TeV Analysis of PWN Component 3HWC J2031+415

Ian Herzog
Email: igherzog@mtu.edu
Michigan Technological University
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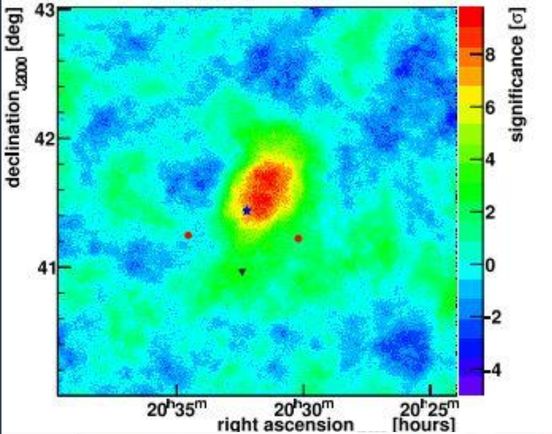
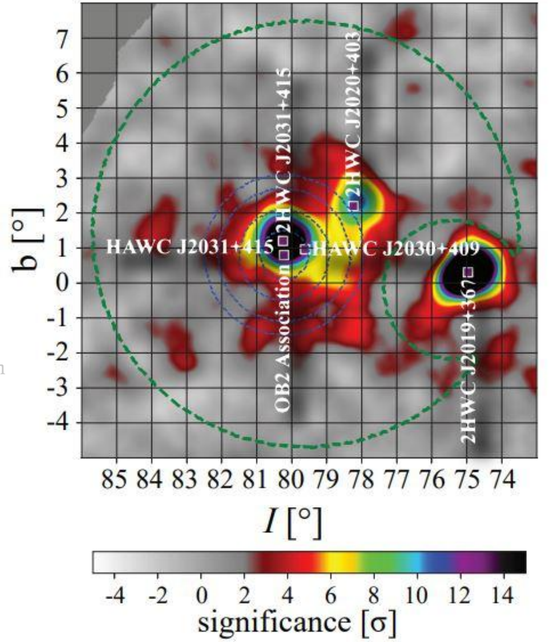
High Altitude Water Cherenkov Gamma-Ray Observatory
Michigan Tech

Previous work on 3HWC J2031+415

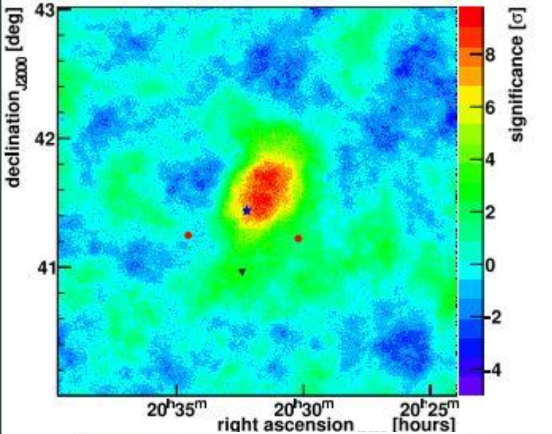
- ❖ HEGRA
  - ➢ Discovered TeV J2032+4130
- ❖ VERITAS
  - ➢ Asymmetric gaussian shape
  - ➢ First implied probable PWN
  - ➢ Hypothesized PSR J2032+4127 as PWN
- ❖ HAWC
  - ➢ Cocoon star cluster emission analysis
  - ➢ Modelled 3 sources
    - ■ J2031, J2030, J2020
    - ■ (307.82, 41.51), (307.65, 40.93), (30.27, 40.50)



Observations of the unidentified gamma-ray source TeV J2032+4130 by VERITAS
E. Aliu *et al* 2014 *ApJ* 783 16



Abeysekara *et al.* HAWC observations of the acceleration of very-high-energy cosmic rays in the Cygnus Cocoon. *Nat Astron* (2021).



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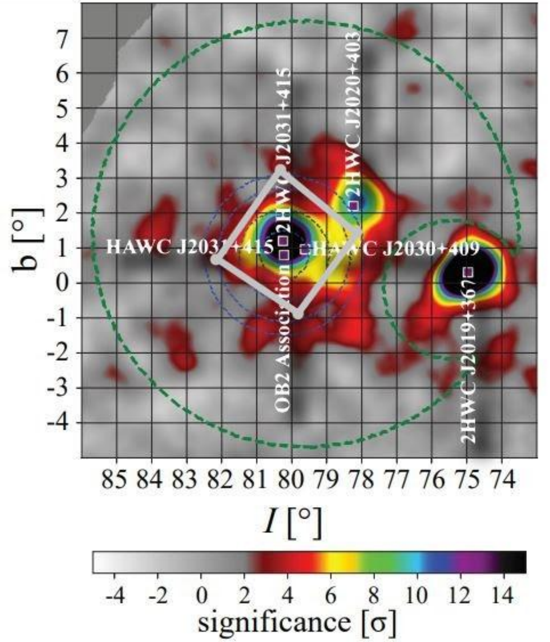
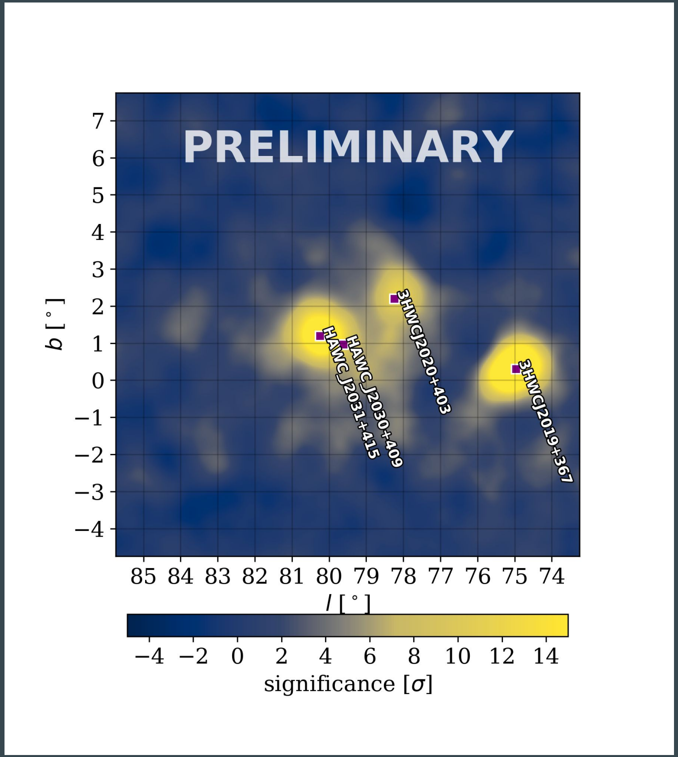


Modified to show approximate VERITAS' region shown above;
Abeysekara *et al.* HAWC observations of the acceleration of very-high-energy cosmic rays in the Cygnus Cocoon. *Nat Astron* (2021).

A closer look at 3HWC J2031+415

- ❖ 2 components to emission
  - ➢ HAWC J2030+409 → Cocoon
  - ➢ HAWC J2031+415 → PWN
- ❖ Secondary source
  - ➢ 3HWC J2020+403 → Gamma Cygni
- ❖ PWN focus
  - ➢ 1343 days of data
  - ➢ Reconstructed energies > 1 TeV

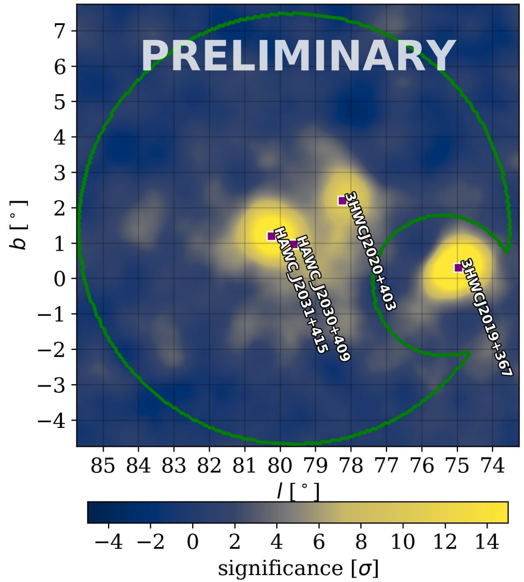


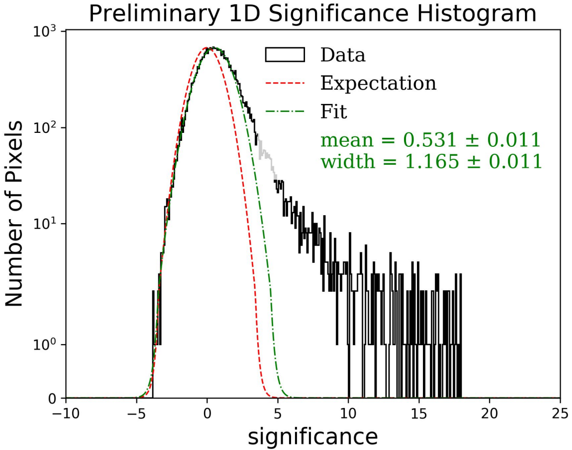
Modelling the region

- ❖ Model 3 sources
  - ➢ 3HWC J2020+403 — Powerlaw
  - ➢ HAWC J2030+409 — Powerlaw
  - ➢ HAWC J2031+415 — Powerlaw with cutoff
    - ■ All extended symmetric 2D gaussians

$$\frac{dN}{dE} = N_o\left(\frac{E}{E_p}\right)^{\gamma} * e^{\frac{-E}{E_c}}$$

- ❖ Region of interest (ROI)
  - ➢ Green contour
  - ➢ mask on 3HWC J2019+367

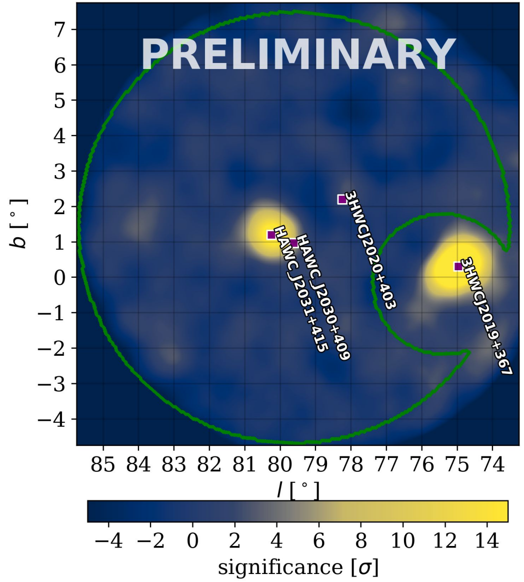


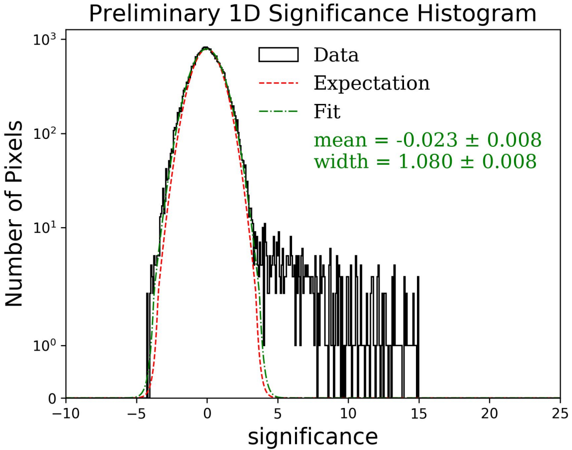


PWN Isolation process

Parameters	Cocoon (J2030)	Gamma Cygni (J2020)
Index γ	Free	Free
Flux normalization N_o	Free	Free
Gaussian width σ	Free	Fixed

For Gamma Cygni fixed width: arXiv:1907.08572 **[astro-ph.HE]**



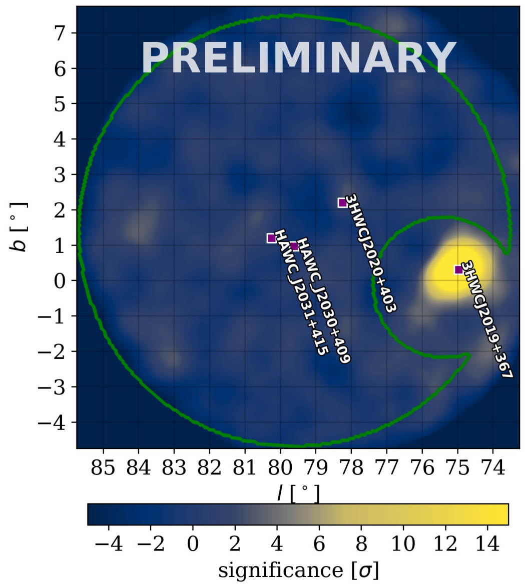


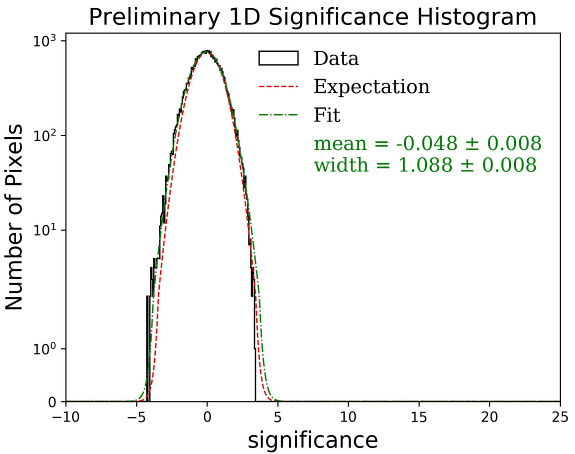
PWN Modelling

All uncertainties presented are statistical only

Fit parameters	J2031+415 (PWN)
σ (deg)	$0.27^{+0.021}_{-0.02}$
N_o (1/(cm^2*TeV*s))	$1.32^{+0.17}_{-0.14} * 10^{-13}$
γ	$-1.96^{+0.17}_{-0.14}$
E_c (TeV)	39^{+20}_{-12}
E_p (TeV)	4.9

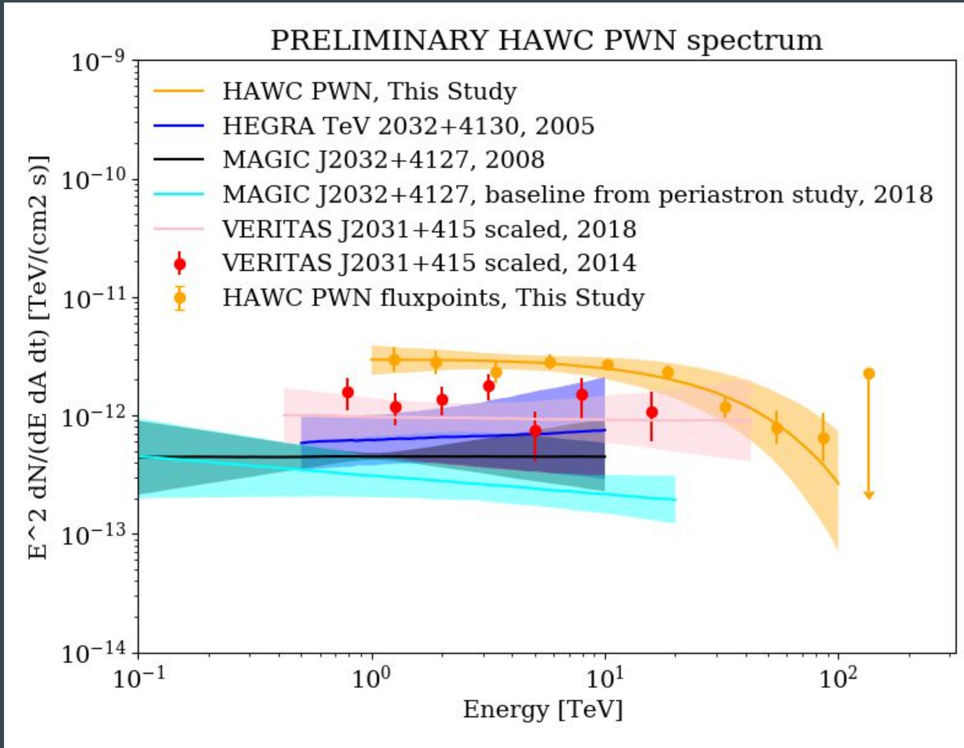
$$\frac{dN}{dE} = N_o\left(\frac{E}{E_p}\right)^{\gamma} * e^{\frac{-E}{E_c}}$$





Spectral Comparison

- ❖ HAWC's sensitivity at high energies reveals cutoff in spectrum
  - ➢ Power law with exponential cut off in good agreement
- ❖ Discrepancy with VERITAS
  - ➢ Used multisource fit
  - ➢ Scaling factor: 1.49



Energy Morphology study

General overview

- Determine source shape with changing energy
- Binning data
  - Binning scheme
    - Energy
    - % array hit
  - Don't have enough data per bin
  - Not all bins are used
- Need method
  - Straight fitting may not be practical
  - Enter slicing method

A. U. Abeysekara et al, "Measurement of the Crab Nebula Spectrum Past 100 TeV with HAWC" 2019 ApJ 881 134

Table 1. Energy bins

Bin	Low energy (TeV)	High energy (TeV)
a	0.316	0.562
b	0.562	1.00
c	1.00	1.78
d	1.78	3.16
e	3.16	5.62
f	5.62	10.0
g	10.0	17.8
h	17.8	31.6
i	31.6	56.2
j	56.2	100
k	100	177
l	177	316

Table 2. $\mathcal{B}$ bins

Bin number	Low fraction hit	High fraction hit
1	0.067	0.105
2	0.105	0.162
3	0.162	0.247
4	0.247	0.356
5	0.356	0.485
6	0.485	0.618
7	0.618	0.740
8	0.740	0.840
9	0.840	1.00

What energy bands?

- Band 1 (1 - 3.16 TeV)
  - Bins c, d
- Band 2 (3.16 - 10 TeV)
  - Bins e, f
- Band 3 (10 - 56.2 TeV)
  - Bins g, h, i
- Band 4 (56.2 - 316 TeV)
  - Bins j, k, l

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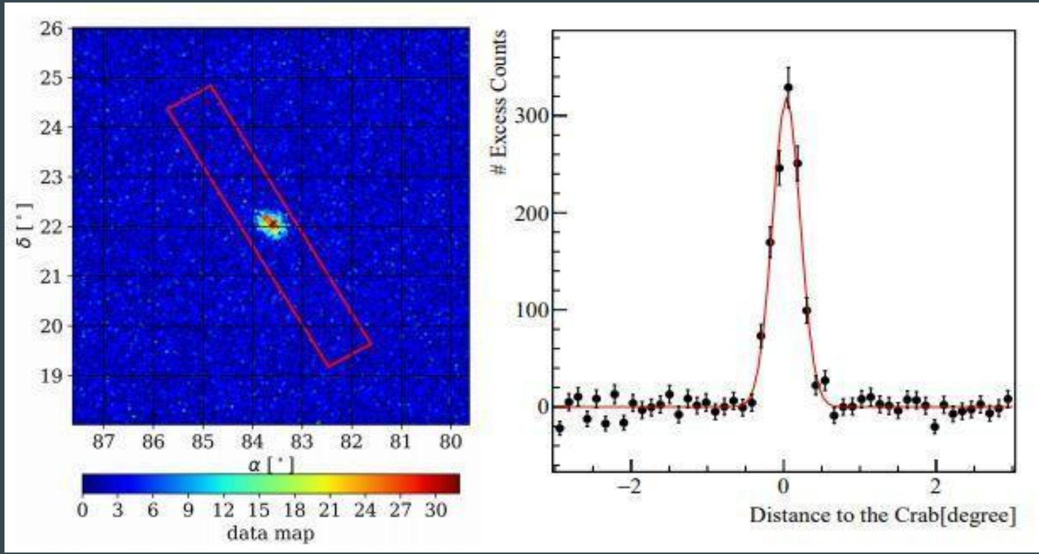
Slicing Method

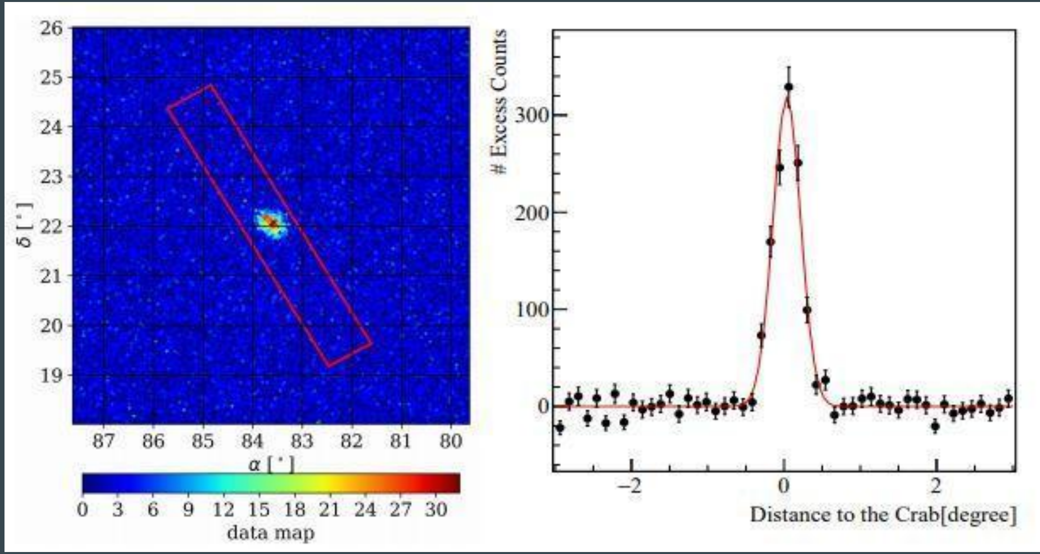
- ❖ Takes rectangular region
  - ➢ Angle is crucial
  - ➢ Defined as line connecting J2031 and PSR J2032+4127
- ❖ Slice into “bins”
  - ➢ 50 bins used
- ❖ Sum excess counts
- ❖ Plot and fit Gaussian
  - ➢ PSF’ is 1 sigma width



Joshi, V. “Reconstruction and Analysis of Highest Energy gamma-rays and its Application to Pulsar Wind Nebulae”, PhD Thesis, Ruperto-Carola University, Germany

Slicing Method continued

- Compare simulated sources
  - HAWC J2031+415 PL
  - Crab PL
  - Not limited by events
- How do the PSF' compare?
  - Use simulated Crab for bin selection
  - Well documented behavior



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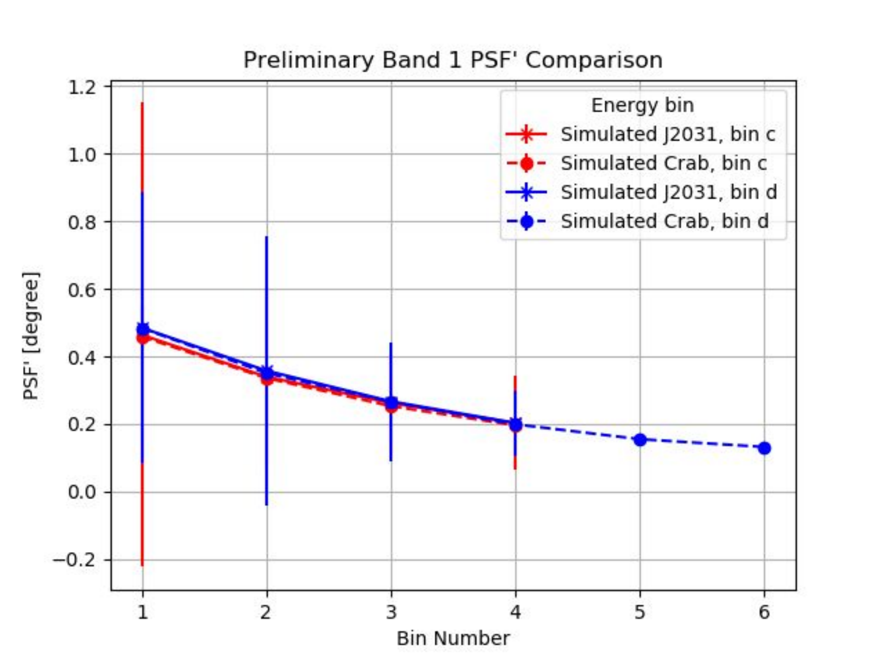
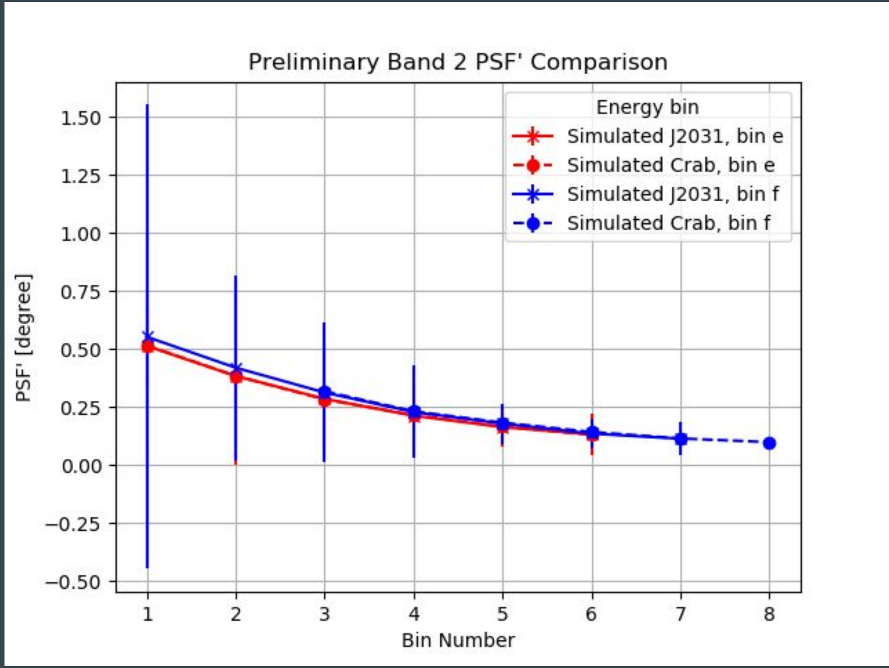
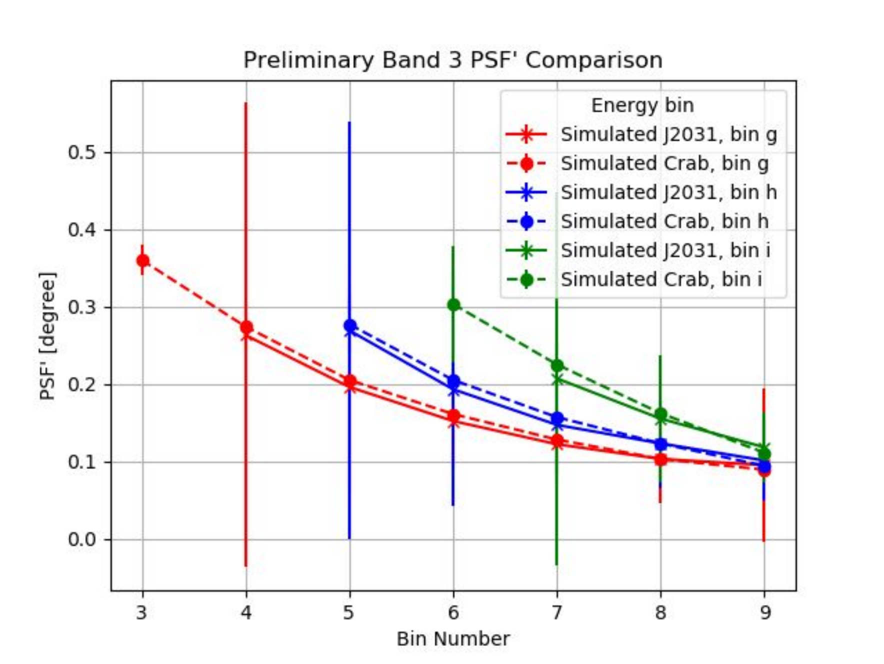
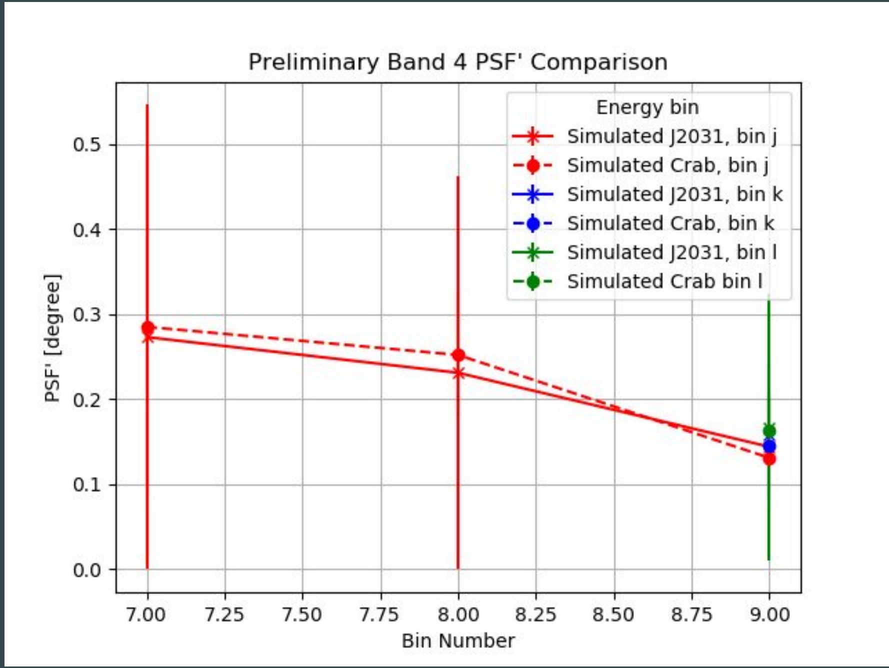
HAWC J2031+415 vs Crab simulation





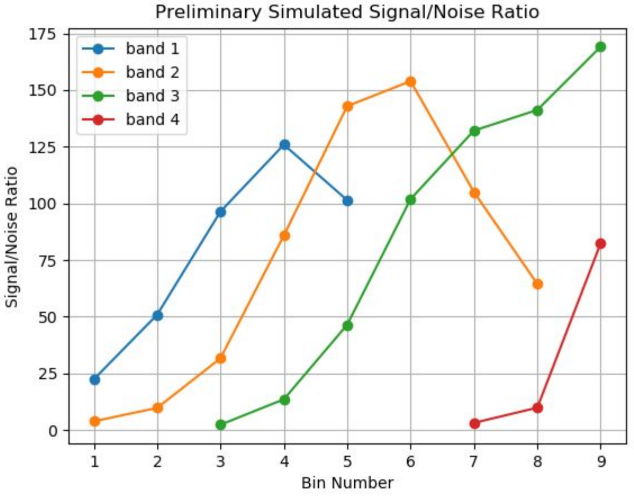
HAWC J2031+415 vs Crab simulation continued

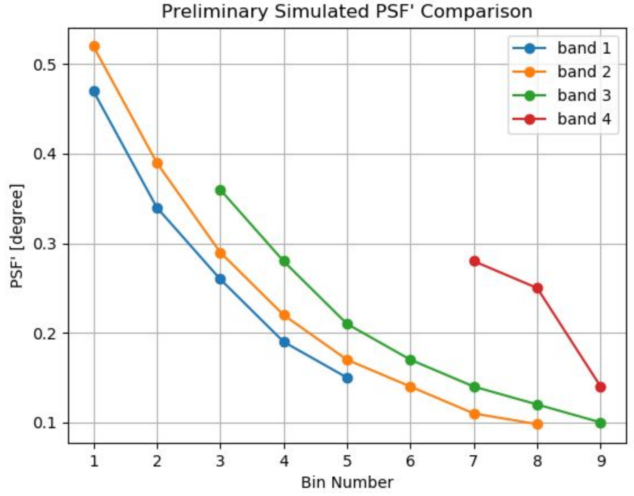




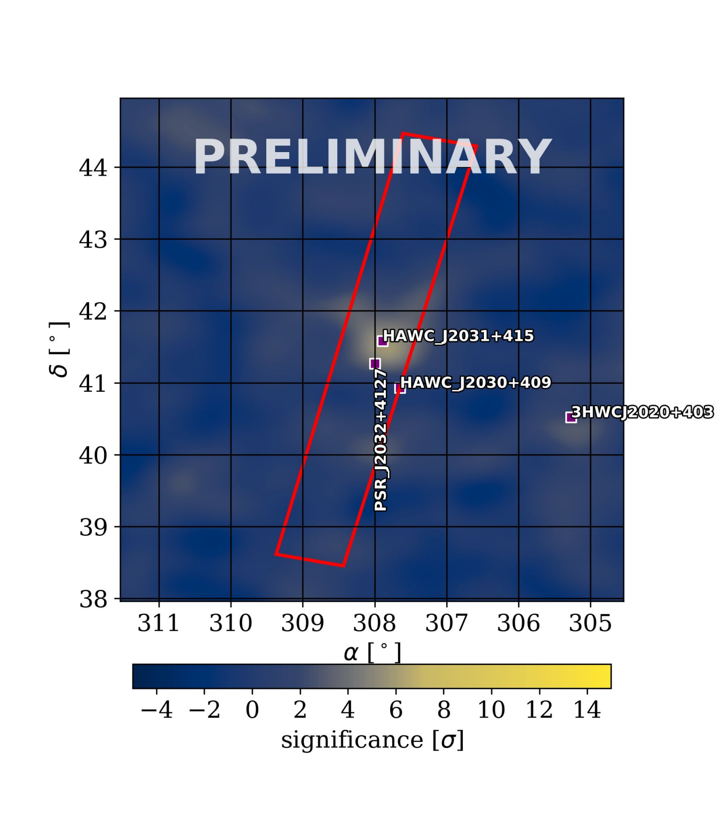
Bin cutting

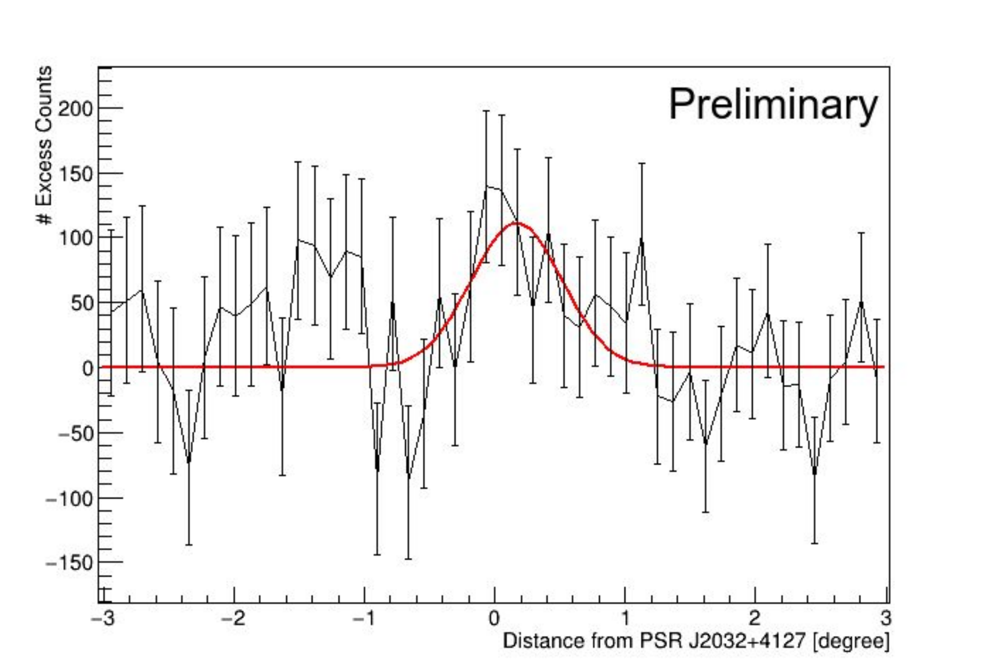
- ❖ Pick best S/N value
- ❖ Keep any following bins
  - ➢ If lower, PSF' roughly within 25% of best S/N PSF'
- ❖ Maximize "good" data
  - ➢ Band 1 = 3c 3d, 4c, 4d
  - ➢ Band 2 = 5e, 5f, 6e, 6f, 7f
  - ➢ Band 3 = 7g, 7h, 7i, 8g, 8h, 8i, 9g, 9h, 9i
  - ➢ Band 4 = 8j, 9j, 9k, 9l
- ❖ Dataset
  - ➢ Take subtracted data as excess



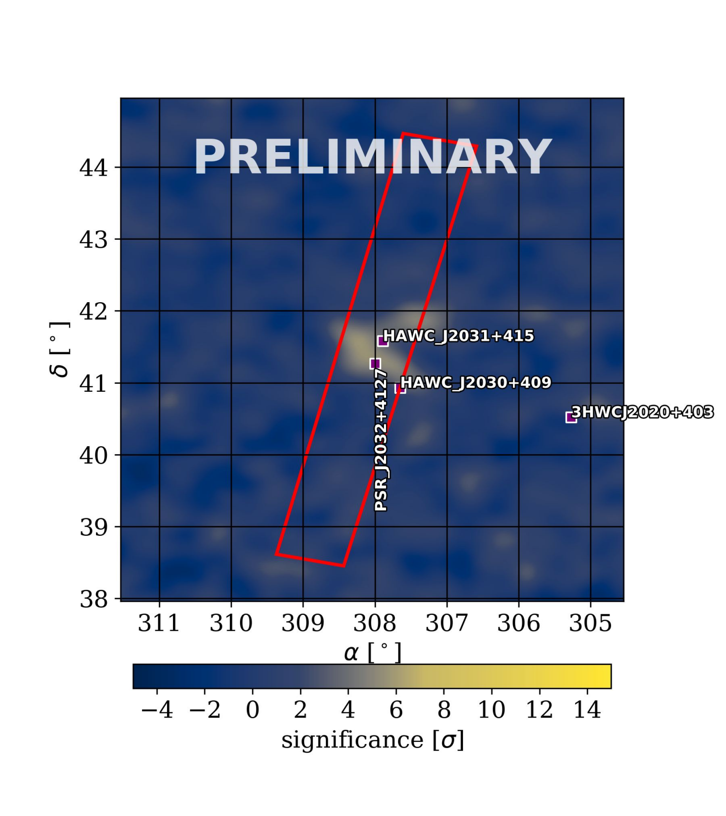


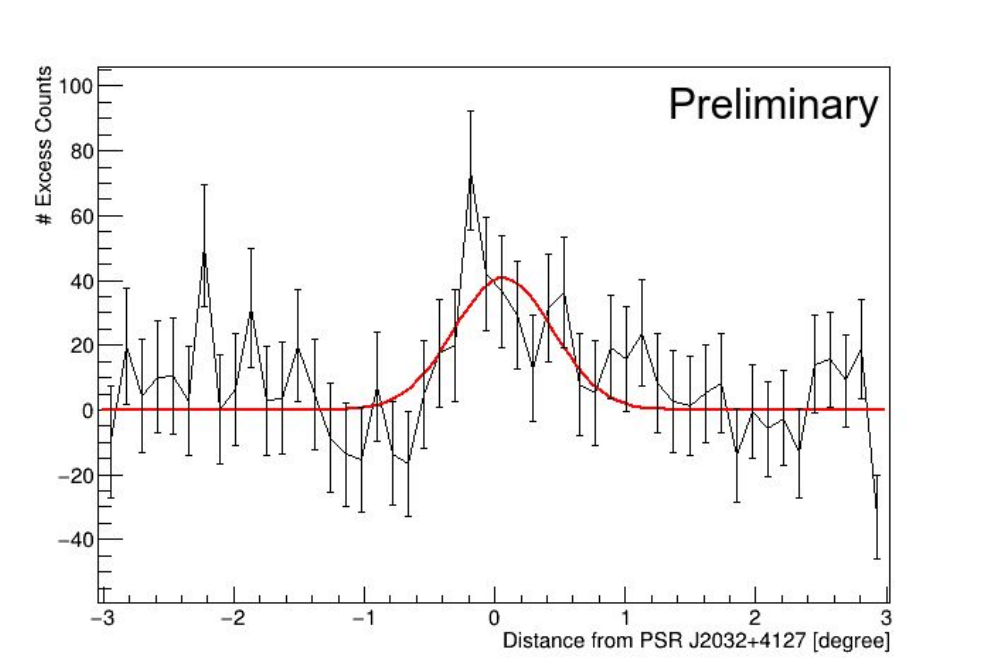
Band 1 (1 - 3.16 TeV)



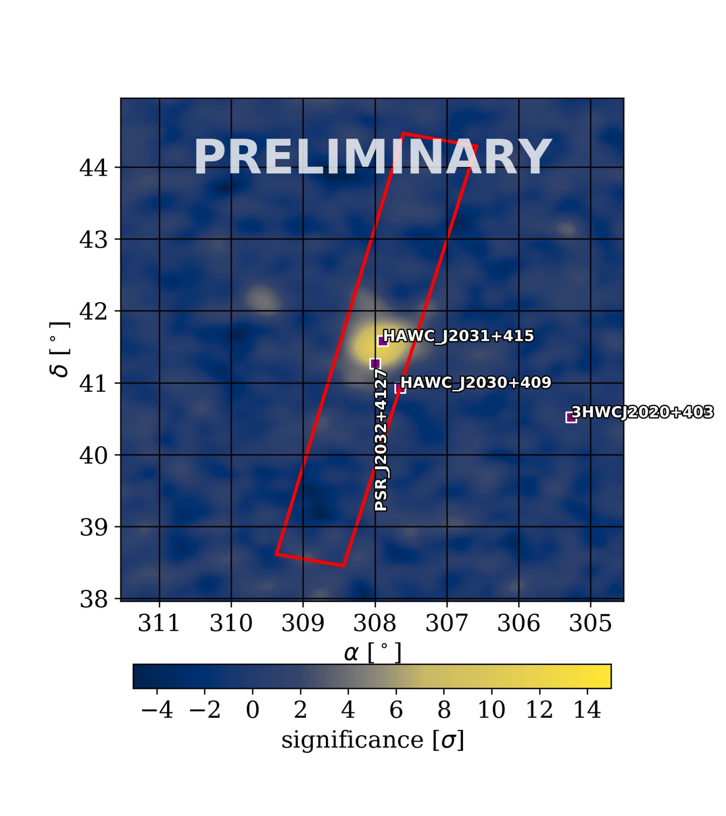


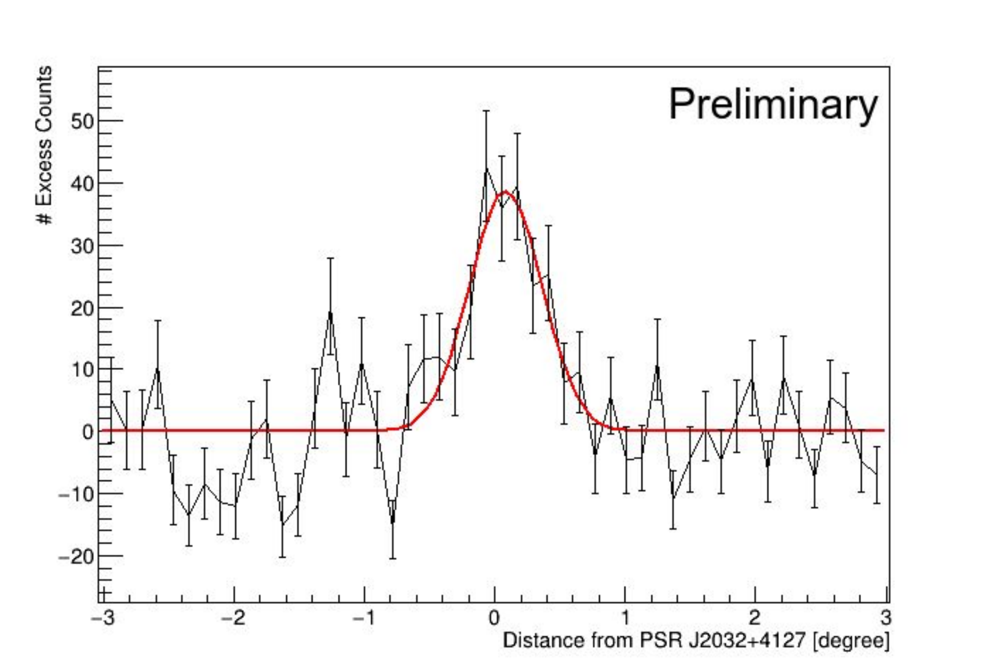
Band 2 (3.16 - 10 TeV)



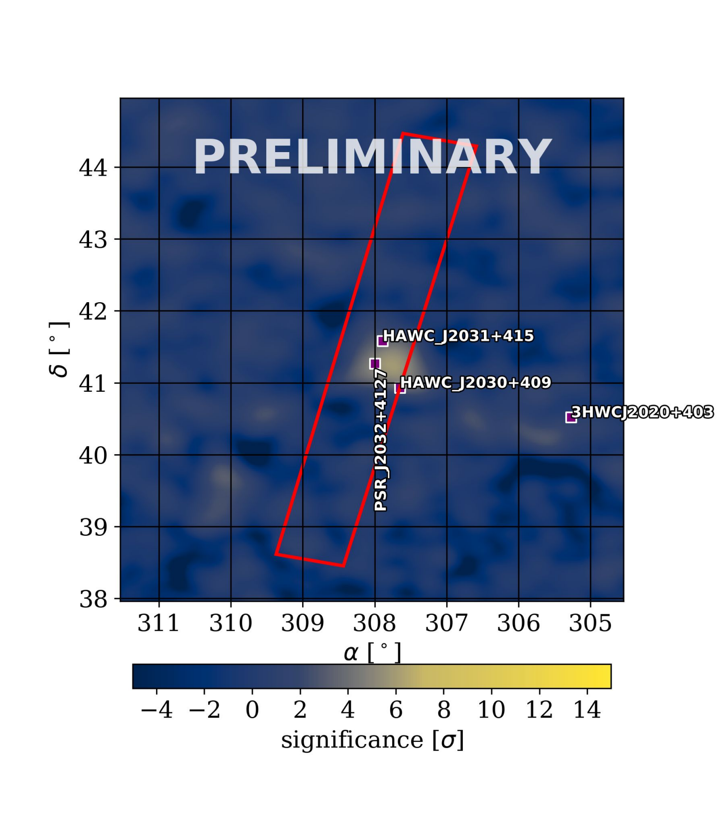


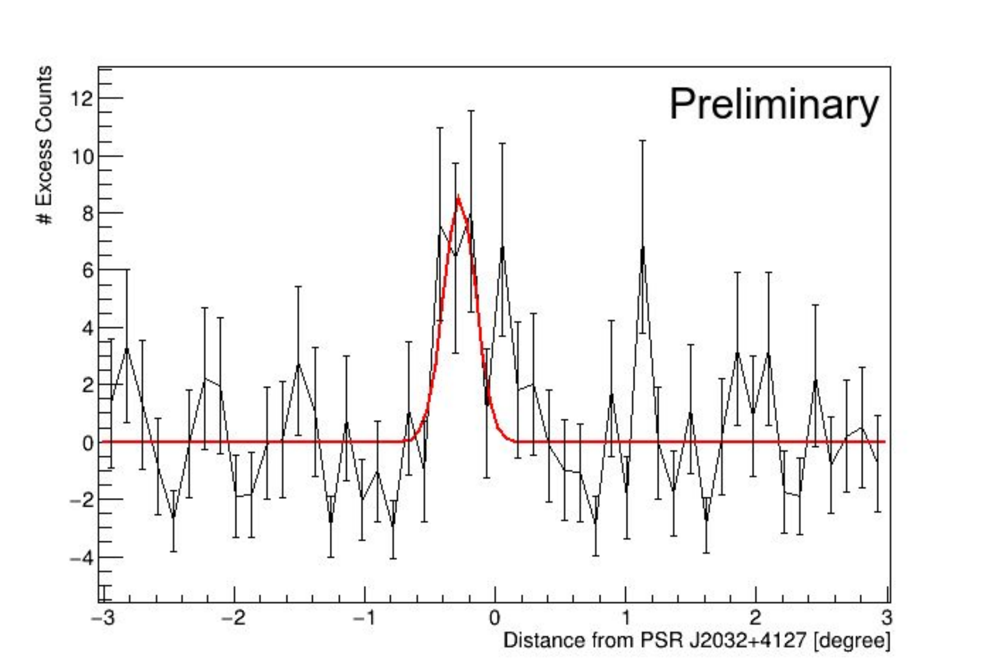
Band 3 (10 - 56.2 TeV)



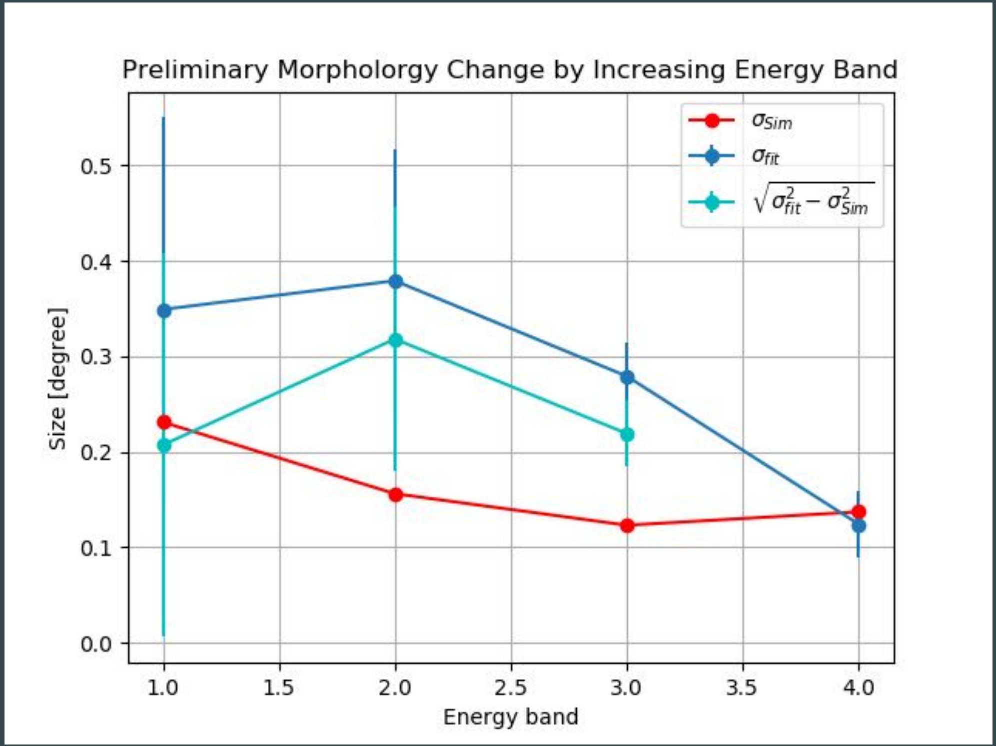


Band 4 (56.2 - 316 TeV)





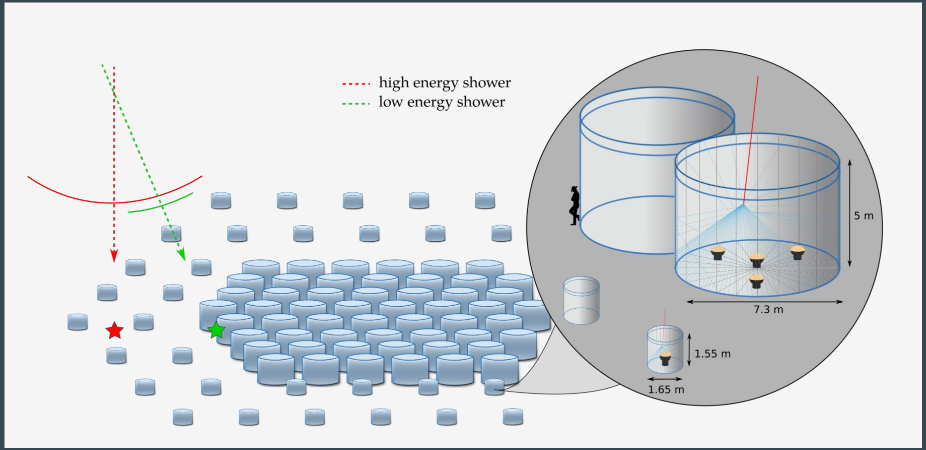
Final morphology result



Future Work

HAWC array and outriggers

- ❖ Investigate emission cause
  - ➢ Hadronic or leptonic
- ❖ Outriggers
  - ➢ Greatly increase sensitivity to > 10 TeV events
  - ➢ Better constrain analysis parameters.



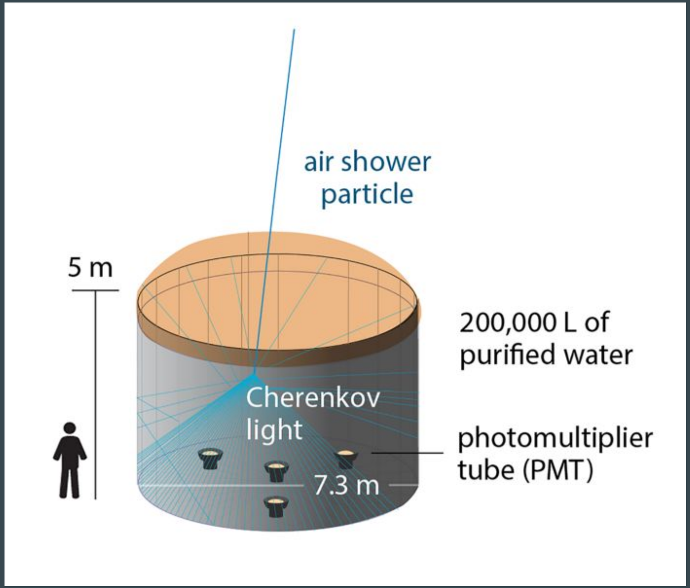
HAWC outriggers and array, courtesy of Armelle Jardin-Blicq

Thank you! Questions?

Backup Slides

HAWC Array

Number of tanks	300
Coverage	2/3 of the sky daily
Duty cycle	> 95%
Area (central array)	22,000 m^2
Area (outriggers)	100,000 m^2
Sensitivity	300 GeV $\rightarrow$ >100 TeV



HAWC vs VERITAS fit parameters

All uncertainties presented are statistical only

HAWC fitting

Fit parameters	J2031+415 (PWN)
σ (deg)	$0.27^{+0.021}_{-0.02}$
N_o (1/(cm^2*TeV*s))	$1.32^{+0.17}_{-0.14} * 10^{-13}$
γ	$-1.96^{+0.17}_{-0.14}$
E_c (TeV)	39^{+20}_{-12}
E_p (TeV)	4.9

VERITAS fitting

Fit parameters	J2031+415
Semi-major (deg)	0.16 ± 0.02
Semi-minor (deg)	0.07 ± 0.01
Tilt angle (deg)	23 ± 6
N_o (1/(cm^2*TeV*s))	$(9.5 \pm 1.6) * 10^{-13}$
γ	2.10 ± 0.14

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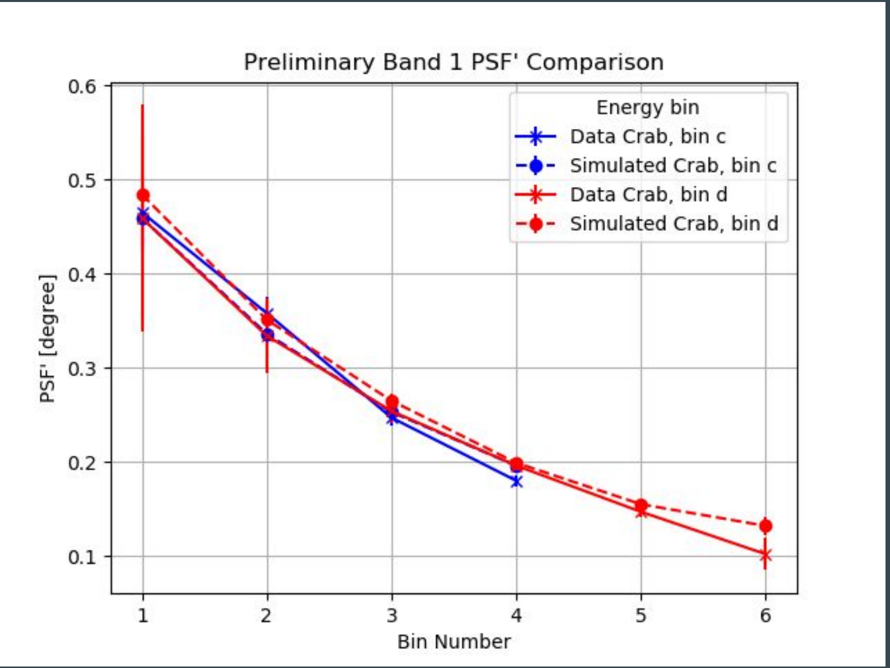
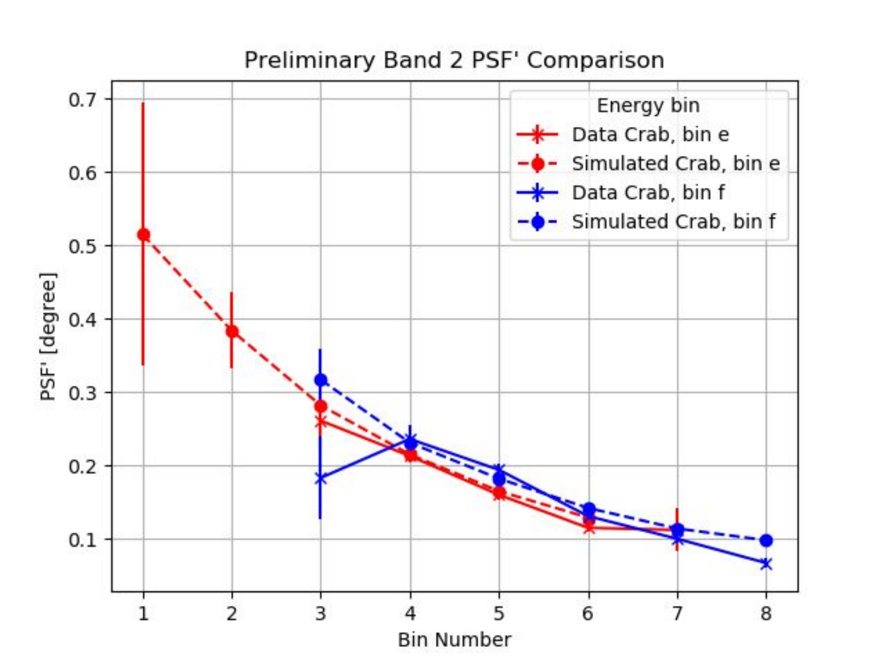
J2031, J2030 and J2020 fit parameters

All uncertainties presented are statistical only

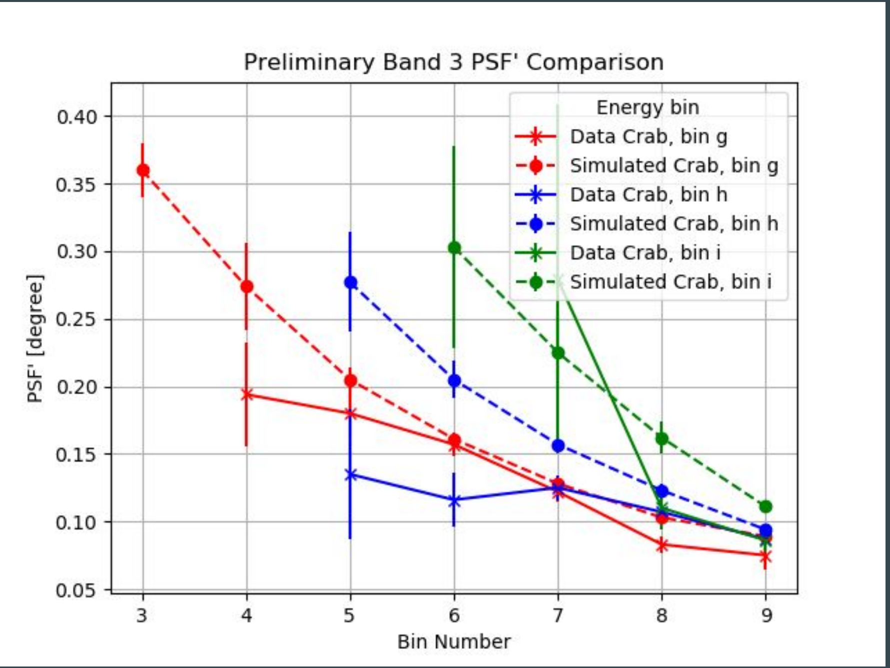
Fit parameters	J2031+415 (PWN)	J2030+409 (Cocoon)	J2020+403 (Gamma Cygni)
σ (deg)	$0.27^{+0.021}_{-0.02}$	2.18 ± 0.17	0.63 (fixed)
N_o (1/(cm^2*TeV*s))	$1.32^{+0.17}_{-0.14} * 10^{-13}$	$(8.9 \pm 0.9) * 10^{-13}$	$57^{+1.1}_{-0.9} * 10^{-13}$
γ	$-1.96^{+0.17}_{-0.14}$	-2.64 ± 0.05	-2.88 ± 0.12
E_c (TeV)	39^{+20}_{-12}	----------------------------	----------------------------------
E_p (TeV)	4.9 (fixed)	4.2 (fixed)	4.2 (fixed)
Fit parameters	372.1	151.9	43.0

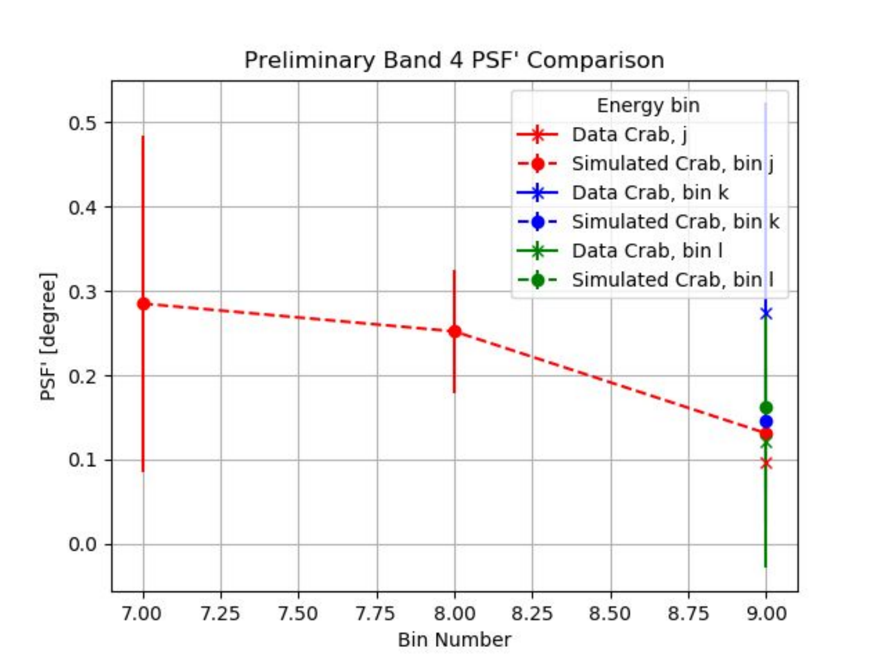
Crab data vs simulation

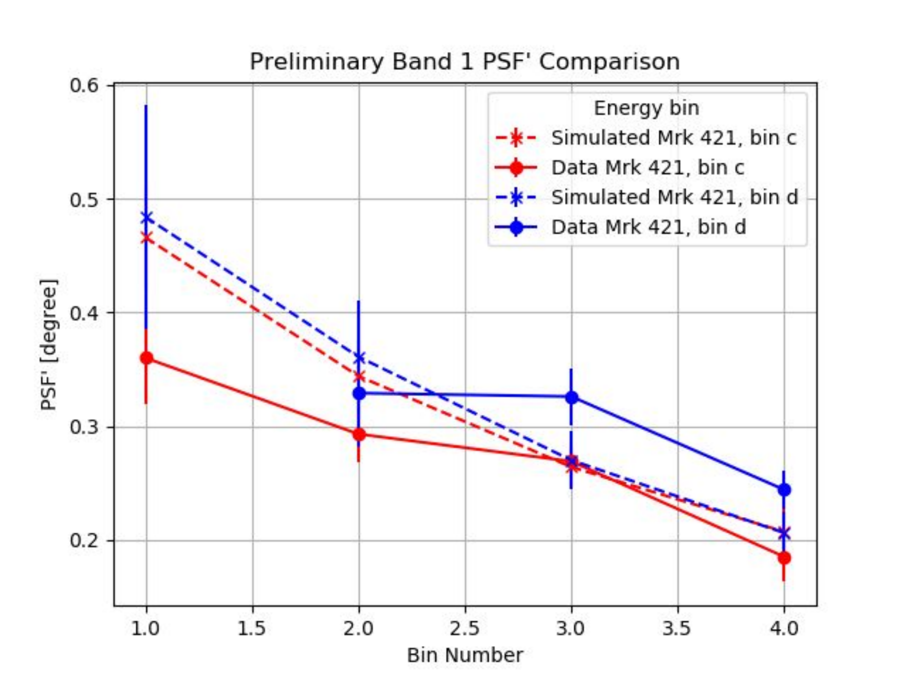


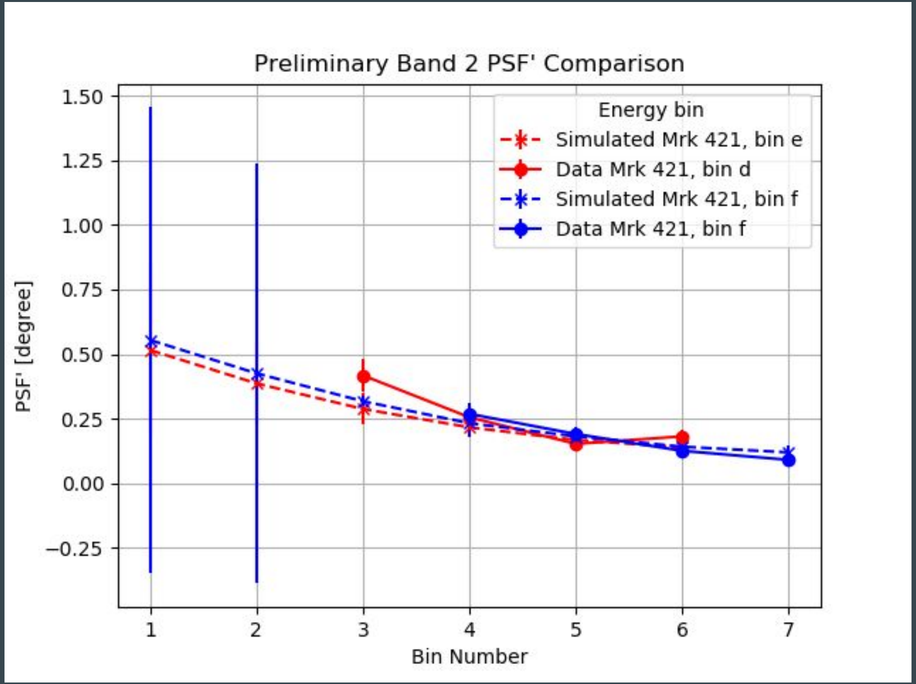


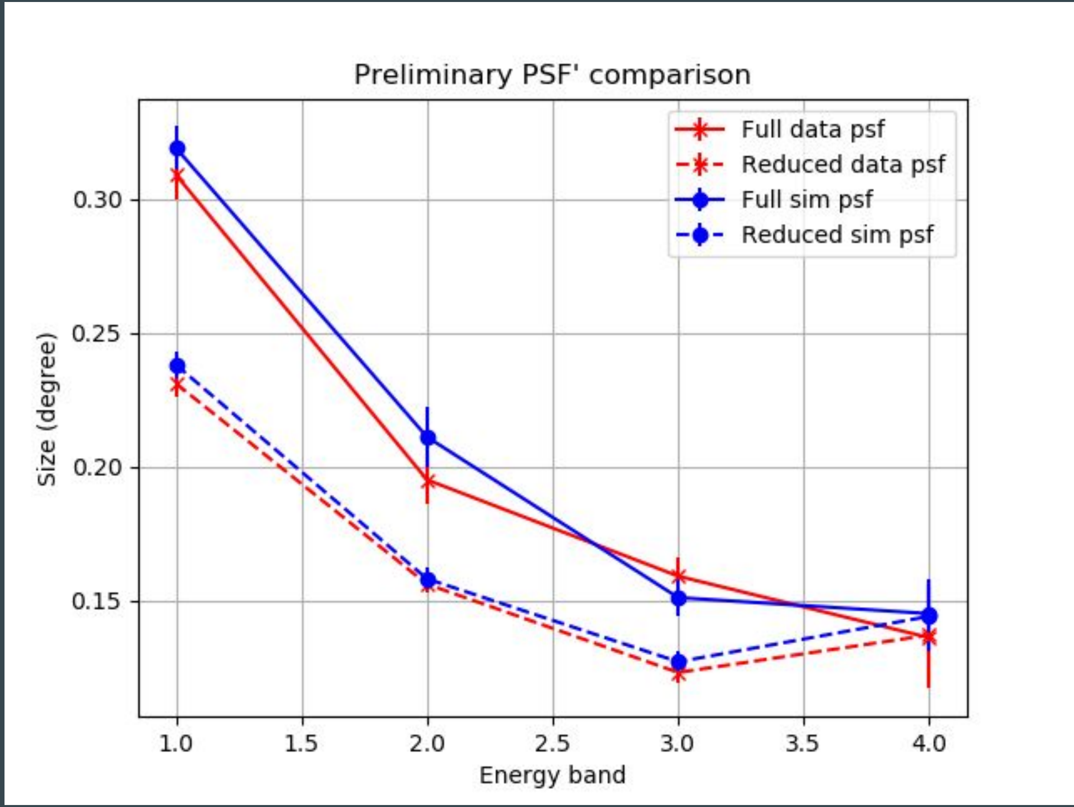
Crab data vs simulation continued






Preliminary Band 1 PSF' Comparison
Energy bin
Simulated Mrk 421, bin c
Data Mrk 421, bin c
Simulated Mrk 421, bin d
Data Mrk 421, bin d
PSF' [degree]
Bin Number
0.6
0.5
0.4
0.3
0.2
1.0
1.5
2.0
2.5
3.0
3.5
4.0


Preliminary Band 2 PSF' Comparison
Energy bin
Simulated Mrk 421, bin e
Data Mrk 421, bin d
Simulated Mrk 421, bin f
Data Mrk 421, bin f
PSF' [degree]
Bin Number
1.50
1.25
1.00
0.75
0.50
0.25
0.00
−0.25
1
2
3
4
5
6
7


Preliminary PSF' comparison
Full data psf
Reduced data psf
Full sim psf
Reduced sim psf
Size (degree)
0.30
0.25
0.20
0.15
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Energy band