The spectrum of the light component of TeV cosmic rays measured with HAWC

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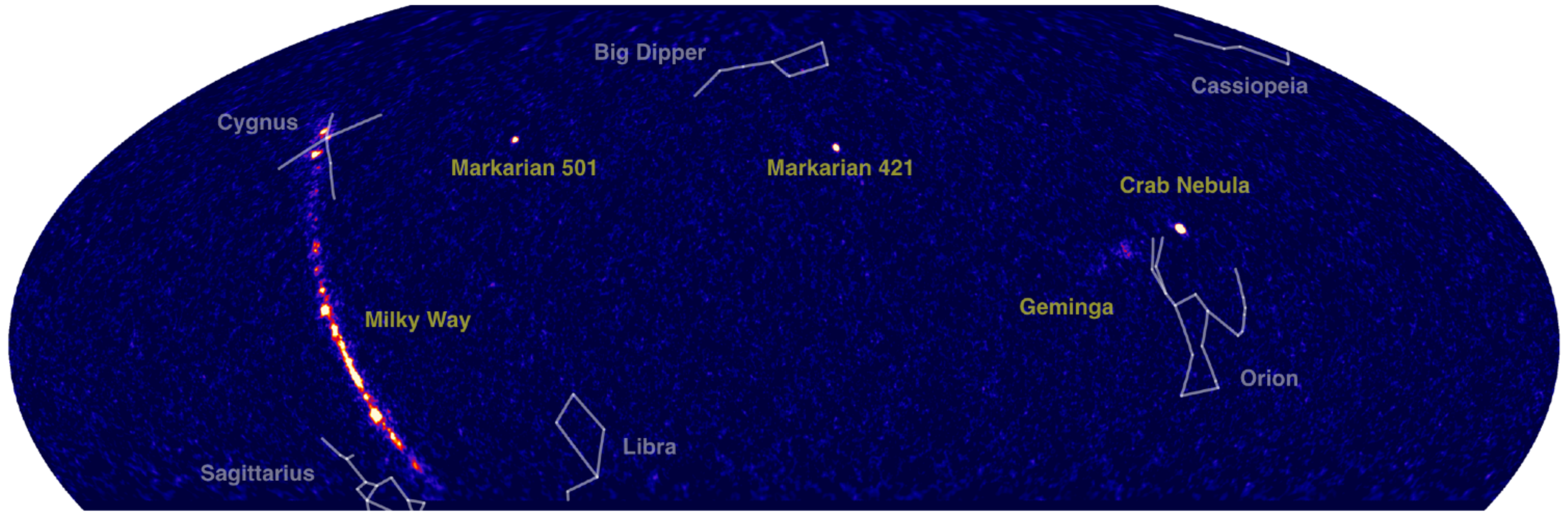


γ- and cosmic-ray detector:

- Air-shower observatory
- Ground-based Cherenkov array
  E = 100 GeV - 100 TeV

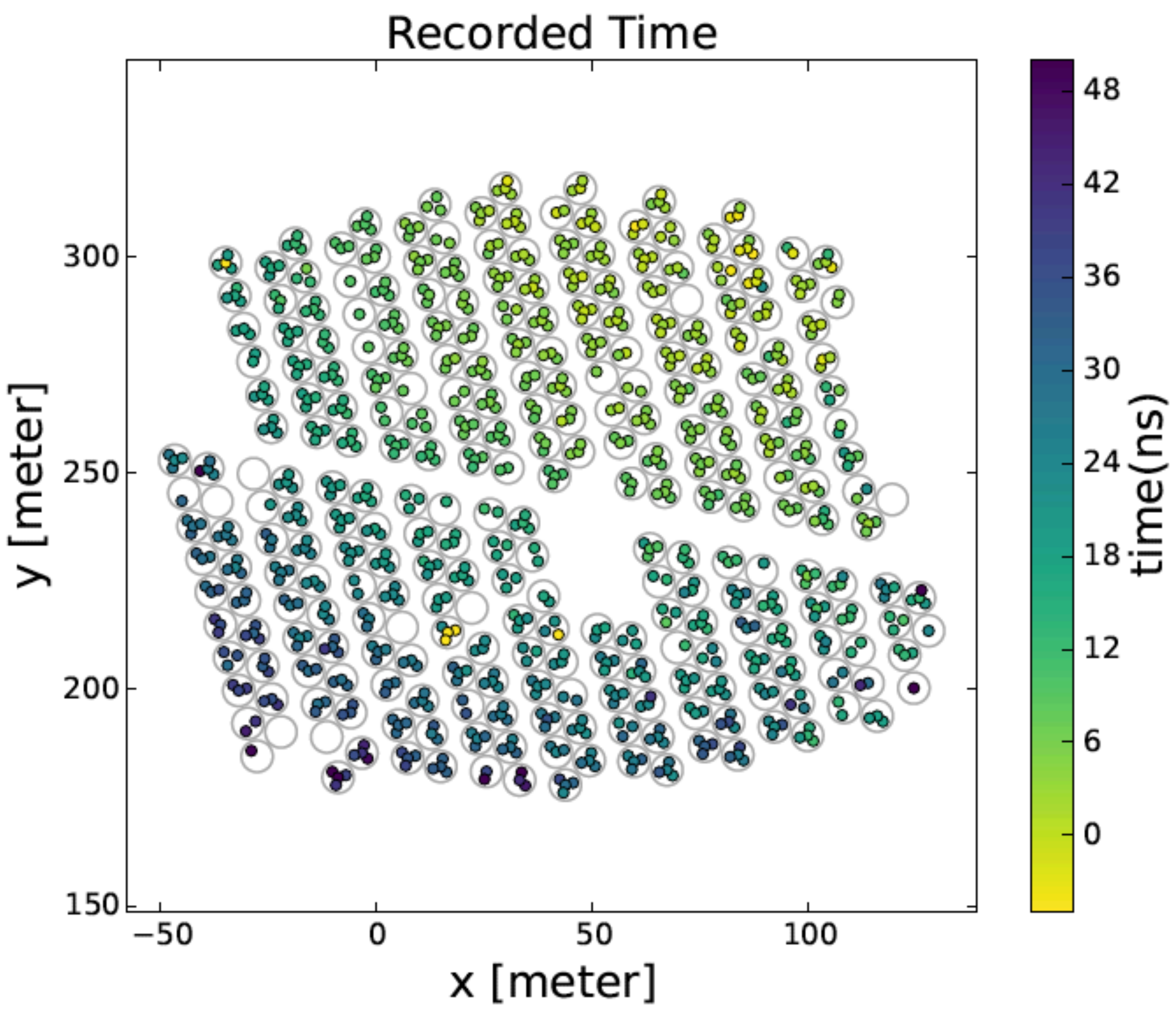
Set-up:

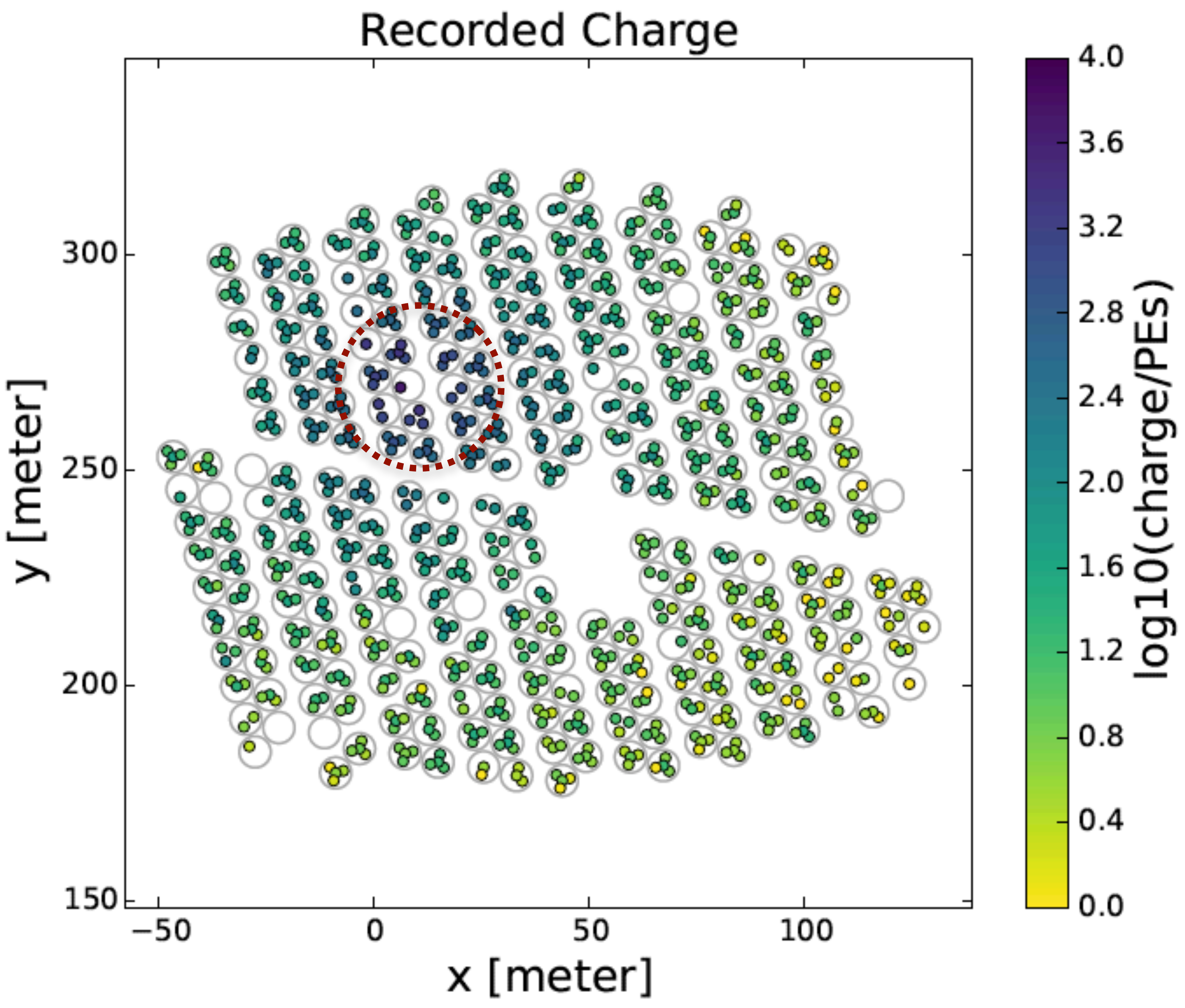
- 22 000 m^2 surface
- 300 densely packed water Cherenkov detectors (200,000 ℓ of water + 4 PMTs)

Location:

- Volcano Sierra Negra, Puebla, Mexico
- 19° N and 97° W
- 4100 m a.s.l. (640 g/cm^2)

1) The HAWC γ-ray observatory

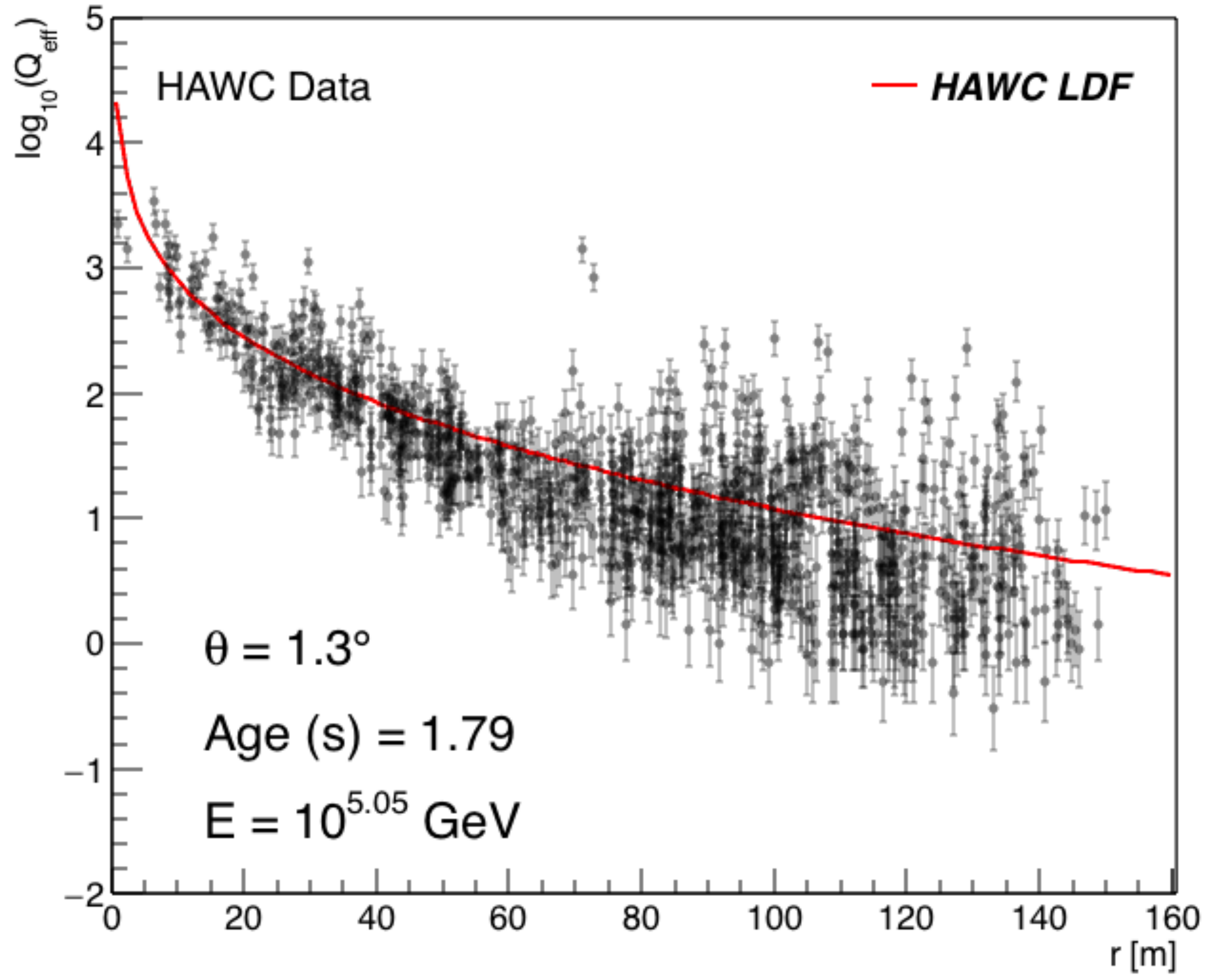


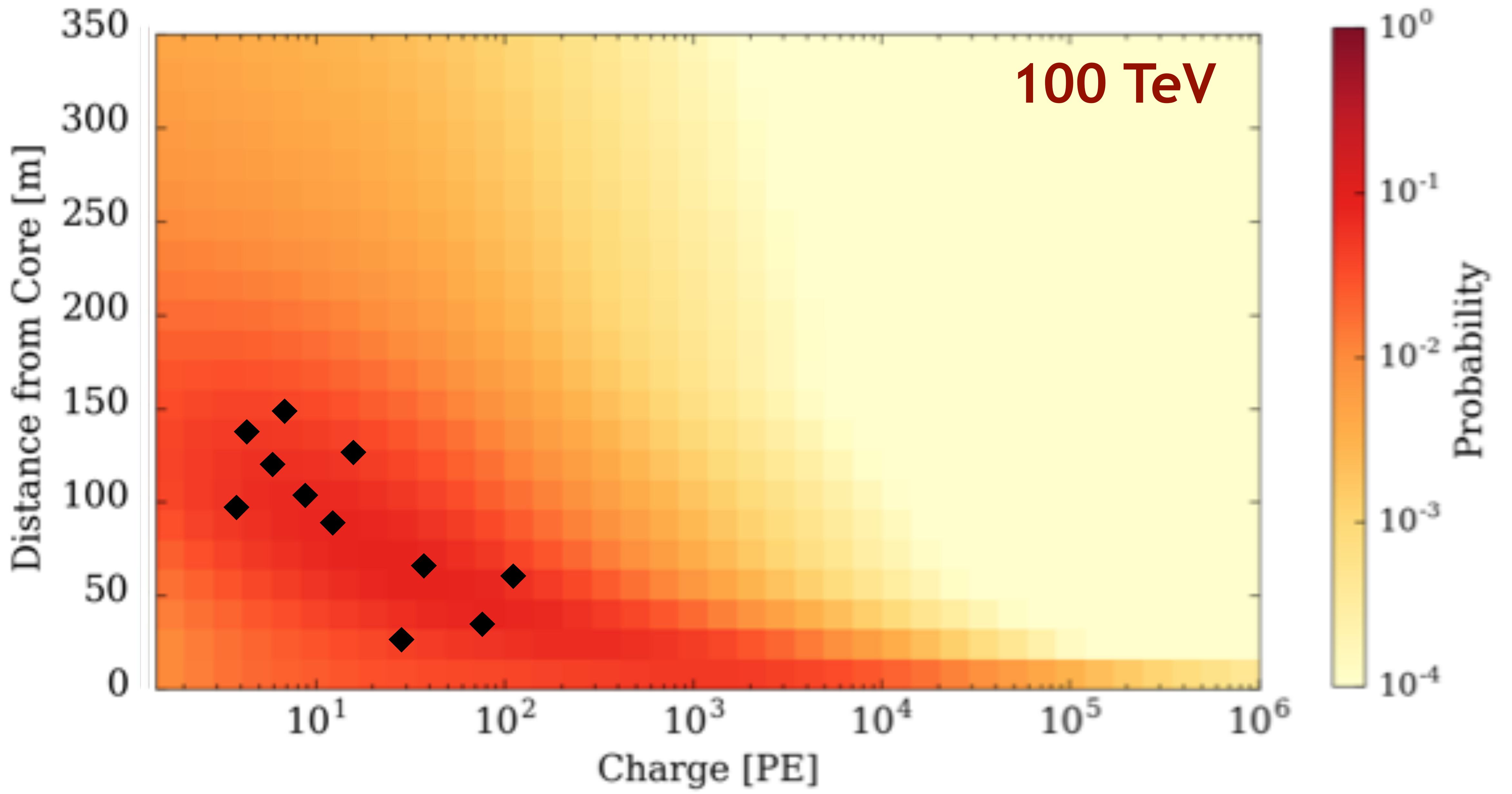


- From hit times at PMTs, deposited charged, number of PMT's with signal:
  - Core location, (X_c, Y_c)
  - Arrival direction, θ
  - Fraction of hit PMT's, f_{hit}
  - Lateral charge profile, Qeff(r)
  - ...

[HAWC Coll., ApJ 843 (2017) 39]

2) EAS age and energy estimations





- **Lateral age parameter** (***s***):
  - Obtained event-by-event
  - Fit of Qeff(r) with NKG-like 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]

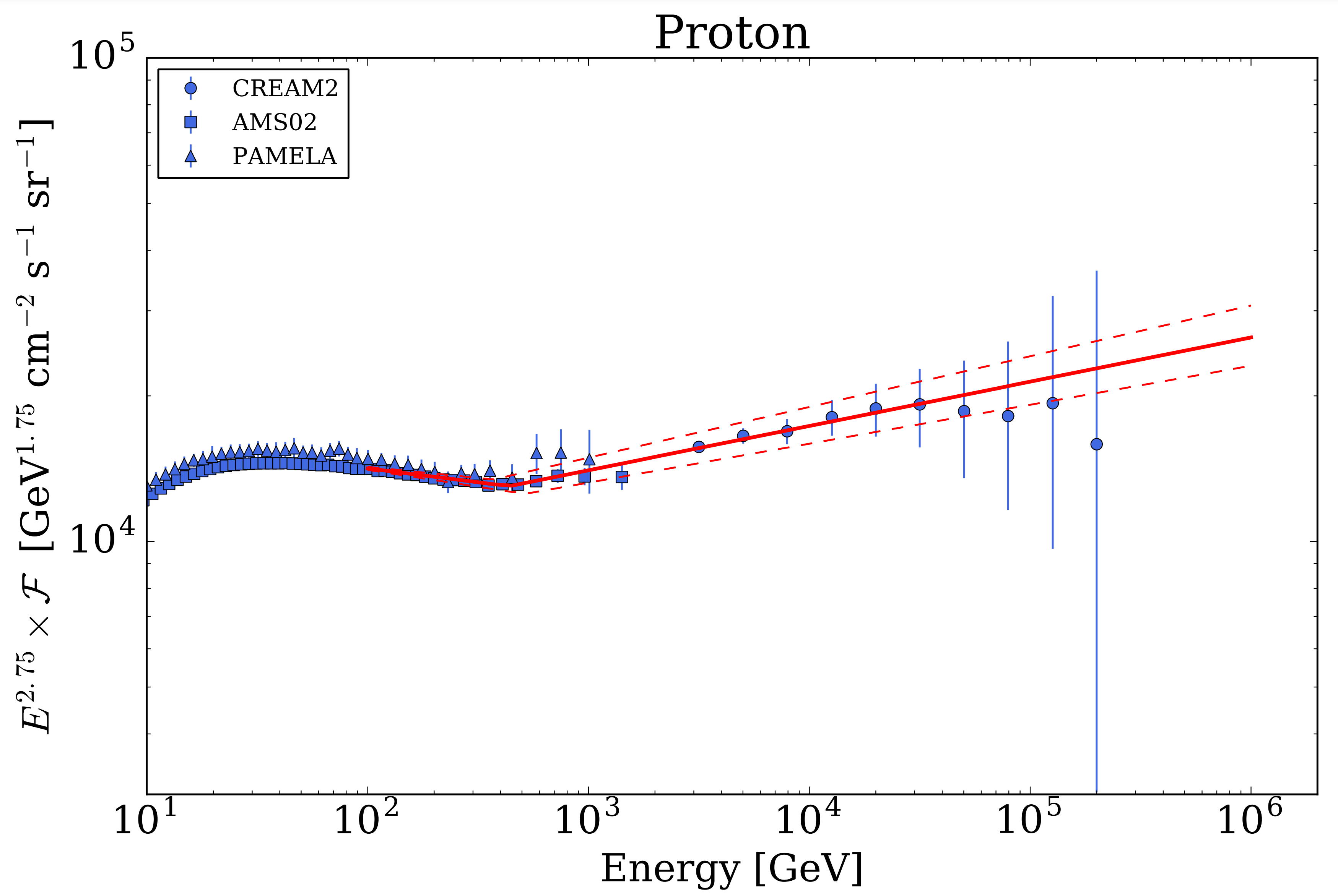
J.A. Morales Soto et al., Poster PS1-199, PoS(ICRC2019)359

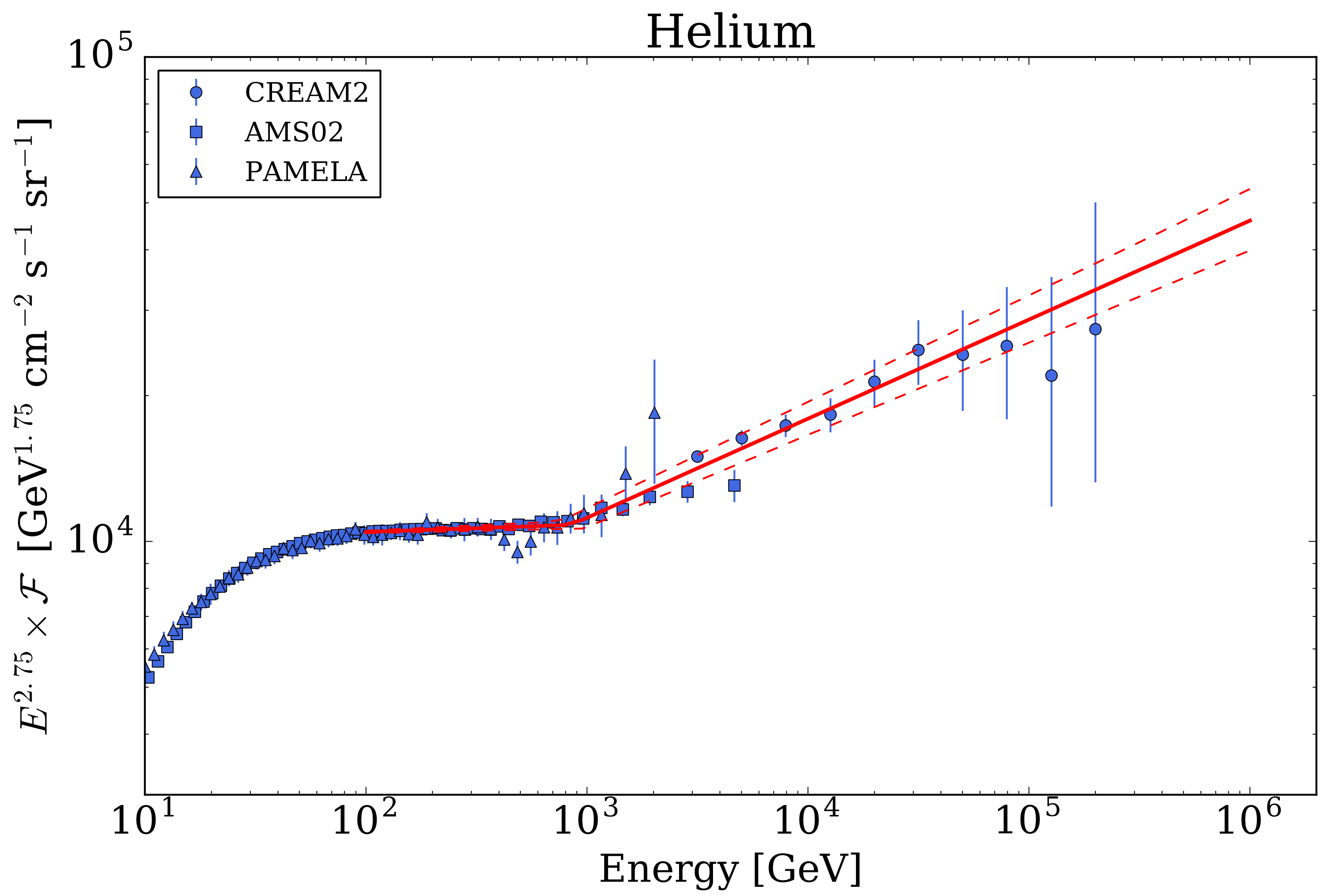
- **EAS primary energy**:
  - Produce LDF tables of MC protons**:** Binning in r, Qeff, θ and E
  - Maximum likelihood to find table that best fits the Qeff(r) distribution of the event, from which **E** is obtained.

[HAWC Collab., PRD 96 (2017); Z. Hampel-Arias' PhD thesis, 2017]

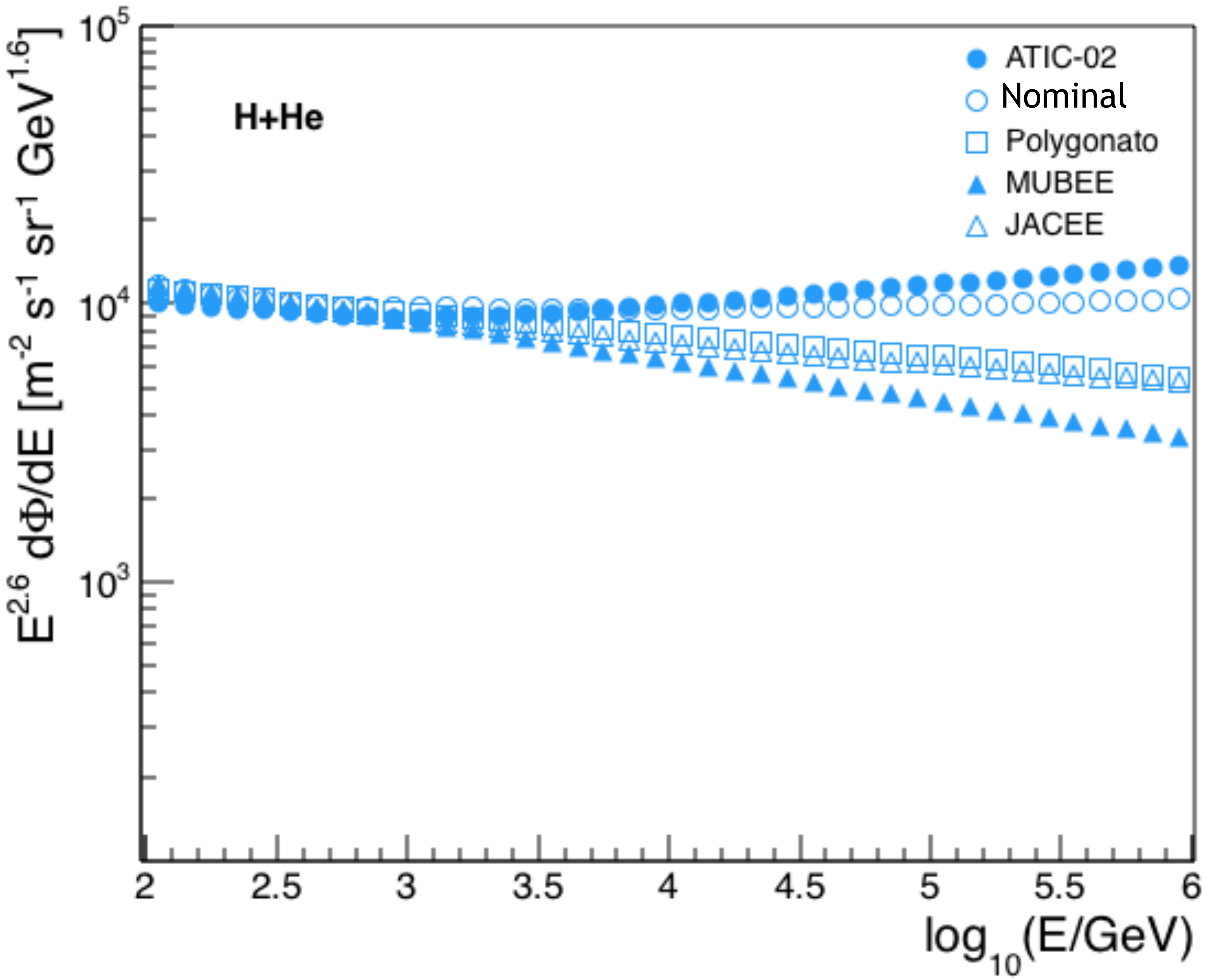
3) MC simulations

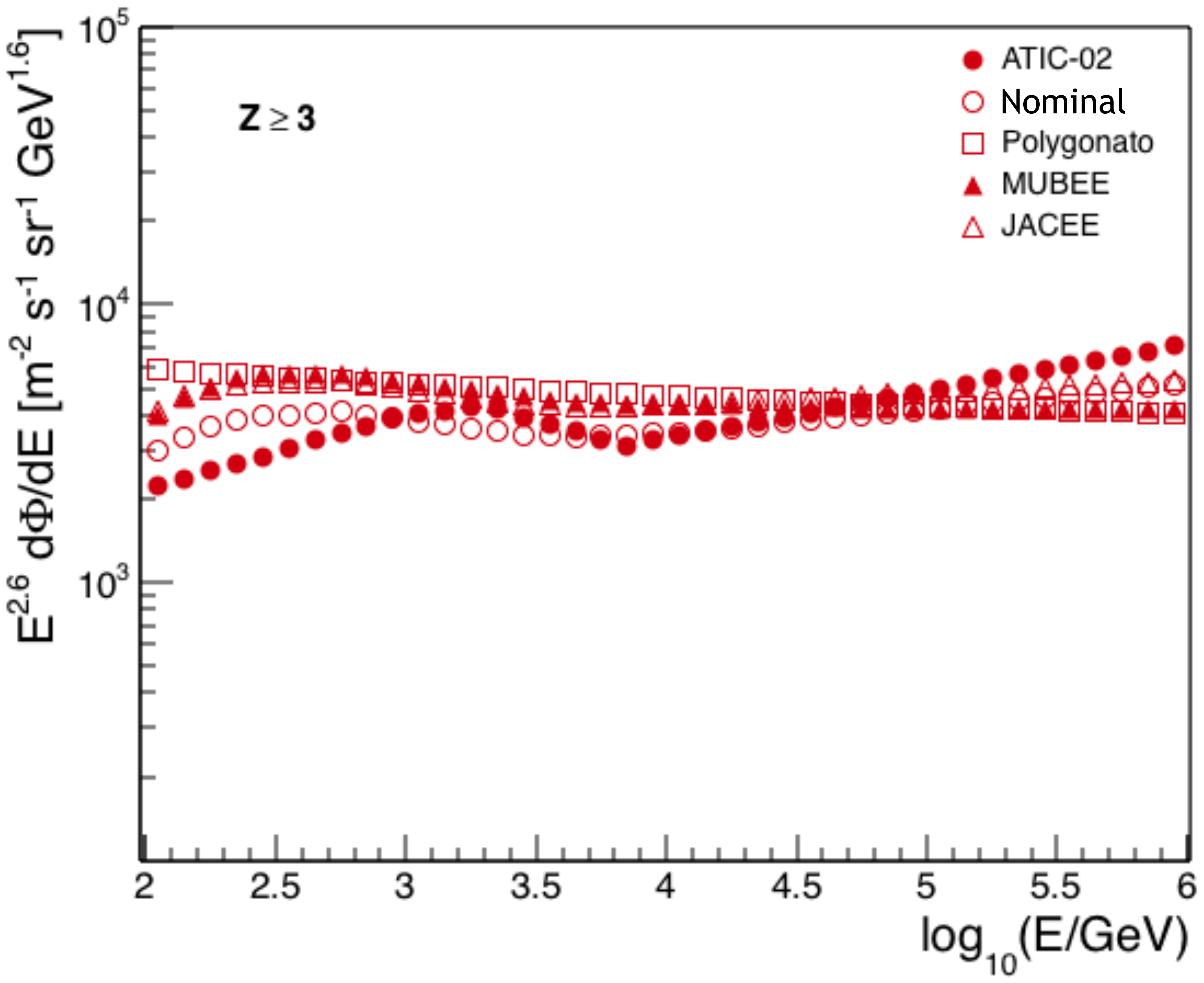
- CORSIKA v 7.40 for EAS simulation.
- Fluka/QGSJET-II-03 as low/high-energy interaction models.
- Full simulation of detector response with GEANT 4.
- $\theta < 70^o$; $A_{thrown} \sim 3 \times 10^6\ m^2$
- Primary nuclei:
  - H, He, C, O, Ne, Mg, Si, Fe
  - E = 5 GeV – 3 PeV
  - E^{-2} spectra weighted to follow double power-laws derived from fits to **AMS02** (2015), **CREAM-II** (2009 & 2011) and **PAMELA** (2011) data.





Composition models





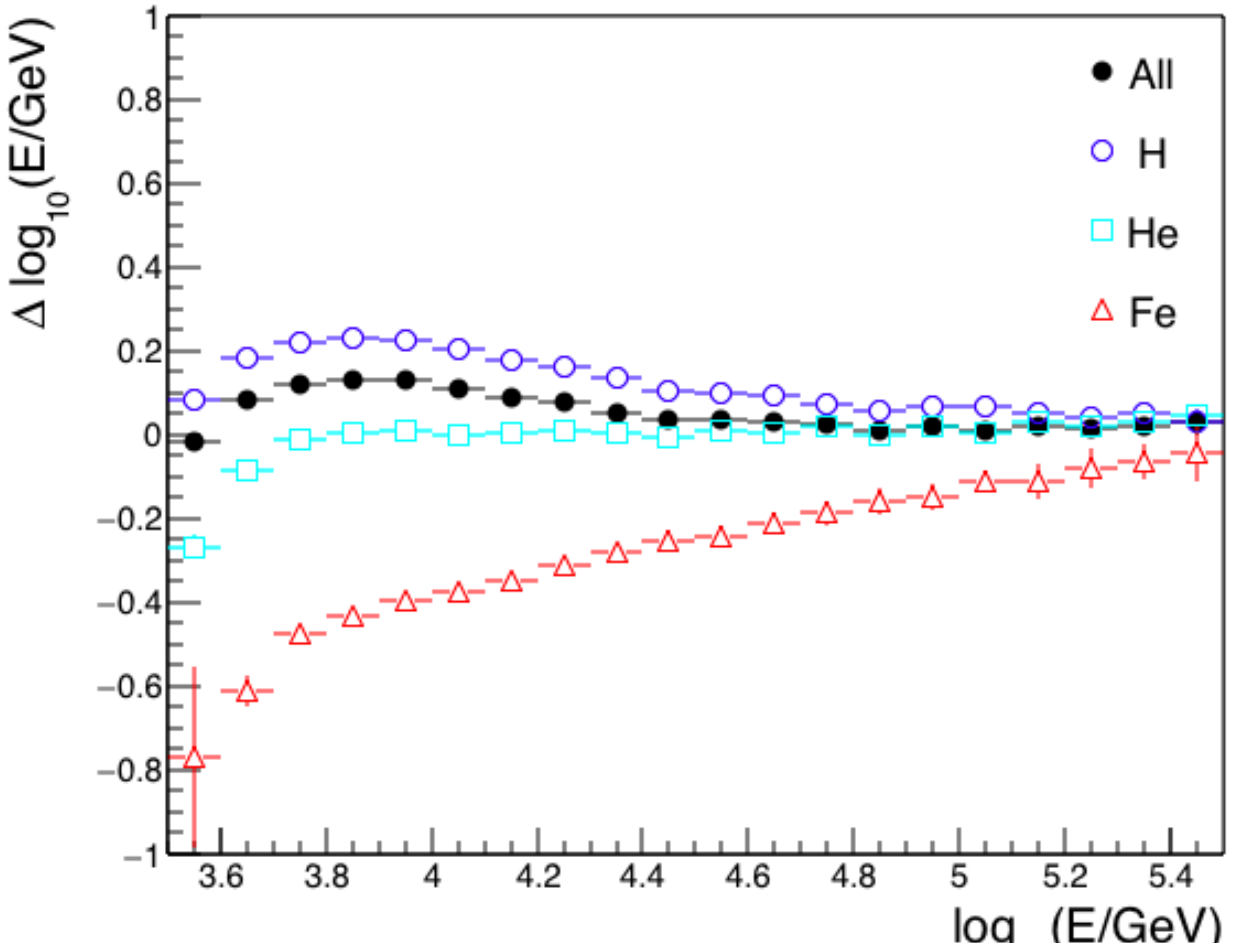
- But also use different composition models for studies of systematics

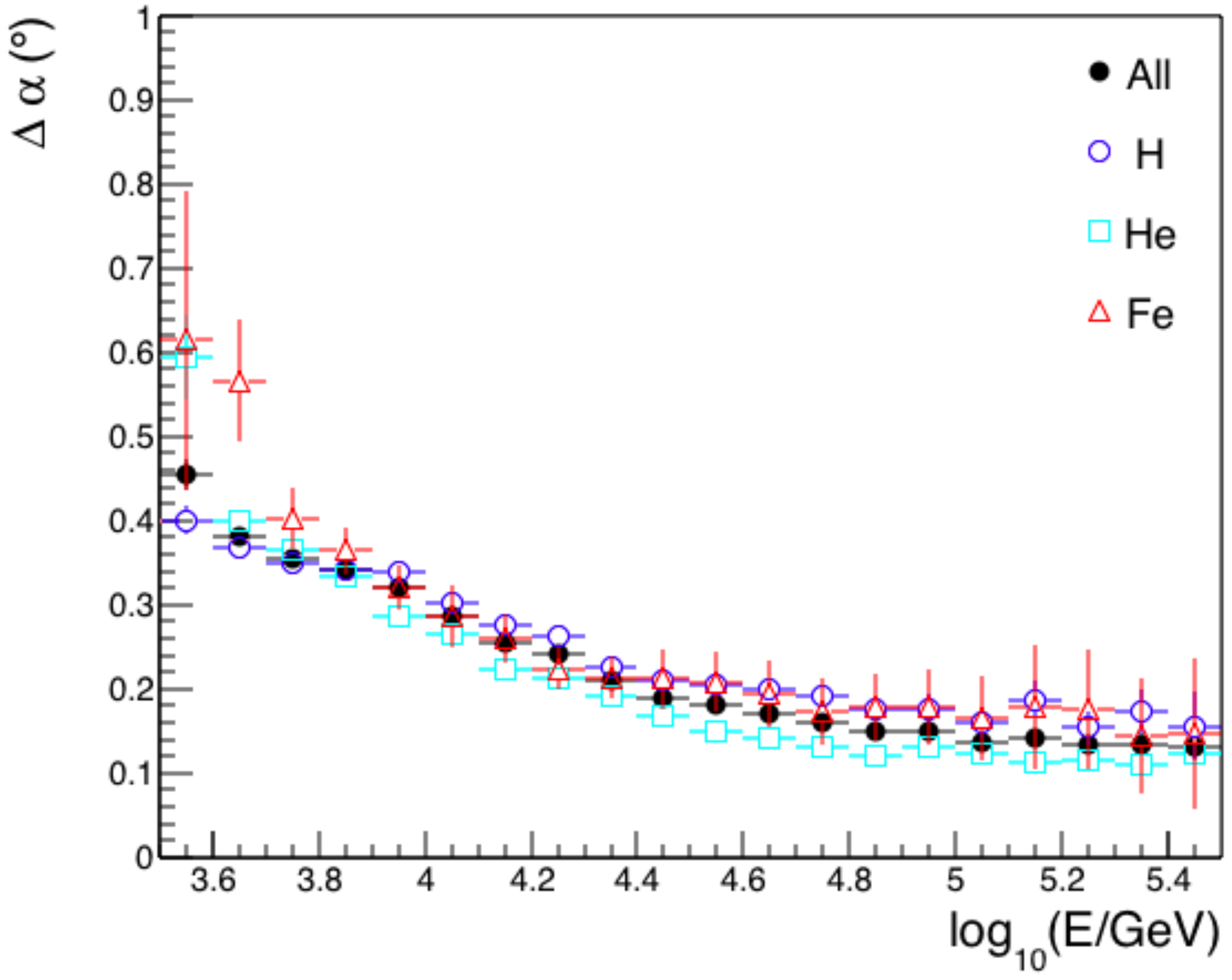
Selection cuts

- Important to reduce systematic effects on results:
  - $\theta < 16.7^{\circ}$
  - Successful core and arrival direction reconstruction
  - Activate at least 60 PMTs within 40 m from core
  - On-array EAS cores
  - Multiplicity threshold $N_{hit} \geq 75$ PMTs
  - Fraction hit (# of hit PMT's/# available channels) ≥ 0.3
  - $\log_{10}(E/GeV) < 5.5$

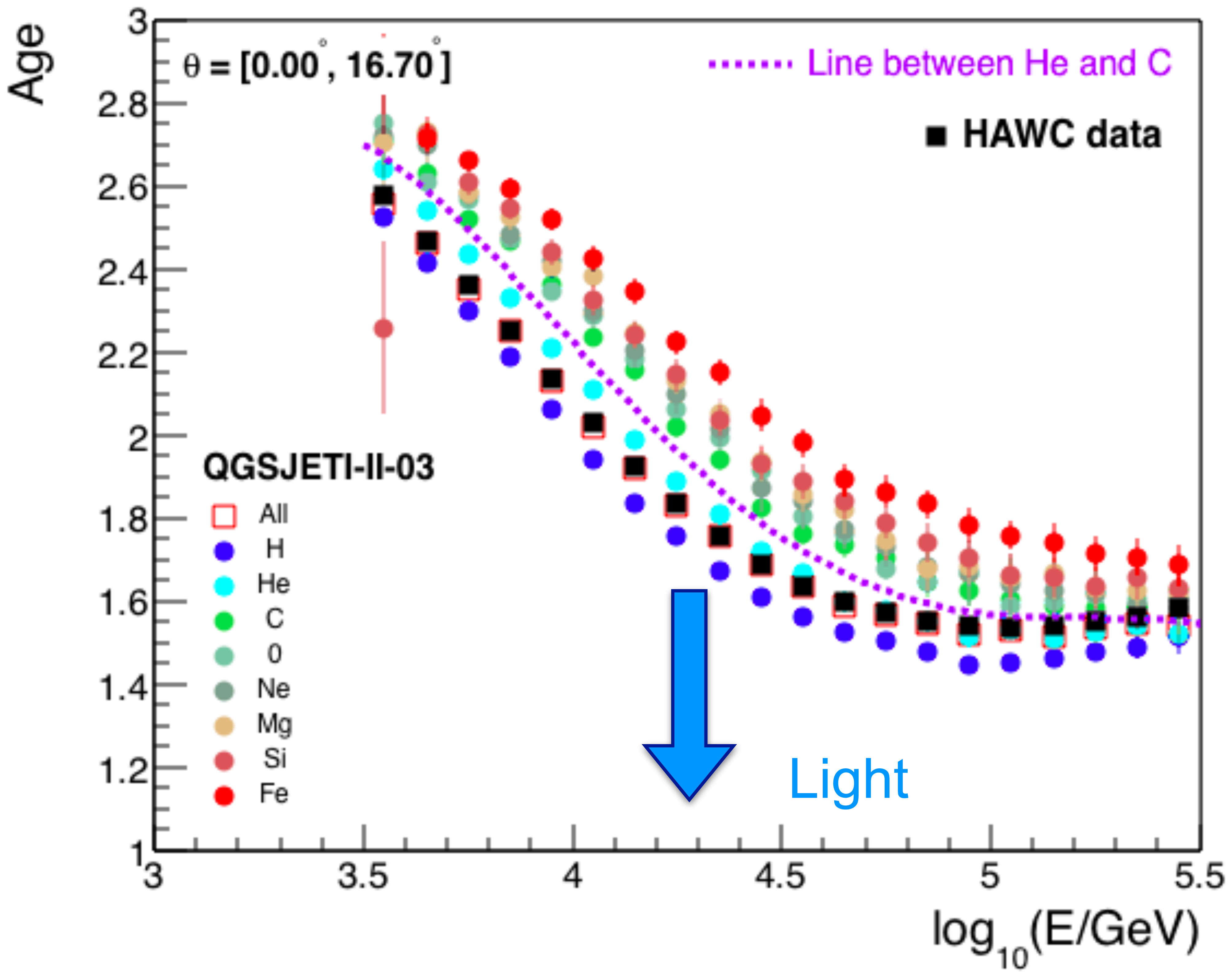
- Bias:

E ≥ 10 TeV:	
$\Delta core_{res}$	≤ 9 m
$\Delta \log_{10}(E/GeV)$	≤ 0.12
$\Delta\alpha$	≤ 0.3°

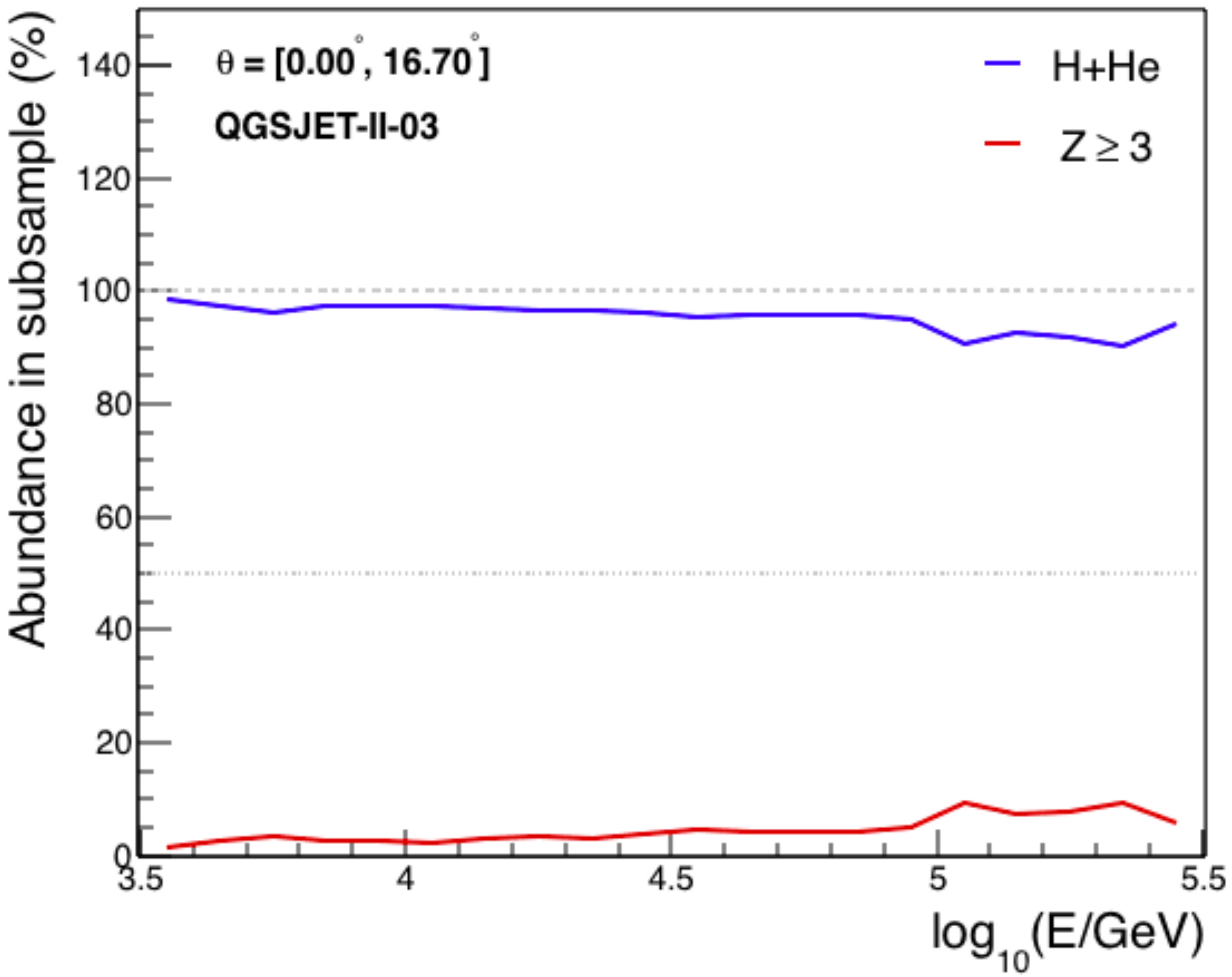




Select a sample enriched with light nuclei

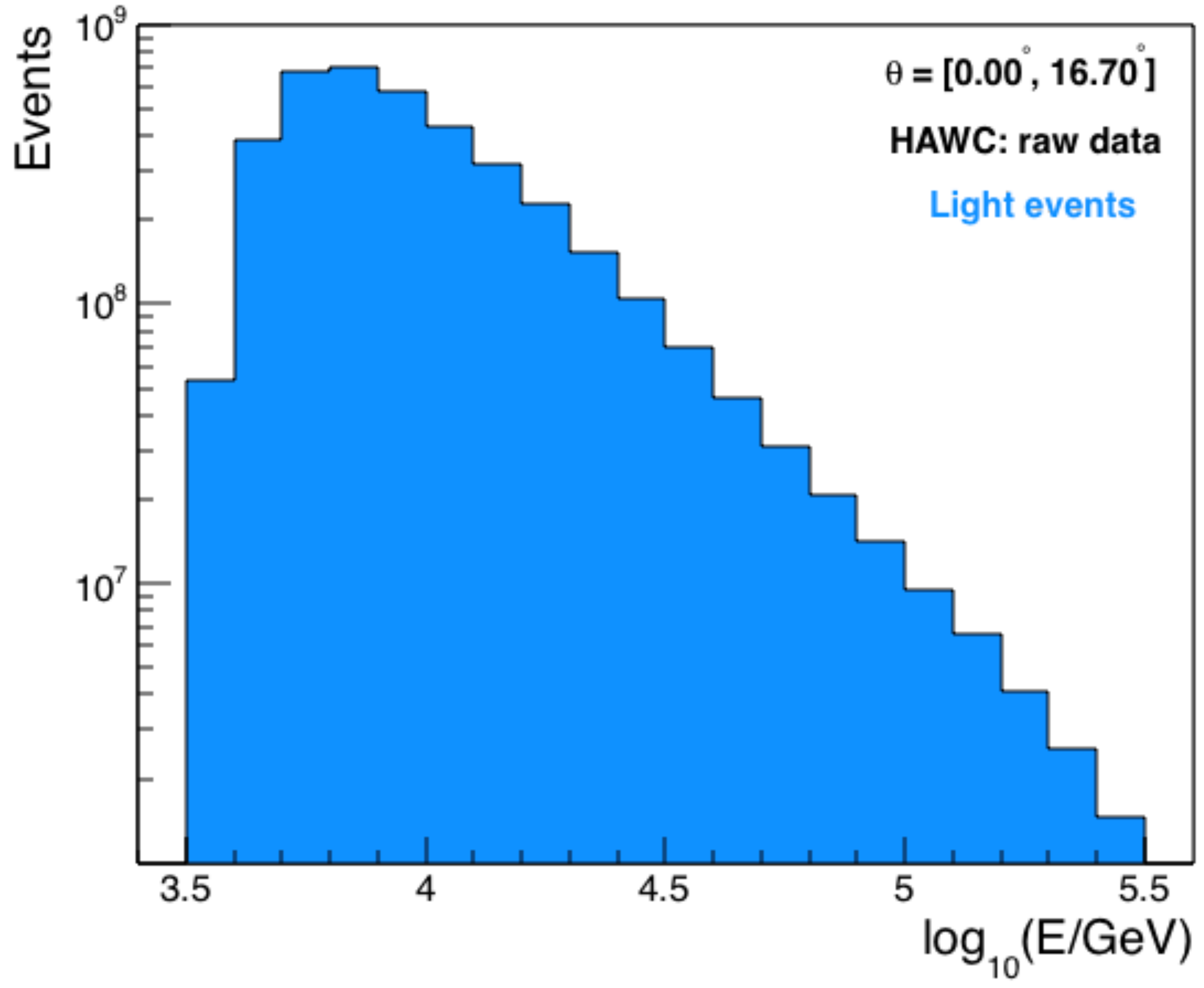


- Age parameter is sensitive to composition
- Select a subsample using a cut on the age
  - Subsample must be enriched with nuclei to study



- Content of H + He in subsample
  - More than 90% of H and He in subsample

Build raw energy spectrum of subsample: $N_{raw}(E)$



- Experimental data used for analysis:

  HAWC-300

  Δt_{eff} = 3.24 years (94% livetime)

  (June/11/15-Nov/28/18)

  $\Delta\Omega$ = 0.27 sr

Total events	: 3 x 10^{12} EAS
+ selection cuts:	5.8 x 10^{9} EAS
+ age cut:	3.8 x 10^{9} EAS

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

$$N^{Raw}(E^R_j) = \sum_i P(E_j \mid E^T_i)\, N^{Unf}(E^T_i)$$

- Solve for $N^{Unf}(E^T_i)$ using Bayesian unfolding

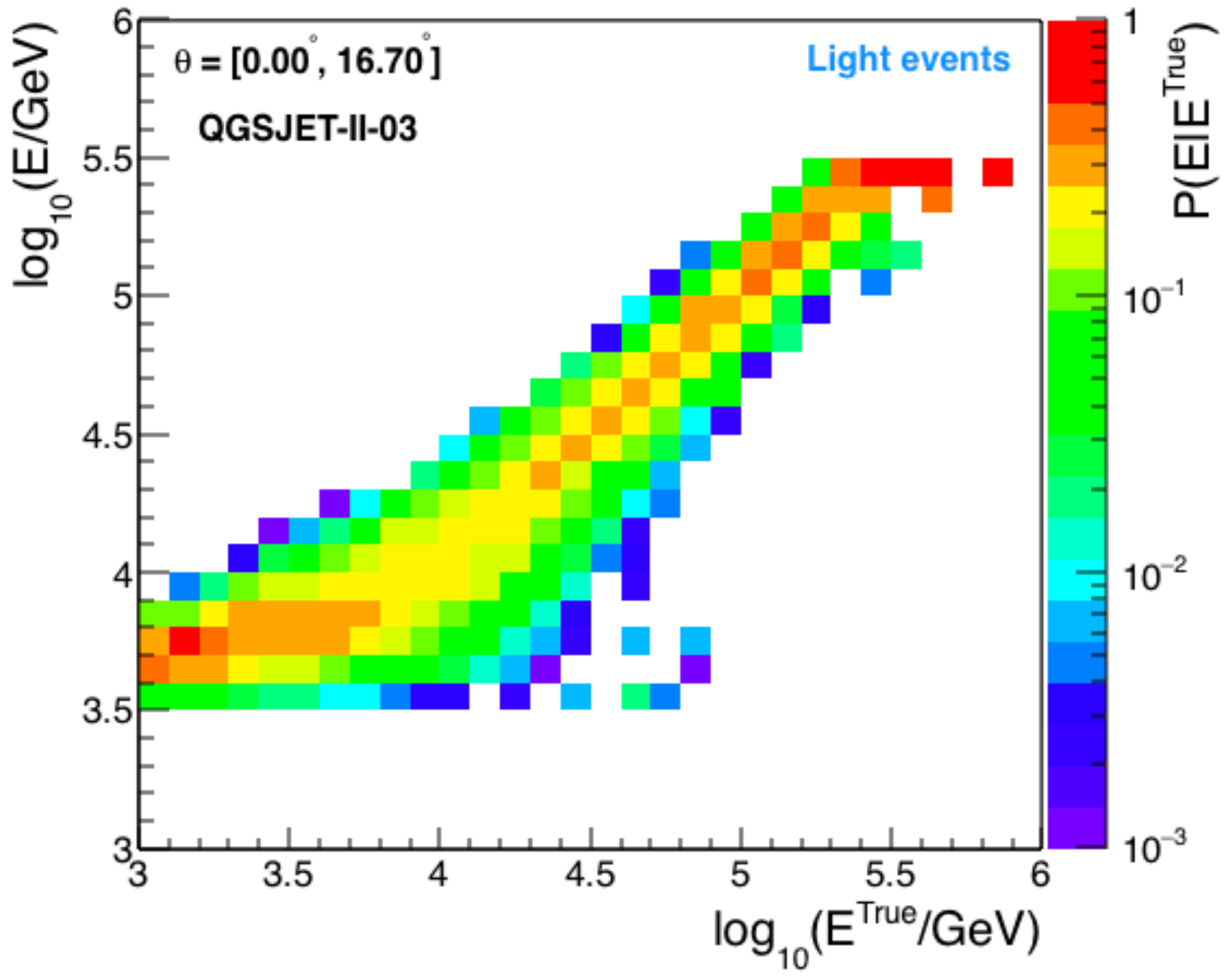
  [G. D' Agostini, DESY 94-099]

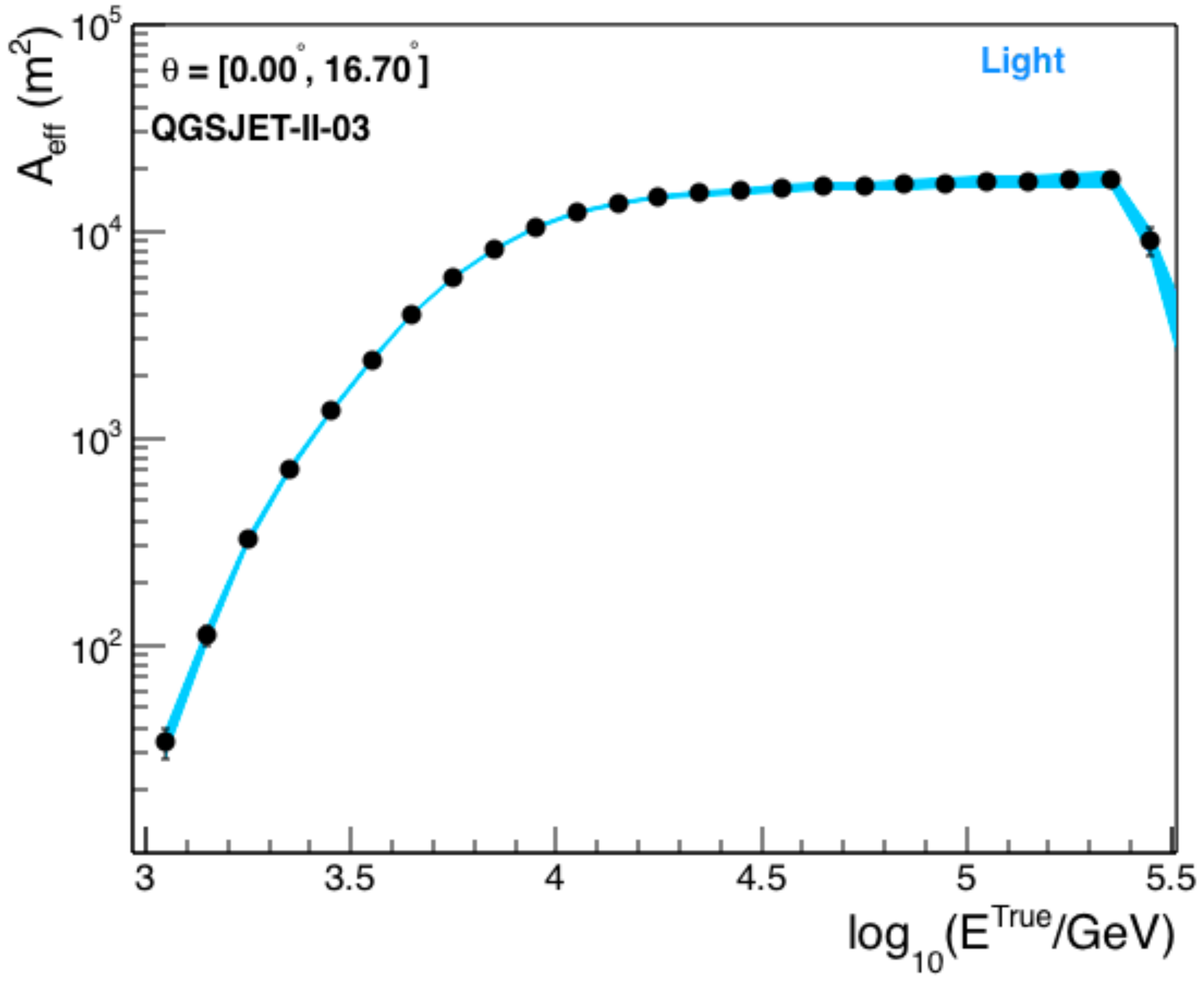
- Stopping criterium: Minimum of weighted mean squared error

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

[G. Cowan, Stat. Data analysis, Oxford Press. 1998]

Obtain response matrix and effective area from MC simulations





- $P(E_j \mid E^T_i)$: response matrix from MC
  - Linear response E > 10 TeV for MC

- Estimate corrected effective area

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

- Correction factor due to contamination of heavy events:

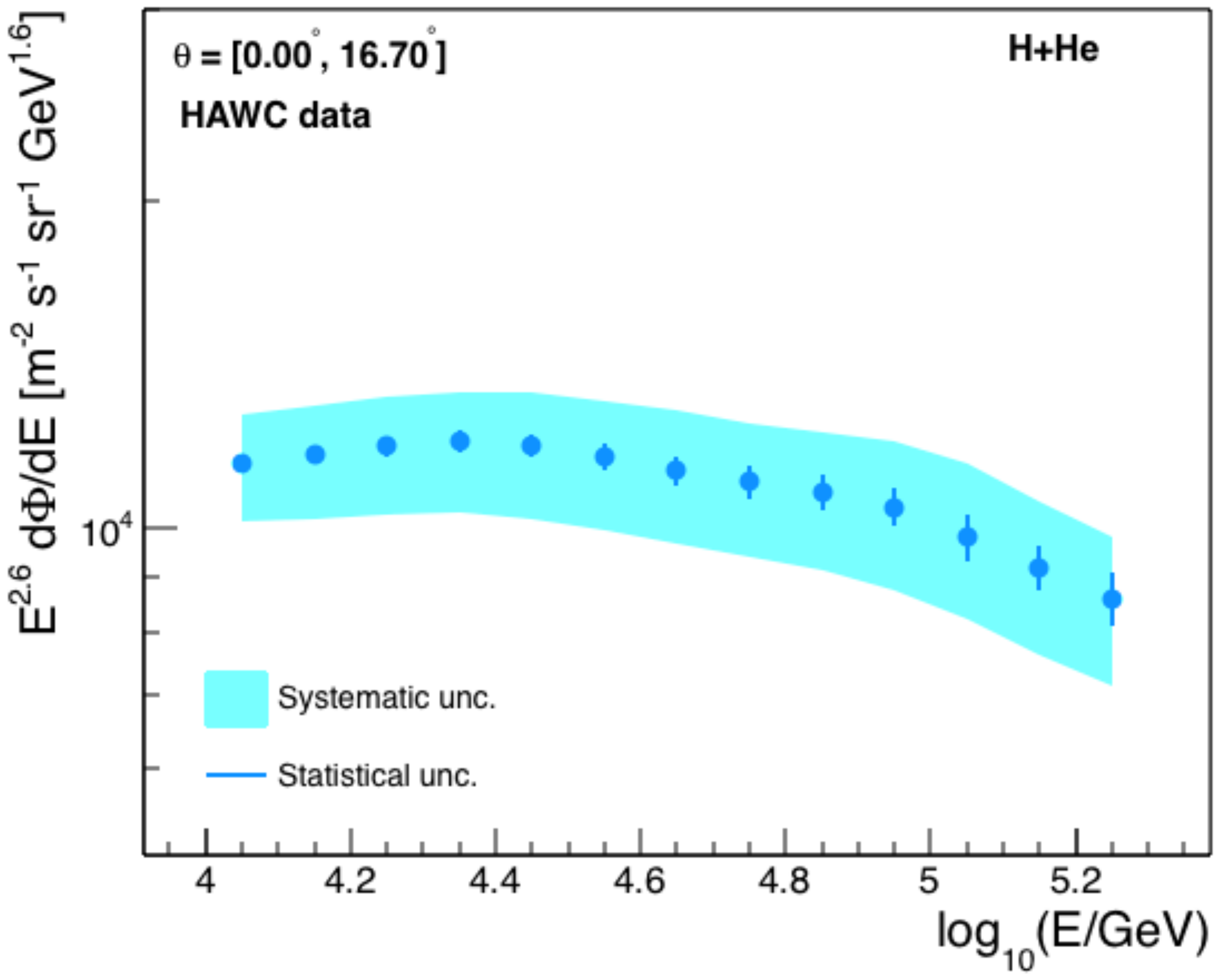
$$f_{corr} = (N_{light} / N_{light}^{H+He})$$

- Effective area of H+He in sub-sample:

$$A_{eff}^{H+He}(E^T_i) = A_{thrown} \frac{\cos\theta_{max} + \cos\theta_{min}}{2} \varepsilon^{H+He}(E^T_i)$$

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

H+He



- Energy spectrum was calculated as:

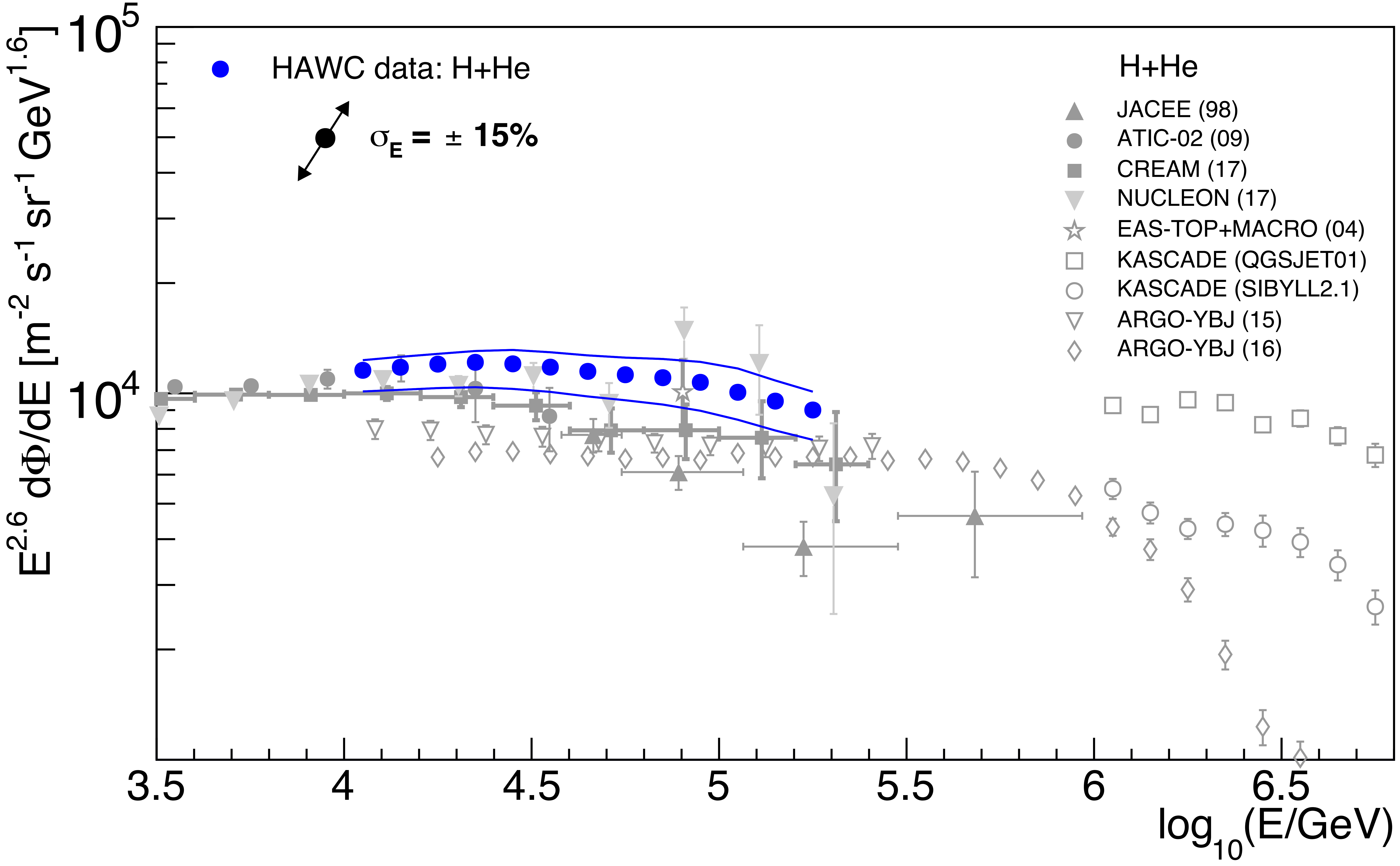
$$\Phi = N^{Unf}(E^T)/(\Delta t_{eff} \cdot \Delta \Omega \cdot A_{eff}(E^T) \cdot \Delta E^T)$$

log_{10}(E/GeV) = 4.95

	Relative error Φ (%)
Statistical	**+/- 4.0**
Exp. Data	+/- 0.02
Response matrix	+/- 4.0
Systematic	**+14.8/-16.1**
Composition	-14.7
Aeff	+7.8/- 5.8
Cut at He or C	+1.7/-3.0
Gold unfolding	-0.4
Seed unfolding	+0.10/-0.08
Smoothing unfold.	+1.4/-0.52
Bin size	-0.4
PMT Qeff	+12.0
PMT Qres	+2.8
Total	**+15.3 /-16.6**

Unfolded HAWC spectrum

H+He



Fit of spectrum

H+He

1. Use following functions:

—> Single power law:

$$d\Phi(E)/dE = \Phi_0 E^{\gamma 1}$$

—> Double power law:

$$d\Phi(E)/dE = \Phi_0 E^{\gamma 1}[1 + (E/E_0)^{\varepsilon}]^{(\gamma 2 - \gamma 1)/\varepsilon}$$

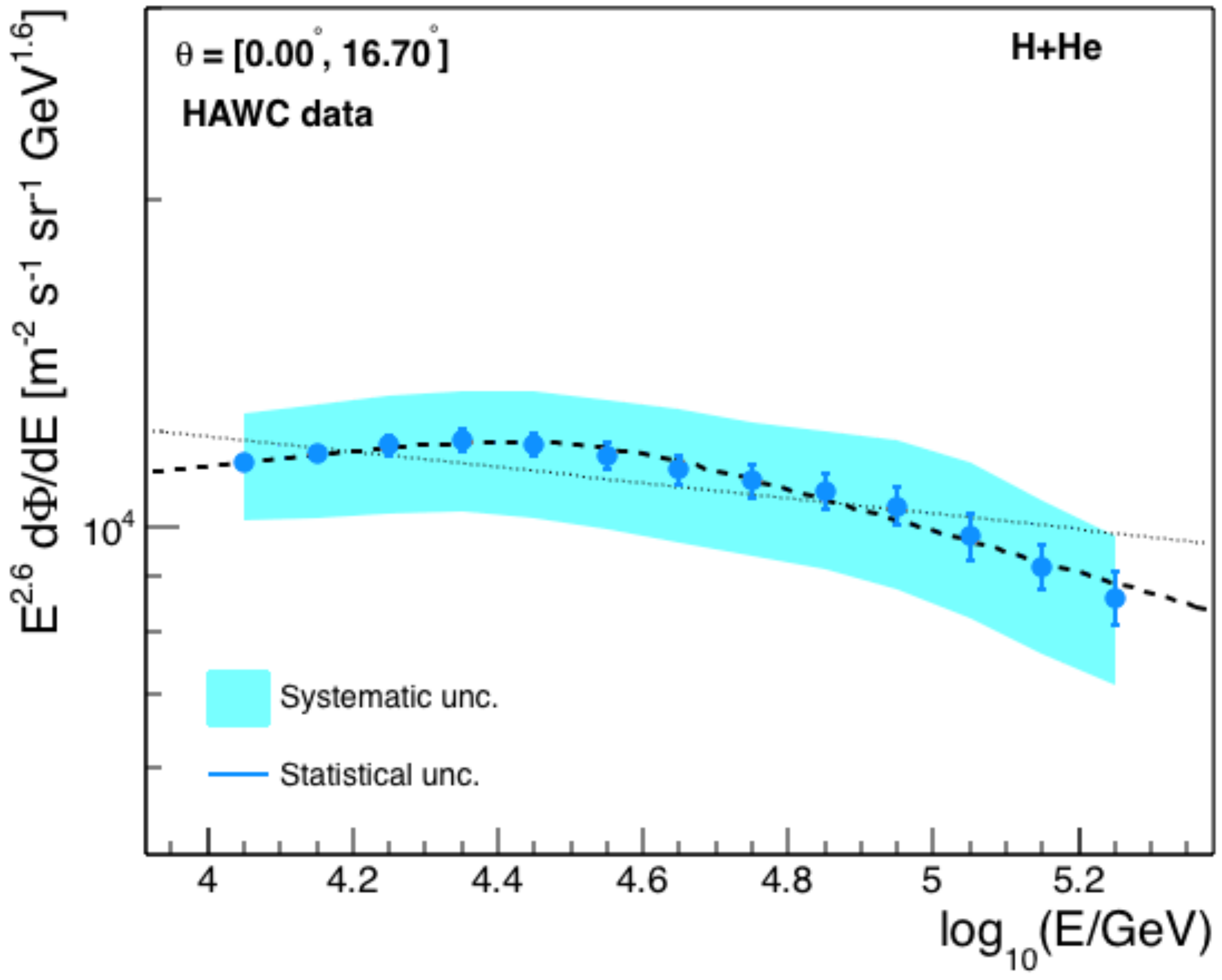
2. Minimize χ^2 with MINUIT and take into account correlation between points:

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

PDG (2017)

Fit of spectrum

H+He



- **Test Statistics:**
  $\Delta\chi^2/\Delta ndof = 9.86$

  p-value ≤ 1.25 x 10^{-4}

-> 3.67σ deviation from scenario with single power-law: unlikely that data is described by a single power-law.

- Results for the double power-law fit:

γ_1 = -2.53 ± 0.05

γ_2 = -2.79 ± 0.04

$\Delta\gamma$ = -0.26 ± 0.07

$log_{10}(E_0/GeV)$ = 4.50 ± 0.16

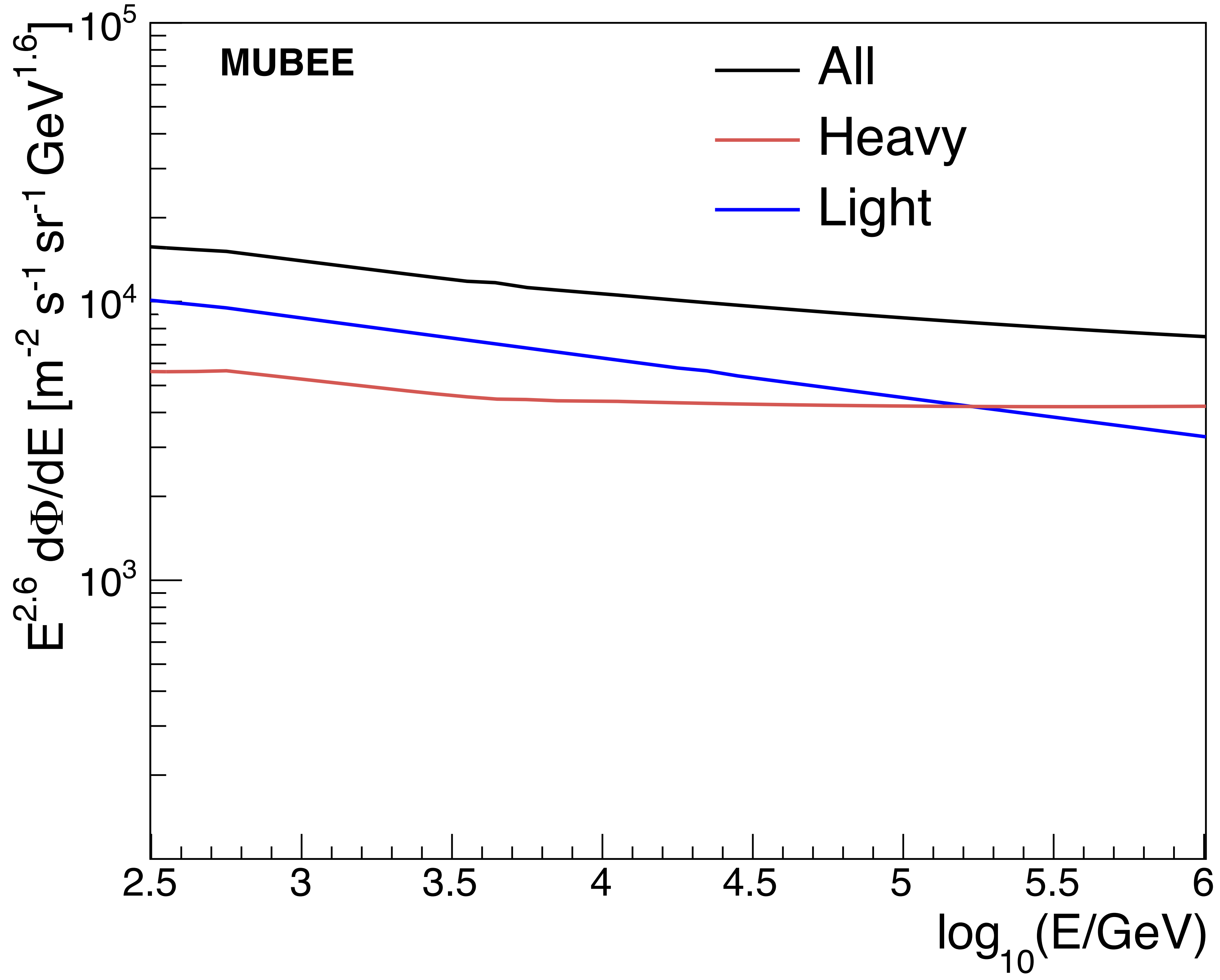
7) Summary

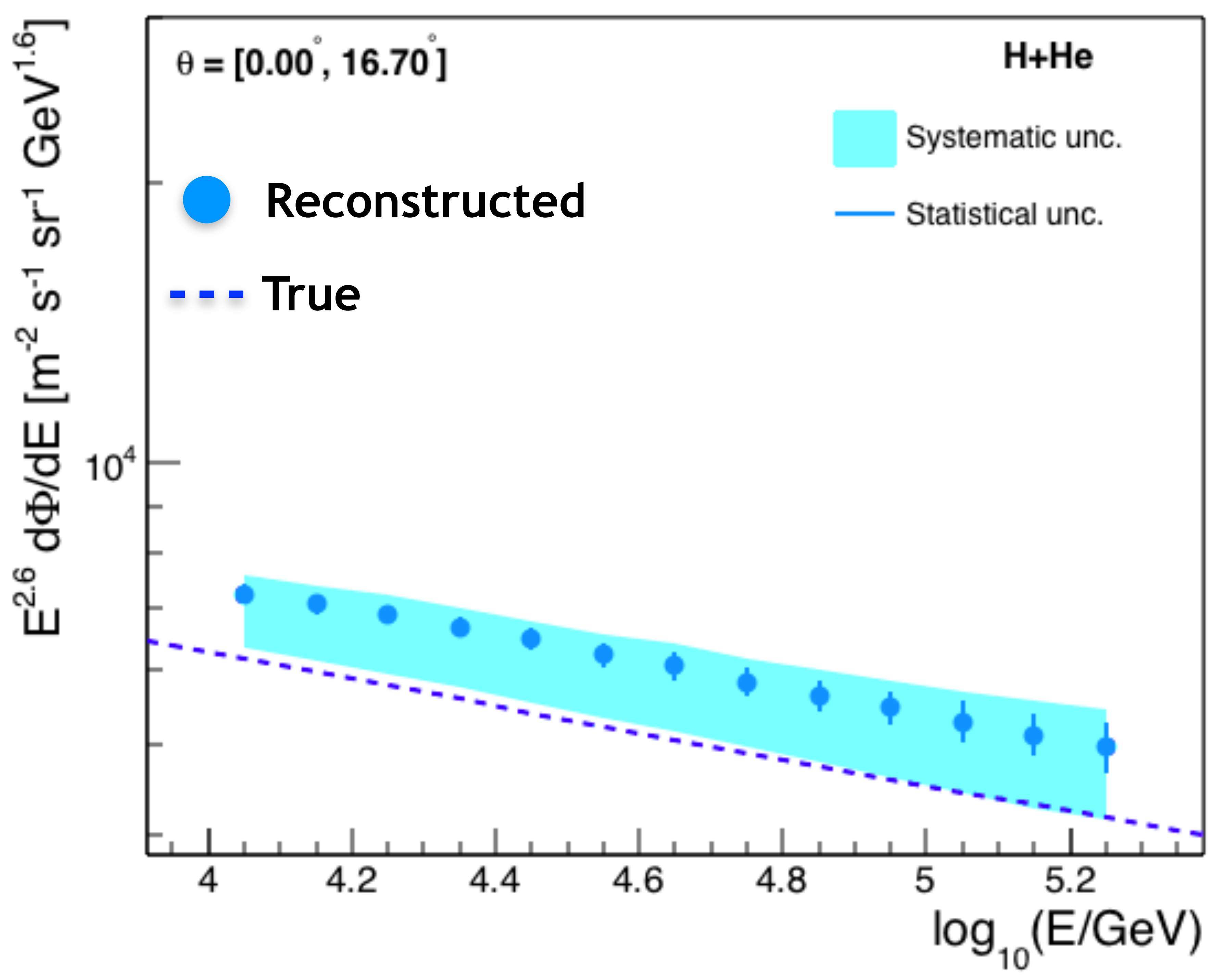
- The lateral age parameter is sensitive to the composition of cosmic rays at HAWC.
- A first analysis of cosmic ray composition with HAWC has allowed to reconstruct the spectrum of the light component (H+He) of cosmic rays in the range E = [10 TeV, 200 TeV].
- The light spectrum of cosmic rays is in agreement with data from NUCLEON and EAS-TOP, but above estimations from ATIC-2, CREAM-II/-III, JACEE and ARGO-YBJ.
- Cosmic ray spectrum of H+He mass group is not described by a single power-law.

Thank you

Backup slides

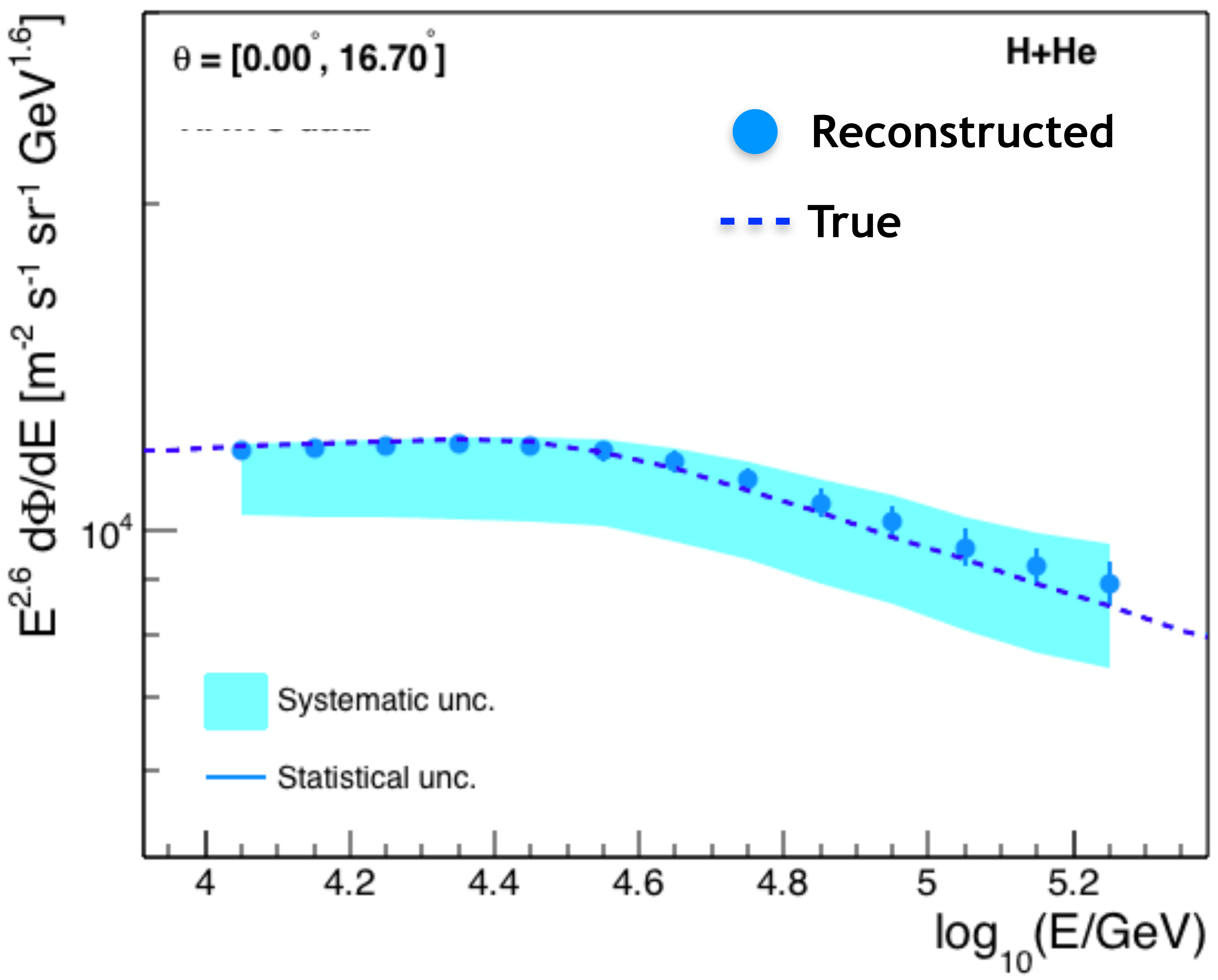
Check performance of method with MC simulations: Reconstruct model with lower light/heavy ratio





When the **abundance of the heavy component** is **above that of the nominal** model used to reconstruct the data, then the **light component of CR's is overestimated, but the shape of the spectrum is preserved.**

Check performance of method with MC simulations: presence of a kink



Reconstruct nominal model but **with a kink** in the light component of CR's at

$\log_{10}(E_0/\mathrm{GeV}) \sim 4.5$

The kink is reconstructed

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