LHAASO Prospects: Spectra of Cosmic Ray Species and ARGO-YBJ Results

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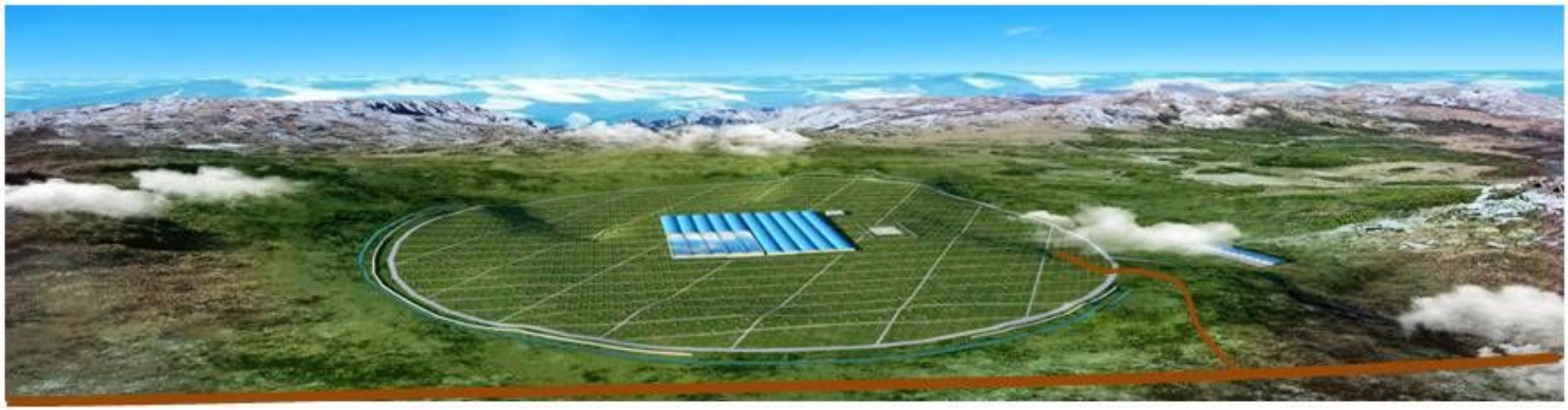
LHAASO at Mt. Haizi, Sichuan, China

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



Water Cherenkov Detector

90,000 m^2

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 road and first 3 Muon Detectors

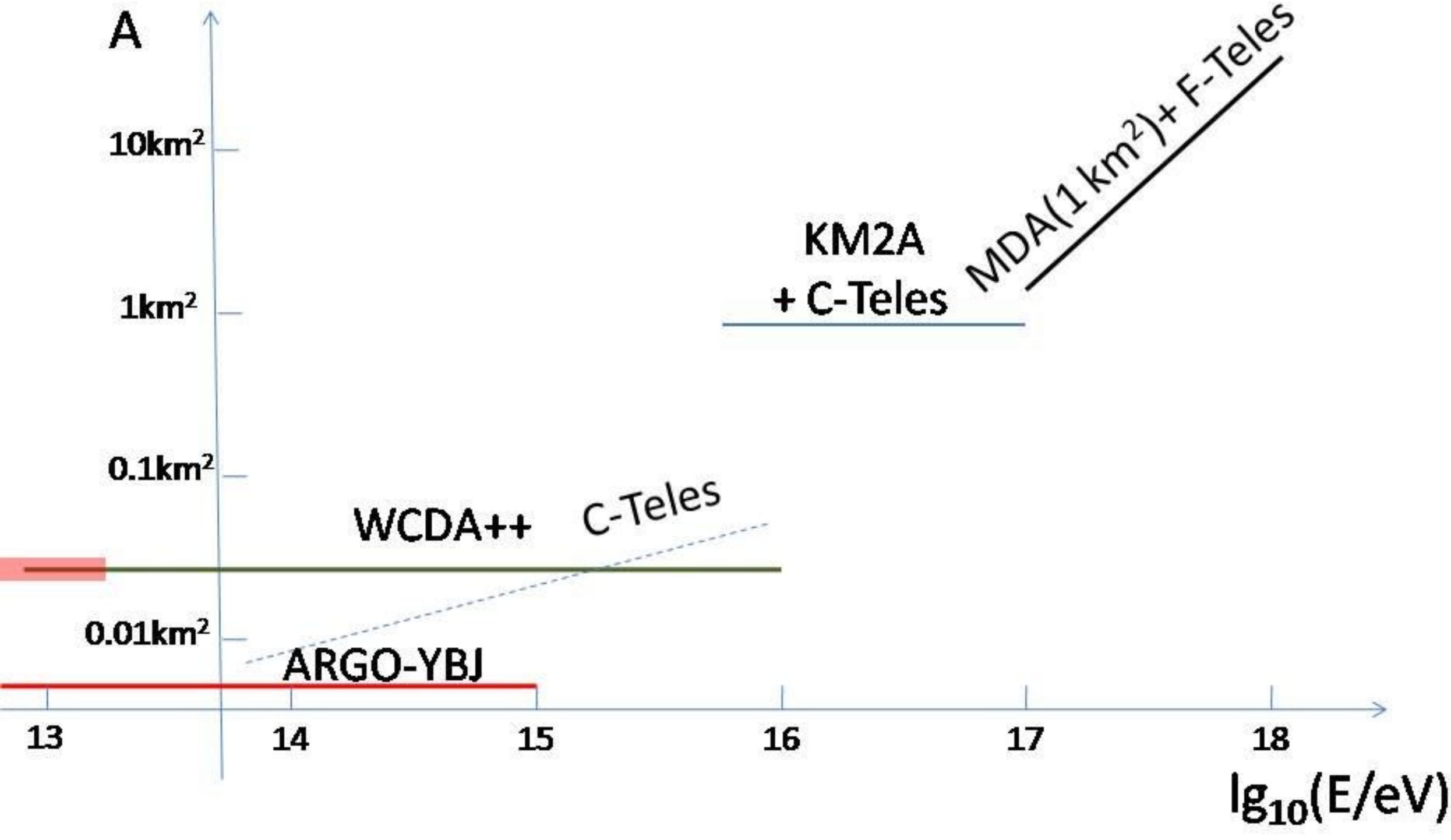
Outline

Part 1： LHAASO

- 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
- Summary

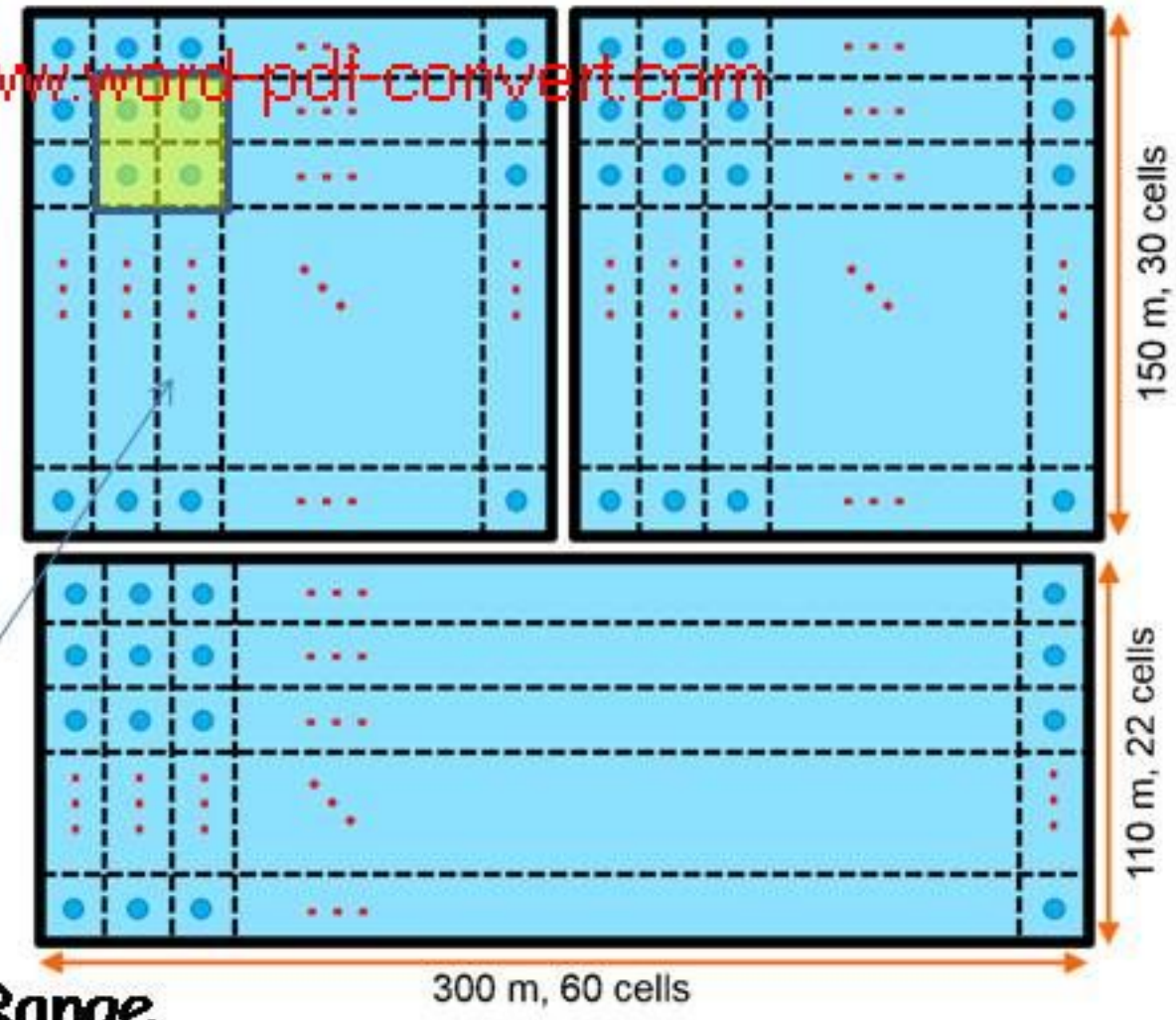
Part 2： ARGO-YBJ results

Aperture of LHAASO for CR events

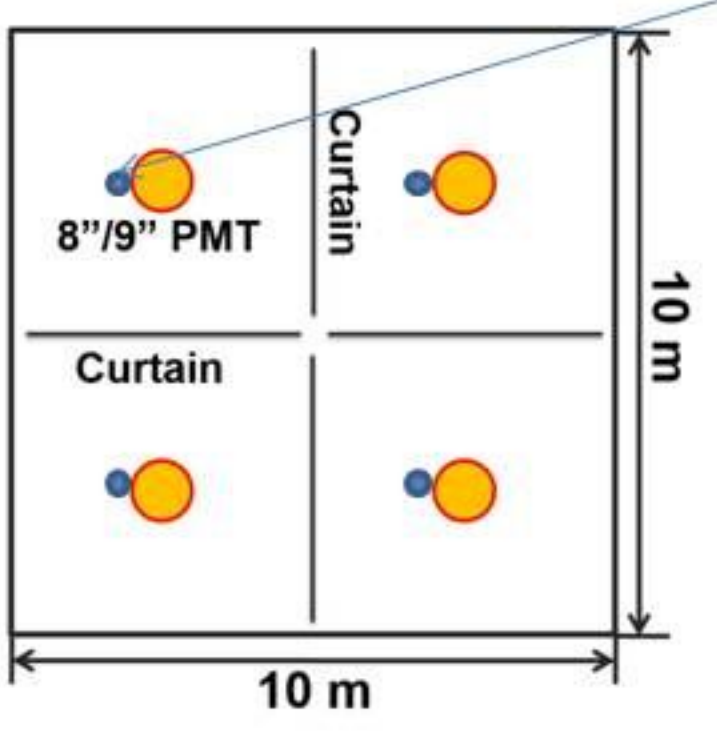


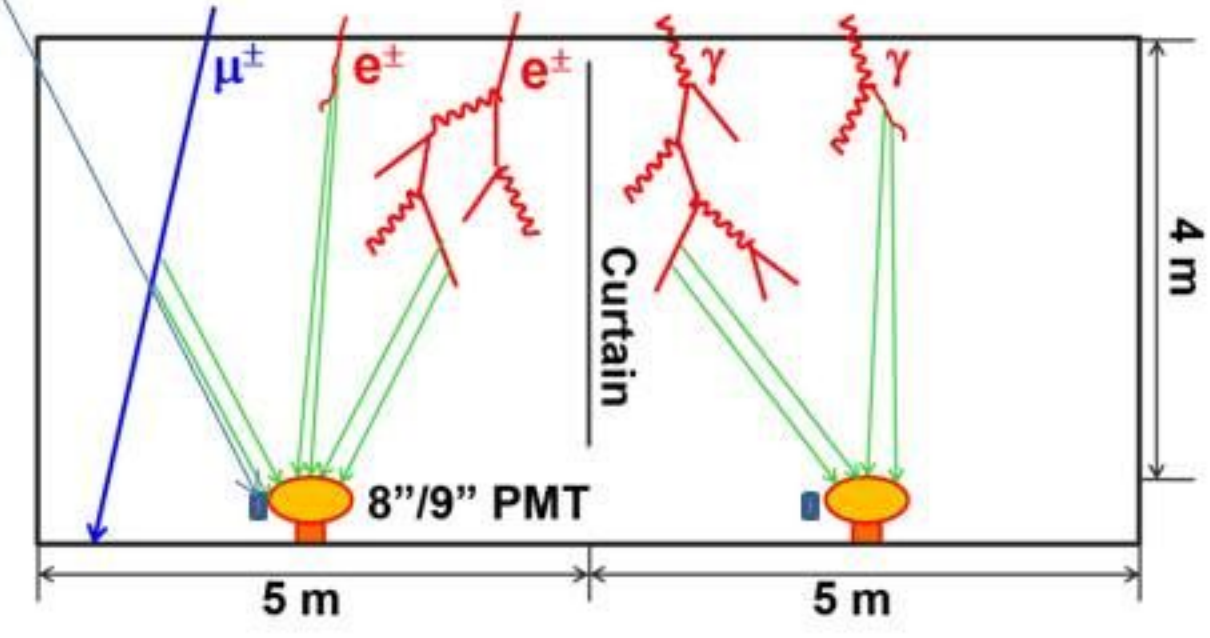
Water Cherenkov Detector Array

- 3 water ponds:
  - 78,000 m^2 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

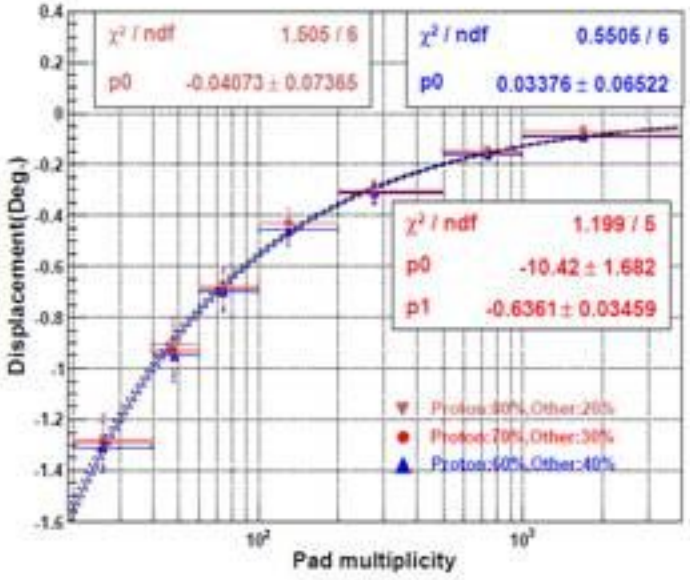


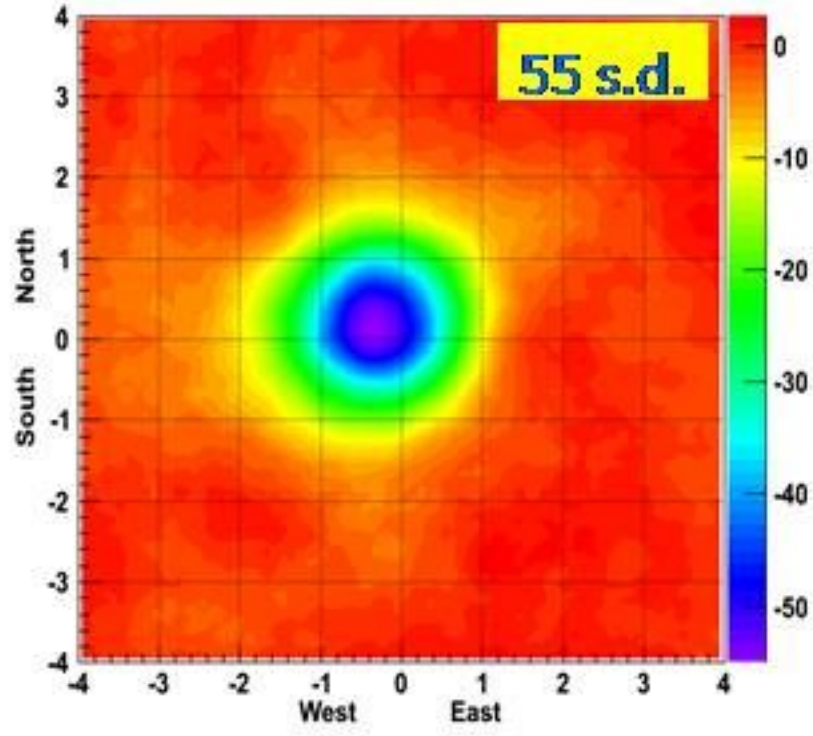


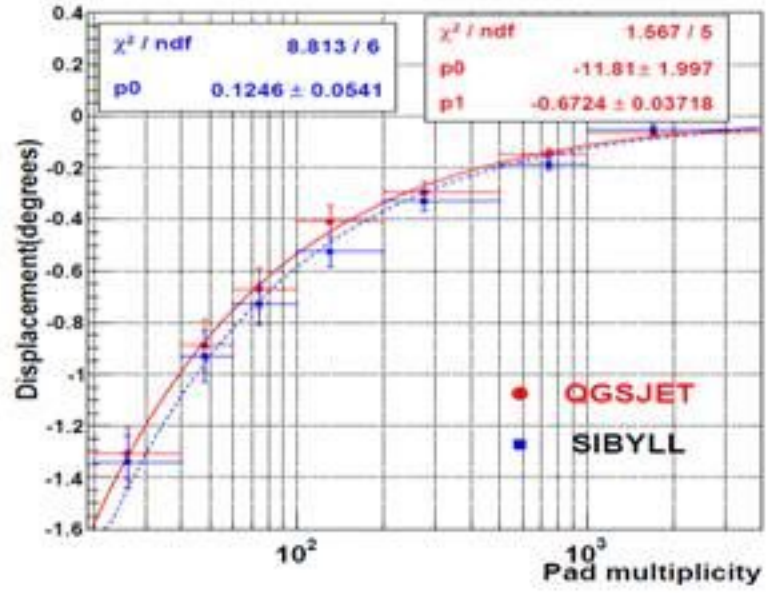
ARGO-YBJ : Moon Shadow displacement

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

1 – 30 (TeV/Z)







The energy scale uncertainty: smaller than 13%:

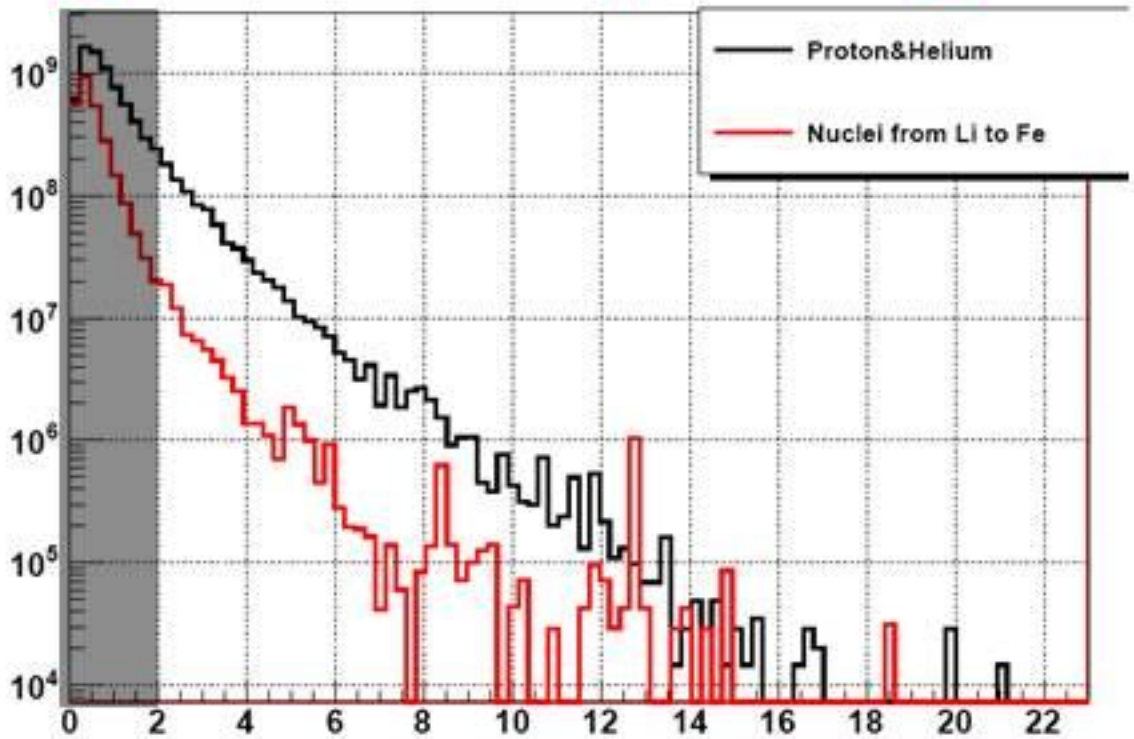
- the assumed primary CR chemical composition (7%)
- the uncertainties of different hadronic models (6%)
- statistical uncertainty (8%)

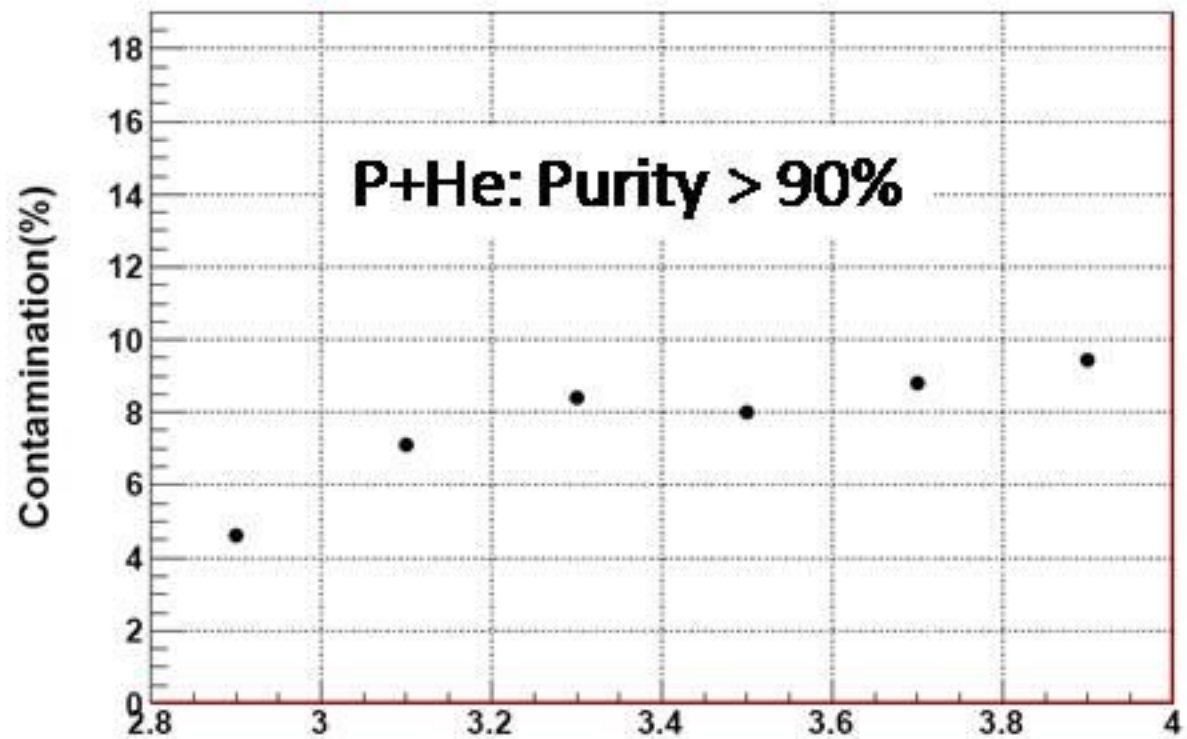
An example

For LHAASO 1/4:

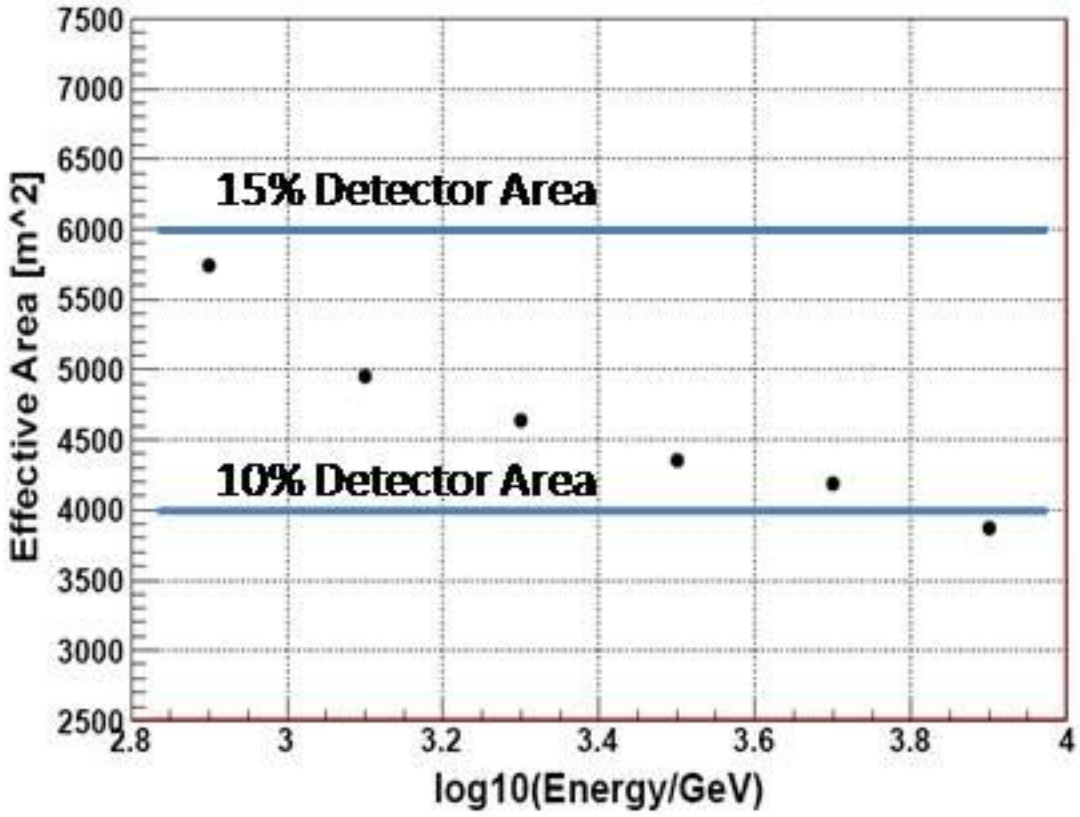
- Sensitivity: same after p+He selection
- Angular Resolution: 0.3°
- Pure Proton+Helium: 90% purity
- Hadronic Model: 5% (estimated)
- Overall: <10% within 1 year

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

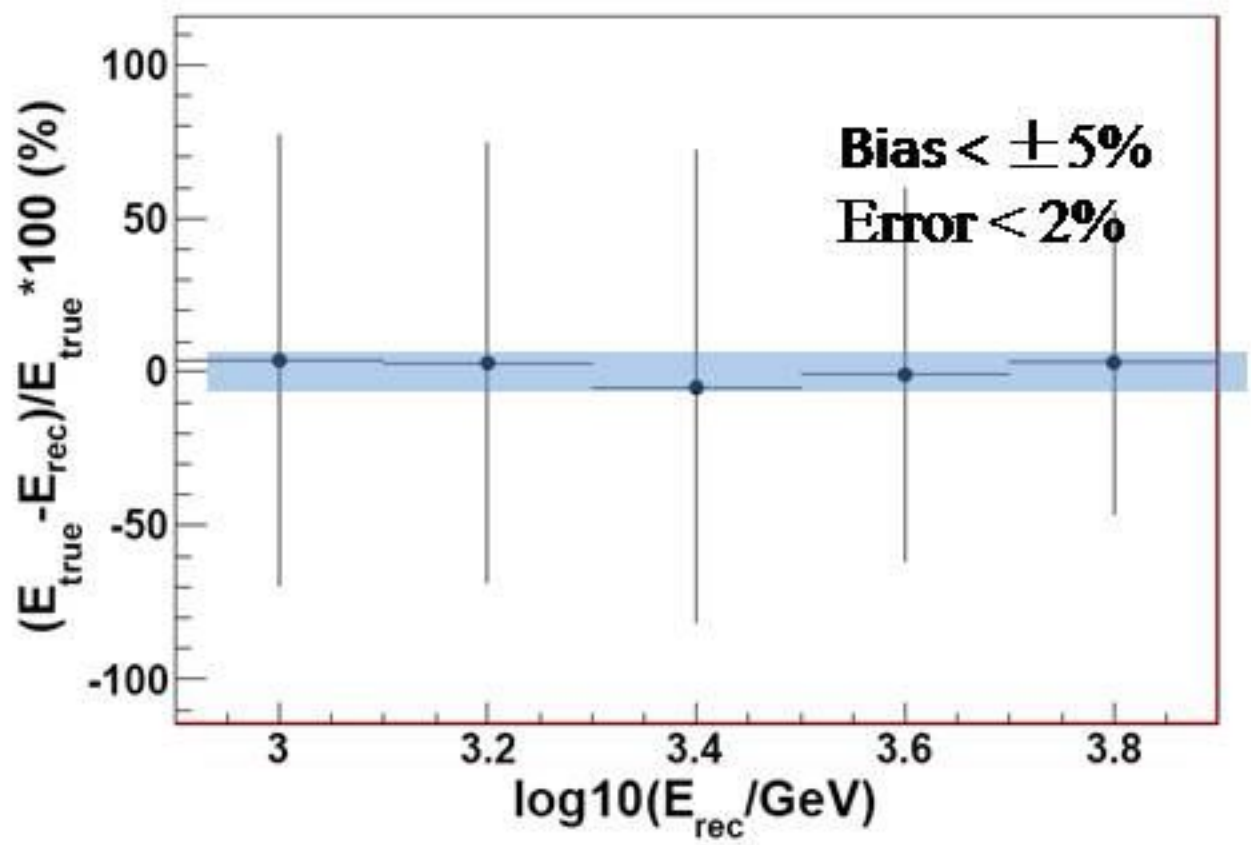




nFit/cxPE2

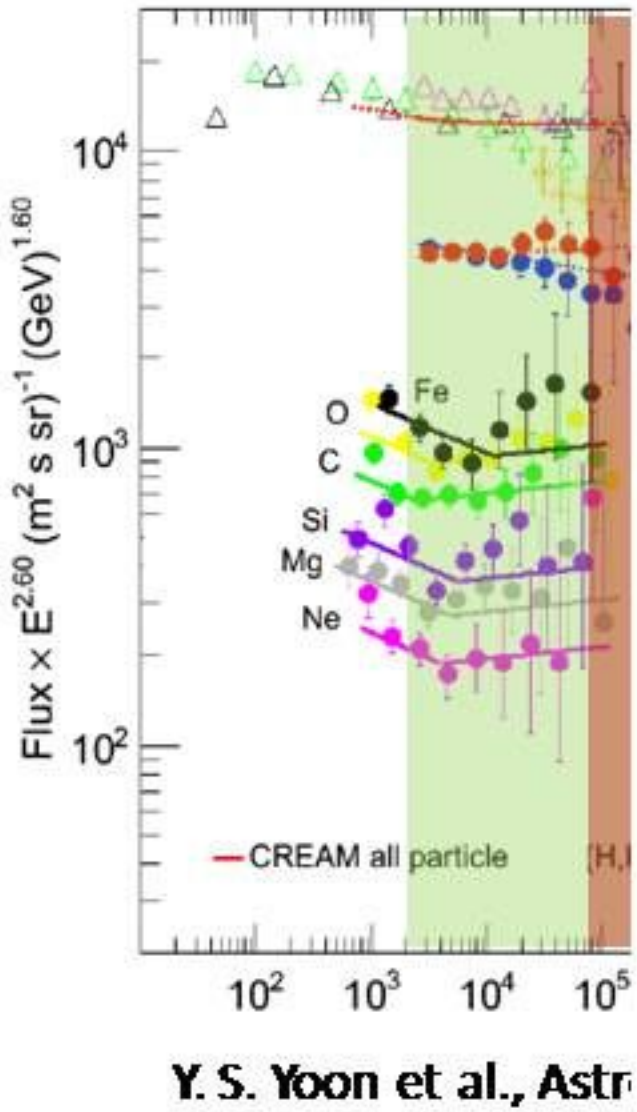


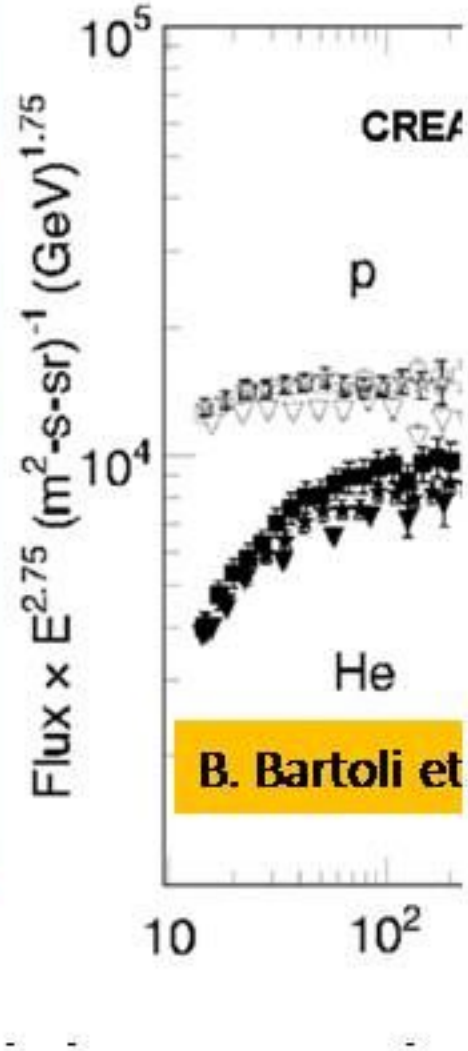
log10(Energy/GeV)

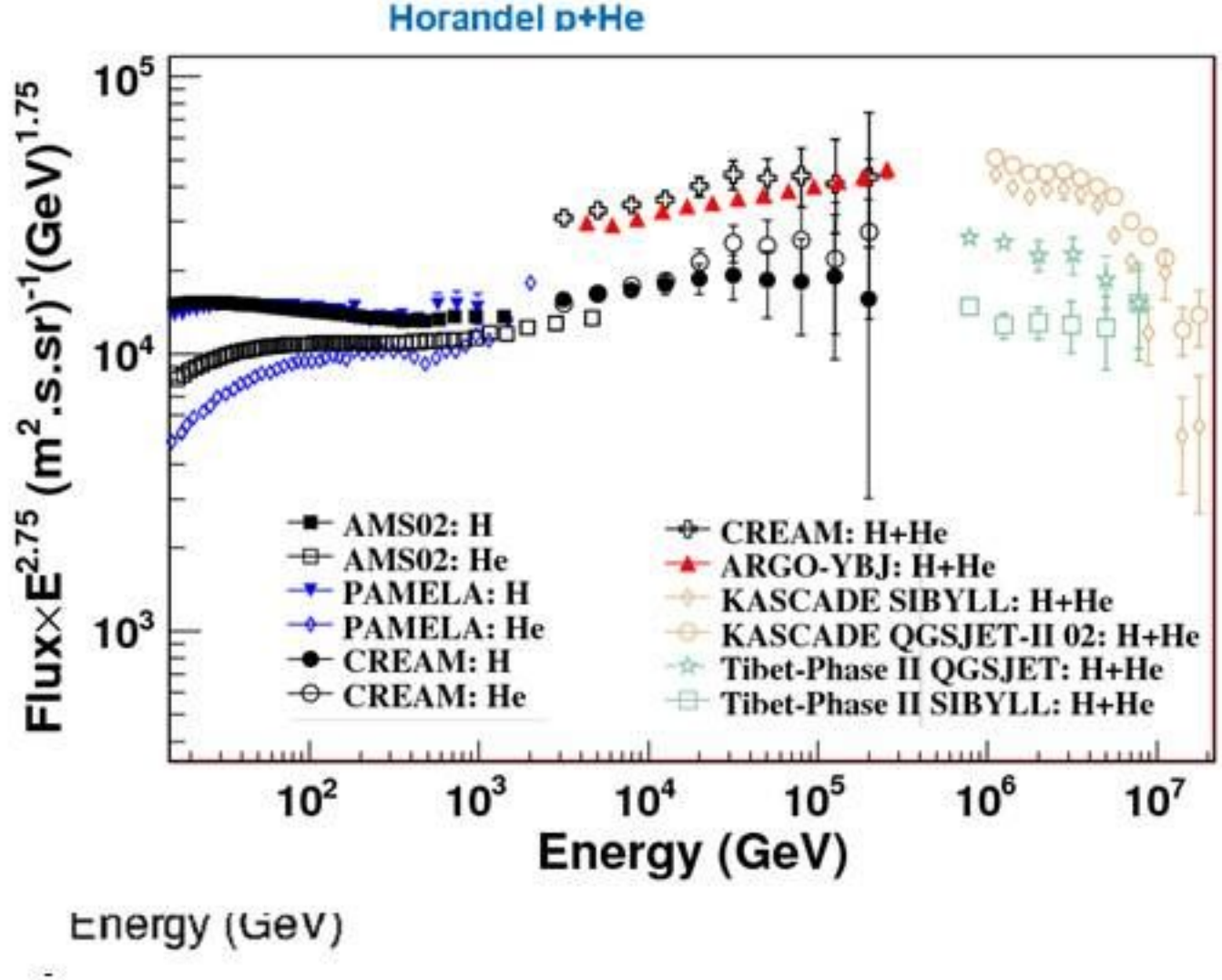


cross-calibration between the experiments

- **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**



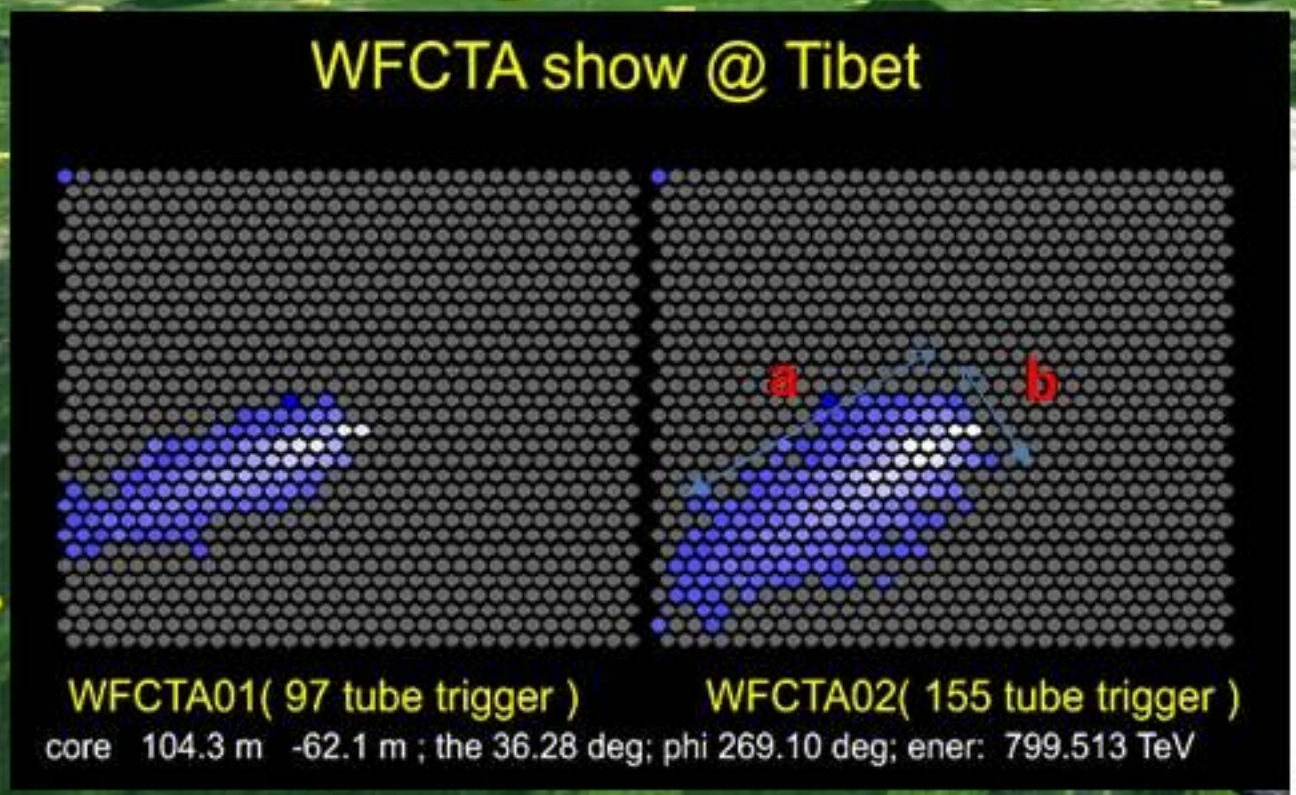


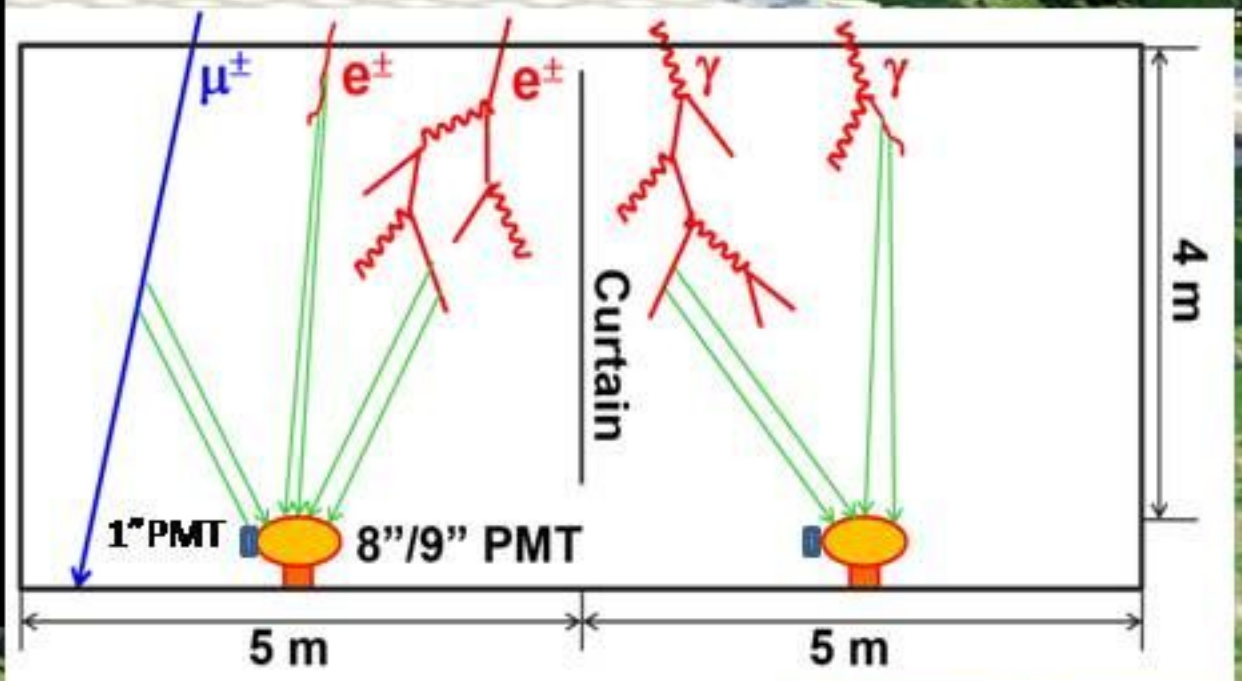


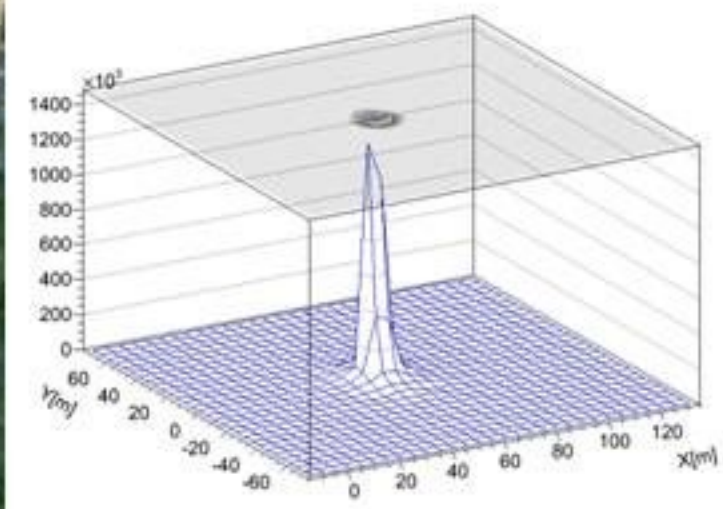
Selection for Individual Species (0.1-10 PeV)

- 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)

Water Cherenkov Detector
22,500 m², WCDA++

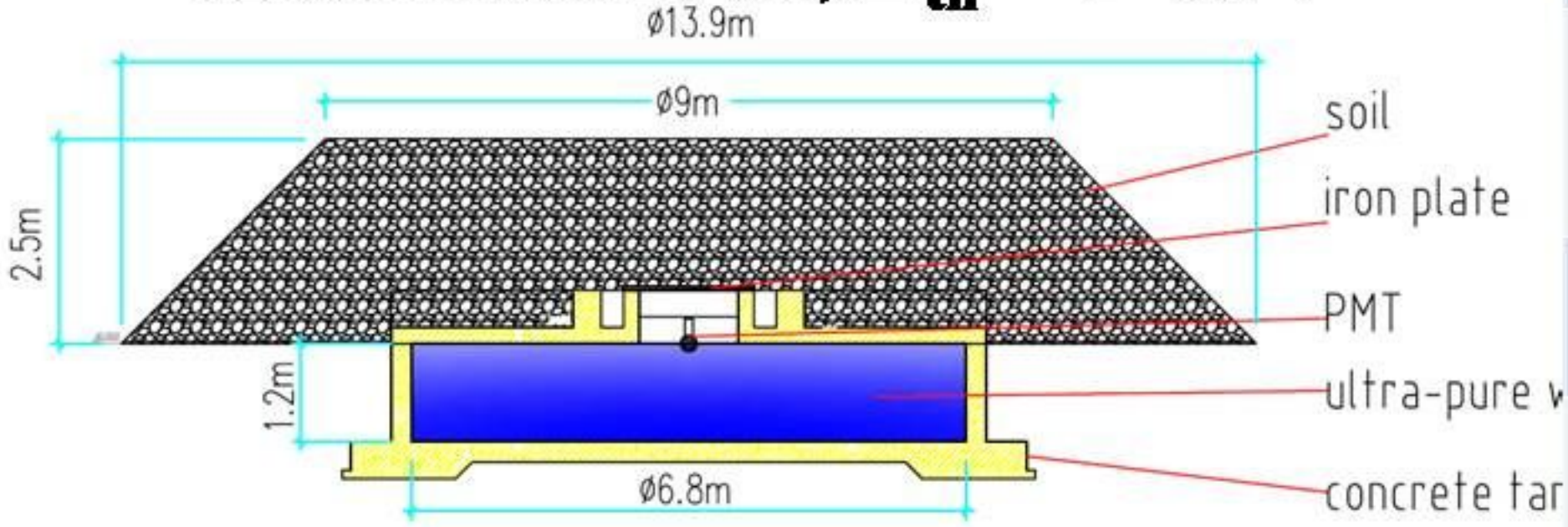


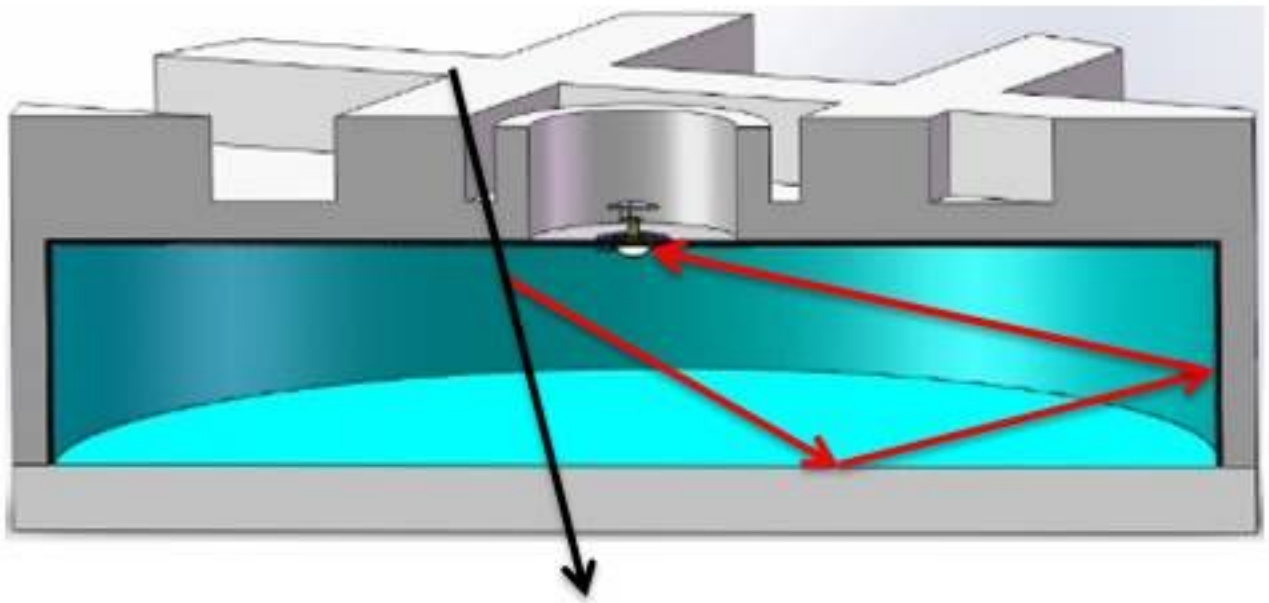




Muon Detector

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

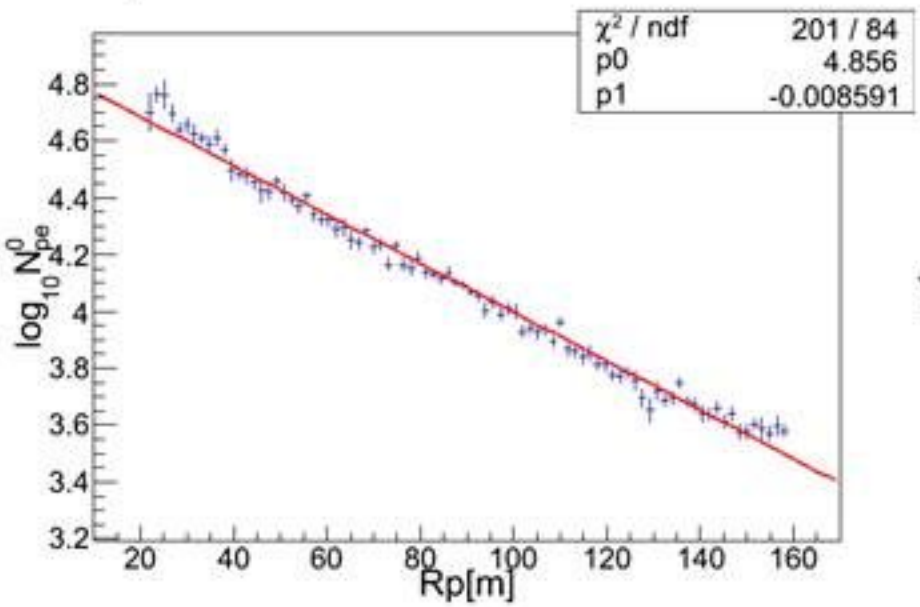


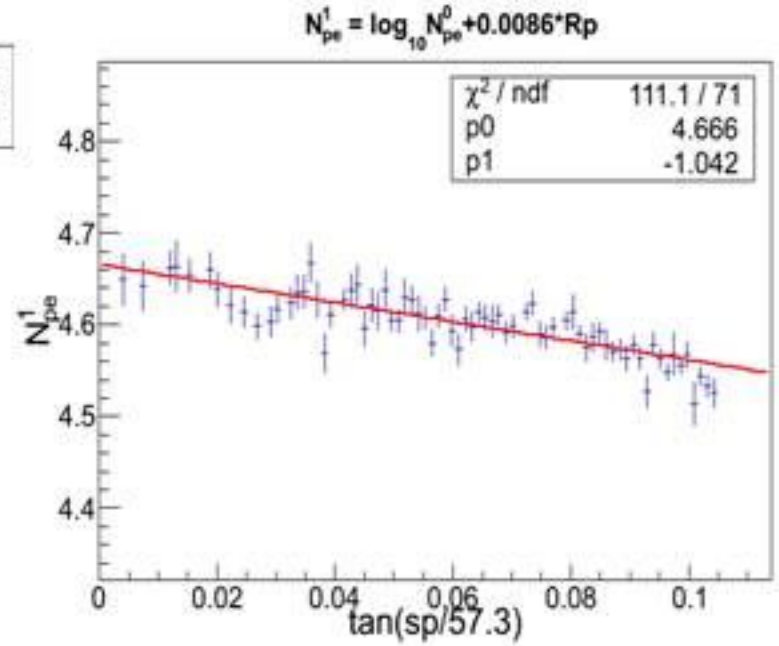


Item	Value
Area	36 m²
Detection efficiency	>95%
Purity of N_μ	>95%
Time resolution	<10 ns
Dynamic range	1-10,000 particles
Particle counting resolution	25% @ 1 particle 5% @ 10,000 particles
Aging (<20%)	>10 years
Spacing	30 m
number	1221

Energy Estimator: N^0_{pe}

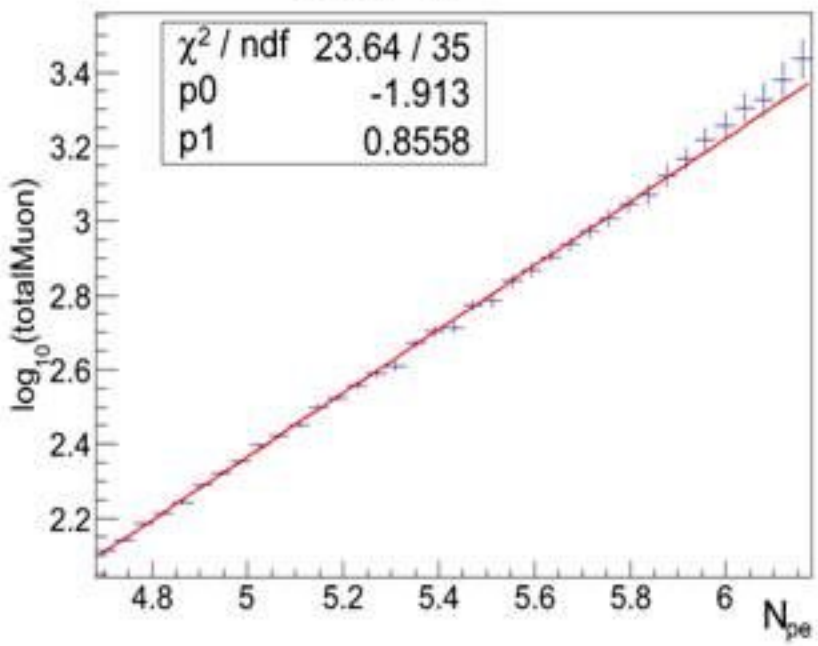
R_p, incidence angle dependence

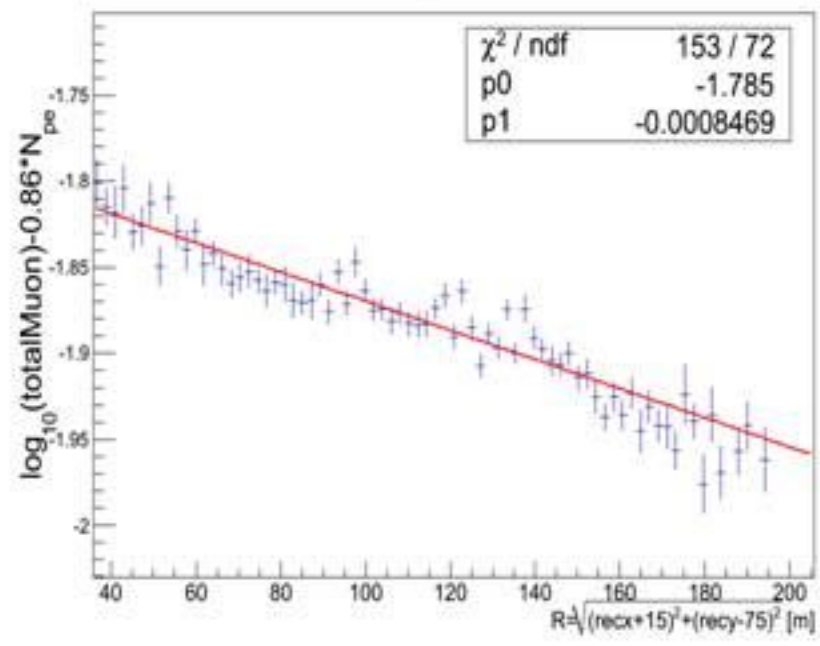




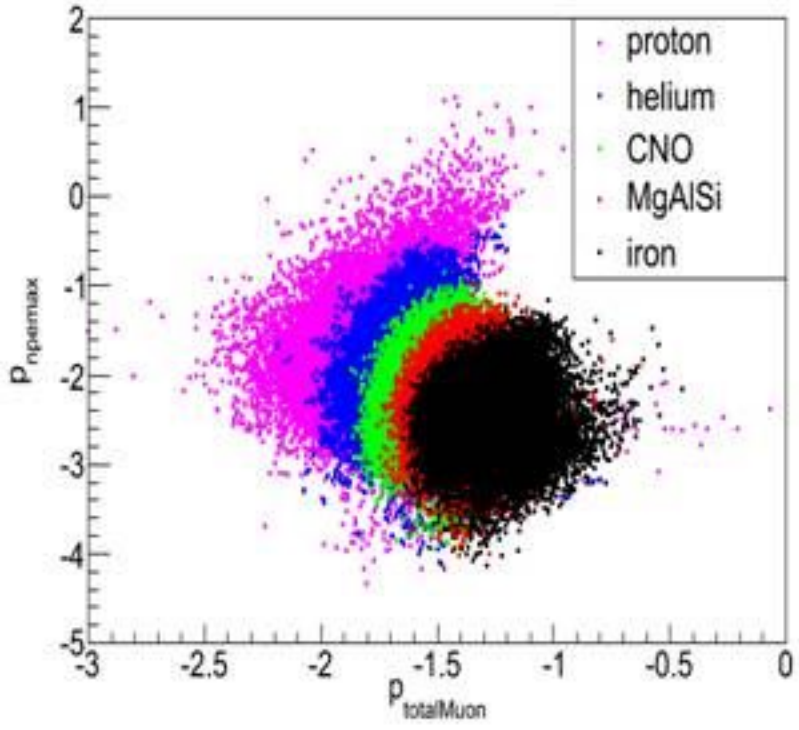
Muon Content: Total N_μ

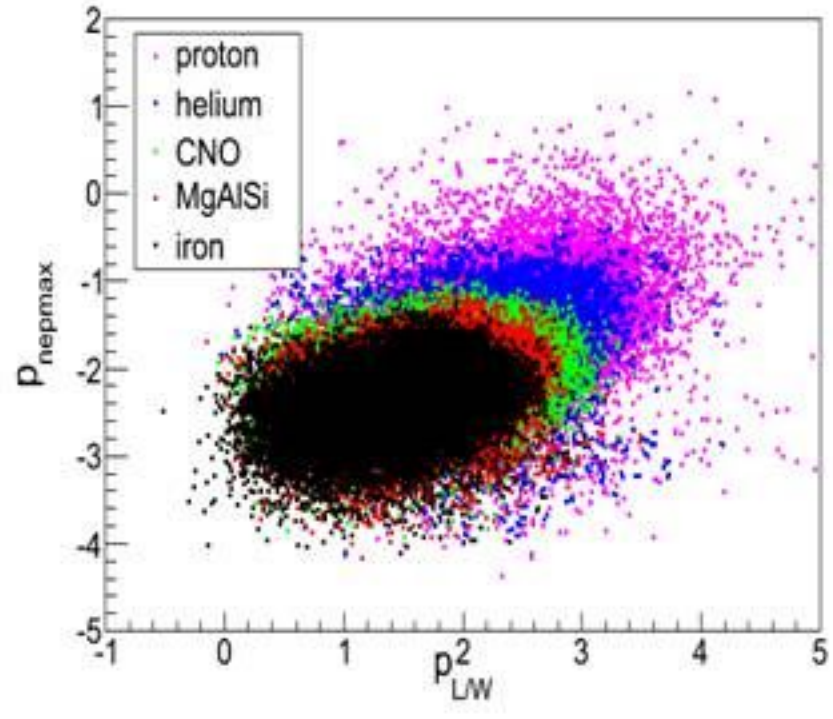
Energy ,core distance dependence

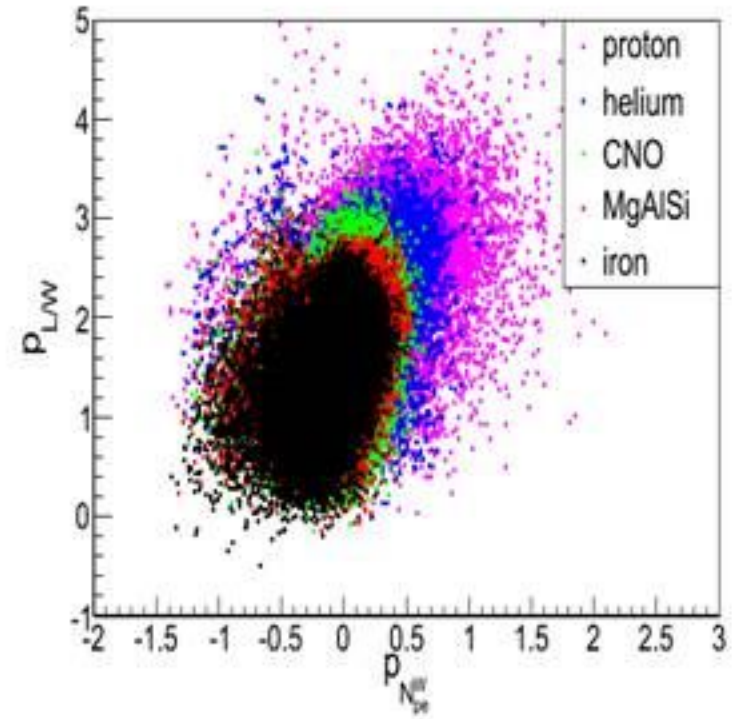


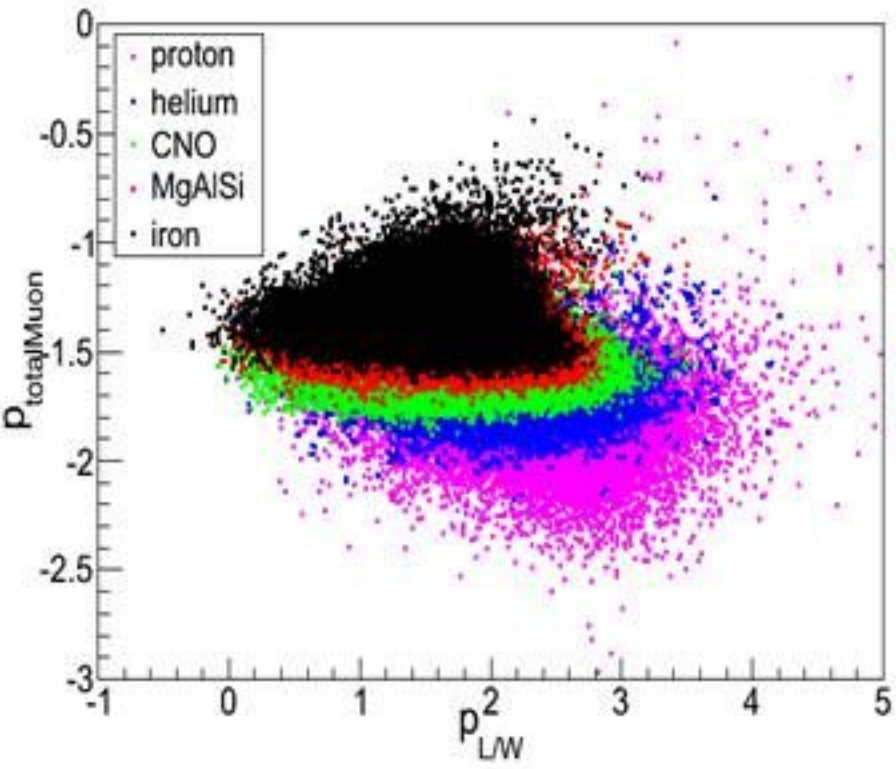


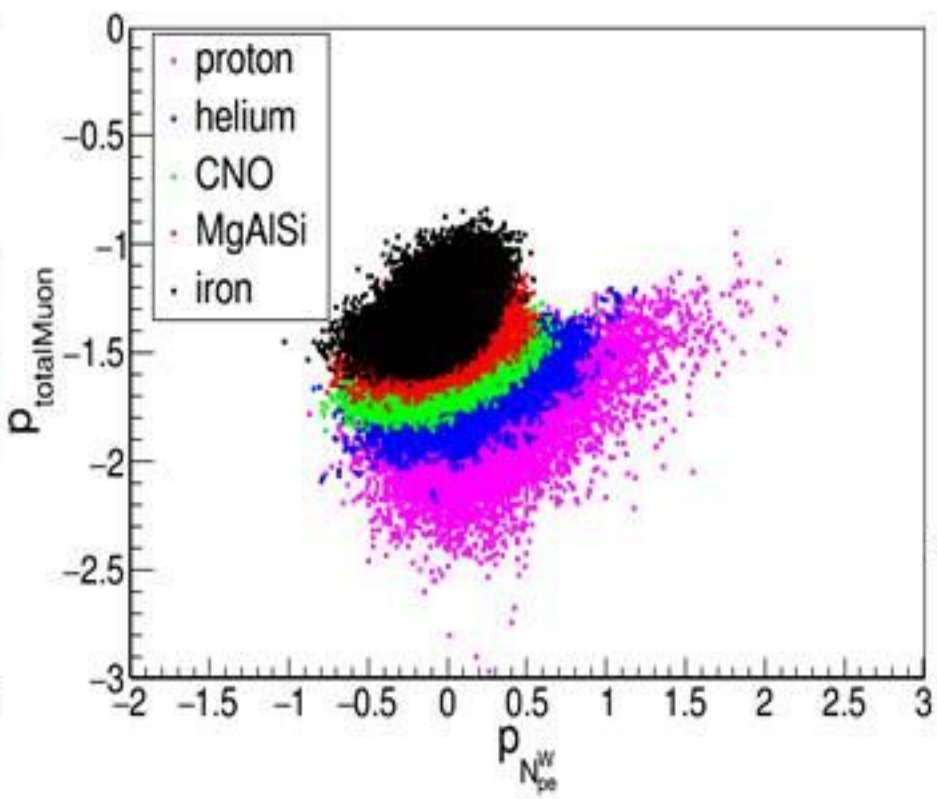
Multi-parameter Analysis







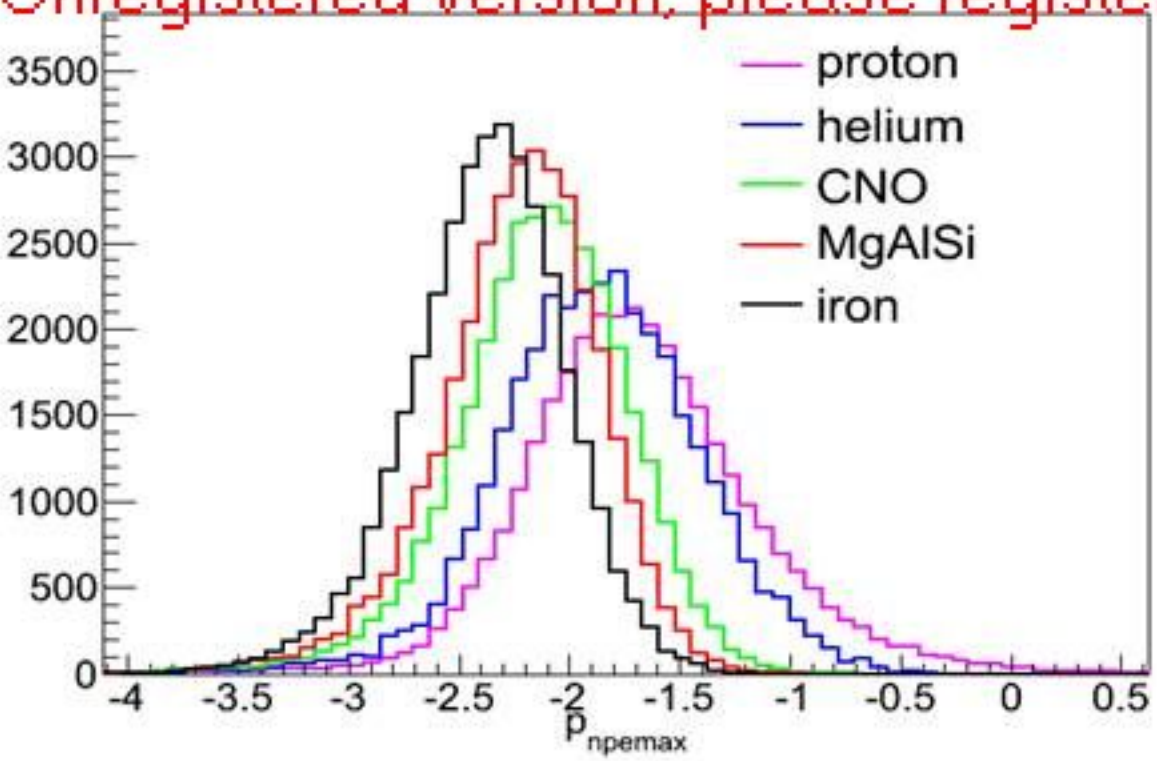


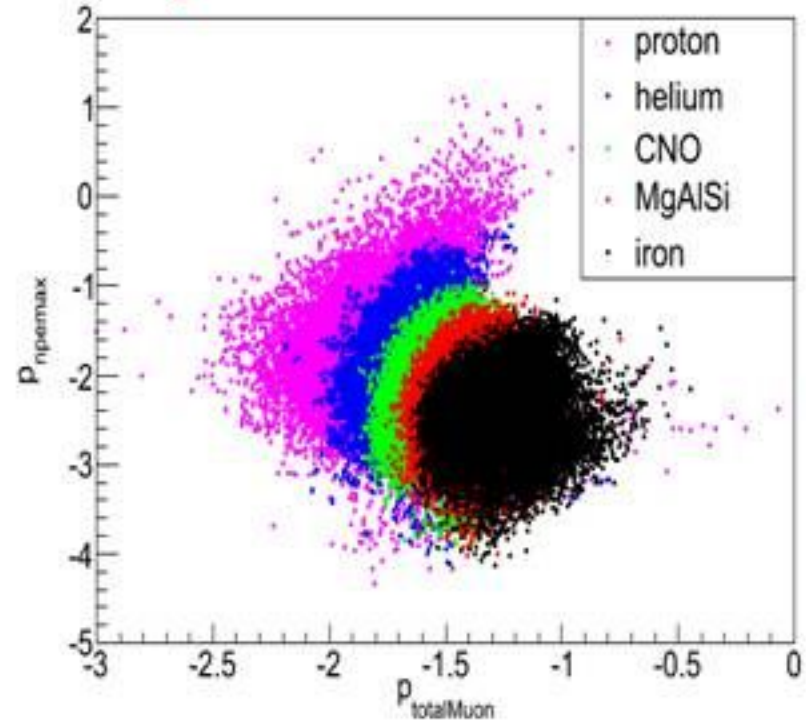


One-to-one Correlation

An example:

μ-content vs. E-flux at core

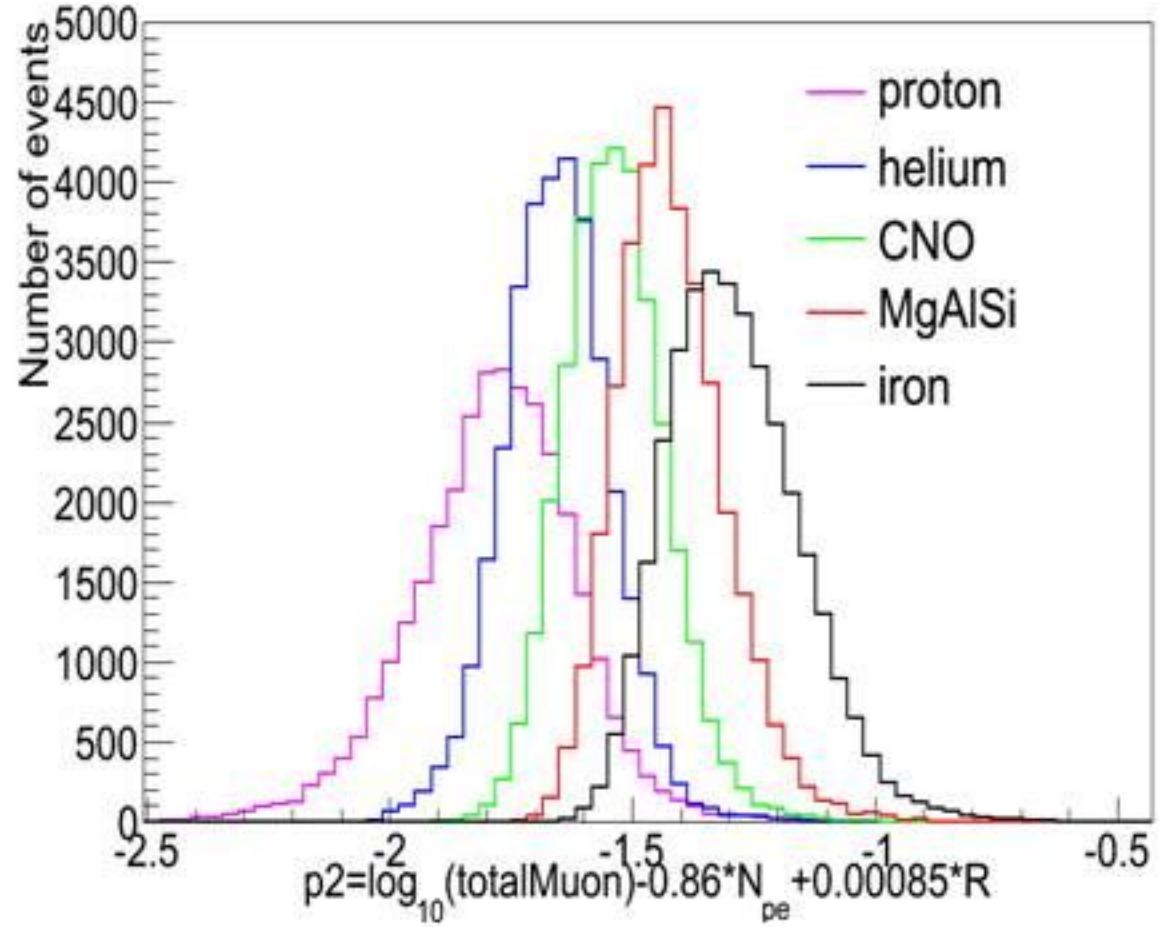


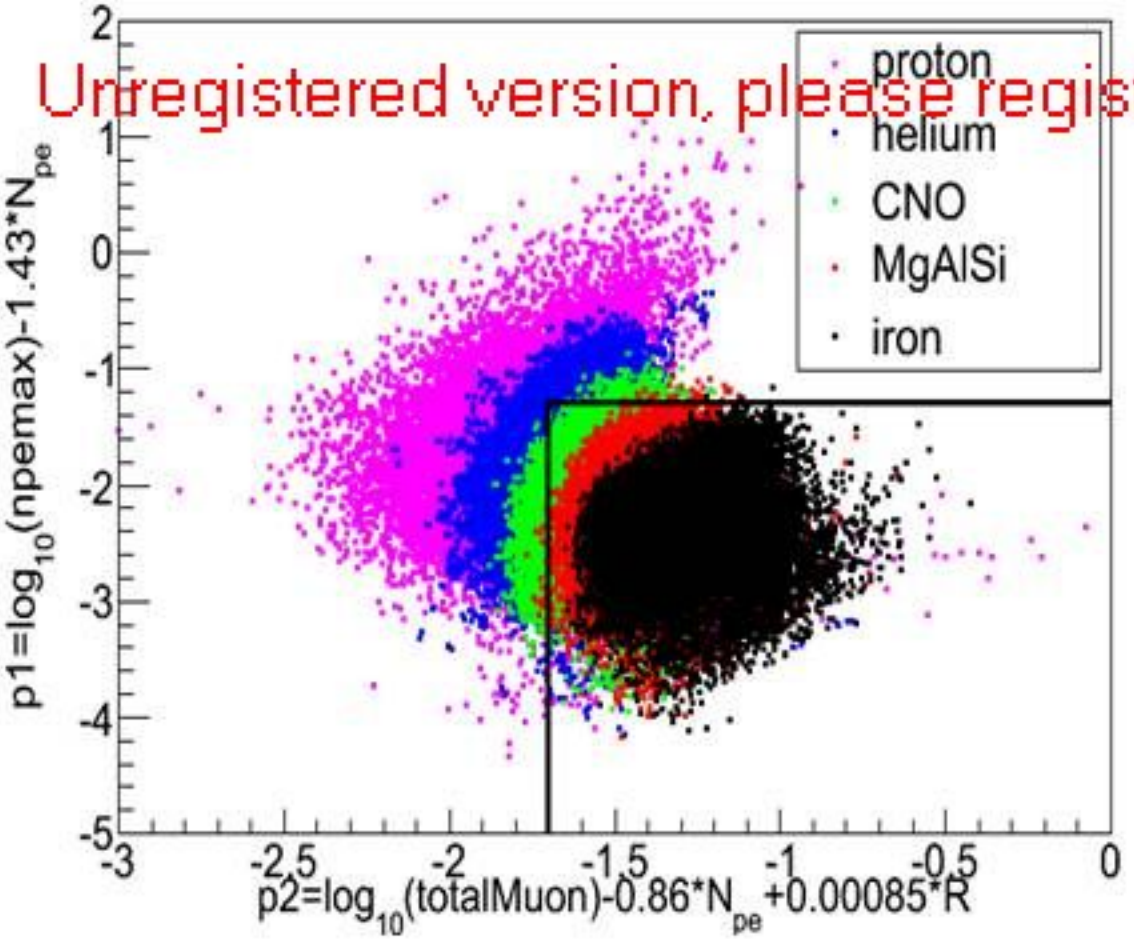


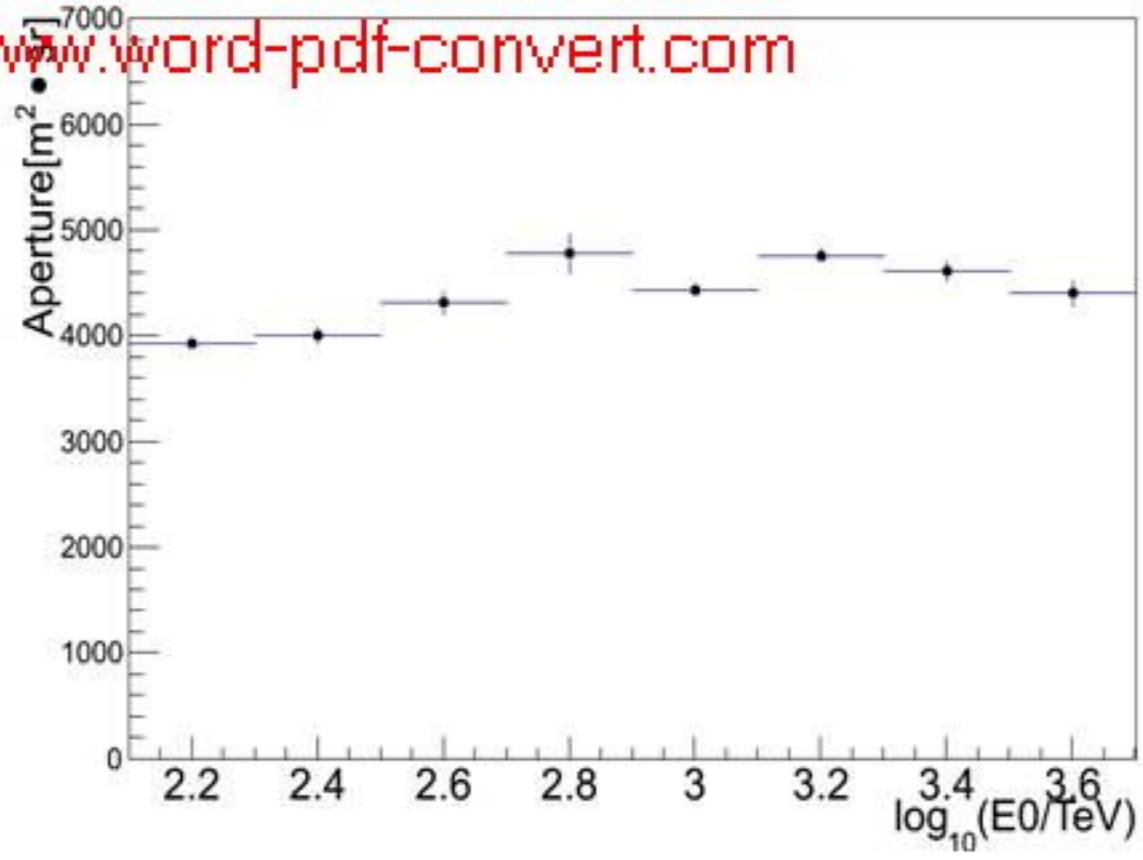
p2 = log10(totalMuon)+0.00085*R - 0.86*Npe

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

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





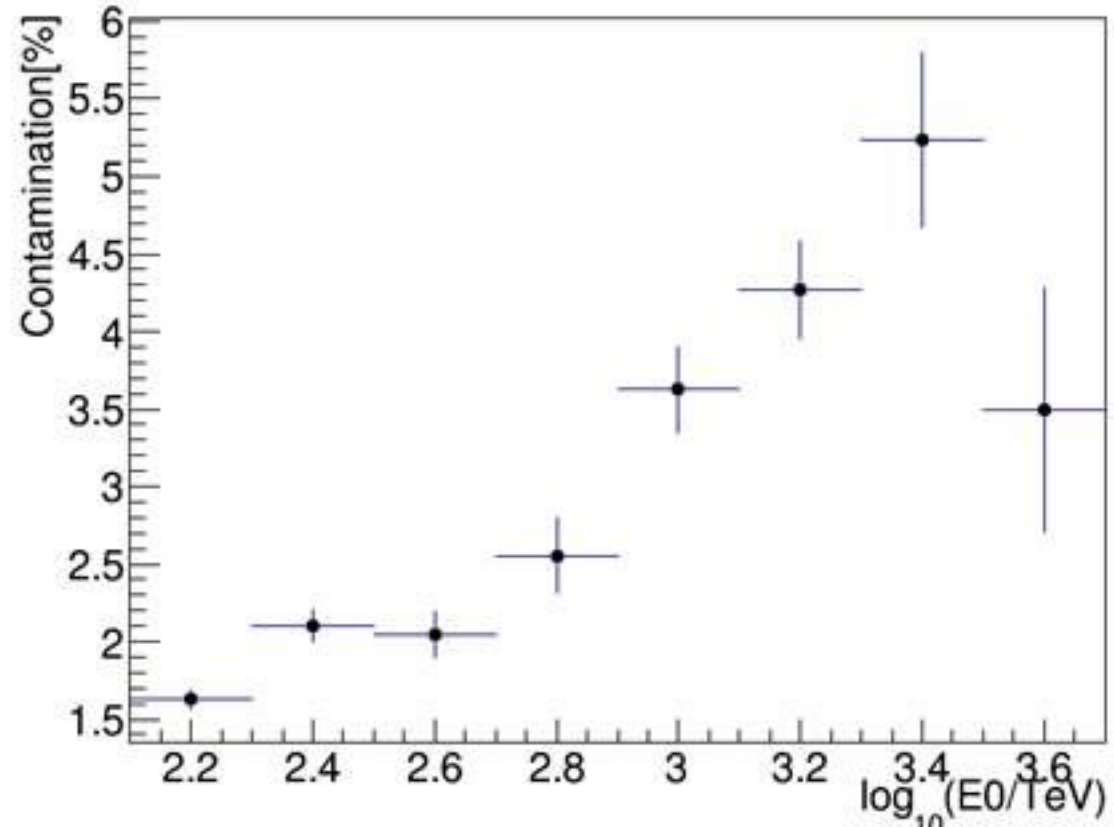


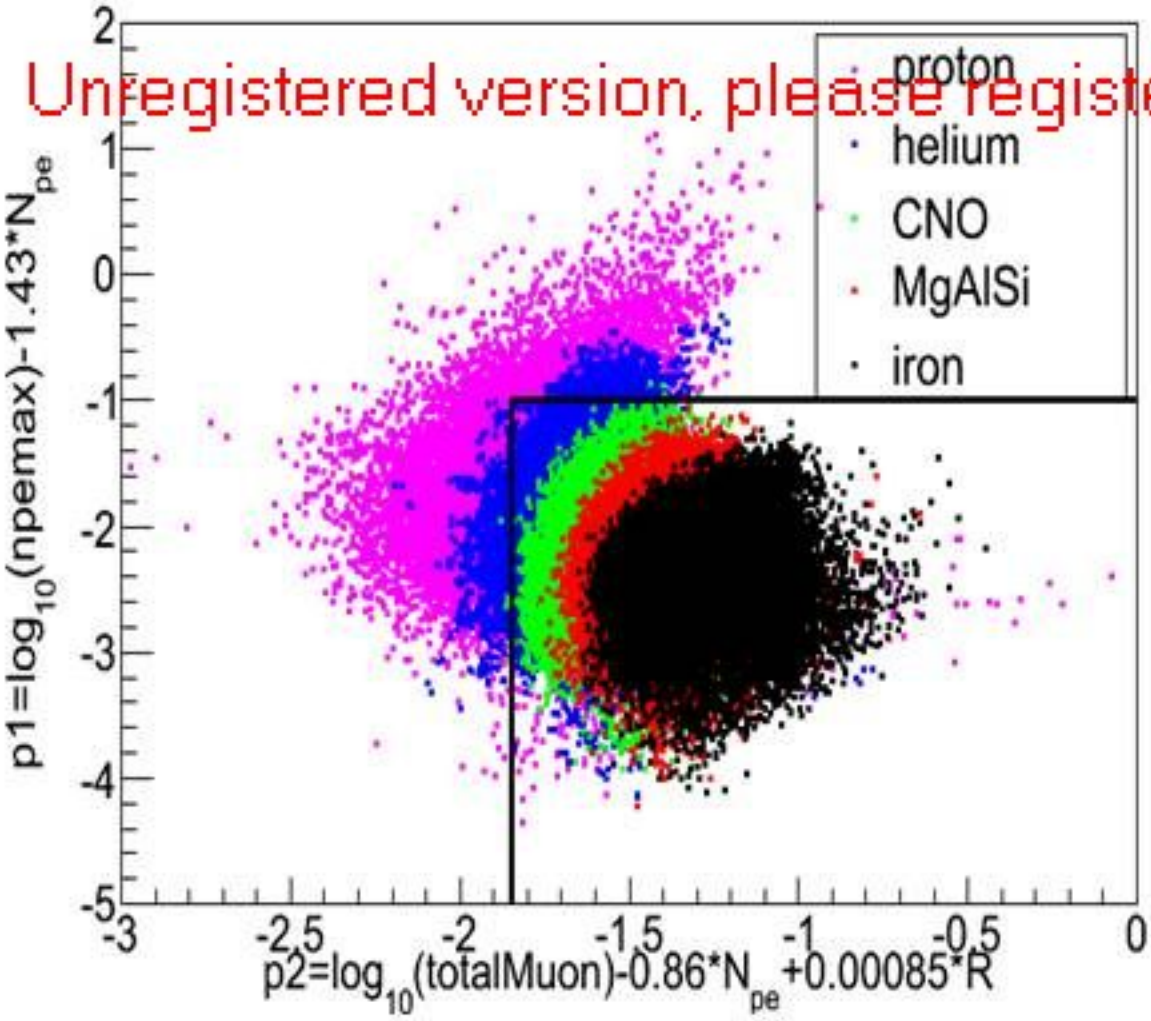
CutA: for p+He

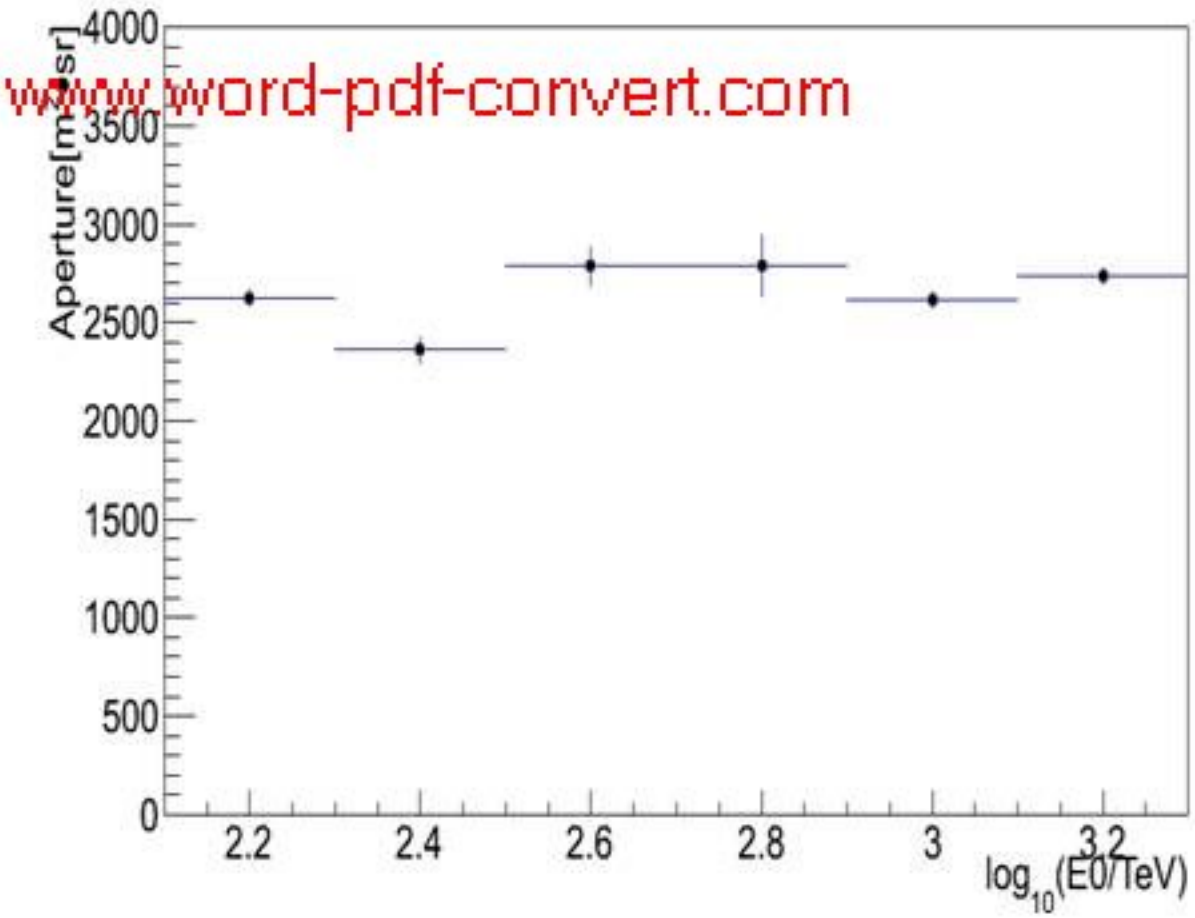
p1>-1.28 or p2<-1.70

aperture: 12 tels

contamination :Horandel model





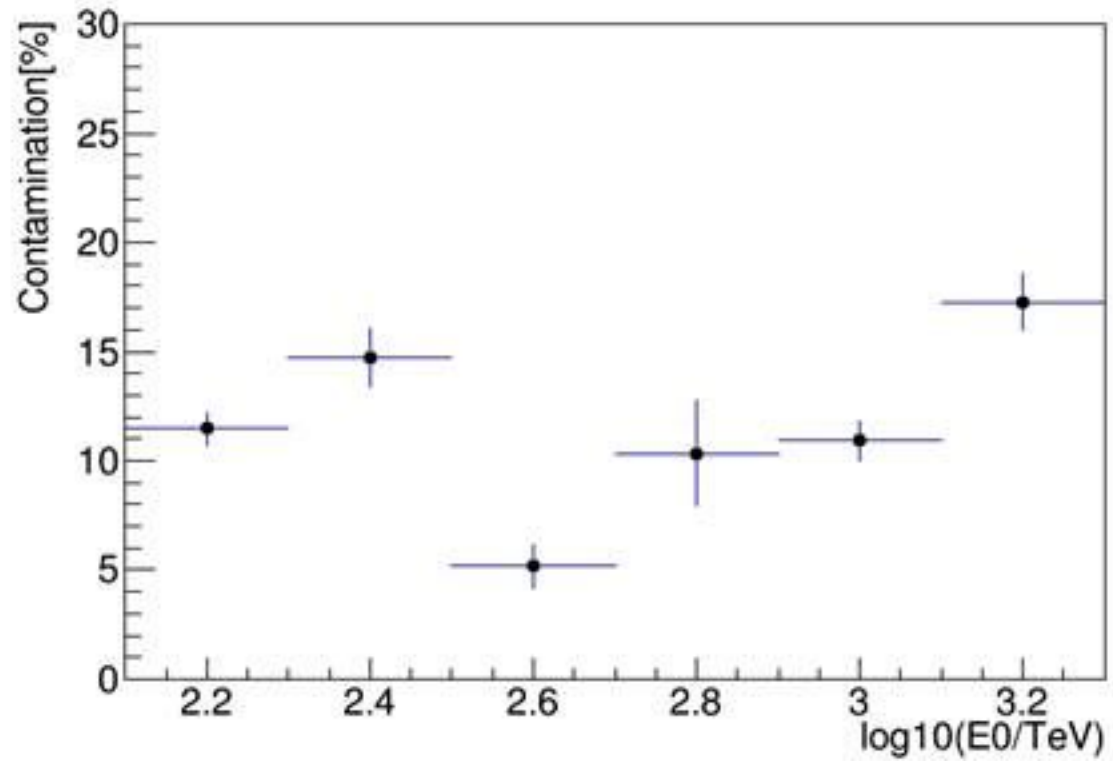


CutA: for p

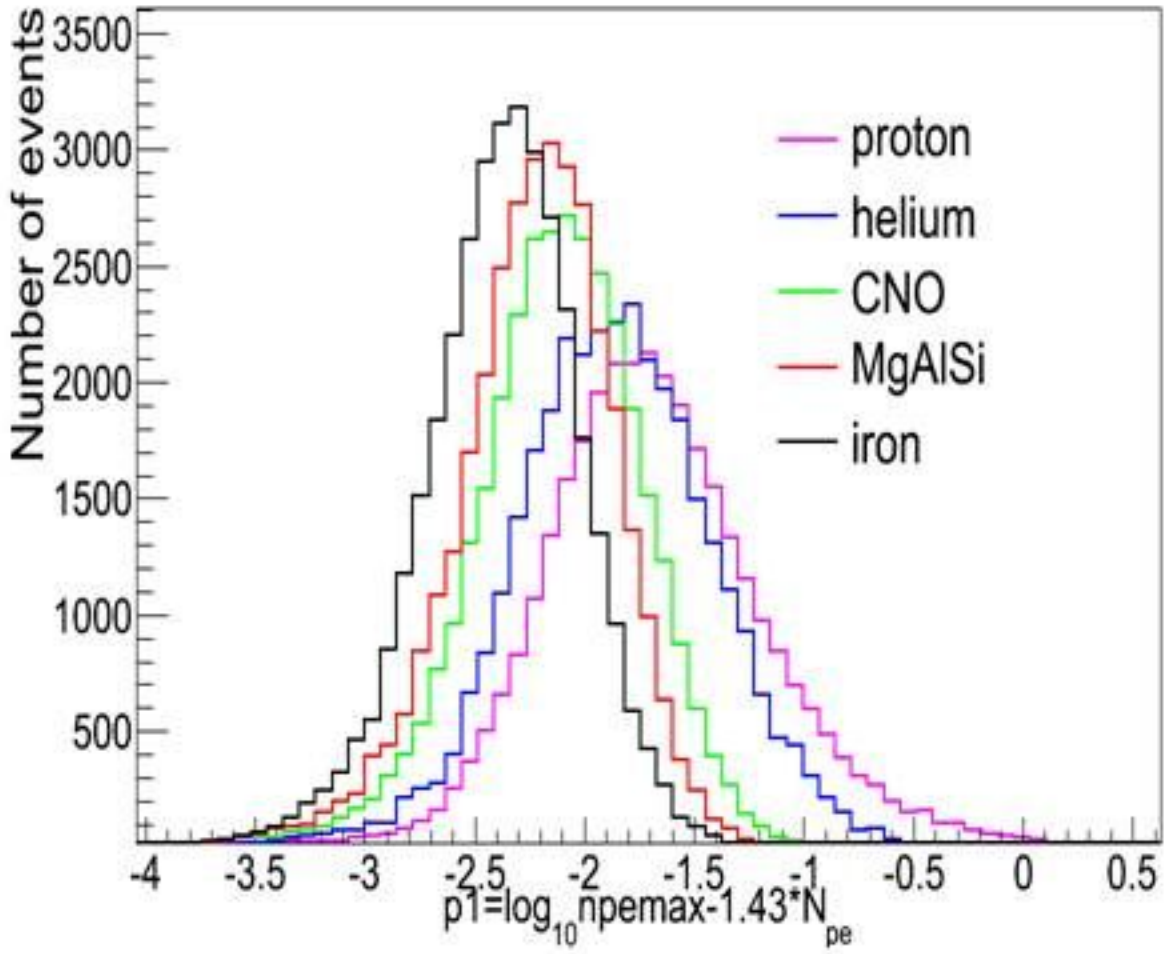
p1>-1. or p2<-1.85

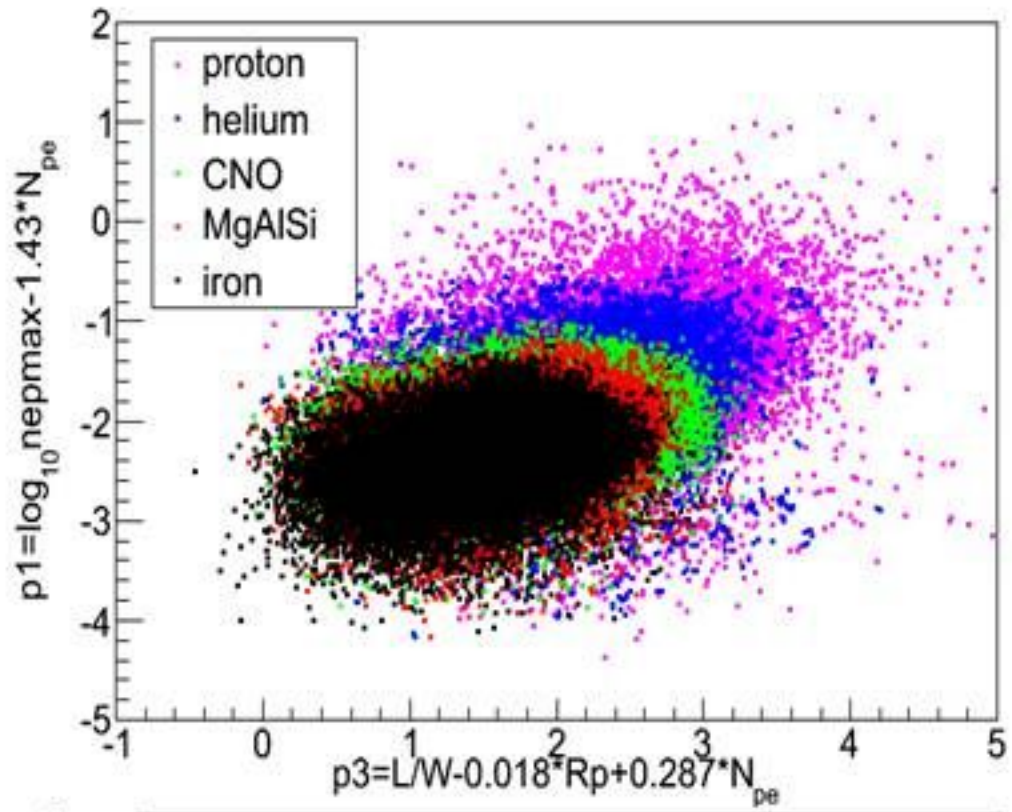
aperture: 12 tels

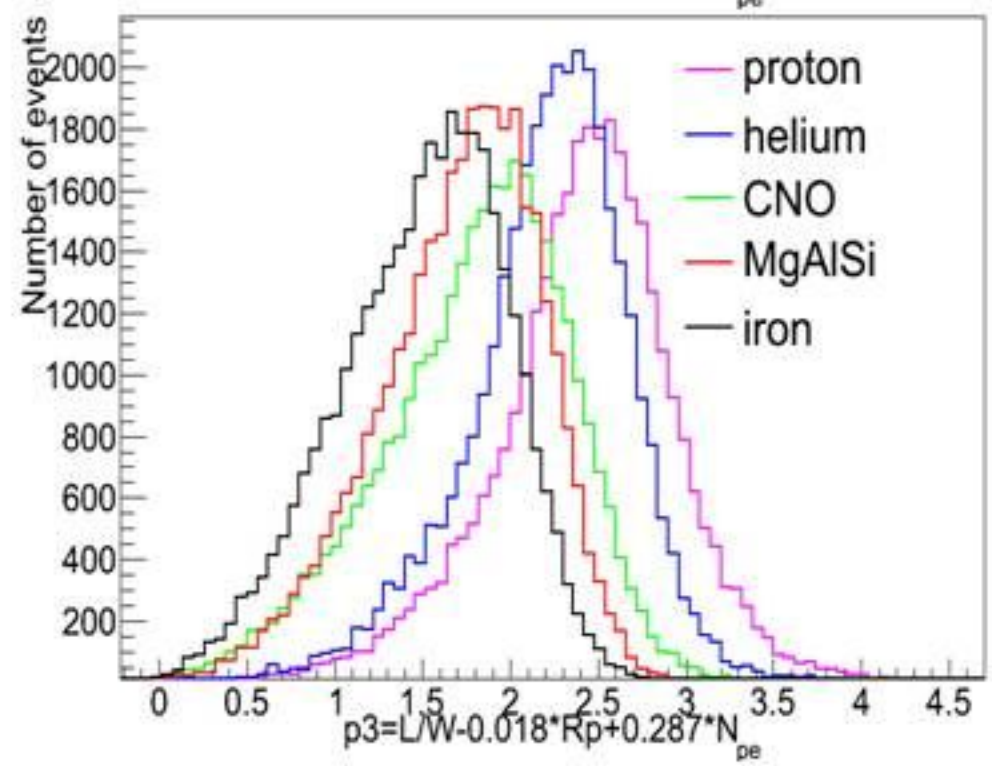
contamination :Horandel model



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







P1 = log10(npemax)-1.43*Npe

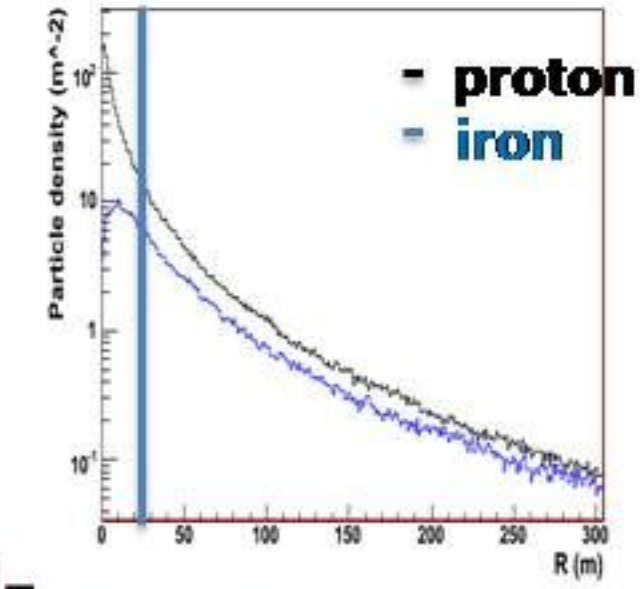
p3 = L/W-0.018*Rp+0.287*Npe

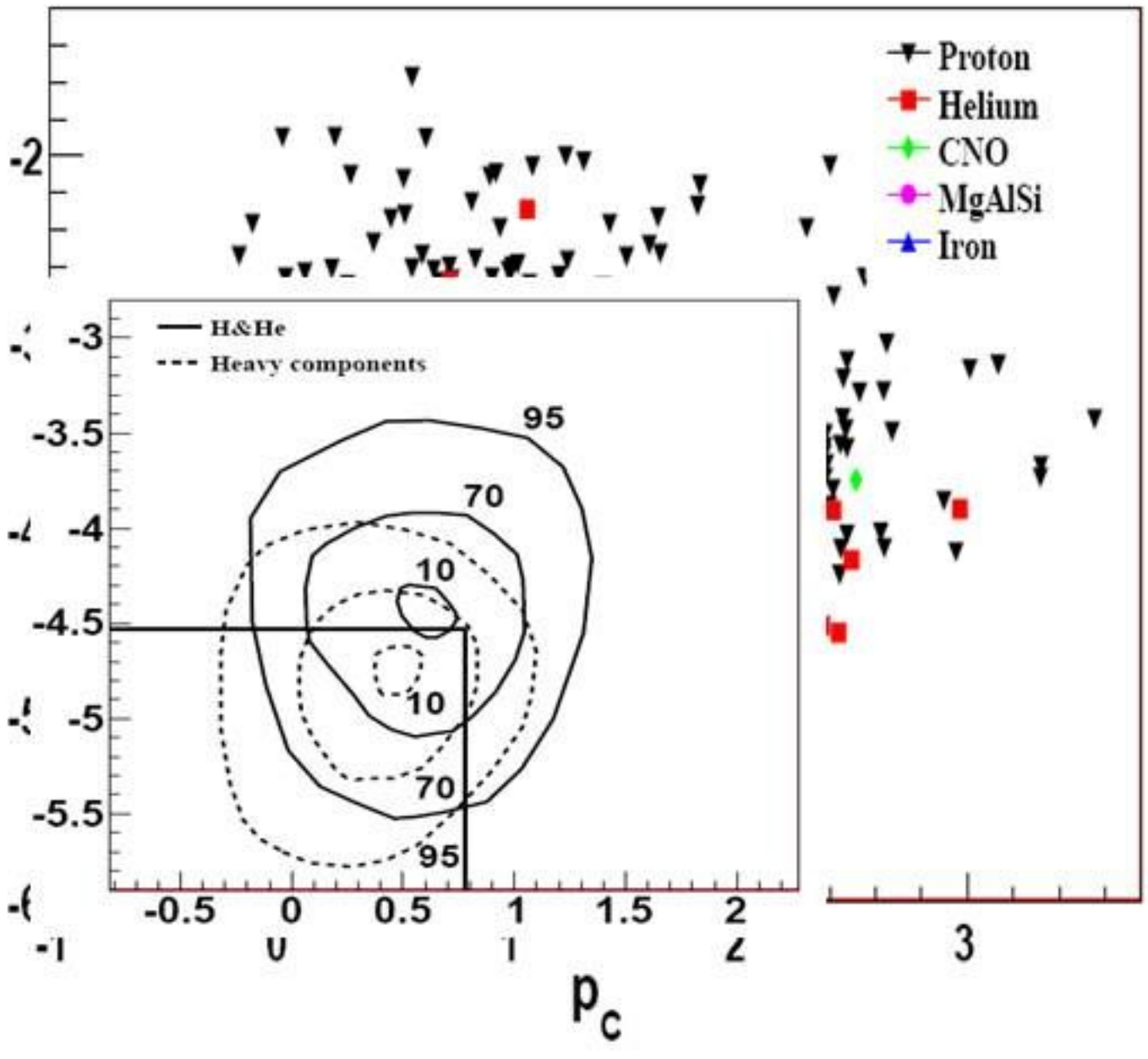
The similar analysis is used in ARGO-YBJ and C-telescope joint experiment with 1/40 aperture

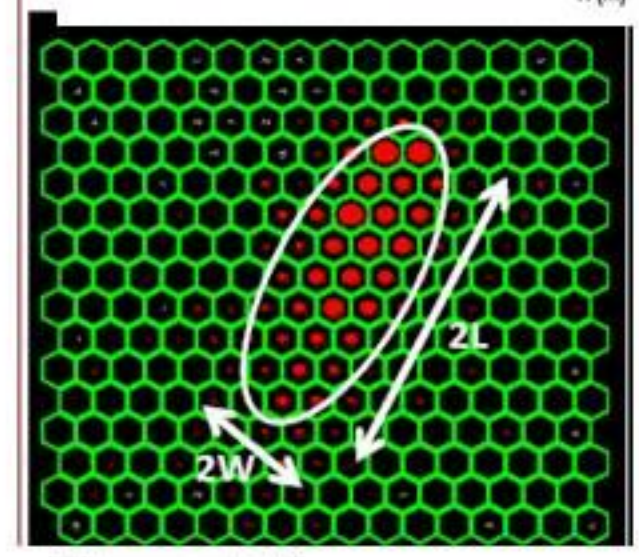
RPC array (ARGO-YBJ) & Cherenkov Telescope (LHAASO)

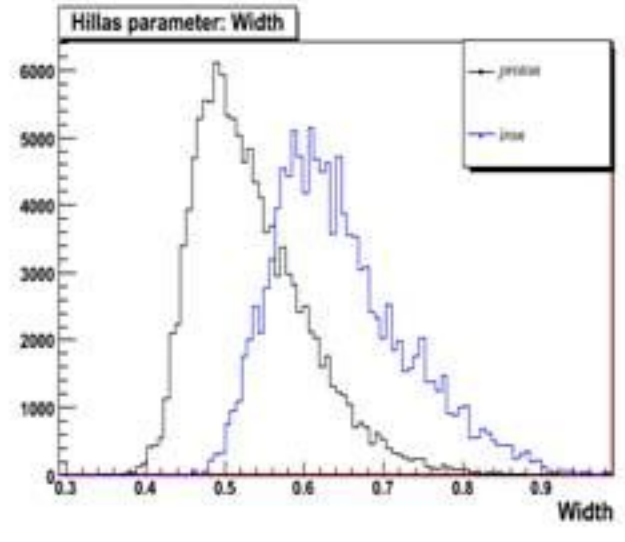
$$p_L = log_{10}N_{max} - 1.44log_{10}N_0^{pe}$$

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

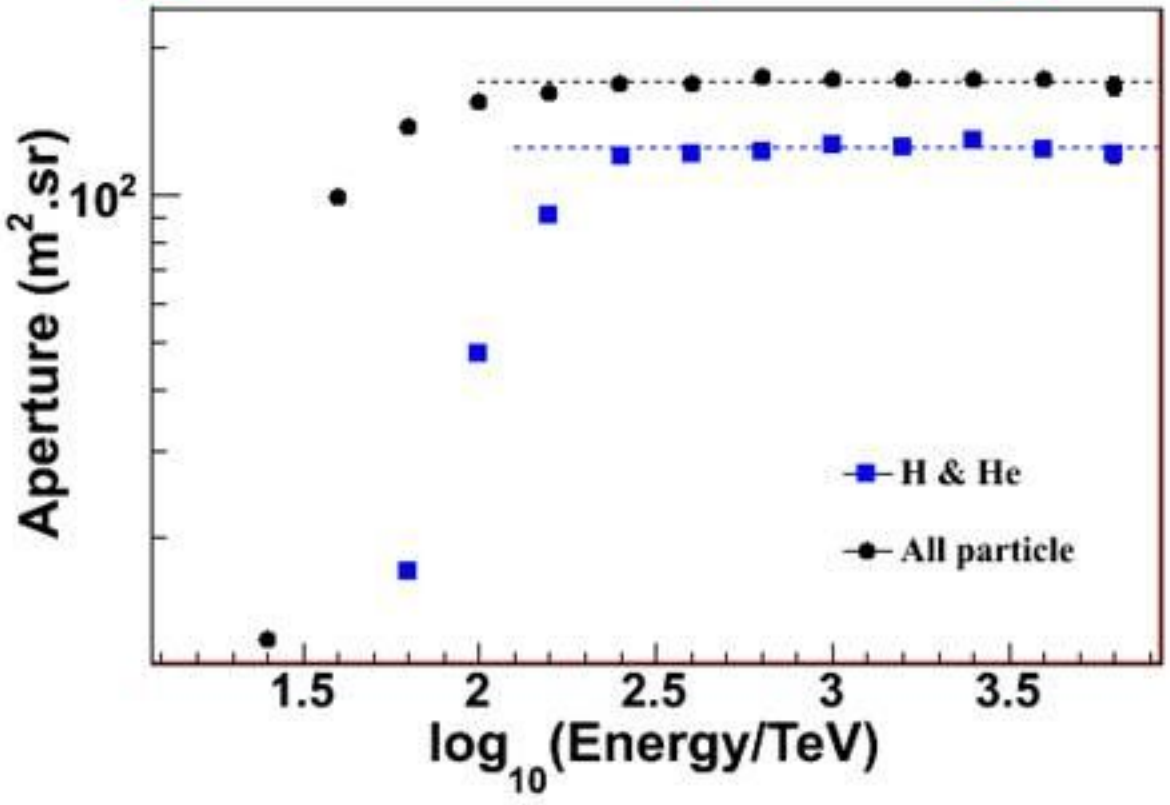


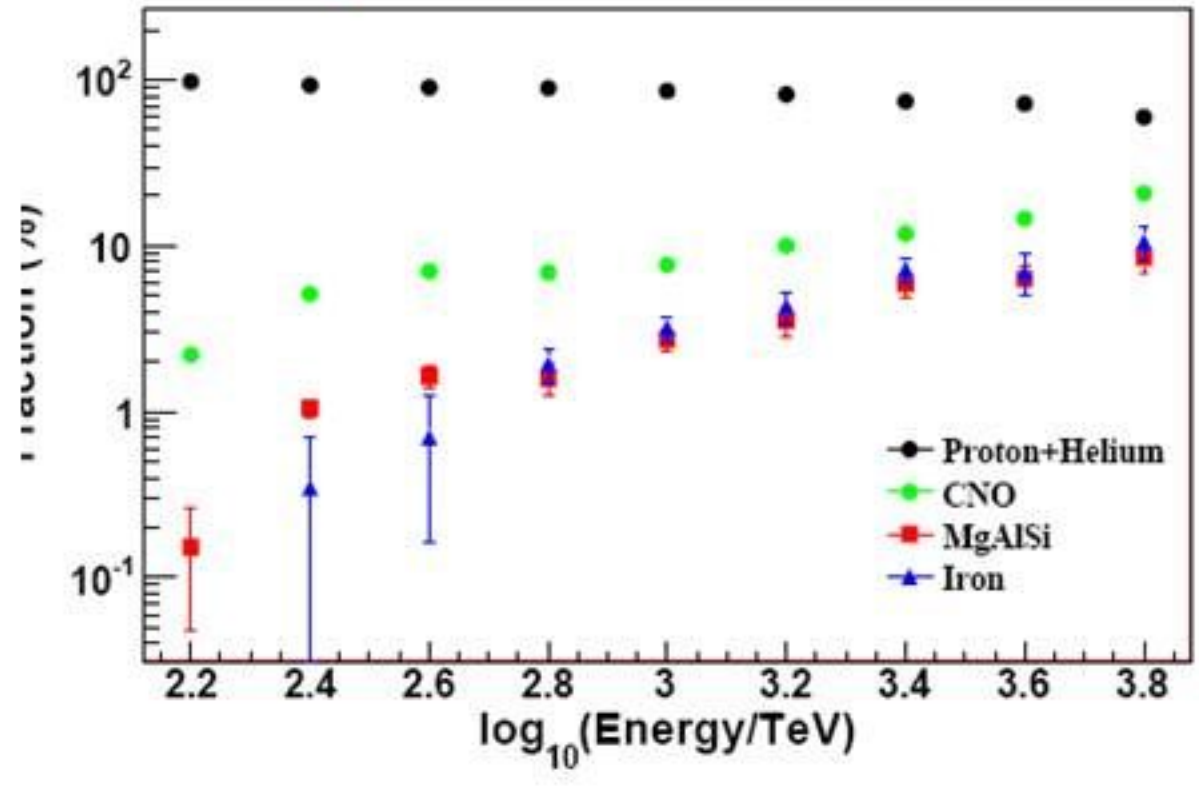






J.R. Hörandel, Nucl. Instr. Meth. Phys. Res. A, 22, 1533 (2007)

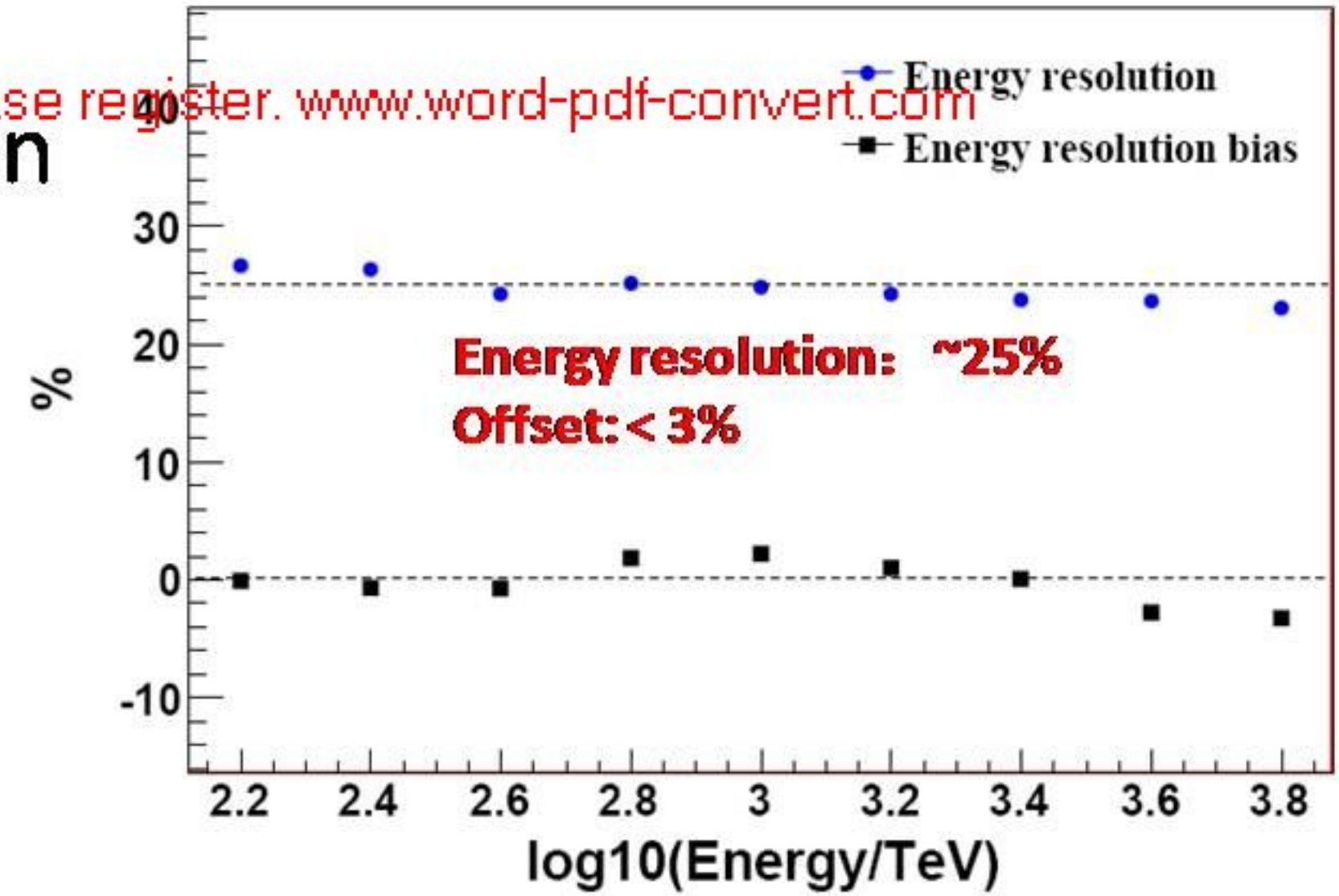


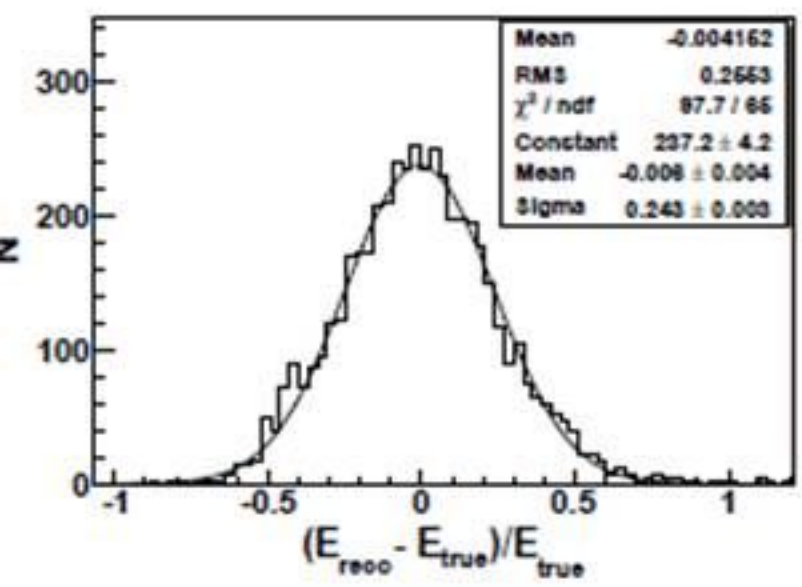


- A simple geometrical calculation gives an aperture of 163 m^2 sr
- The aperture of H&He: ~120 m^2 sr above 300 TeV;
- The purity of H&He showers: ~93% below 700 TeV;
- The contamination of heavy nuclei increases with energy: 13% @ 1 PeV, gradually increases to 27% @ 3 PeV;
- The contamination of heavy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

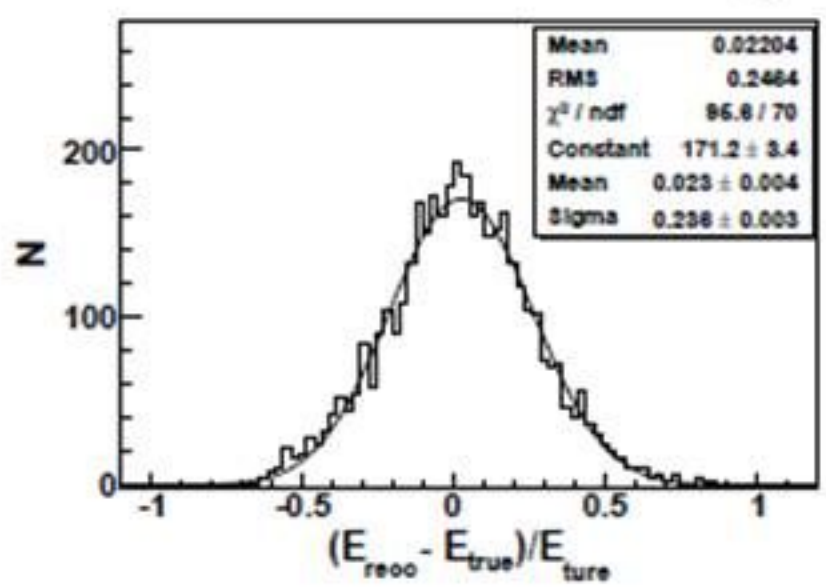
E-reconstruction

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

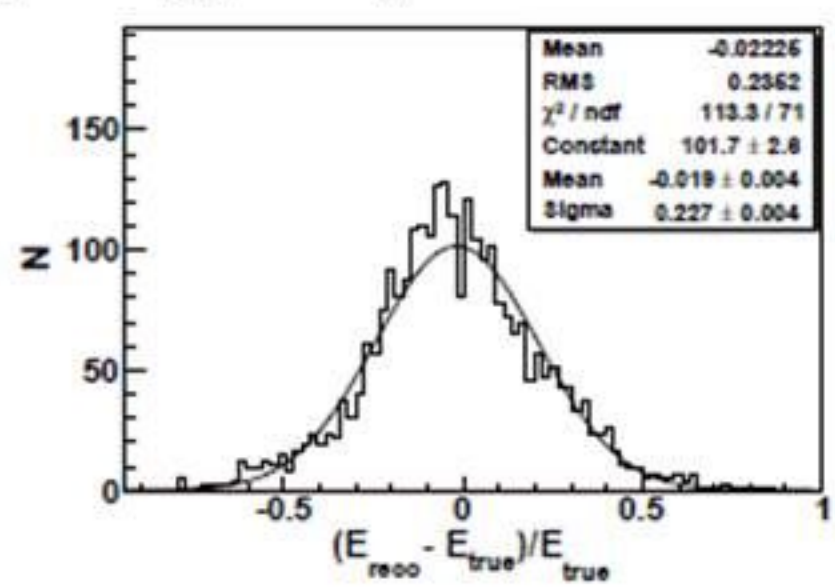




300 TeV

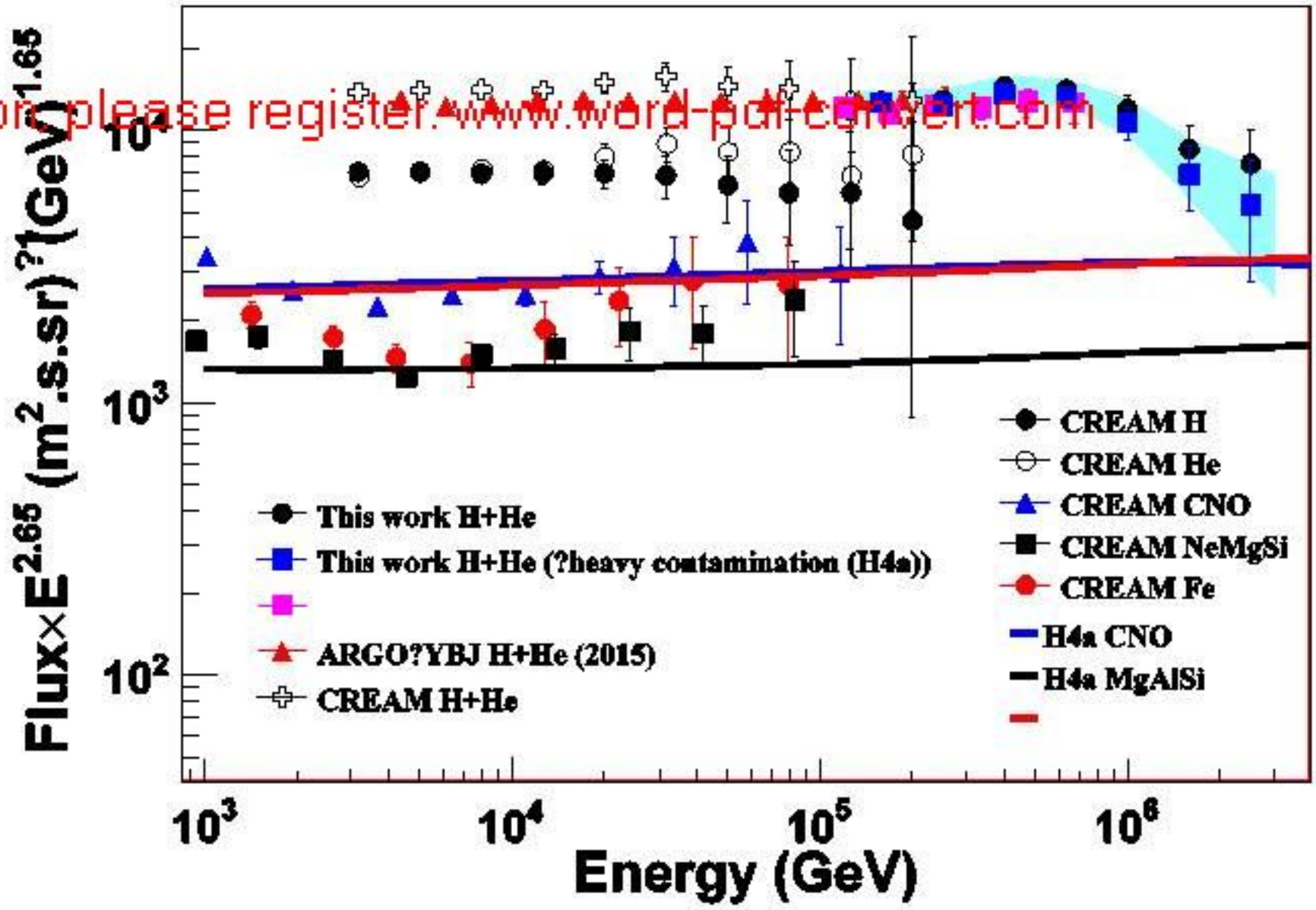


1 PeV



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

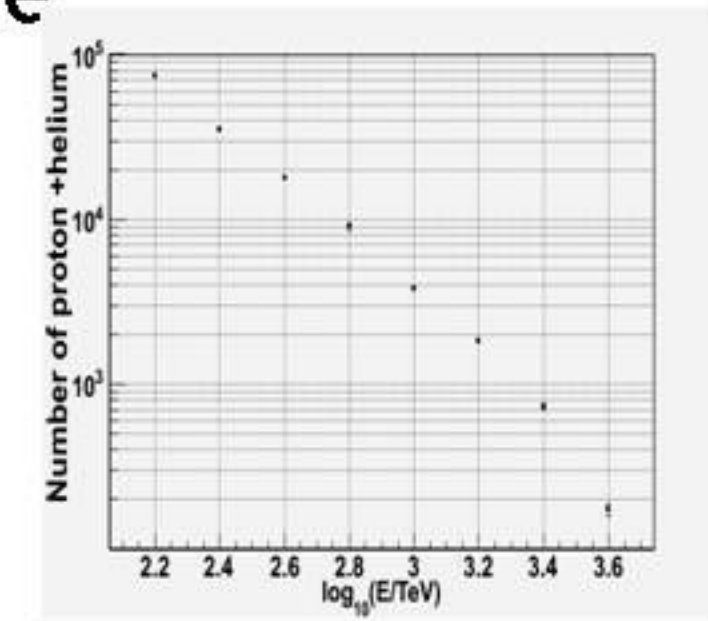
  (with heavy contamination subtracted J.R. Hörandel, Modern Physics Letter A, 22, 1533 (2007)

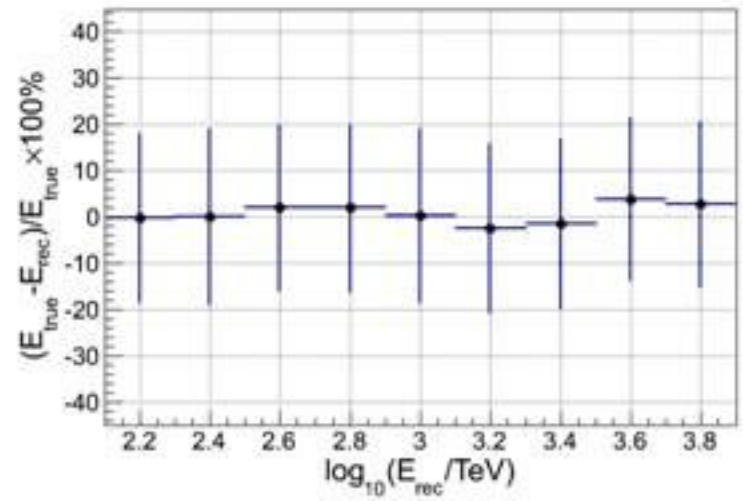
  -2.56 ± 0.05 and -3.24 ± 0.36 below and above the knee

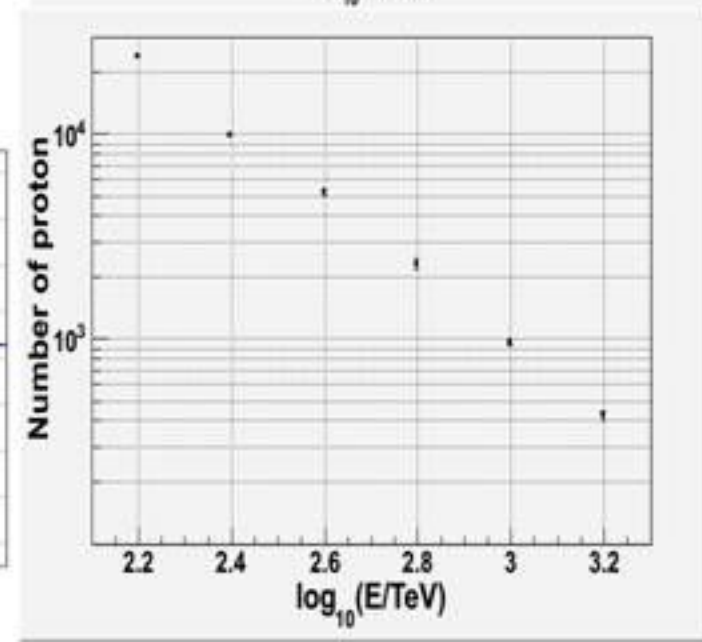
  (without heavy contamination subtracted)
  - Below the knee, consistent with ARGO-YBJ, which is consistent with CREAM

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 confirmed at lower energy end by the space borne experiments

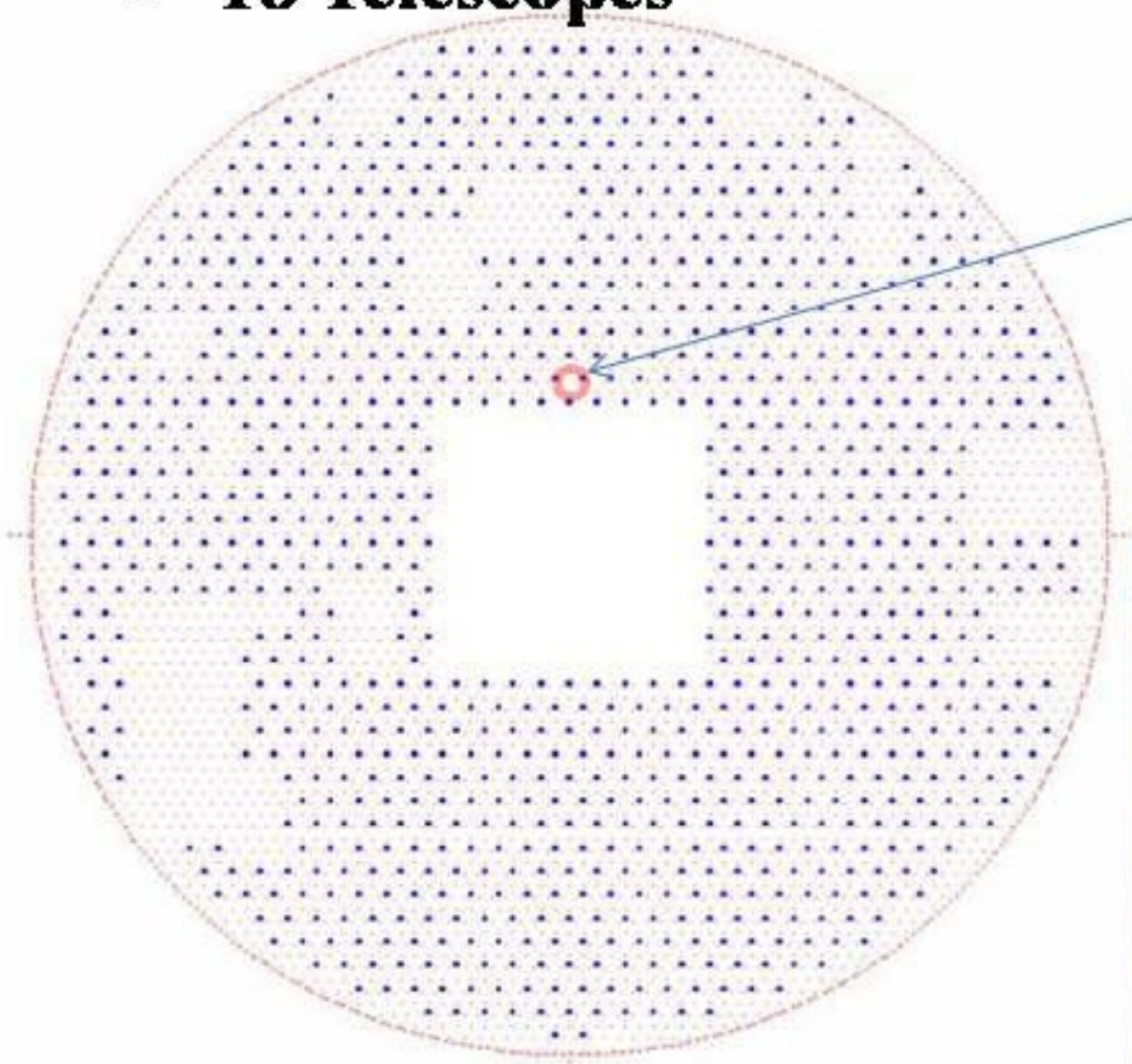


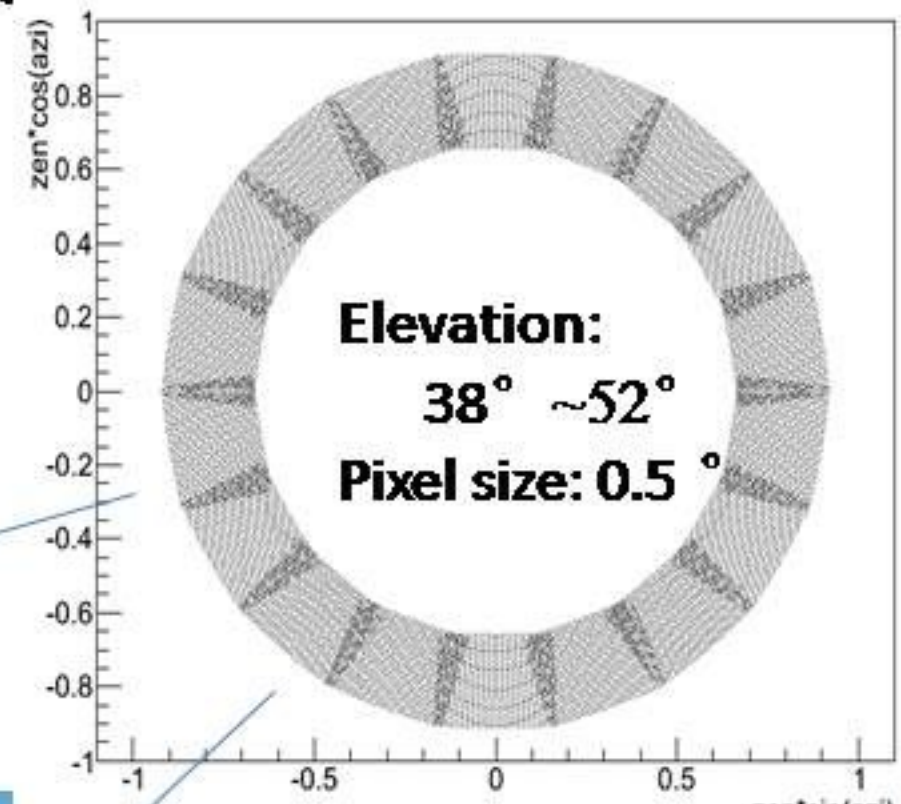


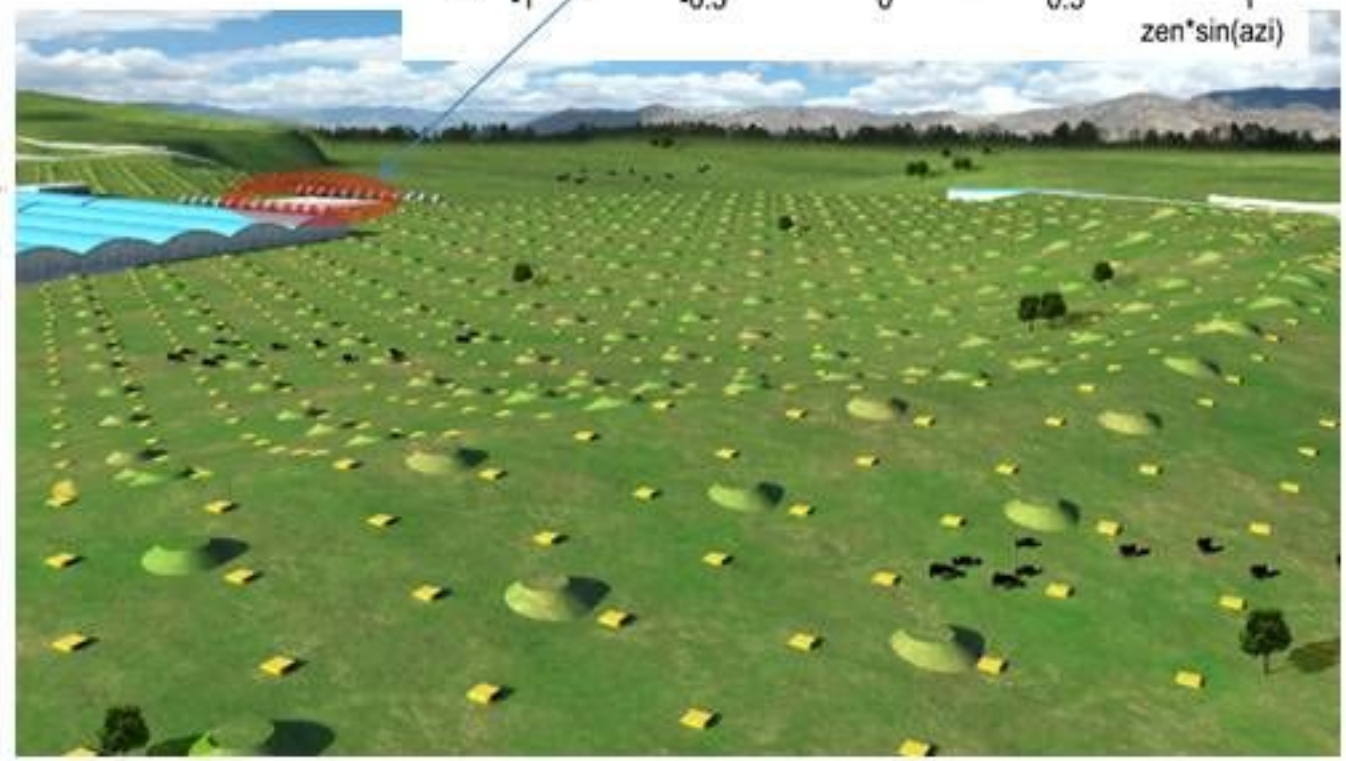


The Scintillation + MD Array + WFCTA for CRs above 10 PeV

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

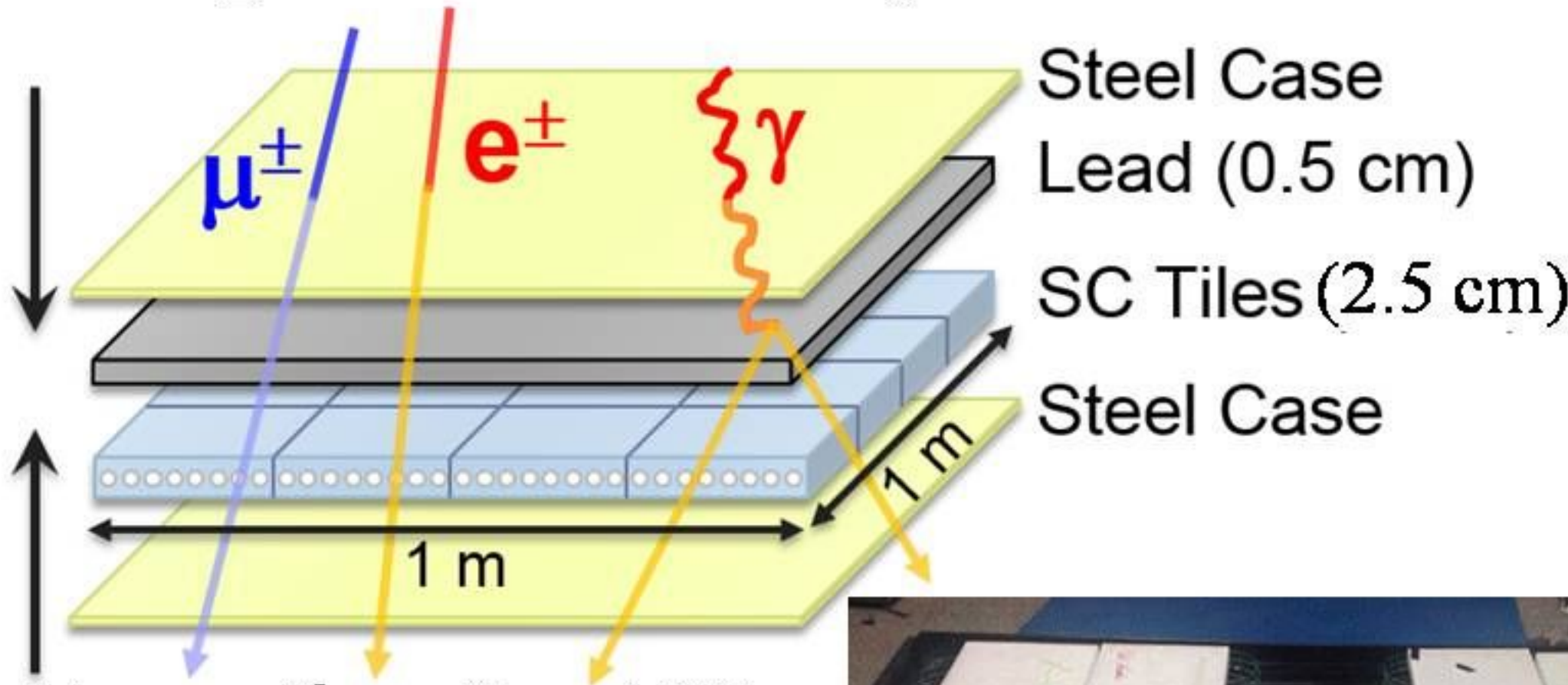






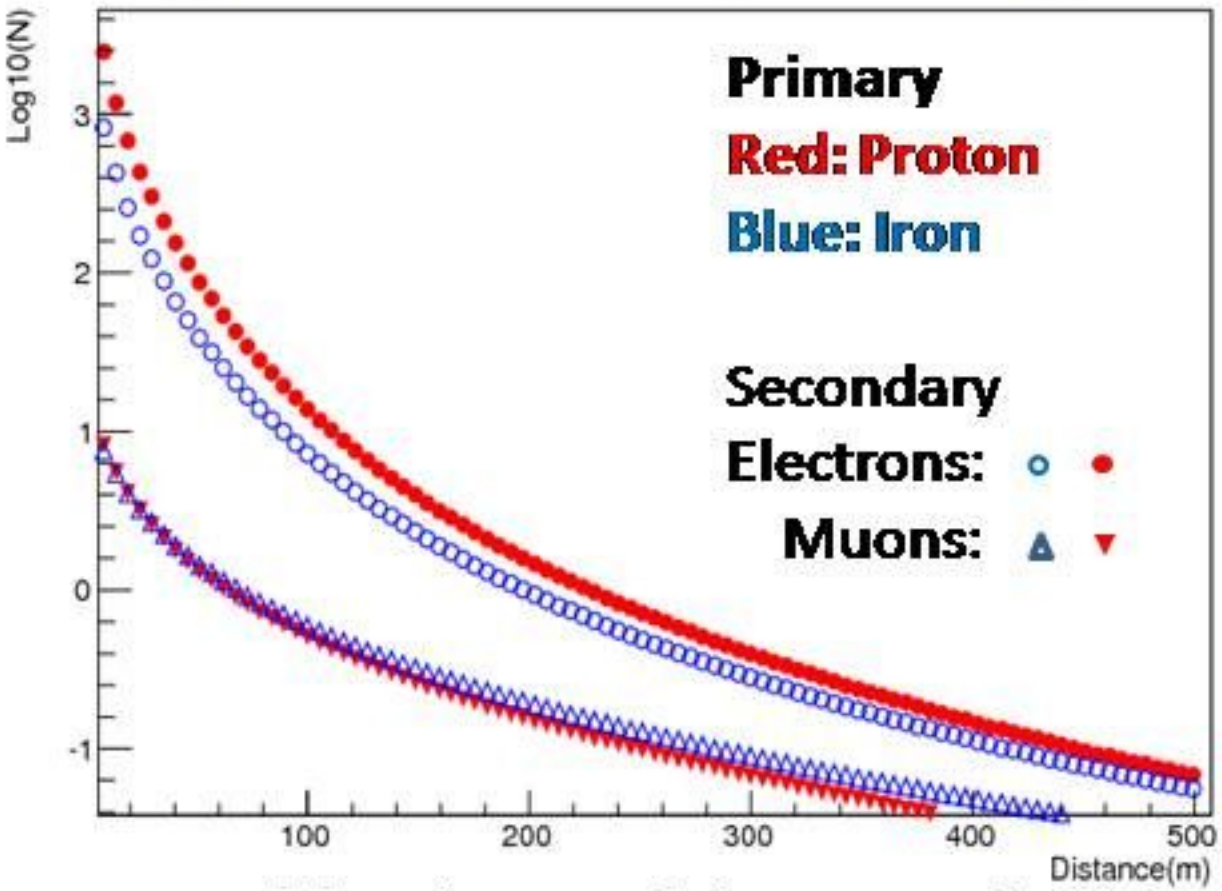
Electromagnetic Particle Detector (ED)

using sacintillator plat/WS fiber/PMT

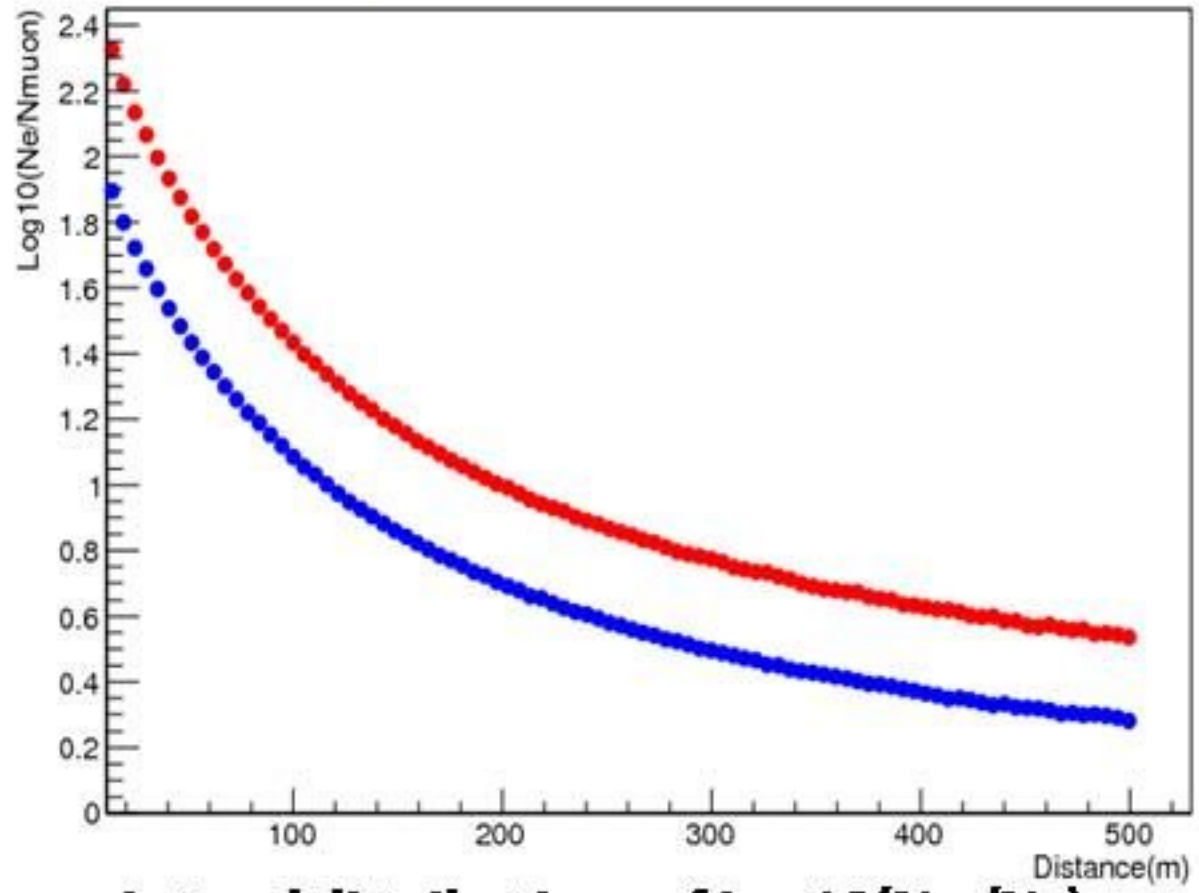


- **Non-uniformity <10%**
  - **tiles: <5%**
  - **fibers: 11%/$\sqrt{32}$**
  - **PMT gains: adjustable HV**

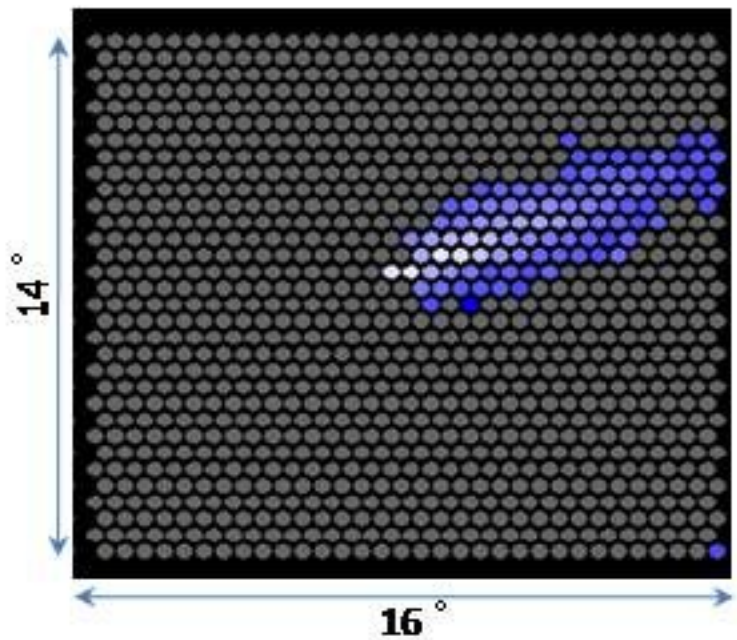
The lateral distribution

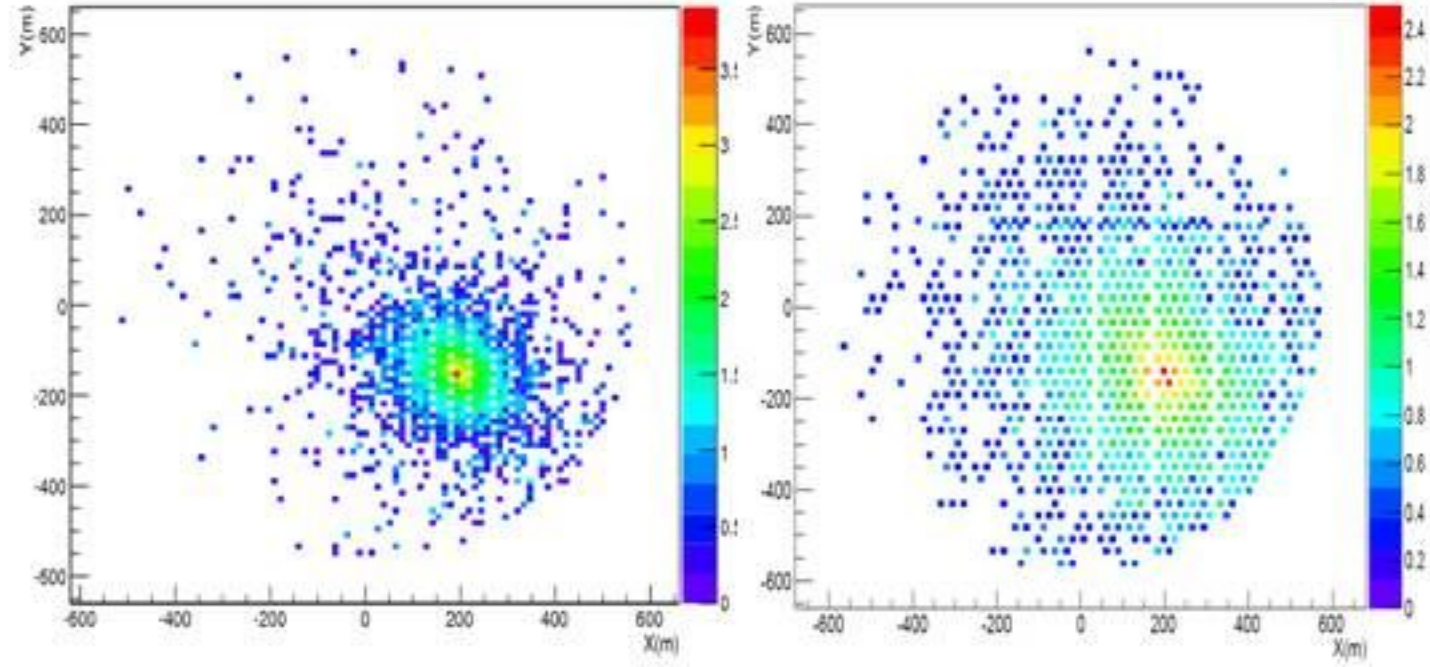


Lateral distribution of electron and muon



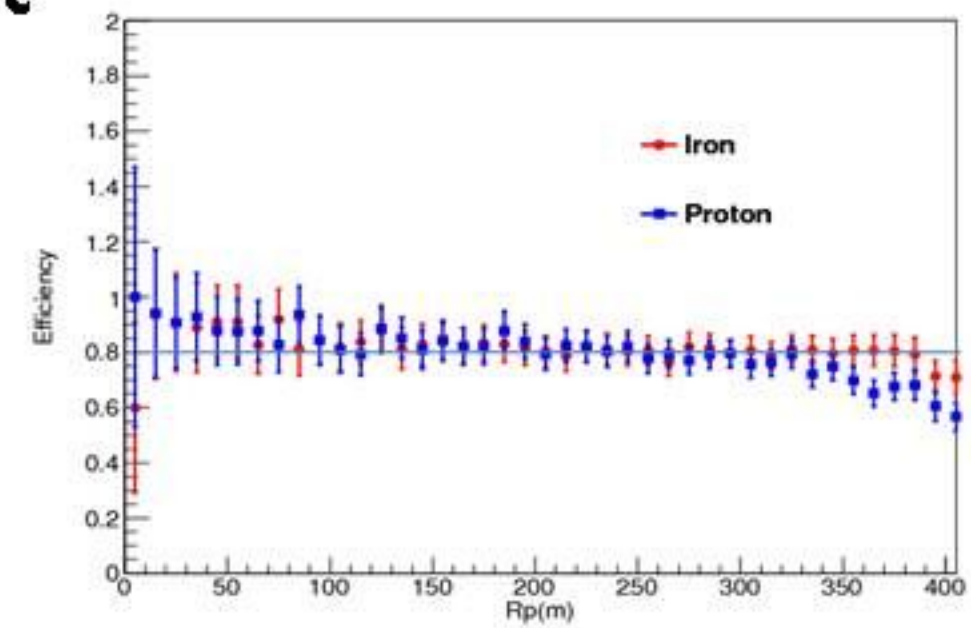
Lateral distributions of $Log10(N_{ch}/N_{\mu})$





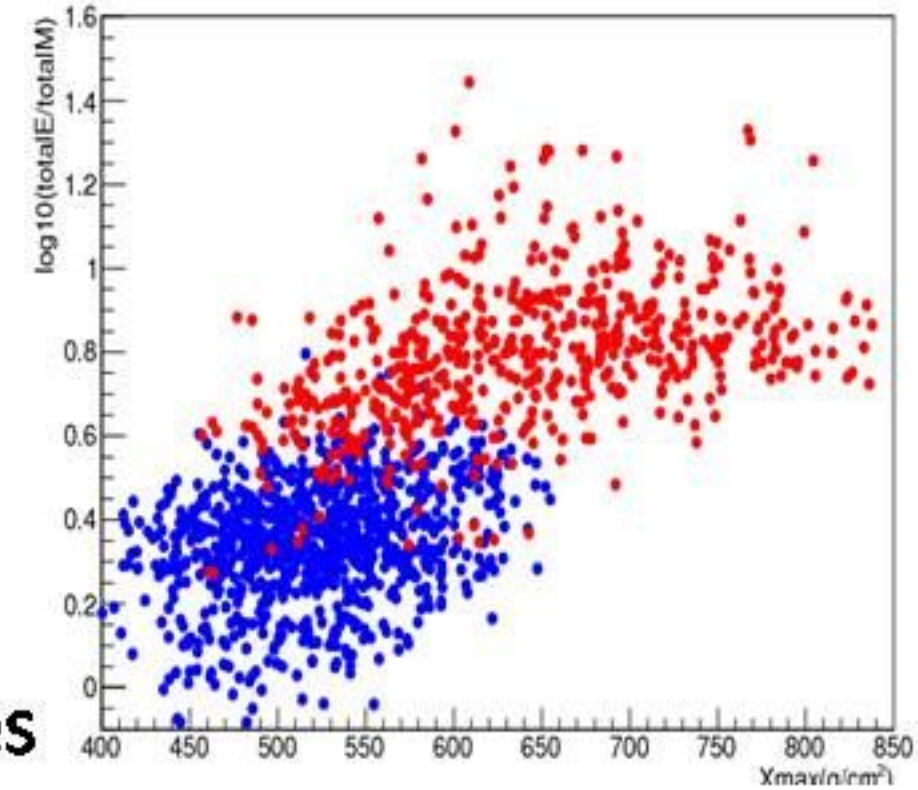
Prospects

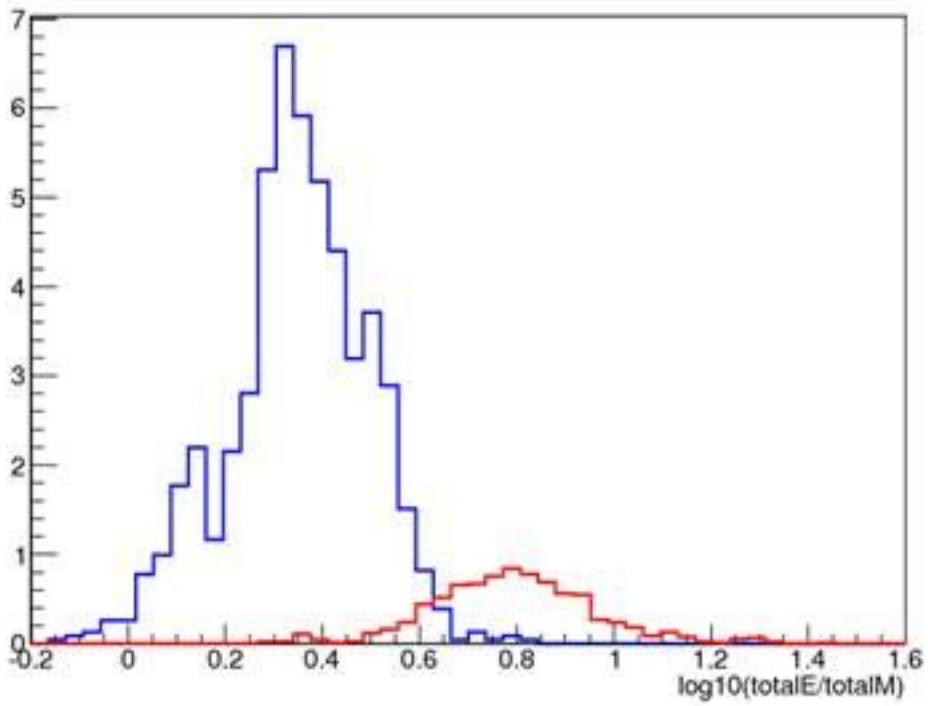
- AS core resolution: <3 m (EDA)
- AS arrival direction resolution: ≤0.2° (EDA)
- Trigger efficiency for E>7 PeV: >80% up to 350 m
- Energy resolution for clean Fe samples: ~15% (CT)
- E-scale: overlap with the combined experiment of WFCTA + WCDA++

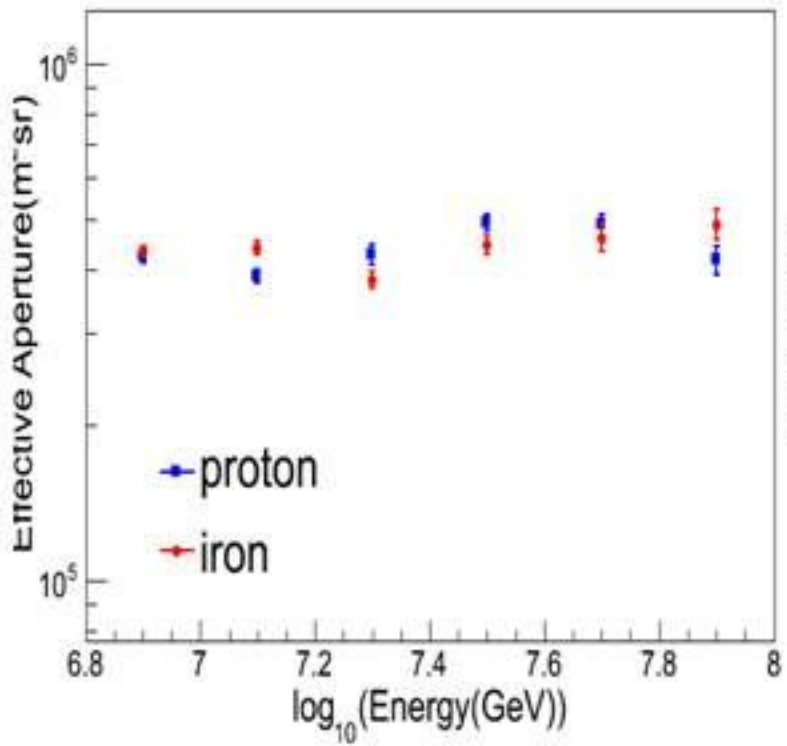


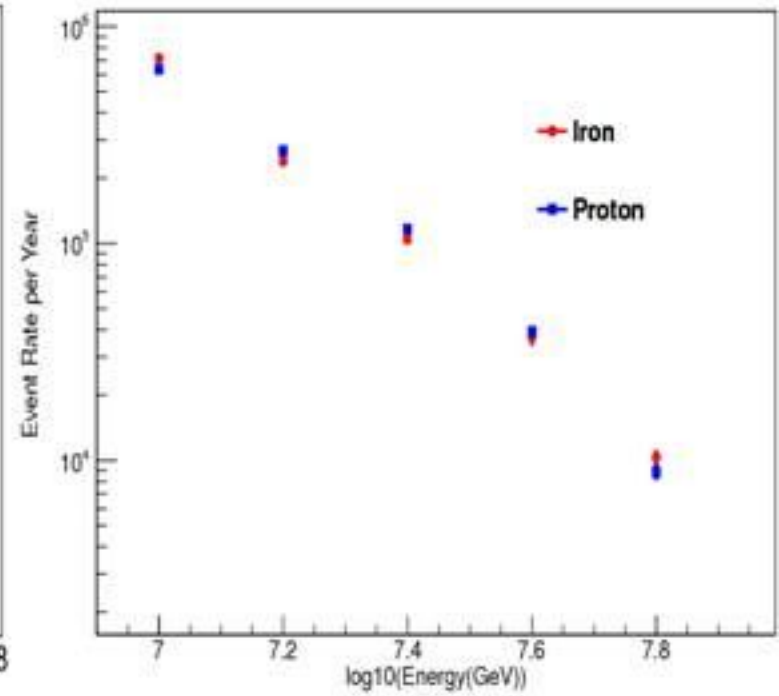
Unbiased measurement to species

- Aperture: ~0.45X10^6 m^{2}sr
- Iron selection:
- μ-content and X_{max} with a resolution about 50 g/cm^2 (estimated)
- 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

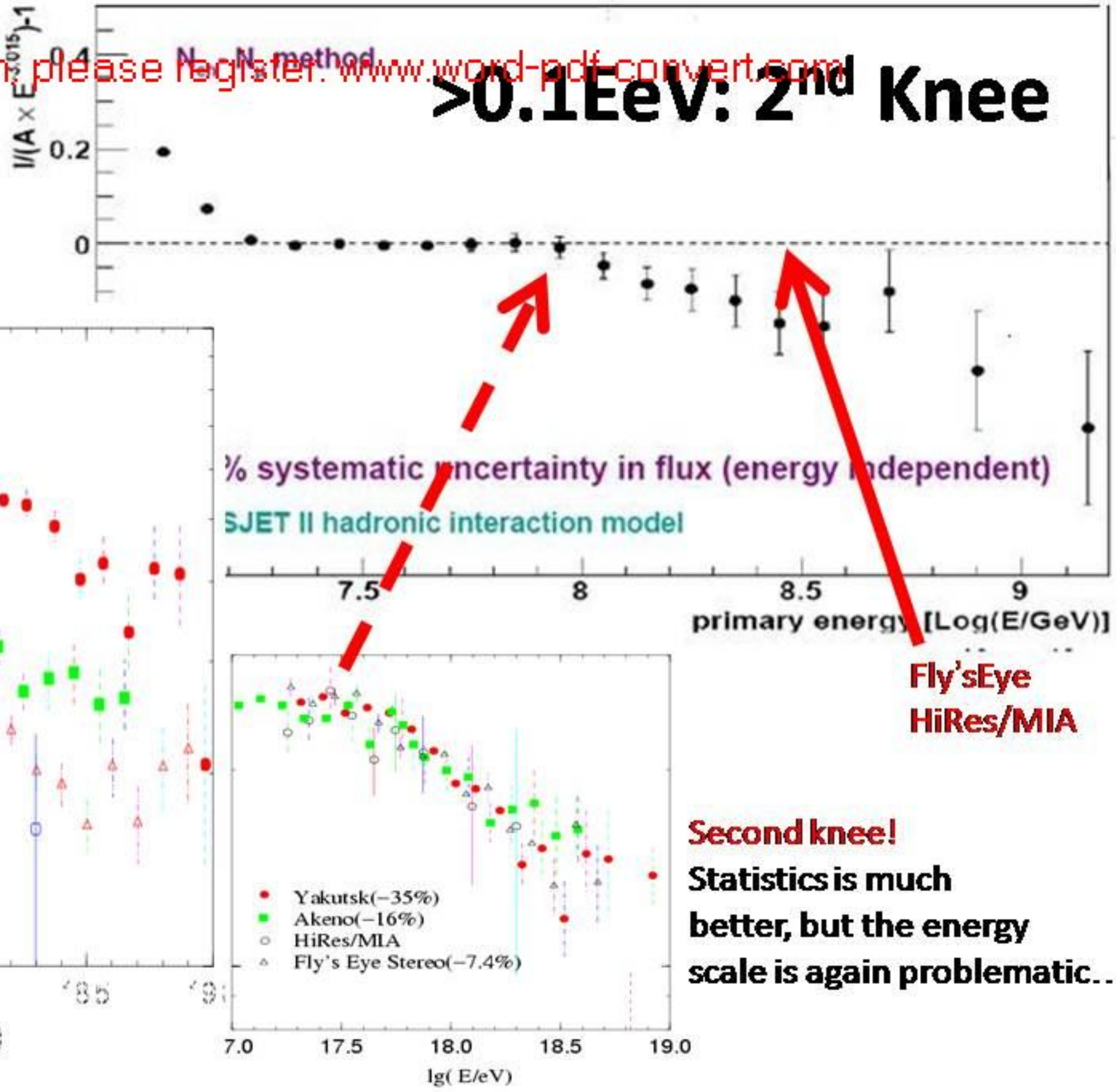








>0.1EeV: 2nd Knee



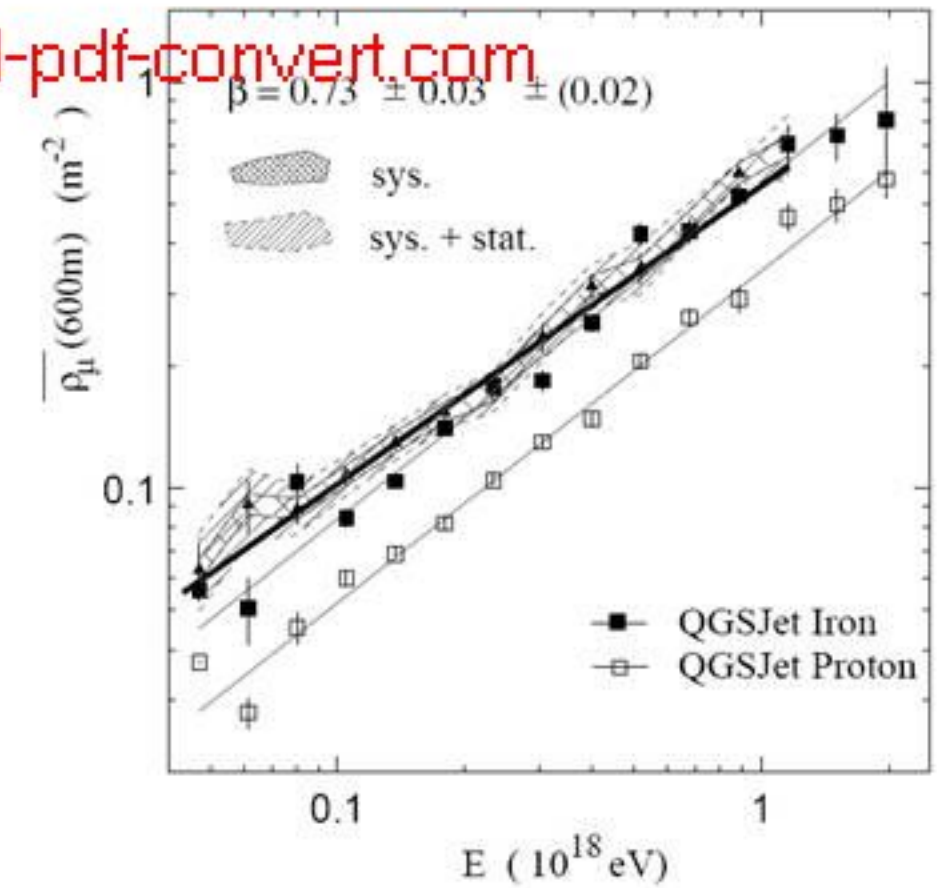
Second knee!

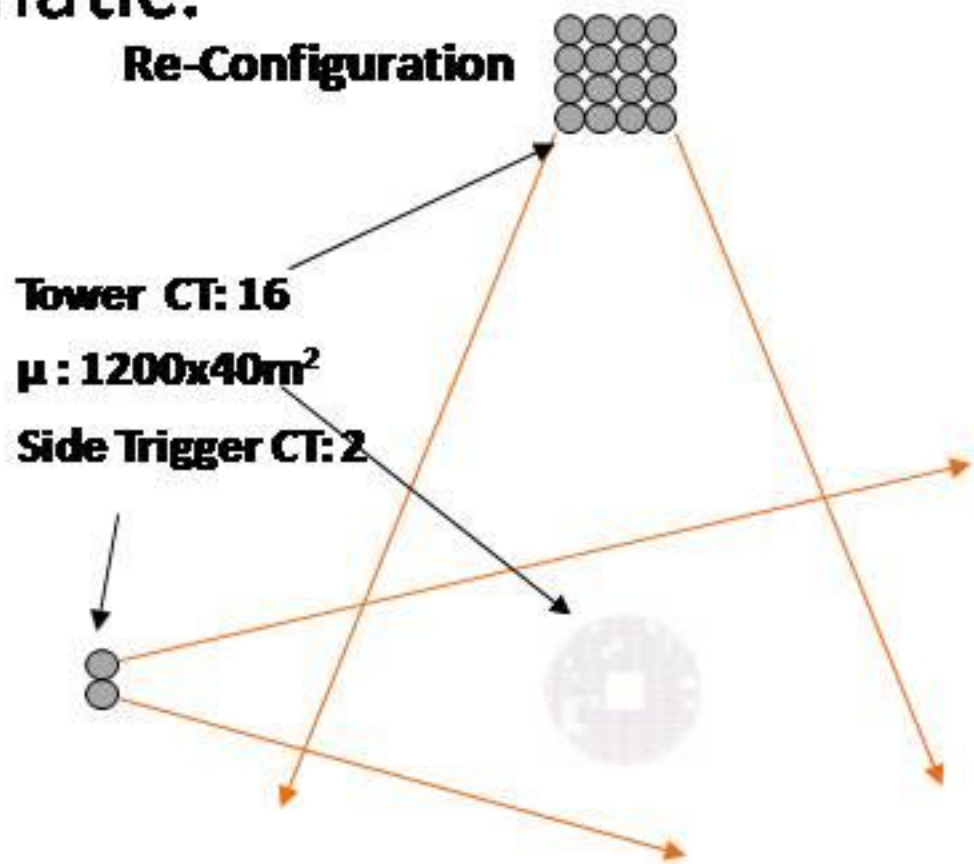
Statistics is much better, but the energy scale is again problematic…

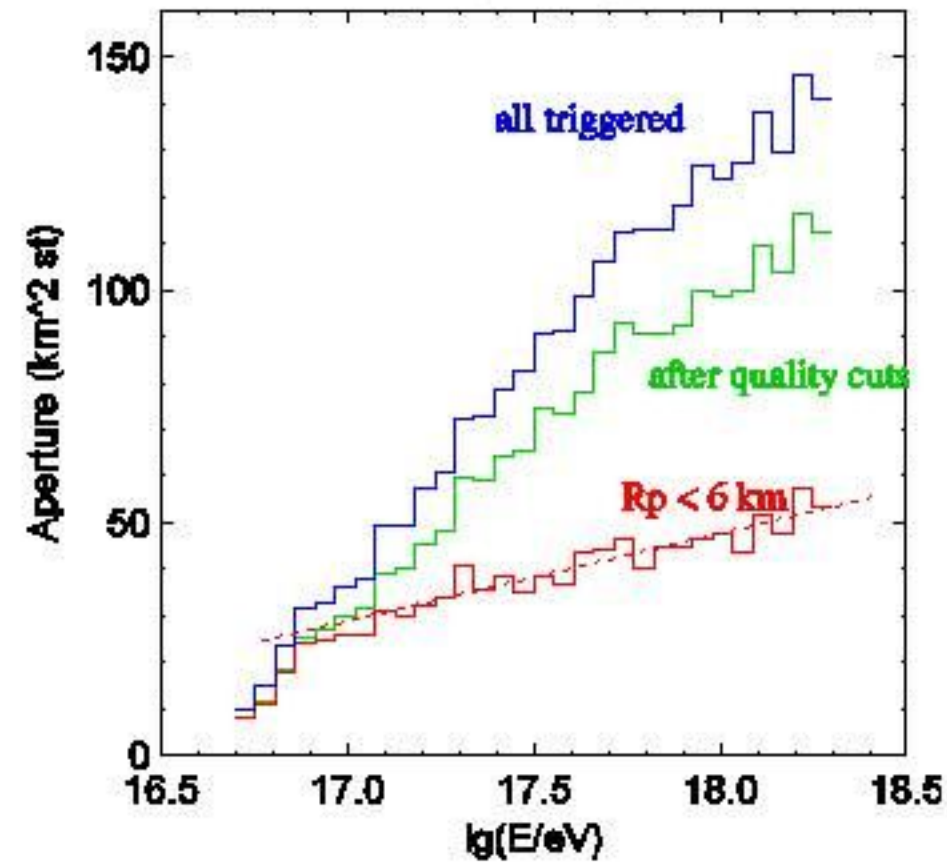
Still Energy Scale

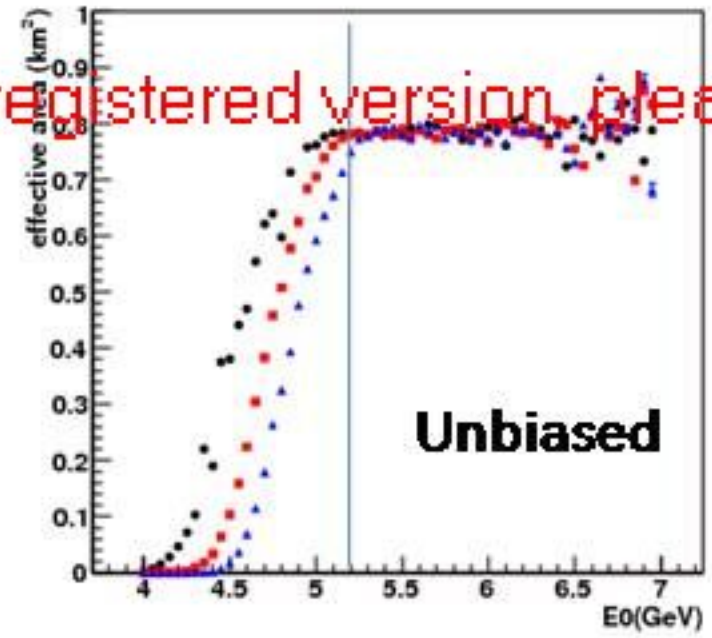
- Calibration between C-tele and F-tele
- Calibration between TUNKA and F-tele
- Calibration between LHAASO/F-tele and other F-tele arrays?

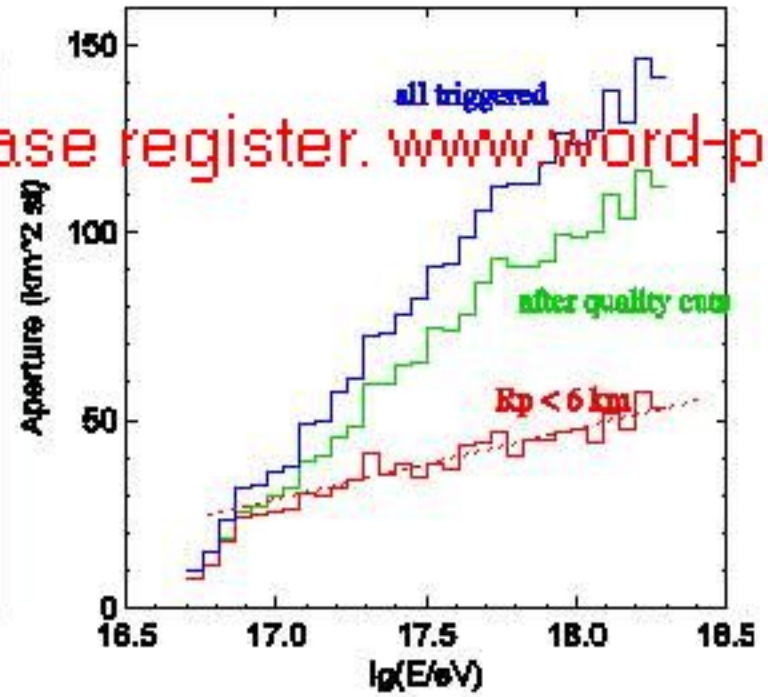
But not only..... muon-content is also problematic.

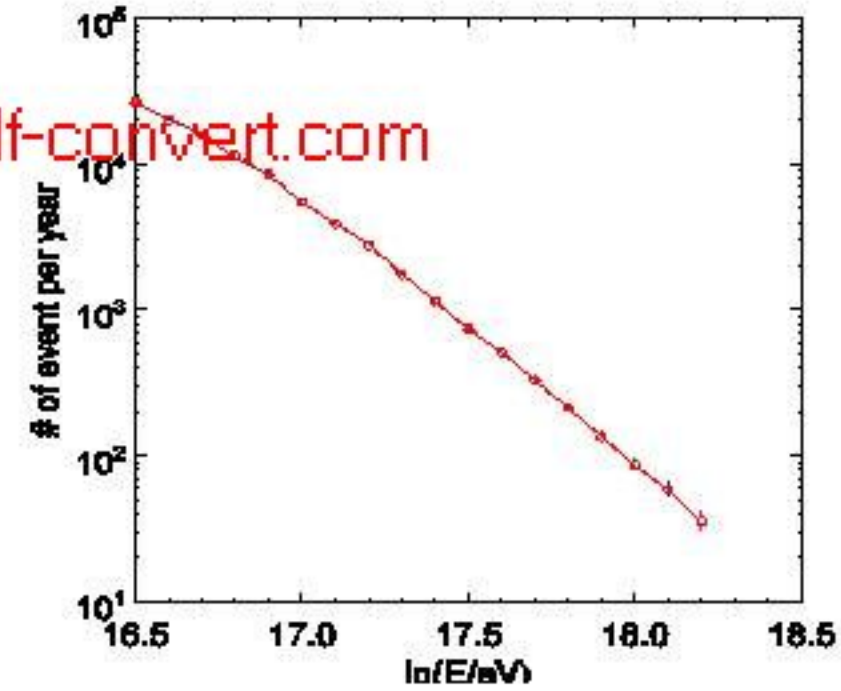


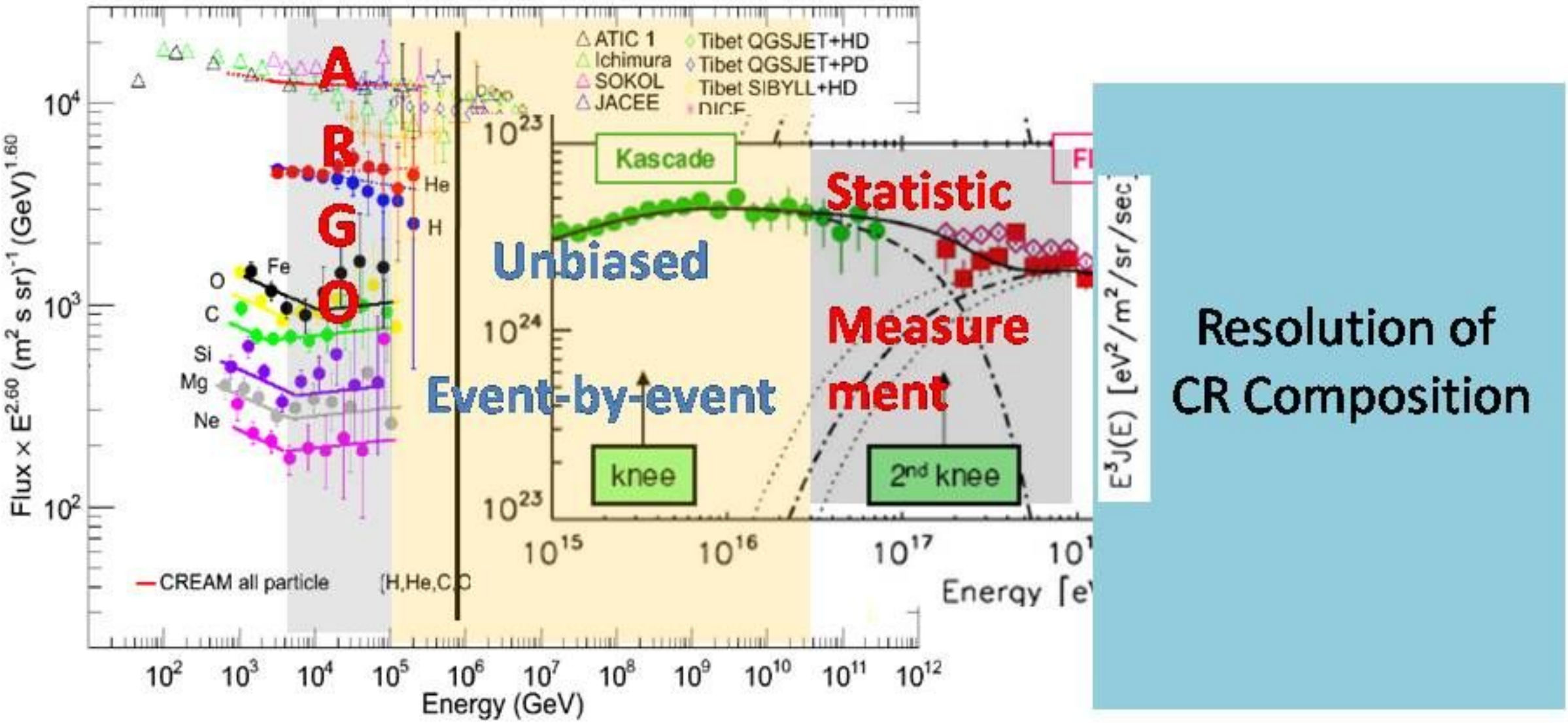












Resolution of
CR Composition

Summary on LHAASO

- 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 second knee of the all particle spectrum and the composition are expected to be measured with a calibrated energy scale which is picked at much lower energy

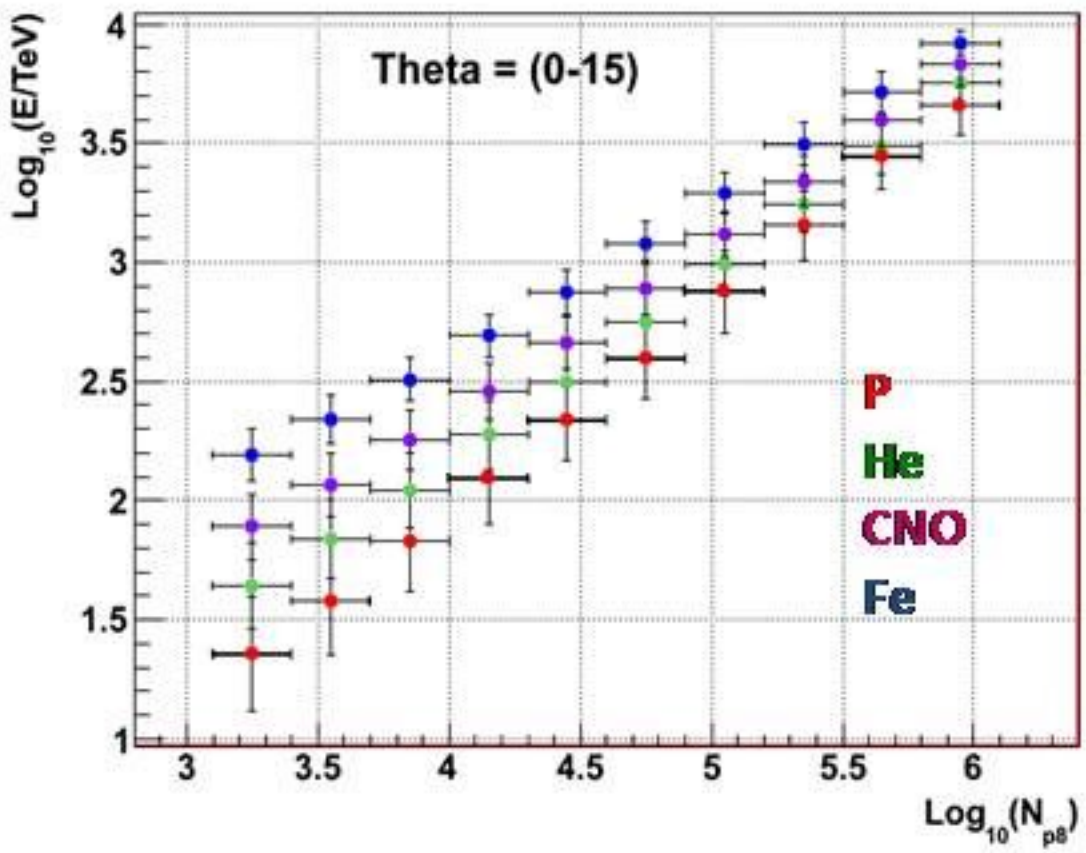
2nd Part for Antonio Surdo

ARGO-YBJ results using vertical Showers

1st Analysis (I) – LDF approach

MC: truncated size Np_8 as energy estimator

- **Event selection:** - Core reconstructed in a central detector fiducial area
  - Reconstructed zenith angle <15°
- **Np_8 (number of particles within 8m from the core):**
  - well correlated with primary energy
  - not biased by finite detector size effects
  - weakly affected by shower fluctuations

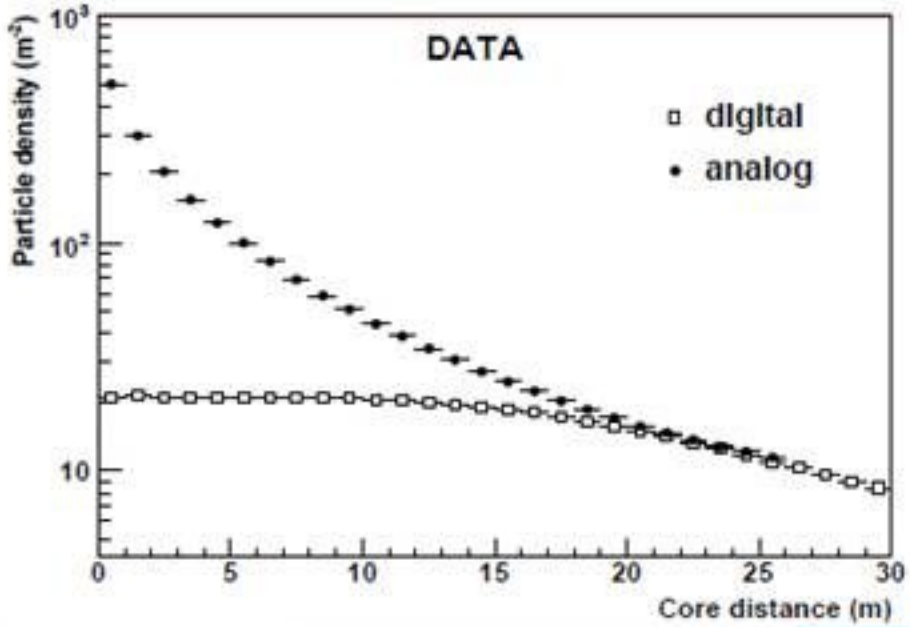


Look for information on the shower age in order to have a mass independent energy estimator

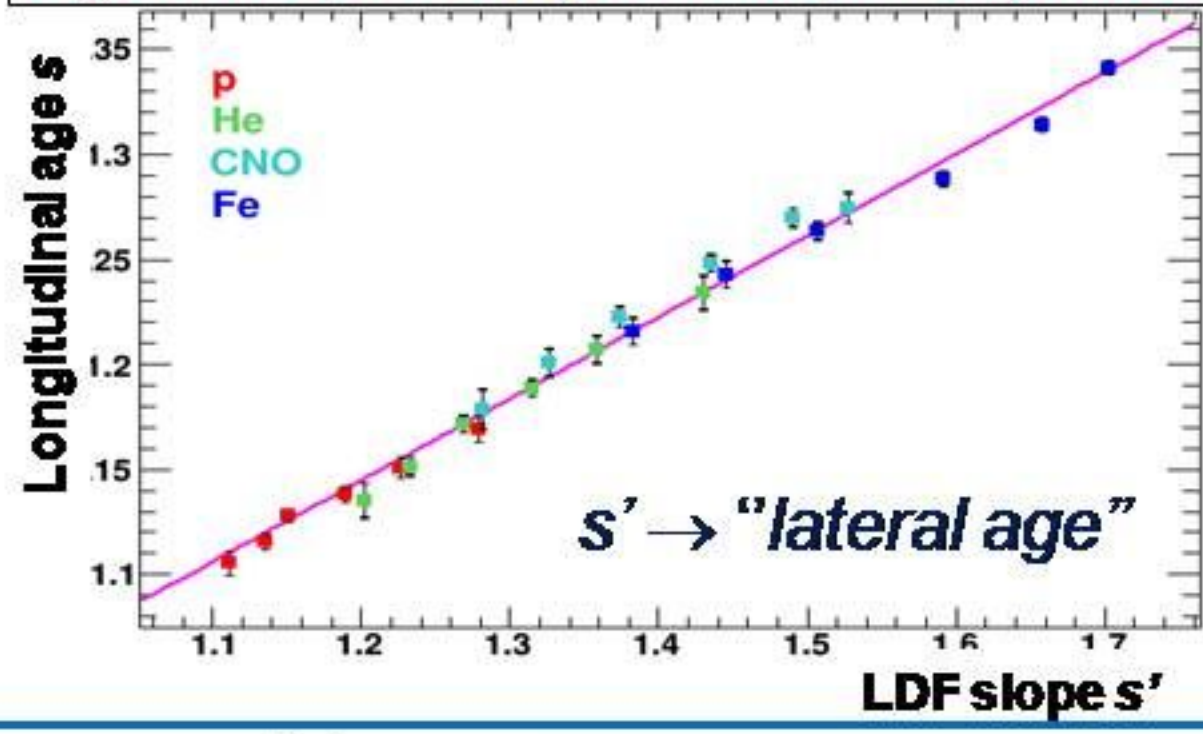
(I) – LDF and shower age

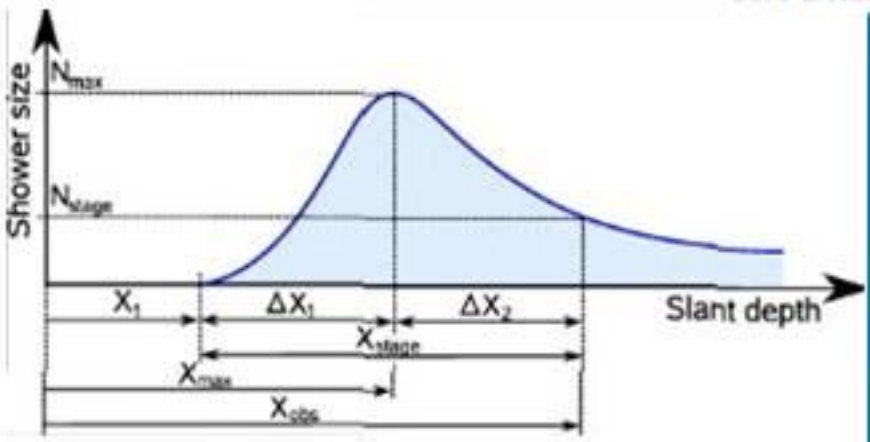
With the analog data we can study the particle distribution by means of a Lateral Distribution Function (LDF) without saturation near the core. Well fitted by a modified NKG function:

$$\rho'_{NKG} = A \cdot \left(\frac{r}{r_0}\right)^{s'-2} \cdot \left(1+\frac{r}{r_0}\right)^{s'-4.5}$$



The LDF slope *s'* is related to the shower age *s* independently on the primary mass



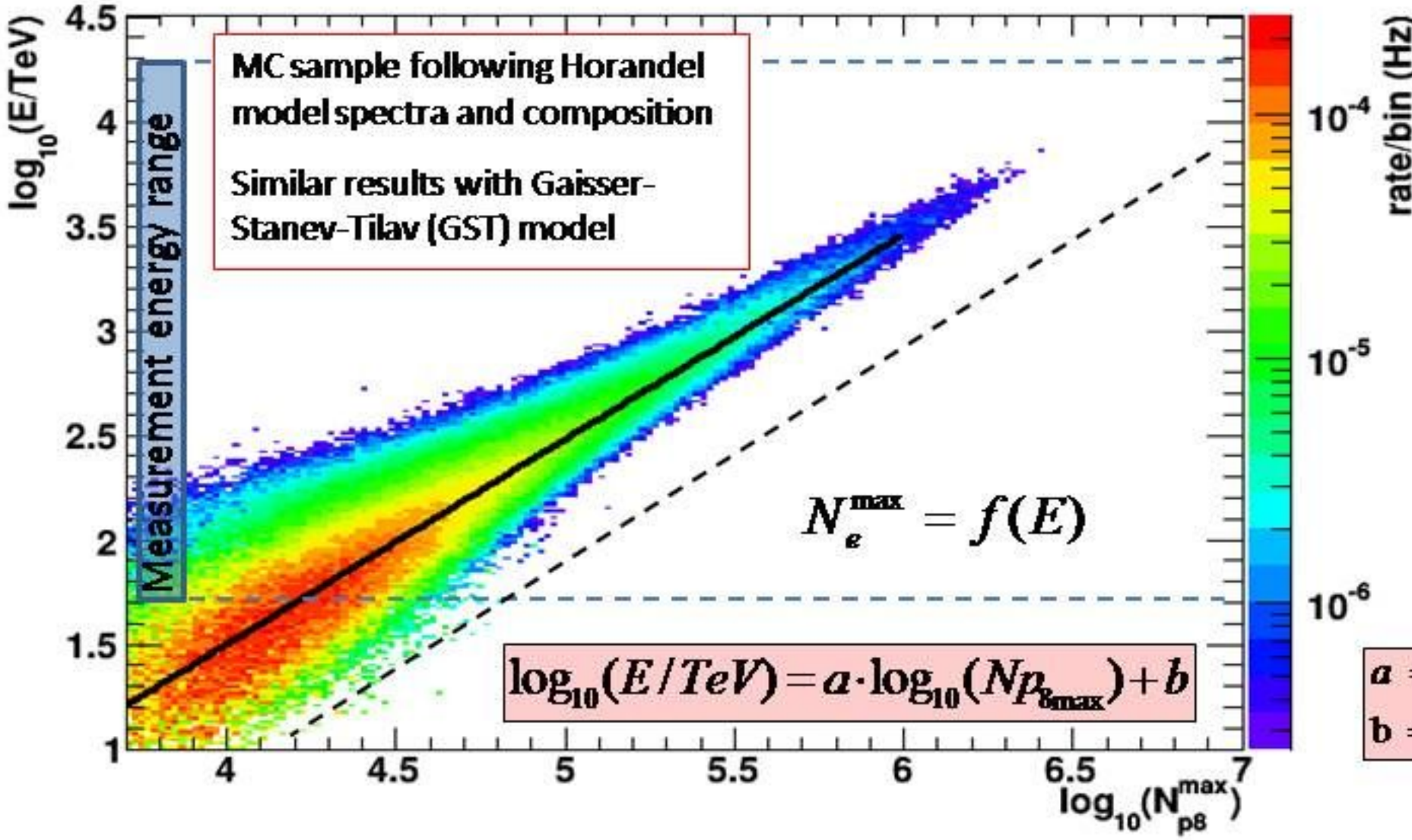


Assume an exponential absorption after the shower maximum → Get the correct signal at maximum (Np_{8max}) from Np_8 and *s'* (fit parameter) measured for each event

$$Np_{8\max} \approx Np_8 \cdot e^{\frac{h_0 \sec\theta - X_{\max}(s')}{\lambda_{abs}}}$$

Also checks with Gaisser-Hillas, Greisen, and Gaussian-in-age profiles

(I) – Mass independent Energy reconstruction



In excellent agreement with total-size-vs-E theoretical plot. The shift is simply due to the fact that we are using the truncated size

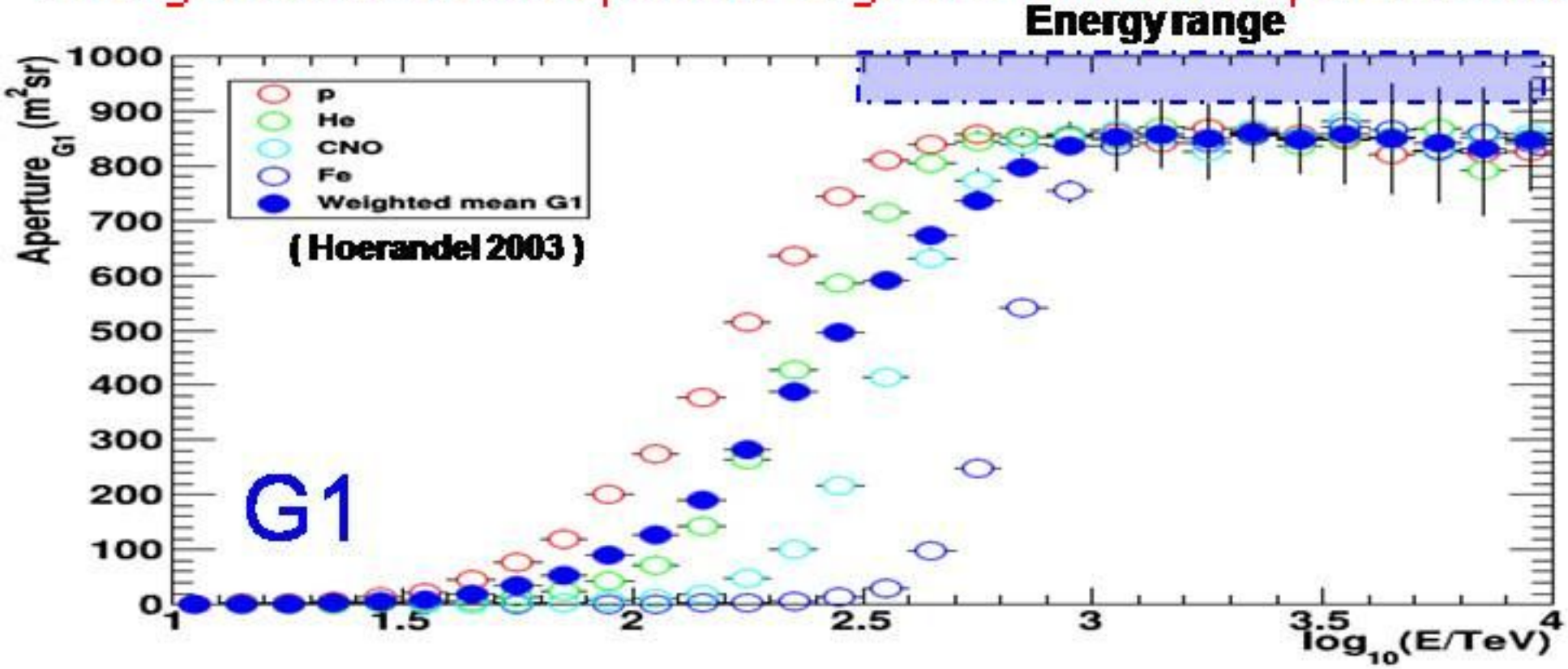
$a = (0.98 \pm 0.01)$

$b = (-2.42 \pm 0.05)$

The measurement of Np_8 and the (age correlated) LDF slope s' allows estimating the truncated size at the shower maximum Np_{8max}

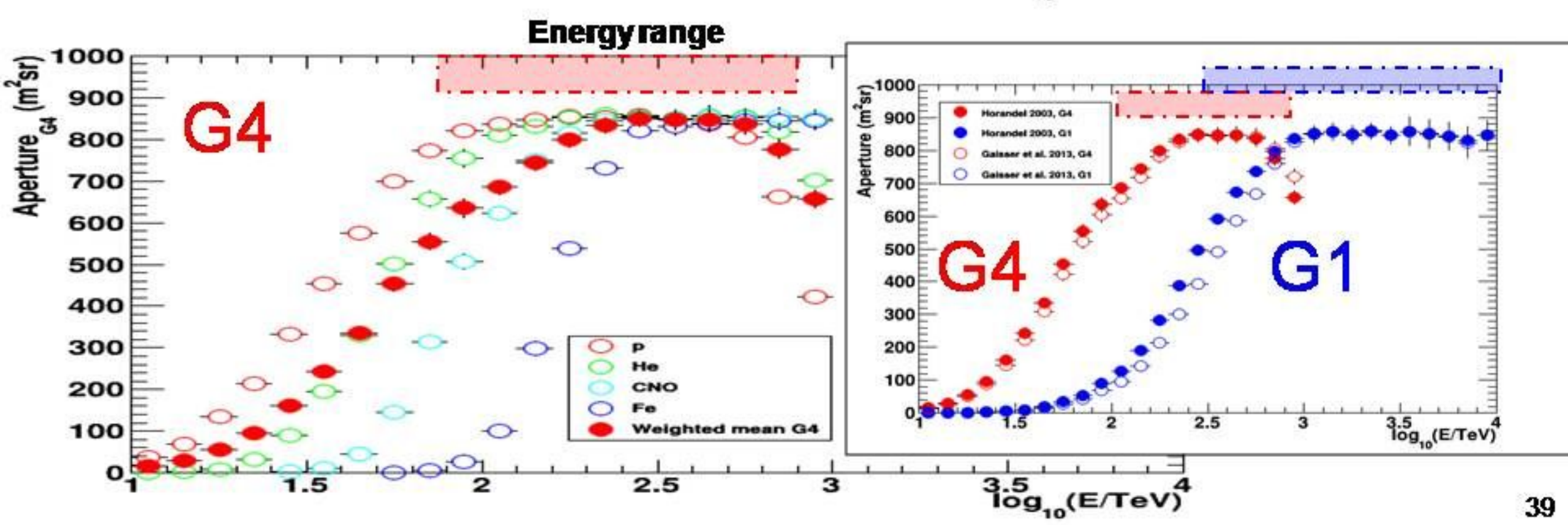
This ensures a mass independent Energy determination.

(I) - Apertures for all-particle spectrum



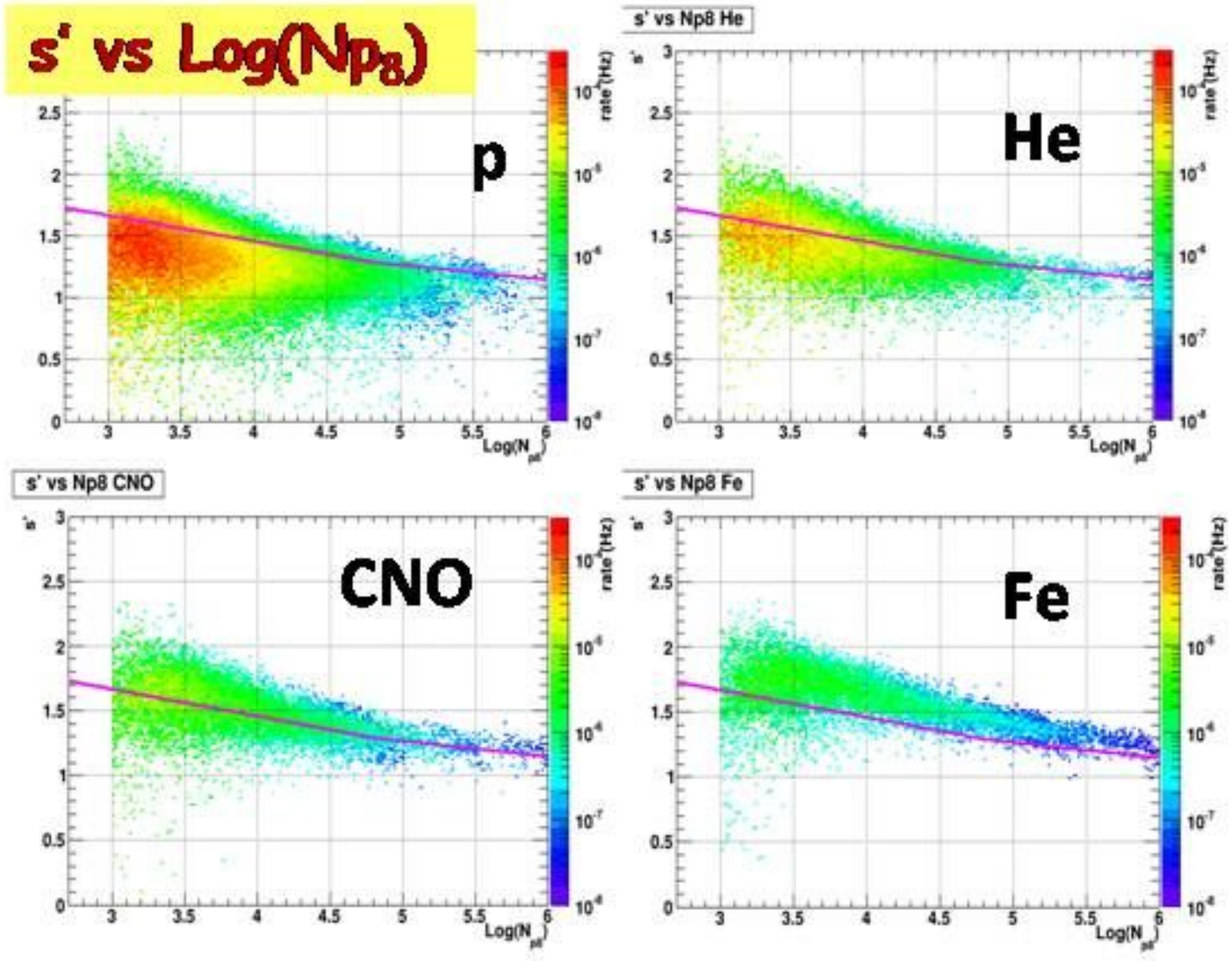
No dependence on mass composition above 250 TeV

Below 200 TeV dependence at the level of 5%

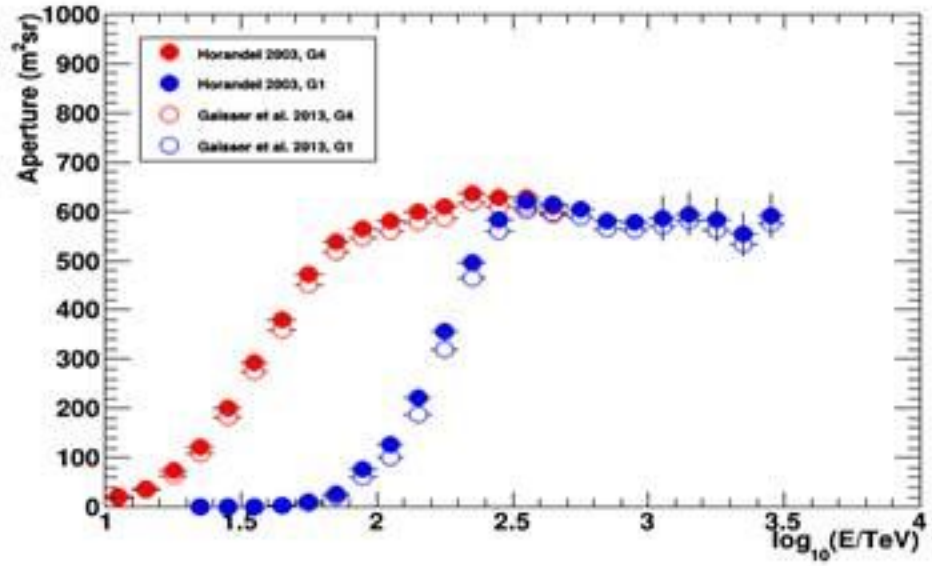


(I) - p and He selection (MC Hoerandel spectra and normalizations)

Sensitivity of s' to the primary mass used to select light component (p+He)



Apertures for the p+He spectrum

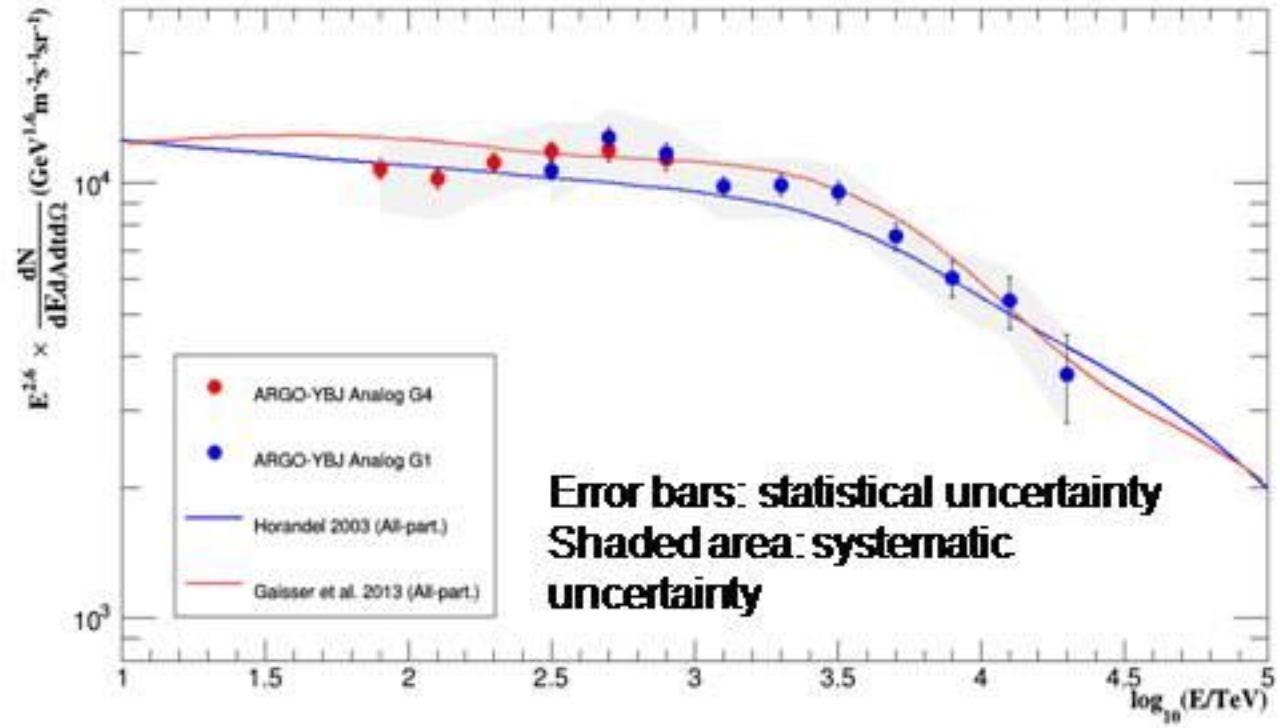


CNO (and Fe) contamination below 15% (assuming Hoerandel / GST fluxes). Included in the sistematics.

(I) - All-particle and p+He spectrum

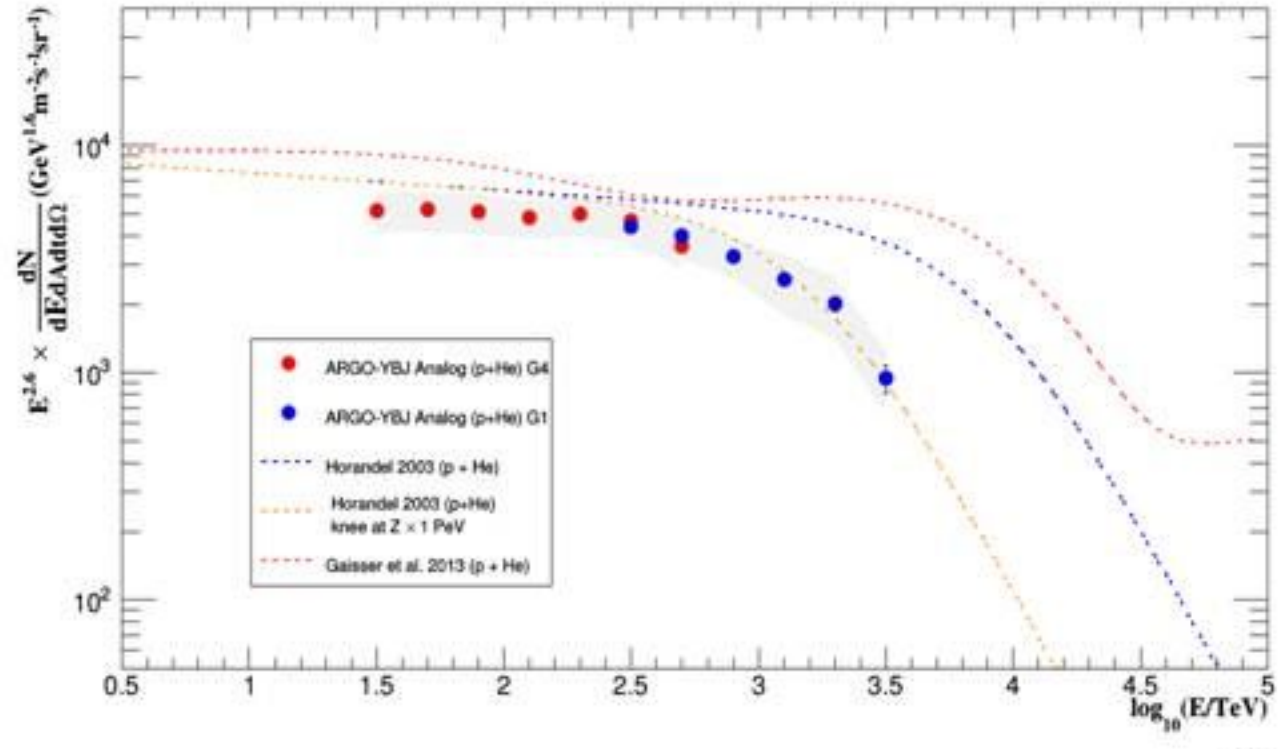
ALL-PARTICLE SPECTRUM

- Consistent picture with models and previous measurements
- Nice overlap with the two gain scales (different data set, …)
- Suggest spectral index of −2.6 below 1 PeV and smaller at larger energes



P+He SPECTRUM

- Same considerations as for the all-particle spectrum
- Gradual change of the slope starting around 700 TeV
- Flux systematics as for the all particle spectrum ⊕ < 15% mainly for the CNO contamination → Overall < 20 %



2nd Analysis (II) - Bayesian Approach

Digital Data — p+He Spectrum

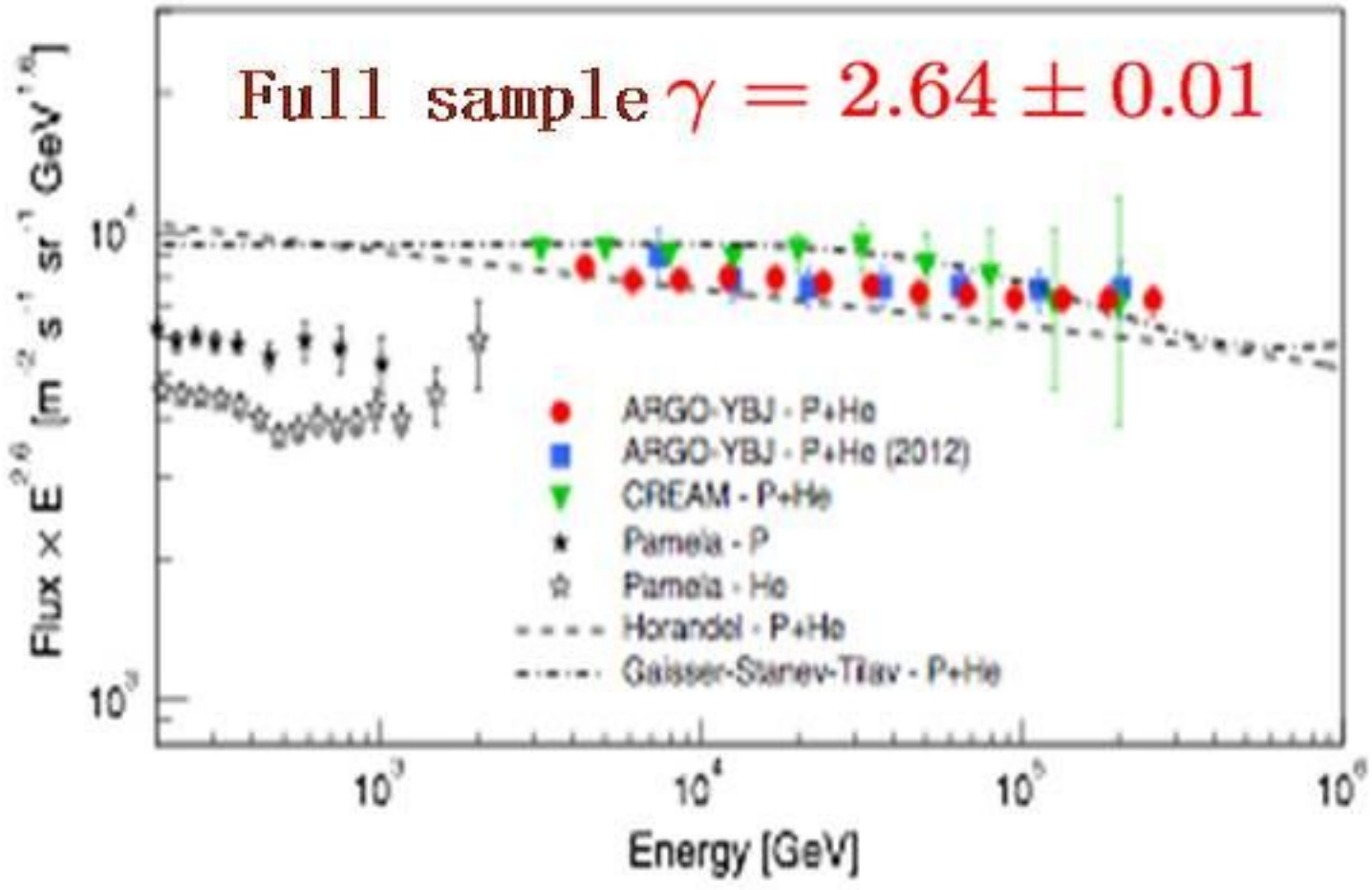
- ➡ Excellent stability over a long period
- ➡ Overlap with direct measurements in a wide energy region
- ➡ Total systematic uncertainty ~ 5%

3 - 300 TeV energy range:

Extension of the previous ARGO-YBJ light component spectrum measurement in the low energy region

FLUX @ 50 TeV

YEAR	Flux x 10^{-9} ± tot. err
2008	4.53 ± 0.28
2009	4.54 ± 0.28
2010	4.54 ± 0.28
2011	4.50 ± 0.27
2012	4.36 ± 0.27



(II) – Analog Data: all-particle & p+He

10 – 3000 TeV energy range

Fiducial cuts

- ➡ Reconstructed zenith angle
- ➡ Core Position internal
- ➡ Shower size inside 8m, N_p^{8m}

G1

p+He:

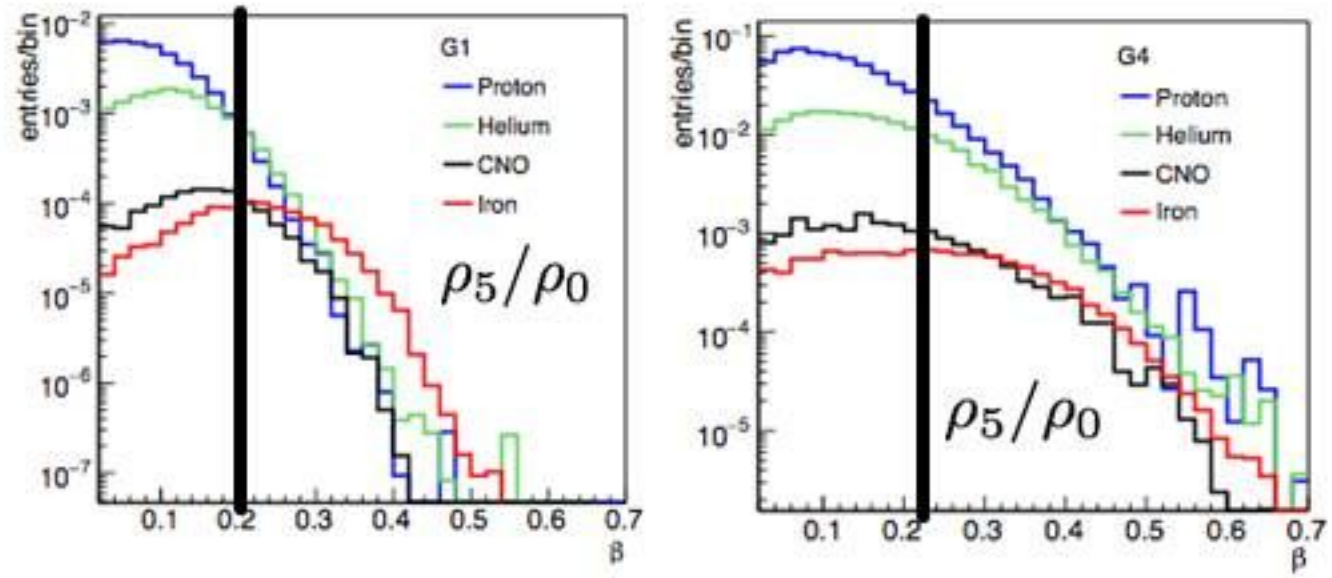
10^2 - $3\cdot10^3$ TeV

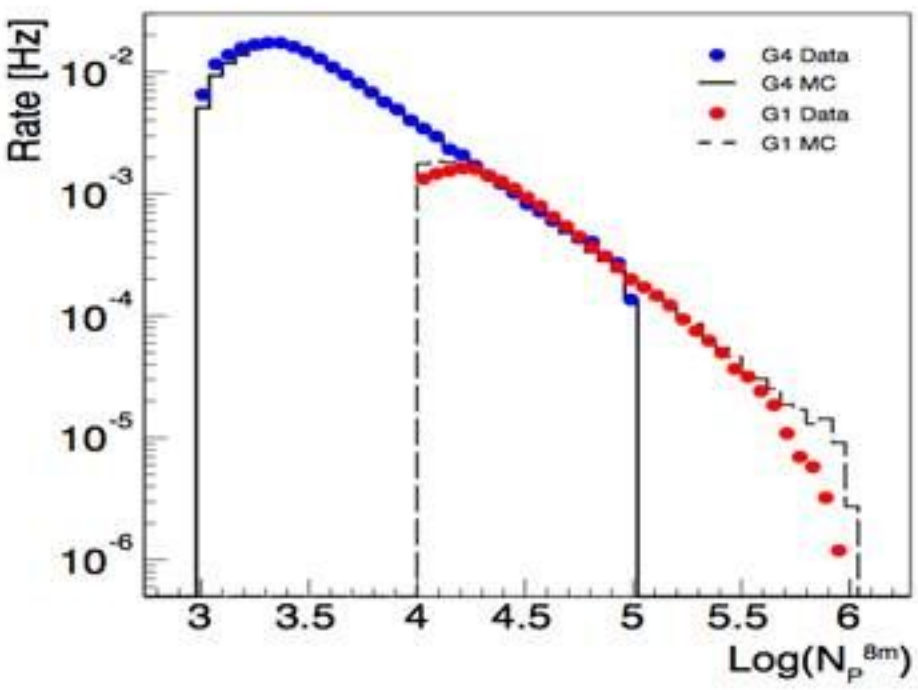
G4

All-part: 40 - 800 TeV

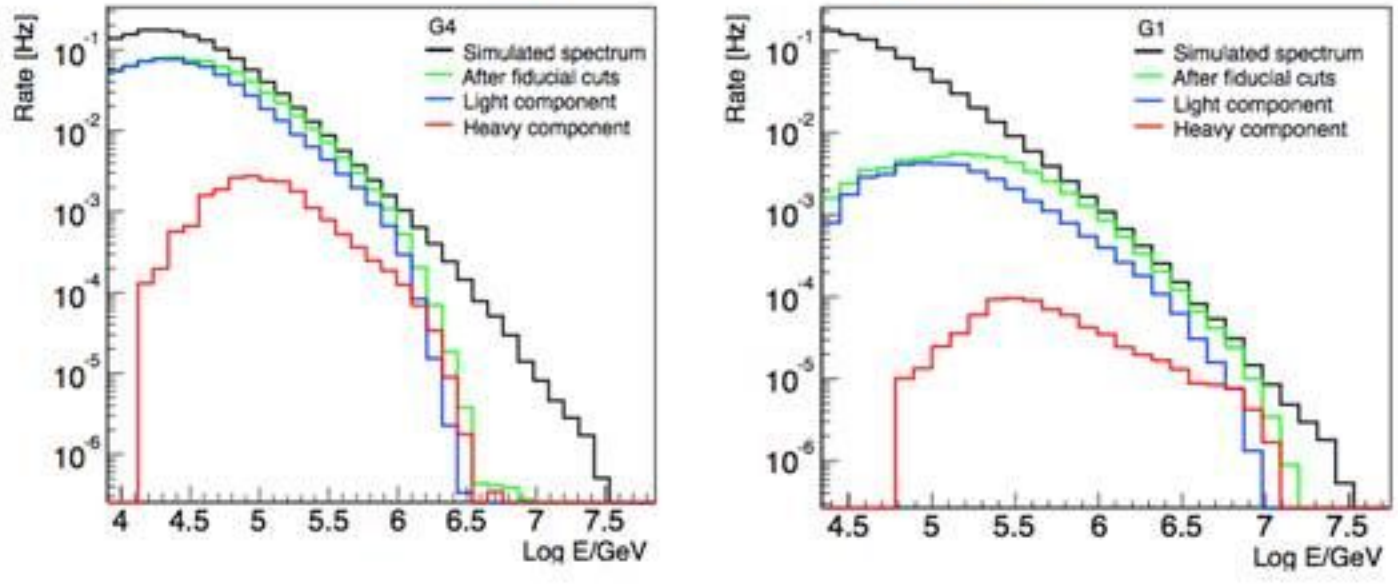
p+He: 10 -100 TeV

Light/Heavy discrimination from LDF





Showers mainly produced by light elements



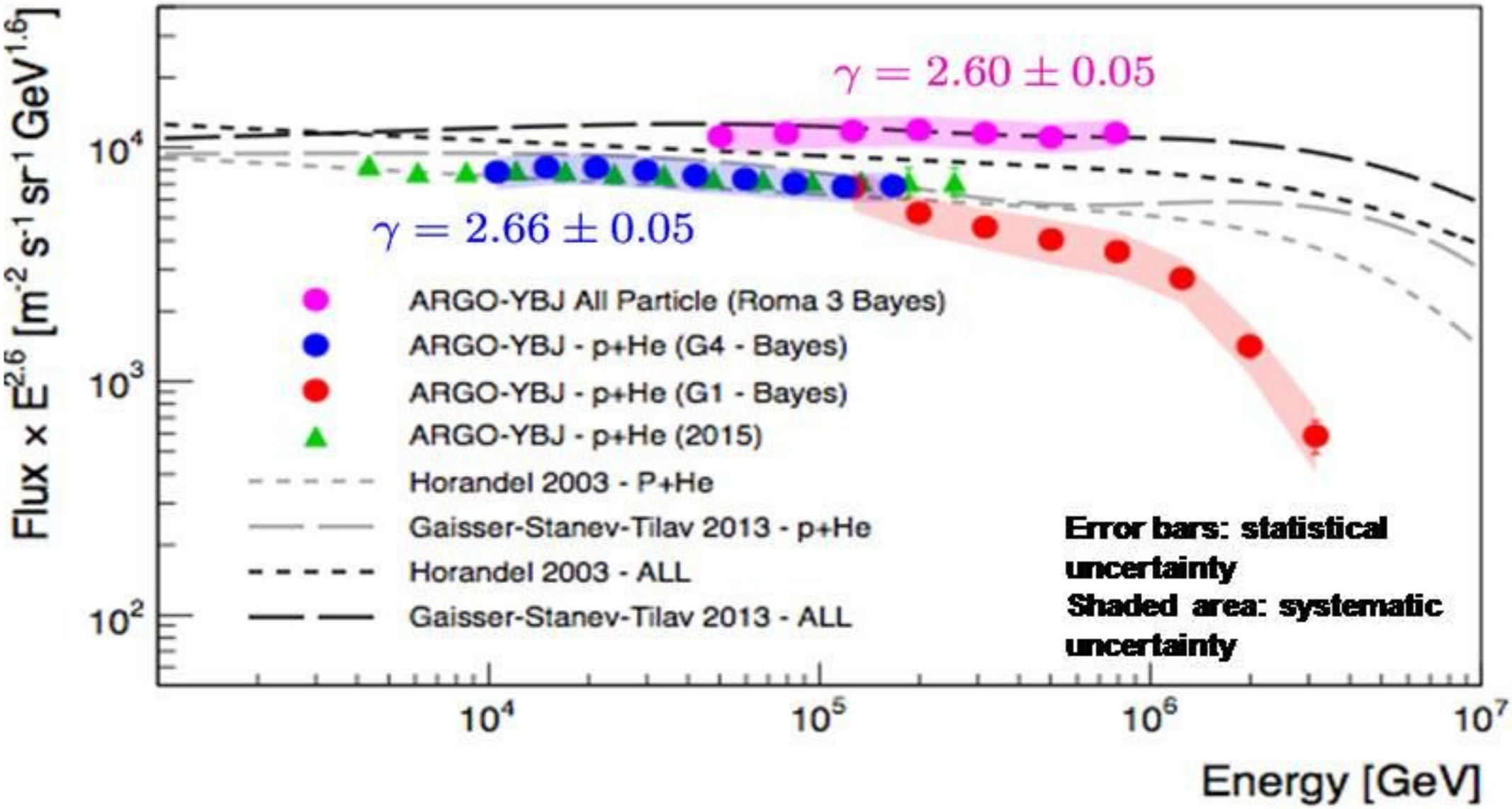
(II) All-particle & p+He spectrum

P+HE SPECTRUM

- Overlap with direct measurements in a wide energy region
- ➡ Gradual change of the spectral index at E ~ 700 TeV
- ➡Consistent with the Digital Readout data (different data set)
- ➡Systematics ~10%
- ➡ ~10-12% of contamination of heavy elements (mainly CNO) at the highest energies

ALL-PARTICLE SPECTRUM

- ➡ Good agreement with other experiments
- ➡Systematics ~10%



Conclusions on ARGO-YBJ analysis

- All-particle spectrum in the energy range 80 TeV – 20 PeV using the analog readout
  - Good agreement with other experiments
- P+He spectrum by using the analog readout data
  - 10-100 TeV energy range
    - Good agreement with the digital analysis
  - 100-3000 TeV energy range
    - Evidence of a gradual change of the spectral index at energies around 700 TeV