The energy spectrum of the H+He mass group of cosmic rays in the TeV region measured with HAWC

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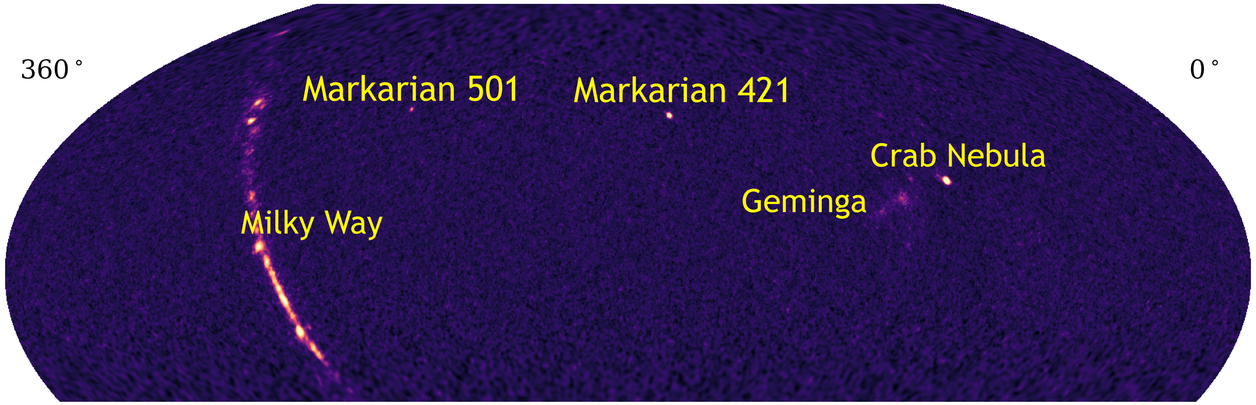
1) The HAWC γ-ray observatory

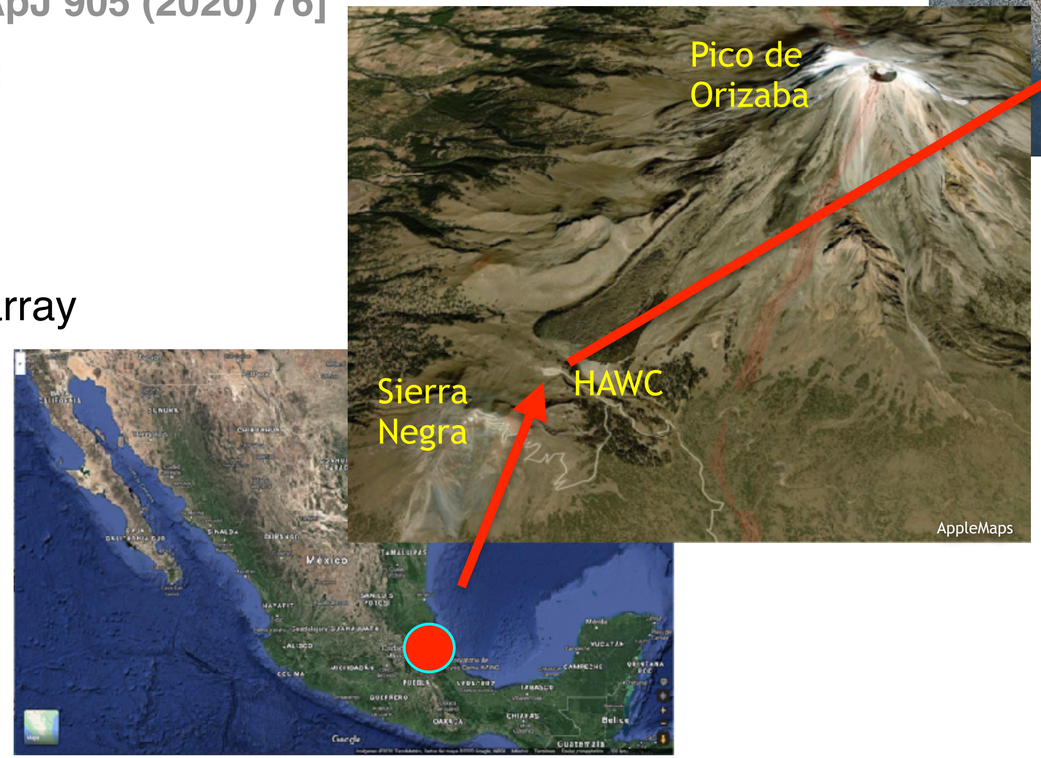


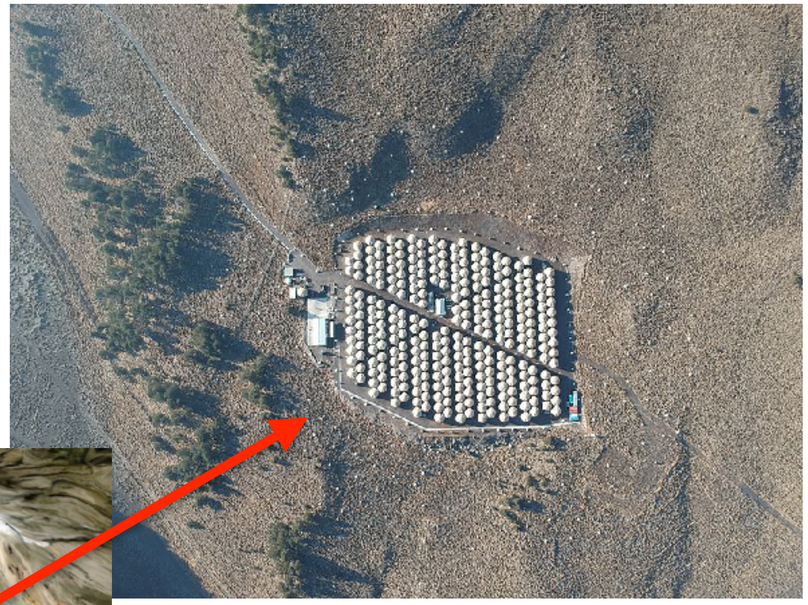
[HAWC Collab., ApJ 905 (2020) 76]

γ- and cosmic-ray detector:

E_γ = 100 GeV - 100 TeV
E_{cr} = 100 GeV - 1 PeV

- Air-shower observatory
- Ground-based Cherenkov array



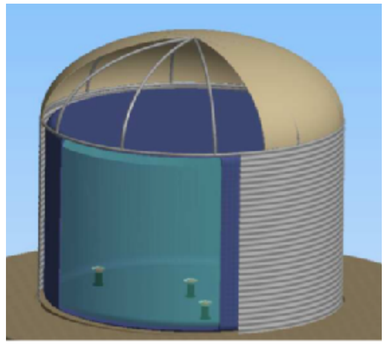


Location:

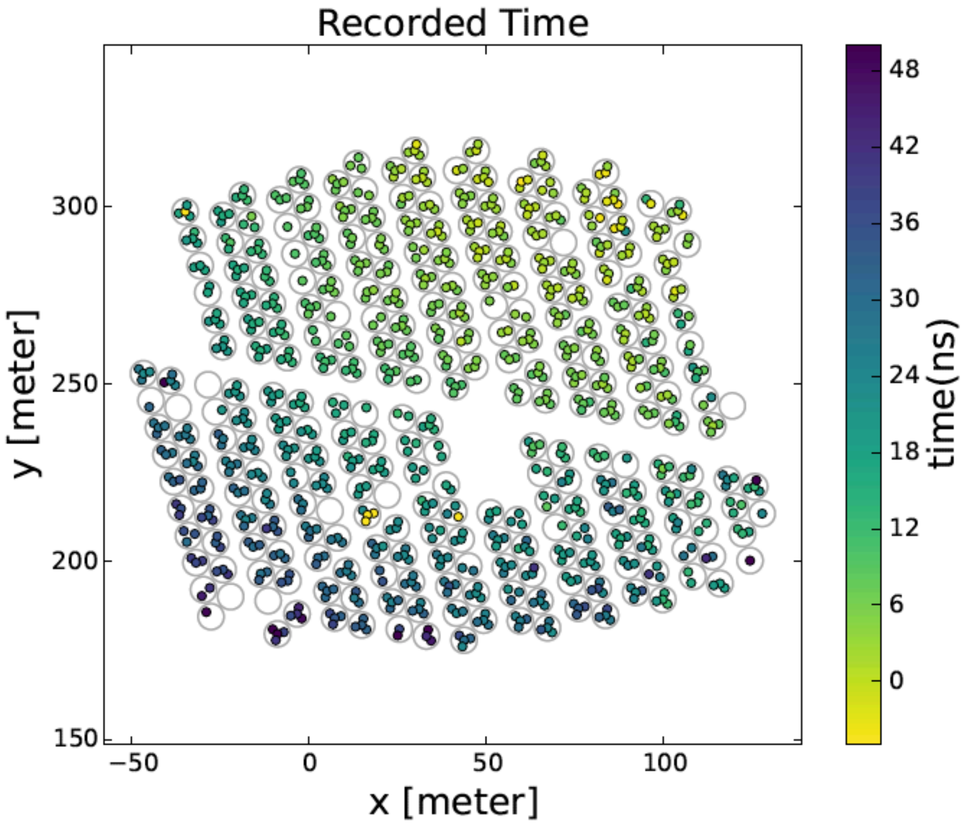
- Sierra Negra Volcano, Puebla, Mexico
- 19° N and 97° W
- 4100 m a.s.l. (640 g/cm²)

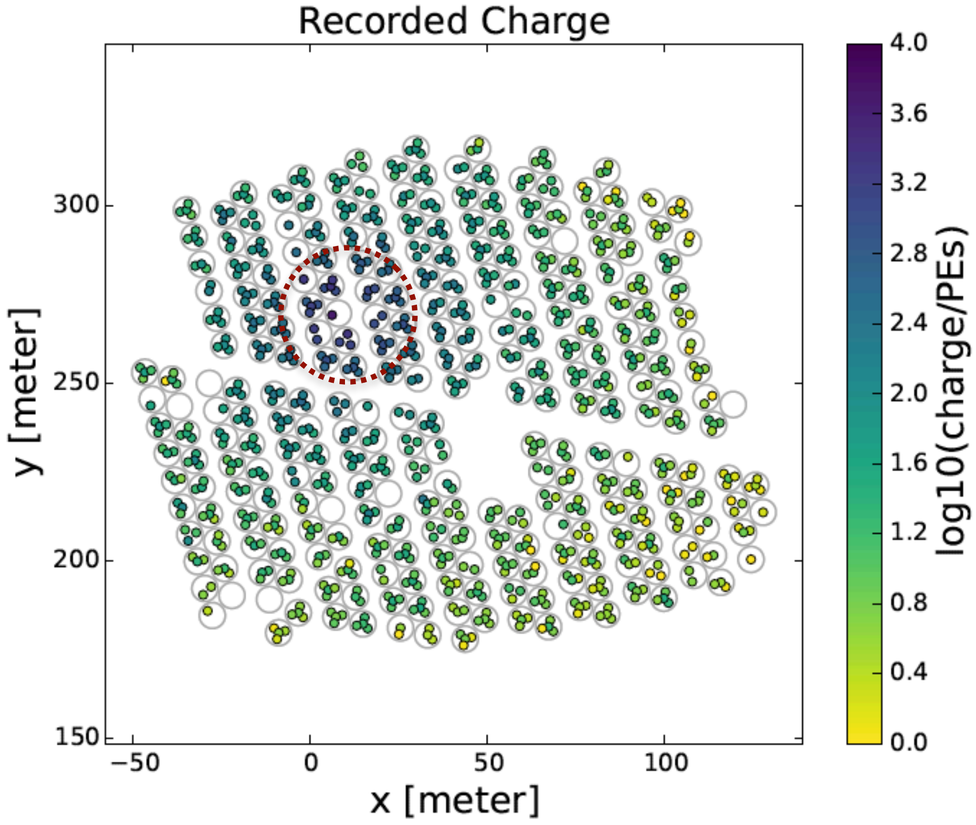
Set-up of central detector:

- 22 000 m² surface
- 300 densely packed water Cherenkov detectors (200,000 ℓ of water + 4 PMTs)



1) The HAWC γ-ray observatory

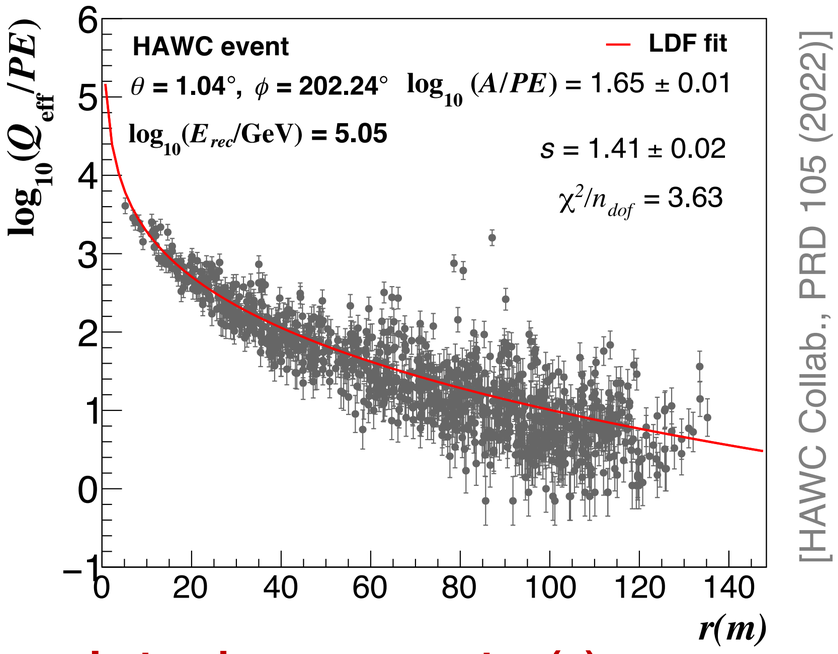




- From hit times at PMTs, deposited charged, number of PMT's with signal:
  - Core location, (X_c, Y_c)
  - Arrival direction, θ
  - Fraction of hit PMT's, f_{hit}
  - Lateral charge profile, Qeff(r)
  - ...

[HAWC Coll., ApJ 843 (2017) 39]

2) EAS age and energy estimations



[HAWC Collab., PRD 105 (2022)]

Lateral age parameter (*s*)

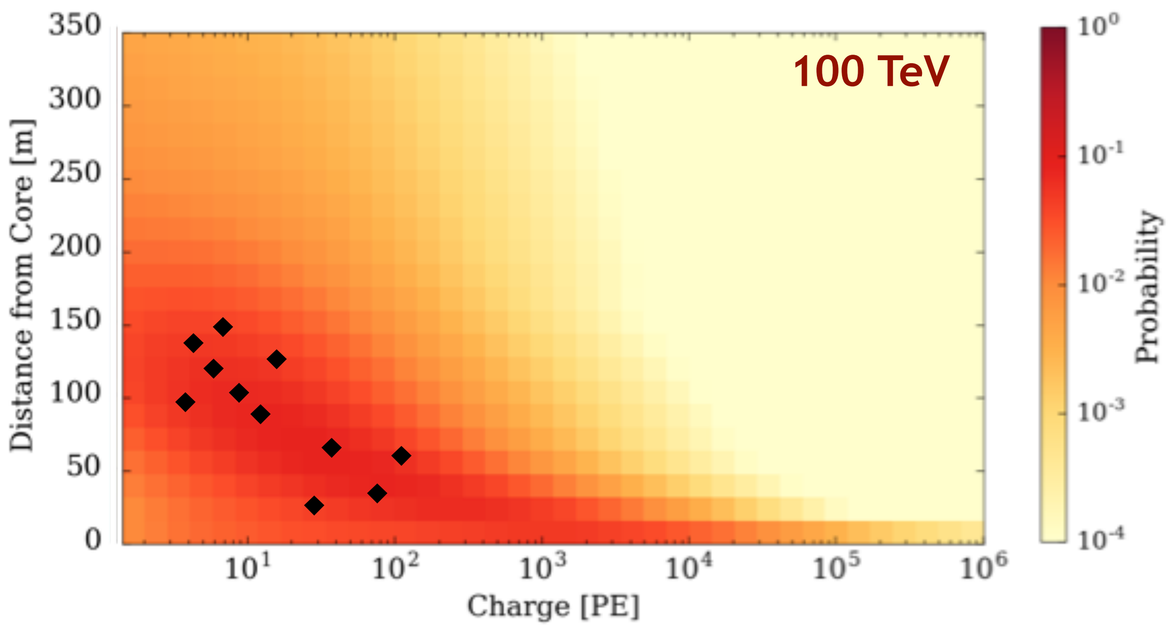
- Obtained event-by-event
- Fit of Qeff(r) with a NKG-like function:

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

with r_0 = 124.21 m.

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

[HAWC Collab., APJ 881 (2017); J.A. Morales Soto et al., PoS(ICRC2019 359 (2019)]



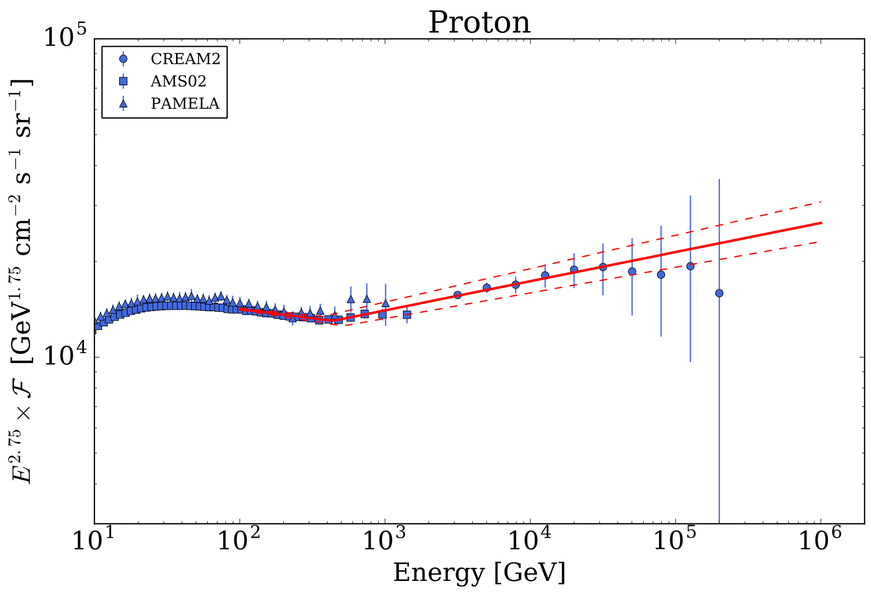
EAS primary energy:

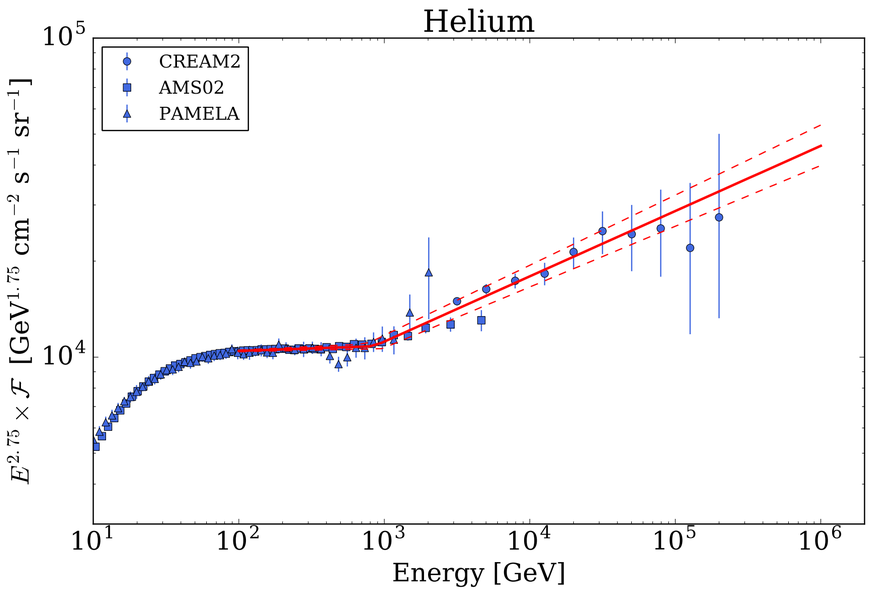
- Produce LDF tables of MC protons**:**
  Binning in r, Qeff, θ and E
- Maximum likelihood to find table that best fits the Qeff(r) distribution of the event, from which **E** is obtained.

[HAWC Collab., PRD 96 (2017); Z. Hampel-Arias' PhD thesis, 2017]

3) MC simulations

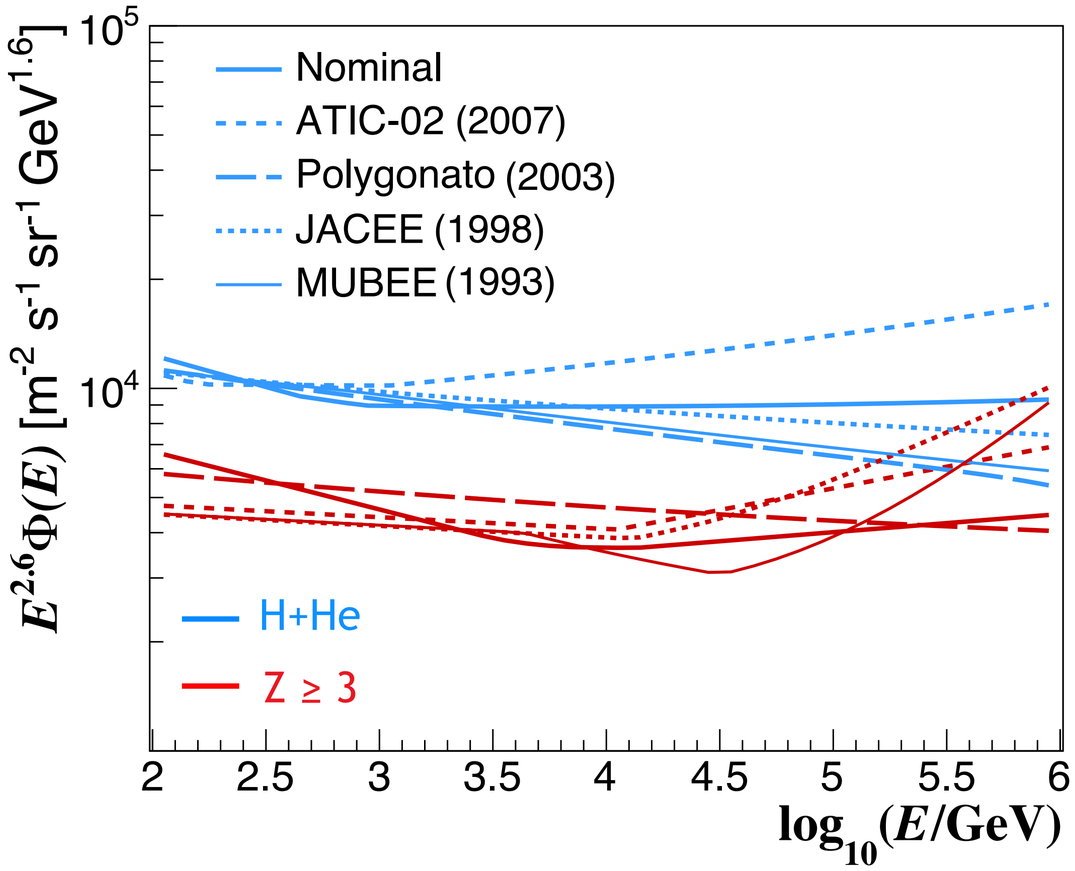
- CORSIKA v 7.40 for EAS simulation.
- **Fluka/QGSJET-II-04** as low(E_{lab} < 80 GeV)/high-energy interaction models for the main analysis.
- Fluka/EPOS-LHC simulations to study effect of hadronic interaction model.
- Full simulation of detector response with GEANT 4.
- $\theta < 70^o$; $A_{thrown} \sim 3 \times 10^6$ m^2
- Primary nuclei:
  - H, He, C, O, Ne, Mg, Si, Fe
  - E = 5 GeV – 3 PeV
  - E^{-2} spectra weighted to follow broken power-laws derived from fits to **AMS02** (2015), **CREAM-II** (2009 & 2011) and **PAMELA** (2011) data. **[HAWC Collab., PRD 96 (2017)]**

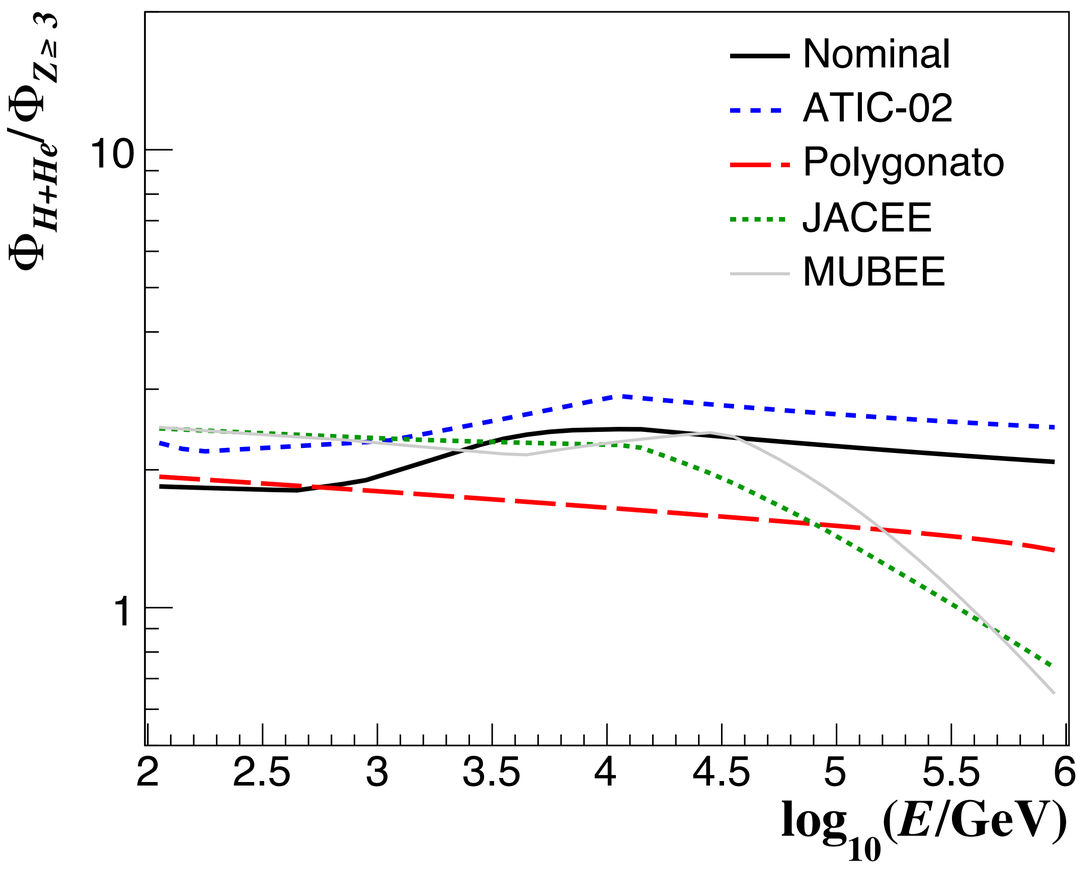




3) MC simulations

Composition models



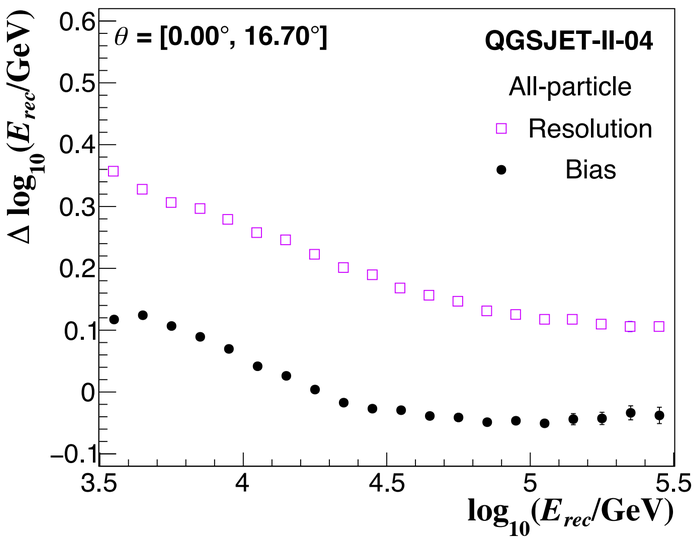


- But also use different composition models for studies of systematics

4) Data selection

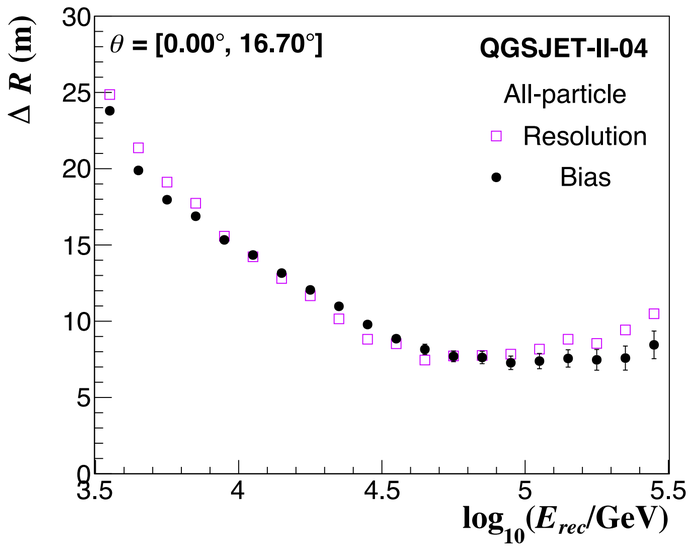
Selection cuts

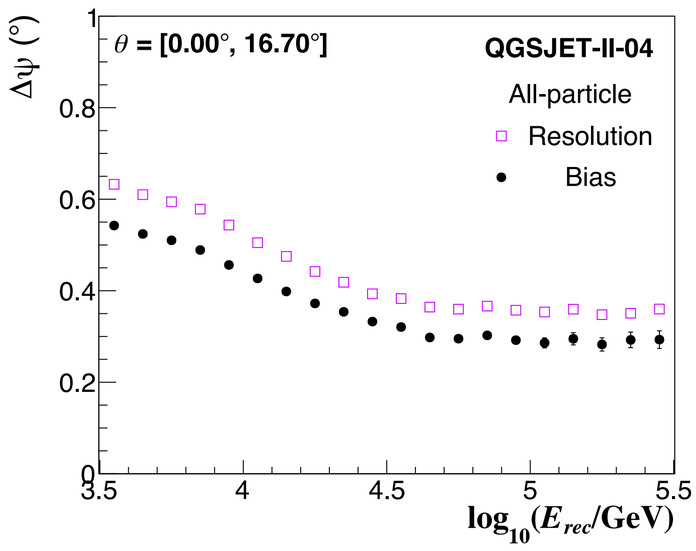
- Important to reduce systematic effects on results:
  - $\theta < 16.7^\circ$
  - Successful core and arrival direction reconstruction
  - Activate at least 40 PMTs within 40 m from core
  - Fraction hit (# of hit PMT's/# available channels) ≥ 0.2
  - $\log_{10}(E/\mathrm{GeV}) = [\,3.5, 5.5]$



- Resolution:

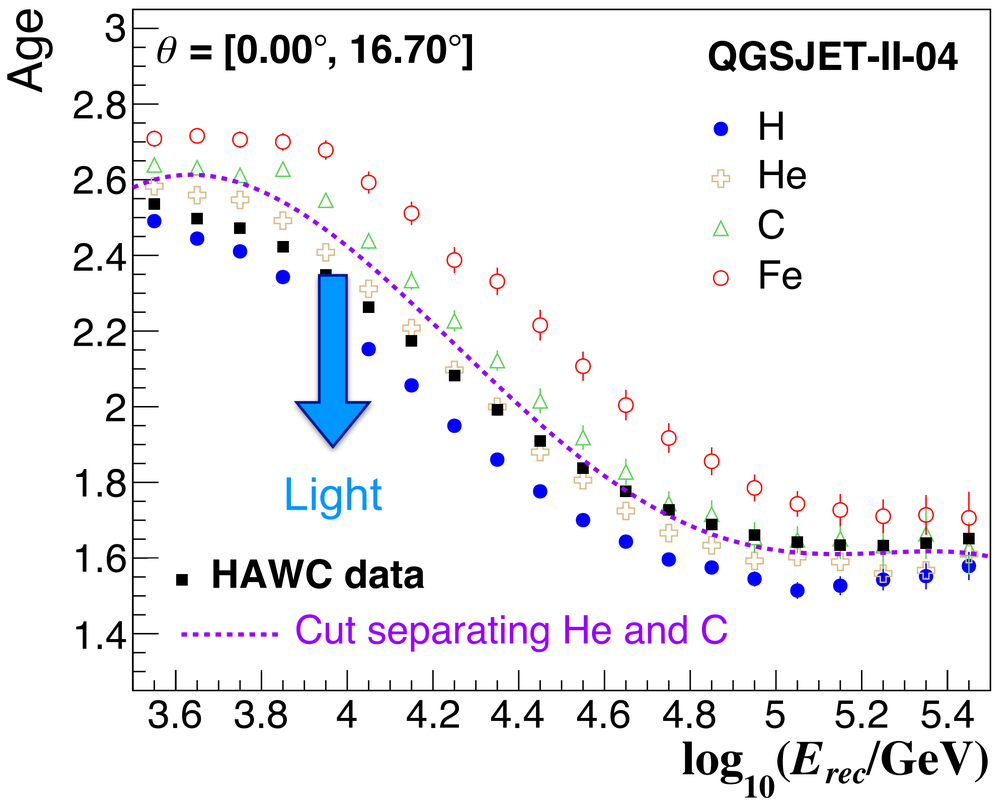
E ≥ 10 TeV:	
Δcore	≤ 15 m
$\lvert\Delta\log_{10}(E/\mathrm{GeV})\rvert$	≤ 0.26
$\Delta\Psi$	≤ 0.55°

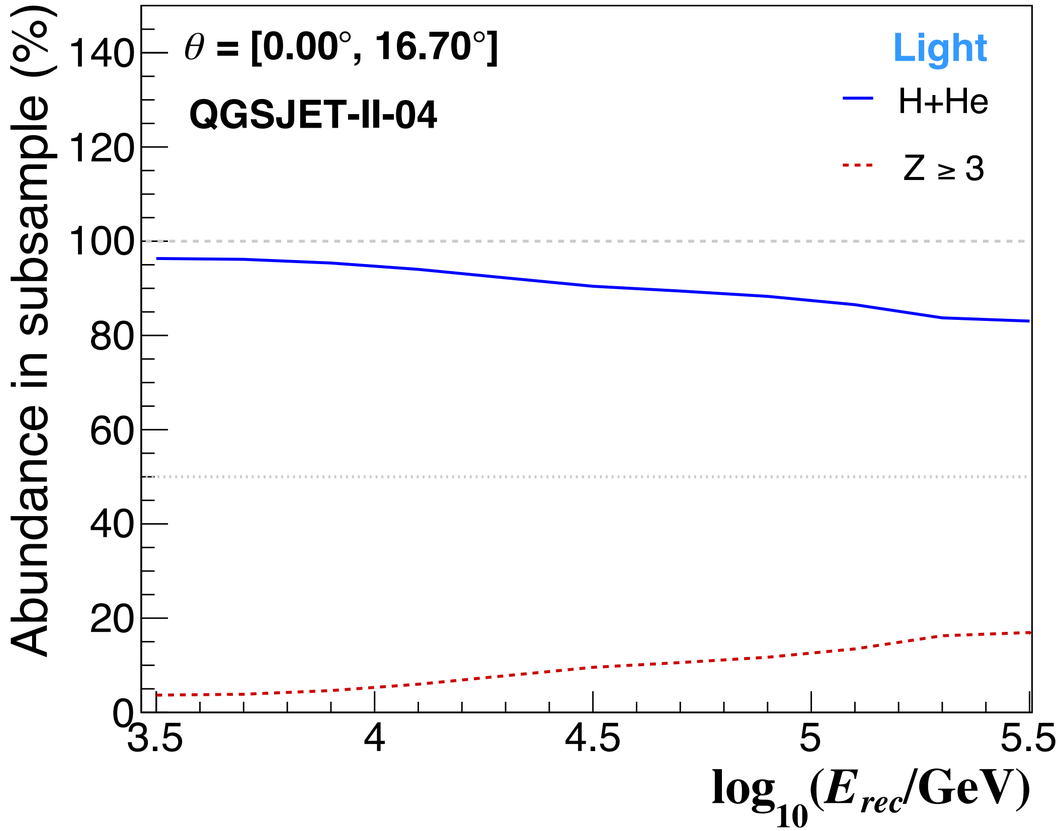




5) Analysis

Select a sample enriched with light nuclei



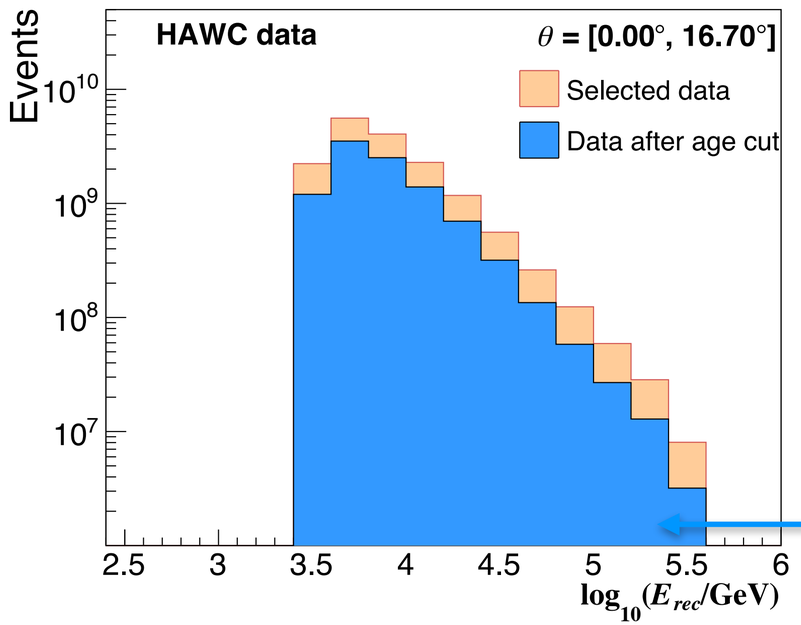


- Age parameter is sensitive to composition
- Select a subsample using a cut on the age
  - Subsample must have a large relative abundance of H and He.

- Content of H + He in subsample
  - More than 82% of H and He in subsample

5) Analysis

Build raw energy spectrum of subsample: $N_{raw}(E_{rec})$



- Experimental data used for analysis:

  HAWC-300

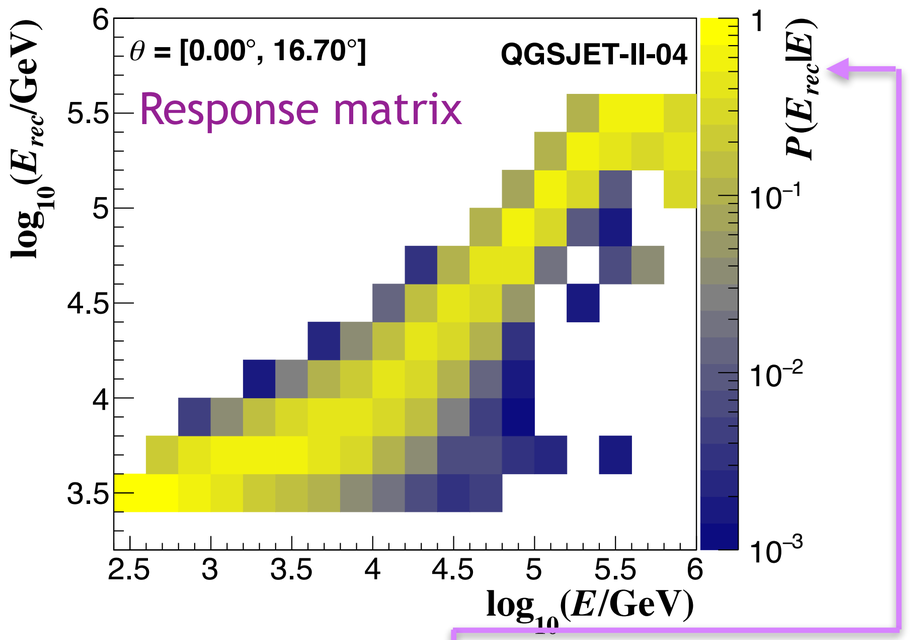
  Δt_{eff} = 3.74 years (94% livetime)

  (June/11/15-June/03/19)

  $\Delta\Omega$ = 0.27 sr

Total events	: 2.9 x 10^{12} EAS
+ selection cuts:	1.6 x 10^{10} EAS
+ age cut:	9.9 x 10^{9} EAS

Correct $N_{raw}(E_{rec})$ for migration effects



$$N^{Raw}(E_{rec,\,j}) = \Sigma_i\, P(E_{rec,\,j} \mid E_i)\, N^{Unf}(E_i)$$

- Solve for $N^{Unf}(E_i)$ using Bayesian unfolding

  [G. D' Agostini, DESY 94-099]

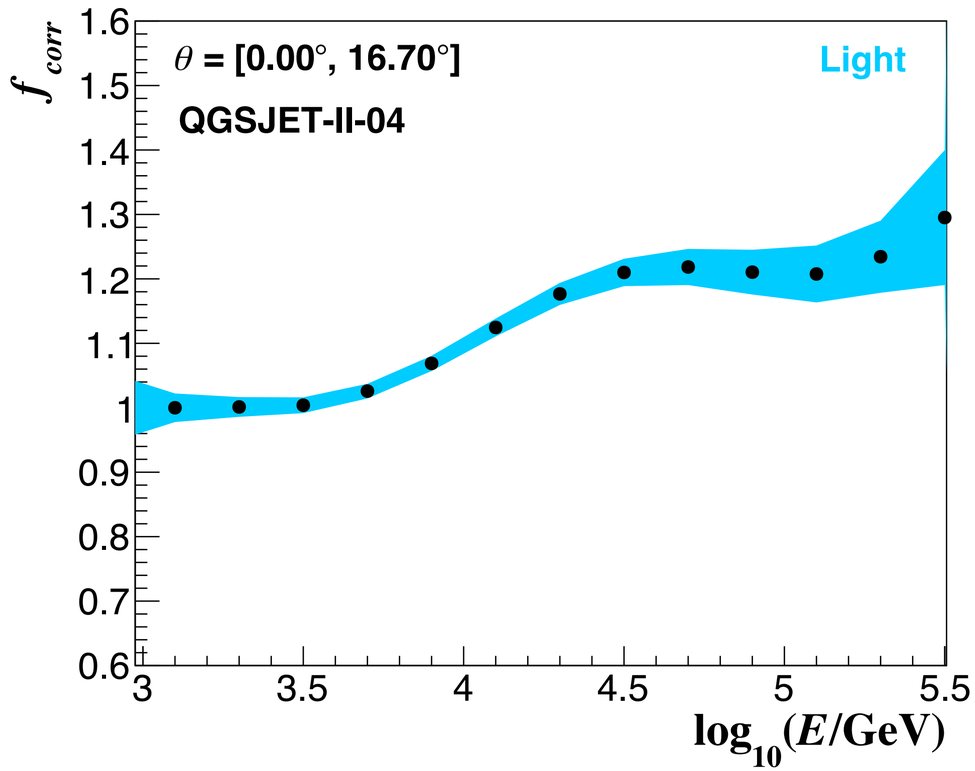
- Stopping criterium: Minimum of weighted mean squared error

  [G. Cowan, Stat. Data analysis, Oxford Press. 1998]

$$WMSE = \frac{1}{N_{points}} \sum_{i}^{N_{points}} \frac{stat_i^2 + sys_i^2}{n_i}$$

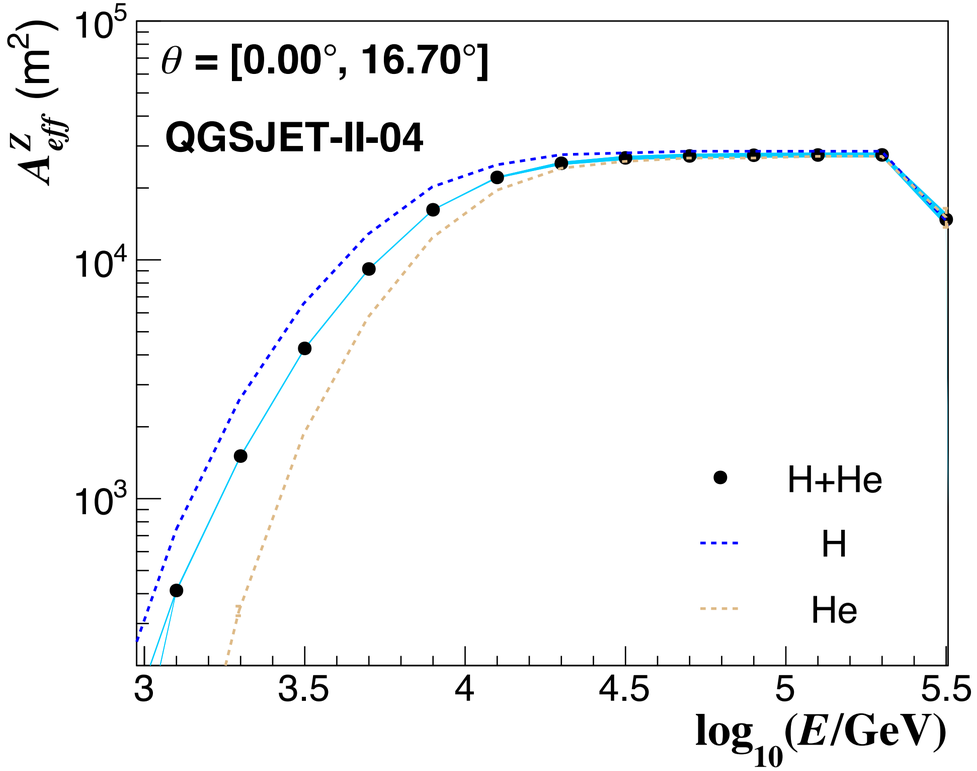
5) Analysis

Obtain effective area from MC simulations



- Correction factor due to contamination of heavy events

$$f_{corr} = (N_{light} / N_{light}^{H+He})$$

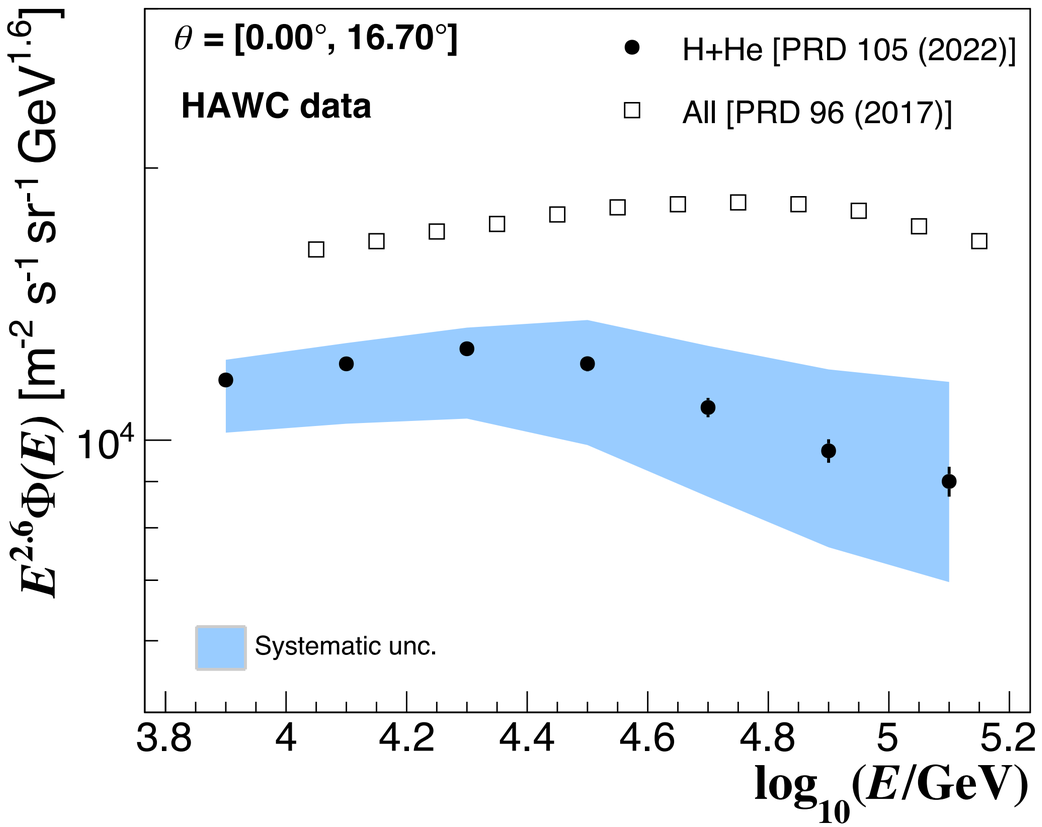


- Effective area of H+He in subsample

$$A_{eff}^{H+He}(E_i) = A_{thrown}\, \varepsilon^{H+He}(E_i)\, \frac{\cos\theta_{max} + \cos\theta_{min}}{2}$$

6) H + He energy spectrum

Get energy spectrum from N^{Unf} and effective area



- Energy spectrum was calculated as:

$$\Phi = N^{Unf}(E)/[\Delta E^{T} \cdot \Delta t_{eff} \cdot \Delta\Omega \cdot f_{corr}(E) \cdot A_{eff}^{H+He}(E)]$$

Statistical and systematic uncertainties

H+He

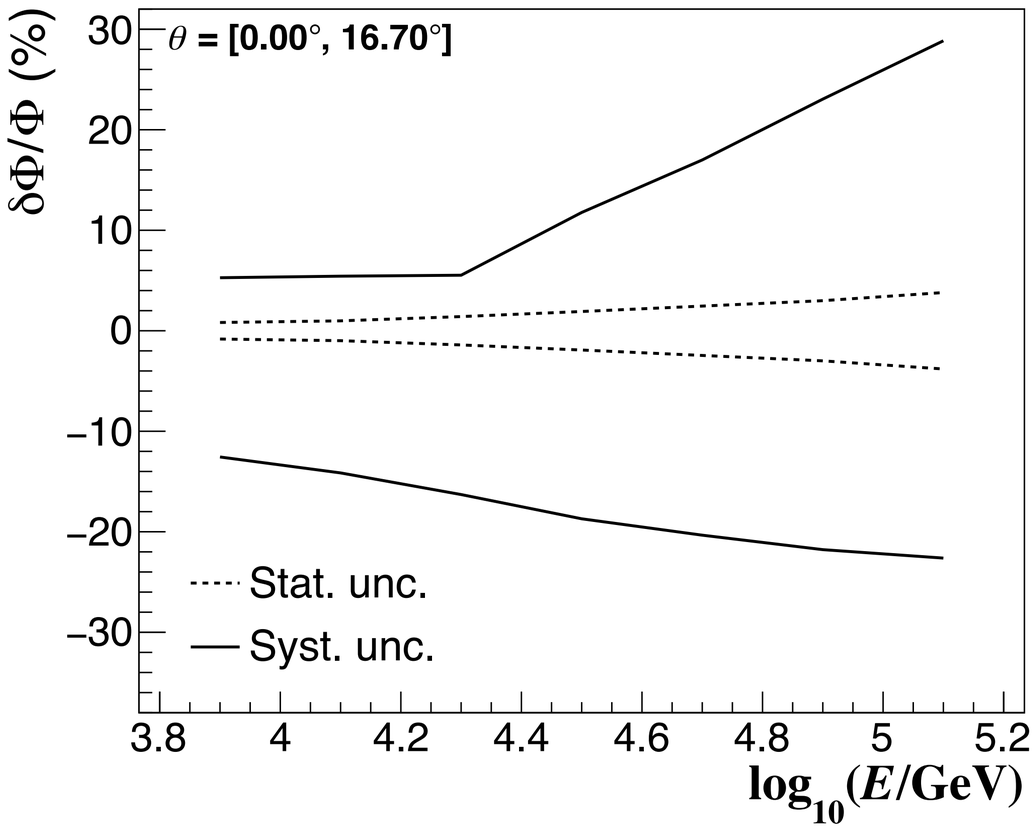
$\log_{10}$(E/GeV) = 4.5 (32 TeV)

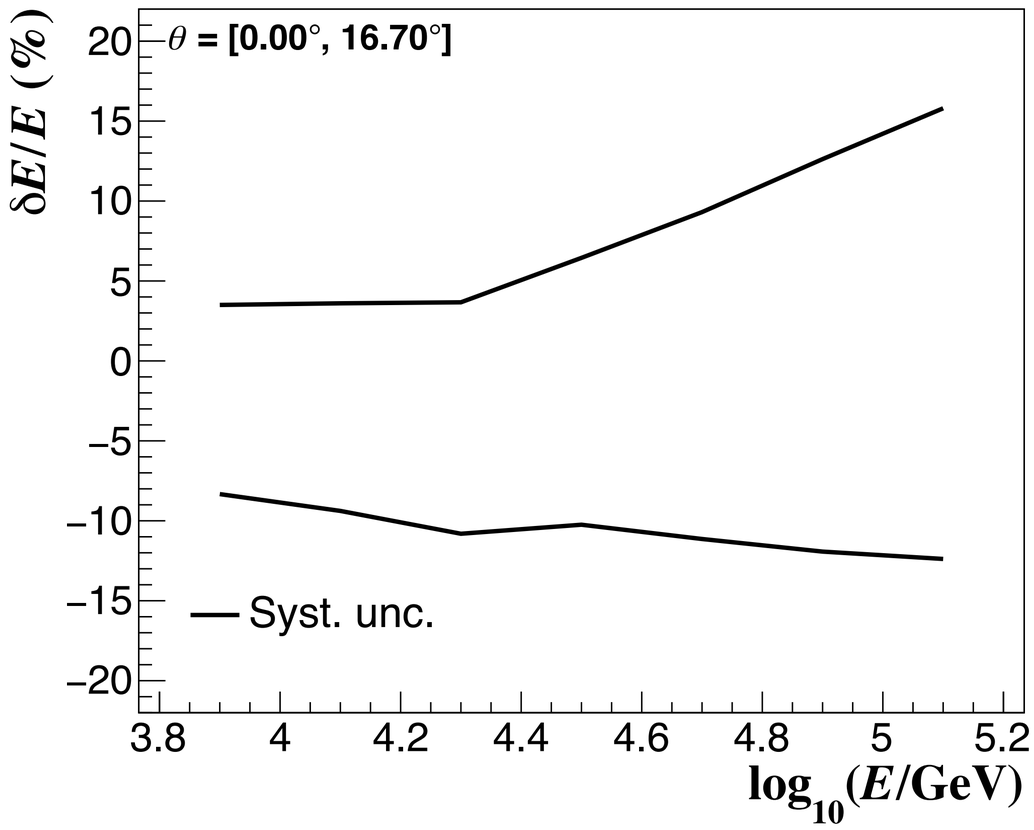
	Relative error Φ (%)
Statistical	**+/- 1.92**
Exp. Data	+/- 0.01
Response matrix	+/- 1.92
Systematic	**+11.77/-18.71**
Composition	+0.86/-17.25
Aeff	+1.85/-2.04
Cut at He or C	+2.87/-0.75
Gold unfolding	+1.23
Seed unfolding	-1.42
Smoothing unfold.	+3.73/-1.32
PMT efficiency	+5.00
PMT threshold	+2.33/-1.53
PMT charge	+1.83
PMT late light	+8.77/-0.14
Hadronic model	-6.47
Total	**+11.93/-18.81**

6) H + He energy spectrum

Statistical and systematic uncertainties

H+He





6) H + He energy spectrum

Fit of spectrum

H+He

1. Use following functions:

—> Single power law:

$$d\Phi(E)/dE = \Phi_0 E^{\gamma 1}$$

—> Broken power law:

$$d\Phi(E)/dE = \Phi_0 E^{\gamma 1}[1 + (E/E_0)^{\varepsilon}]^{(\gamma 2 - \gamma 1)/\varepsilon}$$

2. Minimize χ^2 with MINUIT and take into account correlation between points:

$$\chi^2 = \sum_{i,j} [\Phi_i^{data} - \Phi^{fit}(E_i)] [V_{stat}^{Tot}]^{-1}_{ij} [\Phi_j^{data} - \Phi^{fit}(E_j)]$$

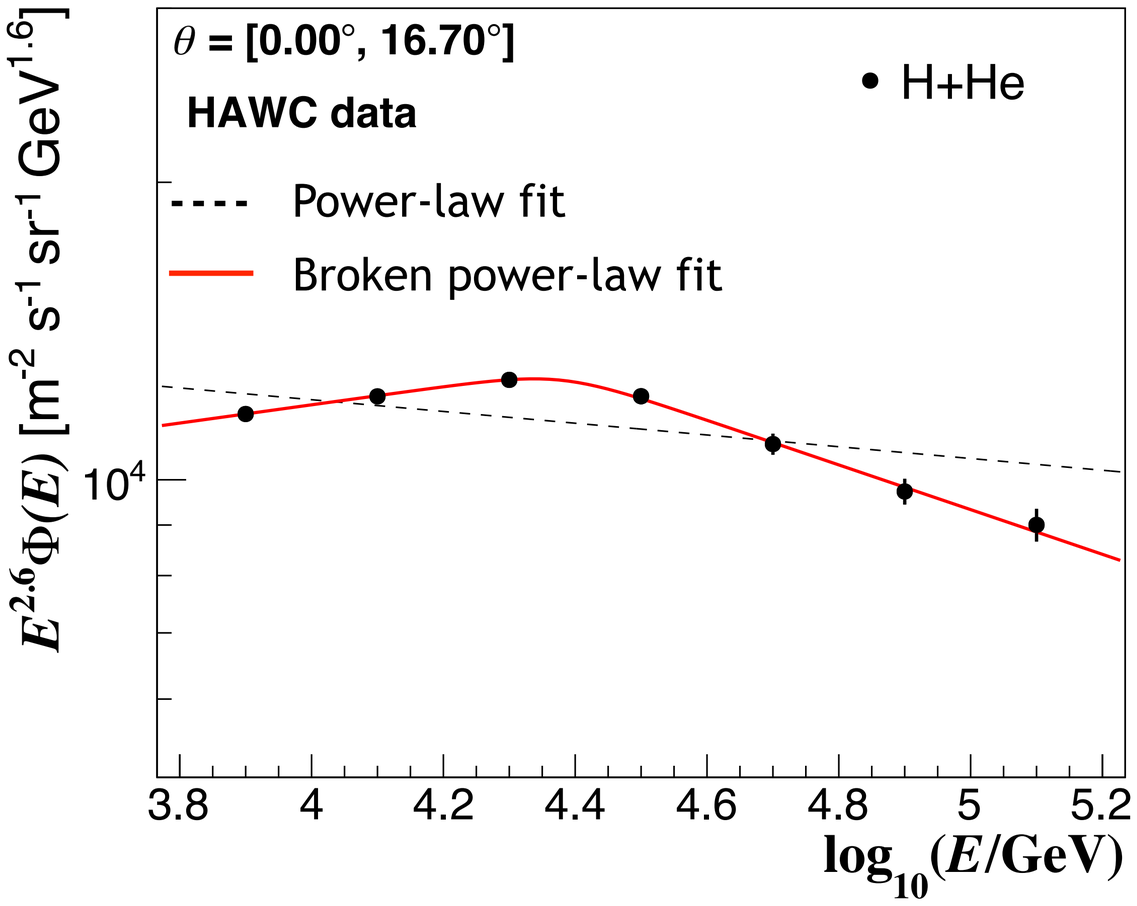
[C. Patrignani et al. (PDG), Chin. Phys. C, 40 (2016) and (2017) update]

6) H + He energy spectrum

Fit of spectrum

H+He

[HAWC Collab., PRD 105 (2022)]



- **Test Statistics:**

  TS = - $\Delta\chi^2$ = 177.25

  p-value = 2 x 10^{-5}

-> 4.1σ deviation from scenario with single power-law.

- Results for the double power-law fit:

  γ_1 = -2.51 ± 0.02

  γ_2 = -2.83 ± 0.02

  $\Delta\gamma$ = -0.32 ± 0.03

  $\log_{10}(E_0/\mathrm{GeV})$ = 4.38 ± 0.06

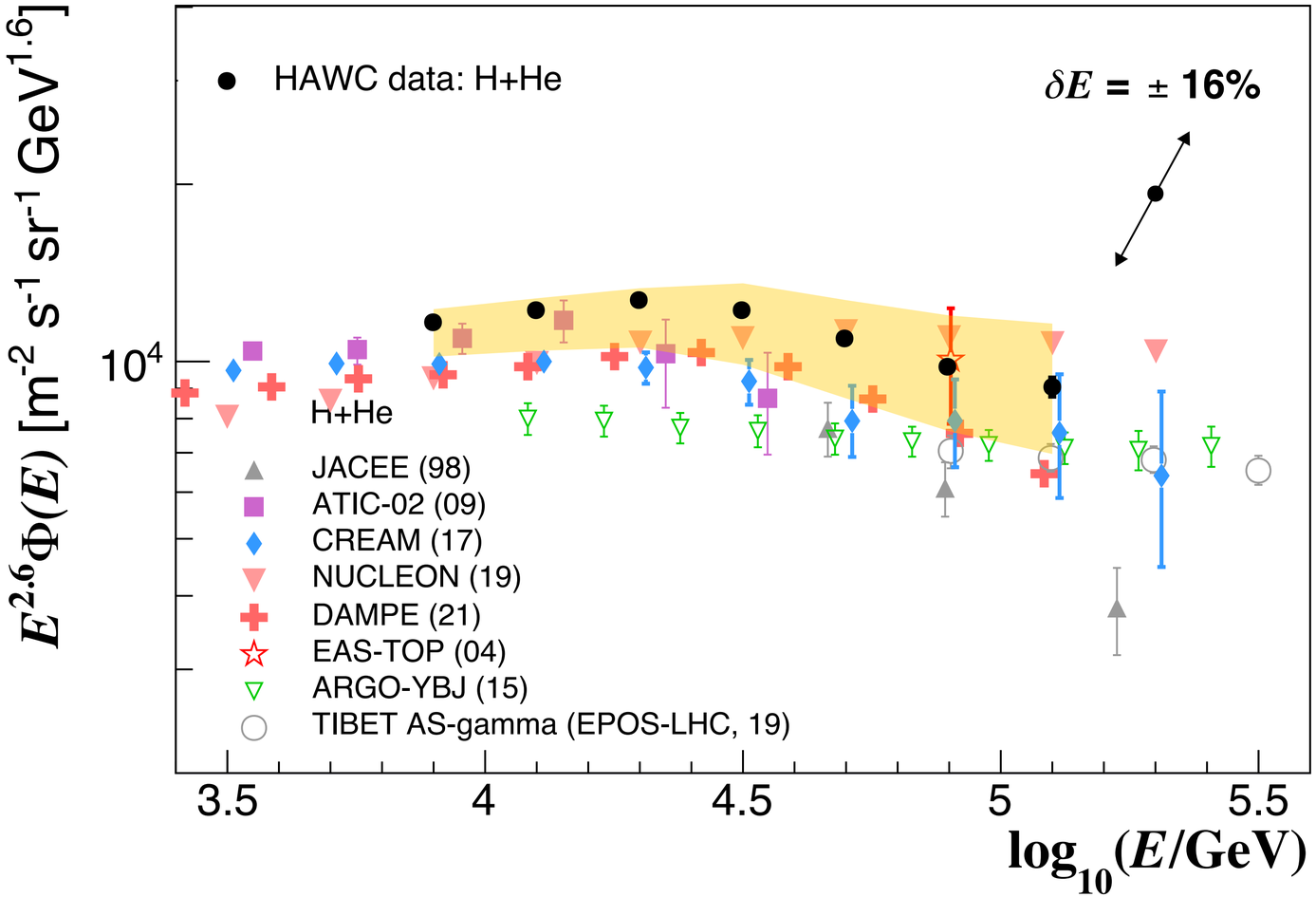
  - **$E_0 = 24.0^{+3.6}_{-3.1}$ TeV**

6) H + He energy spectrum

Comparison with measurements from other experiments

H+He

[HAWC Collab., PRD 105 (2022)]



- **HAWC** data confirm previous hints from ATIC-2, CREAM I-III and NUCLEON about the existence of a break in the spectrum of the light component of cosmic rays in the 10^4 - 10^5 GeV range.
- **HAWC** result is strengthened by recent DAMPE data.
- **HAWC** data is in agreement with ATIC-2 close to 10^4 GeV.

7) Summary

- A dedicated analysis of cosmic ray composition with HAWC has allowed to reconstruct the spectrum of the light component (H+He) of cosmic rays in the range E = [6 TeV, 158 TeV].

- HAWC results confirm previous hints from ATIC-2, CREAM I-III and NUCLEON that the H+He spectrum of cosmic rays deviates from a power-law behavior in the 10-100 TeV range.

- HAWC data show a break around $24.0^{+3.6}_{-3.1}$ TeV in the cosmic ray spectrum of H+He.

- The study demonstrates that high-altitude water Cherenkov observatories like HAWC can also be used to investigate the composition of cosmic rays at energies as low as 10 TeV.

Thank you