The energy spectrum of the light mass group of TeV cosmic rays as measured with HAWC

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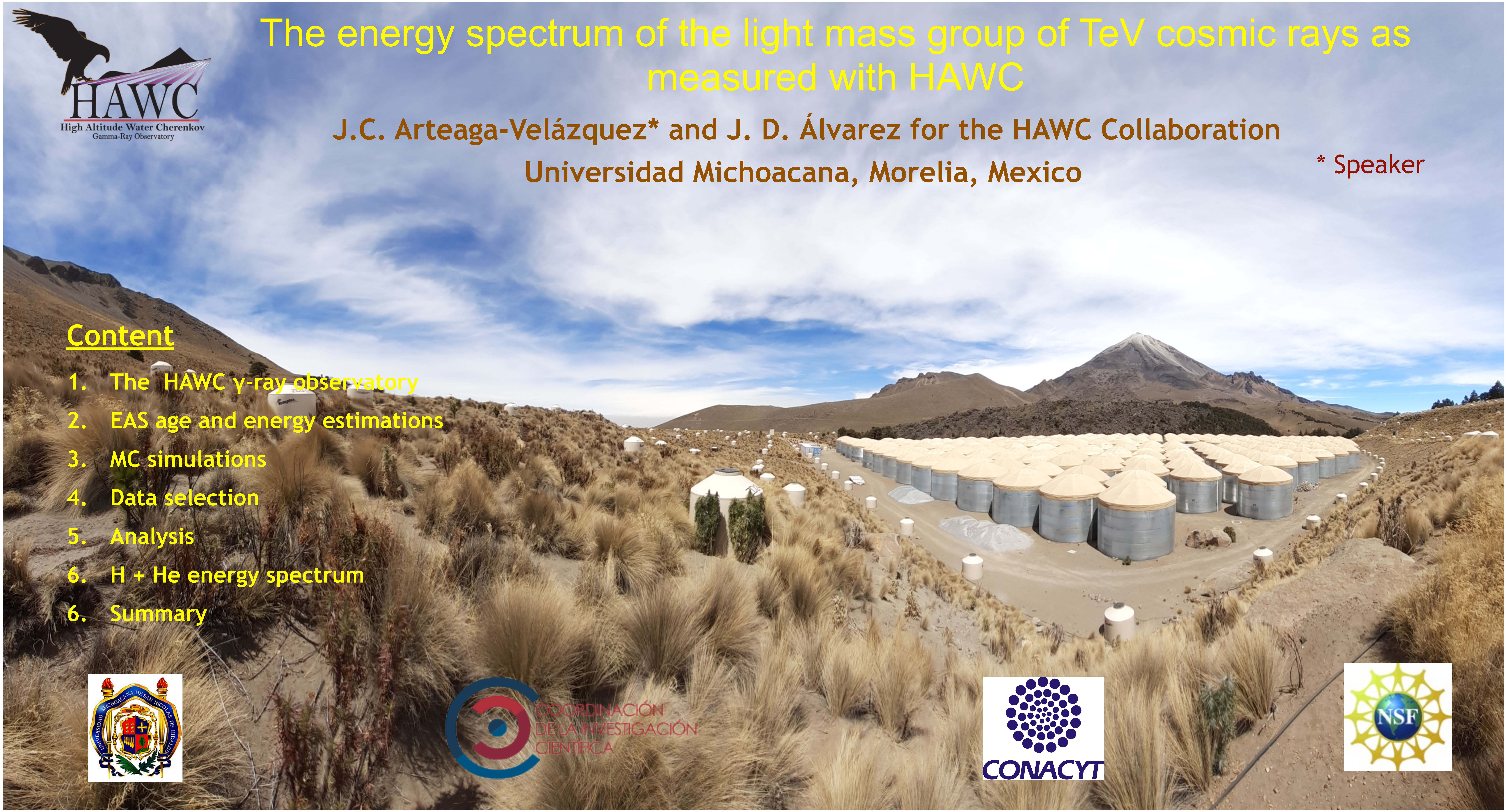

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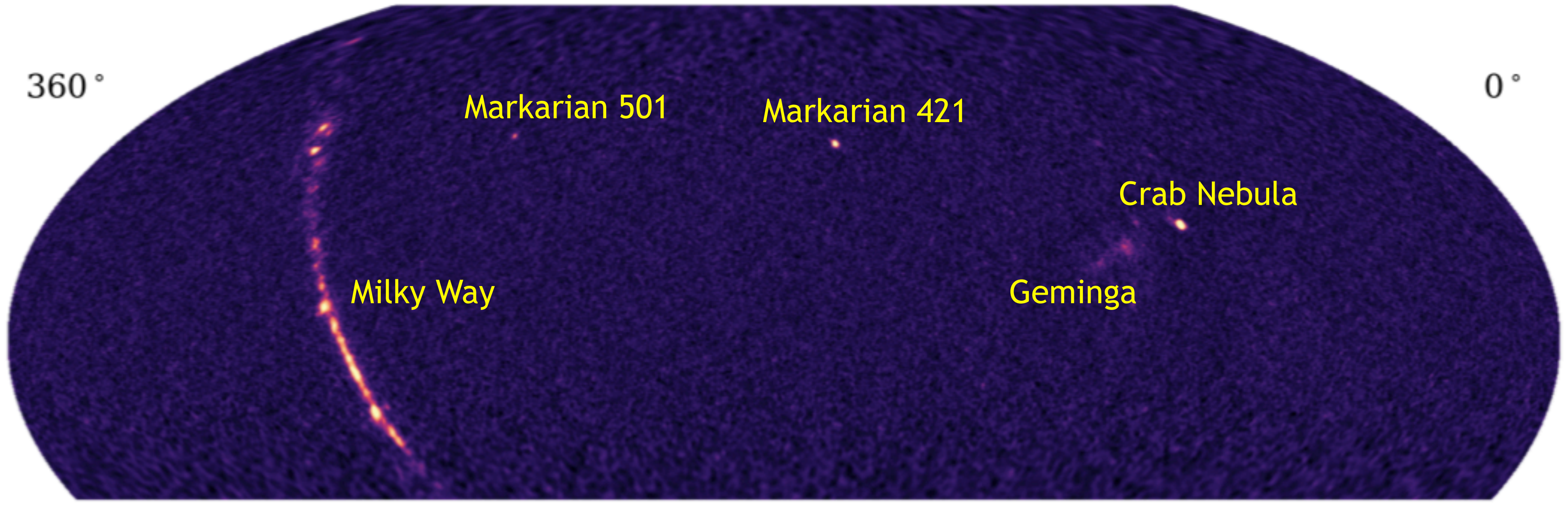
1) The HAWC γ-ray observatory



HAWC Collab., arXiv:2007.08582 **[astro-ph.HE]**

γ- and cosmic-ray detector:

- Air-shower observatory
- Ground-based Cherenkov array

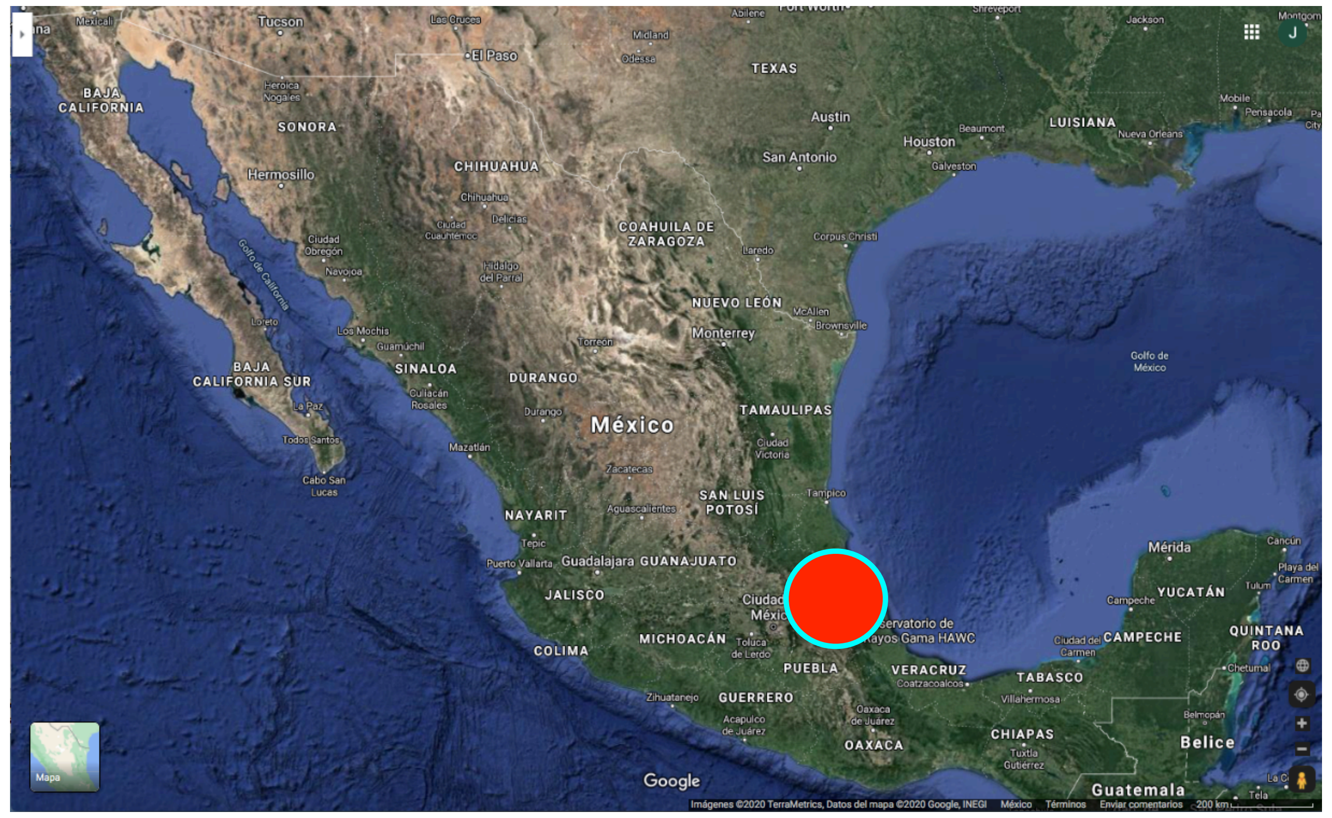
  E = 100 GeV - 100 TeV

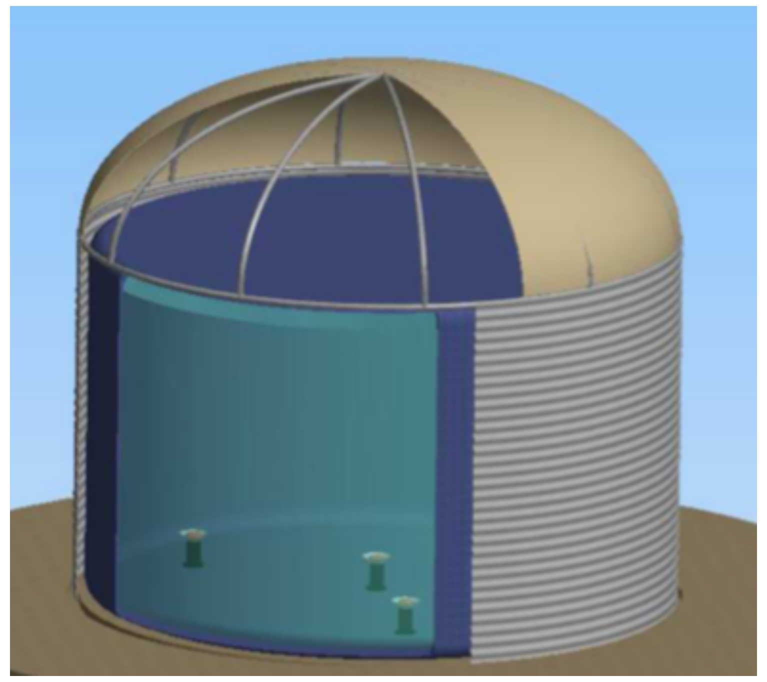
Set-up of central detector:

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

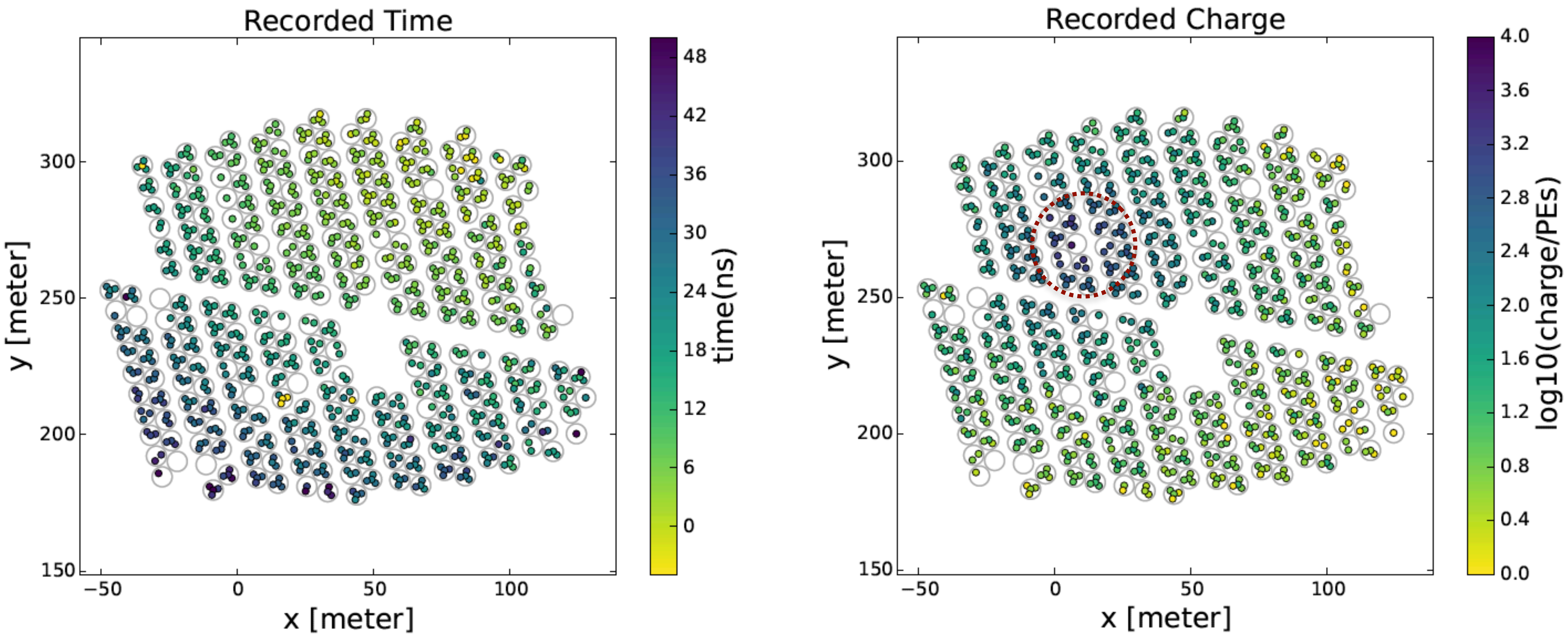
Location:

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





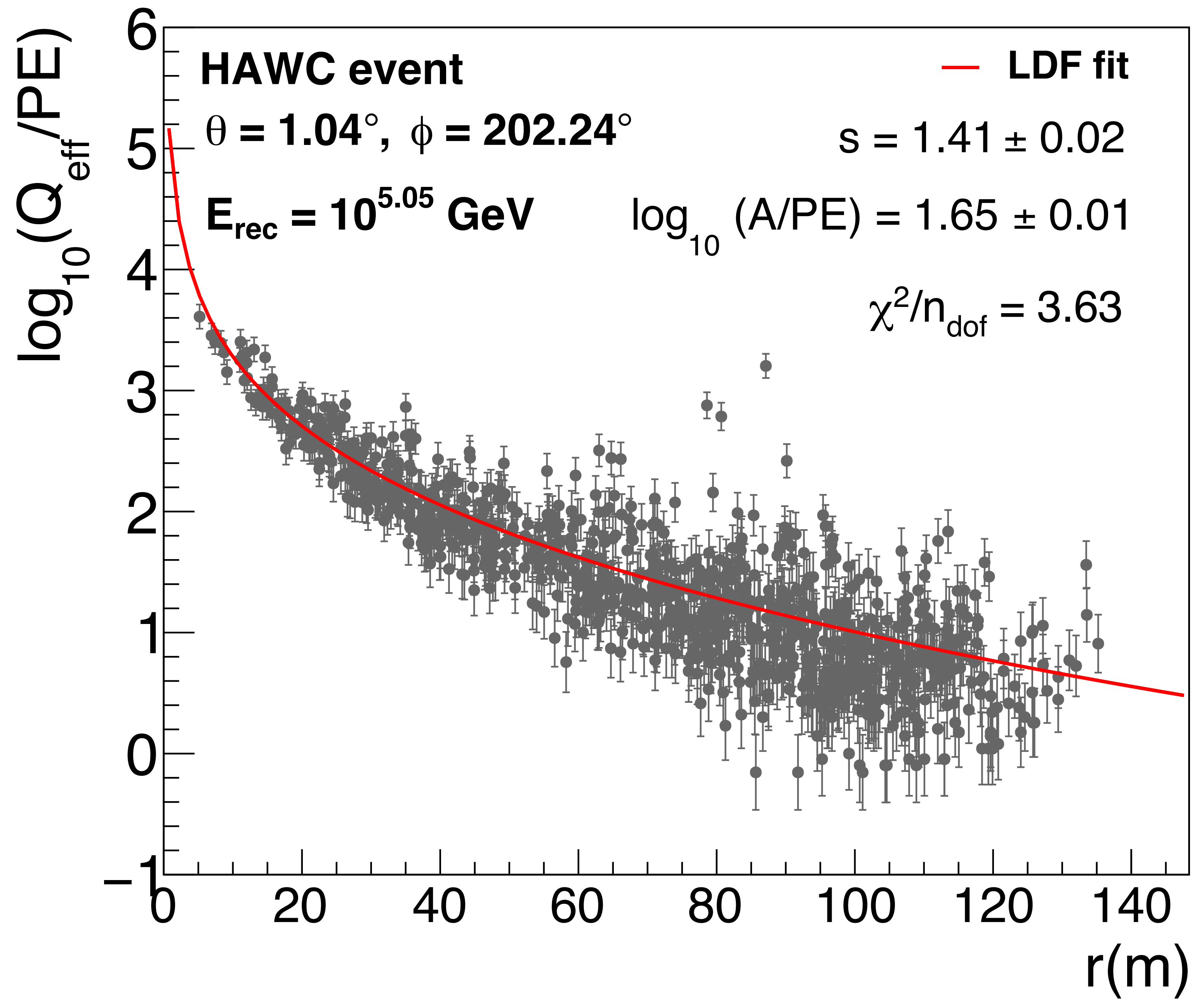
1) The HAWC γ-ray observatory

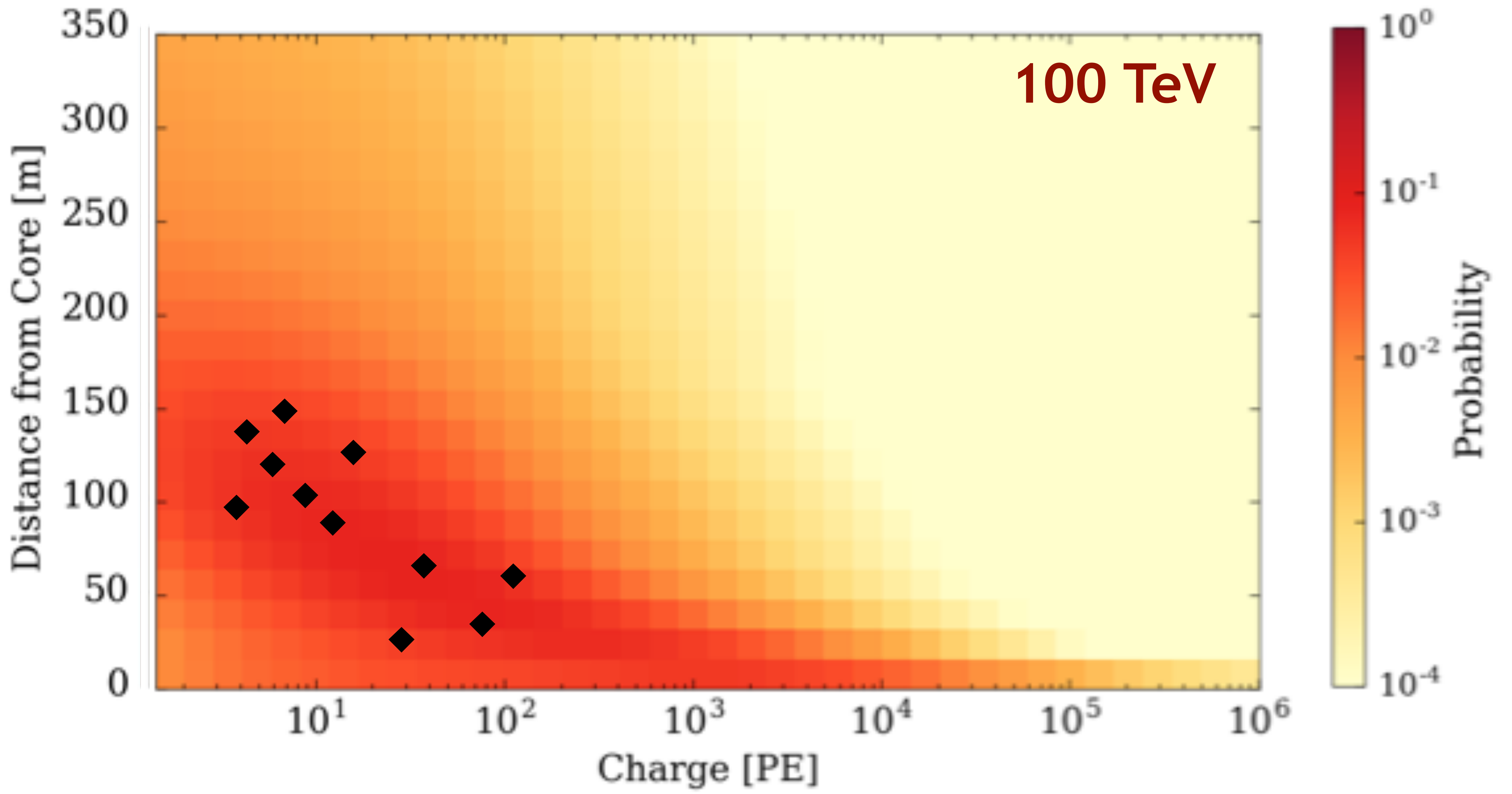


- From hit times at PMTs, deposited charged, number of PMT's with signal:
  - Core location, (X_c, Y_c)
  - Arrival direction, θ
  - Fraction of hit PMT's, f_{hit}
  - Lateral charge profile, Qeff(r)
  - ...

[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 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

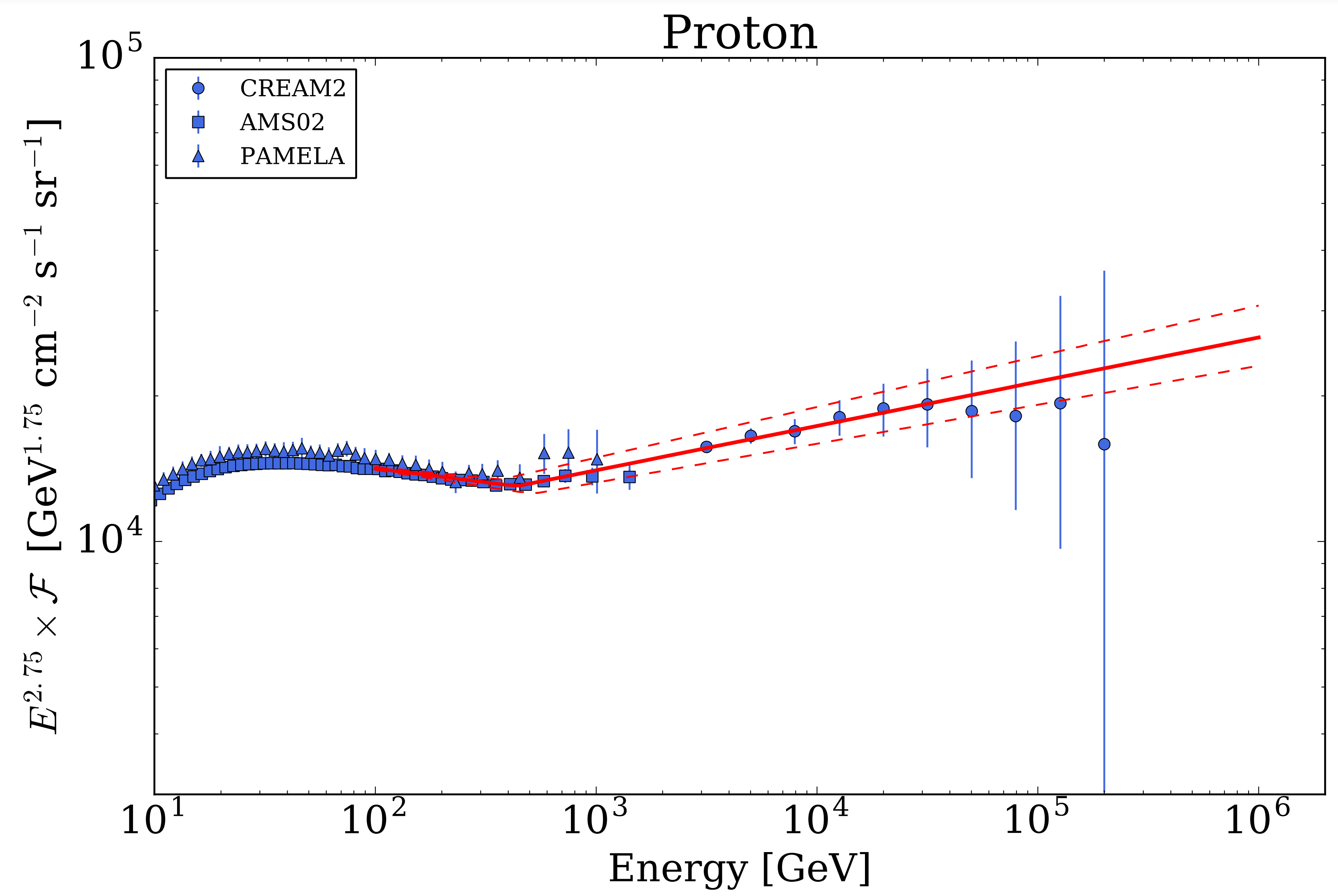
[HAWC Collab., APJ 881 (2017); J.A. Morales Soto et al., PoS(ICRC2019 359 (2019)]

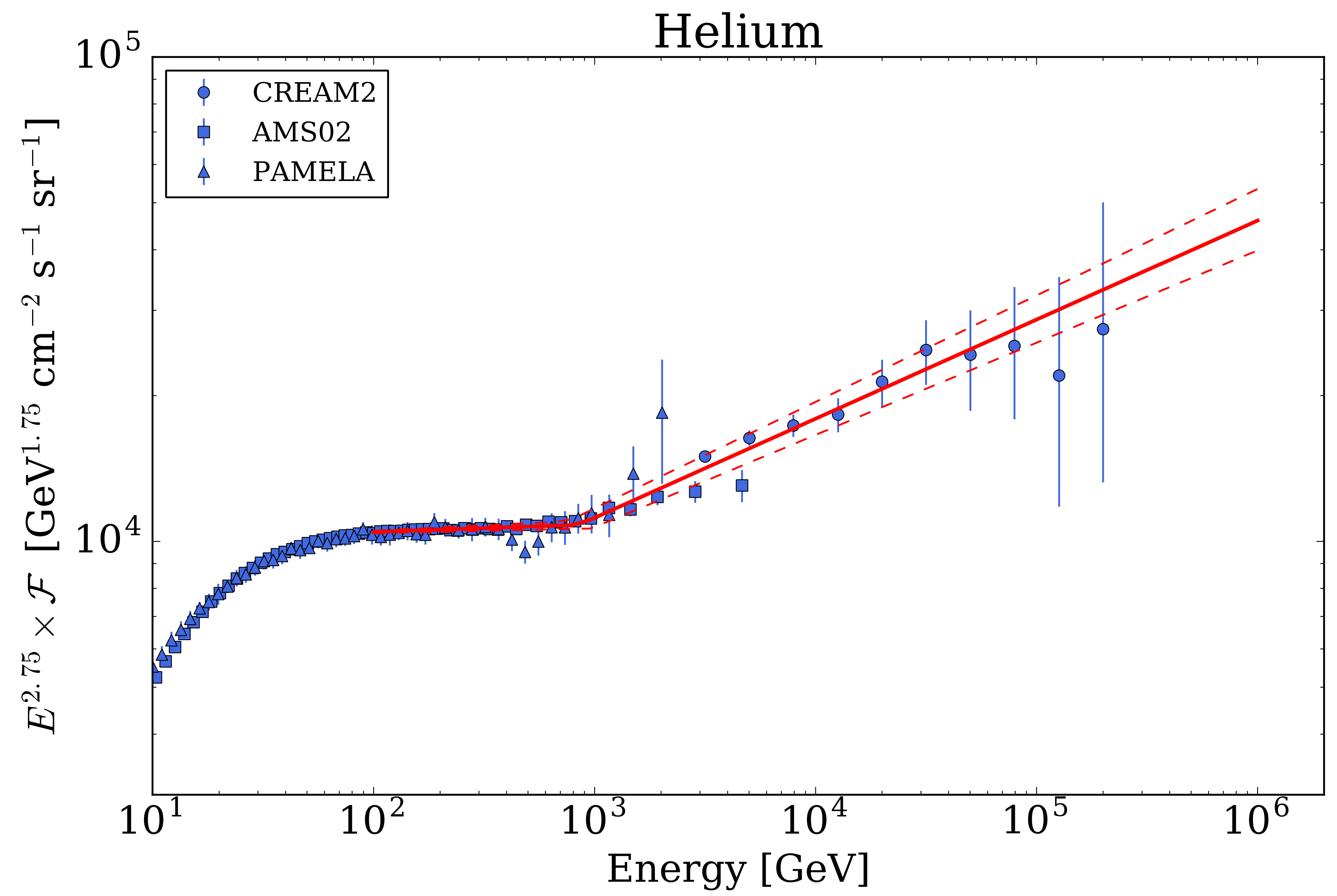
- **EAS primary energy**:
  - Produce LDF tables of MC protons**:** Binning in r, Qeff, θ and E
  - Maximum likelihood to find table that best fits the Qeff(r) distribution of the event, from which **E** is obtained.

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

3) MC simulations

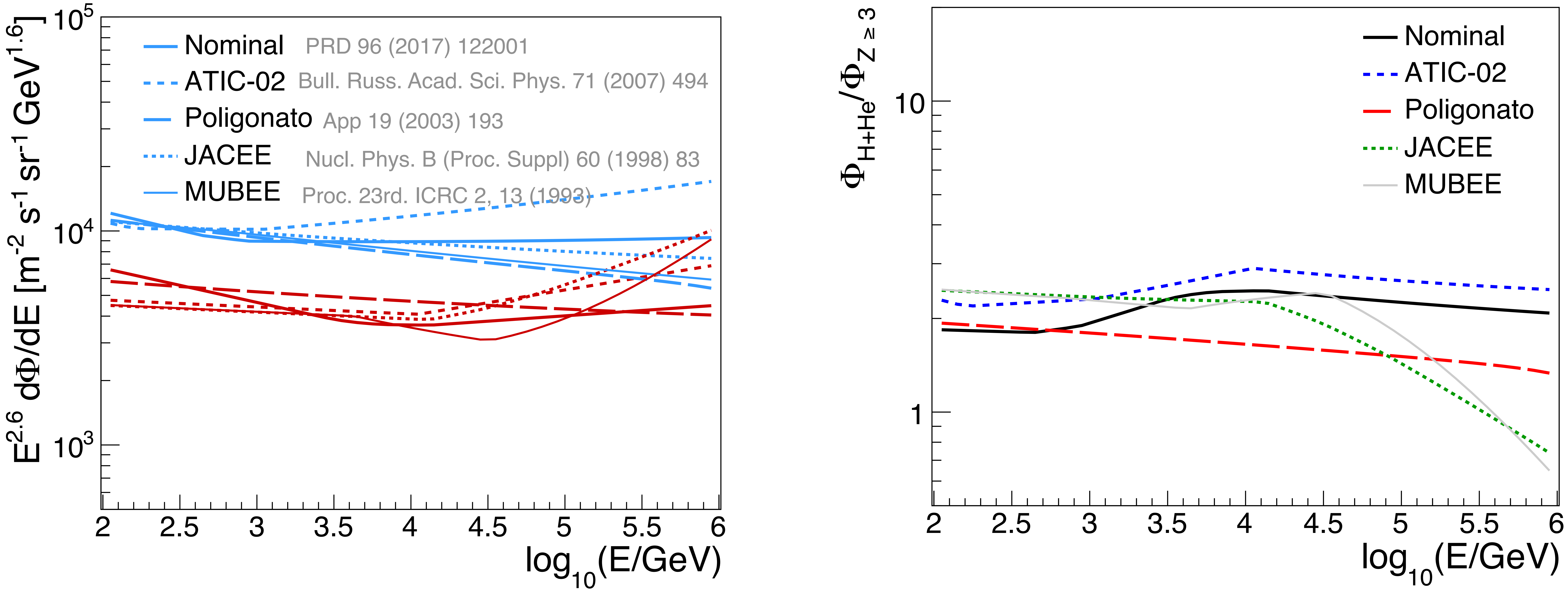
- CORSIKA v 7.40 for EAS simulation.
- Fluka/QGSJET-II-04 as low/high-energy interaction models for the main analysis.
- Fluka/EPOS-LHC simulations to study effect of hadronic interaction model.
- Full simulation of detector response with GEANT 4.
- $\theta < 70^{o}$; $A_{thrown} \sim 3 \times 10^{6}$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





3) MC simulations

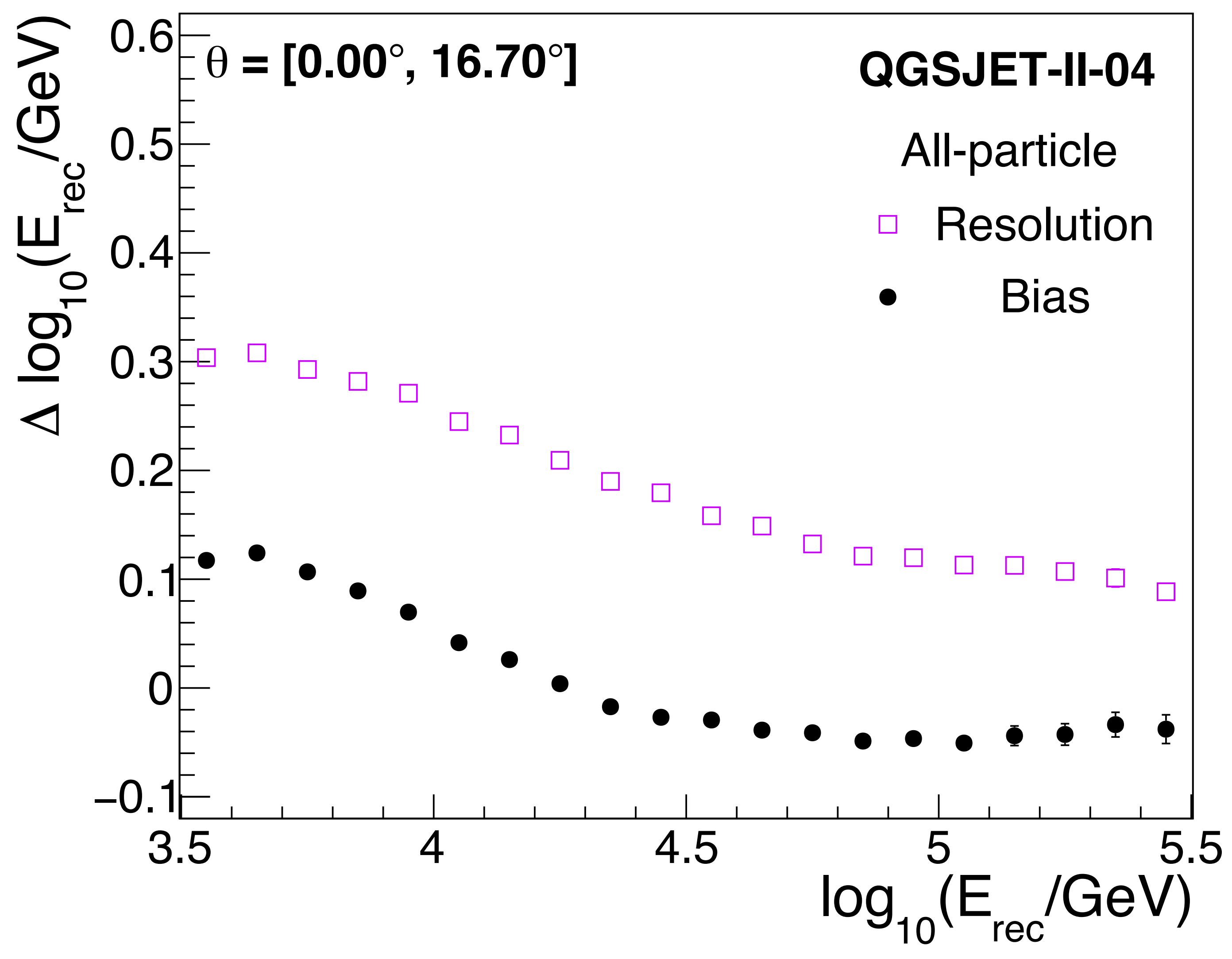
Composition models



- But also use different composition models for studies of systematics

Selection cuts

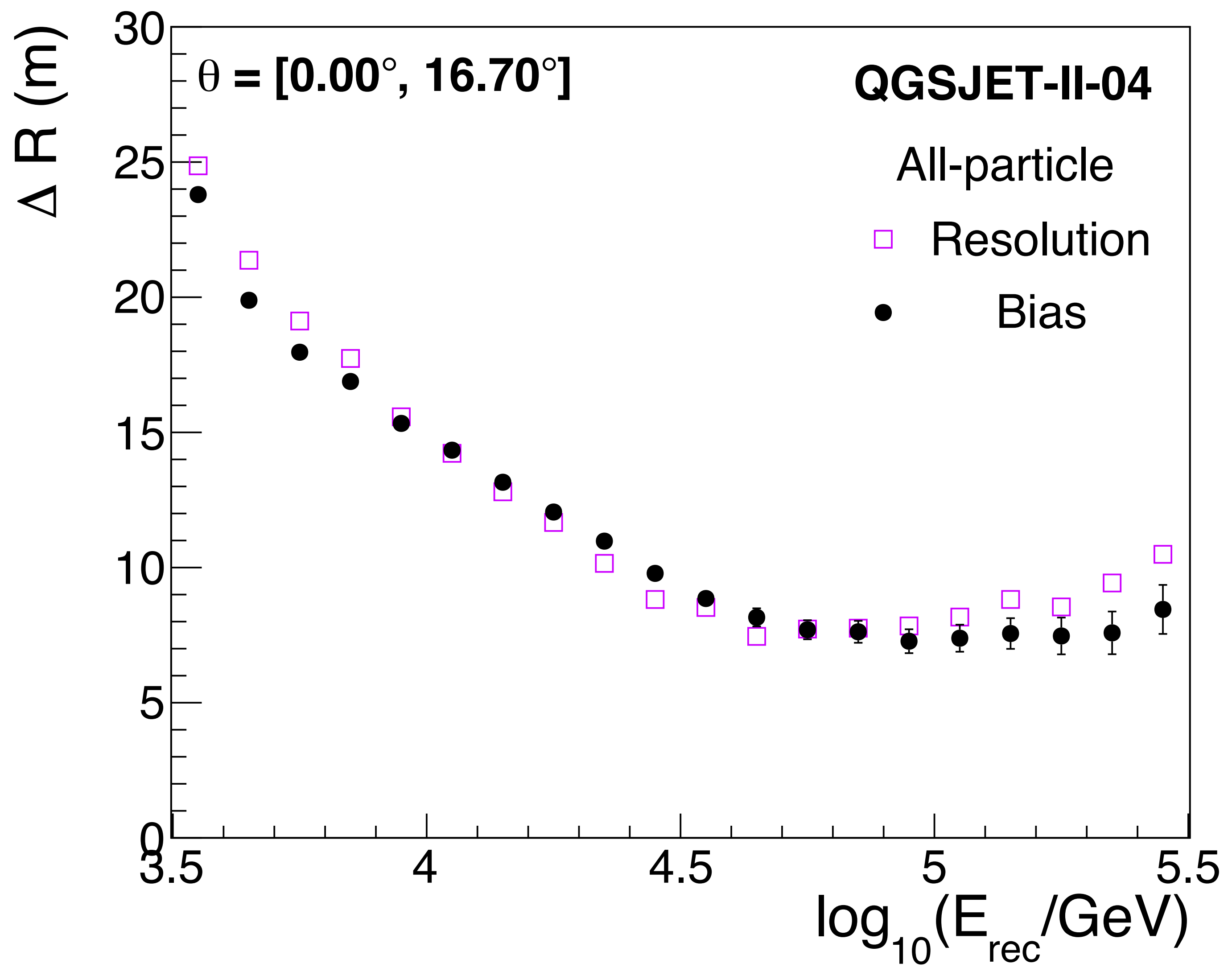
- Important to reduce systematic effects on results:
  - $\theta < 16.7^\circ$
  - Successful core and arrival direction reconstruction
  - Activate at least 40 PMTs within 40 m from core
  - On-array EAS cores
  - Multiplicity threshold $N_{hit} \geq 75$ PMTs
  - Fraction hit (# of hit PMT's/# available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

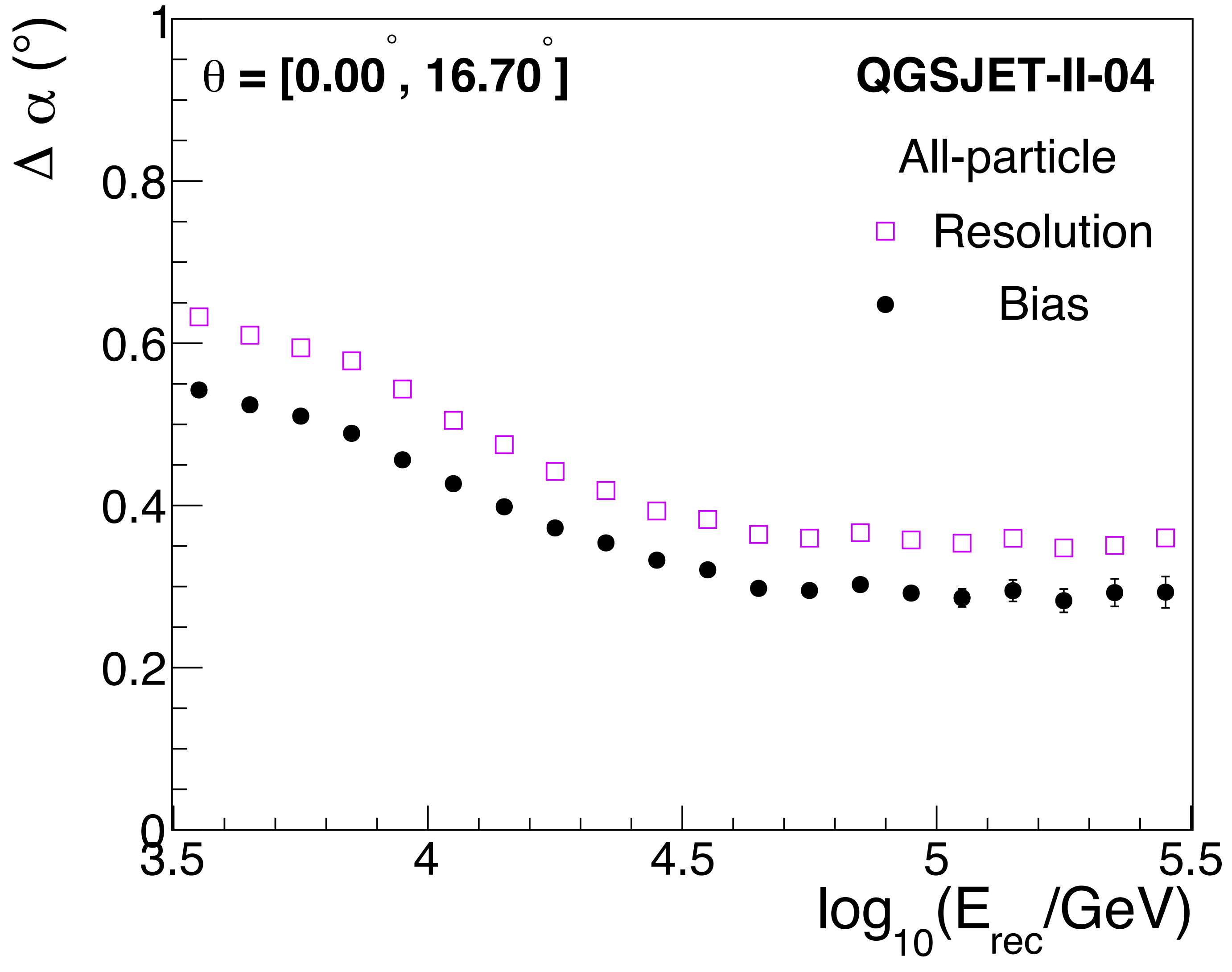


- Bias:

E ≥ 10 TeV:

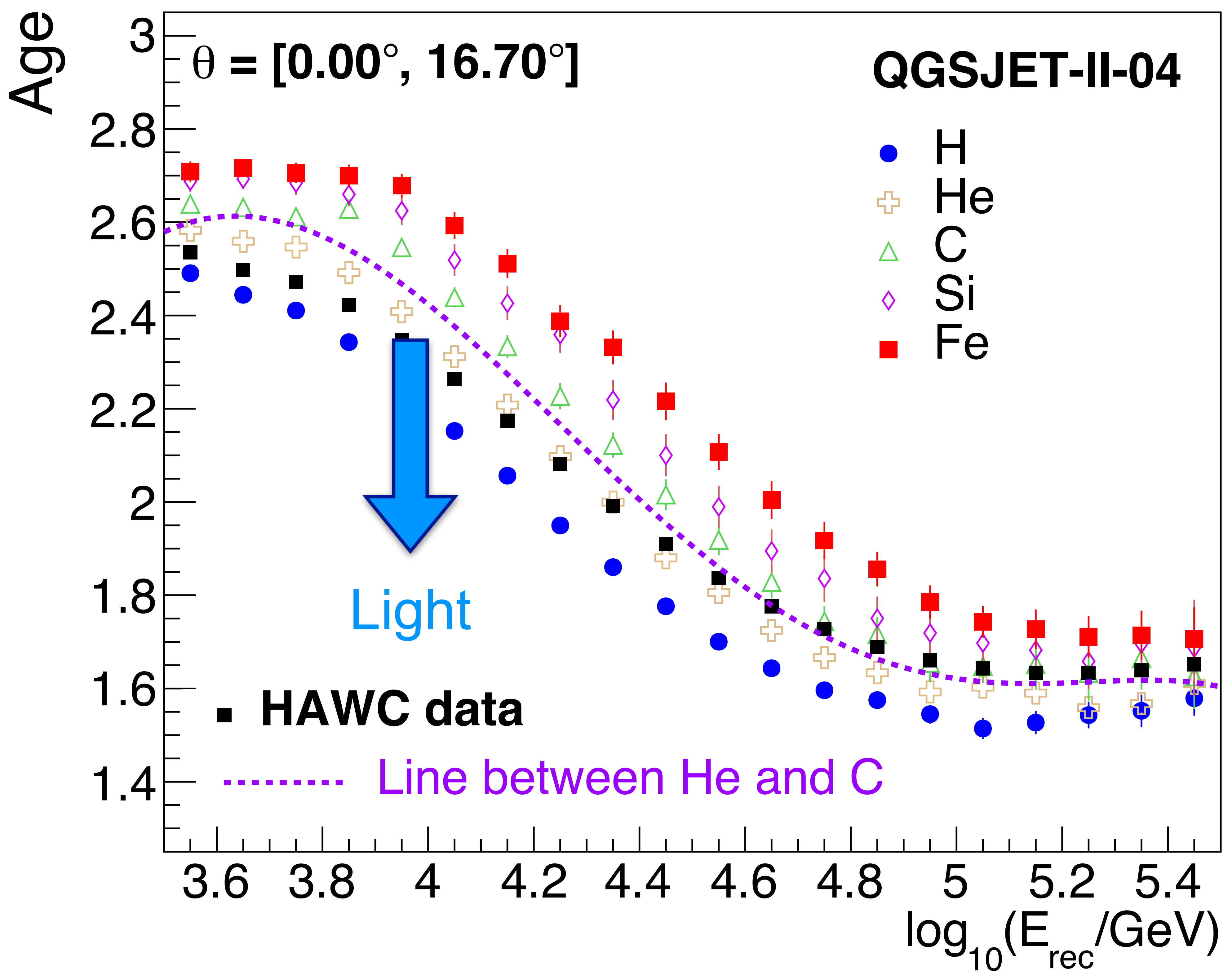
$\Delta core_{res}$	≤ 15 m
$\lvert\Delta\log_{10}(E/GeV)\rvert$	≤ 0.06
$\Delta\alpha$	≤ 0.45°

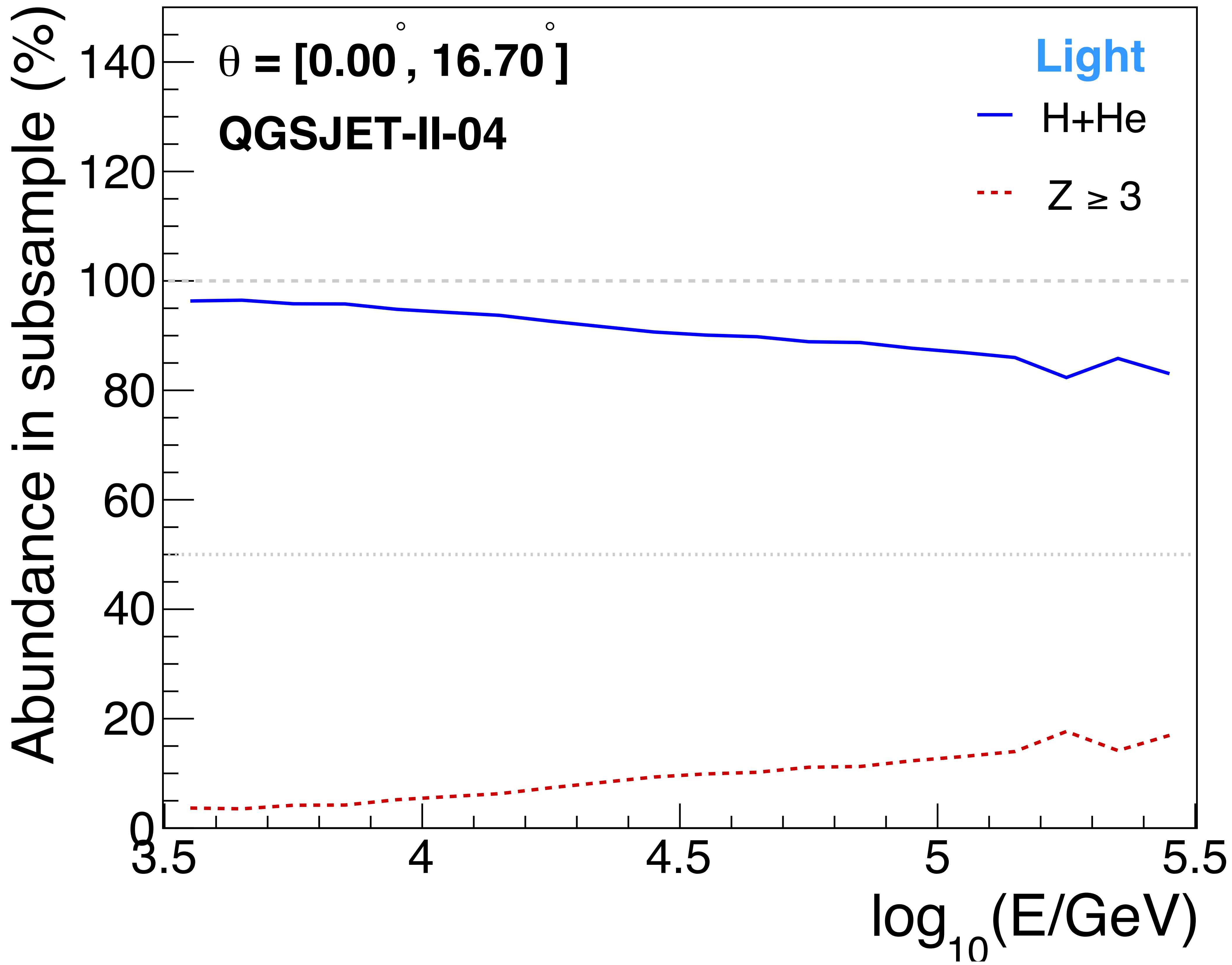




5) Analysis

Select a sample enriched with light nuclei

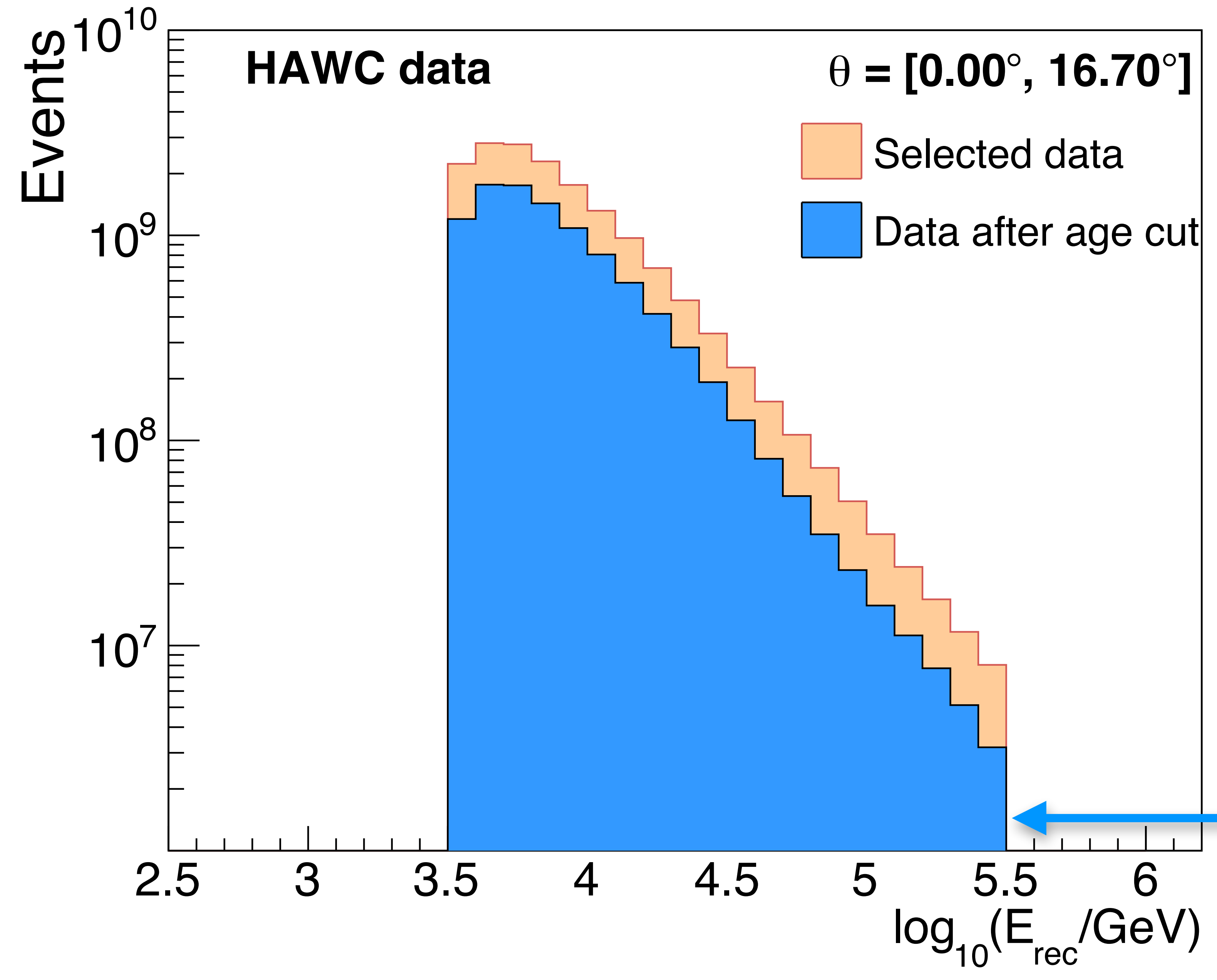




- Age parameter is sensitive to composition
- Select a subsample using a cut on the age
  - Subsample must be enriched with the nuclei to be studied

- 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

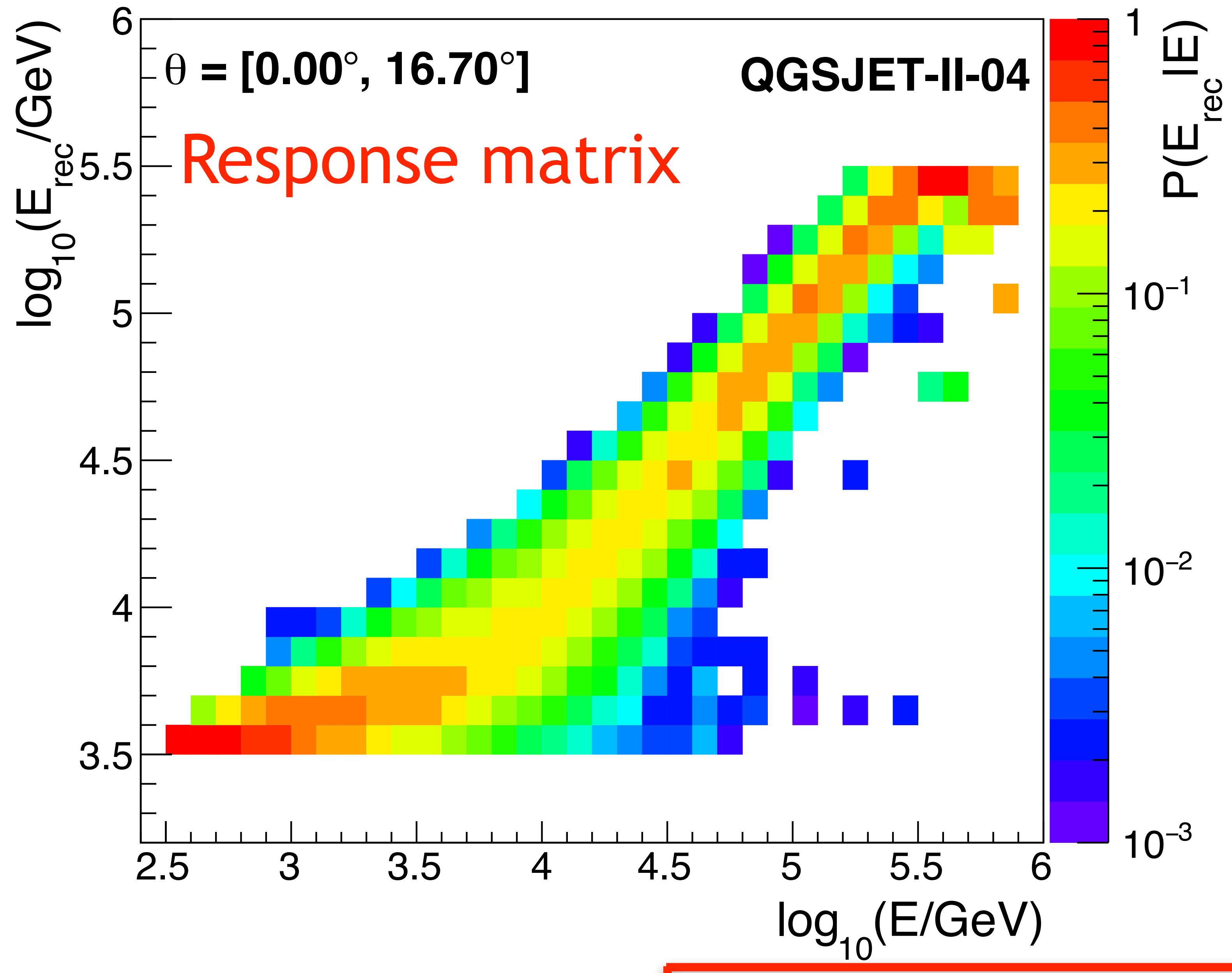
  Δt_{eff} = 3.74 years (94% livetime)

  (June/11/15-June/03/19)

  $\Delta\Omega$ = 0.27 sr

Total events	: 2.9×10^{12} EAS
+ selection cuts:	1.6×10^{10} EAS
+ age cut:	9.9×10^{9} EAS

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

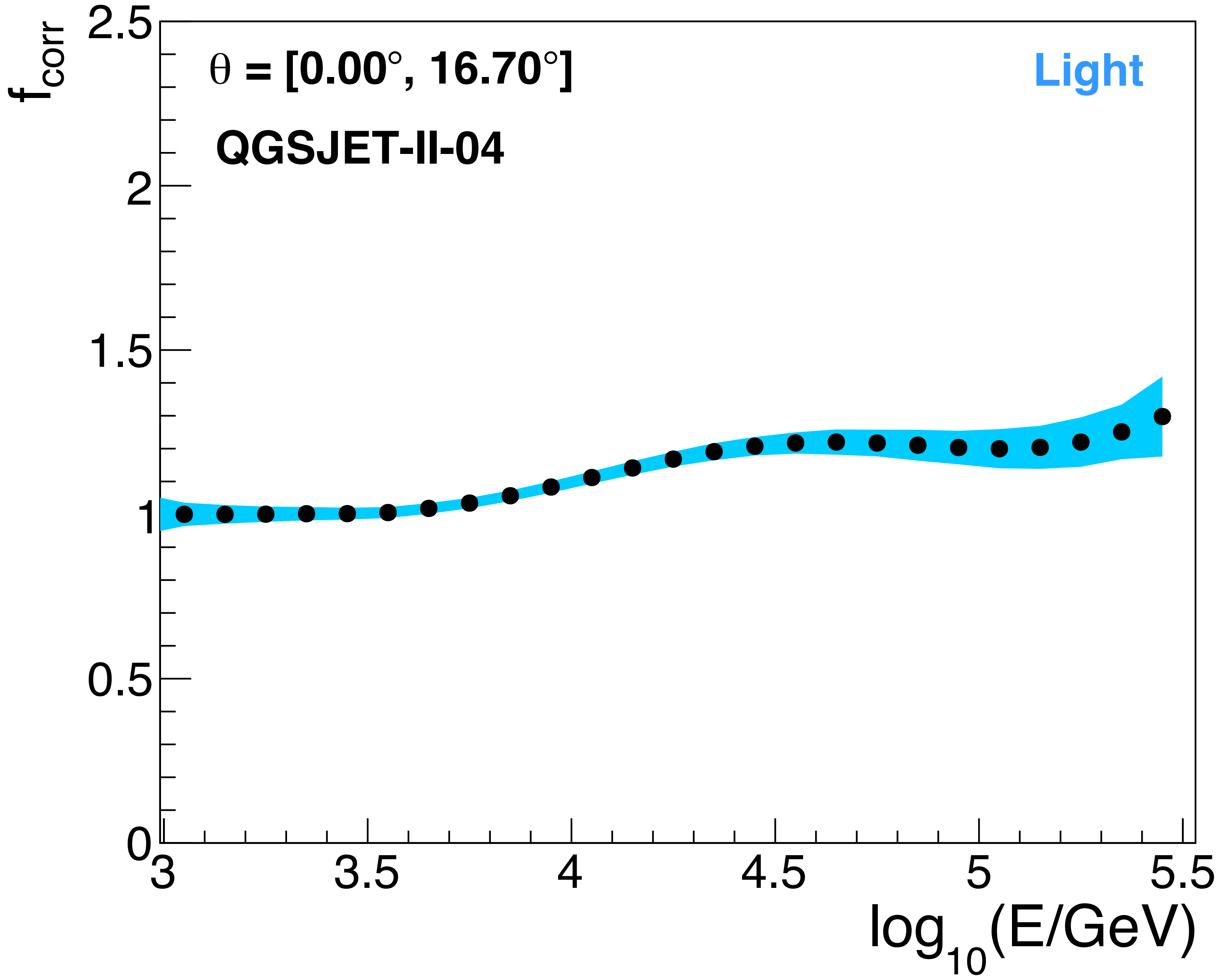


$$N^{Raw}(E^R_j) = \sum_i P(E_j \mid E^T_i)\, N^{Unf}(E^T_i)$$

- 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]

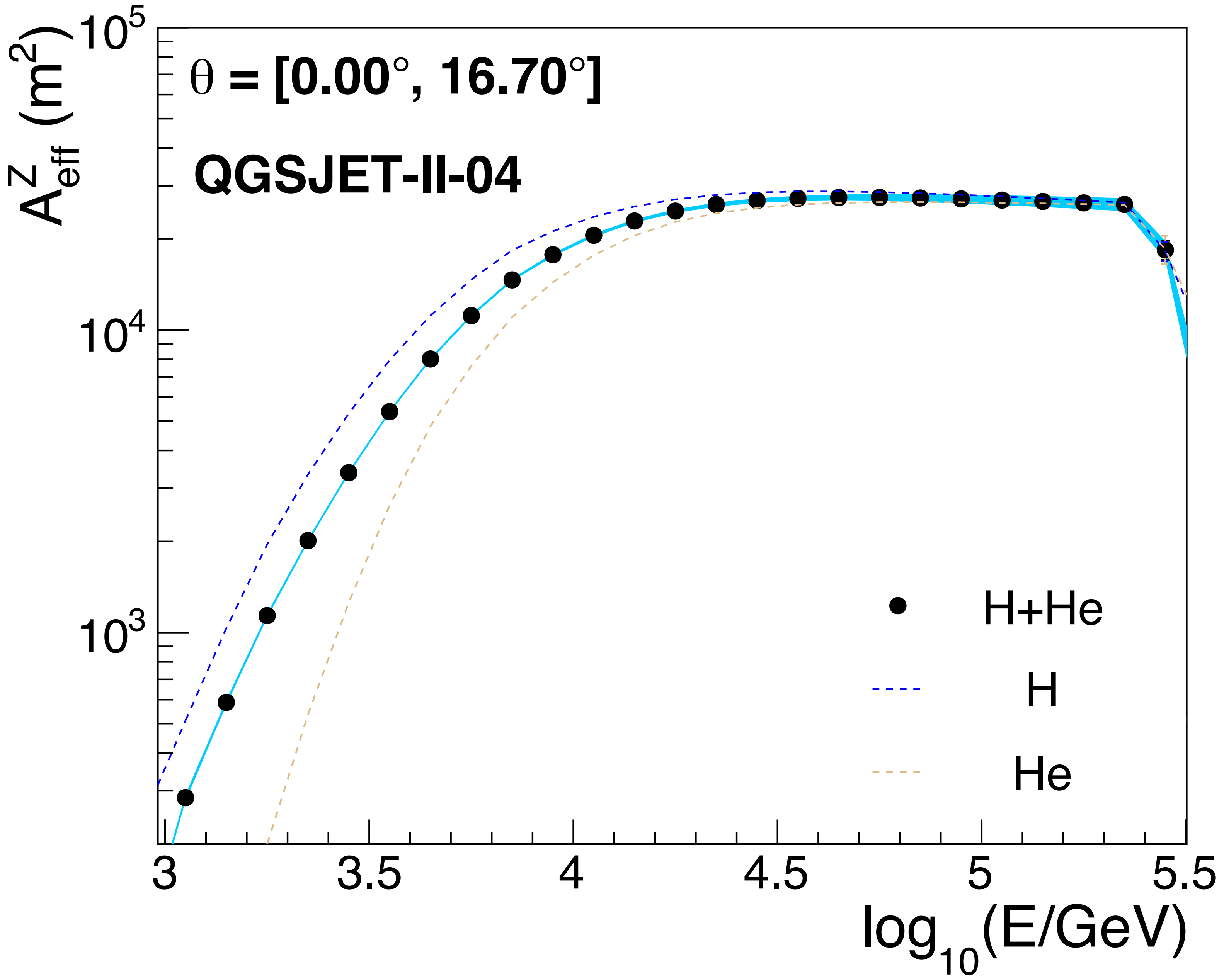
$$\mathrm{WMSE} = \frac{1}{N_{points}} \sum_i^{N_{points}} \frac{stat_i^2 + sys_i^2}{n_i}$$

Obtain effective area from MC simulations



- Correction factor due to contamination of heavy events

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

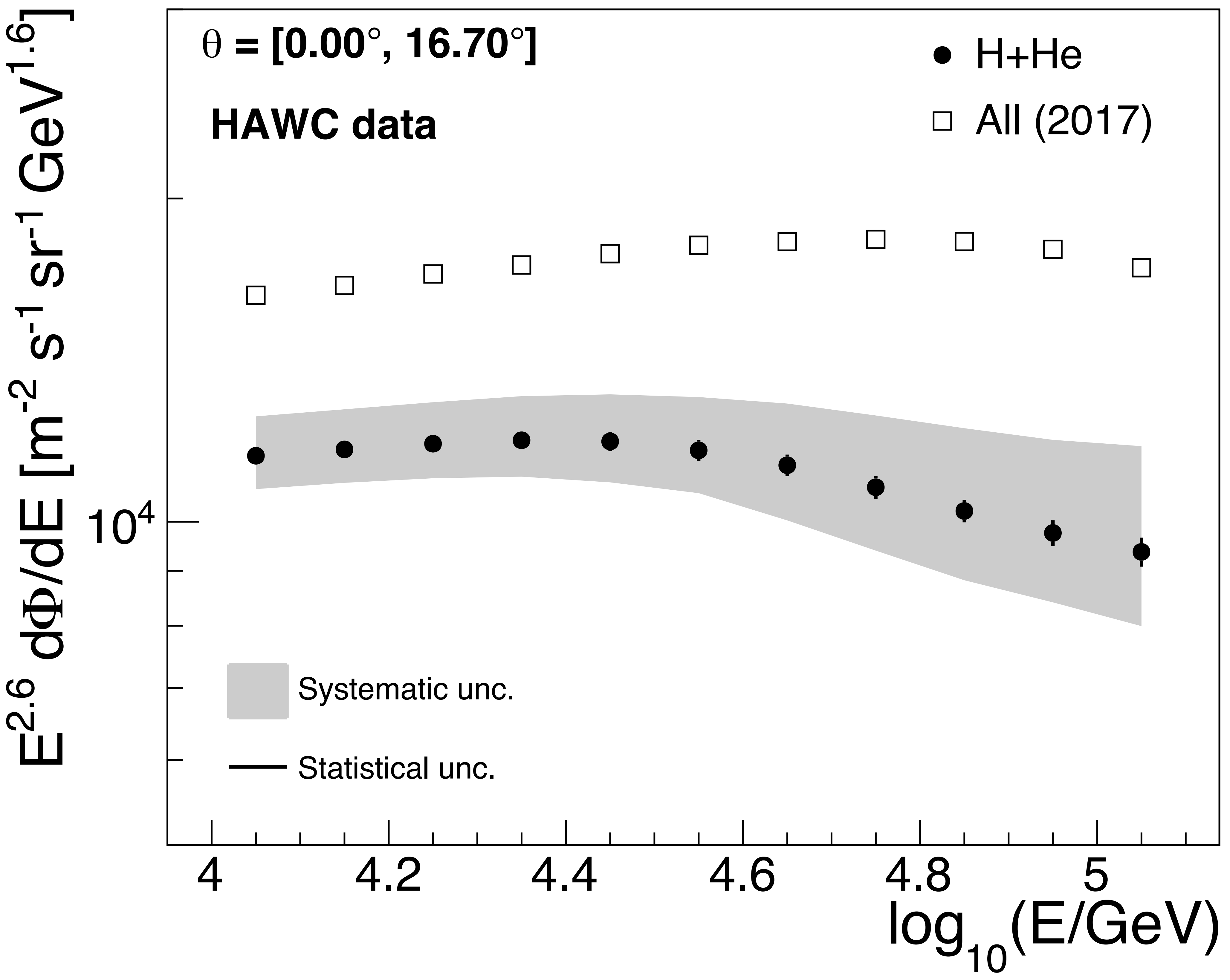


- Effective area of H+He in subsample

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

6) H + He energy spectrum

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



- Energy spectrum was calculated as:

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

Statistical and systematic uncertainties

H+He

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

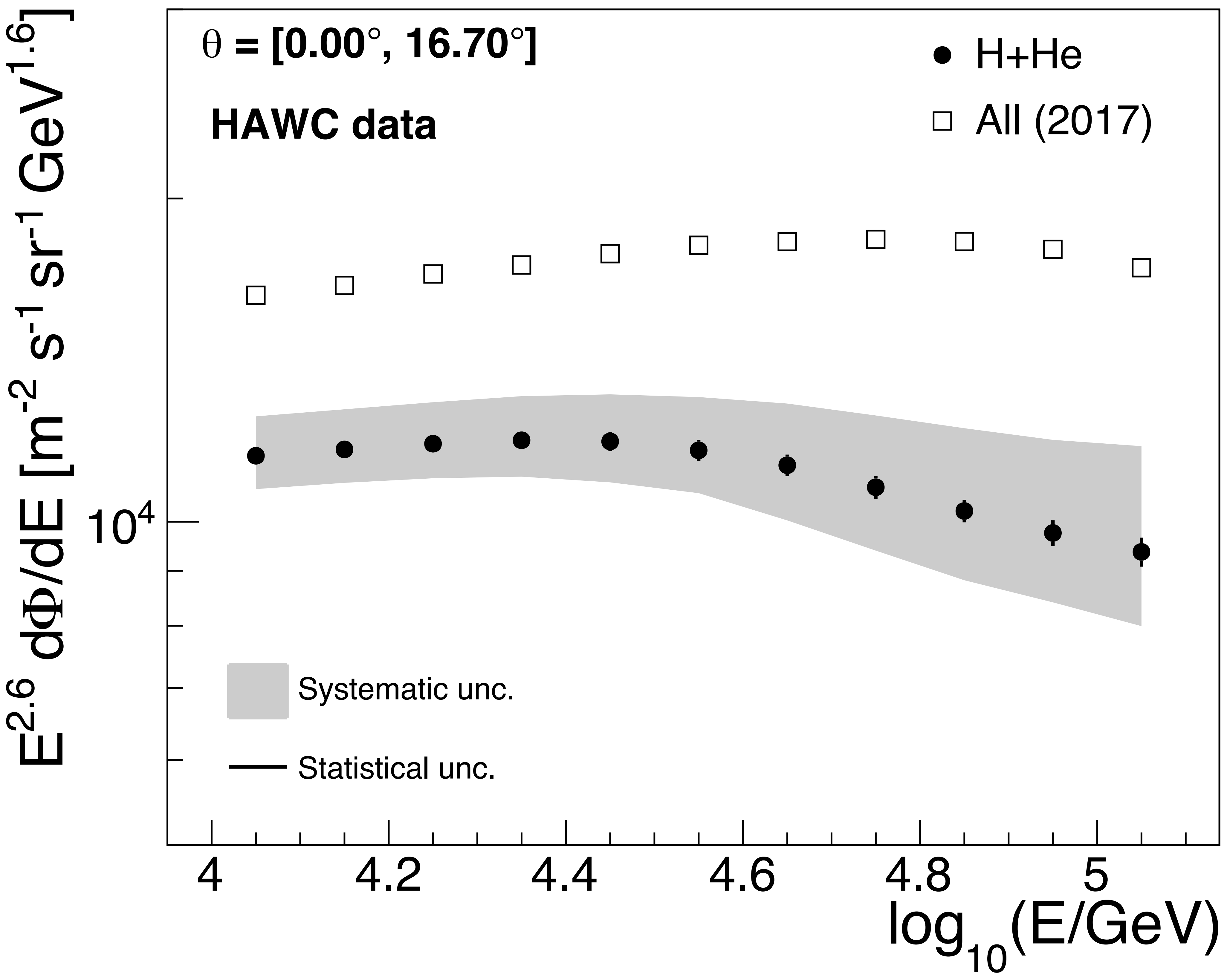
	Relative error Φ (%)
Statistical	**+/- 2.25**
Exp. Data	+/- 0.01
Response matrix	+/- 2.25
Systematic	**+12.10/-8.77**
Composition	+0.41/-5.47
Aeff	+1.33/-1.71
Cut at He or C	+2.43/-2.59
Gold unfolding	-0.41
Seed unfolding	-0.67
Smoothing unfold.	-0.87
Bin size	+0.27
PMT efficiency	+3.99/-0.16
PMT threshold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

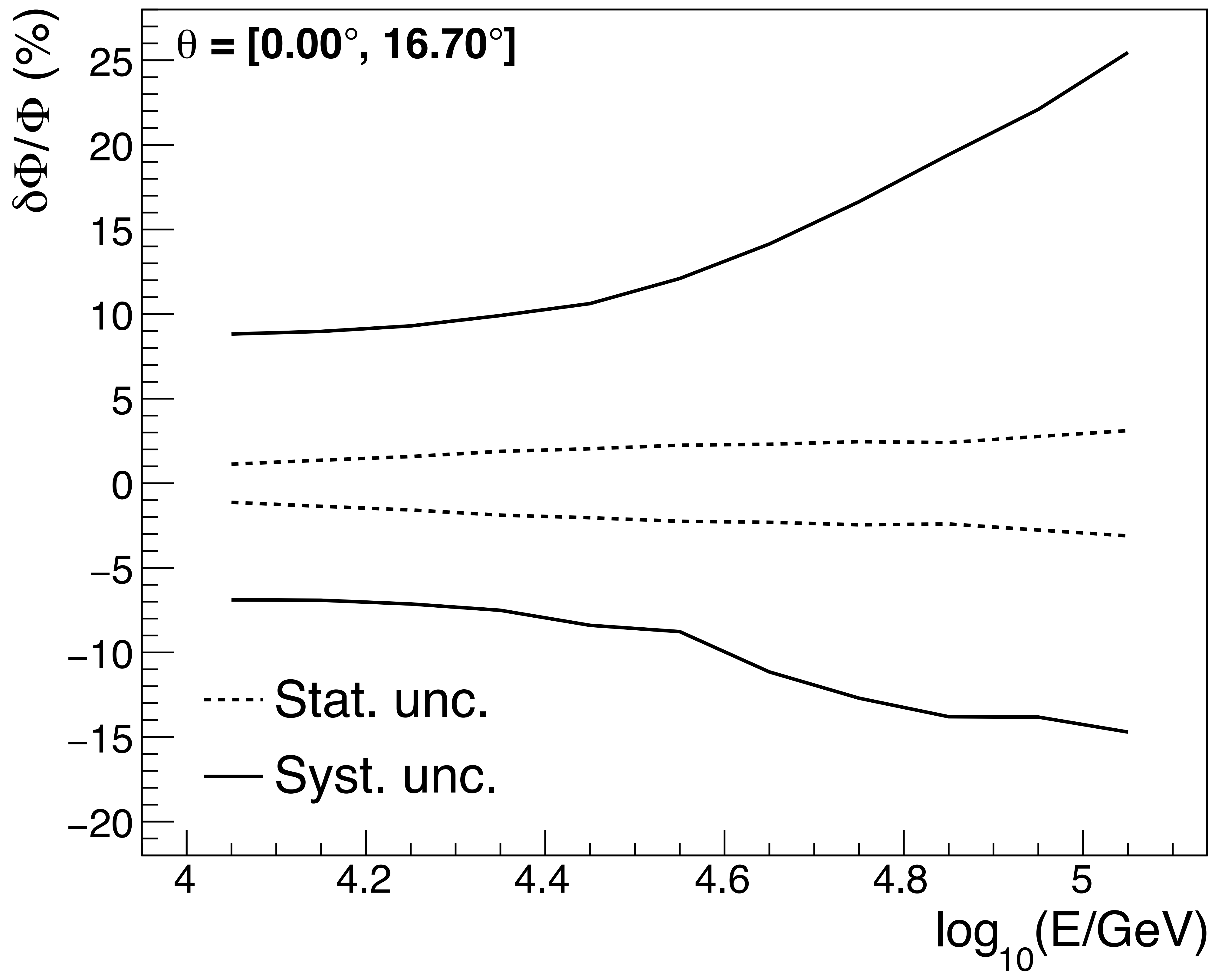
6) H + He energy spectrum

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

Statistical and systematic uncertainties

H+He





- Energy spectrum was calculated as:

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

Fit of spectrum

H+He

1. Use following functions:

—> Single power law:

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

—> Double power law:

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

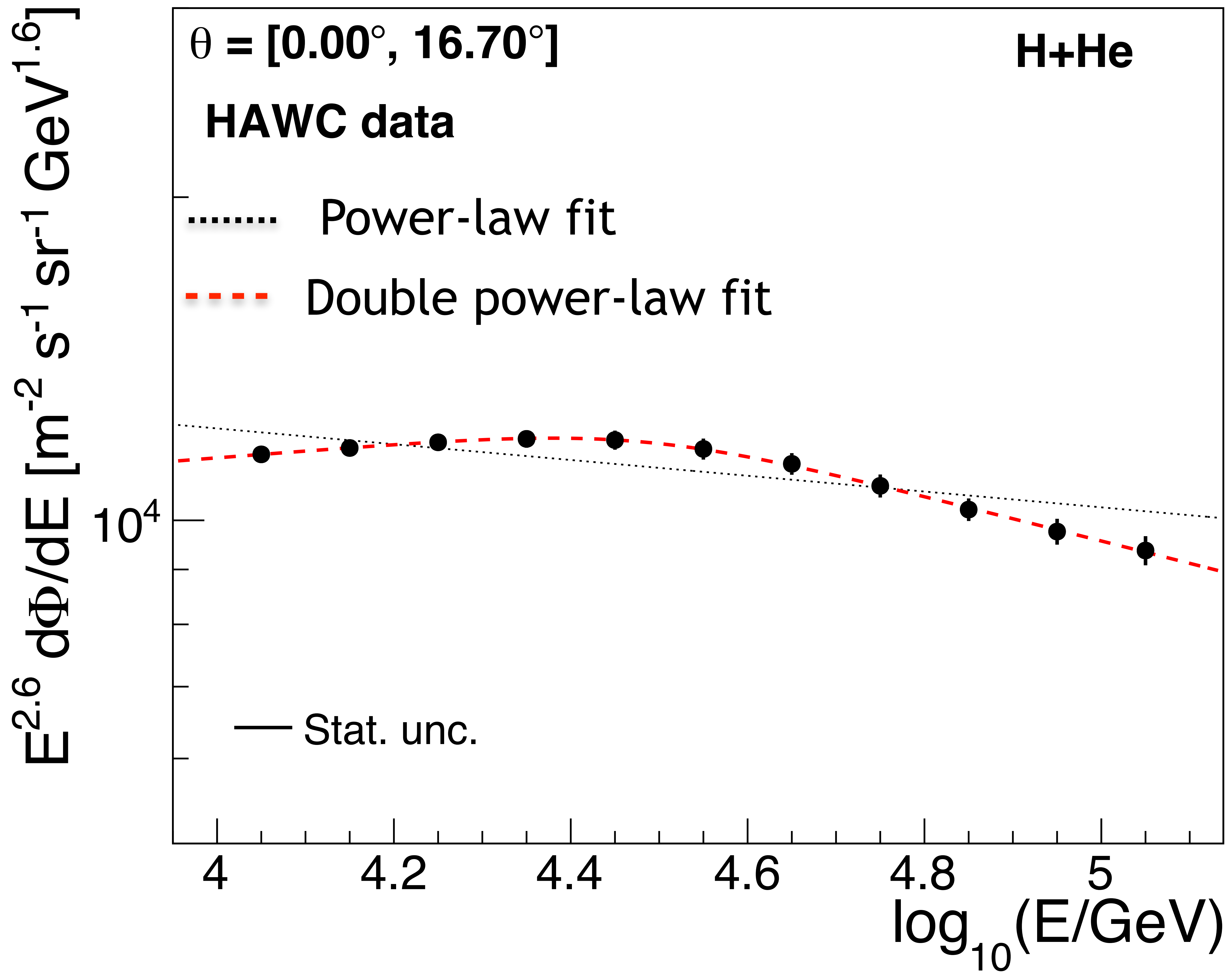
2. Minimize χ^2 with MINUIT and take into account correlation between points:

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

PDG (2017)

Fit of spectrum

H+He



- **Test Statistics:**
  TS = $-\Delta\chi^2 = 42.18$
  p-value ≤ 1.95×10^{-4}

-> 3.6σ deviation from scenario with single power-law: unlikely that data is described by a single power-law.

- Results for the double power-law fit:

$\gamma_1 = -2.54 \pm 0.07$

$\gamma_2 = -2.81 \pm 0.06$

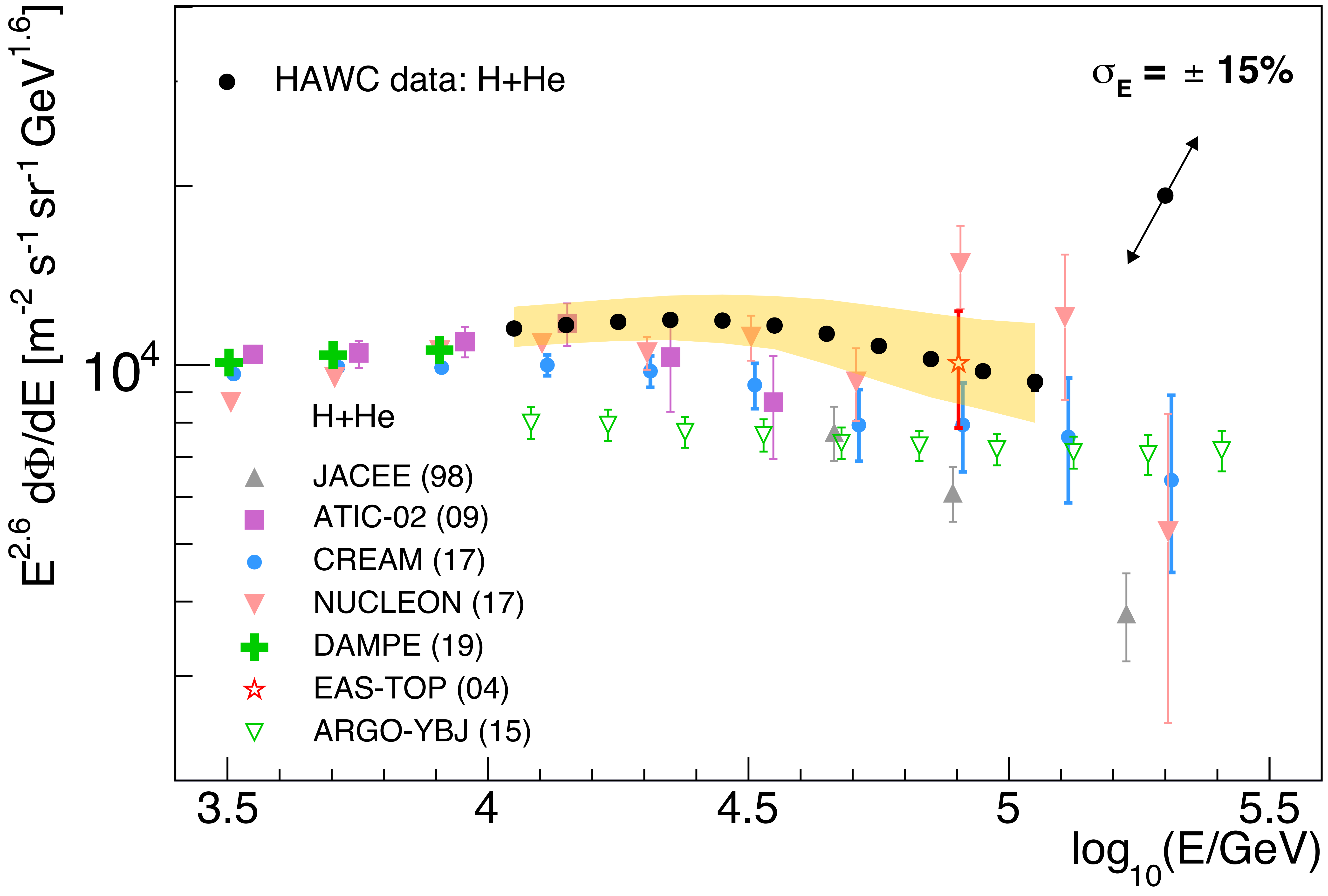
$\Delta\gamma = -0.27 \pm 0.09$

$\log_{10}(E_0/GeV) = 4.48 \pm 0.12$

6) H + He energy spectrum

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** spectrum is shifted to higher energies with regard to ATIC-2 and CREAM data.
- **HAWC** data is in agreement with NUCLEON and EAS-TOP measurements.

7) 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