Cosmic Ray Observations at the TeV Scale with the HAWC Observatory

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Cosmic Rays at TeV Energies

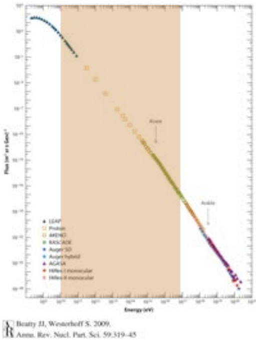
Measurements of cosmic rays at TeV energies provide important probes to understanding the nature and distribution of galactic sources as well as the interstellar environment in which cosmic-ray particles propagate.

Galactic Sources
- Acceleration models
- Source distribution

Diffusive Propagation
- Dust, energy loss
- Magnetic fields

Experimental Probes
- Energy spectrum
- Anisotropy

Requires
- Access to TeV flux
- Long observation times
- Large field of view

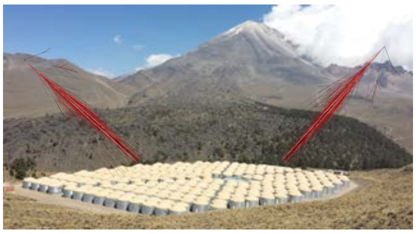


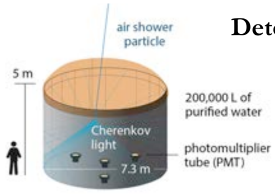
Beatty JJ, Westerhoff S. 2009. Annu. Rev. Nucl. Part. Sci. 59:319–45

The HAWC Observatory

High-Altitude Water Cherenkov

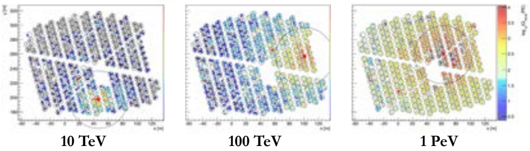
- 4100 m above sea level
- 300 water Cherenkov detectors
- 22,000 m^2 densely packed array
- 95% uptime efficiency
- 2 sr instantaneous field of view (2/3 sky daily)
- Detects cosmic ray showers from 100 GeV – 1 PeV

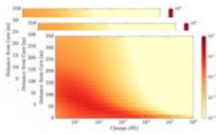




Detection Principle

The charge and timing information is used to reconstruct the **energy**, **arrival direction**, and **identity** of the primary particle.





Energy Estimation

Built **lateral** distribution tables of MC **proton** hit patterns.

Search tables to find most likely energy.

ML for hits to from **distance, charge, zenith, energy** bins.

70 GeV – 1.4 PeV with binwidth 0.1 in logE

Energy scale **verified** via cosmic ray Moon shadow [1].

All-Particle Energy Spectrum[1]

Event Selection

Quality cuts for refined data set.

8.42 x 10^9 events

Cut	% Passing MC	% Passing Data	Data Event Rate [kHz]
No cut (trig. threshold)	100 %	100 %	24.7
Core & angle fit pass	99 %	96 %	23.6
$N_{hit} \geq 75$	31 %	23 %	5.7
$\theta < 17^\circ$	8 %	6 %	1.5
$N_{r40} \geq 40$	2 %	2 %	0.43

Performance

Core res: <10 m

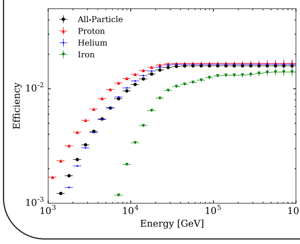
Angle res: 0.5°

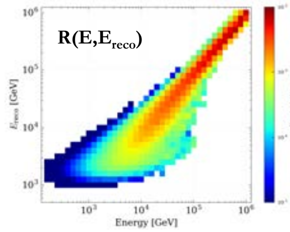
Energy res: <0.23 in logE

Composition

Species: H, ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{56}Fe

Assume broken power law fits to AMS, CREAM, PAMELA data.

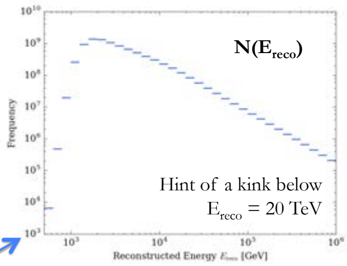




Unfolding the Energy Spectrum

Iterative Procedure[2]:

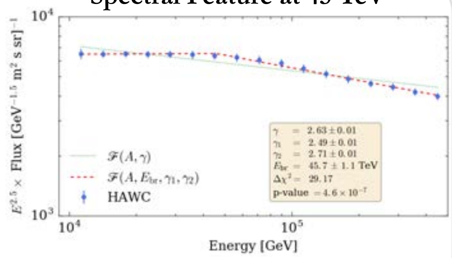
1. Measure distribution of reconstructed energy **N(E$_{reco}$)**.
2. Convolve with **response matrix R** & noninformative **prior**.
3. Iterate till **posterior** convergence (KS-test), final spectrum.



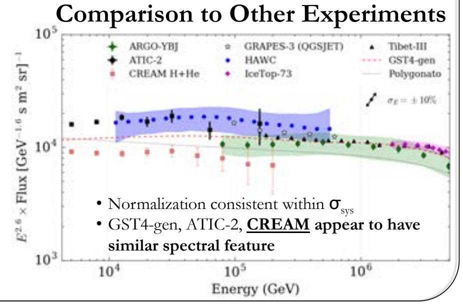
Physical priors like power laws do not influence spectrum

*Injected spectra **do not induce** spectral features*

Spectral Feature at 45 TeV



Comparison to Other Experiments



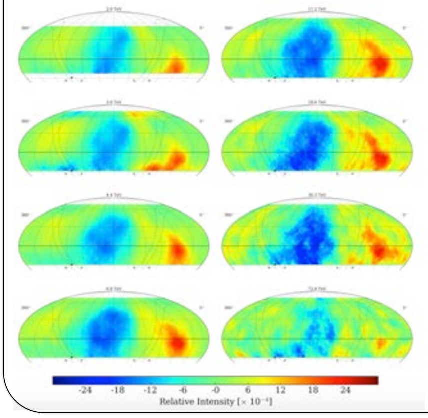
- Normalization consistent within σ_{sys}
- **GST4-gen, ATIC-2, CREAM appear to have similar spectral feature**

Large-Scale Anisotropy

Event Selection

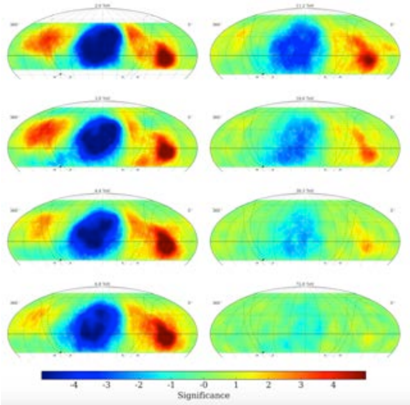
Two years of data with quality cuts relaxed giving **123 billion events.**

Cut	Pass Rate
Shower multiplicity ≥ 75 PMTs	23%
$N_{r40} \geq 1$	65%
$0^\circ \geq$ Zenith Angle $< 60^\circ$	95%
$E_{reco} \geq 10^{3.4}$ GeV	18%
Part of Full Sidereal Day	91%
Total	12%



Map Making

1. Maps binned in E$_{reco}$
2. New LH method[3], yields 100% recoverable large-scale features via iterative correction
3. Fit relative intensity to sph. harmonics

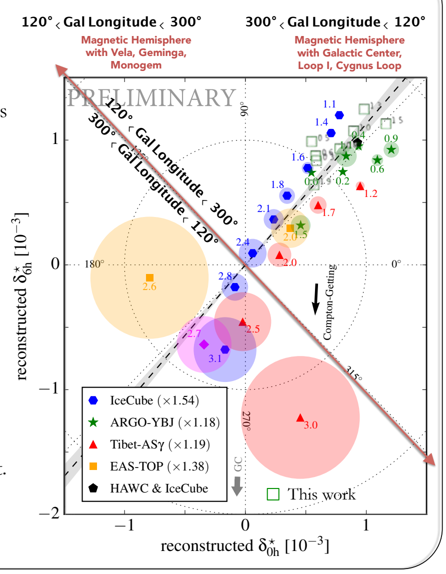


Local Accelerators?

Strong interpretation of LSA[4] suggests the sign of the dipole phase at a given energy identifies the hemisphere in which the dominant source(s) reside.

Summary

- Best E$_{res}$, systematics
- Largest data set for LSA
- Accurate map method
- Phase flip >100 TeV accessible with larger data set.



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References

[1] Alfaro, R. et al., *All-particle cosmic ray energy spectrum measured by the HAWC experiment from 10 to 500 TeV*, Accepted to Phys. Rev. D. 4 Nov, 2017, arXiv:1710.00890.

[2] G. D'Agostini, *A Multidimensional unfolding method based on Bayes' theorem*, Nucl. Instrum. Meth. A 362 (1995) 487.

[3] Ahlers, M., BenZvi, S. Y, Desiati, P., Díaz-Vélez, J. C., Fiorino, D. W., Westerhoff, S., *A new maximum-likelihood technique for reconstructing cosmic-ray anisotropy at all angular scales*, Astrophys. J. 823 (2016) 10.

[4] Ahlers, M. *Deciphering the Dipole of Galactic Cosmic-Rays*, Phys. Rev. Lett. 117 151103.

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