Astroparticle Physics 69 (2015) 61–67

Contents lists available at ScienceDirect

Astroparticle Physics

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

Energy reconstruction of hadron-initiated showers of ultra-high energy cosmic rays

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ARTICLE INFO

Article history:
Received 18 September 2014
Received in revised form 24 March 2015
Accepted 3 April 2015
Available online 9 April 2015

Keywords:
Ultra-high energy cosmic rays
Hybrid experiments
Energy reconstruction

ABSTRACT

The current methods to determine the primary energy of ultra-high energy cosmic rays (UHECRs) are different when dealing with hadron or photon primaries. The current experiments combine two different techniques, an array of surface detectors and fluorescence telescopes. The latter allow an almost calorimetric measurement of the primary energy. Thus, hadron-initiated showers detected by both type of detectors are used to calibrate the energy estimator from the surface array (usually the interpolated signal at a certain distance from the shower core $S(r_0)$) with the primary energy. On the other hand, this calibration is not feasible when searching for photon primaries since no high energy photon has been unambiguously detected so far. Therefore, pure Monte Carlo parametrizations are used instead.

In this work, we present a new method to determine the primary energy of hadron-induced showers in a hybrid experiment based on a technique previously developed for photon primaries. It consists on a set of calibration curves that relate the surface energy estimator, $S(r_0)$, and the depth of maximum development of the shower, X_{max}, obtained from the fluorescence telescopes. Then, the primary energy can be determined from pure surface information since $S(r_0)$ and the zenith angle of the incoming shower are only needed. Considering a mixed sample of ultra-high energy proton and iron primaries and taking into account the reconstruction uncertainties and shower to shower fluctuations, we demonstrate that the primary energy may be determined with a systematic uncertainty below 1% and resolution around 16% in the energy range from $10^{18.5}$ to $10^{19.6}$ eV. Several array geometries, the shape of the energy error distributions and the uncertainties due to the unknown composition of the primary flux have been analyzed as well.

1. Introduction

The energy spectrum of cosmic rays extends by more than 10 orders of magnitude from below 1 GeV to more than 10^{20} eV. The energy spectrum follows a power law as $E^{-\gamma}$, where γ is around 3.0 in the whole energy range. It is so steep that direct measurements are not feasible above 100 TeV. At higher energies, the properties of the primary cosmic ray are determined indirectly from the measurement of the extensive air shower (EAS) it produces after colliding with molecules of the atmosphere.

The highest energy EASs have been traditionally studied using two different techniques. The first one is based on telescopes that collect the fluorescence light emitted by atmospheric Nitrogen molecules excited by secondary particles of the EAS (e.g., Fly's Eye, HiRes). This allows to determine the longitudinal profile of the shower and it is considered to be close to a calorimetric measurement of the UHECR primary energy. However, fluorescence light can only be observed during moonless nights and, consequently, this technique can only be applied to $\sim 13\%$ of the incoming events [1]. The second technique involves an array of detectors located at ground level, mainly scintillators (e.g., Volcano Ranch, AGASA, KASCADE) or water Cherenkov tanks (e.g., Haverah Park), whose duty cycle is close to 100%. Thus, the lateral distribution of secondary particles at ground level can be inferred from the discrete sampling of the shower front. The lateral distribution is fitted assuming an appropriate parametrization (called the lateral distribution function, LDF). The interpolated signal at a certain optimum distance, $S(r_0)$, is used as the energy estimator, which can be related to the primary energy thorough, for instance, Monte

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http://dx.doi.org/10.1016/j.astropartphys.2015.04.001

Carlo (MC) parametrizations. The optimum distance, r_0, is traditionally fixed for each detector since it is assumed to be only dependent on the array spacing and geometry [2], although some studies suggest the convenience of calculating the optimum distance for each individual shower taking into account its primary energy and direction [3].

The current experiments, on the other hand, use hybrid techniques for $S(r_0)$ calibration. The Pierre Auger Observatory [4], taking data since 2004, pioneers the simultaneous use of water Cherenkov detectors and fluorescence telescopes, while the Telescope Array Observatory [5], operating since 2008, combines scintillators and telescopes. Events detected simultaneously by both the surface and fluorescence detectors are called *hybrid*. Hybrid events allow the calibration of $S(r_0)$ with primary cosmic ray energy [6]. Thus, the energy of each event detected by the surface detector alone can be determined almost independently of MC simulations. Systematic errors in energy estimate are greatly reduced in this way [7,8]. These calibrations assume that the primaries are nuclei and, therefore, they cannot be directly applied to photon-initiated showers. In addition, no photon event has been unambiguously identified up to now by any experiment so a proper calibration for photons is not possible with this technique. Therefore, each experiment relies on MC simulations to infer the primary energy of photon events [9–13].

The method used for photon searches by Auger in Ref. [13] was first proposed in Ref. [14]. This method takes into account the well-known universality of the electromagnetic component of EAS [15–17] and the small muon fraction of the photon-initiated showers. The calibration curve, that is obtained from MC simulations, relates $S(r_0)$, the zenith angle of the incoming shower, θ, and X_{max}. Thus, the primary energy of photon primaries can be determined with resolution of $\sim$20–25% [13,14].

In this work, we show how to modify that method to be applicable to hadron-initiated showers where the muon component is significant, especially, in case of water Cherenkov arrays which enhanced their contribution to the total measured signal. The additional advantage is that the same method could be used to infer the primary energy for both, photon and hadron showers. Moreover, in case of hadron-initiated showers the method can be calibrated with hybrid events reducing the systematic uncertainties coming from the high energy hadronic models used for shower simulations.

2. Shower and detector simulations

The simulation of the atmospheric showers is performed with the AIRES Monte Carlo program (version 2.8.4a) [18] using QGSJET-II-03 [19] as the hadronic interaction model. The input primary energy goes from $\log(E/\mathrm{eV}) = 18.5$ to 19.6 in 0.1 steps. Approximately 2000 events have been simulated per energy bin for both, proton and iron primaries. The zenith angle has been selected following a sine–cosine distribution from 0 to 60 degrees, while the azimuth angle is uniformly distributed from 0 to 360 degrees. X_{max} is obtained from these simulations.

Given the energy, the zenith and azimuth angles of the shower, the detector response is simulated with our own code, previously tested in Refs. [3,20,21]. Following the original proposal in Ref. [14], we select a triangular array of cherenkov detectors separated 1.5 km and $S(r_0 = 1000\ \mathrm{m}) \equiv S(1000)$ as the energy estimator. The real core is randomly located inside an elementary cell while the reconstructed core position is determined by fluctuating the real one with a Gaussian function whose standard deviation depends on the primary energy, composition and the distance between detectors (see Ref. [3] for more details).

The signal collected at each station for a given shower is set assuming a *true* lateral distribution function of the form,

$$S(r) = S(1000) \times \left(\frac{r}{r_0}\right)^{-\beta} \times \left(\frac{r+r_s}{r_0+r_s}\right)^{-\beta}, \qquad (1)$$

where r_s = 700 m, r_0=1000 m, the distance to the shower axis r is in meters, $S(1000)$ is in VEM (vertical equivalent muons, unit for the energy deposited by a vertical muon in a water tank [4]) and $\beta(\theta, S(1000))$ is given by (based on work by T. Schmidt et al. [22] as presented in Maris [23]),

$$\beta(\theta, S(1000)) = \begin{cases} a + b(\sec\,\theta - 1) & \text{if } \sec\,\theta < 1.55 \\ a + b(\sec\,\theta - 1) & \\ +f(\sec\,\theta - 1.55)^2 & \text{if } \sec\,\theta > 1.55 \end{cases} \qquad (2)$$

where $a = 2.26 + 0.195\log(e), b = -0.98, c = 0.37 - 0.51\,\sec\,\theta + 0.30\,\sec^2\theta, d = 1.27 - 0.27\,\sec\,\theta + 0.08\,\sec^2\theta$, $e = c\,S(1000)^d$ and $f = -0.29$.

A realistic $S(1000)$ to be used in Eqs. (1) and (2) is obtained from,

$$\begin{aligned} E &= A\,(S_{38})^B, \\ S(1000)(\theta) &= S_{38} \times \left[1 + Cx - Dx^2\right], \end{aligned} \qquad (3)$$

where $x = \cos^2(\theta) - \cos^2(38^o)$. A, B, C and D are constants given in Ref. [23] for QGSJetII-03, iron and proton primaries. In addition, shower to shower fluctuations for each primary are emulated by fluctuating the value from Eq. (3) with a Gaussian distribution whose standard deviation is taken from Fig. 3 in Ref. [24].

Finally, the signal assigned to each station is fluctuated using a Poissonian distribution whose mean is given by the *true* LDF. We adopt $S_{th} = 3.0$ VEM and $S_{sat} = 1221$ VEM as trigger and saturation thresholds respectively [3].

Next, the lateral distribution of particles is fitted using a functional form given by,

$$\log S(r) = a_1 + a_2\left[\log\left(\frac{r}{r_0}\right) + \log\left(\frac{r+r_s}{r_0+r_s}\right)\right], \qquad (4)$$

where the slope of the LDF and the normalization constant are free parameters while the core position is fixed in the reconstructed one. The values of χ^2/ndf are good if at least 3 stations are included in the fit, a minimum condition for shower reconstruction that is fulfilled for almost every event above the energy threshold of the detector. Finally, the reconstructed $S(1000)$ is determined as the interpolated value from the fit at 1000 meters from the shower axis. In this method, event by event fluctuations and reconstruction uncertainties are properly taken into account.

The problem of saturation is common to all surface arrays, specially when dealing with high energy vertical showers. The consequent lack of detectors close to the core produces large uncertainties in the LDF fit and affects the reconstructed $S(r_0)$. The Auger Collaboration, for example, has developed sophisticated algorithms to estimate the signal of a saturated detector [25]. Nevertheless, the analysis of such uncertainties and how to minimize them is beyond the scope of the present work so saturated events are discarded here.

The simulation set has been divided into two samples. In each sample, an equal number of proton and iron primaries have been mixed for each energy bin. The first sample represents the hybrid events and it is used to determine the calibration curves as it will be explained in the next Sections. Typical values for their reconstruction uncertainties are considered, so their real energy, zenith angle and X_{max} are fluctuated with Gaussian distributions whose standard deviations are 15% [6,8], 1° [26,27] and $20\ \mathrm{g/cm^2}$ [28] respectively. The second sample, which represents data from the surface detector alone, is used for reconstruction and only their reconstructed S(1000) and zenith angle are needed. Thus, to