ALL-PARTICLE COSMIC-RAY ENERGY SPECTRUM MEASURED WITH HAWC

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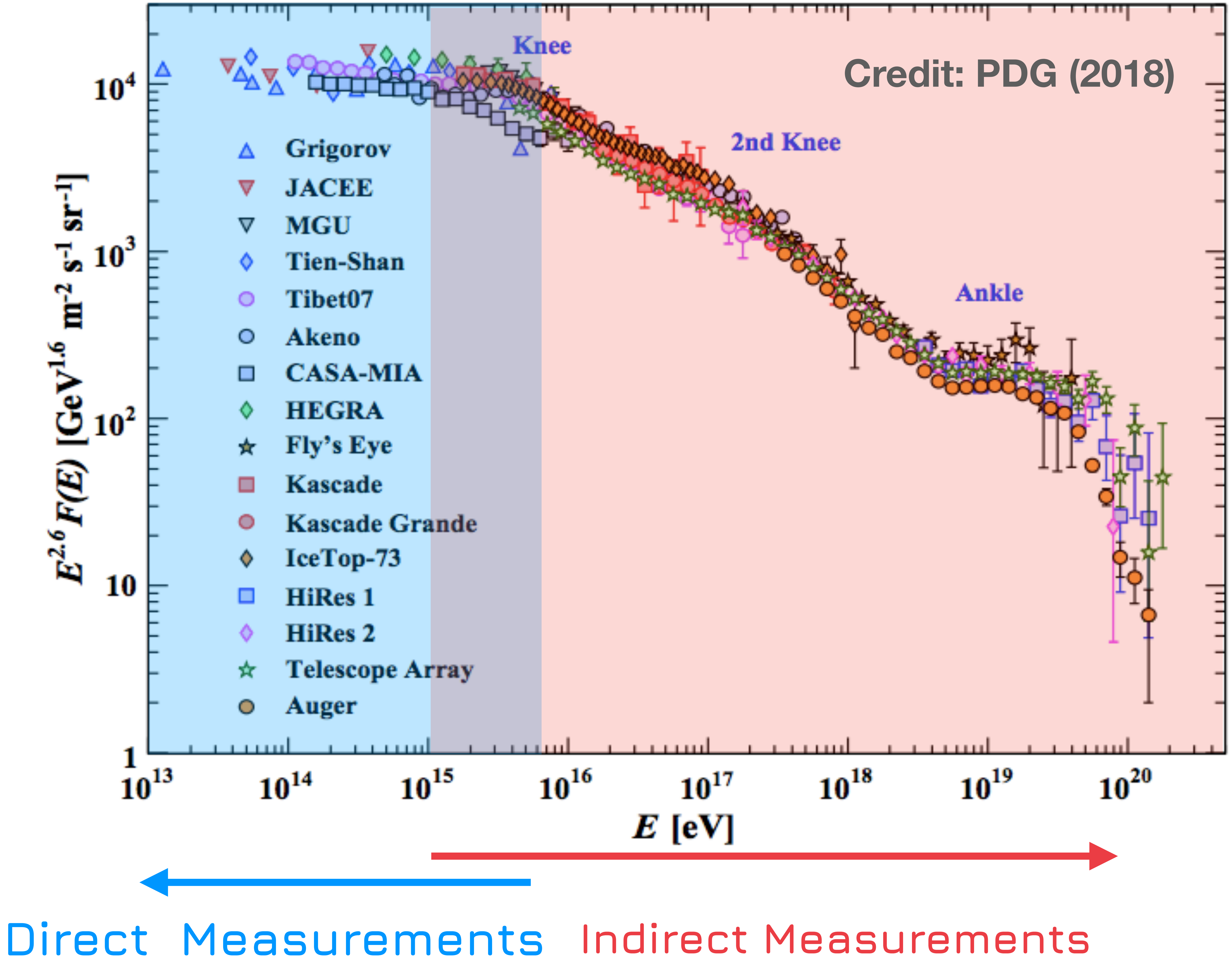
OUTLINE

1. Introduction.
2. The HAWC Observatory.
3. Analysis and results.
4. Conclusions.

Introduction

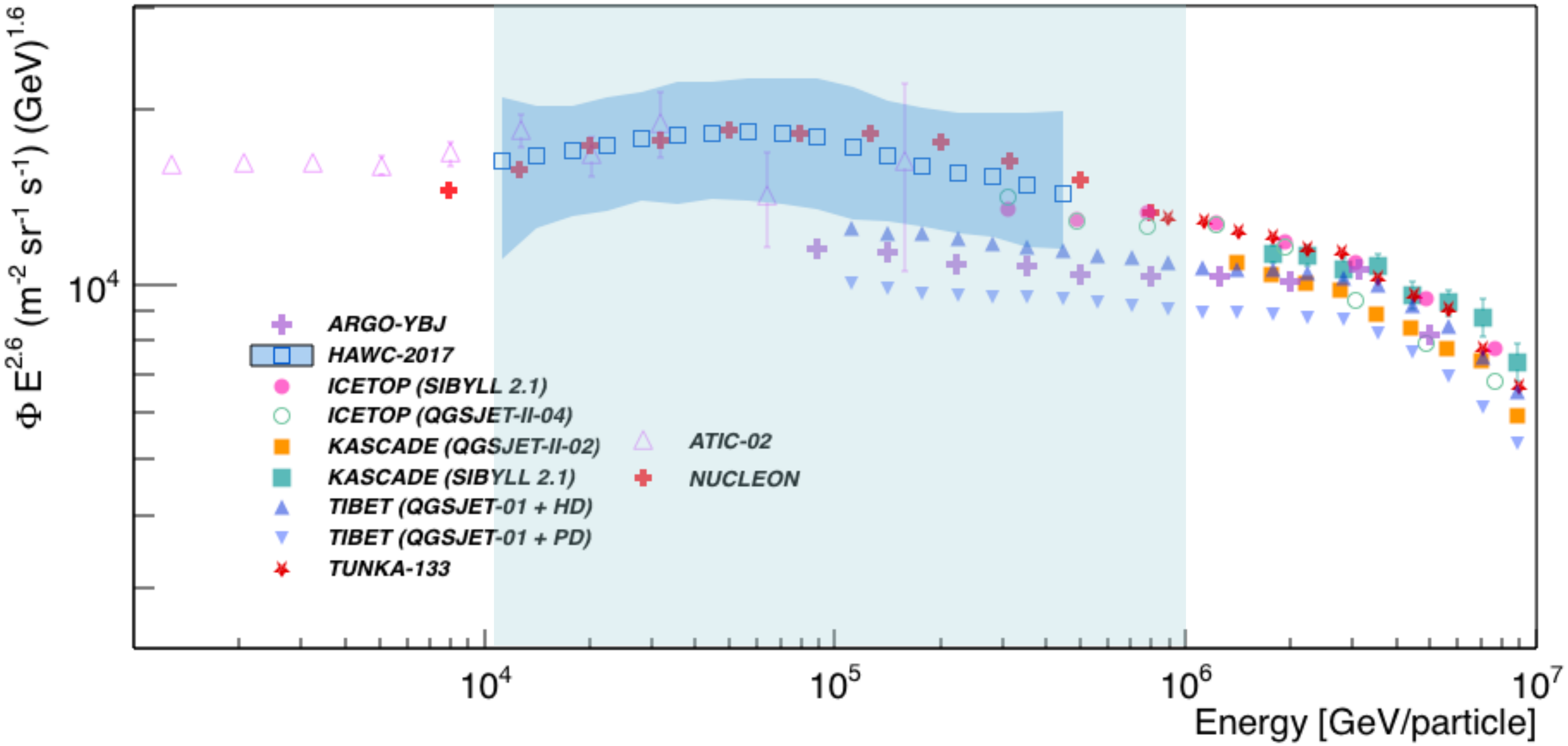
1.1 ENERGY SPECTRUM OF COSMIC RAYS



- The energy spectrum of cosmic rays contains key information, which can help to unravel some of the mysteries behind the origin and propagation of these particles.
- Yet, the spectrum has not been completely explored, in particular between 1 TeV and 1 PeV.

1.1 ENERGY SPECTRUM OF COSMIC RAYS

HAWC's previous result: measurement of the all-particle energy spectrum *from 10 to 500 TeV* with 8 months of data [1].

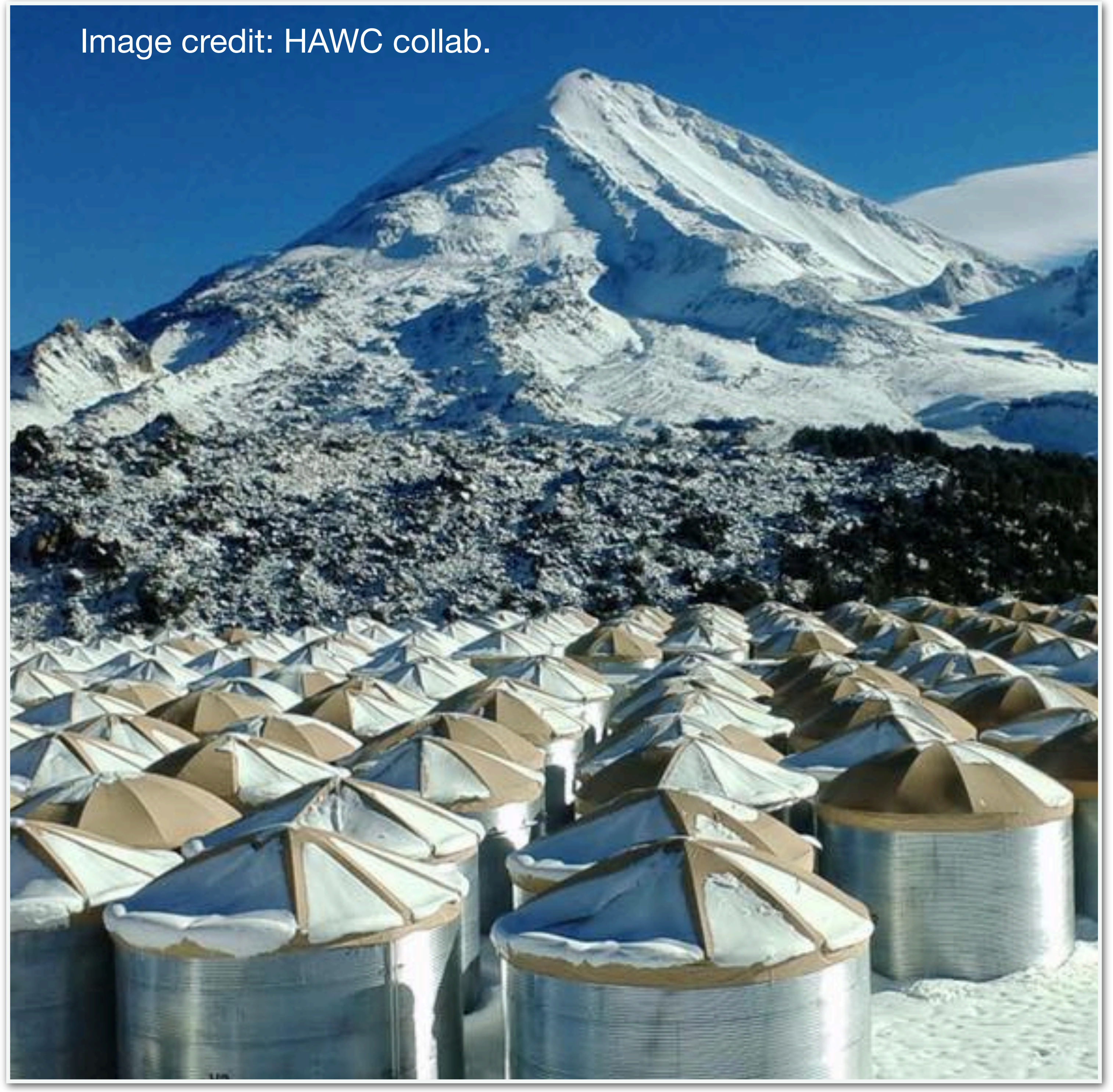


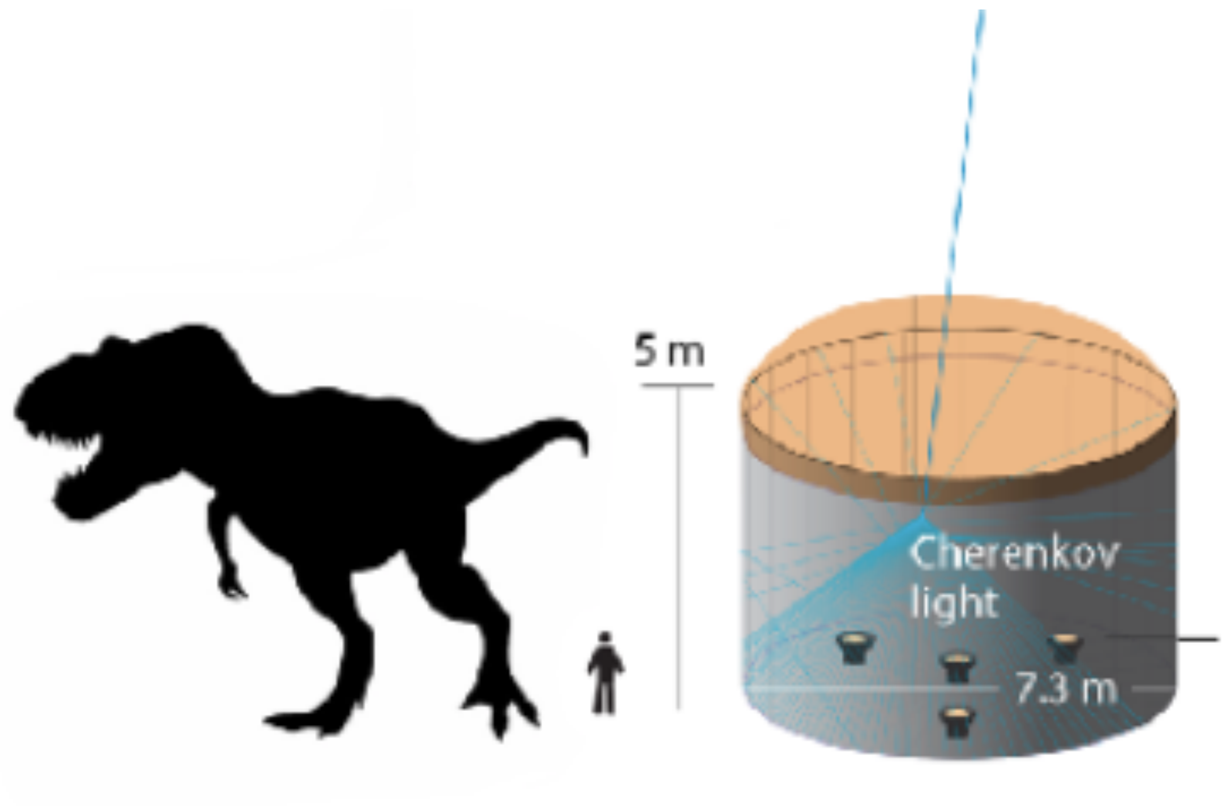
Our main goal is to extend this study up to 10^{15} eV with HAWC using improved statistics.

The HAWC Observatory

2.1 HAWC

- Among the main scientific objectives of HAWC are: to extend astrophysical measurements of gamma rays up to 100 TeV, as well as to study cosmic rays between 100 GeV and 1 PeV [2].
- Located between Pico de Orizaba and Sierra Negra volcanoes.
- 4100 m a.s.l.
- Area of 22000 m^2 (62% physical coverage).
- 300 Water Cherenkov detectors.
- 1200 photomultipliers.

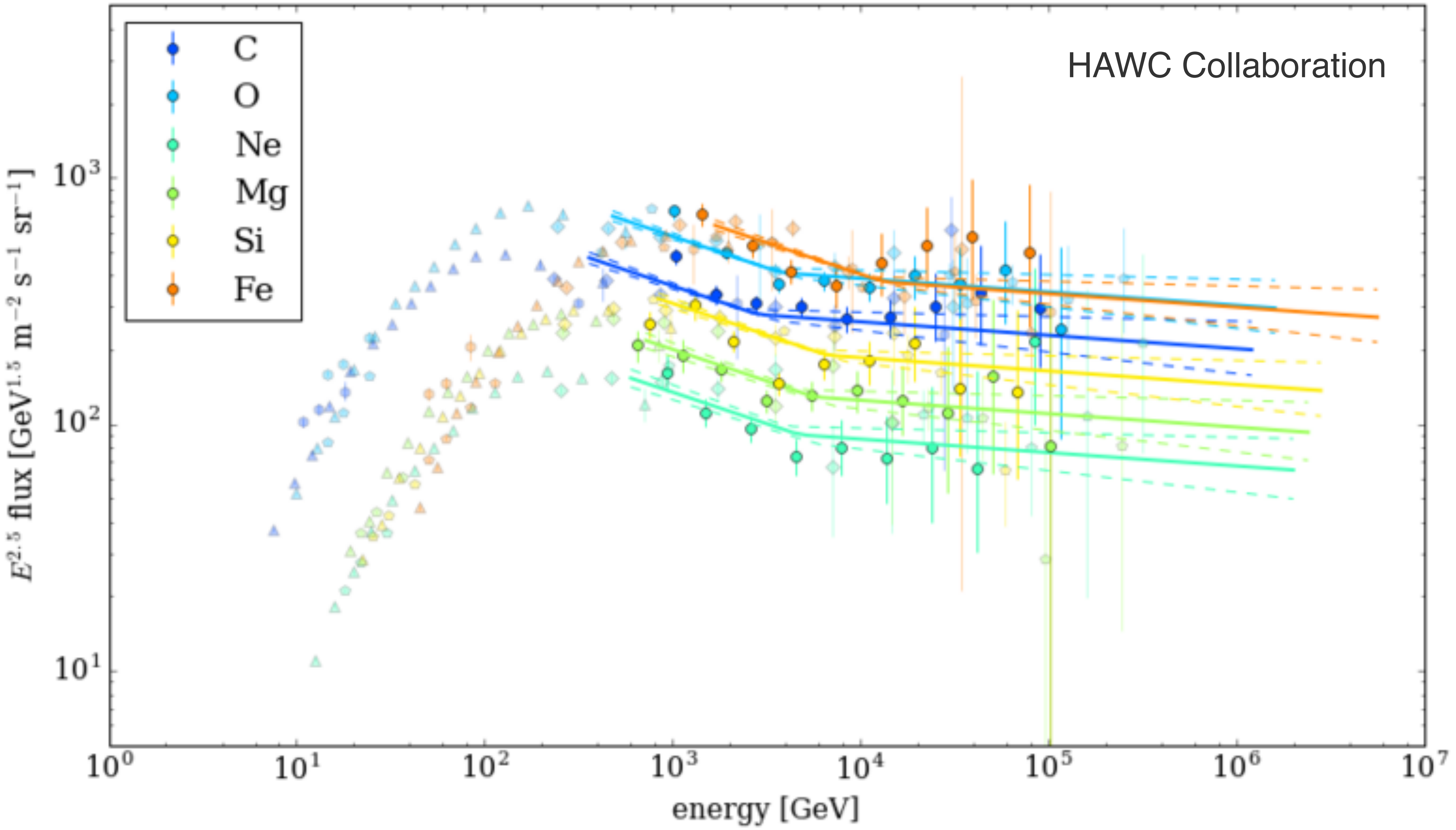




2.2 SIMULATIONS

- Showers were simulated with Corsika (v7.4) [3].
- Hadronic interaction models: FLUKA [4] ($E < 80$ GeV) and QGSJet-II-04 [5] ($E \geq 80$ GeV).
- The interactions between secondary particles and HAWC's detectors were simulated with GEANT4 [6].

- Simulated nuclei: ^{1}H, ^{4}He, …, ^{56}Fe. Spectra were weighted according to fits to CREAM, PAMELA and AMS [1].
- E = 5 GeV - 3 PeV.
- Homogeneously distributed over a circular area with 1000 m of radius.
- Isotropic flux.



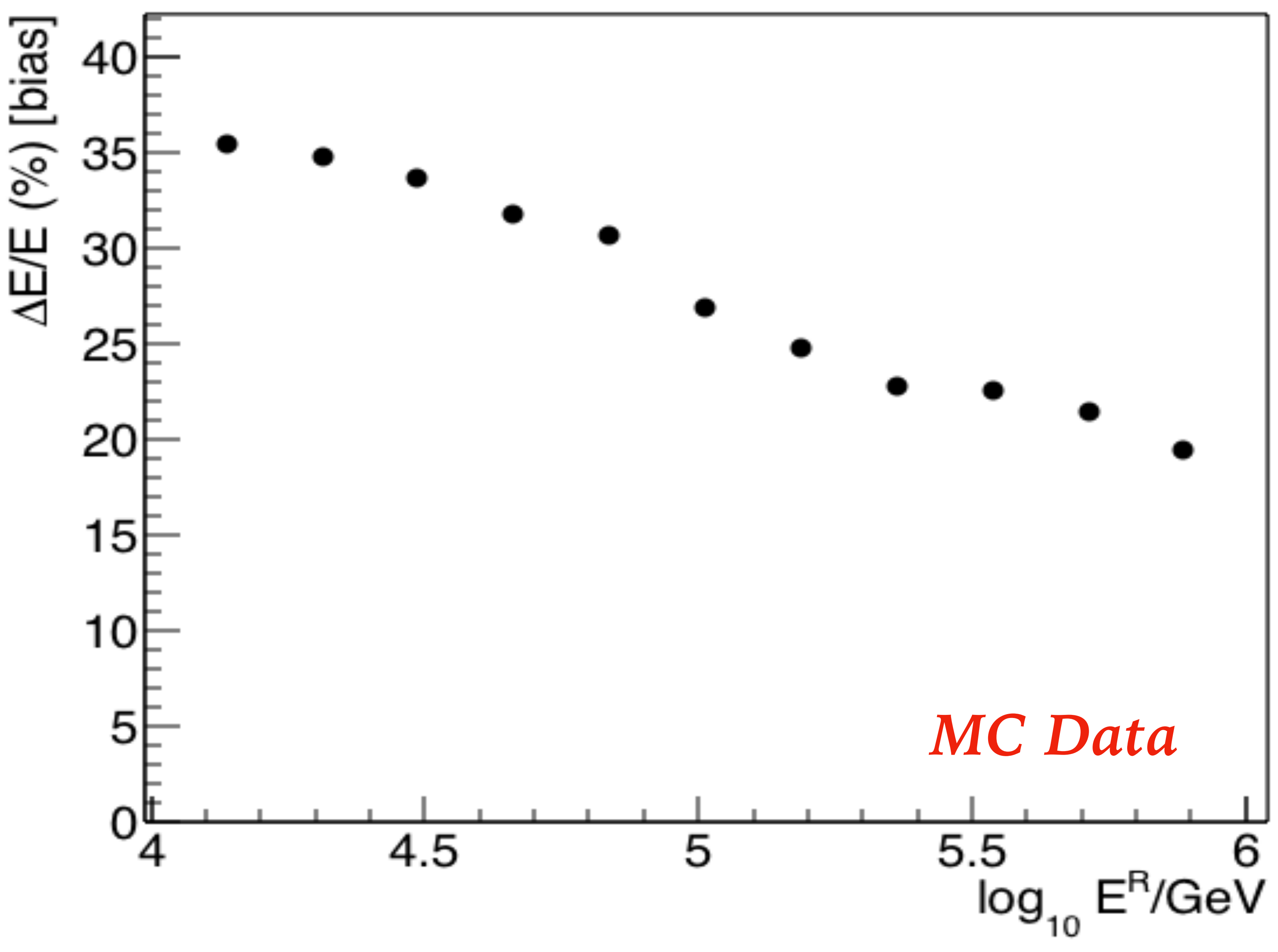
2.3 DATA SELECTION

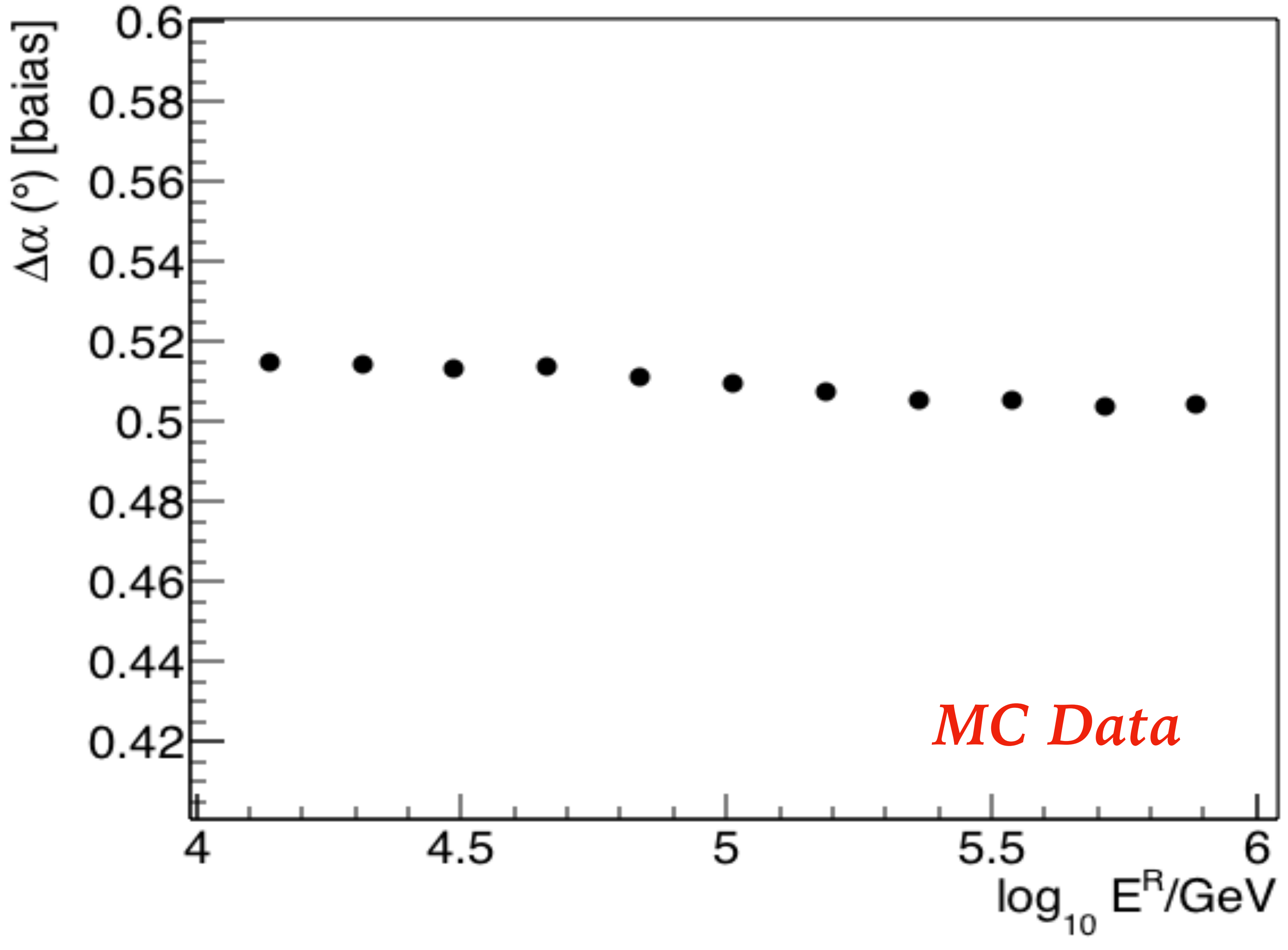
- Some quality cuts were applied to HAWC's data (simulated and measured) to diminish the systematic effects in the core position and the arrival direction.

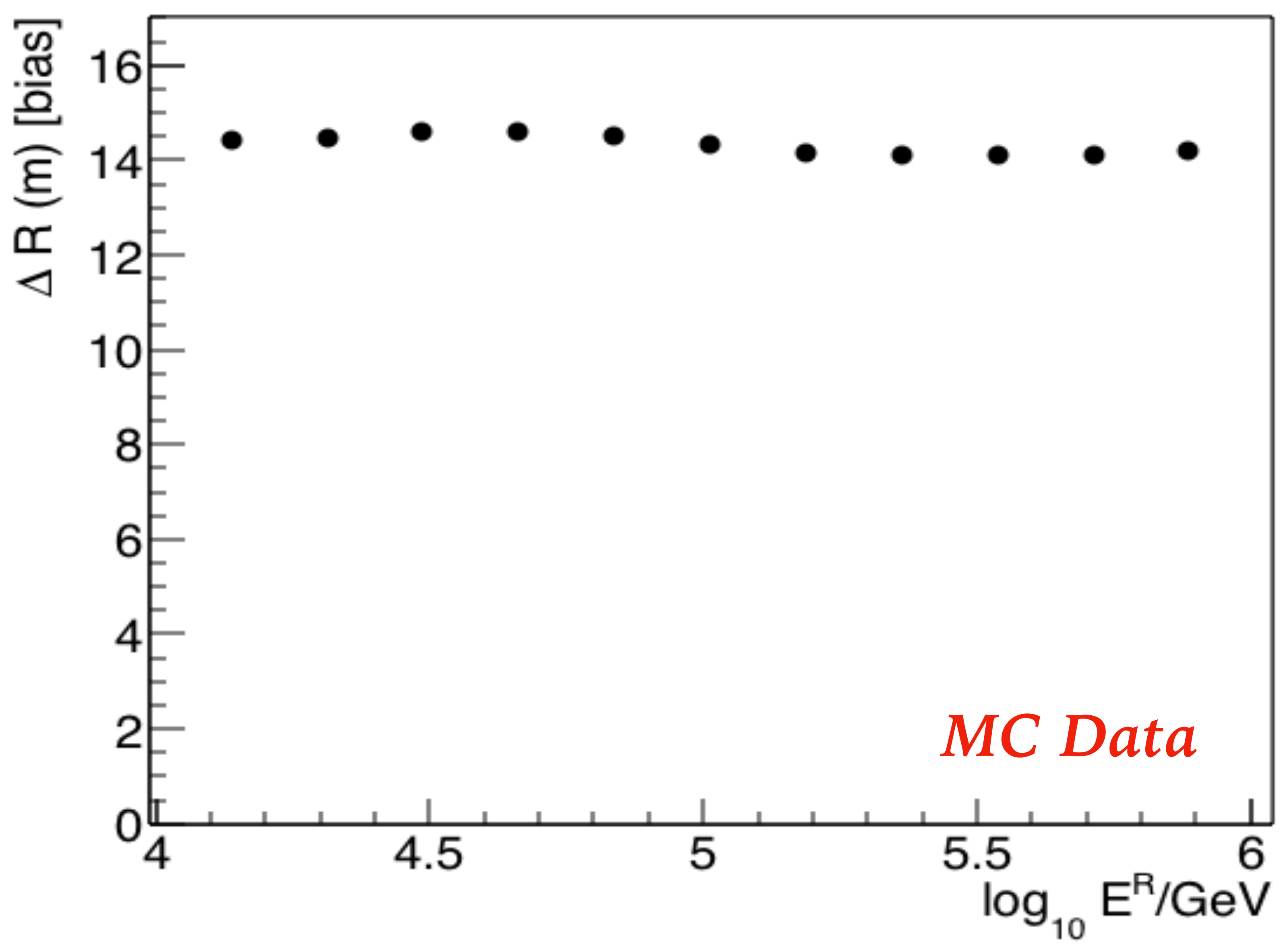
- The selected events:

  - with $\theta < 35°$,
  - activated at least 60 channels in a radius of 40 m from the shower core.
  - fell inside HAWC's area,
  - registered signal in, at least, 75 channels from a total of 1200,
  - and activated more than 30% of the available channels.

2.4 ENERGY, ANGULAR AND CORE POSITION BIAS







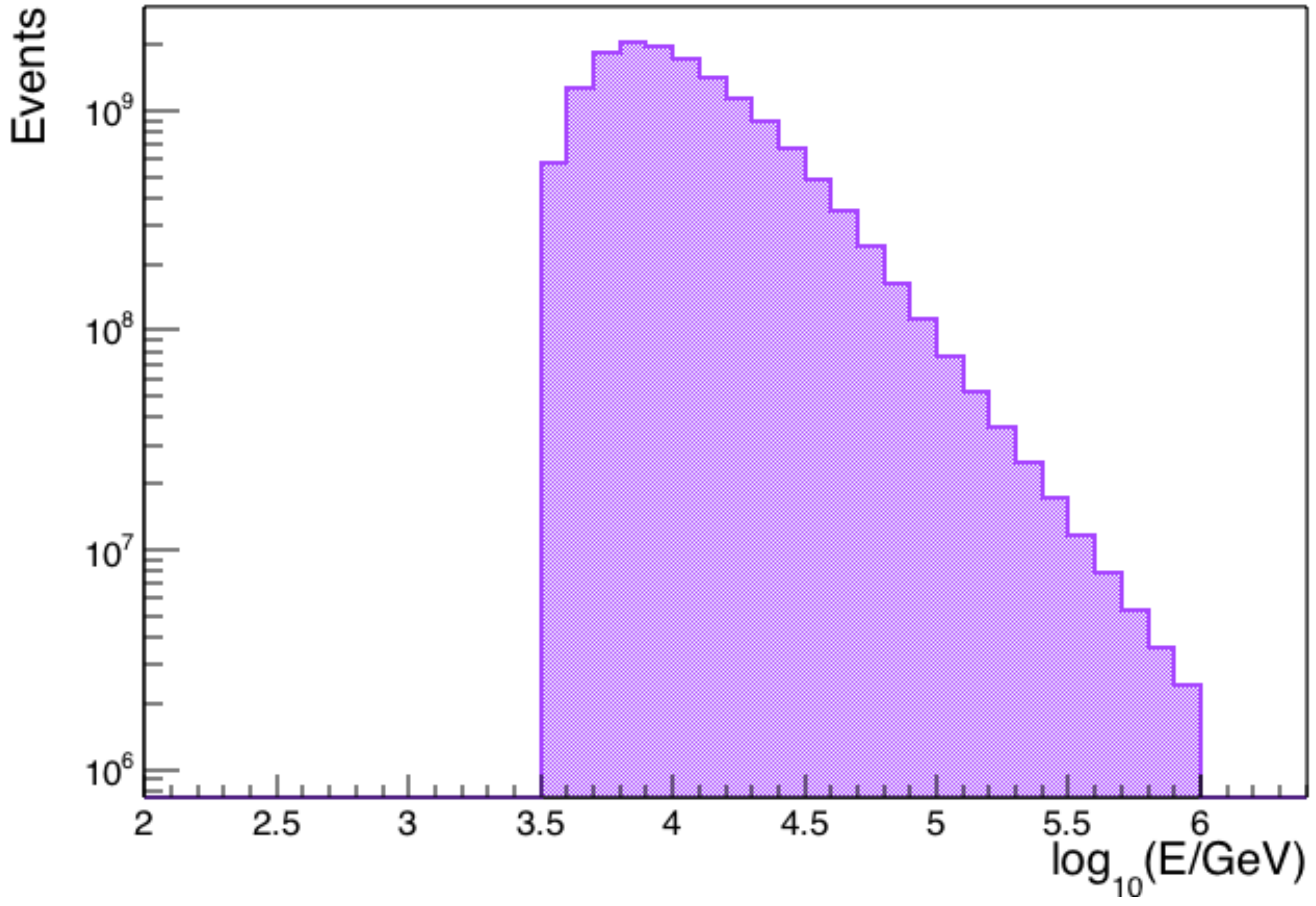
$$@\ E = 10^4\ \text{GeV} \begin{cases} \Delta\alpha = 0.52^\circ \\ \Delta R = 14.5m \\ \Delta E/E = 36\,\% \end{cases}$$

Analysis and results

3.1 HAWC'S MEASURED DATA

- A subsample of events taken from January 1st, 2018 to December 31st, 2019 were selected for this work.

- Only air showers within $E = 10^{3.5} - 10^{6}$ GeV were employed.



$N(E^R)$: Measured energy distribution after quality cuts

Total time	#events before cuts	#events after cuts
703 days	1.3638×10^{12}	1.5052×10^{10}

3.2 ENERGY SPECTRUM ESTIMATION

From $N(E^R)$ we get $N(E^T)$

How? Iterative procedure, Bayesian Unfolding [7,8,9]

1) $P(E_j^R \mid E_i^T)$ .... Response Matrix (calculated from MC data)

2) $P(E_i^T \mid E_j^R) = \dfrac{P(E_j^R \mid E_i^T) P_0(E_i^T)}{\sum_l^{n_c} P(E_j^R \mid E_l^T) P_0(E_l^T)}\,.$ .... Bayes formula

3) $N(E_i^T) = \sum_{j=1}^{n_E} P(E_i^T \mid E_j^R) N(E_j^R) = \sum_{j=1}^{n_E} M_{ij} N(E_j^R)\,.$ .... True event distribution

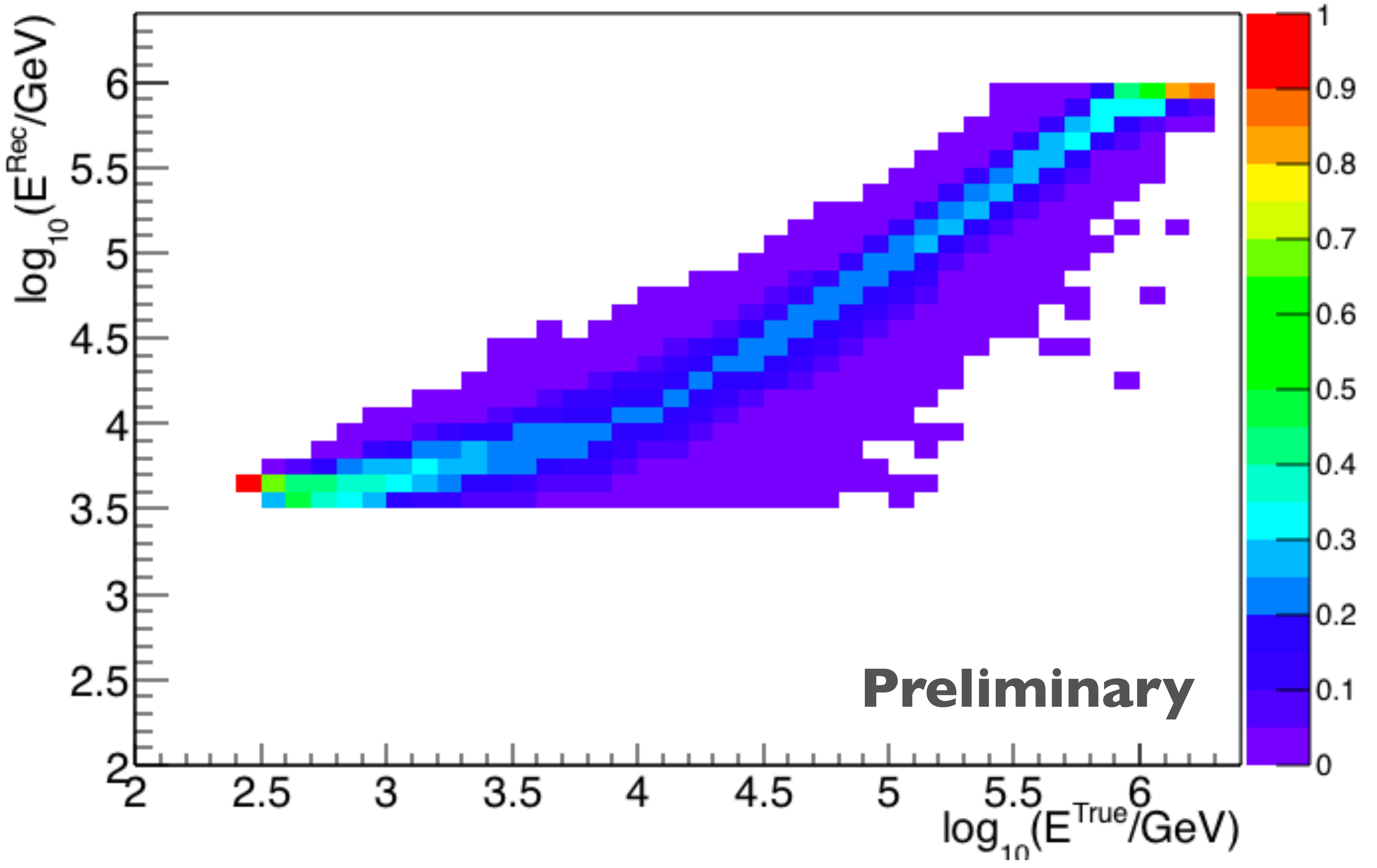
4) $P(E_i^T) \equiv \dfrac{N(E_i^T)}{\sum_{i=1}^{n_c} N(E_i^T)} = \dfrac{N(E_i^T)}{N_{true}}\,.$ .... Final probability

5) $WMSE = \dfrac{1}{n} \sum_{i=1}^{n} \dfrac{\bar{\sigma}_{stat,i}^2 + \bar{\delta}_{bias,i}^2}{N(E_i)}$ .... Weighted mean squared error (The minimum is employed as a stopping criteria for the iteration depth)

3.2 ENERGY SPECTRUM ESTIMATION

Inputs from MC data

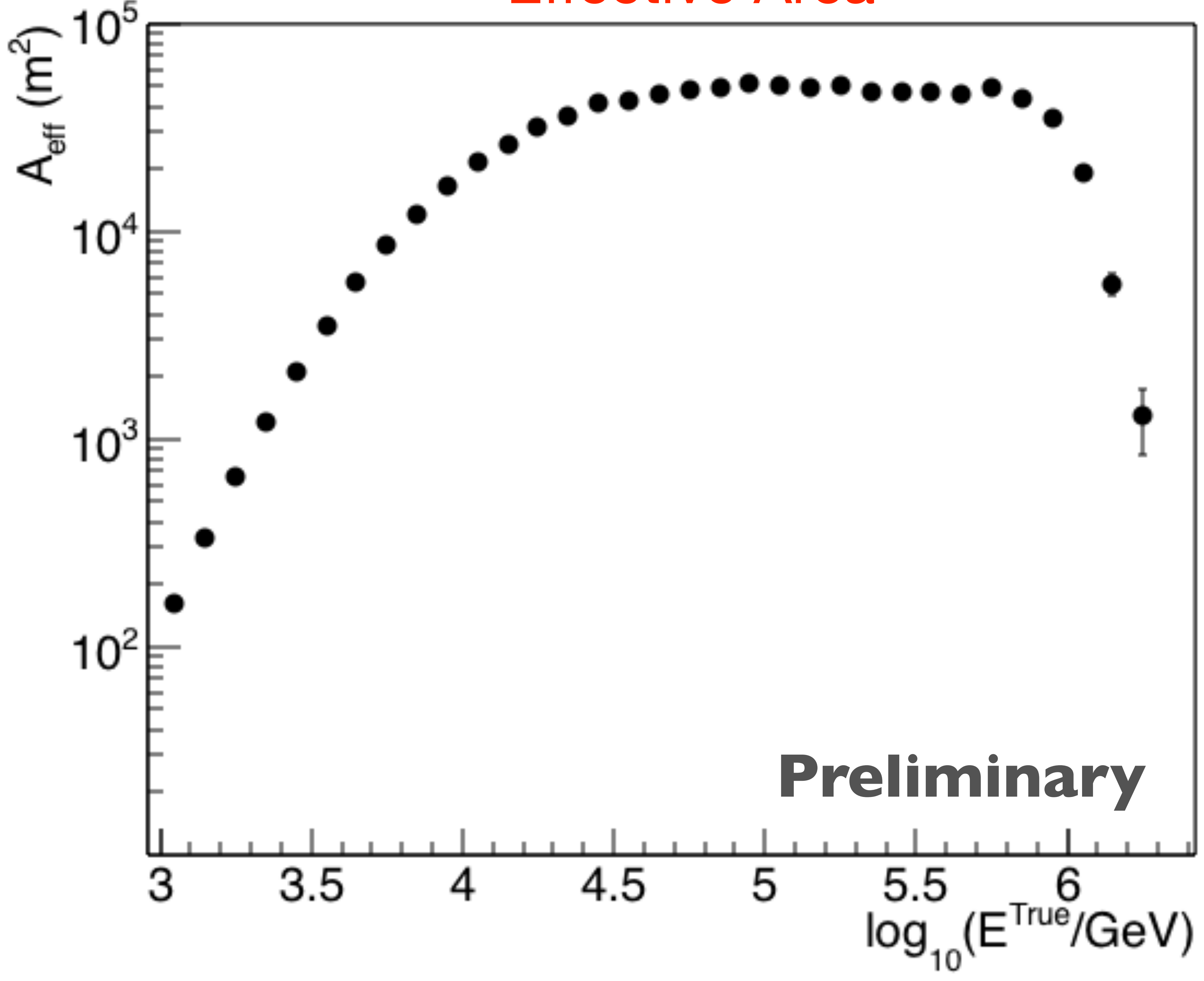
Response Matrix



HAWC's response becomes linear for

E > 10^4 GeV

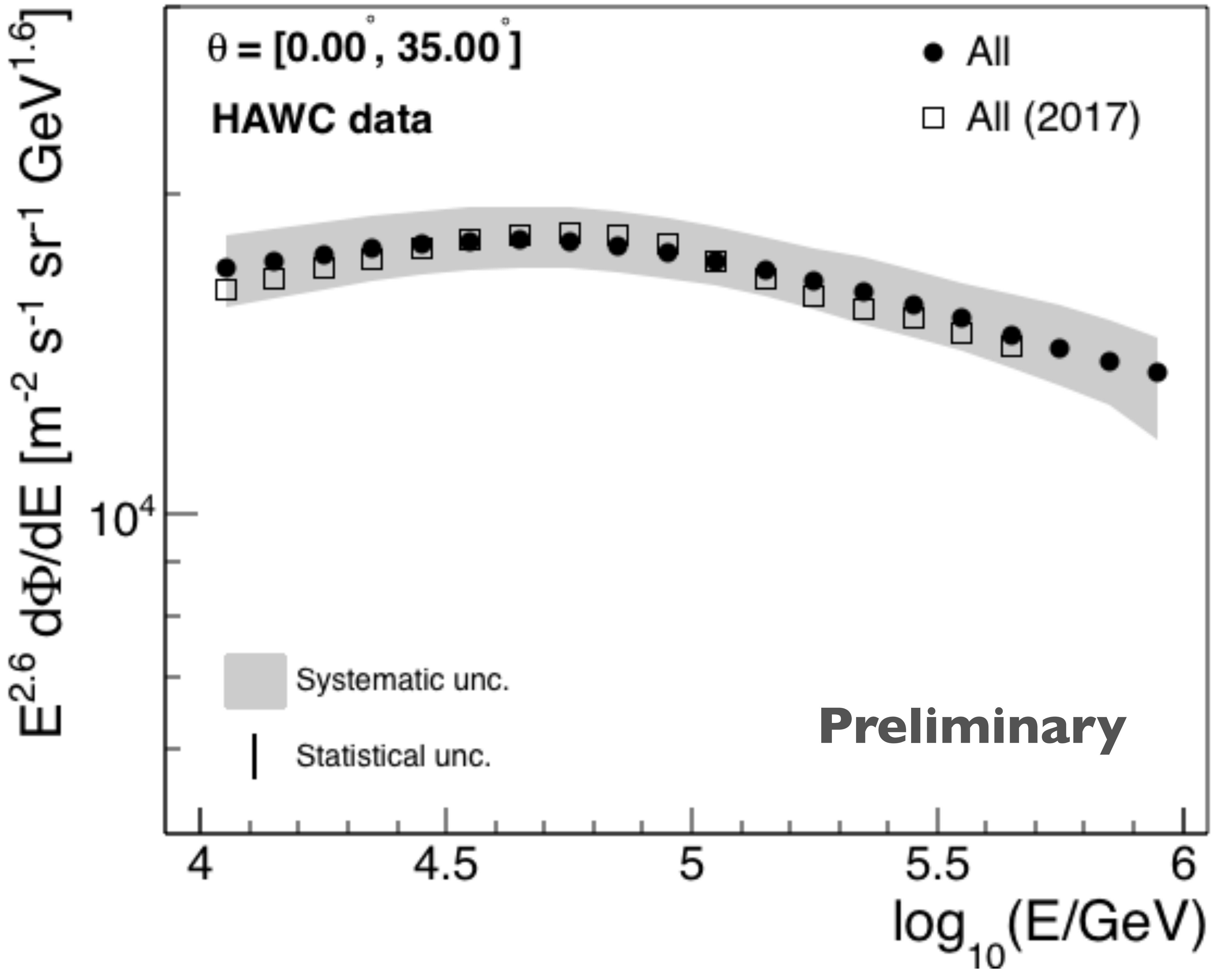
Effective Area



Maximum trigger and reconstruction efficiency for E > 10^4 GeV

$$A_{eff}(E) = A_{thrown} \cdot \epsilon(E)$$

3.2 ENERGY SPECTRUM ESTIMATION



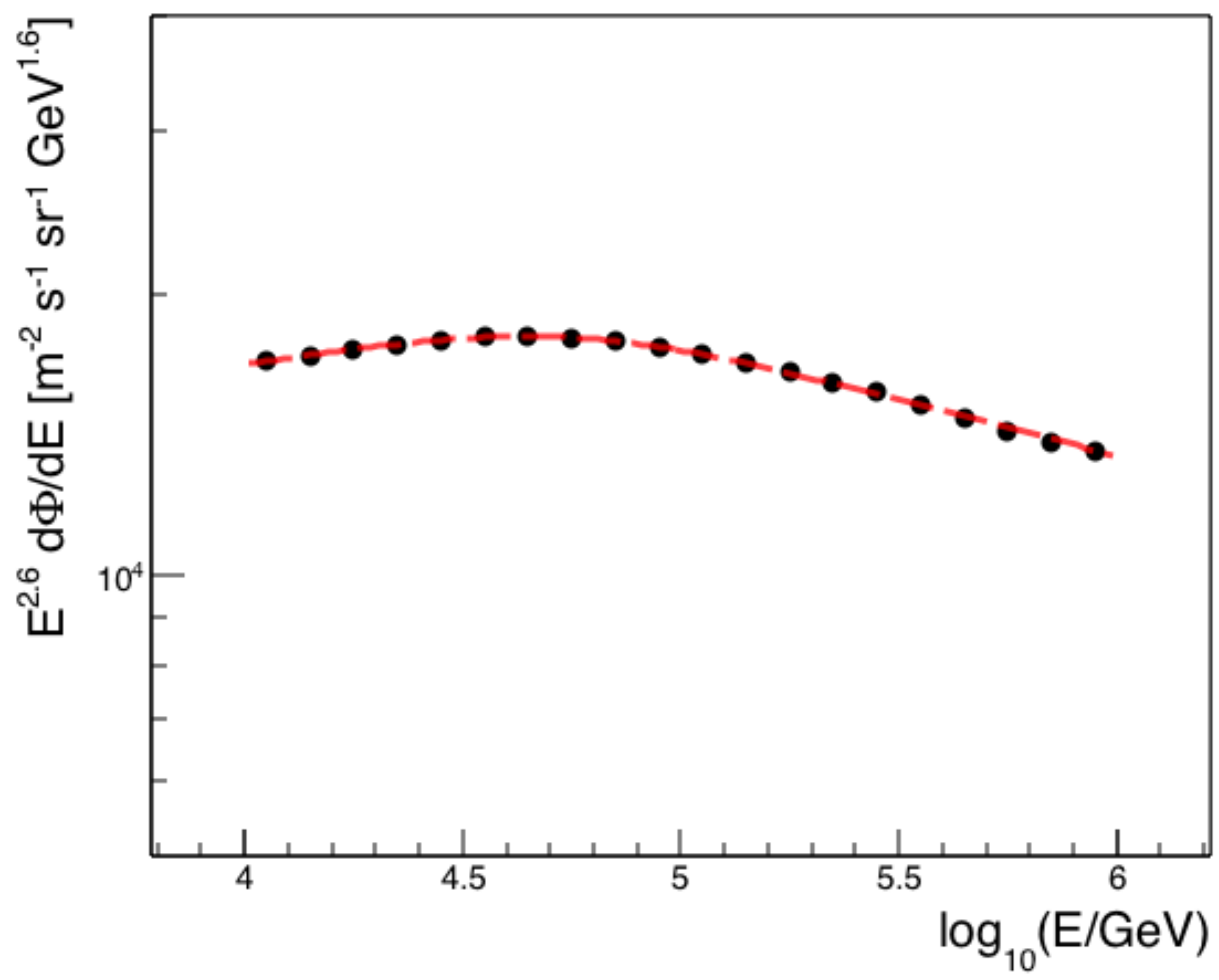
All-particle cosmic ray energy spectrum measured by HAWC

$$\Phi(E) = \frac{N(E^R)}{\Delta E \Delta t \left(\int_0^{2\pi} \int_{\theta 1}^{\theta 2} cos(\theta) d\Omega \right) A_{eff}}$$

Systematic error band contributions [7]:

1. PMT efficiency,
2. PMT late light,
3. PMT threshold,
4. PMT charge,
5. zenith angle,
6. unfolding technique,
7. seed and smoothing in unfolding,
8. effective area,
9. bin size,
10. composition model.

3.2 ENERGY SPECTRUM ESTIMATION



All-particle cosmic ray energy spectrum measured by HAWC

The spectrum was fitted with a broken power-law:

$$\Phi(E) = \Phi_0 E^{\gamma_1}\left[1 + \left(\frac{E}{E_0}\right)^{\epsilon}\right]^{(\gamma_2-\gamma_1)/\epsilon}$$

using a χ^2 minimization procedure.

$$\Phi_0 = 10^{3.929\pm0.005}\, m^{-2}\, s^{-1}\, sr^{-1}\, GeV^{-1}$$

$$\gamma_1 = -2.526 \pm 0.001$$

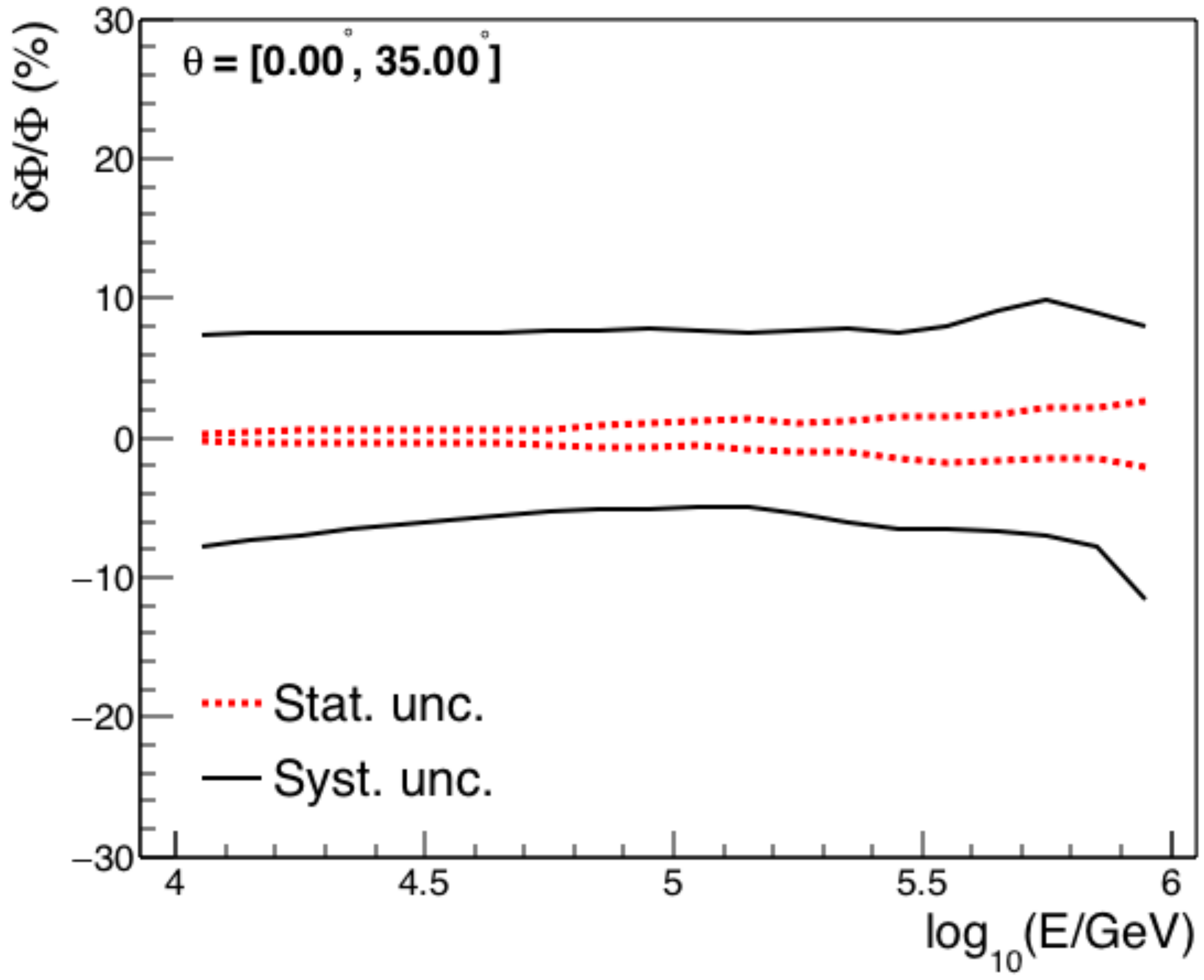
$$\gamma_2 = -2.729 \pm 0.011$$

$$\epsilon = 2.03 \pm 0.37$$

$$E_0 = (50.1 \pm 1.1)\,\text{TeV}$$

The break in the spectrum is shifted to large energies in comparison with the previous HAWC measurement (E_{knee} = 45.7 ± 1.1 TeV) [1].

3.3 UNCERTAINTIES ON THE FLUX



Statistical relative error @ 10^6 GeV:

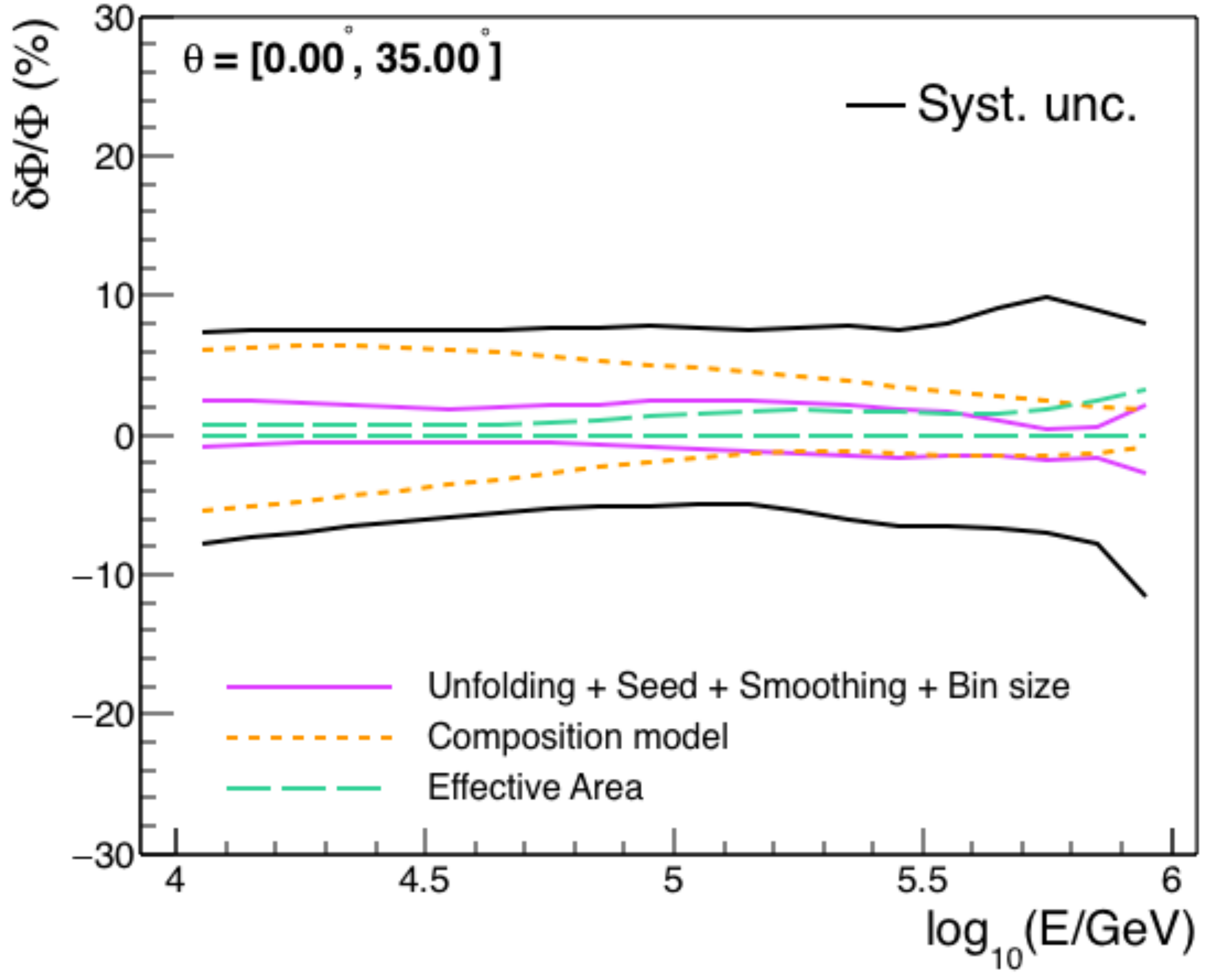
+2.8% -1.8%

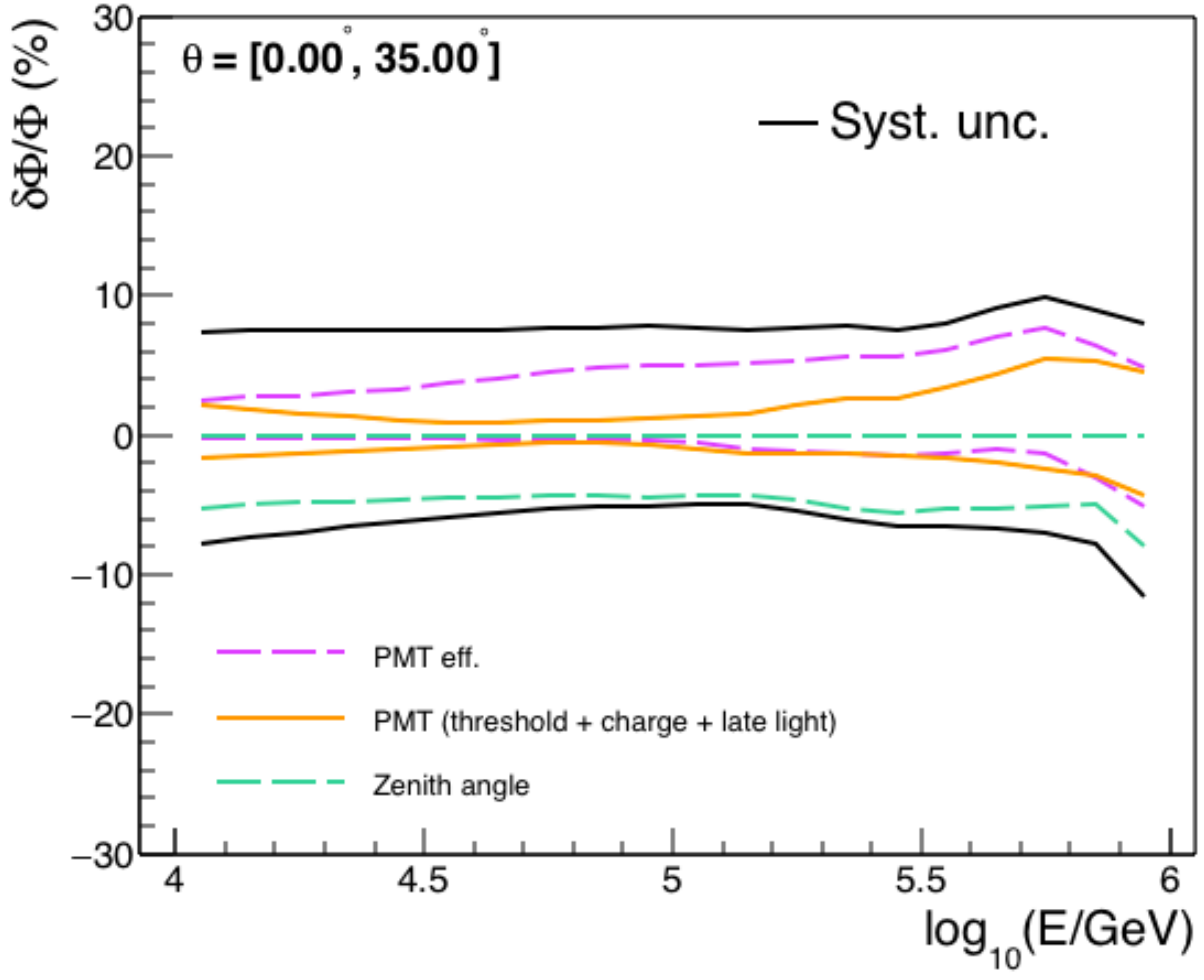
Systematic relative error @ 10^6 GeV:

+8.7% -13%

3.3 UNCERTAINTIES ON THE FLUX

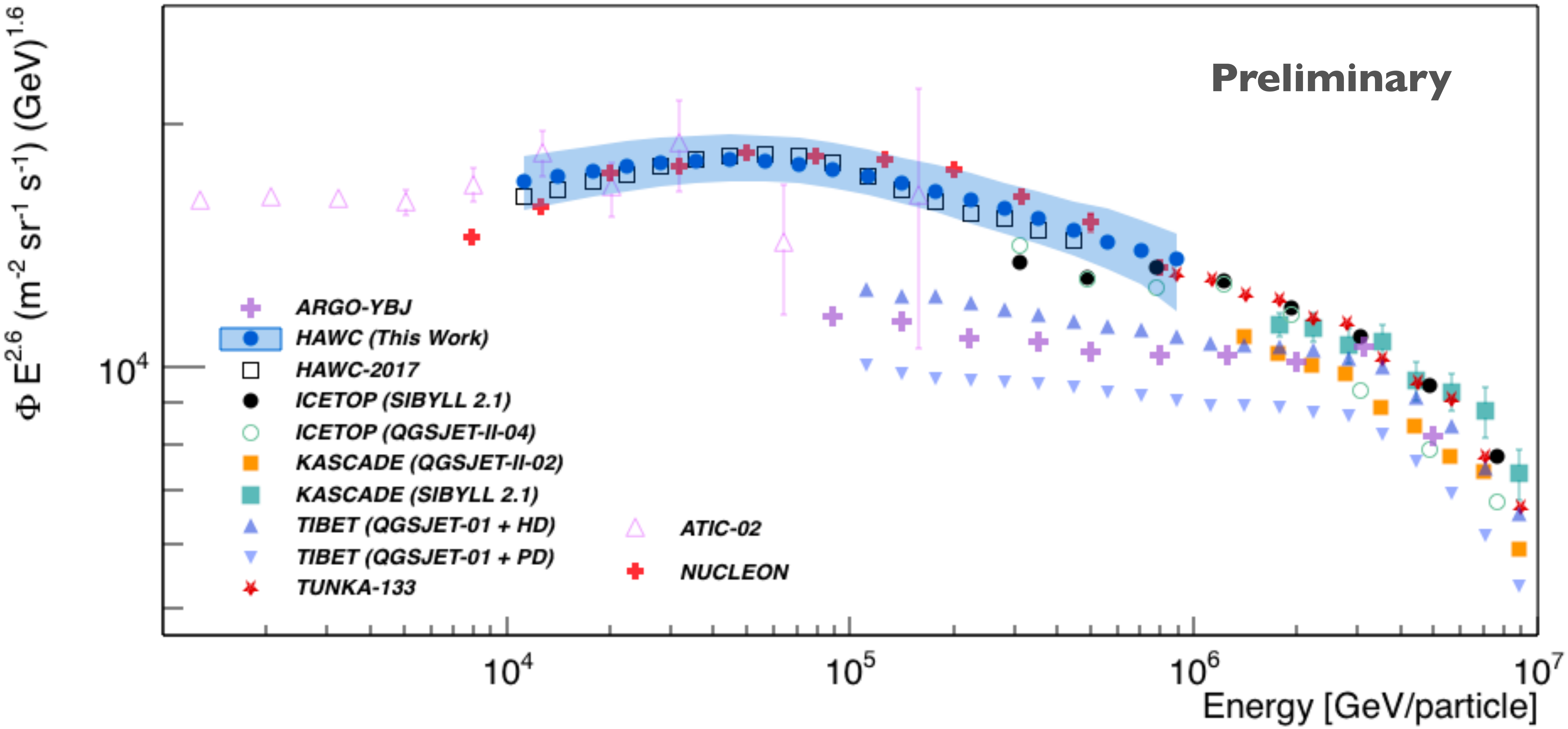
Systematic errors





Systematics dominated by: PMT efficiency, zenith angle and composition model.

3.4 ALL-PARTICLE COSMIC RAY ENERGY SPECTRUM



The all-particle cosmic ray energy spectrum obtained in this work compared with the results from direct and indirect cosmic ray experiments [11,18].

Conclusions

4.1 CONCLUSIONS

- We have extend the measurements of the energy spectrum of cosmic rays with HAWC up to 1 PeV using data with high-statistics.
- In addition to the measurements of NUCLEON, the results of this study offer a first bridge between direct and indirect measurements of the cosmic ray spectrum in the 10 TeV - 1 PeV range.
- We studied several sources of systematic errors. We found that they are dominated by the PMT efficiency, zenith angle, composition model, and bin size uncertainties.
- We found that, at an energy of E = 1 PeV, the statistical error on the flux is between +2.8% and -1.8%, while the corresponding systematic error is between +8.7% and -13%.
- The result of the all particle cosmic ray energy spectrum from this work is in agreement with the measurements from R. Alfaro et al., *PRD 96* (2017) 122001, and the results from NUCLEON [12].
- The systematic error on the flux due to the hadronic interaction model is under study by using the EPOS-LHC model.

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