ALL-PARTICLE COSMIC-RAY ENERGY SPECTRUM MEASURED WITH HAWC

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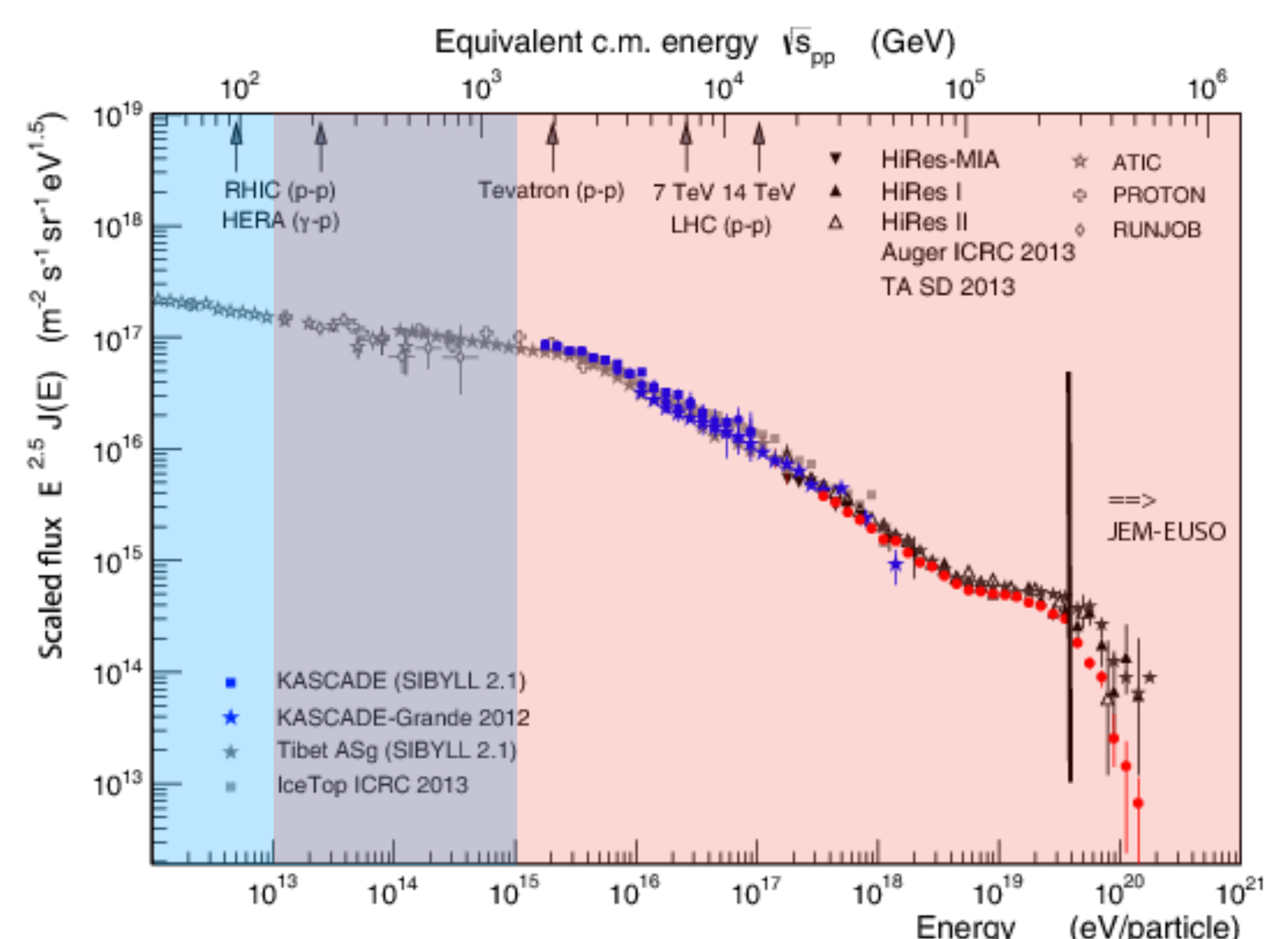
OUTLINE

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

INTRODUCTION

1.2 ENERGY SPECTRUM OF COSMIC RAYS



A. Haungs, et al.,

Direct Measurements ←

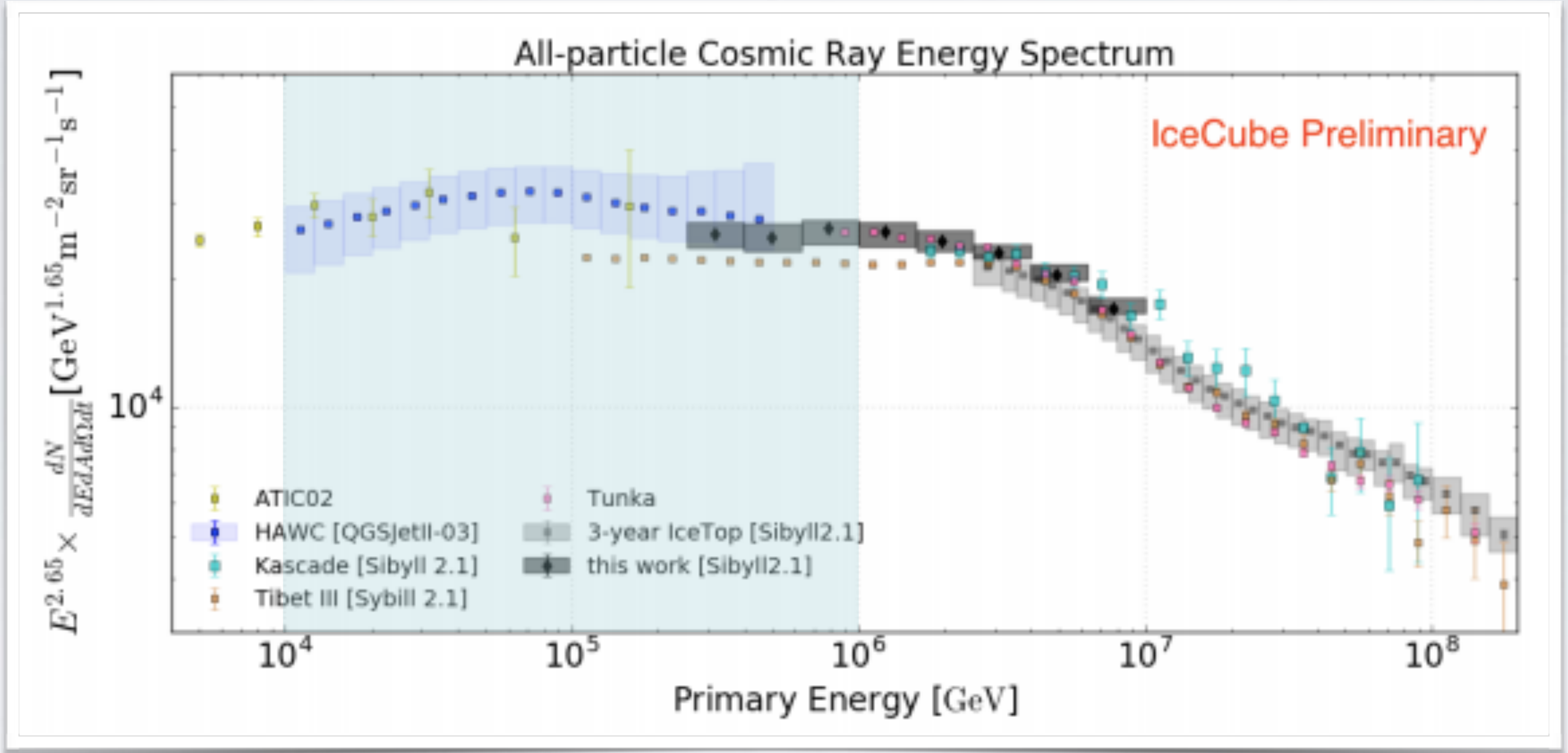
Indirect Measurements →

- 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.

1.2 ENERGY SPECTRUM OF COSMIC RAYS

HAWC's previous result: All-particle cosmic ray energy spectrum measured by the HAWC experiment from 10 to 500 TeV [1], with measurements from 10^4 GeV to $10^{5.5}$ GeV and 8 months of data.

Koirala, R., & Gaisser, T. K. (2019). *arXiv preprint arXiv:1908.07143*.



Our main goal is to extend the study of the all-particle cosmic ray energy spectrum up to 10^{15} eV with HAWC.

HAWC

High Altitude Water Cherenkov
Gamma-Ray Observatory

THE HAWC OBSERVATORY

2.1 HAWC

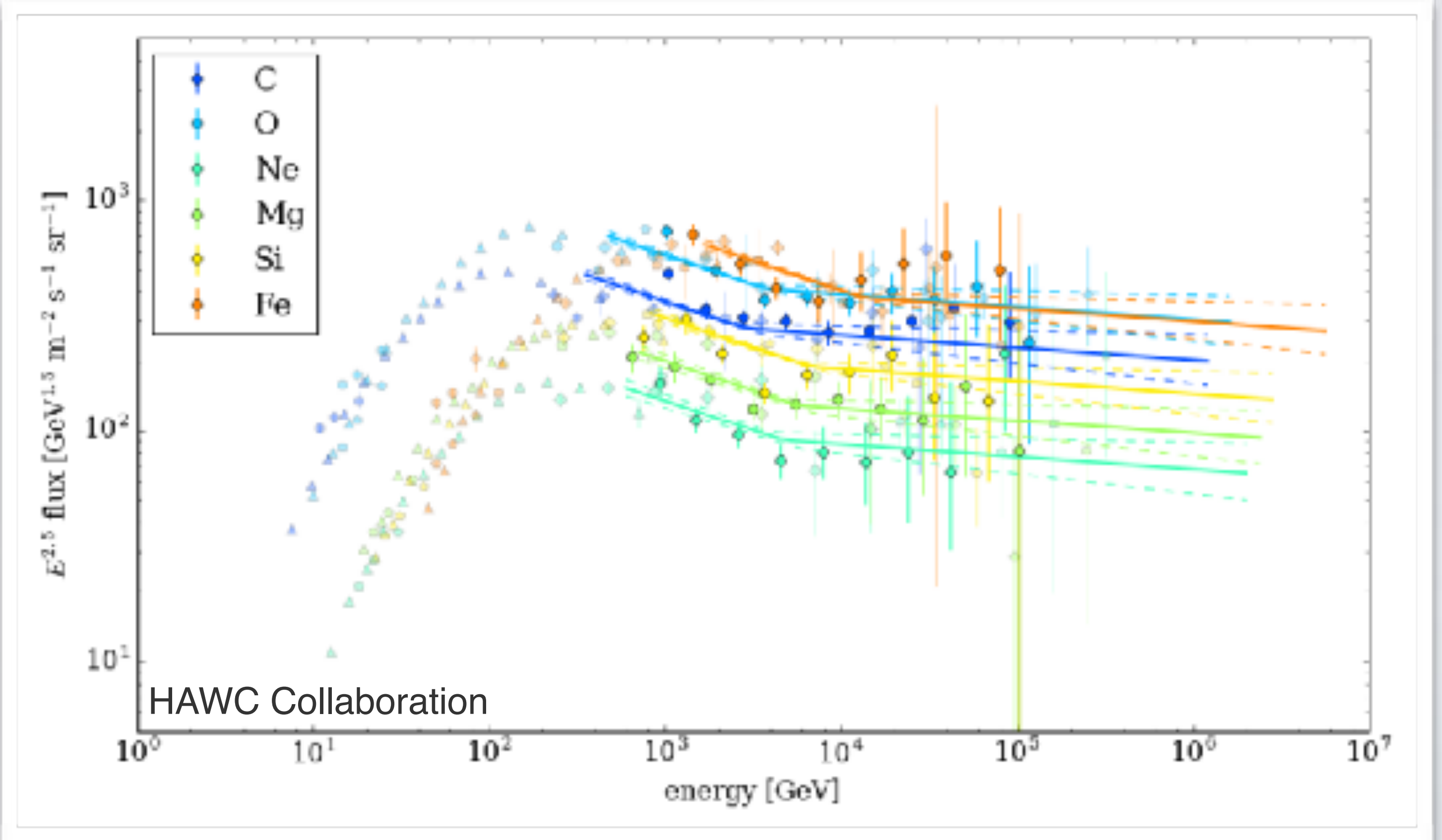
- Among the main scientific objectives of HAWC are: to extend astrophysical measurements of gamma rays up to 100 TeV, as well as to study cosmic rays between 100 GeV and 1 PeV [2].

  - 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.


Image credit: HAWC collab.

2.1 SIMULATIONS

- 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: ^{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.



2.1 HAWC'S MEASURED DATA

- A subsample of events taken during the month of January, 2018 were selected for this work.
- Only air showers within $E = 10^{3,5} - 10^{6}$ GeV were employed.

Total time	#events before cuts	#events after cuts
28.9 days	62,816,068,123	1,080,388,000

2.1 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.

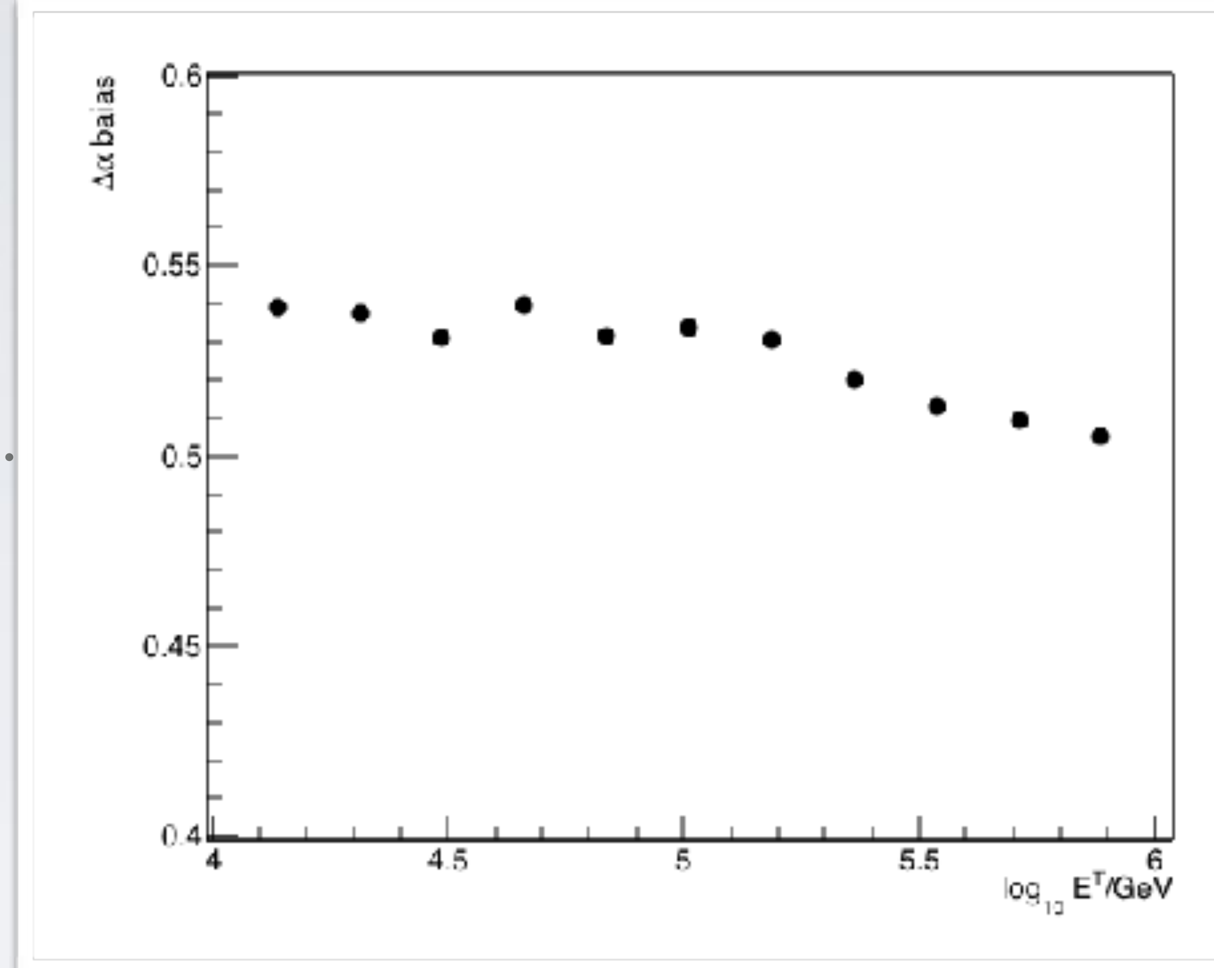
- The selected events:
    - with $\theta < 35^{\circ}$,
    - activated at least 60 channels in a radius of 40 m from the shower core.
    - fell inside HAWC's area,
    - registered signal in, at least, 75 channels from a total of 1200,
    - and activated more than 30% of the available channels.

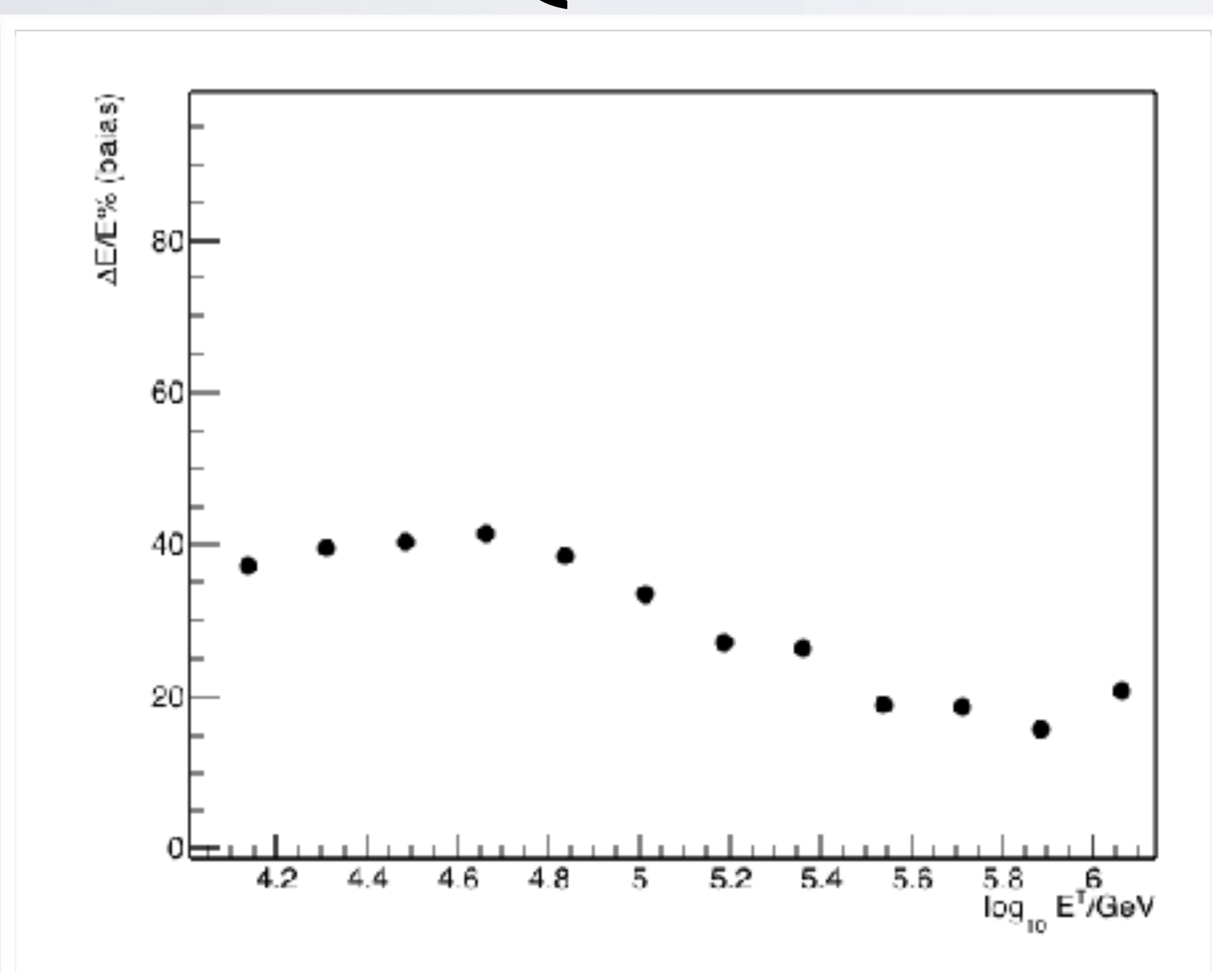
At $E = 10^{4.5}$ GeV:

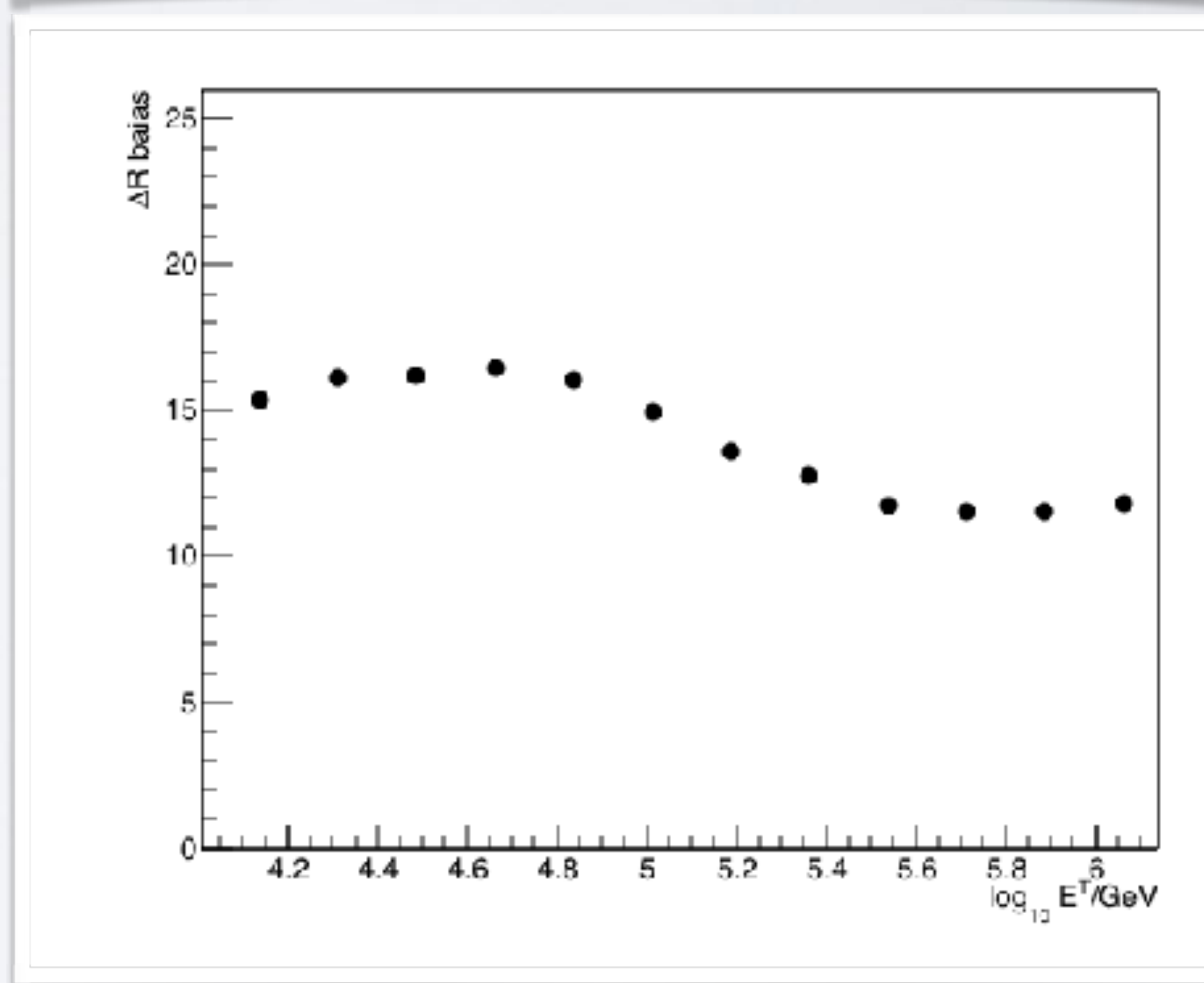
bias in the shower core position:	< 14 m,
bias in the arrival direction:	< 0.41º,
mean error in energy:	< 20%.

2.2 ENERGY, ANGULAR AND CORE POSITION BIAS

@10^6 GeV $\begin{cases} \Delta\alpha = 0.51^\circ \\ \Delta R = 12m \\ \Delta E/E = 25\,\% \end{cases}$







ANALYSIS AND RESULTS

3.1 ENERGY SPECTRUM ESTIMATION

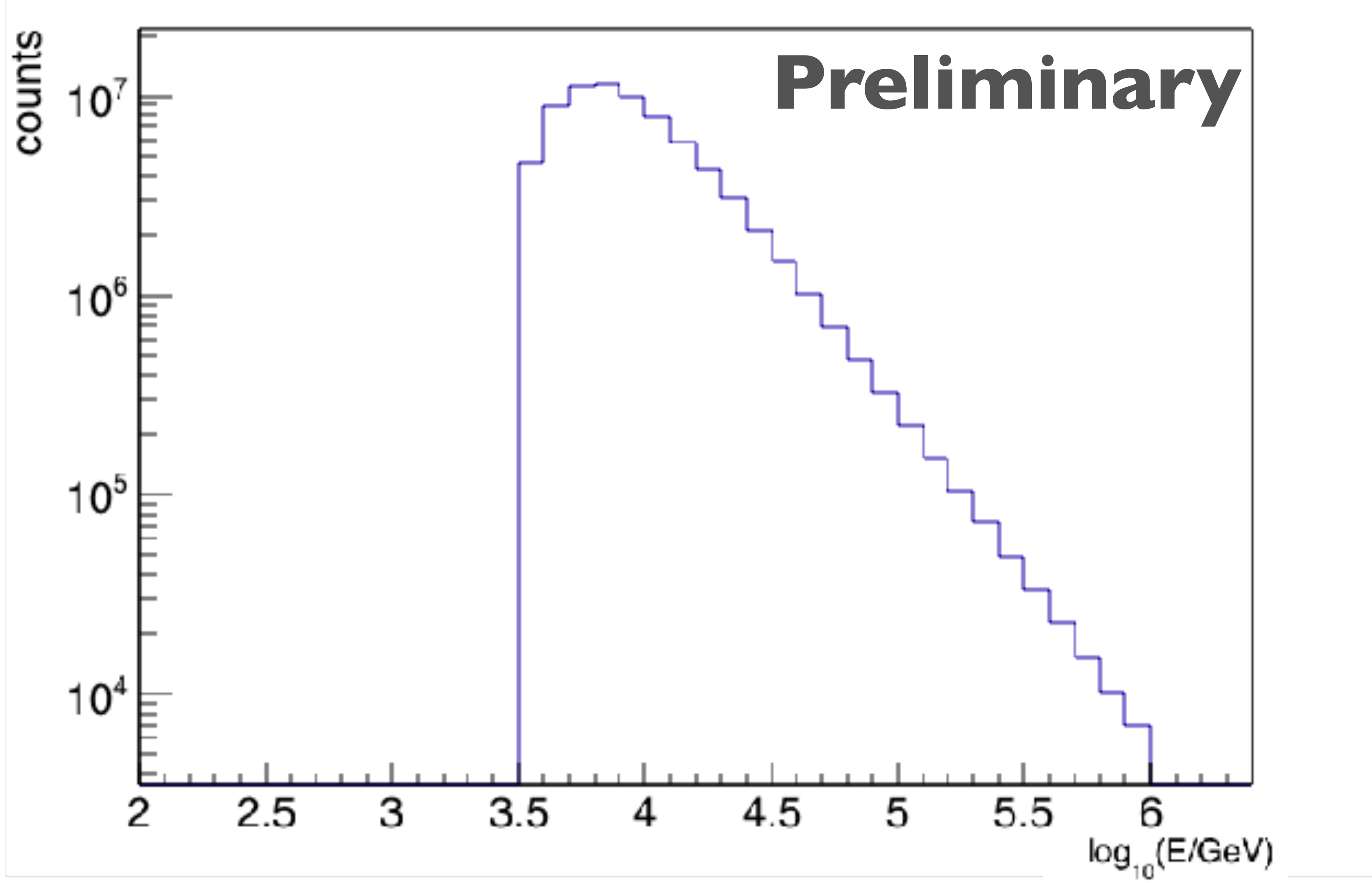
$$\Phi(E) = \frac{N(E^R)}{\Delta E \Delta t \left(\int_0^{2\pi} \int_{\theta 1}^{\theta 2} cos(\theta) d\Omega \right) A}$$

$$\Delta t \approx 2{,}499{,}829.999776\ s$$

$$\theta_1 = 0^\circ, \quad \theta_2 = 35^\circ$$

$$A \approx 25118.86\ m^2$$

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



3.1 ENERGY SPECTRUM ESTIMATION

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

How?

1) $P(E_j^R \mid E_i^T)$ — Response Matrix

2) $$P(E_i^T \mid E_j^R) = \frac{P(E_j^R \mid E_i^T) P_0(E_i^T)}{\sum_l^{n_c} P(E_j^R \mid E_l^T) P_0(E_l^T)}.$$ — 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

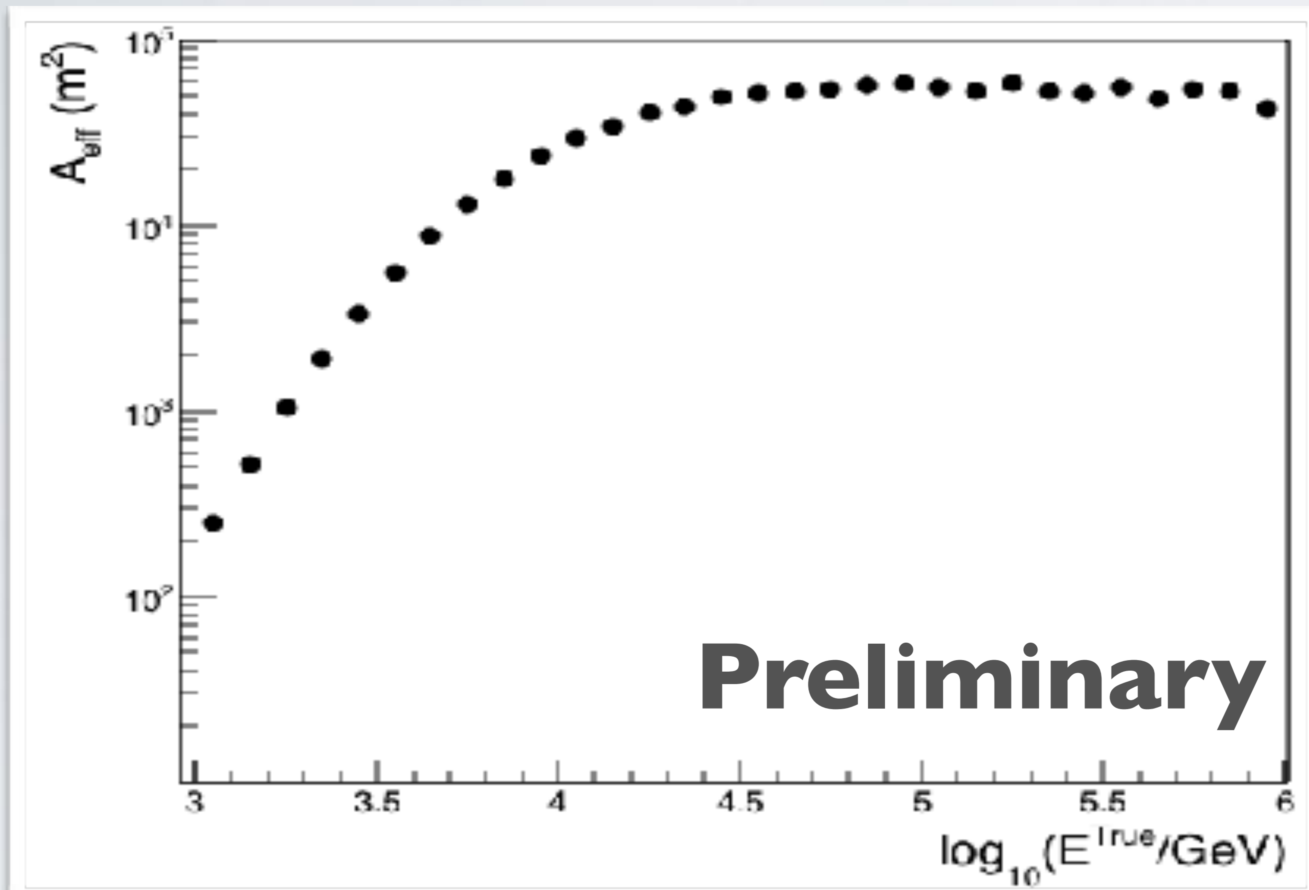
4) $$P(E_i^T) \equiv \frac{N(E_i^T)}{\sum_{i=1}^{n_c} N(E_i^T)} = \frac{N(E_i^T)}{N_{true}}.$$ — Final probability

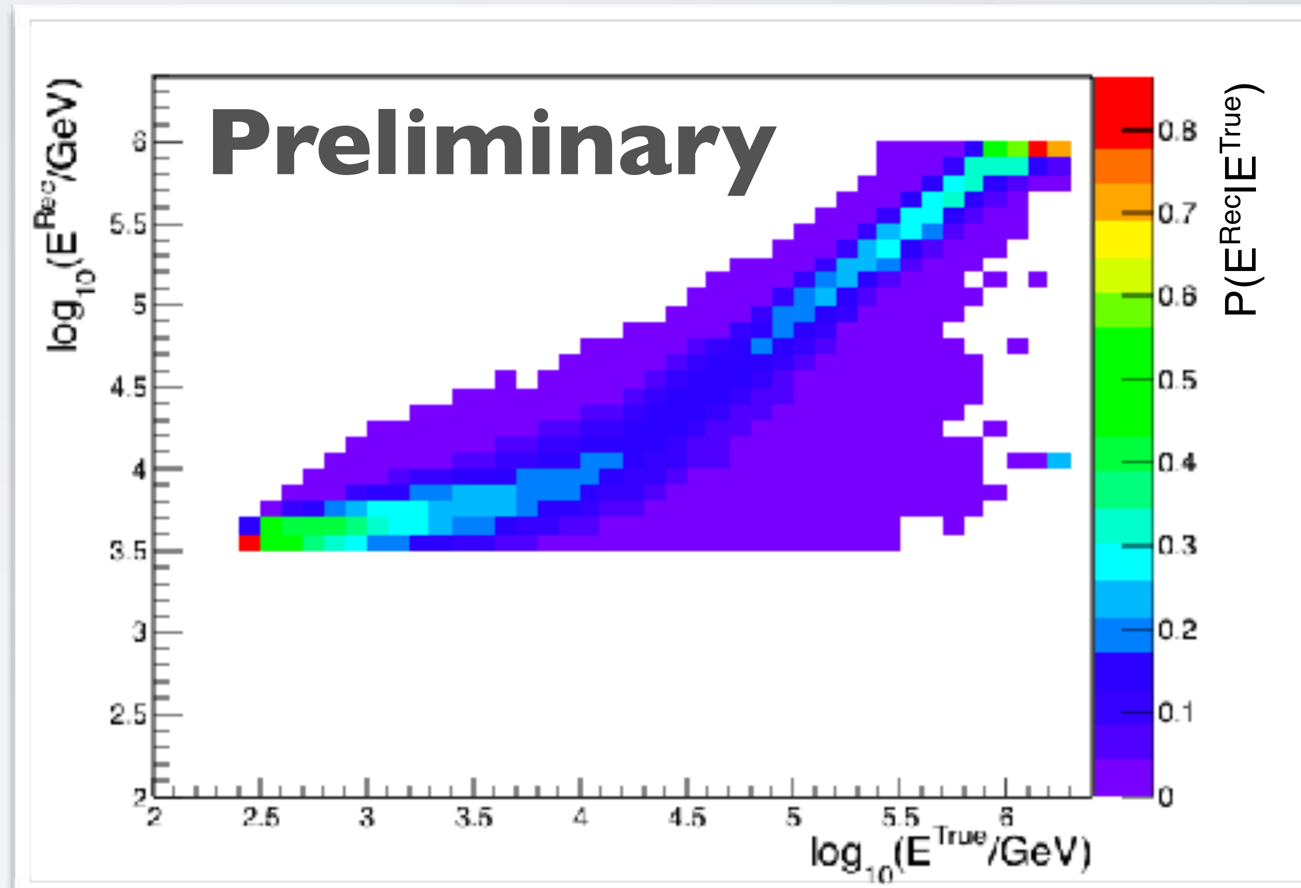
We chose a stopping criteria based on the weighted mean squared error.

G. D'Agostini, "A multidimensional unfolding method based on Bayes' theorem", Nuclear Inst. and Methods in Physics Research, A, vol. 362, n.o 2-3, págs. 487-498, 1995. doi: 10.1016/0168-9002(95)00274-X

3.1 ENERGY SPECTRUM ESTIMATION

Inputs from MC data





Effective Area

Maximum efficiency for

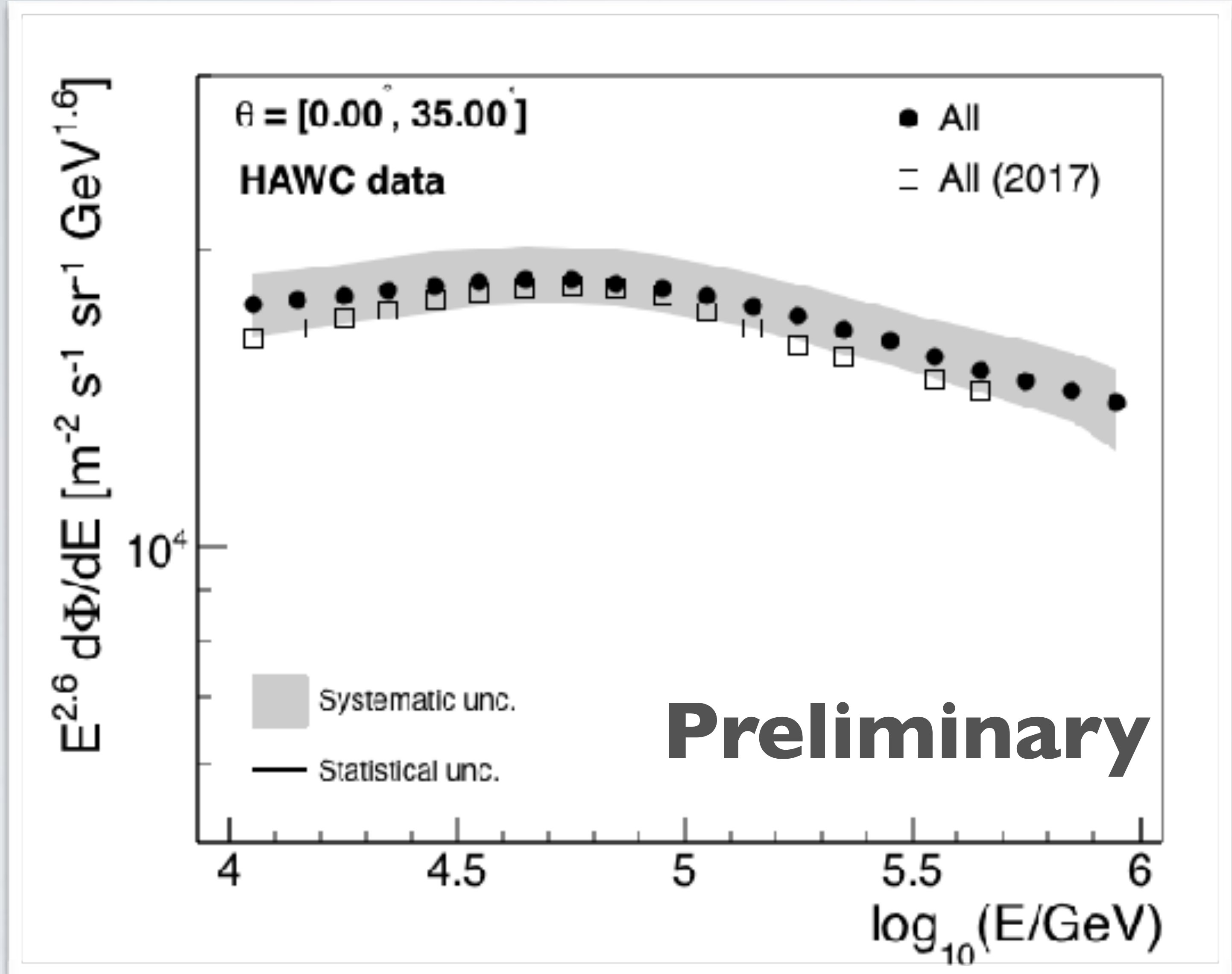
E > 10^4 GeV

Response Matrix

HAWC's response becomes linear

for E > 10^4 GeV

3.1 ENERGY SPECTRUM ESTIMATION

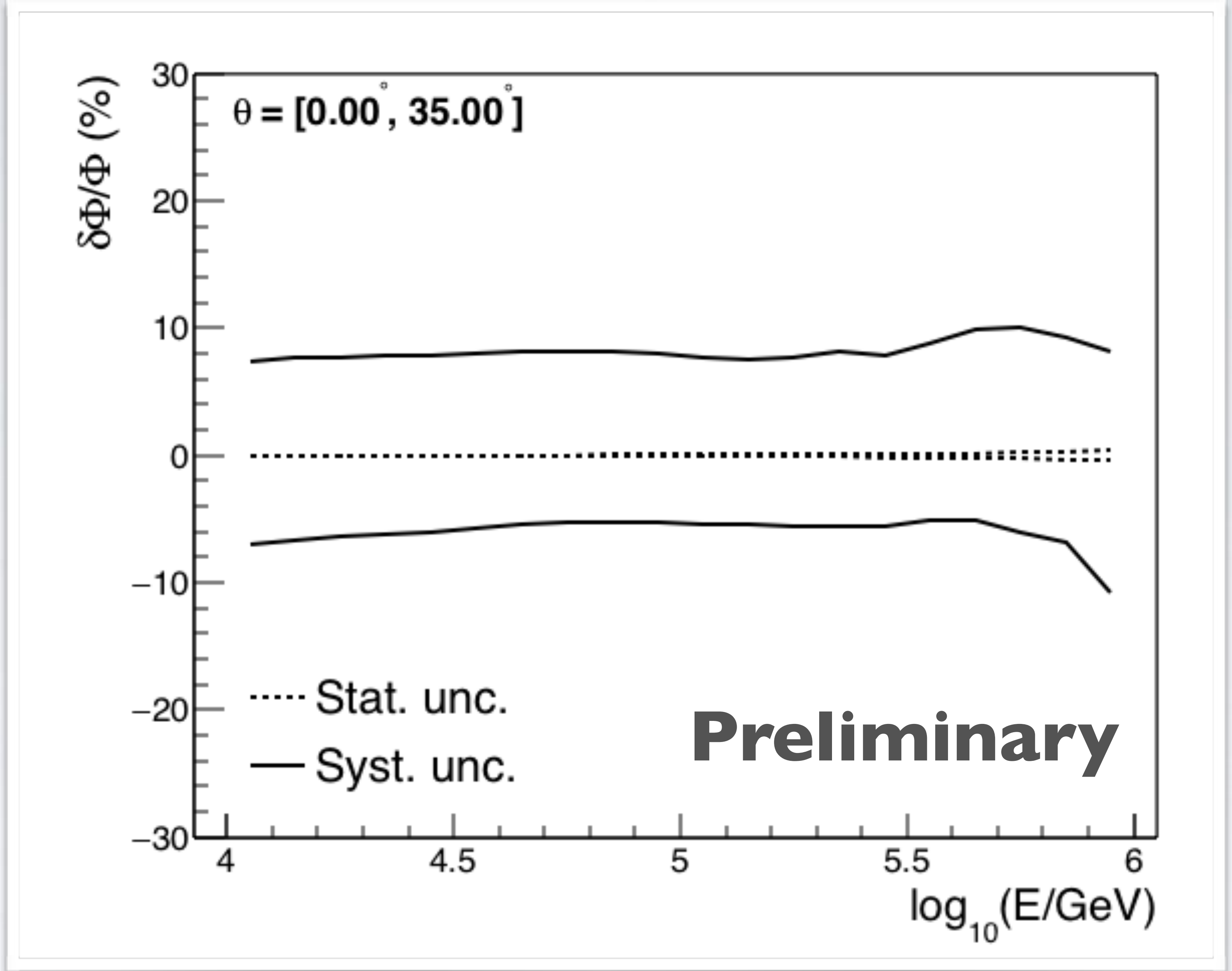


All-particle cosmic ray energy spectrum measured by HAWC

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 UNCERTAINTIES ON THE FLUX

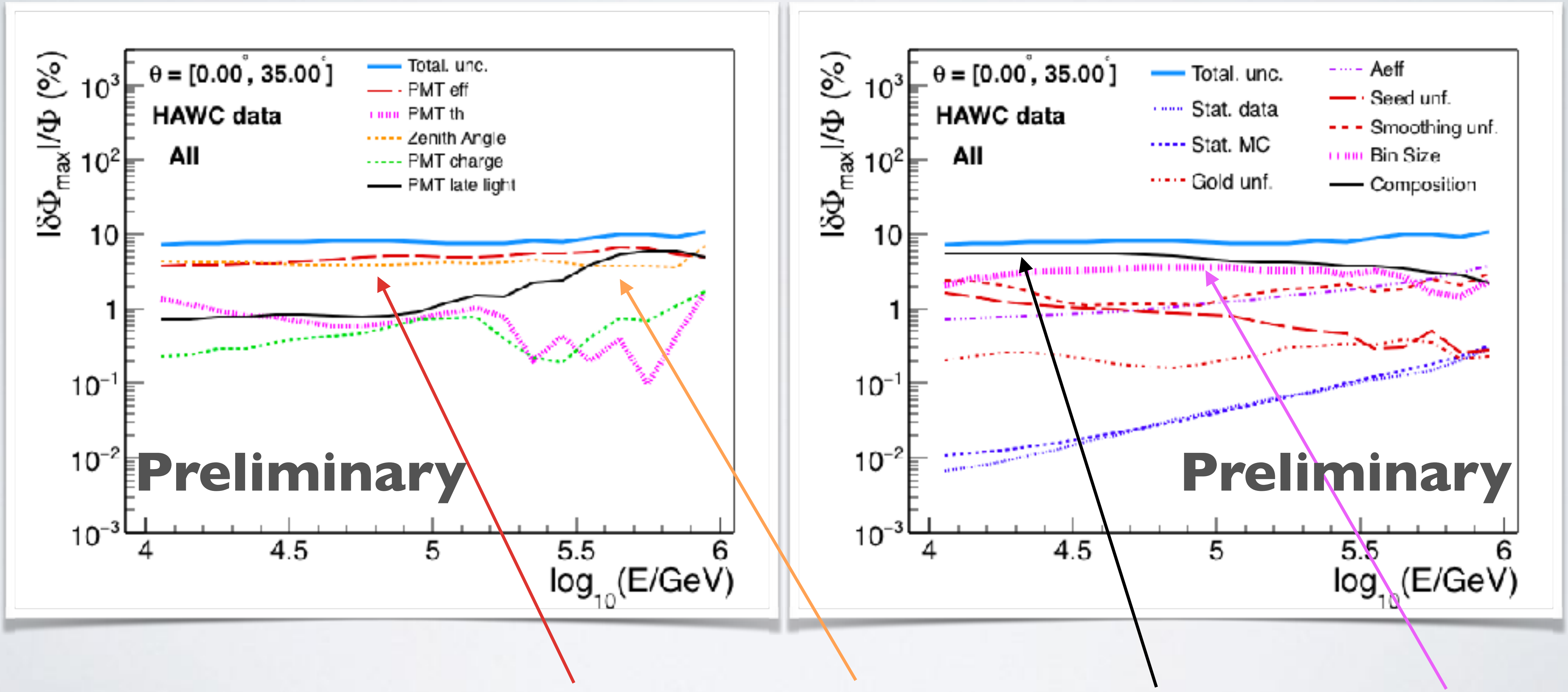


Statistical relative error @ 10^6 GeV: +/- 0.4%

Systematic relative error @ 10^6 GeV: +8.2% -10.7%

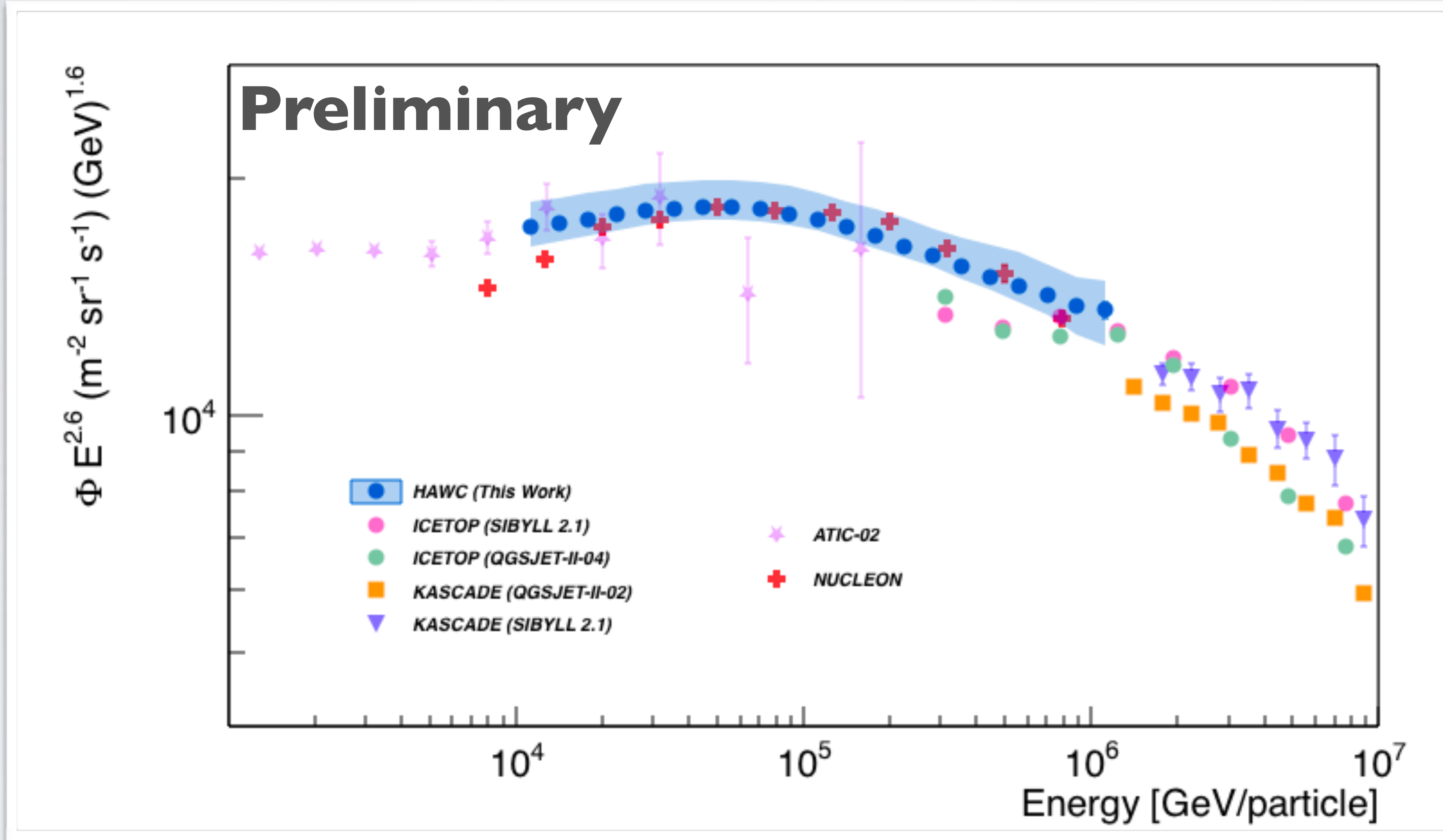
3.2 UNCERTAINTIES ON THE FLUX

Systematic errors



Dominated by systematics in PMT efficiency, zenith angle, composition model and bin size.

3.3 ALL-PARTICLE COSMIC RAY ENERGY SPECTRUM



The all-particle cosmic ray energy spectrum obtained in this work compared with the results from ATIC-02 [8], ICETOP [9], KASCADE [10,11] and NUCLEON [12].

CONCLUSIONS

4.1 FINAL REMARKS

- We were able to extend the measurements of energy spectrum of cosmic rays with HAWC up to 1 PeV.
- We studied several sources of systematic errors. We found that they are dominates 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 +/- 0.4%, while the corresponding systematic error is between +8.2% and -10.7%.
- 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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THANKS!

BIBLIOGRAPHY

[1] R. Alfaro et al., PRD 96 (2017) 122001.

[2] A. U. Abeysekara, et al, ApJ 843.1 (2017): 39.

[3] D. Heck et al., Report No. FZKA 6019, Forschungszen trum Karlsruhe-Wissenhaltliche Berichte (1998).

[4] A. Ferrari, et al., CERN-2005-10 (2005), INFN/TC 05/11, SLAC-R-773; G. Battistoni et al., AIP Conf. Proc. 896 (2007) 31.

[5] S. Ostapchenko , Phys. Rev. D 83 (2011) 014018.

[6] S. Agostinelli et al., NIMA 506 (2003) 250.

[7] A. U. Abeysekara, et al., ApJ 881.2 (2019): 134.

[8] A. D. Panov, et al., Bulletin of the Russian Academy of Sciences: Physics 73.5 (2009): 564-567.

[9] R. Koirala, T. K. Gaisser, et al., POS (ICRC2019) 318.

[10] W. D. Apel, et al., Astroparticle Physics, 47 (2013), 54-66.

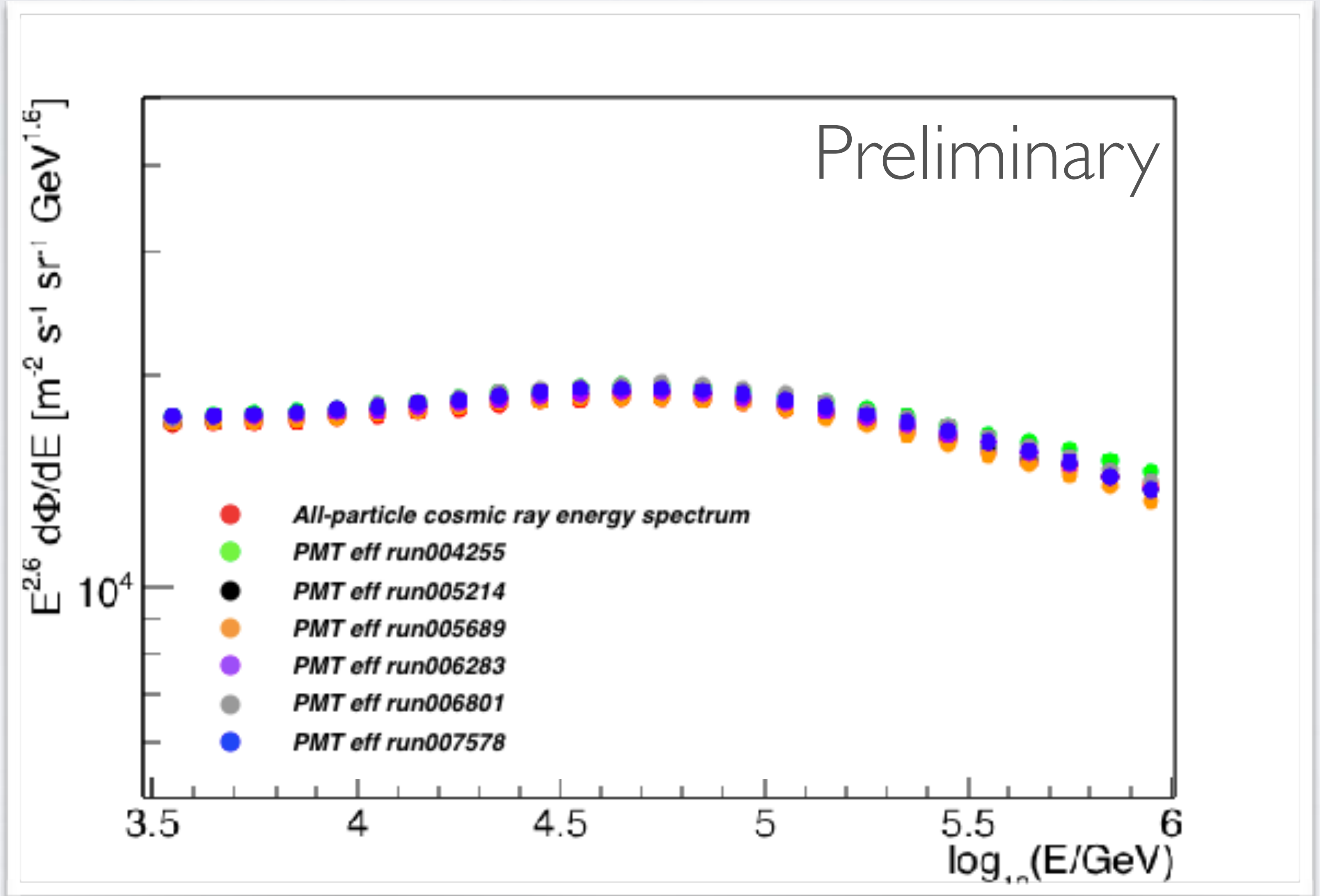
[11] Tea Antoni, et al., Astroparticle Physics 24 (2005) 1–25.

[12] V. Grebenyuk, et al., Advances in Space Research 64.12 (2019): 2546-2558.

BACK UP SLIDES

UNCERTAINTIES ON THE FLUX

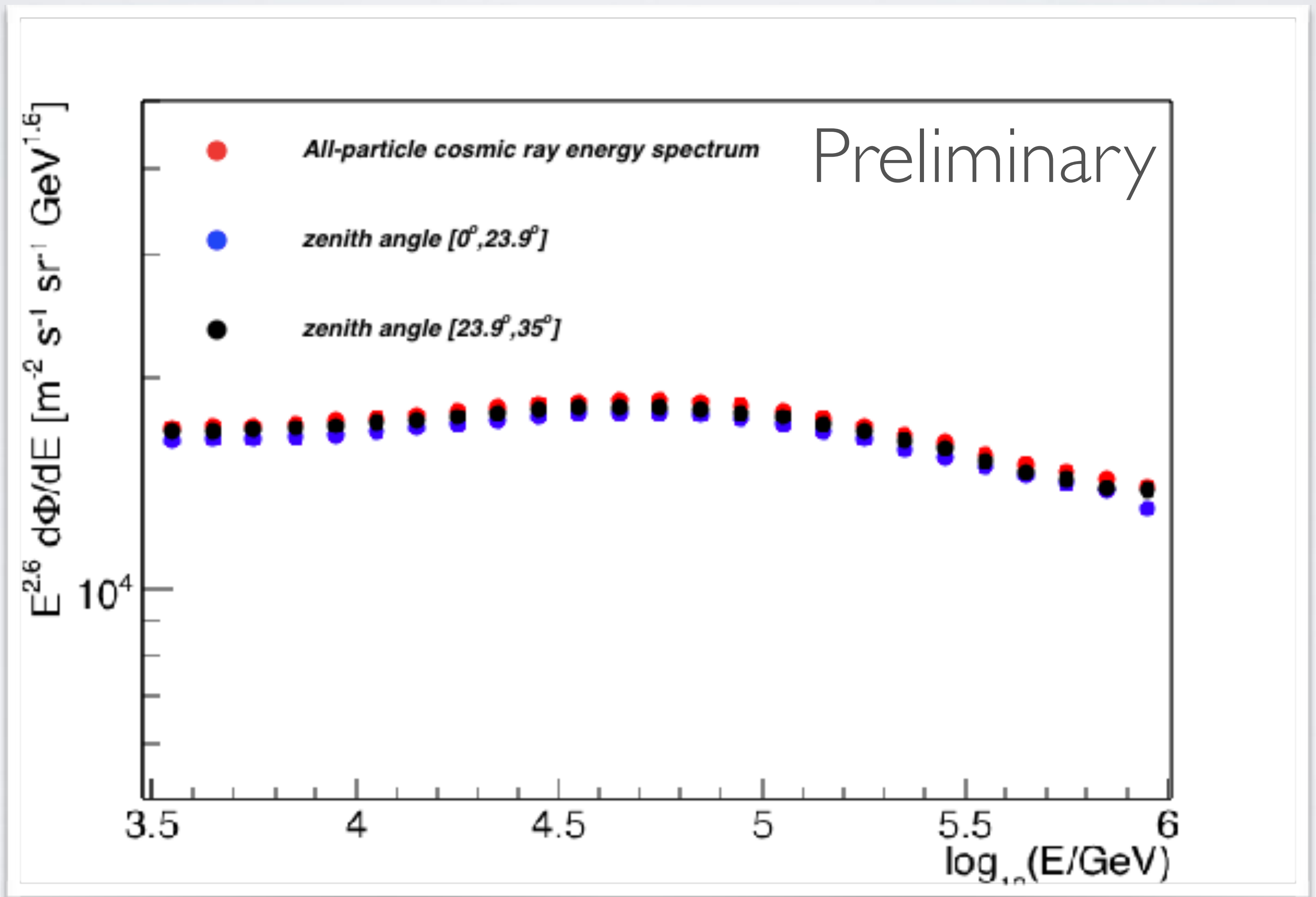
Influence of the PMT efficiency uncertainty in the reconstruction of the energy spectrum.



Energy spectrum due to the PMT efficiency

UNCERTAINTIES ON THE FLUX

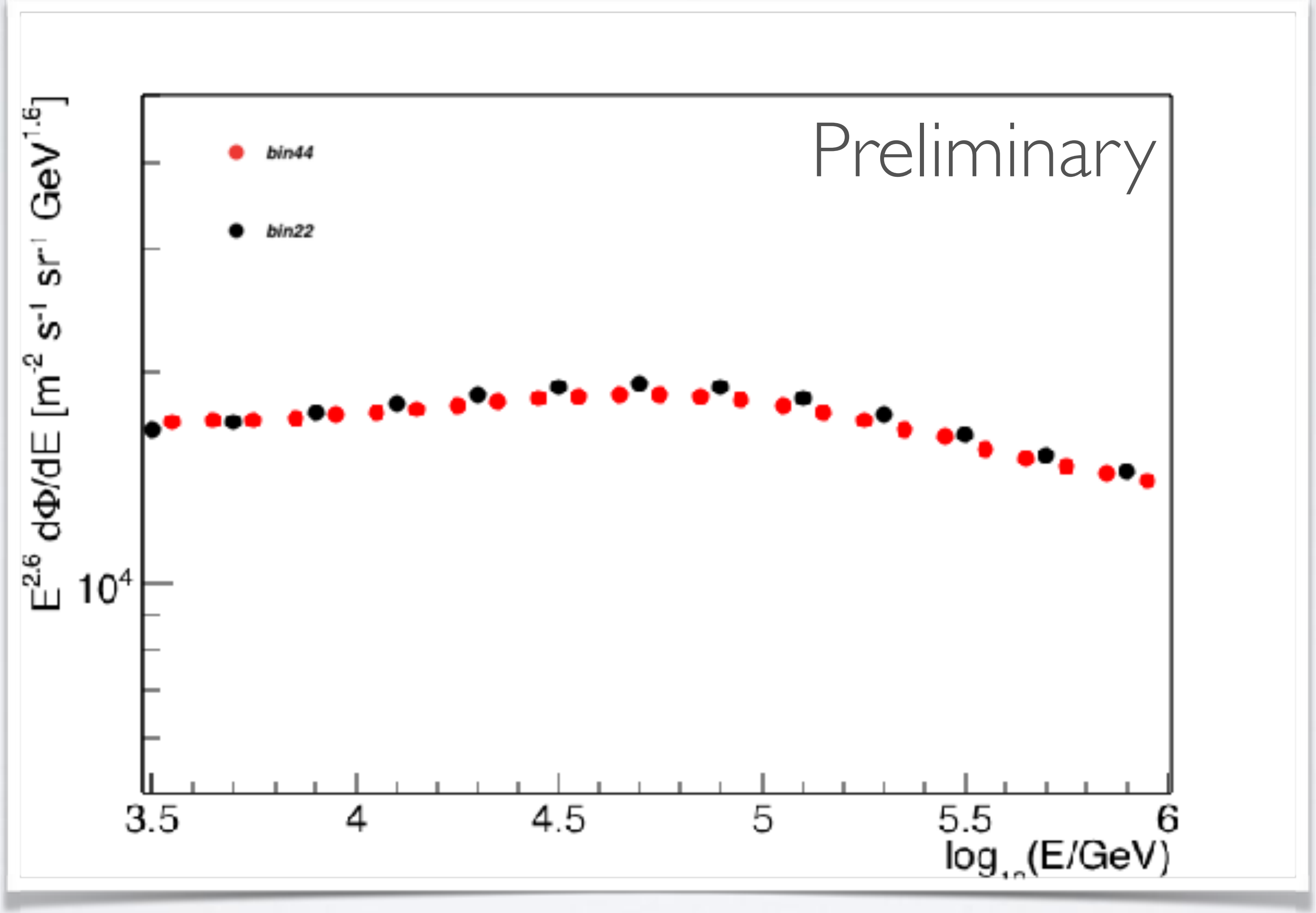
Influence of the zenith angle uncertainty in the reconstruction of the energy spectrum.



Energy spectrum due to the zenith angle.

UNCERTAINTIES ON THE FLUX

Influence of the bin size uncertainty in the reconstruction of the energy spectrum.



Energy spectrum due to the bin size