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Usage of the estimation of the height of the first interaction in gamma/hadron separation for observations with Cherenkov telescopes

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The height of the first interaction of an Extensive Air Shower (EAS) is one of the parameters determining the shower development in the atmosphere. We derived a geometrical method of estimation of such a parameter. We study the influence of the first interaction height on the gamma/hadron separation efficiency. Using Monte Carlo simulations of a subarray of 4 Large Size Telescopes (LST) of the Cherenkov Telescope Array we find that one of the methods of the estimation of the height of the first interaction brings a mild improvement (∼10-20%) in the sensitivity at the lowest energies (30-200 GeV). We test also the method on the MC simulations and data of currently operating MAGIC telescopes.

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1. Introduction

One of the key issues in gamma-ray astronomy with Cherenkov telescopes is the separation of gamma rays from dominant hadronic background. Both gamma rays and hadrons entering the atmosphere cause the generation of Extensive Air Showers (EAS) with somewhat different properties. Especially at the lowest energies, a significant fraction of the hadronic events can imitate a gamma-ray-like EAS (see e.g. [1, 2]). Such events produce electromagnetic showers that are however starting slightly deeper in the atmosphere than genuine gamma rays [3]. The depth at which the EAS develops is normally parametrized in Cherenkov astronomy by the height of the shower maximum parameter, H_{max}. It is defined as the height from which most of the Cherenkov light reaches the telescope and it can easily be determined from the observed geometry in stereoscopic systems of Cherenkov telescopes [4]. On the other hand the height at which the first interaction occurred, while being an important parameter for determining the properties of EAS (see e.g.[5]), is difficult to determine. Templete analysis methods use this quantity as one of the fit parameters [6].

The Cherenkov Telescope Array (CTA) is an upcoming observatory consisting of two large arrays of Cherenkov telescopes located in the Southern and Northern hemispheres [7]. The arrays will be composed of three different types of telescopes and will be able to cover the energy range from ~ 20 GeV up to beyond ~ 300 TeV. The largest telescopes (the Large Size Telescopes, LSTs, [8]), are focussed on providing the best performance at the lowest energies reachable with CTA.

In [9] we studied two simple methods that can be used for the estimation of the first interaction height which can be applied to arrays of Cherenkov telescopes. One of the methods, based on the angular distance between the estimated source position, and the closest pixels that survived the image cleaning, has allowed for a mild gain in the sensitivy in the low-energy range for a subarray of LSTs. In this proceeding we report on those results and derive the resolution of the method for events with different numbers of telescopes recording a given event. We also apply the method to the data from a currently operating array of two Cherenkov telescopes, MAGIC [10].

2. Estimation of the height of the first interaction

The proposed method for the estimation of the height of the first interaction is based on the shape of the shower image. The image of the shower is the two-dimensional angular distribution of the Cherenkov light recorded by the telescope. The pixels closest to the direction of the source on the camera carry the information about the top part of the shower (see Fig. 1). As the passage of the primary gamma ray though the atmosphere does not induce Cherenkov light, the production of Cherenkov light starts only after the first $e^{+}e^{-}$ pair production. Therefore, we use the angular distance between the closest pixel and the reconstructed source position to calculate the height of the first interaction. Using the reconstructed impact position and applying a simple correction for the pixalization of the camera (see [9] for detailed description) this angular distance is converted into the estimation of the height at which the first light from the shower has been observed.

3. Performance of the method for an array of LSTs

We have tested the method on Monte Carlo (MC) simulations of the LST subarray. The MC

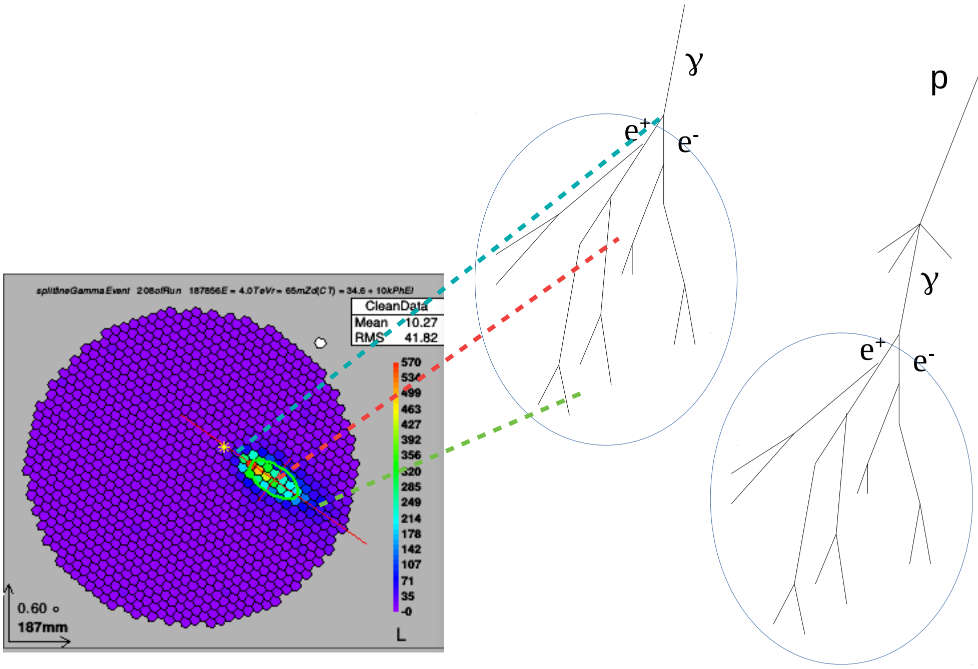

Figure 1: Principle of the estimation of the first interaction height. Center: electromagnetic shower initiated by a gamma ray. Right: proton shower in which in the first hadronic interaction most of the energy is transmitted into π^0 which decays into two gamma rays, which in turn start an electromagnetic cascade (deeper in the atmosphere than in the primary gamma ray in the center part of the figure). Left: the image of the shower with the reconstructed source direction marked with a yellow star. Dashed lines show how the parts of the shower are represented in the image: first Cherenkov photons from the first e^+e^- pair (cyan), shower maximum (red) and last photons from the tail of the shower (green).

simulations were extracted from the CTA *prod-3* data set for the layout optimization of the CTA-North (La Palma) site. The array of 4 selected LSTs corresponds to a quadrangle close to a square with a 100 m side at a mean altitude of 2180 m. The primary particles were simulated to originate from around 20° zenith angle, coming from the North and South directions. Air showers were simulated with `CORSIKA` [11], version 6.990, while the telescope response was obtained using `sim_telarray` [12]. The detailed information about the simulations used as well as about the analysis procedure are given in [9] and references therein.

In Fig. 2 we show the distribution of the reconstructed height of the first interaction as a function of its true value. This method gives the estimate of the height of the first interaction up to ~ 30 km (corresponding to about $12\,\mathrm{g\,cm^{-2}}$). For the showers starting higher a strong bias is seen. The performance of the estimation of the first interaction height does not depend strongly on the direction of the shower with respect to the geomagnetic field. In Fig. 3 we show how the resolution and bias of the reconstructed height of the first interaction depends on the number of telescopes with an image surviving cleaning.

The bias is caused by the fact that high-energy showers can trigger more distant telescopes which are not able to register the Cherenkov light from the top part of the shower due to the angle at which the photons are emitted being too small. Such an effect would produce an underestimation

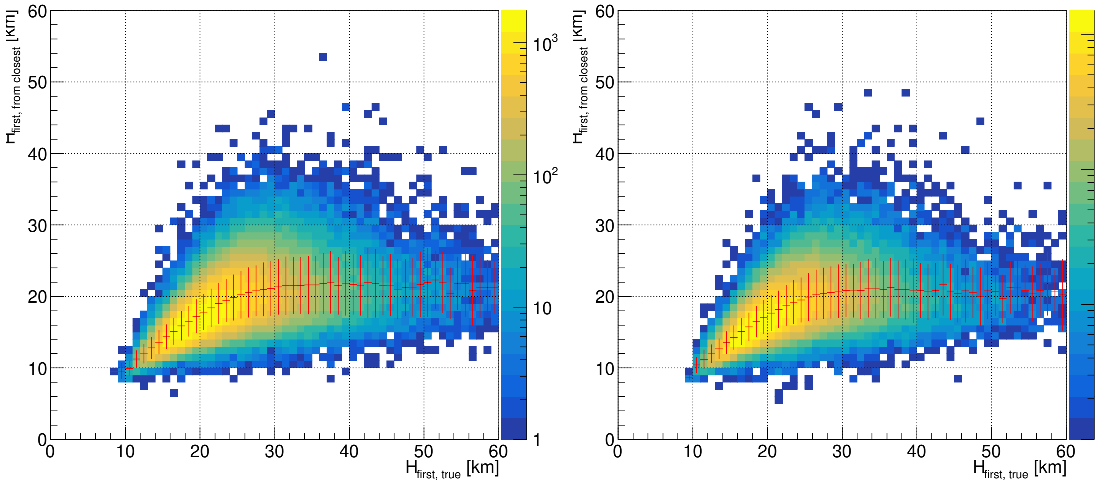

Figure 2: Height of the first interaction reconstructed using the closest pixel information vs the true value of the height of the first interaction. MC simulations of primary gamma rays coming from the South (left panel) and from the North (right panel) are imagined with a subarray of 4 LSTs. Only gamma-like events reconstructed within 0.1° of the nominal source position are shown. The red lines show the average and RMS of the reconstructed first interaction depth as a function of the true value of H_{first}.

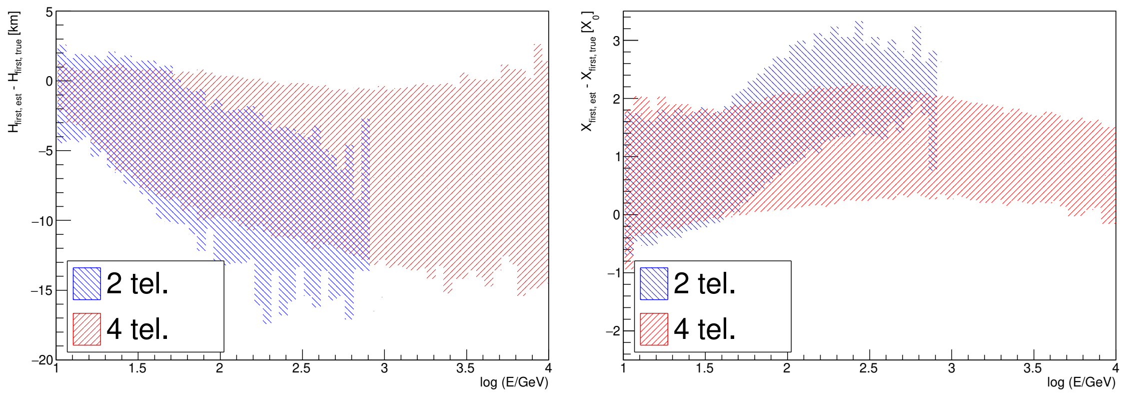

Figure 3: Reconstruction of the height (left panel) and depth (right panel) of the first interaction for the closest pixel method. The shaded region spans bias ± RMS of the difference between the true and reconstructed value at each energy. MC simulations of primary gamma rays coming from the South are imagined with a subarray of 4 LSTs. Only gamma-like events reconstructed within 0.1° of the nominal source position are shown. Red /-dashed lines show events in which image is reconstructed in all 4 telescopes, blue \-dashed lines show events with only 2 images.

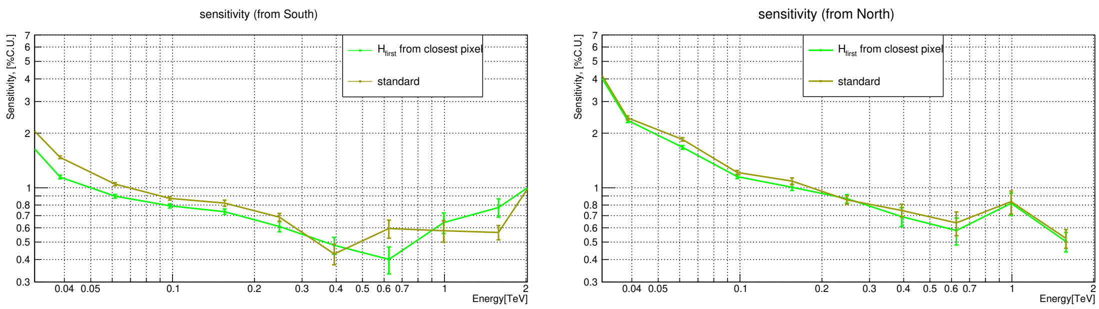

Figure 4: Comparison of differential sensitivities (and their uncertainties) for 50 hrs observations with 4 LST subarray in CTA North Observatory, obtained with standard training parameters (olive) and with an additional inclusion of the estimation of the height of the first interaction in training parameters (green). Left and right panels correspond to the showers coming from the South and North respectively.

of the height of the first interaction, as observed in Fig. 2. For events with only two telescopes recording an image suriving the cleaning (see Fig. 3) the effect is much more pronounced at high energies. Selection of events with only two images after cleaning will favor events with a large impact parameter.

In order to investigate the effect of the estimated first interaction height on the sensitivity we add it to the list of parameters of the gamma/hadron separation random forest (RF) [13]. In this way any simple bias that depends on another parameter used in the RF can be automatically taken into account. We are interested mostly in the possible improvement of the sensitivity below 100 GeV, where the contribution of cosmic-ray electrons in the residual background is not so large (see e.g. [3]). Therefore we have used simulated gamma rays and background from proton events only, hence the sensitivities presented in Fig. 4 are likely to be overly optimistic in the energy range above a few hundred GeV, where a strong contribution from electrons is expected. A slight improvement in sensitivity below $\sim$100 GeV was obtained when the height of the first interaction estimated from the closest pixel method is included in the RF. The improvement is larger in the case of telescopes pointed to the South (at a small angle to the GF) – about 20%, than for the case of observations in the direction of the North (almost perpendicular to the GF) – about 10%.

4. Performance of the method for the MAGIC telescopes

We tested the method of the estimation of the first interaction height on the data from the currently operating array of two 17 m diameter MAGIC telescopes [10]. The telescopes are located on the same site as the simulated LST array.

In the left panel of Fig. 5 we present the resolution of the estimation of the first interaction height for the MAGIC telescopes. The calculations are done on the standard MC simulations of MAGIC, generated with a range of zenith angles (5 to 35 degree) at all azimuth angles. Comparing these results to those shown in Fig. 2 we see that the resolution of the method is worse by a factor of approximately two than for the case of LSTs. As shown in Fig. 3 the number of telescopes in which the image of the shower is obtained is influencing only moderately the performance of the method at the lowest energies. Therefore, the most likely explanation of the worse performance of the reconstruction of the first interaction height for MAGIC is the twice lower light collection

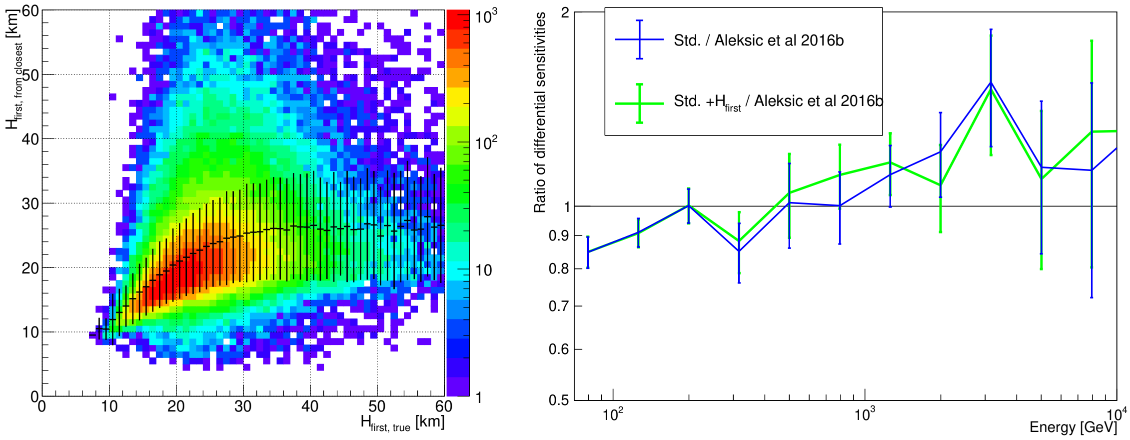

Figure 5: Left panel: first interaction height reconstructed using the closest pixel information vs the true value of the height of the first interaction. MC simulations of primary gamma rays are imagined with an array of 2 MAGIC telescopes. Only events reconstructed within 0.1° of the nominal source position are shown. The black lines show the average and RMS of the reconstructed first interaction depth as a function of the true value of $H_{\rm first}$. Right panel: Ratio of differential sensitivity to the one presented in [14] when the height of the first interaction parameter is included (green) or not included (blue) in the gamma/hadron separation. The sensitivity is calculated for 50 hrs of observations with 2 MAGIC telescopes using Crab nebula data.

efficiency (mainly due to the smaller reflector area), that hampers the collection of the first emitted Cherenkov photons from the first e^+e^- pair in the top part of the shower.

In order to estimate if, despite the worse reconstruction of the first interaction height, some performance improvement can still be achieved, we have used 20 hrs of Crab Nebula data taken between September 2016 and March 2018 at low zenith angle. We perform two analyses: one using only the standard gamma/hadron separation parameters, and the second adding additional information about the estimated height of the first interaction into the gamma/hadron separation parameters of the RF. The sensitivity is calculated according to the excess over square root of background definition. Two additional conditions are applied in the sensitivity calculations: signal to background ratio should be above 5% and the estimated number of excess events should be at least 10. Cut optimization is performed using the methodology described in [14]. In the right panel of Fig. 5 we show the ratio of sensitivity[1] obtained in this analysis to the sensitivity obtained in [14]. In the case of the MAGIC telescopes the estimation of the height of the first interaction with the proposed method does not improve the sensitivity.

5. Conclusions

We have investigated a geometrical method for the estimation of the first interaction height in arrays of Cherenkov telescopes based on the distance to the closest pixel that survives the image cleaning. We have applied the method to both the MC simulations of the planned subarray of 4

[1] A value of the ratio smaller then 1 means better sensitivity.

LSTs and to the MC simulations and data of the currently operating MAGIC telescopes. Despite the simplicity of the method, it has the resolution of the order of a single radiation length in the case of LSTs. In the case of the MAGIC telescopes, the resolution of the method is significantly worse, most probably because of the smaller light collection capabilities of the telescopes. The bias limits the application of the method to showers starting not higher in the atmosphere than ~ 30 km. We have studied the possible improvement of sensitivity by a more efficient background rejection by adding such a parameter to the gamma/hadron separation. In the case of the LST subarray the method brings a moderate gain of 10–20% in the sensitivity at the lowest energies ($\lesssim 100$ GeV). Interestingly, the relative improvement of the sensitivity due to the usage of the estimation of the first interaction height in the gamma/hadron separation depends on the azimuth angle of the observations. The improvement is more significant for the case of the weaker geomagnetic field influence, when also the general performance of the LSTs is better. This can be understood as the accuracy of the method studied will naturally depend also on the angular resolution. On the other hand application of the new method to the MAGIC telescope data does not bring any significant improvement in the sentitivity. Most probably it is connected with the much worse resolution of the estimation of the height of the first interaction then for a LST subarray.

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