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Towards a Measurement of the e^+ e^- Flux above 1 TeV with HAWC

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The High-Altitude Water Cherenkov (HAWC) Observatory records the air showers produced by cosmic rays and gamma rays at a rate of about 20 kHz. While the events observed by HAWC are 99.9% hadronic cosmic rays, this background can be strongly suppressed using topological cuts that preferentially select electromagnetic air showers. Using this capability of HAWC, we can create a sample of air showers dominated by gamma rays and cosmic electrons and positrons. HAWC is one of the few operating observatories capable of measuring showers produced by e^- and e^+ primaries above 1 TeV, and can record these showers from $2/3$ of the sky each day. We describe the sensitivity of HAWC to leptonic cosmic rays, and discuss prospects for the measurement of the e^+ e^- flux and possible approaches for e^+ and e^- charge separation with the HAWC detector.

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1. Introduction

The flux of cosmic electrons and positrons at Earth is a signficant component of the all-particle flux below 10 GeV. However, due to synchrotron and inverse Compton losses, this leptonic flux decreases faster than the $E^{-2.7}$ flux of hadronic cosmic rays at higher energies. Recent measurements of the combined $e^- + e^+$ flux from satellites [1, 2] and ground-based experiments [3, 4] indicate that the spectrum decreases as $E^{-3.05}$ with a cutoff near 800 GeV (Fig. 1). As a result, the $e^- + e^+$ flux at 1 TeV is approximately 0.1% of the flux of hadronic particles.

While the rapidly falling $e^- + e^+$ spectrum makes observations at TeV very challenging, this energy range is of considerable astrophysical interest. The increase in radiative losses as a function of energy implies that above several hundred GeV, the electrons and positrons observed at Earth must originate in Galactic sources < 1 kpc from the solar system [5]. Hence, the characterization of the spectrum at TeV is well-motivated, since features in the spectrum can be used to study the closest accelerators of cosmic electrons.

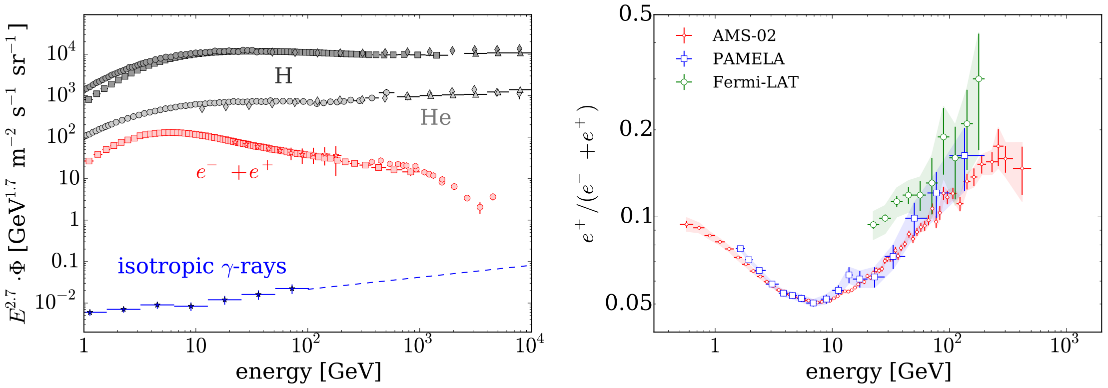

Figure 1: *Left*: the isotropic flux of cosmic protons [6, 7, 8, 9], helium [6, 7, 8], and electrons and positrons [1, 2, 3, 4] at GeV and TeV. The extragalactic isotropic diffuse flux of γ-rays [10] and its extrapolation to TeV, another source of background for the e^+e^- flux, are also plotted. *Right*: the positron fraction measured from 0.5 to 350 GeV [11, 1, 12]. The error bars indicate statistical uncertainties, while the solid shaded regions show the total uncertainties (quadrature sum of statistical and systematic uncertainties).

The relative abundance of positrons to electrons, usually expressed as the ratio $e^+/(e^- + e^+)$, also contains important information about the origin of the leptonic flux at Earth. Measurements of e^- and e^+ at energies between 1 to 100 GeV range have shown that the fraction of positrons in the flux increases from 5% at 10 GeV to $\sim$ 15% at 100 GeV [1, 11, 12]. This observation runs counter to the expectation that cosmic antiparticles are produced in secondary interactions [13] and indicates that the particles originate in a nearby source of primary cosmic rays. The origin of the positron excess is not yet understood, with explanations ranging from a local ($\sim$ 100 pc) source of primary e^- and e^+ such as the Geminga supernova remnant [14] to the production of e^+e^- in dark matter annihilation.

2. The HAWC Observatory

The High Altitude Water Cherenkov Observatory, or HAWC, is a gamma-ray and cosmic-ray detector located 4100 m above sea level in Sierra Negra, Mexico. HAWC is an air shower array comprising 300 close-packed water Cherenkov detectors (WCDs). Each WCD is a light-tight steel tank containing 200 kL of purified water and four hemispherical photomultiplier tubes (PMTs).

The PMTs are used to detect the Cherenkov light produced when air shower particles pass through the water in the tanks. By combining the timing information and spatial pattern of the PMTs triggered by an air shower, the arrival direction and type of the primary particle can be identified.

For example, using simple topological cuts it is possible to discriminate air showers produced by hadronic cosmic rays from the electromagnetic air showers produced by gamma rays, electrons, and positrons. The gamma-hadron discrimination can be used to suppress the very large background of cosmic rays (20 kHz event rate) enough to produce sky maps of gamma-ray sources. More details on the operation of the HAWC detector, the event reconstruction, and background suppression techniques are given in [15].

While construction of the WCDs at the HAWC observatory ended in early 2015, currently 250 out of 300 water Cherenkov tanks are in data acquisition. Therefore, we will use the 250 tank configuration of the detector (HAWC-250) as the baseline for this study.

3. Sensitivity of HAWC to the Flux of $e^- + e^+$

With an instantaneous field of view of about 2 sr, an uptime $> 90\%$, and the capability to discriminate electromagnetic air showers from hadronic air showers, HAWC can be used to observe the isotropic e^- and e^+ flux. The simulated effective area of HAWC for protons, gamma rays, and electrons is plotted as a function of energy in Fig. 2. Air shower particles were produced using CORSIKA [16] and the HAWC-250 detector response was simulated with GEANT4 [17]. The effective areas plotted in Fig. 2 were produced by applying a simple PMT multiplicity cut of $N_{\text{hit}} \geq 27$ (similar to running conditions), a zenith angle cut of $\theta \leq 50^\circ$, and by cutting showers reconstructed $> 2.5^\circ$ from their true direction. No further quality cuts were applied.

Above several hundred GeV, where the HAWC array approaches high trigger efficiency, the effective area for showers initiated by cosmic electrons is similar to the effective areas for protons and γ-rays. As a result, the event rate of electron-induced air showers is expected to be roughly 15 Hz in the full detector. This implies $\sim 5 \times 10^8$ e^- and e^+ showers observed per year with HAWC.

Unfortunately this isotropic flux is affected by multiple sources of background which need to be modeled or removed. The background includes:

- A much larger, but in principle reducible, isotropic flux of hadronic cosmic rays.
- A reducible flux of gamma rays from point sources and Galactic diffuse emission.
- An irreducible background of isotropic extragalactic gamma rays.

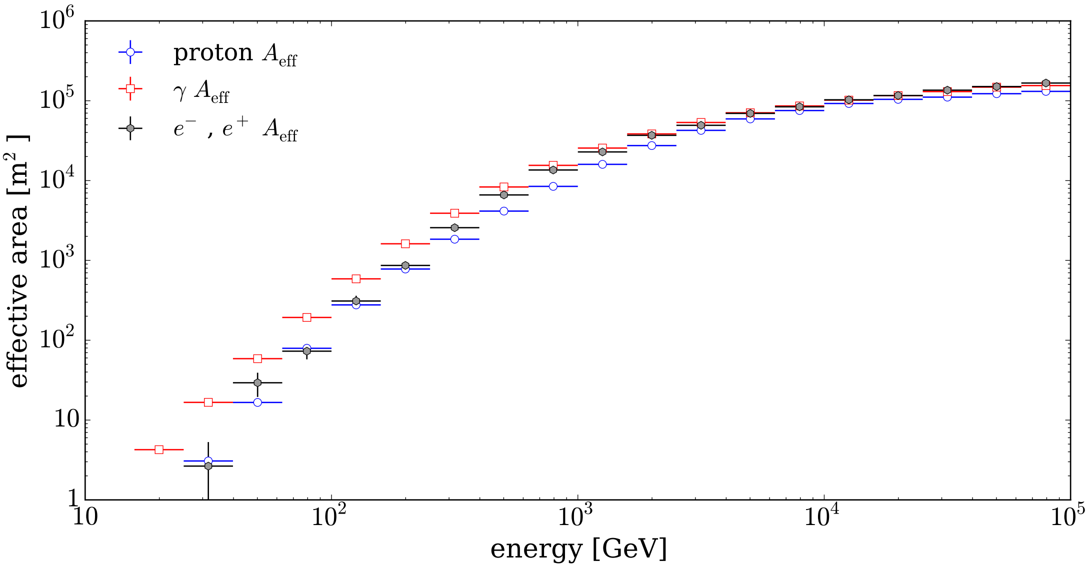

Figure 2:
Simulated effective area of the HAWC-250 observatory after the application of basic quality cuts to the event reconstruction (see text for details). Air showers produced by protons are plotted as open circles, gamma rays as open squares, and electrons and positrons as filled hexagons.

The flux of hadronic cosmic rays is the most significant source of background for this analysis. Because both the signal and background are isotropic, and the signal spectrum is softer than the background spectrum, the only way to measure the $e^- + e^+$ flux is with very strong suppression of the hadronic cosmic rays. The relevant figure of merit for this suppression is the Q-value of the analysis, i.e., the ratio of the signal selection efficiency ε_γ to the background efficiency $\varepsilon_{\rm CR}$,

$$Q = \varepsilon_\gamma/\sqrt{\varepsilon_{\rm CR}}.$$

The current analysis, optimized for point sources of γ-rays, has achieved values of $Q \approx 5$ above several TeV [18]. This is sufficient to detect point sources but not an isotropic flux. By comparison, a value of $Q \approx 30$ would be needed to achieve a signal/background ratio of 1 : 1 in this analysis. The HESS Collaboration was able to achieve a background suppression factor of 10^4 (implying $Q \approx 100$) for their measurement of the $e^- + e^+$ flux [3, 4].

In contrast to the cosmic-ray backgrounds, the γ-ray backgrounds in this analysis are less significant. Point sources and diffuse emission from the Galaxy can be avoided by masking out those regions of the sky. The remaining background from extragalactic isotropic γ-rays cannot be masked out and will pass the selection cuts for electromagnetic showers. However, the extragalactic flux is not expected to contribute significantly to the isotropic signal below 10 TeV. In Fig. 1 we plot a conservative estimate of the contamination of the e^+e^- signal due to the isotropic γ-ray background, extrapolating the $E^{-2.41}$ flux published by Fermi-LAT in 2010 [10]. But the actual contamination is expected to be low in the region of interest (< 10 TeV) since more recent measurements of the isotropic γ rays indicate a spectral cutoff at 250 GeV [19].

The current state of the analysis suggests that due to cosmic-ray backgrounds, it will be difficult to observe the isotropic $e^- + e^+$ spectrum with HAWC. However, the background suppression technique presented in [18] is admittedly naïve. Recent efforts to improve the cosmic-ray rejection power of the analysis indicate that improvements to $Q = 10$ are straightforward [20, 21], and $Q \approx 30$ is possible. These improvements will be the focus of future work.

4. Sensitivity to the Moon Shadow

An extension of the measurement of the e^+ fraction in the cosmic ray flux to TeV is well-motivated. There are currently no measurements above 1 TeV, and while the AMS Collaboration has reported evidence for a turnover in the positron fraction at several hundred GeV (see [12] and Fig. 1) this feature is not sufficient to distinguish between models of e^+ acceleration and dark matter annihilation.

HAWC is capable of discriminating e^+ and e^- showers by observing the shadow of the Moon in the $e^- + e^+$ flux. The Moon shadow is the small deficit in the isotropic flux created by the absorption of electrons and positrons in the lunar surface. However, electrons and positrons from the position of the Moon are deflected in equal but opposite directions by the geomagnetic field. Hence, if the flux of positrons is sufficient, deflections in the geomagnetic field should produce two observable deficits: a shadow in the e^- flux, and a second displaced shadow in the e^+ flux.

The average deflection of a particle of charge Z and energy E at the location of HAWC is [22]

$$\delta\theta \approx 1.6^\circ \cdot Z \left(\frac{E}{\mathrm{TeV}}\right)^{-1}. \tag{4.1}$$

The median energy of cosmic rays observed in HAWC is about 2 TeV. At this energy the geomagnetic deflection will be $\sim 0.8^\circ$, larger than both the angular diameter of the Moon and the point spread function of the detector ($< 0.5^\circ$ above 1 TeV).

The use of the geomagnetic field to discriminate e^+ from e^- is similar to the analysis carried out with Fermi-LAT [1] and the proposal to observe the Moon shadow with the MAGIC telescope [23]. Unlike MAGIC, HAWC is not affected by moonlight or weather conditions and can be used to observe the Moon during all times and seasons. However, the detector has considerably less background suppression capability than an imaging air Cherenkov telescope, so we expect the sensitivity of the two techniques to be approximately the same.

To estimate the time needed to observe the e^- shadow at the 5σ level, we compute the number of transits needed to observe the shadow given the known sensitivity of the detector to the observed shadow in hadronic cosmic rays:

$$N = \left(\frac{5}{\sigma_{\mathrm{CR}}^{N=1}} \cdot \frac{1}{Q} \cdot \frac{\Phi_{\mathrm{CR}}}{\Phi_{e^-}}\right)^2. \tag{4.2}$$

In this expression, $\sigma_{\mathrm{CR}}^{N=1}$ represents the significance of the observation of the Moon shadow in cosmic rays in one transit, and $\Phi_{\mathrm{CR}}/\Phi_{e^-}$ is the ratio of the fluxes of hadrons and electrons.

Fixing the flux ratio and varying $\sigma_{\mathrm{CR}}^{N=1}$ and Q, we produce the plot shown in Fig. 3. In this figure, we note that there are many reasonable combinations of $\sigma_{\mathrm{CR}}^{N=1}$ and Q that define a path to

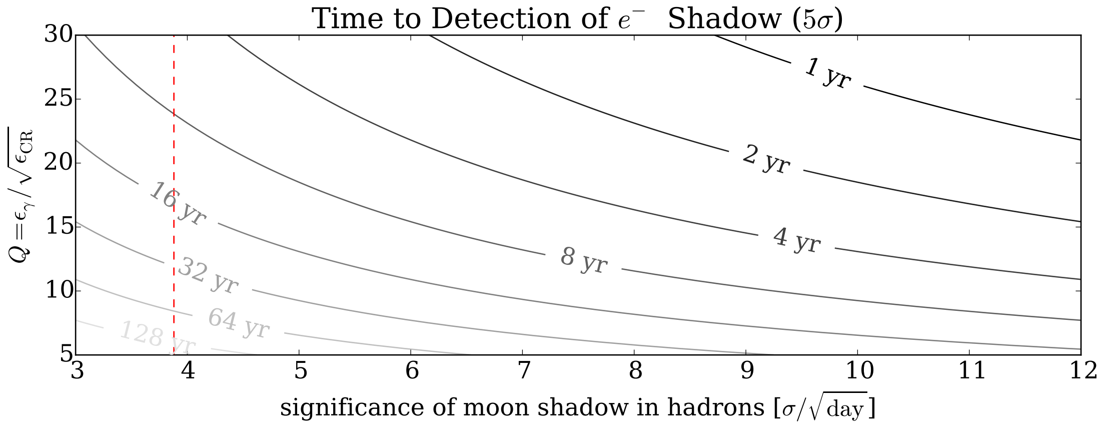

Figure 3: Expected time to detect the electron Moon shadow at the 5σ level as a function of the daily significance of the shadow in hadronic cosmic rays and the Q-value of the analysis cuts. The current daily significance of the Moon shadow in cosmic rays is $< 4\sigma$ and is indicated by a dashed line.

the detection of the Moon shadow. For example, if $\sigma_{\rm CR}^{N=1}$ is between 5σ and 10σ and Q is between 15 and 25, the e^- shadow will be visible with 2 to 4 years of data.

The current significance of the cosmic-ray Moon shadow in data is $\sim 4\sigma$ per transit [24]. This is lower than the prediction from simulations, mainly because the observed detector point spread function is larger than expected. We expect a detection of $> 5\sigma$ per transit will be achieved as our reconstruction techniques and understanding of the detector improve. In addition, the point spread function for the reconstruction of e^- and e^+ showers should be better than for hadronic cosmic rays because the shower axis fit is optimized for electromagnetic showers.

The reduction of $\varepsilon_{\rm CR}$ and corresponding improvement in Q is also critical to this analysis. Fig. 3 indicates that $Q > 15$ (corresponding $\varepsilon_{\rm CR} < 0.5\%$) is likely necessary to observe the e^- shadow during the lifetime of the experiment. Simulations indicate that this level of background suppression and higher is possible with more sophisticated gamma-hadron discrimination than what is currently used in the γ-ray analysis [20, 21].

5. Conclusion

HAWC is a high-uptime air shower array that observes $2/3$ of the sky the each day. While the detector was designed to search for pointlike and extended sources of γ-rays on top of the large background of isotropic cosmic rays, its gamma-hadron discrimination capability can also be used to observe the flux of cosmic electrons and positrons.

As of this writing there are only two published measurements of the $e^- + e^+$ flux at TeV. This situation will change during the next few years as experiments such as AMS, CALET [25], and ground-based observatories improve their methods and statistics. HAWC can contribute to these measurements, though a direct measurement of the leptonic flux is a challenge because of its soft spectrum and the need for very strong hadronic shower suppression. Simulations indicate that the background rejection power of HAWC can be improved substantially and these improvements will be the focus of future work.

HAWC can also be used to estimate the positron fraction above 1 TeV because the geomagnetic field should create two well-separated deficits, or shadows, in the e^+ and e^- flux due to absorption of cosmic rays by the Moon. Given expected improvements in the angular resolution of the detector and optimistic but achievable improvements in the background reduction, the e^- shadow could be detectable at 5σ within 2 to 4 years.

Acknowledgments

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