PROCEEDINGS OF SCIENCE

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

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

PoS(ICRC2021)828

Chad Brisbois[a,*] **on behalf of the HAWC Collaboration**
(a complete list of authors can be found at the end of the proceedings)

[a] *University of Maryland College Park,*
College Park, MD, USA
E-mail: chadb@umd.edu

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.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

1. Introduction

The Multi-Mission Maximum Likelihood (3ML) framework[1] enables multiwavelength data analysis in a statistically consistent way across a wide range of energies [1]. Combined with the 3ML affiliated astromodels[2] package allows the arbitrary definition of one or more sources and their spectra in a flexible way that enables multisource fits to be performed with relative ease. 3ML has plugins for many instruments: HAWC, Fermi-LAT, Swift XRT, all OGIP compliant instruments, POLAR, VERITAS, INTEGRAL/SPI, and KONUS. These allow for an analysis to incorporate information from a wide range of energies so that the best understanding of a source or region in the sky can be reached.

The use of 3ML has been ubiquitous within HAWC for several years. The HAWC plugin for 3ML was originally developed as an internal software tool that was largely inaccessible to those outside the collaboration. However the 3ML framework was heavily embedded in important HAWC analyses [2]. Giacomo Vianello was a HAWC member and wrote the original code for HAWC Accelerated Likelihood (HAL)[3].

2. Motivation

The previous HAWC plugin, called HAWCLike, was written in C++ and was largely restricted to internal use, with some exceptions when the publication required it (see for example [2]). HAWCLike was built on top of an internal framework called LiFF [3]. HAWCLike used spherical harmonics to handle the convolution of the model into the HEALPix projection of the sky in the region of interest in a particular study [3, 4]. However, as fits in more complicated regions of the galaxy needed to be performed, its performance was insufficient for many parameter fits (either many sources or elaborate morphology and spectra). Therefore a new plugin, called HAWC Accelerated Likelihood (HAL), was written in Python. It kept many of the features of the old plugin, and made 3 specific design changes to increase performance by nearly an order of magnitude.

- Perform convolution using Fast Fourier Transforms on a plane projection of the HEALPix grid
- Only reconvolve sources that changed in the previous iteration
- Speed up the evaluation of the likelihood function itself (for example by dropping the factorial term)

3. Demonstration

Using the public HAWC dataset[4], we begin a demonstration of a simple fit to the Crab Nebula, and then to the Crab Nebula with the addition of HAWC J0543+233 [5]. This will show some of

[1]https://github.com/threeML/threeML
[2]https://github.com/threeML/astromodels
[3]https://github.com/threeML/hawc_hal
[4]https://data.hawc-observatory.org/datasets/crab_data

PoS(ICRC2021)828

the capabilities of HAL, so that users of future HAWC data releases will be able to understand and interpret the output.

First, fitting to the Crab nebula, we define a point source using the following code example (taking the position from [6]), another example of which can be found in the HAL README file.

```
# without units energies are in keV
fluxUnit = 1/(astropy.u.TeV * astropy.u.cm ** 2 * astropy.u.s)

crab_spectrum = astromodels.Log_parabola()
crab_source = threeML.PointSource("crab", ra=ra_crab, dec=dec_crab,
                                   spectral_shape=crab_spectrum)

crab_spectrum.piv = 7 * astropy.u.TeV
crab_spectrum.piv.fix = True

crab_spectrum.K = 1e-14 * fluxUnit
crab_spectrum.K.bounds = (1e-35, 1e-10) * fluxUnit

crab_spectrum.alpha = -2.5  # log parabolic alpha (index)
crab_spectrum.alpha.bounds = (-4., 2.)

crab_spectrum.beta = 0.0  # log parabolic beta (curvature parameter)
crab_spectrum.beta.bounds = (-4., 2.)
```

The fit then proceeds to find the parameters crab spectrum which are shown in Table 1. We then define a second model with both the crab and HAWC J0543+233 in it. Below we only show the definition of the model for HAWC J0543+233, with seed values taken from [5], as the Crab Nebula model has already been shown above.

```
hawcj0543_spectrum = astromodels.Powerlaw()
hawcj0543_shape = astromodels.Gaussian_on_sphere()
hawcj0543_source = threeML.ExtendedSource("HAWC_J0543p233", spatial_shape=
                                   hawcj0543_shape, spectral_shape=
                                   hawcj0543_spectrum)

hawcj0543_spectrum.index.value  = -2.3
hawcj0543_spectrum.index.bounds = (-5.0 , -0.5)
hawcj0543_spectrum.index.fix    = False

hawcj0543_spectrum.K.value      = 7.9e-15 * fluxUnit
hawcj0543_spectrum.K.bounds     = (1e-35 , 1e-10) * fluxUnit
hawcj0543_spectrum.K.fix        = False

hawcj0543_spectrum.piv.value    = 7.0 * astropy.u.TeV
hawcj0543_spectrum.piv.fix      = True

hawcj0543_shape.lon0.value     = ra_hawcj0543  * astropy.u.degree
hawcj0543_shape.lat0.value     = dec_hawcj0543 * astropy.u.degree
hawcj0543_shape.lon0.fix       = True
hawcj0543_shape.lat0.fix       = True
```

PoS(ICRC2021)828

```
hawcj0543_shape.sigma.value.   = 1.0 * astropy.u.degree
hawcj0543_shape.sigma.bounds.  = (0.2, 20.0)
```

When fit either way the Crab, being very significant in the data, arrives at the same fit parameters. The inclusion of a dimmer source (HAWC J0543+233) naturally does not affect this result. The best model for more complicated regions containing multiple overlapping extended sources will often change depending on how many sources or parameters are free in that model.

Source	Flux Norm at 7 TeV $[10^{-13}\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$	α	$\beta\ [10^{-1}]$	extent [°]
Crab Nebula [6]	2.51 ± 0.11	-2.63 ± 0.03	1.5 ± 0.3	0*
Crab Nebula (1 source)	2.54 ± 0.06	-2.65 ± 0.02	1.04 ± 0.14	0*
Crab Nebula (2 source)	2.54 ± 0.06	-2.65 ± 0.02	1.04 ± 0.14	0*
HAWC J0543+233 (2 source)	$0.18^{+0.15}_{-0.08}$	-2.25 ± 0.29	0*	0.62 ± 0.24

Table 1: Fit parameters for the two models: one with the Crab Nebula alone, and the 2 source model, with the Crab Nebula and HAWC J0543+233. These are compared to the published version [6]. Parameters labeled with * were fixed to that value in the model.

3.1 Example Plots

It is natural during analysis to produce several plots in order to gain some understanding of whether or not the fit converged to a reasonable value, or display that fit result as a spectral energy distribution. First we look at the residual counts within the ROI. In Figure 1, we see that the model predicts a certain number of counts (events is also used interchangeably) in each bin which is similar to the number of counts we actually observed. When looking at the residual between them (the lower portion of the plot) we see that the model largely describes the region with insignificant differences for the analysis bins. If large deviations between the model and the data is observed, it is good motivation that further additions to the model are warranted. This plot is unique to HAL, given that it directly examines the data and model comparison in each bin.

One might also wish to plot the spectrum for the sources fit in the particular model, as in Figure 2. Here we see that the uncertainty on the spectrum for HAWC J0543+233 is much wider than for the Crab Nebula, as expected. It should be noted here that the $\Delta TS = -2ln\left(\mathcal{L}_0/\mathcal{L}_1\right)$ between the model including HAWC J0543+233 and the Crab compared to a model consisting of only the Crab is 22. This indicates that for this 507 day dataset which is only 3° in radius and centered on the Crab, HAWC J0543+233 is not significantly detected using the typical criterion of a 5σ detection. A dataset which includes a larger area, encompassing more area near HAWC J0543+233 (which is 2.6° away from the center of the dataset) may be able to more significantly detect the source. The functionality for the SED is provided within 3ML, since all instruments will want to produce the SED.

The final plot (see Figure 3) shows the data and model in each bin. It is important to note that Figure 3 is not significance, but rather is counts. The counts are smoothed over 0.17° and each column shows (from left to right) the model, the excess (data - background), the background, and

PoS(ICRC2021)828

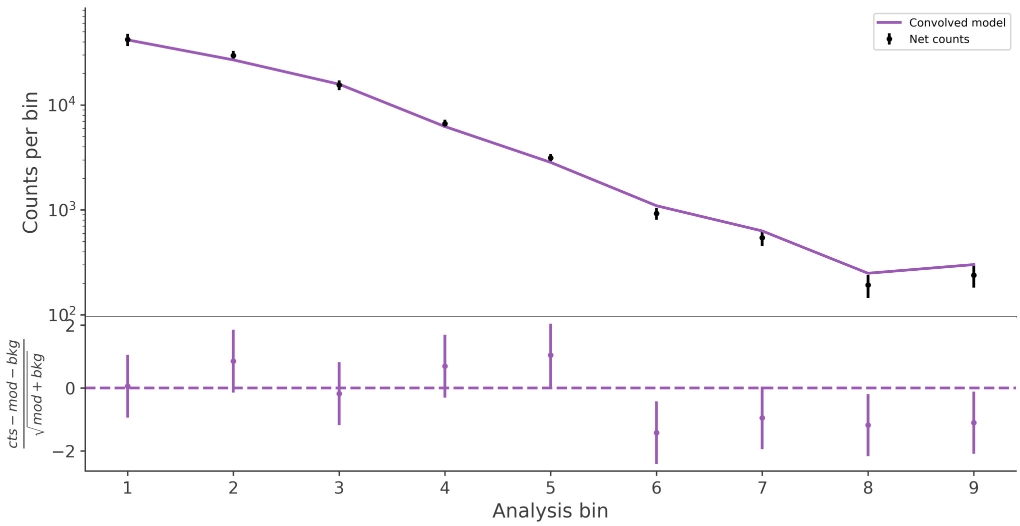

Figure 1: The number of events in each bin within the ROI compared to the model prediction, and the differences below

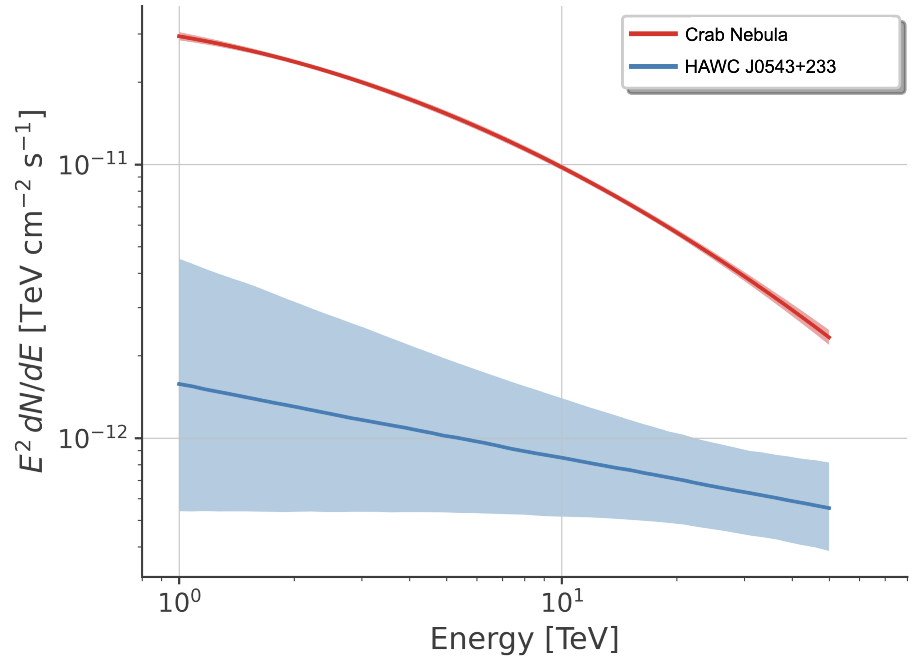

Figure 2: Spectral Energy Distribution (SED) of the Crab and HAWC J0543+233 in 507 days of data.

PoS(ICRC2021)828

the residuals. You can see that the background gets increasingly sparse with bin number, this is due to how few events pass the cuts in those bins (for more information on the bin definitions, see [6]).

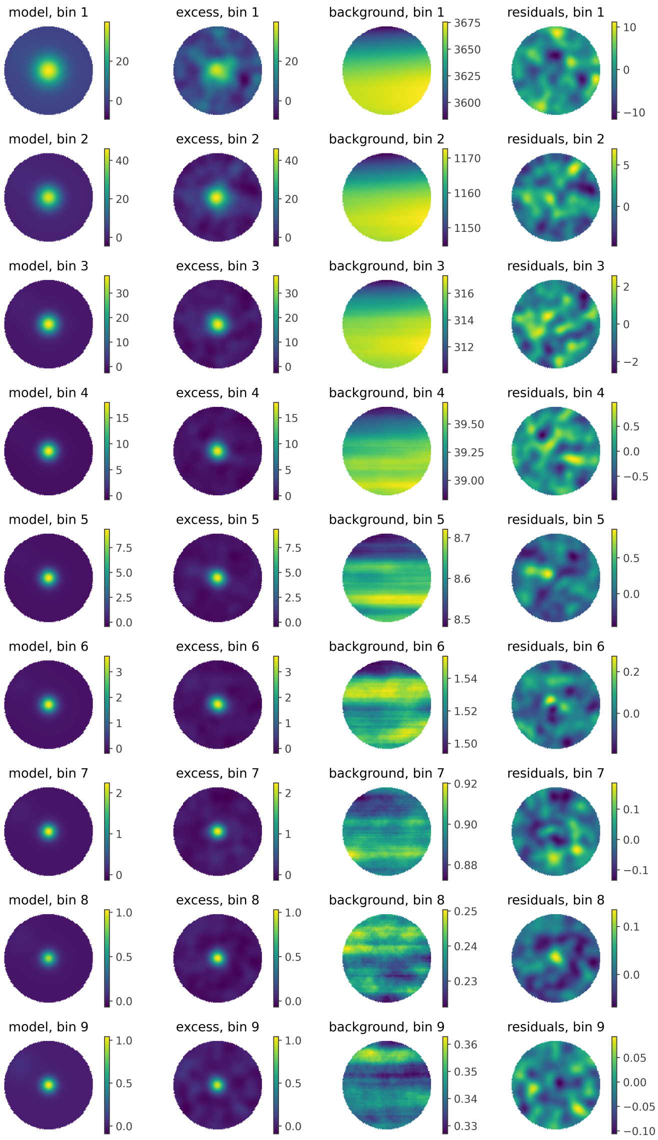

Figure 3: The output of `display_fit` function in HAL, showing the fit in each bin.

4. Conclusions

Here we demonstrated an example analysis in HAWC fitting one and two source models with 3 and 6 parameters. This shows the advantage of using HAWC data for multisource fitting for any region of the galaxy one wishes to analyze. Owing to its speed and ease of use, HAL has become the most used fitting tool in HAWC for galactic and extragalactic analyses. Due to its open source nature, as more HAWC data is released, this tool's ability to benefit the community can only grow.

PoS(ICRC2021)828

Combining HAWC data and multiwavelength data at the fitting stage allows for a consistent model of the data to be built which dramatically aids interpretation of a model once the best fit model is found.

Acknowledgments

We acknowledge the support from: the US National Science Foundation (NSF); the US Department of Energy Office of High-Energy Physics; the Laboratory Directed Research and Development (LDRD) program of Los Alamos National Laboratory; Consejo Nacional de Ciencia y Tecnología (CONACyT), México, grants 271051, 232656, 260378, 179588, 254964, 258865, 243290, 132197, A1-S-46288, A1-S-22784, cátedras 873, 1563, 341, 323, Red HAWC, México; DGAPA-UNAM grants IG101320, IN111716-3, IN111419, IA102019, IN110621, IN110521; VIEP-BUAP; PIFI 2012, 2013, PROFOCIE 2014, 2015; the University of Wisconsin Alumni Research Foundation; the Institute of Geophysics, Planetary Physics, and Signatures at Los Alamos National Laboratory; Polish Science Centre grant, DEC-2017/27/B/ST9/02272; Coordinación de la Investigación Científica de la Universidad Michoacana; Royal Society - Newton Advanced Fellowship 180385; Generalitat Valenciana, grant CIDEGENT/2018/034; Chulalongkorn University's CUniverse (CUAASC) grant; Coordinación General Académica e Innovación (CGAI-UdeG), PRODEP-SEP UDG-CA-499; Institute of Cosmic Ray Research (ICRR), University of Tokyo, H.F. acknowledges support by NASA under award number 80GSFC21M0002. We also acknowledge the significant contributions over many years of Stefan Westerhoff, Gaurang Yodh and Arnulfo Zepeda Dominguez, all deceased members of the HAWC collaboration. Thanks to Scott Delay, Luciano Díaz and Eduardo Murrieta for technical support.

References

[1] G. Vianello, R. Lauer, P. Younk, L. Tibaldo, J.M. Burgess, H. Ayala Solares et al., *The Multi-Mission Maximum Likelihood framework*, in *Proceedings of The 34th International Cosmic Ray Conference — PoS(ICRC2015)*, vol. 236, p. 1042, 2016, DOI.

[2] A.U. Abeysekara, A. Albert, R. Alfaro, C. Alvarez, J.D. Álvarez, R. Arceo et al., *Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth.*, *Science (New York, N.Y.)* **358** (2017) 911.

[3] P. Younk, *A high-level analysis framework for HAWC* , in *Proceedings of The 34th International Cosmic Ray Conference — PoS(ICRC2015)*, vol. 236, p. 948, 2016, DOI.

[4] K.M. Gorski, E. Hivon, A.J. Banday, B.D. Wandelt, F.K. Hansen, M. Reinecke et al., *HEALPix: A Framework for High-Resolution Discretization and Fast Analysis of Data Distributed on the Sphere*, *The Astrophysical Journal* **622** (2005) 759 [0409513].

[5] C. Riviere, H. Fleischhack and A. Sandoval, *HAWC detection of TeV emission near PSR B0540+23*, *The Astronomer's Telegram* **10941** (2017) 1.

PoS(ICRC2021)828

[6] A.U. Abeysekara, A. Albert, R. Alfaro, C. Alvarez, J.D. Álvarez, R. Arceo et al., *Observation of the Crab Nebula with the HAWC Gamma-Ray Observatory*, *The Astrophysical Journal* **843** (2017) 39.

[7] M.F. Corcoran, L. Angelini, I. George, T. McGlynn, K. Mukai, W. Pence et al., *The OGIP FITS Working Group*, in *Astronomical Data Analysis Software and Systems IV*, R.A. Shaw, H.E. Payne and J.J.E. Hayes, eds., vol. 77 of *Astronomical Society of the Pacific Conference Series*, p. 219, Jan., 1995.

PoS(ICRC2021)828

Full Authors List: HAWC Collaboration

A.U. Abeysekara[48], A. Albert[21], R. Alfaro[14], C. Alvarez[41], J.D. Álvarez[40], J.R. Angeles Camacho[14], J.C. Arteaga-Velázquez[40], K. P. Arunbabu[17], D. Avila Rojas[14], H.A. Ayala Solares[28], R. Babu[25], V. Baghmanyan[15], A.S. Barber[48], J. Becerra Gonzalez[11], E. Belmont-Moreno[14], S.Y. BenZvi[29], D. Berley[39], C. Brisbois[39], K.S. Caballero-Mora[41], T. Capistrán[12], A. Carramiñana[18], S. Casanova[15], O. Chaparro-Amaro[3], U. Cotti[40], J. Cotzomi[8], S. Coutiño de León[18], E. De la Fuente[46], C. de León[40], L. Diaz-Cruz[8], R. Diaz Hernandez[18], J.C. Díaz-Vélez[46], B.L. Dingus[21], M. Durocher[21], M.A. DuVernois[45], R.W. Ellsworth[39], K. Engel[39], C. Espinoza[14], K.L. Fan[39], K. Fang[45], M. Fernández Alonso[28], B. Fick[25], H. Fleischhack[51,11,52], J.L. Flores[46], N.I. Fraija[12], D. Garcia[14], J.A. García-González[20], J. L. García-Luna[46], G. García-Torales[46], F. Garfias[12], G. Giacinti[22], H. Goksu[22], M.M. González[12], J.A. Goodman[39], J.P. Harding[21], S. Hernandez[14], I. Herzog[25], J. Hinton[22], B. Hona[48], D. Huang[25], F. Hueyotl-Zahuantitla[41], C.M. Hui[23], B. Humensky[39], P. Hüntemeyer[25], A. Iriarte[12], A. Jardin-Blicq[22,49,50], H. Jhee[43], V. Joshi[7], D. Kieda[48], G J. Kunde[21], S. Kunwar[22], A. Lara[17], J. Lee[43], W.H. Lee[12], D. Lennarz[9], H. León Vargas[14], J. Linnemann[24], A.L. Longinotti[12], R. López-Coto[19], G. Luis-Raya[44], J. Lundeen[24], K. Malone[21], V. Marandon[22], O. Martinez[8], I. Martinez-Castellanos[39], H. Martínez-Huerta[38], J. Martínez-Castro[3], J.A.J. Matthews[42], J. McEnery[11], P. Miranda-Romagnoli[34], J.A. Morales-Soto[40], E. Moreno[8], M. Mostafá[28], A. Nayerhoda[15], L. Nellen[13], M. Newbold[48], M.U. Nisa[24], R. Noriega-Papaqui[34], L. Olivera-Nieto[22], N. Omodei[32], A. Peisker[24], Y. Pérez Araujo[12], E.G. Pérez-Pérez[44], C.D. Rho[43], C. Rivière[39], D. Rosa-Gonzalez[18], E. Ruiz-Velasco[22], J. Ryan[26], H. Salazar[8], F. Salesa Greus[15,53], A. Sandoval[14], M. Schneider[39], H. Schoorlemmer[22], J. Serna-Franco[14], G. Sinnis[21], A.J. Smith[39], R.W. Springer[48], P. Surajbali[22], I. Taboada[9], M. Tanner[28], K. Tollefson[24], I. Torres[18], R. Torres-Escobedo[30], R. Turner[25], F. Ureña-Mena[18], L. Villaseñor[8], X. Wang[25], I.J. Watson[43], T. Weisgarber[45], F. Werner[22], E. Willox[39], J. Wood[23], G.B. Yodh[35], A. Zepeda[4], H. Zhou[30]
[1]Barnard College, New York, NY, USA, [2]Department of Chemistry and Physics, California University of Pennsylvania, California, PA, USA, [3]Centro de Investigación en Computación, Instituto Politécnico Nacional, Ciudad de México, México, [4]Physics Department, Centro de Investigación y de Estudios Avanzados del IPN, Ciudad de México, México, [5]Colorado State University, Physics Dept., Fort Collins, CO, USA, [6]DCI-UDG, Leon, Gto, México, [7]Erlangen Centre for Astroparticle Physics, Friedrich Alexander Universität, Erlangen, BY, Germany, [8]Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla, Puebla, México, [9]School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA, USA, [10]School of Physics Astronomy and Computational Sciences, George Mason University, Fairfax, VA, USA, [11]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [12]Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de México, México, [13]Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Ciudad de México, México, [14]Instituto de Física, Universidad Nacional Autónoma de México, Ciudad de México, México, [15]Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland, [16]Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, SP, Brasil, [17]Instituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad de México, México, [18]Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla, Puebla, México, [19]INFN Padova, Padova, Italy, [20]Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, Ave. Eugenio Garza Sada 2501, Monterrey, N.L., 64849, México, [21]Physics Division, Los Alamos National Laboratory, Los Alamos, NM, USA, [22]Max-Planck Institute for Nuclear Physics, Heidelberg, Germany, [23]NASA Marshall Space Flight Center, Astrophysics Office, Huntsville, AL, USA, [24]Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA, [25]Department of Physics, Michigan Technological University, Houghton, MI, USA, [26]Space Science Center, University of New Hampshire, Durham, NH, USA, [27]The Ohio State University at Lima, Lima, OH, USA, [28]Department of Physics, Pennsylvania State University, University Park, PA, USA, [29]Department of Physics and Astronomy, University of Rochester, Rochester, NY, USA, [30]Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China, [31]Sungkyunkwan University, Gyeonggi, Rep. of Korea, [32]Stanford University, Stanford, CA, USA, [33]Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL, USA, [34]Universidad Autónoma del Estado de Hidalgo, Pachuca, Hgo., México, [35]Department of Physics and Astronomy, University of California, Irvine, Irvine, CA, USA, [36]Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, Santa Cruz, CA, USA, [37]Universidad de Costa Rica, San José , Costa Rica, [38]Department of Physics and Mathematics, Universidad de Monterrey, San Pedro Garza García, N.L., México, [39]Department of Physics, University of Maryland, College Park, MD, USA, [40]Instituto de Física y Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México, [41]FCFM-MCTP, Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, Chiapas, México, [42]Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA, [43]University of Seoul, Seoul, Rep. of Korea, [44]Universidad Politécnica de Pachuca, Pachuca, Hgo, México, [45]Department of Physics, University of Wisconsin-Madison, Madison, WI, USA, [46]CUCEI, CUCEA, Universidad de Guadalajara, Guadalajara, Jalisco, México, [47]Universität Würzburg, Institute for Theoretical Physics and Astrophysics, Würzburg, Germany, [48]Department of Physics and Astronomy, University of Utah, Salt Lake City, UT, USA, [49]Department of Physics, Faculty of Science, Chulalongkorn University, Pathumwan, Bangkok 10330, Thailand, [50]National Astronomical Research Institute of Thailand (Public Organization), Don Kaeo, MaeRim, Chiang Mai 50180, Thailand, [51]Department of Physics, Catholic University of America, Washington, DC, USA, [52]Center for Research and Exploration in Space Science and Technology, NASA/GSFC, Greenbelt, MD, USA, [53]Instituto de Física Corpuscular, CSIC, Universitat de València, Paterna, Valencia, Spain

PoS(ICRC2021)828