Hadron Finder – a novel method for gamma/hadron separation for Atmospheric Imaging Cherenkov Telescopes

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Abstract: One of the main experimental challenges for the ground-based gamma-ray astronomy is the discrimination between gamma rays and hadrons, particularly for gamma rays of energies below 200 GeV. We have developed a novel analysis method, the Hadron Finder, which actively searches for hadrons by exploiting previously cleansed-out information from the event image. The method is based on the elementary hadronic and nuclear collision dynamics. We demonstrate the performance of the method using the Crab Nebula data, taken recently by the MAGIC Telescope. We report substantial background reduction (by factor 2.6), and boost in the detection significance (from 8.6 σ to 11.9 σ) for a data sample at ~185 GeV.

Introduction

Ground-based very-high-energy (VHE) gamma-ray astronomy is a very rapidly developing section of high-energy astroparticle physics. Nearly all discoveries in this field during the last 20 years have been made by the so-called imaging air Cherenkov telescopes (IACT), which record the weak Cherenkov light flashes from particle showers in the atmosphere, induced by the VHE cosmic gamma rays.

The success stems mainly from the ability of IACTs to differentiate the rare gamma-ray events from the many-orders-of-magnitude more abundant hadronic events. In general, the separation is based on tiny differences between the electromagnetic and hadronic showers in the recorded Cherenkov light images.

The standard event reconstruction strategy is to actively search for those shower properties that are characteristic for a gamma ray event. Specifically, the signature of a gamma ray is the presence of an isolated, compact cluster in the image, which may correspond to an electromagnetic shower (EMS). However, that signature is not unique to gamma rays, because hadronic showers regularly contain strong electromagnetic sub-showers[1]. On average, an EM sub-shower created in the first generation of a hadronic cascade carries one third of the initial energy of a hadron. Thanks to its compactness, such an EMS is likely to present the dominant feature in the image of a hadronic event.

As we will discuss below in more detail, at low energies, the hadronic component of a hadronic shower progressively spreads out in area and decreases in density, making its partial overlap with a progressively more compact EMS less likely. That is why a 'clean,' isolated EMS cluster is not a unique signature of a cosmic gamma ray.

Our gamma-hadron separation method, in contrast, actively searches for an exclusive property of a hadronic shower, a property that is not shared by a gamma-ray shower. In other

[1]An electromagnetic shower within a hadronic shower is created mainly by a pair of gamma rays from a decay of a neutral pion.

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words, our strategy is to positively identify hadrons, rather than gamma rays.

The Hadron Finder (as we accordingly named our method) searches for the so-called 'Cherenkov Rain,' i.e. Cherenkov light that originates specifically from the hadronic component of a hadronic shower (including also smaller EMS sub-clusters created within the hadronic cascade). The Cherenkov Rain is therefore a low-intensity Cherenkov light, irregularly spread over the entire IACT camera plane (and wider).

Somewhat ironically, Cherenkov Rain is precisely the same image information that has been traditionally vigorously eliminated in the first stages of a standard analysis, in the process often referred to as 'image cleaning.' Only a very small fraction of Cherenkov Rain would survive to be effectively used for gamma-hadron discrimination – the part that would accidentally fall over the dominant EM cluster. While at energies above 300 GeV a substantial overlap of Rain and the EMS cluster is a regular event, at low energies the overlap becomes less likely. That is because the number of Cherenkov photons in the Rain decreases with decreasing cosmic ray energy, but also because the angular spread of particles within a hadronic shower becomes wider[2].

The presence of Cherenkov Rain in hadronic events is clearly visible in Fig. 1, which presents the simulated photon distribution in the MAGIC camera plane for two gamma rays, and two hadronic events.

Below energies of approximately 150 GeV, one has to deal with three additional background contributions: (a) cosmic electrons, (b) long-flying high-altitude charged particles with $\beta > \beta_{\text{Cherenkov-threshold}}$, and (c) Wide-angle tracks above Cherenkov threshold. Like the pairs of gamma rays originating from decays of neutral pions, cosmic electrons (a) also create EM showers that are indistinguishable from the EM showers of primary cosmic gamma rays. However, since these events do not contain Cherenkov Rain, or any other feature that comes on top of an EMS, they may not be distinguished from cosmic gamma rays. The cosmic electrons are therefore setting the limit of the irreducible isotropic background, and no solution for a further possible reduction is currently in sight. However, this effect is very weak and may be neglected at energies of ~100 GeV. A new problem for large diameter IACTs is that the high-altitude, single, straight (including small angle elastic scattering), high-energy charged particles (b) can produce a sizeable amount of photoelectrons (phe) in a pattern that can resemble a low-energy γ–shower image[3]. The large-distance photoelectrons are also occurring in γ-showers, but normally with a lower density. The classical image analysis for the gamma/hadron separation will often fail for cases (b) and (c), but such events will also be accompanied by some Cherenkov Rain, so Hadron Finder should be helpful again.

We have developed and tested the Hadron Finder method using various data from the MAGIC Telescope. MAGIC is the largest (17m mirror

[2]A fundamental property of the particle production process in high-energy hadronic and nuclear collisions is the virtual independence of the average transverse momentum of a created particle on the collision energy (for pions, $\langle p_T \rangle$~400 MeV/c). Consequently, hadronic showers of lower energies have a wider angular spread around the shower axis than the showers of higher energies.

[3]In small-diameter IACTs, a pool of photoelectrons is an automatic signature of a shower because each photon must originate from a different shower track. This automatism is lost for large-diameter IACTs

diameter) and most sensitive operating single IACT, with a trigger energy threshold of only 60 GeV. In this paper, we demonstrate the current performance of this still developing method, using a subset of recent Crab Nebula measurements.

Analysis and the Results

The first step in the Hadron Finder analysis is the determination of the setting for the threshold intensity of the Cherenkov Rain. The threshold should be high enough to minimize the influence of the night sky background, and at the same time low enough to capture the weak Cherenkov Rain signals (basically, one and more photoelectrons per pixel). We have determined the threshold empirically, through a comparison of data that are highly enriched with gamma rays, with purely hadronic data. For the presented example, the optimal threshold of 8 ADC counts was determined, which roughly corresponds to 1.5 photoelectrons per pixel. In the following step, we count all the camera pixels that exceed this threshold, and we call them “rainy pixels.” Note that we have excluded from our consideration those pixels that were previously selected as the constituents of the hypothetical EM cluster (by the standard method). Our analysis is therefore complementary to the standard analysis. We have used gamma-ray candidate events that were pre-selected by the standard separation method, and then searched for hadrons among them.

Fig. 2 shows the distribution of events as a function of the number of rainy pixels for the ON-Crab, and the OFF-Crab data. The ON-Crab data were taken on the Crab Nebula source, and they contain gamma rays, while the OFF-Crab data consist entirely of hadronic background events. The presented plots are limited in the Hillas α angle parameter to the interval $0<\alpha<12$ deg. These events belong to the size parameter interval of 400-450 photoelectrons(corresponding to the energy peak at 185 GeV). Note that on the right side, for events with a large number of rainy pixels, the two (properly normalized) distributions virtually coincide. Fig. 2 therefore clearly confirms our expectation that hadronic events contain a sizeable amount of rain, whereas gamma-rays do not. We use precisely this difference for gamma-hadron separation.

Further, we calculated the detection significance of the Crab source as a function of the upper limit on the accepted number of rainy pixels. The resulting distribution peaks at 11.9 standard deviations (σ), which is a great improvement over the significance of 8.6 σ, obtained by the standard method. This result clearly indicates the power of the method, and the amount of information contained in Cherenkov Rain.

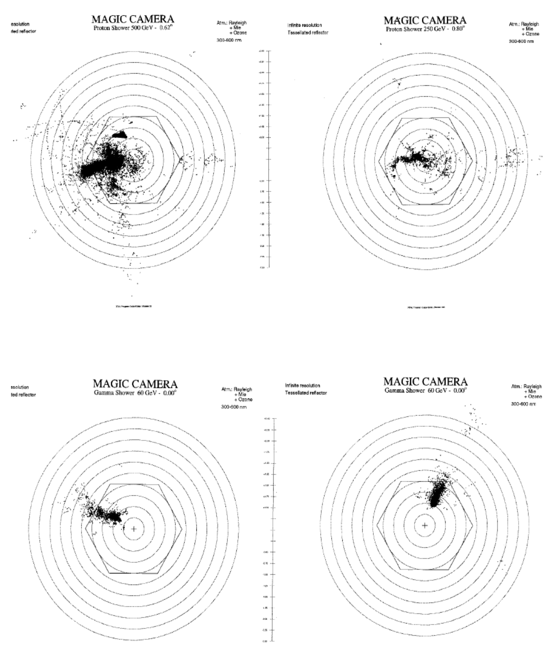

Fig. 1 Photon hits in the MAGIC camera; Monte Carlo simulation. Cherenkov Rain is clearly visible.

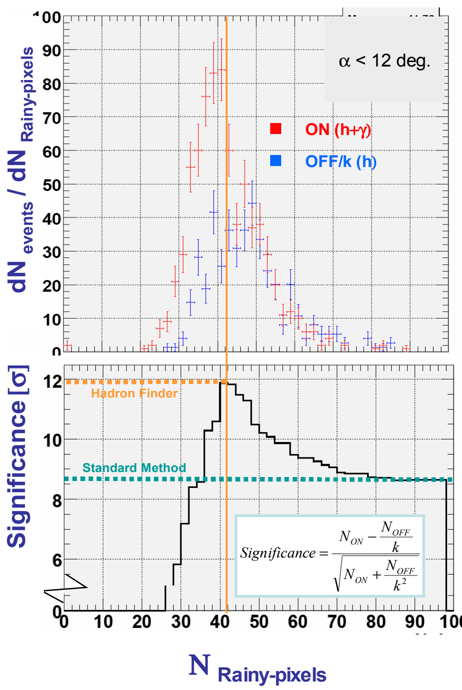

Fig.2 Top: distribution of ON-Crab (red) and OFF-Crab (blue) events as a function of the number of rainy pixels. Bottom: Hadron Finder assigns events with a large number of rainy pixels as hadron candidates. The vertical orange line presents a cut between hadron candidates to the right, and gamma-ray candidates to the left, which optimizes detection significance (defined in the inset).

The maximum significance of 11.9 σ corresponds to the limit of 42 rainy pixels per event. With this cut, in Fig. 3 we compare the resulting alpha-distributions for the hadron and gamma-ray candidates, to the original gamma-ray candidate distributions obtained from the standard method. The plot on the left shows that Hadron Finder identifies ~65% of hadrons within the OFF-Crab data. The same fraction of ON-Crab gamma ray candidates were identified as hadrons, as shown in the figure on the right. On top of the hadron contribution, we see a small peak at low alpha angles, which corresponds to the gamma rays that Hadron Finder has wrongly assigned to hadrons (i.e. sacrificed with the particular choice of significance optimization, $N_{Rainy\text{-}pixels}<42$). The middle plot in Fig. 3 confirms that the majority of gamma rays are correctly assigned as gamma-ray candidates, while the hadronic background is suppressed by a large factor of ~2.6, consistent with the observed gain in significance.

Let us stress that this achievement came exclusively from the information hidden in the previously cleansed-out Cherenkov Rain. In spite of the high performance, we still see a lot of opportunity for substantial improvements, because we have not fully exhausted the information hidden in the Cherenkov Rain.

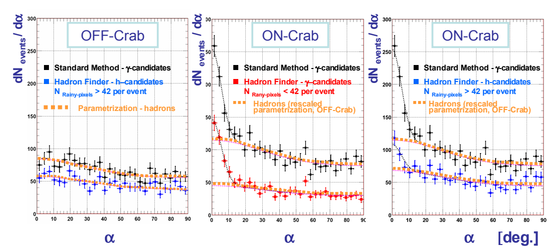

Fig. 3 Distributions of events as a function of the Hillas α parameter. Based on the number of rainypixels in the camera (see Fig. 2), Hadron Finder identifies hadron candidates (left and right), and the 'left-over events,' i.e. the gamma ray candidates (middle).

We used the parametrization of the OFF-crab distribution to fit the hadronic baseline in all the other distributions.

Conclusion

While the novel Hadron Finder method for gamma-hadron separation is still under development, the presented results strongly underline its unique potential. We also see a lot of space for further improvements.