The all-particle cosmic ray energy spectrum measured with HAWC

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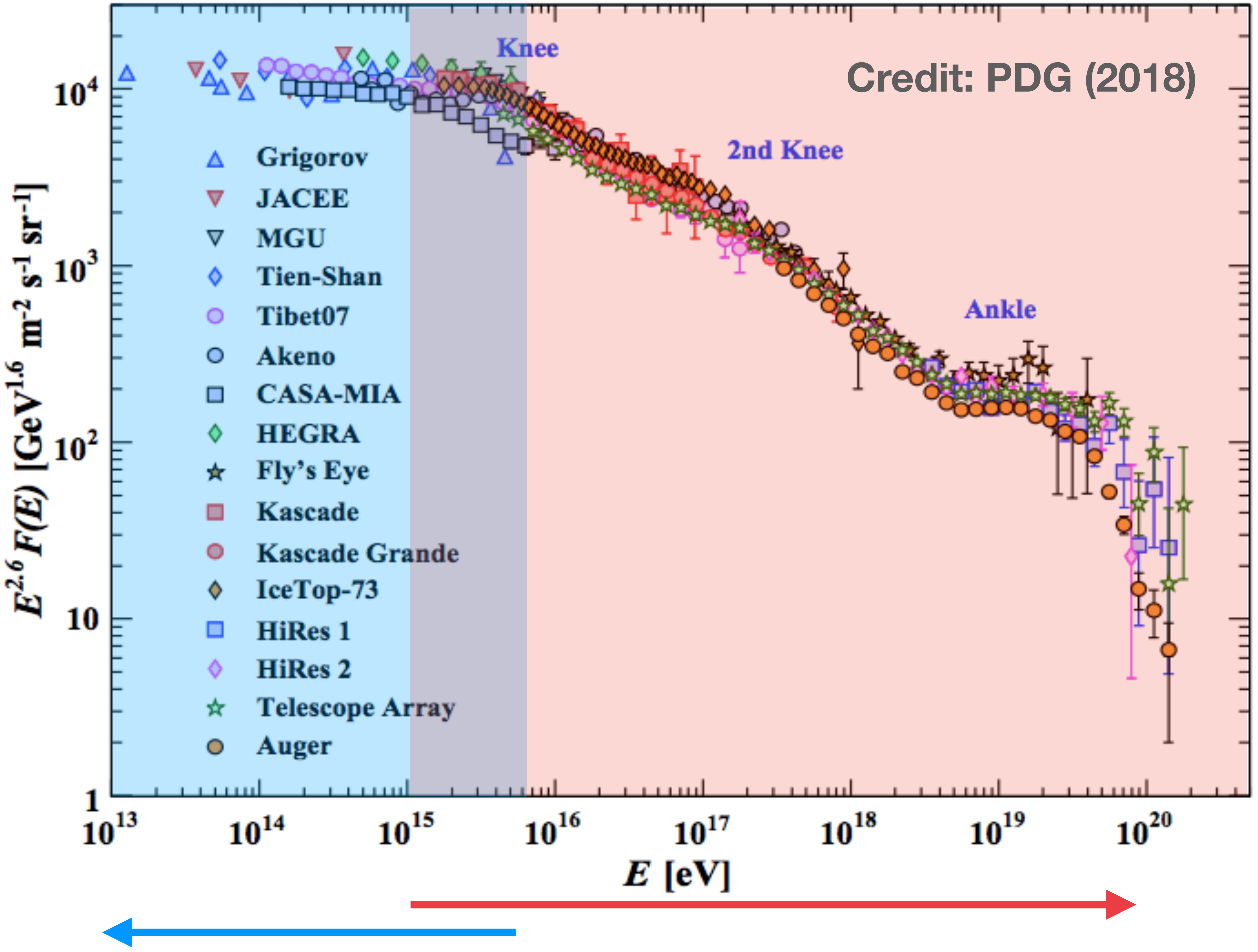
OUTLINE

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

Introduction

1.1 ENERGY SPECTRUM OF COSMIC RAYS

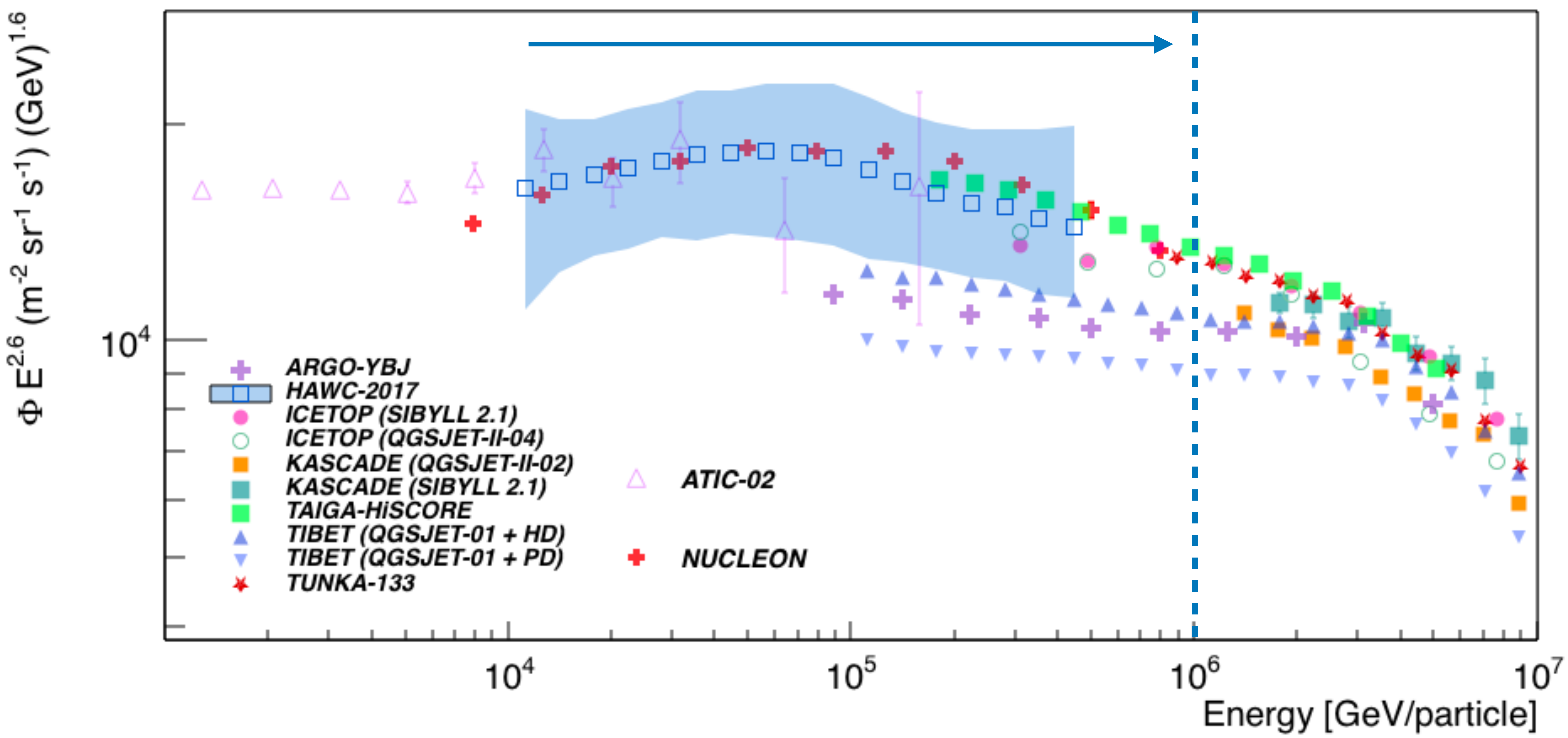


Direct Measurements Indirect Measurements

- 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].



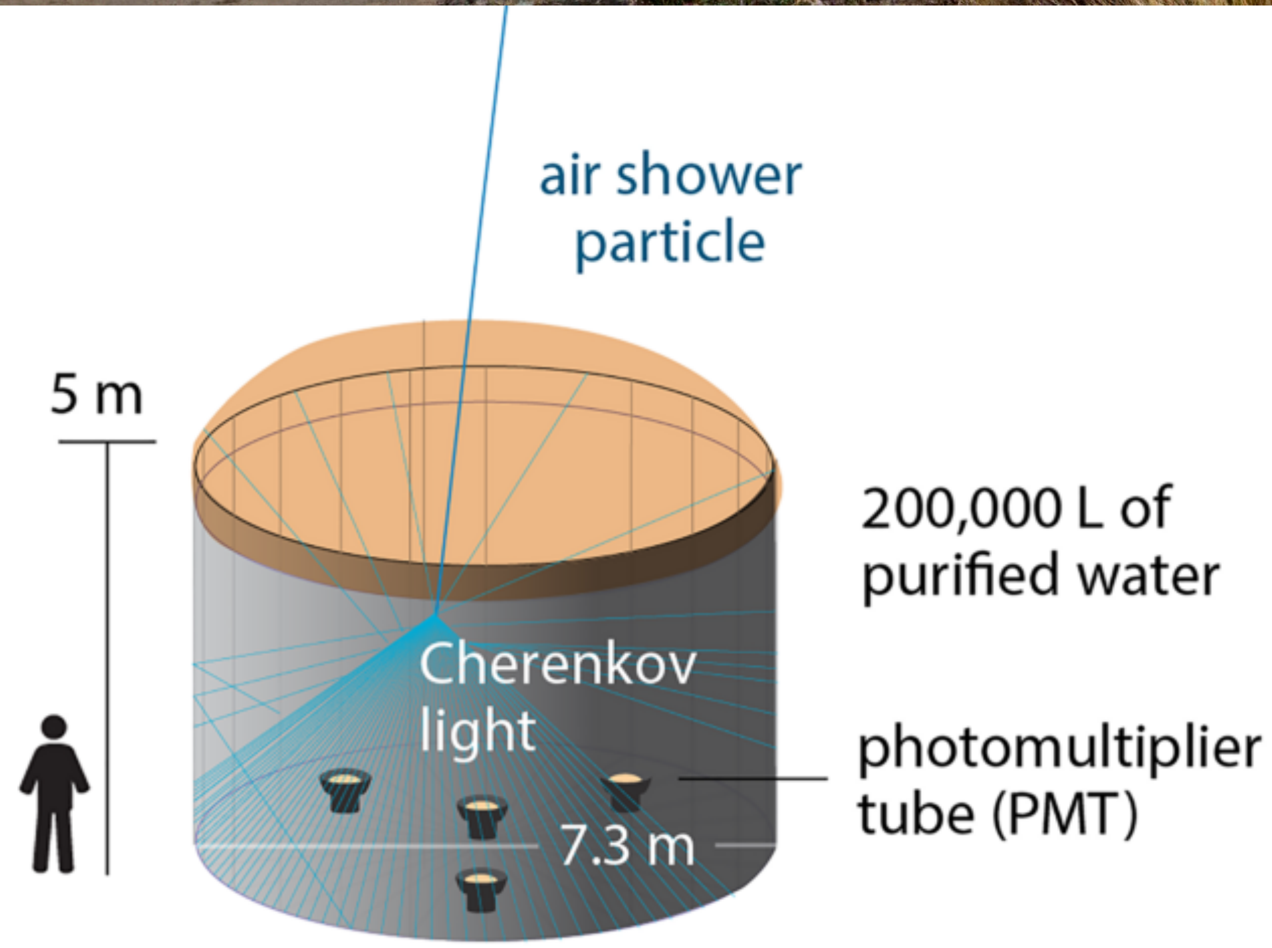
Our main goals are:

- To extend this study up to 10^{15} eV with HAWC using improved statistics.
- Reduce the systematic effects using simulations that provide a better description of the detector.

The HAWC Observatory

2.1 HAWC

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



2.2 SIMULATIONS

- 1.3 x10^7 showers were simulated with Corsika (v7.4) [2].
- Hadronic interaction models: FLUKA [3] ($E < 80$ GeV) and QGSJet-II-04 [4] ($E \geq 80$ GeV).
- The interactions between secondary particles and HAWC's detectors were simulated with GEANT4 [5].
- Simulated nuclei: H, He, C, O, Ne, Mg, Si, Fe. Spectra were weighted according to fits to AMS-2 [6,7], CREAM I - II [8,9], and PAMELA [10]. Details of the nominal composition model are given in [1].
- E = 5 GeV - 3 PeV.
- Shower cores are homogeneously distributed over a circular area with 1000 m of radius centered at HAWC, with a simulated zenith angle between 0° and 70°, azimuthally symmetric. Also, they are generated with a $\sin\theta\cos\theta$ distribution.

2.3 DATA SELECTION

- Some quality cuts were applied to HAWC's simulated and measured data to diminish the systematic effects in the energy resolution, the core position and the arrival direction.
- Selected events:
  - Zenith angle $\theta < 35^\circ$,
  - activated at least 60 channels in a radius of 40 m from the shower core,
  - and activated more than 30% of the available channels.

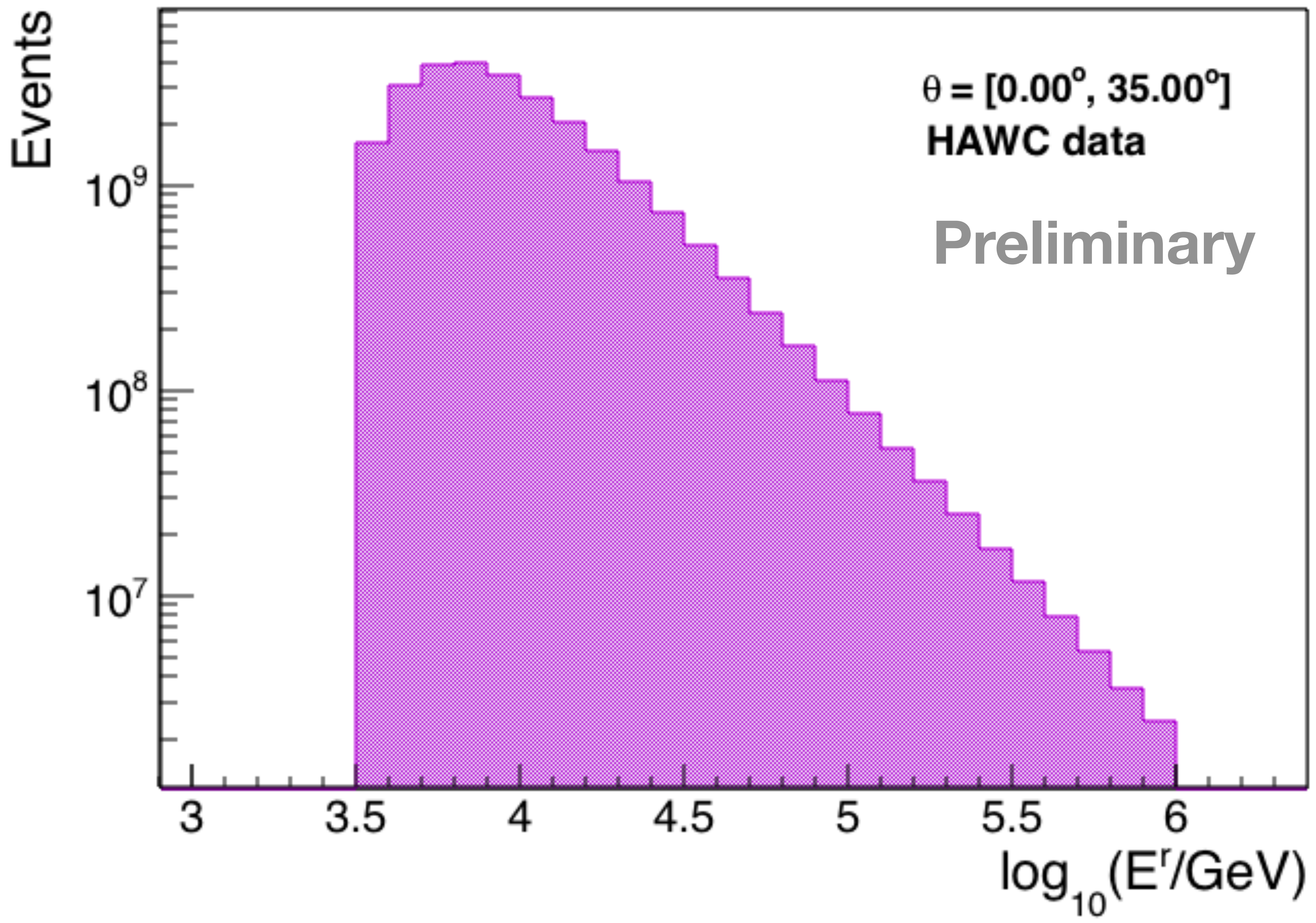
2.4 ENERGY, ANGULAR AND CORE POSITION BIAS

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

Analysis and results

3.1 HAWC'S MEASURED DATA

- Data 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 effective time: 703 days.
- Number of events before the cuts: 1.3638×10^{12}.
- Number of events after the cuts: 1.5052×10^{10}.

From this energy distribution we can reconstruct the *raw energy spectrum*, which must be corrected for migration effects. To correct for such effect, an *unfolding technique* was implemented.

3.2 ENERGY SPECTRUM ESTIMATION

From $N(E^R)$ we get the unfolded energy distribution $N(E)$

How? Iterative procedure, Bayesian Unfolding [11-13]

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

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

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

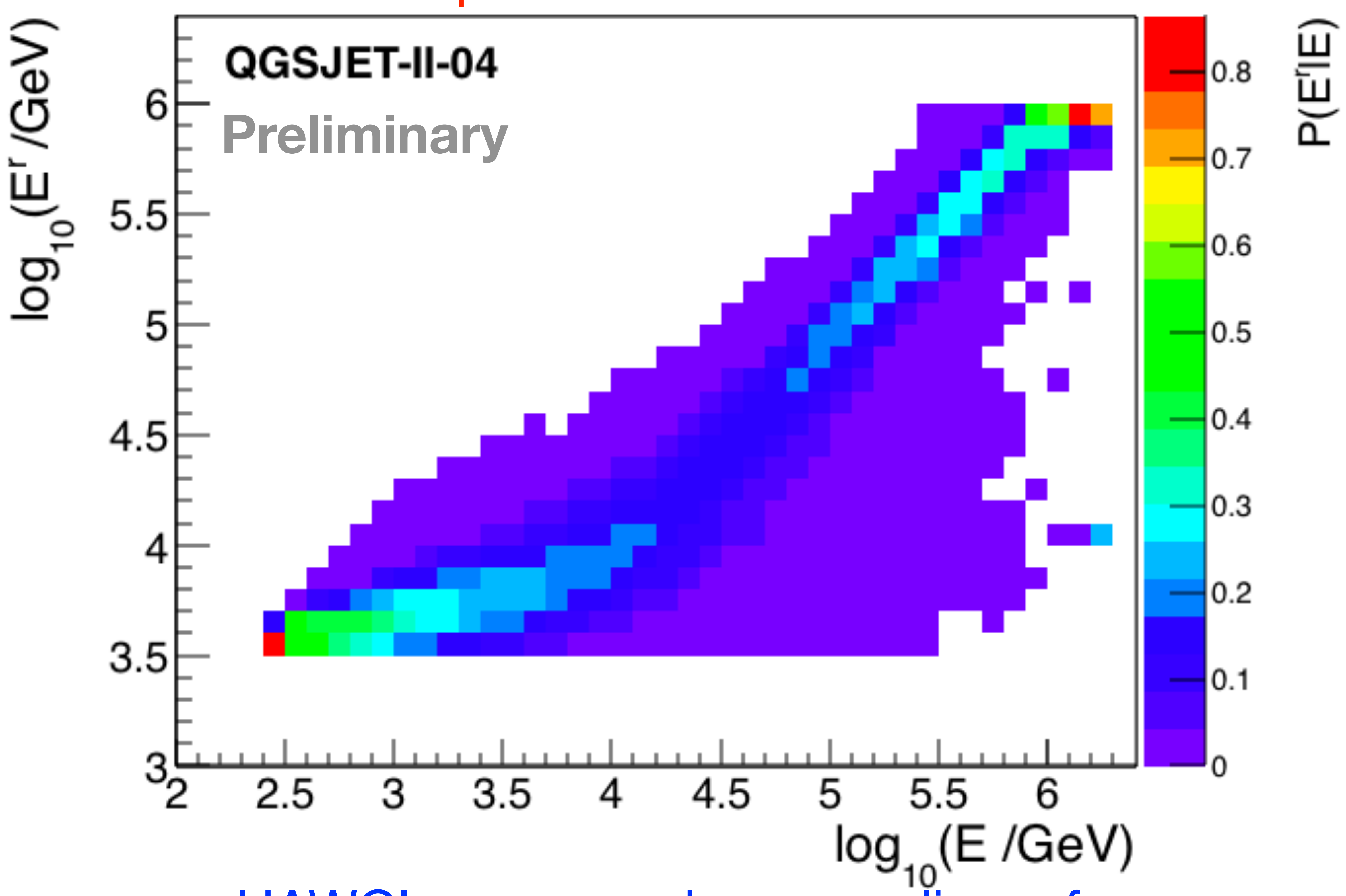
4) $P(E_i) \equiv \dfrac{N(E_i)}{\sum_{i=1}^{n_c} N(E_i)} = \dfrac{N(E_i)}{N_{true}}$. .... Final probability

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

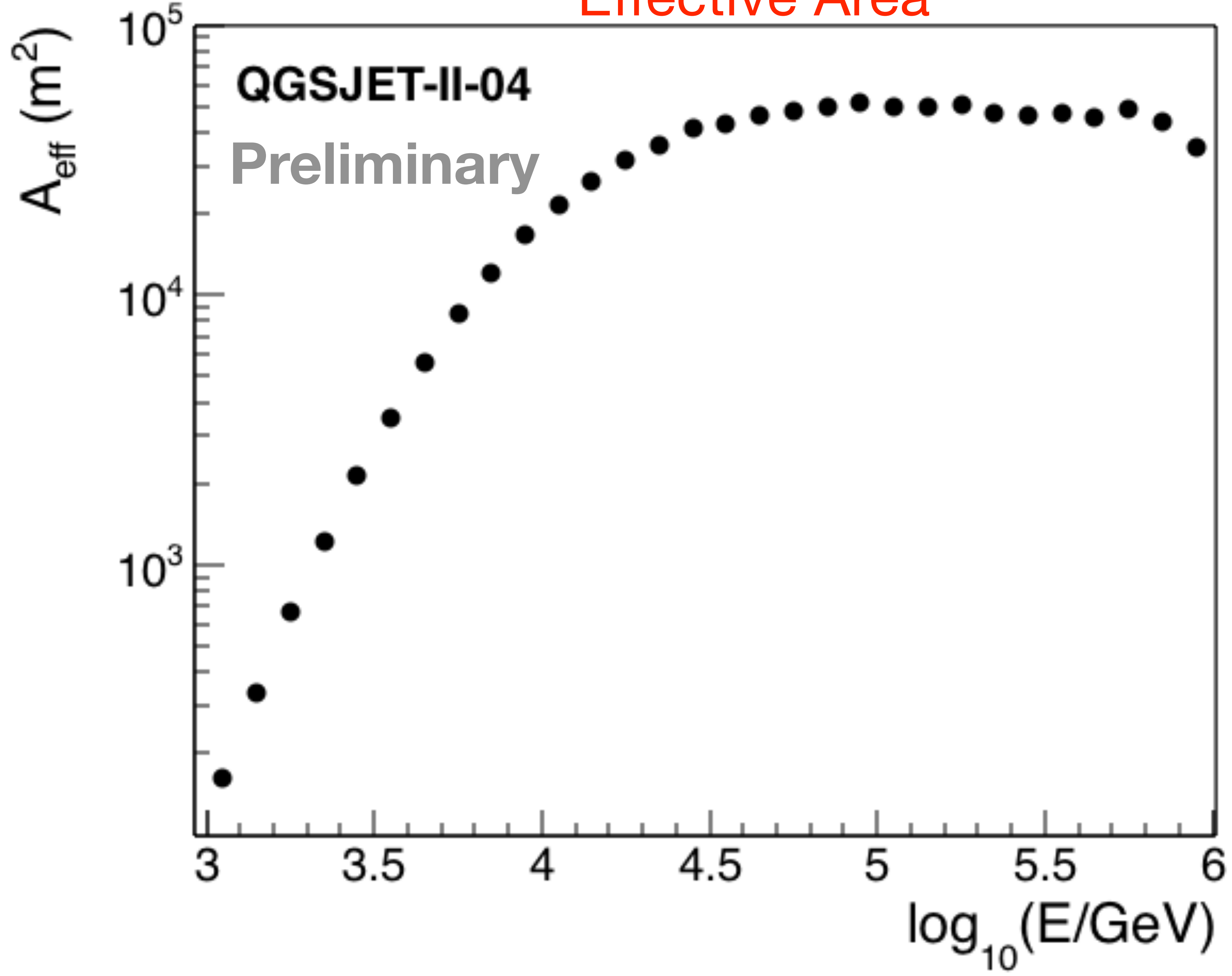
Response Matrix



HAWC's response becomes linear for

E > 10^4 GeV

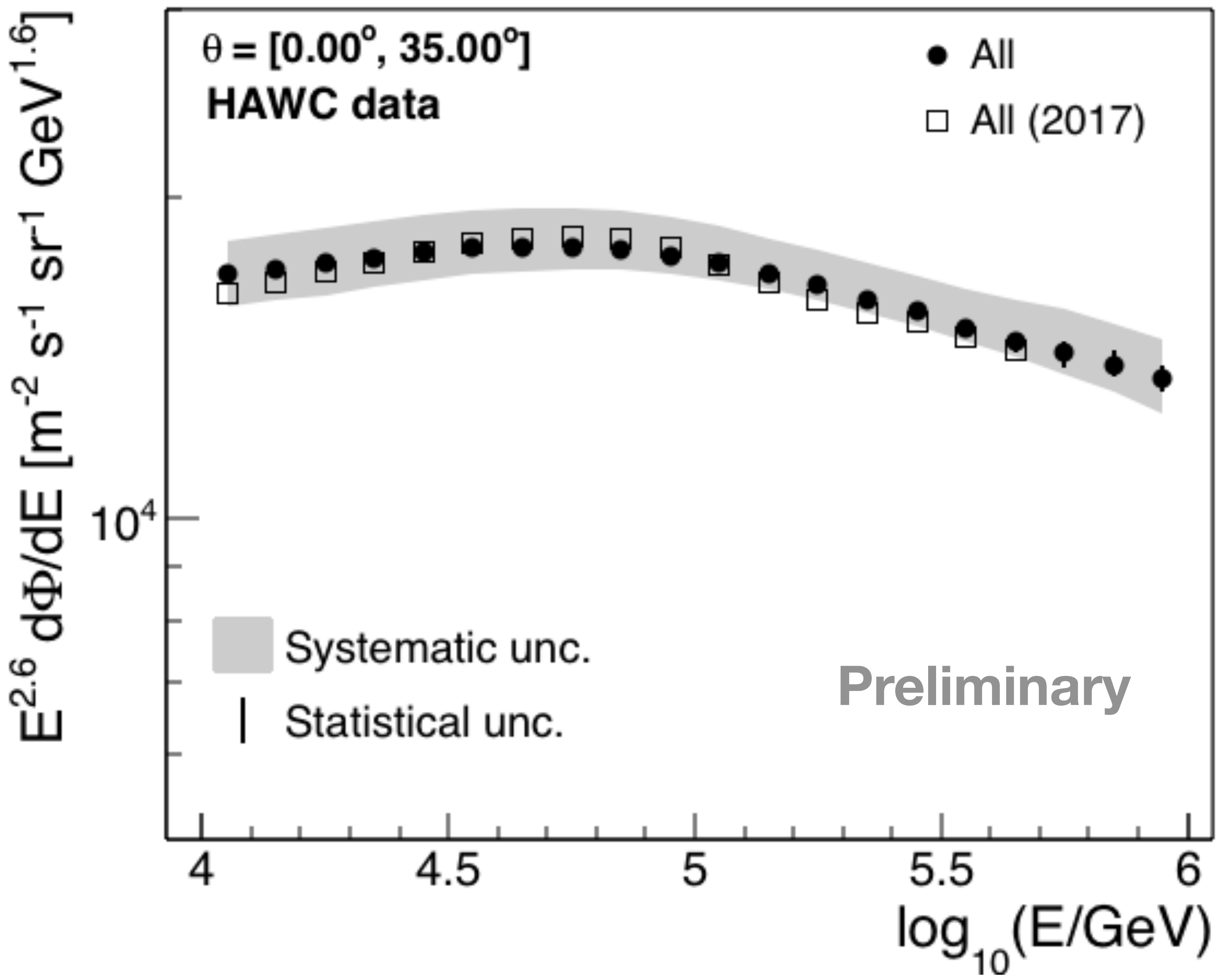
Effective Area



Maximum trigger and reconstruction efficiency for E > $10^{4.5}$ GeV

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

3.2 ENERGY SPECTRUM ESTIMATION



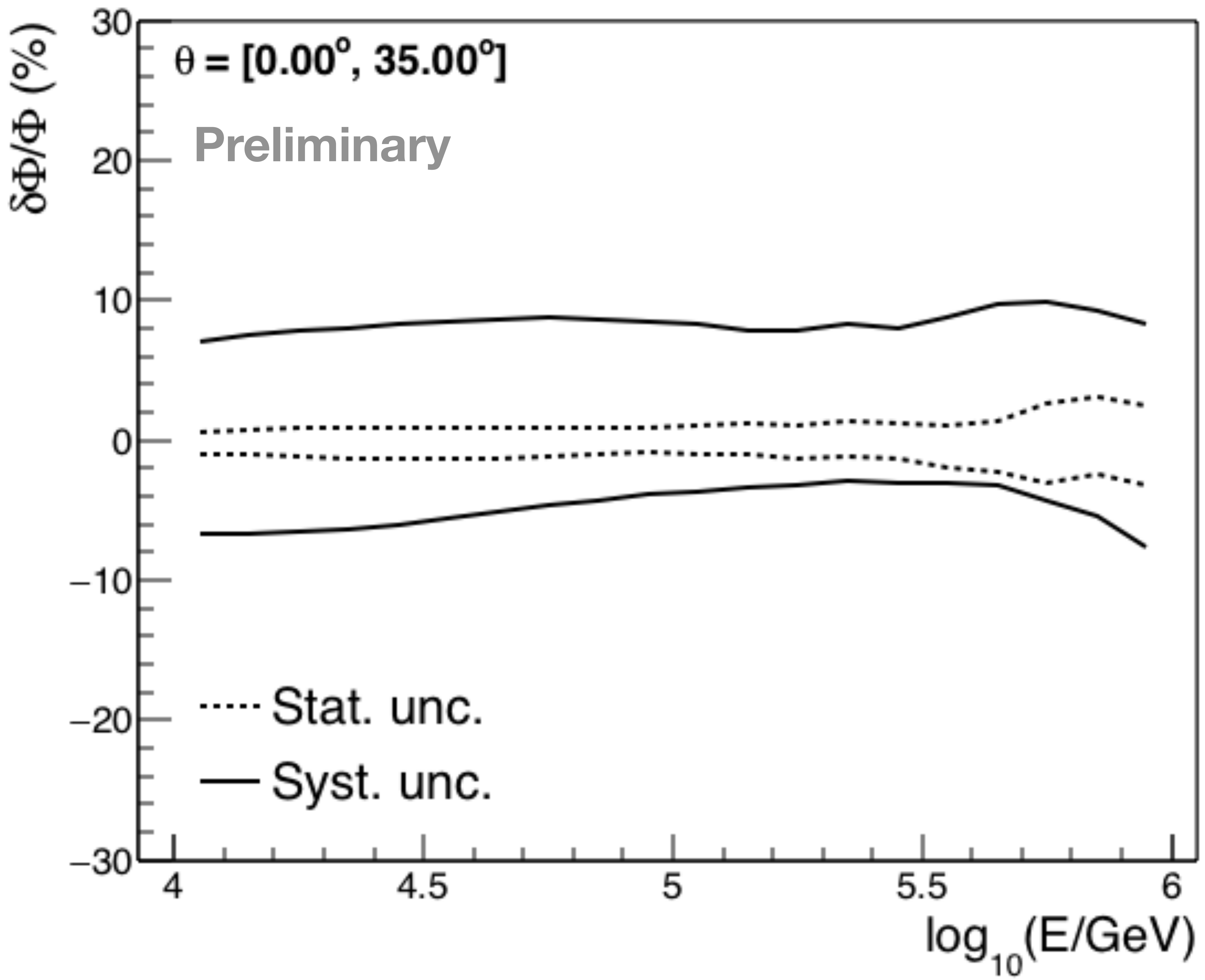
All-particle cosmic ray energy spectrum measured with HAWC

$$\Phi(E) = \frac{N(E)}{\Delta E \; \Delta t \; \Delta\Omega \; A_{eff}}$$

Contributions to the systematic error band:

1. PMT charge,
2. PMT efficiency,
3. PMT late light,
4. PMT threshold,
5. composition model (Poligonato model [14], the GSF model [15], and two models derived from fits to measurements from ATIC-2 [16] and JACEE [17]),
6. effective area,
7. seed and smoothing in unfolding,
8. unfolding technique (checked with reduced cross-entropy [18]),
9. bin size.

3.3 UNCERTAINTIES ON THE FLUX



Statistical relative error @ 10^5 GeV:

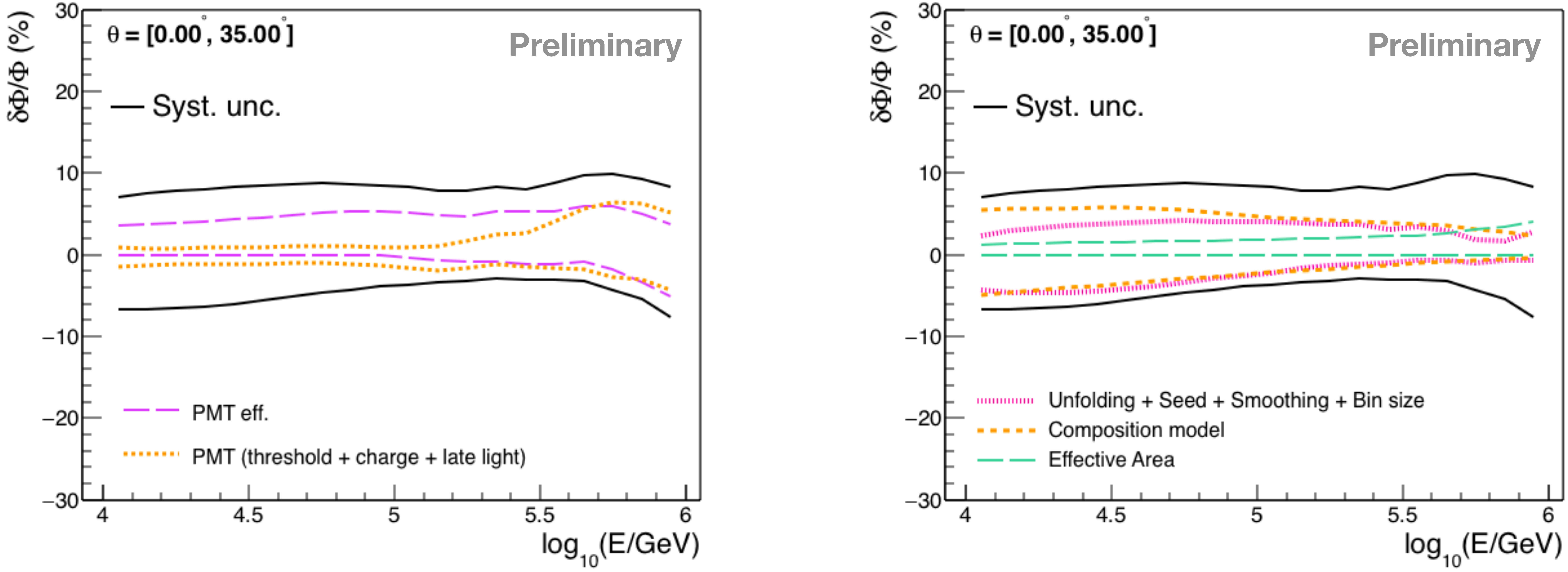
This work:	+1%	-0.9%
HAWC 2017 [1]:	<< 1 %	

Systematic relative error @ 10^5 GeV:

This work:	+8.2%	-3.6%
HAWC 2017 [1]:	+26.4%	-24.7%

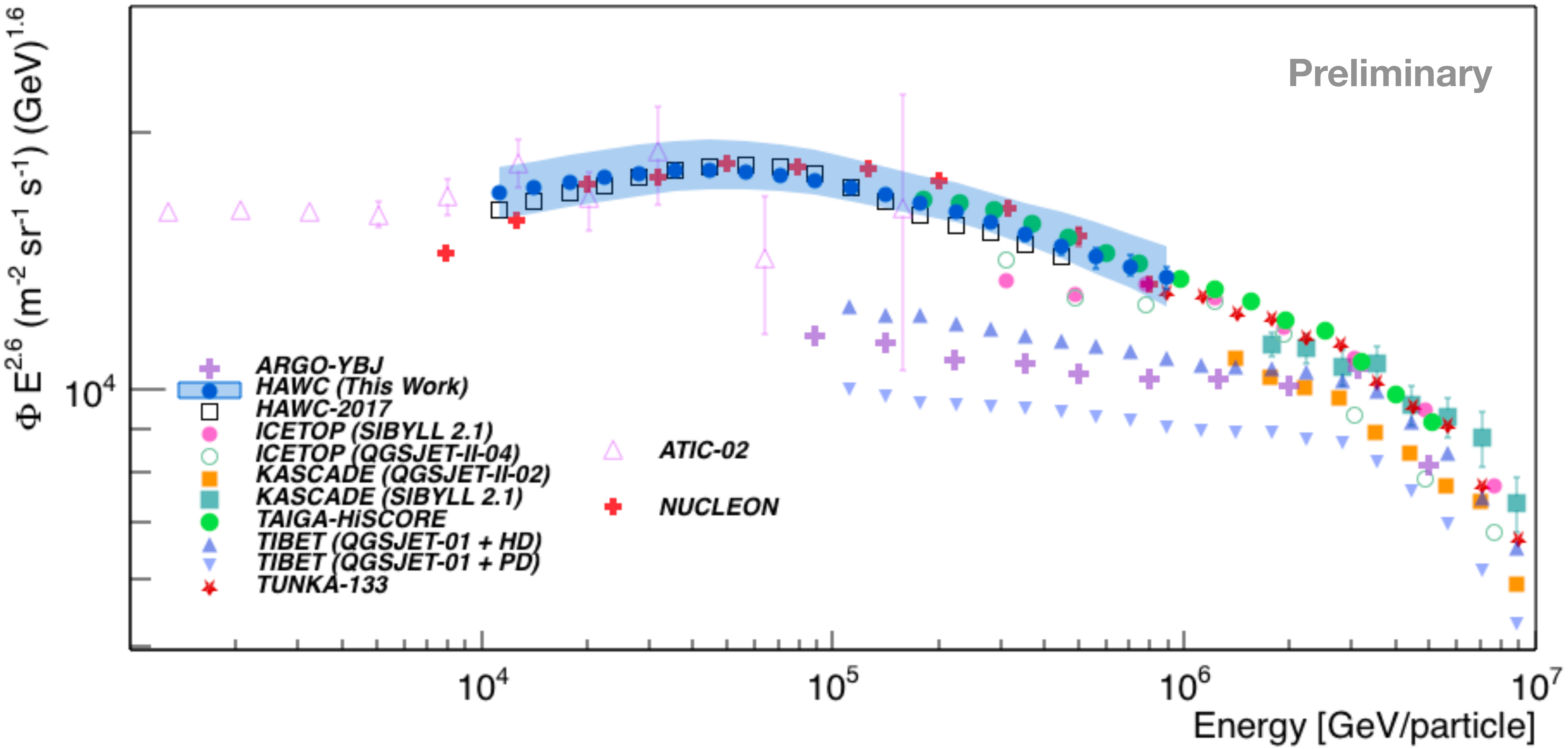
3.3 UNCERTAINTIES ON THE FLUX

Systematic errors



Systematics dominated by: PMT efficiency, effective area and composition model.

3.3 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 [14-22].

3.3 FIT OF THE SPECTRUM

$$\Phi(E) = \Phi_0 E^{\gamma_1}$$ Power Law

$$\Phi_0 = 10^{4.38\pm0.01}\, m^{-2}\, s^{-1}\, sr^{-1}\, GeV^{-1}; \qquad \gamma_1 = -2.632 \pm 0.001$$

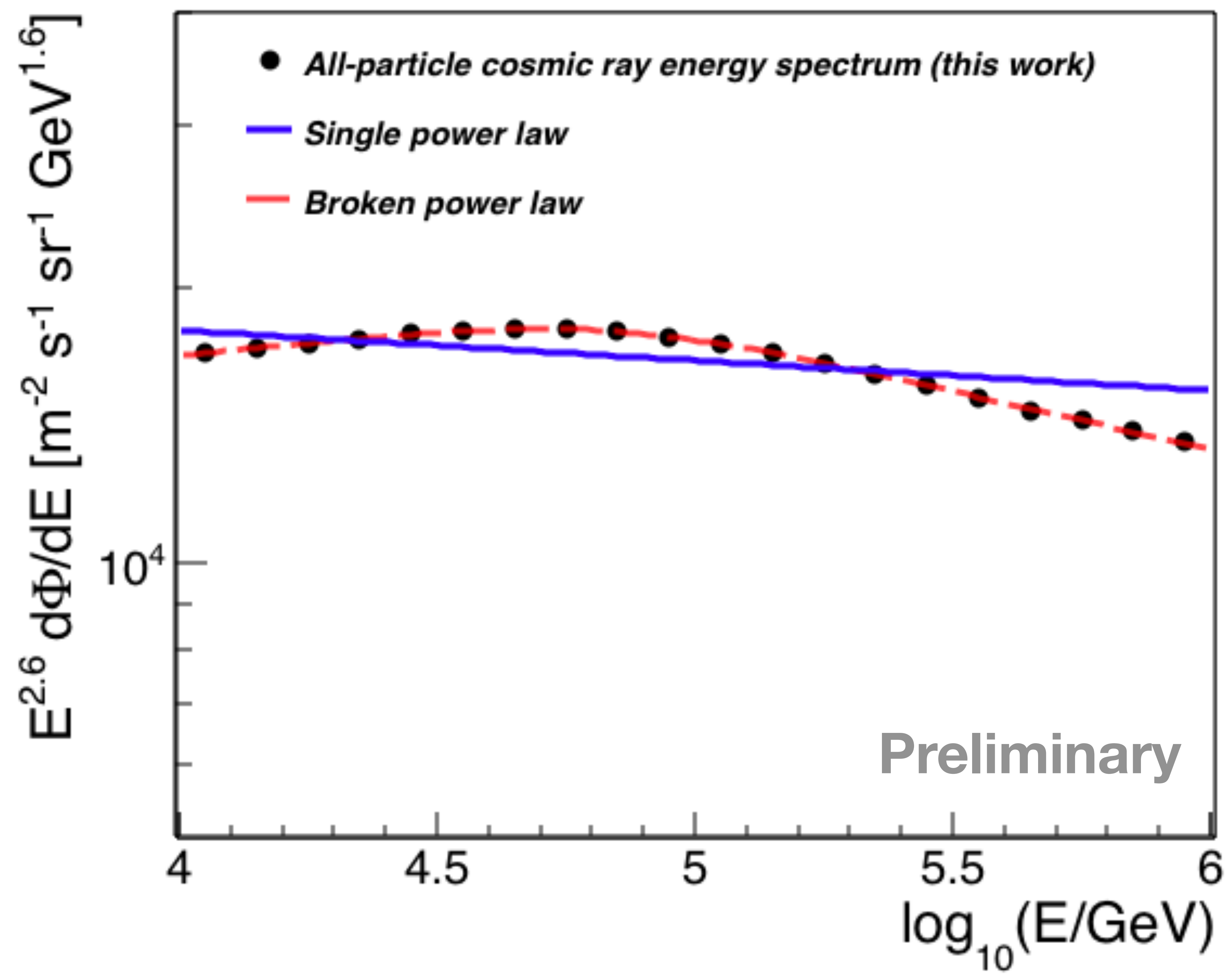
$$\chi_0^2 = 492.23, \quad NDOF = 18.$$

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

$$\Phi_0 = 10^{4.01\pm0.05}\, m^{-2}\, s^{-1}\, sr^{-1}\, GeV^{-1} \qquad \epsilon = 3.04 \pm 1.51$$

$$\gamma_1 = -2.54 \pm 0.01 \qquad E_0 = (69.1 \pm 7.5)\ \text{TeV}$$

$$\gamma_2 = -2.72 \pm 0.01 \qquad \chi_1^2 = 0.61, \quad NDOF = 15.$$



$$TS = -\Delta\chi^2 = -(\chi_1^2 - \chi_0^2)$$

$$TS_{obs} = 491.62$$

3.3 FIT OF THE SPECTRUM

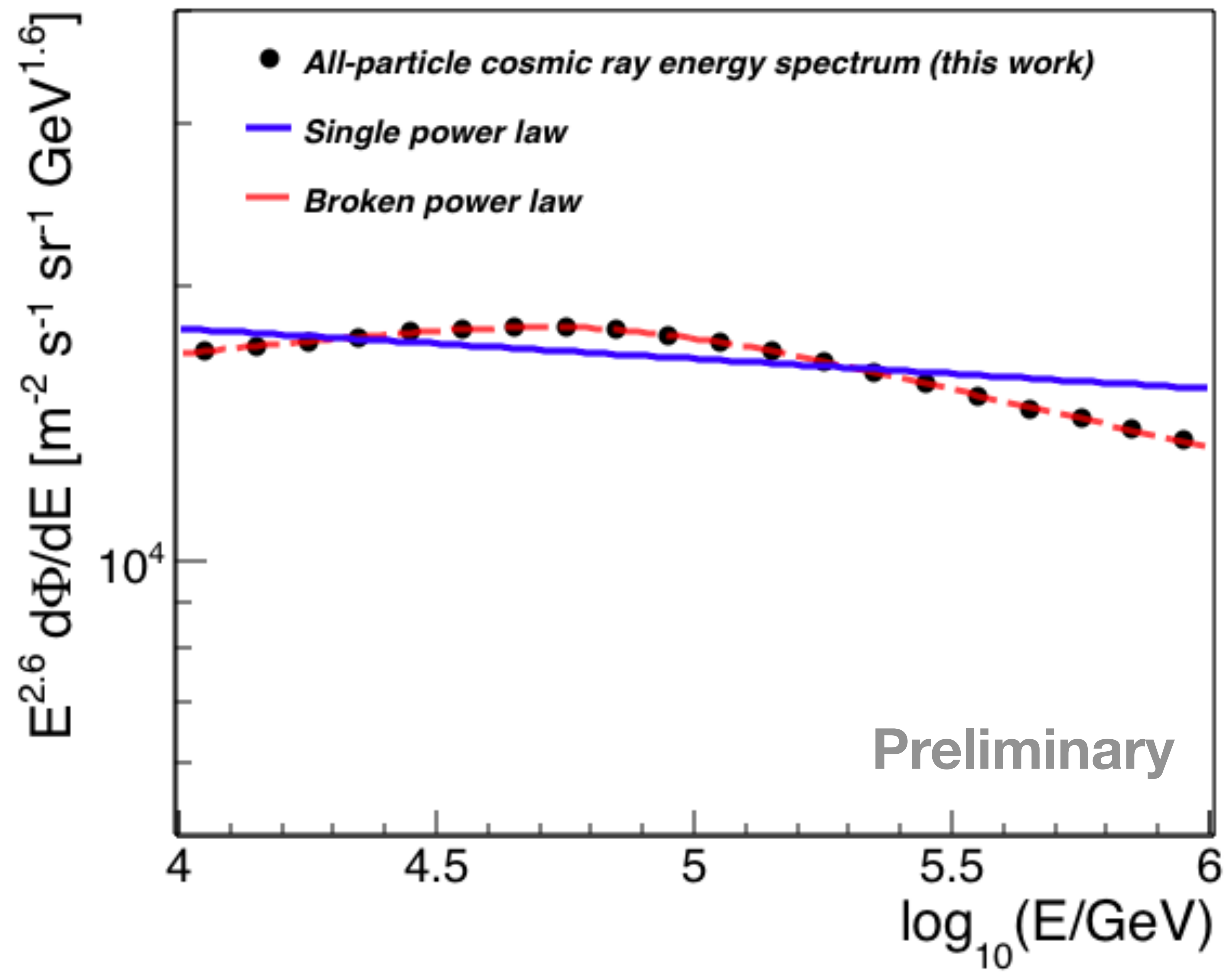
By generating toy MC spectra with correlated data points using our covariance matrix and the result of the fit with the power-law model [23], it was found:

p-value for T_{obs} is

$p < 2 \times 10^{-6}$

This means that the broken power-law scenario is favored by the data with a significance of at least:

4.6σ



Conclusions

4 CONCLUSIONS

- We have extended the measurements of the total energy spectrum of cosmic rays with HAWC up to 1 PeV using a data set with high-statistics. When comparing the systematic uncertainties between this result and the result from HAWC in 2017 [1], the systematic uncertainty was reduced at $E = 10^5$ GeV. The statistical error reported in [1] only considers the size of the experimental data.
- The spectrum from this work is in agreement with the measurements from HAWC obtained in 2017 [1] and the results from NUCLEON [18].
- By means of an statistical analysis, we observed a knee like structure in the the total spectrum of cosmic rays in the TeV energy regime. The position of the bump was found at $E = (69.1 \pm 7.5)$ TeV. When compared to the position of the break found in [1] at $E = (45.7 \pm 1.1)$ TeV, it is shifted to higher energies.
- In addition to the measurements of NUCLEON [18], HAWC's result on the all-particle energy spectrum offer a bridge between direct and indirect measurements of the cosmic ray spectrum in the 10 TeV - 1 PeV range.

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