Astroparticle Physics 97 (2018) 88–95

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

F_γ: A new observable for photon-hadron discrimination in hybrid air shower events

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ARTICLE INFO

Article history:
Received 2 June 2017
Revised 12 September 2017
Accepted 17 October 2017
Available online 21 October 2017

Keywords:
Photons
Cosmic rays
Hybrid detector
Lateral distribution function
LDF

ABSTRACT

To search for ultra-high-energy photons in primary cosmic rays, air shower observables are needed that allow a good separation between primary photons and primary hadrons. We present a new observable, F_γ, which can be extracted from ground-array data in hybrid events, where simultaneous measurements of the longitudinal and the lateral shower profile are performed. The observable is based on a template fit to the lateral distribution measured by the ground array with the template taking into account the complementary information from the measurement of the longitudinal profile, i.e. the primary energy and the geometry of the shower. F_γ shows a very good photon-hadron separation, which is even superior to the separation given by the well-known X_{max} observable (the atmospheric depth of the shower maximum). At energies around 1 EeV (10 EeV), F_γ provides a background rejection better than 97.8 % (99.9 %) at a signal efficiency of 50 %. Advantages of the observable F_γ are its technical stability with respect to irregularities in the ground array (i.e. missing or temporarily non-operating stations) and that it can be applied over the full energy range accessible to the air shower detector, down to its threshold energy. Furthermore, F_γ complements nicely to X_{max} such that both observables can well be combined to achieve an even better discrimination power, exploiting the rich information available in hybrid events.

1. Introduction

The discovery of ultra-high-energy (UHE) photons, i.e. photons with an energy larger than $\sim 10^{18}\,\mathrm{eV} = 1\,\mathrm{EeV}$, in primary cosmic rays would be of particular interest not only for the field of astroparticle physics, but also for related fields such as particle physics, astrophysics and fundamental physics [1]. For example, UHE photons are tracers of the Greisen–Zatsepin–Kuzmin (GZK) process, i.e. the interactions of UHE protons, propagating through the Universe, with photons from the cosmic microwave background (CMB). In these interactions, neutral pions are produced via the Delta resonance ($p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0$). These pions subsequently decay into pairs of UHE photons with energies at typically 10 % of the energy of the primary UHE proton. If these predicted GZK photons are observed on Earth, it would be an indicator for the GZK process being the reason for the observed suppression in the energy spectrum of UHE cosmic rays (UHECR) [2]. Observing UHE photons could also help to pinpoint the very sources of UHECR, since photons, unlike charged cosmic rays, are not deflected by magnetic fields. The attenuation length for photons in the EeV range varies between some 100 kpc at 1 EeV and a few Mpc at 10 EeV [3], encompassing possible galactic and nearby extragalactic sources. The detection of UHE photons is of great interest for fundamental physics as well. For instance, the registration of a single photon in the EeV range could improve existing bounds on Lorentz invariance violation in the context of a modified Maxwell theory by several orders of magnitude [4]. In addition, observing the particle cascade initiated by a UHE photon in the atmosphere allows testing particle interactions at extreme energies and searching for new physics [1,5].

Due to their small incoming flux (less than one particle per square kilometer per year), UHE cosmic particles impinging on the Earth can only be detected indirectly through the measurement of the air showers they initiate when entering the Earth's atmosphere. For the identification of primary photons in the recorded air shower data, the challenge is to separate photon-induced showers from those initiated by hadrons. Thus, the differences between

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https://doi.org/10.1016/j.astropartphys.2017.10.004
0927-6505/

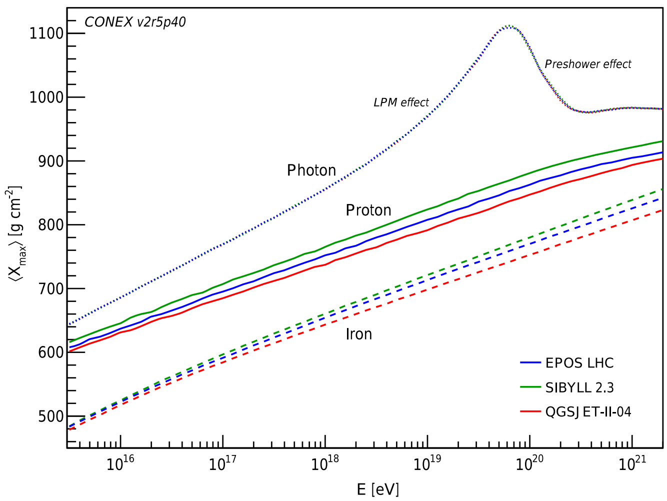

Fig. 1. Average atmospheric depth of the shower maximum, $\langle X_{max}\rangle$, as a function of the primary energy for simulated air showers initiated by photons, protons and iron nuclei. The simulations have been done using the Conex simulation code [6,7] with three different hadronic interaction models (EPOS LHC [8], SIBYLL 2.3 [9,10] and QGSJET-II-04 [11]). For the calculation of the preshower effect, the location of the Pierre Auger Observatory in Argentina has been used. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

these two classes of air showers are of great importance. Air showers initiated by UHE photons develop, on average, deeper in the atmosphere than air showers of the same primary energy initiated by hadrons. This can be expressed through the observable X_{max}, which describes the atmospheric depth of the shower maximum (see Fig. 1). At larger energies, additional effects like the Landau–Pomeranchuk–Migdal (LPM) effect and preshower processes above the atmosphere, which further influence the shower development, have to be taken into account [1]. X_{max} has become a key observable for current cosmic-ray research, mostly due to the fact that it can be accessed directly using the air-fluorescence technique. Current air shower experiments like the Pierre Auger Observatory [12] or the Telescope Array [13] are following a hybrid approach, where fluorescence detectors are complemented by a ground array of particle detectors. The typical X_{max} resolution of e.g. the Pierre Auger Observatory is better than $26\,\mathrm{g\,cm^{-2}}$ at energies around $10^{17.8}$ eV, improving with energy to about $15\,\mathrm{g\,cm^{-2}}$ above $10^{19.3}$ eV [14]. This is much smaller than the differences in the average X_{max} between photon- and hadron-induced air showers at these energies ($\sim 100\,\mathrm{g\,cm^{-2}}$ at 10^{18} eV and $\sim 160\,\mathrm{g\,cm^{-2}}$ at 10^{19} eV, cf. Fig. 1).

To fully exploit this hybrid approach and to improve the photon-hadron separation power, it is useful to complement the observable X_{max} with an additional observable that is based on the data from the ground array. In the past, observables such as the curvature of the shower front or the risetime of the signals in the detectors of the ground array have been used in the context of the search for photons [15,16]. However, such observables can only be reliably estimated when a minimum number of detectors of the ground array have triggered. For example, at least five detectors are needed to determine the curvature of the shower front with acceptable accuracy. This effectively places a lower limit—for past analyses typically at 10 EeV—on the energy region that can be accessed with an analysis based on these observables. At lower energies, i.e. in the EeV range, the observable S_b [17] has been successfully used in past analyses [3,18–20]. S_b is based on the sum of the signals S_i, measured in the individual detectors i of the ground array, weighted by the distances r_i of the detectors to the shower axis:

$$S_b = \sum_i S_i \left(\frac{r_i}{1000\,\mathrm{m}}\right)^b, \quad (1)$$

with the free parameter b, which has to be fixed for a given analysis [21].

Air showers initiated by photons have, on average, a smaller S_b than air showers induced by hadrons of the same primary energy [21]. However, an observable like S_b can be significantly affected by any incompleteness in the detector array, which would lead to an underestimation of the true value. Such an incompleteness may be due to the borders of the array, due to missing detectors (important e.g. during the deployment phase of the array), or due to temporarily non-operating detectors. As an example for the latter effect, let us assume that at any time, 1 % of the detectors from the ground array are temporarily non-operating. For an array geometry where the detectors are arranged on a hexagonal grid, this means that 6 % of all events contain at least one non-operating detector in the first hexagon around the detector measuring the largest signal. When also the second hexagon is considered, about 18 % of all measured events are affected. Special care must then be taken, e.g. in the event selection, to prevent an underestimation of the S_b value for a given event due to these incompletenesses, which could mimic the expected behaviour of a photon-induced air shower. This holds especially at energies not far from the energy threshold of the experiment, where usually only very few detectors of the ground array are triggered and an omission of a signal from a detector can alter the S_b value substantially.

In this paper, we describe a new observable, called F_γ, which can be used at all energies down to the threshold set by the shower array. This observable exploits, similarly to S_b, the lateral distribution of the density of secondary particles from the air shower on ground level and is, as will be discussed later, complementary to X_{max}. Unlike S_b, missing stations will not alter the central value of F_γ (but only increase its uncertainty), leading to an improved stability of the observable. The lateral distribution can be described by a lateral distribution function (LDF), which can be determined from the ground-array data. The shape of the LDF depends on the type of the primary particle initiating the air shower: for photon-induced air showers, which on average exhibit a smaller number of secondary muons and a larger X_{max} compared to hadron-induced air showers of the same primary energy, the LDF is steeper, leading to a smaller signal in the detectors of the ground array compared to the signal measured from hadron-induced air showers at the same distance from the shower core. F_γ is based on a fit of the LDF. Therefore, it is largely unaffected by incompletenesses of the ground array. In addition, F_γ can be determined for events with very few triggered detectors in the ground array (even just a single one), hence it can be applied also to lower-energy events, where observables such as the curvature of the shower front cannot be determined.

In the following sections, we describe how the observable F_γ is defined and evaluate the performance of the observable in distinguishing photon-induced air showers from those induced by hadrons by using Monte Carlo (MC) simulations of air showers.

2. Description of the observable

2.1. General idea

The observable F_γ is based on a template fit of an LDF to the data recorded by the ground array. In this fit, we assume the primary particle initiating the air shower was a photon, and we determine the expected signal recorded in a detector of the ground array at a reference distance under this assumption. In this fit, two things will be different between photon- and hadron-induced