Measurement of the total cosmic ray energy spectrum using HAWC in the TeV regime

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OUTLINE

Introduction.

The HAWC Observatory.

Analysis and results.

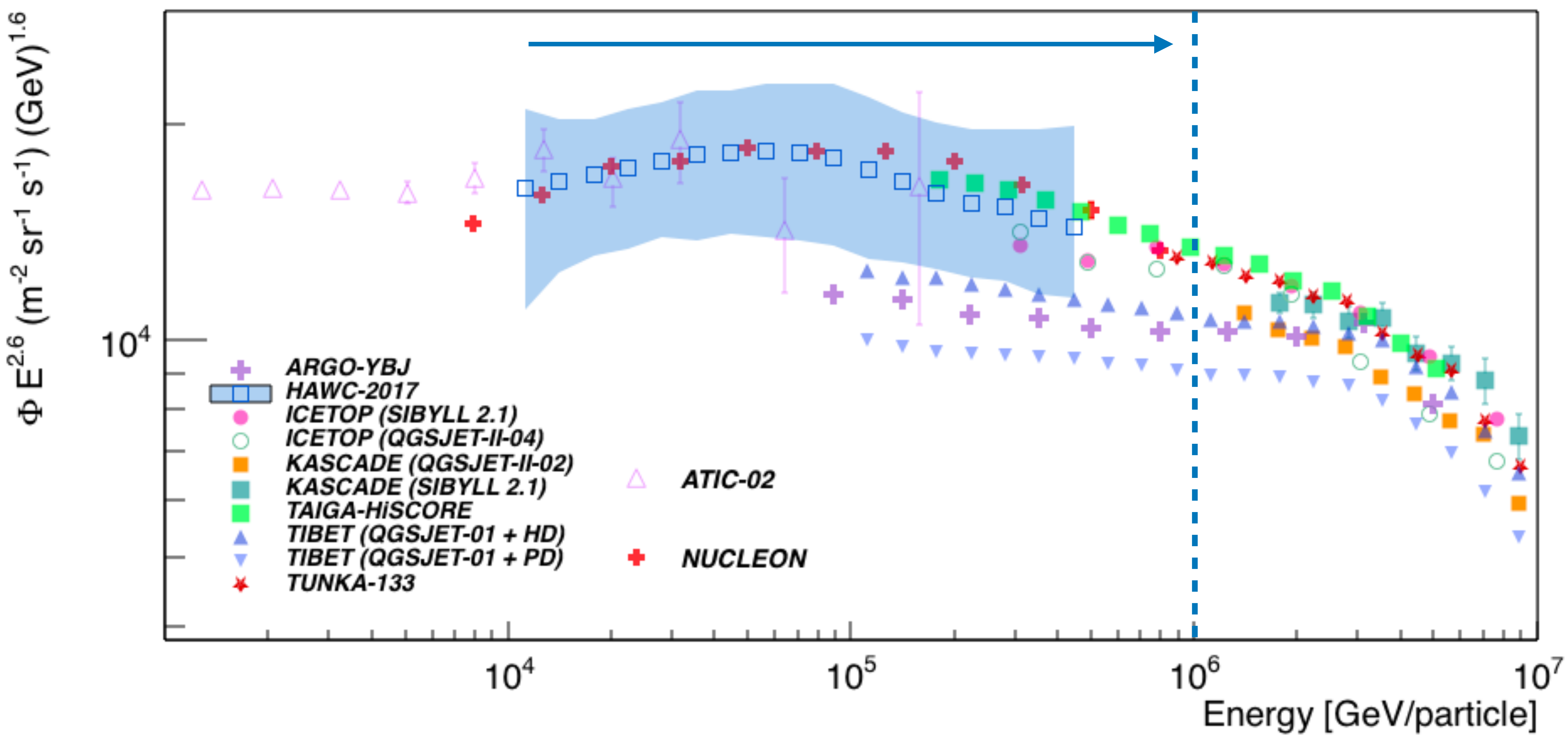
Conclusions.

High Altitude Water Cherenkov
Gamma-Ray Observatory

Introduction

1.1 ENERGY SPECTRUM OF COSMIC RAYS

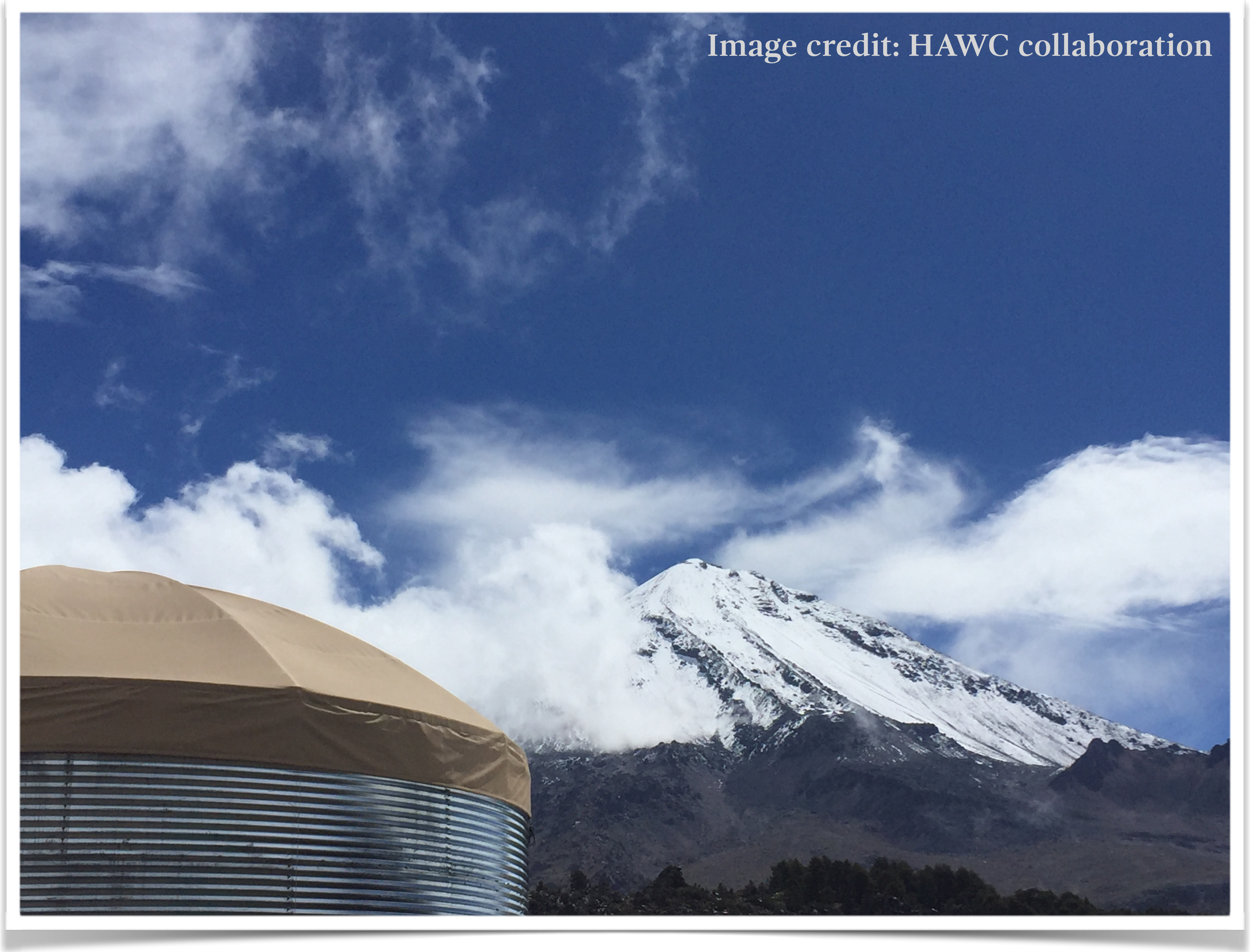
HAWC's previous result: measurement of the all-particle energy spectrum from 10 to 500 TeV with 8 months of data [1].



Our main goals are:

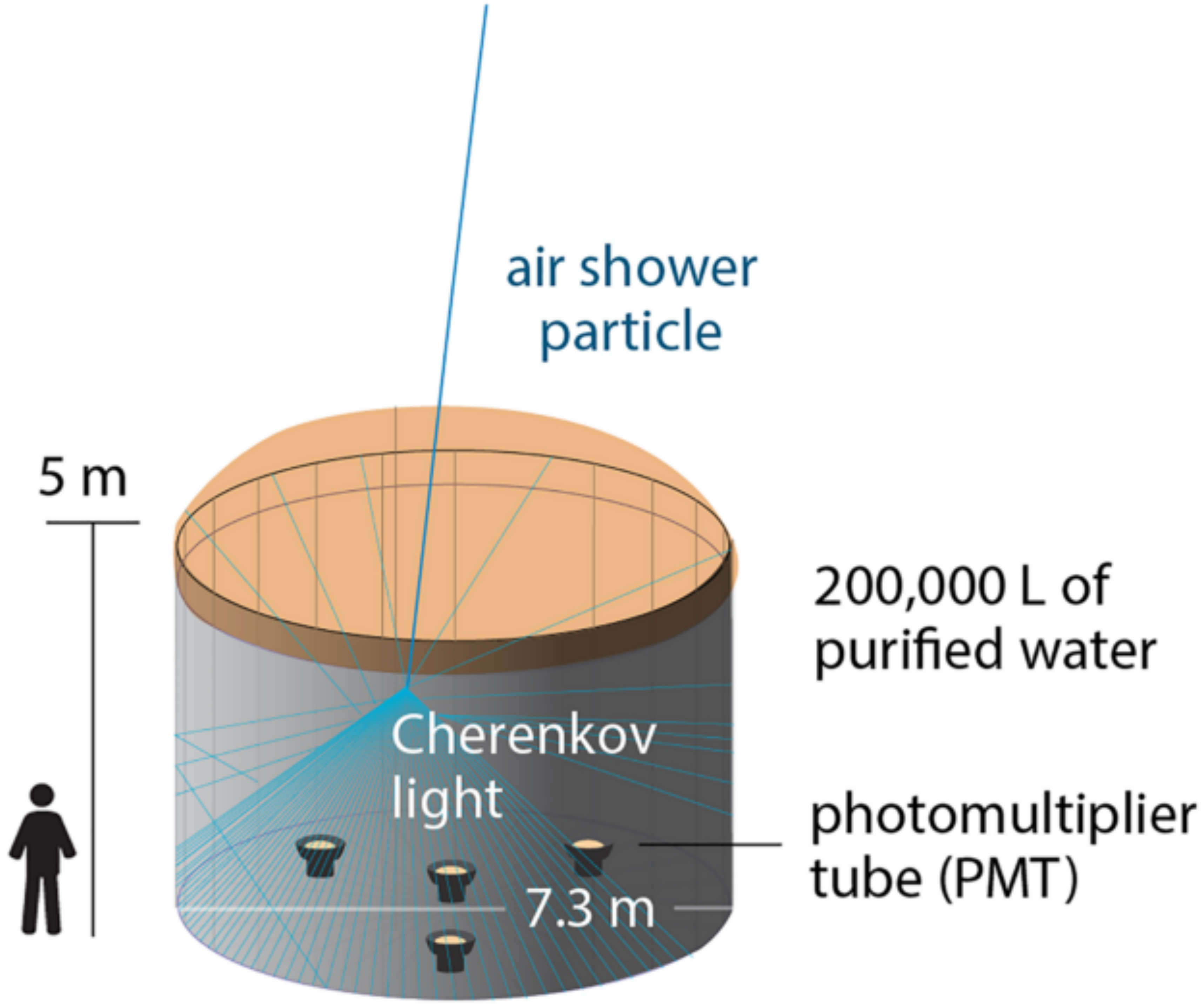
- To extend this study up to 10^{15} eV with HAWC.
- To increase the statistics in the analysis.
- To reduce PMT systematic uncertainties using improved simulations on the performance of the detector [2].

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 ≥ 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 made with a broken power-law 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.

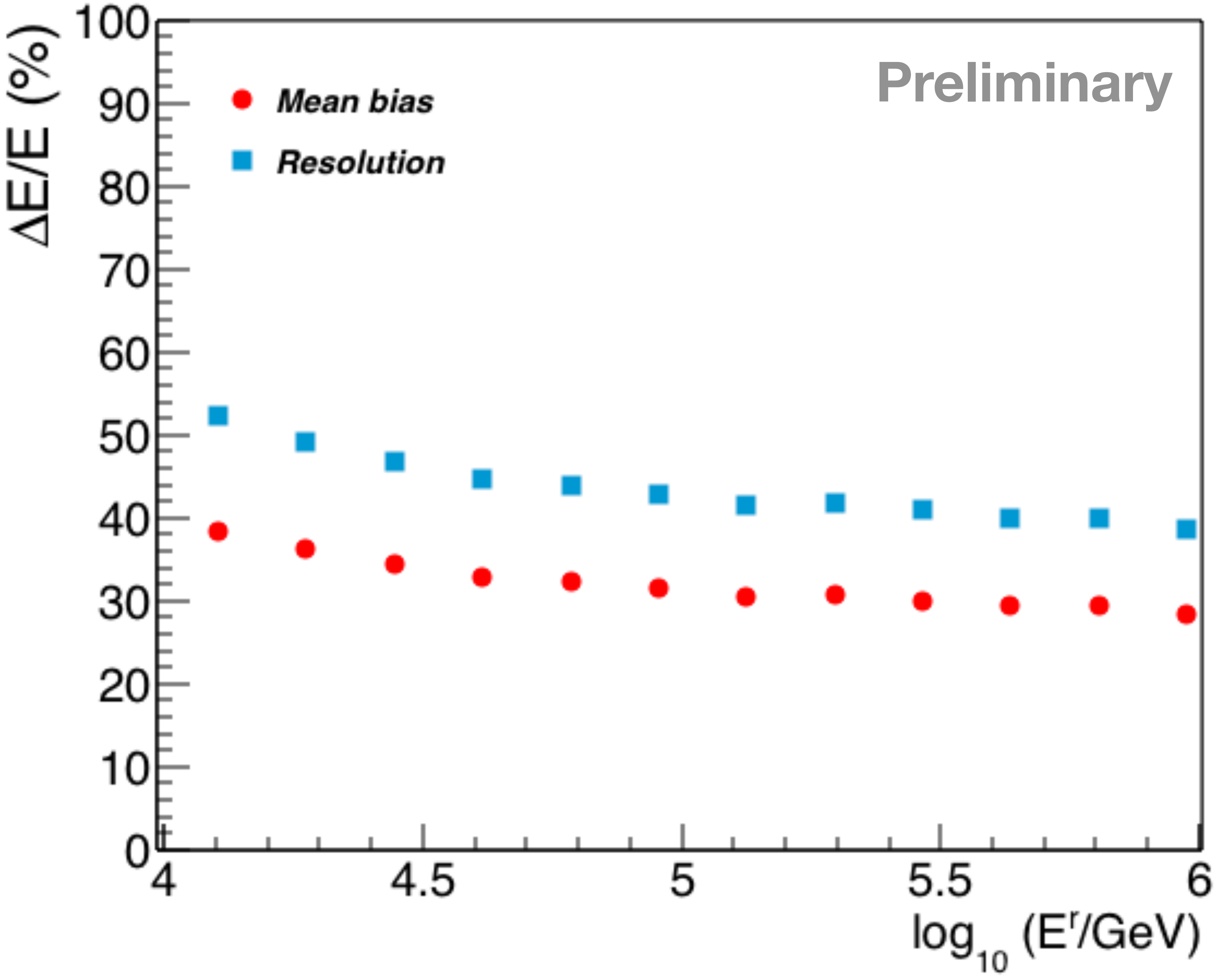
2.3 DATA SELECTION

- 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 $\theta < 35^o$,
- 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.

2.3 DATA SELECTION



E^r: reconstructed energy

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

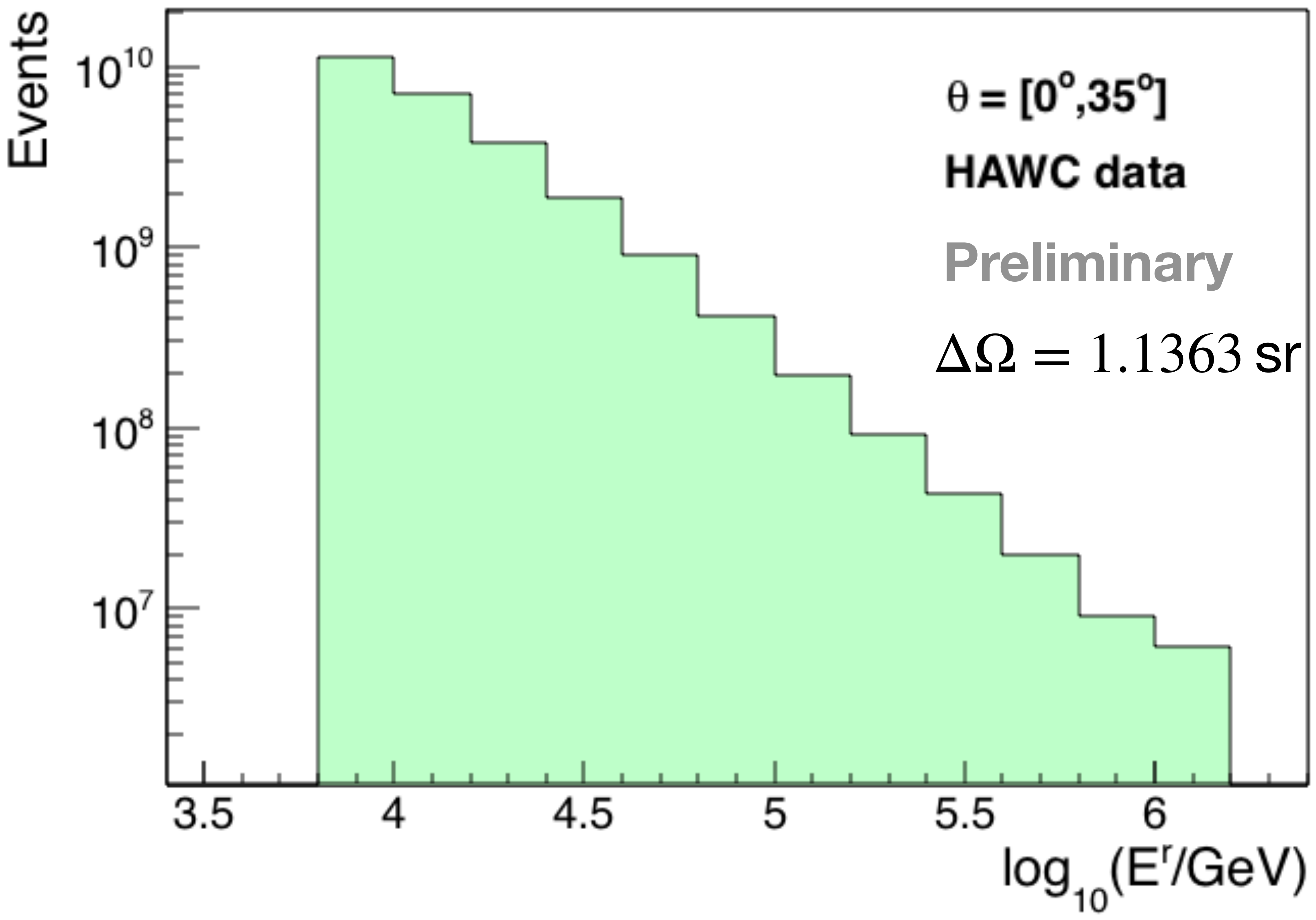
$\Delta E/E = 29\,\%$

$\Delta R = 11.8\,m$

$\Delta\psi = 0.5^{\circ}$

Analysis and results

3.1 HAWC'S MEASURED DATA



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

- Data from January 1st, 2018 to December 31st, 2019 were selected for this work, with a total effective of 1062 days.
- After the quality cuts were applied, we have a total of 3.9×10^{10} events in the data sample.
- Only air showers within the interval $E = 10^{3.8} - 10^{6.2}$ GeV were employed.

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) $P(E_j^R | E_i)$ .... Response Matrix (calculated from MC data)

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

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

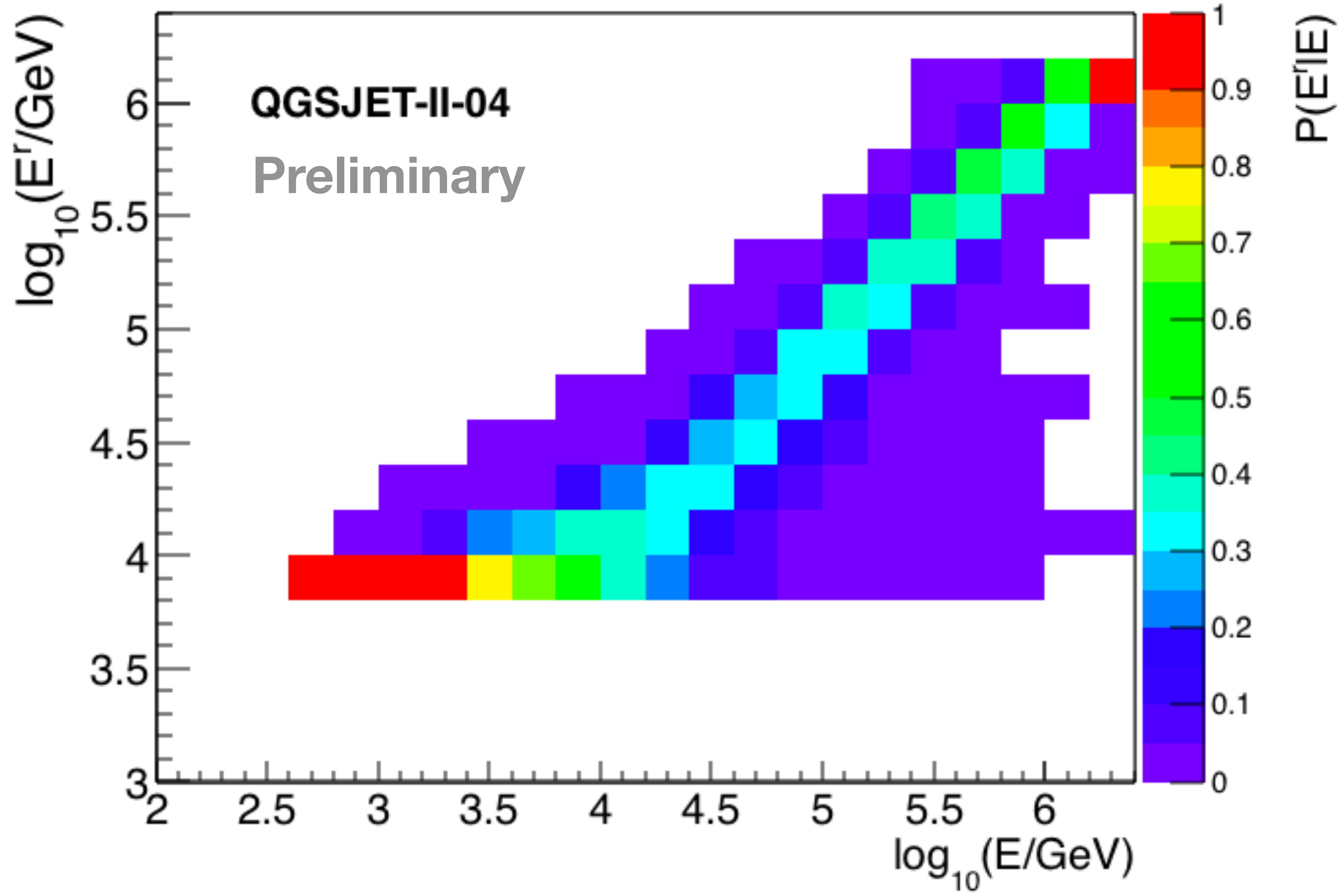
4) $P(E_i) \equiv \dfrac{N(E_i)}{\sum_{i=1}^{n_c} N(E_i)} = \dfrac{N(E_i)}{N_{true}}$. .... Final probability

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

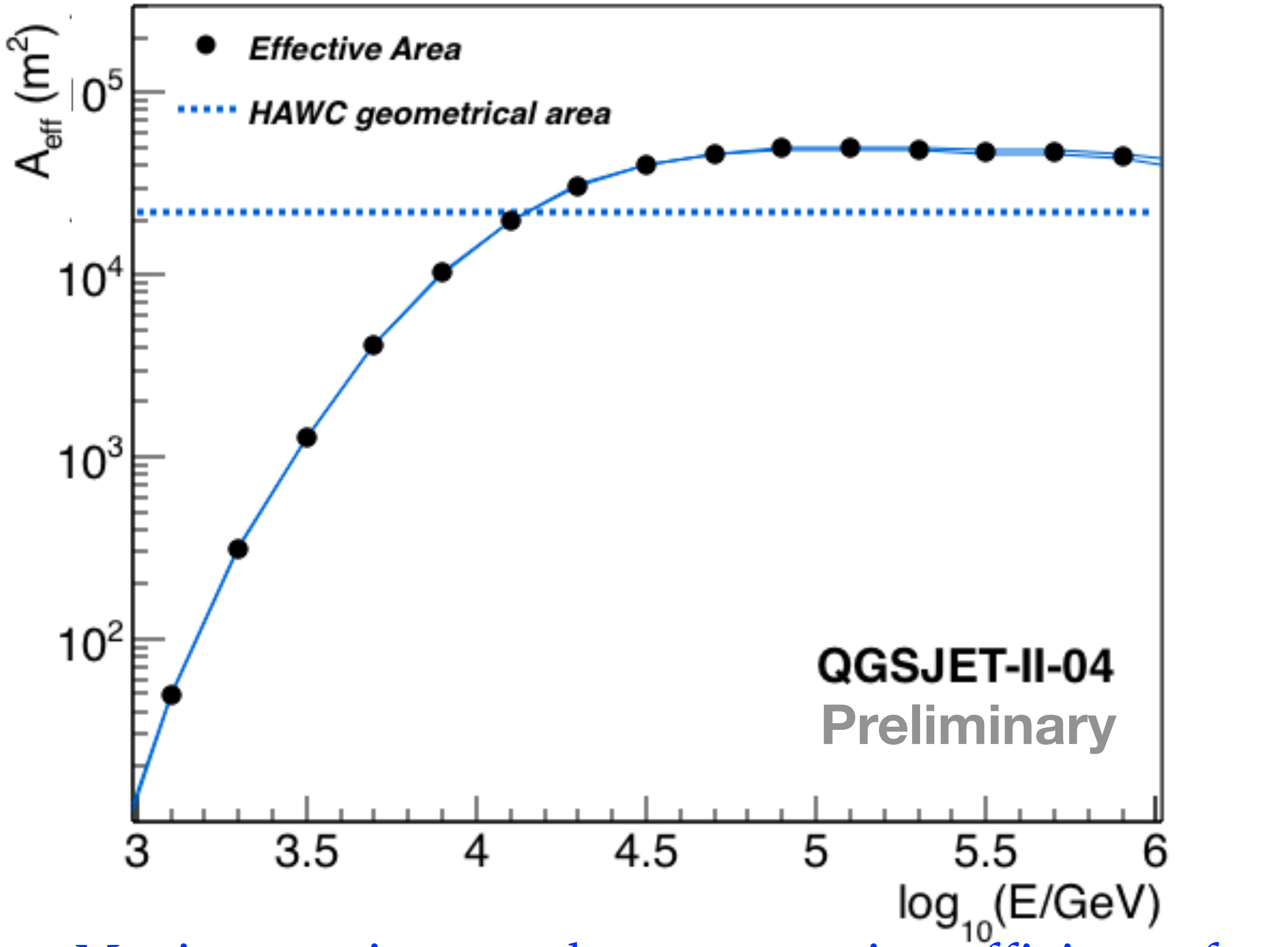
Response Matrix



HAWC's response becomes linear for

$E > 10^4$ GeV

Effective Area

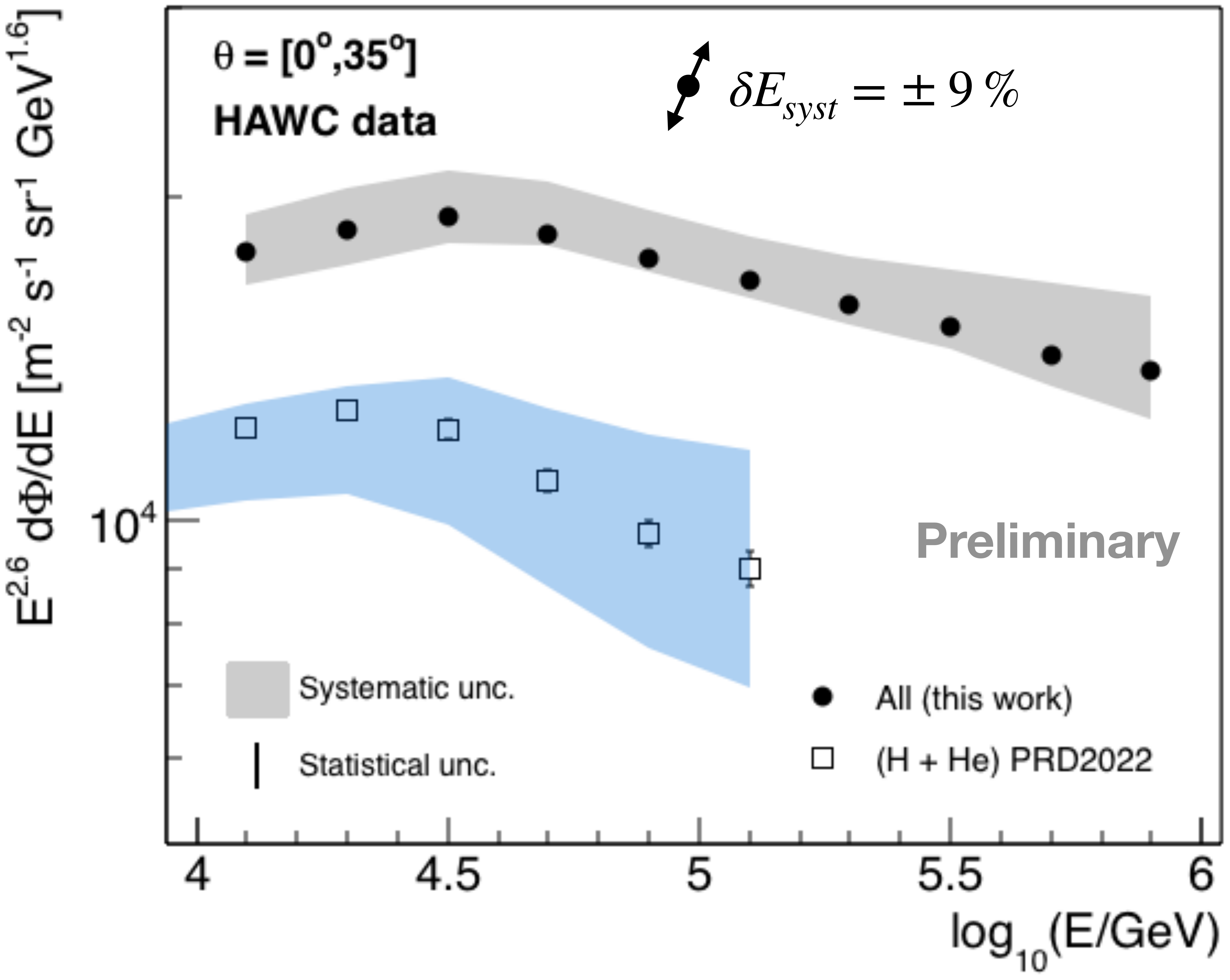


Maximum trigger and reconstruction efficiency for

$E > 10^{4.5}$ GeV

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

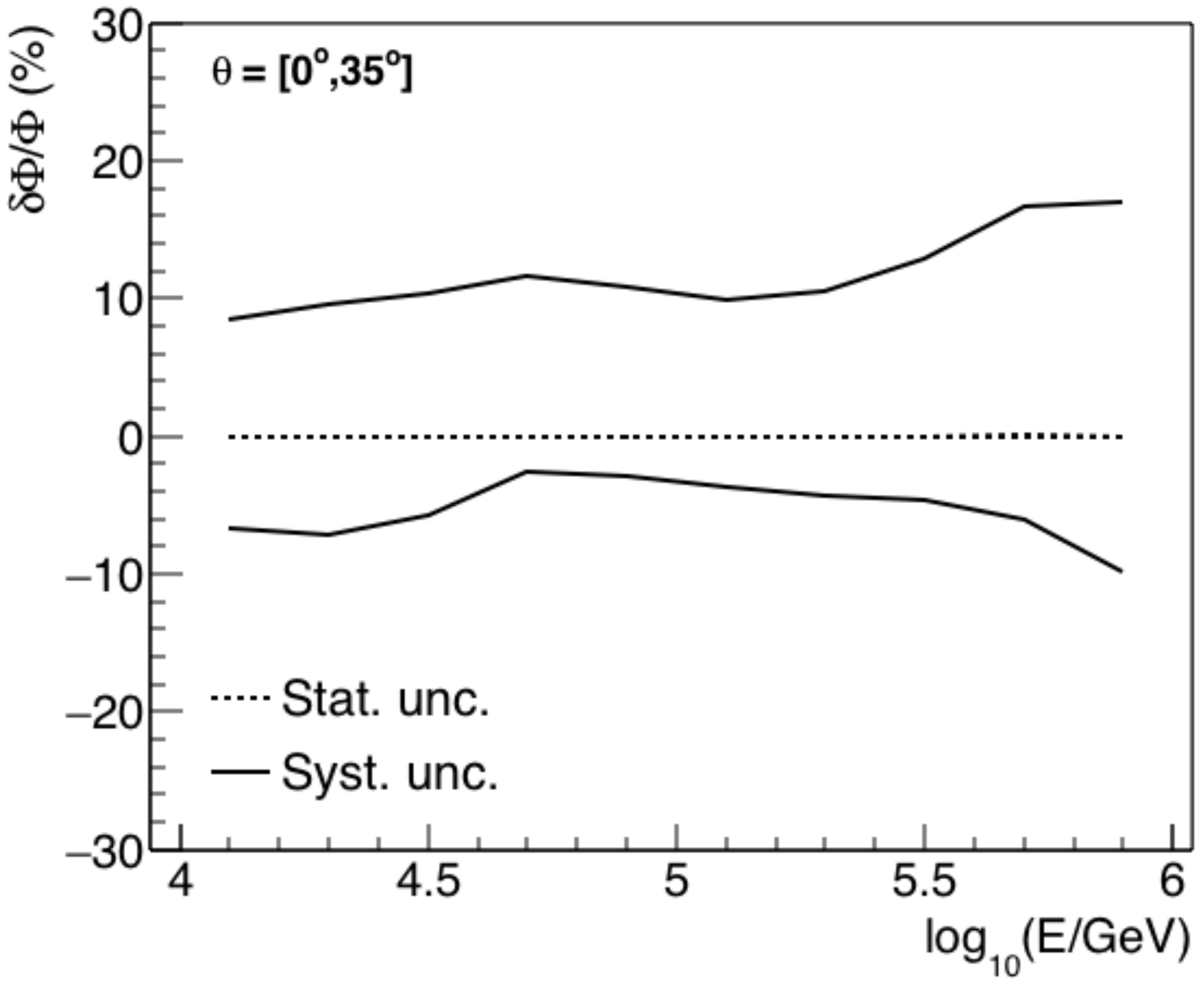
3.2 ENERGY SPECTRUM ESTIMATION



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

All-particle cosmic ray energy spectrum measured with HAWC

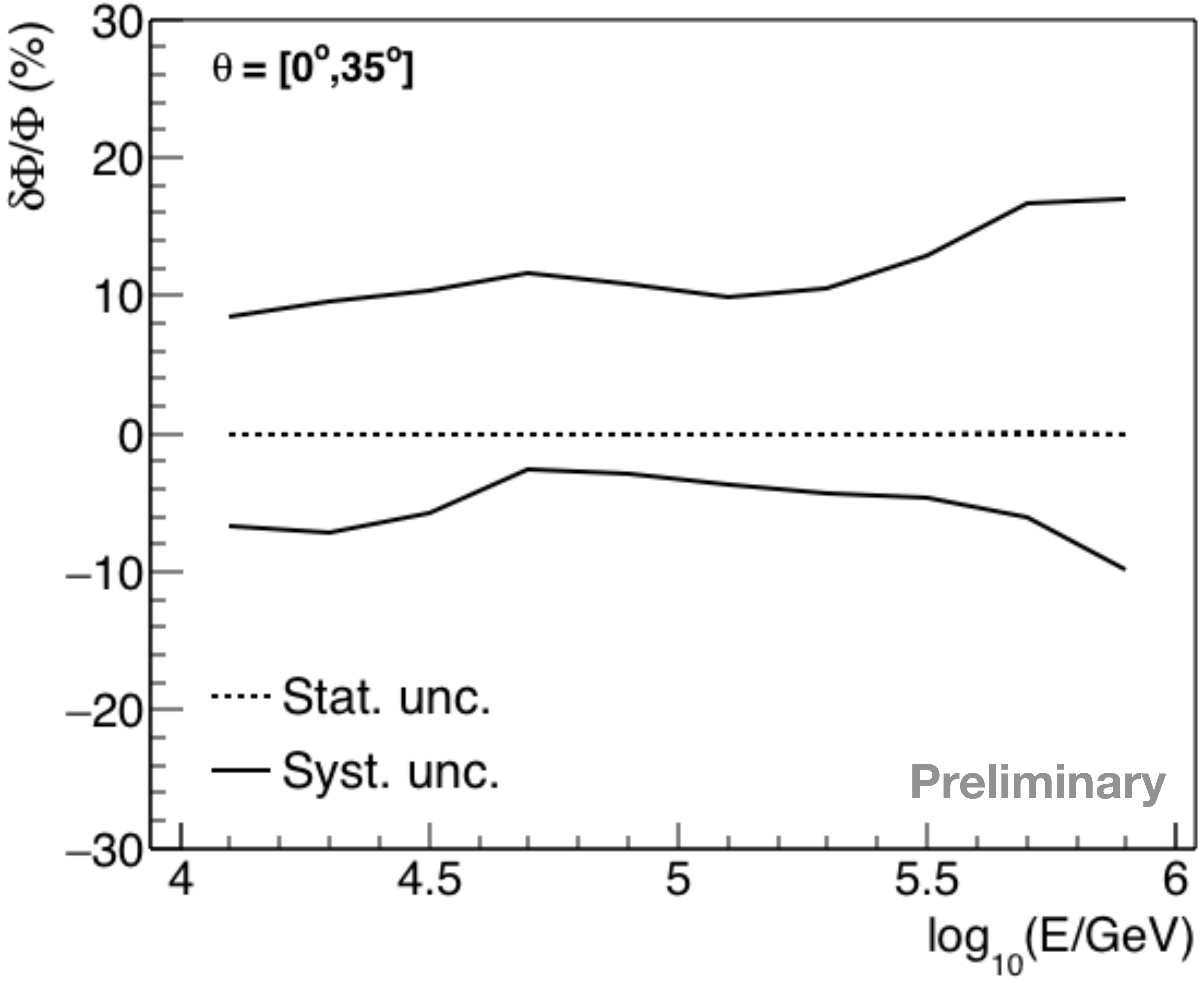
3.3 UNCERTAINTIES ON THE FLUX



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



Statistical relative error @ 10^5 GeV:

This work: ±0.01%

HAWC 2017 [1]: << 1 %

Systematic relative error @ 10^5 GeV:

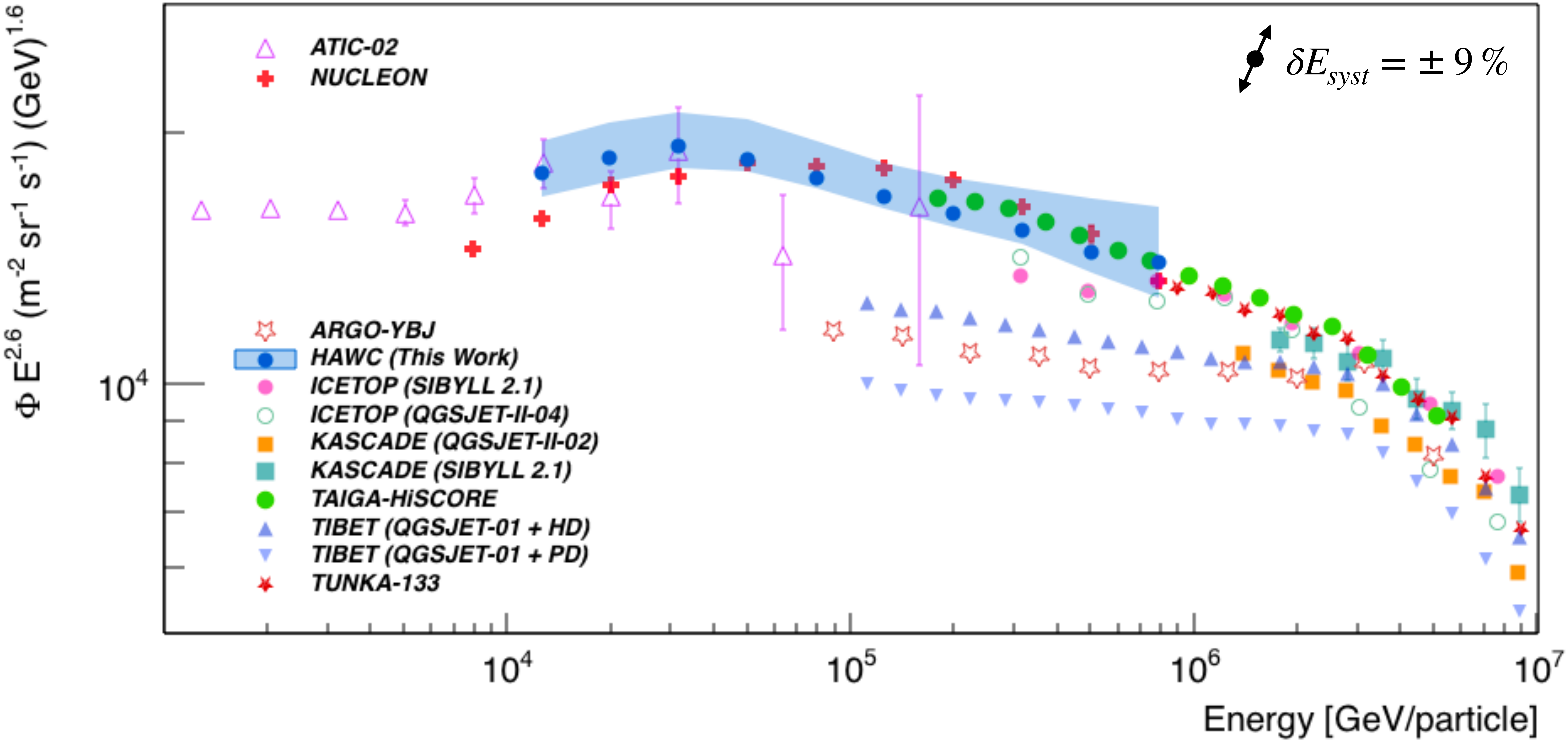
This work: +9.8% / -3.7%

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

3.3 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%**

3.4 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

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

$$\chi_0^2 = 418.8, \quad NDOF = 8.$$

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

$$\gamma_2 = -2.70 \pm 0.01$$

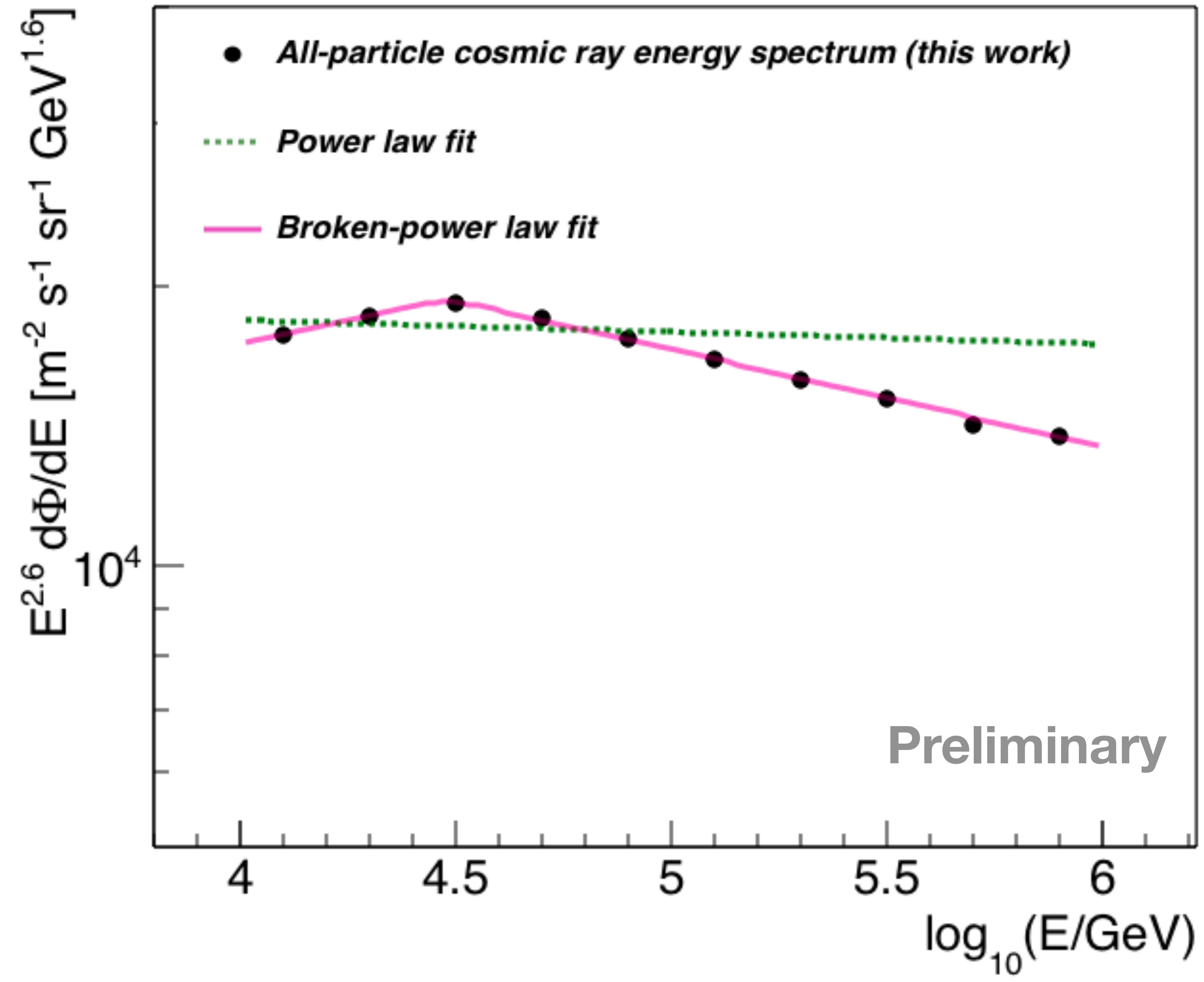
$$\epsilon = 5.0 \pm 0.4$$

$$\Phi_0 = 10^{3.85\pm0.05}\, m^{-2}\, s^{-1}\, sr^{-1}\, GeV^{-1}$$

$$E_0 = 32.20^{+2.37}_{-2.21}\ \text{TeV}$$

$$\gamma_1 = -2.50 \pm 0.01$$

$$\chi_1^2 = 3.8, \quad NDOF = 5.$$



3.5 FIT OF THE SPECTRUM

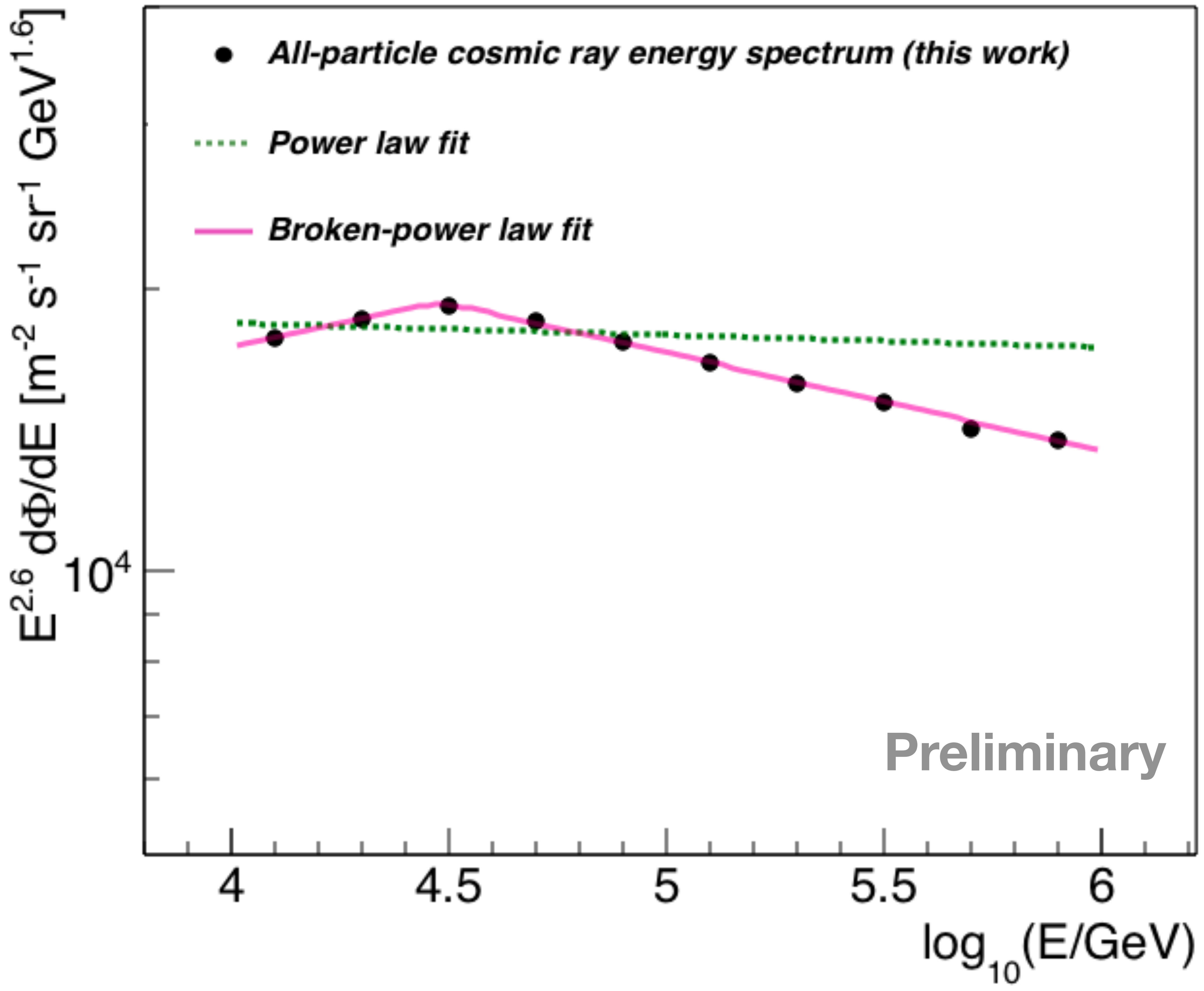
$$TS = -\Delta\chi^2 = -(\chi_1^2 - \chi_0^2)$$

$$TS_{obs} = 415.0$$

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

Image credit: HAWC collaboration

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 we found that the position of the break is located at around 32 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.

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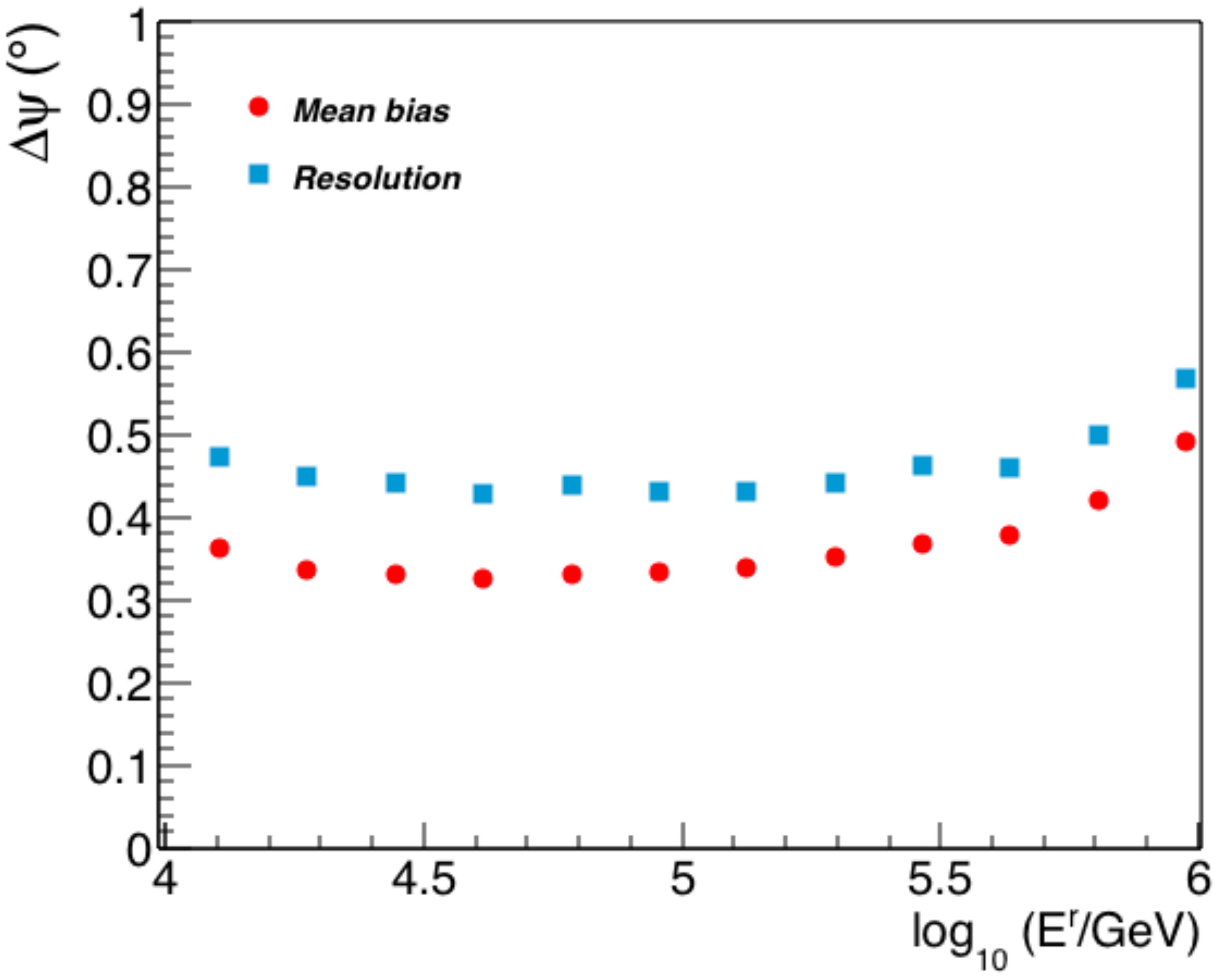
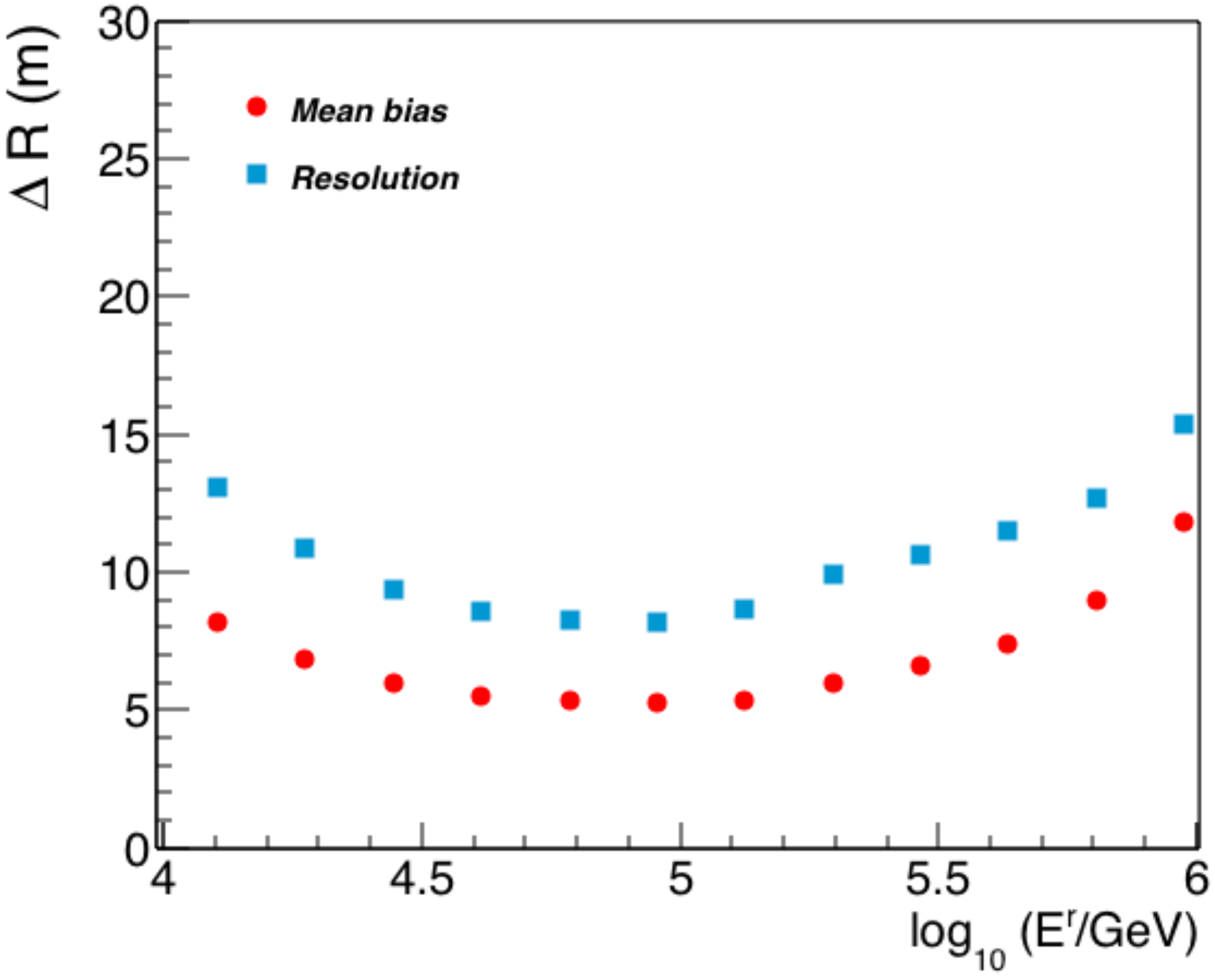
ANGLE AND CORE BIAS AND RESOLUTION

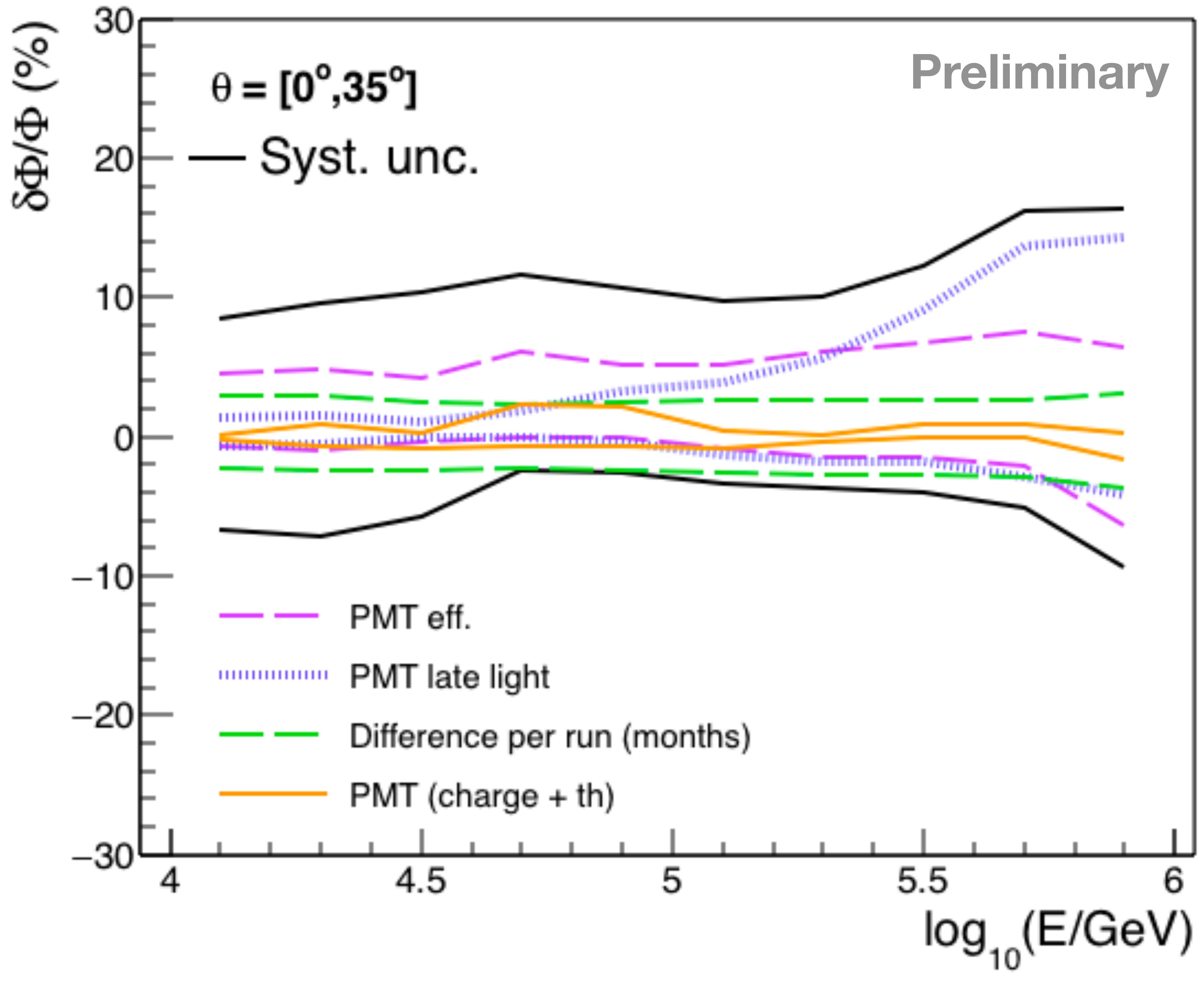


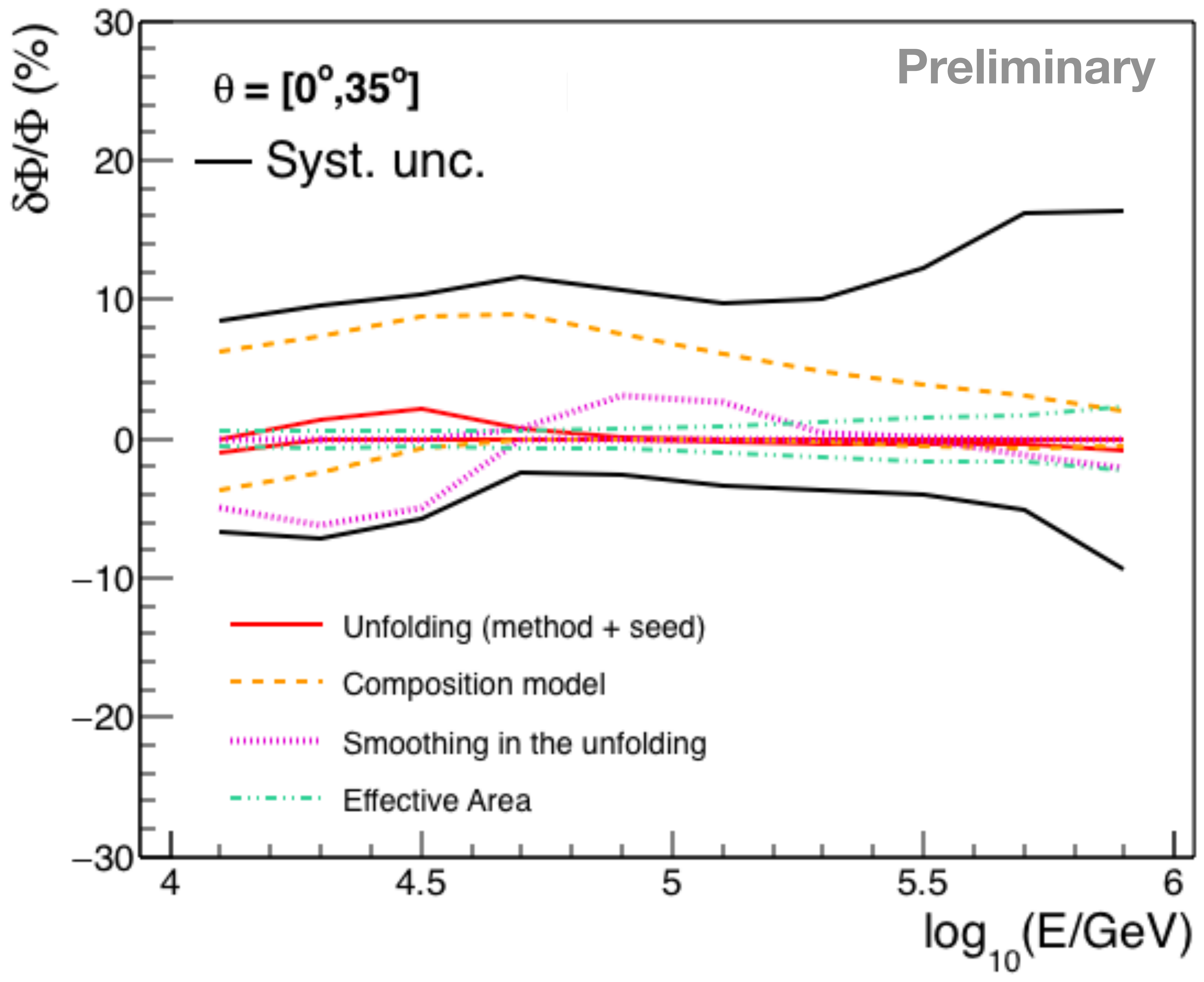
Resolution and bias in arrival direction



Resolution and bias in core position

UNCERTAINTIES ON THE FLUX





UNCERTAINTIES ON THE PRIMARY ENERGY