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Limits on the Diffuse Gamma-Ray Background with HAWC

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The high-energy Diffuse Gamma-Ray Background (DGRB) is expected to be produced by unresolved extra-galactic objects such as active galactic nuclei, starburst galaxies and gamma-ray bursts. At TeV energies, observations or stringent limits on the DGRB could have significant multi-messenger implications, such as constraining the origin of TeV-PeV astrophysical neutrinos detected by IceCube. With its continuous sensitivity to gamma rays from a few hundred GeV to several hundred TeV and its wide field-of-view, the High Altitude Water Cherenkov (HAWC) observatory is well-suited to significantly improve searches for the DGRB. In this work, strict cuts have been applied to the HAWC dataset to better isolate gamma-ray air showers from background hadronic showers. The sensitivity to the DGRB was then verified using 535 days of Crab data and Monte Carlo simulations, leading to new limits on the DGRB >10 TeV.

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1. Introduction

Isotropic emission of gamma rays uncorrelated with any known sources are expected to be the main provenance of the Diffuse Gamma-Ray Background (DGRB). In 1975, the SAS-2 satellite [1] had first reported the measurement of a fainter extragalactic component of the DGRB, which was later confirmed by EGRET [2] in 1998. The DGRB being uncorrelated to any known emission source, its diffuse extragalactic component is hypothesized to originate from unresolved Active Galactic Nuclei, starburst galaxies and γ-ray bursts [3].

The High Altitude Water Cherenkov (HAWC) gamma-ray observatory is located at an altitude of 4100 meters in the state of Puebla, Mexico. It is sensitive to sources with declinations between -26 and +64 degrees, has a duty cycle of >95% and a wide field-of-view of $\sim$ 2 sr. With its 300 water Cherenkov detectors, HAWC was built to detect gamma rays in the energy range between 300 GeV to more than 100 TeV.

2. Data Processing and Selection

For ground-based detectors, such as HAWC, hadronic Cosmic Rays (CRs) are the main source of background to high-energy photon observation. Fortunately, above several TeV, the air showers produced by high-energy CRs and gamma rays differ in shape but also in composition. Two gamma/hadron separation parameters have been defined using these characteristics. Compactness [5, 6] is designed to identify muons in air showers, whereas PINCness [7] measures the smoothness of the lateral charge distribution function of air showers. By quantifying the clumpiness of air showers most of the cosmic ray contamination can further be removed.

In this work we use 535 days of data from HAWC, taken from November 2014 to June 2016. We implement a 2D binning scheme [4] focusing on high energy events with reconstructed energies above 10 TeV (bins g to l) and where more than 61.8% of the PMTs available were hit (bins 7 to 9). Although this analysis does not include more recent HAWC data, it was chosen for having been very well characterized when it comes to its gamma/hadron behavior with respect to the Monte Carlo simulation.

Previous studies have been performed using the HAWC observatory to set limits on the DGRB [8–10]. In this work, the DGRB region of interest is a strip centered on the Crab nebula's location. Within the strip, bright known γ-ray sources – i.e. the Crab, Geminga and the Galactic Plane – have been removed to avoid contamination. The resulting DGRB strip has an area of 0.57 sr and is shown in Figure 1.

3. Limits on the DGRB

3.1 Crab Studies

To evaluate the performance of the HAWC simulation, we compare our data to the expected γ-ray signal from the Crab nebula. The Monte Carlo simulation of gamma-rays is then made to follow the best-fit HAWC Crab spectrum [4]

$$\left.\frac{dN}{dE}\right|_{\text{Crab}} = 2.35 \times 10^{-13} \left(\frac{E}{7\ \text{TeV}}\right)^{-2.79-0.10\times\ln(E/7\ \text{TeV})} (\text{TeV cm}^2\ \text{s})^{-1} \quad (1)$$

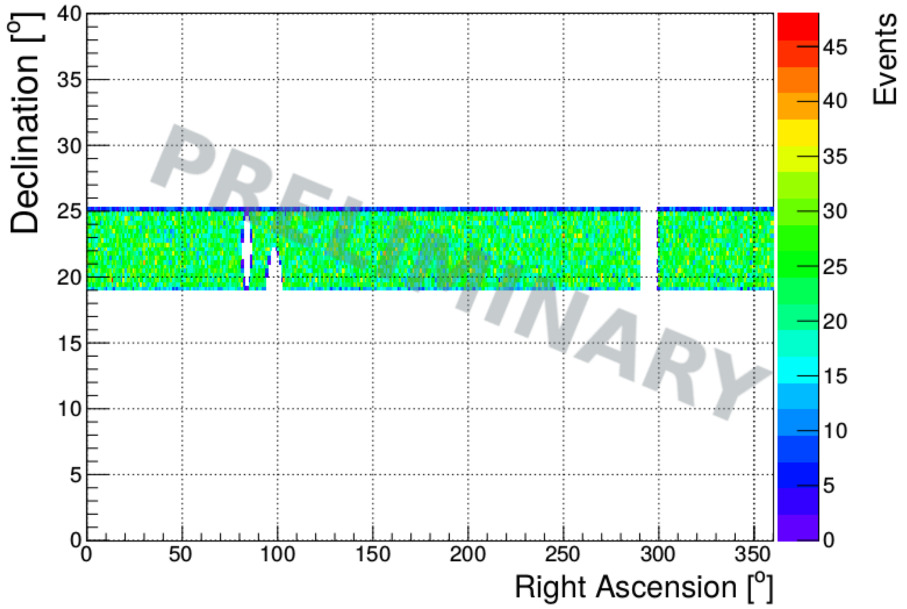

Figure 1: Map of the Diffuse Gamma-Ray Background strip

Only bins with reliable data/simulation agreement were considered, as verified using the Crab nebula.

As we apply tighter gamma/hadron separation cuts, few events remain and we must rely on Poisson statistics. For a binned likelihood analysis, the log-likelihood is calculated as the sum of the log of the Poisson probability to observe N^{obs} events in a bin given that the model predicts N^{pred}

$$\ln\mathcal{L} = \sum_{i}^{\text{bins}} N_i^{obs}\log(N_i^{pred}) - \sum_{i}^{\text{bins}} N_i^{pred} \tag{2}$$

where N^{obs} is set as the number of events in our DGRB strip and N^{pred} depends on the number of simulated Crab events. However we do not perform a joint likelihood; in order to calculate the best estimate for the overall scale of the spectrum, the bins are not summed but treated as separate independent "experiments". The 95% one-sided upper limit – $2\Delta\ln\mathcal{L} = 2.71$ – is calculated in each bin and the one with the lowest value is selected, as it would be the one with the most expansive limit.

By spreading the HAWC Crab spectrum over the 0.57 sr solid angle of the DGRB strip, we can then calculate the 95% containment level of the best estimate for the overall scale of the spectrum, referred to as $\beta_{95\%}$

$$\left.\frac{d^2N}{dEd\Omega}\right|_{95\%} = \beta_{95\%} \times \left.\frac{dN}{dE}\right|_{\text{Crab}} \tag{3}$$

For the energy bins studied, chosing the $\beta_{95\%}$ with the lowest value will lead to their corresponding fraction hit bin, the results of which can be found in Table 1. Furthermore, Figure 2 shows the upper-limits for each energy bin compared to other observations and limits.

Energy bin	Fraction hit bin	$\beta_{95\%}$	Simulation median energy (TeV)
g	7	308	19
h	8	192	23
i	9	145	40
j	9	57.8	69
k	9	37.1	106
l	9	61.0	168

Table 1: The results of the binned maximum likelihood analysis. For each energy bin and its corresponding fraction hit bin, the column labeled "Simulation median energy" displays the median energy from simulation assuming the HAWC Crab log parabola spectrum.

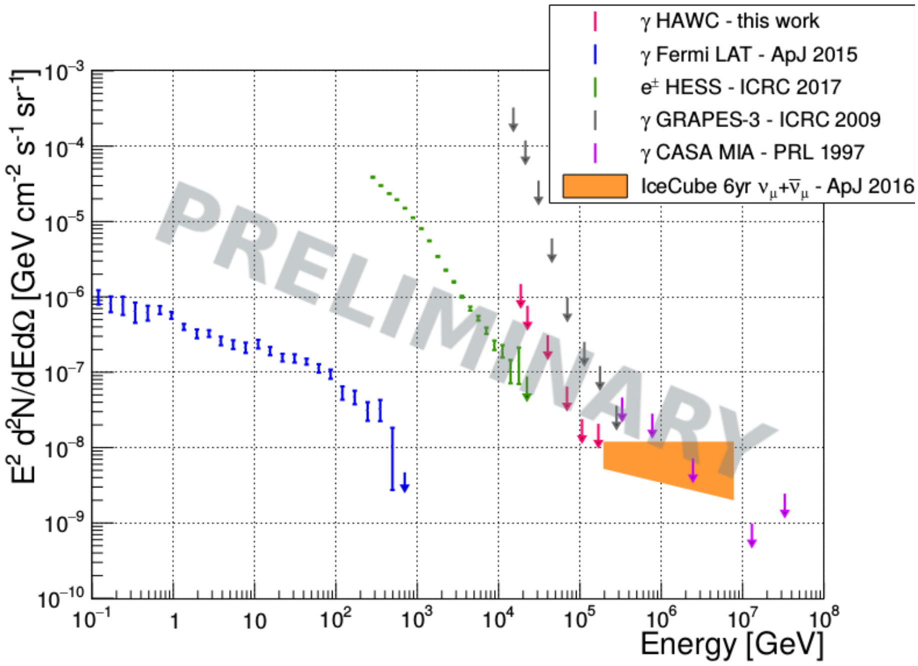

Figure 2: Limits on the DGRB using 535 days of HAWC data compared to the diffuse electron/positron flux observed by HESS [11, 12]. Also shown is the observed IGRB by the Fermi-LAT [13], the gamma-ray flux corresponding to the IceCube $\nu_\mu + \overline{\nu}_\mu$ astrophysical flux [14], as well as previous high-energy limits by GRAPES [15] and CASA-MIA [16].

3.2 Model Testing

Now we evaluate the data in the DGRB strip with respect to the spectra from other models. We then employ the same bins and apply the same cuts as those obtained using the HAWC Crab spectrum, from which we choose the most expansive limit overall.

The gamma-ray production is predicted to have a similar spectrum and flux as the neutrinos seen by IceCube. We made use of a relation between the fluxes of gamma rays and neutrinos from [17] to find the gamma-ray flux corresponding to the best fit with the IceCube unbroken power-law model for the $\nu_\mu + \overline{\nu}_\mu$ astrophysical flux [14]

$$\left.\frac{d^2N}{dEd\Omega}\right|_{\rm IC} = 9.0 \times 10^{-16} \left(\frac{E}{100\ \rm TeV}\right)^{-2.13} (\rm TeV\ cm^2\ s\ sr)^{-1} \tag{4}$$

The HESS observatory has detected an isotropic CR flux of electrons and positrons up to 20 TeV [11, 12]. Although the limits obtained in this work are pushing into an energy range higher than the H.E.S.S. observations, we can still make a comparison with the best fit for the H.E.S.S. electron/positron flux with a smooth broken power law

$$\left.\frac{d^2N}{dEd\Omega}\right|_{\rm H.E.S.S.} = 1.05 \times 10^{-8} \left(\frac{E}{1\ \rm TeV}\right)^{-3.04} \left(1 + \left(\frac{E}{0.94\ \rm TeV}\right)^{\frac{1}{0.12}}\right)^{0.12\times(3.04-3.78)} (\rm TeV\ cm^2\ s\ sr)^{-1} \tag{5}$$

The resulting $\beta_{95\%}$ and $\beta_{\rm best}$ from injecting the previous spectra are shown in Table 2.

	$\beta_{95\%}$	$\beta_{\rm best}$
IceCube spectrum	2.13	1.32
H.E.S.S spectrum	9.60	6.94

Table 2: The results for the model testing. $\beta_{\rm best}$ refers to the best estimate of the overall scale of the spectrum – for which $-2ln\mathcal{L}$ is at its minimum – while $\beta_{95\%}$ corresponds to its 95% containment level.

4. Discussion and Prospects

In addition to DGRB events, the flux observed by HAWC may also include other isotropic events that would be considered as background. One possible component of this flux would be misreconstructed hadrons, due to their gamma-like appearance in the HAWC detector. Another possible source of isotropic emission would be CR electrons and positrons whose air showers are similar to those induced by gamma rays. A better understanding of the expected CR contamination would help break the degeneracy.

Astrophysical pion production emit neutrinos in addition to γ-rays, and so might dark matter annihilations. Interestingly, the best estimate of the overall scale of the spectrum is only 1.32 times the IceCube flux. This value is likely to include a fair amount of CR background and should definitely not be considered as a measurement of the DGRB. Nonetheless, despite being ambiguous, this value is fairly consistent with the IceCube flux itself. Better characterization of residual CRs is underway and could verify the consistency between gamma-ray and neutrino flux.

With the addition of more years of data, upcoming improvements to the HAWC reconstruction algorithms and analytical methods, and the deployment of the outrigger array in 2018, stronger constraints on the previous results are expected. Furthermore, a next-generation Southern Wide-field Gamma-ray Observatory (SWGO)[1] is being considered for the Southern Hemisphere which will extend sensitivity to energies above the tens of PeV.

[1] www.swgo.org

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