Characterizing γ-ray sources with HAL (HAWC Accelerated Likelihood) and 3ML

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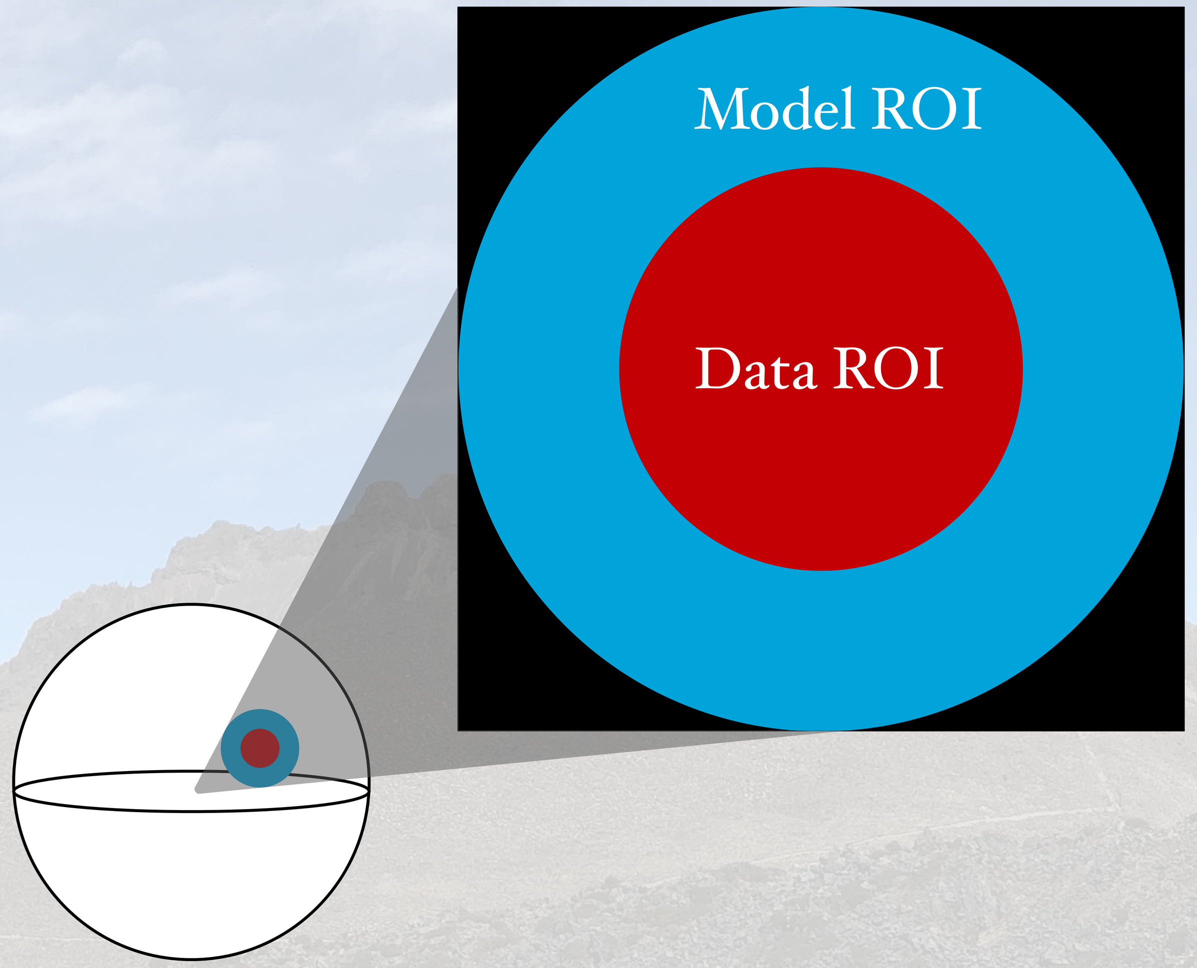
Abstract:

The open-source Multi-Mission Maximum likelihood (3ML) Framework allows for the common analysis of diverse datasets. The ability to consistently fit and characterize astronomical data across many decades in energy is key to understanding the origin of the emission we measure with many different instruments. 3ML uses plugins to encapsulate the interfaces to data and instrument response functions. The user can then define a model with one or multiple sources to describe a given region of interest. The model is fit to the data to determine the locations, spatial shapes, and energy spectra of the sources in the model. The High Altitude Water Cherenkov (HAWC) Observatory, a wide FoV instrument sensitive to energies from 300 GeV to above 100 TeV, has used 3ML for data analysis for several years using a plugin optimized for single source analysis. As multisource fitting became more common, a faster plugin was required. Spectral fits to the Crab Nebula and the nearby source HAWC J0543+233 obtained using HAL, the HAWC plugin for 3ML, will be presented.

Why HAWC Accelerated Likelihood?

The first HAWC Plugin for 3ML was based on a program called LiFF (Likelihood Fitting Framework), and suffered from 3 bottlenecks, which are significantly improved in HAL.

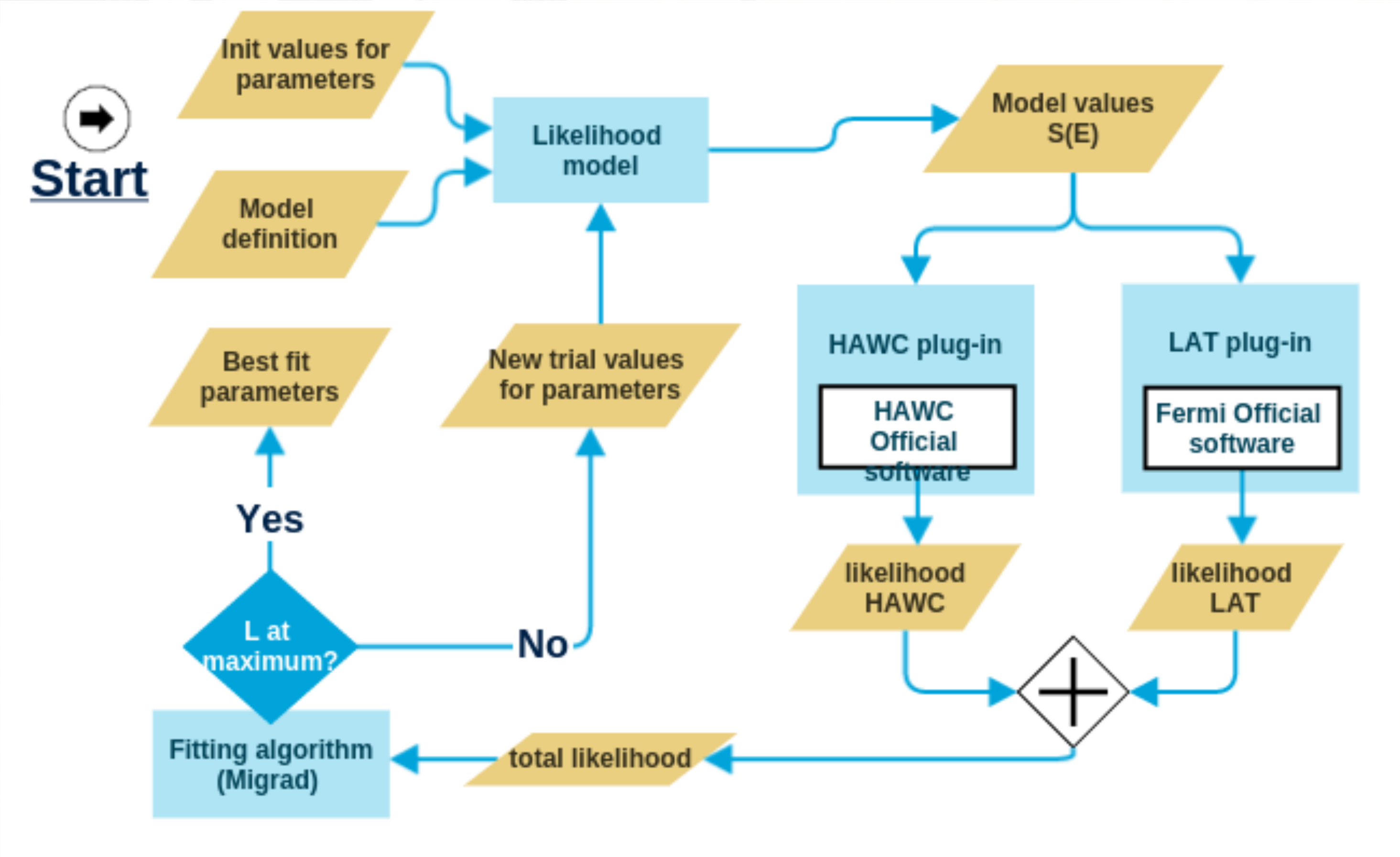
- Slow Convolution for Extended sources
  - Solved using FFTs in a plane projection on the sky rather than Spherical Harmonics on HEALPix grid
- Model Evaluation
  - Only recompute sources that have changed since previous iteration
- Likelihood Evaluation
  - Spend time optimizing the likelihood function itself



3ML & Astromodels

astromodels

The 3ML framework enables multiwavelength data analysis in a statistically consistent way across a wide range of energies [1,2]. Even when used for a single instrument, the astromodels package allows the arbitrary definition of one or more sources and their spectra in a flexible way that enables complex fits to be performed with relative ease [2,3]. Using the HAWC plugin for 3ML, HAL, we can produce a likelihood for that model using the HAWC data, and arrive at an answer for the best-fit model using either frequentist or Bayesian methods. Using other plugins (from Fermi-LAT, Swift XRT, all OGIP-compliant instruments, POLAR, VERITAS, INTEGRAL/SPI, or KONUS) we can examine a region of the sky over very wide energy ranges in order to better understand the emission from the region.



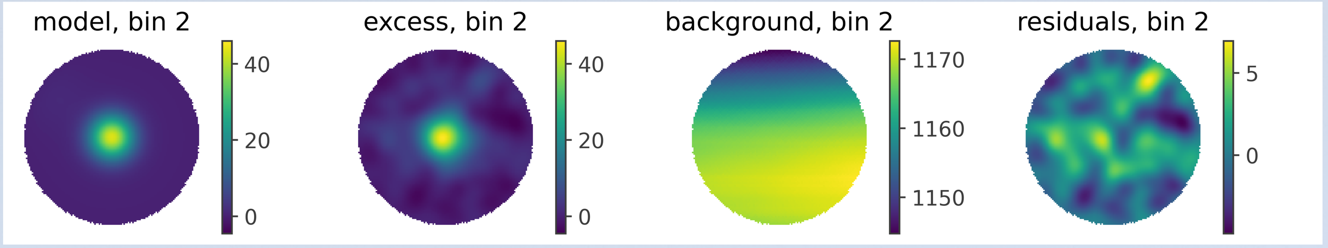
Example Analysis with Crab Nebula and HAWC J0543+233:

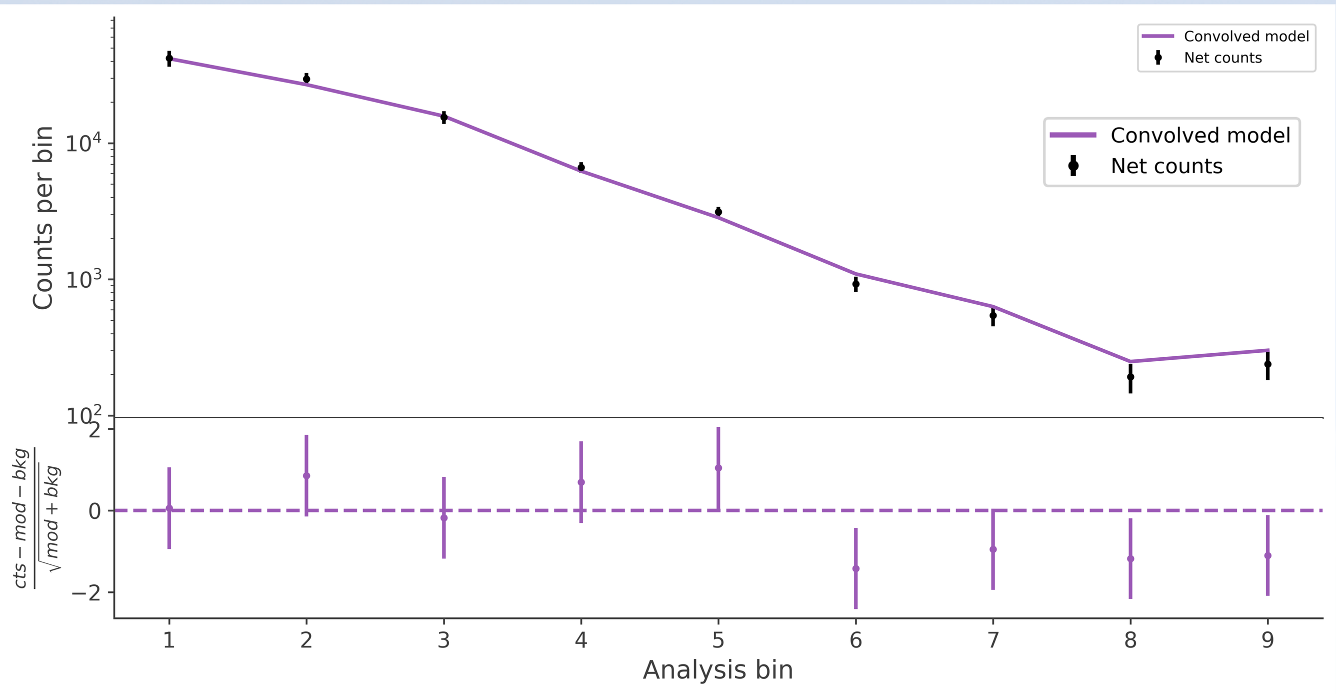
Using the HAWC Public Crab Dataset [4], consisting of 3° around the Crab location corresponding to the same amount of data reported in [5], we fit this region with two models: one with the Crab, and one including the Crab and HAWC J0543+233 [6].

Fit Comparison

The parameters the log parabola spectrum (index α, curvature β) converge to are different from [5] due to updated detector response files. Additionally, HAWC J0543+233 is 2.4° away from the center of the region of interest, so the limited dataset increases the uncertainty for this source. HAWC J0543+233 was fit with a Gaussian morphology, with an extent of 0.62°±0.24°. A larger ROI should be used to draw firm conclusions regarding the spectrum or extent for this source.

Source	Flux Norm at 7 TeV [10^{-13} TeV^{-1} cm^{-2} s^{-1}]	α	β [10^{-1}]
Crab Nebula [4]	2.51±0.11	-2.63±0.03	1.5±0.3
Crab Nebula (1 source)	2.54±0.06	-2.65±0.02	1.04±0.14
Crab Nebula (2 source)	2.54±0.06	-2.65±0.02	1.04±0.14
HAWC J0543+233	$0.18^{+0.15}_{-0.08}$	-2.25±0.29	0 (fixed)



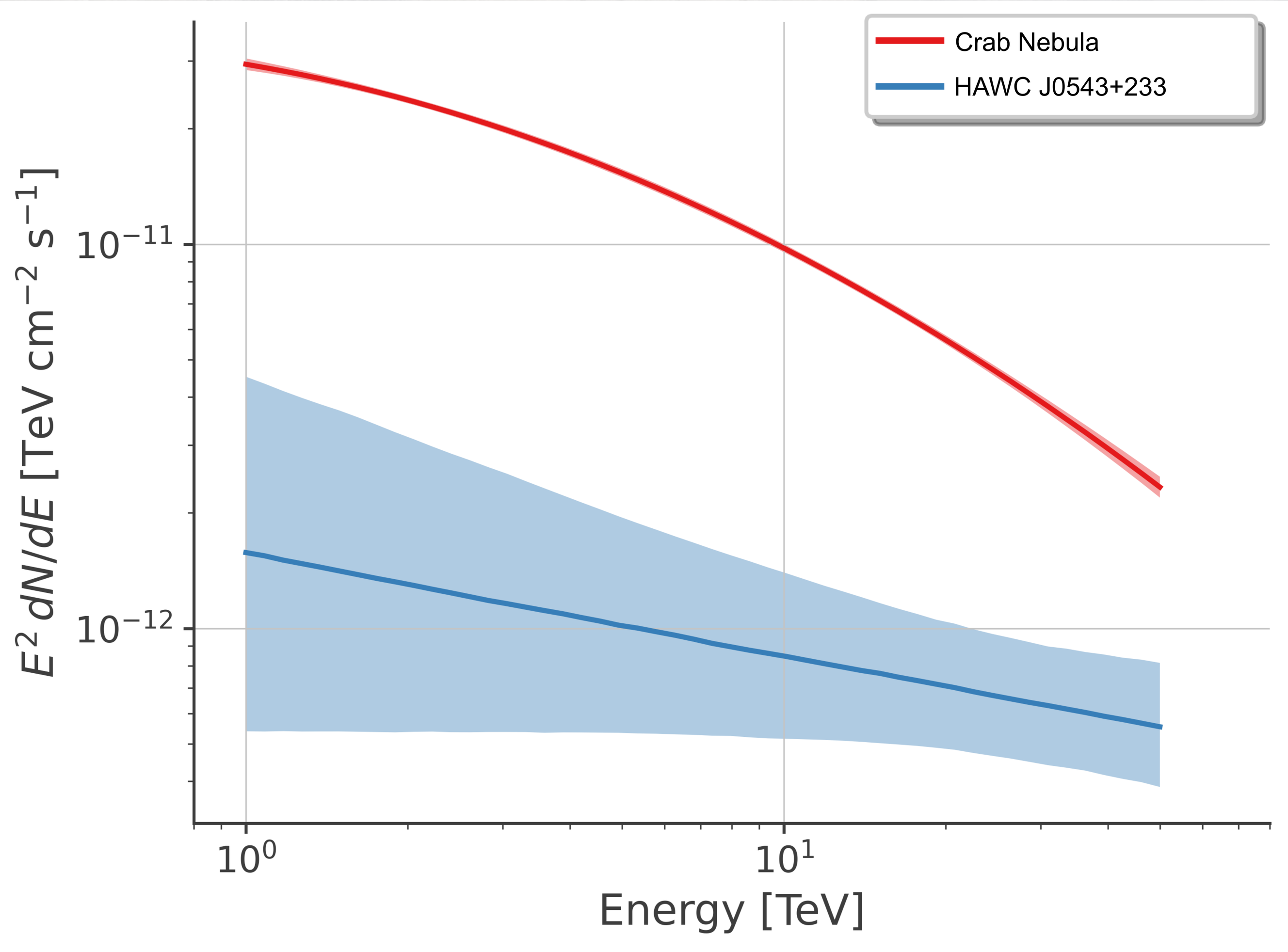


Demonstration Plots

The top right plot shows smoothed counts in the projected plane of the data ROI, for the model, excess, background, and residuals. This output is provided by HAL for each bin in an analysis.

The middle right plot is referred to as the counts residuals plot, where the number of events predicted by the model is compared to the number of events in the data ROI.

The bottom right plot is a spectral energy distribution plot including the Crab Nebula and HAWC J0543+233 in the model including both of them. The much lower significance of HAWC J0543+233 is evident in the very wide error band, relative to the Crab Nebula.



Outlook

Due to HAL's common use within HAWC, it will continue to be used in the future for most analyses. Future public data availability of larger regions of the galaxy will enable the analysis by anyone of HAWC data. This will allow them to combine their data with HAWC, and make new discoveries!

References:

[1] Vianello, G., Robert, L., Younk, P., et al. The Multi-Mission Maximum Likelihood framework (3ML), ICRC, 34, 1042 (2015)

[2] https://github.com/threeML/threeML

[3] https://github.com/threeML/astromodels

[4] https://data.hawc-observatory.org/datasets/crab_data/

[5] Abeysekara, A. U. et al. Observation of the Crab Nebula with the HAWC Gamma-Ray Observatory. Astrophys. J. 843, 39 (2017)

[6] Riviere, Fleischhack, Sandoval, HAWC detection of TeV emission near PSR B0540+23, ATel#10941, (2017)