The all-particle energy spectrum of cosmic rays from 10 TeV to 1 PeV measured with HAWC

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XXXVI Annual Meeting of the Division of Particles and Fields
ONLINE
September 9th, 2022.

OUTLINE

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2. The HAWC Observatory.

3. Analysis and results.

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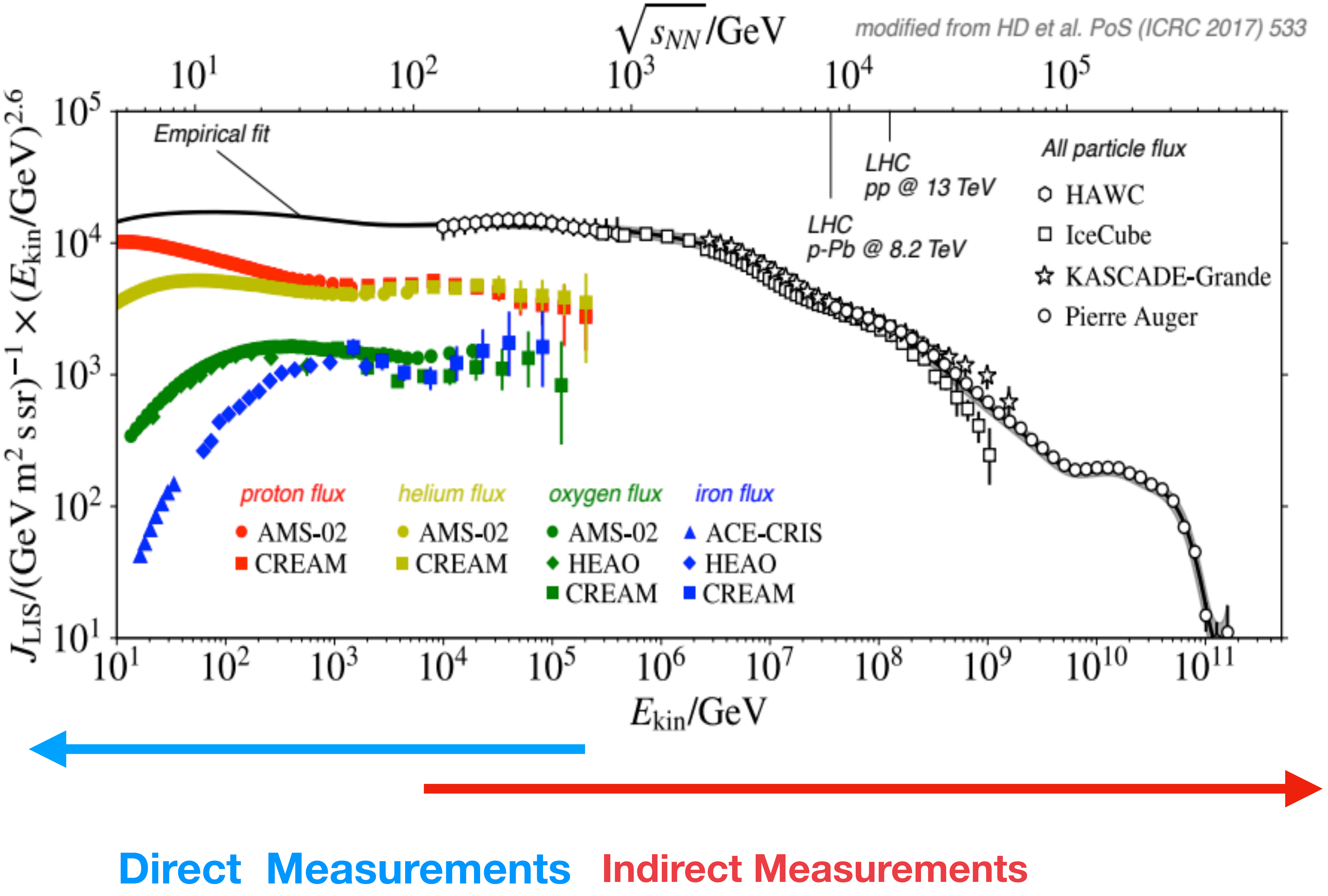
Introduction

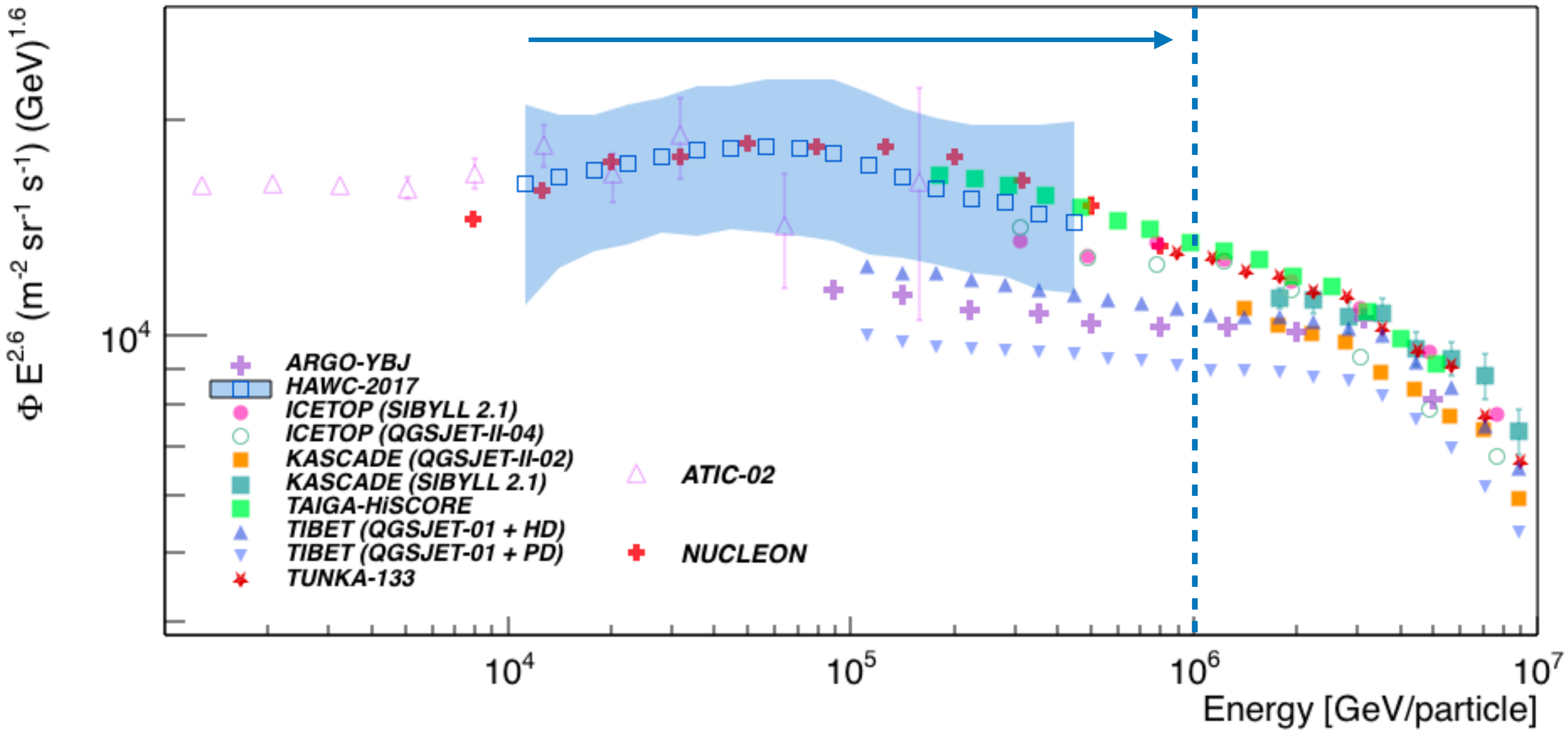
1.1 ENERGY SPECTRUM OF COSMIC RAYS



- 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].



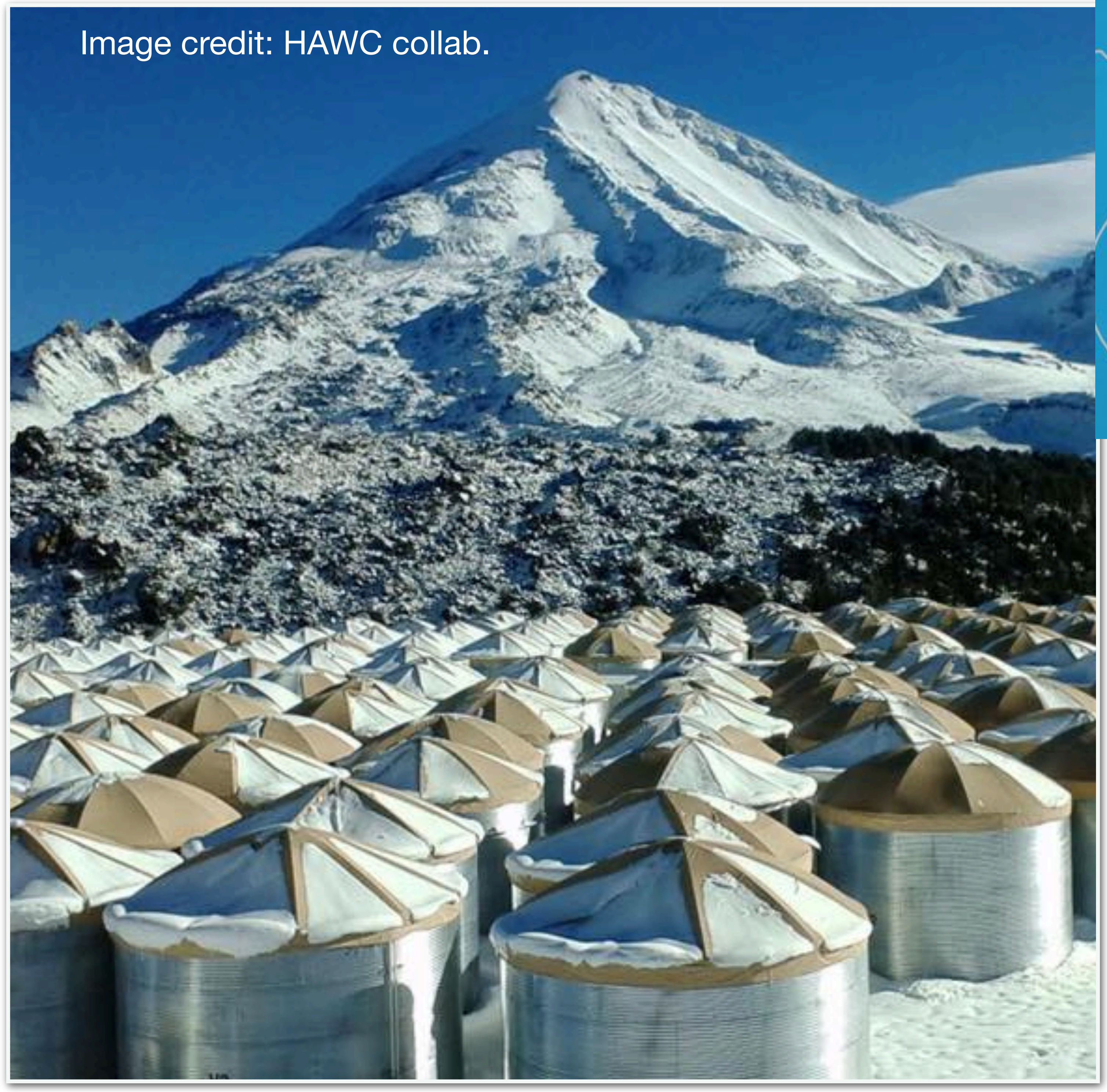
Our main goals are:

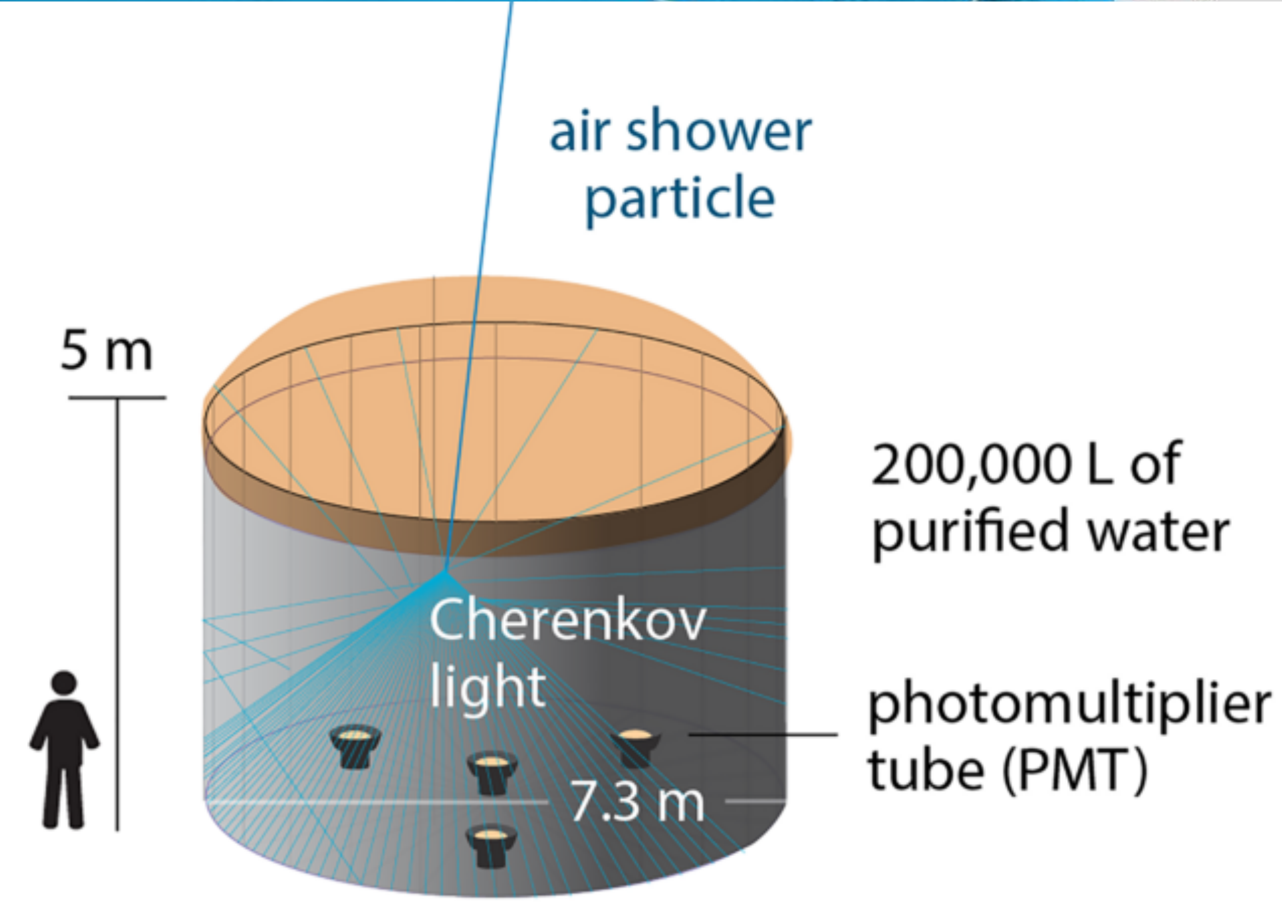
- To extend this study up to 10^{15} eV with HAWC.
- To increase the statistics in the analysis.
- To reduce PMT systematic uncertainties using improved simulations on the performance of the detector [2].

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.





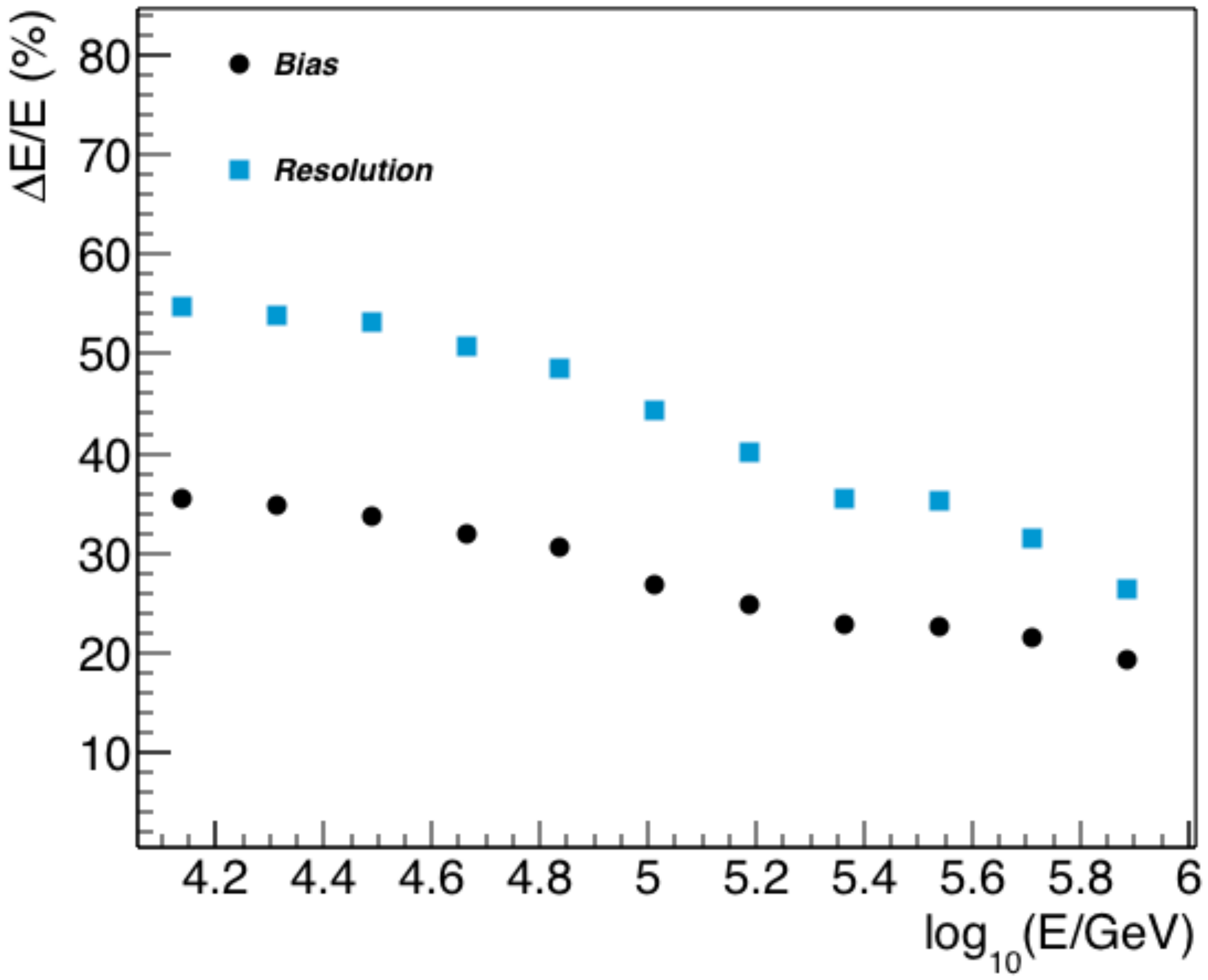
2.2 SIMULATIONS

- 1.3 x10^7 showers were simulated with Corsika (v7.4) [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: H, He, C, O, Ne, Mg, Si, Fe. Spectra were weighted according to fits to AMS-2 [7,8], CREAM I - II [9,10], and PAMELA [11] data. Details of the nominal composition model are given in [1].
- E = 5 GeV - 3 PeV.
- Shower cores are distributed over a circular area with 1000 m of radius centered at HAWC, with zenith angles < 70^{o}.

2.3 DATA SELECTION

- Quality cuts were applied to HAWC's simulated and measured data to diminish the systematic effects in energy resolution, core position and arrival direction.

- Selected events:
  - Succefully reconstructed,
  - zenith angle θ < 35º,
  - activated at least 60 channels in a radius of 40 m from the shower core,
  - shower cores were reconstructed mainly inside HAWC's area,
  - and activated more than 30% of the 1200 available channels.



Resolution in core position, arrival direction and primary energy at E=$10^{5.9}$ GeV:

$\Delta R = 19.5m$ $\Delta\psi = 0.7^{\circ}$ $\Delta E/E = 26\,\%$

Analysis and results

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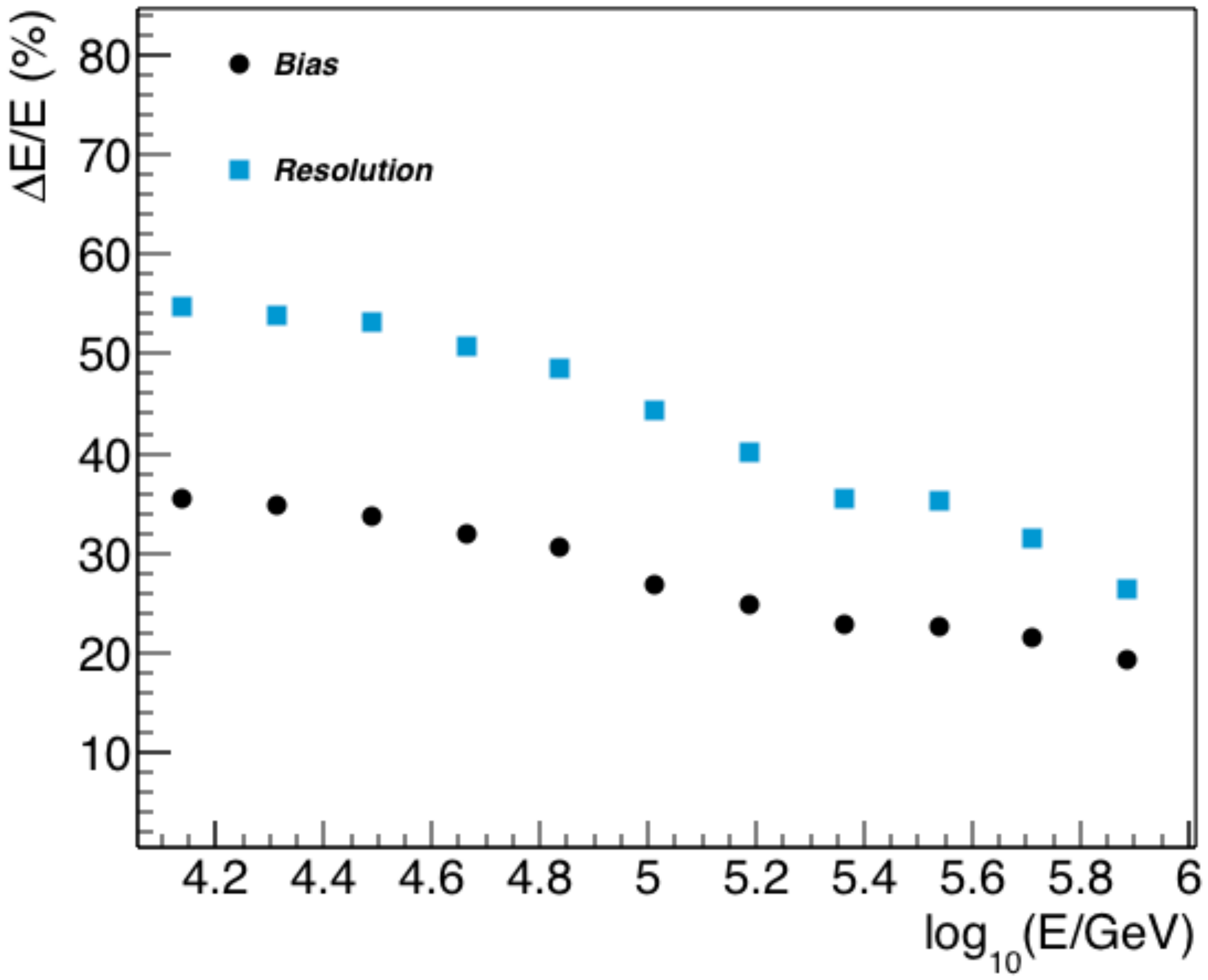

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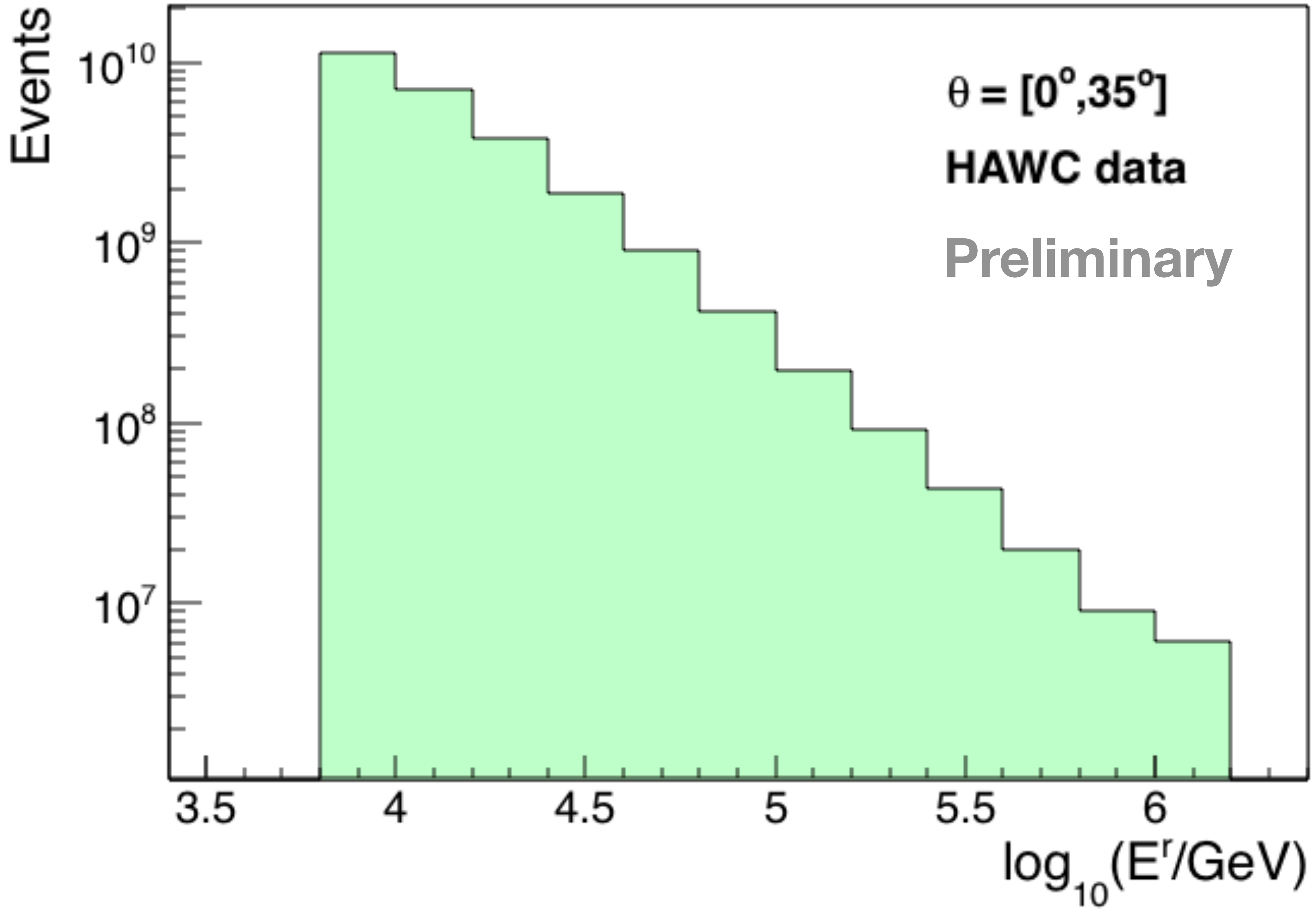
3.1 HAWC'S MEASURED DATA

- Data from January 1st, 2018 to December 31st, 2020 were selected for this work.
- Only air showers within $E = 10^{3.8} - 10^{6.2}$ GeV were employed.



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

Total effective time
1062 days

$$\Delta\Omega = 1.1363 \text{ sr}$$

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3.2 ENERGY SPECTRUM ESTIMATION

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

How? Iterative procedure, Bayesian Unfolding [12-14]

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

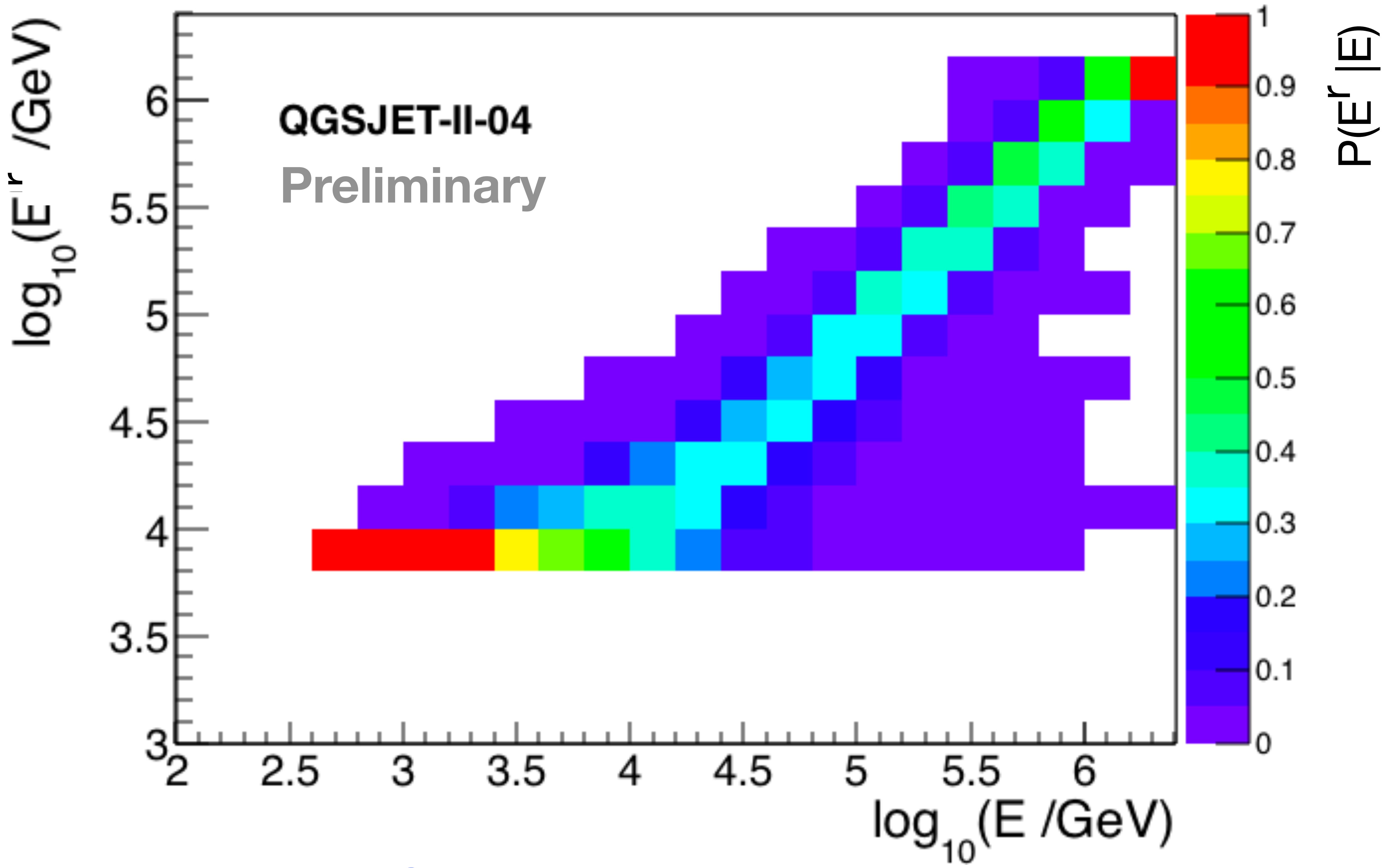
4) $P(E_i) \equiv \dfrac{N(E_i)}{\sum_{i=1}^{n_c} N(E_i)} = \dfrac{N(E_i)}{N_{true}}$ . ... Final probability

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

3.2 ENERGY SPECTRUM ESTIMATION

Inputs from MC data

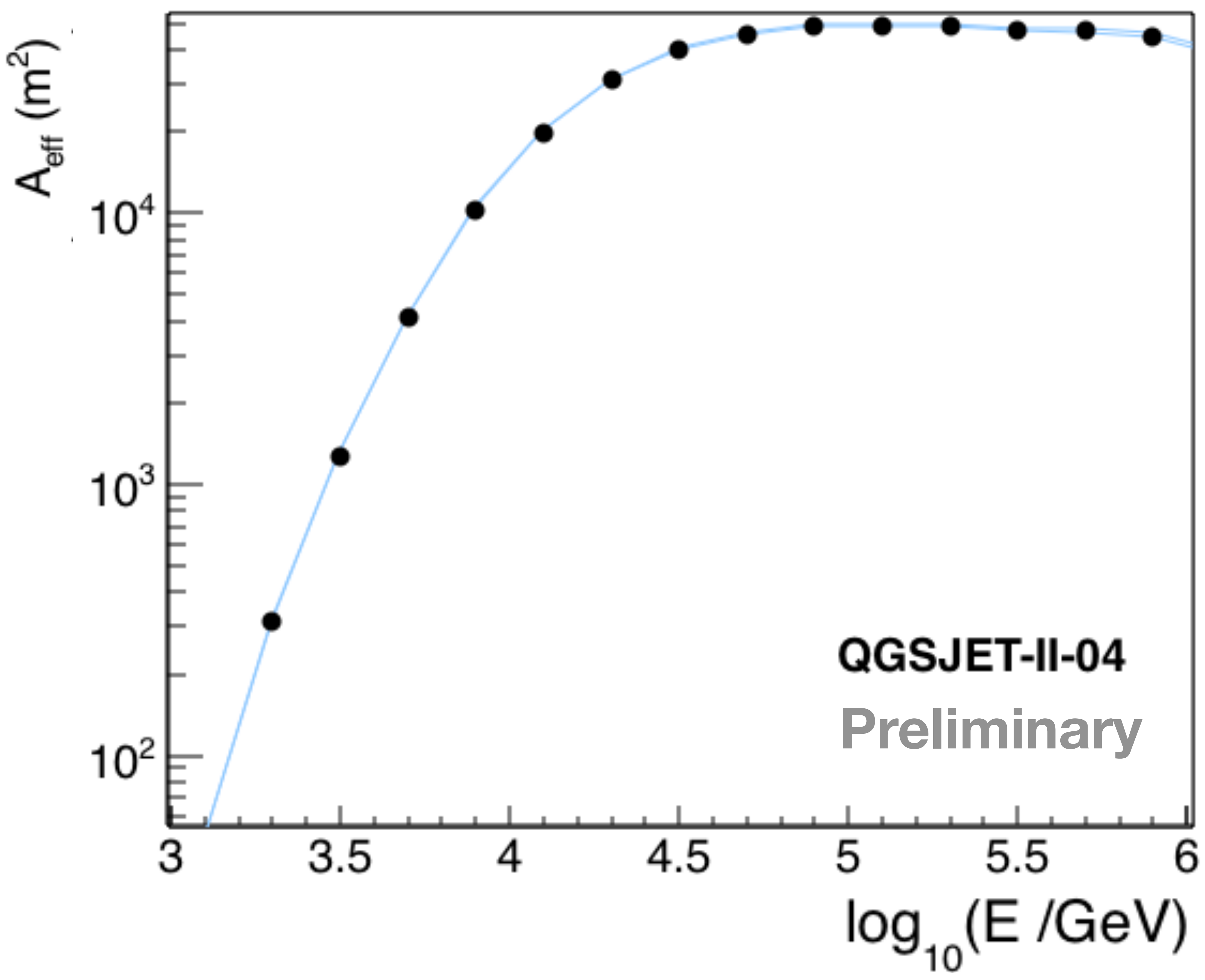
Response Matrix



HAWC's response becomes linear for

E > 10^4 GeV

Effective Area



Maximum trigger and reconstruction efficiency for

E > $10^{4.5}$ GeV

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

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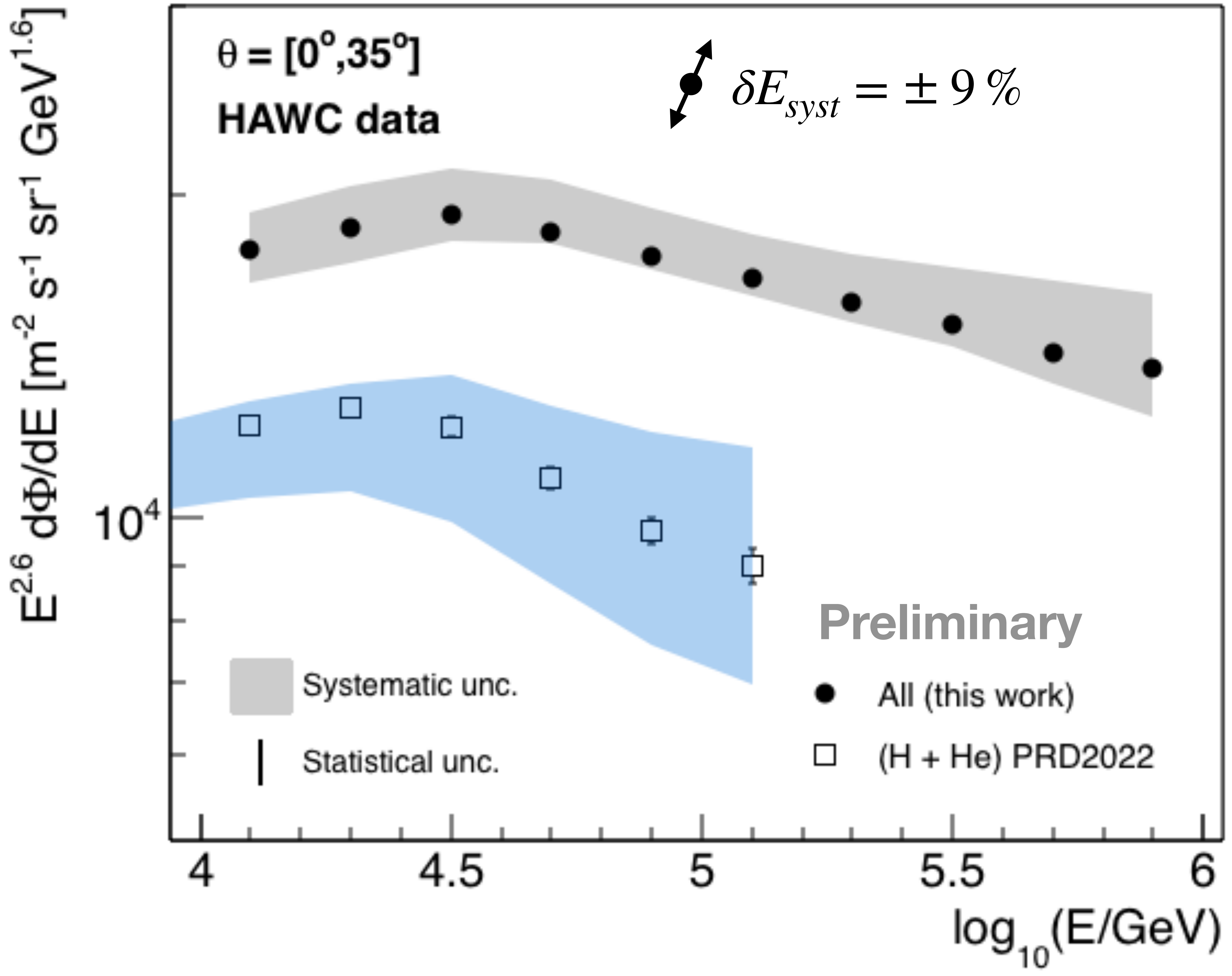
3.2 ENERGY SPECTRUM ESTIMATION



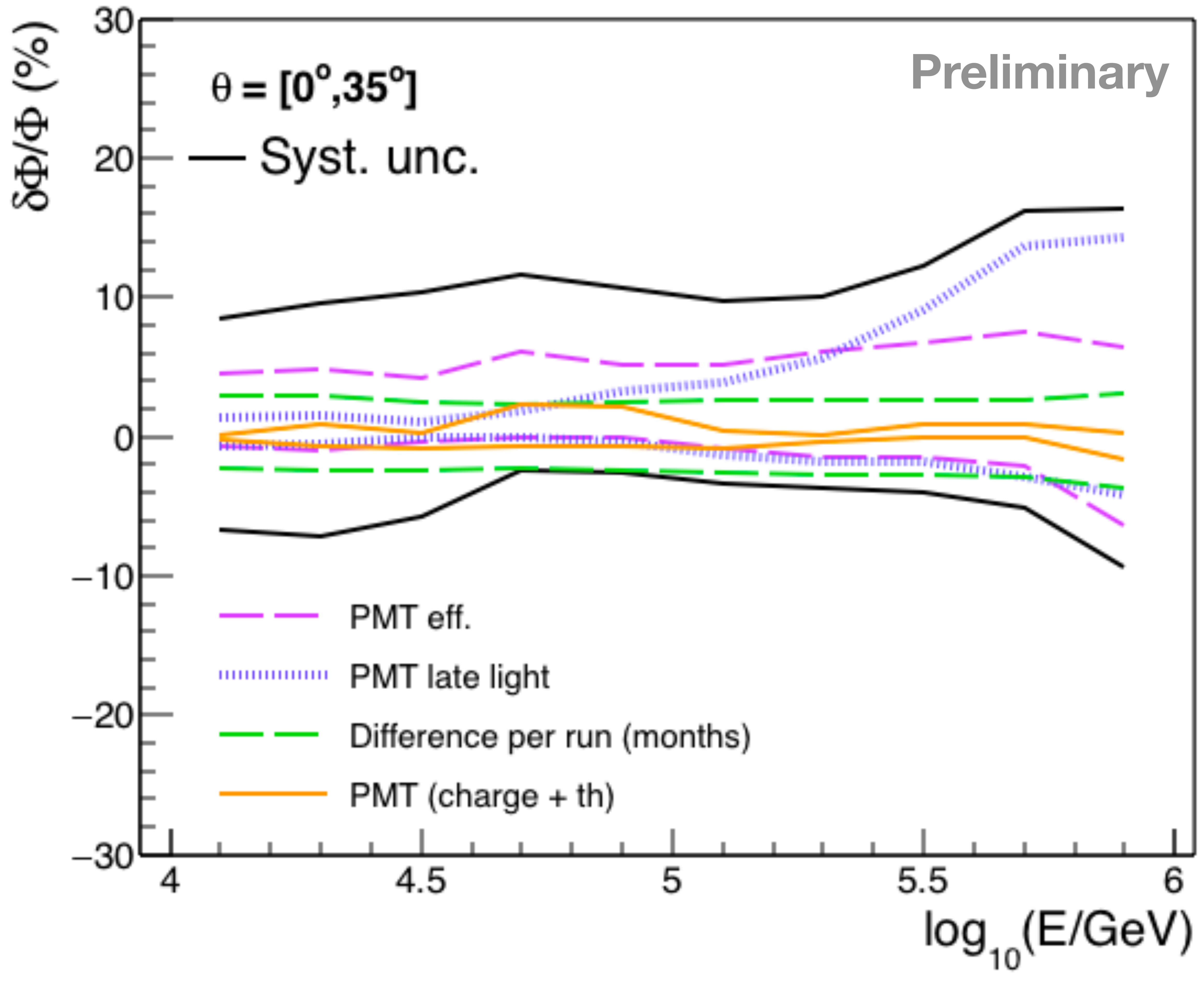
All-particle cosmic ray energy spectrum measured with HAWC

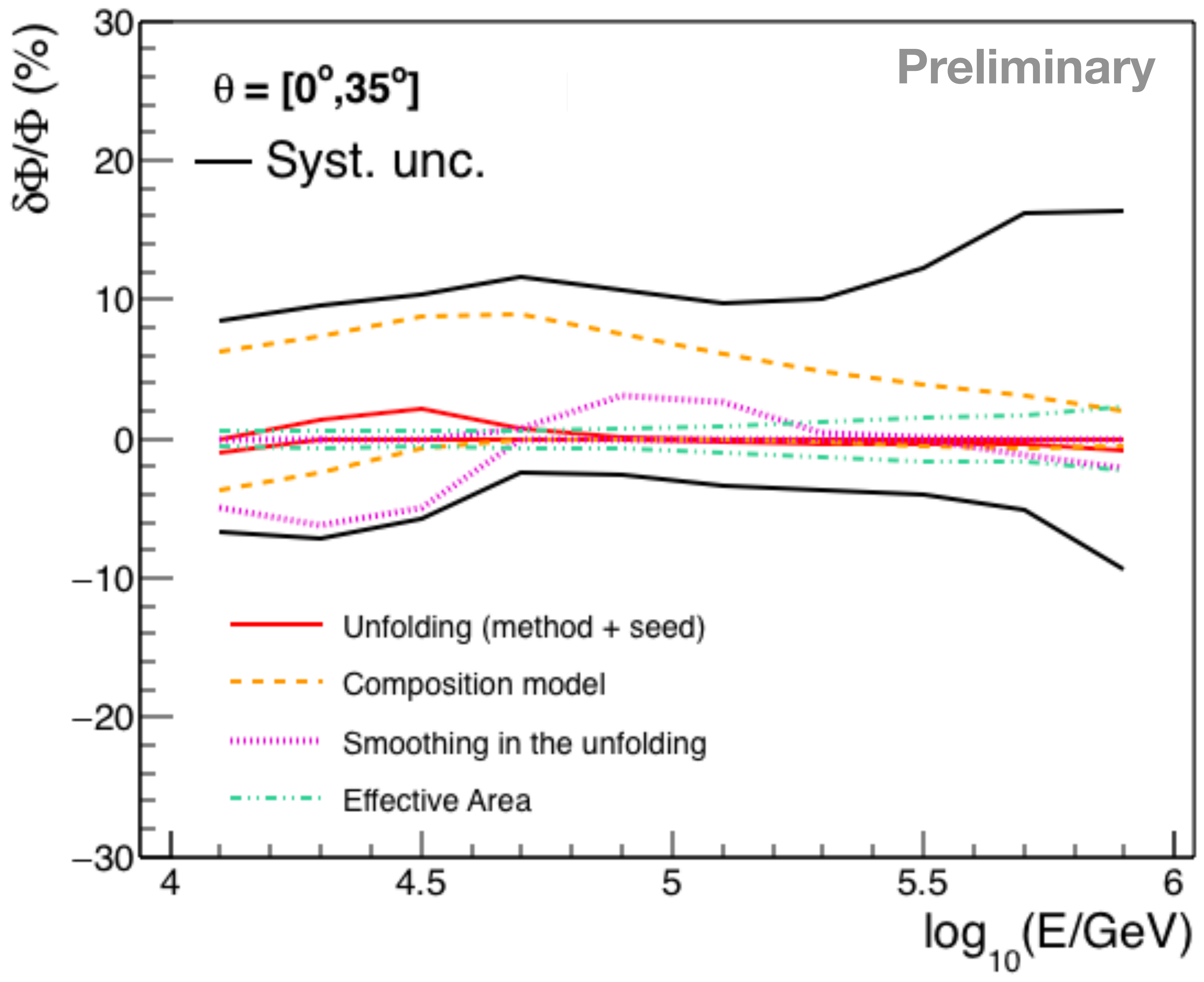
$$\Phi(E) = \frac{N(E)}{\Delta E\ \Delta t\ \Delta\Omega\ A_{eff}}$$

Contributions to the systematic error band:

1. PMT charge,
2. PMT efficiency,
3. PMT late light,
4. PMT threshold,
5. composition model (Poligonato[15], the GSF [16], and two models derived from fits to ATIC-2 [17] and JACEE [18] data),
6. effective area,
7. seed and smoothing in unfolding,
8. unfolding technique (Gold's technique [19], and also checked with the reduced cross-entropy method [20]),
9. differences between runs.

3.3 UNCERTAINTIES ON THE FLUX

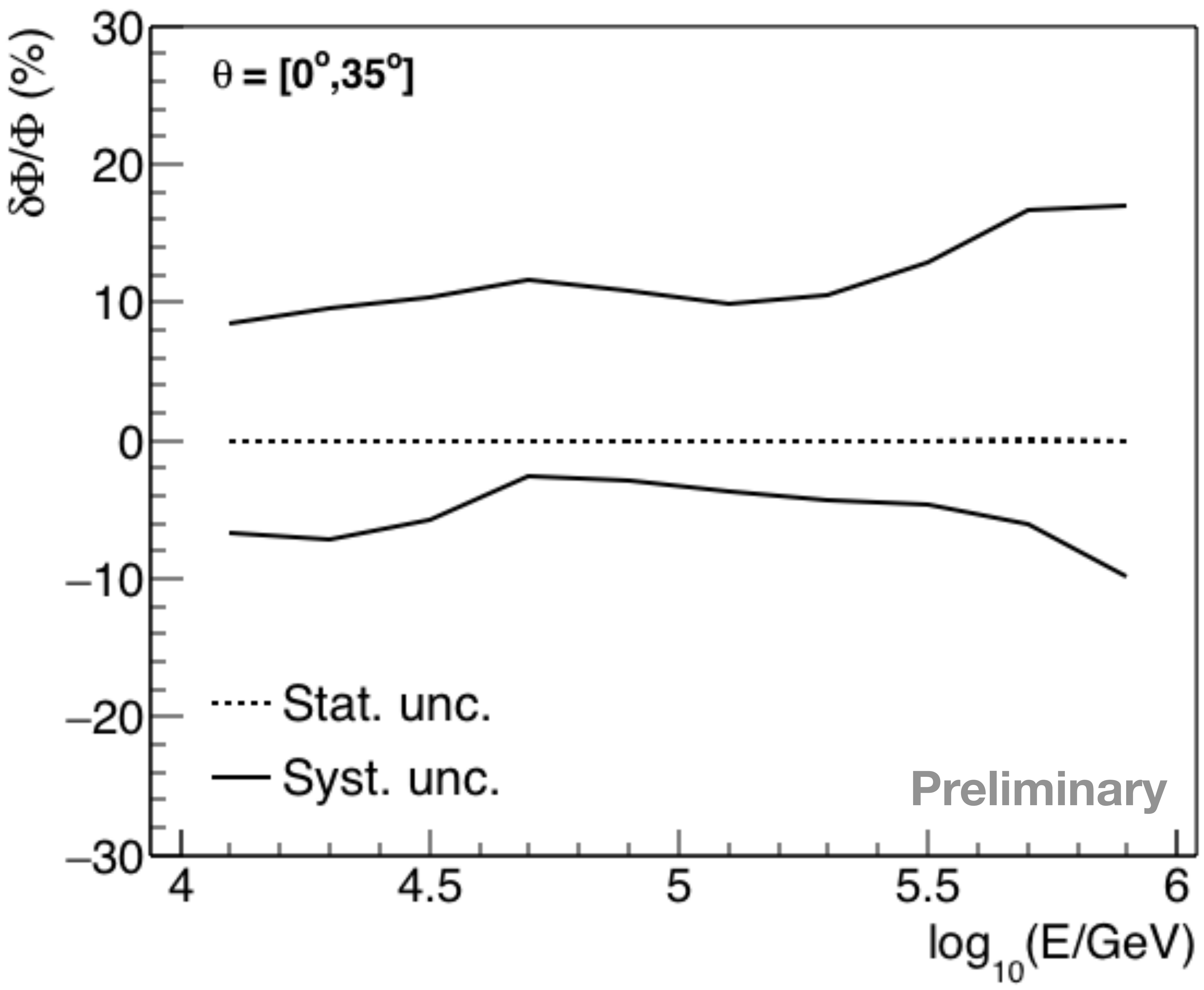




3.3 UNCERTAINTIES ON THE FLUX

Contributions to the systematic error on the flux at E = 10^5 GeV	
PMT charge	+0% / -0.07%
PMT efficiency	+5.2% / -0.9%
PMT late light	+3.9% / -1.3%
PMT threshold	+0.36% / -0.36%
Composition model	+6% / -0.07%
Effective area	+1% / -1%
Seed in the unfolding	+0% / -0.2%
Smoothing in the unfolding	+2.7% / -0%
Unfolding technique	+0% / -0.07%
Differences between runs	+2.5% / -2.5%
TOTAL SYSTEMATIC UNCERTAINTY	**+9.8% / -3.7%**

3.3 UNCERTAINTIES ON THE FLUX



Statistical relative error @ 10^5 GeV:

This work: ±0.01%

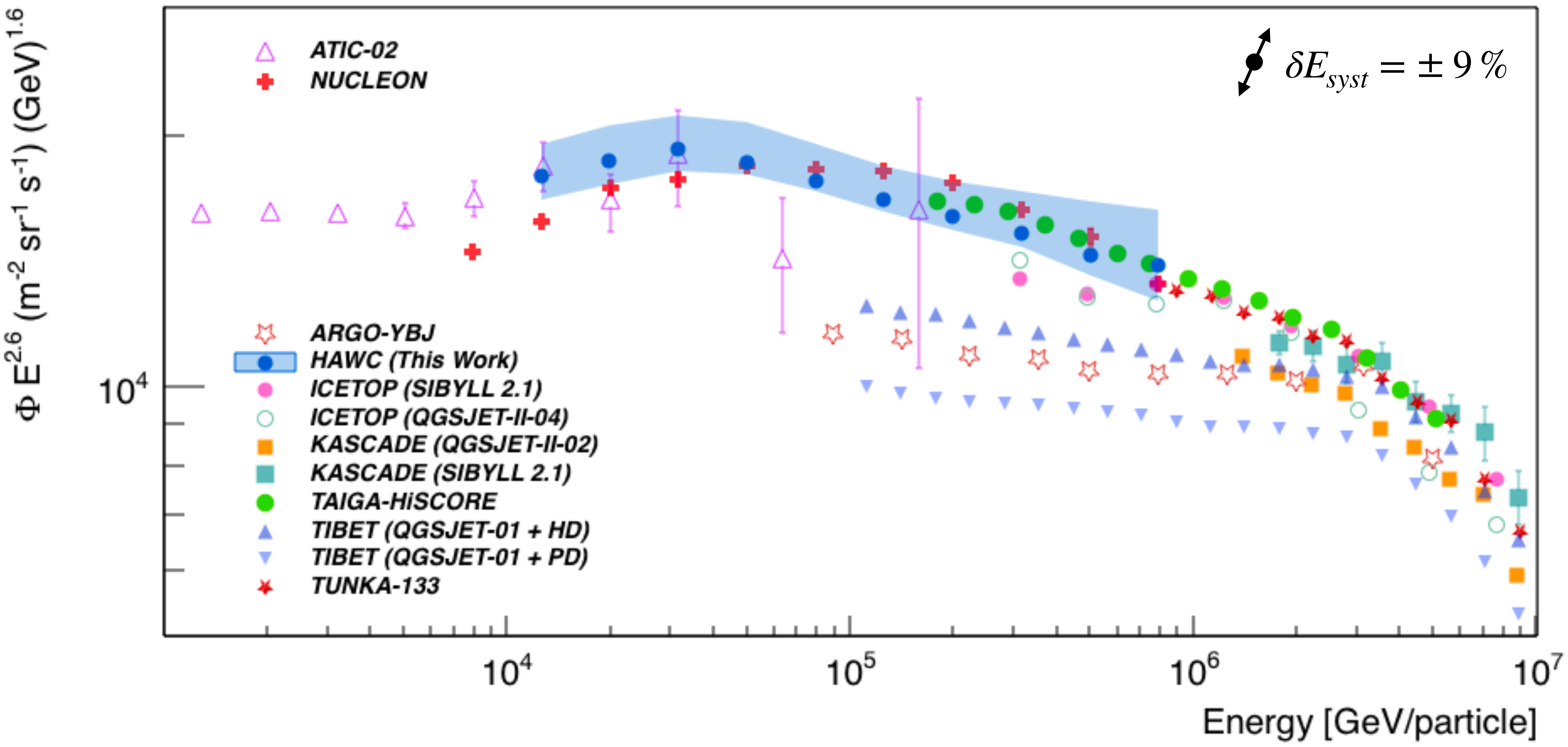
HAWC 2017 [1]: << 1 %

Systematic relative error @ 10^5 GeV:

This work: +9.8% / -3.7%

HAWC 2017 [1]: +26.4% / -24.7%

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 [21-29].

3.5 FIT OF THE SPECTRUM

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

$\Phi_0 = 10^{4.47\pm0.01}\, m^{-2}\, s^{-1}\, sr^{-1}\, GeV^{-1};\quad \gamma_1 = -2.65 \pm 0.001$

$\chi_0^2 = 418.84,\quad NDOF = 8.$

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

Broken-Power Law

$\gamma_2 = -2.70 \pm 0.004$

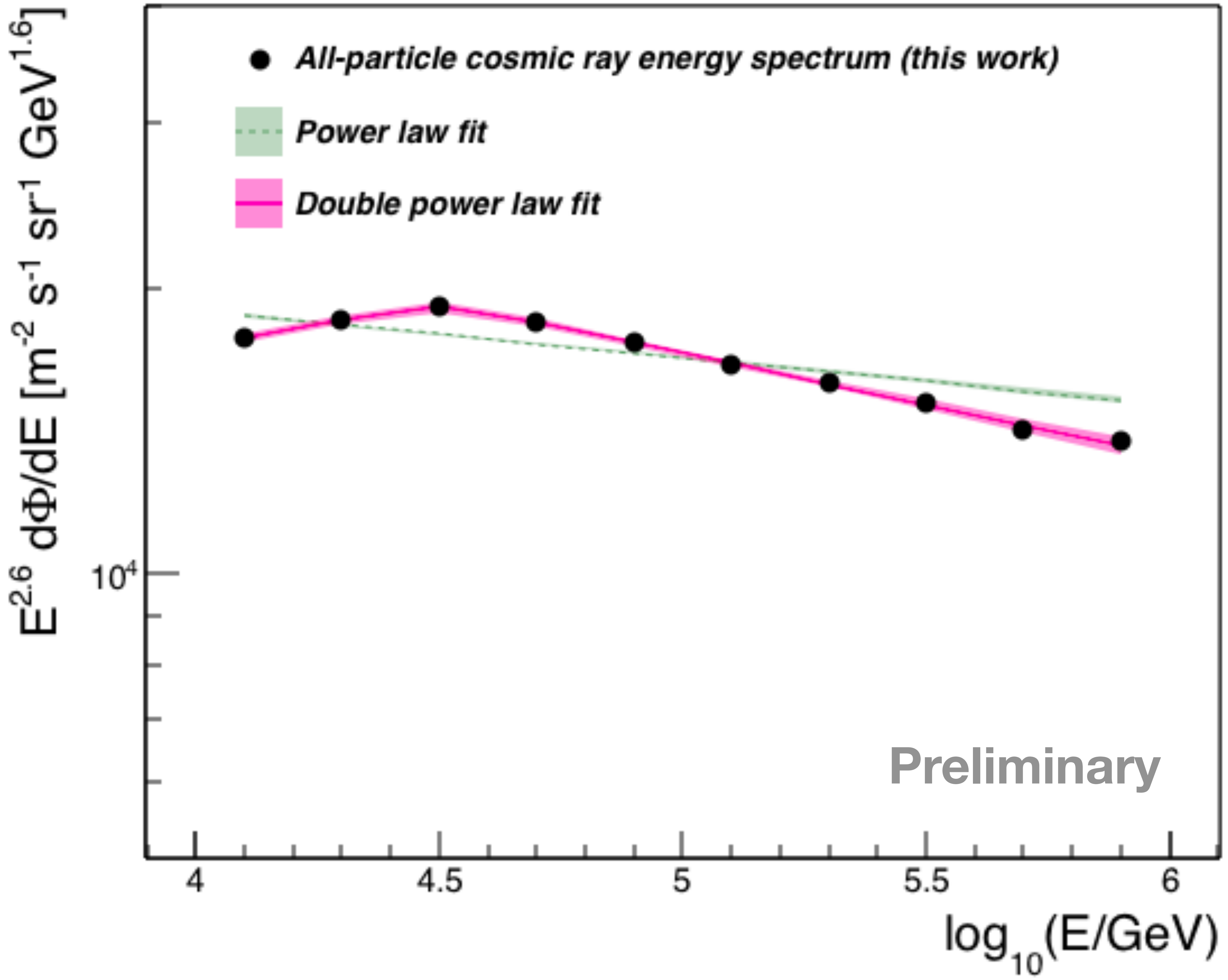
$\epsilon = 9.9 \pm 1.8$

$\Phi_0 = 10^{3.80\pm0.04}\, m^{-2}\, s^{-1}\, sr^{-1}\, GeV^{-1}$

$E_0 = 31.02^{+1.92}_{-1.81}$ TeV

$\gamma_1 = -2.50 \pm 0.01$

$\chi_1^2 = 0.17,\quad NDOF = 5.$



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

$TS_{obs} = 418.67$

By generating toy MC spectra with correlated data points using our covariance matrix and the result of the fit with the power-law model [30], it was found:

$p < 4 \times 10^{-5}$

Significance: 3.9σ

Conclusions

4 CONCLUSIONS

- Since the last Particles & Fields annual meeting,
- we have increase the statistics in the analysis from two years up to three years of total effective time,
- improved our understanding of the systematic effects that are present in the reconstruction of total energy spectrum of cosmic rays,
- and performed a statistical study about the significance of the break seen in the spectrum around 31 TeV.

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 that from HAWC in 2017 [1], the systematic uncertainty on the flux was reduced.
- We confirm the observation of a knee-like structure in the total spectrum of cosmic rays. In this study the position of the break is located at around 31 TeV.
- In addition to the measurements of NUCLEON [19], HAWC's result on the all-particle energy spectrum offers a bridge between direct and indirect measurements of the cosmic ray spectrum.

Project supported by:
Proyecto Conacyt A1-S-46288 and Coordinación de la Investigación Científica de la UMSNH.

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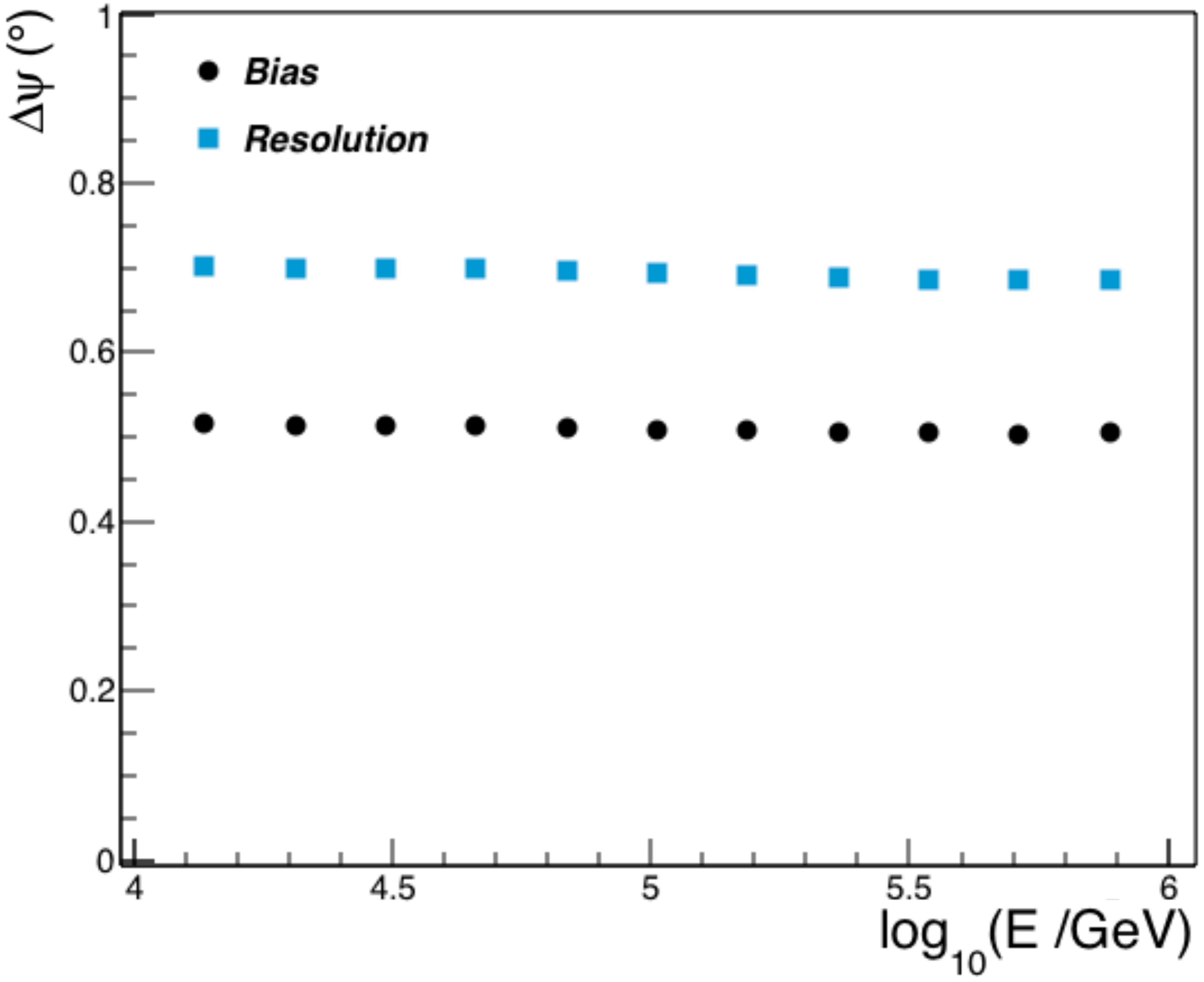
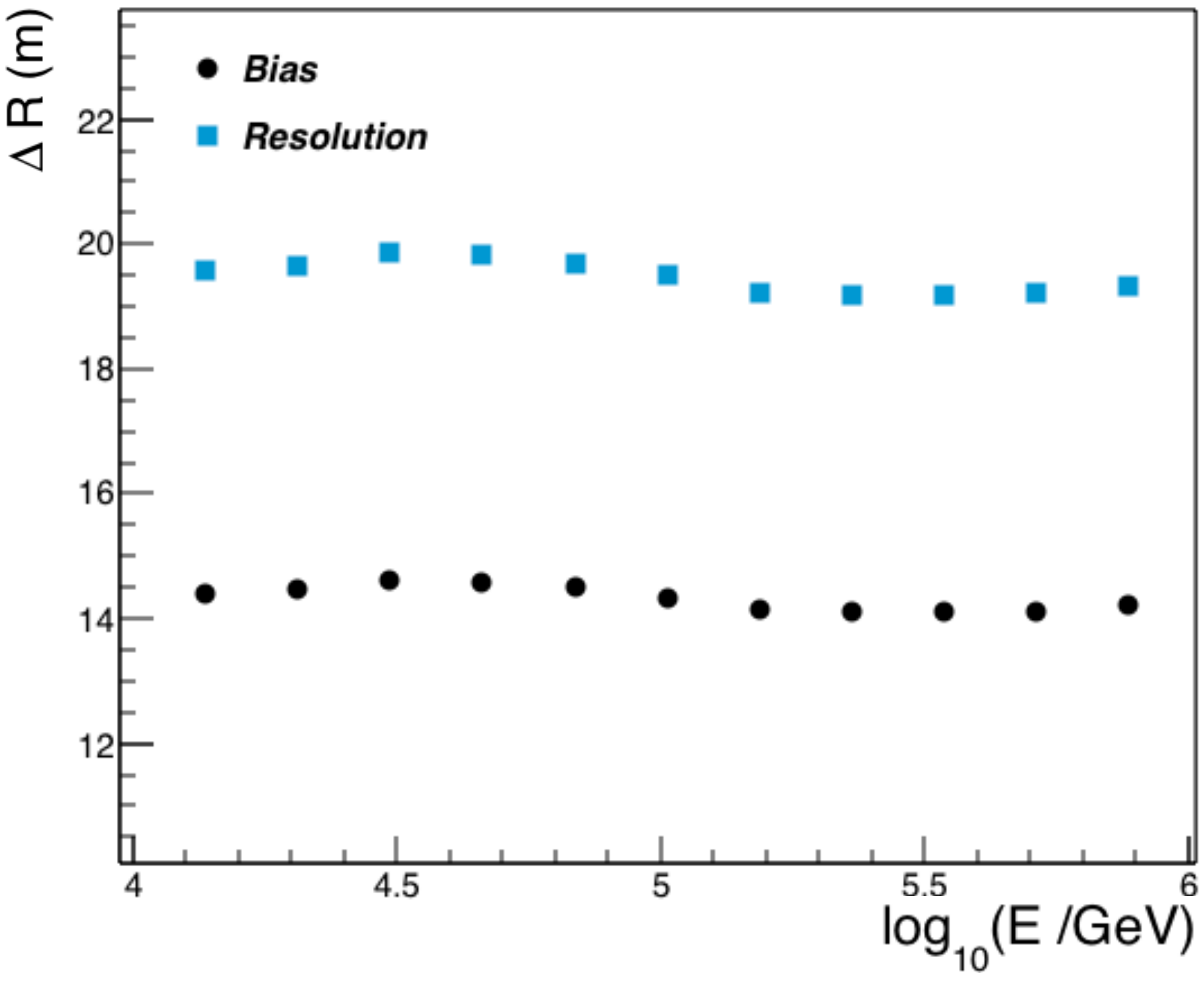
ANGLE AND CORE BIAS AND RESOLUTION



Resolution and bias in arrival direction



Resolution and bias in core position

3.3 UNCERTAINTIES ON THE PRIMARY ENERGY