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Preliminary Cosmic Ray Results from the HAWC's Eye Telescopes

F. Rehbein,[a,*] **R. Alfaro,**[b] **T. Bretz,**[a] **O. Chaparro-Amaro,**[c] **G. Do,**[a] **F. J. González,**[d] **M. M. González,**[d] **A. Iriarte,**[d] **J. Martínez-Castro,**[c] **M. Martínez-Felipe,**[c] **F. Maslowski,**[a] **Y. F. Pérez-Araujo,**[d] **M. Schaufel,**[a] **J. Serna-Franco,**[b] **F. Tischbein**[a] **and I. Torres**[e]

[a] *Physics Institute 3, RWTH Aachen University,*
Sommerfeldstraße 16, 52074 Aachen, Germany.
[b] *Instituto de Física, Universidad Nacional Autónoma de México,*
Ciudad de México, Mexico.
[c] *Centro de Investigación en Computación, Instituto Politécnico Nacional,*
Ciudad de México, Mexico.
[d] *Instituto de Astronomía, Universidad Nacional Autónoma de México,*
Ciudad de México, Mexico.
[e] *Instituto Nacional de Astrofísica, Óptica y Electrónica,*
Puebla, Mexico.
E-mail: `florian.rehbein@rwth-aachen.de`

The compact imaging air-Cherenkov telescope HAWC's Eye was developed to operate with the High-Altitude Water Cherenkov Gamma-Ray Observatory (HAWC). The combination of both detection techniques in a hybrid configuration provides a significant improvement in energy and angular resolution, aiming for improved measurements of the cosmic ray composition above 10 TeV and contributing to the physics program of the observatory. Preliminary results of the first hybrid measurements of the cosmic ray spectrum are presented. After the first HAWC's Eye telescope was brought to the HAWC site in 2017, a second telescope was successfully commissioned in 2019. Two measurement nights have since then recorded the data used in this analysis. The HAWC's Eye events were successfully synchronized with the events recorded from the extensive air-shower array HAWC and further used to characterize the hybrid system. A complete simulation of the hybrid configuration was used to develop algorithms to reconstruct the energy and arrival direction of proton-induced air showers. Those algorithms were successfully applied to the measured cosmic ray events to verify the performance of the hybrid detection. The spectrum reconstructed with HAWC's Eye is consistent with the spectrum reconstructed solely from the coincident HAWC data.

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[*] Presenter

1. Introduction

During the last decades, numerous experiments studied the composition and energy spectrum of the constant flux of ionized particles from space, called cosmic rays. Since the flux of these cosmic rays is steeply falling with energy, large ground-based detectors are needed to measure the highest energies of up to 10^{20} TeV. Such ground-based detectors can not detect cosmic rays directly due to their interactions with the Earth's atmosphere. The result of such interactions are large cascades of secondary particles, known as extensive air showers.

Ground-based particle arrays directly detect the secondary particles forming the shower front. These arrays are composed of numerous stations that cover a large area. Combining data from multiple stations enables the reconstruction of the shower axis, while the number of secondary particles correlates with the cosmic ray energy. When traversing atmospheric matter, the shower particles emit Cherenkov photons. Imaging air-Cherenkov telescopes (IACTs) detect those photons and thereby can take images of the showers. Since Cherenkov photons are emitted at every stage of the shower, IACTs provide measurements of the complete shower development through the atmosphere.

The combination of both detection techniques in a hybrid setup [1] improves the quality of the shower reconstruction, as they provide complementary information of the same shower. Ground-based particle arrays enable a precise reconstruction of the shower axis and position on ground, but only see the showers at one distinct point of their development. In contrary, IACTs collect Cherenkov photons during the whole shower development, but are left with an ambiguous reconstruction of the shower position on ground: Small-energy showers close to the telescope produce similar images as high-energy showers far away. The hybrid setup helps to solve these ambiguities and thereby improves the reconstruction of the showers.

This paper presents a preliminary reconstruction of the cosmic ray spectrum with the hybrid setup of HAWC and two HAWC's Eye telescopes.

2. The HAWC's Eye Telescope as an Extension of the HAWC Gamma-Ray Observatory

The HAWC's Eye telescope [2] is a compact and light-weight IACT based on refractive optics. It serves as an extension of the High Altitude Water Cherenkov Observatory HAWC, with two HAWC's Eye telescopes stationed at the HAWC site since 2019 [3]. The telescope features an enclosed design, utilizing a Fresnel lens with a diameter of 549.7 mm and a focal length of 502.1 mm. The pixelized camera is composed of 61 Silicon Photomultipliers (SiPMs) of type SensL MicroFJ-60035-TSV as photosensors, each of which is equipped with a solid light guide to increase their photosensitive area.

The High Altitude Water Cherenkov Gamma-Ray Observatory HAWC is an extensive air shower array located at an altitude of 4100 m close to the Sierra Negra volcano in Mexico. With a large field of view of almost 2 sr and a high duty cycle of 95 %, it is designed to detect gamma-rays in a broad energy range between 100 GeV and 100 TeV [4].

3. Measurement

The data presented in this paper was recorded in the night of December 19th 2019 with two HAWC's Eye telescopes located in the center of the HAWC observatory at a mutual distance of 40 m and both pointing to the zenith. The weather conditions were ideal for HAWC's Eye due to a moonless and clear night. About 2.5 hours of observation data was taken and successfully synchronized with the HAWC detector by comparing the absolute trigger timestamps of HAWC's Eye with HAWC. With a time window of 100 µs, close to 90 % of all HAWC's Eye events were successfully assigned to a HAWC trigger flag. This fraction corresponds to a total number of about 90 000 synchronized events per telescope. The excess events can be assigned to night sky background.

4. Energy Reconstruction using Hybrid Data

For this study, 362 000 proton-induced air showers were simulated using the program CORSIKA. The key parameters of the CORSIKA configuration are summarized in Table 1. The maximum simulated zenith angle of 8° is chosen according to the HAWC's Eye field-of-view of about 6.8°. Since the maximum distance of the telescope to the shower core is limited by the size of the Cherenkov light cone on ground, the simulated area is set to $500 \times 500\,\mathrm{m}^2$.

Table 1: CORSIKA configuration for the air shower simulations.

Parameter	**Value/Range**
Energy spectrum slope	-1.5
Energy range	1 TeV-100 TeV
Zenith angle	0°
View Cone	8°
Shower core scattering area	$500 \times 500\,\mathrm{m}^2$
Observation height	4100 m
Cherenkov wavelength range	250 nm - 700 nm
Atmospheric model	US standard atmosphere
Magnetic field	27.717 µT (hor.); 29.902 µT (vert.)
Hadronic interaction model	GHEISHA (low-energy); QGSJET (high-energy)

The simulation of the HAWC's Eye detector is part of the ROOT-based MAGIC Analysis and Reconstruction Software MARS [5]. From the shower images, camera pixels that only contain night sky background are removed with an image cleaning algorithm taking the signal amplitude and arrival time into account. The background-subtracted signal distributions are then parametrized by a set of image parameters, which, for example, includes the total signal size and the width and length of the distribution.

The HAWC array is simulated using the GEANT4-based [6] software package HAWCsim. For all triggered showers, the energy, arrival direction, and shower core position are reconstructed with the standard HAWC algorithms [8, 9].

The HAWC parameters are then combined with the HAWC's Eye image parameters for an improved reconstruction. For the energy reconstruction of the triggered hybrid events, the software package ranger [7] is used. Ranger implements the random forest algorithm, a machine learning algorithm based on bootstrapped decision trees. As input, a set of combined HAWC's Eye and HAWC parameters has been optimized for the best possible performance.

The correlation of the reconstructed and Monte Carlo energy of the hybrid events is shown in Figure 1. The red line indicates perfect correlation between the two energies. The distribution shows, that the reconstruction overestimates the primary energy at the smallest energies below about 10 TeV due to the trigger threshold of the hybrid analysis. At the highest energies above 50 TeV, the reconstruction underestimates the true energy due to the limited simulated energy range, leading to a bias for this study.

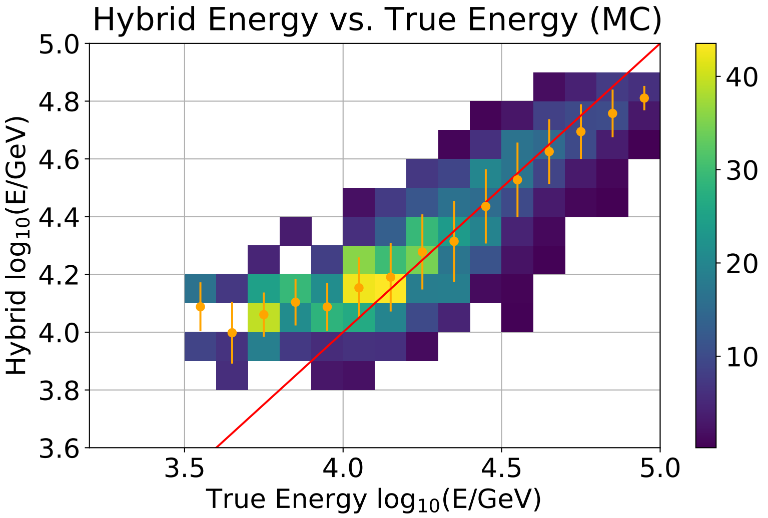

Figure 1: Two-dimensional histogram of the reconstructed energy as a function of the Monte Carlo energy for simulated primary protons. The mean and standard deviation for each bin are shown in orange. The red line shows the line of perfect correlation. The energy threshold induces an overestimation at the smallest energies. At the highest energies close to 100 TeV, the limited simulated energy range causes an underestimation.

The resulting energy resolution, defined as the standard deviation of $\log E_{RF} - \log E_{MC}$ around zero, as a function of the Monte Carlo energy is shown in Figure 2. The resolution of the HAWC energy reconstruction parameter `protonlheEnergy` serves as a reference. Both algorithms have a poorer resolution at smaller energies, i. e. close to the hybrid energy threshold. For all energies below about $10^{4.8}$ GeV, the combination of both detectors provides a significant improvement of the HAWC energy reconstruction. The increase of the resolution above the HAWC curve at the highest energies originates from the discussed bias caused by the limited simulated energy range.

When applying this reconstruction algorithm to the measured data (see Section 5), one has to account for the missing heavier elements in the simulation. Since the HAWC energy reconstruction assumes a mass composition including helium and heavier elements, it should reconstruct the energies of cosmic rays without a bias. Therefore, it can be used as a reference energy to correct the

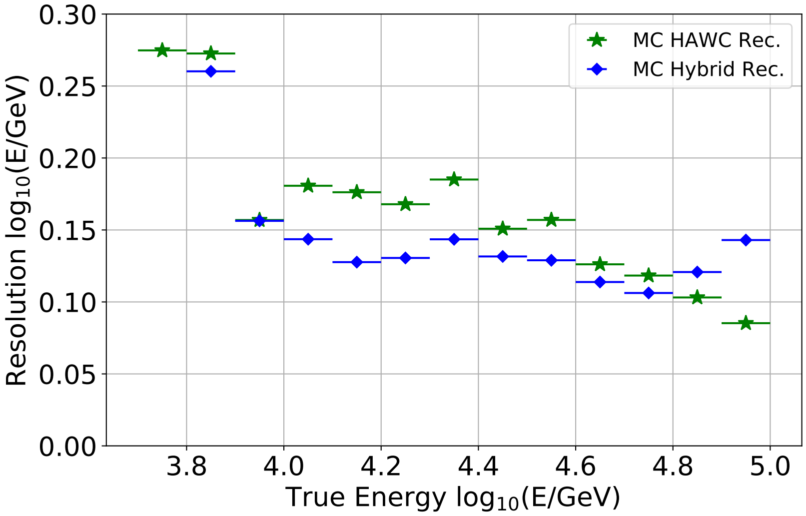

Figure 2: Energy resolution as a function of the Monte Carlo Energy. The green curve represents the energy resolution according to the HAWC reconstruction for synchronized events, the blue curve shows the hybrid reconstruction of the same events, as discussed above. The resolution below 10 TeV and above 50 TeV are biased by the trigger threshold and a limited simulation range respectively.

hybrid reconstruction and minimize the effects following the training with only protons. Therefore, the bias of the hybrid reconstruction with respect to the HAWC reconstruction is calculated in the energy region not affected by edge effects. It shows, that the hybrid reconstruction underestimates the logarithmic energy by -0.13, which will be corrected for in the analysis of the measured data.

To correct the measured flux for detector efficiencies, an effective aperture is obtained from the simulation. It is defined as

$$\mathcal{A}_{eff} = A_{sim} \cdot \Omega_{sim} \cdot \frac{\mathrm{d}N_{trig}}{\mathrm{d}N_{sim}} \tag{1}$$

with the simulated area $A_{sim} = 500 \times 500\,\mathrm{m}^2$, the simulated solid angle of $\Omega_{sim} = 0.06\,\mathrm{sr}$ corresponding to the maximum zenith angle of 8°, the number of triggered events $\mathrm{d}N_{trig}$, and the number of simulated events $\mathrm{d}N_{sim}$ in the respective energy bin.

The effective aperture as a function of the proton energy is depicted in Figure 3. As discussed earlier, the random forest overestimates the low-energy events and underestimates the high-energy events, i. e. events close to the minimum and maximum of the displayed energy range respectively. When displaying the effective aperture as a function of the reconstructed energy, this effect reduces the number of events in the affected energy bins and lowers the effective aperture accordingly. It becomes most prominent in the highest-energy bin, where the number of events is small due to the small proton flux and the reconstruction bias is maximal.

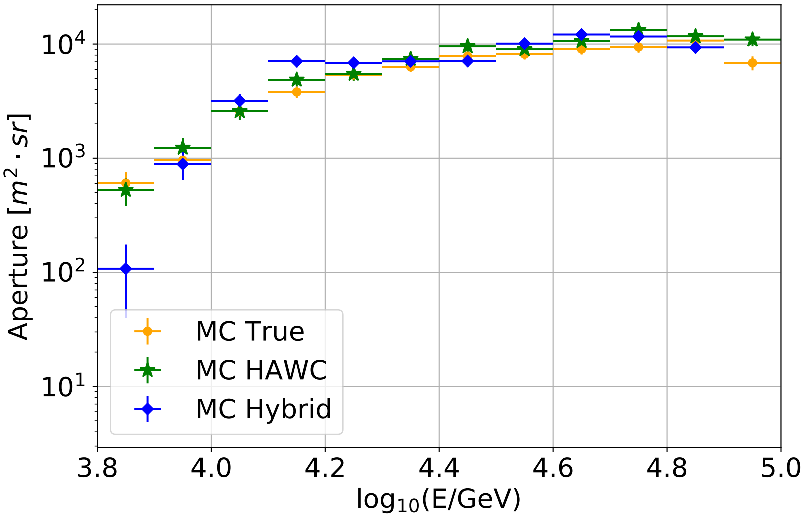

Figure 3: Effective aperture for the detection of proton-induced air showers. The energy reconstruction of the random forest (blue) is plotted against the Monte Carlo energy (yellow) and the HAWC energy (green). All curves display the same events. The errorbars depict the bin width (horizontal) and the statistical errors (vertical) in each energy bin.

5. Cosmic Ray Spectrum

Using the results of the simulated effective aperture, the measured event rates can be transformed into a particle flux. As the spectral index of the simulated spectrum influences the effective aperture and therefore the reconstructed spectrum, it needs to be adjusted in order to match the real index as close as possible. Fitting an exponential spectrum to the reconstructed spectrum results in an estimation of the spectral index. Then, the simulated spectrum was re-weighted according to the estimated spectral index and the calculation of the measured cosmic ray spectrum was repeated, representing one iteration step. After a few iteration steps, the spectral index converges and starts to fluctuate around a certain value. For the final result, 20 iteration steps have been applied to the data.

The resulting cosmic ray spectrum is compared with a previously published and fully analyzed spectrum of the HAWC observatory in Figure 4. For this, the measured spectrum has been included in the corresponding plot from [10] in which the HAWC result has been compared to data from several other observatories.

The reconstructed cosmic ray flux is systematically smaller than the published HAWC spectrum. Cosmic rays in the observed energy range between about 1 TeV and 100 TeV are composed not only of protons, but also heavier elements. Primary particles of different masses induce air showers with different properties and therefore different telescope images. When applying the energy reconstruction algorithm, a systematic bias is induced, since it was only trained with primary protons and thus neglects the heavier primaries in the cosmic ray spectrum. Additionally, no event cuts have been applied to the measured data to select only the lightest components of the cosmic ray spectrum, which means that all masses contribute to the displayed data. Contrary, the spectra from HAWC and the other observatories are obtained using such selection criteria and only contain proton- and helium-induced showers.

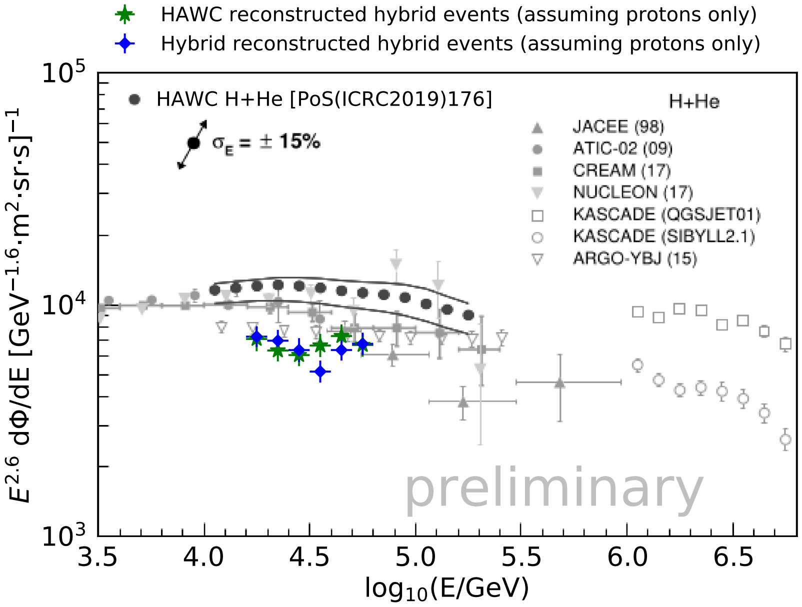

Figure 4: Comparison of the the cosmic ray spectrum reconstructed from the hybrid data of HAWC and HAWC's Eye (green) with previous results from HAWC (black) published in [10]. The blue points show the same triggered hybrid events using the HAWC reconstructed energy as reference. The black lines above and below the HAWC proton and helium spectrum indicate the errorband of its systematic uncertainty. The grey points represent corresponding data from numerous other experiments.

6. Conclusion

Two HAWC's Eye telescopes have been used to measure about 2.5 hours of cosmic ray data. About 90 000 events per telescope were successfully synchronized with the events measured with the HAWC observatory and used to reconstruct the cosmic ray spectrum. Compared to data that has been published for HAWC and other observatories, the spectrum is systematically shifted towards smaller fluxes. The reasons for this shift are not fully understood yet and have to be further investigated.

Deviations may originate from systematic deviations in the light yields such as an inaccurate simulation of the atmosphere and uncertainties of the camera calibration. Such discrepancies lead to deviations in the amount of detected Cherenkov light between simulations and measurements and induce a bias in the energy reconstruction. The sum of these effects could easily add up to a systematic shift in the energy reconstruction of 15 % and explain the differences between the reconstructed cosmic ray spectrum and the published HAWC spectrum.

Not only the hybrid energy reconstruction using the random forest, but also the HAWC energy reconstruction algorithm, when applied to the same events, shows a systematic shift in the cosmic ray spectrum. Thus, the synchronization of HAWC with HAWC's Eye most likely induces an event selection bias. Such a bias could favor the detection of heavier elements and cause a decreased flux for both reconstructed curves.

To investigate the discussed effects, this analysis must be compared in detail with the HAWC analysis and the Monte Carlo dataset should be extended to heavier elements. Possible differences in the simulation, that could induce a bias in the energy reconstruction, have to be analyzed further.

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