All-sky observations with HAWC: latest results

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Abstract. The High Altitude Water Cherenkov (HAWC) observatory is a ground-based air-shower detector designed to study cosmic rays and gamma rays with energies from 100 GeV up to 100 TeV. HAWC simultaneously surveys 2 sr of the northern sky with a high duty cycle > 90% in search for photons from point and extended sources, diffuse emission, transient events and other astrophysical phenomena at multi-TeV scales against the background of cosmic rays. In fact, the study of this background will open also the possibility of doing cosmic ray physics in the GeV – TeV regime and even to perform solar studies at HAWC. The observatory will consist of a densely packed array of 300 water Cherenkov tanks (4.5 m tall and 7.3 m diameter with 4 photomultipliers each) distributed on a 22,000 m² surface. Deployment started in March 2012 on a plateau situated on the Sierra Negra Volcano in the state of Puebla, Mexico, at an altitude of 4100 m. Construction is expected to be finished by the first months of 2015. In the mean time, HAWC has been taking data with a partial array and preliminary results have been already obtained. In this contribution, the results from the latest HAWC observations will be presented.

1. Introduction
Gamma-ray astronomy has received a tremendous boost with the advent of the current generation of detectors based on space-based instruments (such as AGILE [1], Fermi-LAT [2]) and ground-based observatories (e.g. HESS [3], VERITAS [4], MAGIC [5], CANGAROO [6], MILAGRO [7], Tibet-ASγ [8] and Argo-YBJ [9]) equipped with different experimental techniques that complement each other. Together they have explored the gamma-ray window starting at energies of a few MeV up to several TeV. For example, direct detection techniques on board of the Fermi-LAT space telescope have covered the low energy interval from 20 MeV to 300 MeV [2], while indirect detection techniques employed in Earth-bound detectors have extended these measurements up to the 100 TeV regime. The latter has been made possible by the commissioning of a new generation of Imaging Air Cherenkov Telescopes (IACTs), in particular HESS, VERITAS, MAGIC and CANGAROO, and air-shower particle detectors, such as MILAGRO, Tibet-ASγ and ARGO-YBJ, for the 10 GeV – 100 TeV [3, 4, 5, 6] and 100 GeV – 100 TeV [7, 8, 9] energy bands, respectively. However, despite the enormous progress that has been achieved in the last decades in this field, there are still several fundamental questions that are unsolved in gamma-ray astronomy, for instance regarding the production mechanism of the observed gamma rays in astrophysical environments, the possible existence of 100 TeV photon sources and the proposed connection between gamma-ray emitters and the origin of the cosmic rays of the highest energies.

In order to get some answers to the aforementioned enigmas, detailed observations of the 10 – 100 TeV sky with improved sensitivity and large collecting areas are needed. To accomplish
this task, a whole new generation of detectors has been already devised based on existing
detection techniques. Among the experimental efforts that are currently planned to lead this
field in the next decades are the following: the HAWC (High Altitude Water Cherenkov)
observatory [10, 11, 12], LHAASO (Large High Altitude Air Shower Observatory) [13], the
Cherenkov Telescope Array (CTA) [14], the Tunka-HiScore (Hundred Square-km Cosmic Origin
Explorer) detector [15] and the TAIGA (Tunka Advanced Instrument for cosmic ray physics and
Gamma Astronomy) hybrid array [16]. Some of them are being designed to even increase the
sensitivity of the gamma-ray measurements beyond 100 TeV [13, 14, 15, 16]. The first of these
instruments of new generation to detect gamma rays is the HAWC observatory, which is the
successor of the former MILAGRO detector [7].

MILAGRO pioneered the water Cherenkov technique for the detection of air showers induced
by TeV photons from space [7]. The instrument consisted of a 21-million-liter pond dedicated
to survey the sky at energies between 1 and 100 TeV. The operation of the detector showed that
the water Cherenkov technique can be used to study the sky with wide field of views (FOV),
\( \sim 2 \text{sr} \), and duty cycles of over 90\%, although with limited angular and energy resolutions, in
contrast to IACT techniques.

Both, IACTs and water Cherenkov arrays use the same principle to detect air showers: the
Cherenkov light emitted by relativistic charged particles of the shower in a transparent medium.
However, the former detect the Cherenkov light produced by the shower along its development
in the atmosphere, while the latter are limited only to the Cherenkov light emitted inside the
detectors of the array during the passage of the shower.

HAWC is an extensive air shower (EAS) observatory composed of a ground-based Cherenkov
array [10, 12]. The instrument is designed to study the \( \gamma \) and cosmic-ray sky at energies from
100 GeV to 100 TeV with a large instantaneous field of view (\( \sim 2 \text{sr} \)), as well as a high duty
factor (\( > 95\% \)). HAWC will have an improved sensitivity and angular resolution with respect to
MILAGRO [17]. In addition, it will measure with a better energy resolution, a larger effective
area and an increased gamma-hadron rejection [17]. These features will make HAWC an ideal
detector to carry out extensive cosmic- and gamma-ray research of different phenomena and
astrophysical objects. In the field of gamma-ray astronomy, with HAWC it will be possible, for
instance [17, 18, 19]: to monitor the emission from extended sources, the diffuse extragalactic
background and transient events; to study both point emitters and the morphology of extended
sources; and to improve the spectral photon measurements into the 100 TeV regime (which
will help to identify the ultimate origin of the high-energy cosmic rays). Regarding cosmic-ray
research, HAWC will permit the measurement and the study of the flux of cosmic rays from our
Sun and the Milky Way, and in the case of particle physics, HAWC observations will serve to
put constraints on scenarios of new physics and exotic phenomena. Furthermore, there will be
monitoring programs for the prompt detection of transient phenomena [17], which, in addition,
will trigger monitoring campaigns of such events at complementary wavelengths. In this regard,
HAWC will be part of coordinated joint efforts (e.g. GCN [20], AMON [21]) with other
international observatories to carry out multi-messenger and multi-wavelength observations of a
rich variety of astrophysical objects and phenomena in the universe besides transient events. In
summary, the scientific potential of HAWC is vast. In this contribution, a brief review about the
HAWC detector will be presented. The main objectives of the instrument, the characteristics
and the status of the observatory will be described. By the end, some of the latest results
obtained with HAWC, which were presented at the ECRS 2014, will be shown.

2. Science objectives
The HAWC collaboration pursues several scientific objectives in key areas of astronomy,
astrophysics and particle physics. Some of the main objectives are [11, 17, 18, 19]:

- to expand the catalog of TeV gamma-ray sources;
to extend the gamma-ray observations up to 100 TeV;
• to perform analyses of galactic and extragalactic sources;
• to study transient events;
• to carry out solar and galactic cosmic ray studies;
• to constrain scenarios for new physics;
• to initiate and participate in campaigns of multimessenger-observations.

HAWC will allow to extend the gamma-ray observations up to 100 TeV over a large fraction of the sky. This will permit to constrain and study the shape of the TeV spectra of several known GeV sources and even new emitters that might be discovered with the detector. In addition, those measurements will serve to search for high-energy cut-offs in the spectra, whose absence or presence can help to identify the mechanism of high-energy photon production, whether hadronic or leptonic, in several astrophysical gamma-ray objects.

A big variety of sources are planned to be the target for gamma-ray observations with HAWC. In our galaxy, HAWC will monitor point sources, such as the Crab, pulsar wind nebulae (PWN), supernova remnants (SNR) and binary systems; extended sources, e.g. the Cygnus Region, the galactic plane, superbubbles, young star clusters, TeV regions discovered by MILAGRO (MGRO J2019+37 and J2031+41) and the Fermi bubbles; and diffuse emission, for example, from molecular clouds and star clusters [17].

On the other hand, beyond our own galaxy, the HAWC collaboration will target the TeV photon emission from active galactic nuclei (AGNs), gamma-ray bursts (GRBs), the extragalactic background light and previously unknown gamma-ray sources [17].

The study of TeV transient phenomena in galactic and extragalactic environments, e.g. GRBs [22, 23], PWNs and AGNs, will be another priority of HAWC [17]. In this regard, HAWC observations will give an important insight into the mechanisms behind such events and the physical conditions of their sources, which are still among the unanswered questions in modern astrophysics.

In the field of cosmic ray physics, the goals of the HAWC collaboration include the search for the sources of very high-energy cosmic rays and a better understanding of the particle acceleration mechanisms in the cosmos using the TeV gamma-ray observations. In this case, gamma rays are a valuable tool, as they travel to us directly from the source, in contrast to cosmic rays, and are easier to detect than neutrinos. Another important objective for HAWC in this field is to study the distribution and propagation of galactic cosmic rays by using the measurements of the diffuse gamma-ray emission in our galaxy. On the other hand, also of interest for HAWC are the large/small-scale anisotropy measurements of high-energy cosmic rays [19, 24]. The corresponding maps contain information about the interstellar magnetic fields and possible nearby cosmic-ray sources to the Earth. Meanwhile, at lower energies, solar physics studies and the influence of the coronal mass ejections on the flux of galactic cosmic rays (Forbush effect) are also part of the cosmic-ray research agenda of the HAWC collaboration [19].

Science goals of HAWC also include other topics of investigation beyond the gamma- and cosmic-ray physics. By looking at the gamma-ray signals from the center of the Milky Way, distant galaxies and transient objects, HAWC will provide valuable information to constrain the intergalactic magnetic field [18] and several new physics models (for instance, Lorentz invariance violation (LIV), dark matter (DM) and primordial black holes (BH) scenarios [18, 25, 26]) that are deeply linked with fundamental questions in particle physics and cosmology. Even more, HAWC will look also for exotic non-relativistic DM particles, such as Q-balls, which could interact occasionally with the water of the HAWC detector producing an observable signal. For this purpose, the data acquisition (DAQ) system of the HAWC observatory has a dedicated trigger that will search for these events [18, 27].
3. The High Altitude Water Cherenkov detector

3.1. Layout

The HAWC observatory will be a second generation gamma-ray detector using the Water Cherenkov technique that will complement observations with modern IACTs and space gamma-ray telescopes. The apparatus is currently under construction at the central part of Mexico on the northern slope of the volcano Sierra Negra (18° 59′ 41″ N, 97° 18′ 28″ W) in the state of Puebla [10, 11]. The site is located at 4100 m a.s.l., which corresponds to an atmospheric depth of 640 g/cm². At this altitude even secondary showers with energies as low as 10 GeV can be detected with the instrument on the ground [12].

At the HAWC site the average temperature during the year is 4.3° C, and temperatures below zero degrees are observed only 5% of the time. Under these conditions, the water of the Cherenkov detectors has no risk of freezing and thus presents a homogeneous refractive index during the whole year [28]. The HAWC site is located in a seismically active zone. However, the observatory has been designed to resist earthquakes and other environmental conditions as high winds [28]. Regarding volcano risks, Sierra Negra is an extinct volcano. However, at 6 km to the Northeast of the site, there is an active volcano called Pico de Orizaba [28]. In any case, its last major activity was registered in 1545 CE and according to geophysical studies [29] the probability of a minor explosive event is 0.013 per year.

HAWC (see fig. 1, left) will consist of an array of 300 water Cherenkov detectors (WCDs) densely packed over a flat surface of 22,000 m² (≈ 150 m × 150 m) and instrumented with 1200 upward-facing photomultipliers (PMTs) distributed at the bottom of the tanks. The large area of the detector, as compared to the deep and shallow layers of MILAGRO (which covered only 2140 m² and 3528 m², respectively), will improve the gamma-hadron separation, the acceptance for induced gamma-ray showers and the determination of the core location of EAS, which is important to achieve a better angular resolution.

For HAWC, a modular design with tanks was preferred over the single pool one of MILAGRO due to several reasons [30]. First, tanks are less expensive and present a lower cost risk/contingency than a pond. Furthermore, Cherenkov detectors with tanks are a proven technology and offers the possibility of having a flexible and expandable array. Besides,
with tanks, servicing can be done without shutting down the whole detector and, even more importantly, construction and data taking can be performed simultaneously. In addition, water filling is simplified and can be done at a reduced rate. Finally, PMTs in different tanks can be optically isolated. The latter offers additional advantages for the tank design, namely, it reduces the noise rate from single muon events, as the single particles can at most illuminate a few PMTs. On the other hand, it improves the background rejection capabilities of the instrument. Moreover, it reduces redundant measurements from the same shower particles thus improving the angular resolution. In particular, scattered light that produces late tails in the PMT photon timing distributions and contributes to the noise rate in PMTs is efficiently absorbed by the tanks. And even more, by optically isolating the PMTs, it can be used a single layer of PMTs at the detector, instead of two as in MILAGRO [7], for triggering, angular reconstruction and calorimetry measurements.

In Milagro, a shallow layer of PMTs at ~ 1.5 m depth was used for triggering, shower plane reconstruction and reduction of the noise rate due to single muons. However, this shallow layer was a poor calorimeter, as it was close to the surface of the water [31]. For gamma/hadron separation, it is important to have a good calorimetric response, therefore in the Milagro design, an additional deep layer at ~ 6 m was required for calorimetry. In HAWC, the two layers are combined into a single deep one. This is possible because by using optical isolated PMTs, the problem of single muons is reduced and therefore a shallow layer is not needed.

Triggering and data acquisition is controlled from the Counting House, located at the center of the array. The building hosts, among other instruments, a laser system, which is employed for timing and charge calibration of the individual PMT channels, and an electronics facility that provides High voltage power supply for the PMTs. It also hosts the electronics and computing resources used for data taking as well as the on-line reconstruction and on-line analysis [12]. At the East edge of the array an additional facility has been installed. It is called the HAWC utility building (HUB) and contains an external platform, where the plastic liners of the WCDs are tested, and a room with a water filtration plant. In the latter, the water that is going to be used for the WCDs is first treated with a set of filters of 10 µm, charcoal, 5 µm and 1 µm to remove impurities and contaminants. In addition, the water is sterilized by exposition to a UV light source. [28]. The purified water is finally stored in a series of tanks located next to the HUB, from which it is later distributed to the WCDs. Water quality has been checked by measuring the attenuation length at 405 nm from 1 m water samples taken from 26 tanks. The results varied between 5 m and 16 m, with an average over all tanks of 10.4 m [32].

Each HAWC water Cherenkov detector is composed of a galvanized steel tank (7.3 m diameter and 5 m height) lined with a black PVC bag or bladder filled to ~ 4.5 m height (188 000lt) with pure water [28]. The depth of the WCD was selected as a compromise between timing resolution and gamma-hadron separation [33]. In addition, four upward facing PMTs are deployed at the bottom of the tank, three 8-inch Hamamatsu PMTs on a triangle, 6 ft from the center of the tank; and a 10-inch Hamamatsu high quantum efficiency PMT at the center, which improves the detection efficiency of the observatory to low energy air-shower events [12]. Finally, on the top of the tank there is a dome cover (5 ft height) that protects the WCD from the weather and environment [28]. In regard to the steel structures of the WCDs, it is worth mentioning that they are buried 60 cm in the ground to provide a natural anchor for stability and earthquake certification [12]. Once installed, the WCDs will cover 62% of the total physical area [11]. Gaps are being left among the WCDs. They are being reserved to carry out individual maintenance tasks [12].

The DAQ of the HAWC detector is composed of two systems [22]: The main DAQ, which registers the deposited charge and relative arrival times (with ns precision) of the PMT signals generated by the passage of the EAS, and the scaler DAQ, which is used to determine the count rate (inside a window time of 10 ms) of each PMT. The data of the main DAQ are used to
reconstruct the various air-showers observables, including the core location, the arrival direction, the energy and other useful parameters that are employed to discriminate between signal and background events [12]. The data of the scaler DAQ, on the other hand, is complementary to that of the main DAQ, for it provides count rate information on the PMTs, which is useful to monitor the good performance of the detector and is sensitive to transient events – such as gamma-ray bursts (GRBs) and solar events accompanied by the emission of energetic particles. These signals will be observed as statistically significant changes in the scaler rate [22, 23].

3.2. Status
In May 2010, the installation of HAWC’s engineering array, called VAMOS (Verification And Measuring of Observatory System) began. It was built about 170 m Northwest from the center of the current HAWC array [28].

VAMOS consisted of an array of 6 WCDs, instrumented with a total of 36 PMTs, and distributed inside a $25\text{m} \times 25\text{m}$ surface (c.f. figure 1, left). It was fully deployed in June 2011 and continuous DAQ was carried out from October 2011 to May 2012 ($\sim 30\%$ duty cycle). VAMOS data was useful to check the behavior of the HAWC PMTs under different environmental conditions and to perform some first $\gamma$- and cosmic-ray analyses planned for the full HAWC detector (in particular, searches from GRB signals and Forbush decrease studies) [17, 19, 28]. In addition, the experience gained by building and operating VAMOS served to verify and improve the design of the HAWC array and the logistic of the HAWC construction [28].

The building of the HAWC observatory started in March 2012. Its modular design has allowed to take air-shower data while in construction. In summer of 2012, the first 30 full WCDs were installed. HAWC-30, as it was called, started operations by August 2012 and results were presented in [12, 17, 19]. HAWC-95 began data-taking in June 2013, while the full operation phase officially started in September 2013 with HAWC-111. By the end of November 2014, HAWC-250 was completely installed, and in mid-December of 2014, there were already 300 tanks deployed on the field (see fig. 2), with 251 WCDs participating in the DAQ. The full HAWC-300 array will be completed at the beginning of 2015. The observatory is planned to be inaugurated in March of that year. The construction and operation of HAWC has been in charge of the HAWC collaboration, which is composed by several scientists, engineers, postdocs, technicians and students from around 29 institutions in Mexico and the US. Before finishing this section, it should be mentioned that the HAWC results presented in this conference were based

![Figure 2. Picture of the HAWC array. The image was taken on December 15th, 2014 after the installation of the steel frame for the 300th WCD of the observatory.](image-url)
on analyses performed with the data from the HAWC-30, HAWC-95 and HAWC-111 partial detectors.

3.3. Effective area, resolution and gamma-hadron separation

The sensitivity and the performance of the HAWC observatory have been studied with Monte Carlo (MC) simulations. The production and evolution of the cosmic- and gamma-ray induced EAS have been simulated using the CORSIKA v6990 program [34] along with the low- and high-energy hadronic interaction models FLUKA 2011 [35] and QGSJET-II [36]. Meanwhile, the detector and its response to the passage of the particle showers have been modeled using GEANT4 [37].

In fig. 3, the effective area of the full HAWC instrument to gamma rays is presented for different primary energies. Below 1 TeV, it rises with the energy, and at higher energies the effective area becomes practically independent of the energy ($\sim 10^5$ m$^2$). The former, is the result of the increasing probability of a primary particle of producing a detectable shower at the HAWC detector, while the latter, is a consequence of the limited accuracy of the reconstruction of EAS events falling outside the geometrical area of the HAWC array [17].

At energies below 1 TeV, the HAWC instrument will have a bigger effective area than its predecessor, the MILAGRO detector, in particular, at lower energies, i.e. $\mathcal{O}(10)$ GeV, such area will increase the statistics and sensitivity of the HAWC instrument, lowering its energy threshold below that achieved by the MILAGRO detector ($\sim 250$ GeV) [38]. The larger effective area observed in HAWC at low energies results, in the first place, because the altitude of the site is higher than that for the MILAGRO location ($\sim 750$ g/cm$^2$), i.e. HAWC is closer to the EAS maximum than MILAGRO, and, in the second place, due to the extra 10-in high-gain PMTs installed in the HAWC detector, which improve the low-energy response of the instrument.

HAWC will have a much better energy resolution than MILAGRO [17], which will allow to get precise TeV spectra of gamma-ray sources to study the origin of their high-energy emission. At low energies, the energy resolution will be 100%, but it will improve at high energies, reaching values below 50% above $E \geq 10$ TeV (c.f. fig. 4). This energy resolution will imply a significant
improvement over that of first-generation Cherenkov detectors.

The angular resolution ranges from about a degree at the low energy threshold to $\sim 0.1^\circ$ above 10 TeV. The improved angular resolution will allow more precise studies of the gamma-ray emission of point sources and the morphology of extended ones. The MC predictions for the angular resolution of the HAWC detector have been verified experimentally at least for a partial array, in particular for HAWC-30, using the measured width of the cosmic-ray Moon shadow [19]. In this case, at median energies of 2.9 TeV, it was found that the angular resolution of the detector is $1.2^\circ$, which is in good agreement with MC simulations. This value was confirmed by another experimental test performed with the same instrument by comparing independent estimations for the arrival angle of EAS from two equal-area sub-arrays composed of different PMTs from the array (in this case, the angular resolution was $1.3^\circ \pm 0.2^\circ$) [19].

In order to separate the gamma-ray signals from the continuous and dominant background of cosmic ray events, cuts must be applied at HAWC. In particular, rejection of cosmic ray events relies on a parameter called the compactness [39], which measures the clumpiness of the shower signals deposited at the WCDs. This compactness is a muon-content dependent quantity defined as the ratio between the total number of PMTs activated by the shower and the number of photoelectrons recorded in the largest hit channel outside a radius of 40 m from the EAS core. In general, gamma-ray induced showers are composed mostly by electromagnetic particles (photons and electrons), which produce a smooth and compact distribution of deposited charge at ground level, while hadronic EAS created by cosmic ray primaries have also a muonic component that creates a clumpy pattern of signals at the array with large charge depositions at large distances from the shower core (see fig. 5). Therefore, gamma-ray showers will be characterized by a larger compactness value than cosmic ray EAS. HAWC exploits this difference, as well as other variables, to separate the background of cosmic rays from the gamma-ray signals [10, 17, 22].

The expected efficiencies of HAWC-300 (see [10]) to photon and cosmic-ray events after applying
the compactness cut and a cut on the angular distance of events to a Crab-like point source are shown in fig. 6 (left). From this figure, it is seen that the hadron rejection improves with increasing energy. In particular, at $10^{2.5}$ GeV, if events are required to have a compactness greater than 3.1, one retains $\sim 80\%$ of the gamma ray events and only $\sim 50\%$ of the hadron events, yielding a quality factor, $Q$, of 1.13. Meanwhile, at 10 TeV, if all events with compactness $\leq 14.4$ are removed, $60\%$ of the gamma ray events and only $\sim 0.45\%$ of the hadron events are retained. This results in a $Q$ value of $\sim 8.9$. Milagro was only able to achieve $Q$ factors around $1.5 - 2.0$ [7]. Above 10 TeV, the gamma-hadron separation in HAWC is efficient enough to remove all the simulated hadronic events, so the curve presented here is limited by MC statistics.

3.4. Sensitivity to steady sources
The sensitivity of the full HAWC detector to point sources with power-law spectra of the form

$$dN/dE = \Phi_0(E/\text{TeV})^{-\alpha} e^{-(E/E_{\text{cut}})}$$

has been studied using MC simulations [10]. The results have shown that the HAWC-300 observatory will be 15 times more sensitive than MILAGRO, i.e. HAWC will survey the MILAGRO sky 225 times faster at the same significance. Above photon energies of 2 TeV, HAWC will have a sensitivity, at a $5\sigma$ level, down to $5 \times 10^{-13}$ cm$^{-2}$ s$^{-1}$ ($\sim 50$ mCrab) to point sources in a year of data taking over 5 sr (40%) of the sky [10]. In fig. 7, the expected sensitivity of the full HAWC instrument is shown as a function of the energy and in comparison with other gamma-ray detectors. As it can be seen from the abovementioned plot, at 1 TeV, the sensitivity of HAWC in one year of data taking will reach a value equivalent to 50 hr of observation with modern IACTs, while at energies between 10 and 100 TeV, the HAWC observatory will achieve an unprecedented sensitivity in comparison with existing space-telescopes and IACTs. The latter as a result of the altitude, large area and high duty cycle of the HAWC observatory.

The sensitivity of the HAWC detector depends also on the declination of the source and due to the geometrical latitude of the observatory, it is better ($\sim 50$ mCrab) for declination angles between $-5^\circ$ and $45^\circ$ [10] (see fig. 6, right). The expected sensitivity of the HAWC observatory
Figure 6. Left: Efficiency of HAWC to photon and cosmic-ray induced showers after applying the compactness cut [10]. The MILAGRO efficiency to cosmic ray events is also shown for comparison. Above 10 TeV, the gamma-hadron separation is so efficient that removes all the simulated hadronic events. Right: Sensitivity of HAWC to a point source with a power-law spectrum like in eq. 1 presented as a function of declination for two different spectral indexes. The flux presented is the one required to have a $5\sigma$ signal in one year [10].

to a punctual source with a power-law spectrum of the form $E^{-2}$ is presented in fig. 8. HAWC, after one year of data taking, will be sensitive to integral power-law spectra as low as 50 mCrab above 2 TeV over 5 sr ($\sim 40\%$) of the whole sky. For HAWC FOV, most celestial observations are limited to objects within 45° of the local zenith angle, however, measurements at larger zenith angle are possible, for example, of the galactic center ($\theta = 46^\circ$), although with less sensitivity.

Observations of TeV gamma rays with the HESS telescope have shown that most Galactic sources in the TeV range are extended [40]. This could be due to the interactions of cosmic rays with material in the extended vicinity of their acceleration sites. Unfortunately, while IACT facilities, such as HESS, are quite sensitive, it is difficult for such narrow-field instruments to observe the full extent of large sources. In fact, when the source size is much larger than the point spread function of the IACTs, the sensitivity of the telescopes worsens because the background increases. Current observations of extended sources with HESS are clustered around the limit of their sensitivity, suggesting the presence of even more extended sources than currently claimed. In particular, nearby sources may have a larger angular extent than currently reported by IACTs. HAWC will be better suited than IACTs to find out this question due to its large field of view. This feature will allow, in turn, to perform also spectral studies of extended sources with HAWC.

According to MC simulations [10], the expected sensitivity (integral flux $> 2$ TeV) of HAWC to an extended source with a pure power-law spectrum ($\alpha = 2, 3$) and a radius of $R_s = 0.5^\circ$ will be around $5 \times 10^{-13}$ cm$^{-2}$ s$^{-1}$, and for sources with $R_s = 3^\circ$, it is predicted to be of the order of $2 \times 10^{-12}$ cm$^{-2}$ s$^{-1}$.

Subtraction of the gamma-ray emission due to point and extended sources from the total flux of the galactic plane will allow to constrain better the truly diffuse emission at the galaxy [17].

The 100 GeV – 100 TeV diffuse emission measurements with HAWC will be an excellent tool to probe acceleration, propagation and density distribution of cosmic rays at different locations within our Galaxy. The HAWC site is close to the equator and the field of view covers the inner Galaxy all the way to the Galactic center. Using observations from HAWC, nearby regions such as Cygnus at 1 – 2 kpc as well as the more distant inner galaxy (about 10 kpc) will be studied. The Cygnus region could be dominated by very few cosmic-ray accelerators whereas the cosmic
Figure 7. Differential sensitivities per quarter decade of HAWC-100 (1 year) and HAWC-300 (1 and 5 years) [10]. The corresponding sensitivities of Fermi-LAT [41], for 5-years, and two IACTs [42, 43, 44], for 50 hours, are shown for comparison. An upper limit on the Crab flux at 141 TeV derived from the CASA-MIA detector [45] is also displayed together with the measured Crab flux from [46].

rays from the inner Galaxy are from a large collection of sources and will reflect the cosmic-ray spectrum after propagation farther from their origins. These regions are hundreds of square degrees and require the large field of view of HAWC. With its wide FOV, HAWC will be able to study not only the diffuse emission from large areas along the galactic plane, but also from other structures such as the Fermi bubbles [17].

The wide field of view and high duty-cycle of HAWC constitute major advantages for the instrument during the search and monitoring of the evolution of transient events across the sky. With HAWC low-energy threshold, transient phenomena with a minimum flux of $E^2 dN/dE \sim 4 \times 10^{-5}$ erg cm$^{-2}$ s$^{-1}$ at 10 GeV, power-law spectra proportional to $E^{-1.6}$, viewing zenith angle of 20°, and duration of 10$^{-2}$s will be detectable at the 5$\sigma$ level up to a redshift of $z \sim 1$ by the scaler and main DAQ systems [22]. Transients with longer duration and closer events will be detectable at HAWC at much lower fluxes. Specific details on the sensitivity of HAWC to GRBs and AGN flares can be found in [22, 23] and [47], respectively. Here, it will be only mentioned that, in case of GRBs, calculations performed in [23], and based on observations made by Fermi-LAT and other observatories, show that HAWC will be more sensitive to the short-hard variety of GRBs than to the long-soft ones. In addition, the same estimations indicate that 90% of the short-hard GRBs visible at 5$\sigma$ significance to HAWC main (scaler) DAQ system will have a fluence above $3.5 \times 10^{-7}$ erg cm$^{-2}$ (1.7 $\times 10^{-6}$ erg cm$^{-2}$). On the other hand, regarding transient phenomena in AGNs, it was shown in [47] that HAWC will be able to detect highly flaring events (e.g. $\times 10$ quiescent state) within a fraction of a day at a 5$\sigma$ level from Mrk421, Mrk501 and M87, which are within the FOV of the observatory. In particular, an intense outburst with an integral flux of 4 Crab above 1 TeV from these AGNs will be detected within
3.5. Sensitivity to exotic physics

The sensitivity of HAWC to new physics has been also investigated. In [25], the potential of HAWC to detect high-energy photon signals due to DM self-annihilation processes in the galactic center and extragalactic systems (i.e. the Virgo cluster, the M31 galaxy and the dwarf galaxies Draco, Coma Berenices and Segue 1) was studied by means of MC simulations. A variety of weakly interacting massive particles (WIMPs) annihilation channels (into $b\bar{b}, t\bar{t}, \mu^+\mu^-, \tau^+\tau^-, W^+W^-$) with different DM density profiles were analysed. For the galactic center, both the Einasto [48] and the Navarro-Frenk-White (NFW) [49] models were employed, whereas for the extragalactic systems only one model was assumed (NFW for most of them, but for Segue 1, where Einasto was used). 95\% expected limits on the $\langle \sigma v \rangle$ as a function of the dark matter mass ($M_\chi$) were obtained for HAWC-300 assuming that no DM signal is observed above the background in five years of observation time. In fig. 9, as an example, some predicted DM limits are presented for the channel $\chi\chi \to \tau^+\tau^-$. For $M_\chi$ in the interval from $\mathcal{O}(1)$ TeV up to $10^3$ TeV, the analyses performed predict that HAWC will be sensitive to cross sections as low as $\langle \sigma v \rangle \approx 3 \times 10^{-24}$ cm$^3$ s$^{-1}$, depending on the dark matter mass and annihilation channel.

From the dwarf galaxies studied, HAWC will have a better sensitivity to Segue 1, thanks to its strong expected DM annihilation flux and a favorable declination [25]. Other good candidates, in comparison with Segue 1, are the Virgo Cluster under the presence of dark matter substructures in the outlying regions of the halo (which could boost the gamma-ray flux at the source) and M31 with/without boost due to DM sub-halos [25]. The limits for the galactic center, on the other
Figure 9. Expected dark matter limits (95% C.L.) from the observation of dwarf galaxies (left), the Virgo cluster and M31 (right) with HAWC-300 after five years of data taking for the $\tau^+\tau^-$ annihilation channel [25]. The limits were estimated from simulations. Solid lines were calculated for prompt emission (photon radiation from secondary particle decays and charged particles), while the dot-dashed lines include a conservative inverse-Compton component as well (from the scattering of secondary charged particles off low energy background photons). In case of M31 and the Virgo cluster, calculations were carried out assuming a smooth density profile (sm) and a boosted signal from DM substructure in their respective halos (bst). A limit from the MAGIC telescope for Segue 1 [50] (purple dot-dashed curve) is presented in the left figure. On the other hand, two limits from HESS [51] (triple-dot-dashed purple line) and Fermi-LAT [52] (dot-dashed purple line) for the Fornax and Virgo clusters are plotted, respectively, on the right figure. The cross section value for a relic thermal DM particle is also shown and is represented by the lower horizontal line.

hand, are expected to be better than Segue 1 due to a higher photon flux and its proximity to the Earth. However, because of the larger zenith angle at which the galactic center is observed from the HAWC site, those limits will be less competitive than other instruments, such as HESS, except at high $M_\chi$ (above 10 TeV, HAWC should be sensitive to DM cross sections down to $\langle \sigma v \rangle \approx 5 \times 10^{-24} \text{cm}^3\text{s}^{-1}$) [25].

The sensitivity of HAWC-300 to other new physics scenarios, for example Q-balls and primordial black holes, are studied in references [18, 27] and [26], respectively.

4. Latest results with HAWC
4.1. Sky map
A preliminary significance sky map in gamma rays was obtained with 154 days of live time using data from the HAWC-95/111 array, whose layout is displayed in fig. 10 (left). The sky map is shown in fig. 12. To generate the map, a subset of the whole HAWC-95/111 data was reconstructed online during data taking using preliminary calibration and pointing uncertainties. The direct integration technique [53], with $\Delta t \sim 2$ hr of integration time, was used to create the significance map. The analysis was partly optimized on the signal of the Crab Nebula, which is observed at $> 10 \sigma$ (c.f fig. 11, left). Other signals are seen at more than $5 \sigma$ in coincident positions with the galactic plane and extragalactic objects. In particular, multiple regions are detected along the inner region of the galactic plane. This region of the Milky Way contains different kinds of astrophysical sources, such as molecular clouds, stellar clusters, pulsars, SNRs, etc., which may be responsible for the observed emission. At the moment, ongoing analyses are
underway to try to elucidate this question.

On the other hand, > $7\sigma$ and $\sim 6\sigma$ excess emissions are detected from the directions of Markarian 421 (Mrk421) and Markarian 501 (Mrk501), respectively. These two objects are BL Lac galaxies with proven gamma-ray emission (see, for example, [55, 56] and references therein). Mrk421 is one of the closest blazars to Earth ($\sim 130$ Mpc) and was the first extragalactic object detected at very high energies (VHE) [57]. The second one to be discovered at VHE

Figure 10. Left: Layouts of the HAWC-95 array (represented by the big white circles) and the HAWC-111 detector (indicated by the white and gray circles) [54]. The PMTs of low- and high-gain are represented by the open circles and the filled circles, respectively. Right: Estimated energy resolution as a function of declination for the HAWC-95/111 data used in the study of the Moon shadow and the small-scale anisotropies of cosmic rays [54].

Figure 11. Left: Preliminary significance map in the direction of the Crab nebula calculated from the gamma-ray data of HAWC-95/111 with 154 days of live time. Right: Preliminary significance map obtained on Markarian 421 with HAWC-95/111 and data from the period June 13, 2013 to September 12, 2013.
Figure 12. Preliminary sky map (in equatorial coordinates) of 154 days of data with $\sim 1/3$ of the HAWC array. The analysis is optimized on the Crab Nebula. The significance of the Crab Nebula is $>10\sigma$. The galactic plane is clearly visible. An extended excess near right ascension $60^\circ$ is due to cosmic rays (region A in fig. 14). The analysis is still under development to improve the gamma-hadron separation [59].

was Mrk501 [58], which is one of the brightest TeV sources in the sky. In fig. 11, right, a preliminary significance map from the region of Mrk421 as obtained with HAWC-95/111 is displayed. Currently Mrk421 and Mrk501, along with other extragalactic TeV sources, are the target of TeV flare searches with the HAWC array.

Finally, an extended excess near right ascension $60^\circ$ is also observed in the sky map. This is produced by cosmic rays (region A in fig. 14). The main goal of the HAWC observatory is the investigation of VHE photons; however, cosmic ray events are also interesting for several aspects, for example, to study the cosmic ray anisotropies or to validate the detector characteristics, in terms of pointing accuracy and angular resolution, as will be seen below.

4.2. Cosmic ray studies

4.2.1. The shadows of the Moon and the Sun  The Moon and the Sun cause a local deficit on the isotropic flux of cosmic rays observed at Earth, what are called the Moon and the Sun shadows, respectively. With cosmic ray data collected with a partial array of HAWC, both the shadows of the Sun and the Moon have been observed. In particular, the Moon shadow has been seen with a significance of $-23.8\sigma$ in HAWC-95/111 [54]. The shadow of the Moon is observed on the left side of fig. 13 for 113 sidereal days of live time. The plot is presented in moon equatorial coordinates and it is centered at the position of the Moon. A fit to the deficit region with a two-dimensional Gaussian reveals that the Moon shadow has an offset of $-1.05^\circ \pm 0.05^\circ$ in right ascension and of $-0.02^\circ \pm 0.06^\circ$ in declination, and a width of $1.26^\circ \pm 0.05^\circ$. The shift is the result of the deviation of charged cosmic rays due to the Earth’s magnetic field and it is
4.2.2. The small-scale anisotropies

Using data from the HAWC-95/111 detector, small-scale anisotropies at the level of $\sim 10^{-4}$ on angular scales of $\sim 10^\circ$ have been observed in the distribution of TeV cosmic rays [54]. The analysis was based on $49 \times 10^9$ well reconstructed events taken from June 16 of 2013, to February 27 of 2014. According to MC simulations, the whole data set has a median energy of 2 TeV. It should be mentioned that, in general, this quantity depends on the declination, as it can be seen in the right graph of figure 10, which was calculated with MC simulations [54].

HAWC’s sky map for the relative intensity of cosmic rays is presented in the upper panel of figure 14 in equatorial coordinates. The map was obtained using the direct integration method [53], with a smoothing radius of $10^\circ$ and integration time of 24 hr, and by removing large-scale structures greater than $60^\circ$. In the lower part of figure 14, the respective map for the significance of the deviations of the cosmic ray flux from isotropy is also shown. In those maps,
three prominent features are observed [54]. They are called regions A, B and C, respectively. The strongest excess comes from region A, in particular, from the coordinates $\alpha = 57.7^\circ$ and $\delta = -6.3^\circ$. This excess has a significance of 17 $\sigma$ and a relative intensity of $(8.5 \pm 1.0) \times 10^{-4}$ [54]. According to a two-dimensional Gaussian fit, the center of Region A is located at $(\alpha, \delta) = (60.0^\circ \pm 0.7^\circ, -7.1^\circ \pm 0.8^\circ)$ and has a width of $(\Delta \alpha, \Delta \delta) = (7.1^\circ \pm 1.3^\circ, 7.8^\circ \pm 1.3^\circ)$. This region has already been observed by ARGO-YBJ [61] and MILAGRO [62], although, in the latter case, the magnitudes and locations of the peaks differ from the ones measured at HAWC, presumably due to differences in the median energies of the respective observatories.

The region B in the sky map of fig. 14 exhibits an elongated shape, which extends around $\alpha = 120^\circ$ along all the declination range covered by HAWC, as it can be observed also in
the relative intensity map in fig. 14. It has been also observed by ARGO-YBJ [61] and MILAGRO [24]. This structure seems to continue into southern celestial regions, where it could be connected with an excess observed by ICECUBE [63], however, at a slightly different right ascension (α = 122.4°). The significance of region B has a maximum (11.2σ) from the direction of (α, δ) = (122.1°, 43.8°), where the relative intensity has a value of (5.2 ± 0.9) × 10⁻⁴.

Finally, the region C has a significance of 8.2σ and a relative intensity of (2.9 ± 0.6) × 10⁻⁴. It is centered at α = 205.7° and δ = 22.5°. This structure was observed by the ARGO-YBJ Collaboration, who first reported it [61]. On the contrary, at this position, MILAGRO did not observed any significant excess.

The origin of the small-scale anisotropies is not clear yet. Explanations range from conventional astrophysical explanations, such as turbulence in the interstellar magnetic field [64] and effects of the heliosphere [65], up to exotic scenarios, for instance, dark matter self-annihilations in galactic sub-halos close to the Sun [66].

4.3. GRBs limits
On April 27, 2013, during the operation of the HAWC-30 array, Fermi-LAT observed an exceptionally bright GRB [67]. GRB 130427A, as it was named, had the longest gamma-ray duration (20 hr) at E > 100 MeV and the highest energetic photon ever detected, with an energy of 95 GeV [67]. The burst occurred at T₀ = 7:47:06:42 UTC. Unfortunately for HAWC-30, at that time two unfavorable circumstances happened, the first one is that due to maintenance the main DAQ system was turned off and only the scaler DAQ system was taking data, and the second one, that the GRB was at an unfavorable zenith angle of 57° in local coordinates, for which the effective area of the scaler DAQ system of HAWC is reduced by more than 2 orders of magnitude with respect to the zenith (c.f. fig. 15, left). This chain of events reduced any chance of detection of the GRB 130427A with HAWC-30, however, upper limits on the integral gamma-ray flux of the event were established for the interval 0.5 GeV − 1 TeV. Two of these limits are shown in the right plot of fig. 15. They were derived from an analysis of the data inside a time window of T₀ + 11.5 s and T₀ + 33 s assuming two spectral shapes for the source [32]. One of them was obtained by extrapolating a fit of the Fermi-LAT data to TeV energies under the assumption of attenuation of the flux on the extragalactic background light. The other shape consisted only of a E⁻² power-law spectra for three different energy intervals. Expected limits were also estimated for the two DAQ systems of HAWC-300, for an overhead GRB with the same flux as the one discussed above. The limits are shown in fig. 15, right. Clearly, for such hypothetical event, the HAWC-300 detector would provide a clear signal of the GRB [32]. After completion of the observatory, HAWC will be in operations for ten years. In this period of time, better limits and larger chances of detection of GRBs are expected.

5. Conclusions
The HAWC detector is now under construction at the Volcano Sierra Negra, Mexico. Upon completion, HAWC will comprise a 22 000 m² array of 300 Water Cherenkov detectors dedicated to continuously monitor the northern sky in search for air showers from γ and cosmic-rays in the (100 GeV − 100 TeV) energy band. Due to its modular design, HAWC has been taking data during construction. The correct functioning of the detector as well as the analysis pipeline has been demonstrated, for instance with the observation of various sources like the galactic plane, the Crab nebula, Mrk 421 and Mrk 501. In addition, the shadows of the Moon and the Sun have been observed in cosmic rays at TeV energies with the partial array, validating the pointing accuracy and the angular resolution of the detector. The small-scale cosmic-ray anisotropy has also been observed in agreement with previously reported observations by other EAS detectors. Finally, a search for emission from the very bright GRB 130427A, though at an unfavorable zenith angle for HAWC, has also been performed. As no excess was observed, limits were set.
Figure 15. Left: The effective area for the scaler DAQ system HAWC-30 and HAWC-300 for events with zenith angles $\theta$ such that $\cos \theta > 0.9$. The corresponding effective area for HAWC-30 in the direction of the GRB 130427A is also shown [32]. Right: Upper limit on the integral gamma-ray flux of the GRB 130427A from the scaler system of HAWC-30. Two spectral shapes were assumed, one from a fit to the Fermi-LAT data and assuming attenuation of the flux with the extragalactic background light (black line), and another one, using a $E^{-2}$ power-law spectrum for three different energy intervals (black horizontal lines). The expected limits from HAWC-300 for an overhead burst similar to the GRB 130427A, using data from the main DAQ and scaler system, are shown for comparison (green dashed-dotted lines).

With the HAWC detector close to being completed, more data being accumulated and more analyses underway, the HAWC observatory will provide a wealth of novel information about the very high energy universe.

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