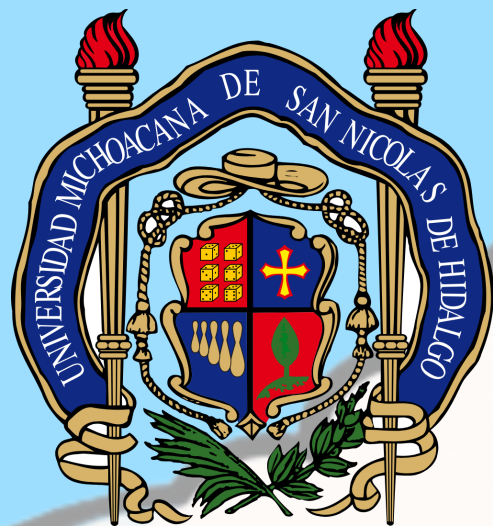




EXPLORING THE ALL-PARTICLE COSMIC-RAY SPECTRUM WITH HAWC

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ISCRA Summer School
Erice, Sicily, Italy
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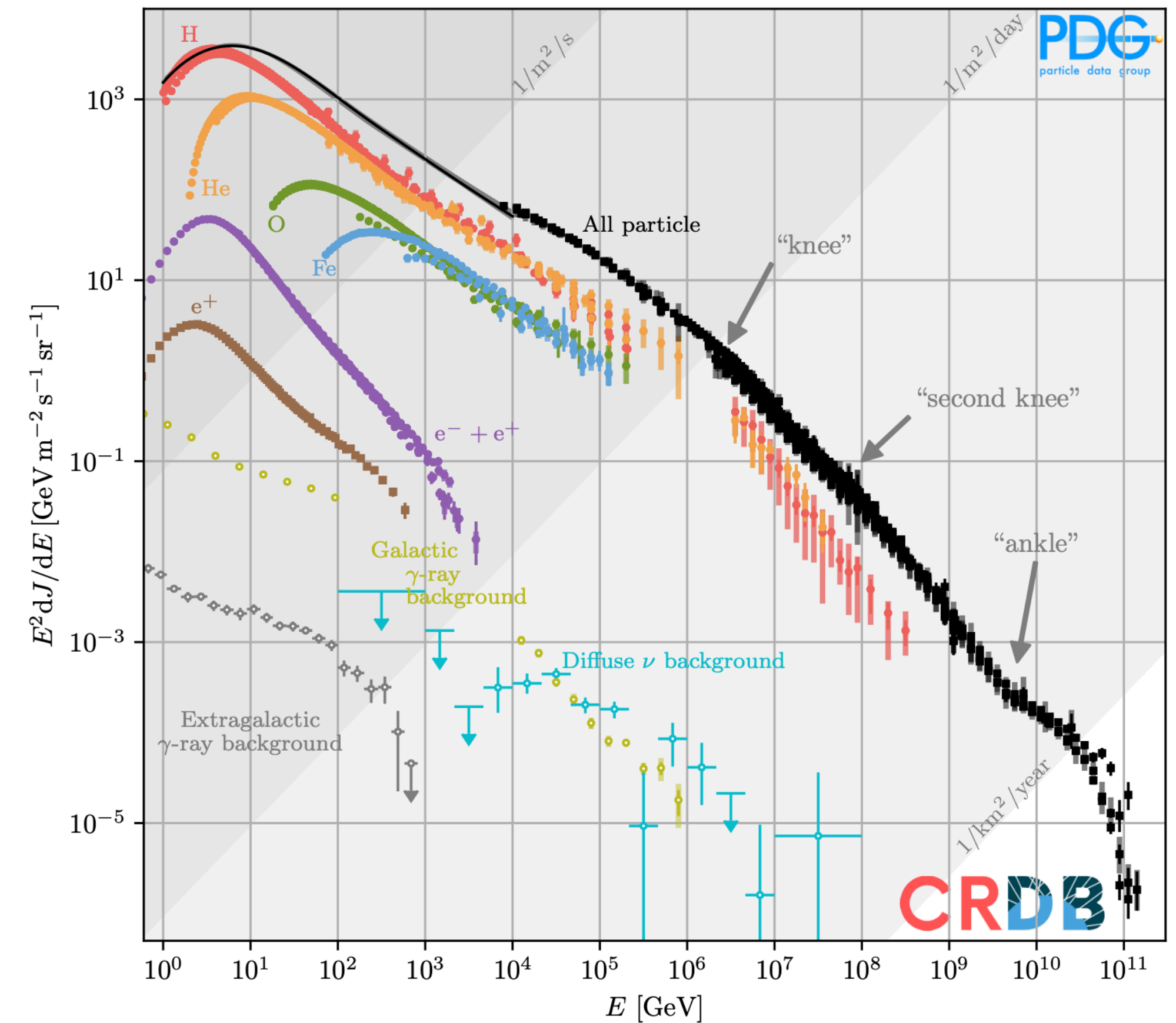


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Background

- The all-particle cosmic ray energy spectrum follows an approximate power-law dependence on energy: $\Phi(E) \propto E^{-\gamma}$
- Deviations from this simple behavior reveal information about:
 - ▶ Cosmic ray sources
 - ▶ Acceleration mechanisms
 - ▶ Propagation through interstellar medium
- ➔ Studying these spectral structures is essential to constrain theoretical models.



R. W. et al (Particle Data Group) 2022

Background

Direct

TeV

Indirect

PeV

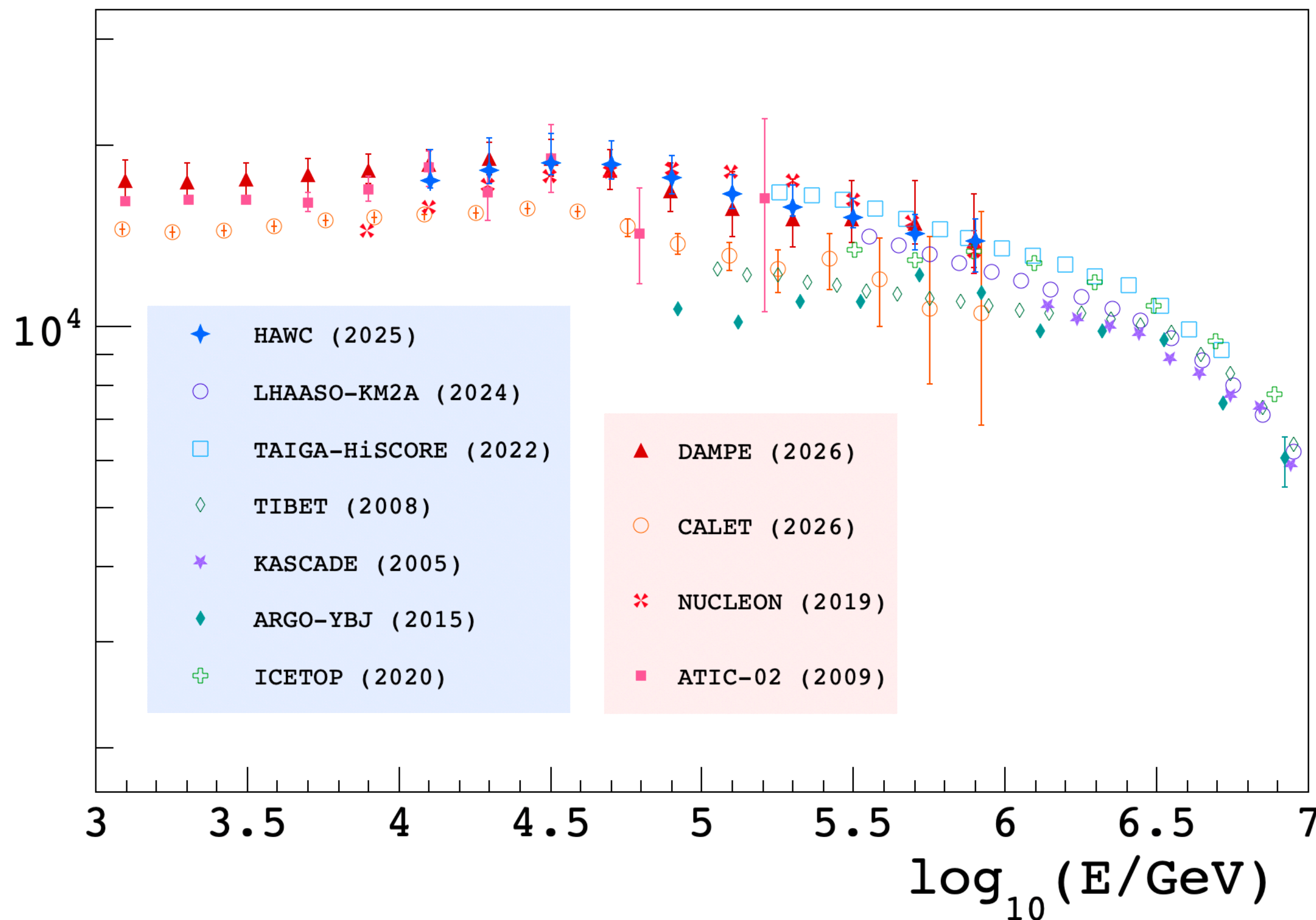


DAMPE
Source: China Daily



AMS
Source: NASA

$E^{2.6} \Phi(E) [m^{-2} \cdot s^{-1} \cdot sr^{-1} \cdot GeV^{1.6}]$



KASCADE
Source: KIT



HAWC
Source: HAWC Observatory

Background

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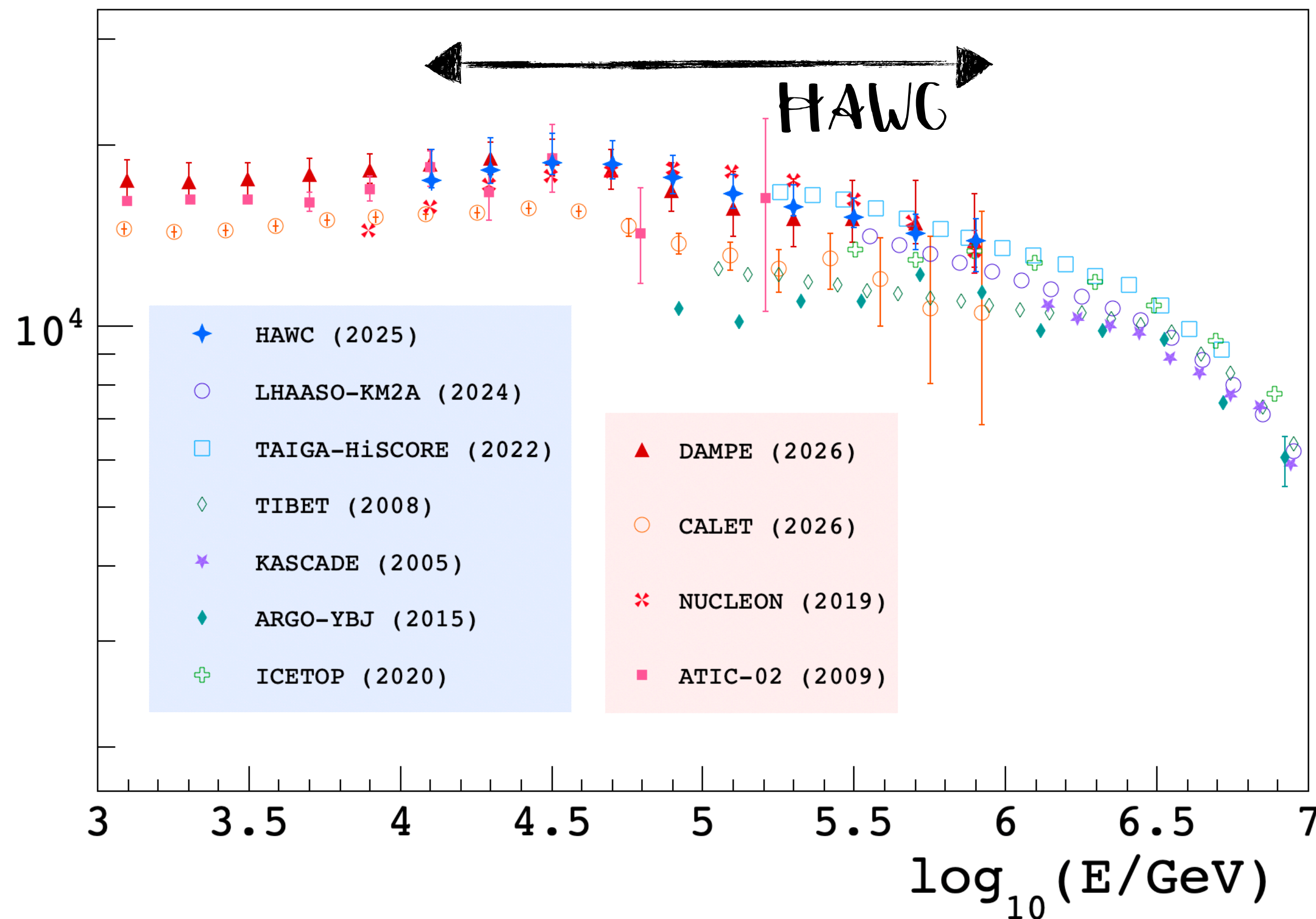


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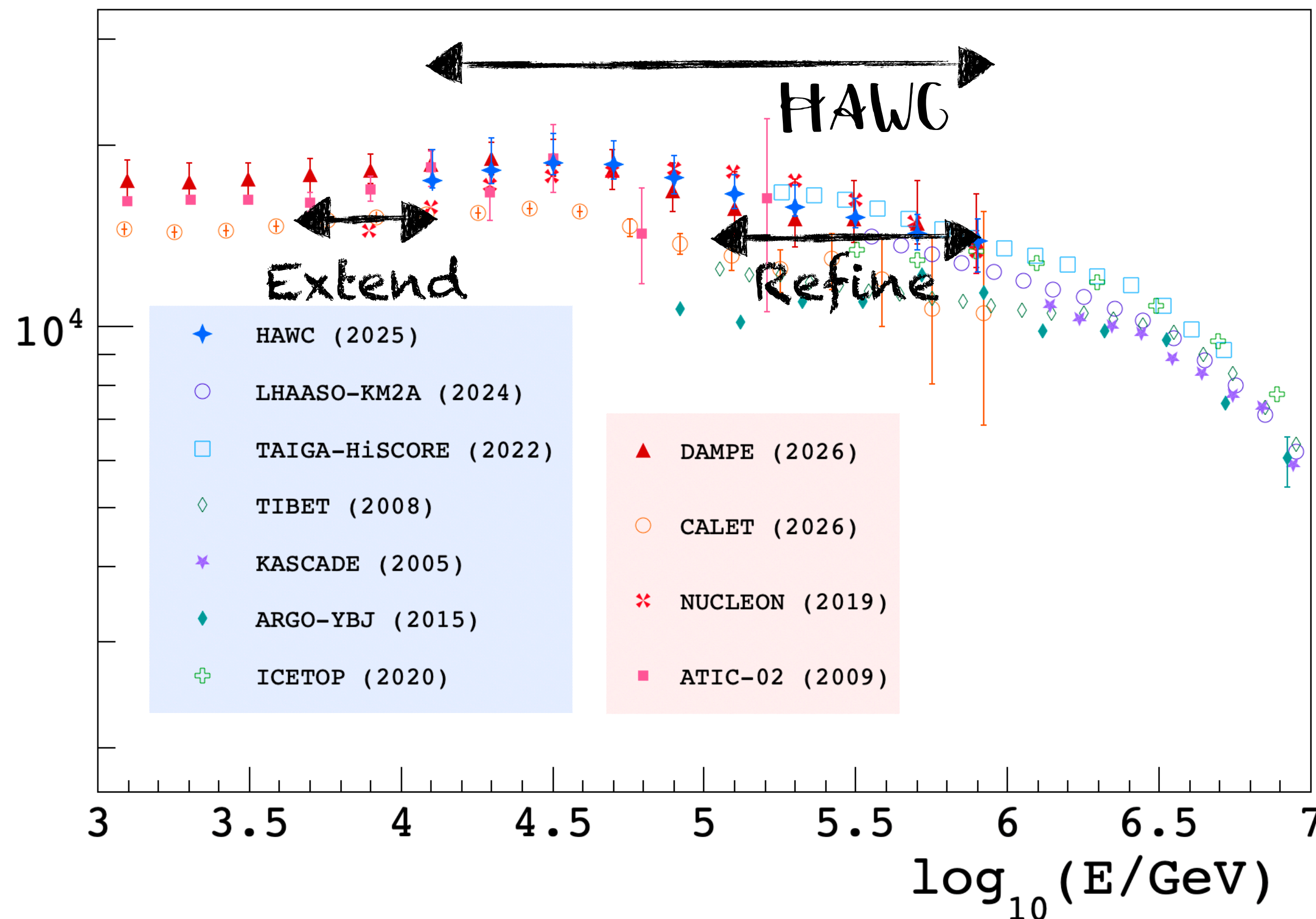


DAMPE
Source: China Daily



AMS
Source: NASA

$E^2 \cdot \Phi(E) [m^{-2} \cdot s^{-1} \cdot sr^{-1} \cdot GeV^{1.6}]$



KASCADE
Source: KIT



HAWC
Source: HAWC Observatory

HAWC: Overview

Gamma & Cosmic Ray Observatory

- ◆ **Location:** Parque Nacional Pico de Orizaba, México
- ◆ **Altitude:** 4100 m a.s.l., atmospheric depth of 637 g/cm^2
- ◆ **Main array:** 300 water Cherenkov detectors, area of $22,000 \text{ m}^2$
- ◆ **Detectors:** 7.3 m of diameter, 5.4 m height, 200,000 liters of water
- ◆ **PMTs:** in each tank 3 PMTs of 8 in and 1 PMT of 10 in
- ◆ **Energy range:** 300 GeV - 100 TeV for gamma rays and TeV-PeV for cosmic rays

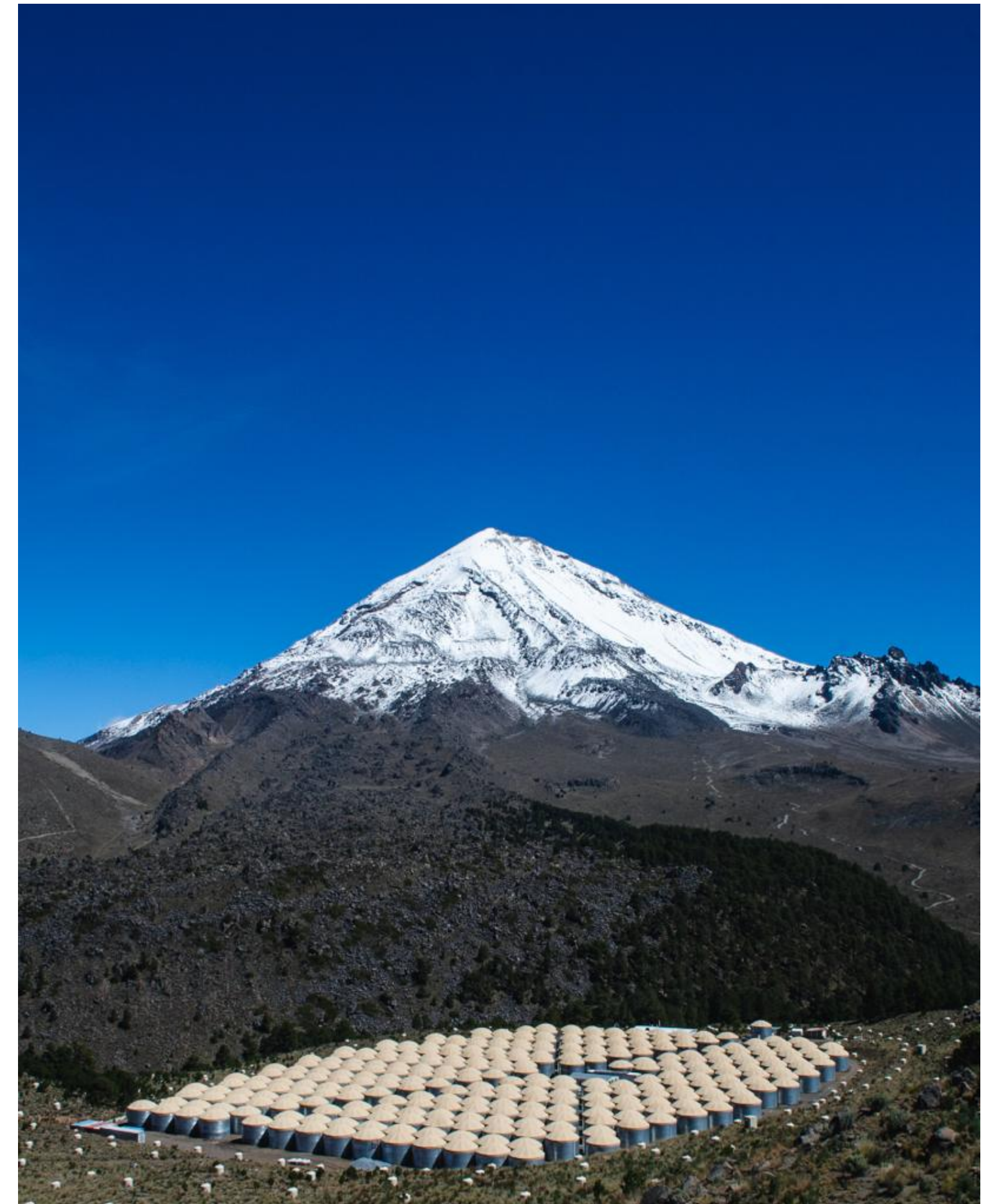
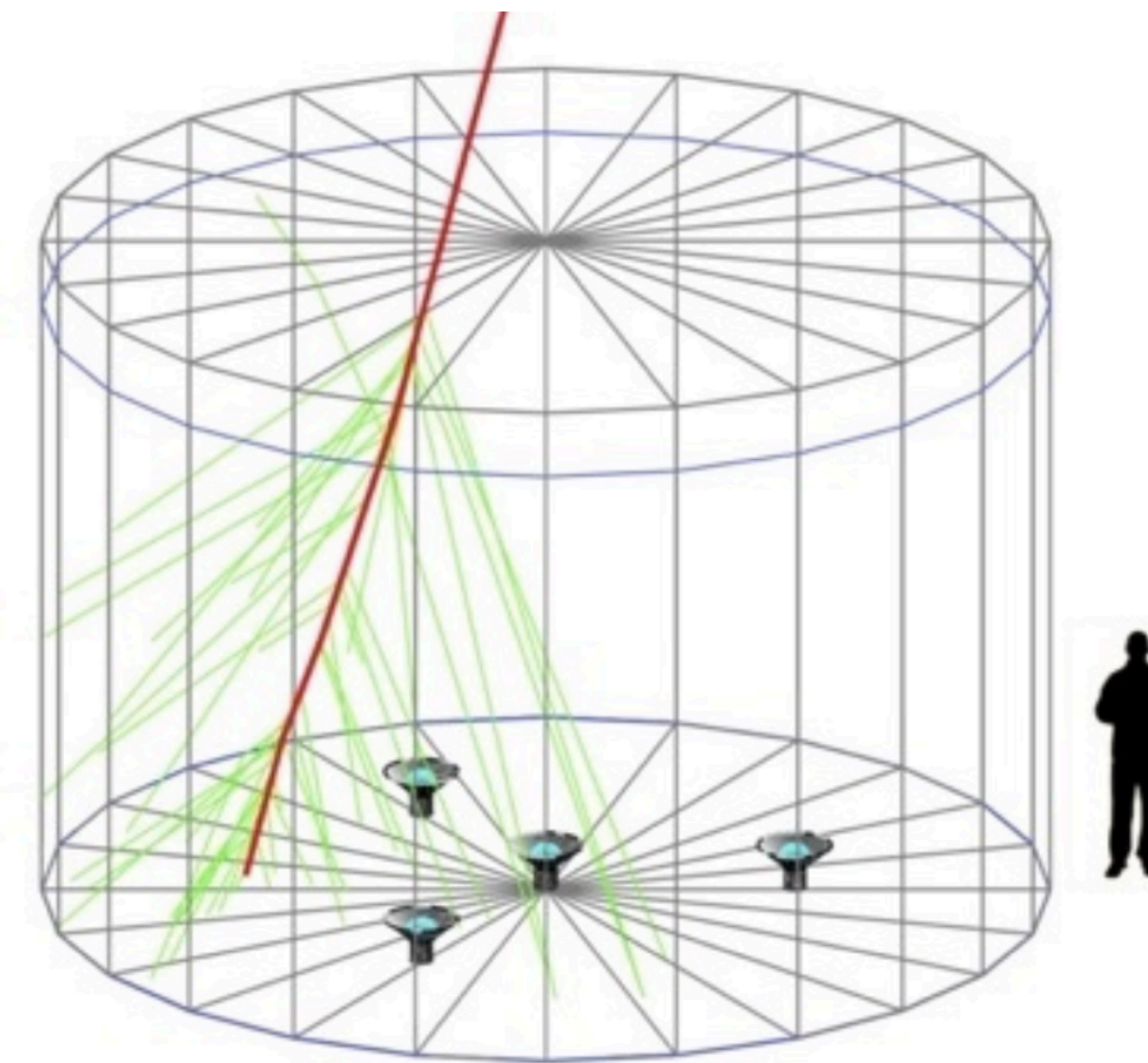
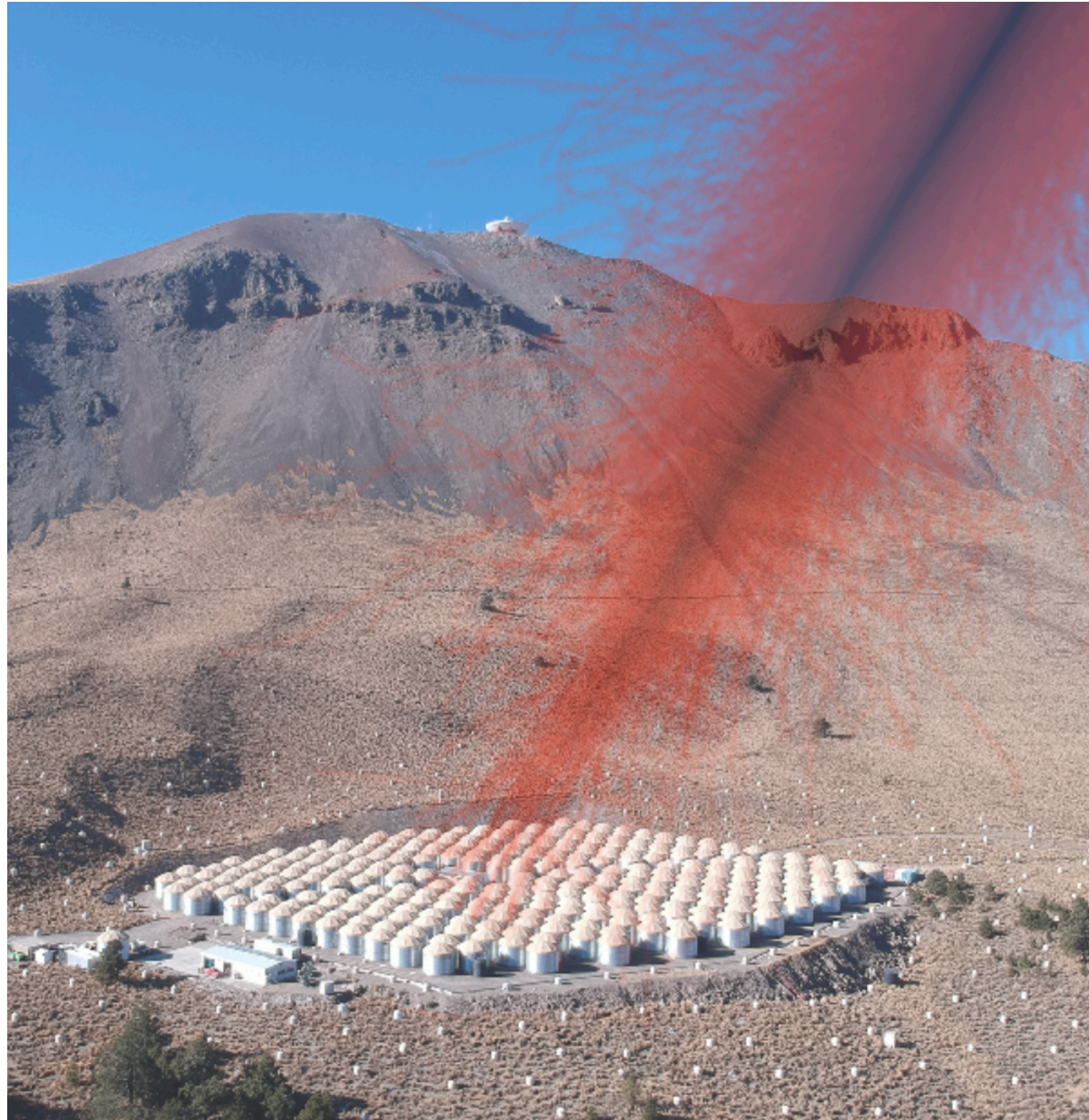
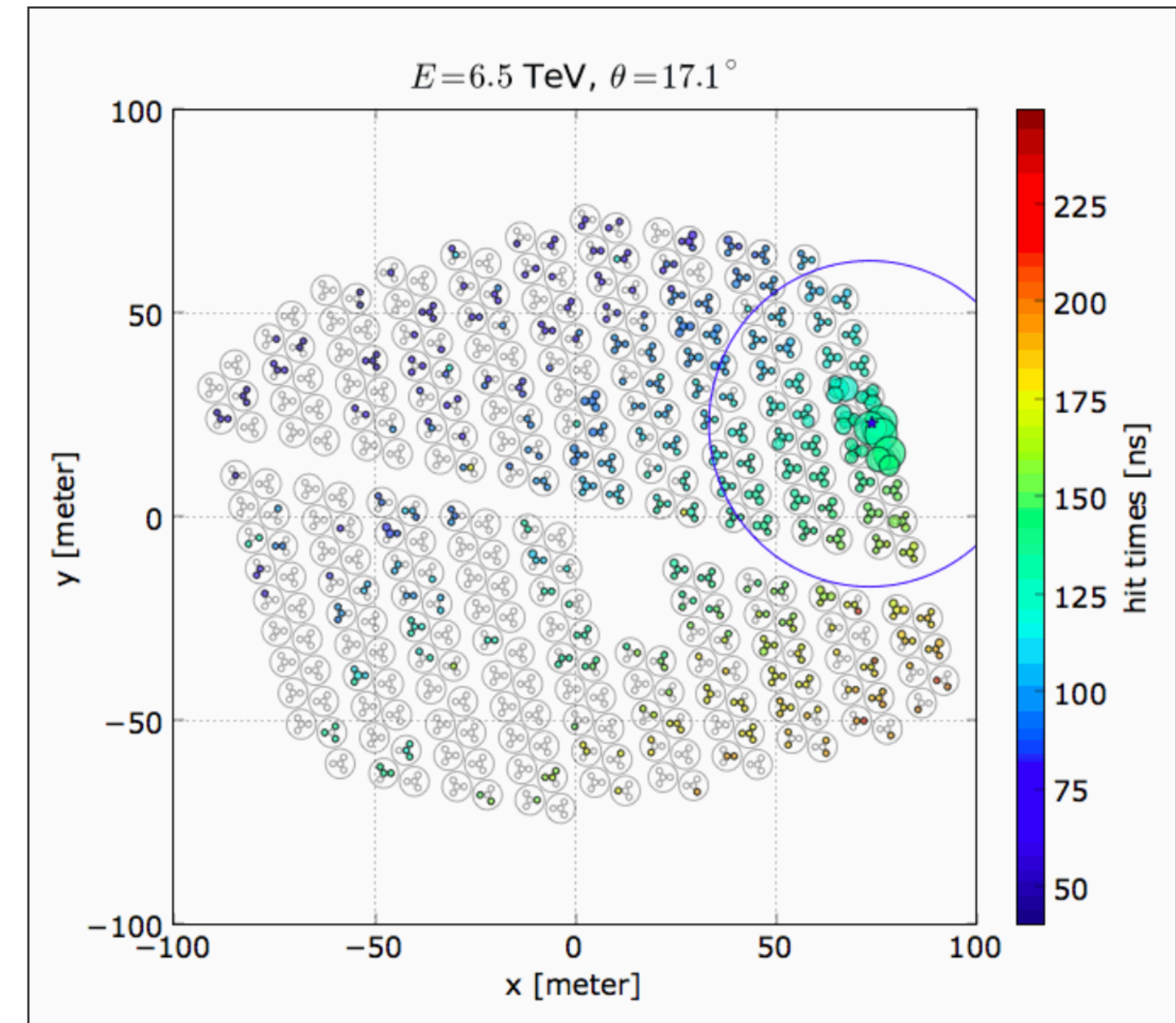


Photo: Pedro Miron

Water Cherenkov Detectors



Simulated
Cherenkov light in a
HAWC WCD

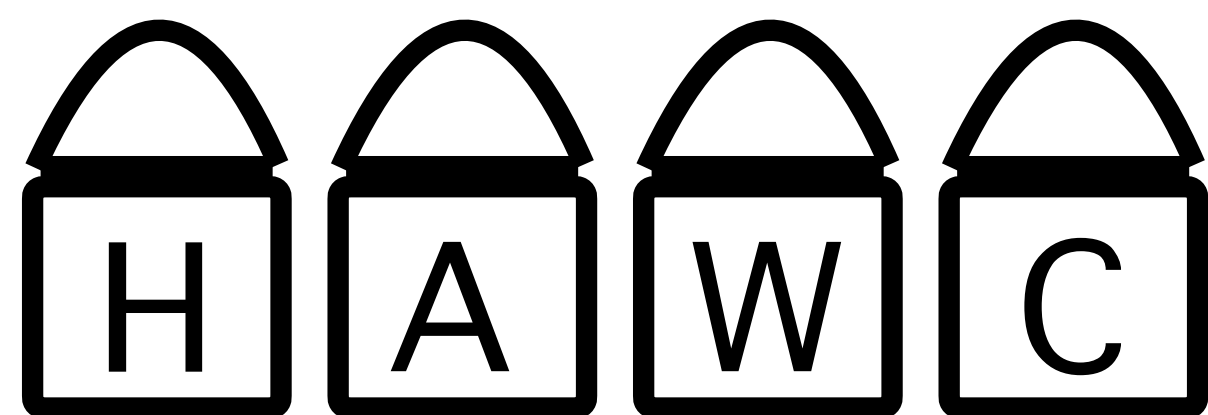


Gamma induced air-shower

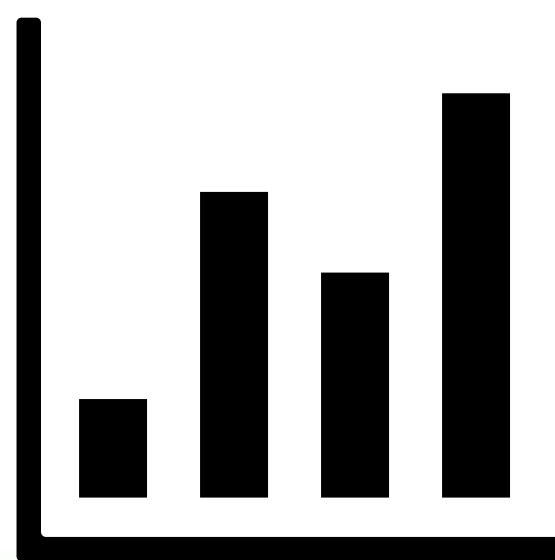
Images: HAWC website

Methodology

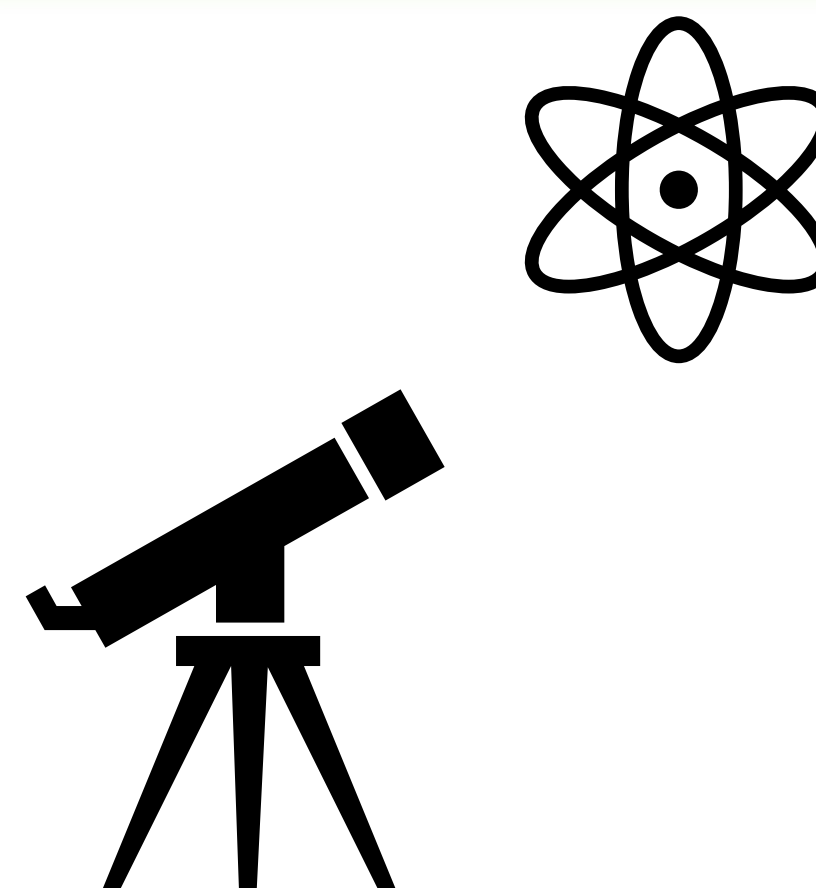
HAWC recollected data



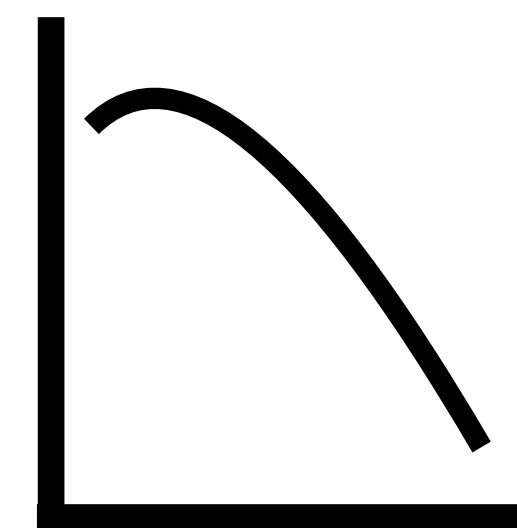
Energy distribution



Correct for detector effects



Energy spectrum

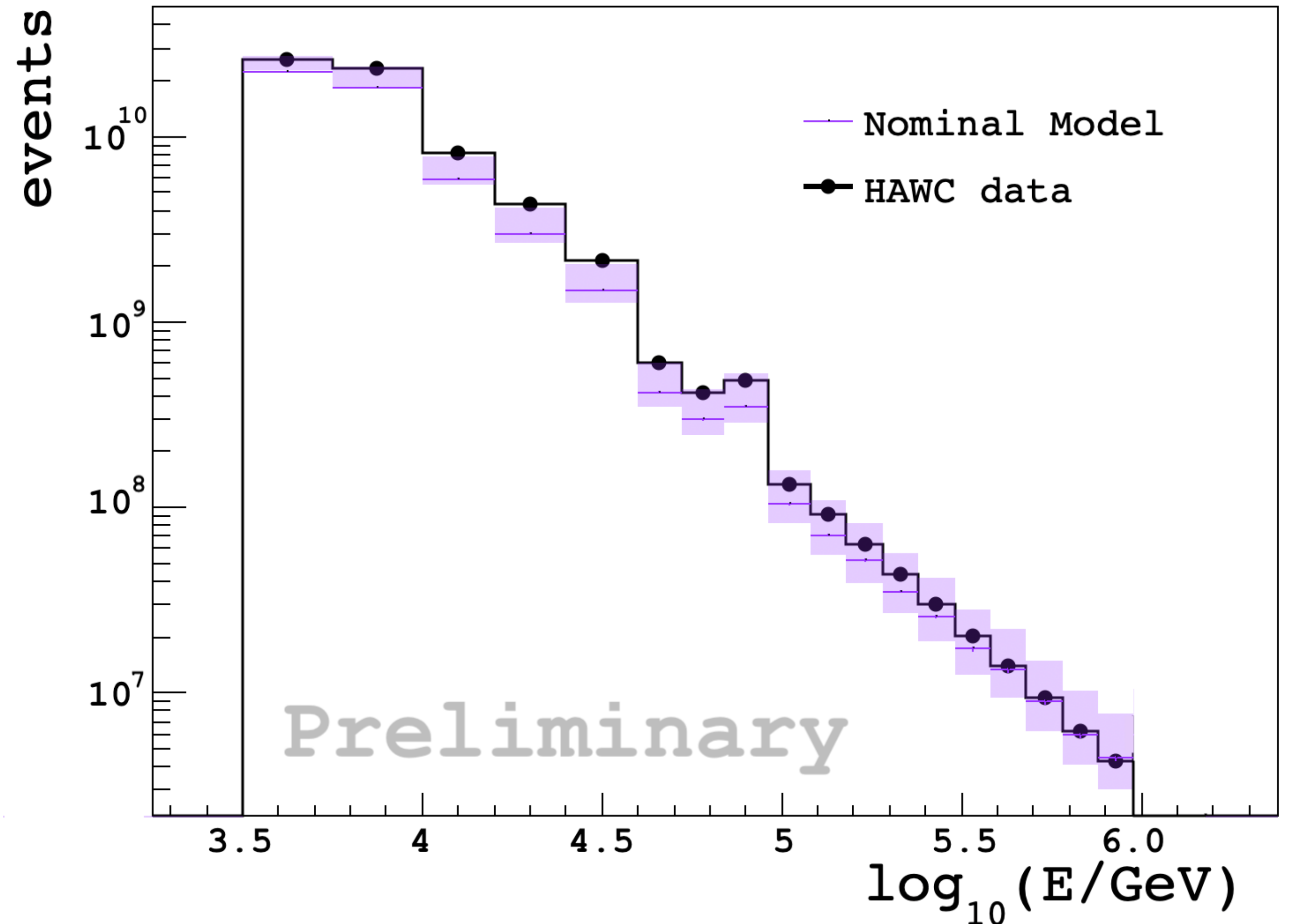


Experimental data

- 5 years of HAWC observation
 - ▶ 1.61×10^8 seconds
 - ▶ June 2016 - December 2020
- Apply selection cuts to reduce fluctuations.
 - ➡ #events $\sim 1.09 \times 10^{11}$

Energy distribution

- Range: $\log_{10}(E_{rec}/\text{GeV}) \in [3.5, 6.0]$
- Binning scheme:
 - ▶ $\Delta_1 = 0.25$ for $\log_{10} E/\text{GeV} \in [3.5, 4.0]$
 - ▶ $\Delta_2 = 0.2$ for $\log_{10} E/\text{GeV} \in (4.0, 4.6]$
 - ▶ $\Delta_3 = 0.12$ for $\log_{10} E/\text{GeV} \in (4.6, 5.08]$
 - ▶ $\Delta_4 = 0.1$ for $\log_{10} E/\text{GeV} \in (5.08, 5.9]$

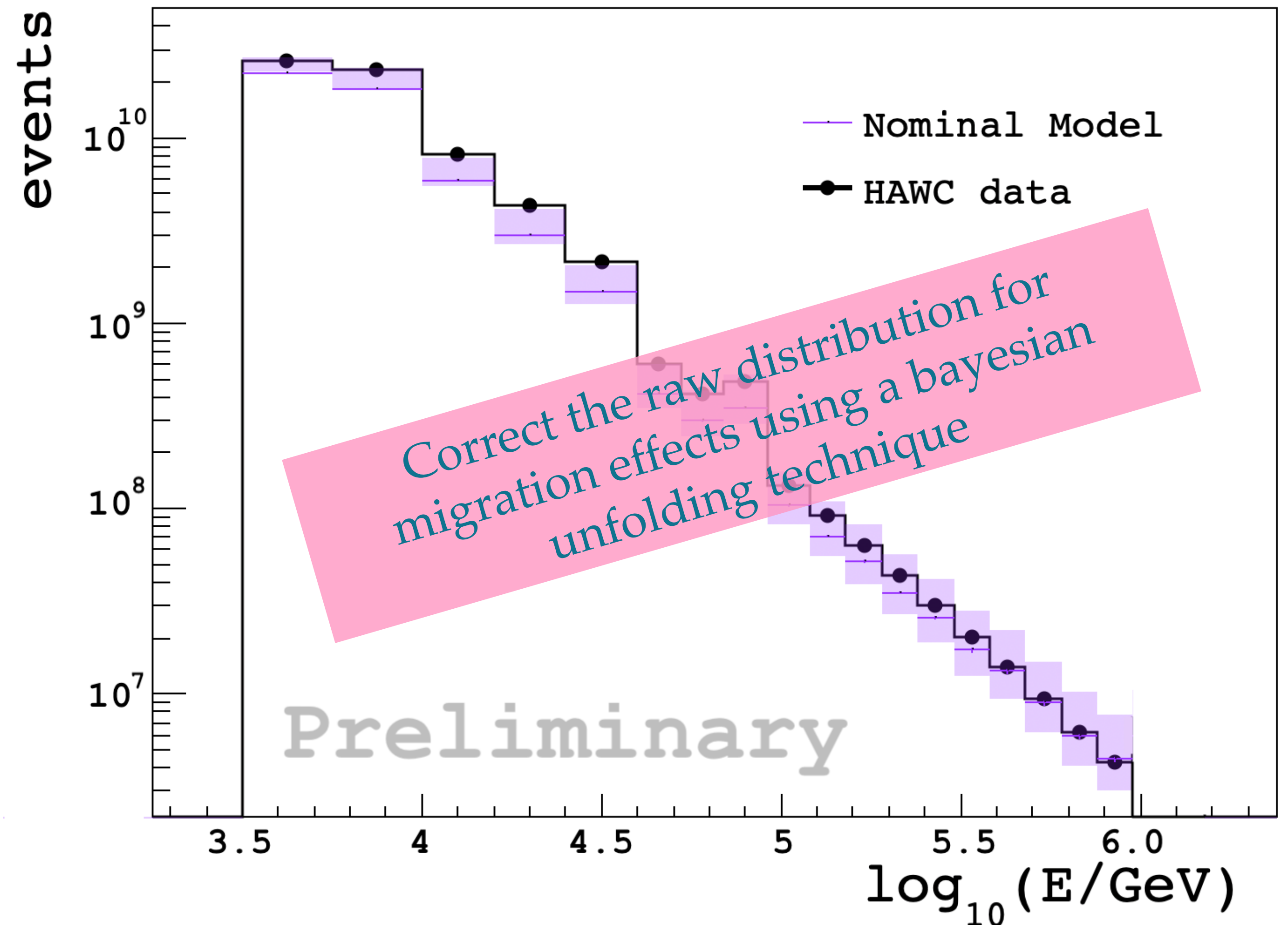


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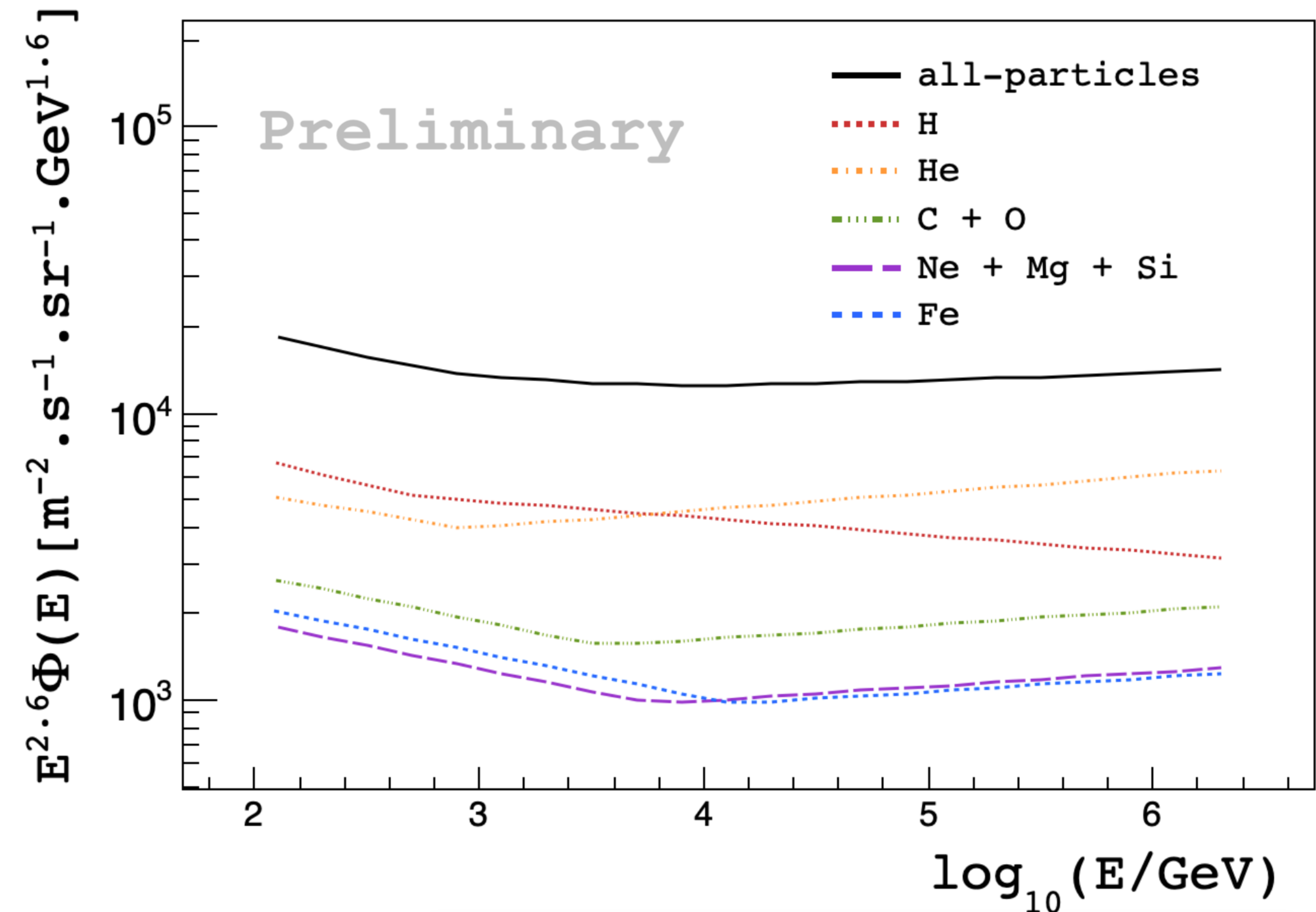
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Monte Carlo simulations

- Shower development: CORSIKA v7.40
- Hadronic models: FLUKA (< 80 GeV), QGSJET-II-04
- Primaries: H, He, C, O, Ne, Mg, Si, Fe
- E^{-2} spectrum
 - ▶ Weighted to reproduce the nominal composition model adopted by HAWC¹
- Same selection cuts as the experimental data



¹Alfaro et al, *Astropart. Phys.*, 2025

Bayesian Unfolding¹

$$N(E_i) = \sum_{j=1}^{nBins} P(E_i | E_{rec,j}) N(E_{rec,j})$$

True energy distribution $\rightarrow N(E_i)$

Smearing matrix $\downarrow P(E_i | E_{rec,j})$

Raw energy distribution $\leftarrow N(E_{rec,j})$

Response matrix

QGSJET-II-04 and nominal model

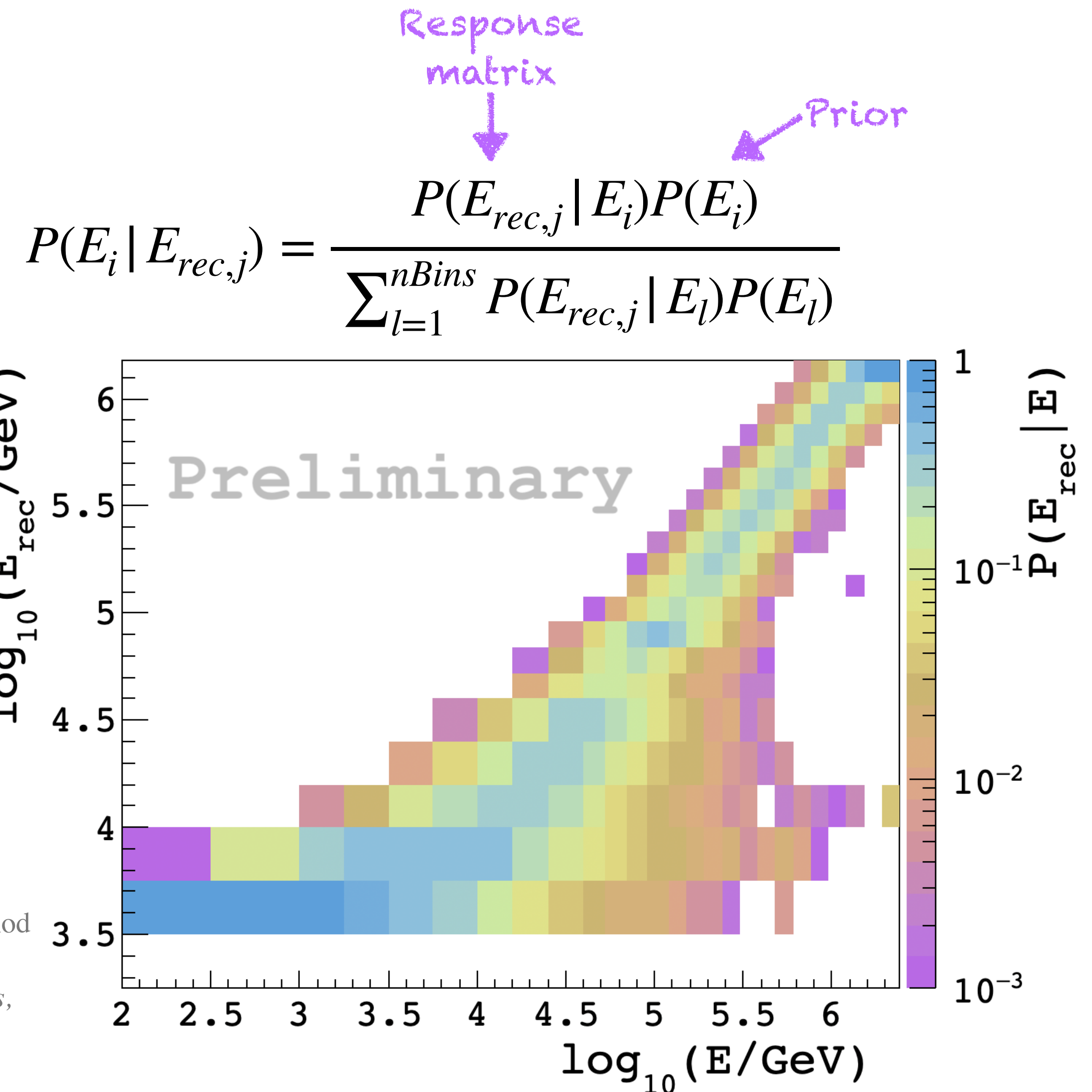
Smoothing method

$$\bar{N}_i = \frac{1}{4} \left(\frac{1}{2} N_{i-1} + 3N_i + \frac{1}{2} N_{i+1} \right)$$

Prior

Energy distribution from our nominal composition model

¹G. D'Agostini, "A multidimensional unfolding method based on Bayes theorem," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 362, no. 2-3, pp. 487–498, 1995.



Energy spectrum

- We compute the all-particle energy spectrum:

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

Bin size at E $\rightarrow \Delta E$

Observation time 2.64×10^7 s $\rightarrow \Delta t$

Solid angle of observation 1.14 sr $\rightarrow \Delta \Omega$

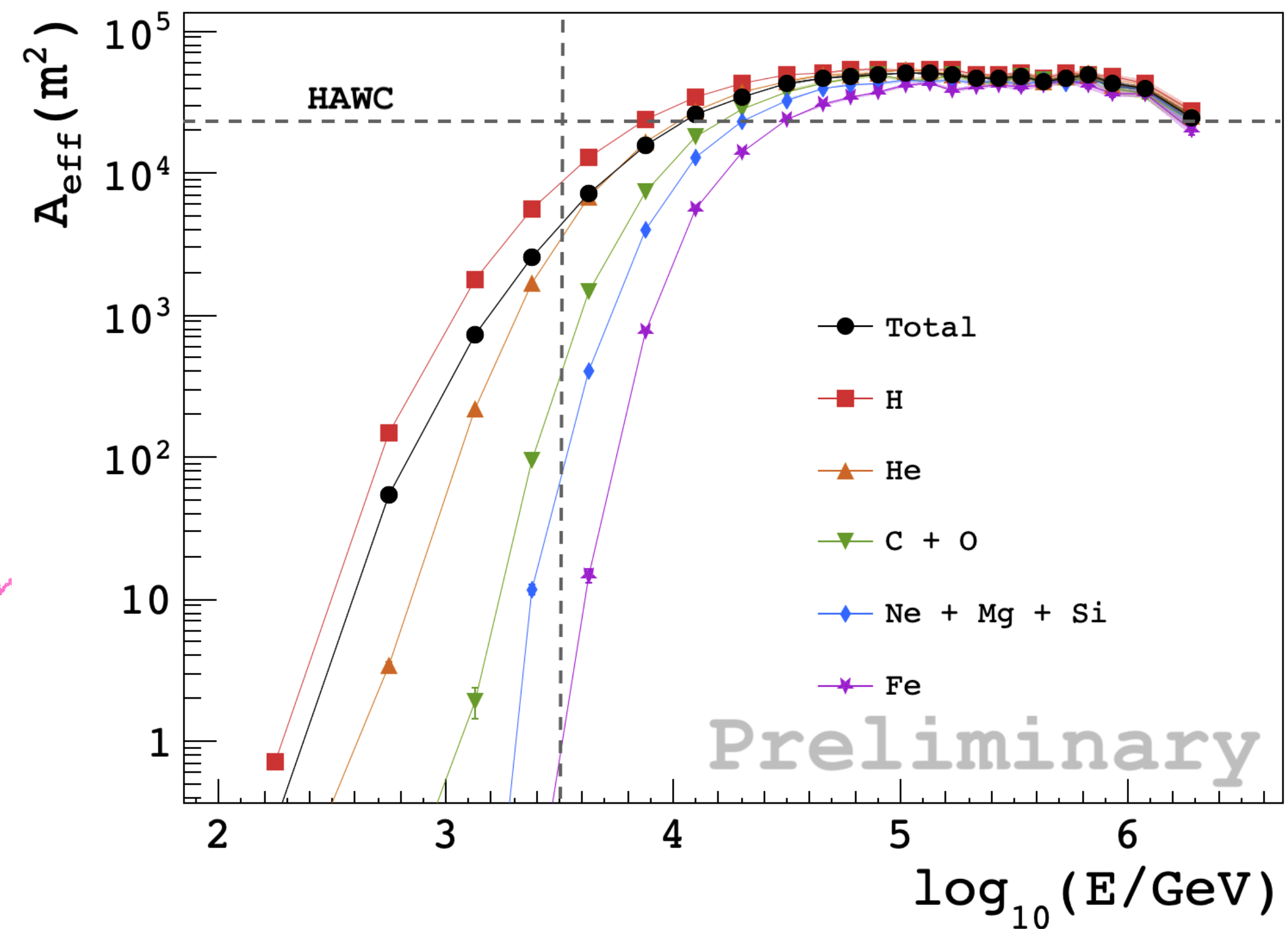
Unfolded distribution $N(E)$

- A_{eff} is defined as:

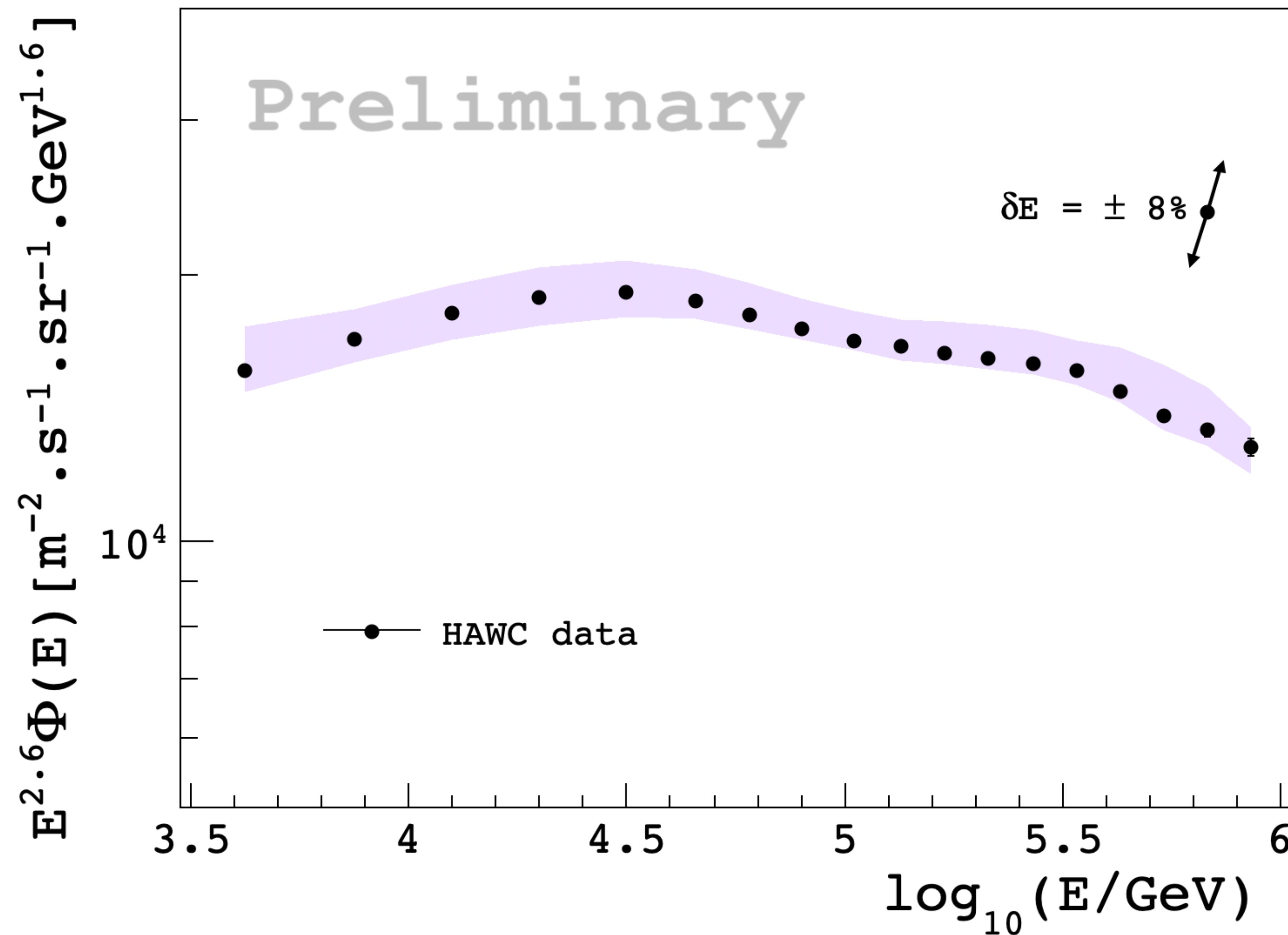
$$A_{eff} = A_{thrown} \epsilon(E)$$

Trigger and reconstruction efficiency $\epsilon(E)$

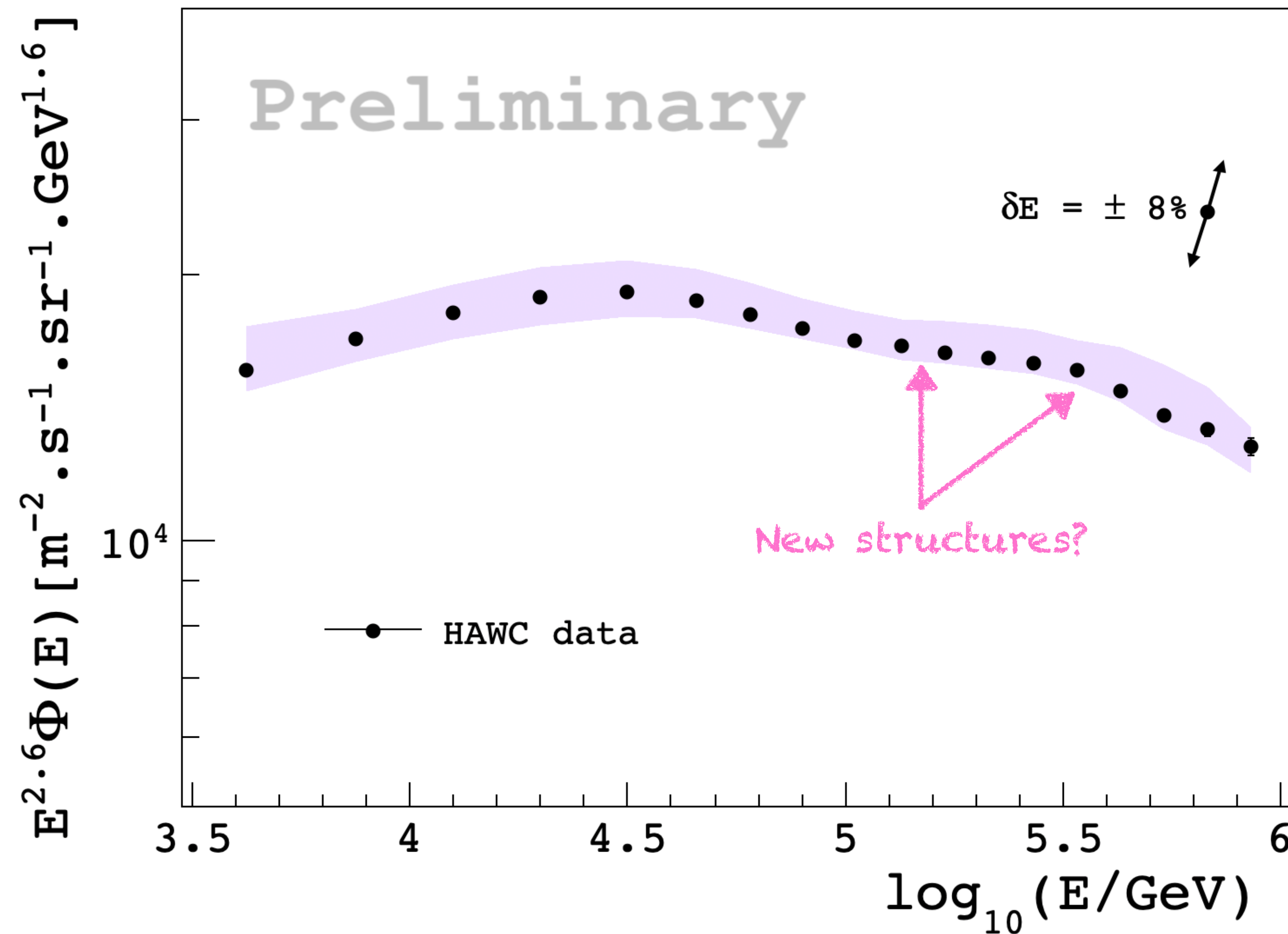
Simulated throwing area 2.85×10^6 m² $\rightarrow A_{thrown}$



The all-particle cosmic ray energy spectrum measured by HAWC



The all-particle cosmic ray energy spectrum measured by HAWC



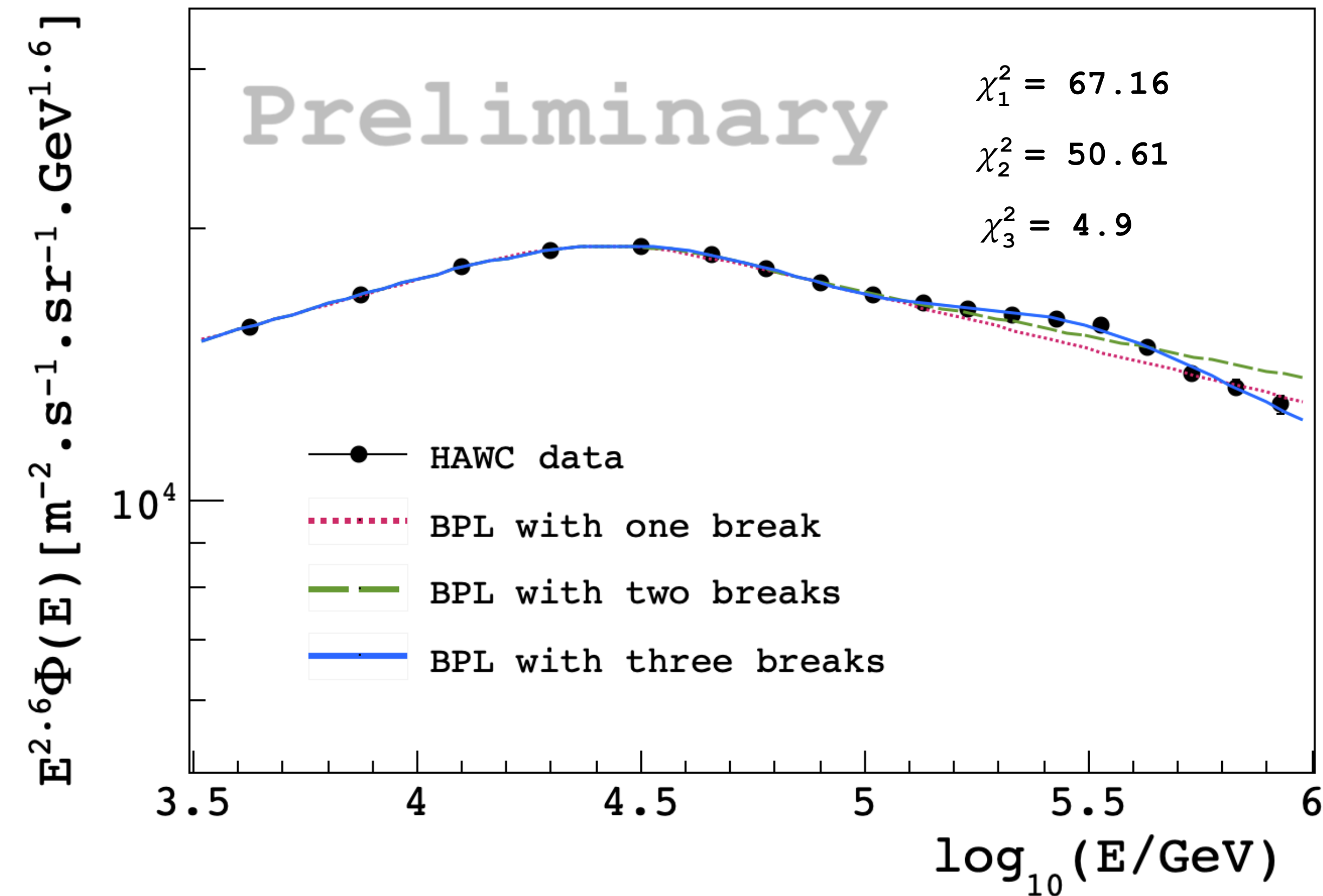
Analysis of the shape of the spectrum

- Possible **hardening** at $\log E / \text{GeV} \sim 5$, and a second **softening** around $\log E / \text{GeV} \sim 5.5$
- We test which model is preferred by the data:

1 break $\rightarrow$
$$\Phi_1(E) = \Phi_0 E^{\gamma_1} \left[1 + \left(\frac{E}{E_0} \right)^{\epsilon_1} \right]^{(\gamma_2 - \gamma_1)/\epsilon_1}$$

2 breaks $\rightarrow$
$$\Phi_2(E) = \Phi_0 E^{\gamma_1} \left[1 + \left(\frac{E}{E_0} \right)^{\epsilon_1} \right]^{(\gamma_2 - \gamma_1)/\epsilon_1} \cdot \left[1 + \left(\frac{E}{E_1} \right)^{\epsilon_2} \right]^{(\gamma_3 - \gamma_2)/\epsilon_2}$$

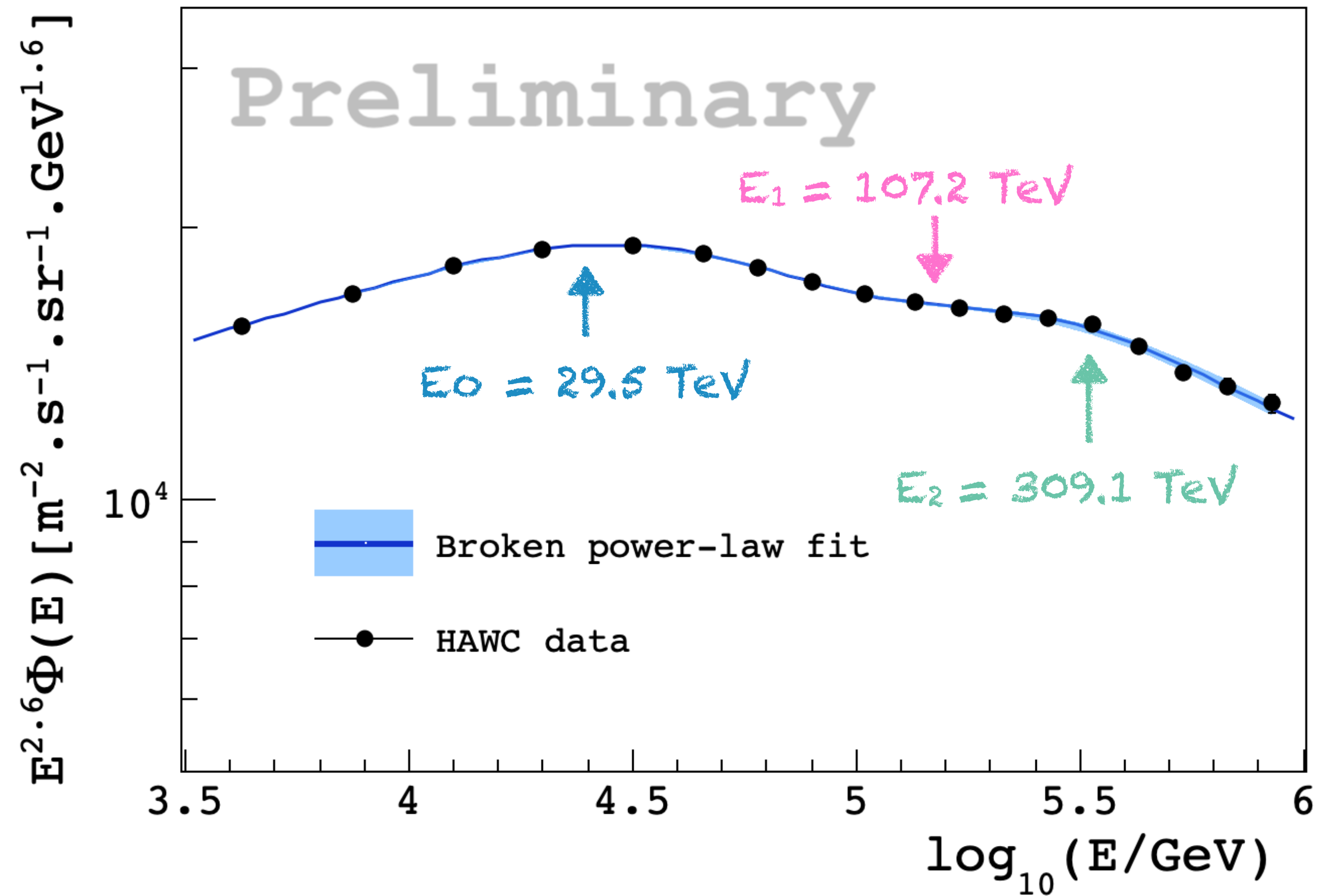
3 breaks $\rightarrow$
$$\Phi_3(E) = \Phi_0 E^{\gamma_1} \left[1 + \left(\frac{E}{E_0} \right)^{\epsilon_1} \right]^{(\gamma_2 - \gamma_1)/\epsilon_1} \cdot \left[1 + \left(\frac{E}{E_1} \right)^{\epsilon_2} \right]^{(\gamma_3 - \gamma_2)/\epsilon_2} \cdot \left[1 + \left(\frac{E}{E_2} \right)^{\epsilon_3} \right]^{(\gamma_4 - \gamma_3)/\epsilon_3}$$



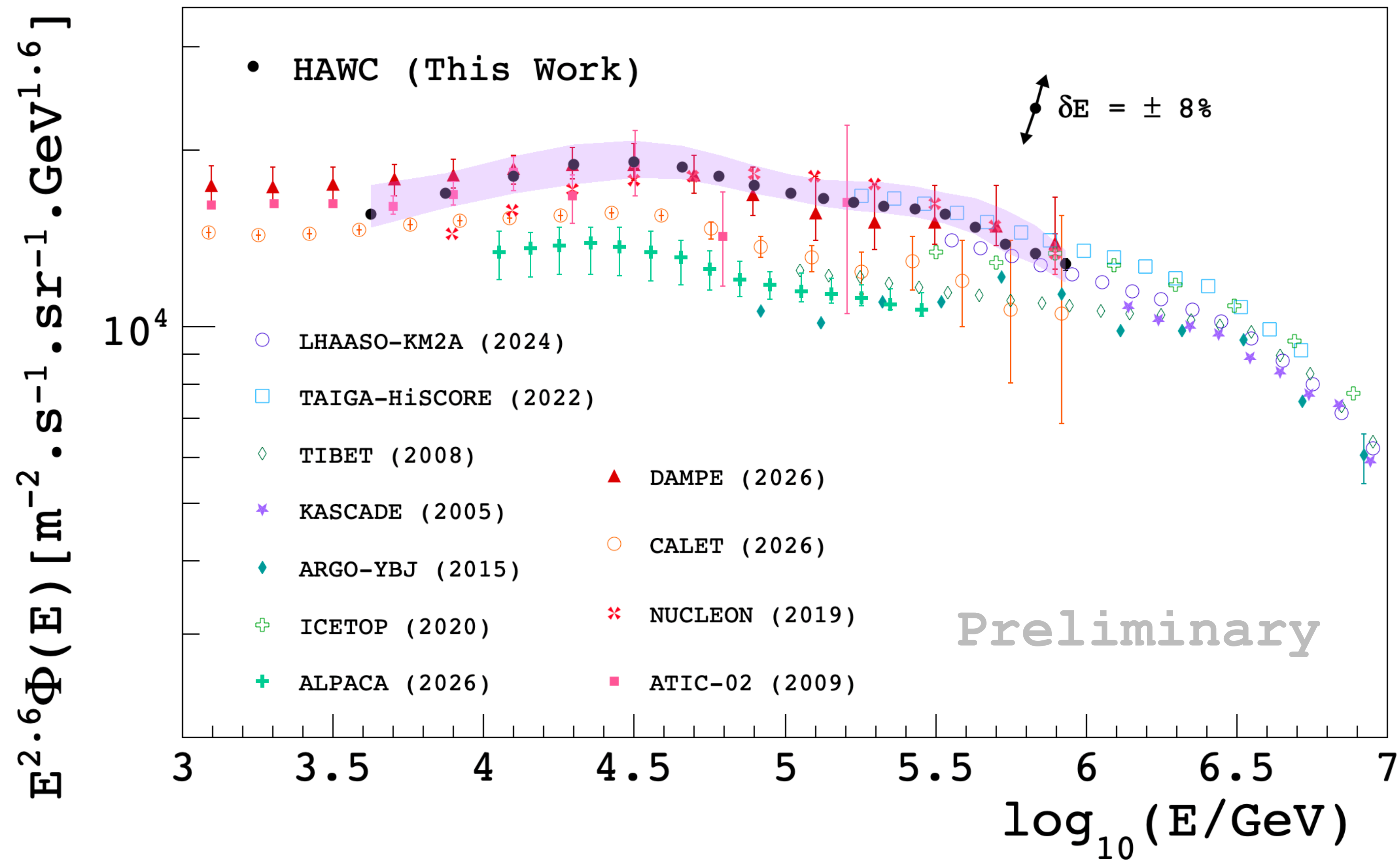
Fit results

➔ Using as a test statistic $TS = \Delta\chi^2$, it was found that the 3-break model is preferred over the simpler hypothesis by at least 4σ !!

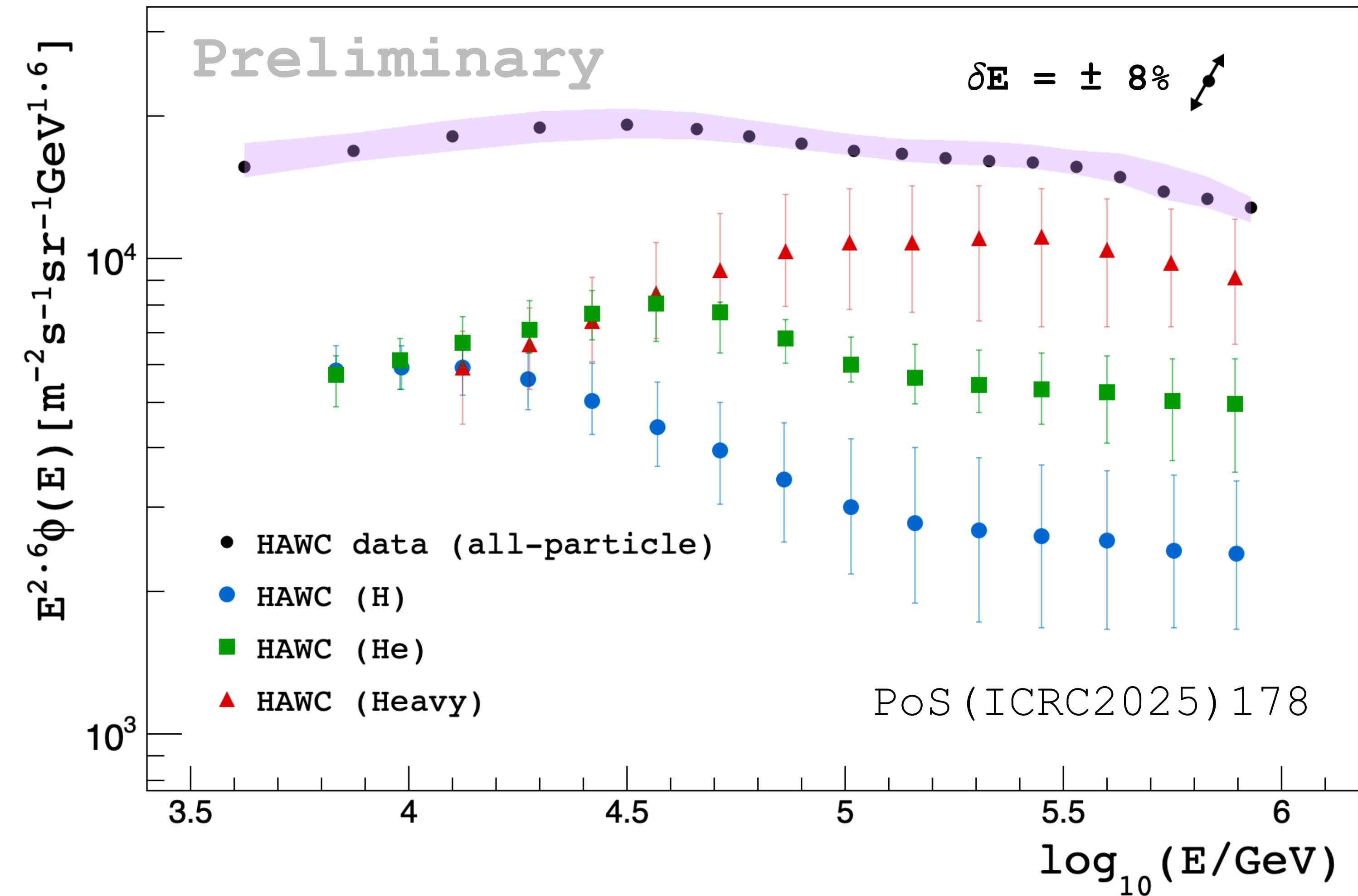
	$\Phi_3(E)$
Φ_0 ($\text{m}^2 \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$)	$10^{3.66 \pm 0.0004}$ (stat.) $^{+0.008}_{-0.001}$ (syst.)
E_0 (TeV)	29.5 ± 1.0 (stat.) $^{+6.7}_{-4.2}$ (syst.)
E_1 (TeV)	107.2 ± 10.1 (stat.) $^{+13.7}_{-9.4}$ (syst.)
E_2 (TeV)	309.1 ± 21.2 (stat.) $^{+30.5}_{-34.4}$ (syst.)
γ_1	-2.45 ± 0.0001 (stat.) $^{+0.057}_{-0.001}$ (syst.)
γ_2	-2.79 ± 0.0003 (stat.) $^{+0.19}_{-0.01}$ (syst.)
γ_3	-2.61 ± 0.02 (stat.) $^{+0.68}_{-0.12}$ (syst.)
γ_4	-2.84 ± 0.04 (stat.) $^{+0.07}_{-0.41}$ (syst.)
ϵ_1	2.7 ± 0.2 (stat.) $^{+1.4}_{-0.5}$ (syst.)
ϵ_2	6.4 ± 0.3 (stat.) $^{+0.6}_{-1.4}$ (syst.)
ϵ_3	5.6 ± 0.5 (stat.) $^{+3.4}_{-3.1}$ (syst.)
χ^2	4.9



Comparison with other experiments



Comparison with mass-group spectra



PoS

PROCEEDINGS
OF SCIENCE

Probing the mass composition of TeV cosmic rays with HAWC

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Conclusions

- ◆ We reported the **all-particle cosmic-ray spectrum** from **3.9 TeV to 1PeV** using five years of data from **HAWC**
- ◆ The spectrum, reconstructed via a Bayesian unfolding method using the QGSJET-II-04 hadronic interaction model, confirms the presence of a **knee-like feature** at 29.5 ± 1.0 (stat.) $^{+6.7}_{-4.2}$ (syst.) TeV.
- ◆ We find evidence for two additional fine structures: a **hardening** at 107.2 ± 10.1 (stat.) $^{+13.7}_{-9.4}$ (syst.) TeV followed by a **softening** at 309.1 ± 21.2 (stat.) $^{+30.5}_{-34.4}$ (syst.) TeV
- ◆ This could be evidence of a relatively nearby young source injecting cosmic rays and producing the observed fine structures.



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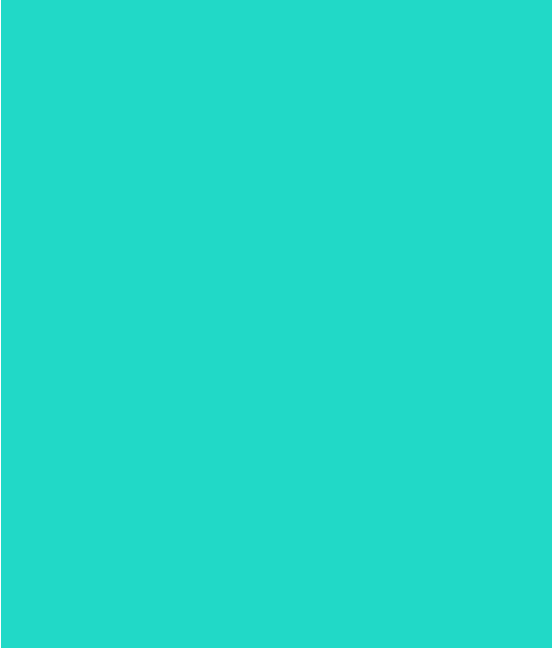
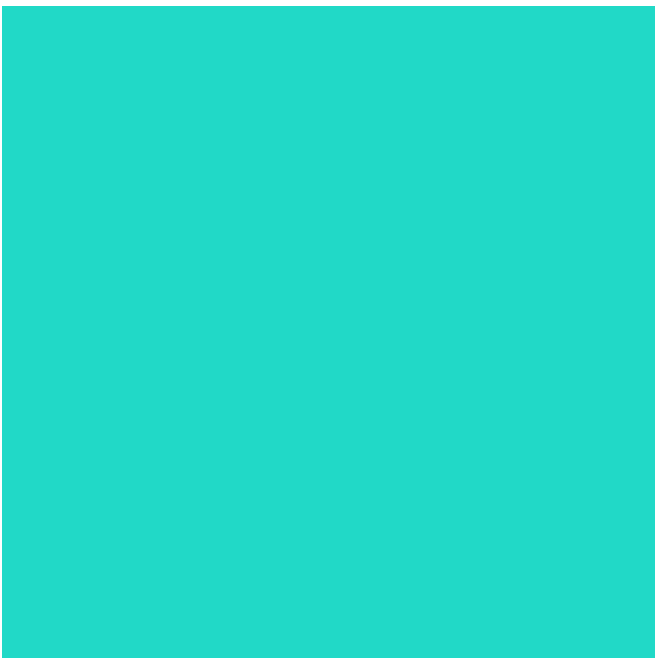


Thank you!



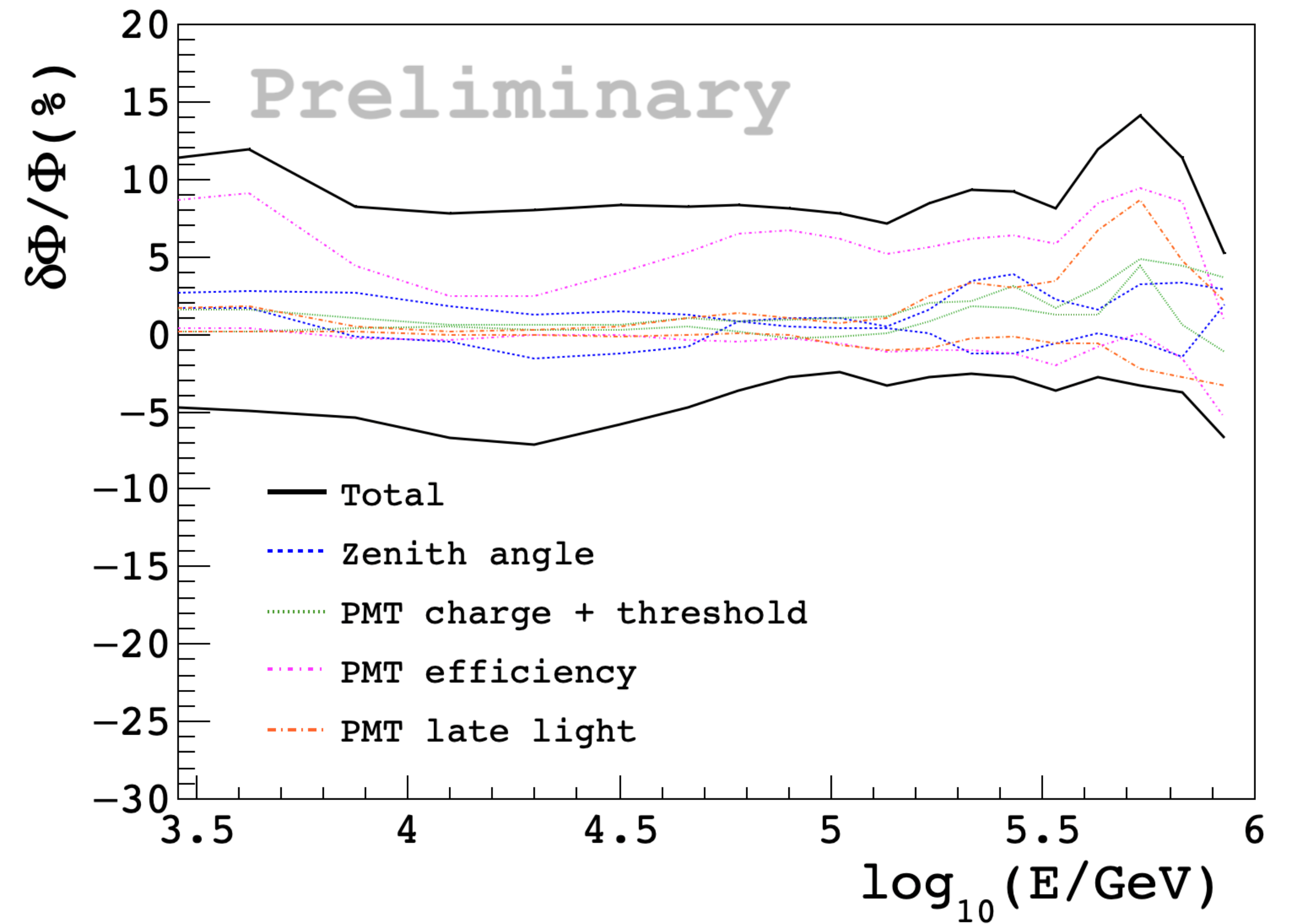
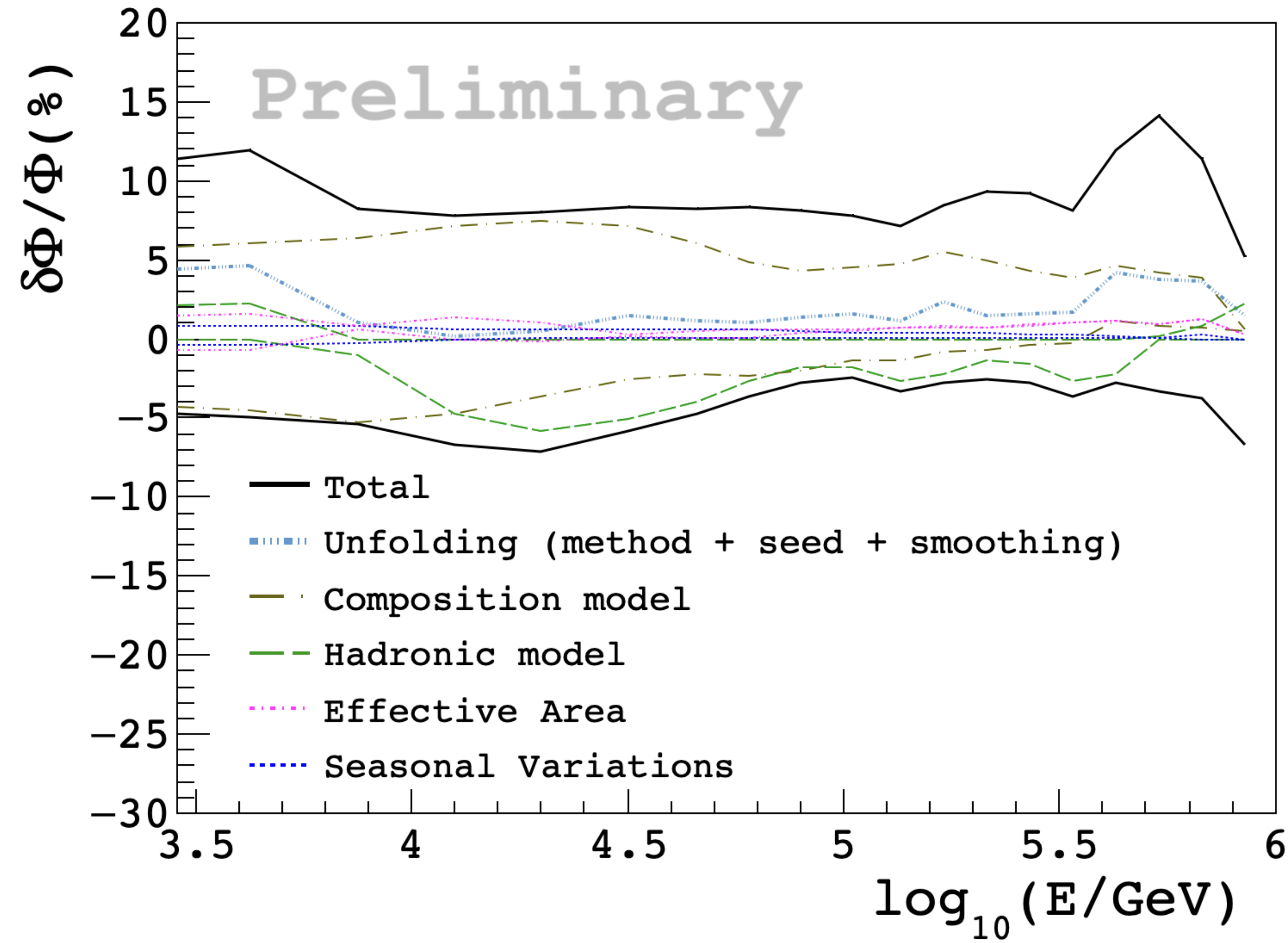
Gracias





Backup

Uncertainties



Bootstrap procedure for significance estimation

Generate a set of 100,000 Monte Carlo spectra with correlated data points:

1. We construct a spectrum with the simplest model:

$$\Phi(E) = \Phi_0 E^\gamma \left[1 + \left(\frac{E}{E_0} \right) \right]^{(\gamma_2 - \gamma_1)/\epsilon_1}$$

2. We compute the energy distribution via:

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

Parent distribution

3. The content of each bin is fluctuated according to a Gaussian distribution centered on the expected value $N(E) \rightarrow$ independent statistical realizations of the parent distribution.

4. The elements of the detector response matrix are fluctuated before applying the unfolding procedure $\rightarrow$ statistical uncertainties arising from the finite size of the MC sample

Bootstrap procedure for significance estimation

5. Each toy distribution is unfolded using the same reconstruction algorithm applied to the real data.

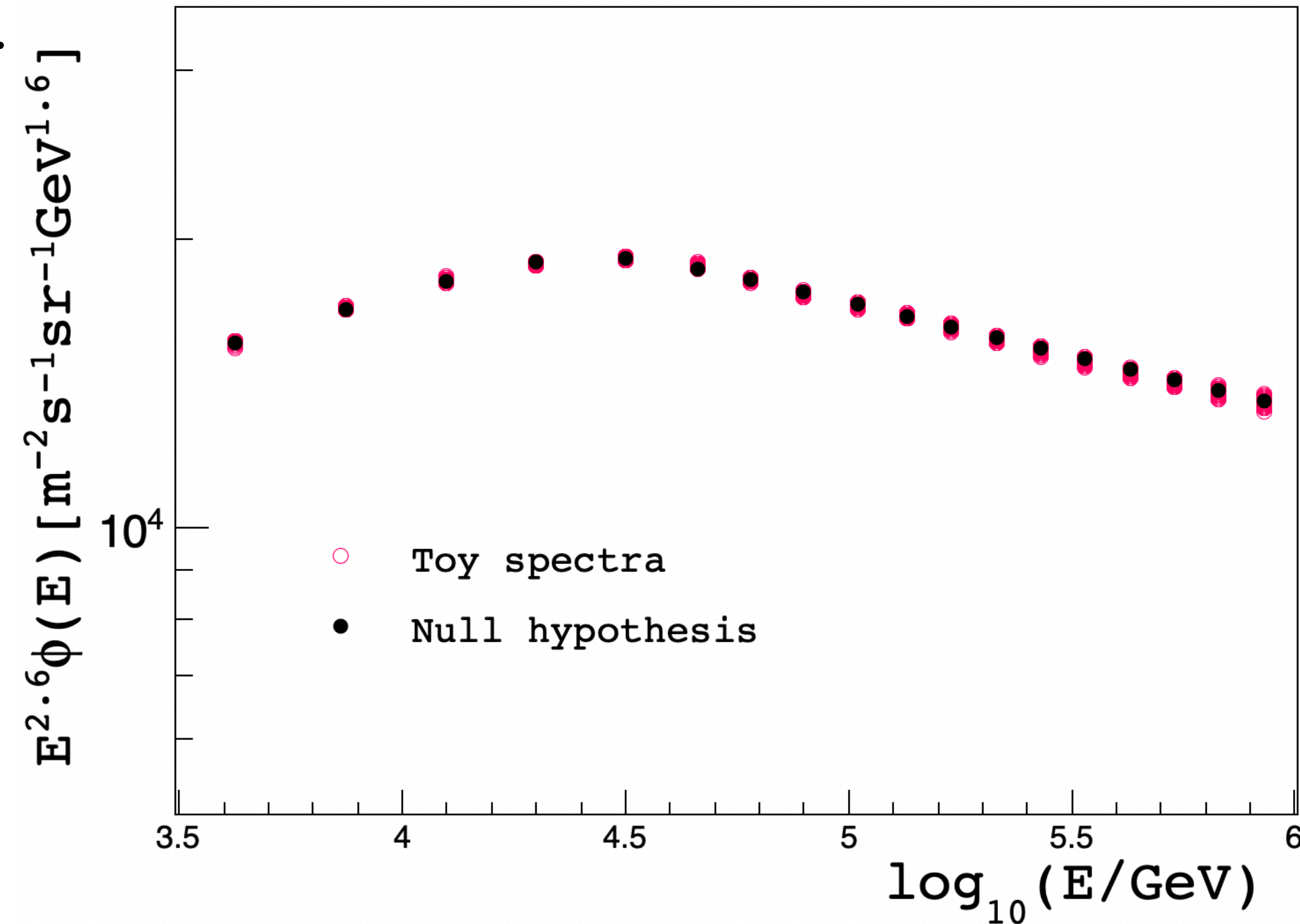
➔ **Ensemble of unfolded toy spectra with correlations, regularization effects and possible algorithmic biases incorporated into the statistical evaluation.**

6. We compute the TS for each toy

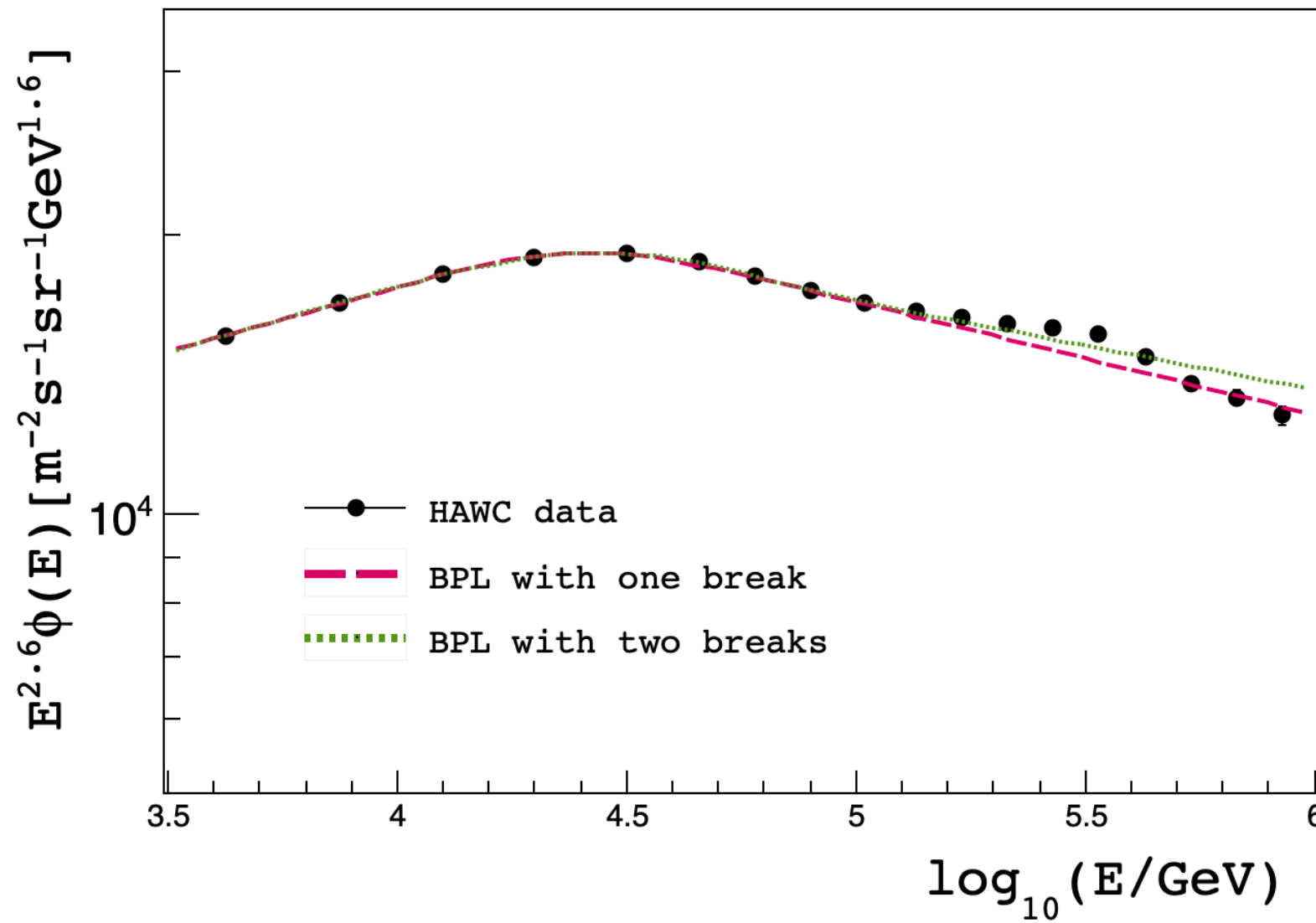
$$TS_{toy} = -\Delta\chi^2 = -(\chi_{alt}^2 - \chi_{null}^2)$$

7. Finally, the p-value will be given by:

$$p = \frac{\text{\#toys with } TS_{toy} > TS_{obs}}{\text{\#generated toys}}$$



Results

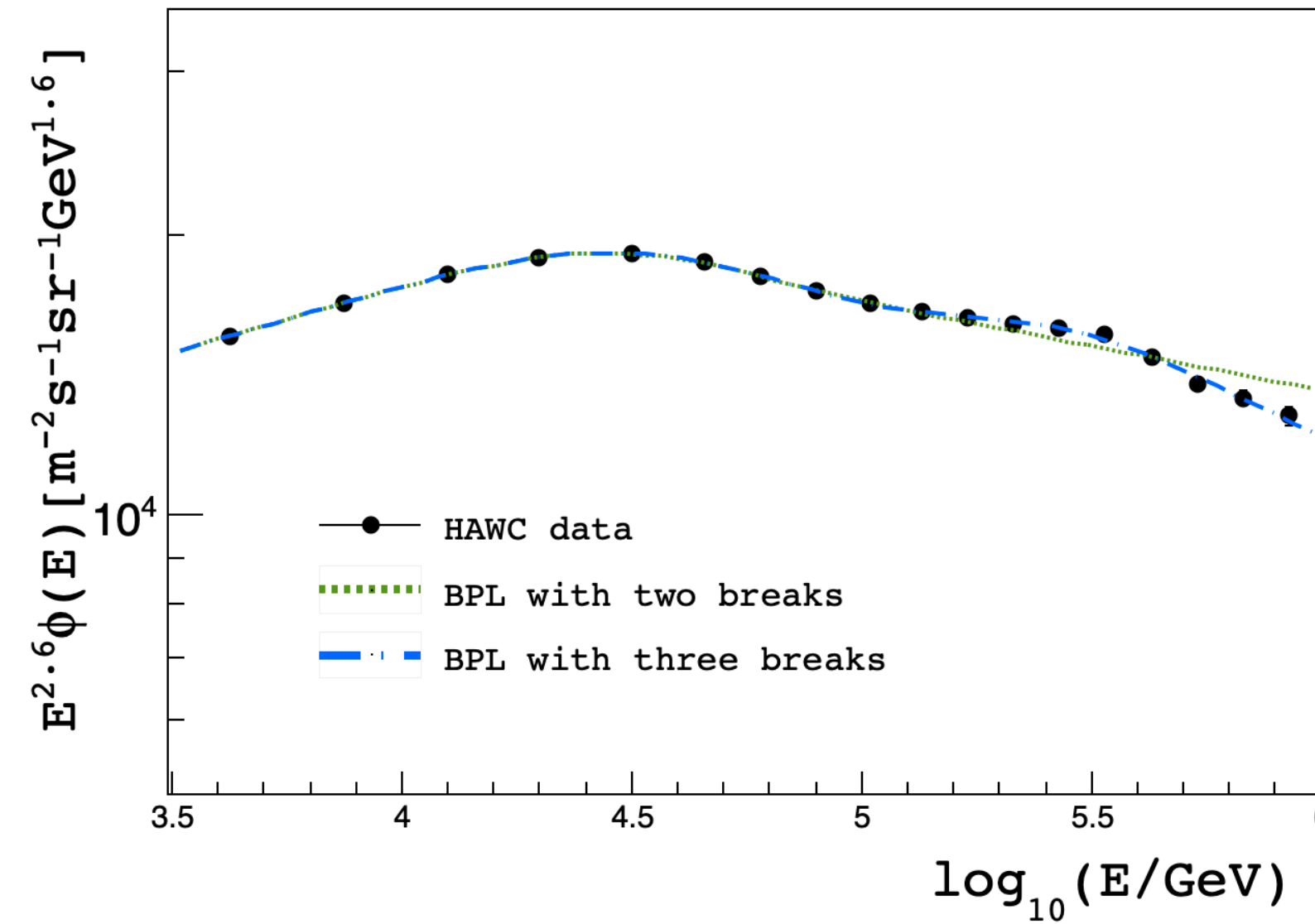


$$\chi_{1b}^2 = 67.1612 \quad \chi_{2b}^2 = 50.61$$

$$TS_{obs} = 16.55$$

1796 / 100,000 toys

p-value = 0.01796 o 2.09σ

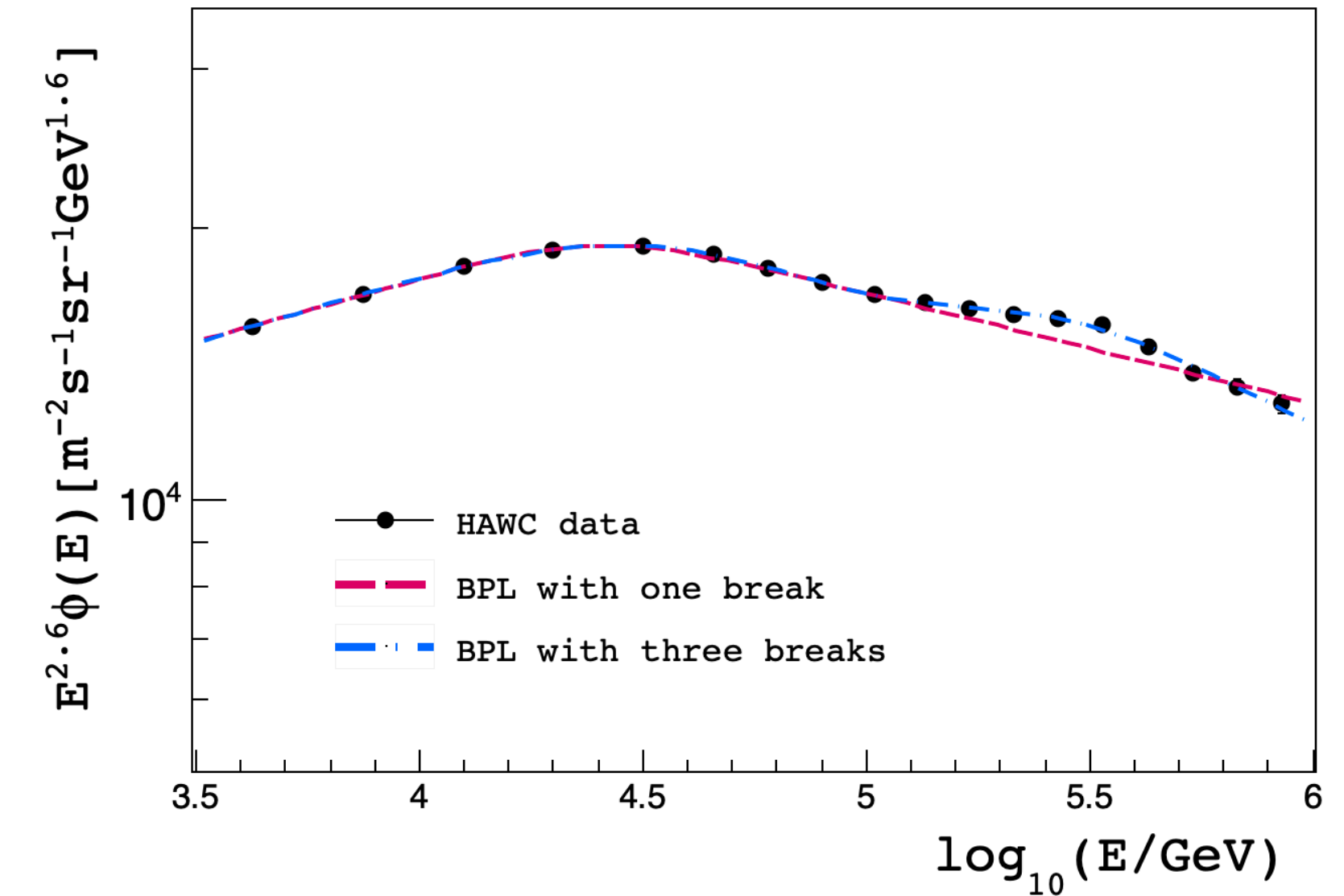


$$\chi_{2b}^2 = 50.61 \quad \chi_{3b}^2 = 4.90$$

$$TS_{obs} = 45.71$$

1 / 100,000 toys

p-value = $1\text{e-}5$ o 4.26σ



$$\chi_{1b}^2 = 67.1612 \quad \chi_{3b}^2 = 4.9$$

$$TS_{obs} = 62.26$$

0 / 100,000

p-value at least 4.26σ

Bootstrap procedure for significance estimation

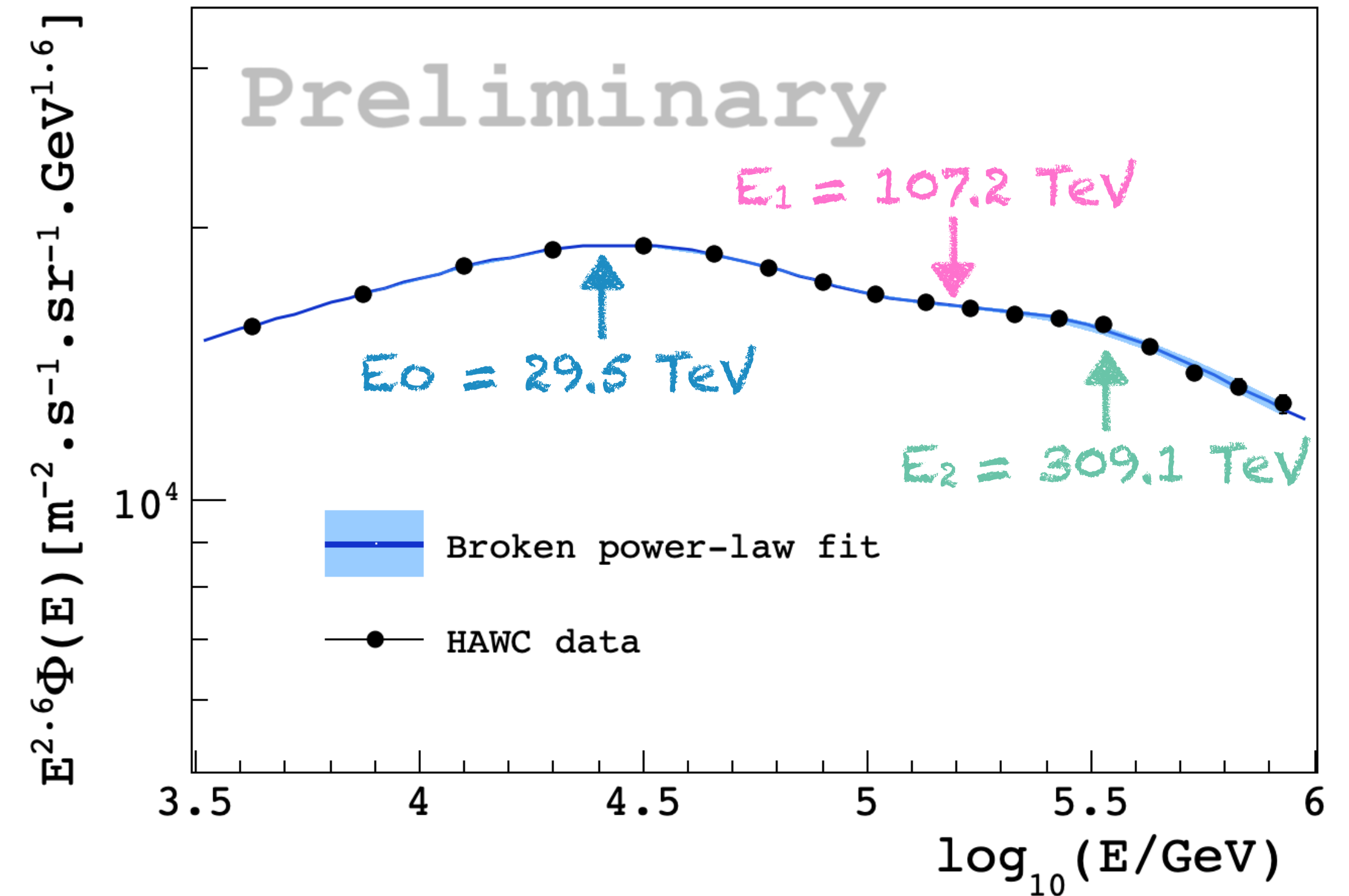
- Models were compared using the test statistic:

$$TS = -\Delta\chi^2 = -(\chi_{alt}^2 - \chi_{null}^2)$$

considering all three pairs of hypothesis (1, 2 and 3 break models)

- The significance was evaluated with 100,00 bootstrap MC toy spectra, generated under the null hypothesis.
- The p -value was obtained from the fraction of toys:

$$p = \frac{\text{\#toys with } TS_{toy} > TS_{obs}}{\text{\#generated toys}}$$

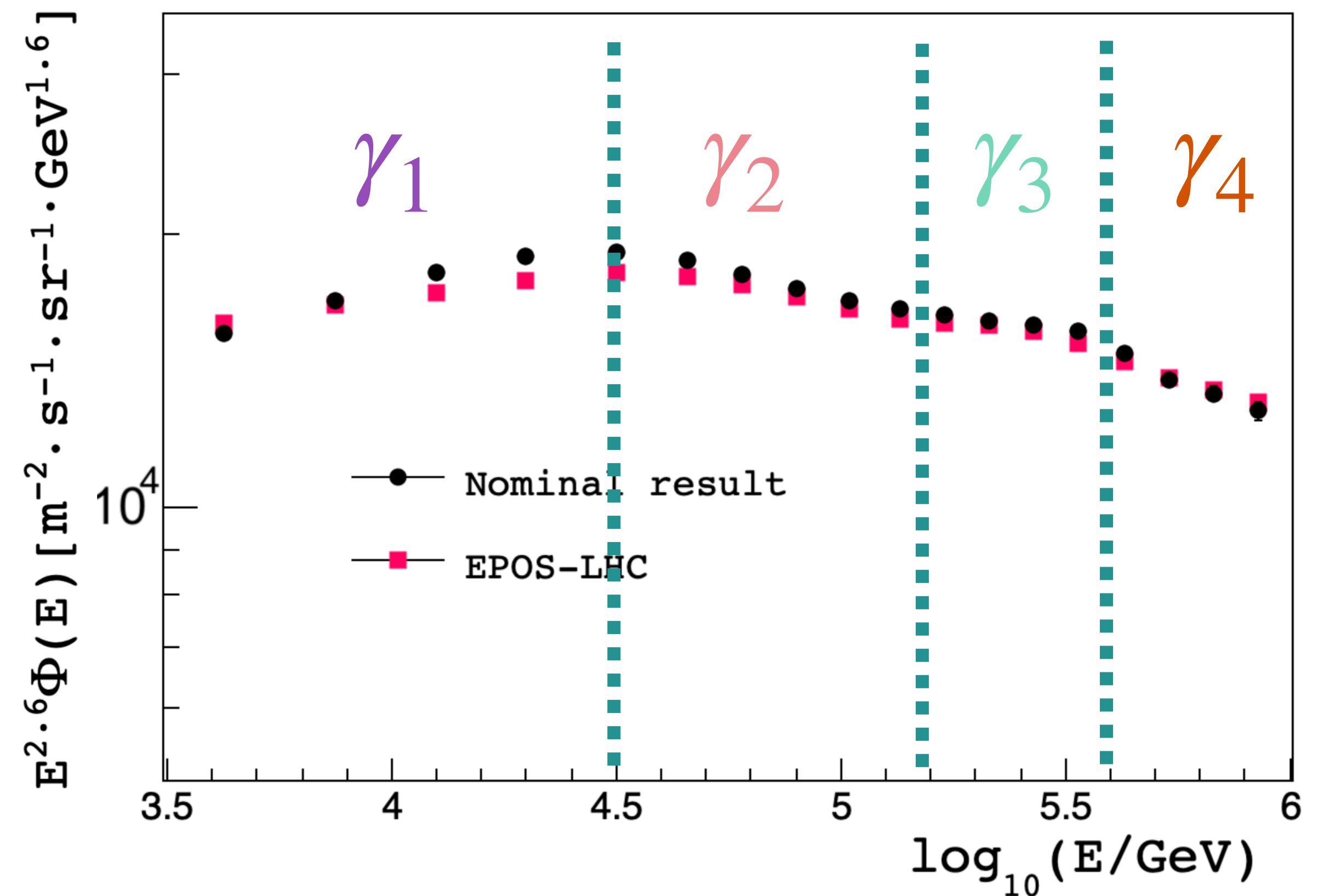


Test statistic	Number of toys with $TS > TS_{obs}$	Significance [σ]
TS_1	1796	2.1
TS_2	1	4.3
TS_3	0	> 4.3

➡ The three-break model is strongly preferred over simpler hypothesis!

Systematic effects on the significance of the results

- First, we fit the nominal spectrum and obtain the change in the spectral index associated with each spectral break: $\Delta\gamma = \gamma_2 - \gamma_1$
- Next, we evaluate each source of systematic uncertainty (composition and hadronic interaction models, seasonal variations, unfolding method, etc.) and repeat the fit.



Systematic effects on the significance of the results

- ◆ For each systematic source, we evaluate how the value of $\Delta\gamma$ changes with respect to the nominal result.
- ◆ Finally, we calculate the significance of each spectral break:

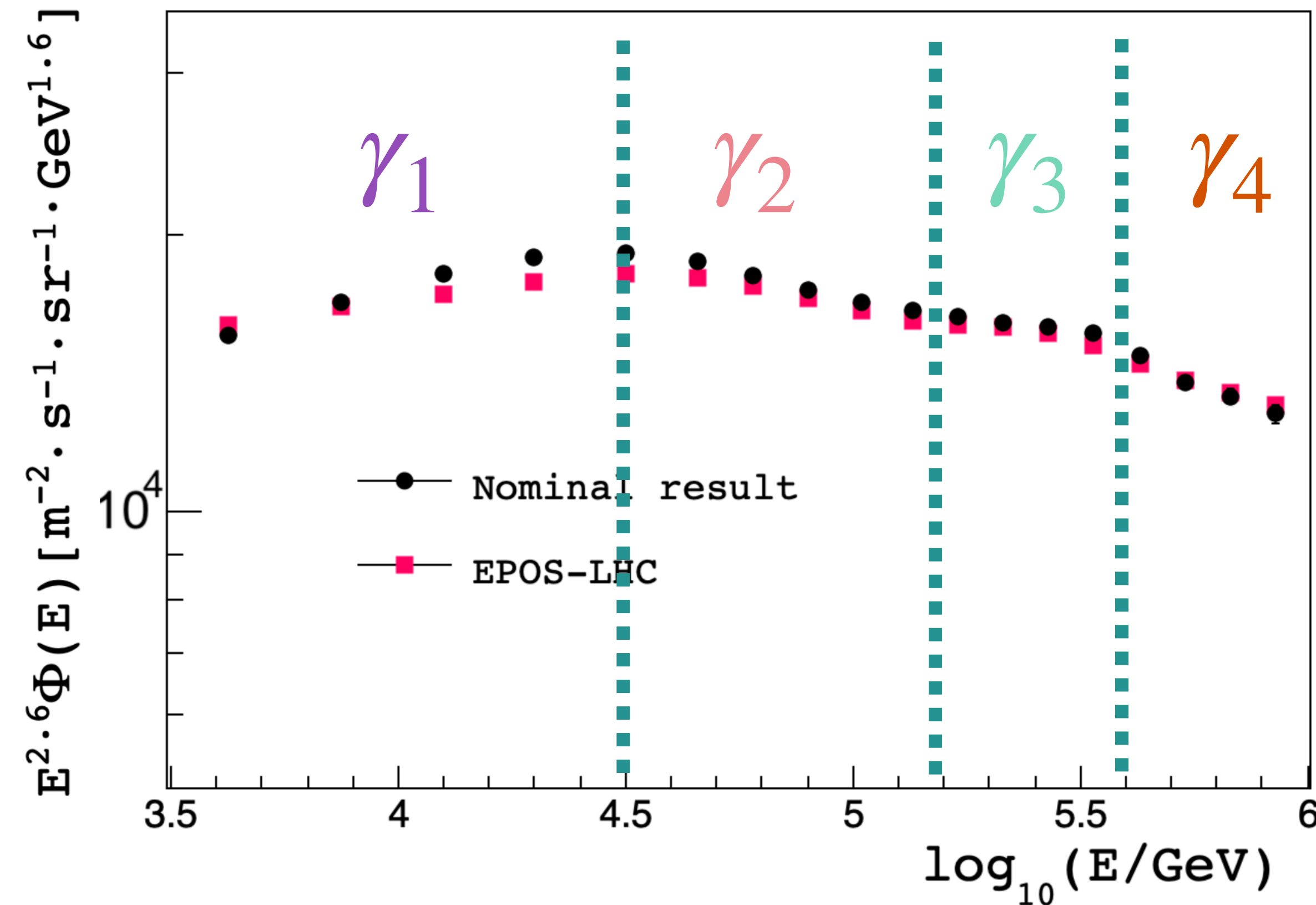
$$s = \frac{\overline{\Delta\gamma}}{\sigma_{tot}} \quad \sigma_{tot} = \sqrt{\sigma_{stat}^2 + \sigma_{sist,\pm}^2}$$

- ◆ Where the systematic uncertainty is estimated from the spread of the variations of each systematic source around the nominal value:

Change in the k -spectrum

$$\sigma_{sist,\pm}^2 = \sum_k (\Delta\gamma_{k,\pm} - \overline{\Delta\gamma})^2$$

Nominal result



Systematic effects on the significance of the results

	First break	Second break
$\Delta\gamma$	-0.32 ± 0.008 (stat.) $^{+0.08}_{-0.06}$ (syst.)	$+0.13 \pm 0.009$ (stat.) $^{+0.08}_{-0.1}$ (syst.)
Significance	3.3σ	2.5σ

	Third break
$\Delta\gamma$	-0.20 ± 0.006 (stat.) $^{+0.11}_{-0.09}$ (syst.)
Significance	2.8σ