MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Drifting instruments and the VODF

The case of HAWC (and SWGO)

Astroparticle symposium 2022

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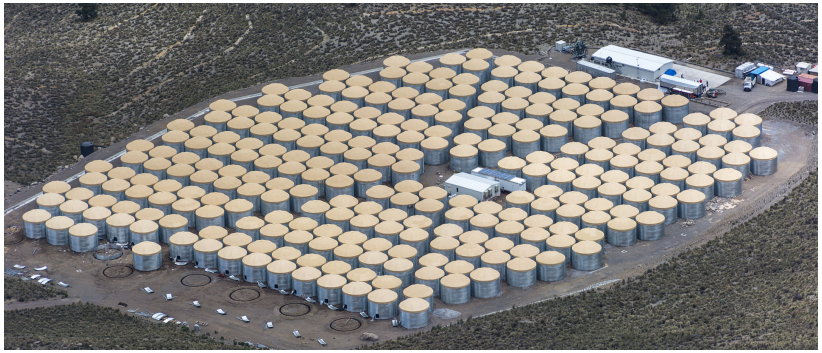
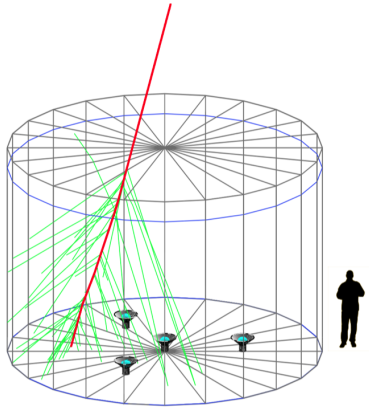
SWGO
The Southern Wide-field Gamma-ray Observatory

The HAWC observatory

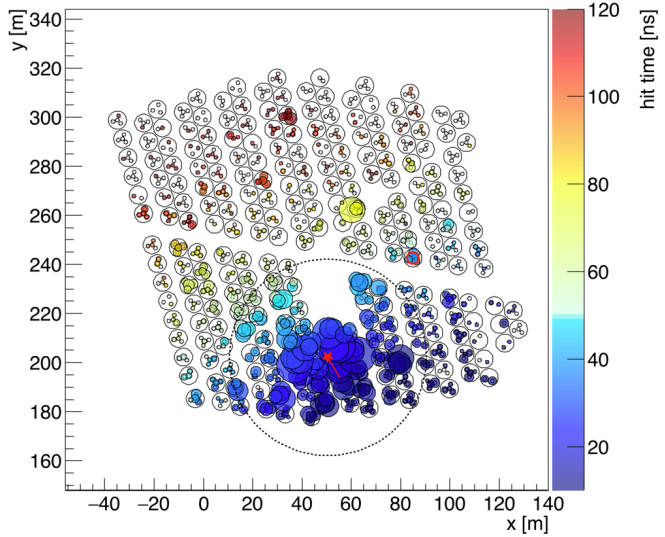




- An array of 300 tanks located in the flanks of the Sierra Negra in Mexico
- Very high duty cycle, with (almost) continuous observations
- Views 2/3 of the sky every day (including during the day!) → 24h long runs
- Very large data volume (500 MB/s raw → 20 MB/s reduced data ~ 2TB/day)
- Designed for the range 100 GeV to 100 TeV
- Typical zenith range used < 60°

The fHit binning scheme

- Properties of reconstructed events in HAWC depend very strongly on the **number of tanks that were triggered** → **fHit** parameter
- Very different PSF and G/H separation threshold between bins
- Very different file sizes between bins!
- Together with energy axis → 2D bins.
- **different event types**

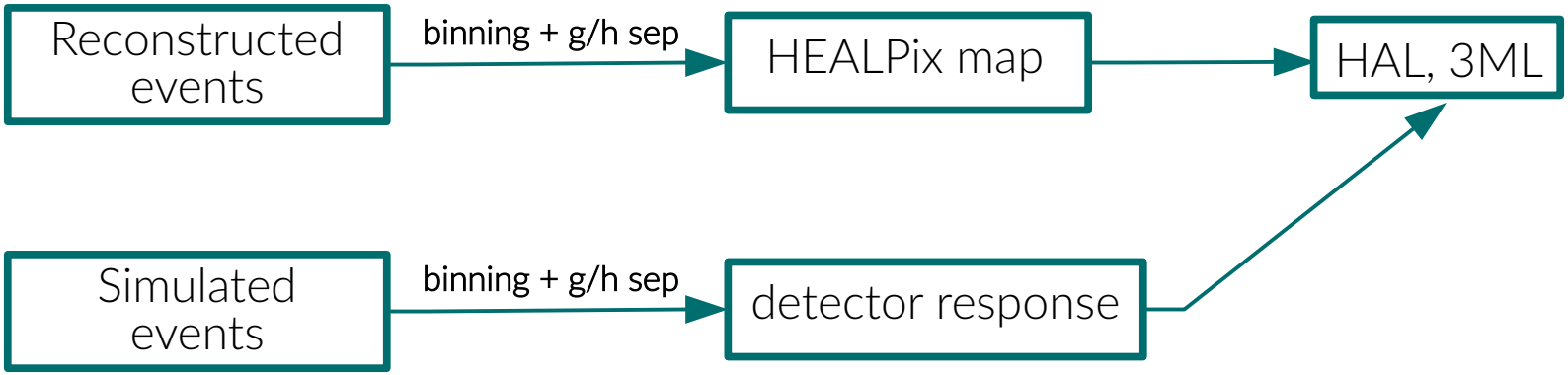


Bin number	Low fraction hit	High fraction hit
1	0.067	0.105
2	0.105	0.162
3	0.162	0.247
4	0.247	0.356
5	0.356	0.485
6	0.485	0.618
7	0.618	0.740
8	0.740	0.840
9	0.840	1.00

Bin	$\hat{E}$ energy range (TeV)
c	1-1.78
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

The standard HAWC analysis workflow

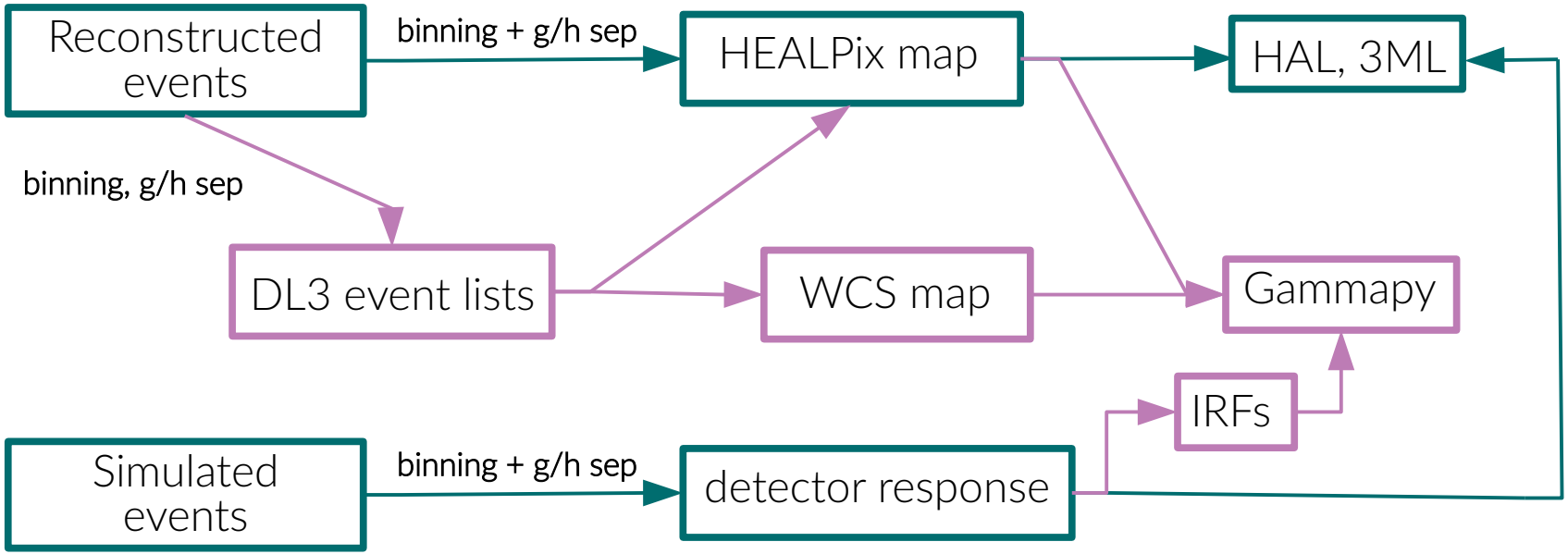
standard



Issues: time information lost, spatial binning fixed, map-making extremely computationally intensive process

The expanded HAWC analysis workflow using Gammapy

expanded



HAWC analysis using DL3 products – event lists

- DL3: gamma-like events, with "science ready" parameters
- Mandatory columns: EVENT_ID, TIME, RA, DEC
- Can keep any other field that is relevant (e.g. fHit or core location)
- PRO: Time dimension isn't lost!
- PRO: Map-making becomes much more flexible and faster
- CON: Depending on cut tightness, file sizes can be a problem → need to find a right balance for the smallest unit of time that defines an event list file

- **much larger file sizes**
- **concept of "observation" not well defined**
- **event types!**

HAWC Collaboration: Validation of standardized data formats and tools for particle detector arrays.

Event ID	R.A (deg)	Dec. (deg)	Energy (TeV)	Time (s)	Core X (m)	Core Y (m)	Bin ID
1	296.401	18.649	6.698	1132183230.200404	50.4	212.8	7f
2	305.046	27.225	7.063	1132183236.213954	-30.7	214.9	7f
3	16.556	14.990	7.709	1132183250.7916136	-37.1	214.9	6f

Table 2: Simplified entries of an event list. Note that the real precision of the numbers has been reduced for formatting convenience.

HAWC analysis using DL3 products – event lists

- Existing standard was remarkably compatible with the needs of drifting instruments
- Only one change needed: make pointing information more flexible in file header
- Definition of observation mode “DRIFT”

In addition to the OGIP-defined values (`POINTING` , `RASTER` , `SLEW` and `SCAN`), we define the option `DRIFT` to accomodate ground-based wide-field instruments, in which local zenith/azimuth coordinates remain constant. In this case, the header keywords `RA_PNT` and `DEC_PNT` are no longer mandatory, and instead `ALT_PNT` and `AZ_PNT` are required.

- `OBS_MODE` **type: string**
  - Observation mode. See notes on OBS_MODE below.
- `RA_PNT` **type: float, unit: deg**
  - Pointing Right Ascension (see RA / DEC). Not mandatory if `OBS_MODE=DRIFT` , but average values could optionally be provided.
- `DEC_PNT` **type: float, unit: deg**
  - Pointing declination (see RA / DEC). Not mandatory if `OBS_MODE=DRIFT` , but average values could optionally be provided.
- `ALT_PNT` **type: float, unit: deg**
  - Pointing Altitude (see Alt / Az). Only mandatory if `OBS_MODE=DRIFT`
- `AZ_PNT` **type: float, unit: deg**
  - Pointing azimuth (see Alt / Az). Only mandatory if `OBS_MODE=DRIFT`

HAWC analysis using DL3 products– IRFs

- Instrument response functions describe the combined detection abilities and precision of an instrument data-taking and reconstruction procedure
- Angular resolution (PSF): accuracy of reconstruction of the direction of the incident gamma-ray,
- Energy resolution (EDISP): accuracy of reconstruction of the energy of the incident gamma-ray,
- Effective area (AEFF): detection probability of the incident gamma-ray,
- Residual hadronic background: expected residual hadronic background by misclassified events
- All derived from simulations except sometimes background (when you have data!)

HAWC analysis using DL3 products – IRFs

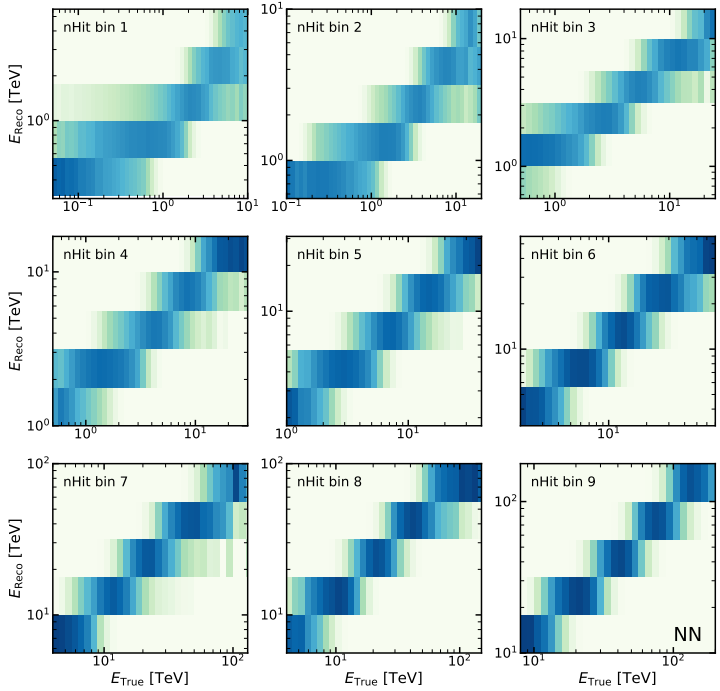
- In IACTs, IRFs are typically given as a function of energy (reconstructed and/or true) and offset from pointing position
- The latter is obviously not very useful for an instrument like HAWC
- The HAWC response depends on energy and zenith
- Two options:
    1. Zenith binned IRFs → Need to be integrated with relevant source path before being used
    2. Declination binned IRFs → Case 1 but integrated for 1 source transit
- Case 1 needed for transits, case 2 more practical for longer exposure analysis

HAWC analysis using DL3 products – declination binned-IRFs

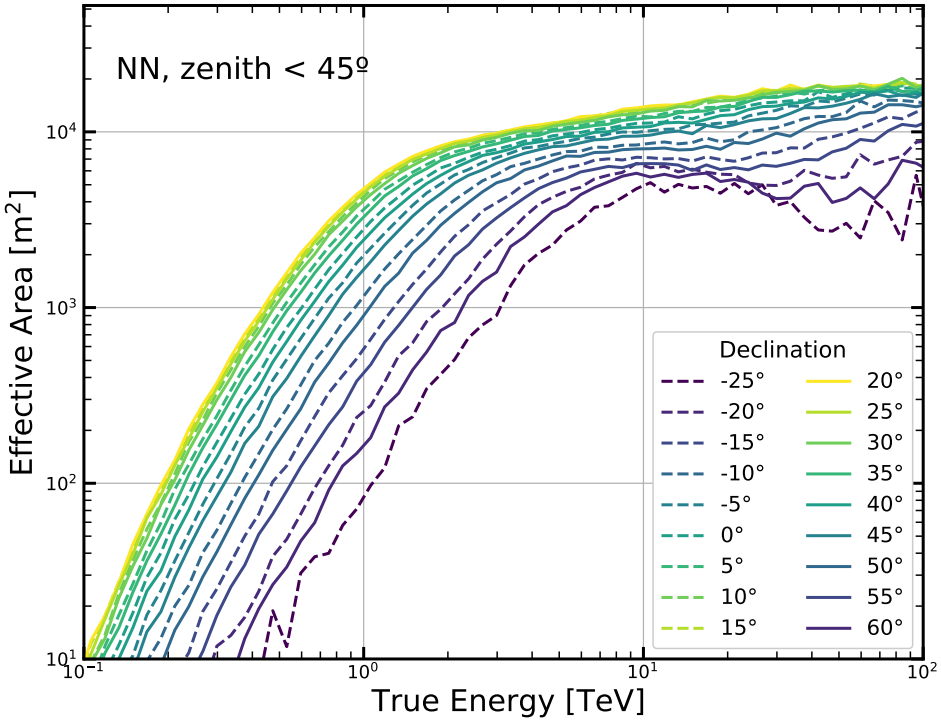
- For a given Earth location, the path that any source covers on the sky depends on its declination
- For example, at HAWC location, the Crab transits near zenith, but HAWC J1825-134 doesn't get very high
- The relevant quantity is the fraction of the time that a source spends in each zenith band → weights
- Use this weights to integrate the zenith-dependent response
- "Declination-binned" = full-sky map

```
class IRFMap:
    """IRF map base class for DL4 instrument response functions"""
```

HAWC analysis using DL3 products – declination binned-IRFs



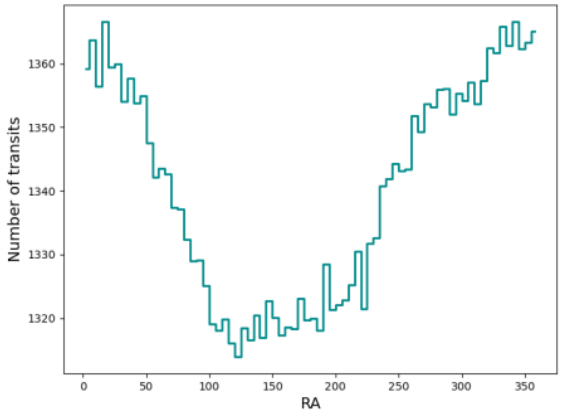
Crab location



HAWC analysis using DL3 products– exposure and GTI

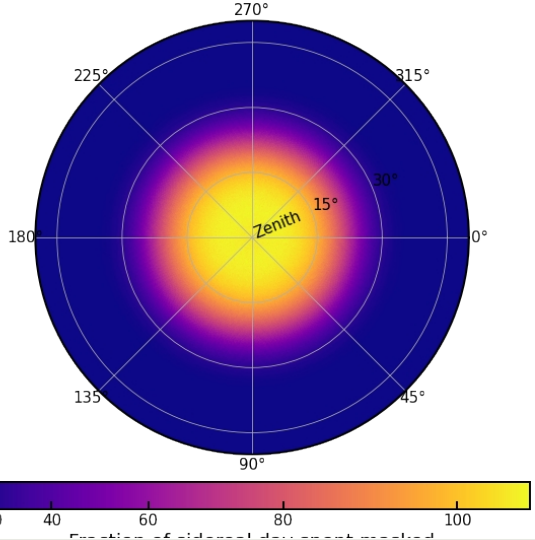
- Another useful quantity defined by the standard are the “Good-time intervals” or GTI
- Defined in the same way as in for the Fermi-LAT
- Time intervals during which the detector is on and taking data continuously
- In HAWC: we determine data quality at the “sub-run” level (125 seconds of data)
- Use GTIs to estimate the number of transits (depends on R.A.!) contained in an event list
- Combine with effective area for 1 transit

START	STOP
float64	float64
1168135330.0	1168135455.0
1168135455.0	1168135580.0



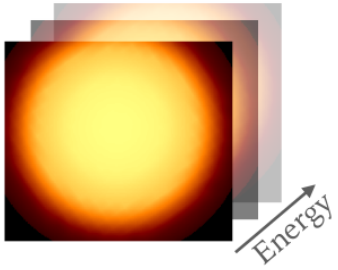
HAWC analysis using DL3 products – background

- Derived using data in regions where no gamma-ray sources are expected
- Again can be described as a rate as a function of zenith or as a full-sky map
- Which one is useful depends on the type of analysis

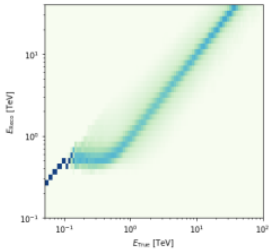


IACT "DL4" Data Model

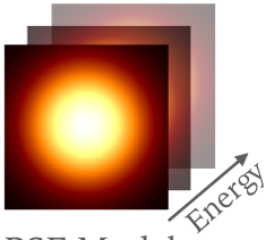
$$N_{Pred} = N_{Bkg} + \mathrm{EDISP}(\mathrm{PSF}(\mathscr{E} \cdot f_{Src}))$$



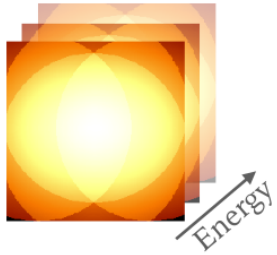
BKG Model



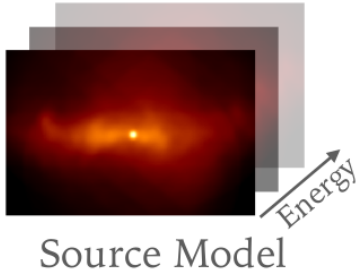
Energy Dispersion Matrix



PSF Model



Exposure
(effective Area x livetime)



Source Model

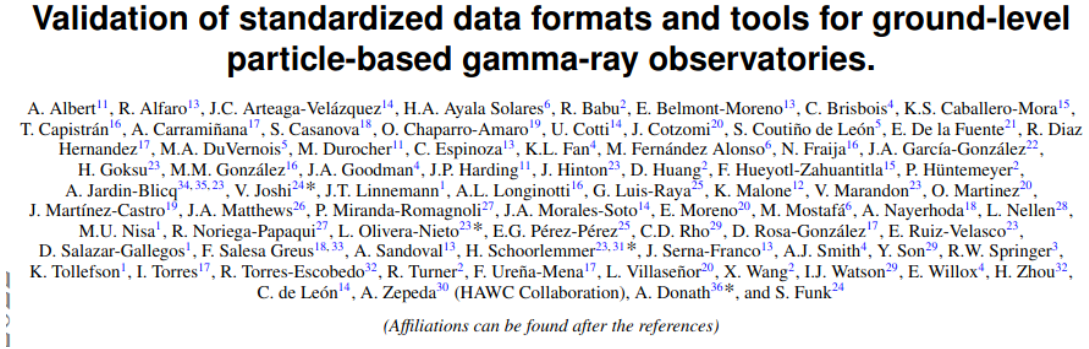
HAWC PSF is given in reco energy

Validation using Gammapy

Once all of the ingredients are ready, we set out to test the scheme in several steps

1. Basic low level checks
2. Point source analysis
3. Extended source analysis
4. Time-domain analysis
5. Joint analysis with other gamma-ray instruments

published in A&A!



Validation of standardized data formats and tools for ground-level particle-based gamma-ray observatories.

A. Albert[11], R. Alfaro[13], J.C. Arteaga-Velázquez[14], H.A. Ayala Solares[6], R. Babu[2], E. Belmont-Moreno[13], C. Brisbois[4], K.S. Caballero-Mora[15], T. Capistrán[16], A. Carramiñana[17], S. Casanova[18], O. Chaparro-Amaro[19], U. Cotti[14], J. Cotzomi[20], S. Coutiño de León[5], E. De la Fuente[21], R. Diaz Hernandez[17], M.A. DuVernois[5], M. Durocher[11], C. Espinoza[13], K.L. Fan[4], M. Fernández Alonso[6], N. Fraija[16], J.A. García-González[22], H. Goksu[23], M.M. González[16], J.A. Goodman[4], J.P. Harding[11], J. Hinton[23], D. Huang[2], F. Hueyotl-Zahuantitla[15], P. Hüntemeyer[2], A. Jardin-Blicq[34,35,23], V. Joshi[24]*, J.T. Linnemann[1], A.L. Longinotti[16], G. Luis-Raya[25], K. Malone[12], V. Marandon[23], O. Martinez[20], J. Martínez-Castro[19], J.A. Matthews[26], P. Miranda-Romagnoli[27], J.A. Morales-Soto[14], E. Moreno[20], M. Mostafá[6], A. Nayerhoda[18], L. Nellen[28], M.U. Nisa[1], R. Noriega-Papaqui[27], L. Olivera-Nieto[23]*, E.G. Pérez-Pérez[25], C.D. Rho[29], D. Rosa-González[17], E. Ruiz-Velasco[23], D. Salazar-Gallegos[1], F. Salesa Greus[18,33], A. Sandoval[13], H. Schoorlemmer[23,31]*, J. Serna-Franco[13], A.J. Smith[4], Y. Son[29], R.W. Springer[3], K. Tollefson[1], I. Torres[17], R. Torres-Escobedo[32], R. Turner[2], F. Ureña-Mena[17], L. Villaseñor[20], X. Wang[2], I.J. Watson[29], E. Willox[4], H. Zhou[32], C. de León[14], A. Zepeda[30] (HAWC Collaboration), A. Donath[36]*, and S. Funk[24]

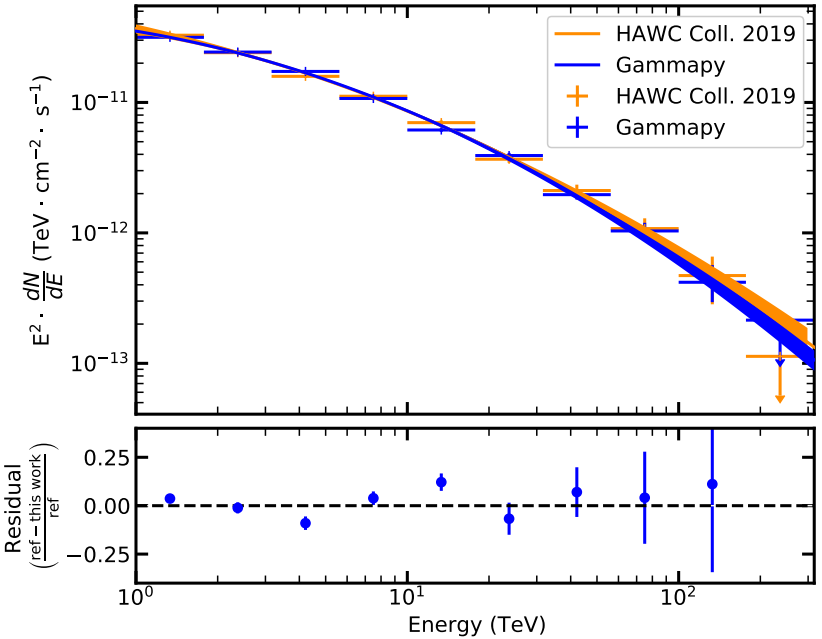
(Affiliations can be found after the references)

Validation – point source: the Crab

- Fit a combined spatial+spectral model jointly between all the relevant fHit bins
- Use both the dataset derived from event lists and the standard HAWC HEALPix map

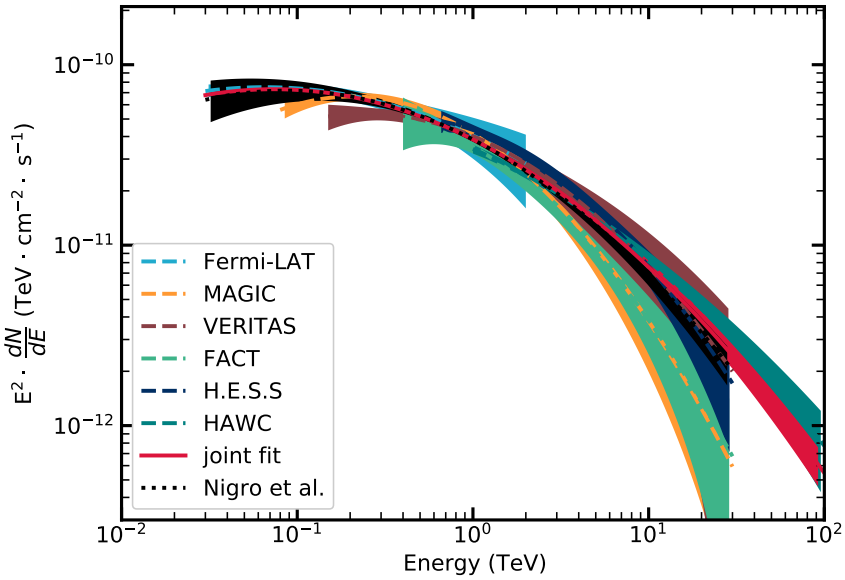
	ϕ_0 (10^{-13} TeV^{-1} cm^2 s^{-1})	α	β
From events	2.39±0.04	2.79±0.02	0.113±0.007
Reference	2.35±0.04	2.79±0.02	0.10±0.01
From map	2.35±0.05	2.79±0.02	0.12±0.01

Table 4: Likelihood fit results for the Crab Nebula. The fit result obtained the DL3 products is given in the row labeled "From events". The fit result obtained using the standard HAWC map products is given in the "From map" row. The values in the "reference" column are taken from Abeysekara et al. (2019).



Validation – joint fit

- Using public data from 5 other gamma-ray instruments
- Repeat the exercise in Nigro et al 2019 and perform a joint analysis of the Crab Nebula
- Most datasets very small, final result not the point → **proof of concept**
- The HAWC data and IRFs used for this plot **have been released together with the paper**



Summary and outlook

- Successfully exported and validated HAWC data to DL3
- Very few changes to the data format/analysis tool were needed for this, although some workarounds are still required to cover more analysis cases
- None of the further required changes are a conceptual roadblock: they just need work
- The HAWC public data release will facilitate this work by providing a test dataset
- The Southern Wide-field Gamma-ray Observatory (SWGO) is planning to use VODF formats from the start, including the currently ongoing IRF production
- Key points: pointing optional or allowed in alt/az coordinates, event types, file sizes, how to best access data, tools to go from zenith-binned to declination binned quantities……