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

Lake Deployment of Southern Wide-field Gamma-ray Observatory (SWGO) Detector Units

Hazal Goksu[a,*] and Werner Hofmann[a,b] on behalf of the SWGO Collaboration
(a complete list of authors can be found at the end of the proceedings)

[a,b] *Max Planck Institut fur Kernphysik (MPIK), Saupfercheckweg 1, Heidelberg, Germany*
E-mail: hgoksu@mpi-hd.mpg.de, werner.hofmann@mpi-hd.mpg.de

The Southern Wide-field Gamma-ray Observatory (SWGO) will be a next-generation high altitude gamma-ray survey observatory in the southern hemisphere consisting of an array of water cherenkov detectors. With its energy range, wide field of view, large duty cycle and location it will complement the other existing and planned gamma-ray observatories. In this contribution we describe the lake concept for SWGO, an alternative to a HAWC-like design with individual water tanks and a LHAASO-style design with artificial ponds. In the lake concept, bladders filled with clean water are deployed near the surface of a natural lake, where each bladder is a light-tight stand-alone unit containing one or more photosensors. We will give an overview of the advantages and challenges for this design concept and describe the first results obtained from prototyping.

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

*Presenter

PoS(ICRC2021)708

1. Introduction to the Lake Concept

Water Cherenkov detectors (WCD) record air shower particles coming from high-energy gamma rays at the ground level and provide a wide field-of-view along with an approximately 100% duty cycle. The High-Altitude Water Cherenkov Observatory (HAWC) [1] and more recently Large High Altitude Air Shower Observatory (LHAASO) [2] have been using this technique to observe the gamma-ray sky from the northern hemisphere.

Southern Wide-field Gamma Ray Observatory (SWGO) [3, 4] will be a next-generation gamma-ray survey observatory in the southern hemisphere that will consist of an array of water Cherenkov detectors. The reference design for SWGO detector units uses dual-volume water tanks, with an upper electromagnetic volume for timing and energy and a lower volume to help with muon identification and saturation recovery. The lake concept is one of the alternative designs for SWGO, for which bladders filled with clean water are deployed near the surface of a natural lake, where each bladder is a light-tight stand-alone unit containing one or more photosensors.

One advantage of the lake design is the anticipated reduced cost compared to the HAWC-like tank designs, achieved by omitting the expensive tank structures, which also brings about less civil engineering requirements on site. Moreover, there are likely fewer constraints on unit dimensions for the bladders, making it possible to optimize for best performance based on simulations. Muon detection is also expected to be improved by this design, since sideways entry of electromagnetic energy into the muon volume is suppressed, compared to spaced tanks. Finally, floating detector units allow reconfiguring the detector according to evolving science needs, e.g. with a dense configuration for lowest energy thresholds, or spread-out groups of detector units for maximum array area and best high-energy response.

On the other hand there is no previous experience for such a design, increasing R&D effort and risks. In addition, the lake option reduces the choice of sites and brings restrictions on array geometry since outrigger units may not be trivial to arrange. There is also the potential that this design will have higher maintenance requirements and the detector units may have a reduced lifetime. A proper assesment of these will be needed as part of the R&D efforts. Finally, the geometry calibration appears to be more complex in the lake design. Strategies for monitoring the position of the bladders and of the photomultiplier tube (PMT) position inside each bladder will need to be developed.

2. Candidate Lakes in Peru

The array of bladders need to be deployed in a natural lake that has sufficiently high altitude. The Lake Sibinacocha area in Peru, at an altitude of 4892 m, has three lakes that are suitable candidates (for an overview on the site search for SWGO detectors, see [6]). One of these is the Lake Sibinacocha itself, with a 30 km^2 area. Near this lake are two smaller lakes, Cocha Uma and Cochachaca, each with an area of more than 1 km^2. According to a recently conducted depth profile survey (shown in Figure 1 for lake Cocha Uma), the smaller lakes have a depth of up to 30 m. The figure illustrates that a 1 km^2 array of bladders can be deployed in Cocha Uma, in an area of at least 15 m depth (shown by the blue data points). There is also a weather station on site that provides continuous information on wind and other weather conditions.

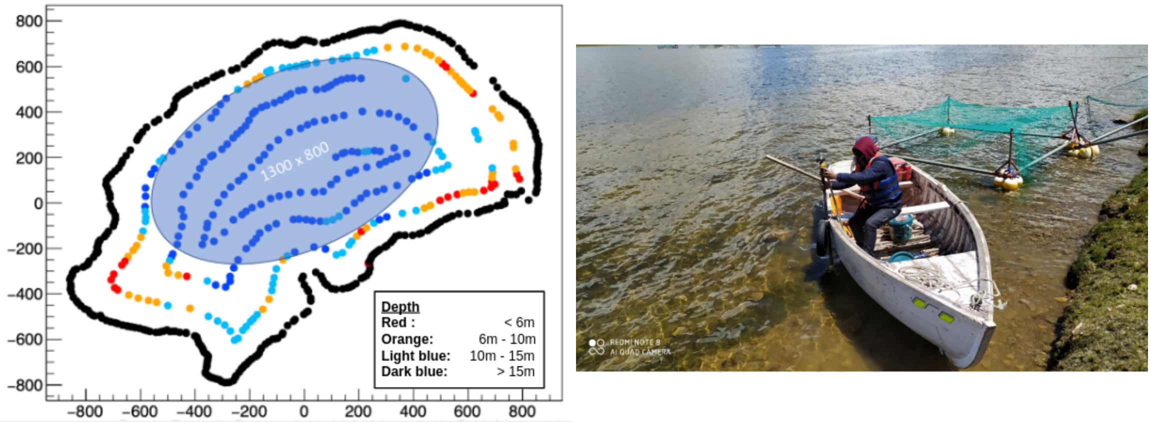

Figure 1: Potential Lake Candidate. *Left:* Depth survey results for Lake Cocha Uma show that the maximum depth is around 33 m. The survey shows that a 1 km^2 detector array is possible. *Right:* The depth survey was carried out for three nearby Peruvian lakes.

3. Detector Unit Design

3.1 Geometry

As stated in Section 1, each bladder is a light-tight stand-alone unit filled with clean water, with an upper electromagnetic volume for timing and energy and a lower volume to help with muon identification and saturation recovery.

The exact dimensions remain to be optimized based on simulations, however the first prototype was envisioned with a top cell that is four meters deep and a lower cell that is two meters. The lower cell will be lined with diffuse reflecting material and the top cell may be partly lined [7]. Each cell has a PMT that detects the cherenkov light inside the bladder. The two PMTs form a mechanical unit, with one facing downwards and the other one facing upwards, as can be seen from Figure 2. A hatch on the top face of the bladder can provide easy access to the inside of the bladder for maintenance and insertion of the PMT, while ring floaters attached to the top of the bladder keep it afloat and add stability. Additional structures at the bottom part may be added for further stability.

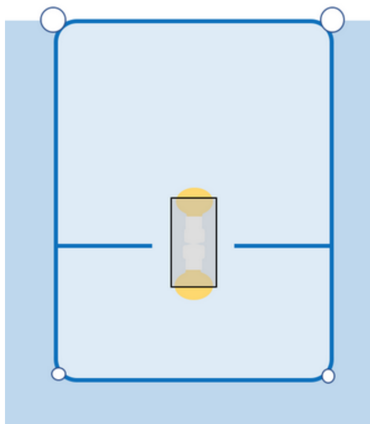

Figure 2: The prototype unit design with a membrane separating the two compartments.The PMTs are housed in one support.

3.2 Wave loads

The deployment of individual detector units inside a natural lake brings along the question of wave loads, since the lake will have waves which have a potential to damage the bags and to vary the position of the bags and the PMTs inside them.

Preliminary studies show that the bladders would experience maximum deformation when the wave length is twice the size of the bladder. The wind speed and size of the lake are important parameters that will affect the wavelength and height of the waves. Wave height increases with fetch (the distance over which wind interacts with the water surface), favoring smaller lakes. Little is documented about waves in the lakes considered and deployment of wave monitoring equipment is being planned. Hydrodynamics simulations are ongoing to estimate the wave-induced deformation of bladders, and the resulting loads on the bladder material as well as the movement of the PMT unit inside the bladder.

3.3 Prototyping Steps

A protoyping phase to explore the lake option is underway. A first step was to perform tests on small transparent bladders, investigating mechanical stability and floating characteristics. The second step is to deploy a simple single-cell bladder of (nearly) full size, equipped with a PMT, in a lake simulation tank. Following this, a realistic full sized bladder will be designed and tested, based on the lessons learned from the simple bladder. The final step in the plan is the deployment of a proof of concept array in a natural lake. In parallel simulations will be carried out. The prototyping phase is anticipated to require two years and the R&D phase is planned to last until late 2023.

4. Prototyping Efforts at MPIK

4.1 Preparatory Material Tests

Requirements on bladder materials include (a) mechanical strength and durability, (b) light tightness, (c) reflectivity of the inner liner, and (d) lack of contamination of the purified water inside the bladder. At the Max Planck Institut für Kernphysik (MPIK), preparatory material tests are being carried out regarding these properties.

For reflectivity studies, a preliminary setup with a xenon lamp, monochromator and an integrating sphere exists. This setup allows us to sweep through a range of wavelengths (400 nm to 700 nm) and measure diffuse reflectivity for materials being considered for the inner liner of the bladders. Light tightness is presently being measured by inserting a PMT inside a light tight tube and illuminating a (≈ 4 cm ^{2}) window covered by the material under test. Water quality measurements are carried out by monitoring the evolution of transmissivity and conductivity of highly purified water (initial absorption length >10 m) placed into several buckets that house different material samples.

4.2 Lake Simulation Tank

At MPIK a water simulation tank (Figure 3) was prepared during the year 2020 for the testing of the lake concept for SWGO. The tank is 7 meters in height and 10 meters in diameter. Detector signals are routed to a small cabin next to the tank that is equipped with a computer and the *FlashCam* Data Acquisition(DAQ) system [8]. Throughout the studies, *FlashCam* DAQ has a readout window of 128 samples and takes one sample every 4 nanoseconds, giving a total of 512 ns readout. A water filtration system provides filtered, decalficied water for filling the bladders.

Figure 3 also illustrates the planned deployment of simple single-cell bladders, with a lower bladder serving for muon identification, along with a realistic dual-cell prototype detector that is planned to be deployed after the simple bladder deployment is successfully completed. A small water Cherenkov muon tagger unit at the bottom of the tank provides additional identification and information on the location of muons.

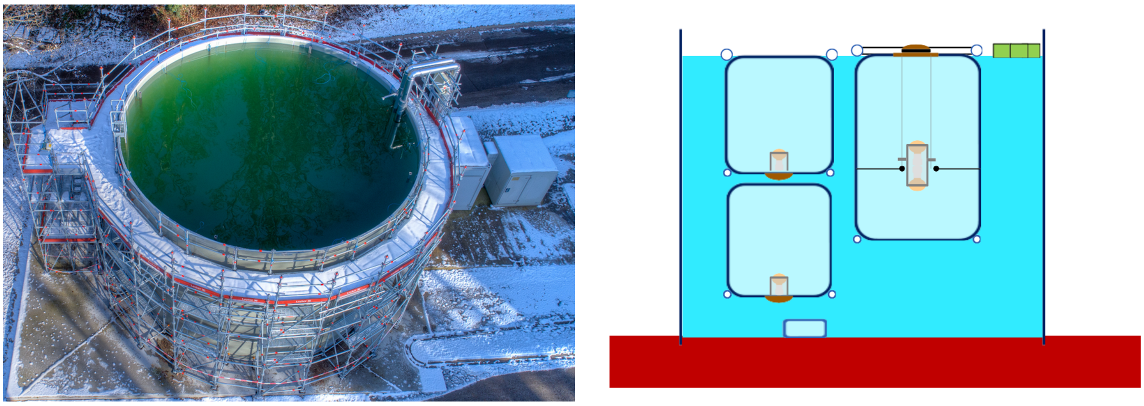

Figure 3: Lake Simulation Tank *Left:* The Lake simulation tank at MPIK has a 10 meter diameter and is 7 meters in height. *Right:* Illustration of testing steps: Two generation-0 bladders are seen on the left, next to them is the generation-1 bladder. Each bladders has a PMT inside. Sitting at the bottom is a muon tagger.

4.3 Muon Taggers

Two muon taggers were built to provide well defined particle trajectories. The muon taggers consist of a 8 inch Hamamatsu R5912 PMT inside a commercial black barrel of 41 cm diameter and 75 cm length, filled with clean water (Figure 5). The inside of the barrel is lined with reflective material (white teflon for the initial tests, and Tyvek 1082D later).

The taggers were tested outside the water tank using a coincidence of trigger scintillation counters placed on top of and under the tagger. The self-triggered rate of the taggers was about 20 Hz, compatible with GEANT4 simulations [5] of the tagger (Figure 4). The right plot in Figure 4 shows the signal detected from the tagger approximately two months after it was deployed inside the lake simulation tank. In units of photoelectrons (p.e.), the signal peak is at around 100 p.e.. We monitor the signal from the muon tagger weekly and have not observed any degradation.

4.4 Small-sized Bladders

After studies at MPIK of bladder production by hot air welding, bladders for initial tests were ordered from a commercial company. As a first step, 1:10 scale transparent bladders of 60 cm height were studied (Figure 5).

Visual inspections of the bladder's shape stability under impact, waves and additional weight were carried out by using an underwater web camera. In addition to tests for shape stability, different filling options were also explored. A bladder that is 100% filled results in large stress on the bladder material in case of bladder deformations by waves or impact. We found that a filling of about 90% of the maximal bladder volume is a good compromise. At this fill level, after deformation from impacts or waves, the bladder restores its original shape.

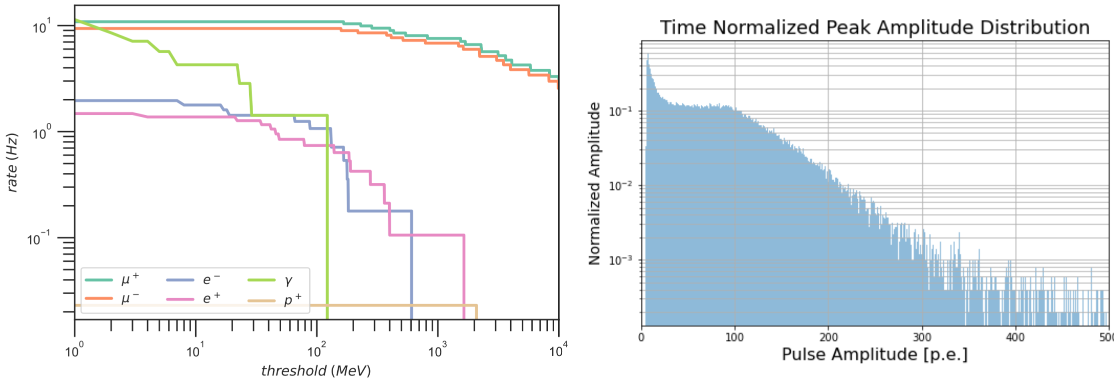

Figure 4: *Left:* GEANT4 simulations showing muon tagger rate, as a function of the threshold above which particles trigger. The muon rate is ≈ 20 Hz. *Right:* The peak amplitude distribution for the muon tagger sitting inside the lake simulation tank, taken in May, two months after its deployment. The muon peak appears at ≈ 100 photoelectrons.

(a)

Figure 5: *Left:* The deployment of the muon tagger into the lake simulation tank. The muon tagger is a plastic barrel with a white reflective coating inside, filled with clean water. *Right:* Three simple transparent bladders suspended by floater pipes, used in the mechanical stability tests.

4.5 The Full-sized Bladder

The next stage of prototyping concerned simple (nearly-)full-sized bladders. Two bladders made of 0.9 mm black PVC material were procured from the commercial company Mayer Luftwerbung. (Later more realistic bladders will likely use multi-layer bladders, as used in Auger [9], HAWC and LHAASO.) The bladders are approximately 2.5 meters and 3.5 meters high and 3 meters in diameter. These bladders will be deployed inside the lake simulation tank after necessary modifications. In order to prepare the first bladder for deployment, it was equipped with a 60 cm circular hatch at the bottom section, and with a small entry port for light pulser signals at the top section (Figure 6). An 8 inch Hamamatsu R5912 PMT is attached to directly to the larger hatch. Closing the initial version of this hatch air tight and light tight proved to be a challenge and required several iterations.

Light tightness tests were carried out by measuring – for the air-inflated bladder – the single photoelectron rate of the PMT using the *FlashCam* DAQ and it was seen that the bladder is not fully light tight, with a rate of approximately 7 kHz during the day. Whether this is due to imperfect light tightness of the bladder material or of the bladder ports remains to be resolved. Once it is deployed in the tank and filled with filtered water, data taking is planned during night time.

Experience with this initial bladder showed that the solution with the underwater hatch carrying the PMT is not optimal. Since the later design concepts for a realistic dual-cell bladder foresee access and deployment of the PMT unit through an above-water hatch on top of the bladder, we considered producing the second version of a simple bladder with a hatch on the top section, with the PMT suspended from the top.

Figure 6: The first simple full-sized bladder undergoing a light tightness test. A PMT is directly mounted to the hatch.

5. Outlook

Already the initial steps of prototyping towards the lake concept have provided significant insights and valuable input for the design of the next prototypes.

After the testing of the 0th generation bladders detailed in Section 4.5, a next generation bladder with an improved design will be deployed in the simulation tank. The design of this improved bladder is currently under consideration based on the experience with the 0th generation bladder. It is planned to have a membrane in the middle, instead of two separate cells, with a PMT attachment scheme, suspended with strings from a hatch that is at the top side of the bladder, as pictured in Figure 3. Due to possible difficulties in attaching reflective material to the inner surface of the bladder, studies on having an entirely black bladder are also being conducted.

Various simulation activities are starting or ongoing. These concern (a) simulations of air shower detection with the lake detector, towards optimization of the detector unit geometry also in view of muon detection; (b) simulations to explore how well the vertical and transverse positions of the bladder and PMT need to be known; and finally (c) hydrodynamic simulations to determine wave loads on bladders and the resulting strength requirements, using smoothed particle hydrodynamics (SPH) simulations, where water is simulated as a collection of little particles.

Acknowledgments

The SWGO Collaboration acknowledges the support from the agencies and organizations listed here: `https://www.swgo.org/SWGOWiki/doku.php?id=acknowledgements`.

References

[1] A. U. Abeysekara et al. (HAWC Collaboration), *Astrophys. J.* **843**, 39 (2017).

[2] G. D. Sciascio et al. (LHAASO Collaboration), *Nucl. Part. Phys. Proc.* **279 - 281**, 166-173 (2016).

[3] A. Albert et al. (SGSO Alliance), arXiv:1902.08429 (2019).

[4] J. Hinton (SWGO Collaboration), *PoS ICRC2021* (2021) 023. https://pos.sissa.it/395/023/

[5] S. Agostinelli et al., *Nucl. Instrum. Methods Phys. Res.***A 506** 205-303 (2003).

[6] M. Doro (SWGO Collaboration). *PoS ICRC2021* (2021) 689. https://pos.sissa.it/395/689/

[7] S. Kunwar (SWGO Collaboration). *PoS ICRC2021* (2021) 902. https://pos.sissa.it/395/902/

[8] F. Werner et al., Performance Verification of the FlashCam Prototype Camera for the Cherenkov Telescope Array , arXiv:1612.09528 (2016).

[9] The Pierre Auger Cosmic Ray Observatory , *Nucl. Ins. and Methods in Phys. Research Section A 798, P. 172-213* (2015). https://doi.org/10.1016/j.nima.2015.06.058.

Full Authors List: SWGO Collaboration

P. Abreu[1], A. Albert[2], E.O. Angüner[3], C. Arcaro[4], L.H. Arnaldi[5], J.C. Arteaga-Velázquez[6], P. Assis[1], A. Bakalová[7], U. Barres de Almeida[8], I. Batković[4], J. Bellido[9], E. Belmont-Moreno[10], F. Bisconti[11], A. Blanco[1], M. Bohacova[7], E. Bottacini[4], T. Bretz[12], C. Brisbois[13], P. Brogueira[1], A.M. Brown[14], T. Bulik[15], K.S. Caballero Mora[16], S.M. Campos[17] A. Chiavassa[11], L. Chytka[7], R. Conceição[1], G. Consolati[18], J. Cotzomi Paleta[19], S. Dasso[20], A. De Angelis[4], C.R. De Bom[8], E. de la Fuente[21], V. de Souza[22], D. Depaoli[11], G. Di Sciascio[23], C.O. Dib[24], D. Dorner[25], M. Doro[4], M. Du Vernois[26], T. Ergin[27], K.L. Fan[13], N. Fraija[8], S. Funk[28], J.I. García[17], J.A. García-González[29], S.T. García Roca[9], G. Giacinti[30], H. Goksu[30], B.S. González[1], F. Guarino[31], A. Guillén[32], F. Haist[30], P.M. Hansen[33], J.P. Harding[2], J. Hinton[30], W. Hofmann[30], B. Hona[34], D. Hoyos[17], P. Huentemeyer[35], F. Hueyotl-Zahuantitla[16] A. Insolia[36], P. Janecek[7], V. Joshi[28], B. Khelifi[37], S. Kunwar[30], G. La Mura[1], J. Lapington[38], M.R. Laspiur[17], F. Leitl[28], F. Longo[39], L. Lopes[1], R. Lopez-Coto[4], D. Mandat[7], A.G. Mariazzi[33], M. Mariotti[4], A. Marques Moraes[8], J. Martínez-Castro[40], H. Martínez-Huerta[41], S. May[42], D.G. Melo[43], L.F. Mendes[1], L.M. Mendes[1], T. Mineeva[24], A. Mitchell[44], S. Mohan[35], O.G. Morales Olivares[16], E. Moreno-Barbosa[19], L. Nellen[45], V. Novotny[7], L. Olivera-Nieto[30], E. Orlando[39], M. Pech[7], A. Pichel[20], M. Pimenta[1], M. Portes de Albuquerque[8], E. Prandini[4], M.S. Rado Cuchills[9], A. Reisenegger[46], B. Reville[30], C.D. Rho[47], A.C. Rovero[20], E. Ruiz-Velasco[30], G.A. Salazar[17], A. Sandoval[10], M. Santander[42], H. Schoorlemmer[30], F. Schüssler[48], V.H. Serrano[17], R.C. Shellard[8], A. Sinha[49], A.J. Smith[13], P. Surajbali[30], B. Tomé[1], I. Torres Aguilar[50], C. van Eldik[28], I.D. Vergara-Quispe[33], A. Viana[22], J. Vícha[7], C.F. Vigorito[11], X. Wang[35], F. Werner[30], R. White[30], M.A. Zamalloa Jara[9]

[1] Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Av. Prof. Gama Pinto 2, 1649-003 Lisboa, Portugal
[2] Physics Division, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, United States
[3] Aix Marseille Univ, CNRS/IN2P3, CPPM, 163 avenue de Luminy - Case 902, 13288 Marseille cedex 09, France
[4] University of Padova, Department of Physics and Astronomy & INFN Padova, Via Marzolo 8 - 35131 Padova, Italy
[5] Centro Atómico Bariloche, Comisión Nacional de Energía Atómica, S. C. de Bariloche (8400), RN, Argentina
[6] Universidad Michoacana de San Nicolás de Hidalgo, Calle de Santiago Tapia 403, Centro, 58000 Morelia, Mich., México
[7] FZU, Institute of Physics of the Czech Academy of Sciences, Na Slovance 1999/2, 182 00 Praha 8, Czech Republic
[8] Centro Brasileiro de Pesquisas Físicas, R. Dr. Xavier Sigaud, 150 - Rio de Janeiro - RJ, 22290-180, Brazil
[9] Academic Department of Physics – Faculty of Sciences – Universidad Nacional de San Antonio Abad del Cusco (UNSAAC), Av. de la Cultura, 733, Pabellón C-358, Cusco, Peru
[10] Instituto de Física, Universidad Nacional Autónoma de México, Sendero Bicipuma, C.U., Coyoacán, 04510 Ciudad de México, CDMX, México
[11] Dipartimento di Fisica, Università degli Studi di Torino, Via Pietro Giuria 1, 10125, Torino, Italy
[12] RWTH Aachen University, Physics Institute 3, Otto-Blumenthal-Straße, 52074 Aachen, Germany
[13] University of Maryland, College Park, MD 20742, United States
[14] Durham University, Stockton Road, Durham, DH1 3LE, United Kingdom
[15] Astronomical Observatory, University of Warsaw, Aleje Ujazdowskie 4, 00478 Warsaw, Poland
[16] Facultad de Ciencias en Física y Matemáticas UNACH, Boulevard Belisario Domínguez, Km. 1081, Sin Número, Terán, Tuxtla Gutiérrez, Chiapas, México
[17] Facultad de Ciencias Exactas, Universidad Nacional de Salta, Avda. Bolivia N° 5150, (4400) Salta Capital, Argentina
[18] Department of Aerospace Science and Technology, Politecnico di Milano, Via Privata Giuseppe La Masa, 34, 20156 Milano MI, Italy
[19] Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla, C.P. 72592, México
[20] Instituto de Astronomia y Fisica del Espacio (IAFE, CONICET-UBA), Casilla de Correo 67 - Suc. 28 (C1428ZAA), Ciudad Autónoma de Buenos Aires, Argentina
[21] Universidad de Guadalajara, Blvd. Gral. Marcelino García Barragán 1421, Olímpica, 44430 Guadalajara, Jal., México
[22] Instituto de Física de São Carlos, Universidade de São Paulo, Avenida Trabalhador São-carlense, nº 400, Parque Arnold Schimidt - CEP 13566-590, São Carlos - São Paulo - Brasil
[23] INFN - Roma Tor Vergata and INAF-IAPS, Via del Fosso del Cavaliere, 100, 00133 Roma RM, Italy
[24] Dept. of Physics and CCTVal, Universidad Tecnica Federico Santa Maria, Avenida España 1680, Valparaíso, Chile
[25] Universität Würzburg, Institut für Theoretische Physik und Astrophysik, Emil-Fischer-Str. 31, 97074 Würzburg, Germany
[26] Department of Physics, and the Wisconsin IceCube Particle Astrophysics Center (WIPAC), University of Wisconsin, 222 West Washington Ave., Suite 500, Madison, WI 53703, United States
[27] TUBITAK Space Technologies Research Institute, ODTU Campus, 06800, Ankara, Turkey
[28] Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics, Erwin-Rommel-Str. 1, D 91058 Erlangen, Germany
[29] Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, Ave. Eugenio Garza Sada 2501, Monterrey, N.L., 64849, México
[30] Max-Planck-Institut für Kernphysik, P.O. Box 103980, D 69029 Heidelberg, Germany
[31] Università di Napoli "Federico II", Dipartimento di Fisica "Ettore Pancini", and INFN Napoli, Complesso Universitario di Monte Sant'Angelo - Via Cinthia, 21 - 80126 - Napoli, Italy
[32] University of Granada, Campus Universitario de Cartuja, Calle Prof. Vicente Callao, 3, 18011 Granada, Spain

PoS(ICRC2021)708

[33] IFLP, Universidad Nacional de La Plata and CONICET, Diagonal 113, Casco Urbano, B1900 La Plata, Provincia de Buenos Aires, Argentina
[34] University of Utah, 201 Presidents' Cir, Salt Lake City, UT 84112, United States
[35] Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931, United States
[36] Dipartimento di Fisica e Astronomia "E. Majorana", Catania University and INFN, Catania, Italy
[37] APC–IN2P3/CNRS, Université de Paris, Bâtiment Condorcet, 10 rue A.Domon et Léonie Duquet, 75205 PARIS CEDEX 13, France
[38] University of Leicester, University Road, Leicester LE1 7RH, United Kingdom
[39] Department of Physics, University of Trieste and INFN Trieste, via Valerio 2, I-34127, Trieste, Italy
[40] Centro de Investigación en Computación, Instituto Politécnico Nacional, Av. Juan de Dios Bátiz S/N, Nueva Industrial Vallejo, Gustavo A. Madero, 07738 Ciudad de México, CDMX, México
[41] Department of Physics and Mathematics, Universidad de Monterrey, Av. Morones Prieto 4500, San Pedro Garza García 66238, N.L., México
[42] Department of Physics and Astronomy, University of Alabama, Gallalee Hall, Tuscaloosa, AL 35401, United States
[43] Instituto de Tecnologías en Detección y Astropartículas (CNEA-CONICET-UNSAM), Av. Gral Paz 1499 - San Martín - Pcia. de Buenos Aires, Argentina
[44] Department of Physics, ETH Zurich, CH-8093 Zurich, Switzerland
[45] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México (ICN-UNAM), Cto. Exterior S/N, C.U., Coyoacán, 04510 Ciudad de México, CDMX, México
[46] Departamento de Física, Facultad de Ciencias Básicas, Universidad Metropolitana de Ciencias de la Educación, Av. José Pedro Alessandri 774, Ñuñoa, Santiago, Chile
[47] Department of Physics, University of Seoul, 163 Seoulsiripdaero, Dongdaemun-gu, Seoul 02504, Republic of Korea
[48] Institut de recherche sur les lois fondamentales de l'Univers (IRFU), CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
[49] Laboratoire Univers et Particules de Montpellier, CNRS, Université de Montpellier, F-34090 Montpellier, France
[50] Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), Luis Enrique Erro 1, Puebla, México