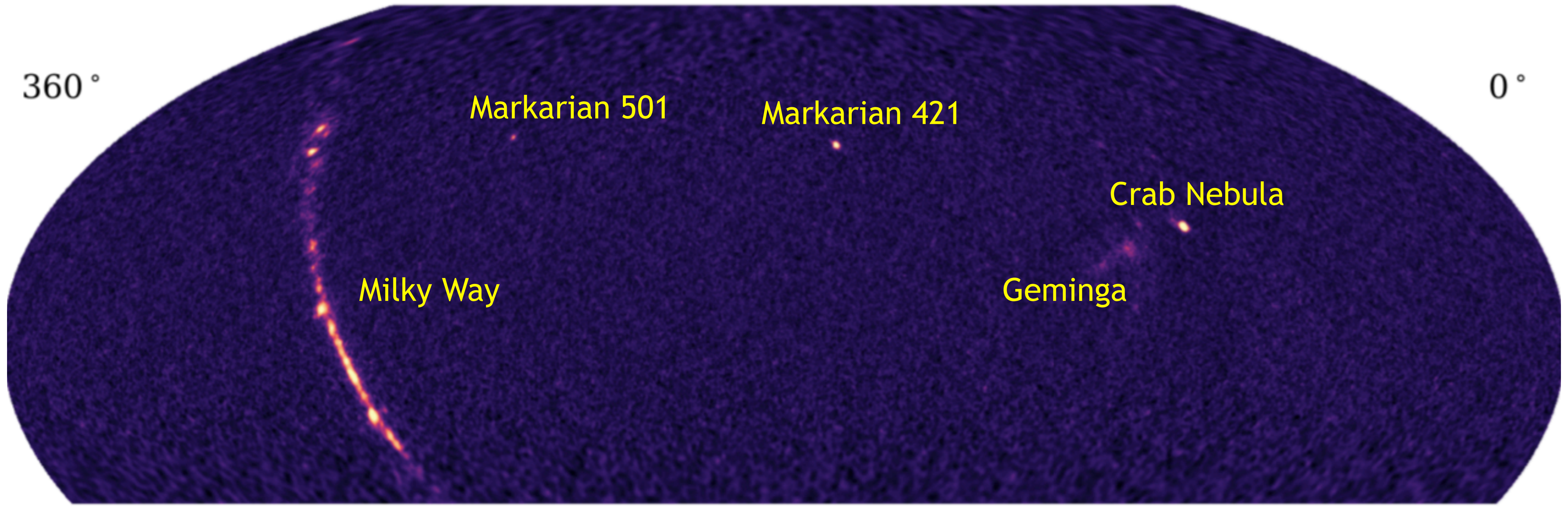
HAWC measurements of the energy spectra of cosmic ray protons, helium and heavy nuclei in the TeV range

J.C. Arteaga-Velázquez for the HAWC Collaboration
Universidad Michoacana, Morelia, Mexico

Content

1) The HAWC γ-ray observatory



[HAWC Collab., APJ 905 (2020) 76]

γ- and cosmic-ray detector:

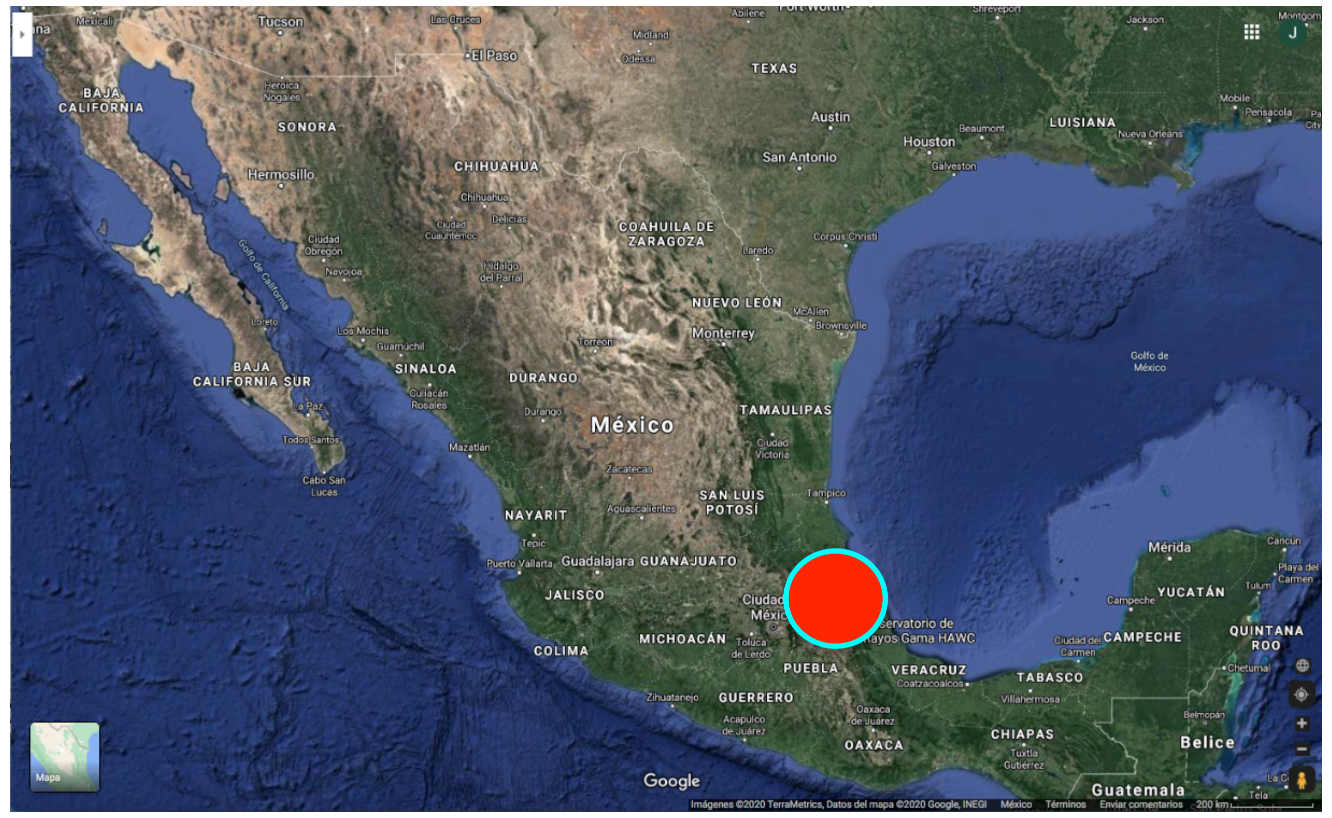
- Air-shower observatory
- Ground-based Cherenkov array
  E = 100 GeV - 100 TeV

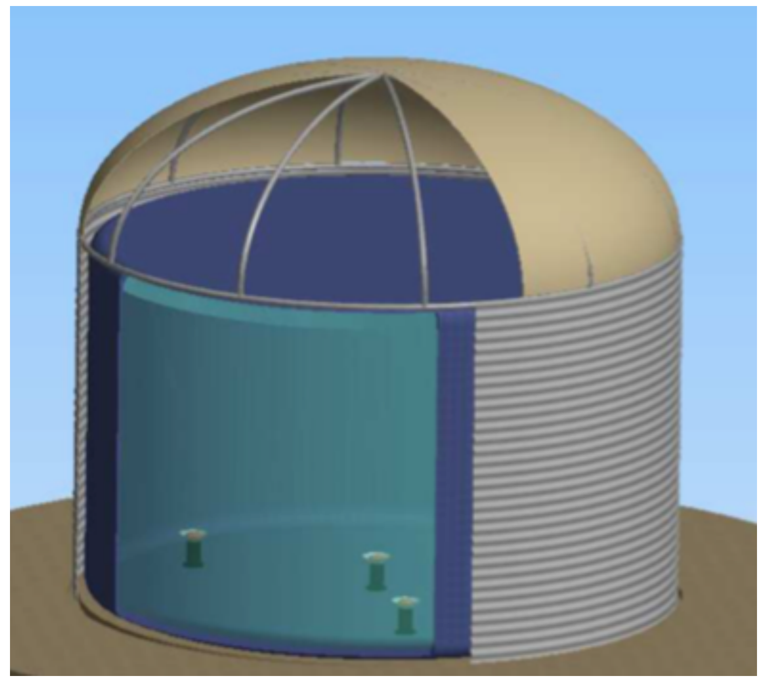
Set-up of central detector:

- 22 000 m^2 surface
- 300 densely packed water Cherenkov detectors (200,000 ℓ of water + 4 PMTs)

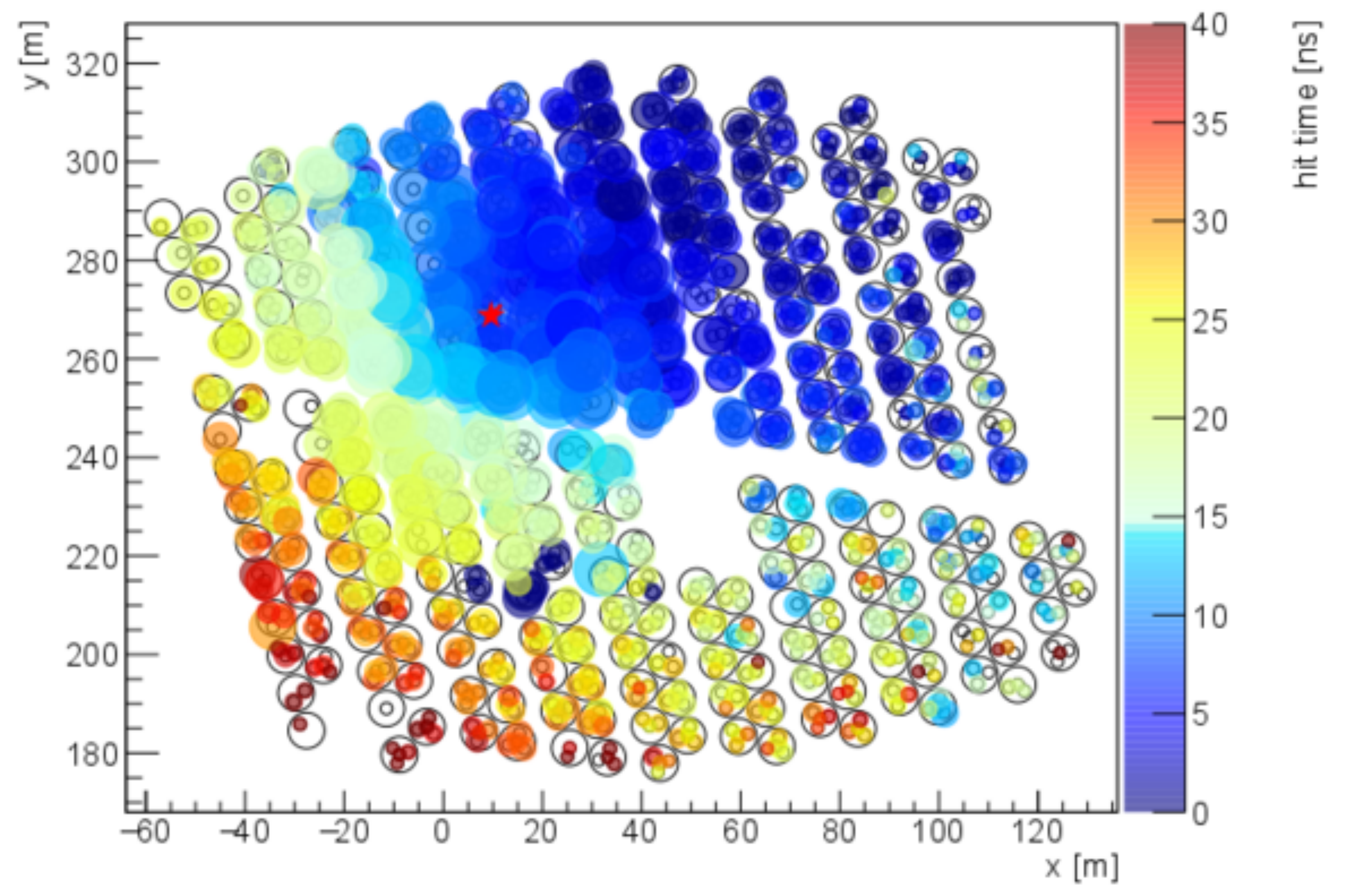
Location:

- Sierra Negra Volcano, Puebla, Mexico
- 19° N and 97° W
- 4100 m a.s.l. (640 g/cm^2)





1) The HAWC γ-ray observatory



EAS reconstruction from hit times, effective charge, number of PMT's with signal:

- Core location, (X_c, Y_c),
- Arrival direction, θ,
- Primary energy, E,
- Lateral charge profile, Qeff(r), …

Lateral age parameter (*s*):

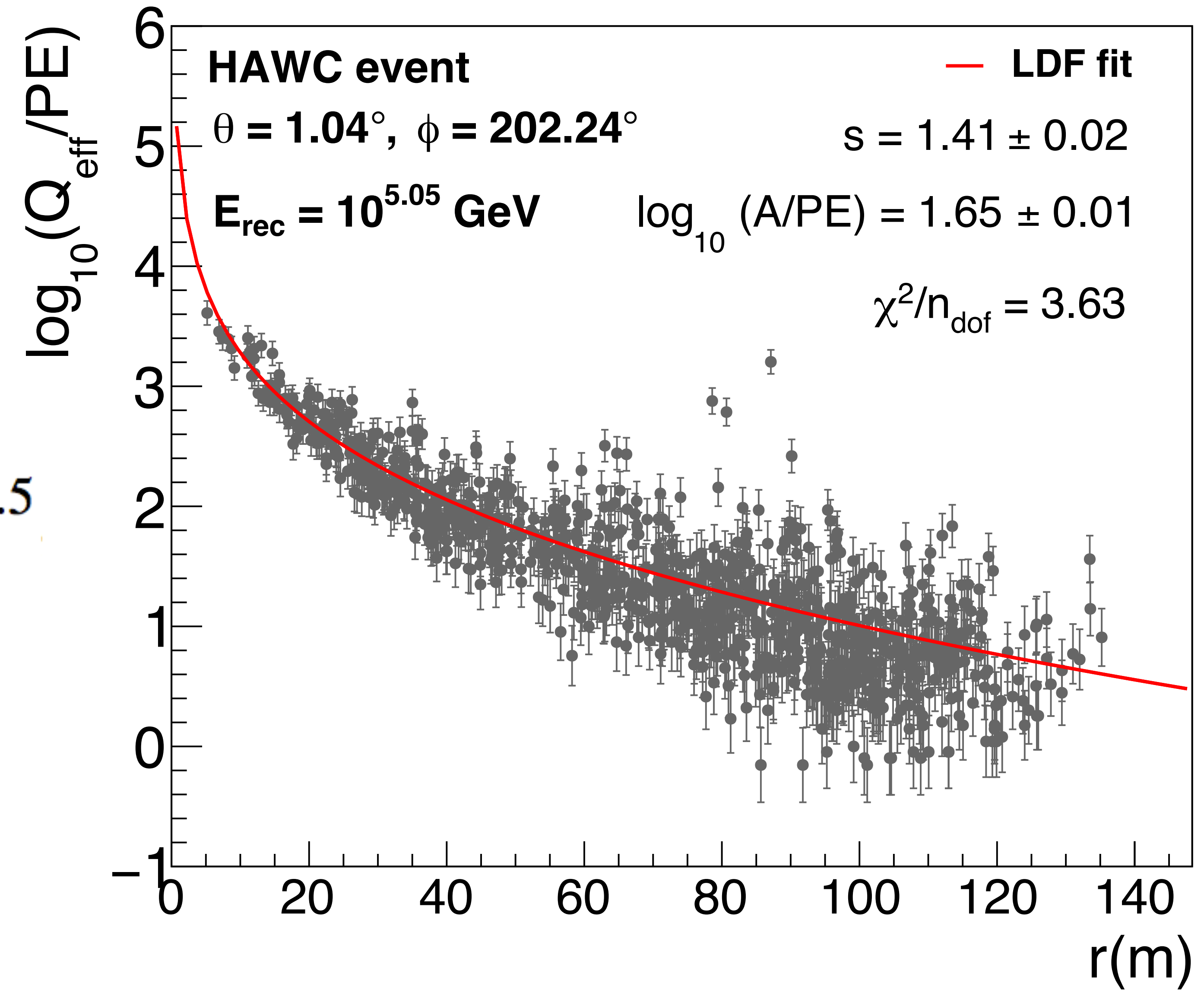
- Sensitive to composition
- Fit Qeff(r), event-by-event, with a NKG-like function:

$$f_{ch}(r) = A \cdot (r/r_0)^{s-3} \cdot (1 + r/r_0)^{s-4.5}$$

with r_0 = 124.21 m.

A, ***s*** are free parameters

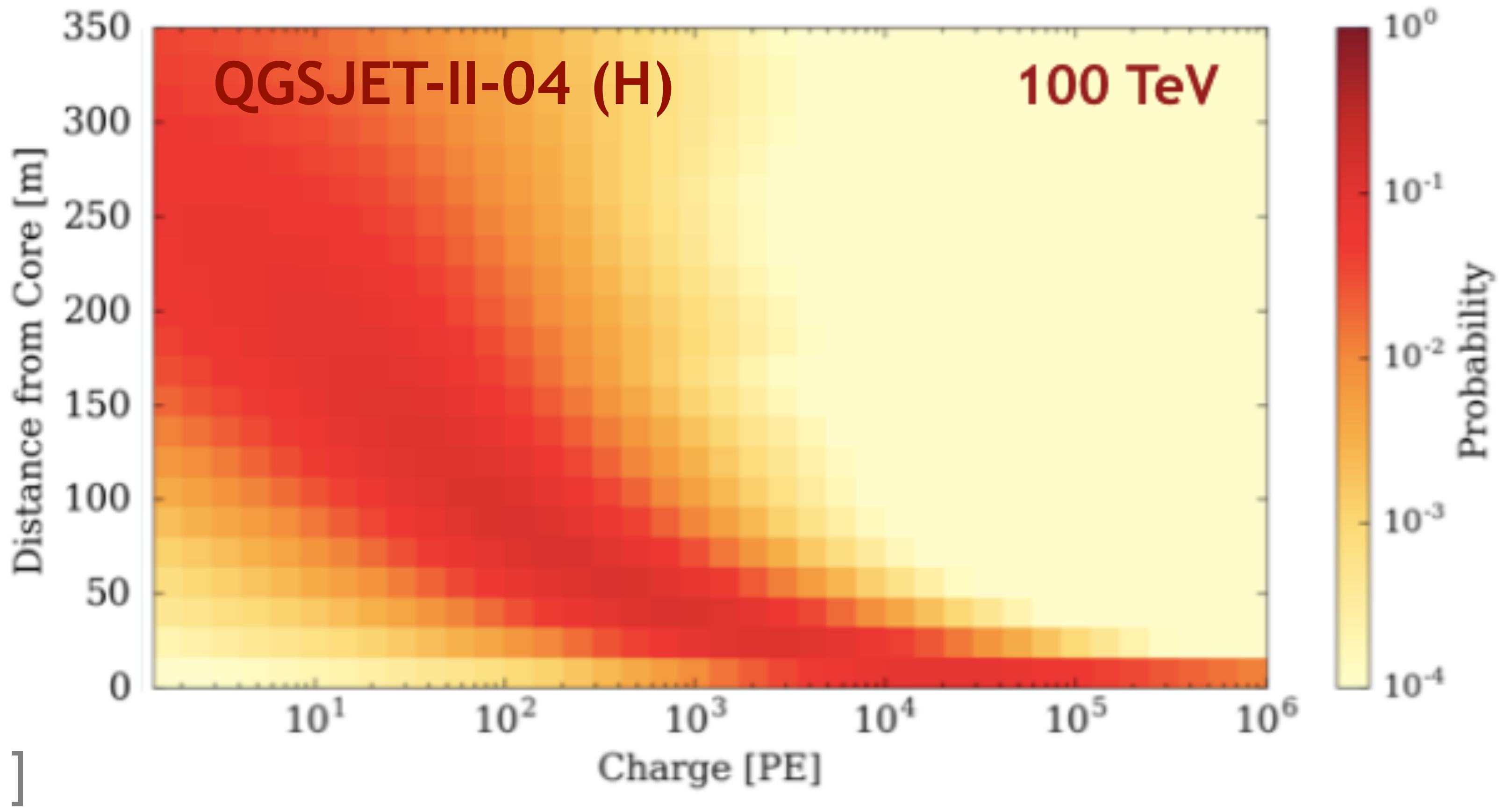
[HAWC Collab., APJ 881 (2019) 134]



Primary energy:

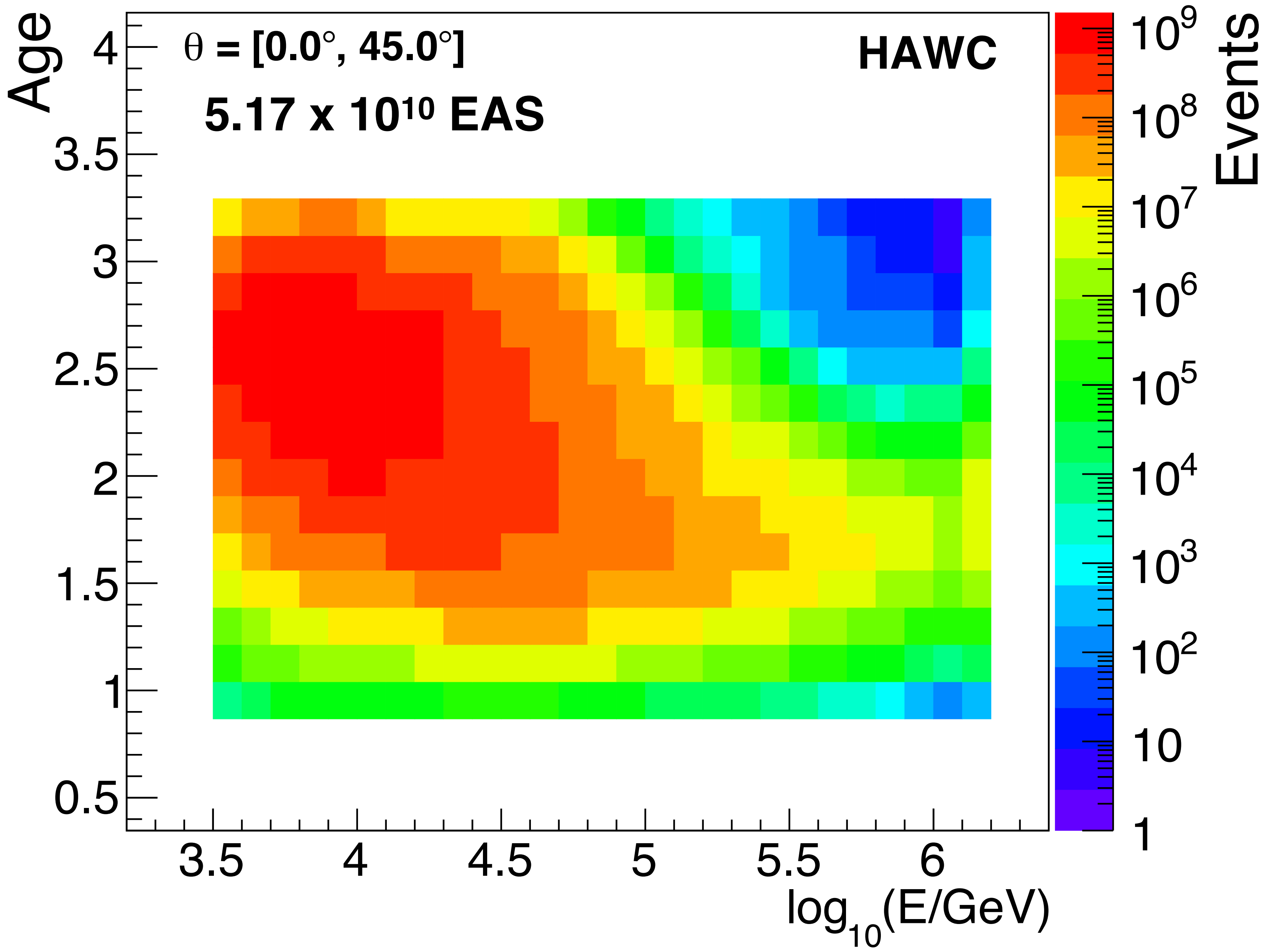
- Calibration with a maximum likelihood procedure.
- Comparison of Qeff(r) data with MC predictions for H.
- Binning in r, Qeff, θ and E.

[HAWC Collab., PRD 96 (2017) 122001]



2) Analysis procedure

- Unfold **shower age vs $\log_{10}$(E)** data to find the **elemental spectra for H, He and heavy nuclei** (Z > 2).



$$n(s, \log_{10} E) = T_{\text{eff}}\, \Delta\Omega \sum_{j=1} \sum_{E_T} P_j(s, \log_{10} E | \log_{10} E_T)\, A_{\text{eff},j}(E_T)\, \Phi_j(E_T)\, \Delta E_T$$

$n(s, \log_{10} E)$: # events per (s, $\log_{10} E$) bin.

$P_j(s, \log_{10} E| \log_{10} E_T)$: response matrix for EAS from mass group j (reconstruction and fluctuations).

A_{eff} : effective area = $A_{\text{thrown}}\, \varepsilon_{\text{eff}}$.

$\Phi_j(E_T)$: spectrum for mass group j.

HAWC data

- January/01/16 - June/03/19
- T_{eff} = 3.21 years
- $\Theta < 45^{\circ}$
- Successfully reconstructed
- $f_{\text{hit}} \geq 0.2$
- Hit PMT's within radius of 40 m > 40
- s = [1, 3.2]
- $\log_{10}$ (E/GeV) = [3.5, 6.2]

Apply Gold's unfolding algorithm

[R.Gold, Report ANL-6984, 1964]

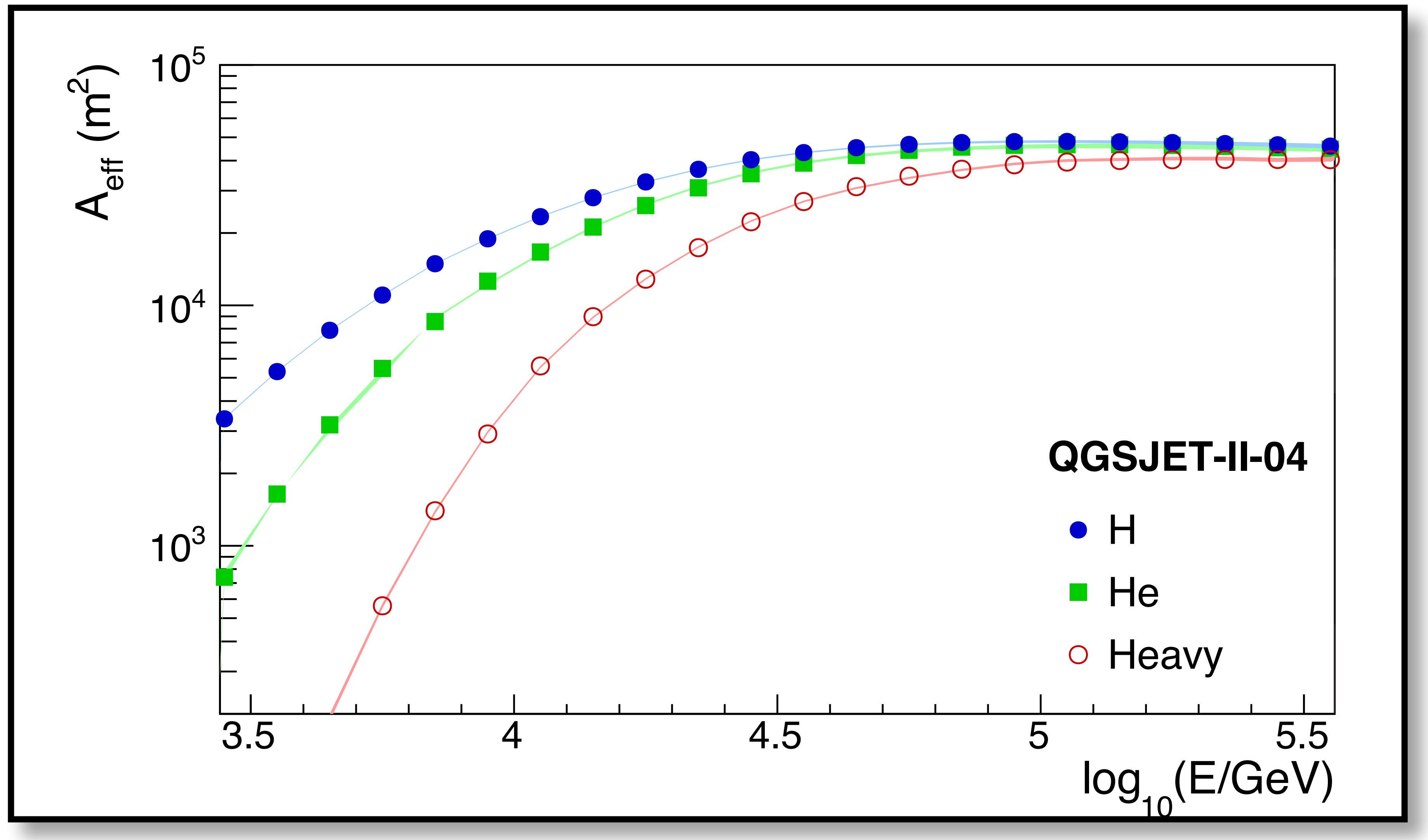
[KASCADE Collab., App 24 (2005) 1]

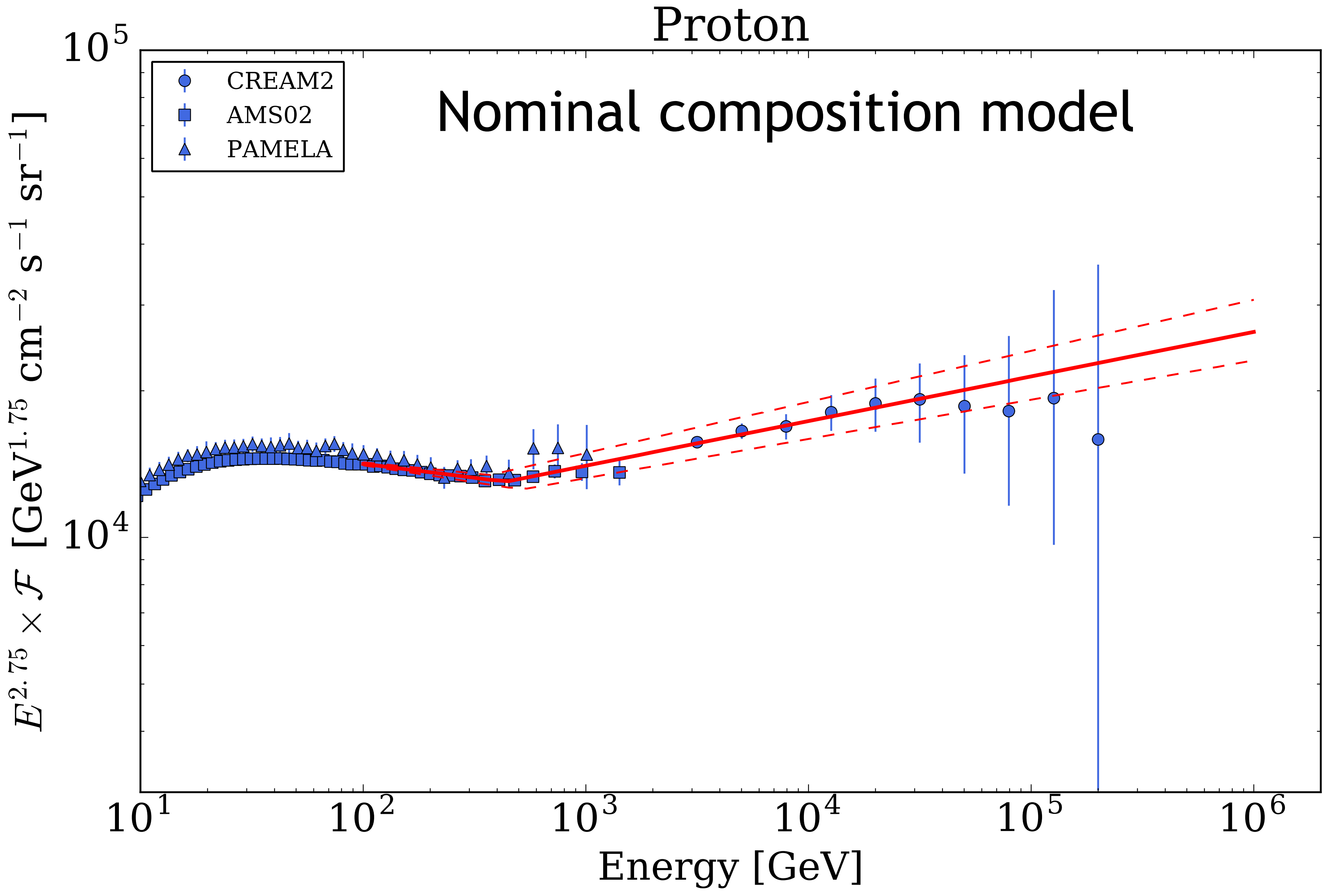
Bins:
$\Delta \log_{10}$ (E/GeV) = 0.1
$\Delta s = 0.17$

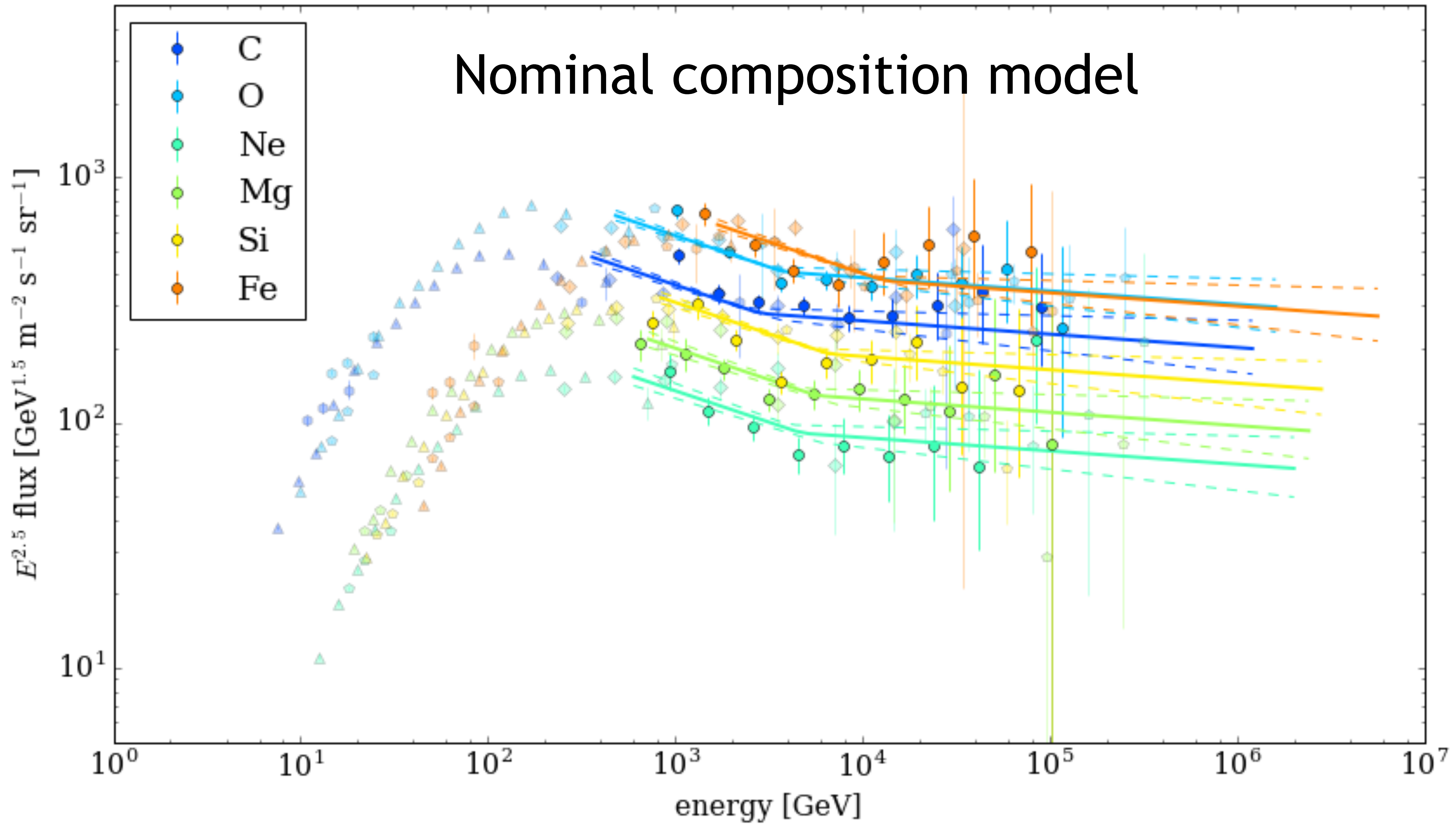
2) Analysis procedure

MC data is used to build the response matrix and effective area

- CORSIKA v7.4 (Fluka/QGSJET-II-04)
- E = 5 GeV - 2 PeV.
- $\theta < 70^o$
- Cosmic ray species: H, He, C, O, Ne, Mg, Si, Fe.
- E^{-2} spectra weighted to follow double power-laws derived from fits to **AMS-2** (2015), **CREAM-II** (2009 & 2011) and **PAMELA** (2011) data.







2) Analysis procedure

Gold's unfolding procedure

- Use **matrix formalism**:

  $N_{data} = P\, N_{unfold}$

- **Introduce statistical errors** using new response matrix

  $P' = (C\,P)^T (CP),$

  and new unfolded vector

  $N'_{data} = (C\,P)^T\, C\, N_{data}$

  where

  $C_{ij} = \delta_{ij}/\sigma_i\,; \quad (\sigma_i = 1/\sqrt{n_i})$

- N_{unfold} is found **iteratively** using the set of equations:

$$N^{k+1}_{unfold,\,i} = \frac{N^k_{unfold,\,i}\, N'_{data,\,i}}{\sum_j P'_{ij}\, N^k_{unfold,\,j}},$$

- Priors given by nominal composition model.

- **Smoothing** intermediate spectra with ROOT-CERN libraries (353HQ-twice algorithm).

- **Stopping criterium**: Minimum of Weighted Mean Square Error:

$$WMSE = \frac{1}{m} \sum_j^m \frac{\sigma^2_{stat,\,j} + \delta^2_{bias,\,j}}{N_{unfold,\,j}}$$

[R.Gold, Report ANL-6984, 1964]

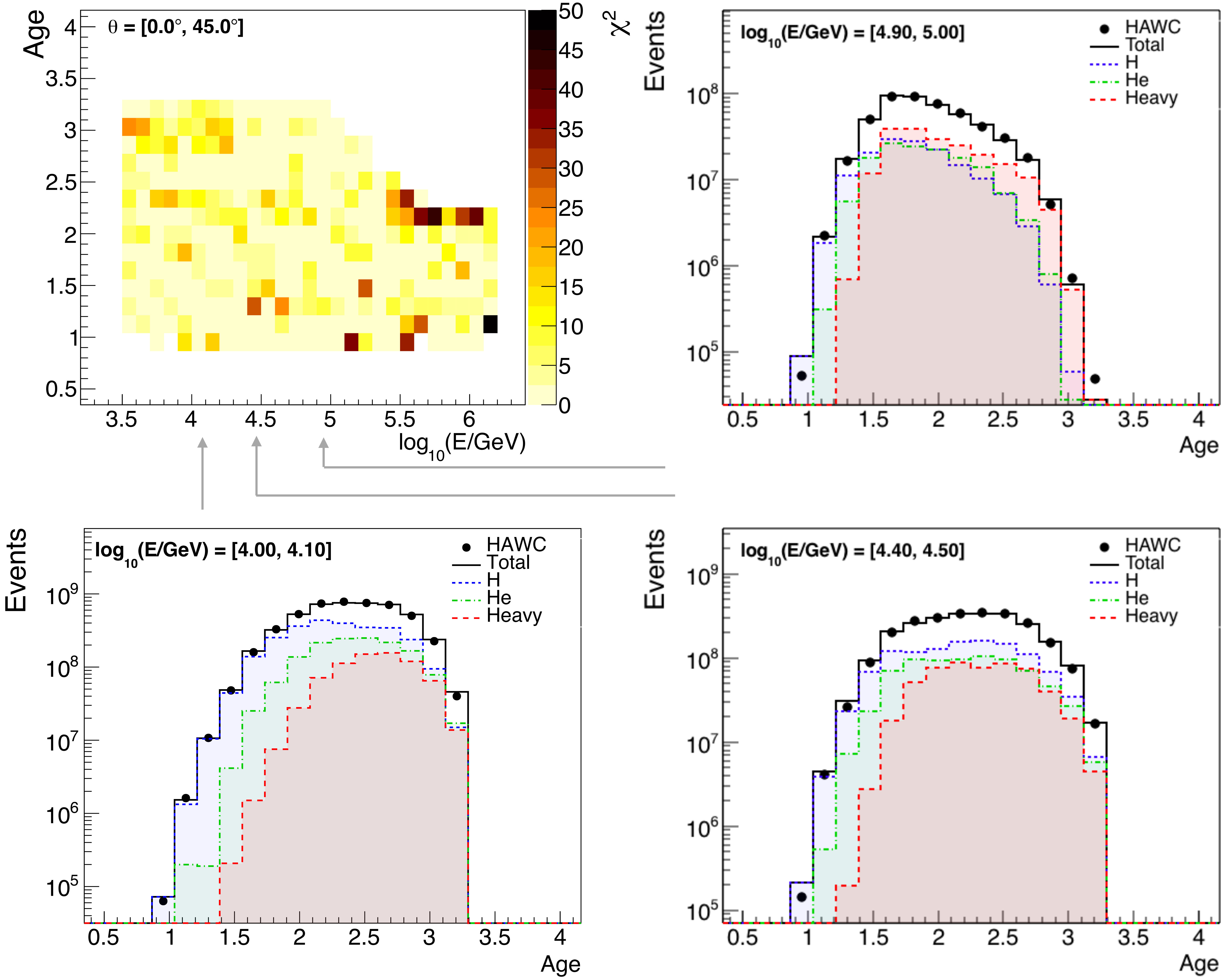
[KASCADE Collab., App 24 (2005) 1]

3) Results

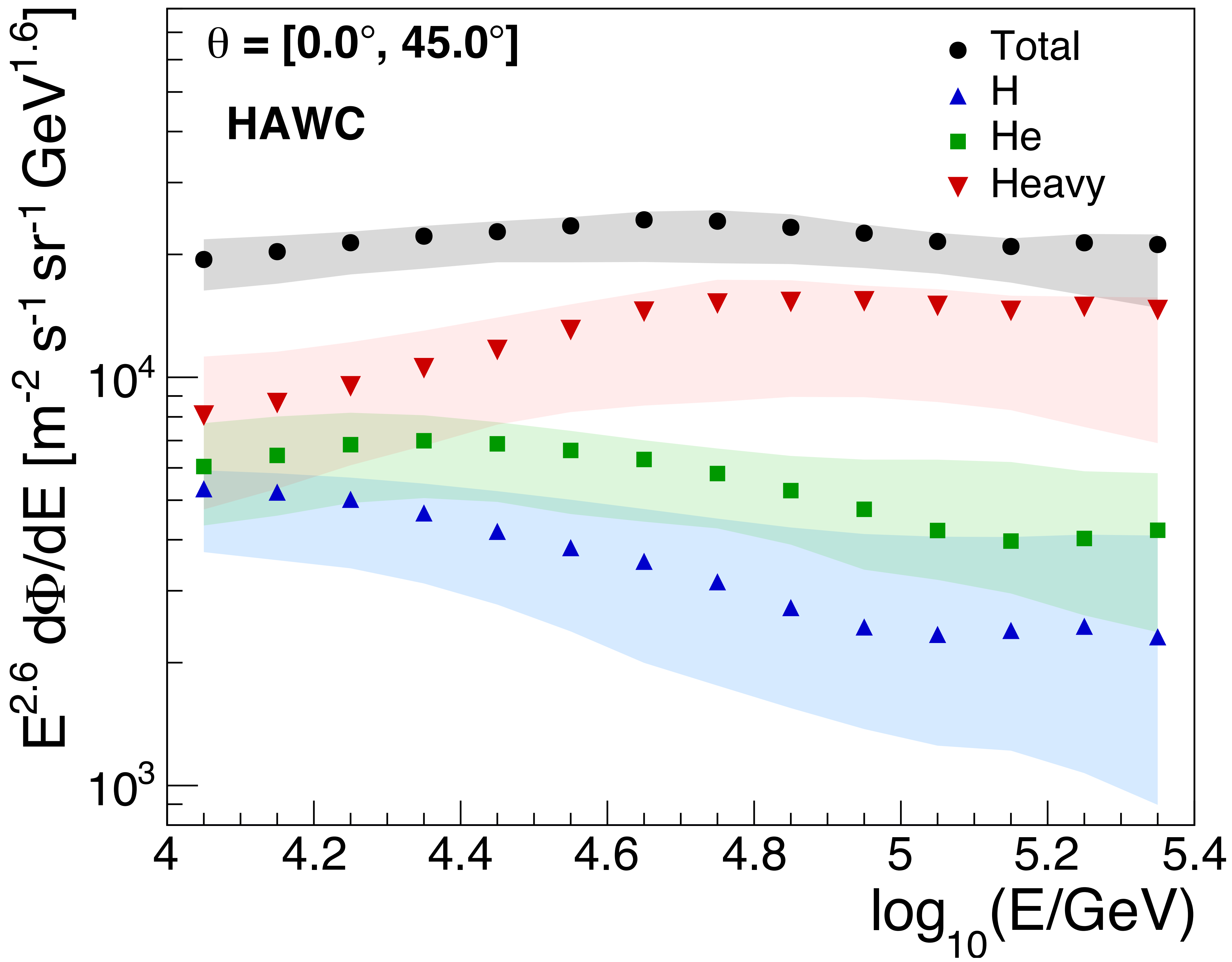
- χ^2/n.d.f = 5.02

$$\chi^2 = \sum_j \frac{(N_{data,\,j} - N_{forward,\,j})^2}{\sigma^2_{stat,\,j} + \sigma^2_{MC,\,j}}$$

- Good description of data except for old EAS at low and high energies.

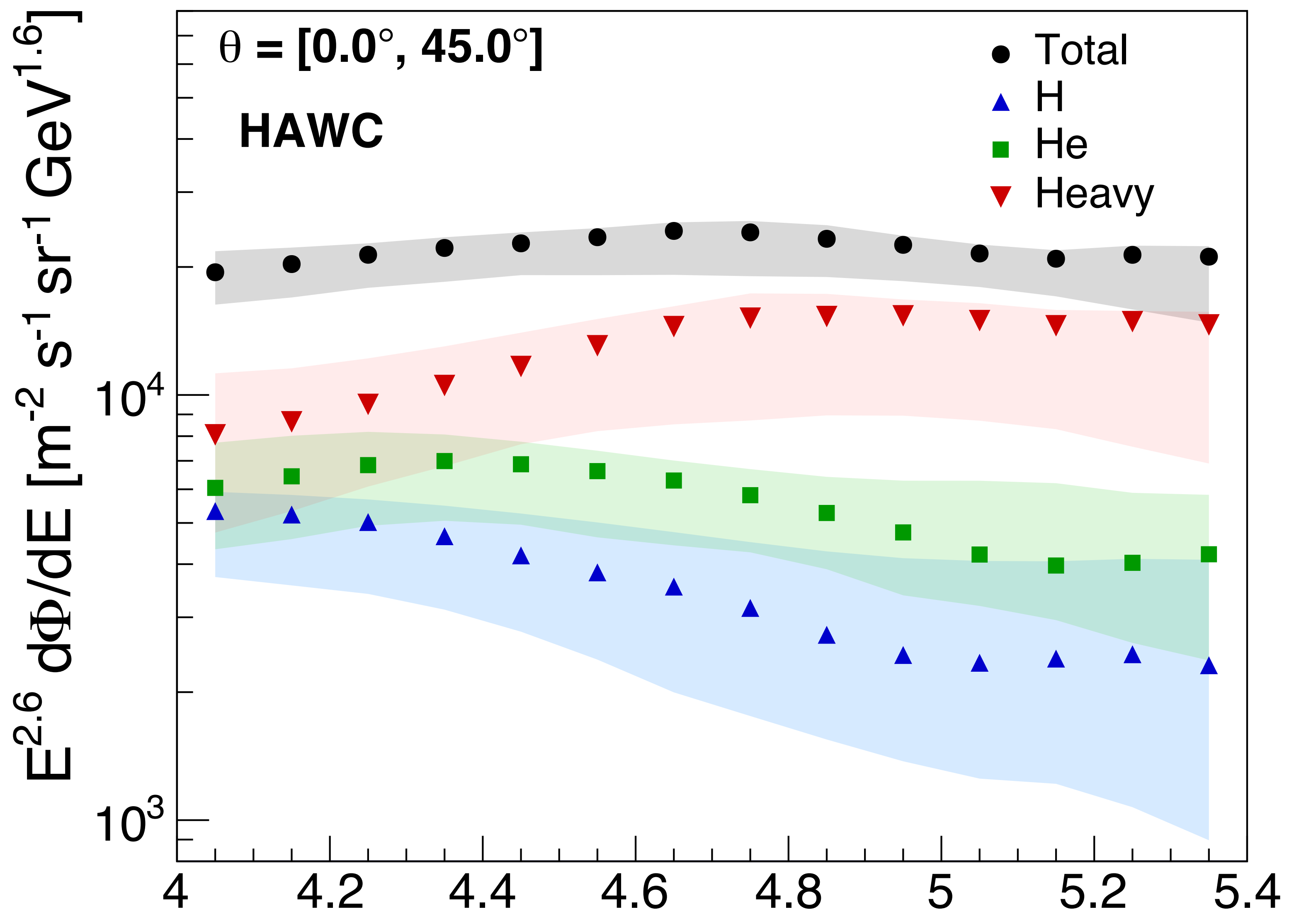


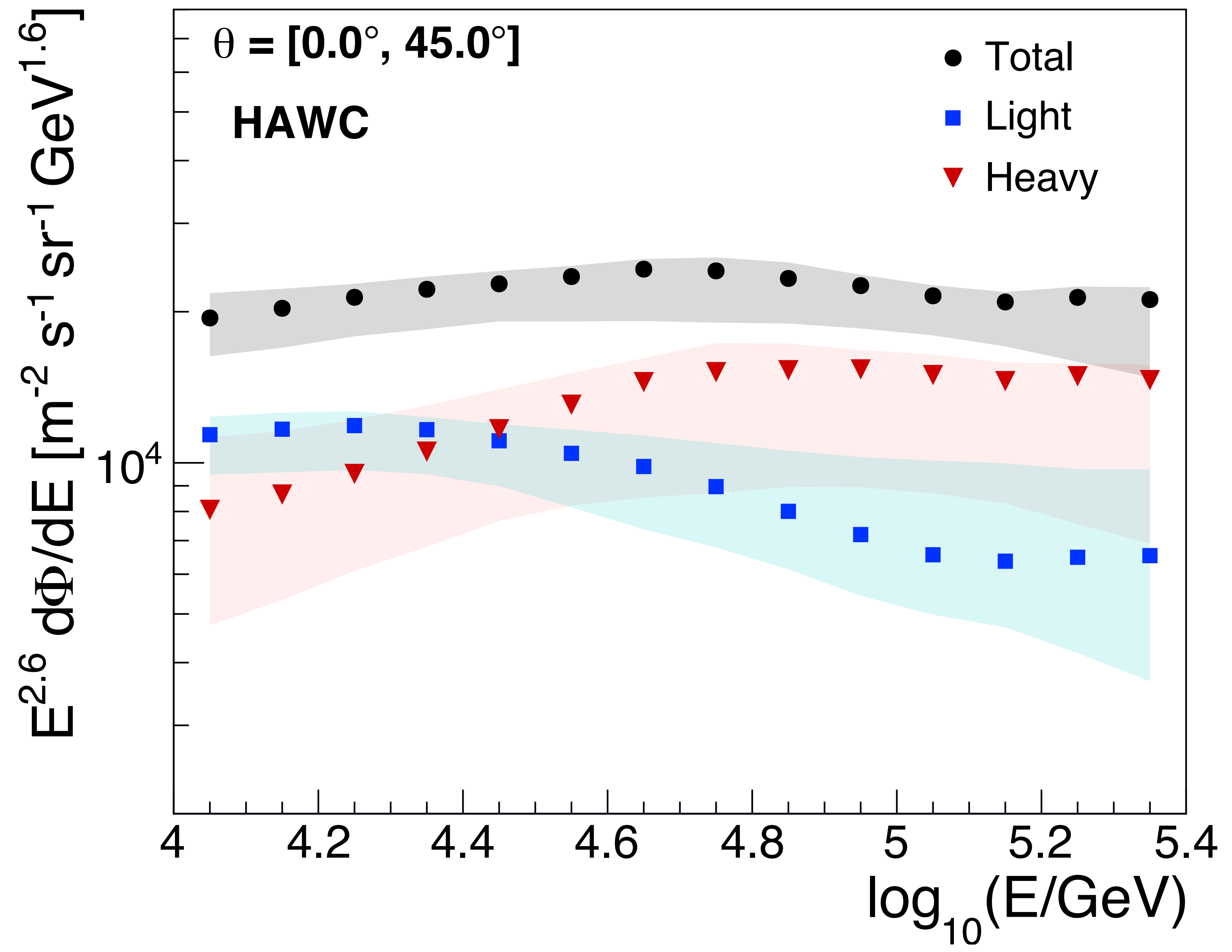
3) Results



- **Statistical errors** < 0.05%.
- **Systematic errors** < 78%
  - Statistics of the MC data set + Effective area (< 7%).
  - Uncertainties in parameters of the PMTs (< 55%).
  - Hadronic interaction model: EPOS-LHC (< 30%).
  - Unfolding procedure: bias, seed, reduced cross entropy technique (< 14%) .
  - Bias in shower age (< 20%).
  - Cosmic ray composition model: GSF, poligonato, JACEE, ATIC-02 (< 19%).

3) Results





- The elemental spectra do not follow a power-law function.
- HAWC data show fine structure ($> 5\sigma$) between 10 TeV and 251 TeV:
  - **Softenings** at $\mathcal{O}$(10 TeV) for H, He and $Z > 2$.
  - Hints for **hardenings** close to 100 TeV for H and He.
- $\Phi_H(E)/\Phi_{He}(E) < 1$ for E = [10 TeV, 100 TeV].
- Composition becomes heavier from 10 TeV to 100 TeV.
- Bump in the the all-particle spectrum at ∼ 46 TeV reported by HAWC in 2017 is due to the superposition of individual softenings in the spectra of light and heavy mass groups.

  [HAWC Collab., PRD 96 (2017) 122001]
- Knee-like feature at ∼ 32 TeV in spectra of H+He observed by HAWC in 2019 comes from individual cuts in spectra for H and He.

  [HAWC Collab., PoS(ICRC2019) 176]

3) Results

Fits

$$\Phi(E) = \Phi_0 E^{\gamma_1}\left[1+\left(\frac{E}{E_0}\right)^{\varepsilon_0}\right]^{(\gamma_2-\gamma_1)/\varepsilon_0}\left[1+\left(\frac{E}{E_1}\right)^{\varepsilon_1}\right]^{(\gamma_3-\gamma_2)/\varepsilon_1}$$

	E_0(TeV)	E_1(TeV)	γ_1	γ_2
H	14.1 +2.2/-0.4	103 +1/-4	-2.6 +0.2/-0.5	-3.1 ± 0.3
He	25.3 +1.1/-0.8	152 +11/-9	-2.2 +0.1/-0.3	-3.1 +0.4/-0.1
Z > 2	51 ± 1	__	-2.1 ± 0.3	-2.6 +0.04/-0.2

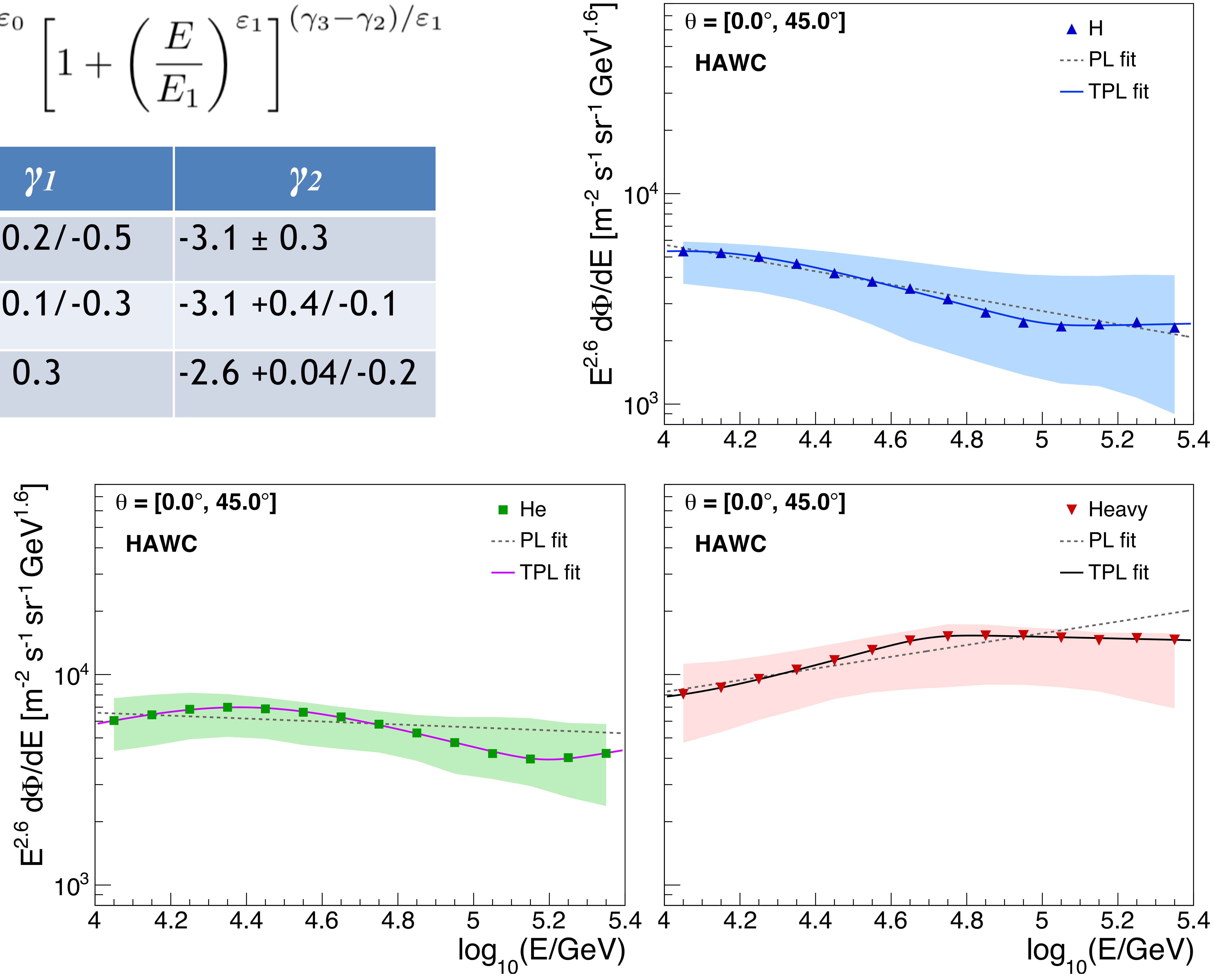
In the table, total errors are shown

E_0: Energy 1st break.

E_1: Energy 2nd break.

γ_1: spectral index before E_0.

γ_2: spectral index after E_0.



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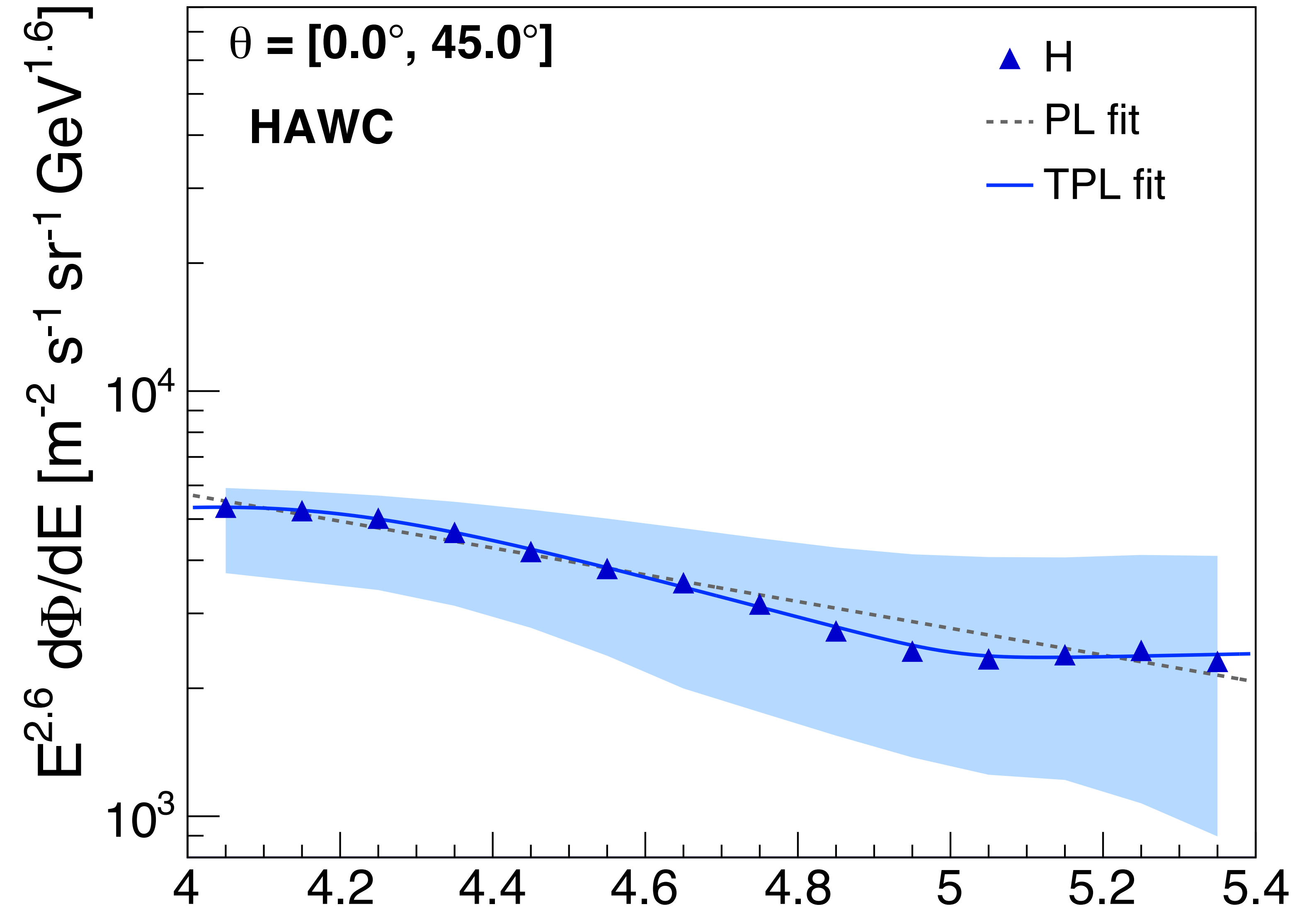
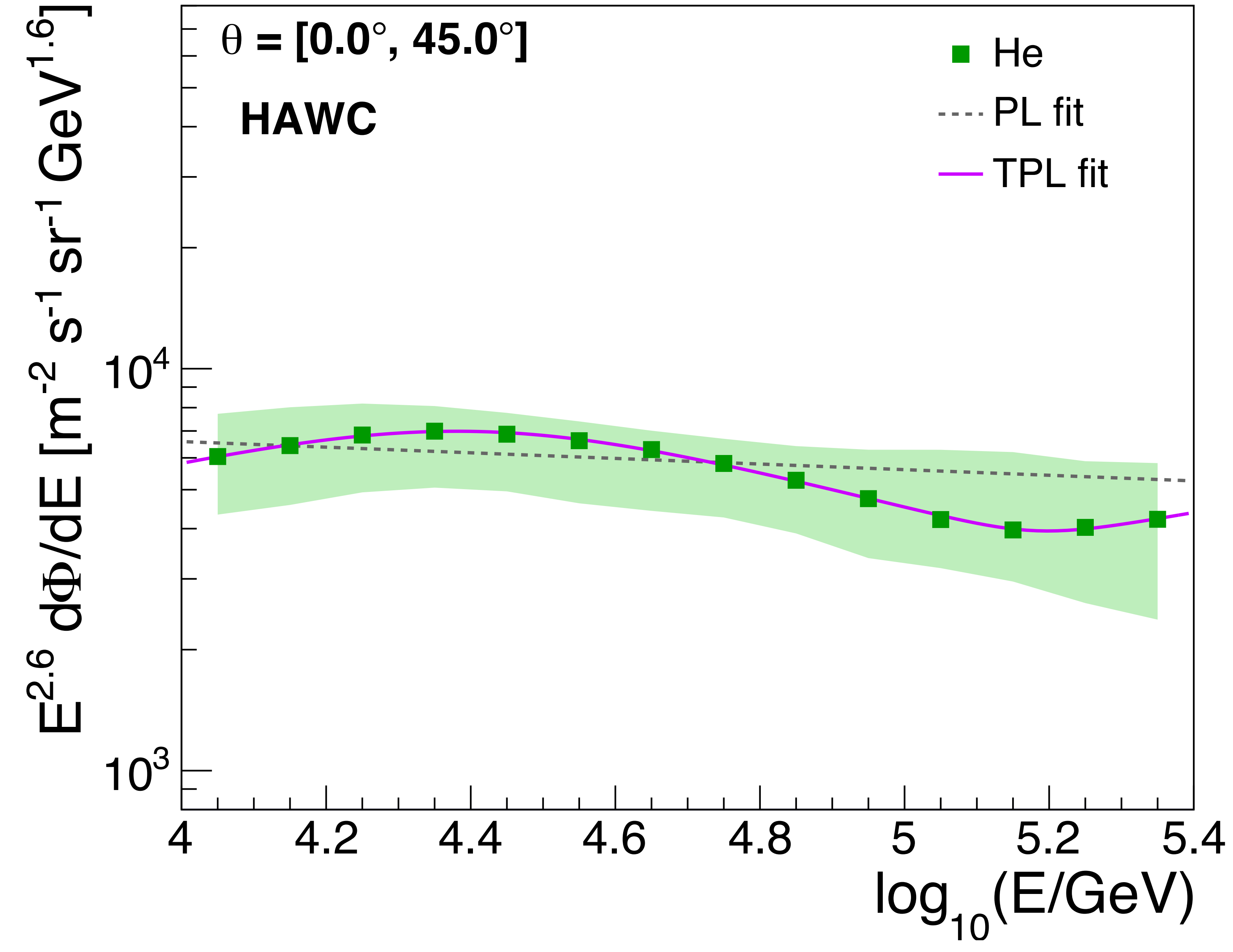
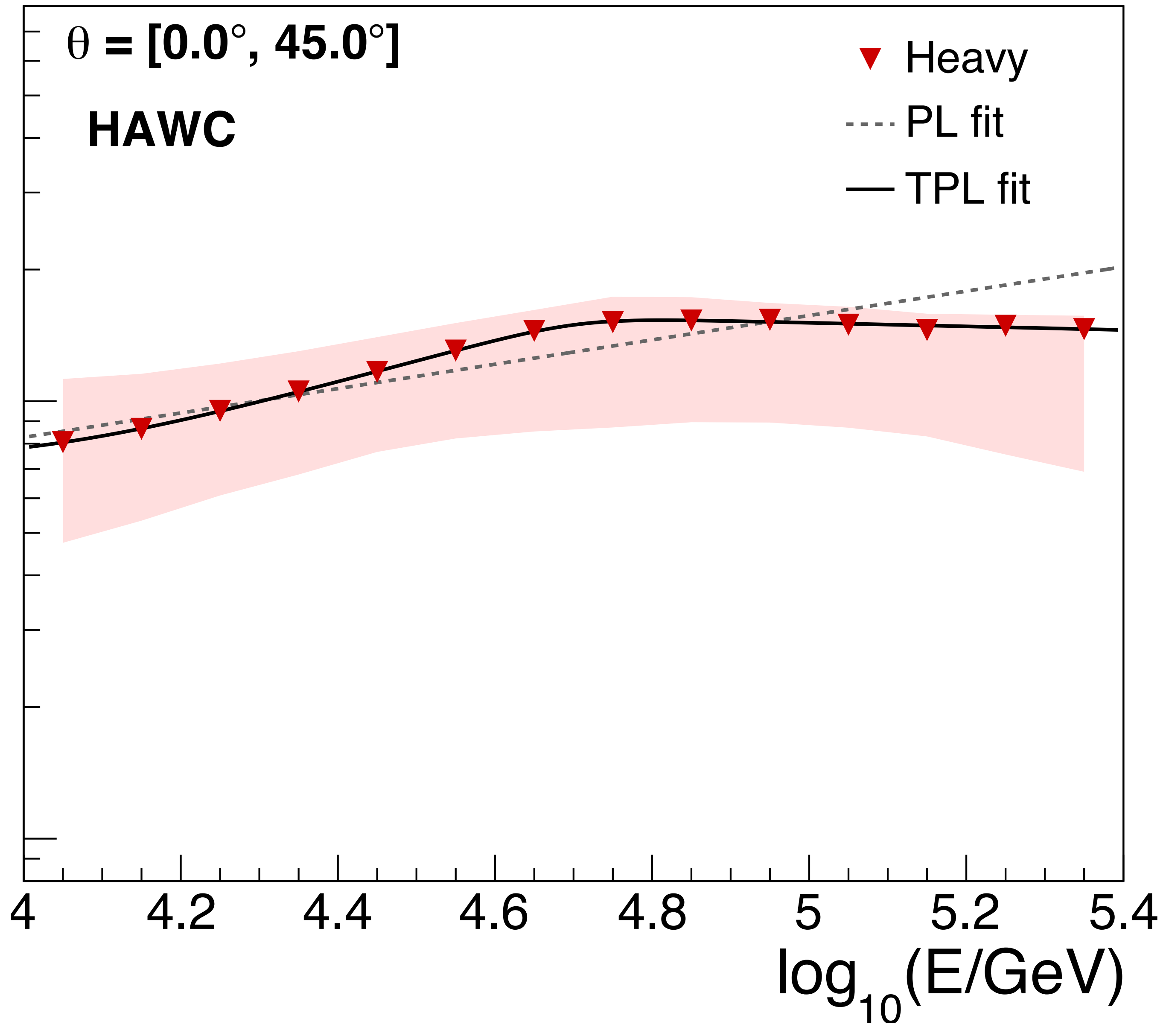


Position of the softenings seems to increase with the primary mass.

$$E_{0,\,He}/E_{0,\,H} = 1.8^{+0.3}_{-0.1}$$





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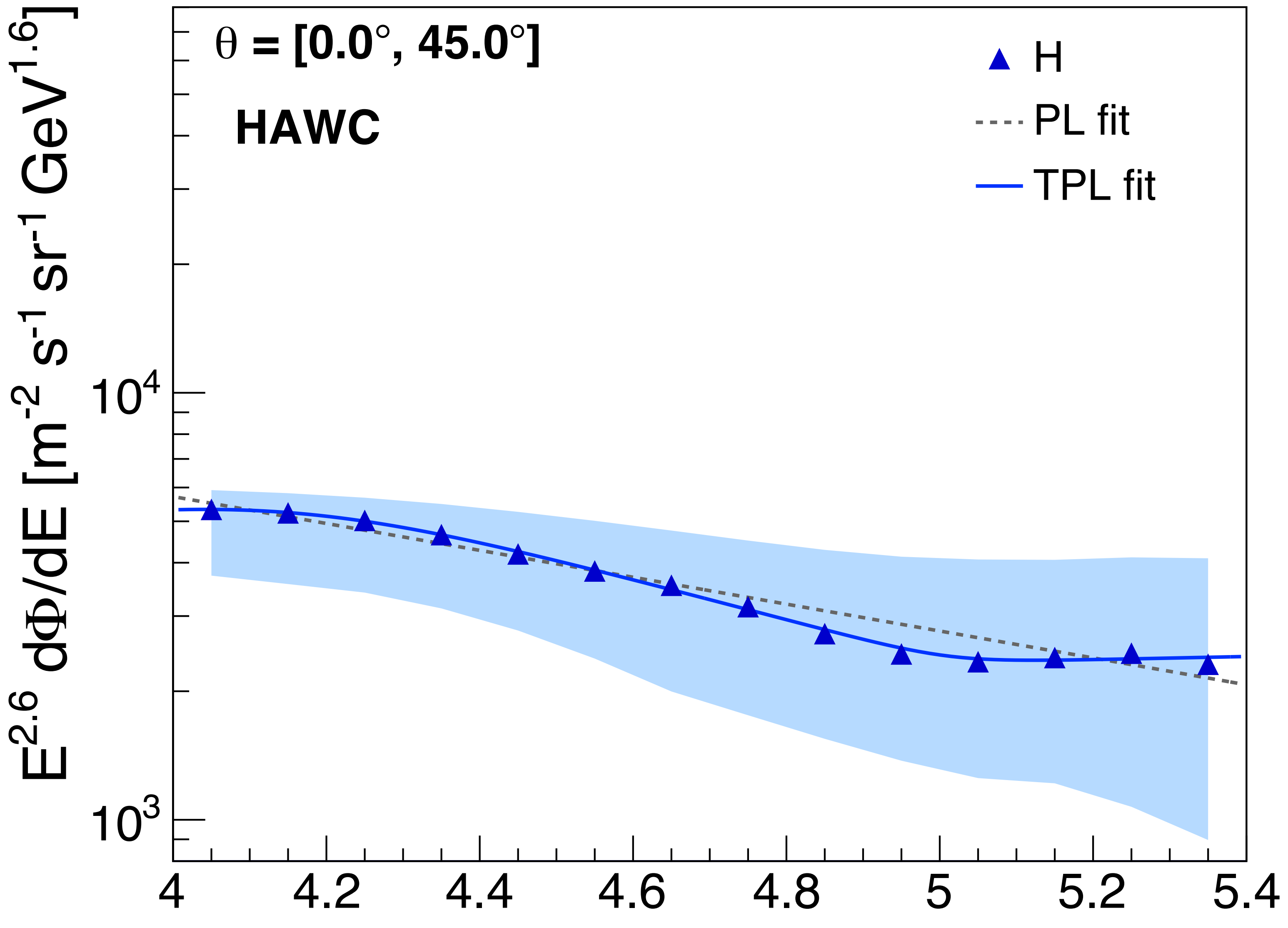
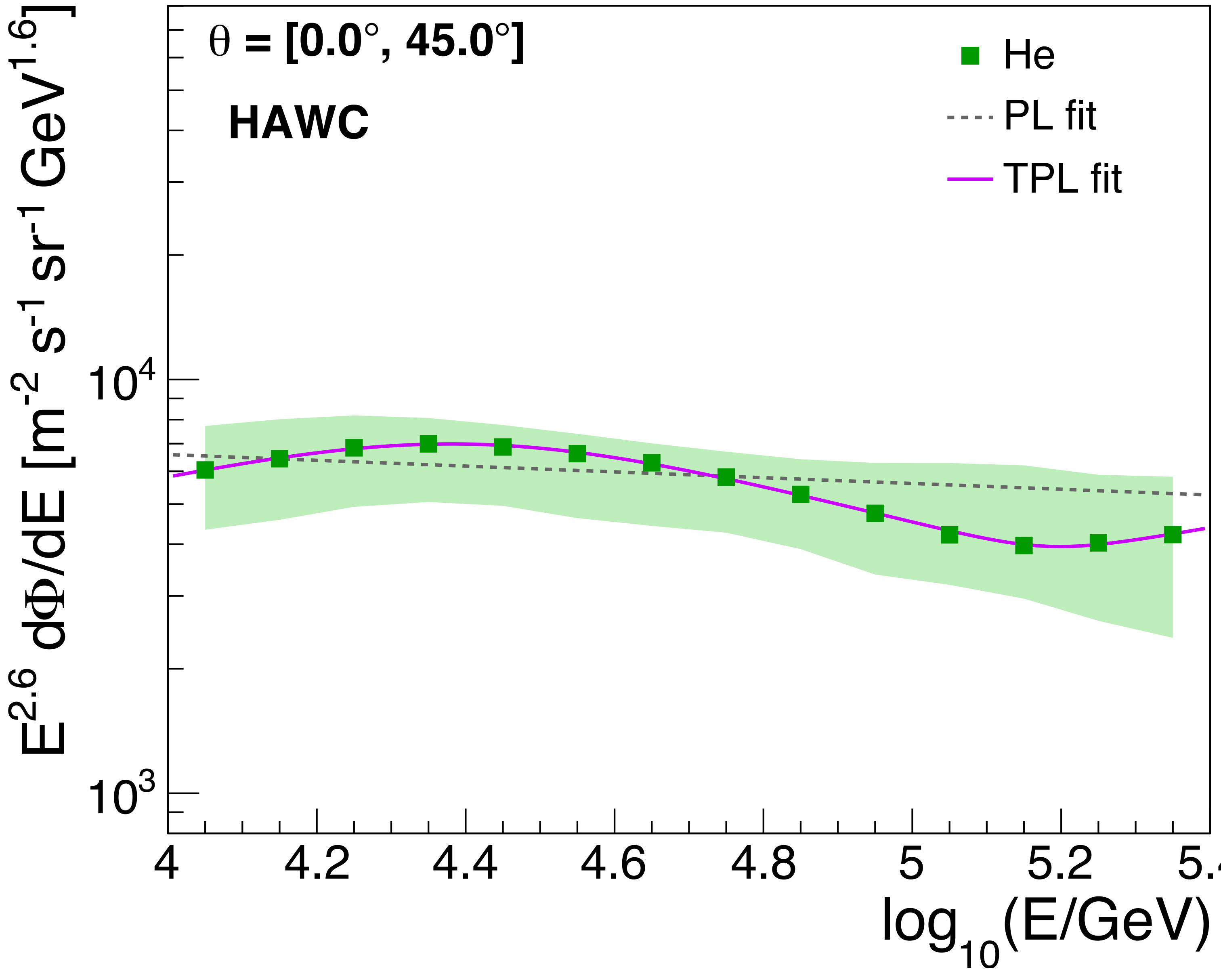
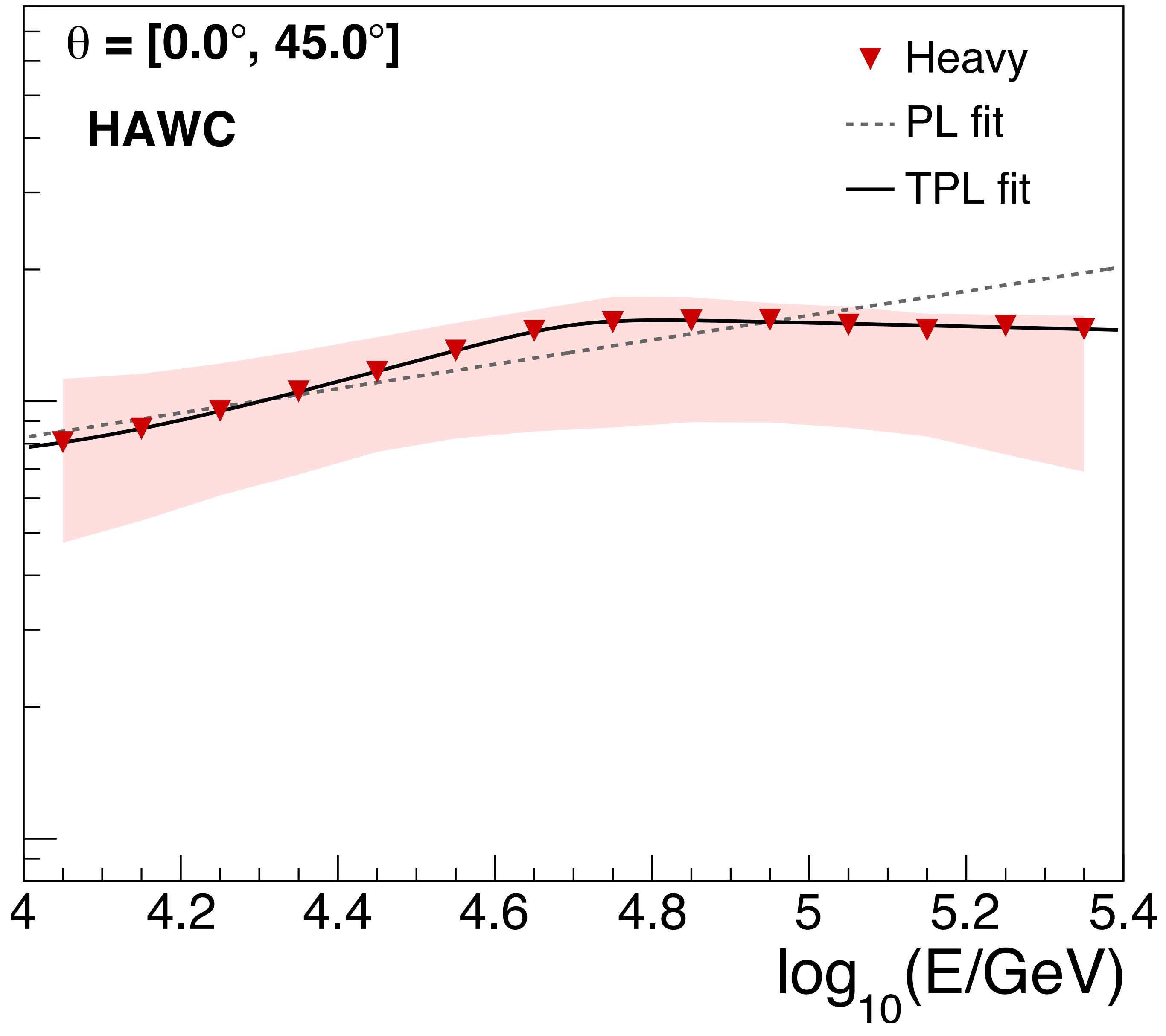


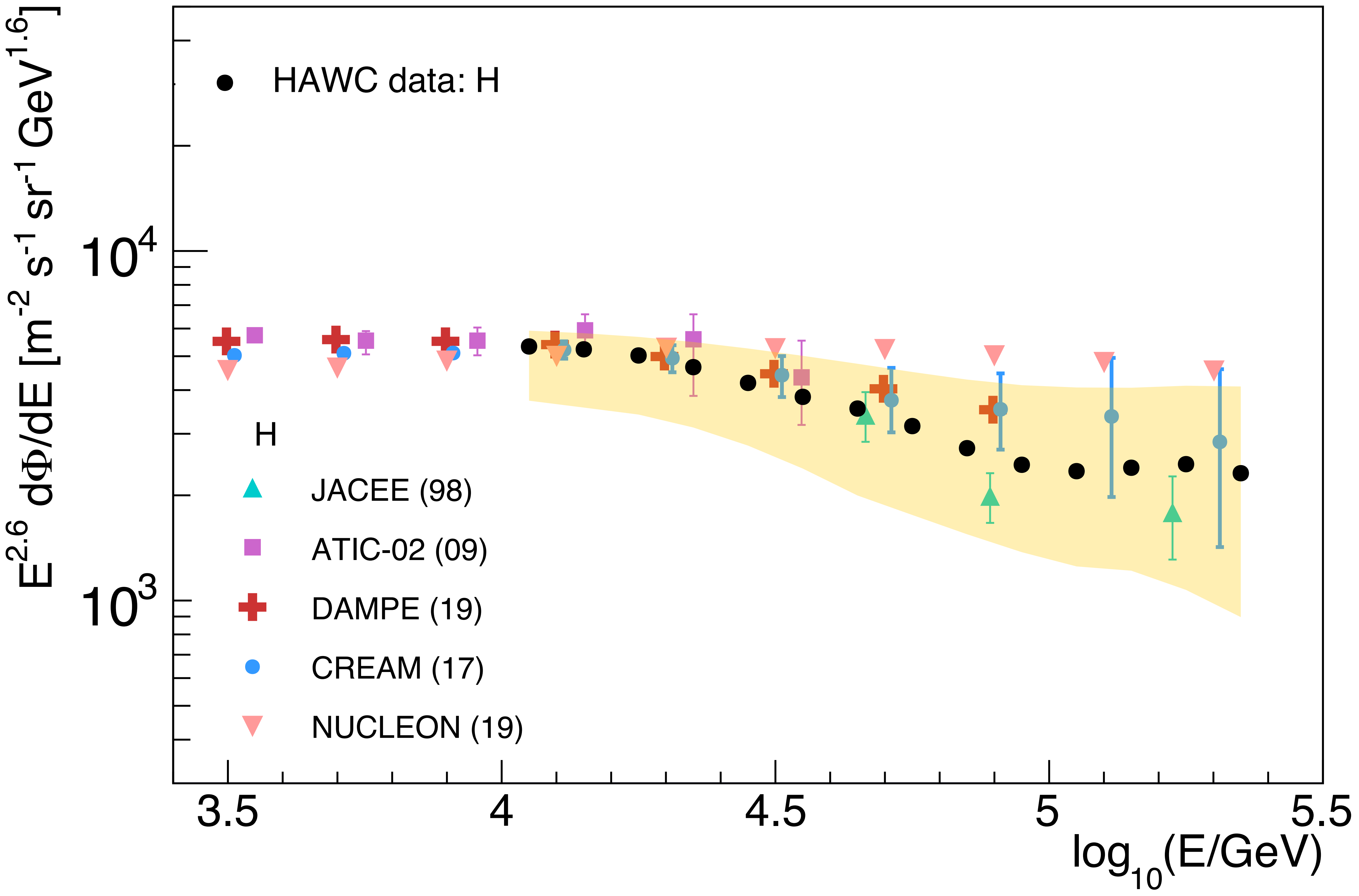
- Spectra for He and Heavy nuclei seem to be harder than that for protons, before E_0.
- Spectra for H and He seem to have a similar γ_2.
- Spectral index just above E_0 for spectrum of heavy nuclei seems to be harder than those for H and He primaries.

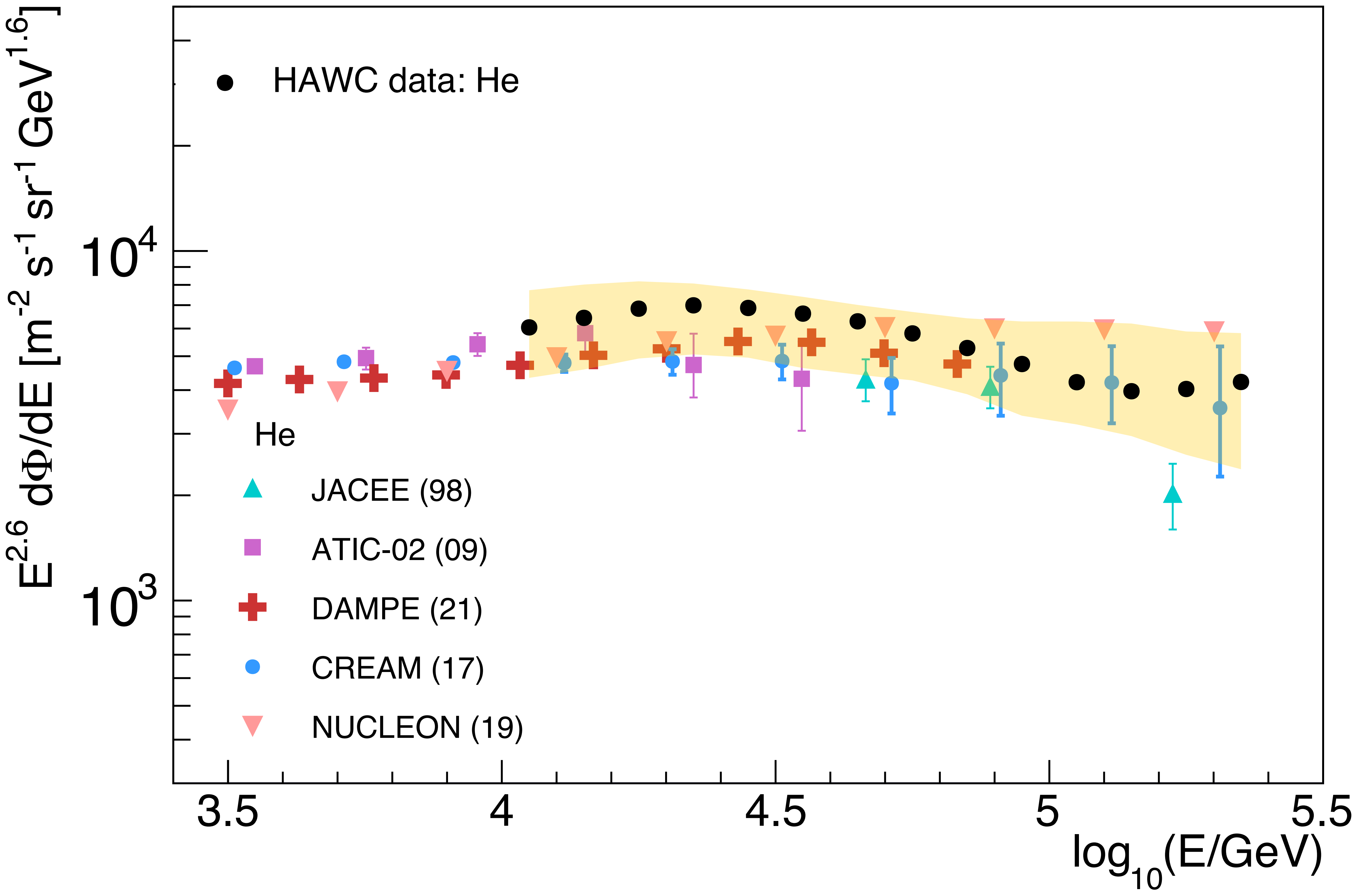




3) Results

H and He spectra: Comparison with other experiments

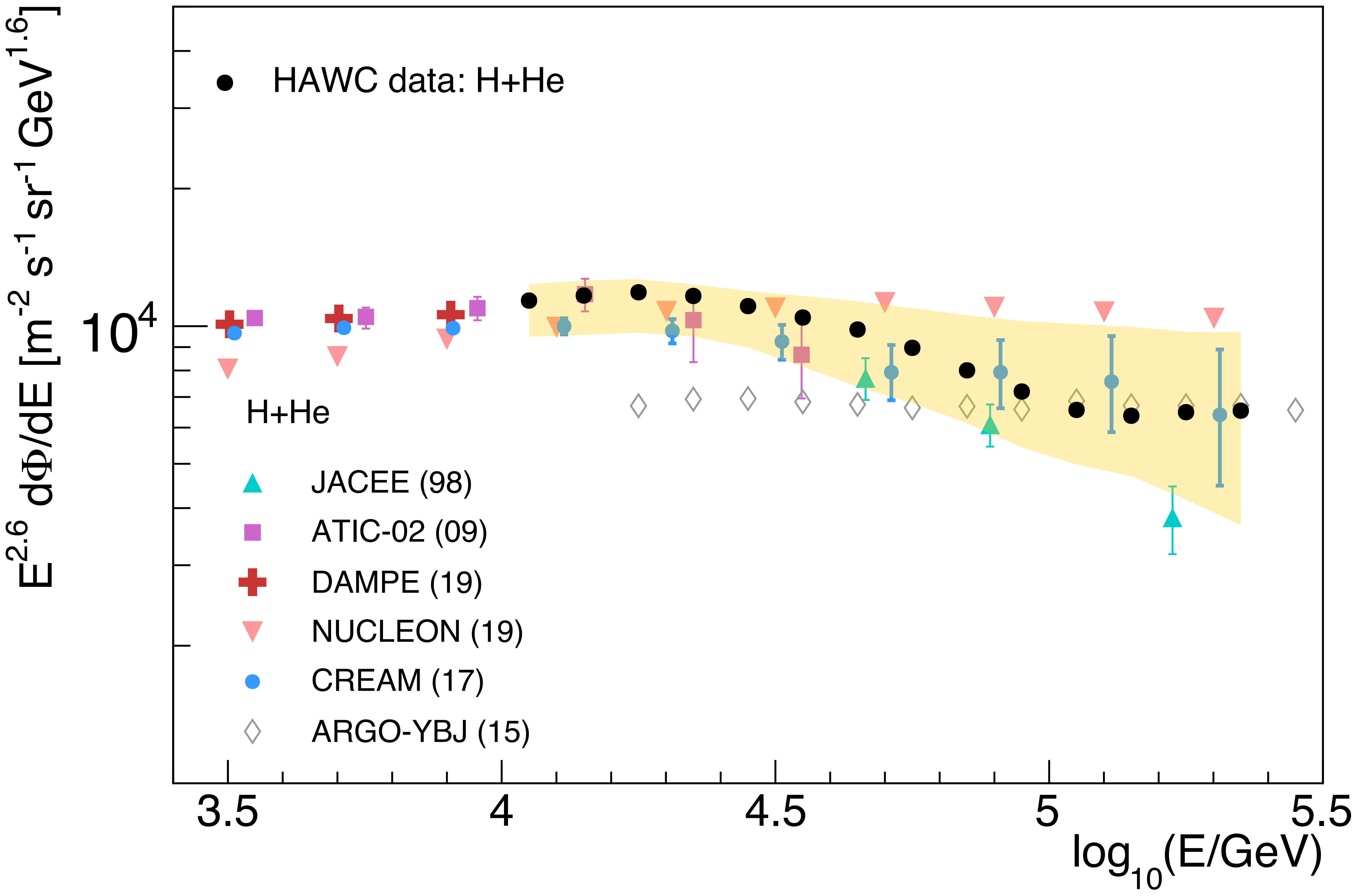


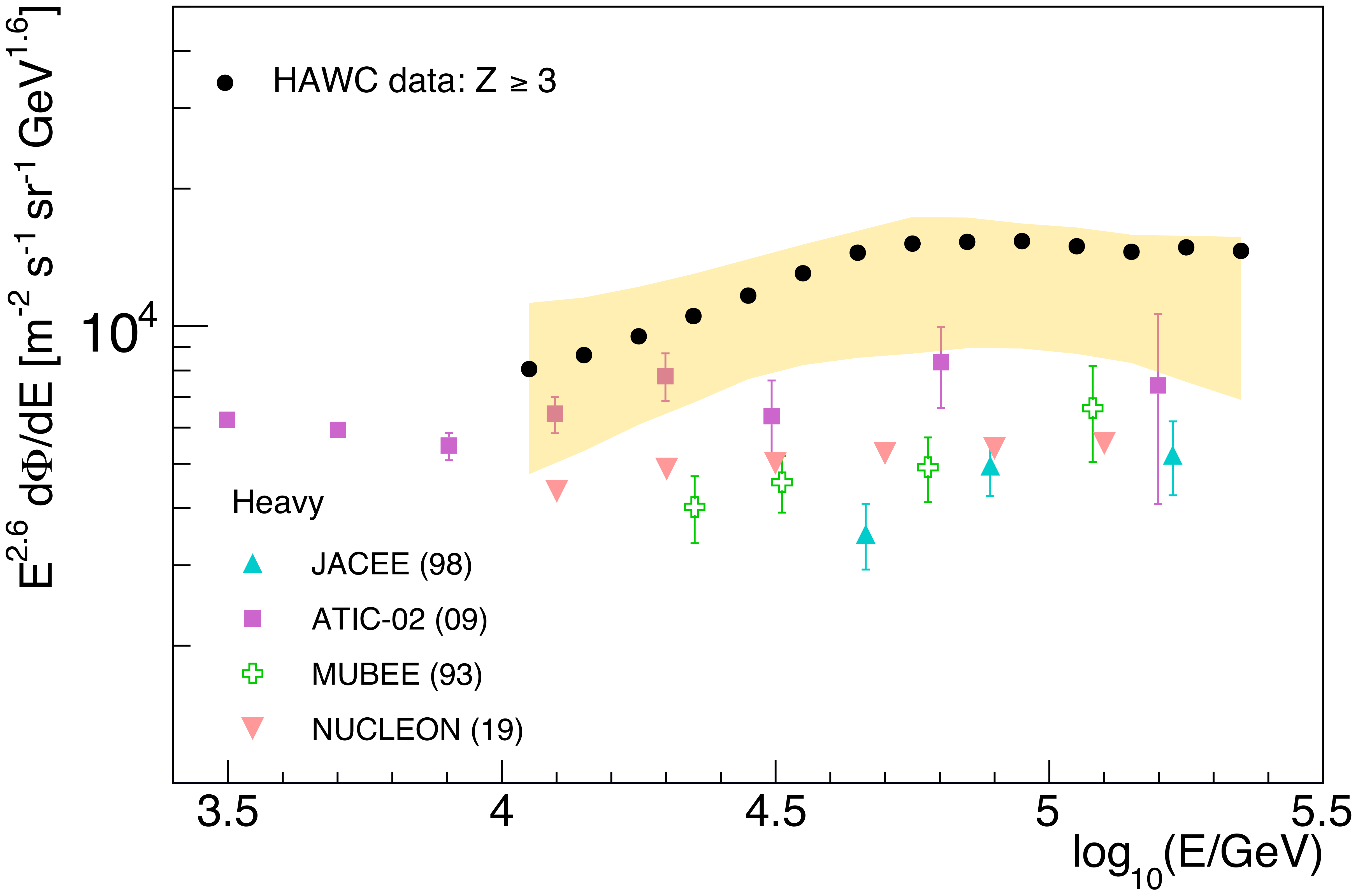


- Good agreement of **HAWC** with direct data from **DAMPE**, **ATIC-02** and **CREAM I-III** within systematic errors.
- **HAWC** confirms softenings at tens of TeV observed by **DAMPE**, first hinted by **ATIC-02**, **CREAM** and **NUCLEON**.

3) Results

Light (H + He) and Heavy (Z > 2) spectra: Comparison with other experiments





- Good agreement of **HAWC** with **ATIC-02, CREAM** and **JACEE** within systematic errors.
- **ARGO-YBJ** disagrees with **HAWC** data for E < 50 TeV.

- Agreement of **HAWC** with **ATIC-02** within systematic errors.
- **HAWC** data is above **NUCLEON**, **MUBEE** and **JACEE** observations.

4) Conclusions

- We have estimated the elemental energy spectra for H, He and heavy nuclei (Z >2) with HAWC for E = [10, 251] TeV.

- HAWC results reveal individual softenings at tens of TeV, whose positions seem to move to higher energies for heavy primaries. ($E_{0,\,He} / E_{0,\,H} = 1.8^{+0.3}_{-0.1}$, agreement with *Z*-dependent scenario).

- HAWC confirms the TeV knee-like features observed recently by DAMPE (2019&2021) for the spectra of H and He.

  —> First time that high-statistics data on cosmic ray composition from direct and EAS experiments are compared.

  —> There is potential in observatories like HAWC to perform TeV composition research on cosmic rays.

- Cosmic ray composition becomes heavier at high energies within the range 10 - 100 TeV.

- HAWC hints to possible hardenings close to 100 TeV in the spectra of H and He.

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Thank you