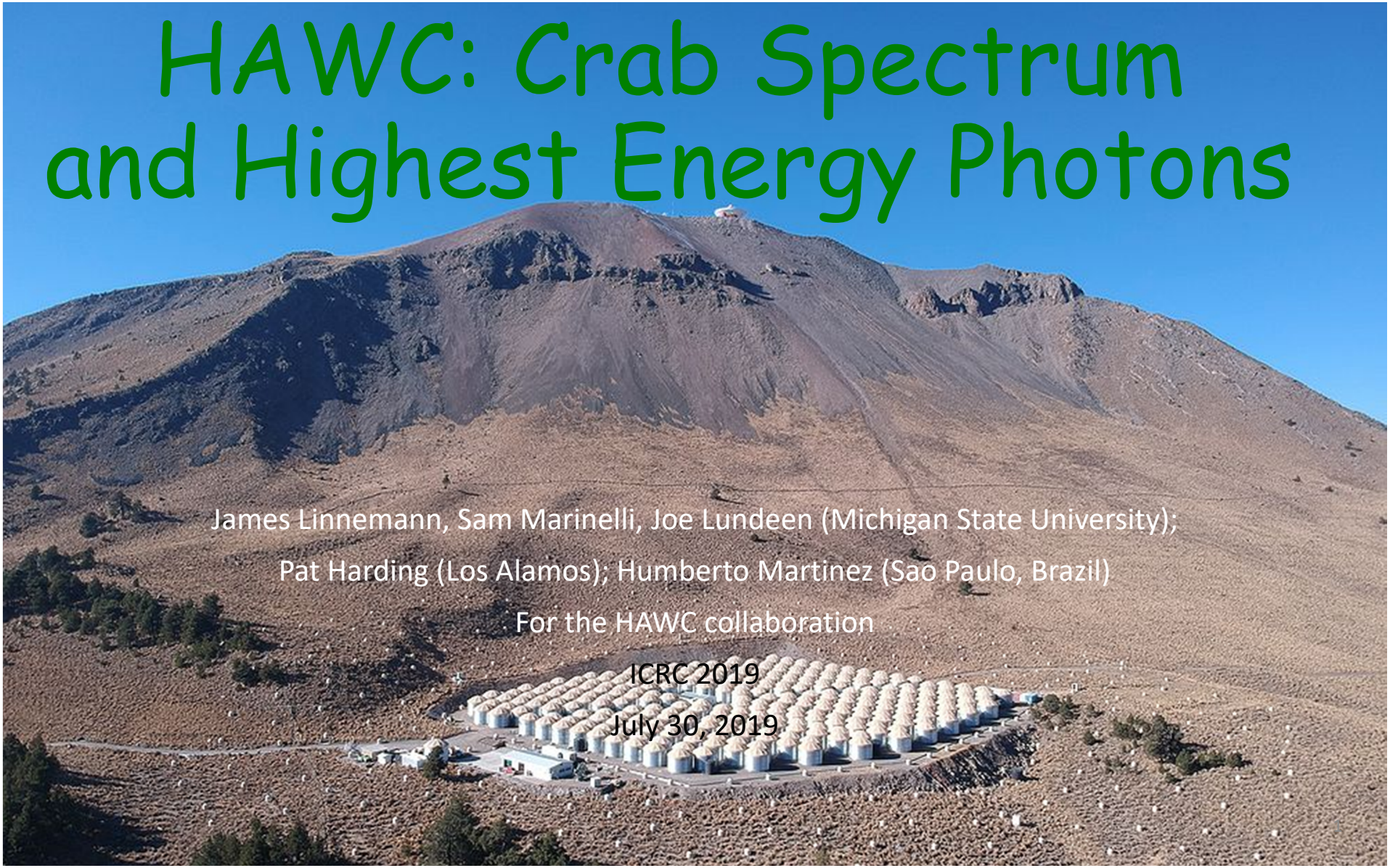
HAWC: Crab Spectrum and Highest Energy Photons



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Pat Harding (Los Alamos); Humberto Martinez (Sao Paulo, Brazil)

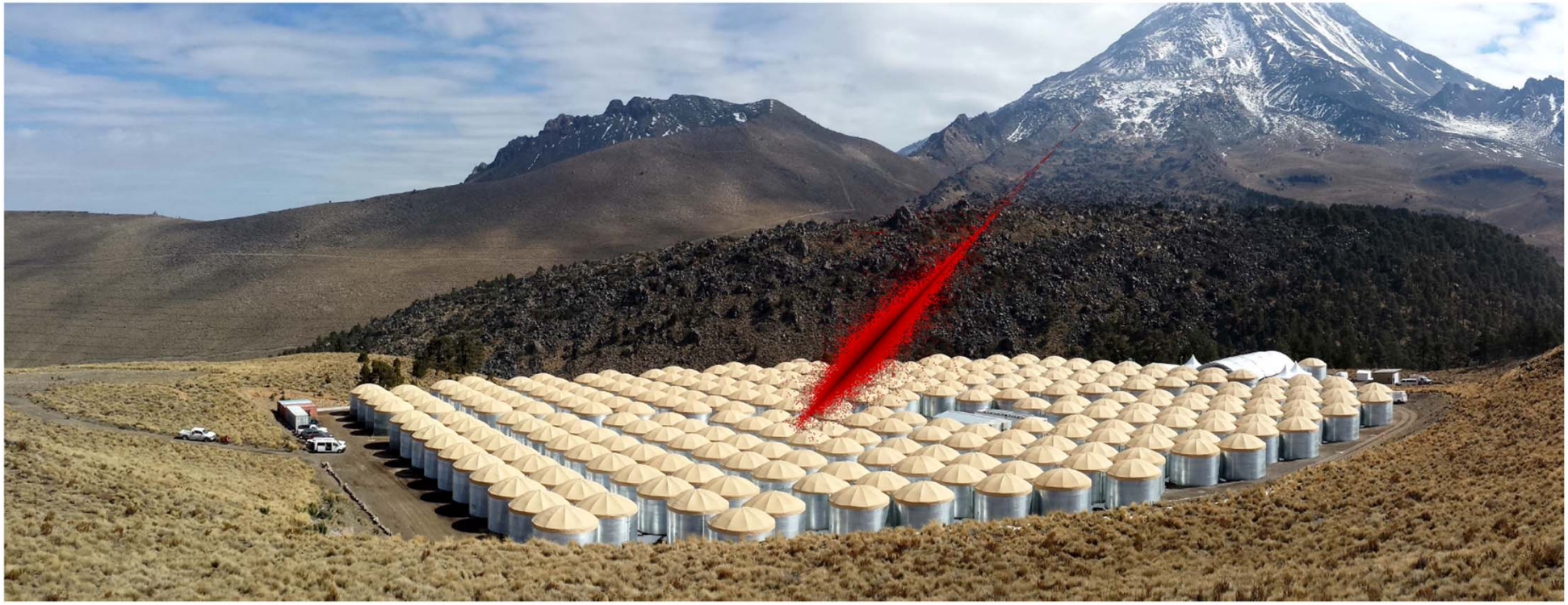
For the HAWC collaboration

ICRC 2019

July 30, 2019

The High-Altitude Water-Cherenkov (HAWC) observatory

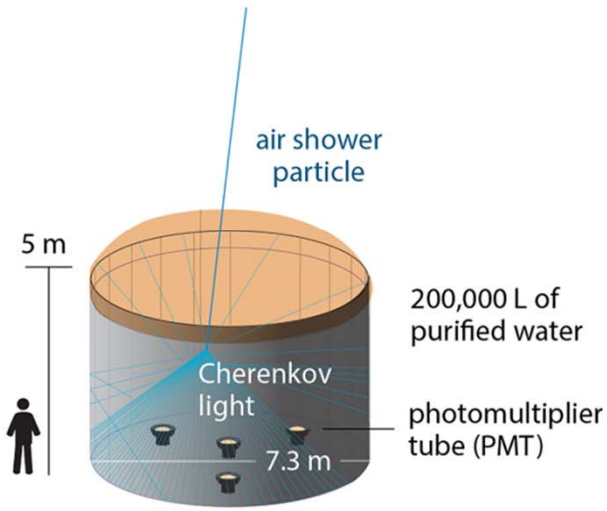
- A γ-ray observatory located 4100 m above sea level on the Sierra Negra volcano in Puebla, Mexico.

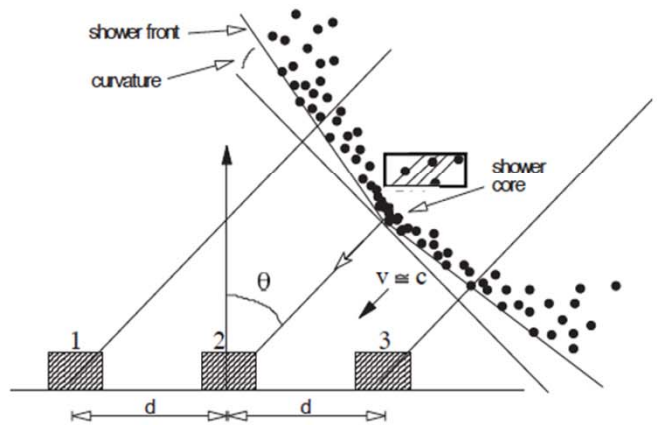


HAWC has 300 Water Cherenkov Tanks

Measure extensive photon air shower particles reaching ground level

- Timing used to determine shower direction.





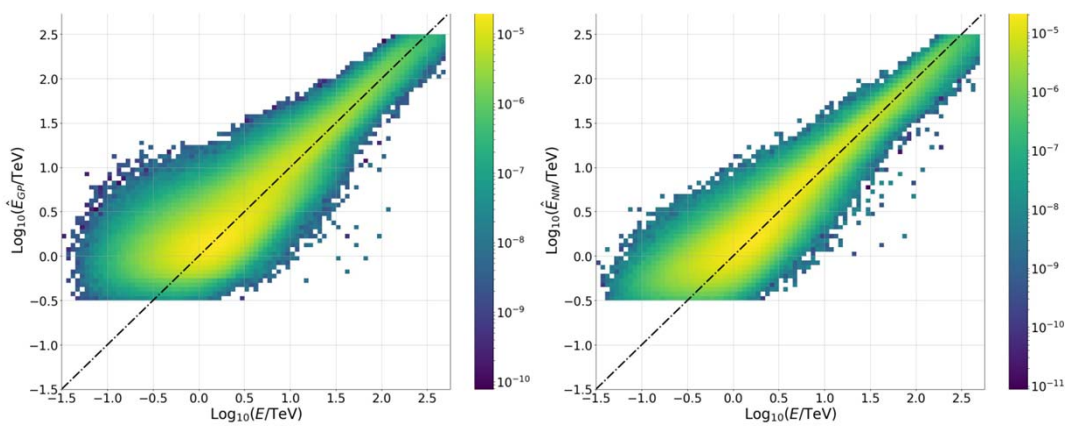
Two improved HAWC photon energy estimators

event by event energy to above 100 TeV

Performance on Simulation

GP

NN



GP: lateral distribution at 40m

corrections for zenith angle

NN: Neural Net with shower size, location, lateral distribution rings, zenith angle

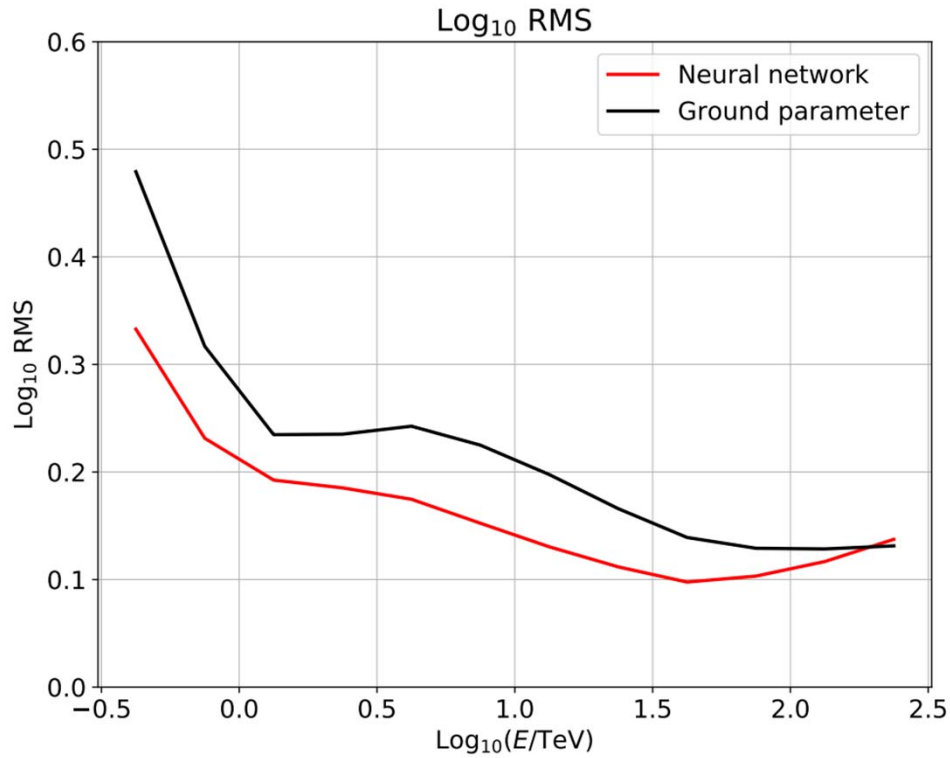
NN architecture 15:15:14:1

https://arxiv.org/pdf/1905.12518.pdf

Good resolution especially > 10 TeV

LogNormal resolution function

RMS = bias ⊕ resolution



Resulting Crab Spectrum: 1 to 100 TeV

Best fit is log parabola

$$\Phi_o \left(\frac{E}{7TeV} \right)^{\alpha + \beta LogE(TeV)}$$

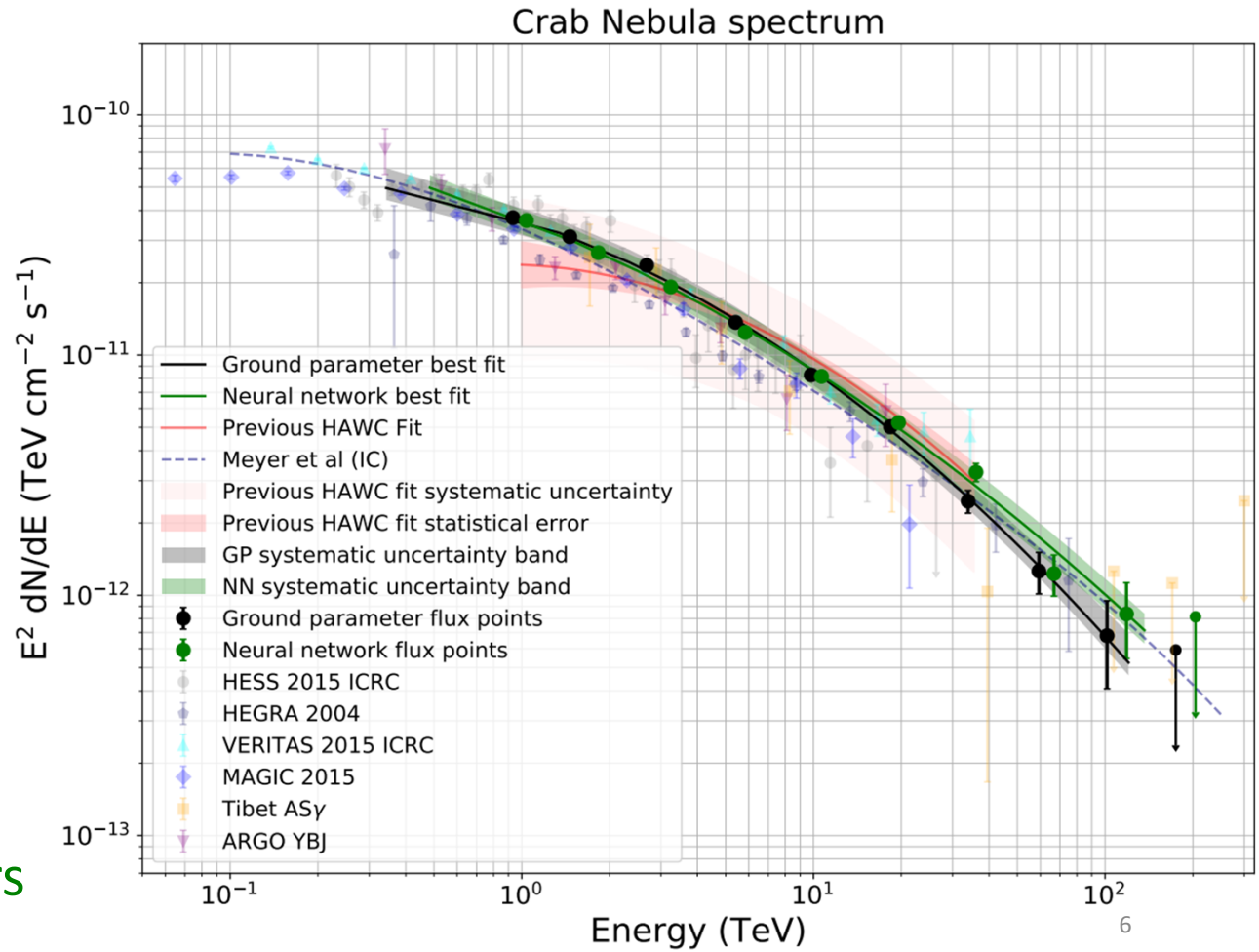
NN fit:

α = -2.73(2) β = -.06(1)

GP fit:

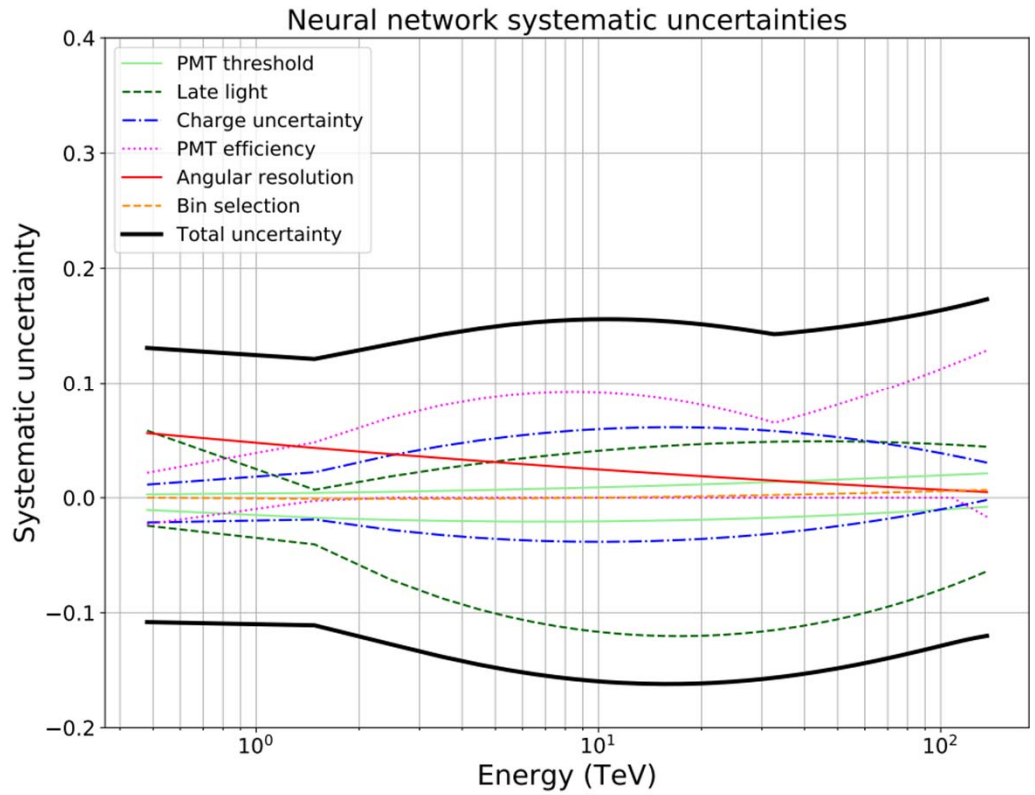
α = -2.79(2) β = -.10(1)

Estimators agree within errors



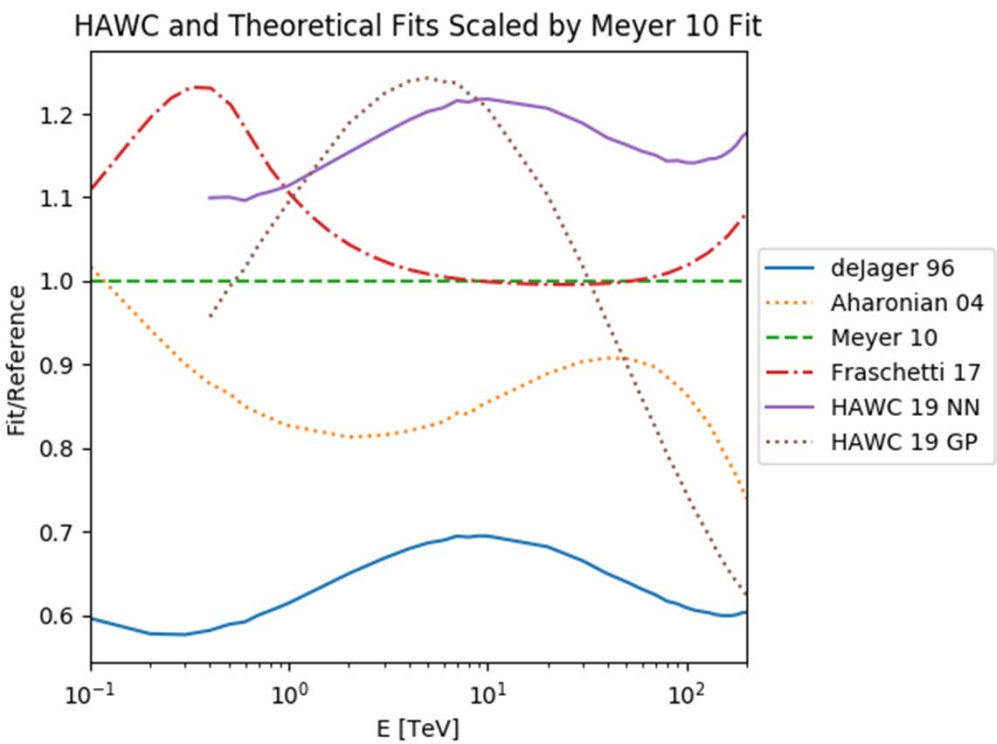
Systematics are in good control

Plot shows fractional uncertainty in $E^2 dN/dE$ (for NN)



Compare Spectral Fits on Linear Scale

HAWC and several IC theory fits



Normalize to Meyer et al 2010

https://arxiv.org/abs/1008.4524

All theory curves are IC fits

Meyer 2010: IC fit to wide spectrum, several target photon populations

2010 compromise E scale (Fermi, IACT)

Fraschetti & Pohl:

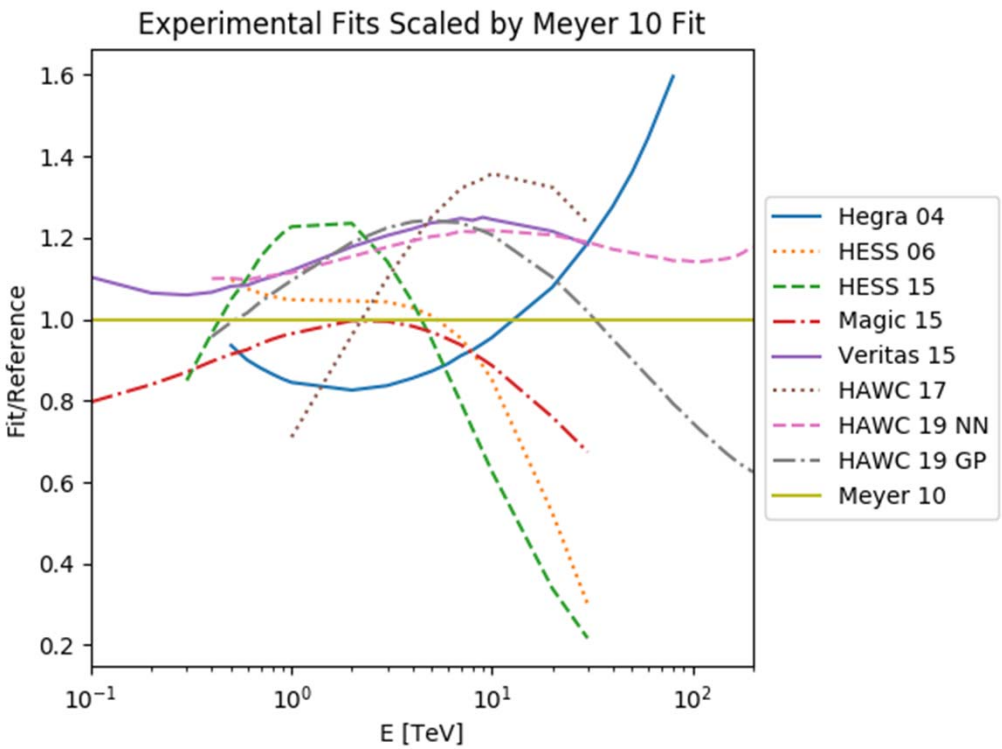
log parabola e spectrum + SSC + CMB

Close to Meyer above 1 TeV

Both agree with HAWC within 20%

Compare Experimental Fits

Linear scale; normalized to Meyer 2010 fit



1-10 TeV agreement within 20%

More variation above 10 TeV

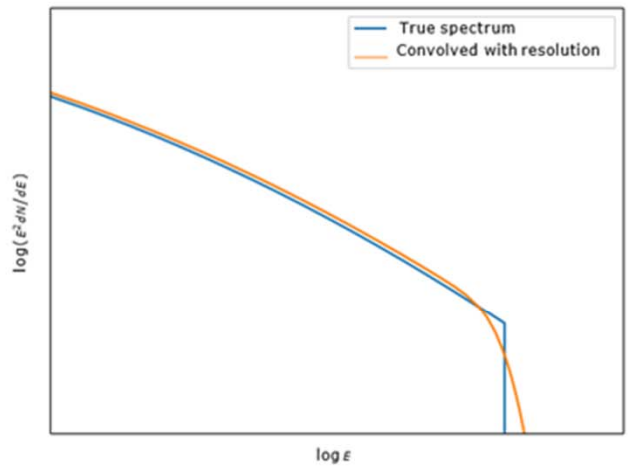
All log-parabola except Hegra

Parameters depend on Energy range

- even more below .1 TeV
- Most IACT data stopped at ~ 40 TeV
- Fits emphasize lower energies (smaller error bars)

Searching for High Energy Photons

- True high-energy photons can be "spoofed" in two ways: by background (hadronic) events or by misreconstructed lower-energy photons.
- So compute expected number of background and misreconstructed events above some energy E_{cut} and compute p-value of observed count under this Poisson mean.
- Adjust E_{cut} to achieve 95% (or desired) confidence level.



$$\Phi_{observed}(E) = \Phi_{emitted}(E)\,\Theta(E_{cut} - E).$$

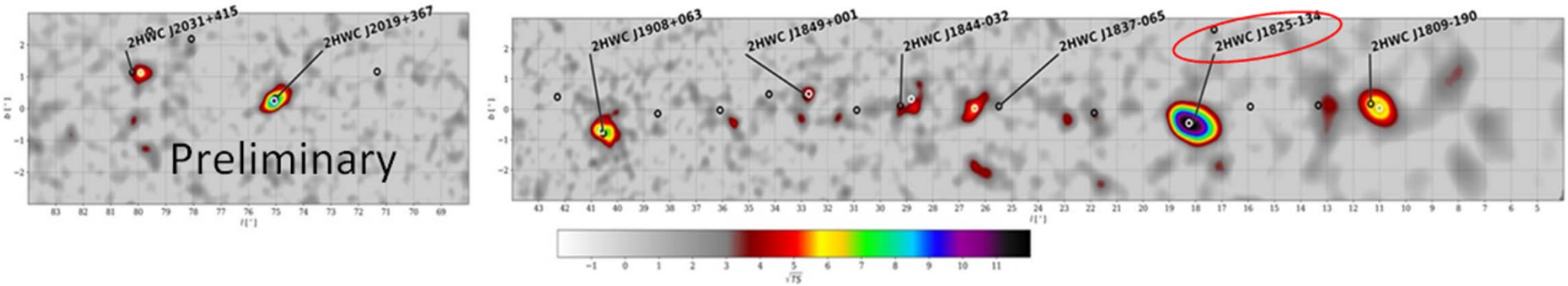
Nice property

- Result is independent of shape of $\Phi_{emitted}(E)$ above E_{cut}, so robust against uncertainties about highest-energy photon acceleration at source.

Same technique as in LIV limits

See H. Martinez talk 7/31 GAI 11c

Sources: the Crab Nebula plus HE sources in Galactic Plane



Seven sources from high-energy catalog (above 56 TeV Ereco):
Crab, 2HWC J1825−134, HAWC J1839−057, 2HWC J1844−032, 2HWC J1908+063, 2HWC J2019+367, and 2HWC J2031+415. See talk by K. Malone GA12b

Crab modeled with log-parabola spectrum. Others modeled with exponentially cut off power-law spectra.

Use NN estimator (best estimated resolution); top 2 bins refined to 6 bins (decade/12 wide)

To minimize psf dependence, chose top hat for source each where significance stops changing

The sources do not prefer a fit with hard cutoff

Calculate p value for hard cutoff

=Pr{randomly worse change in L(cutoff)/L(no cutoff)},

than observed, if no actual cutoff

Flat distribution with mean .5, if no cutoff

Lowest p value is .294

that source prefers a cutoff by < 2 σ

No statistically significant evidence of hard cutoffs

Proceed to set limits

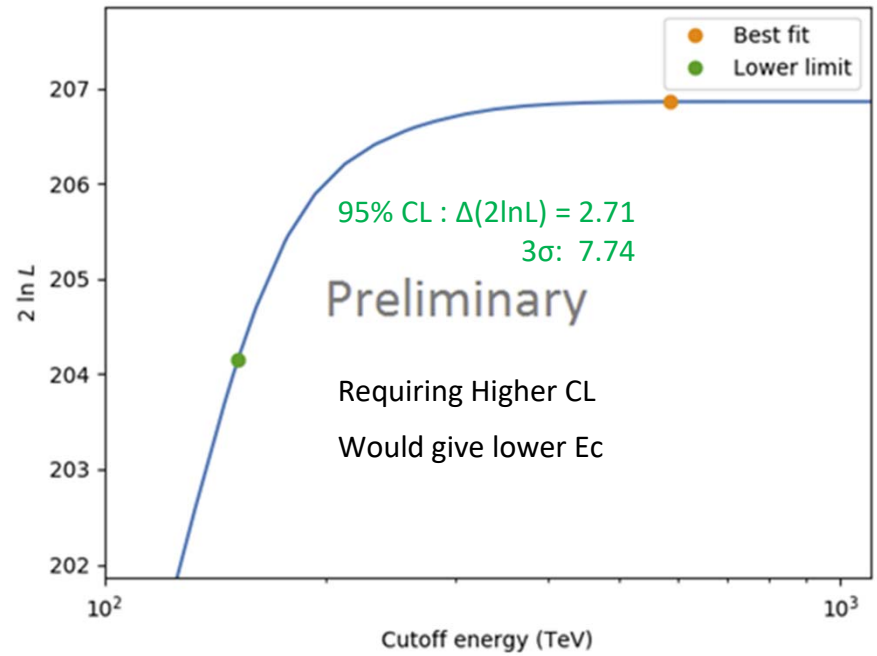
Source Preliminary	P value
2HWC J1825-134	1.000
2HWC J1908+063	.990
Crab (HAWC)	1.000
2HWC J2031+415	.714
2HWC J2019+367	.828
HAWC J1839-057	.357
2HWC J1844-032	.294

Walk down Likelihood Curve

to 95% and 99.73% (3σ) limits:

Lower Limits on Photon Energy Observed

Source Preliminary	Ec(95%) TeV	Ec(3σ) TeV
2HWC J1825-134	253	168
2HWC J1908+063	213	156
Crab (HAWC)	152	96
2HWC J2031+415	144	78
2HWC J2019+367	121	86
HAWC J1839-057	79	66
2HWC J1844-032	77	63
Crab (HEGRA)		56 (2.7σ)



Summary

New HAWC Crab spectrum to 100 TeV

using newly-improved HAWC energy estimation

Paper in press (ApJ) and arxiv 1905.12518

Photons > 100 TeV observed in 5 sources at 95% CL (253 TeV)

and 2 sources at 3σ (168 TeV)

Publication on LIV limits and Highest Energy Photon in preparation