The spectrum of the light component of TeV cosmic rays measured with HAWC

J.C. Arteaga-Velázquez* and J. D. Álvarez for the HAWC Collaboration
Universidad Michoacana, Morelia, Mexico

* Speaker

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6. Summary
1) The HAWC $\gamma$-ray observatory

- **γ- and cosmic-ray detector:**
  - Air-shower observatory
  - Ground-based Cherenkov array
  - $E = 100$ GeV - $100$ TeV

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

- **Location:**
  - Volcano Sierra Negra, Puebla, Mexico
  - 19° N and 97° W
  - 4100 m a.s.l. ($640$ g/cm$^2$)
From hit times at PMTs, deposited charged, number of PMT's with signal:
- Core location, \((X_c, Y_c)\)
- Arrival direction, \(\theta\)
- Fraction of hit PMT's, \(f_{hit}\)
- Lateral charge profile, \(Q_{eff}(r)\)

2) EAS age and energy estimations

- **Lateral age parameter** \((s)\):  
  - Obtained event-by-event  
  - Fit of \(Q_{\text{eff}}(r)\) with NKG-like function:  
  
  \[
  f_{\text{ch}}(r) = A \cdot (r/r_0)^{s-3} \cdot (1 + r/r_0)^{s-4.5}
  \]

  with \(r_0 = 124.21\) m.  
  \(A, s\) are free parameters

  [Kelly Malone, APS 2017]

- **EAS primary energy**:  
  - Produce LDF tables of MC protons:  
    Binning in \(r, Q_{\text{eff}}, \theta\) and \(E\)  
  - Maximum likelihood to find table that best fits the \(Q_{\text{eff}}(r)\) distribution of the event, from which \(E\) is obtained.

CORSIKA v 7.40 for EAS simulation.

Fluka/QGSJET-II-03 as low/high-energy interaction models.

Full simulation of detector response with GEANT 4.

$\theta < 70^\circ$; $A_{\text{thrown}} \sim 3 \times 10^6$ m$^2$

Primary nuclei:
- H, He, C, O, Ne, Mg, Si, Fe
- $E = 5$ GeV – 3 PeV
- $E^{-2}$ spectra weighted to follow double power-laws derived from fits to AMS02 (2015), CREAM-II (2009 & 2011) and PAMELA (2011) data.
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 60 PMTs within 40 m from core
  - On-array EAS cores
  - Multiplicity threshold $N_{\text{hit}} \geq 75$ PMTs
  - Fraction hit (# of hit PMT’s/# available channels) $\geq 0.3$
  - $\log_{10}(E/\text{GeV}) < 5.5$

- Bias:

  $E \geq 10 \text{ TeV}:
  \begin{align*}
  \Delta r_{\text{res}} & \leq 9 \text{ m} \\
  \Delta \log_{10}(E/\text{GeV}) & \leq 0.12 \\
  \Delta \alpha & \leq 0.3^\circ
  \end{align*}$
More than 90% of H and He in subsample

- Age parameter is sensitive to composition
- Select a subsample using a cut on the age
  - Subsample must be enriched with nuclei to study

Content of H + He in subsample
- More than 90% of H and He in subsample
Build raw energy spectrum of subsample: $N_{\text{raw}}(E)$

- Experimental data used for analysis:
  
  HAWC-300
  
  $\Delta t_{\text{eff}} = 3.24$ years (94% livetime)
  
  (June/11/15-Nov/28/18)
  
  $\Delta \Omega = 0.27$ sr
  
  Total events: $3 \times 10^{12}$ EAS
  
  + selection cuts: $5.8 \times 10^9$ EAS
  
  + age cut: $3.8 \times 10^9$ EAS

Correct $N_{\text{raw}}(E)$ for migration effects

- Solve for $N_{\text{Unf}}(E_{T_i})$ using Bayesian unfolding
  
  [G. D’Agostini, DESY 94-099]

- Stopping criterium: Minimum of weighted mean squared error
  
  $WMSE = \frac{1}{N_{\text{points}}} \sum_{i}^{N_{\text{points}}} \frac{\text{stat}_{i}^2 + \text{sys}_{i}^2}{n_{i}}$
  
5) Analysis

### Obtain response matrix and effective area from MC simulations

- **P(E|E_{T1}):** response matrix from MC
  - Linear response \( E > 10 \text{ TeV} \) for MC

- Estimate corrected effective area
  \[
  A_{\text{eff}}(E_{T1}) = f_{\text{corr}}(E_{T1}) \cdot A_{\text{eff}}^{\text{H+He}}(E_{T1})
  \]
  - Correction factor due to contamination of heavy events:
    \[
    f_{\text{corr}} = \frac{N_{\text{light}}}{N_{\text{light}^{\text{H+He}}}}
    \]
  - Effective area of H+He in sub-sample:
    \[
    A_{\text{eff}}^{\text{H+He}}(E_{T1}) = A_{\text{thrown}} \cos \theta_{\text{max}} + \cos \theta_{\text{min}} \epsilon_{\text{H+He}}(E_{T1})
    \]

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J.C Arteaga - HAWC CR spectrum

36th ICRC, Madison, WI, July 2019
6) H + He energy spectrum

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

$$\Phi = N^{\text{Unf}}(E^T)/(\Delta t^{\text{eff}} \cdot \Delta \Omega \cdot A^{\text{eff}}(E^T) \cdot \Delta E^T)$$

- Energy spectrum was calculated as:

$\log_{10}(E/\text{GeV}) = 4.95$

<table>
<thead>
<tr>
<th>Relative error $\Phi$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Statistical</strong></td>
</tr>
<tr>
<td>+/- 4.0</td>
</tr>
<tr>
<td><strong>Exp. Data</strong></td>
</tr>
<tr>
<td>+/- 0.02</td>
</tr>
<tr>
<td><strong>Response matrix</strong></td>
</tr>
<tr>
<td>+/- 4.0</td>
</tr>
<tr>
<td><strong>Systematic</strong></td>
</tr>
<tr>
<td>+14.8/-16.1</td>
</tr>
<tr>
<td><strong>Composition</strong></td>
</tr>
<tr>
<td>-14.7</td>
</tr>
<tr>
<td><strong>Aeff</strong></td>
</tr>
<tr>
<td>+7.8/-5.8</td>
</tr>
<tr>
<td><strong>Cut at He or C</strong></td>
</tr>
<tr>
<td>+1.7/-3.0</td>
</tr>
<tr>
<td><strong>Gold unfolding</strong></td>
</tr>
<tr>
<td>-0.4</td>
</tr>
<tr>
<td><strong>Seed unfolding</strong></td>
</tr>
<tr>
<td>+0.10/-0.08</td>
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<tr>
<td><strong>Smoothing unfold.</strong></td>
</tr>
<tr>
<td>+1.4/-0.52</td>
</tr>
<tr>
<td><strong>Bin size</strong></td>
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<tr>
<td>-0.4</td>
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<tr>
<td><strong>PMT Qeff</strong></td>
</tr>
<tr>
<td>+12.0</td>
</tr>
<tr>
<td><strong>PMT Qres</strong></td>
</tr>
<tr>
<td>+2.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
<tr>
<td>+15.3/-16.6</td>
</tr>
</tbody>
</table>
6) H + He energy spectrum

Unfolded HAWC spectrum

HAWC data: H+He

\[ E^2 \frac{d^2\Phi}{dE} \text{ [m}^2\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{1.6}] \]

\[ \sigma_E = \pm 15\% \]

H+He

- JACEE (98)
- ATIC-02 (09)
- CREAM (17)
- NUCLEON (17)
- EAS-TOP+MACRO (04)
- KASCADE (QGSJET01)
- KASCADE (SIBYLL2.1)
- ARGO-YBJ (15)
- ARGO-YBJ (16)
6) H + He energy spectrum

Fit of spectrum

1. Use following functions:
   —> Single power law:
   \[ \frac{d\Phi(E)}{dE} = \Phi_0 E^{\gamma_1} \]

   —> Double power law:
   \[ \frac{d\Phi(E)}{dE} = \Phi_0 E^{\gamma_1} \left[ 1 + \left( \frac{E}{E_0} \right)^{\epsilon} \right]^{(\gamma_2 - \gamma_1)\epsilon} \]

2. Minimize \( \chi^2 \) with MINUIT and take into account correlation between points:

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

   PDG (2017)
6) H + He energy spectrum

Test Statistics:
\( \Delta \chi^2/\Delta \text{ndof} = 9.86 \)

p-value \( \leq 1.25 \times 10^{-4} \)

\( \rightarrow \) 3.67\( \sigma \) deviation from scenario with single power-law: unlikely that data is described by a single power-law.

Results for the double power-law fit:

\( \gamma_1 = -2.53 \pm 0.05 \)
\( \gamma_2 = -2.79 \pm 0.04 \)
\( \Delta \gamma = -0.26 \pm 0.07 \)
\( \log_{10}(E_0/\text{GeV}) = 4.50 \pm 0.16 \)
The lateral age parameter is sensitive to the composition of cosmic rays at HAWC.

A first 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 $E = [10\ TeV, 200\ TeV]$.

The light spectrum of cosmic rays is in agreement with data from NUCLEON and EAS-TOP, but above estimations from ATIC-2, CREAM-II/-III, JACEE and ARGO-YBJ.

Cosmic ray spectrum of H+He mass group is not described by a single power-law.
Backup slides
When the abundance of the heavy component is above that of the nominal model used to reconstruct the data, then the light component of CR’s is overestimated, but the shape of the spectrum is preserved.
Check performance of method with MC simulations: presence of a kink

Reconstruct nominal model but with a kink in the light component of CR’s at

\[ \log_{10}(E_0/\text{GeV}) \sim 4.5 \]

The kink is reconstructed

The reconstructed \( \Delta \gamma \) is smaller than the actual one due to contamination from the heavy component.