Gamma-ray Sky at Extreme High Energy with HAWC

- First Generation Spectral Analysis
- Geminga/B0656+14 and Local Positrons
- Galactic Plane Integral
- High-Energy Analysis and 50 TeV Skymap
High Altitude Water Cherenkov Detector

- 4100 meter site in Mexico
- 20,000 m² detector area.
- 300 4.5m high, 7.3m diameter Water Cherenkov Detectors
- 100 GeV - 100 TeV Sensitive Energy Range
- Angular resolutions of 1.3° (1 TeV) - 0.2° (>10 TeV)

Strengths:
- Wide field-of-view
- Continuous operation
- Extreme high-energy reach

Operated near-continuously since Nov 2014

Main Background: Hadronic cosmic rays
Crab Nebula: 400 photons/day
Background: 15000 cosmic rays/second
Gamma Rays (signal) vs Hadronic Cosmic Rays (background)

Large Events > 75% PMTs Hit

Cosmic Rays: 15000 Per Second
Gamma Rays: 400 Per Day from the Crab
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25-Month Skymap

Crab Nebula $>100\sigma$

PRELIMINARY
HAWC Event Sizes

Events categorized based on their size.
Crab Nebula: Binned in Event Size

- **E ~ 1 TeV**: 11% - 16% of PMTs Hit
- **E > 10 TeV**: >85% of PMTs Hit

Data maps for different energy ranges, showing the distribution of events categorized based on their size.
25-Month Sky Map

PRELIMINARY Crab Nebula

> 100 \sigma

E > 10 \text{ TeV}

> 85% of PMTs Hit

Crab Nebula: Binned in Event Size

Counting Excess Events

(i.e. counting photons)
Counting Excess Events (i.e., counting photons)

Spectral Measurement

\[ E^2 \frac{dN}{dE} \text{ [TeV/cm}^2\text{s]} \]

\[ 10^{-10}, 10^{-11}, 10^{-12} \]

Energy [TeV]

25-Month Skymap

Extended Emission around Geminga
250 pc away

PRELIMINARY
25-Month Skymap

Positron Fraction at Earth: Dark Matter or Local Pulsars?

Extended TeV Emission around Geminga (J0633+1746) and Monogem (B0656+14)

Coincidentally similar pulsars:

- Geminga (J0633+1746)
  - $\dot{E} = 3.2 \times 10^{34}$ erg/sec
  - $\tau = 3.42 \times 10^5$ yr
  - $d = 250$ pc
  - Diameter: 5.5 deg
  -Extent: 24 pc

- B0656+14
  - $\dot{E} = 3.8 \times 10^{34}$ erg/sec
  - $\tau = 1.1 \times 10^5$ yr
  - $d = 288$ pc
  - Diameter: 4.5 deg
  -Extent: 23 pc
Geminga (J0633+1746)

\[ E = 3.2 \times 10^{34} \text{ erg/sec} \]
\[ \tau = 3.42 \times 10^5 \text{ yr} \]
\[ d = 250 \text{ pc} \]

Diameter: 5.5 deg
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B0656+14

\[ E = 3.8 \times 10^{34} \text{ erg/sec} \]
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Diameter: 4.5 deg
Extent: 23 pc
25-Month Skymap

PRELIMINARY
25-Month Skymap

- HAWC data allows direct measurement of electron diffusion constant.
- Interpretation as the dominant source of local positrons is difficult.
25-Month Skymap

PRELIMINARY
\[ \pi^- \rightarrow e^- \nu_\mu \bar{\nu}_\mu \nu_e \]
\[ \pi^+ \rightarrow e^+ \nu_\mu \bar{\nu}_\mu \nu_e \]
\[ \pi^0 \rightarrow \gamma \gamma \]

Pion decay: Roughly 3:1 ratio of neutrinos to photons expected. Neutrinos roughly half the energy.

HAWC data can only account for ~5% of the IceCube flux. (~10% extrapolating for the missing part of the plane)

Compare to 16% for IceCube’s own measurement.

The Galactic plane contribution to the IceCube flux is heavily constrained by the HAWC observations.
25-Month Skymap

PRELIMINARY
Fluxes and upper limits for any DC point in our FOV.

• 2HWC Catalog (507-day) Dataset
• Public URL Available Soon
HAWC Energy Analysis: Two Approaches

Parametrized model based on light level at 40 meters from shower axis.

Discretized charge profile (plus shower parameters) fed to a Neural Network.
HAWC Energy Analysis: Two Approaches

1 TeV: HAWC is Fully Efficient

PRELIMINARY

Parametrized Ground Parameter Estimate

Neural Network Estimate

PRELIMINARY
HAWC Energy Analysis: Two Approaches

Crab Spectrum
Parameterized Model and Neural Net Energy Reconstructions

Preliminary
HAWC Energy Analysis: Two Approaches

1 TeV: HAWC is Fully Efficient

Parametrized Ground Parameter Estimate

Neural Network Estimate

True vs. estimated energy
Energy Resolution and Dynamic Range
Size Bins vs Reconstructed Energy Bins
Energy Resolution and Dynamic Range
Size Bins vs Reconstructed Energy Bins

Example: A Soft Spectrum vs a Hard Spectrum with a Cutoff

\[ E^2 \frac{dN}{dE} \text{ TeV}/(\text{cm}^2 \text{ s}) \]

\[ \log_{10}(E/\text{TeV}) \]

- \( E^{-2.5} \)
- \( E^{-2.3} e^{-E/46\text{TeV}} \)
Energy Resolution and Dynamic Range
Size Bins vs Reconstructed Energy Bins

These spectra are nearly identical in the 9-bin analysis and easily distinguishable in the new energy analysis.
Teaser Results: The Extreme VHE Sky

HAWC > 1 TeV

Many caveats: Reconstructed E only. Systematics pending. Analysis in progress...
If the spectra are hard, we should see emission past 100 TeV...
Teaser Results: The Extreme VHE Sky

HAWC > 50 TeV
(1 deg smoothing)

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Teaser Results: The Extreme VHE Sky

HAWC > 50 TeV
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Many caveats: Reconstructed E only. Systematics pending.
Analysis in progress…
If the spectra are hard, we should see emission past 100 TeV…

Crab Nebula
(Point Source Hypothesis)

MGRO J2019+37
MGRO J1908+06
HESS J1825-137
Outrigger Array
(High-Energy Extension Array)

• Core localization permits angular and energy reconstruction over larger area.
• 4x the Effective Area of HAWC at 10 TeV.
• Data-taking starts Dec 2017. Completion ~April 2018.
Summary

3 Years of HAWC
• Sensitive from 100 GeV to >100 TeV
• 3 Years of data in near-final configuration
• Basic Event Size Analysis:
  • 2HWC Survey, New TeV Sources
  • Geminga/B0656+14, Particle accelerators in our back yard: Challenge Local Positron Explanation
• Constraints on Galactic neutrino sources
• 507-day all-sky dataset soon to available online

Energy Analysis
• Maturing rapidly
• Greatly improves energy resolution and dynamic range
• First results indicate emission in > 50 TeV dataset.