Measuring High-Energy γ-Ray Spectra with HAWC

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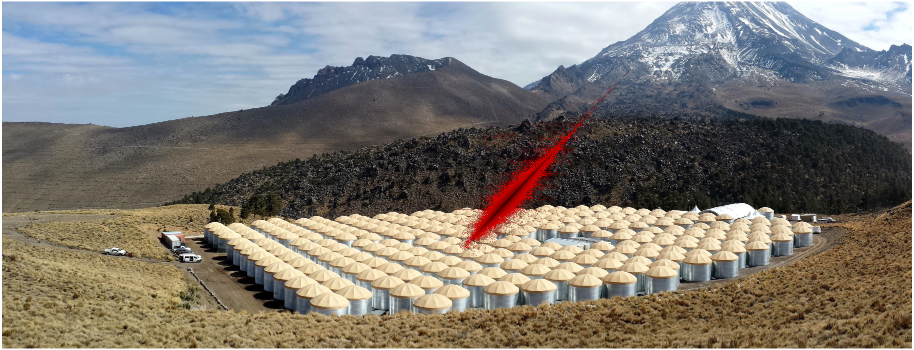
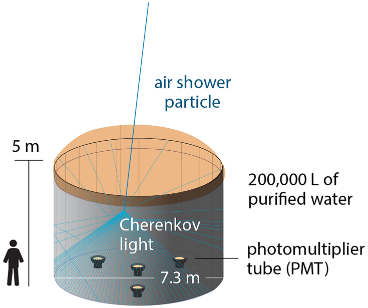
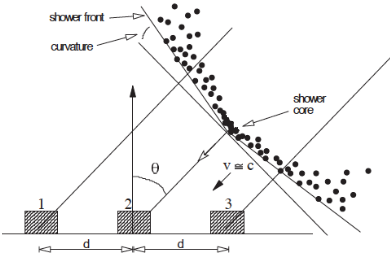
The High-Altitude Water-Cherenkov observatory

- Detects TeV γ rays at 4100 m on the Sierra Negra mountain in Puebla, Mexico.
- 1200 PMTs in 300 water-filled tanks detect Cherenkov light from air showers.
- Timing used to determine shower direction.



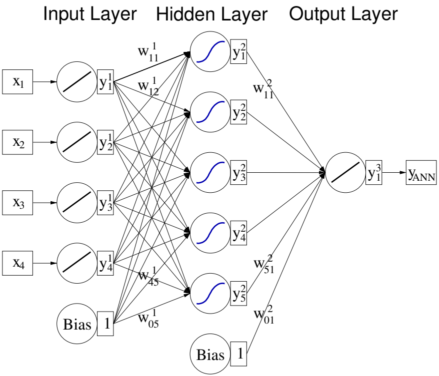
HAWC tanks


air shower
particle
5 m
200,000 L of
purified water
Cherenkov
light
photomultiplier
tube (PMT)
7.3 m


shower front
curvature
shower
core
θ
v ≅ c
1
2
3
d
d

HAWC energy estimation via artificial neural network (NN)

- Using Toolkit for Multivariate Analysis[1].
- NN maps several event-wise variables to estimate of primary energy.
- 479 free parameters chosen by training on Monte Carlo (MC).



[1] http://tmva.sourceforge.net/.

NN input variables

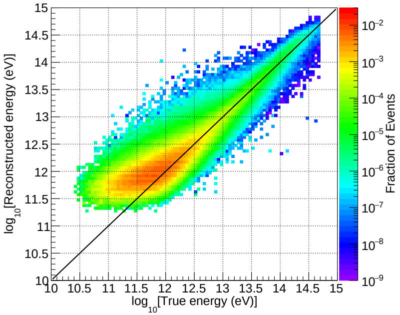
- Input variables chosen to characterize shower size and geometry.

Shower characteristic	Input variables
Energy deposited in the detector	• Fraction of PMTs hit • Fraction of tanks hit • Normalization of lateral-distribution fit
Fraction of ground energy landing on the detector	• Distance of shower core from detector center
Fraction of primary energy reaching the ground	• Zenith angle • Lateral energy distribution

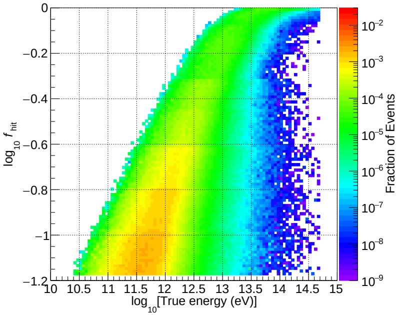
Performance on simulation

- NN energy better correlated with MC truth than currently used variable (fraction of PMTs hit).
- Ability to determine energies beyond 100 TeV.

NN energy



Fraction of PMTs hit

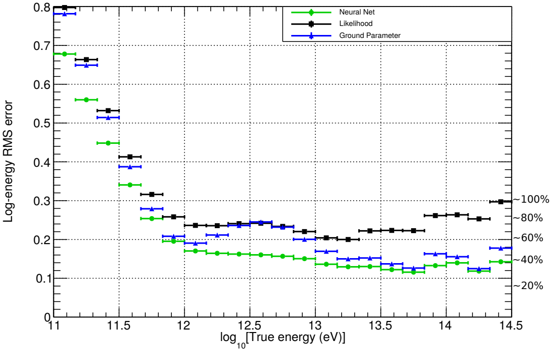


RMS error

- RMS error of ∼32% at highest energies.
- Use of lateral distribution compensates for fluctuations in height of first interaction.

Other techniques

- Ground Parameter energy-reconstruction method described by Kelly Malone on August 8 at 15:00.



HAWC Crab spectrum using NN

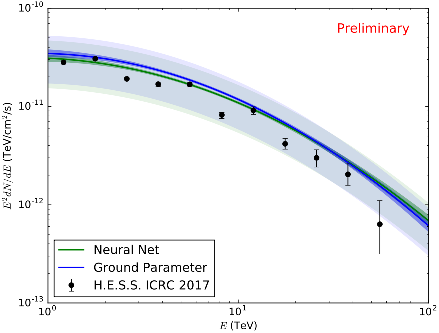
- Events binned two-dimensionally in fraction of PMTs hit and NN energy.
- Poisson-likelihood forward-folded fit is applied to these bin contents.
- Crab modeled as point source with log-parabola γ-ray spectrum:

$$\frac{dN}{dE} = k\left(E/E_0\right)^{-\alpha-\beta\ln(E/E_0)}. \tag{1}$$

- Fit serves as proof of principle for energy reconstruction but may also constrain high-energy Crab physics.

Crab fit result

- Statistical errors using new energy variables are smaller than in published HAWC result[2].
- Systematics analysis in progress. Assuming 50% flux systematic from published analysis, fits with new energy variables are compatible with H.E.S.S. measurement.



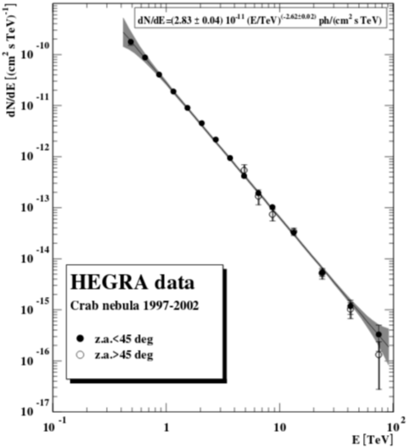
Dark band – statistical error
Light band – systematic error

[2] https://arxiv.org/abs/1701.01778.

HEGRA Crab Nebula spectrum (Aharonian et al. 2014)

- Stat. errors at highest energies comparable to HEGRA's. Might be improved with tuned cuts.

$\langle E \rangle$ [TeV]	$E_{\rm low} - E_{\rm high}$ [TeV]	$d\Phi/dE \pm \sigma_{stat}$ $[(\rm cm^2\,s\,TeV)^{-1}]$	N_{on}	N_{off} [a]	S [b] $[\sigma]$
0.365	0.316-0.422	$(1.97 \pm 1.17) \cdot 10^{-10}$	105	333	3.9
0.487	0.422-0.562	$(1.76 \pm 0.24) \cdot 10^{-10}$	369	705	14.1
0.649	0.562-0.750	$(8.78 \pm 0.53) \cdot 10^{-11}$	1012	1356	29.8
0.866	0.750-1.000	$(4.02 \pm 0.13) \cdot 10^{-11}$	2119	2108	50.0
1.155	1.000-1.334	$(1.87 \pm 0.09) \cdot 10^{-11}$	2829	2772	58.2
1.540	1.334-1.778	$(9.05 \pm 0.26) \cdot 10^{-12}$	2458	2220	56.1
2.054	1.778-2.371	$(4.51 \pm 0.12) \cdot 10^{-12}$	2017	1600	48.9
2.738	2.371-3.162	$(2.16 \pm 0.07) \cdot 10^{-12}$	1510	1114	47.3
3.652	3.162-4.217	$(9.33 \pm 0.36) \cdot 10^{-13}$	950	645	38.6
4.870	4.217-5.623	$(4.18 \pm 0.20) \cdot 10^{-13}$	579	330	31.7
6.494	5.623-7.499	$(1.93 \pm 0.12) \cdot 10^{-13}$	345	187	23.3
8.660	7.499-10.000	$(1.02 \pm 0.07) \cdot 10^{-13}$	238	111	21.4
13.335	10.000-17.783	$(3.28 \pm 0.31) \cdot 10^{-14}$	414	420	19.7
23.714	17.783-31.622	$(5.28 \pm 0.70) \cdot 10^{-15}$	150	242	10.2
42.170	31.622-56.234	$(1.10 \pm 0.25) \cdot 10^{-16}$	69	141	5.7
74.989	56.234-100.000	$(2.05 \pm 1.01) \cdot 10^{-16}$	36	104	2.7

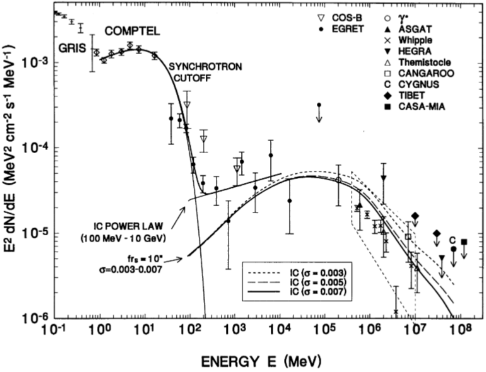


Implications of measurement for PWN modeling

- Interpretation of HAWC result requires understanding at what energies spectrum is being measured.
- High-energy γ spectrum sensitive to highest-energy electron acceleration.

Models

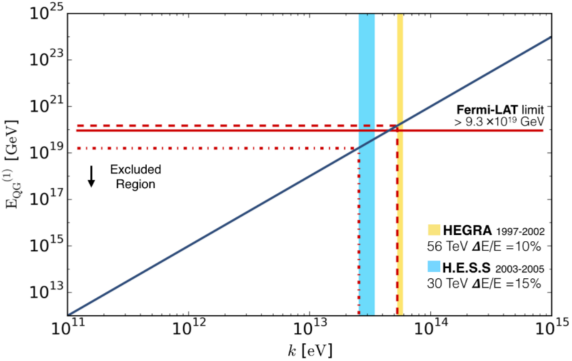
- De Jager et al. model PWN high-energy inverse-Compton emission.
- Atoyan and Aharonian (1995) also suggest bremsstrahlung could play a role if PWN inhomogeneous.



De Jager et al. (1996).

Sensitivity to Lorentz-invariance violation

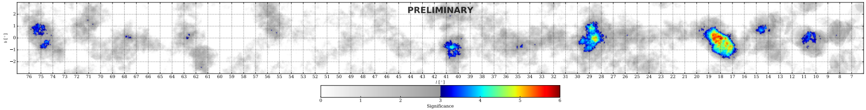
- Lorentz-invariance-violating models predict γ decay to e^+e^- above some energy.
- Detection of high-energy γ rays constrains this energy scale.
- HAWC Crab spectrum will imply some limit.



Martínez-Huerta and Pérez-Lorenzana (2017).

Future work

- Crab analysis not yet optimized. Must tune cuts etc. to new spectral-fitting technique.
- Galactic plane in 56–100 TeV map, made with 1° extended-source model and assuming 2.63 spectral index, shows several known sources.
- With new energy variables, HAWC can attempt measurements of these sources' spectra at unprecedented energies.

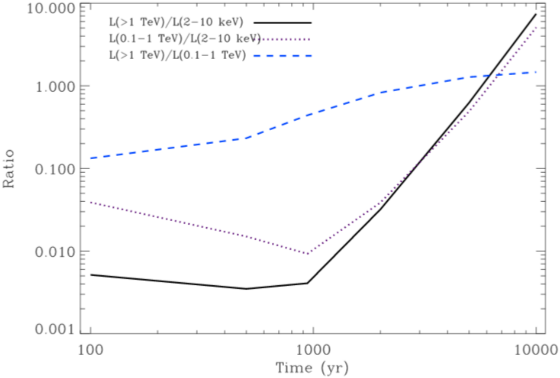


Bonus round

- Backup slides.

Sensitivity to time variability

- Martín et al. numerically models time dependence of spinning down pulsar/PWN.
- Cooling time for PeV electrons is ∼1 month.
- HAWC could look for spectral variations on this time scale.



Martín et al. (2012).