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The background from single π^0 events in the IACT observations

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A system of Imaging Air Cherenkov Telescopes (IACTs) can be triggered by hadronic events containing Cherenkov light from at most two electromagnetic subcascades, which are products of a single π^0 decay. The recorded images of those showers have similar shapes to the primary γ-ray events. Therefore, they are hardly reducible background for observations using IACTs. In this paper, the impact of the single π^0 events on the efficiency of the γ/hadron separation was studied using the Monte Carlo simulations. The fraction of events containing the light from the single π^0 in the expected total protonic background depends on the trigger threshold, reflector area and altitude of the observatory. The calculated quality factors are anti-correlated with contributions of single π^0 events in the proton initiated showers with primary energies below 200 GeV. The occurrence of the single π^0 images is one of main reasons for the deterioration of the γ/hadron separation efficiency at low energy.

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1. Introduction

The γ/hadron separation in Imaging Air Cherenkov Telescopes becomes much more difficult below 100 GeV (see e.g. [1, 2]) because of a few effects. First, in a low energy region larger fluctuations of the image parameters are expected due to the larger fluctuations of the Cherenkov light density at ground [3, 4]. Second, the image parameters are changed by the geomagnetic field [5, 6]. Third, a primary electron or positron initiated shower can trigger a IACTs system [7]. Fourthly, the system of IACTs may be triggered by Cherenkov photons produced by electrons and positrons from at most two electromagnetic subcascades, which are a products of a single π^0 decay in the hadron initiated shower [8, 9].

The last effect is investigated in this paper. On the one hand single π^0 images may be slightly wider as the primary γ-ray events due to a separation angle between two products of the π^0 decay. On the other hand, they start deeper in the atmosphere what results in the narrower distributions of charged particles in the electromagnetic subcascades in comparison to the shower initiated by primary γ rays. Therefore the single π^0 images should have very similar shapes to the primary γ-ray images what results in a worsening of the γ/hadron separation efficiency. The results presented here are based on Monte Carlo (MC) simulations. We show that the total fraction of the single π^0 events in the expected protonic background depends on the altitude of the observatory, telescope size, trigger threshold and multiplicity of triggered IACTs. A contribution of the single π^0 events in the total protonic background, which is calculated in the interval of the average SIZE, decreases with the average SIZE. The scaled WIDTH and scaled LENGTH [11] are applied for a selection of γ rays out of the hadron induced showers. The strong anti-correlation between calculated quality factors and the contributions of the single π^0 events indicates that the occurrence of the single π^0 events (before a primary γ-rays selection) is one of the main reasons of the significant reduction of the γ/hadron separation efficiency at low energies.

2. Monte Carlo Simulations

The CORSIKA code version 6.023 [12] was used for MC simulations of the Extensive Air Shower (EAS) development in the atmosphere. The GHEISHA [13] and VENUS [14] interaction models have been applied for the low (i.e. for particles with primary momentum below 80 GeV/c) and high energy ranges. The standard code was adapted in order to have additional information about each π^0 decay and each electromagnetic subcascade produced in the shower.

Four 230 m^2 telescopes placed in the corners of a diamond were chosen as an example of IACT system. The side length of the diamond was fixed to 85 m and diagonals to 85 m and 147 m for the simulated altitude of the observatory equal to 2200 m a.s.l.. All distances between IACTs were reduced by a factor of 0.75 in the case of the altitude equal to 4 km a.s.l.. Both the geomagnetic field and night sky background (NSB) were fixed to those at MAGIC site (La Palma) [17]. Each simulated telescope has a parabolic shape with a focal length of 17 m. The mirror dish has a diameter of 17 m. The camera has hexagonal shape that covers in total almost 4°. The shape of the inner part of the camera that is used for a trigger is also hexagonal. This part covers in total 2.9°. The diameter of the pixel was fixed to 0.1°. The 3NN trigger logic was chosen as a trigger condition for a single telescope. The results presented in this paper were obtained for the trigger thresholds: 3, 4 and 5 photoelectrons (phe.) which correspond to the signal of 3, 4 and 5 photoelectrons arriving exactly at the same time, respectively. More detailed information about the simulated system can be found in [10]. Four sets of MC have been perform: i) one for the 230 m^2 telescopes at the altitude of 2.2 km a.s.l; ii) one for the same telescope size at the altitude of 4 km a.s.l; iii) two for telescopes with the area of 160 m^2 and 100 m^2 located at 2.2 km. The simulations of smaller telescopes (with the area of 160 m^2 and 100 m^2) were obtained by reducing only the mirror dish of the described above IACT.

In each MC set we have simulated 22 million of showers initiated by primary proton with energies between 30 GeV and 1 TeV with a differential spectral index of -2.75 [15, 16]. The impact parameter was distributed randomly within a circle (radius of 1.2 km on the plane perpendicular to the shower axis) around the geometrical centre of the telescope system. The proton showers were simulated within a cone with a full-opening angle of 11° at a zenith angle of 20° and an azimuth of 0° (showers directed to the north). The showers induced by primary γ ray were simulated in the energy range between 10 GeV and 1 TeV with a differential spectral index of -2.6 [1]. The impact parameter was randomly distributed within a circle of 350 m radius. 1 million of the showers induced by primary γ-ray events were simulated at fixed zenith of 20° and the azimuth of 0° in each MC set.

3. Results and Discussions

In the results presented below we call a single π^0 events (or images) those triggered showers that have more than 90% of total SIZE formed by Cherenkov light from the same single π^0 sub-cascade in each recorded image. The rest of SIZE may be formed from Cherenkov photons from hadronic and muonic part of the shower.

Figure 1 shows the primary energy distributions of the triggered proton showers (dashed) and single π^0 events (solid histograms) obtained from simulations with the trigger threshold of 3 phe.. Events with all recorded SIZEs larger than 10 phe. are plotted. Three possible required trigger conditions: at least one, two and three triggered telescopes are plotted in panels a, b and c respectively. The distributions of single π^0 events are much steeper than that of all triggered events for energies above 100 GeV, regardless on the MC set. Most of the hardly reducible background are proton induced events with primary energy below 200 GeV. We have estimated that between 90% (for coincidences of all four telescopes) and 95% (for at least 1 triggered IACT) of the single π^0 events with all recorded SIZEs larger than 20 phe. have a primary energy below 200 GeV. This fraction does not depend on the trigger threshold and the altitude of the observatory, but slightly decreases with the telescope area - however absolute differences between results for 230, 160 and 100 m^2 are lower than 3%.

The fraction of single π^0 events in the proton background was calculated from all MC sets for primary energies below 1 TeV. Three panels of Figure 2 demonstrate how this fraction depends on the trigger threshold for a multiplicity of the triggered telescopes equal to 1, 2 and 3, respectively. The results from the same MC set show that, the fraction of single π^0 events decreases with the trigger threshold and with the multiplicity of the triggered telescopes because IACTs system is triggering by proton at higher energies that less probably appear to be the single π^0. Due to the same reason higher fractions of hardly reducible background are expected for the system located at

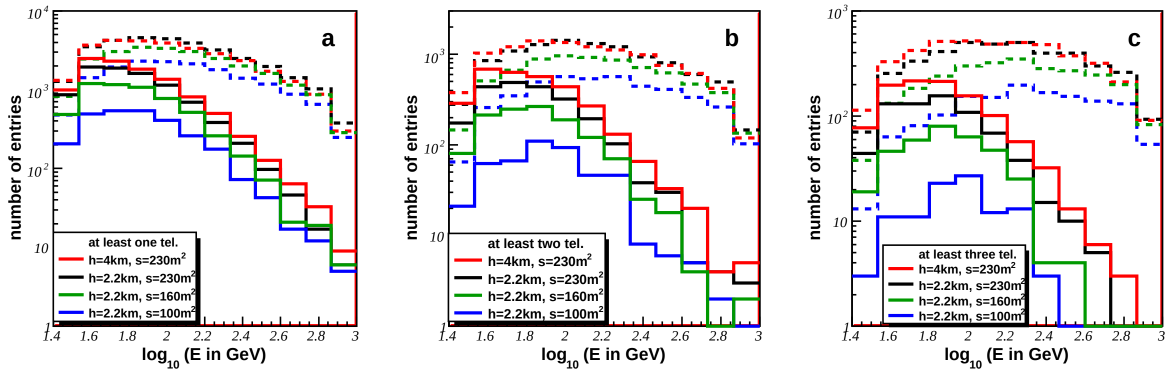

Figure 1: The energy distributions of the single π^0-ray events (solid) and all triggered showers initiated by primary proton (dashed histograms) for: **a)** at least one; **b)** at least two; **c)** at least three triggered IACTs at the triggered threshold of 3 phe.. Only showers with the SIZE parameter of each recorded image larger than 10 phe. are plotted.

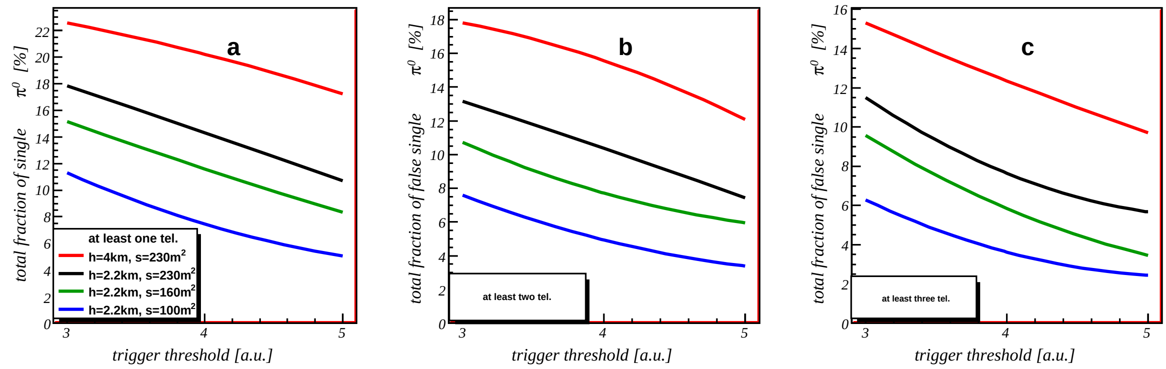

Figure 2: Fraction of the single π^0 events in the protonic background as a function of the trigger threshold for: **a)** at least one; **b)** at least two; **c)** at least three triggered telescopes. The fraction was calculated for energies below 1 TeV

4 km (red) than at 2.2 km a.s.l and for larger (black) than smaller (green and blue lines in Figures) reflection areas. For at least two triggered IACTs the contribution of the single π^0 events in the protonic background reduces from 13% to 8% in case of 230 m^2 IACTs (black) and from 8% to 4% in case of 100 m^2 telescopes (blue lines in Fig. 2b) when trigger threshold increases from 3 to 5 phe.. Note that the presented values, that were calculated for 220 m^2 telescopes at altitude of 2.2 km, are consistent with the results obtained for a slightly smaller trigger area of the camera [8].

The ratio of the number of the single π^0 events to the number of all triggered protons versus the average SIZE is presented in Figure 3. This ratio was calculated separately in each histogram bin for the trigger threshold of 3 phe. and SIZE parameter of all recorded images larger than 20 phe.. The results show that the contribution of hardly reducible background decreases with the <SIZE>. For at least one or two triggered IACTs, approximately 40%-60% of the proton initiated

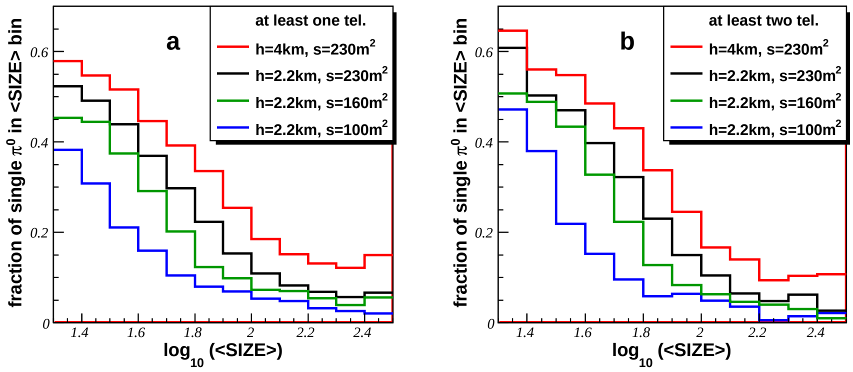

Figure 3: The ratio of the number of single π^0 events to the number of all triggered proton shower versus $<$SIZE$>$ for the trigger threshold equal to 3 phe.: **a)** at least one; **b)** at least two; **c)** at least three triggered telescopes. The ratio was calculated in each histogram bin separately.

showers are the single π^0 events in the lowest presented $<$SIZE$>$ bin (below 25 phe.). In the fixed $<$SIZE$>$ bin the higher fraction is expected for the simulated altitude of 4 km than for 2.2 km. The ratio of the number of the single π^0 events to the number of all triggered protons increases with the telescope area. We have checked that that more 95% of single π^0 events have the average SIZE below 300 phe., regardless on the altitude of the observatory, mirror area, trigger threshold and number of triggered IACTs. In case of at least 2 triggered IACTs between 65% (at trigger threshold of 5 phe.) and 90% (at trigger threshold of 3 phe.) of the hardly reducible background has the $<$SIZE$>$ parameter smaller than 100 phe., This fraction was calculated for events with all recorded SIZEs higher than 20 phe.. Similar values were obtained from all MC sets, thus this percentage does not depend on both the altitude of the observatory and telescope area.

The method of the γ/hadron separation used in this study is based only on so-called scaled WIDTH (WIDTH$_S$) and scaled LENGTH (LENGTH$_S$) [11]. Those two image parameters describe an image shape. The distributions of average WIDTH$_S$ and LENGTH$_S$ parameters are presented in Figure 4a and 4b for at least two triggered telescopes at the trigger threshold equal to 3 phe.. Events with all image SIZEs larger than 20 phe. are plotted in those figures. The histograms of all triggered events for primary γ ray (purple solid) and proton (dashed histograms) are normalized to 1. Appropriate factors were used to scale histograms of the single π^0 events (solid: red, black, green and blue histograms). It is seen in Figure 4a and 4b, that the primary γ rays cannot be effectively separated from the single π^0 events by using image parameters describing the image shape only.

In order to estimate how the occurrence of the single π^0 events affects the efficiency of the γ/hadron separation, whole sample of triggered events was split into five intervals of $<$SIZE$>$ (from 20 to 50, from 50 to 100, from 100 to 200, from 200 to 300 and above 300 phe.). The γ/hadron separation method was applied in each $<$SIZE$>$ interval. Primary γ-ray candidates are selected as events that have all recorded images with WIDTH$_S$ and LENGTH$_S$ in the range between -1.5 and 1.5. We have used the quality factor (QF) to demonstrate the efficiency of the γ-ray selection from the hadronic background [18]. Additionally the contribution of the single π^0 events in the total

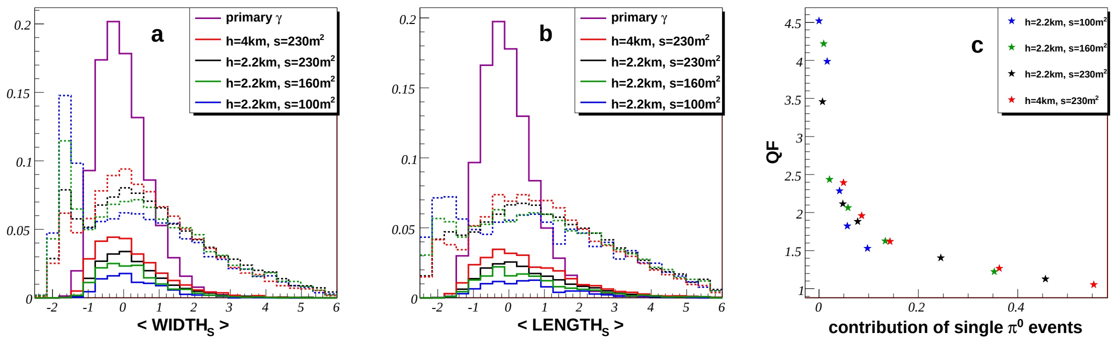

Figure 4: a) The mean WIDTH$_S$ distribution. **b)** The mean LENGTH$_S$ distribution. The results presented in Fig. 4a and 4b were obtained for at least two triggered IACTs at the trigger threshold of 3 phe. and all recorded image SIZE larger than 20 phe.. **c)** The quality factor versus the contribution of the single π^0 events in proton background before the γ/hadron separation for at least two triggered IACTs at the trigger threshold of 4 phe. (only events with all image SIZEs larger than 20 phe. were taken into account in the γ/hadron separation.

protonic background was calculated in those chosen intervals of <SIZE> before the primary γ-ray selection. Figure 4c shows the dependence between QF and the contribution of the hardly reducible background obtained from all MC sets for at least two triggered IACTs at the trigger threshold of 4 phe.. The quality factor decreases with the fraction of the single π^0 events. Similar dependences between those two variables were obtained for all simulation sets.

Finally we calculated the correlation coefficients between the quality factor and the contribution of the single π^0 events in the protonic background (before a γ-ray selection). The correlation coefficients which were obtained from all five <SIZE> intervals are presented in the Table 1 for at least 2 triggered IACTs at the trigger threshold of 3 phe.. We have checked that presented values almost do not depend on the trigger threshold. The results of smaller telescope areas (i.e. 100 and 160 m^2) and high multiplicity of triggered telescopes (i.e. 3 and 4) showed that any proton initiated shower remains after γ/hadron separation for <SIZE> above 300 phe. or/and between 200 and 300 phe.. In those cases the correlation coefficients were not calculated. The values presented in the Table 1 demonstrate the strong anti-correlation between the γ/hadron separation efficiency and the contribution of the single π^0 events what proves that the occurrence of this kind of background in one of the main reasons of the deteriorating of the primary γ-ray selection efficiency at low energies.

4. Conclusions

Our results lead to three important conclusions. At first, a single π^0 events can be detected by systems of IACTs in the investigated telescope sizes between 100 m^2 and 230 m^2. At second, this kind of background is mainly caused by proton initiated showers with the primary energy below 200 GeV. At third, the vast majority of the single π^0 events have <SIZE> smaller 300 phe.. Two

Table 1: Correlation coefficients between the QF and the contribution of the single π^0 events before the γ-ray selection for a trigger threshold of 3 phe..

minimal number of trigg. IACTs	h = 4 km s = 230 m^2	h = 2.2 km s = 230 m^2	h = 2.2 km s = 160 m^2	h = 2.2 km s = 100 m^2
1	-0.99	-0.98	-0.97	-0.89
2	-0.94	-0.82	-0.76	-0.75
3	-0.89	-0.71	-0.62	
4	-0.86	-0.60		

last conclusions do not depend on the altitude of the observatory, mirror area, trigger threshold and the number of triggered IACTs.

The estimated fraction of the single π^0 events in the protonic background in the energy range between 30 GeV and 1 TeV decreases with the trigger threshold and the number of triggered telescopes because these two qualities play an important role in a determination of the favoured energy range of primary particle that can be recorded by the system. This fraction is higher for the observation altitude of 4 km than for 2.2 km a.s.l., for a fixed trigger conditions (i.e. threshold and required multiplicity of triggered IACTs). The fraction of the single π^0 events in all triggered proton showers increases with the mirror area of the telescope.

The contribution of the single π^0 events in protonic background that is calculated in the $<$SIZE$>$ interval diminishes with the average SIZE, for all simulations sets. This contribution is larger at altitude of 4 km than at 2.2 km a.s.l.. for the fixed $<$SIZE$>$ bin. The fraction of the single π^0 events in the $<$SIZE$>$ bin increases with the telescope mirror area since the energy threshold of the system decreases with the telescope size.

We have shown that the single π^0 and primary γ-ray events have similar shapes. The distributions of average WIDTH and LENGTH parameters indicate no possibilities of effective separation between the single π^0 and primary γ-ray events. As a results the strong anti-correlation between the efficiency of the γ/hadron separation (based on parameters describing an image shape) and the contribution of the single π^0 events (before γ-ray selection) has been found. This correlation is weaker for higher multiplicity of triggered IACTs and smaller mirror areas because in those cases, the system is triggered mostly by higher energy protons. The occurrence of the hardly reducible background from the single π^0-ray events is one of the main reasons of the degradation of both the efficiency of the γ/hadron separation and as a result sensitivity of a system of IACTs in the low energy range.

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