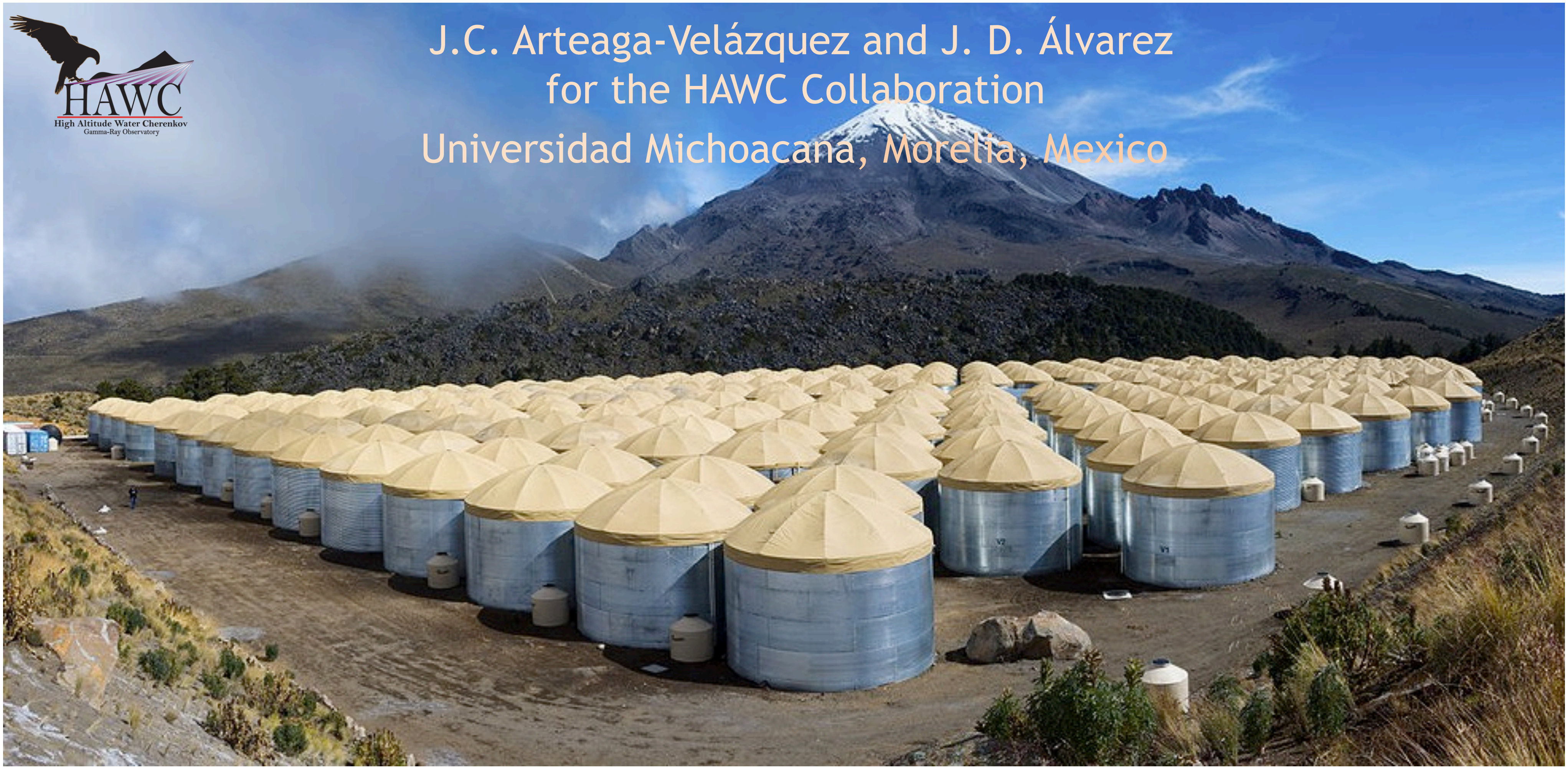
The light component of the cosmic ray spectrum measured with HAWC



J.C. Arteaga-Velázquez and J. D. Álvarez
for the HAWC Collaboration
Universidad Michoacana, Morelia, Mexico

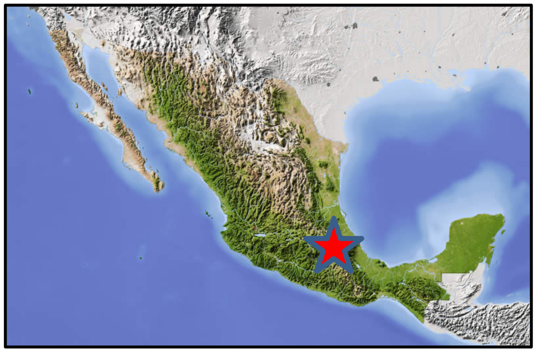
Overview

High Altitude Water Cherenkov
Gamma-Ray Observatory

1. The HAWC observatory
2. Cosmic rays a HAWC
3. Motivations
4. Cosmic ray observables
5. MC simulations and selection cuts
6. Performance
7. The path to the all particle spectrum
8. Composition

CONACYT

The HAWC observatory



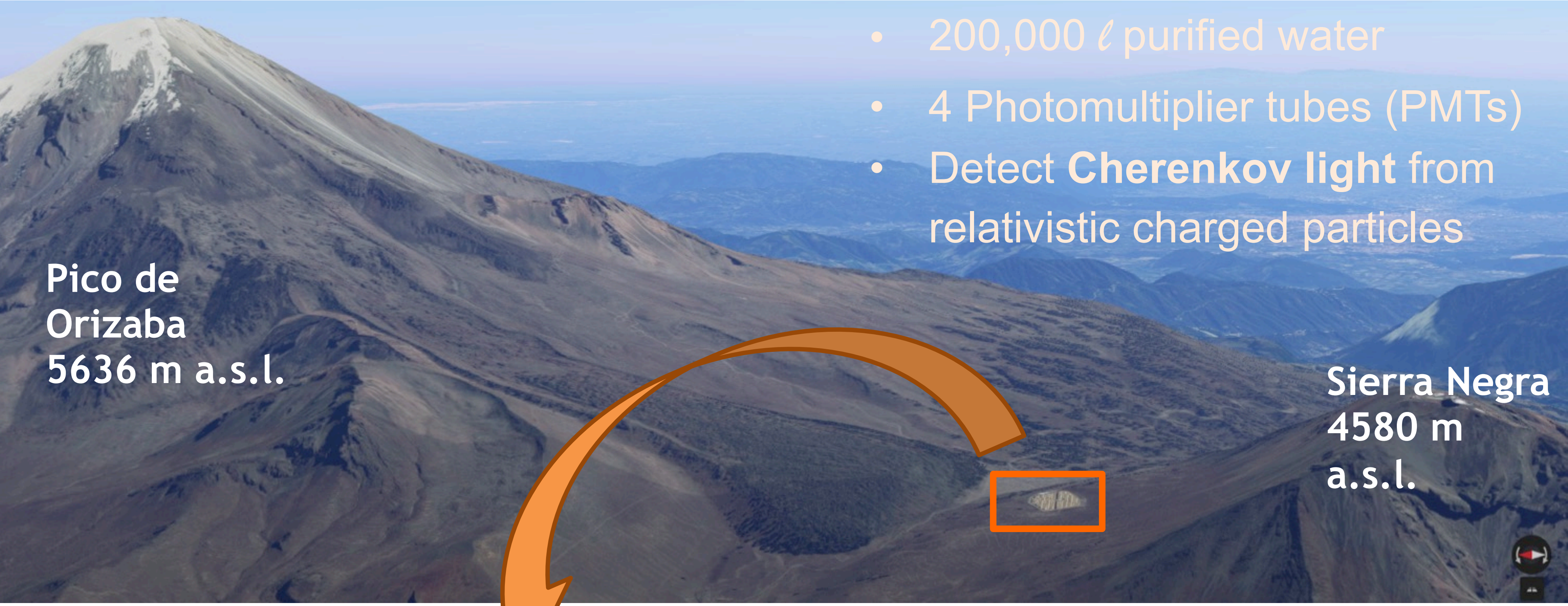
- On a plateu between Pico de Orizaba and Sierra Negra volcanoes, Puebla, Mexico
- 19° N and 97° W
- 4100 m a.s.l. (640 g/cm^2)

The HAWC observatory

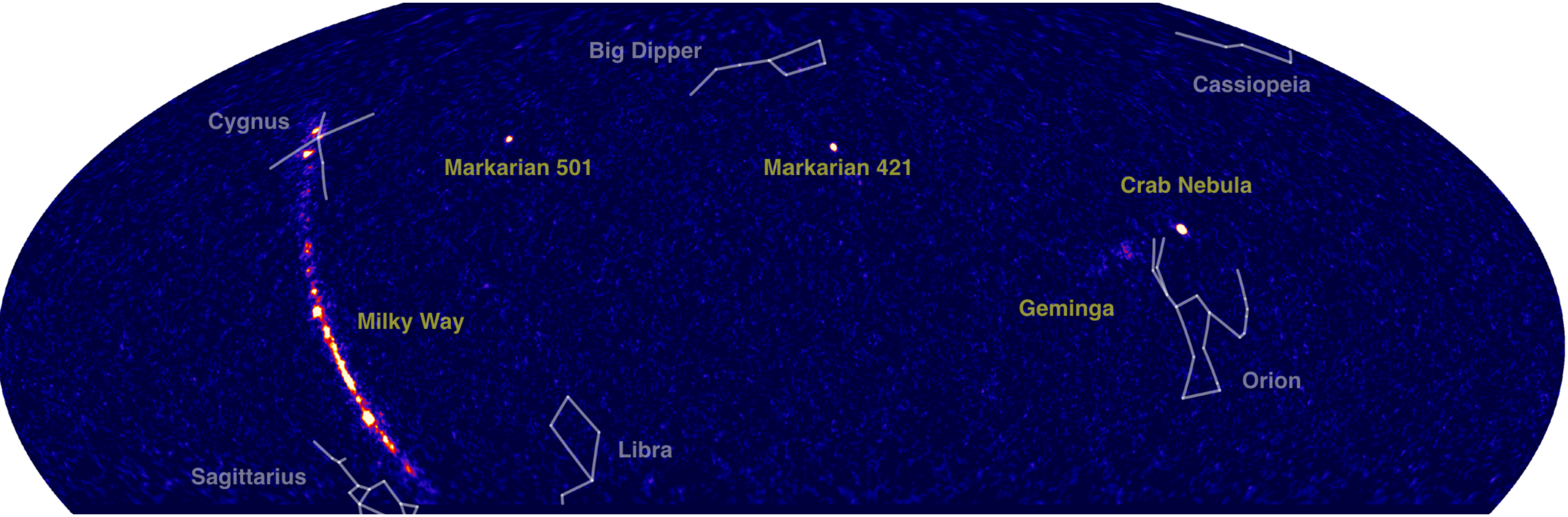
- 22 000 m^2 surface
- 300 densely packed water Cherenkov detectors

The HAWC observatory

- 200,000 ℓ purified water
- 4 Photomultiplier tubes (PMTs)
- Detect **Cherenkov light** from relativistic charged particles



The HAWC observatory



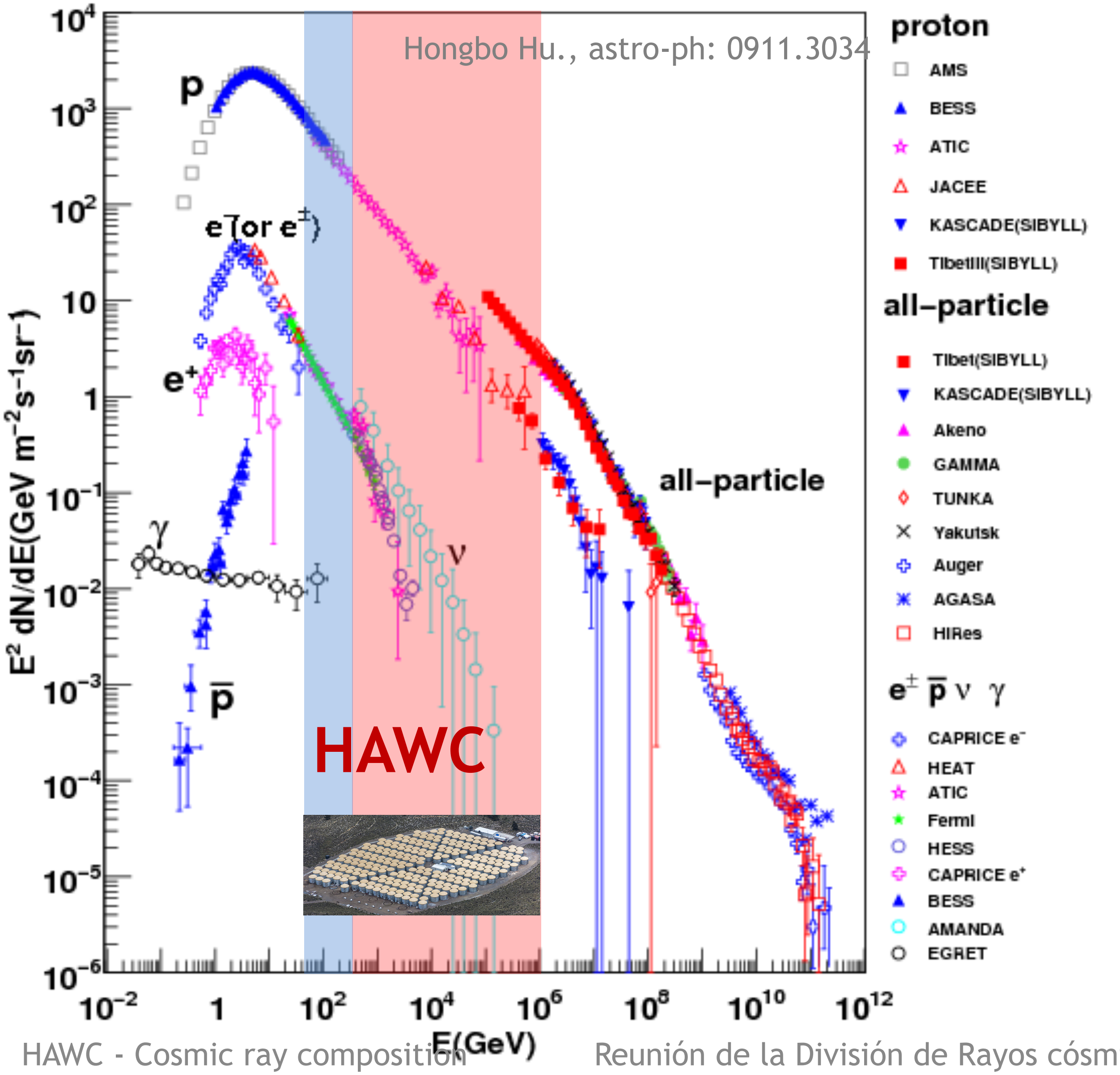
Gamma-ray detector

- Designed to study gamma ray sky
- Primary energy interval
  E = 100 GeV – 100 TeV
- Instantaneous field of view 2 sr
- Duty cycle > 95 %

Cosmic rays at HAWC

Scaler mode:
Through enhancements in the PMT rates

TDC mode:
Study PMT's hit in EAS event

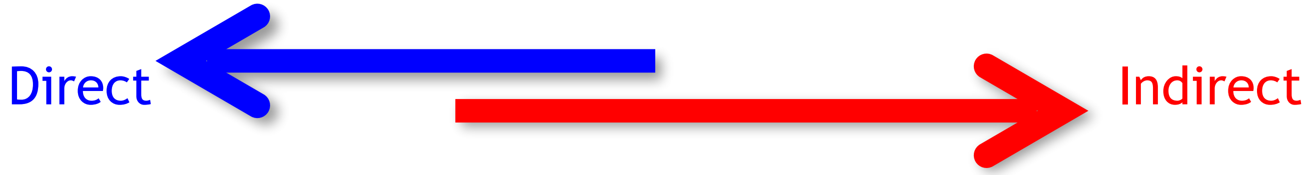

Hongbo Hu., astro-ph: 0911.3034

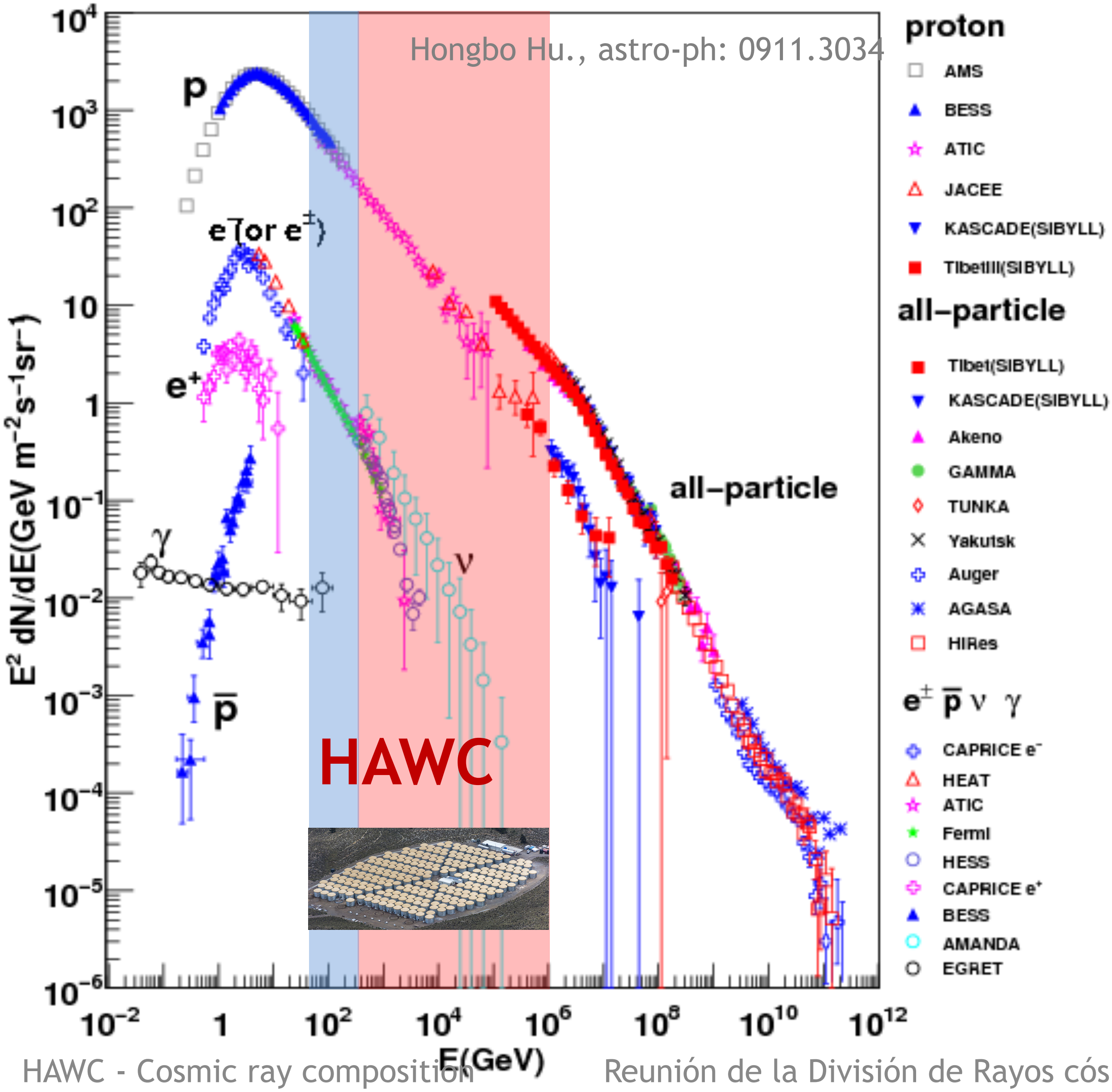
- CR EAS energy interval:
  100 GeV – 1 PeV
- 99.9 % of events are hadronic
- Trigger rate: 25 kHz
- CR rate @ E = 1 TeV:

  + 10^3 times greater than flux of the brightest γ-ray source

S. BenzVi, D. Fiorino, et al., ICRC 2015, #216
A. Smith, ICRC 2015, #397

Motivation





Region between E = 10^{13} -10^{15} eV

- Limit between direct/indirect detection
- Composition fairly explored
- New structures?

These questions can be addressed with HAWC

Motivation

Hillas (H3a) model

T.K. Gaisser, Astrop. Phys. 35 (2012) 80; Frontiers of Physics 8 (2013)

- Three cosmic populations

- Knees and other features produced by loss of magnetic confinement.

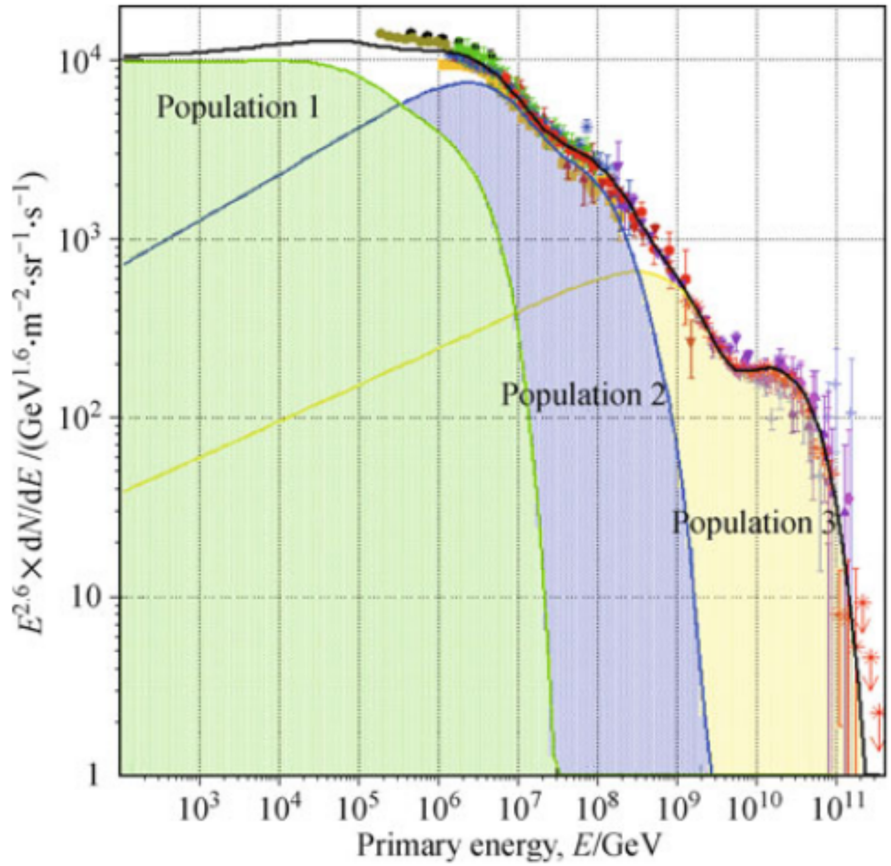
$$\phi_i(E) \;=\; \Sigma_{j=1}^{3}\, a_{i,j}\, E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right].$$

- Population 1: SNR (E_{max} ~100 TeV)

- Population 2: Galactic pevatron (PWN, hypernovae, galactic center, etc.)

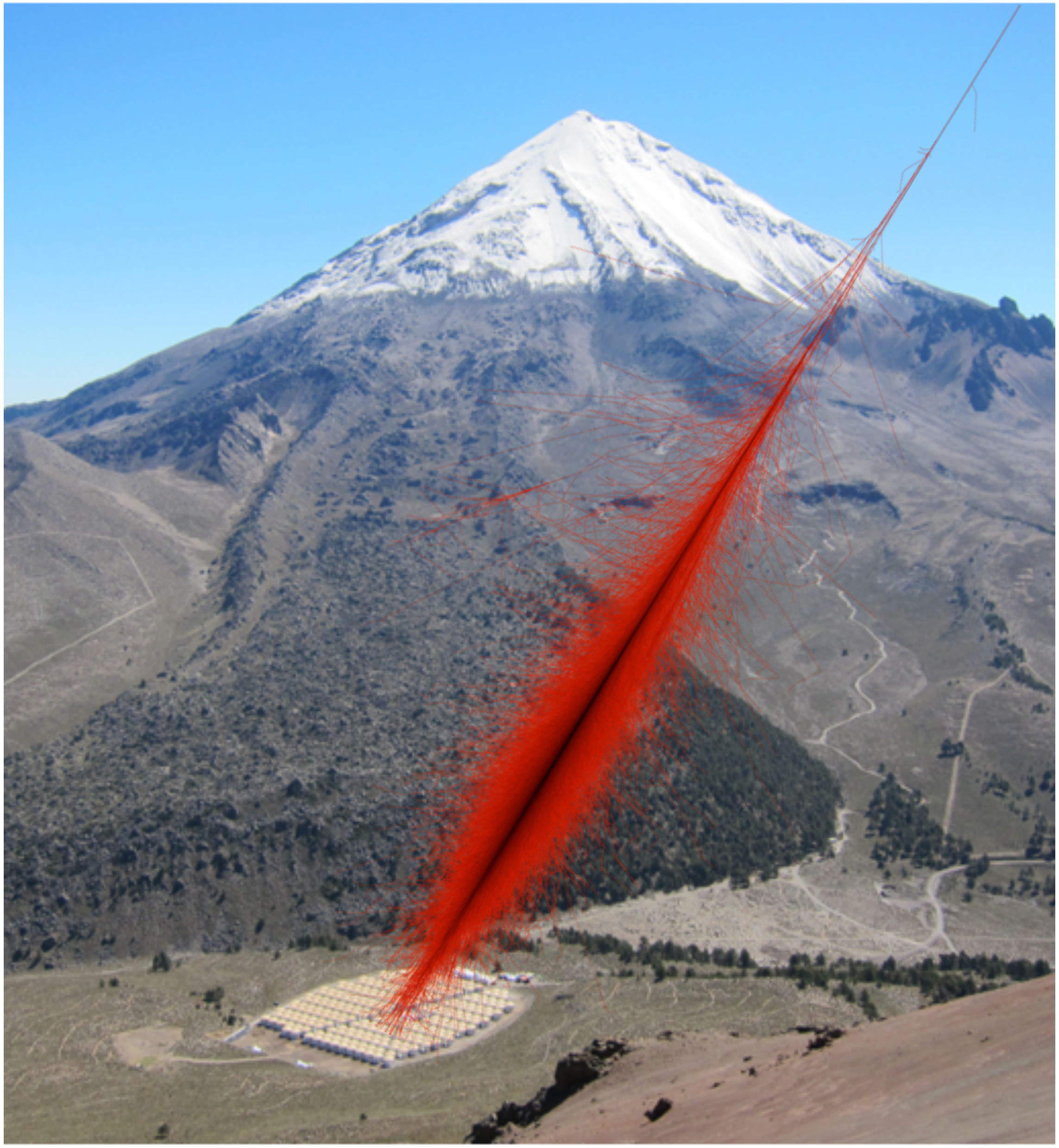
- Population 3: Extragalactic origin.

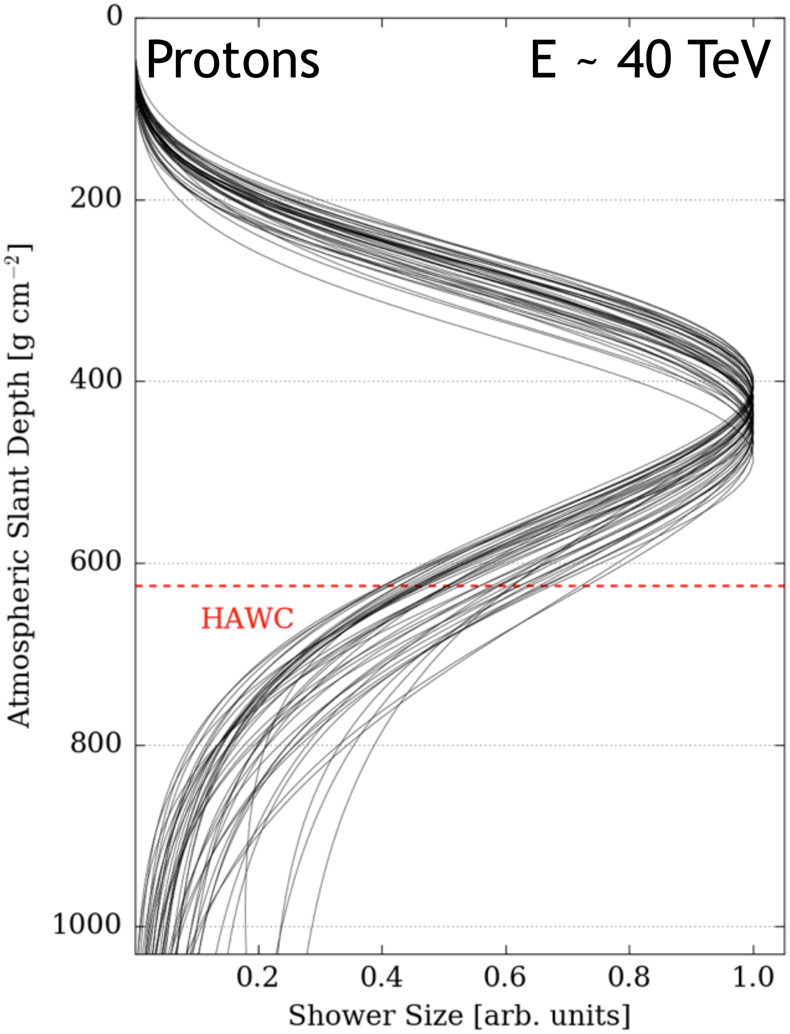
Source	Rc (GV)
Population 1	1.2×10^5
Population 2	4.0×10^6
Population 3	1.3×10^9



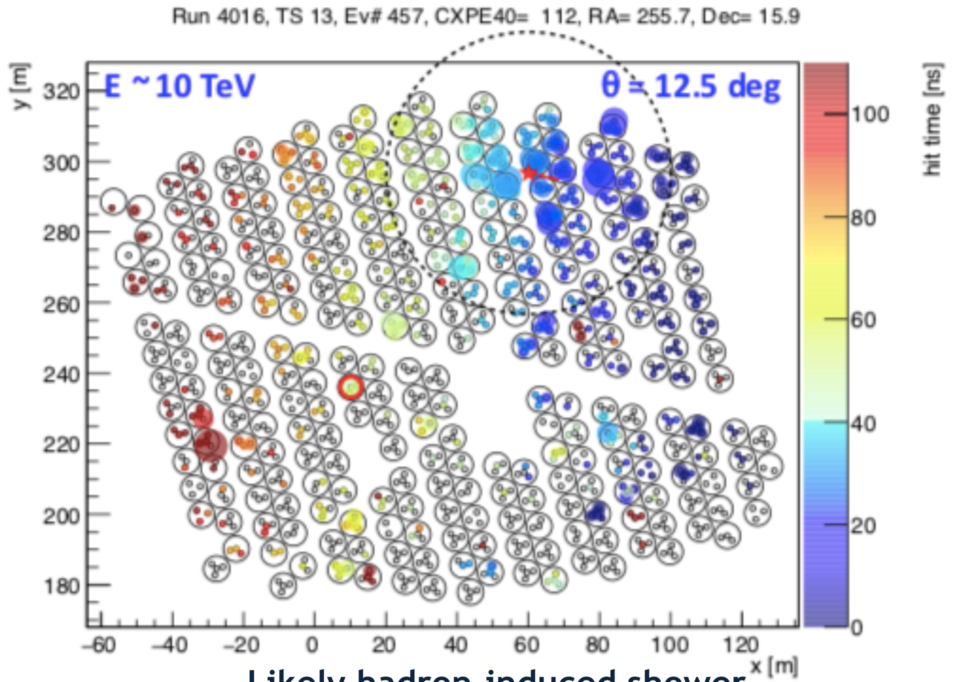
Cosmic ray observables

- HAWC measurements performed after Xmax

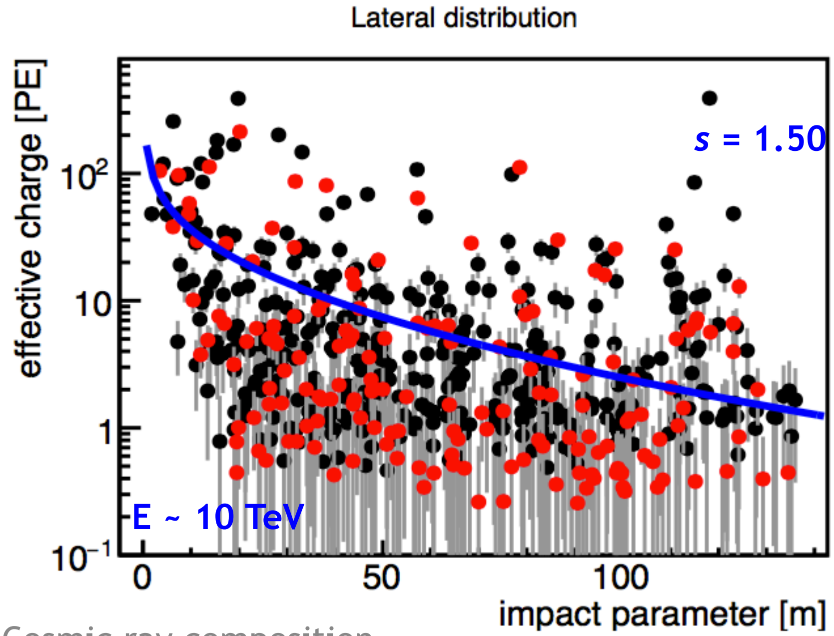




Cosmic ray observables



Likely hadron-induced shower



- From **deposited charged, hit times** at PMTs, **number of PMT's** with signal:
  - Core location, (X_c, Y_c)
  - Arrival direction, θ
  - Fraction of hit PMT's, f_{hit}
  - Lateral age of LDF, *s*
  - Energy of primary, E

HAWC Coll., ApJ 843 (2017) 39

- Lateral age parameter:
  - Obtained **event-by-event**
  - Fit wit NKG-based function:

$$f_{ch}(r) = A \cdot (r/r_0)^{s-3} \cdot (1 + r/r_0)^{s-4.5}$$

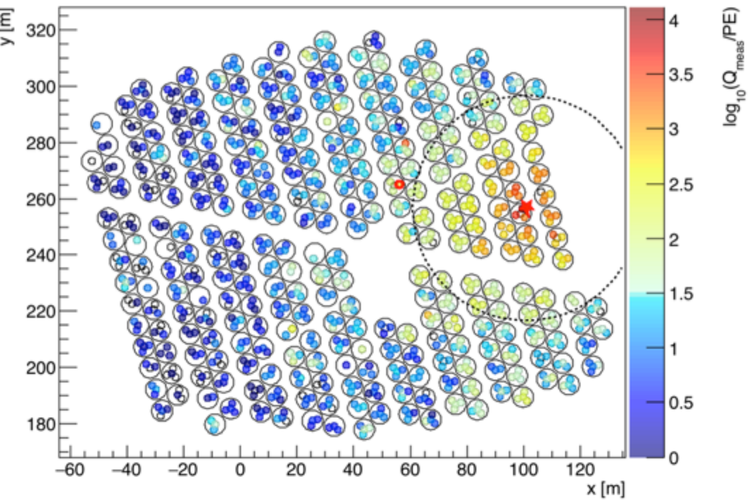
with r_0 = 124.21 m.

A, ***s*** are free parameters

Kelly Malone, APS 2017

Cosmic ray observables

Energy estimation



Built **lateral** distribution tables of MC **proton** shower hit patterns for range of simulated:

- Energies
- Arrival directions

Tables encode **average** shower footprint

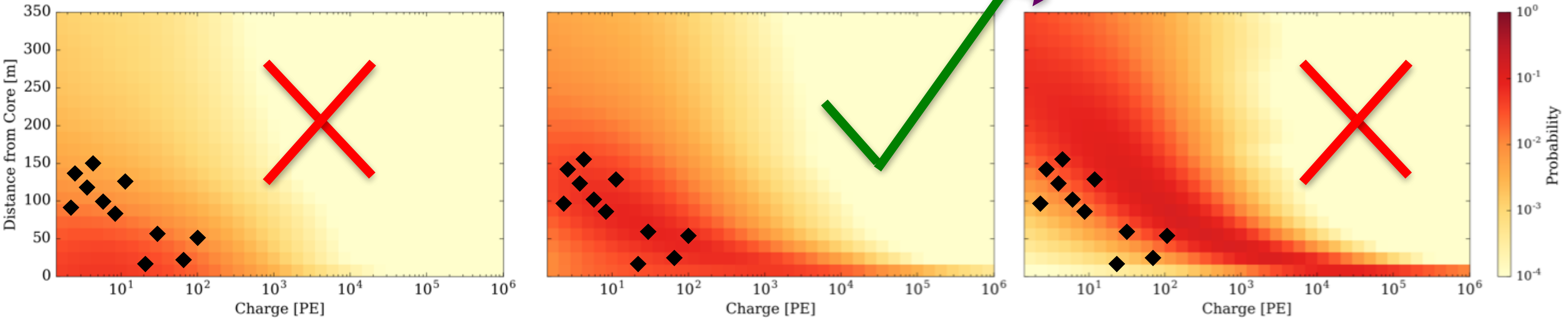
Energy binning: $\Delta\log E/\text{GeV} = 0.1$

HAWC Collab., PRD 96 (2017)

Z. Hampel-Aris' PhD thesis, 2017

Shower of unknown energy

10 TeV **100 TeV** **1 PeV**



Maximum likelihood for hits to come from **distance, charge, zenith, energy** bins.

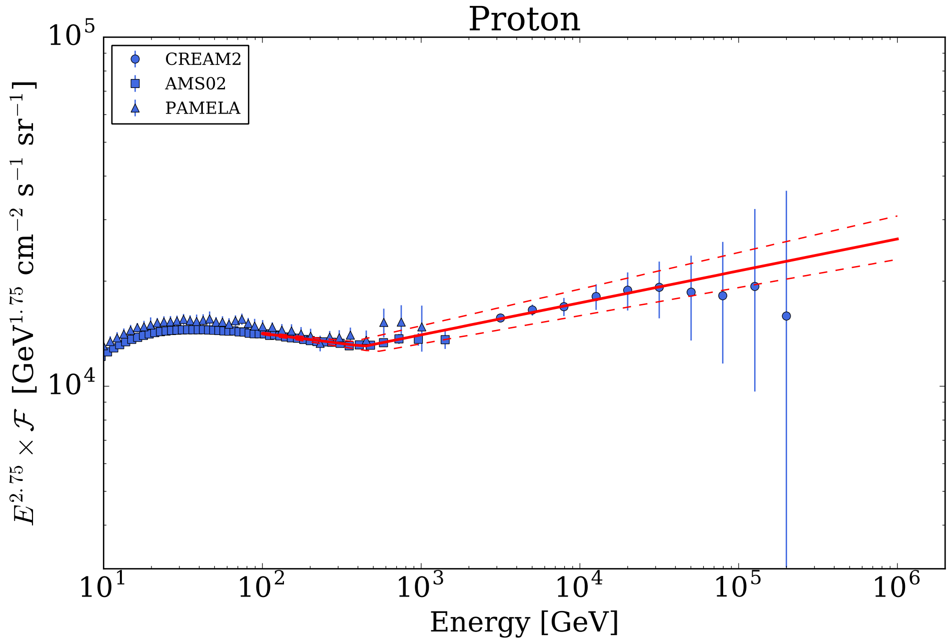
MC simulations

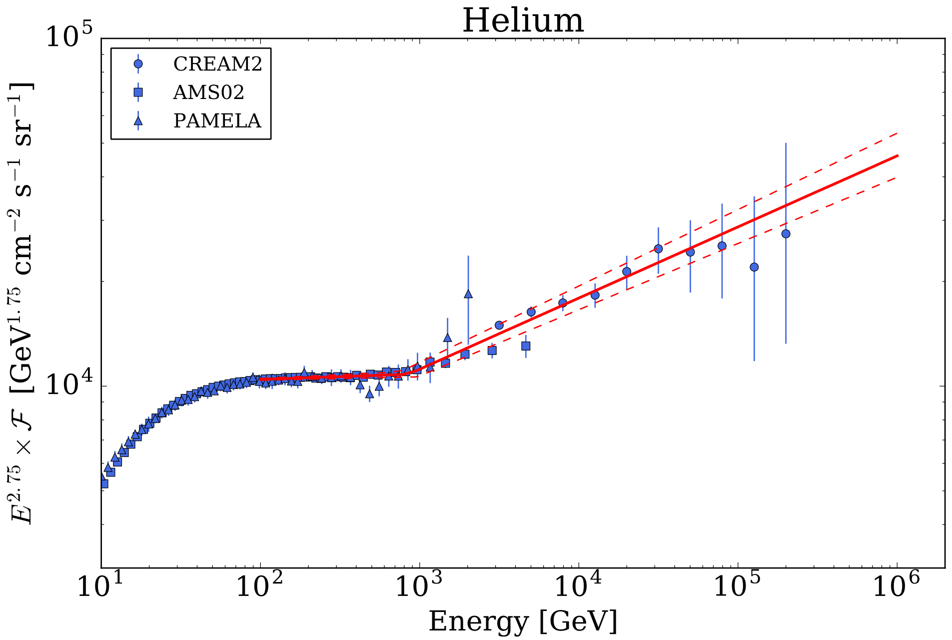
- **Fluka/QGSJET-II-03** as low/high-energy interaction models

- Full simulation of detector response with GEANT 4.

- Zenith angle < 70°; A_{thrown}~3 x 10^6 m^2

- Primary nuclei:
  - H, He, C, O, Ne, Mg, Si, Fe
  - E = 5 GeV – 3 PeV
  - E^{-2} spectra weighted to follow a double power-law derived from fits to **AMS02 (2015)**, **CREAM-II (2009 & 2011)** and **PAMELA (2011)** data.
  - For systematic studies other models are included.



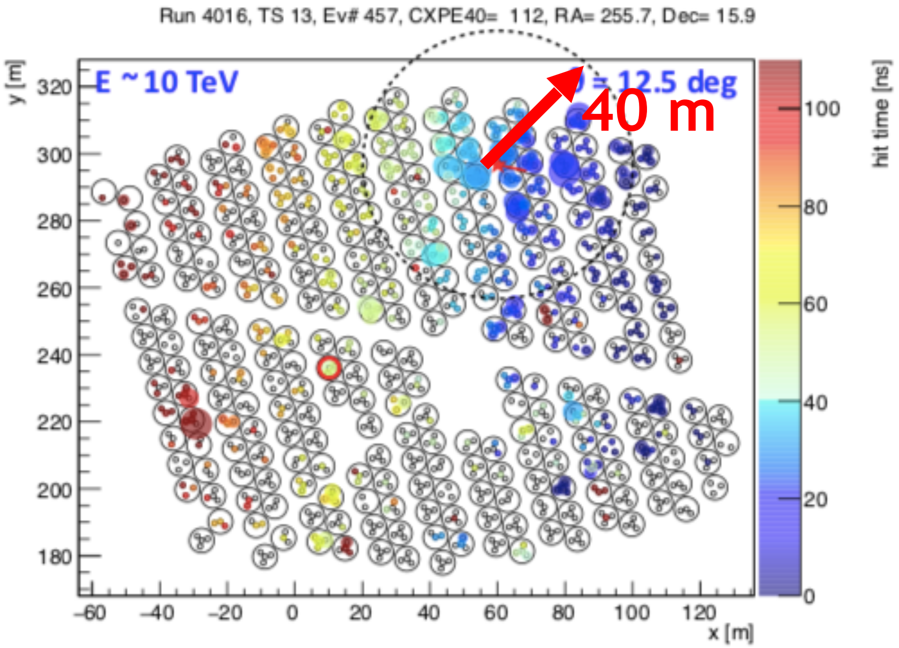


Selection cuts

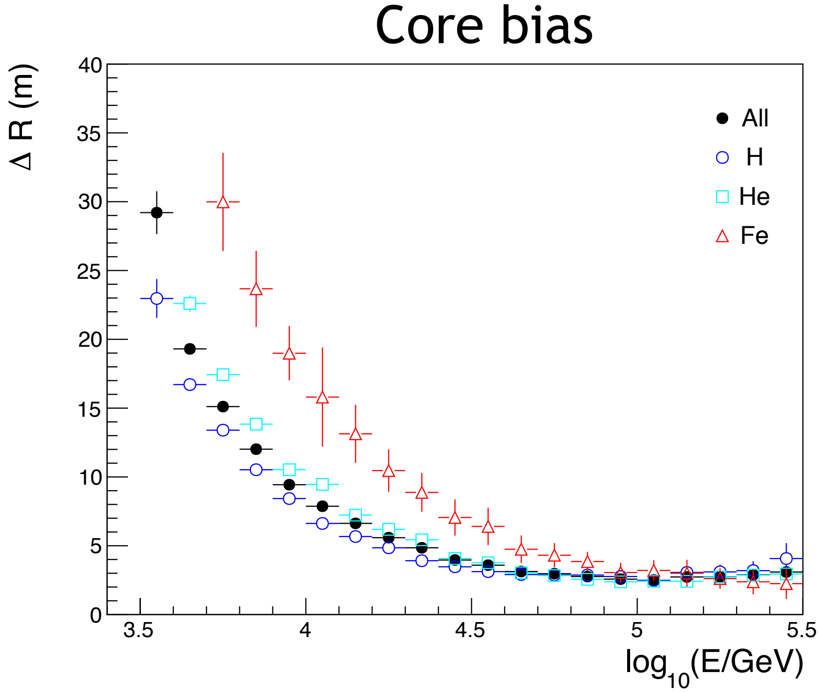
- Selected to reduce systematic effects on Energy:
  - $\theta < 16.71°$
  - Multiplicity threshold $N_{hit} \geq 75$ PMTs
  - Successful core and arrival direction reconstruction
  - Activate at least 60 PMTs within 40 m from core $N_{r40} \geq 60$
  - Shower core inside HAWC area
  - Fractionhit (# of hit PMT's/# available channels) ≥ 0.3
  - $\log_{10}(E/GeV) < 5.5$

E ≥ 10 TeV:

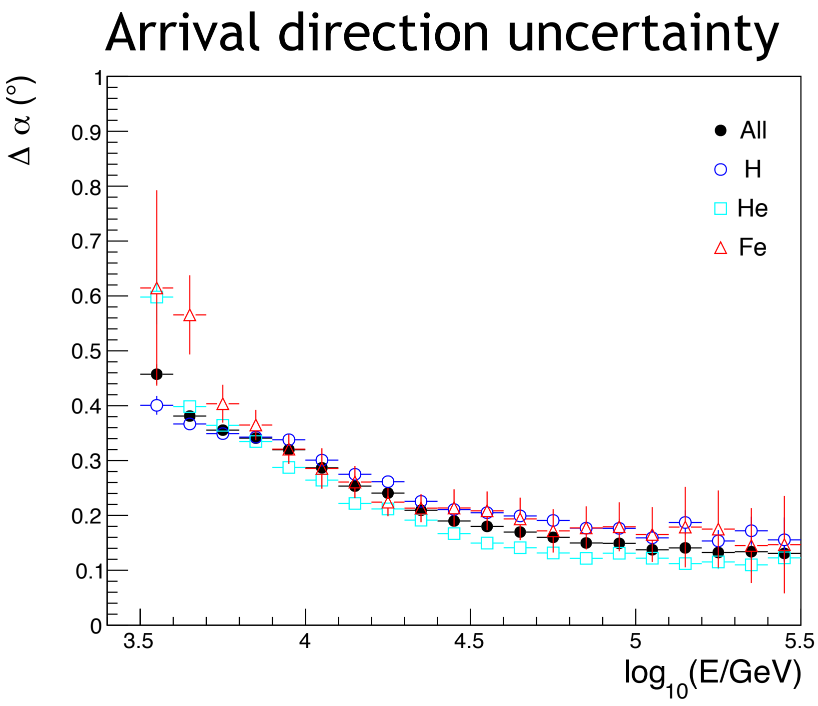
$\Delta core_{res}$	≤ 10 m
$\Delta \log_{10}(E/GeV)$	≤ 0.12
$\Delta\theta_{res}$	$\leq 0.3^{o}$



Core bias



Selection cuts

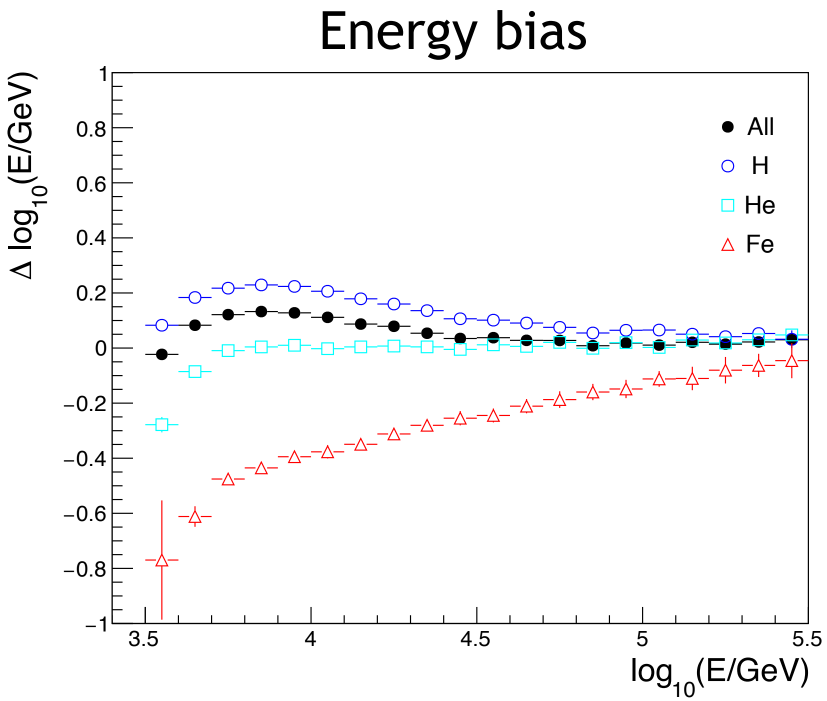


E ≥ 10 TeV:

$\Delta core_{res}$ ≤ 10 m

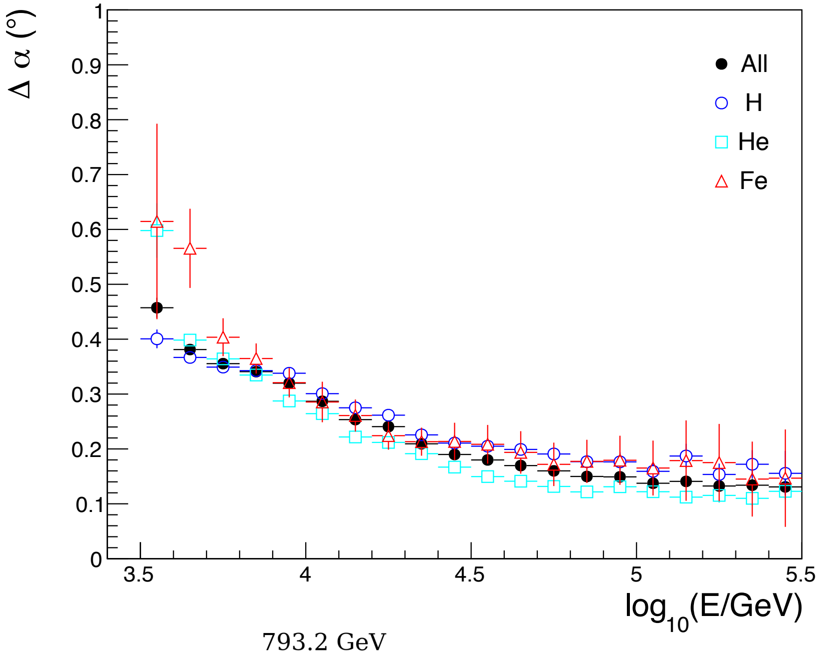
$\Delta\log_{10}(E/GeV)$ ≤ 0.12

$\Delta\theta_{res}$ ≤ 0.3°



Selection cuts

Arrival direction uncertainty



E ≥ 10 TeV:

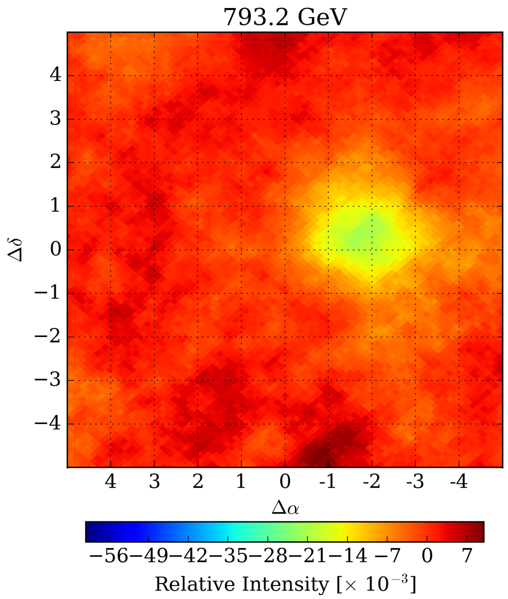
$\Delta core_{res}$ ≤ 10 m

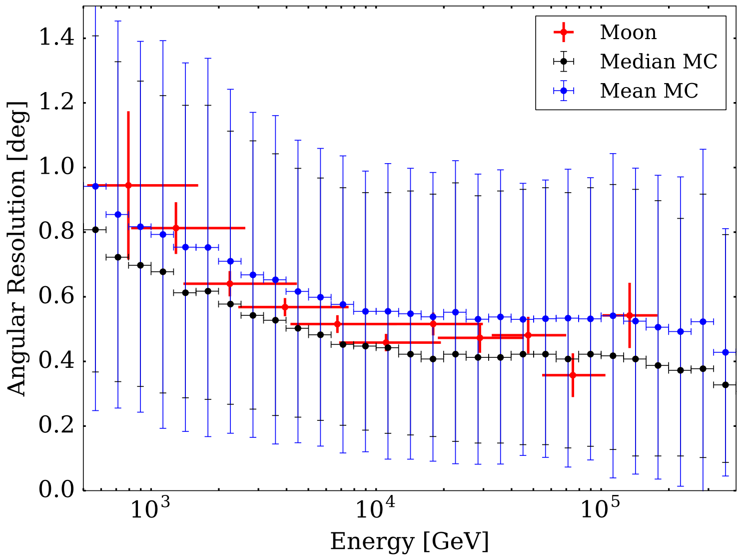
$\Delta \log_{10}(E/GeV)$ ≤ 0.12

$\Delta\theta_{res}$ ≤ 0.3°

HAWC Collab., PRD 96 (2017)

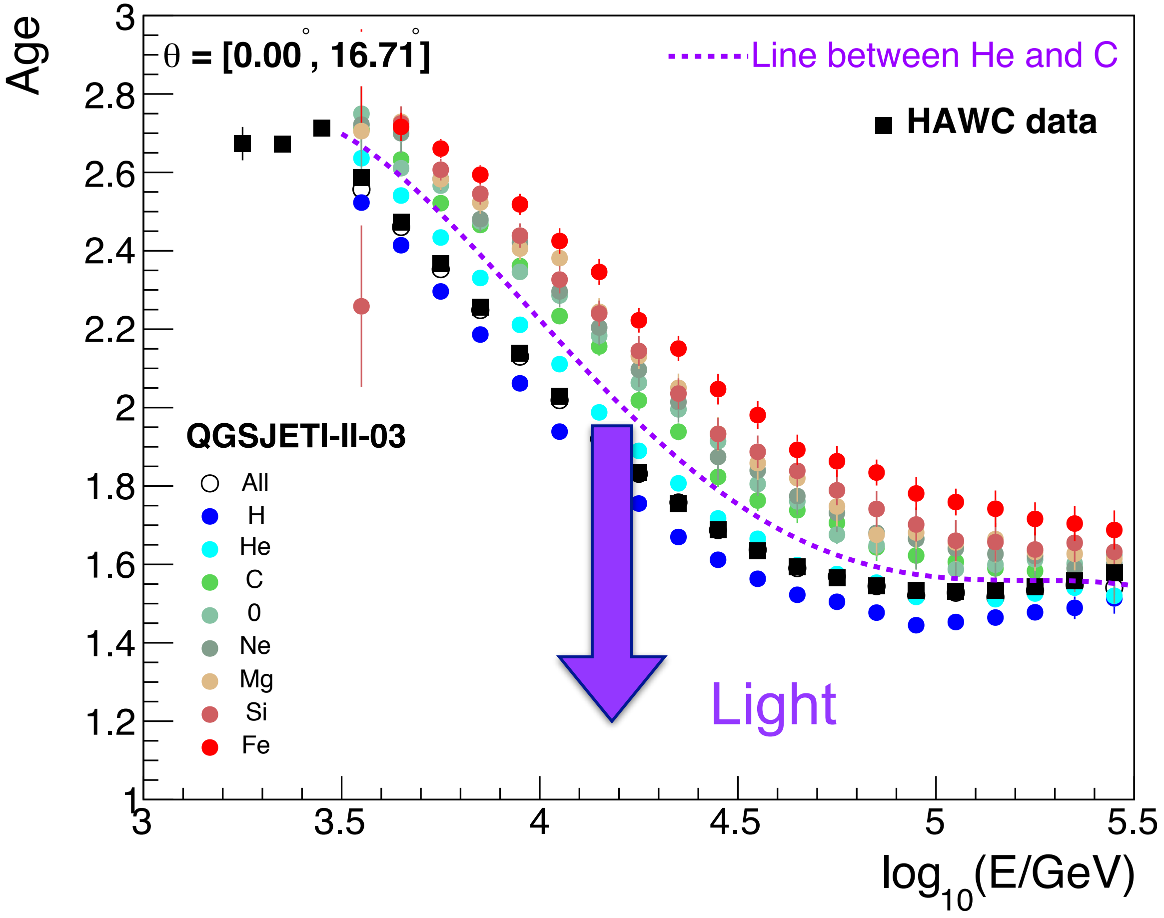
Checked with moon shadow





Analysis

Selection of sample enriched with light nuclei



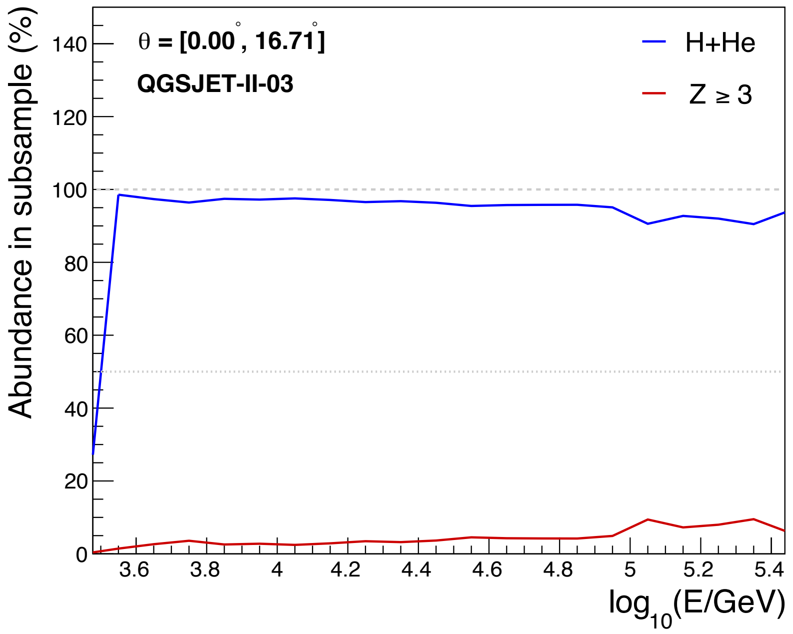
Component to study

- H + He

Age parameter is sensitive to composition

Select a subsample using a cut on s

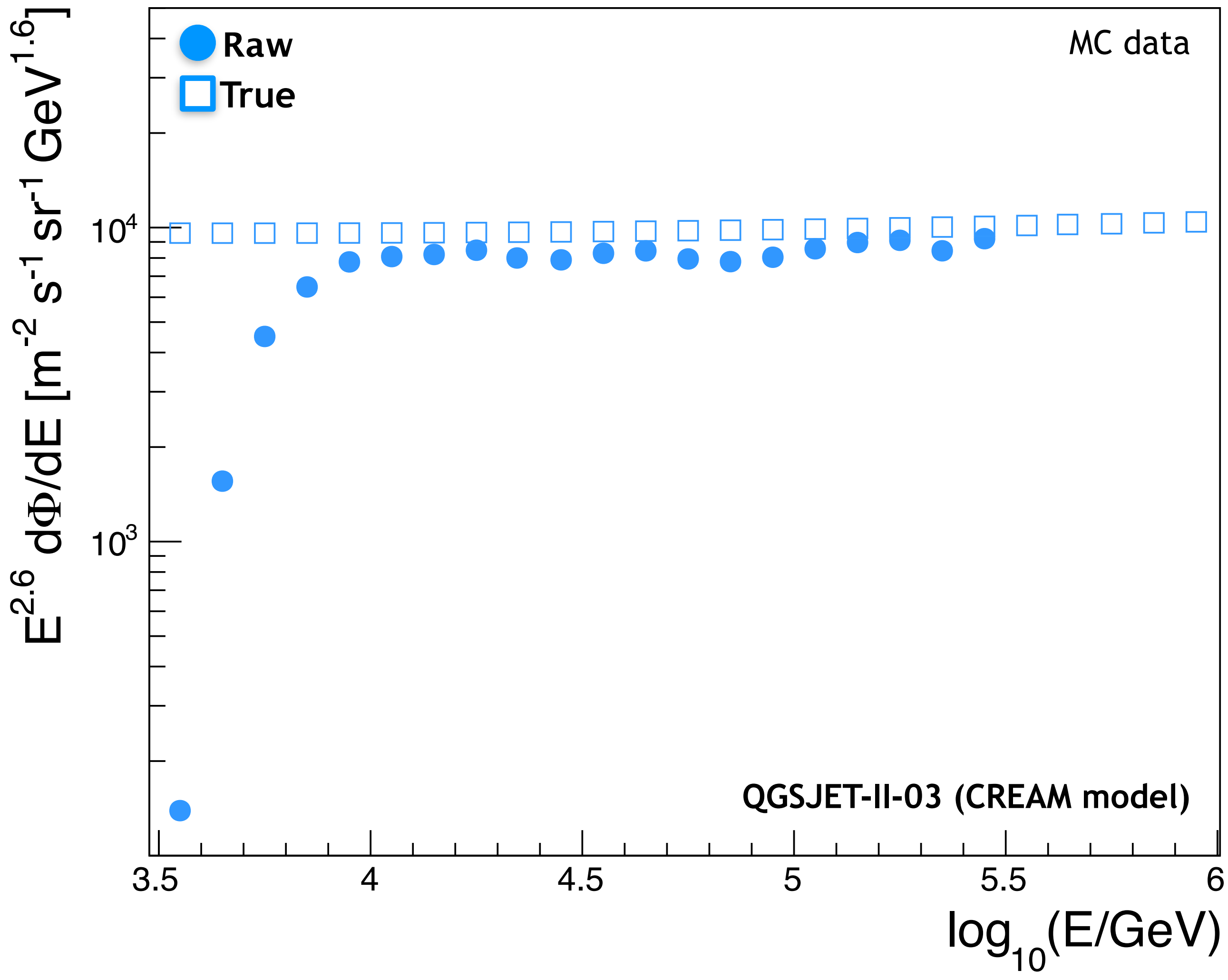
- More than 90% of H and He in subsample



Analysis

Build the raw energy histogram of subsample, $N_{raw}(E)$

Not corrected for efficiency/migration effects



Analysis

Correct $N_{raw}(E)$ for migration effects by unfolding

Unfolding:

- Apply Bayesian method* to correct for migration effects

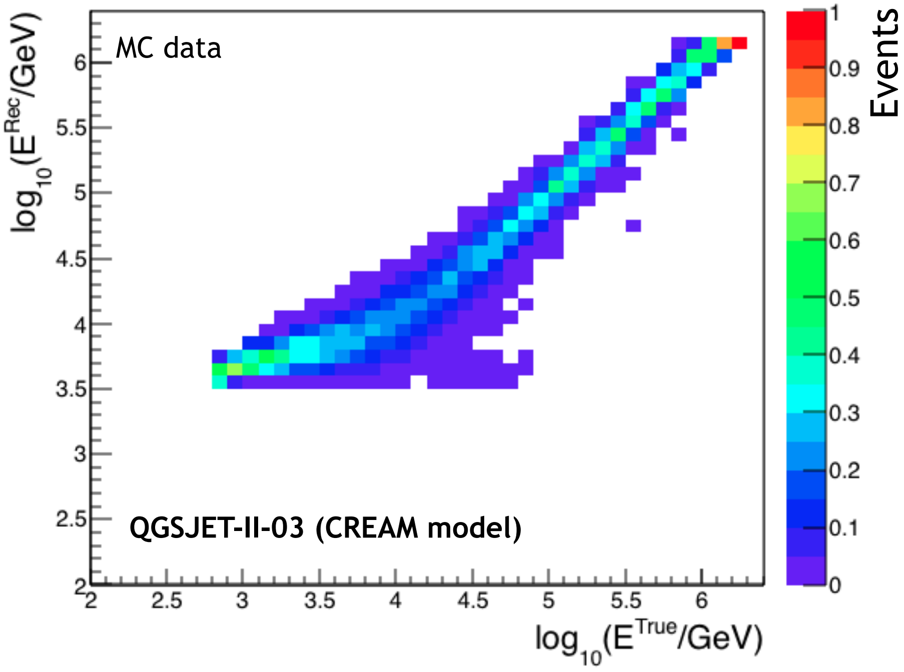
$$N^{Raw}(E^R_j) = \Sigma_i \, P(E^R_j \,|\, E^T_i) \, N^{Unf}(E^T_i)$$

- ROOT: Smooth method + power law

- Stopping criterium: Minimum of weighted mean squared error

$$\mathrm{WMSE} = \frac{1}{N_{points}} \sum_{i}^{N_{points}} \frac{stat_i^2 + sys_i^2}{n_i}$$

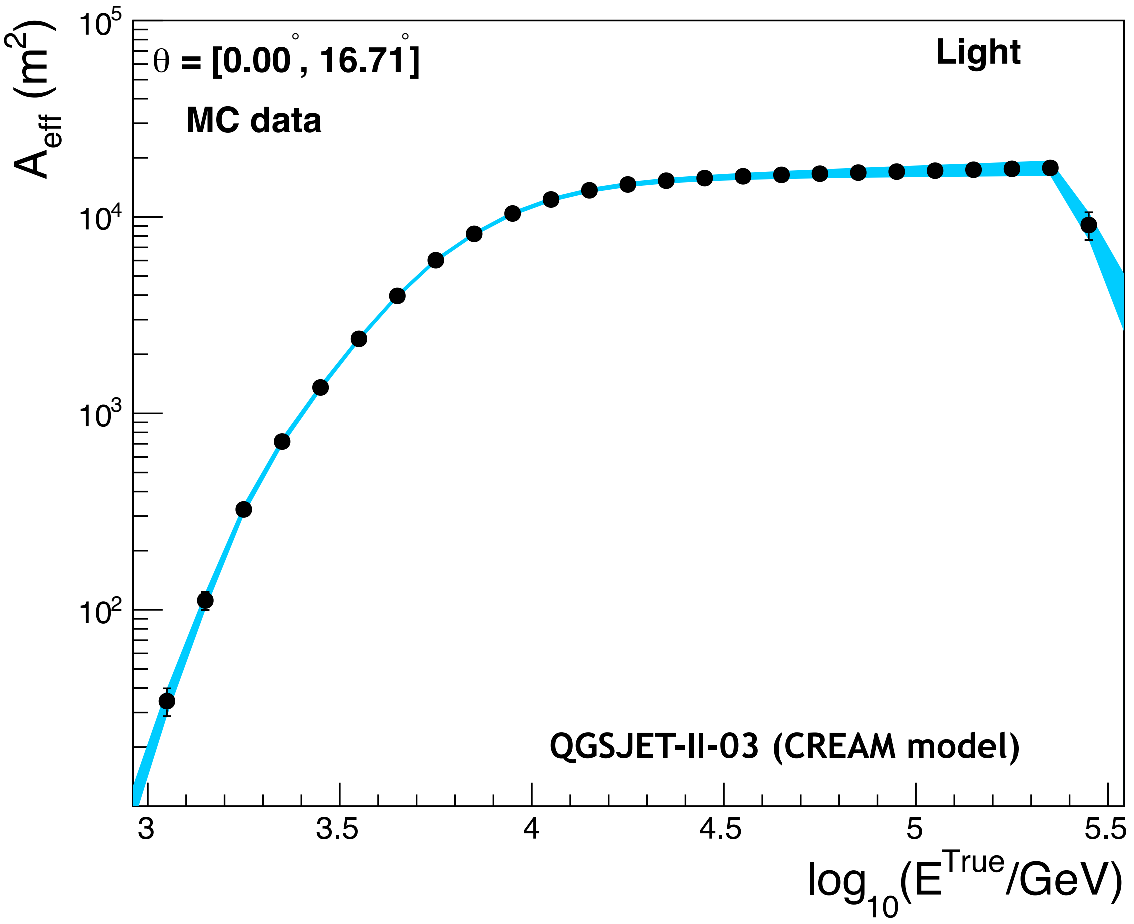
Response Matrix



- Linear response E > 10 TeV for MC

Analysis

Estimate effective area of the subsample and correct for heavy nuclei



- Taking into account the inefficiency

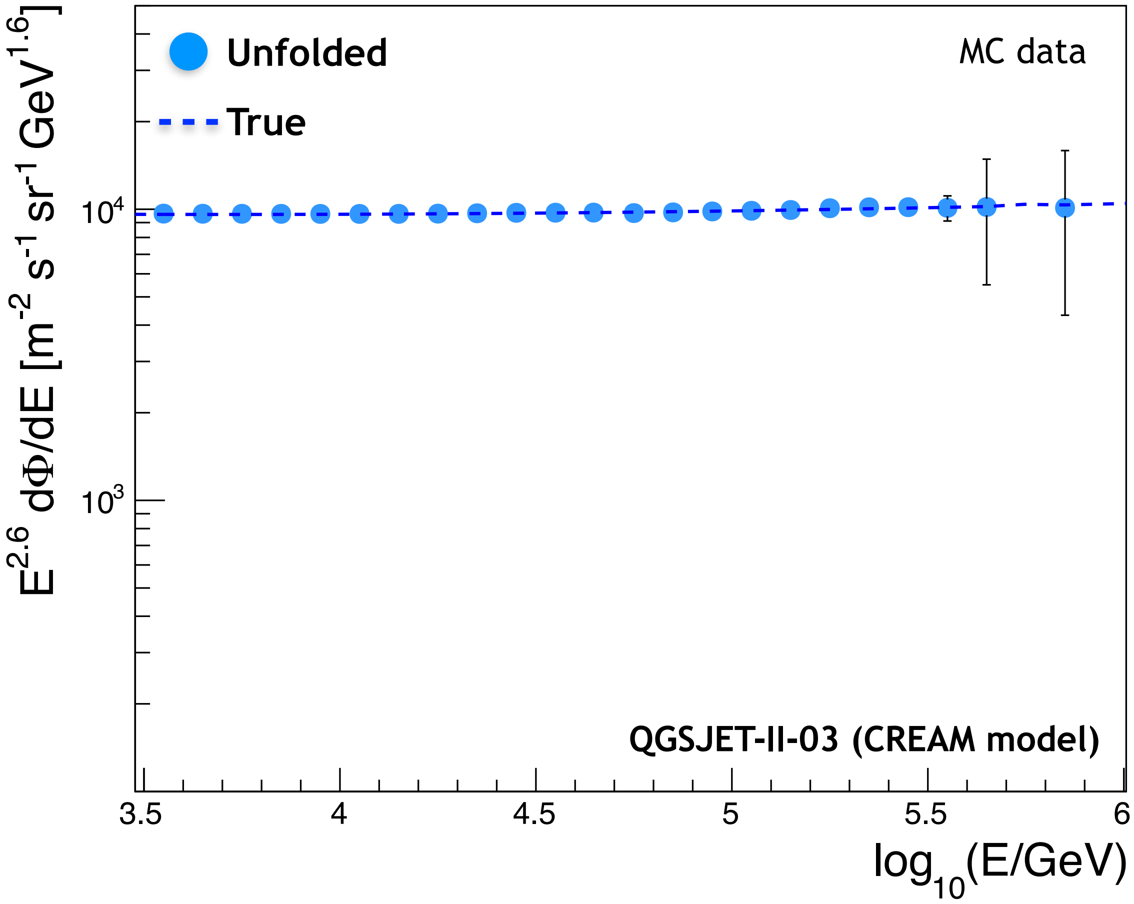
$$A_{eff}(E^T_i) = f_{corr,i} \cdot A_{eff}^{H+He}(E^T_i)$$

$$f_{corr} = (N_{light} / N_{light}^{H+He})$$

Not all events in subsample are due to H or He

Analysis

Get energy spectrum from N^{Unf} and effective area

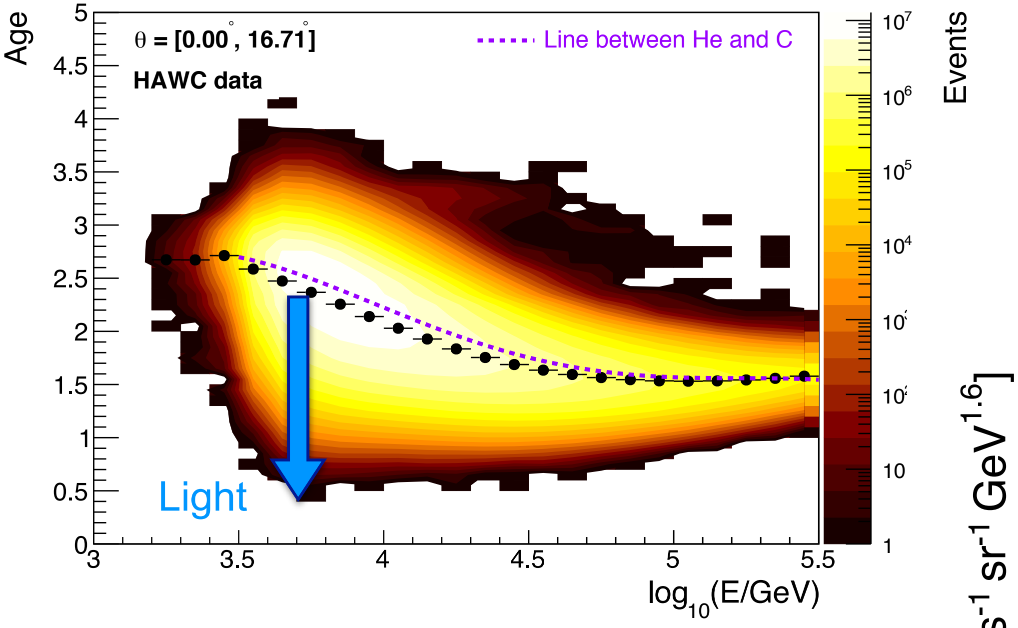


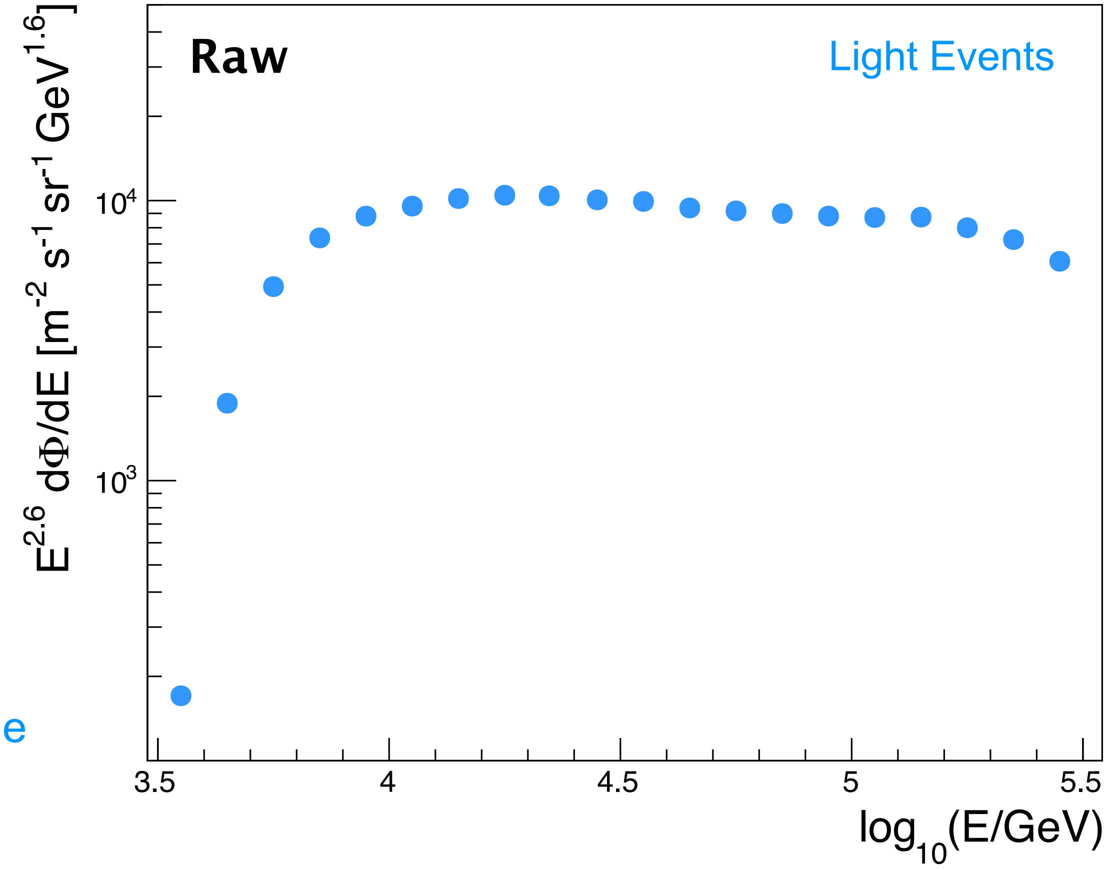
- Energy spectrum was calculated as:

$$\Phi = N^{Unf}(E^T)/(\Delta t \cdot \Delta\,\Omega \cdot A_{eff}(E^T) \cdot \Delta E^T)$$

Analysis

Measured data





Experimental data used for analysis:

HAWC-300

T_{eff} = 100.6 days

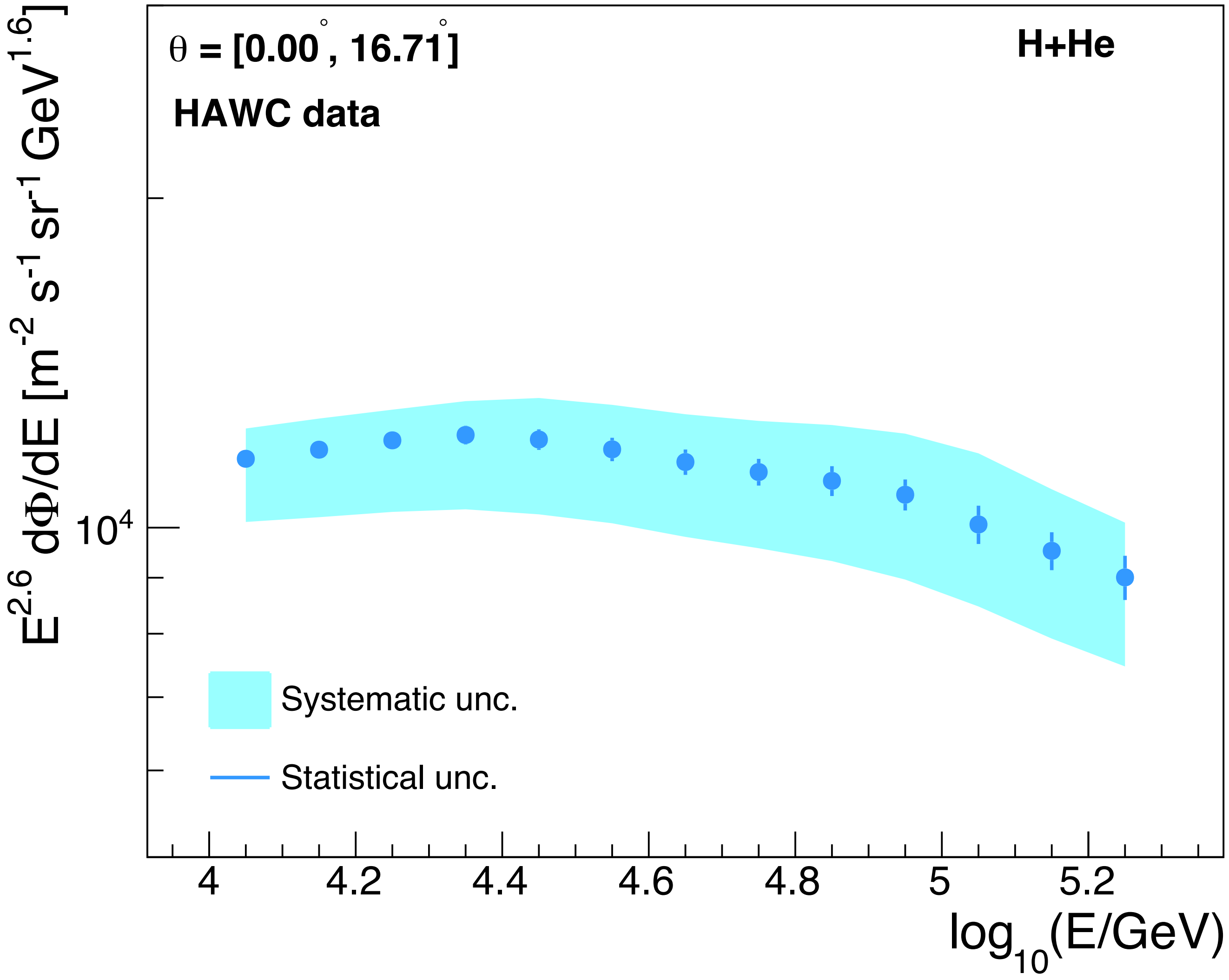
4.9 million of showers

3.2 million of showers for selected subsample

Results

Unfolded HAWC spectrum

H+He

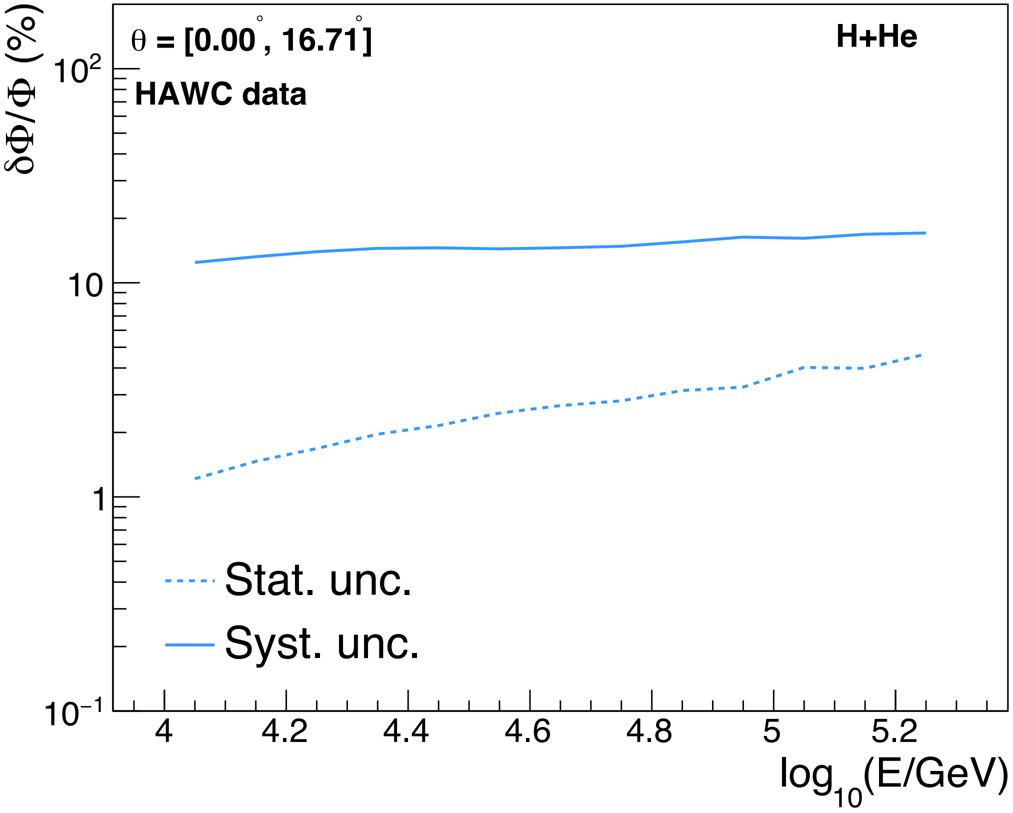


Analysis

Unfolded HAWC spectrum

H+He

Statistical and systematic uncertainties



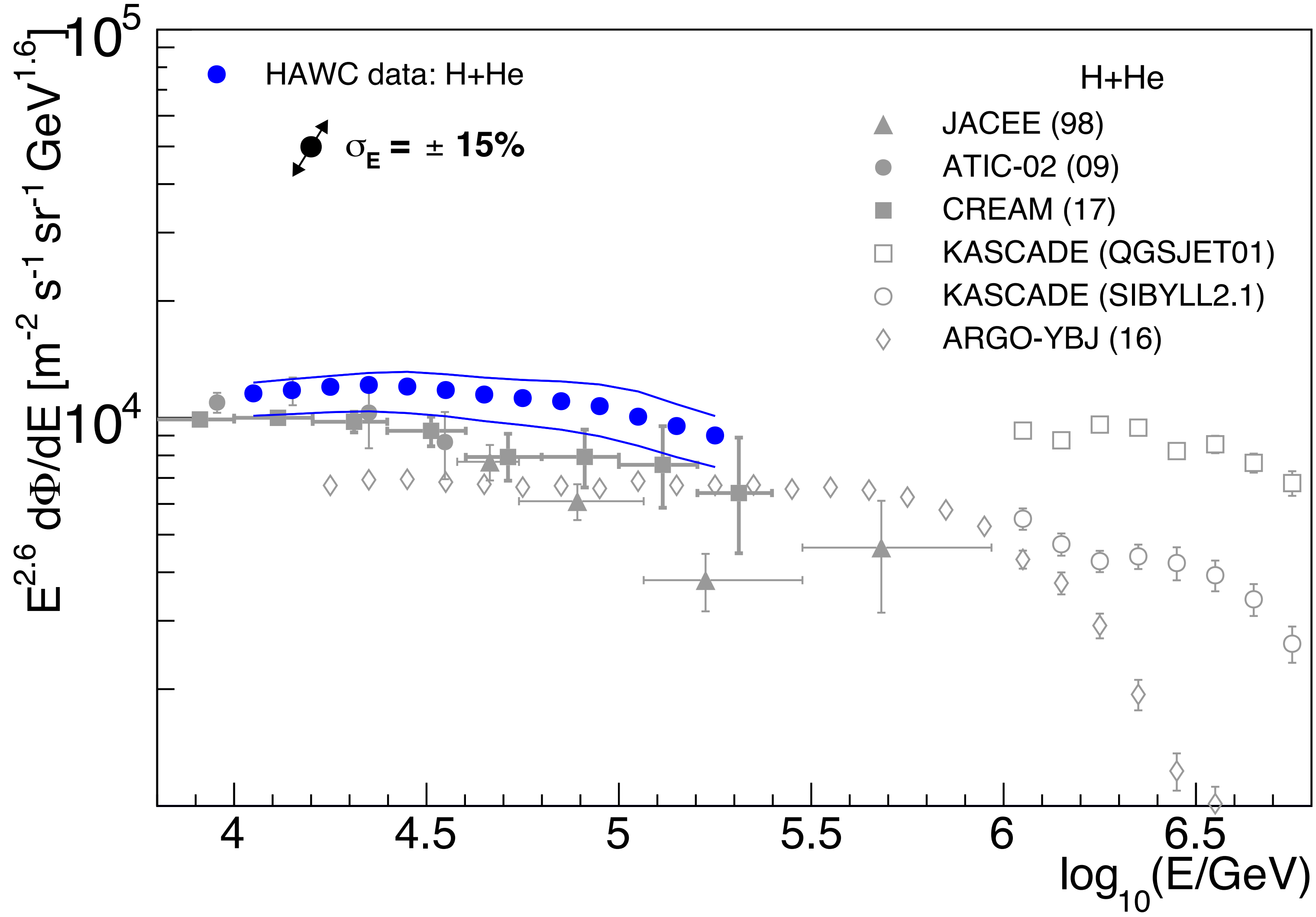
$\log_{10}$(E/GeV) = 4.95

	Relative error Φ (%)
Statistical	**+/- 3.3**
Exp. Data	+/- 0.1
Response matrix	+/- 3.3
Systematic	**+13.7/-16.3**
Composition	-14.7
Aeff	+6.7/- 5.8
Cut at He or C	-3.9
Gold unfolding	-0.3
Seed unfolding	-0.7
Smoothing unfold.	-1.1
Bin size	-1.2
PMT Qeff	+11.4
PMT Qres	+3.5
Total	**+14.1 /-16.7**

Results

Unfolded HAWC spectrum

H+He



Results

Fit of spectrum

H+He

1. Use following functions:

—> Single power law:

$$\frac{\mathrm{d}\Phi(E)}{\mathrm{d}E} = \Phi_0 \; E^{\gamma_1}$$

—> Double power law:

$$\frac{\mathrm{d}\Phi(E)}{\mathrm{d}E} = \Phi_0 \; E^{\gamma_1} \left[1 + \left(\frac{E}{E_{\mathrm{knee}}} \right)^{\varepsilon} \right]^{(\gamma_2 - \gamma_1)/\varepsilon}$$

2. Minimize χ^2 with MINUIT and take into account correlation between points:

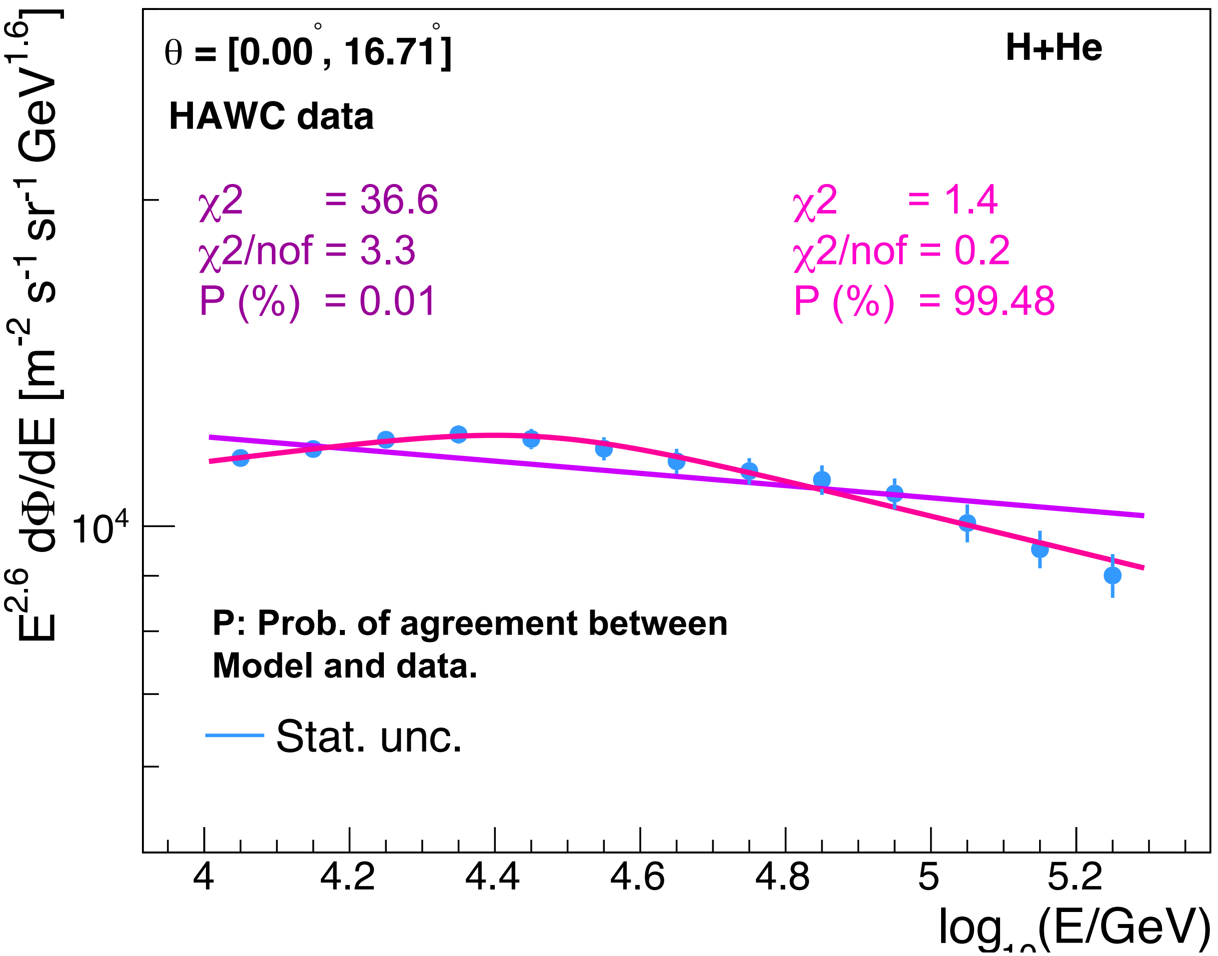
$$\chi^2 = \sum_{i,j} [\Phi_i^{\mathrm{data}} - \Phi^{\mathrm{fit}}(E_i)] \, [V_{\mathrm{stat}}^{\mathrm{Tot}}]^{-1}_{ij} \, [\Phi_j^{\mathrm{data}} - \Phi^{\mathrm{fit}}(E_j)]$$

PDG (2017)

Results

Fit of spectrum

H+He



Results of parameters for the double power-law fit:

$\gamma_1 = -2.51 \pm 0.05$

$\gamma_2 = -2.77 \pm 0.04$

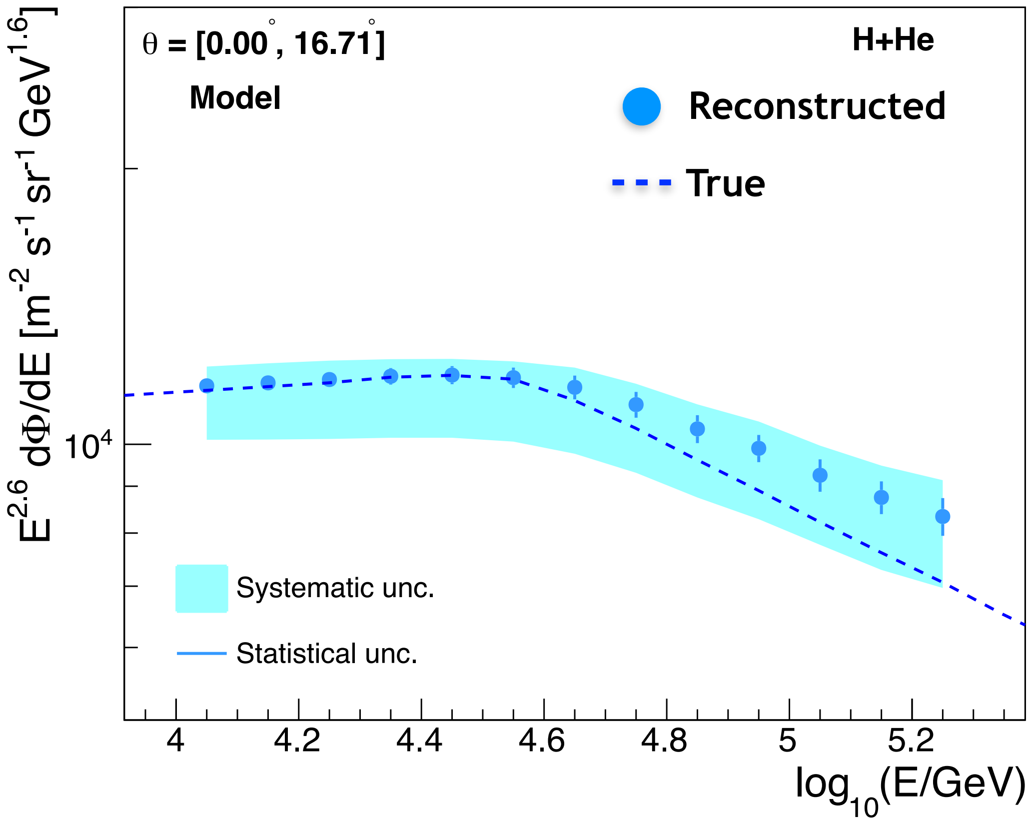
$\Delta\gamma = -0.26 \pm 0.06$

$\log_{10}(E_{knee}/GeV) = 4.47 \pm 0.13$

Results

Check performance of method with MC simulations

H+He



Use **MC simulations** following the CREAM-II model, but **with a kink** in the light component of CR's:

$\log_{10}(E_{knee}/GeV) \sim 4.5$

The kink is reconstructed

The reconstructed **Δγ is smaller than the actual one** due to contamination from the heavy component.

Conclusion

- The lateral age parameter is sensitive to the composition of cosmic rays at HAWC.

- A first analysis of cosmic ray composition with HAWC has allowed to reconstruct the spectrum of the light component (H+He) of cosmic rays in the range E = [10, 158] TeV.

- The reconstructed spectrum of H+He shows a knee ($\Delta\gamma = -0.26 \pm 0.06$) @ $E = 30^{+10}_{-8}$ TeV.

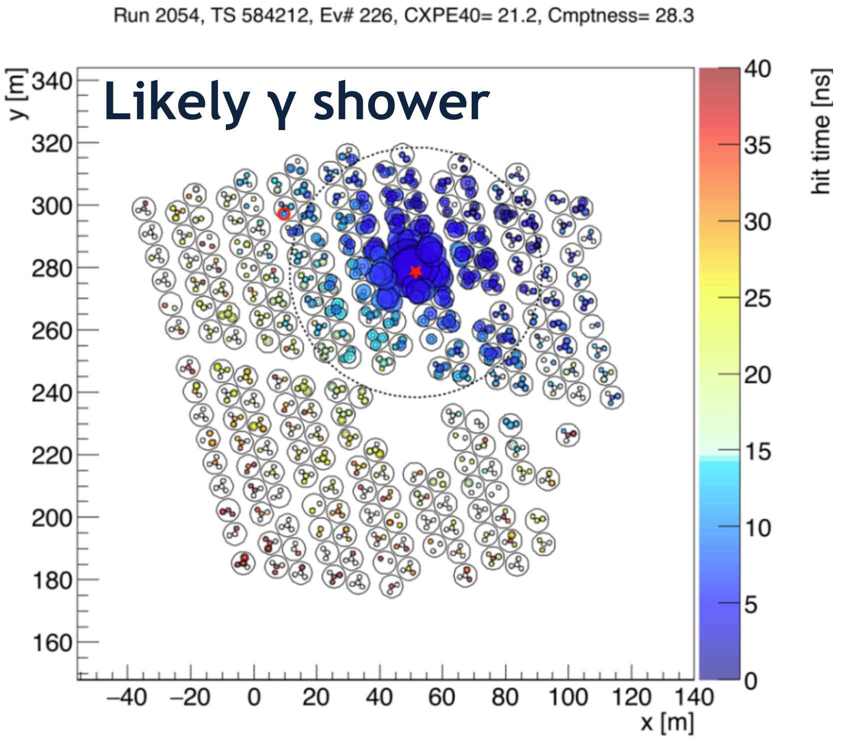
- Studies on the heavy component of cosmic rays are also underway.

Backup slides

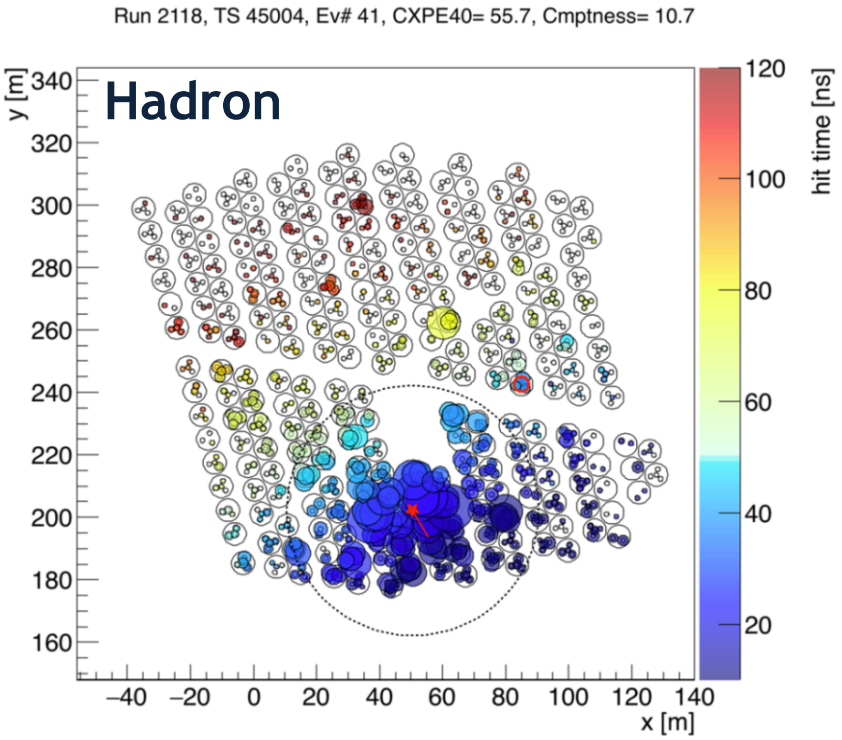
The HAWC observatory

γ/hadron separation

- Separate gamma-ray events from background using distribution of charged deposition

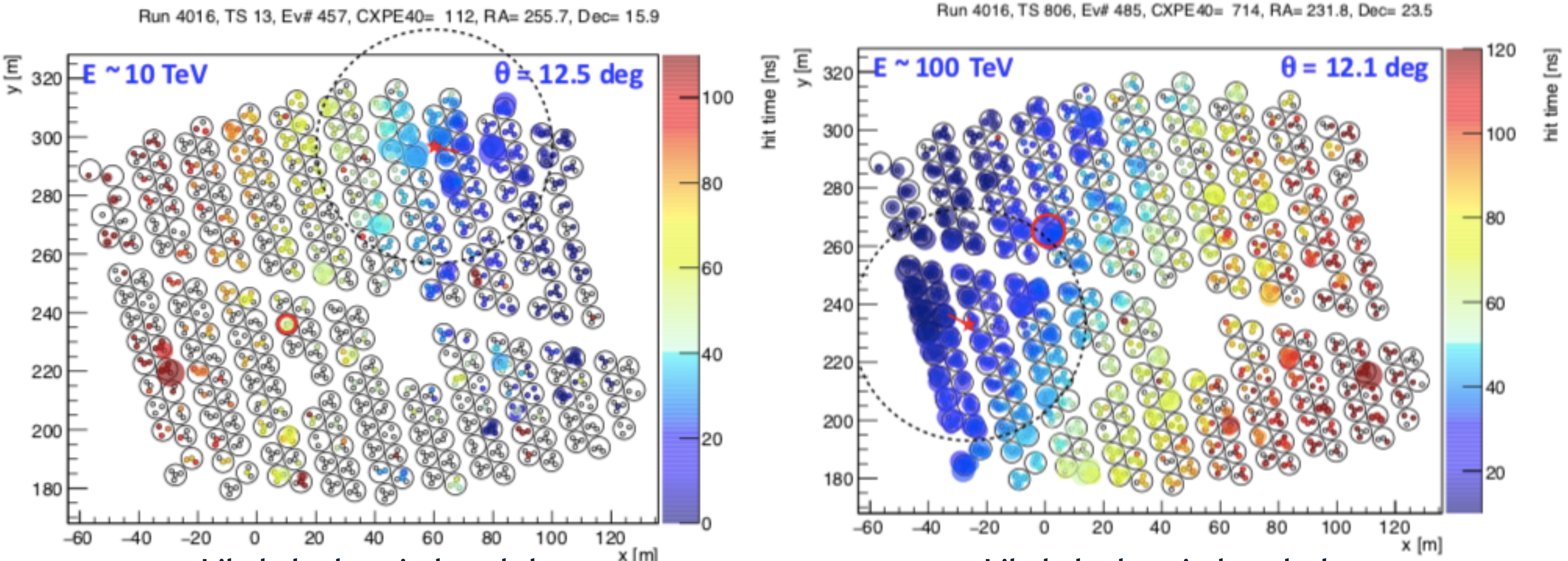


γ: compact cores/smoothed distribution



Hadron: energetic clumps far from core

Cosmic ray observables



Likely hadron-induced shower

Likely hadron-induced shower