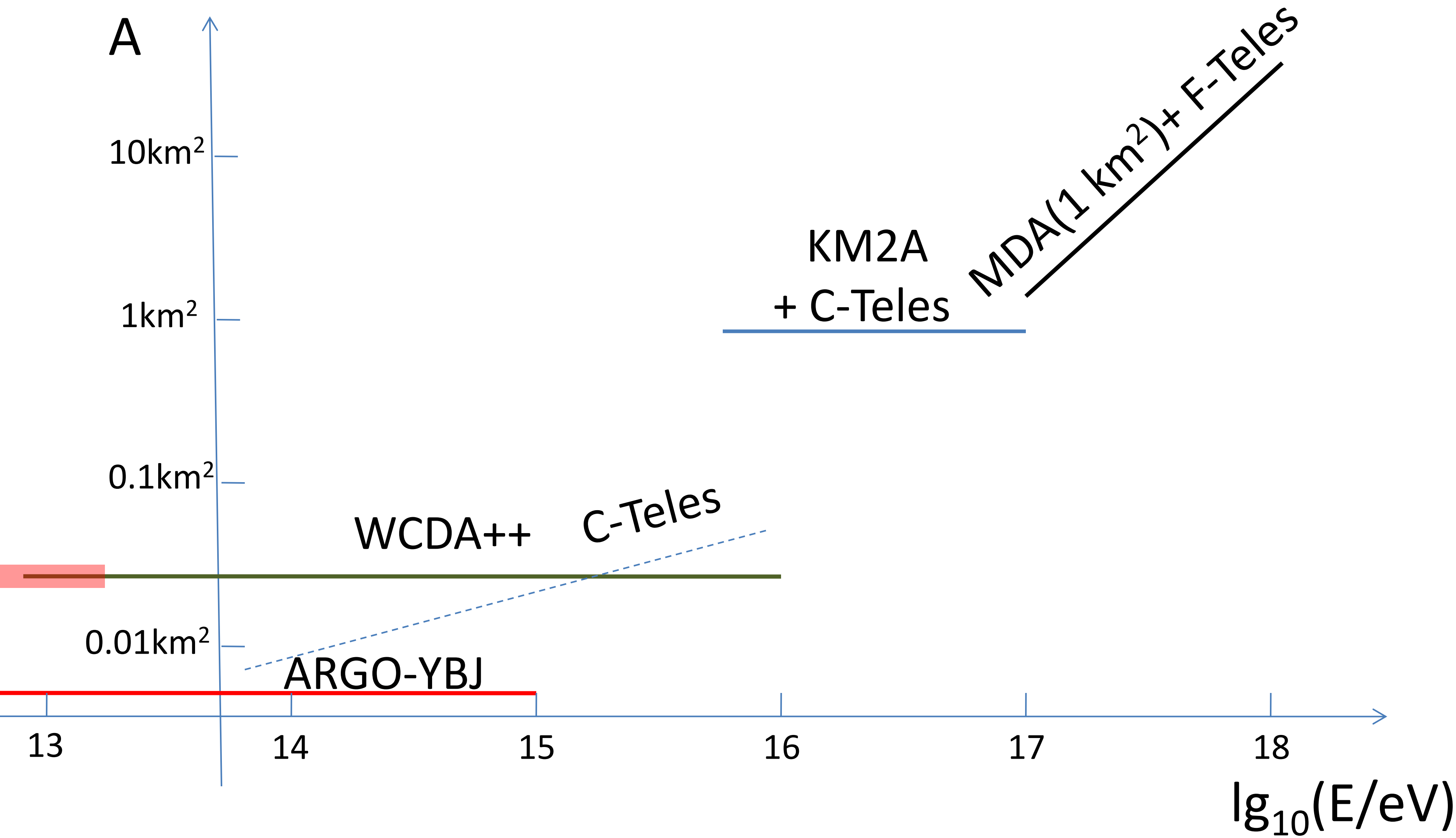
- Miscellaneous:
  - Gamma rays from dark matter;
  - Sun storm & IMF.

Outline

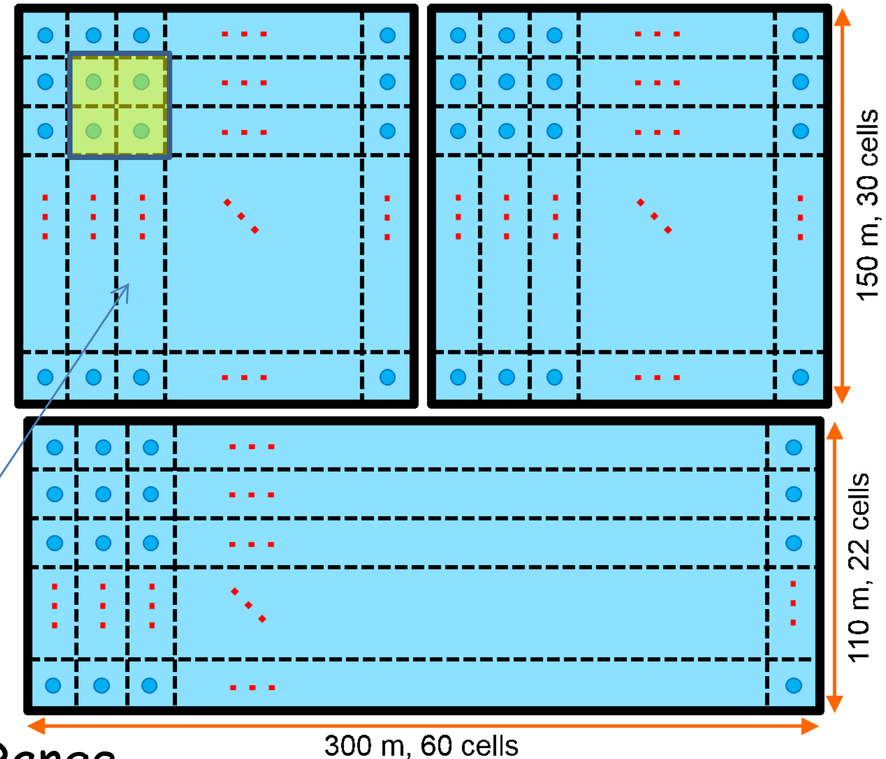
- Absolute Energy Scale at 10TeV
- Cross-Calibration with Space-borne Measurements
- Separation between Species (0.1-10 PeV)
- The Knees at 0.7, 1.4, ~3 PeV ......
- Composition above 10 PeV & the Knee at ~18 PeV
- The second Knee of All Particle Spectrum
- Status of the project
- Summary

Aperture of LHAASO for CR events

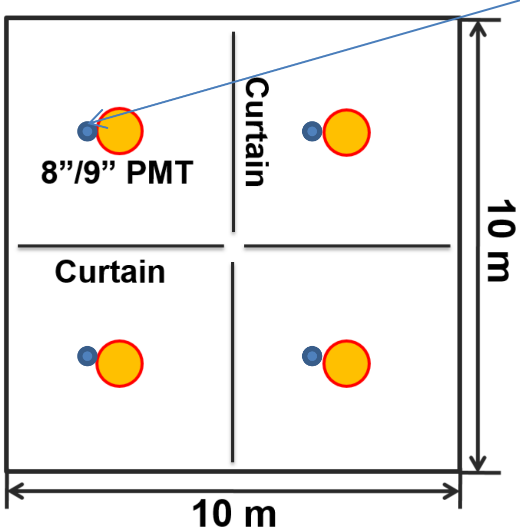


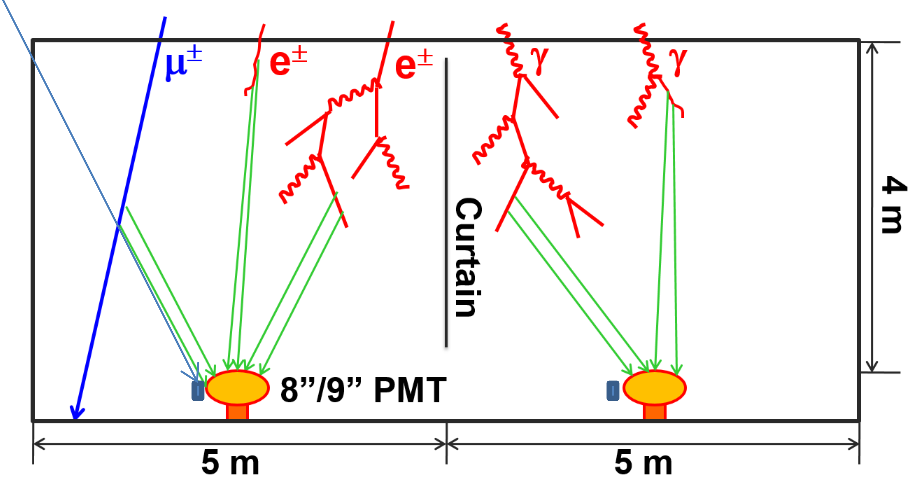
Water Cherenkov Detector Array

- 3 water ponds:
  - 78,000 m² in total;
  - 4 m effective depth;
  - 3120 cells, with an 8"/9" PMT in each cell;
  - Cells are partitioned with black curtains.



- WCDA++: 1"PMTs enhance Dynamic Range

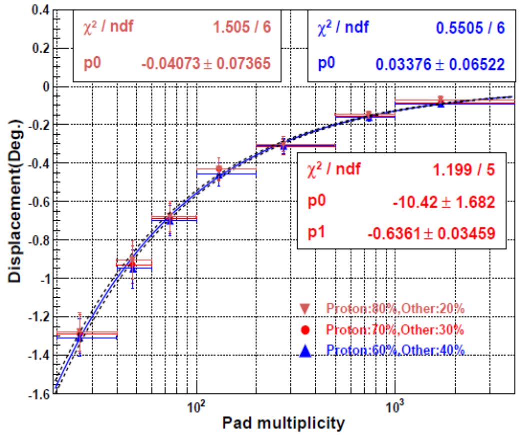


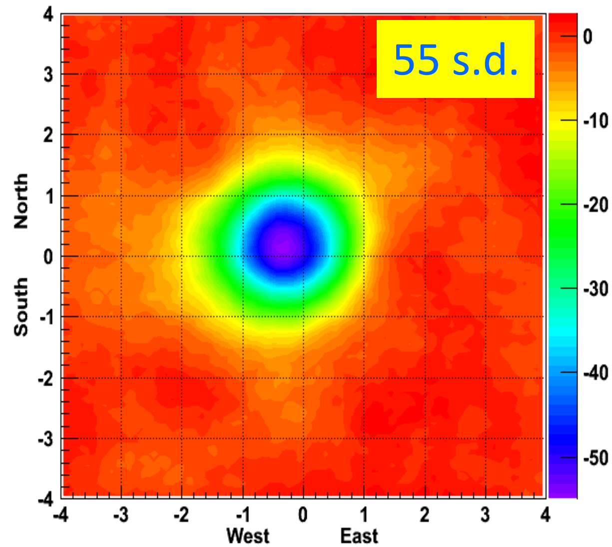


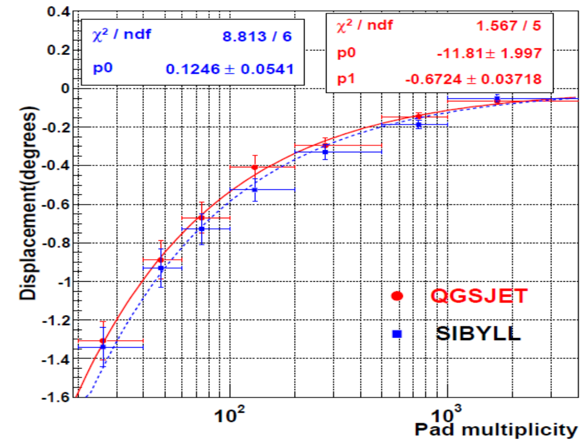
ARGO-YBJ : Moon Shadow displacement

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

1 – 30 (TeV/Z)







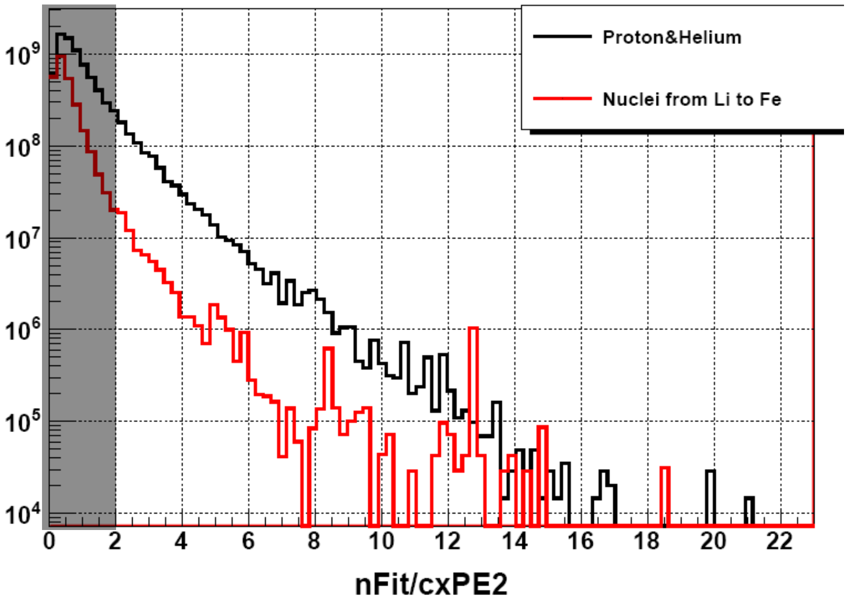
The energy scale uncertainty: smaller than 13%:

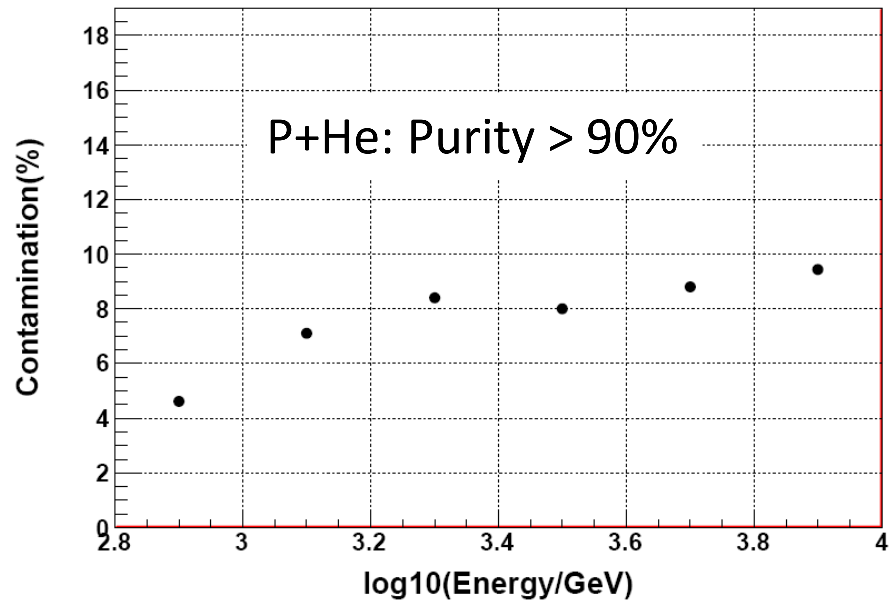
- the assumed primary CR chemical composition (7%)
- the uncertainties of different hadronic models (6%)

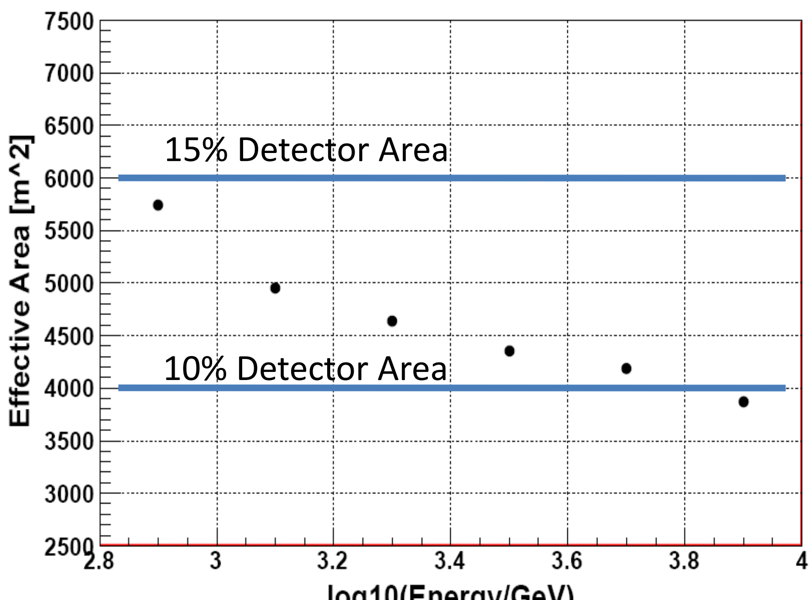
For LHAASO 1/4:

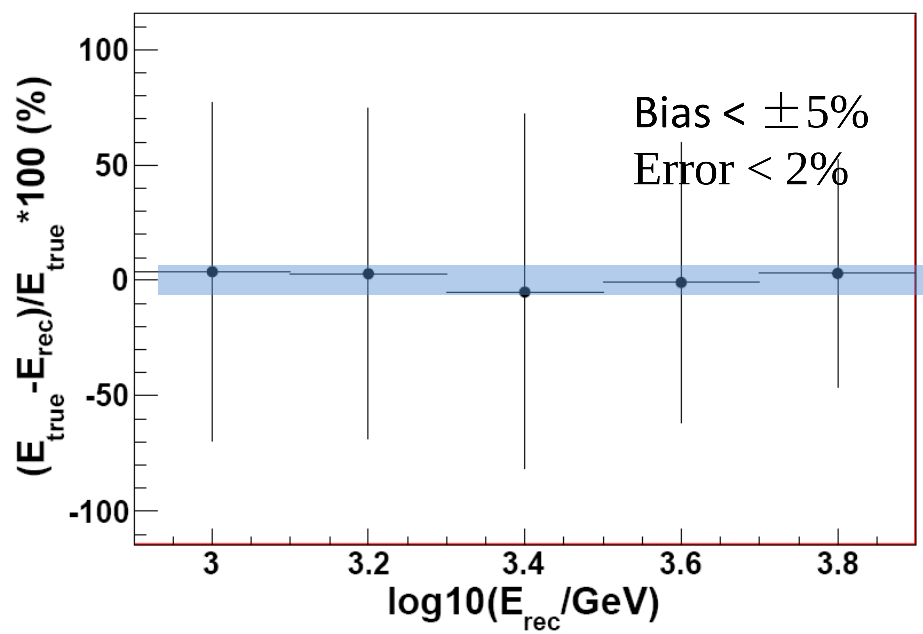
- Sensitivity: same after p+He selection
- Angular Resolution: 0.3°
- Pure Proton+Helium: 90% purity
- Hadronic Model: 5% (estimated)
- Overall: <10% within 1 year

Vertical events (θ<30°). The composition uncertainty is greatly suppressed.



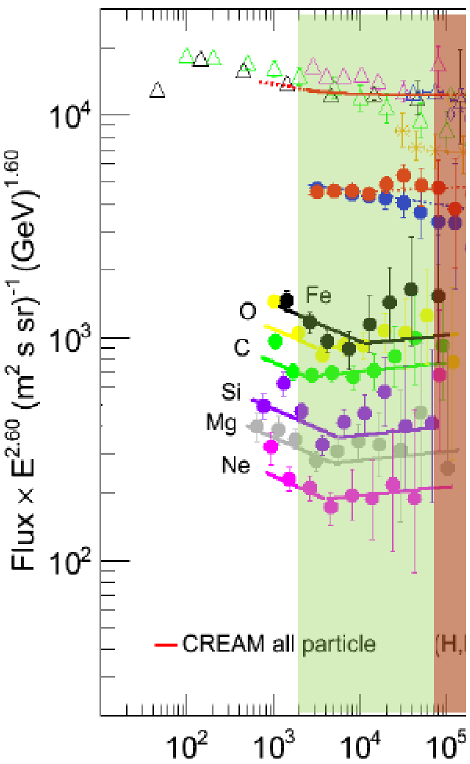




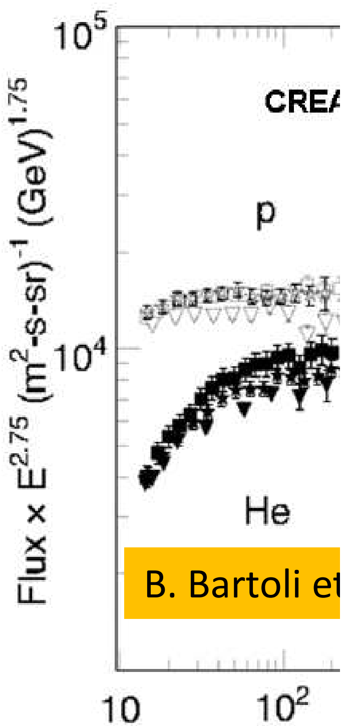


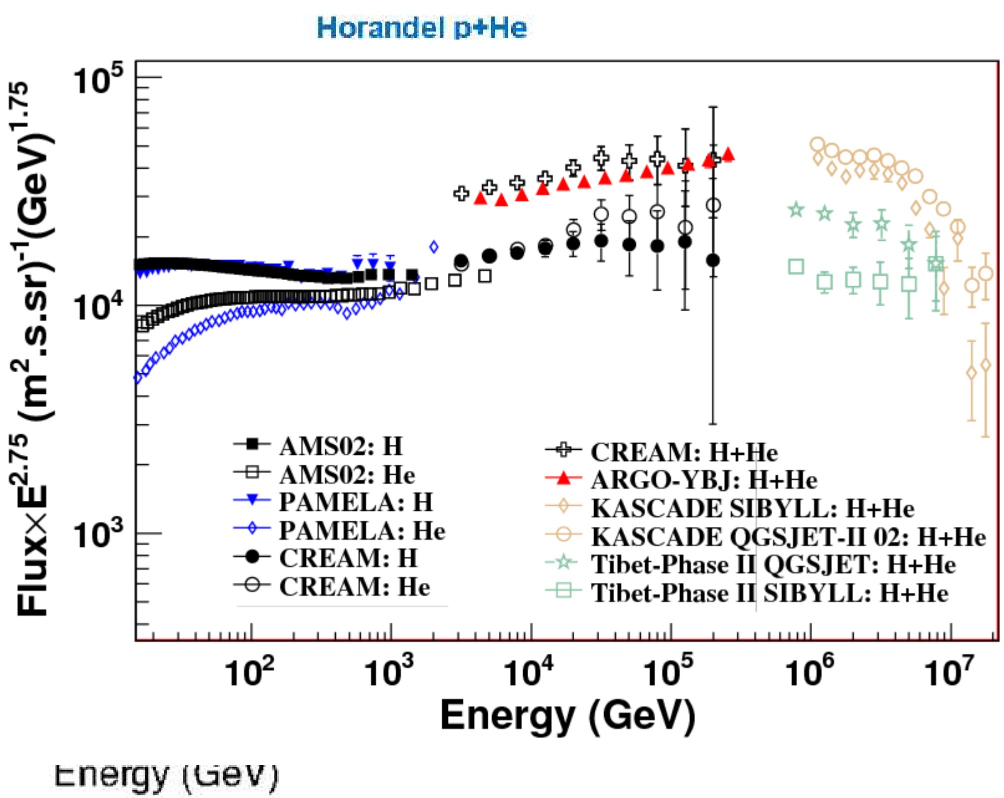
cross-calibration between the experiments

- Aim: To bridge between space borne and ground based experiments
- CREAM: energy spectrum of single element up to 100TeV
- ARGO-YBJ（H&He)： 7TeV-200TeV
- AMS02 confirmed the energy scale



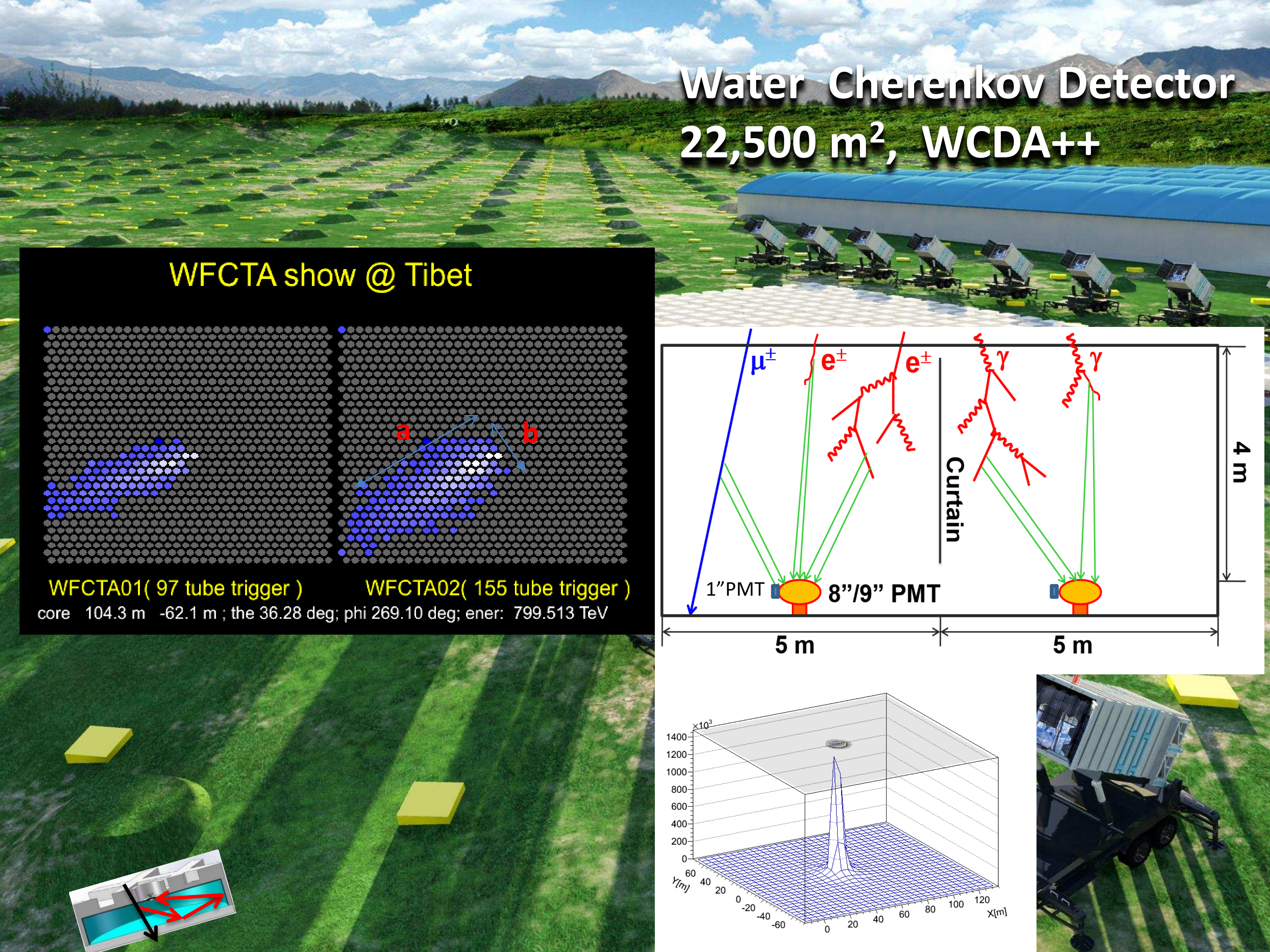
Y. S. Yoon et al., Astr





Selection for Individual Species (0.1-10 PeV)

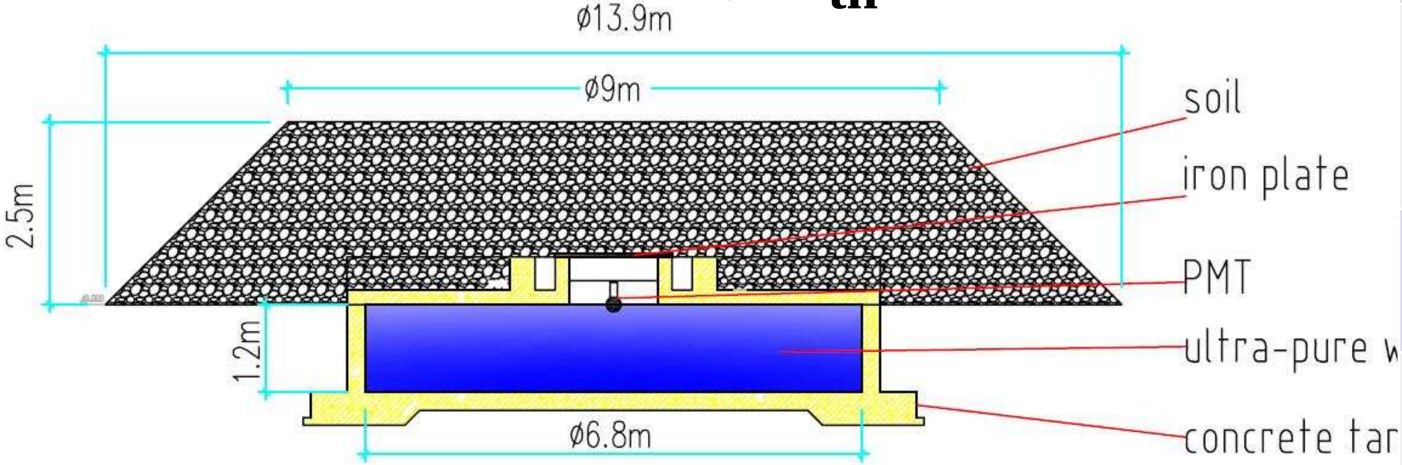
- Multi-parameter measurement of Air Showers

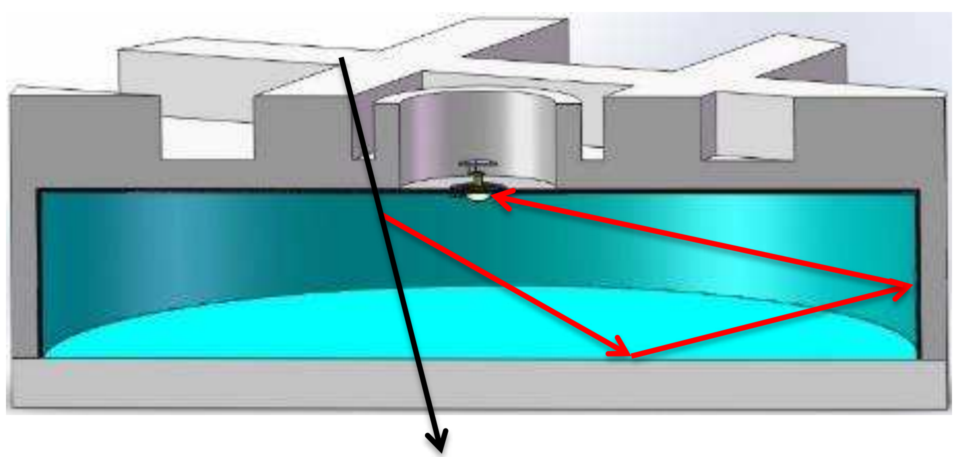


Water Cherenkov Detector
22,500 m^2, WCDA++
WFCTA show @ Tibet
a
b
WFCTA01(97 tube trigger)
WFCTA02(155 tube trigger)
core 104.3 m -62.1 m ; the 36.28 deg; phi 269.10 deg; ener: 799.513 TeV
$\mu^\pm$
$e^\pm$
$e^\pm$
γ
γ
Curtain
4 m
1"PMT
8"/9" PMT
5 m
5 m
$\times10^3$
1400
1200
1000
800
600
400
200
0
Y[m]
60 40 20 0 -20 -40 -60
X[m]
0 20 40 60 80 100 120

Muon Detector

- **Water Cherenkov detector underneath soil, E_{th} ~ 1 GeV**



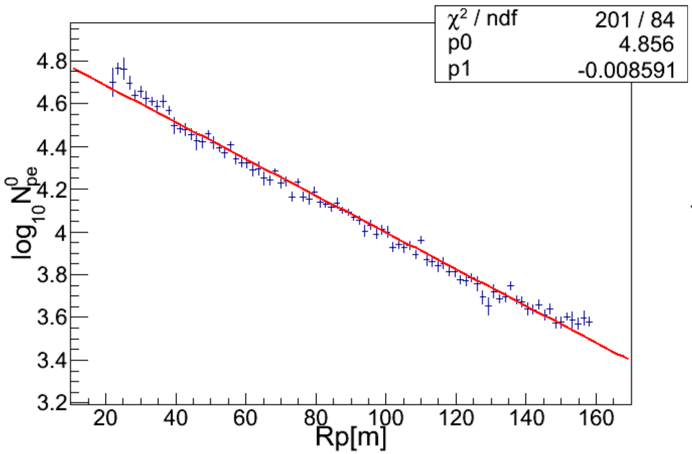


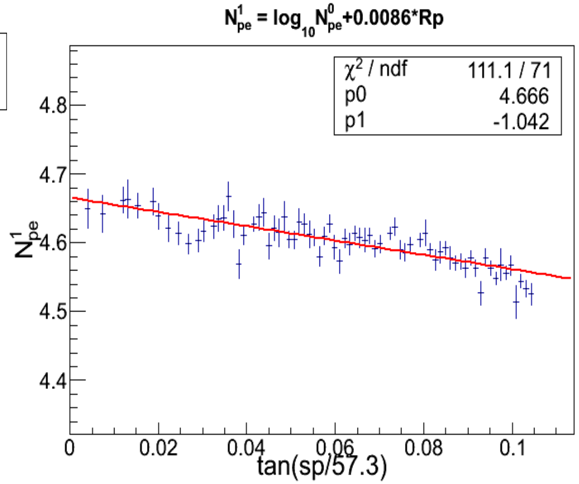
Item	Value
Area	36 m²
Detection efficiency	>95%
Purity of N_μ	>95%
Time resolution	<10 ns
Dynamic range	1-10,000 particles
Particle counting resolution	25% @ 1 particle 5% @ 10,000 particles
Aging (<20%)	>10 years
Spacing	30 m
number	1221

Parameters and performance

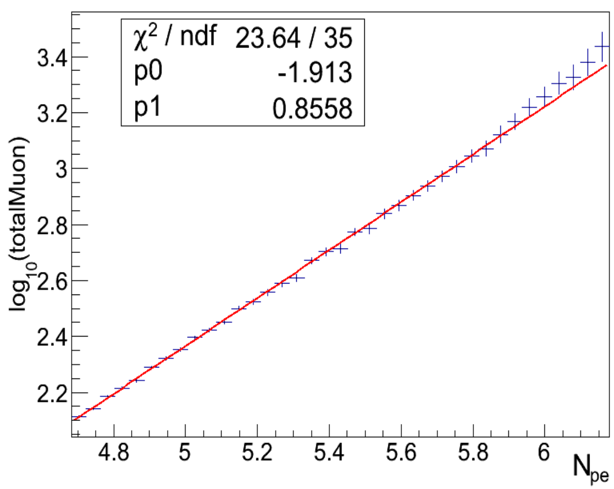
- Multi-parameter measurement of Air Showers
  - Shower energy: Air Cherenkov Telescopes
  - Shower Image Shape (p_3): Air Cherenkov Telescopes
  - Energy flux near AS core (p_1): WCDA++
  - Muon content (p_2): Muon Detector Array
  - Remaining AS Energy (p_4): WCDA & WCDA++
- Shower Core Resolution: 3m (WCDA++)
- Shower Direction Resolution: 0.3° (WCDA)

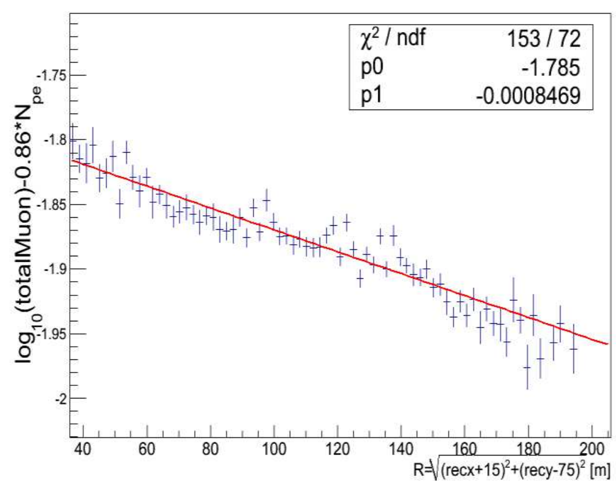
Energy Estimator: N^0_{pe}
R_p, incidence angle dependence



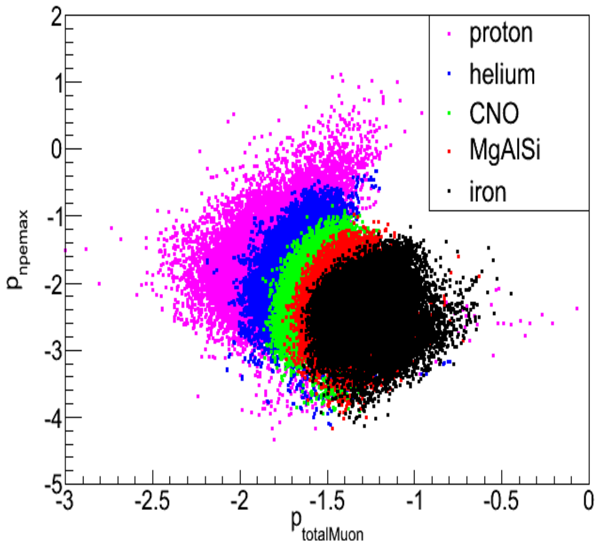


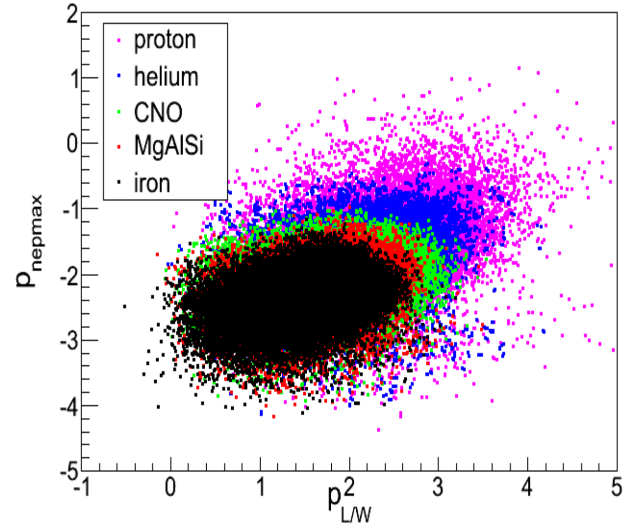
Muon Content: Total N_μ
Energy ,core distance dependence

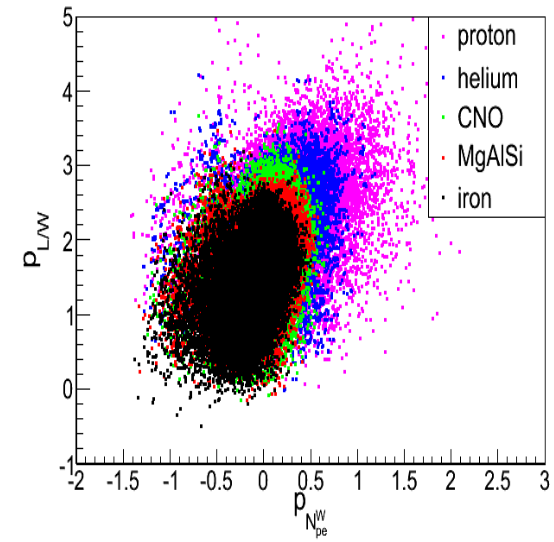


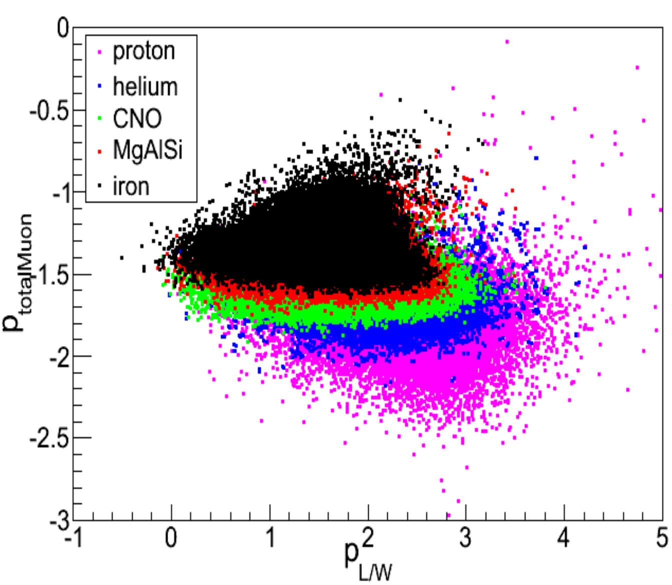


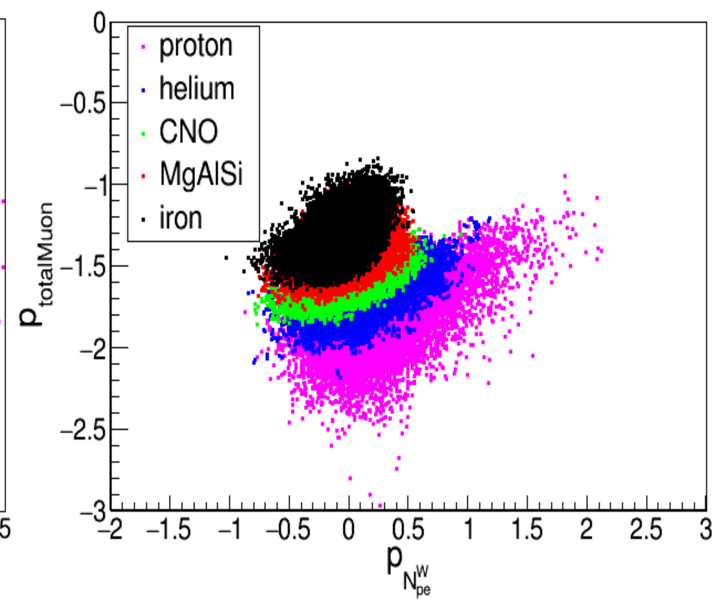
Multi-parameter Analysis







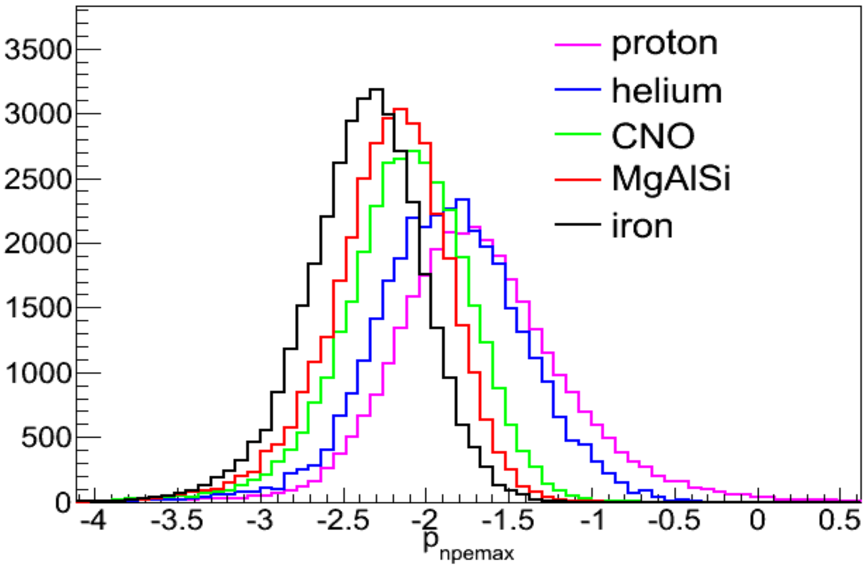


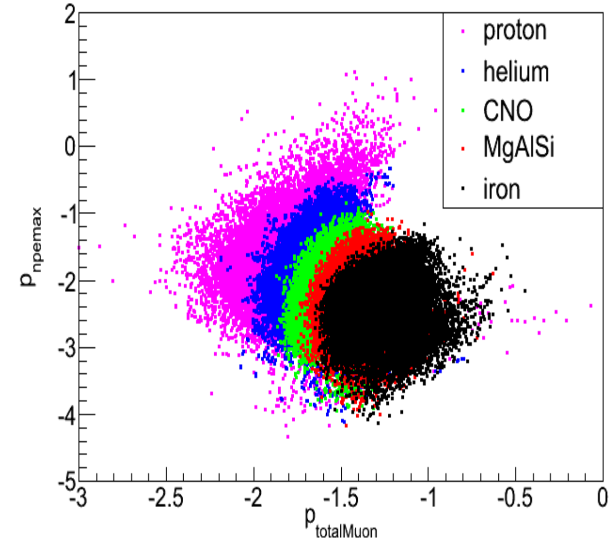


One-to-one Correlation

An example:

μ-content vs. E-flux at core

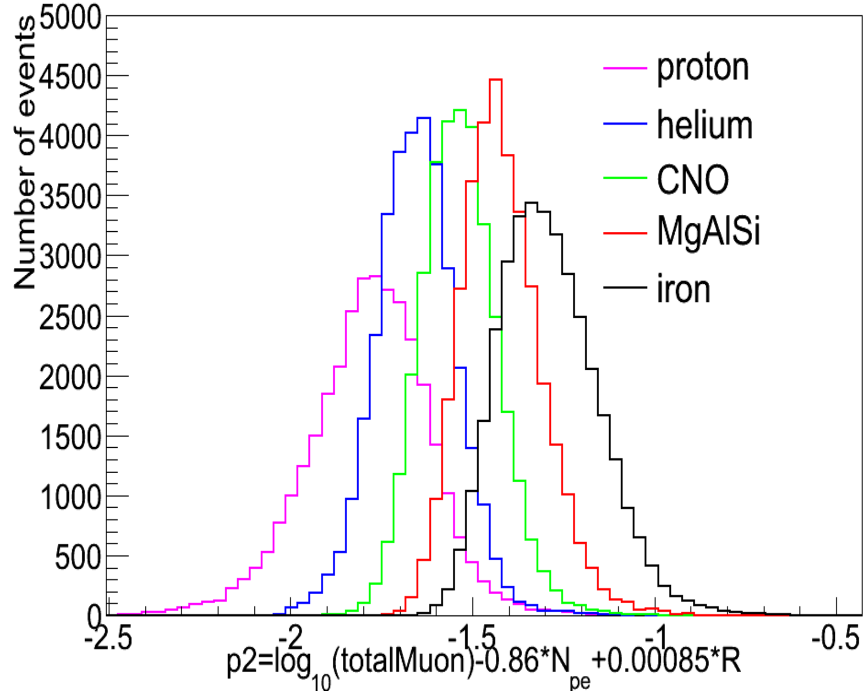


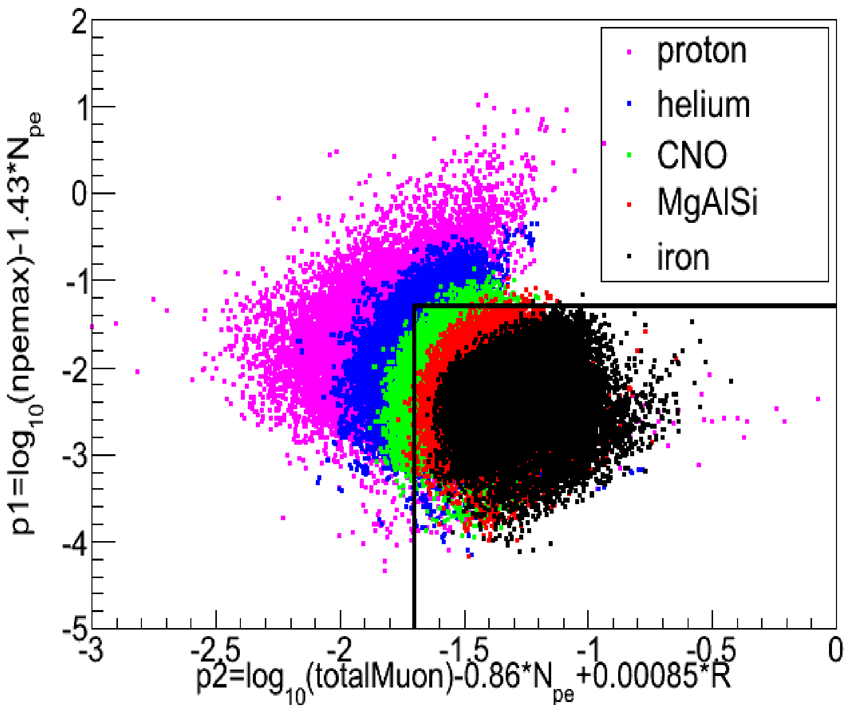


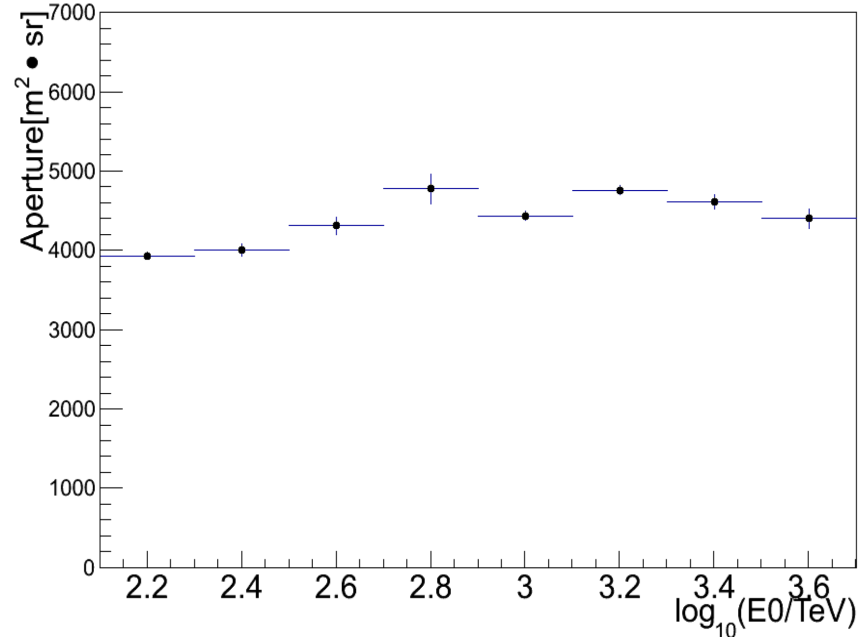
p2 = log10(totalMuon)+0.00085*R - 0.86*Npe

$$R=\sqrt{(recx+15)^2+(recy-75)^2}$$

p3 = L/W-0.018*Rp+0.287*Npe





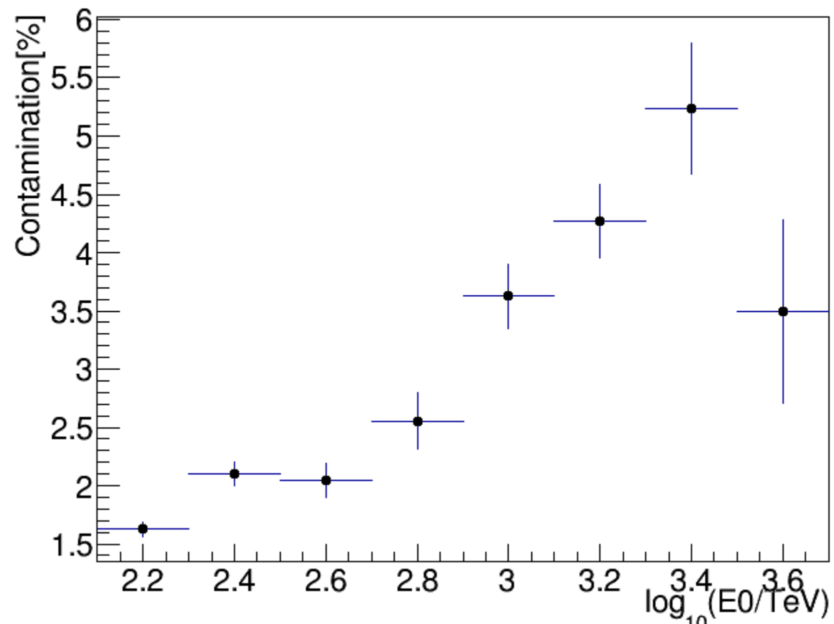


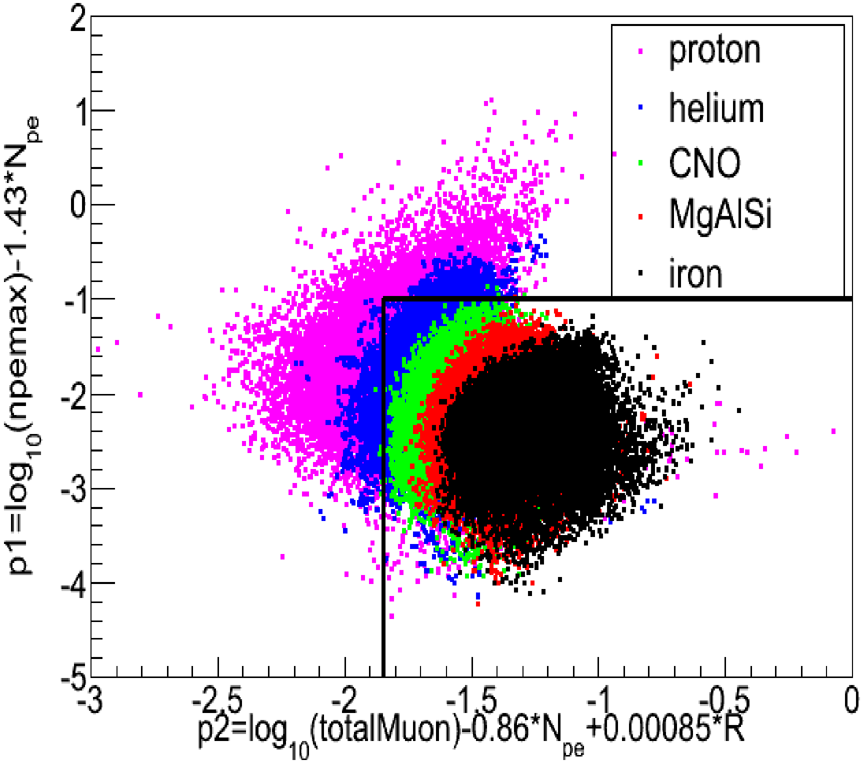
CutA: for p+He

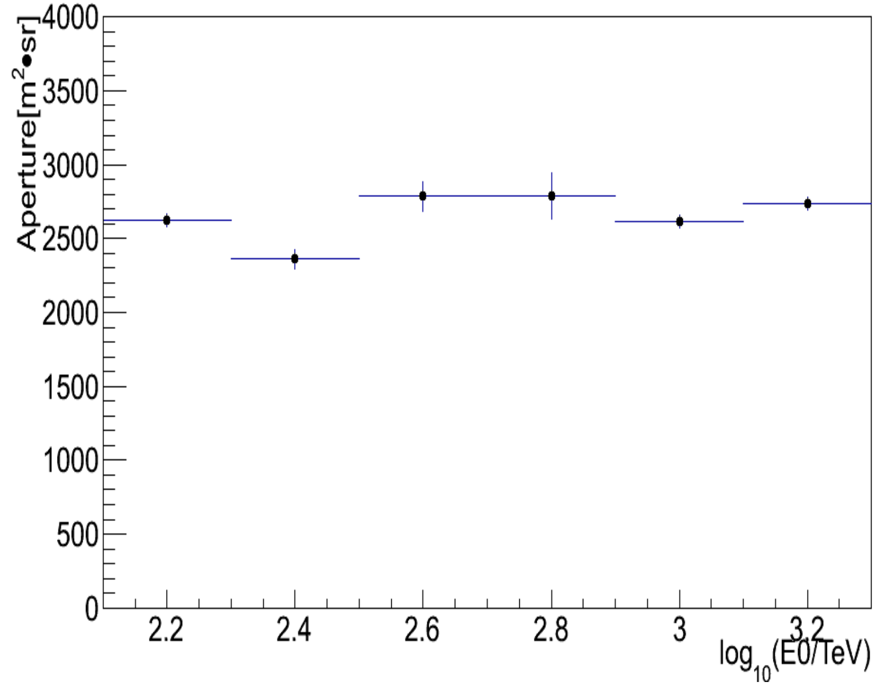
p1>-1.28 or p2<-1.70

aperture: 12 tels

contamination :Horandel model





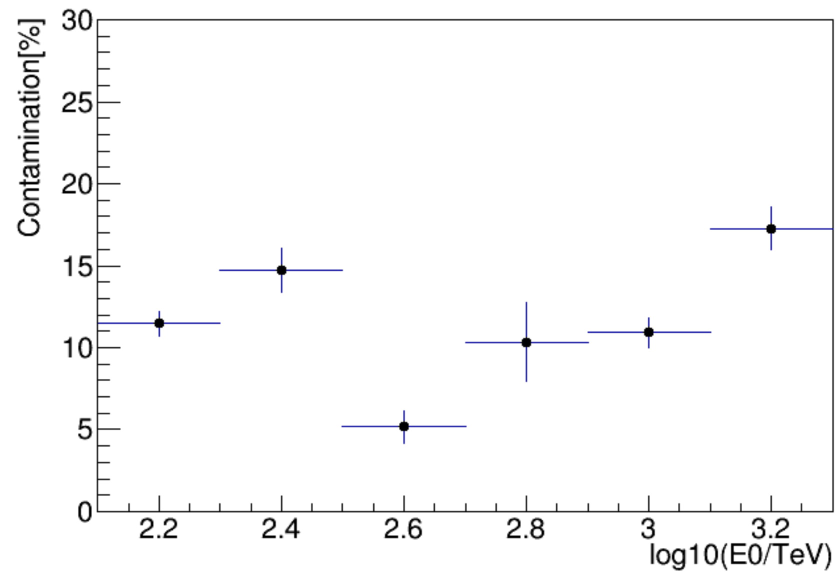


CutA: for p

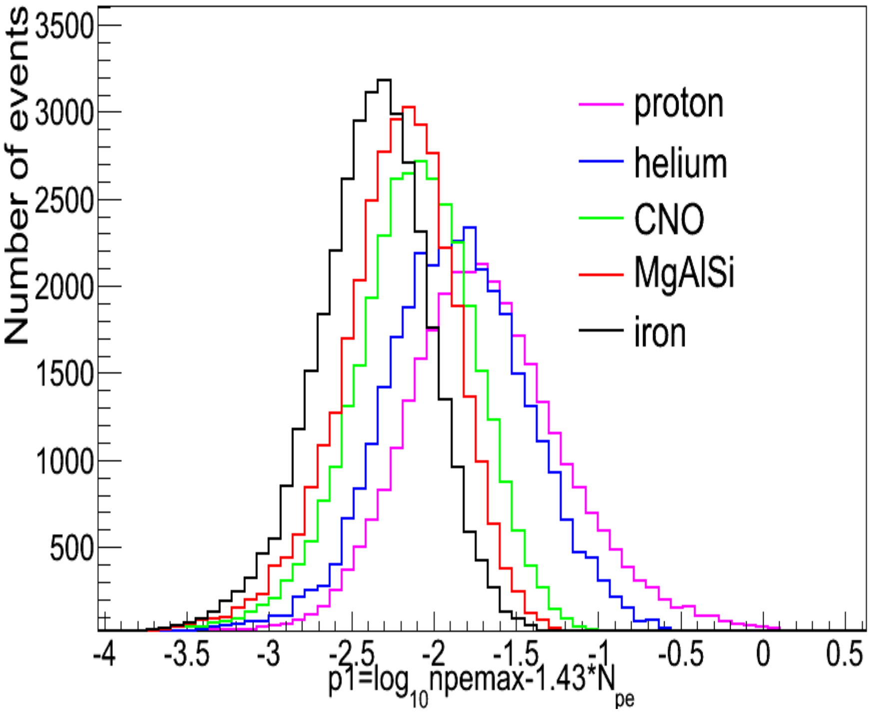
p1>-1. or p2<-1.85

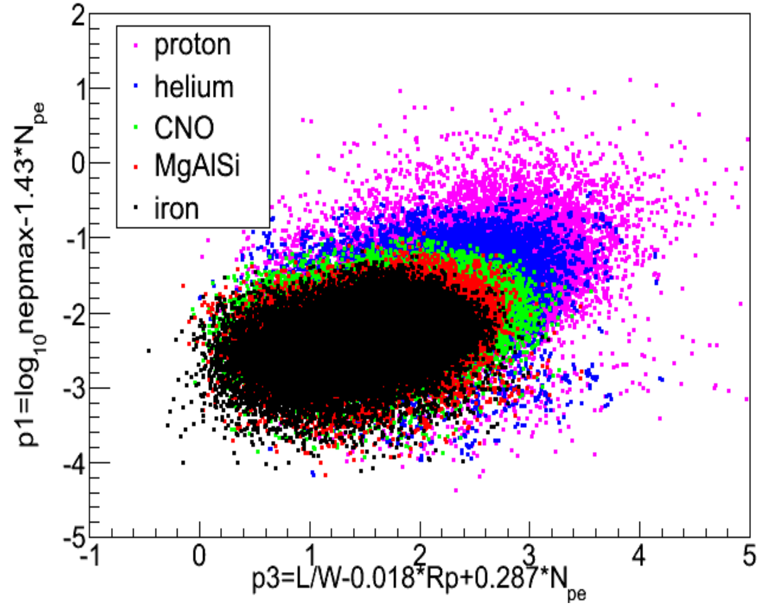
aperture: 12 tels

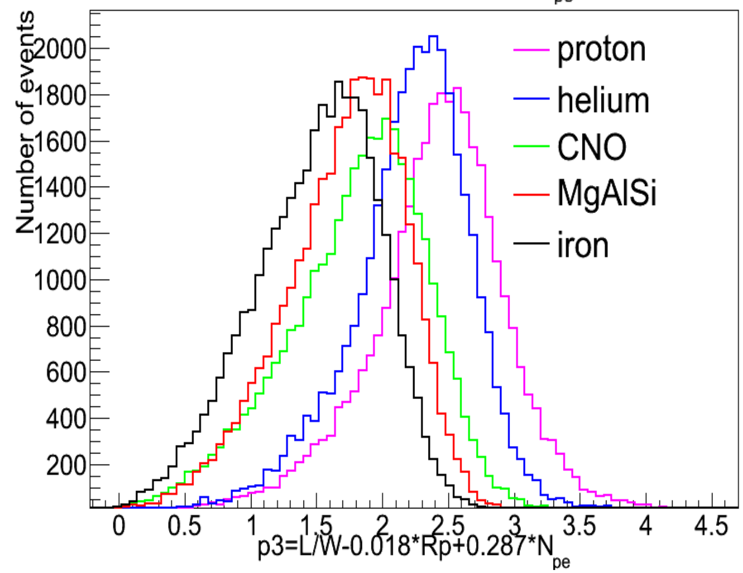
contamination :Horandel model



The other example: Cherenkov image shape vs. E-flux near the core







P1 = log10(npemax)-1.43*Npe

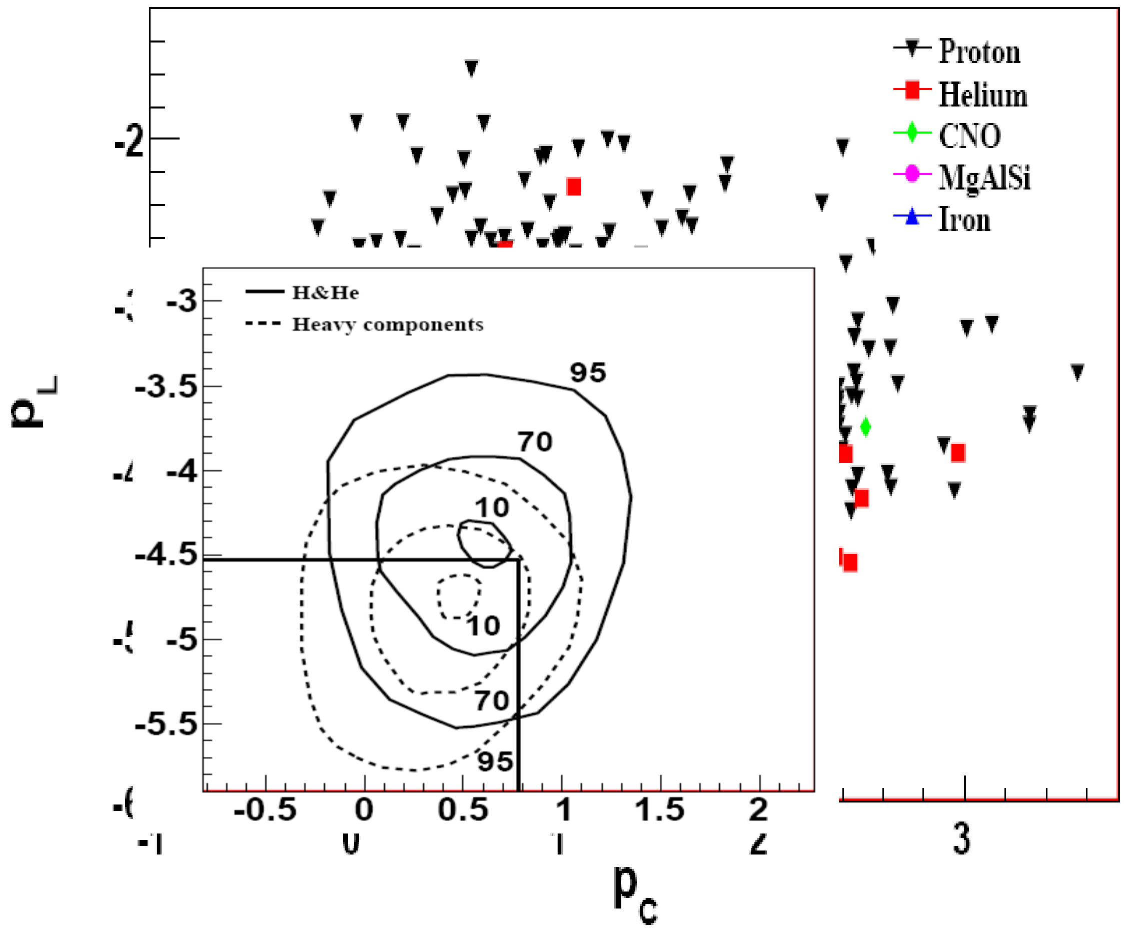
p3 = L/W-0.018*Rp+0.287*Npe

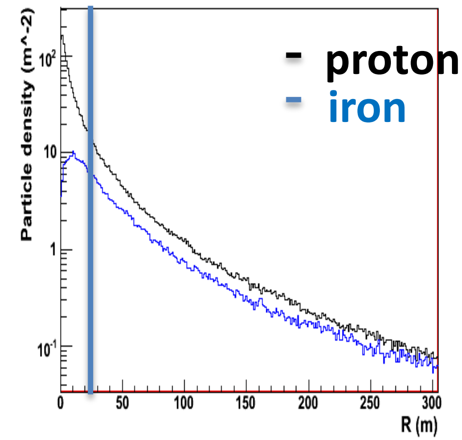
The similar analysis is used in ARGO-YBJ and C-telescope joint experiment with 1/40 aperture

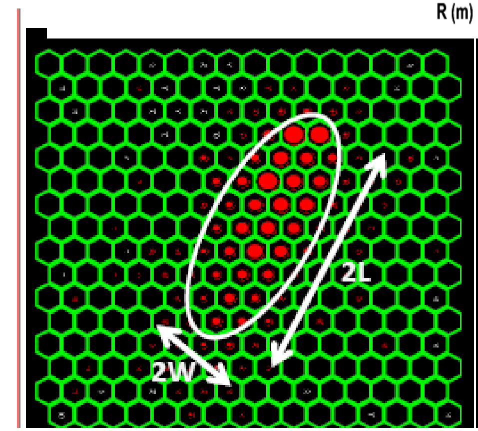
RPC array (ARGO-YBJ) & Cherenkov Telescope (LHAASO)

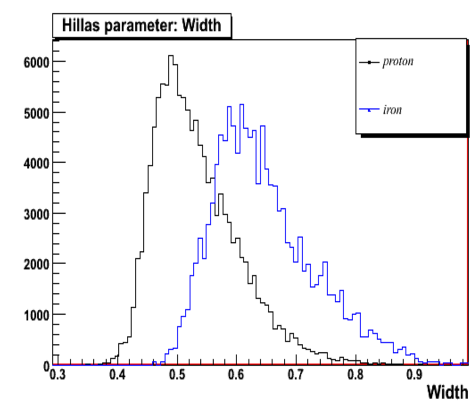
$$p_L = log_{10}N_{max} - 1.44 log_{10}N_0^{pe}$$

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

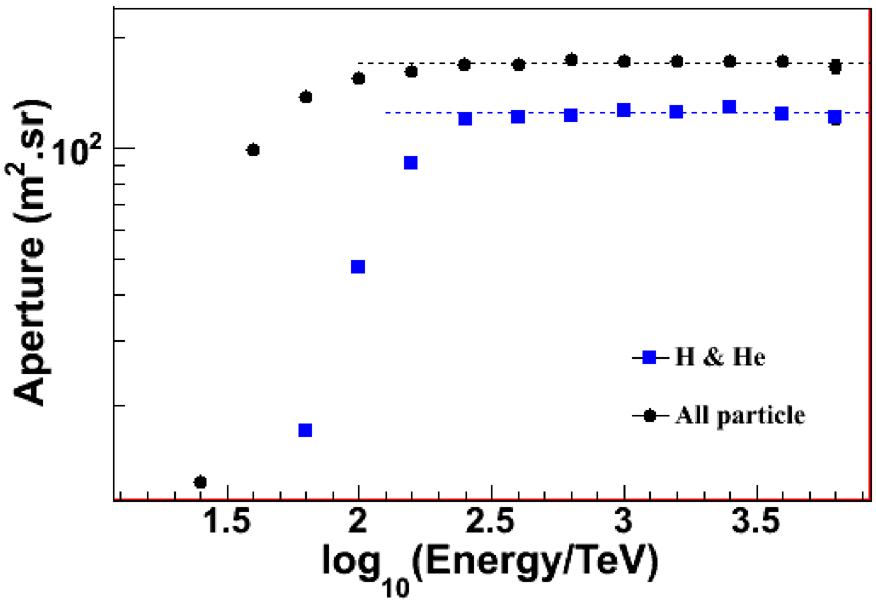


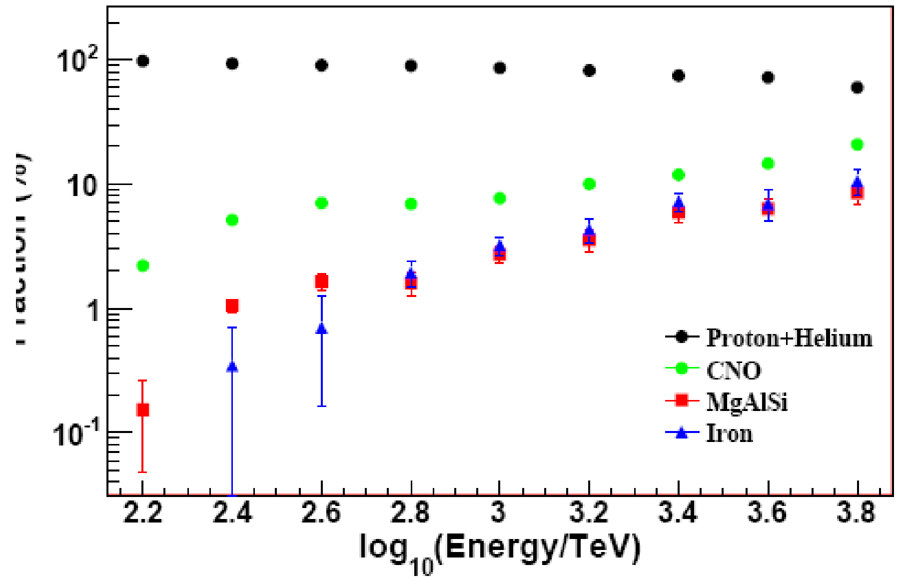






J.R. Hörandel, Modern Physics Letter A, 22, 1533 (2007)

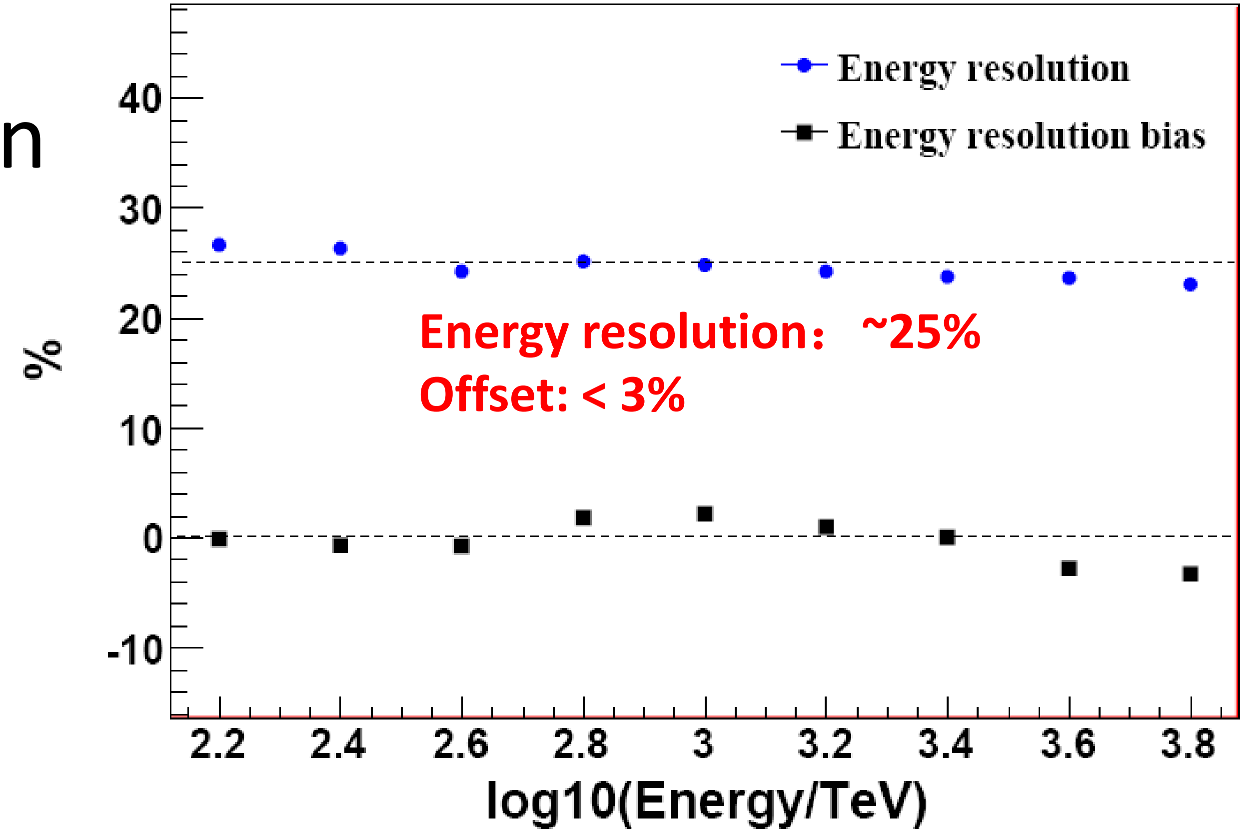


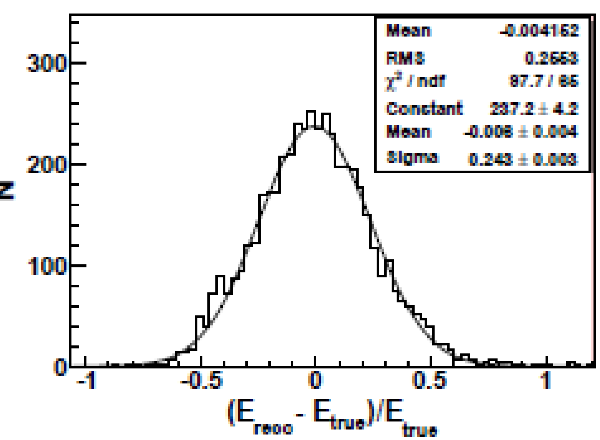


- A simple geometrical calculation gives an aperture of 163 m^2 sr
- The aperture of H&He: ~120 m^2 sr above 300 TeV;
- The purity of H&He showers: ~93% below 700 TeV;
- The contamination of heavy nuclei increases with energy: 13% @ 1 PeV, gradually increases to 27% @ 3 PeV;
- The contamination of heavy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

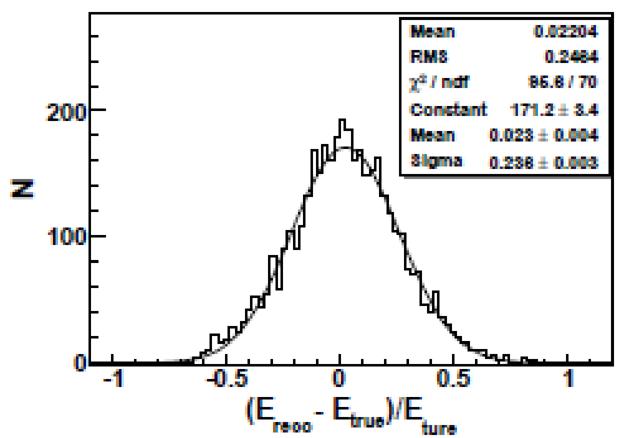
E-reconstruction

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

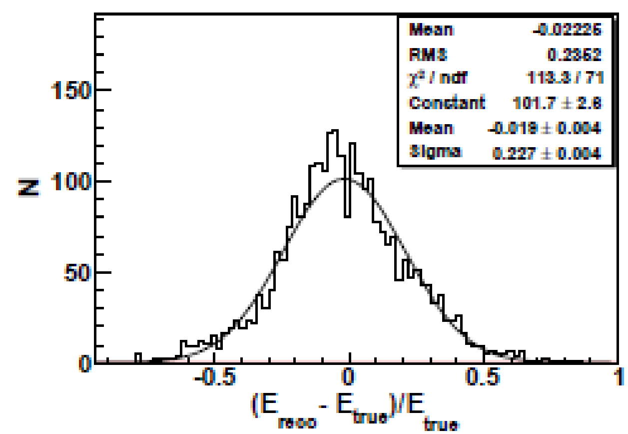




300 TeV

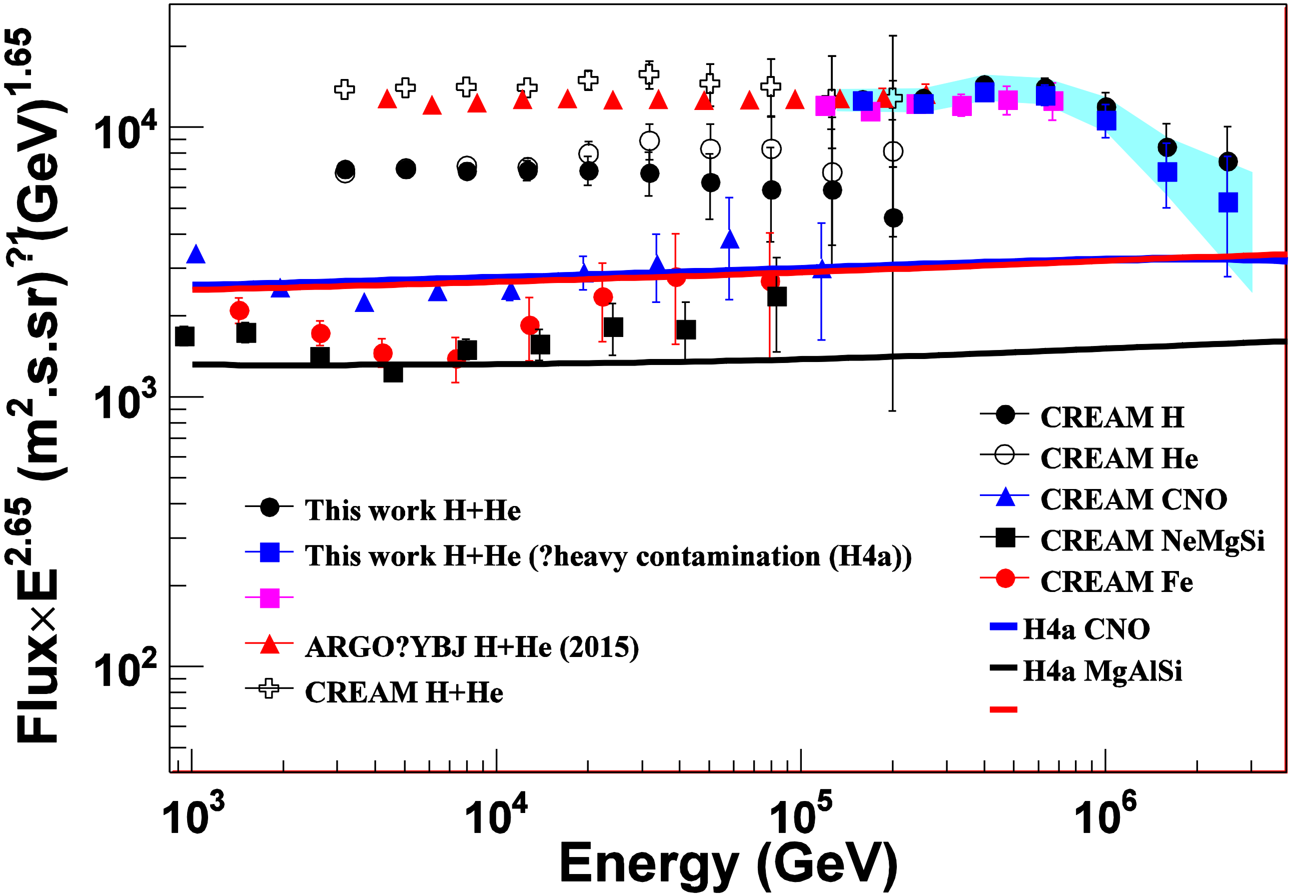


1 PeV



3 PeV

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



- The knee of H&He spectrum at **(700±230)** TeV is clearly measured
  - Broken power law fits data well with indices

    -2.62 ± 0.05 and -3.58 ± 0.50 below and above the knee

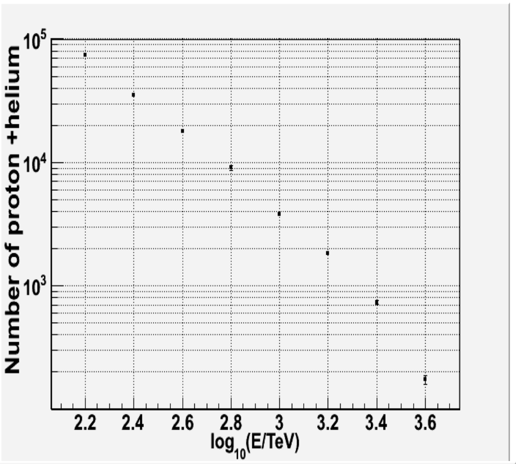
    (with heavy contamination subtracted J.R. Hörandel, Modern Physics Letter A, 22, 1533 (2007)

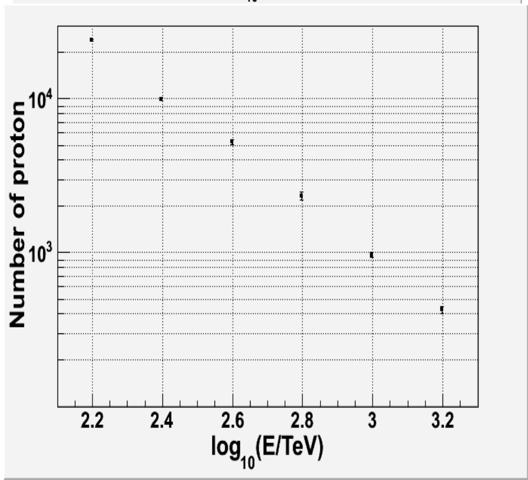
    -2.56 ± 0.05 and -3.24 ± 0.36 below and above the knee

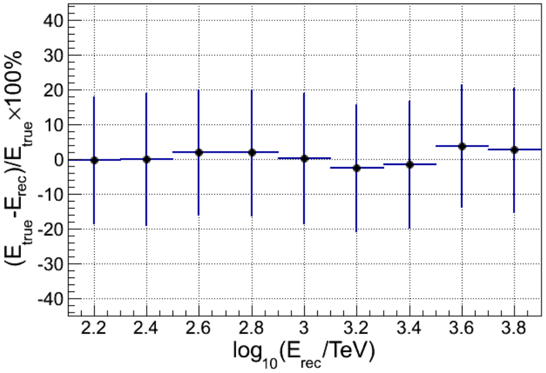
    (without heavy contamination subtracted)
  - Below the knee, consistent with ARGO-YBJ, which is consistent with CREAM

Prospects for knees at <10 PeV

- With a factor of 40 of the aperture and at least two more parameters, LHAASO will analysis the data using neural network technique & measure
  - Pure proton spectrum with purity > 90%
  - P+He spectrum with purity > 95%
  - Fe spectrum with purity > 70% (estimated)
  - ……
- Energy Scale can be cross checked at lower energy end by the space borne experiments

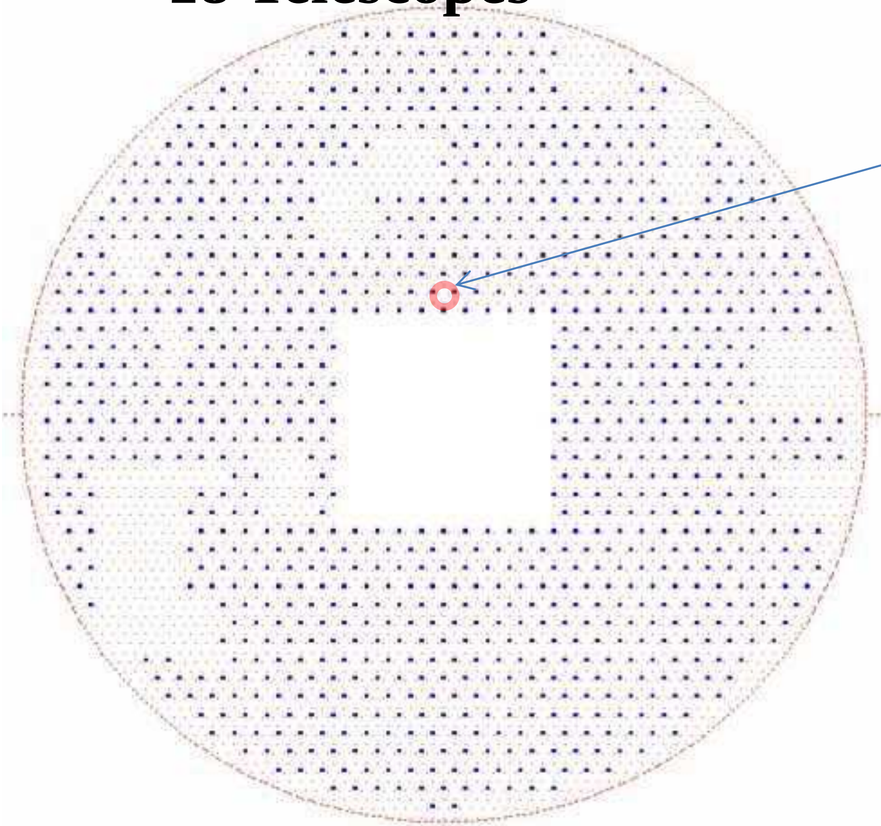


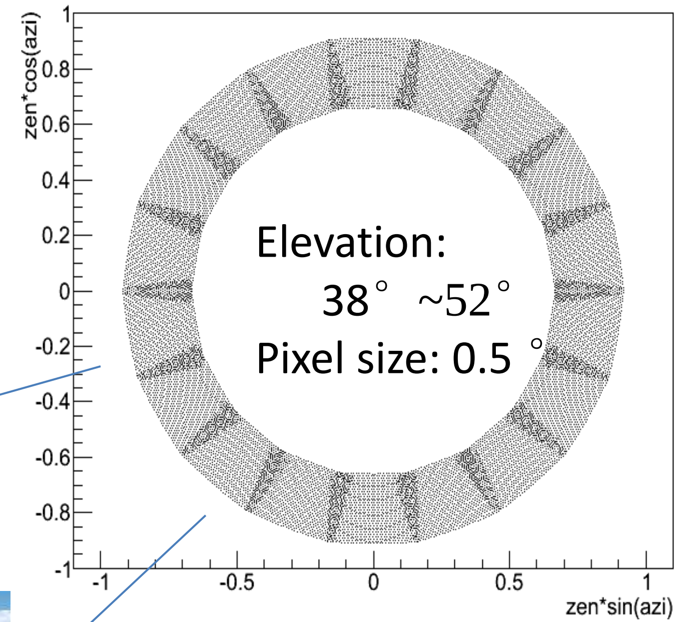


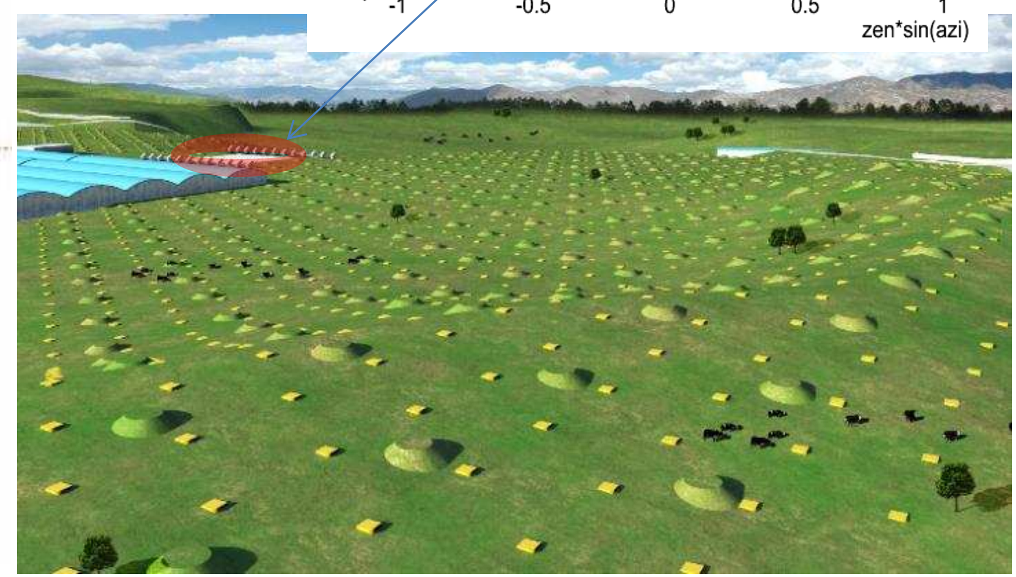


The Scintillation + MD Array + WFCTA for CRs above 10 PeV

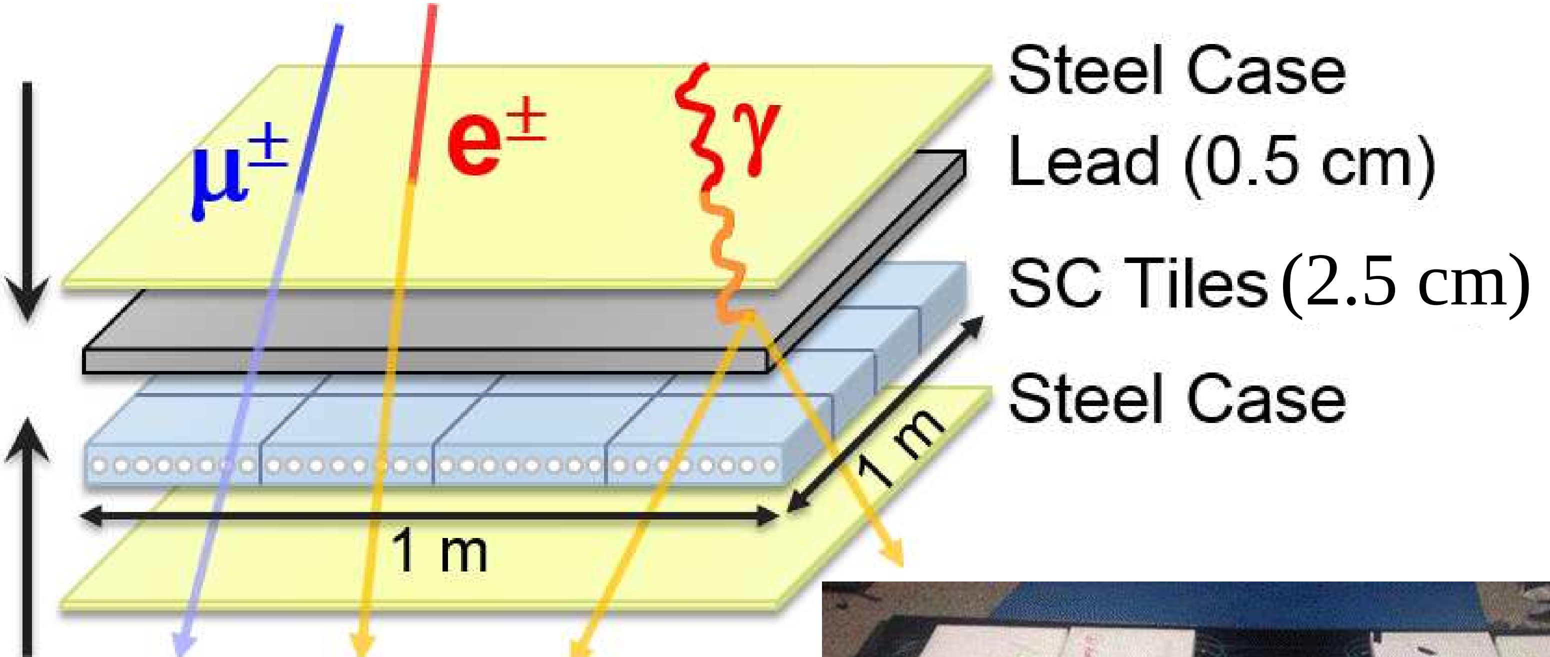
- **5195 EDs, 1 m^2 each, 15m spacing**
- **1146 MDs, 36 m^2 each, 30m spacing**
- **18 Telescopes**





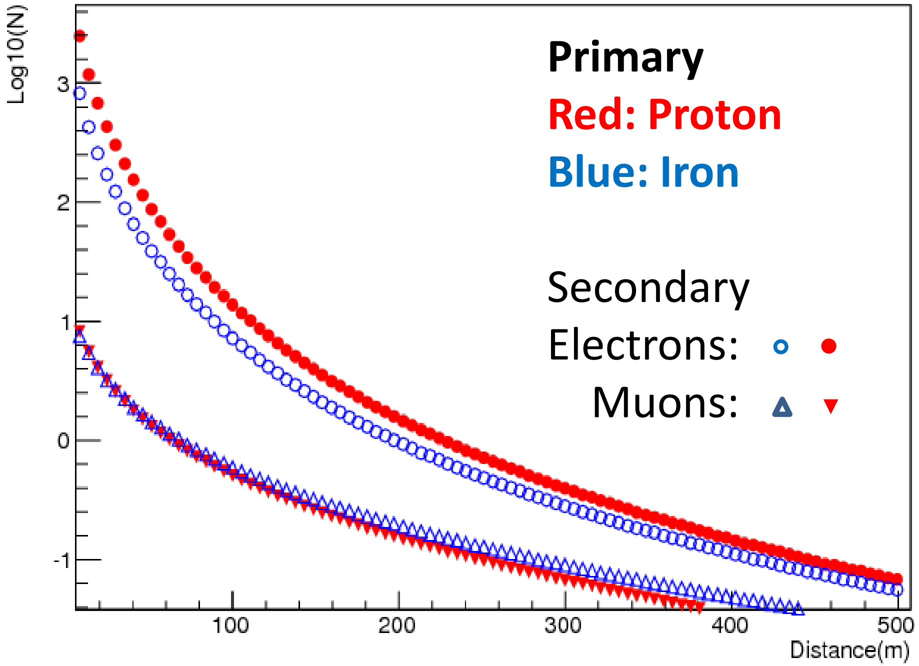


Electromagnetic Particle Detector (ED) using sacintillator plat/WS fiber/PMT

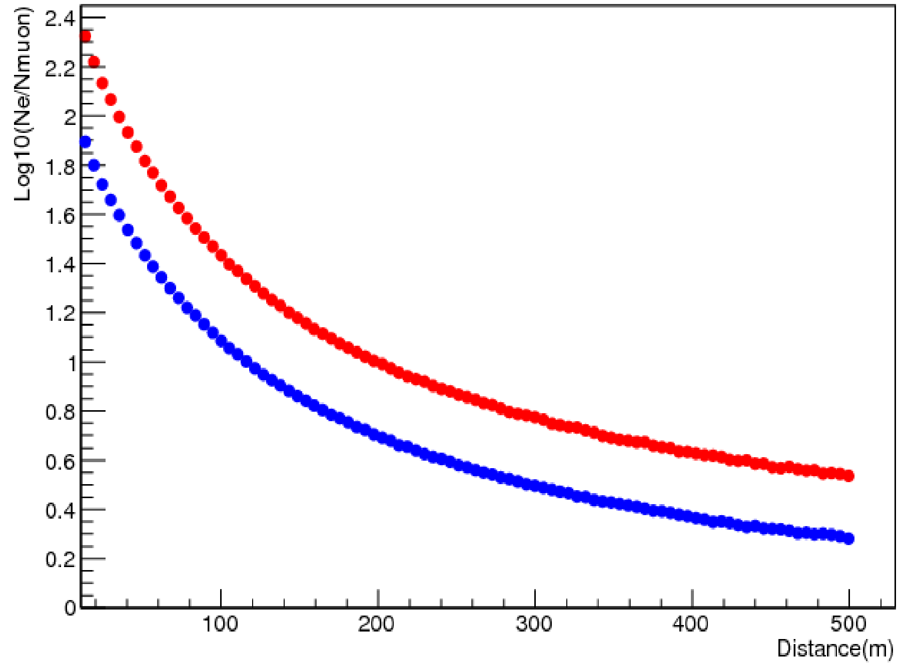


- **Non-uniformity <10%**
  - **tiles: <5%**
  - **fibers: 11%/√32**
  - **PMT gains: adjustable HV**

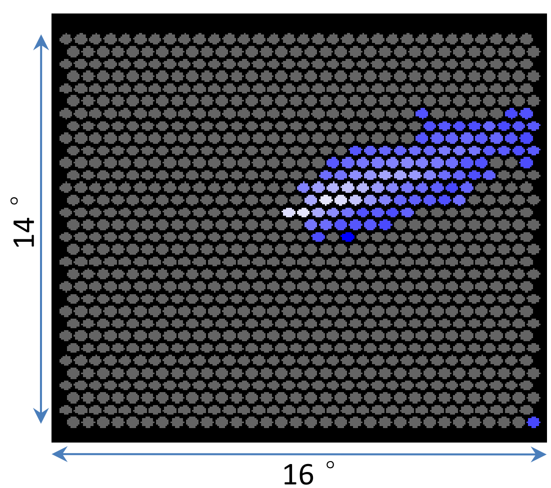
The lateral distribution

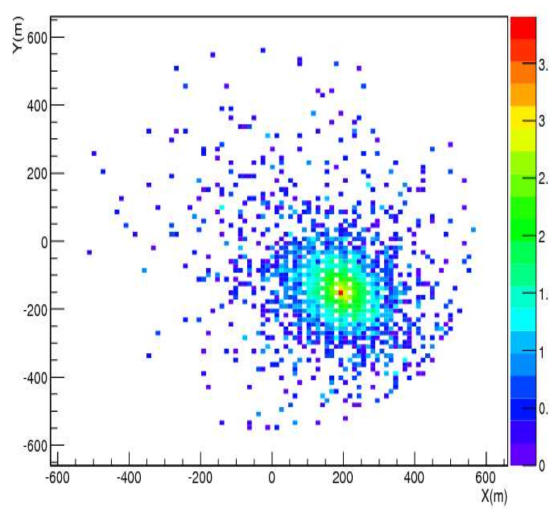


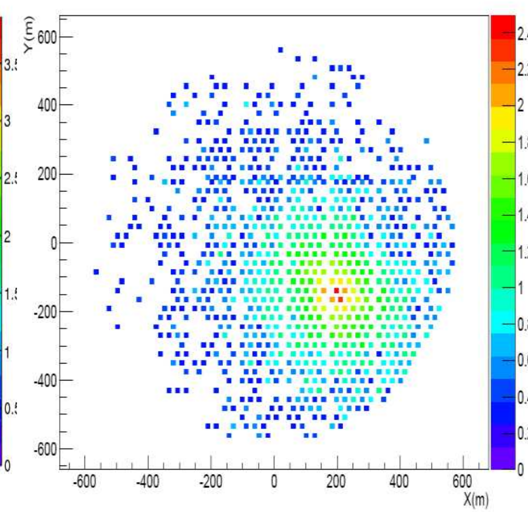
Lateral distribution of electron and muon



Lateral distributions of Log10(N_{ch}/N_{μ})

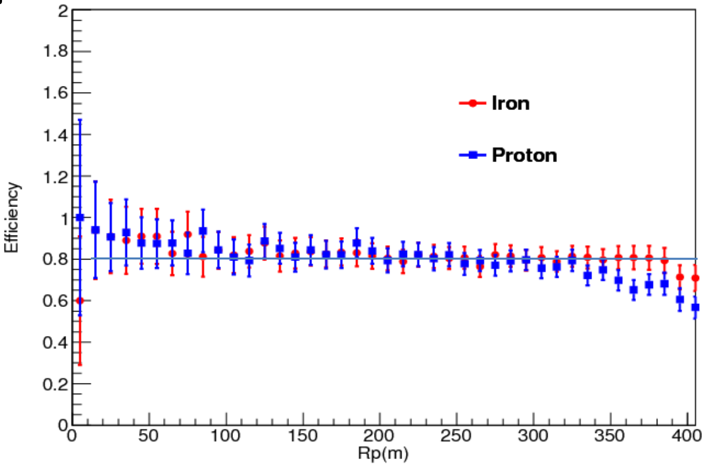






Prospects

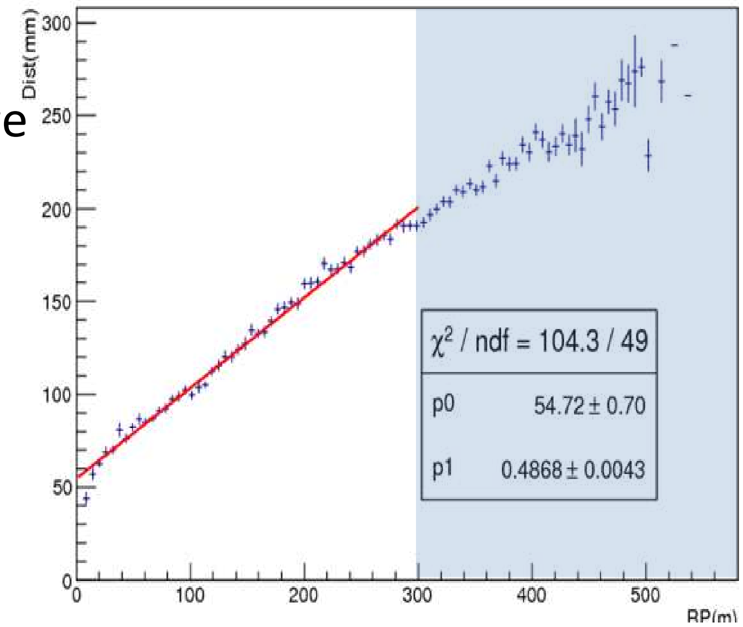
- AS core resolution: <3 m (EDA)
- AS arrival direction resolution: ≤0.2° (EDA)
- Trigger efficiency for E>7 PeV: >80% up to 350 m
- Energy resolution for clean Fe samples: ~15% (CT)
- E-scale: overlap with the combined experiment of WFCTA + WCDA++

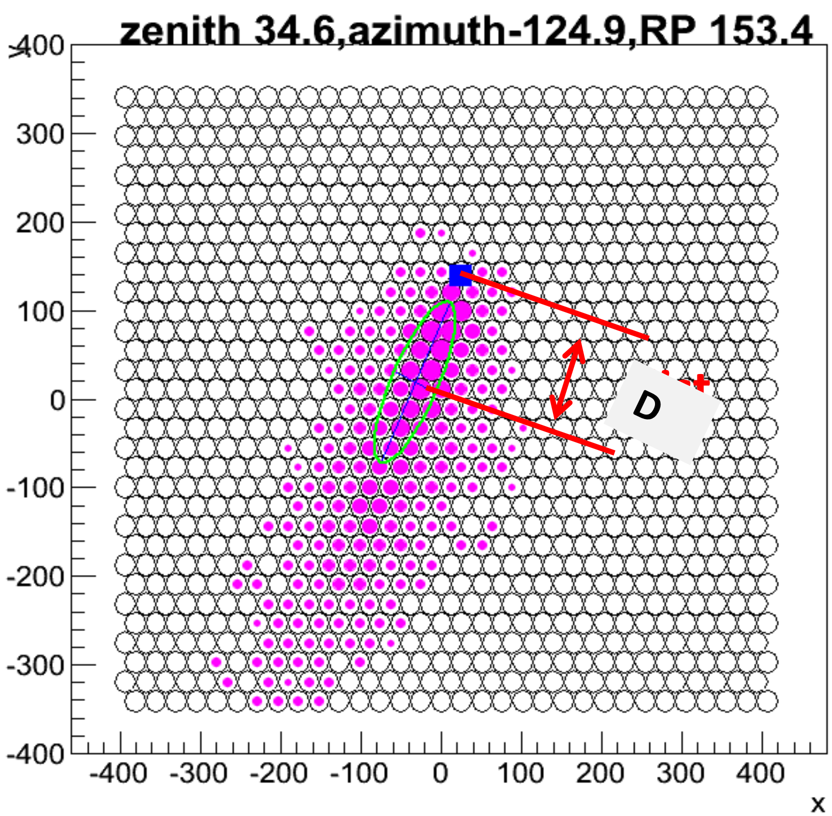


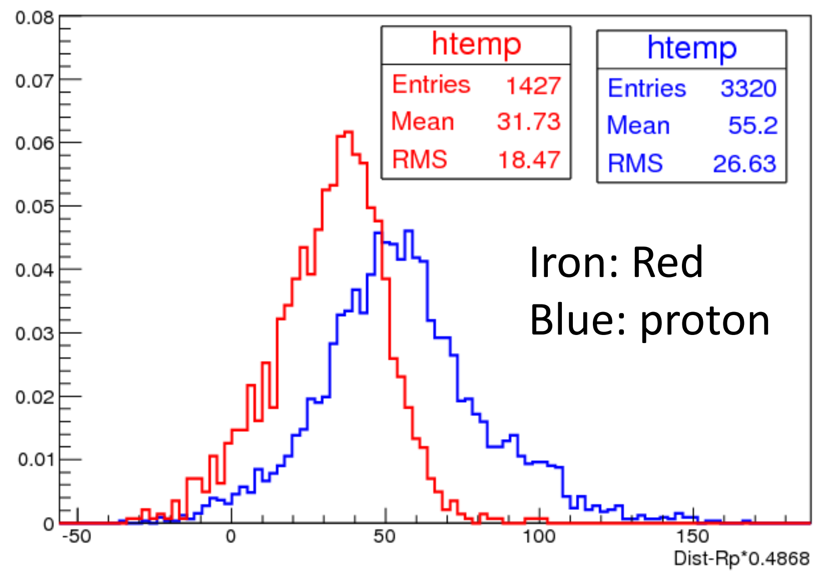
X_{max} Reconstruction

- **D**: angular distance between the shower direction and the gravity center of the image
- **D** is R_p dependent
- For events with R_p smaller than 300m,

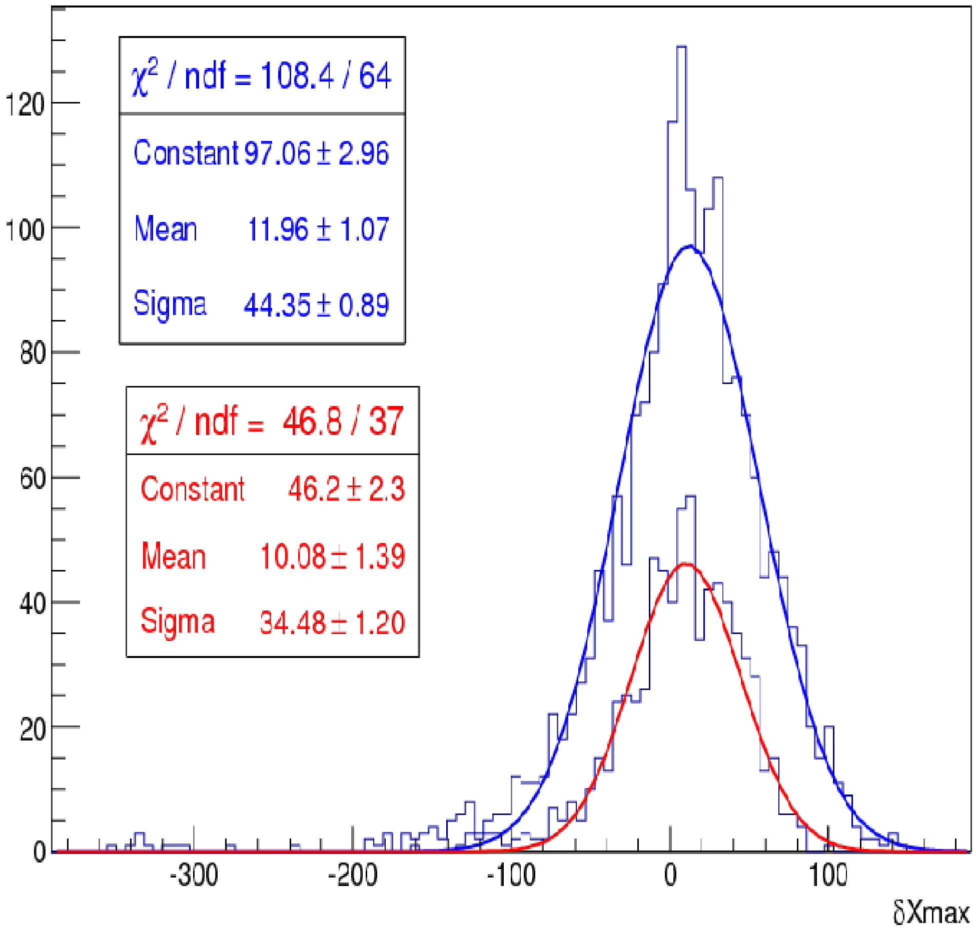
$$D \sim 0.4868 * R_p \ (0<R_p<300)$$

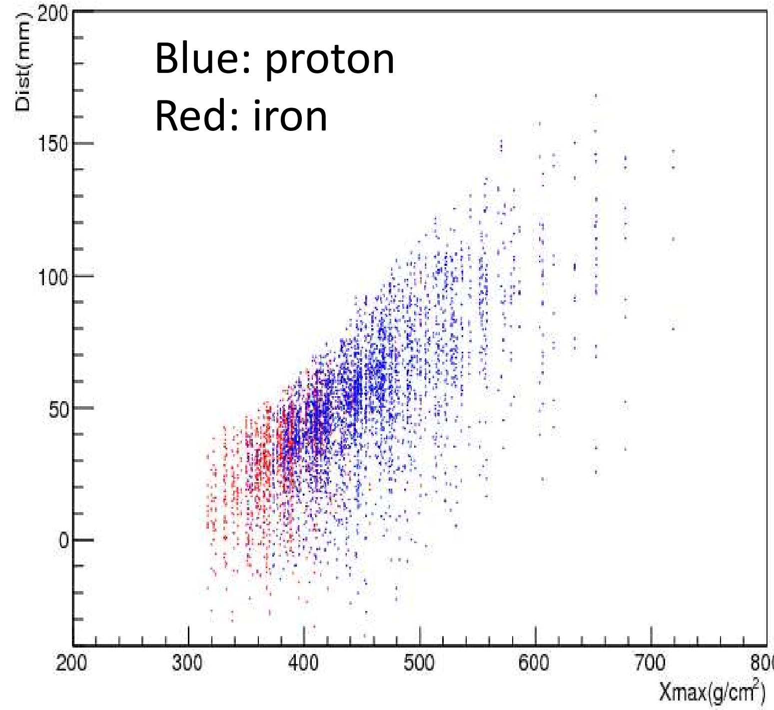


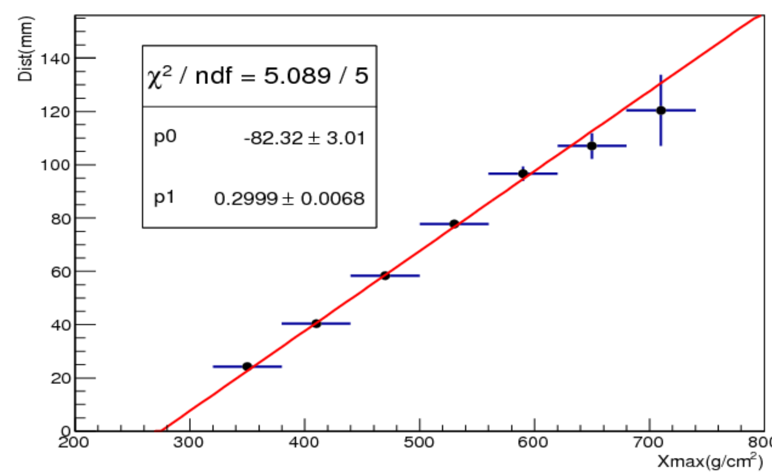




- X_{max} reconstruction:
  $((D-0.4868*R_p)+82.32)/0.2999$

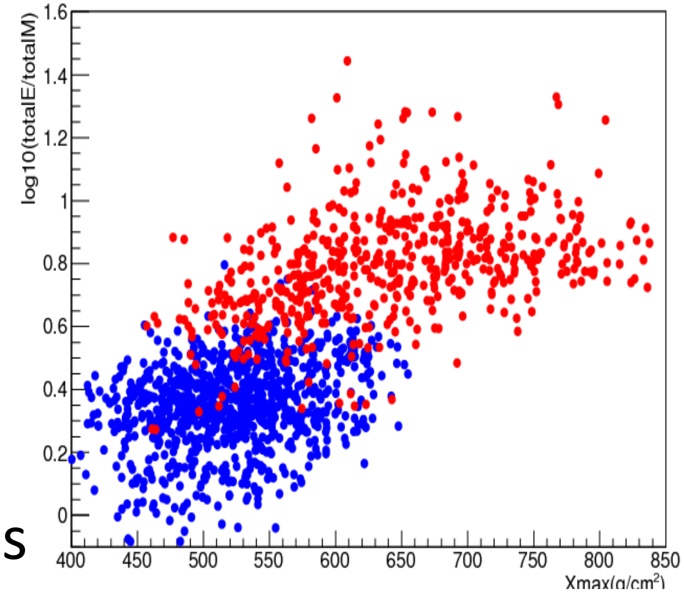


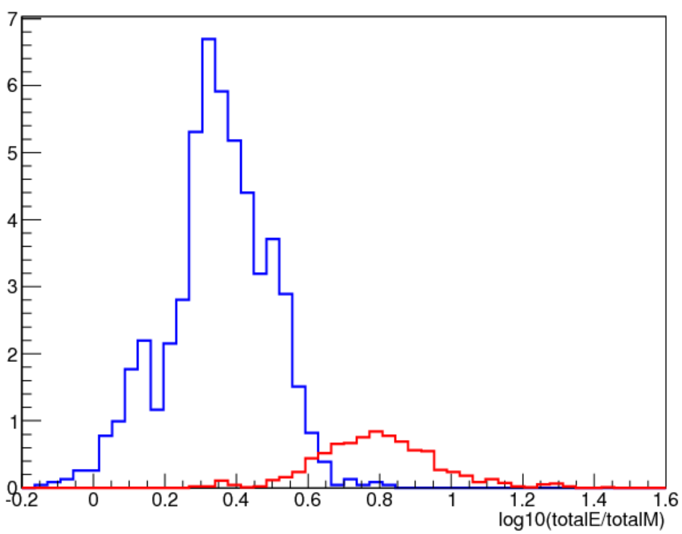


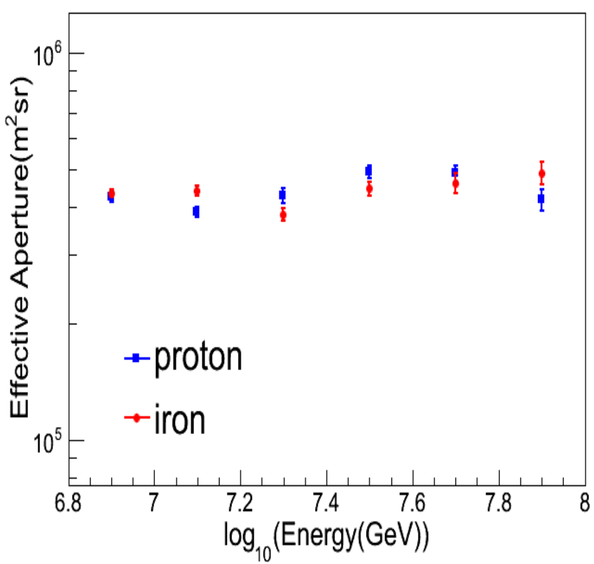


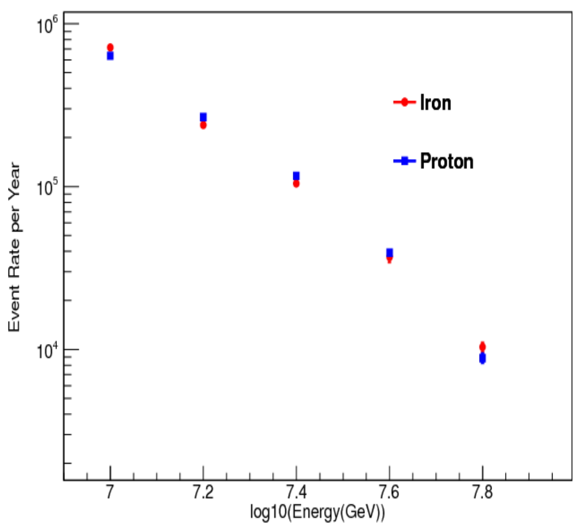
Unbiased measurement to species

- Aperture: ~0.45X10^6 m^2sr
- Iron selection:
  - μ-content and X_{max} with a resolution about 50 g/cm^2
  - Expected Fe event rate: 0.2M/yr with a duty cycle of 5%
- The goal: the spectrum of pure Fe or mixed heavy components and their knees









Status: Civil Construction Schedule

- Conceptual design and feasibility are approved two weeks ago
- **Environment impact review is passed.**
- Electrical power line construction in bidding procedure
  - 35kV power line for 29km and a transferring station 35 kV to 10 kV at site
  - 4 months to finish construction work after the company being selected in bidding
- Water cannels construction is also under bidding
- The road connecting to the main transportation high way is already built
- Sites of 1200 MD's are surveyed. The field preparation is actually started
- The deep geo-survey for WCDA pools is planned to be done in summer
  - The construction of the No.1 pool and tanks will start in **2017**

Construction and installation of muon-detectors
& environment protection facility



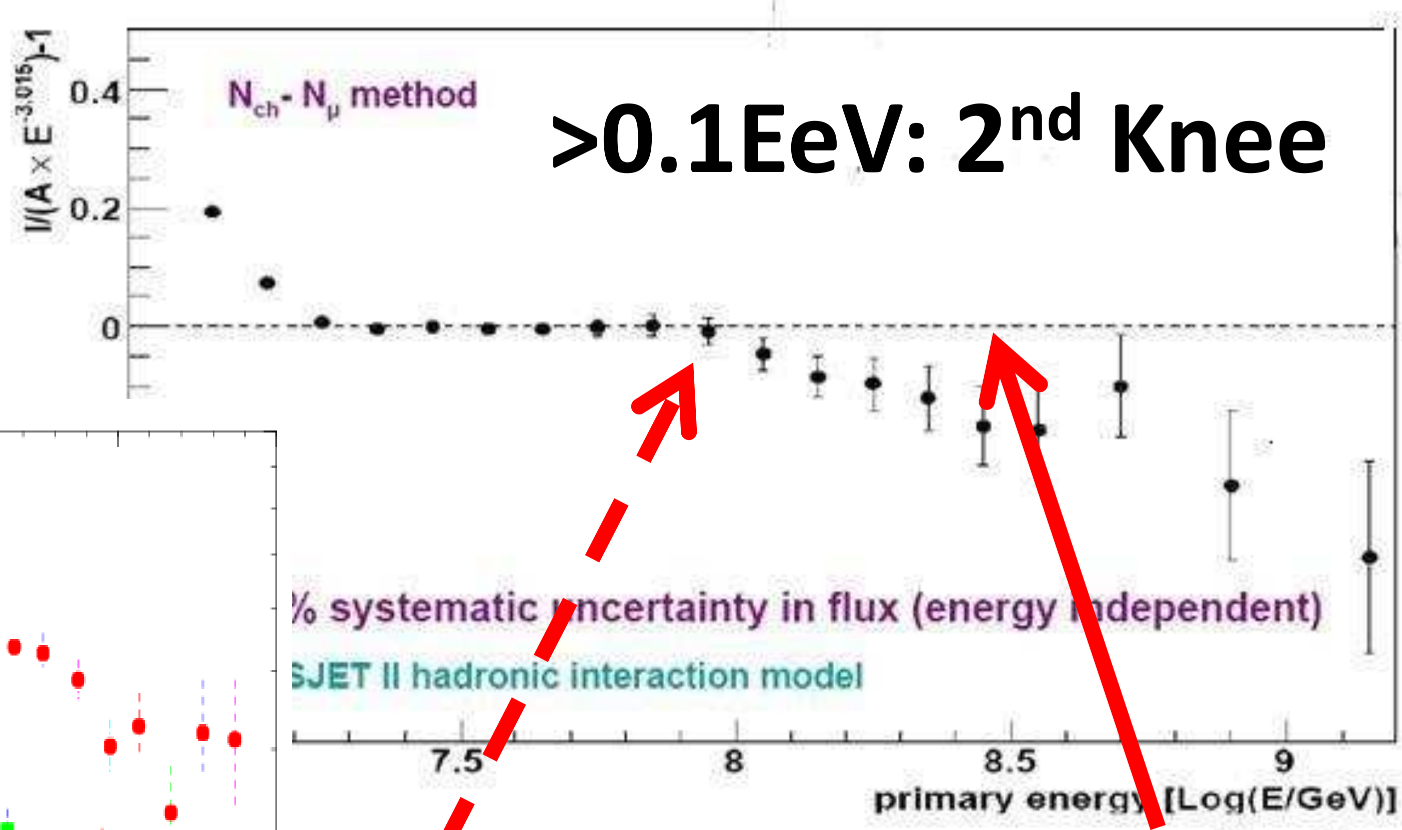


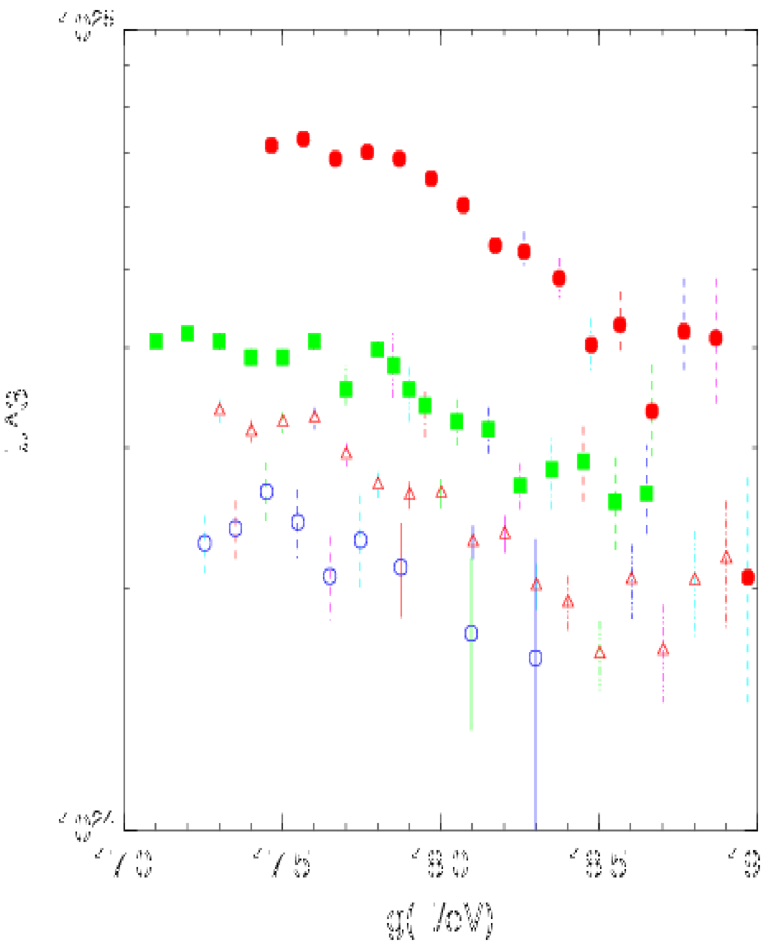

VOLVO

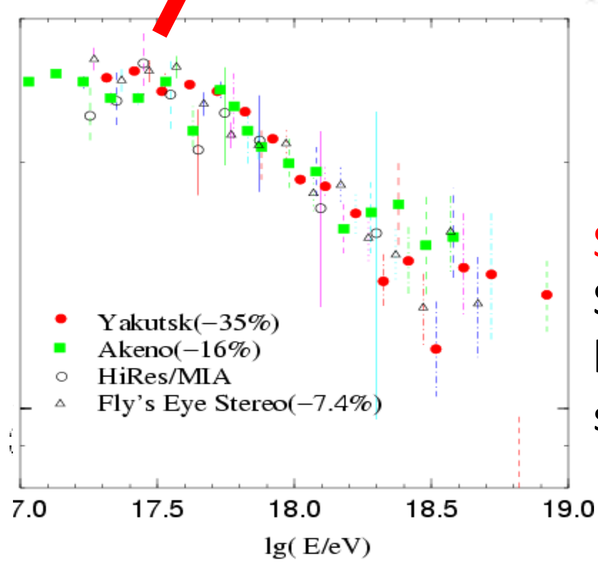
Summary

- Absolute Energy Scale at 10TeV could be established by using moon shadow technique
- Great opportunity for cross-calibration with space-borne Measurements
- Separation between species can be done at energy of 0.1-10 PeV
- The Knees at 0.7, 1.4, ~3 PeV … and 18 PeV are expected to be fixed on the individual spectra
- The schedule is fixed:
  - Civil construction is finished by April, 2017
  - Construction of No.1 pool & tanks: start around April, 2017
  - Detector installation starts by the end of 2017
  - Physics data taking in 2018 with ¼ LHAASO array

>0.1EeV: 2nd Knee







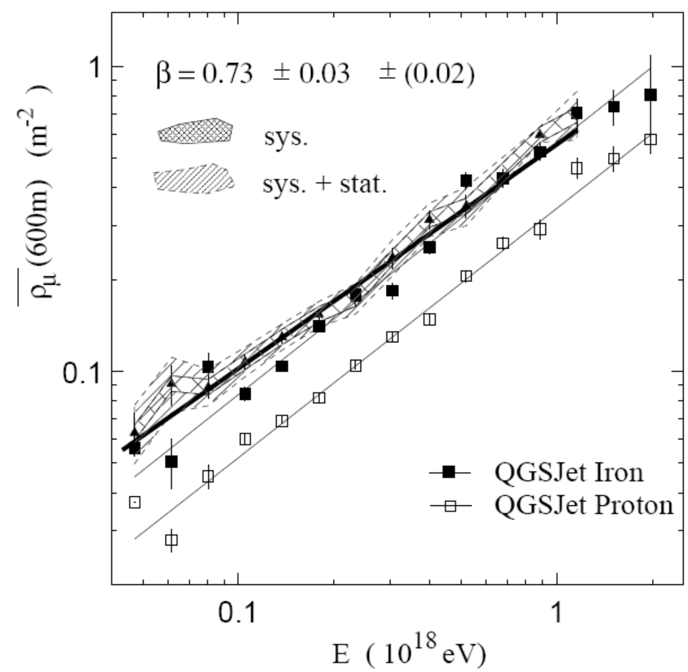
Fly'sEye
HiRes/MIA

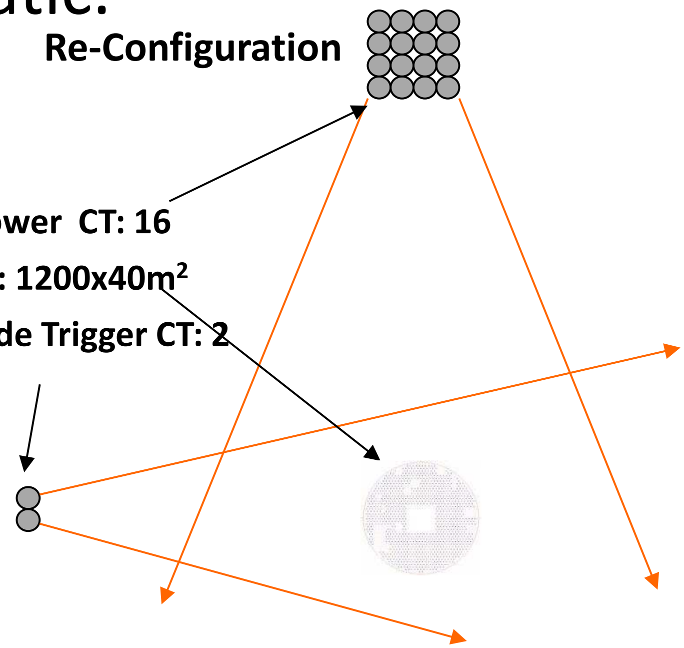
Second knee!
Statistics is much better, but the energy scale is again problematic…

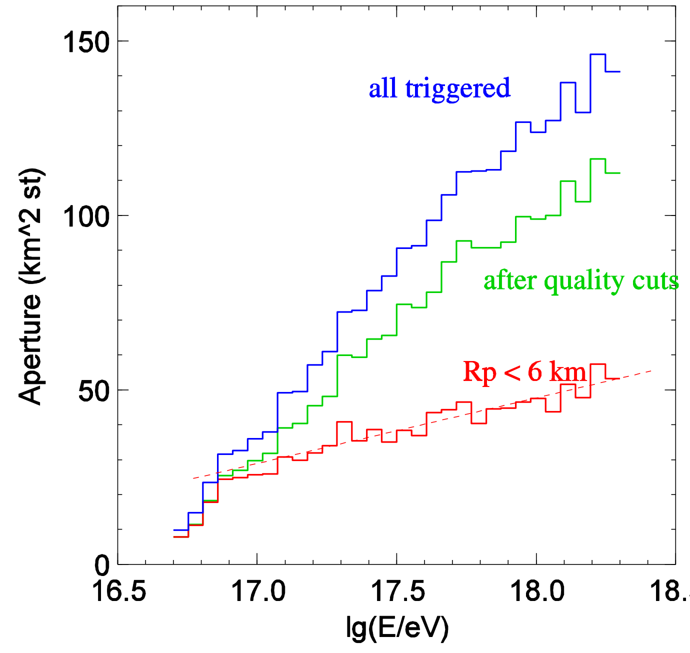
Still Energy Scale

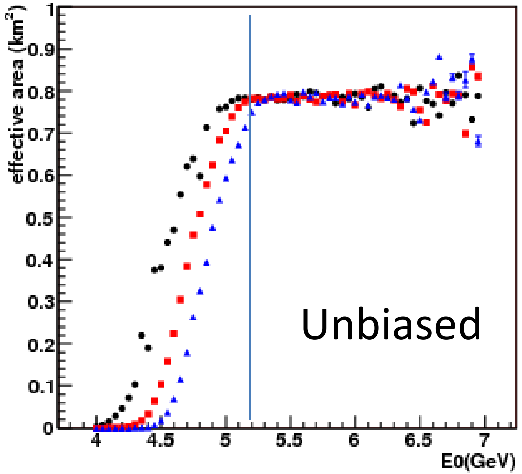
- Calibration between C-tele and F-tele
- Calibration between TUNKA and F-tele
- Calibration between LHAASO/F-tele and other F-tele arrays?

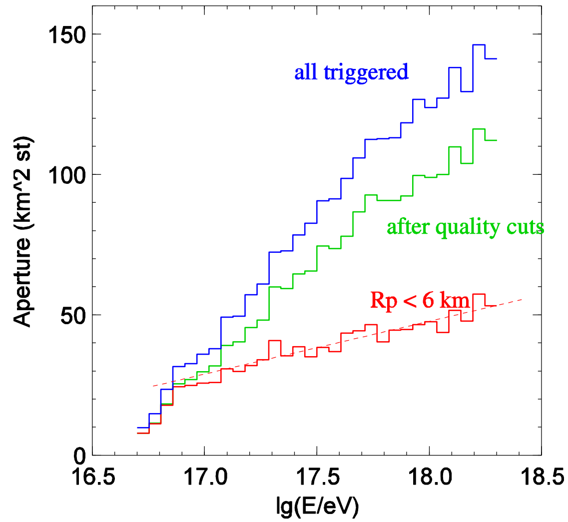
But not only…… muon-content is also problematic.

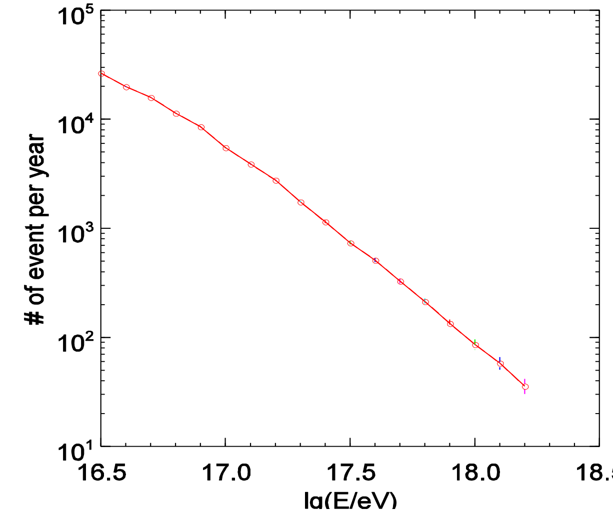


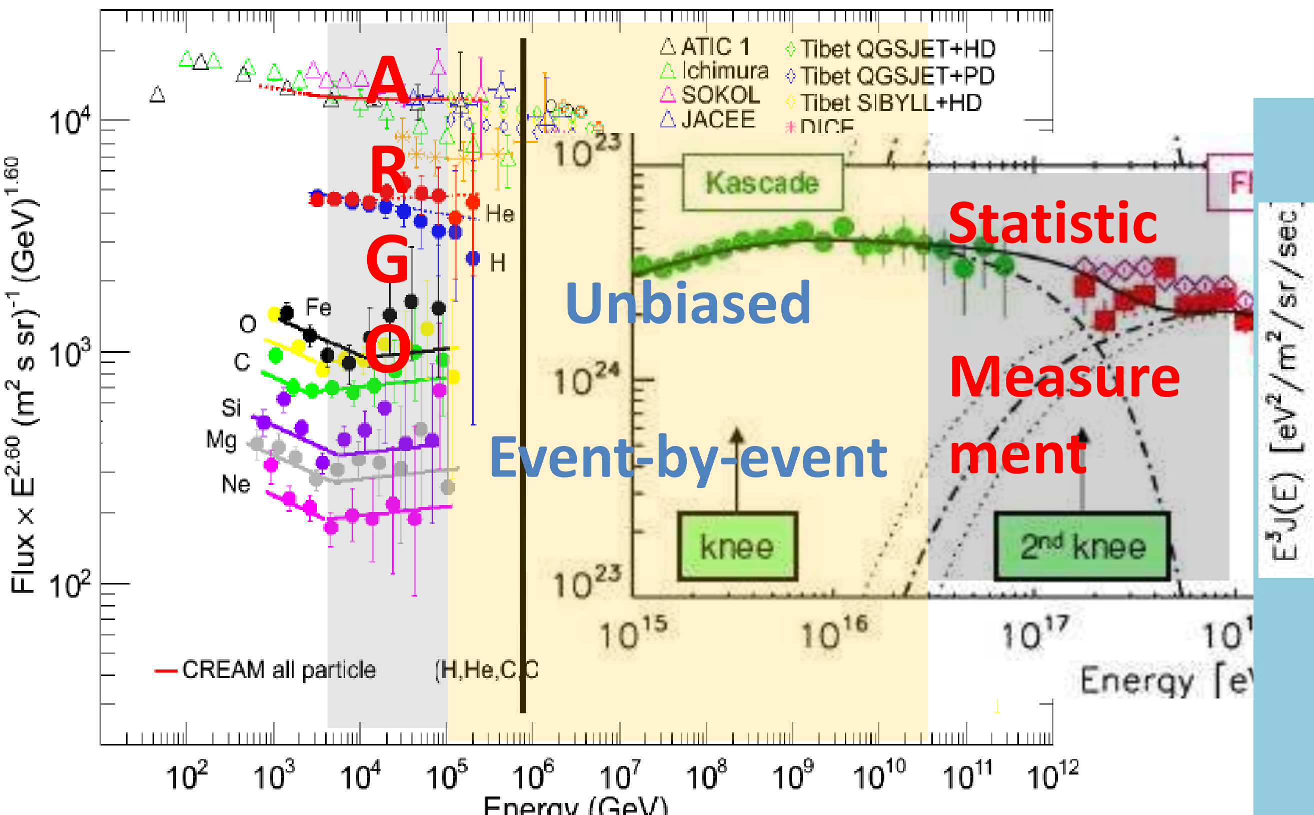












Resolution of
CR Composition