# Investigation of the Proton plus Helium cosmic ray spectrum in the 10 TeV - 126 TeV energy region with HAWC

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## Content

## Cosmic rays

- One of the most energetic and enigmatic form of radiation from outer space

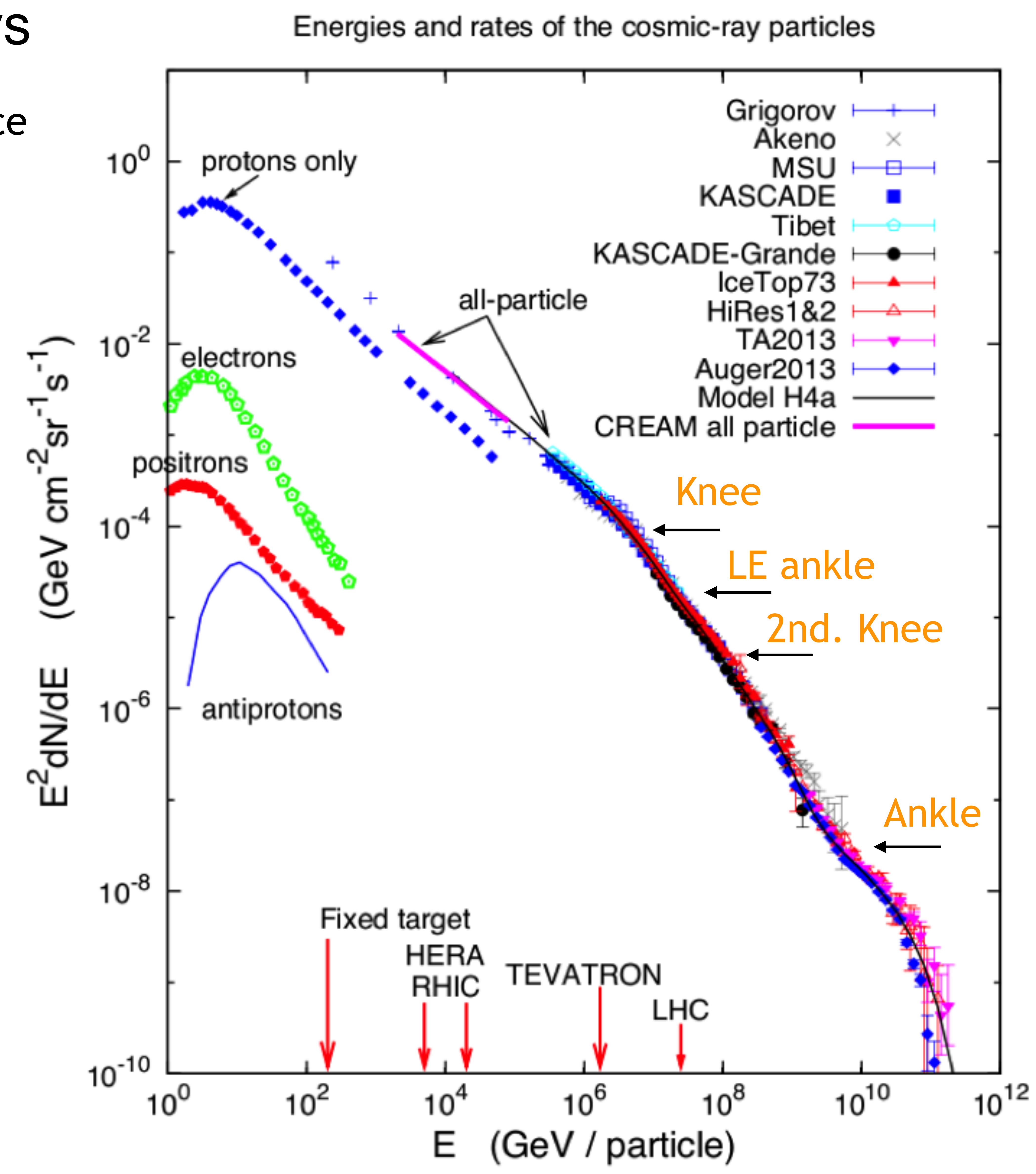
- **Composed** by atomic nuclei:
  - Atomic nuclei (99 %) :
    H (85%), He (3%), Z ≥3 (3%)
  - Electrons (1 %)
  - Traces of antiparticles

- **Energy** ranges from 100 MeV to $10^{20}$ eV and spectrum follows roughly a power law $F(E) = E^{-\gamma}$.

- **Origin** in cataclysmic galactic (E < $10^{17}$ eV) and extragalactic (E > $10^{17}$ - $10^{18}$ eV) events.

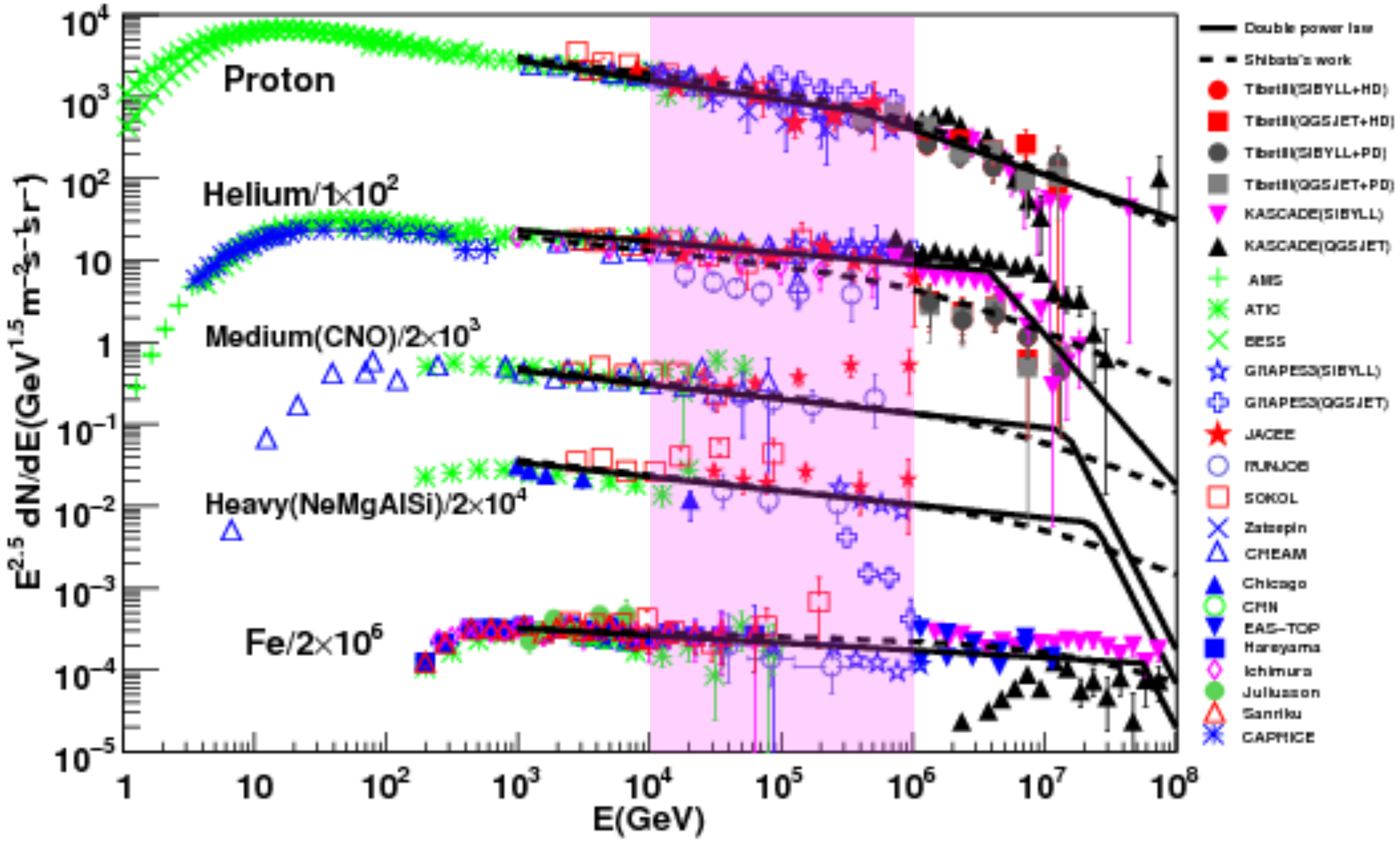
- **Unknown** questions:
  - Origin of the features of spectrum
  - Sources.
  - Propagation.
  - Acceleration mechanism.

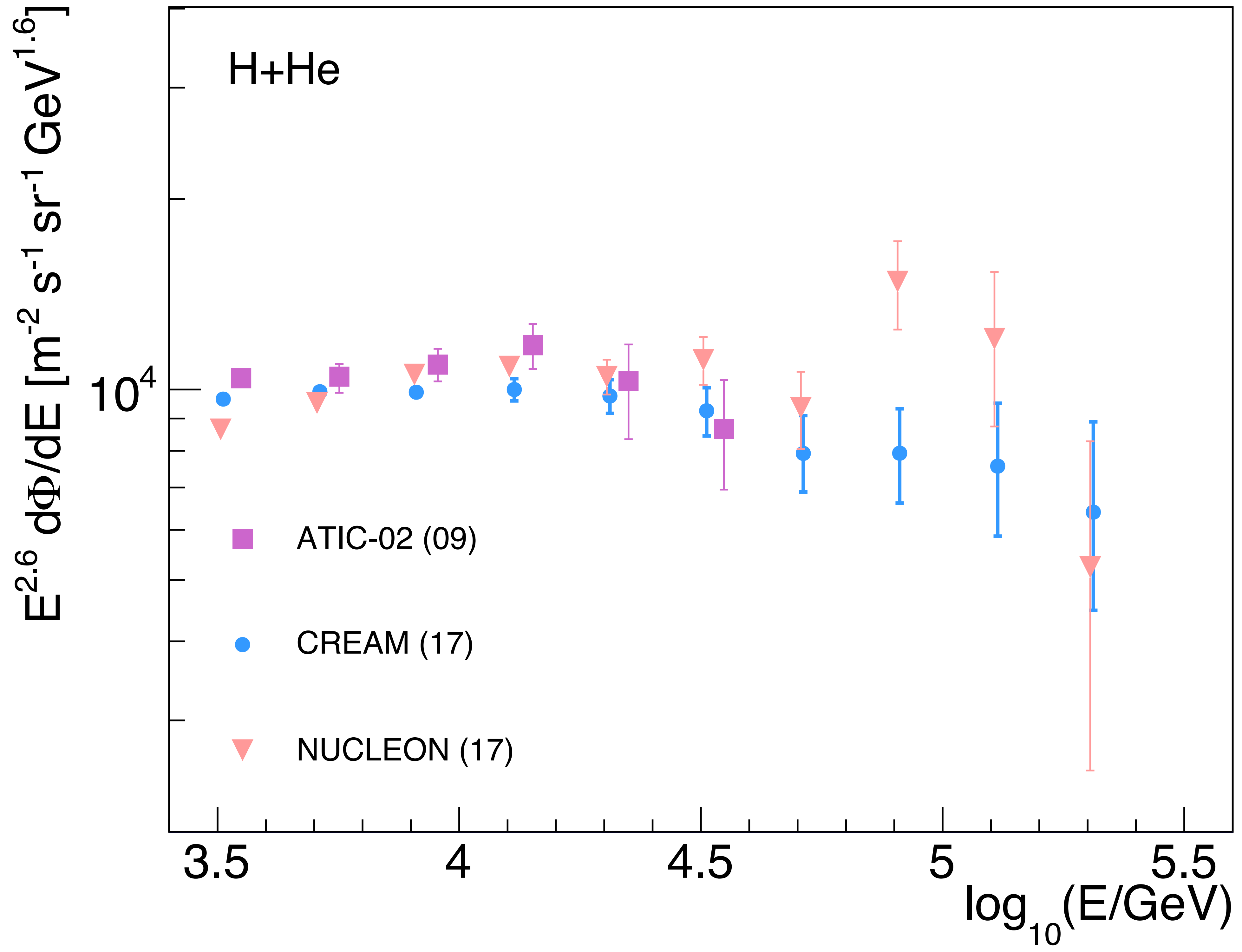
Data:
- Spectrum.
- Composition.
- Arrival times.
- Multimessenger / multiwavelength.



Research of the cosmic ray composition of cosmic rays for **E = 10 TeV - 1 PeV**

H. Hu, arXiv:0911.3034 **[astro-ph.HE]**

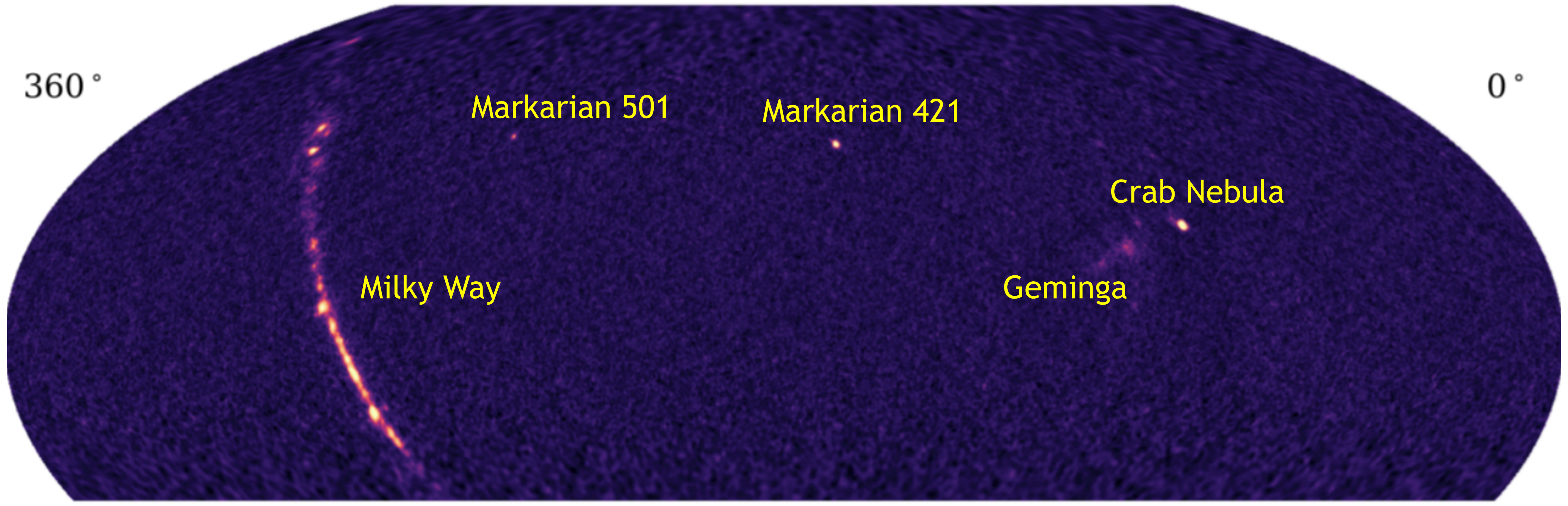



- Region at the limit between direct/indirect detection
- Barely studied
- Detailed exploration has just started

Early measurements with ATIC-02, CREAM-II/III and NUCLEON have hinted the existence of a break in spectrum of H+He nuclei @ O(10 TeV).

# 2) The HAWC γ-ray observatory




HAWC Collab., Astrophys. J. 905 (2020) 76.

**γ- and cosmic-ray detector:**

- Air-shower observatory
- Ground-based Cherenkov array

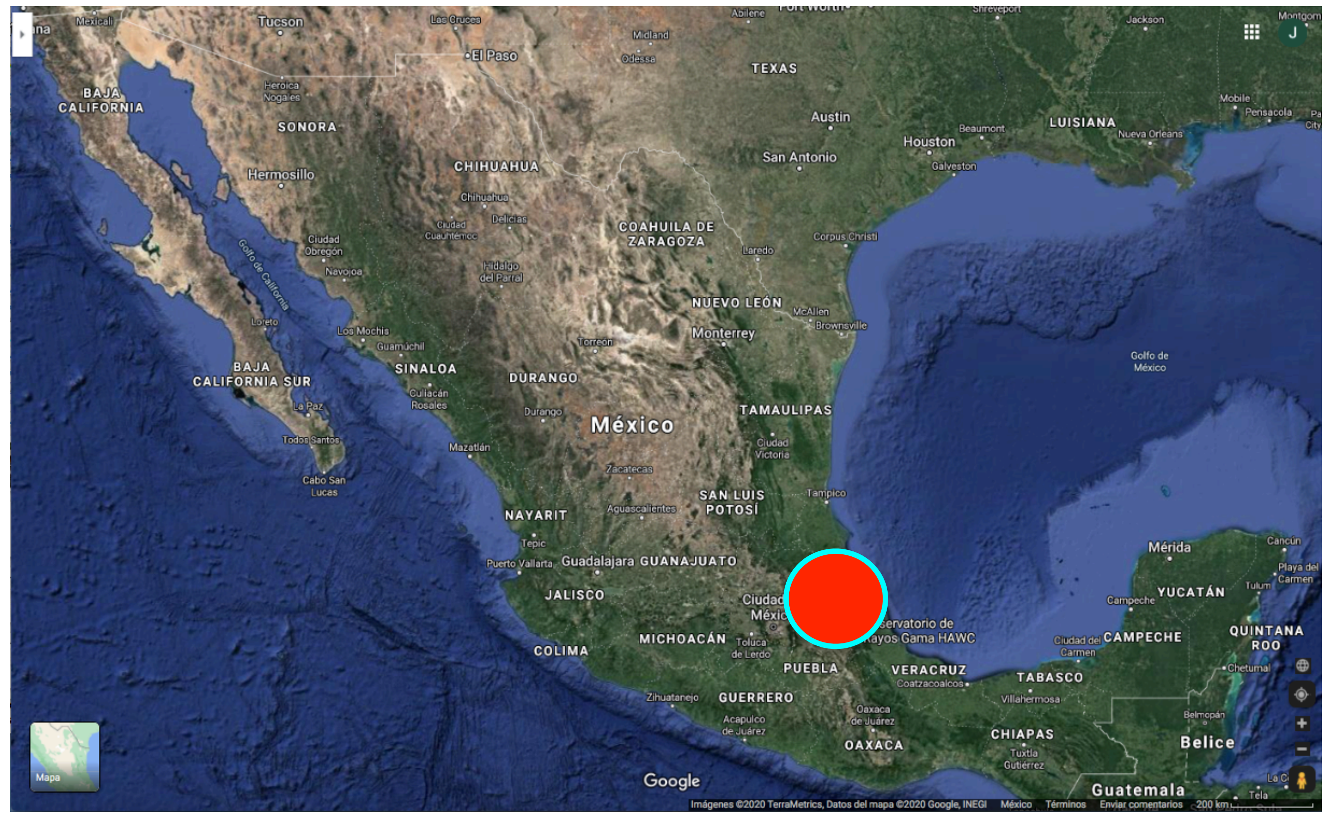
  E = 100 GeV - 100 TeV

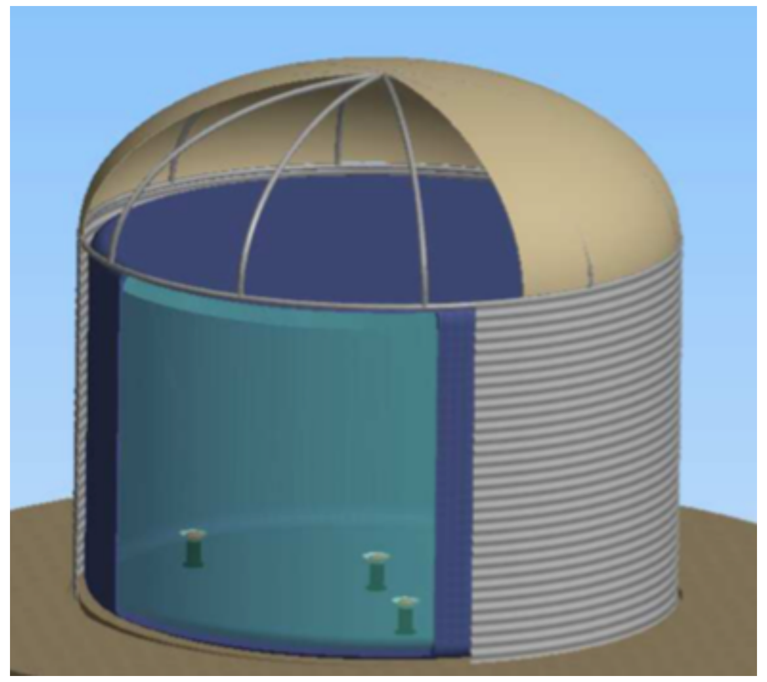
**Set-up of central detector:**

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

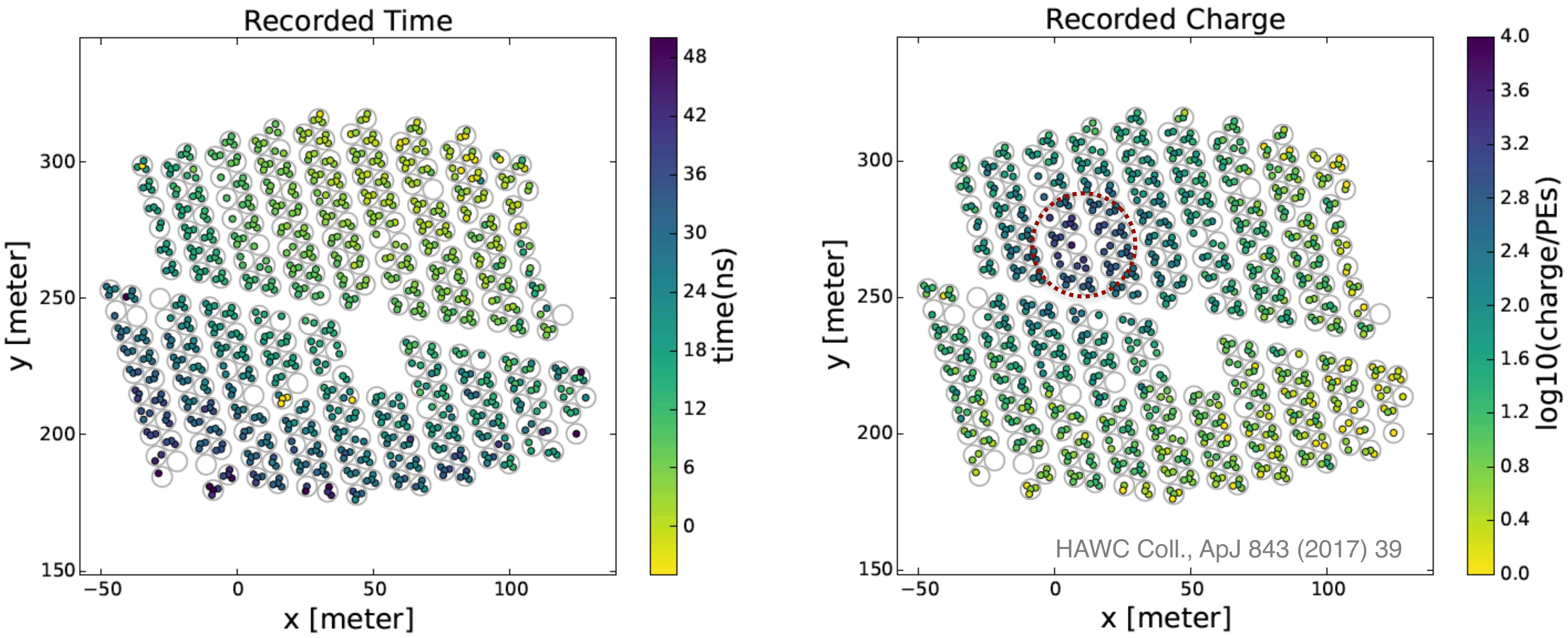
**Location:**

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



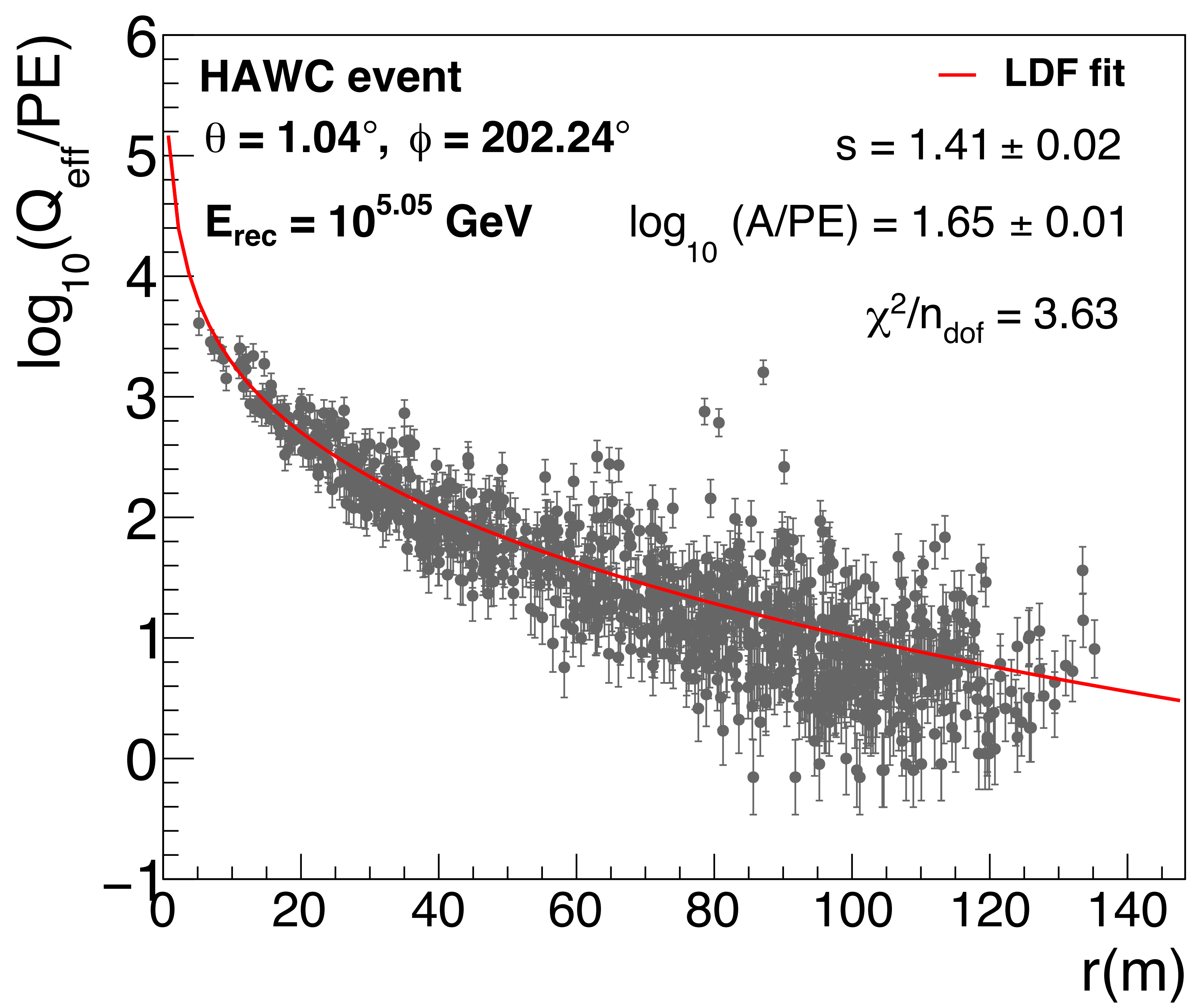



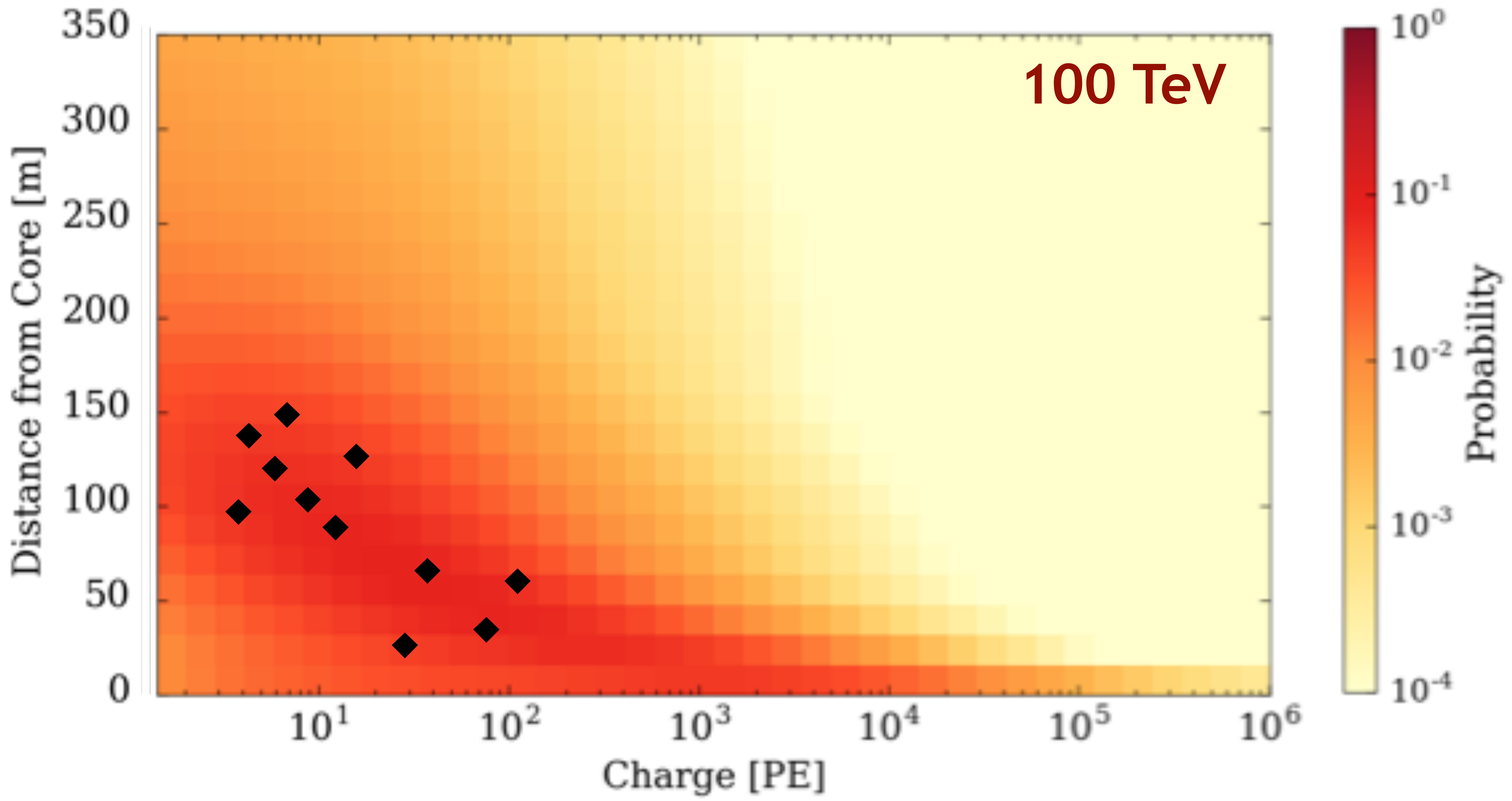
# 2) The HAWC γ-ray observatory




- 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)
  - ...

# 3) EAS age and energy estimations




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

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

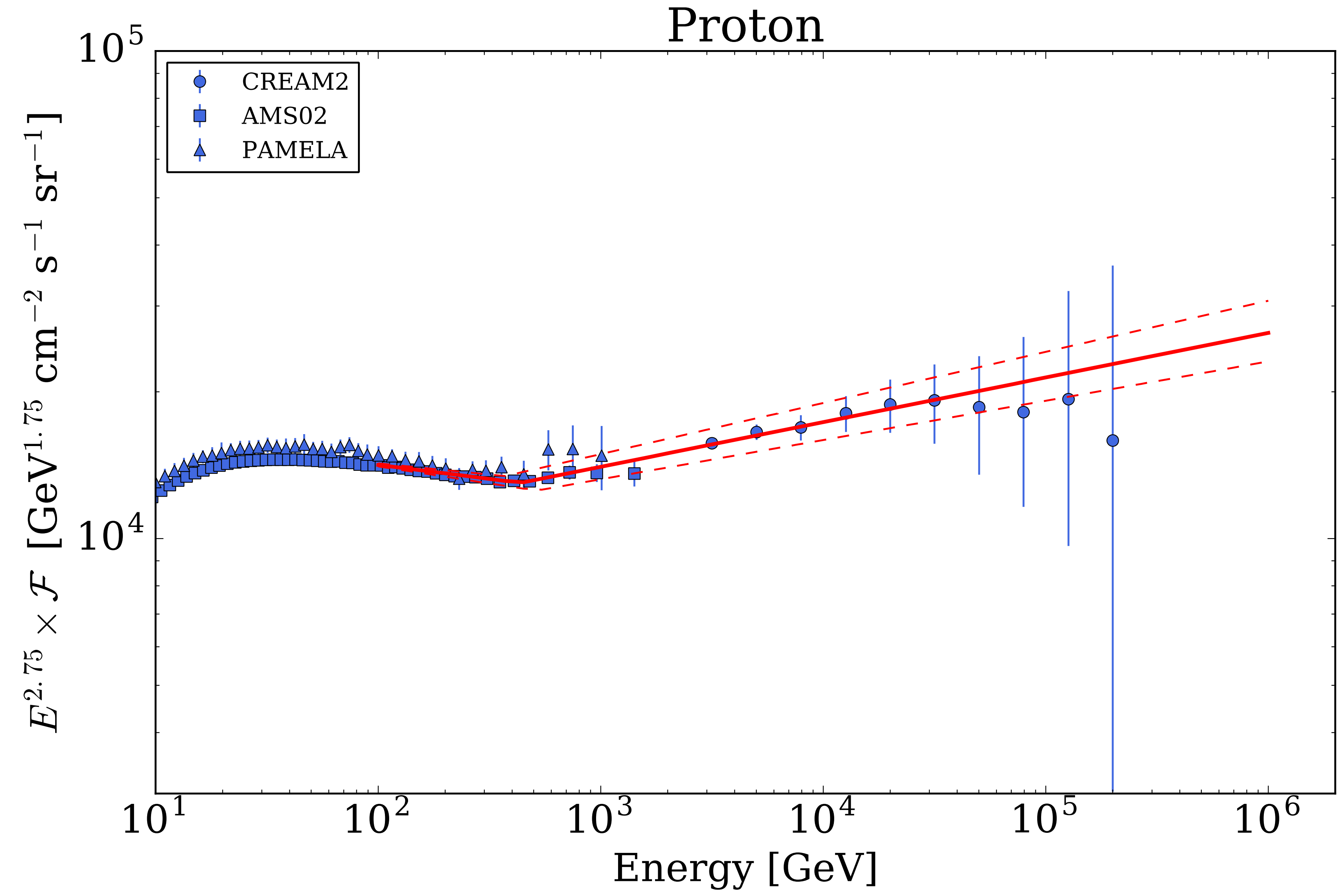
with $r_0$ = 124.21 m.
*A*, ***s*** are free parameters

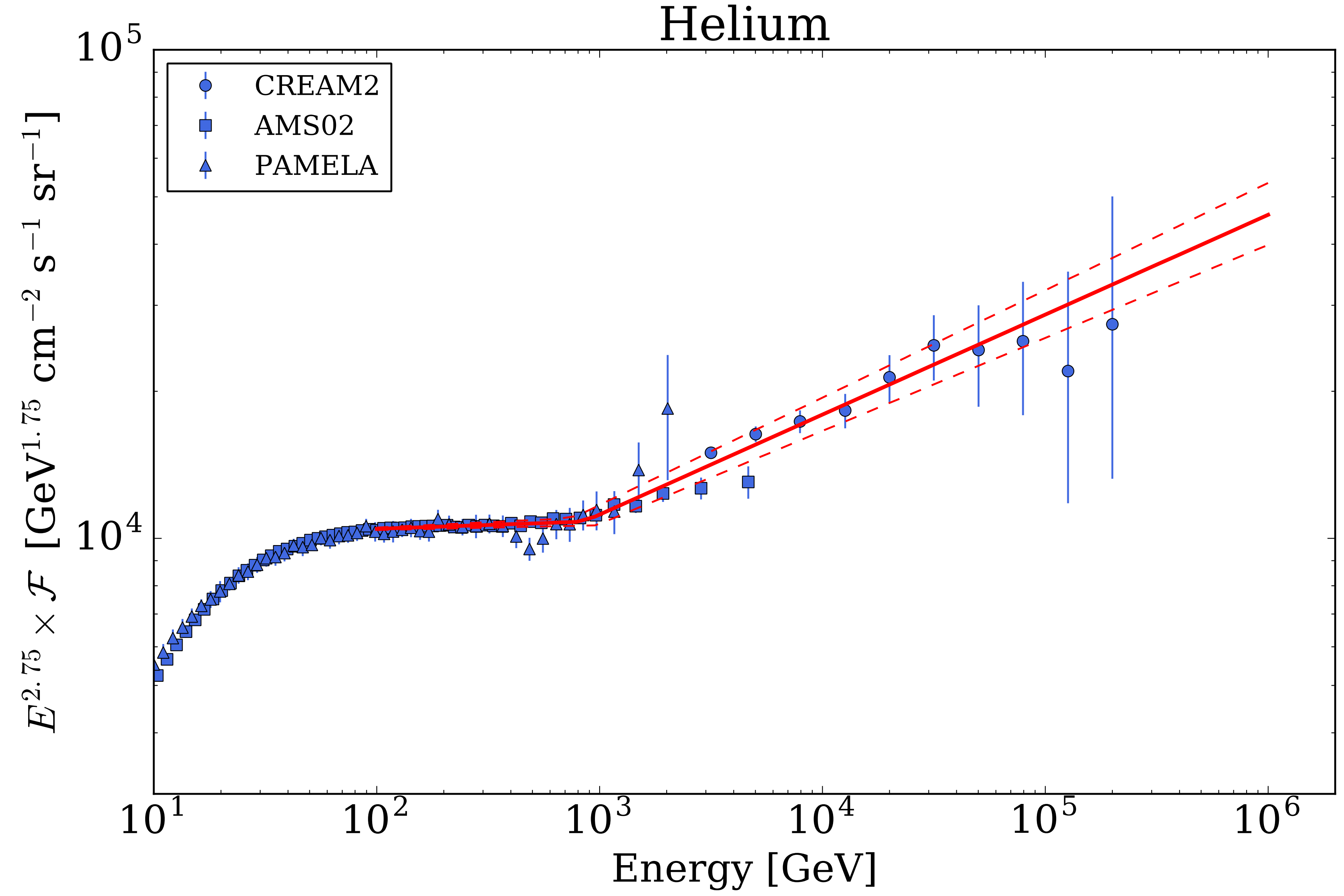
[HAWC Collab., APJ 881 (2017); J.A. Morales Soto et al., PoS(ICRC2019 359 (2019)]

- **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.

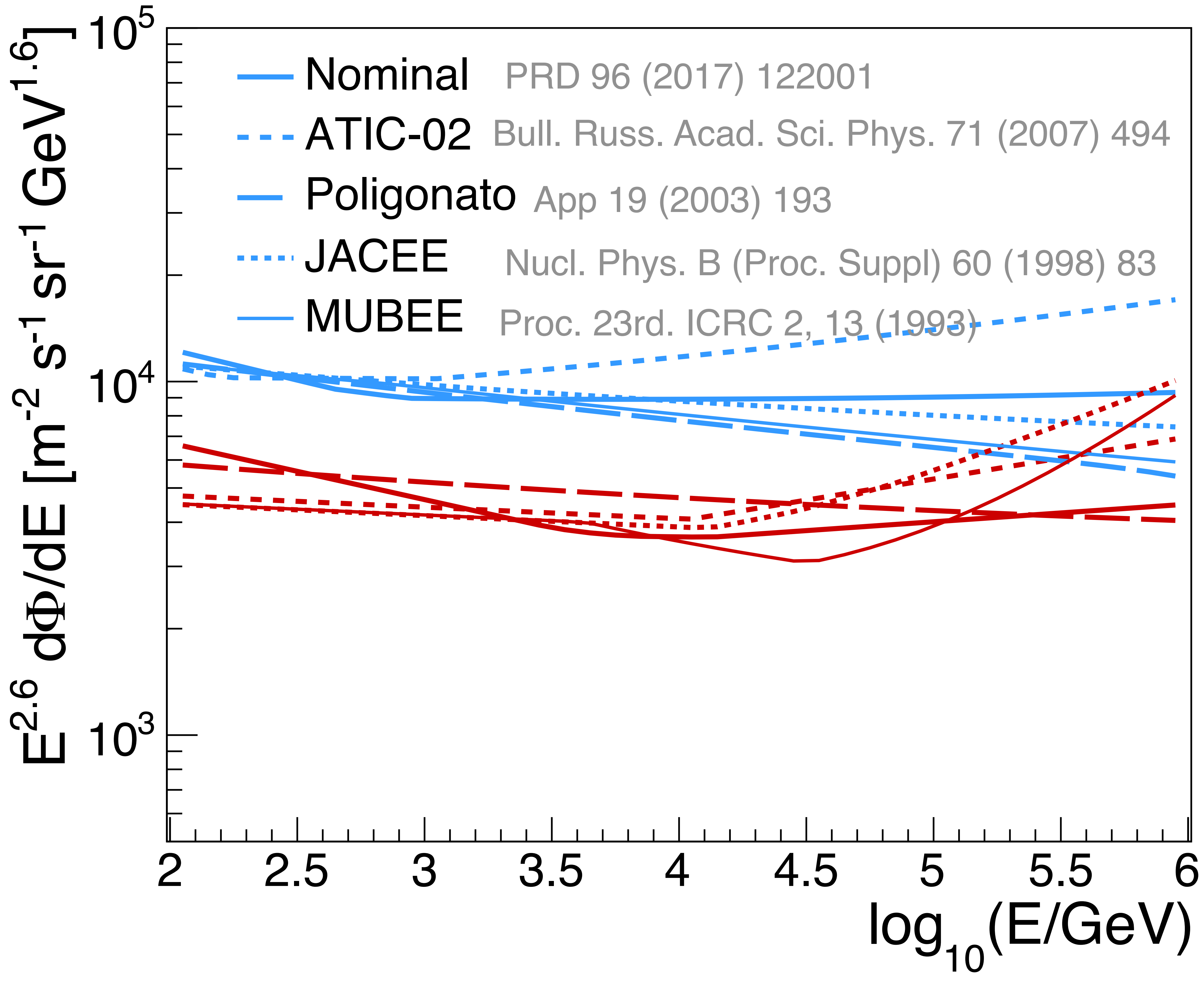
[HAWC Collab., PRD 96 (2017); Z. Hampel-Arias' PhD thesis, 2017]

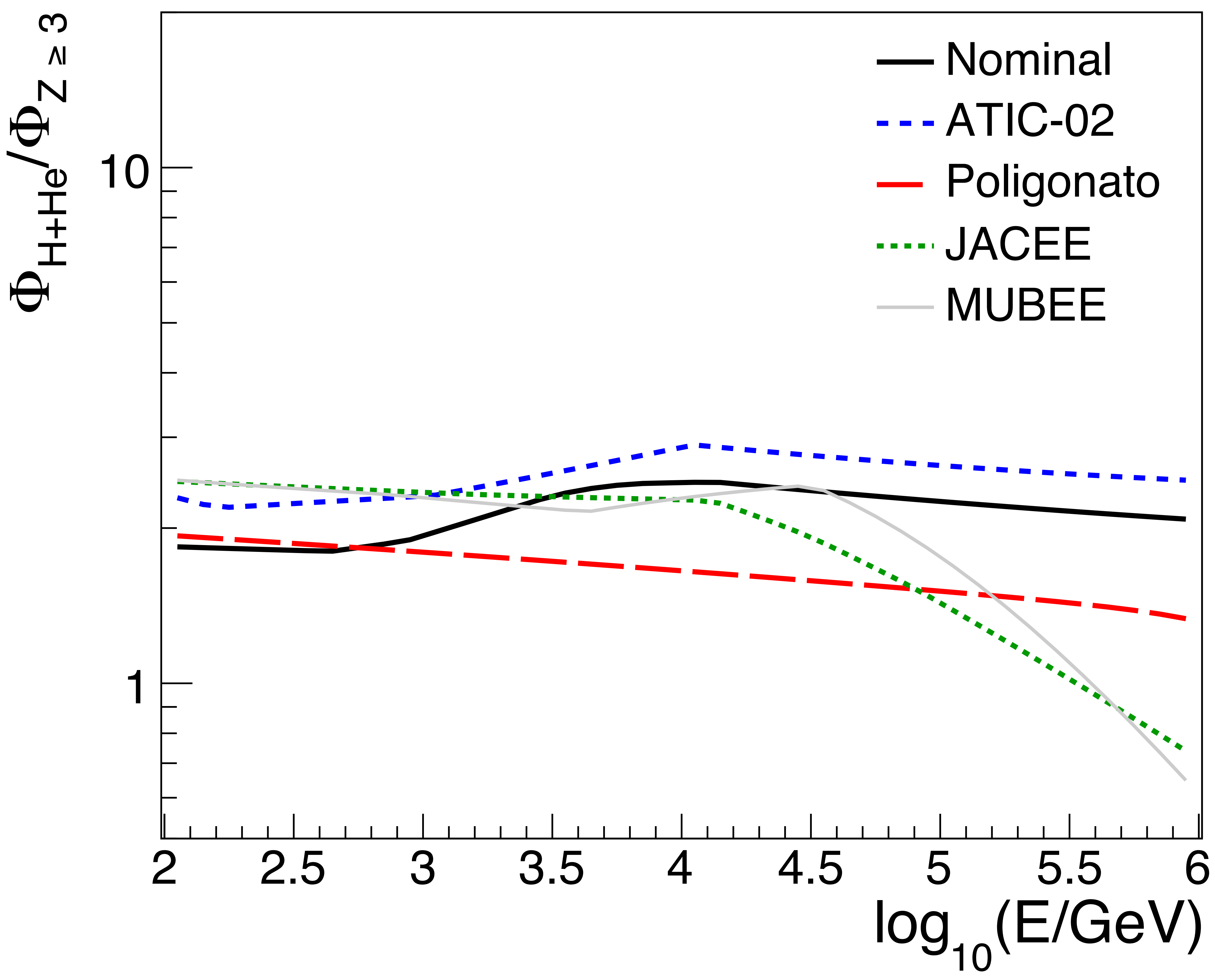
- CORSIKA v 7.40 for EAS simulation.
- Fluka/QGSJET-II-04 as low/high-energy hadronic interaction models for the main analysis.
- Fluka/EPOS-LHC simulations to study effect of high energy hadronic interaction model.
- Full simulation of detector response with GEANT 4.
- $\theta < 70^o$; $A_{thrown} \sim 3 \times 10^6$ 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

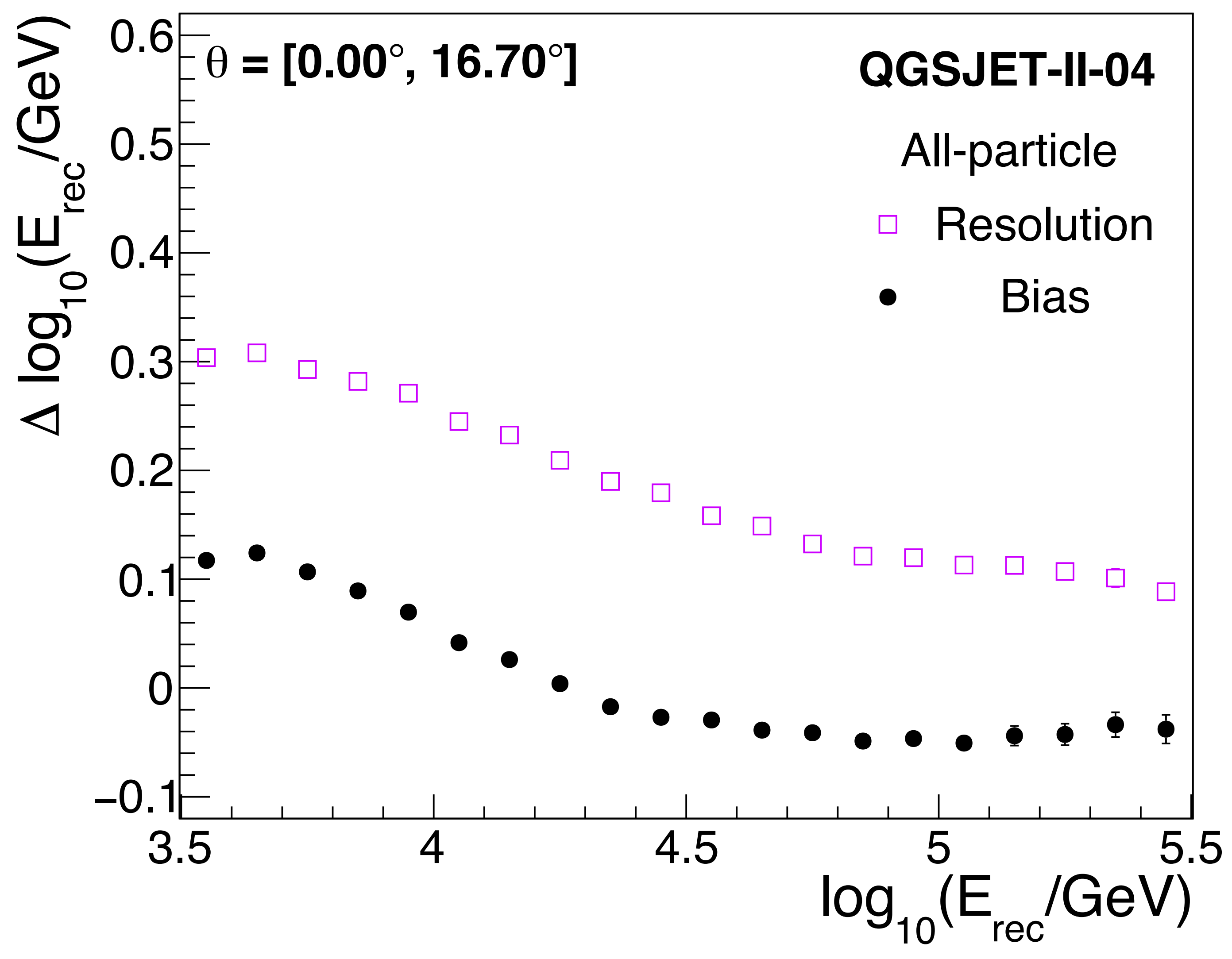
## Selection cuts

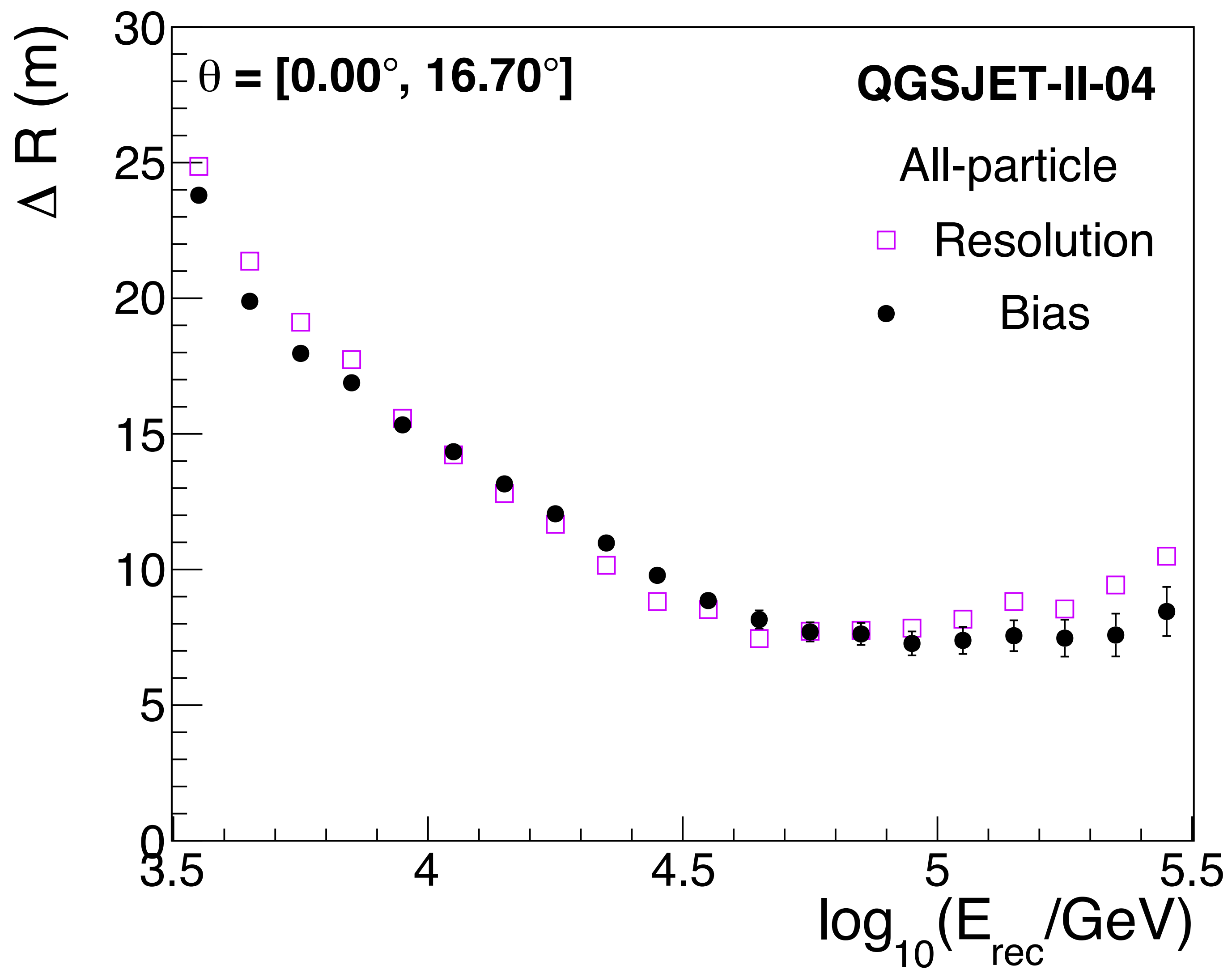
- Important to reduce systematic effects on results:
  - $\theta < 16.7^\circ$
  - Successful core and arrival direction reconstruction
  - Activate at least 40 PMTs within 40 m from core
  - Mainly on-array EAS cores
  - Multiplicity threshold $N_{hit} \geq 75$ PMTs
  - Fraction hit (# of hit PMT's/# available channels) ≥ 0.2
  - $\log_{10}(E/GeV)$ = [ 3.5, 5.5]

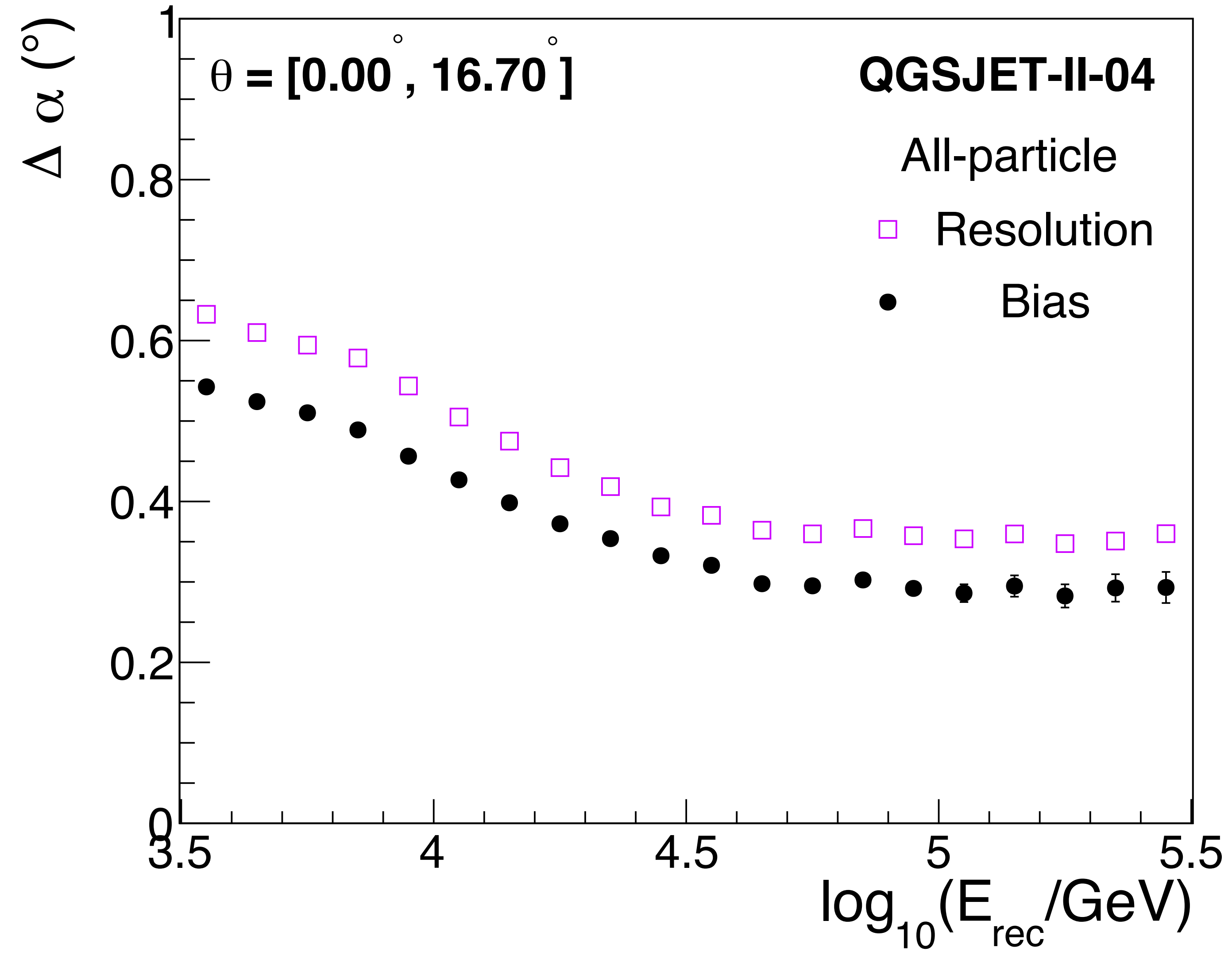
- Bias:

**E ≥ 10 TeV:**

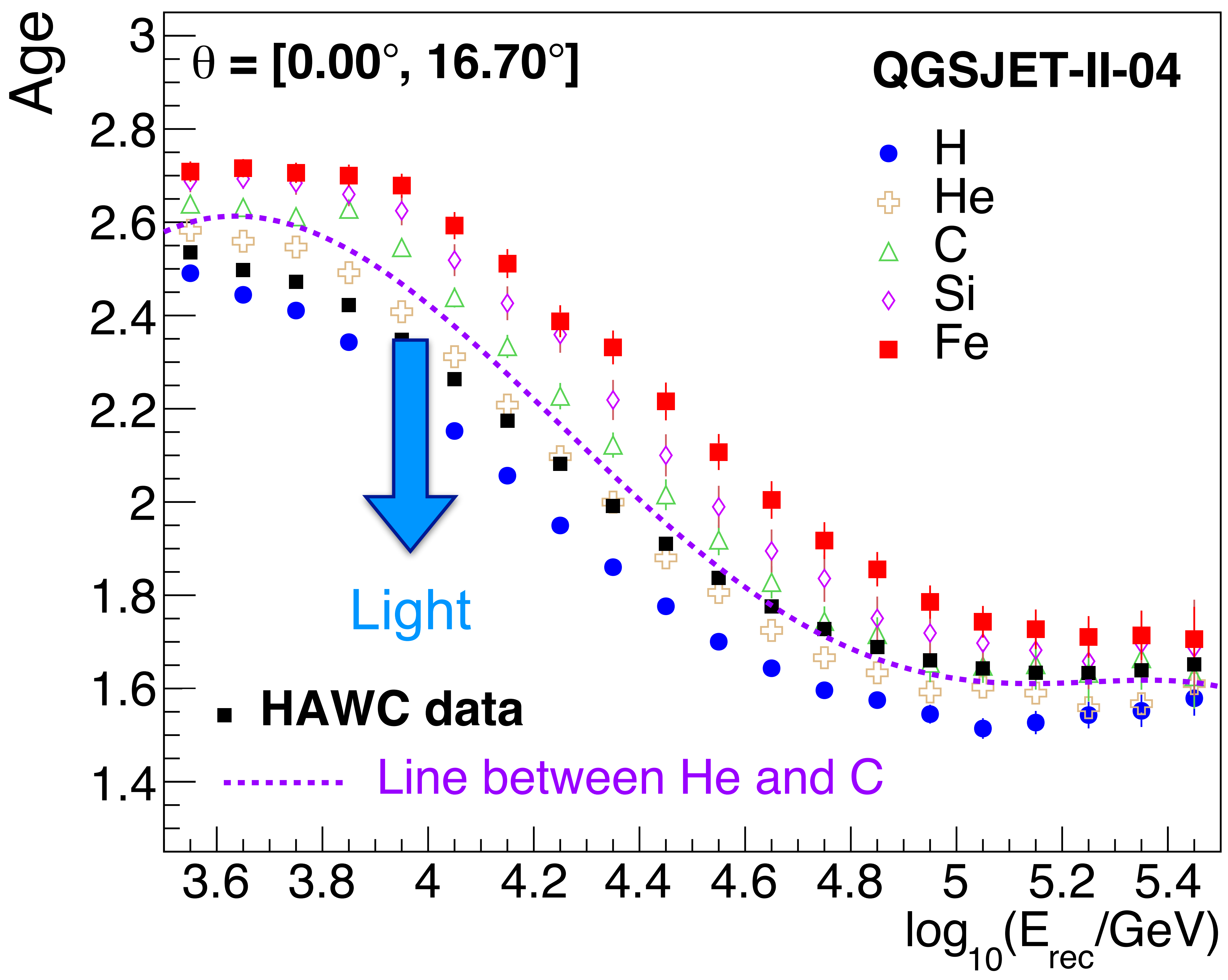
| | |
|---|---|
| $\Delta core_{res}$ | ≤ 15 m |
| $\lvert\Delta \log_{10}(E/GeV)\rvert$ | ≤ 0.06 |
| $\Delta\alpha$ | ≤ 0.45° |

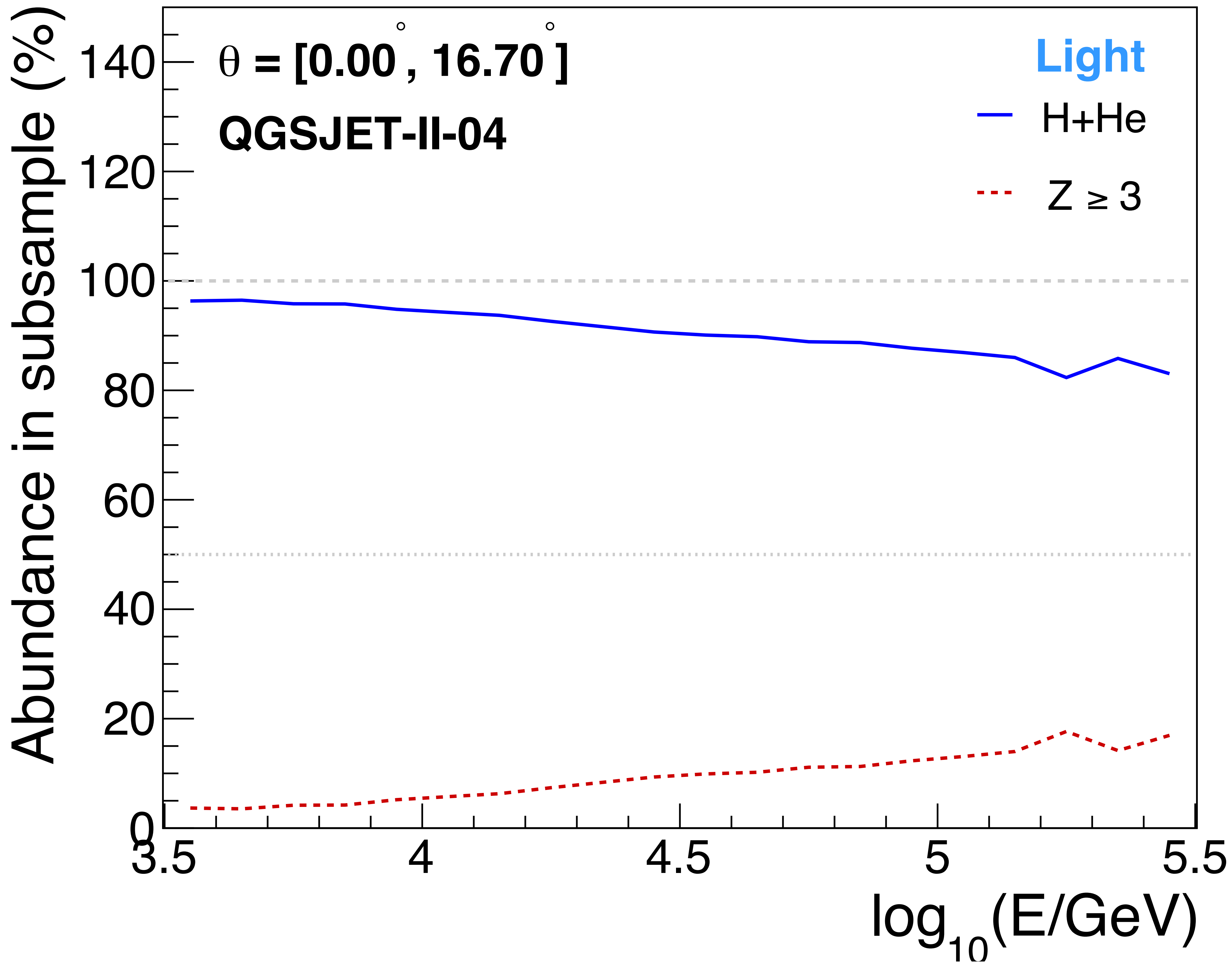


**Select a sample enriched with light nuclei**

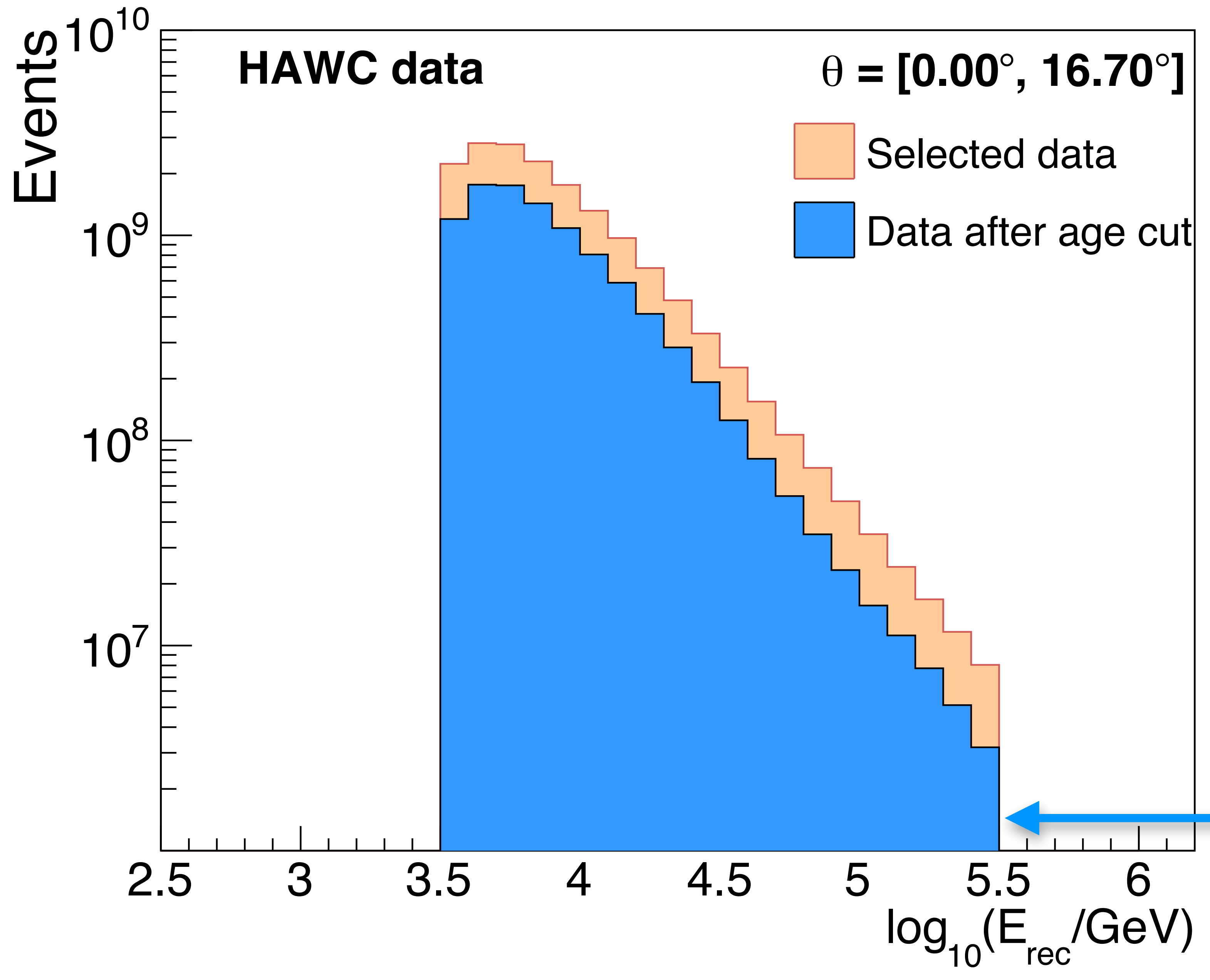



- Age parameter is sensitive to composition
- Select a subsample using a cut on the age
  - Subsample must be rich in H and He nuclei

- Content of H + He in subsample
  - More than 82% of H and He in subsample

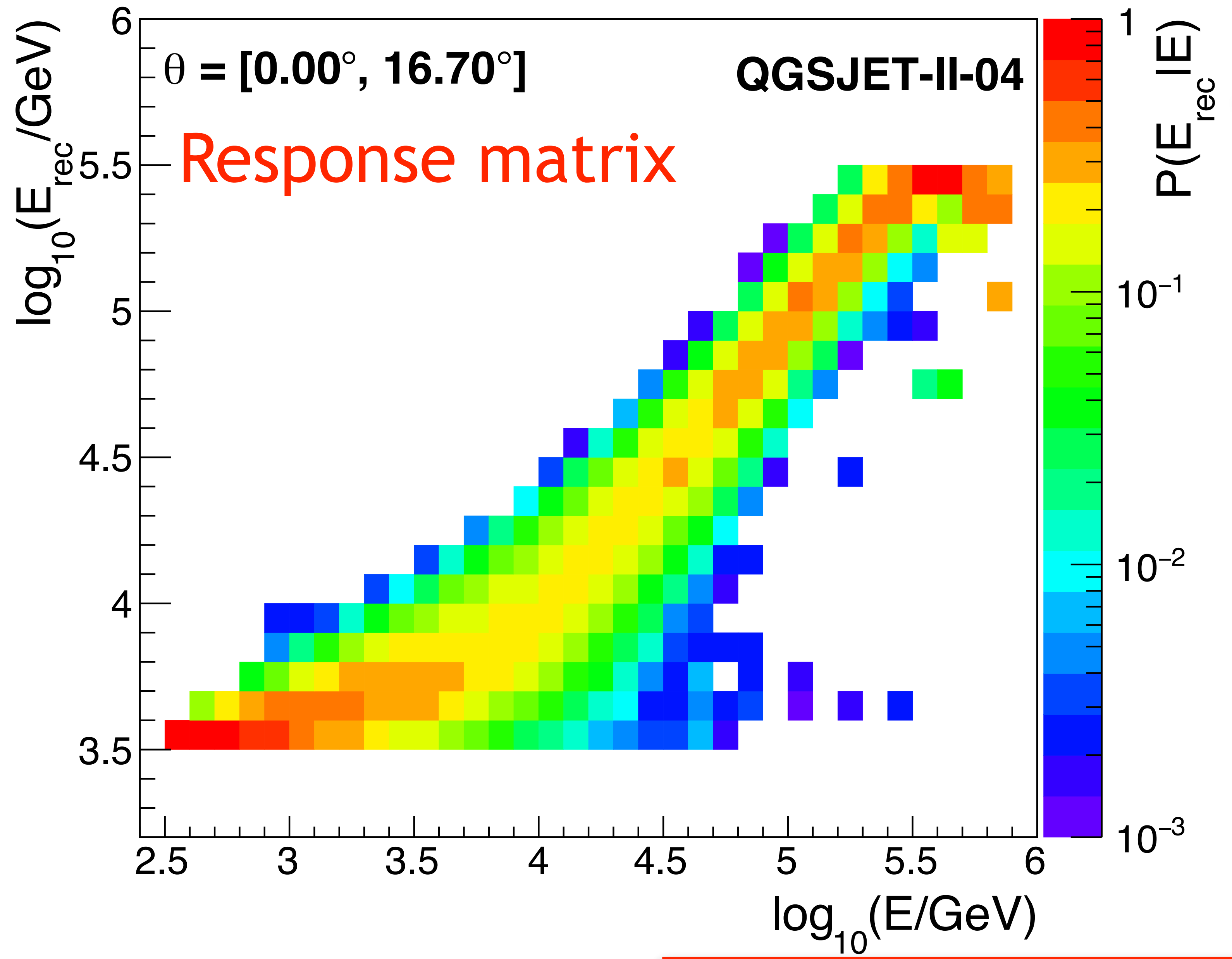
**Build raw energy spectrum of subsample: $N_{raw}(E)$**




- Experimental data used for analysis:
  HAWC-300
  $\Delta t_{eff}$ = 3.74 years (94% livetime)
  (June/11/15-June/03/19)
  $\Delta\Omega$ = 0.27 sr

| | |
|---|---|
| Total events | : $2.9 \times 10^{12}$ EAS |
| + selection cuts: | $1.6 \times 10^{10}$ EAS |
| + age cut: | $9.9 \times 10^{9}$ EAS |

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

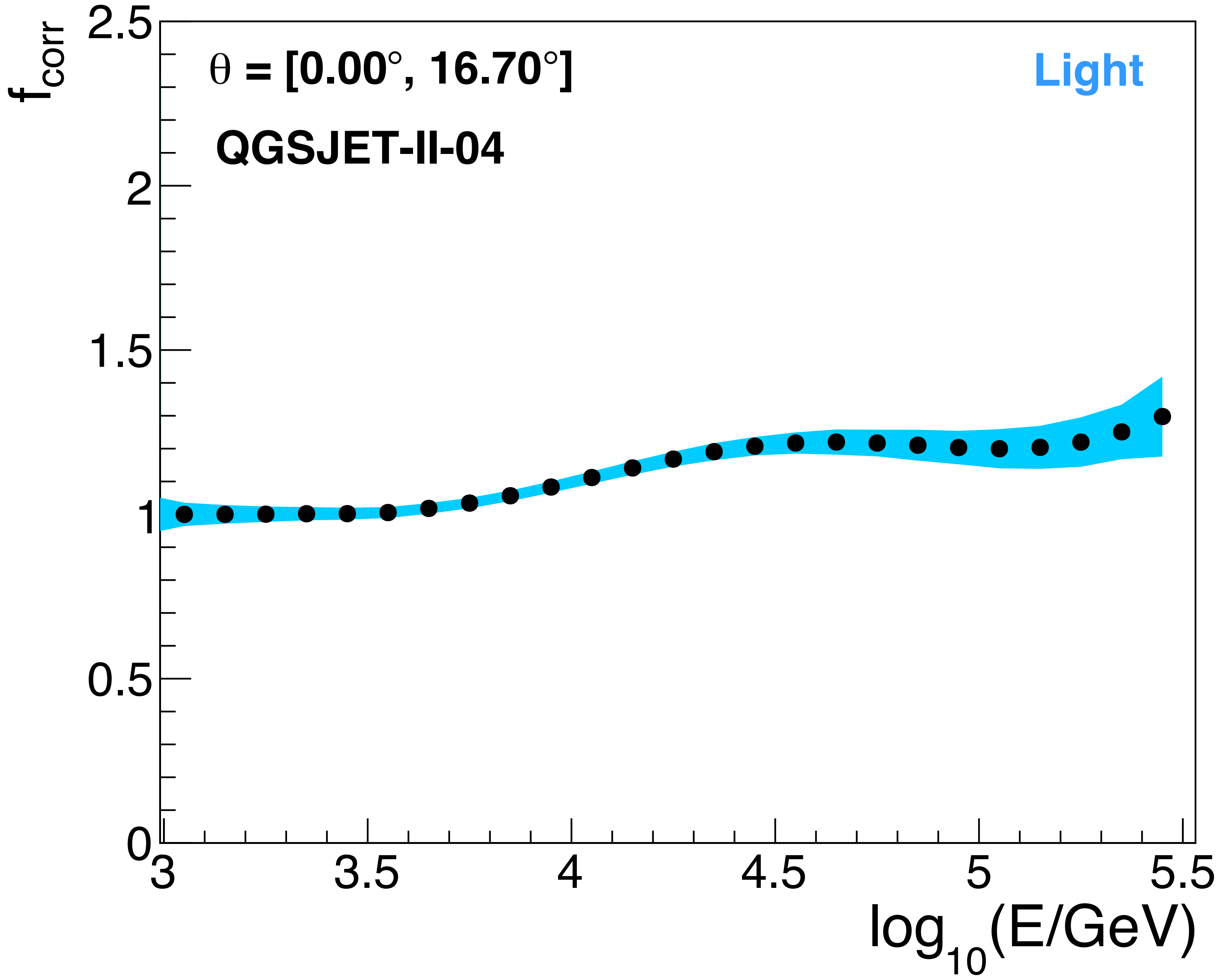



$$N^{Raw}(E^R_j) = \sum_i P(E_j \mid E^T_i)\, N^{Unf}(E^T_i)$$

- Solve for $N^{Unf}(E^T_i)$ using Bayesian unfolding
  [G. D' Agostini, DESY 94-099]
- Stopping criterium: Minimum of weighted mean squared error
  [G. Cowan, Stat. Data analysis, Oxford Press. 1998]

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

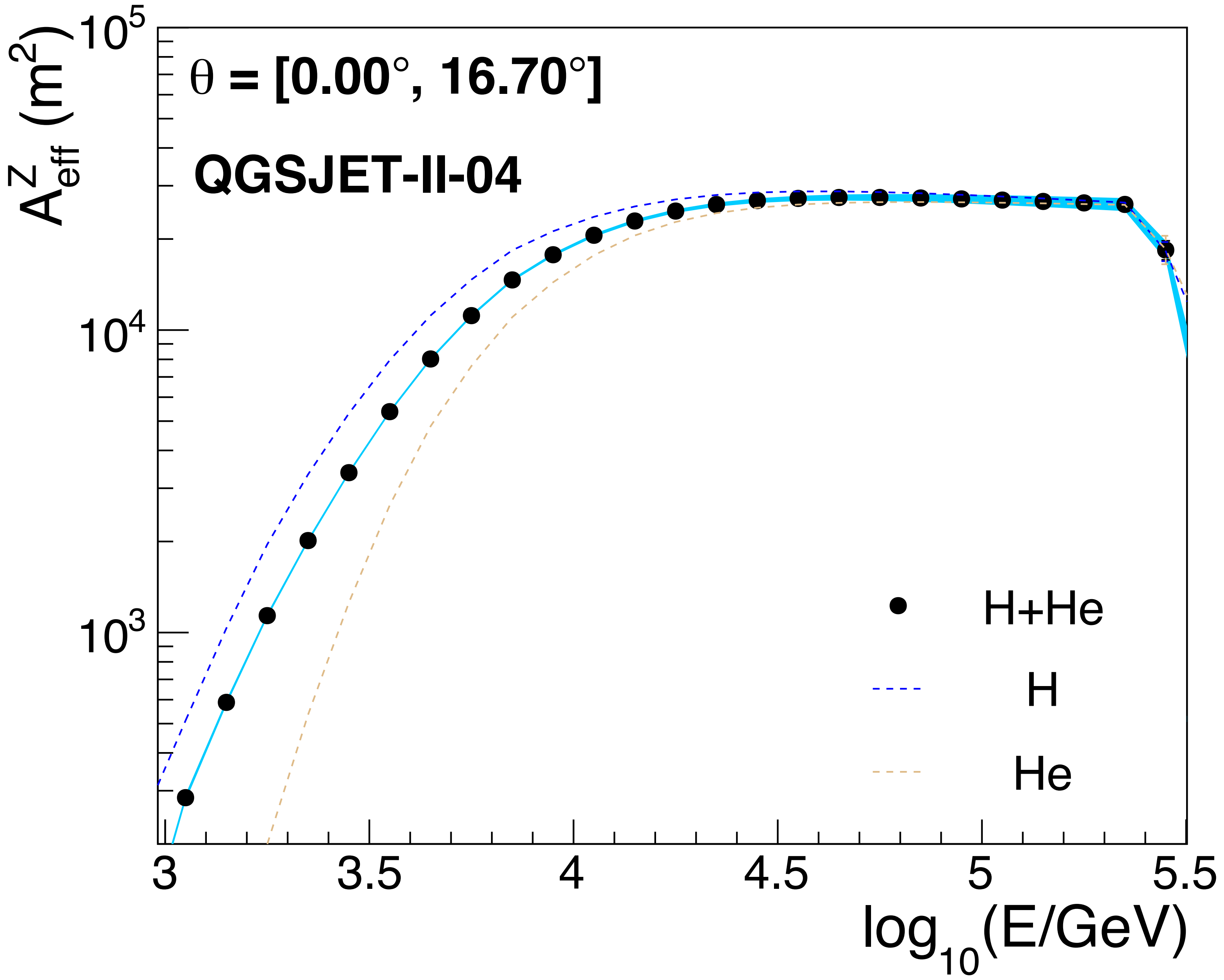
## Correct for contamination of heavy elements




- Correction factor due to contamination of heavy events

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

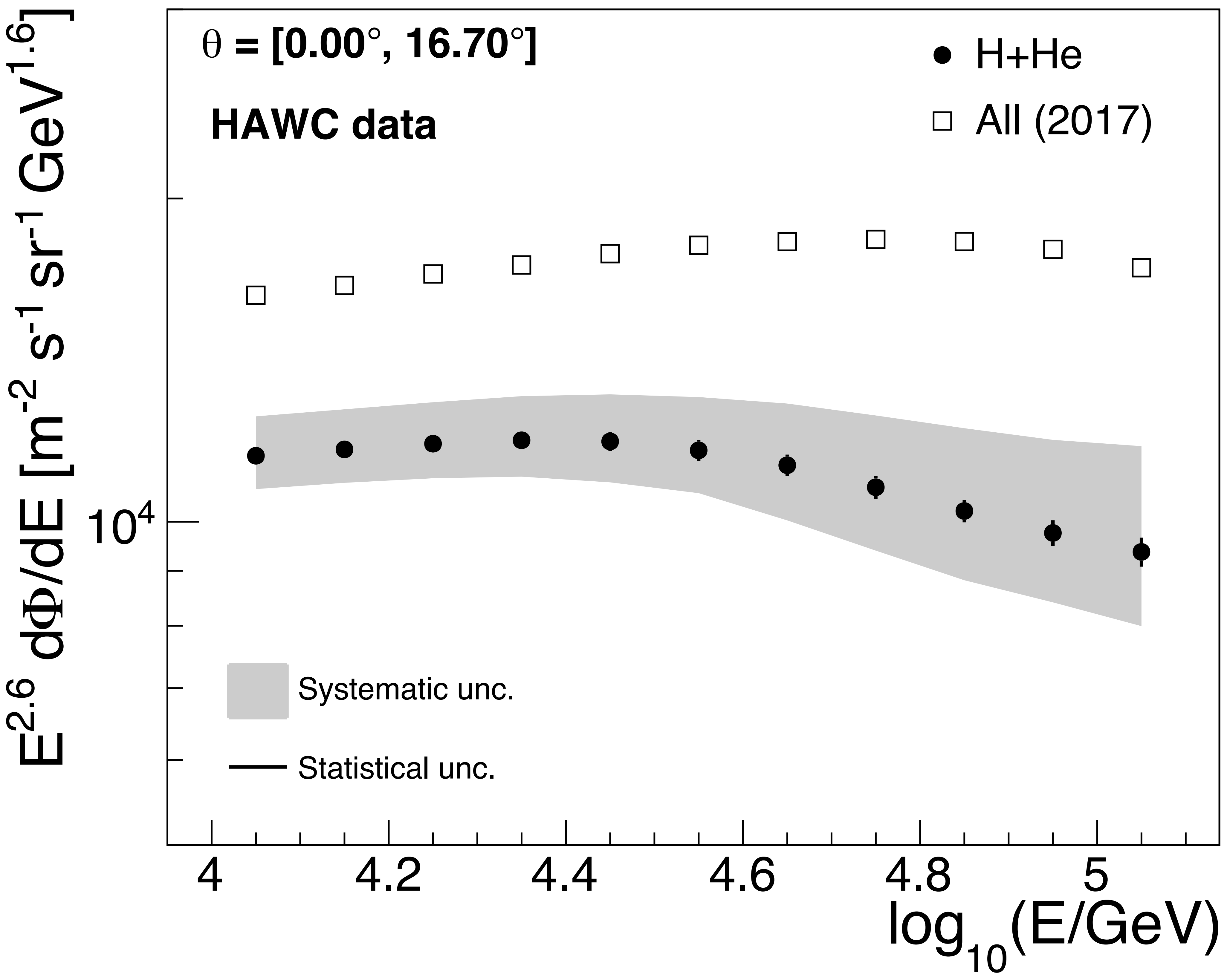
## Obtain effective area from MC simulations




- Effective area of H+He in subsample

$A_{eff}^{H+He}(E_i) = A_{thrown}\, \varepsilon^{H+He}(E_i)$

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




- Energy spectrum was calculated as:

$$\Phi = N^{Unf}(E^T)/[\Delta E^T \cdot \Delta t_{eff} \cdot \Delta\,\Omega \cdot f_{corr}(E^T) \cdot A_{eff}^{H+He}(E^T)]$$

- **HAWC** data shows a break in the spectrum of H+He nuclei at around $E \approx 30$ TeV.

New cosmic ray accelerators besides PeV Supernova Remnants?

V. I. Zatsepin and N. V. Sokolskaya, Astron. Astrophys. 458, 1 (2006); Astron. Lett. 33, 25 (2007)

Local CR source at distances of O(100 pc)?

M. Kachelriess, A. Neronov, and D. V. Semikoz, Phys. Rev. Lett. 115, 181103 (2015).

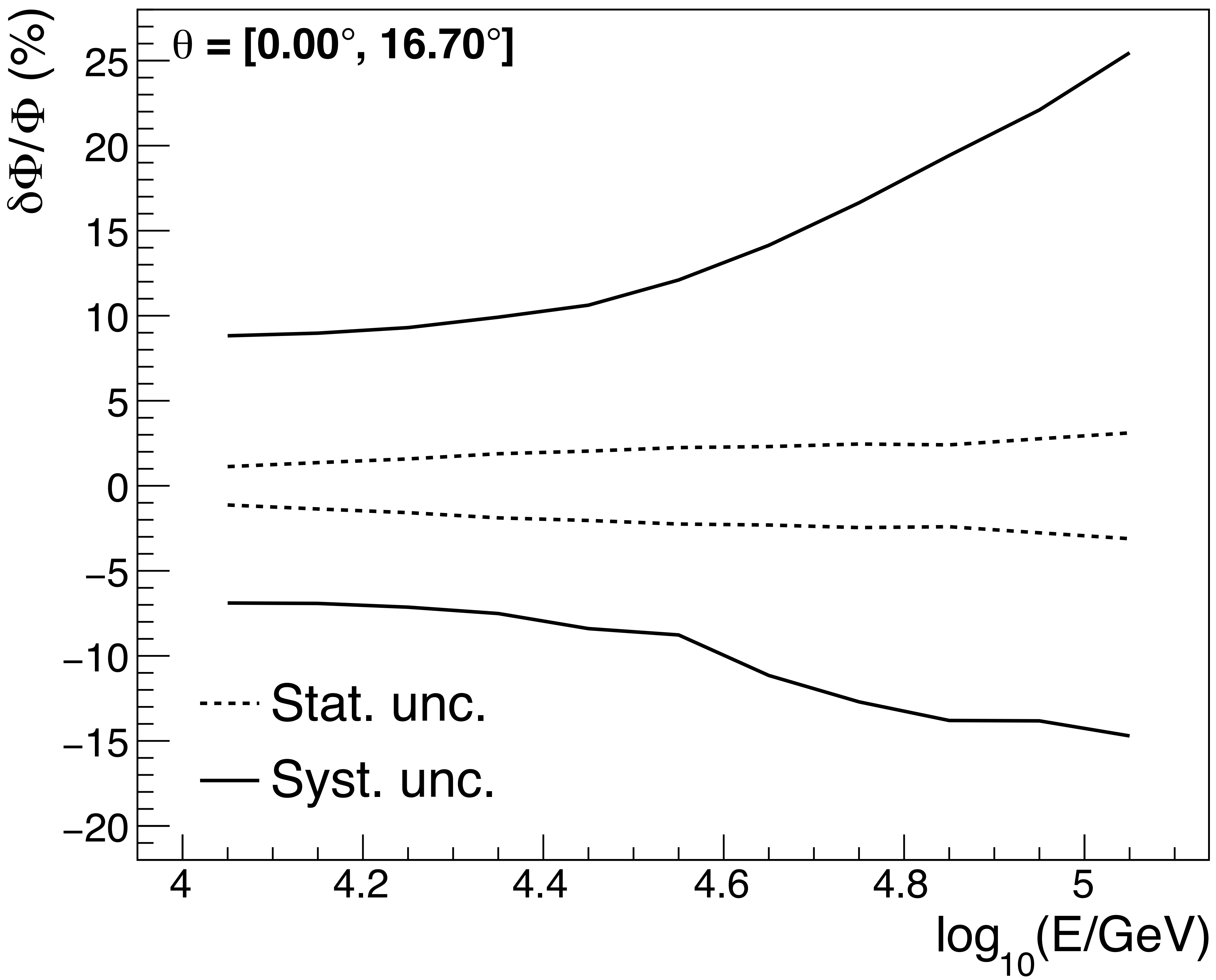
Modifications to standard mechanism of CR acceleration in astrophysical shocks?

V. Ptuskin et al., Astrophys. J. 763, 47 (2013).

## Statistical and systematic uncertainties

$\log_{10}(E/GeV) = 4.55$

| | Relative error Φ (%) |
|---|---|
| **Statistical** | **+/- 2.25** |
| Exp. Data | +/- 0.01 |
| Response matrix | +/- 2.25 |
| | |
| **Systematic** | **+12.10/-8.77** |
| Composition | +0.41/-5.47 |
| Aeff | +1.33/-1.71 |
| Cut at He or C | +2.43/-2.59 |
| Gold unfolding | -0.41 |
| Seed unfolding | -0.67 |
| Smoothing unfold. | -0.87 |
| Bin size | +0.27 |
| PMT efficiency | +3.99/-0.16 |
| PMT threshold | +1.48/-0.71 |
| PMT charge | +0.84 |
| PMT late light | +10.94/-1.97 |
| Hadronic model | -5.62 |
| | |
| **Total** | **+12.31/-9.05** |



# 7) H + He energy spectrum

**Fit of spectrum**

**1.** Use following functions:

—> Single power law:

$$d\Phi(E)/dE = \Phi_0 E^{\gamma_1}$$

—> Broken power law:

$$d\Phi(E)/dE = \Phi_0 E^{\gamma_1}[ 1 + (E/E_0)^{\varepsilon} ]^{(\gamma_2 - \gamma_1)/\varepsilon}$$

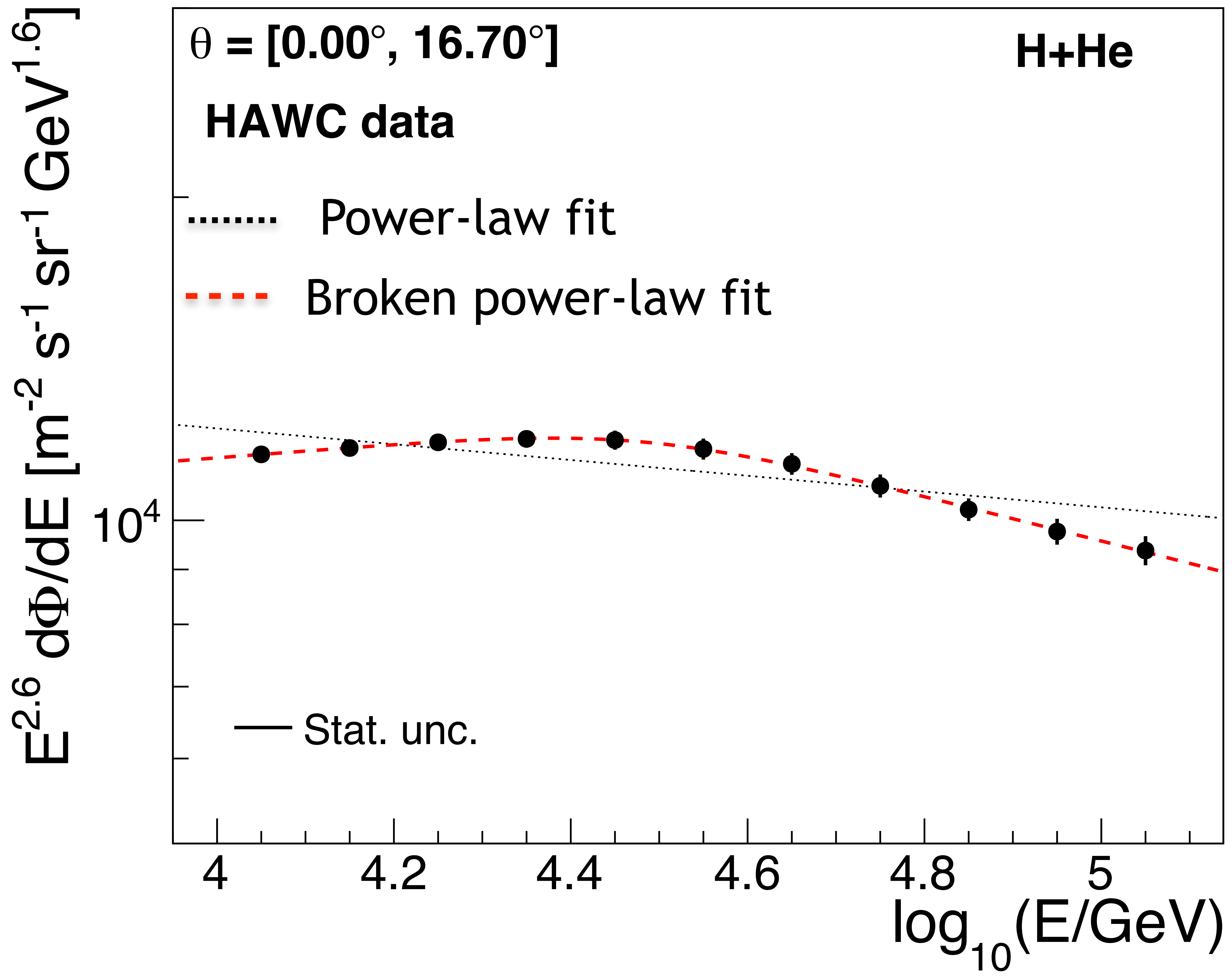
**2.** Minimize $\chi^2$ with MINUIT and take into account correlation between points:

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

PDG (2017)

# 7) H + He energy spectrum

**Fit of spectrum**




- **Test Statistics:**
  $TS = -\Delta\chi^2 = 42.18$
  **p-value ≤ 4 x $10^{-5}$**

-> 3.9σ deviation from scenario with single power-law: unlikely that data is described by a single power-law.

- Results for the broken power-law fit:

$\gamma_1 = -2.54 \pm 0.07$

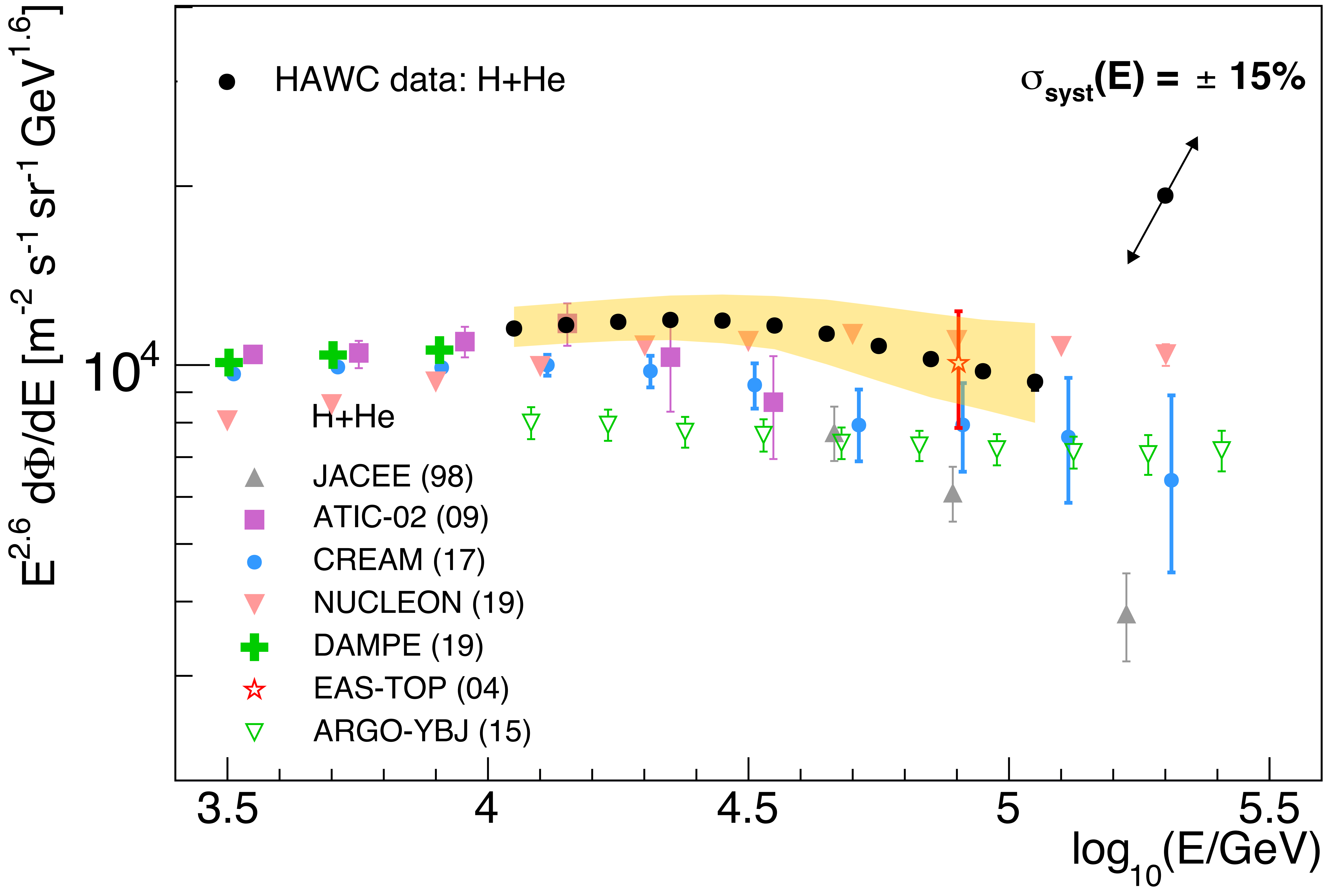
$\gamma_2 = -2.81 \pm 0.06$

$\Delta\gamma = -0.27 \pm 0.09$

$E_0 = 30.2^{+9.6}_{-7.3}$ TeV

**Comparison with measurements from other experiments**

**H+He**




- **HAWC** data confirm previous hints from ATIC-2, CREAM I-III and NUCLEON about the existence of a break in the spectrum of the light component of cosmic rays in the 10 - 100 TeV range.
- **HAWC** does not support ARGO-YBJ result that the spectrum of light nuclei follows a single power-law in the TeV range.

# 8) Summary

- 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, 126 TeV].

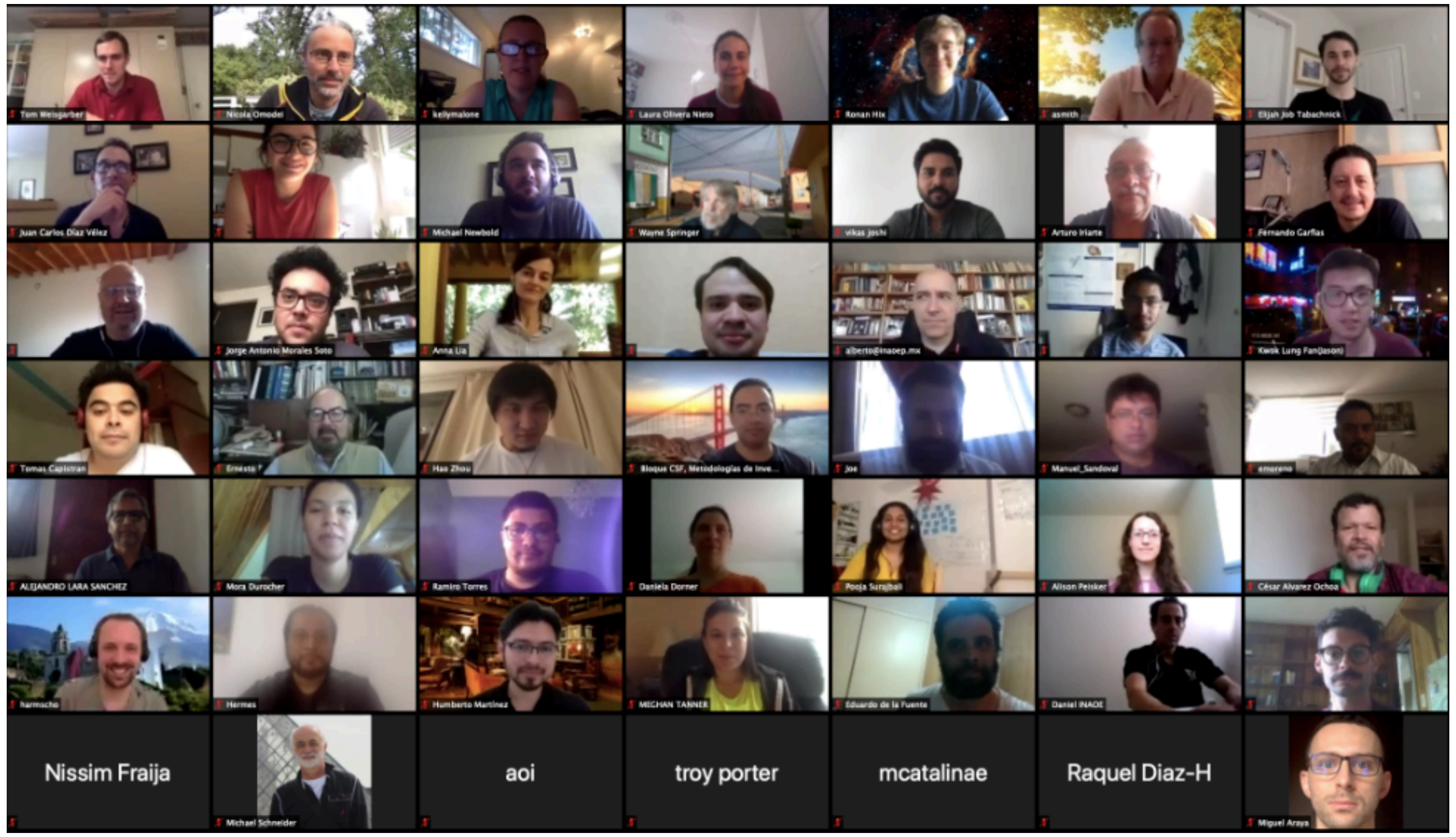
- The light spectrum of cosmic rays is in agreement with data from NUCLEON and EAS-TOP, but above estimations from ATIC-2, CREAM-II/-III, JACEE and ARGO-YBJ.

- HAWC data show that the cosmic ray spectrum of H+He exhibits a new break around $30.2^{+9.6}_{-7.3}$ TeV.

- The study demonstrates that high-altitude water Cherenkov observatories like HAWC can also be used to study the composition of cosmic rays at energies as low as 10 TeV.

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

# Thank you




# Backup: Statistical and systematic uncertainties