Measurable Difference in Cherenkov Light between Gamma and Hadron Induced EAS.

Hervé Cabot[1], Christian Meynadier[1], Dorota Sobczyńska[2],
Barbara Szabelska[3], Jacek Szabelski[1,3], Tadeusz Wibig[2]

[1] Université de Perpignan, Groupe de Physique Fondamentale,
52 av. Villeneuve, 68860 Perpignan Cedex, France
[2] University of Łódź, Experimental Physics Dept.,
ul. Pomorska 149/153, 90-236 Łódź, Poland
[3] Soltan Institute of Nuclear Studies, 90-950 Łódź, Box 447, Poland

Abstract

We describe the possibly measurable difference in the Cherenkov light component of EAS induced by an electromagnetic particle (i.e. e^+, e^- or γ) and induced by a hadron (i.e. proton or heavier nuclei) in TeV range.
The method can be applied in experiments which use wavefront sampling method of EAS Cherenkov light detection (e.g. THEMISTOCLE, ASGAT).

1   Introduction

We refer to the Extensive Air Shower (EAS) experiments which are detecting cosmic rays (CR) in TeV energy range and are using Cherenkov light signal. The primary goal is to identify and measure gamma ray flux from astrophysical objects. Positive results obtained by the Whipple Collaboration [16, *Vacanti et al., 1988*] and by the THEMISTOCLE Collaboration [2, *Baillon et al., 1993*] are encouraging. (For the review of current status see vol. 1 of *the Proceedings of XXIV ICRC, Roma*, 1995, or *the Proceedings of the Padova Workshop on TeV Gamma – Ray Astrophysics "Towards a Major Atmospheric Cherenkov Detector–IV", Sept. 11–13, 1995, ed. M. Cresti*).

There are two different methods currently used in this area: "imaging" and "wavefront sampling". We refer here to the "wavefront sampling" method, which detects the Cerenkov light simultaneously in number of places distributed on the field of the size larger than 200 m. The timing and the signal amplitudes are used to identify and classify the event. (The method has been developed and is used by the THEMISTOCLE and ASGAT groups and is planned to be used by the CELESTE group at the Themis site in the French Pyrenees).

The main problem is to distinguish the gamma ray induced events from the larger background of proton induced showers, which is very difficult to achieve by examining the EAS on the Cherenkov light cone shape and the signal amplitudes in each detector. The DC signal from the Crab nebula direction has been found (only) due to very good angular resolution ($\approx$ 2.5 mrad), tracking the source on the sky [2, *Baillon et al., 1993*]. Thus the increase in number of events was obtained when the detectors where centred on the source direction as compared with the off–source measurements (no identification of nature of primary particle was applied).

Here we pay attention to the Cherenkov light produced by muons. We demonstrate that the Cherenkov light from muon observed at the distance of few tens of meters from the EAS core can arrive several nanoseconds before the "main" signal produced by electrons and positrons. Identification of "muon" signal can be used as identification of hadronic origin of parent energetic CR particle. At TeV energy range the ratio of number of muons in proton showers to the number of muons in electromagnetic (E–M) showers is about 100, if calculated for similar Cherenkov light intensity at 50 m from EAS core (i.e. few muons with E_μ > 10 GeV in E–M showers, and few hundred muons in proton showers). In this paper we present results of theoretical analysis of the problem (approximate calculations and results of the Monte Carlo simulation) and we address the hardware requirements which should be met for experimental identification of that effect.

2   Approximate calculations

To demonstrate how Cherenkov light produced by the muon can come before the light produced by electrons and positrons it could be useful to perform approximate calculations and clarify the picture of the event.

The Cherenkov light is emitted when a charged particle is passing through the air (or other matter) with velocity greater than local phase velocity of light. The velocity of light is equal to $v_{air} = c/n$, where c is the speed of light in vacuum and n is the local refraction index.

We are interested in the observations at the lateral distance of more than 50 m from the EAS core (crossing point of CR particle trajectory and ground surface). Most of E–M particles of EAS at TeV energies are closer to the CR particle trajectory and the E–M cascade develops few kilometers above the ground, not reaching the level 2 km a.s.l., and most of Cherenkov light is emitted by e^+/e^- at altitudes $3 - 12$ km a.s.l.

Muons with energy above 5 GeV are faster than light in the atmosphere at sea level. They can produce Cherenkov radiation near to the detector. This light can be detected earlier than the Cherenkov light from E–M cascade.

Muons are decay products of hadrons originated near to CR particle trajectory. Energetic muons can reach the observation level and can generate Cherenkov radiation near to the detector. The energy threshold for muon to produce Cherenkov radiation in the atmosphere is about 5 GeV, so such muons are relativistic, and they might not decay flying several kilometers.

We compare the time of flight of light emitted at the level h reaching the surface at distance r from the EAS core with the time of flight of muon with energy E_μ which was emitted at the same altitude h and reaching the same place at the distance r. We set the time reference point t_0 at the time of h/c.

l is the distance travelled by light and muon ($l = \sqrt{r^2 + h^2}$).

For muons:

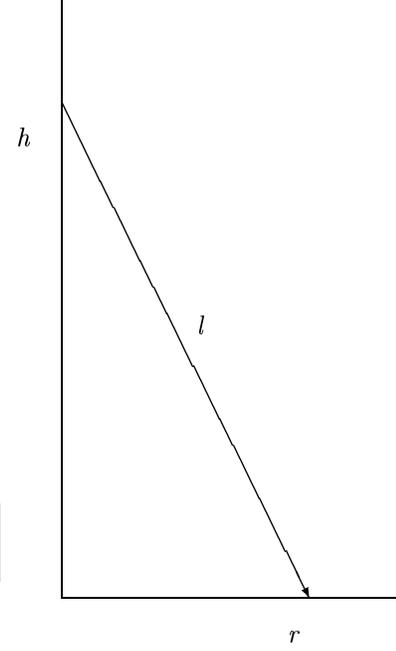$$\Delta t_\mu = -\frac{h}{c} + \frac{l}{v_\mu}$$

$$v_\mu = c \cdot \beta_\mu$$

$$\beta_\mu = \sqrt{1 - \frac{1}{\gamma_\mu^2}}$$

$$\gamma_\mu = \frac{E_\mu}{m_\mu c^2}$$

$$E_\mu >> m_\mu c^2$$

$$\frac{1}{\beta_\mu} \approx 1 + \frac{1}{2}\left(\frac{m_\mu c^2}{E_\mu}\right)^2 + \frac{3}{8}\left(\frac{m_\mu c^2}{E_\mu}\right)^4$$

$$\Delta t_\mu = -\frac{h}{c} + \frac{\sqrt{r^2 + h^2}}{c} \cdot \left[1 + \frac{1}{2}\left(\frac{m_\mu c^2}{E_\mu}\right)^2 + \frac{3}{8}\left(\frac{m_\mu c^2}{E_\mu}\right)^4\right]$$

For light it is necessary to take into calculation the variation of refraction index with the altitude. For the form: $n = 1 + \eta$ the approximate dependence is valid for these calculations [10, *Hillas, 1982*]: $\eta = \eta_0 \cdot exp(-h/h_0)$, where $\eta_0 = 2.9 \cdot 10^{-4}$, $h_0 = 7.1$ km.

$$\Delta t_l = -\frac{h}{c} + \frac{1}{c}\int_0^{\sqrt{r^2 + h^2}} (1 + \eta)\, dx$$

$$\eta = \eta_0 \cdot exp\left(\frac{-x}{h_0}\frac{h}{\sqrt{r^2 + h^2}}\right)$$

$$\Delta t_l = \frac{1}{c}\left\{\sqrt{r^2 + h^2} - h + \frac{h_0}{h}\sqrt{r^2 + h^2} \cdot \eta_0 \cdot \left[1 - exp\left(\frac{-h}{h_0}\right)\right]\right\}$$

Using above formulae for light and muons we evaluate for a given distance r the minimum Δt varying the height of production h, however limited to 12 km. That limit has a physical justification, since most of EAS of these energies are well developed above 2 km (820 g/cm^2) and below 12 km a.s.l. (195 g/cm^2). Without the limit the Δt_μ is still smaller for higher energy muons. Results are compiled in the Figure 1.

We would like to underline two features presented in the Figure 1:

- Δt_l (represented by solid line) is nearly linearly proportional to the distance r;
- muons with energy above 10 GeV at the distances $r > 100\ m$ can arrive 3 nsec before the Cherenkov light of e$^+$/e$^-$ origin; for $E_\mu > 30\ GeV$ it could be up to 6 nsec difference.

We are going to discuss the second point in some details in following sections since this feature can help to distinguish between gamma and hadron induced events.

Here we have listed some simplifications used in the approximate calculations presented in this work (Figure 1). In our opinion they do not have large influence on Δt, however it is worth to know better the picture of real events.

- All charged particles with velocity $v > c/n$ ($n -$ refraction index), can produce Cherenkov radiation. In the atmosphere (since n is altitude dependent) the minimal energy for e$^+$/e$^-$ is 21.2 MeV at sea level and about 40 MeV at 10 km, and for muons: 5 GeV at sea level, and 10 GeV at 10 km.
- Mean lifetime for muons is $\tau = 2.2 \cdot 10^{-6}$ sec which corresponds to 31 km for 5 GeV muon. Some muons can decay and the probability of decay depends on energy.
- Cherenkov light is not emitted in the direction of charged particle, but at the angle θ_c to the particle trajectory (surface of the cone) ($\cos(\theta_c) = 1/(\beta \cdot n)$, where $\beta = v/$c). For relativistic
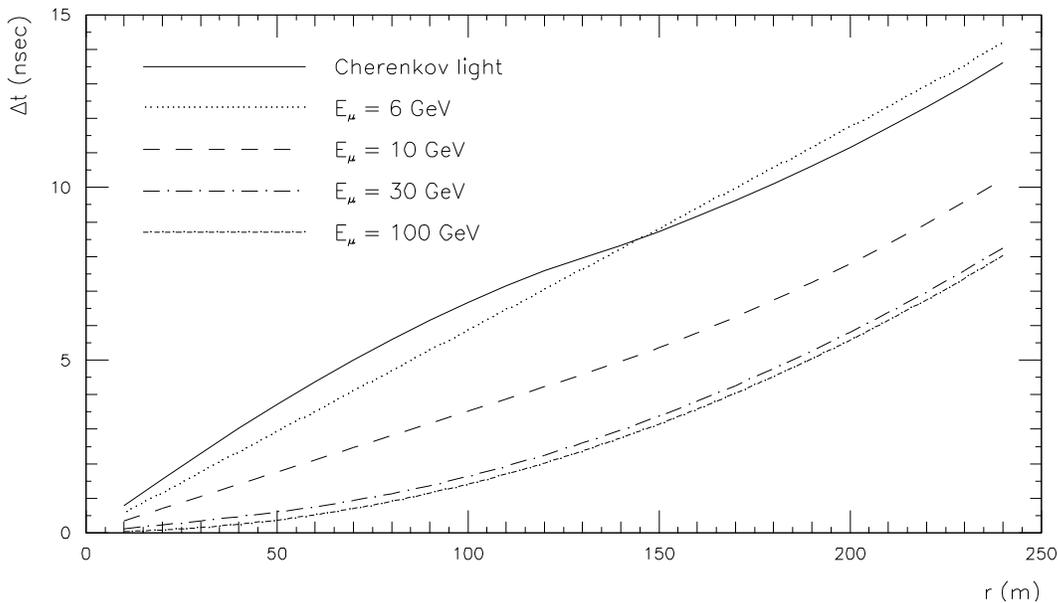
Figure 1: The approximate relative time differences Δt_l and Δt_μ for Cherenkov light and muon. t_0 is the arrival time of ultrarelativitic particle at the EAS core. Δt is the time with respect to t_0. It is shown that energetic muons, and Cherenkov light produced by them, can precede Cherenkov light produced by e^+, e^- of EAS by several nanoseconds.

particles ($\gamma > 100$) in the atmosphere $\theta_c \approx 20$ mrad at the sea level and $\theta_c \approx 12$ mrad at about 12 km. These values are comparable with the acceptance angle of many Cherenkov light EAS detectors. Therefore the combined trajectory: charged particle and emitted light do not make a straight line and Δt evaluation and acceptance geometry are complicated.

– There are large fluctuations in EAS development. Very important role plays the level of the first interaction of CR particle. Normally, if first interaction is deeper in the atmosphere more Cherenkov light is produced, because the E–M cascade develops in volume of larger refraction index n. For muons the situation is opposite: we expect more muons if the first interaction takes place higher in the atmosphere, because in low density media the decay of meson to muon is more likely.

– E–M cascade has lateral spread of tens of meters. Cherenkov photons can travel different distance than assumed in our approximate calculations and the Δt_l might be a little smaller due to this geometry.

– Some of Cherenkov photons can be scattered or absorbed in the atmosphere, and therefore are lost. Atmospheric transmission due to Rayleigh scattering, aerosol (Mie) scattering and absorption in ozone are discussed in our earlier works [1, *Attallah et al., 1995*].

– Let E_{CR} be the energy of CR particle which collides with nucleon of air nucleus. The center of mass reference frame has $\gamma_{cm} \approx \sqrt{E_{CR}/2\ GeV}$. If particle produced in collision would be pion ($m_\pi = 0.14\ GeV$) with Feynman's $x_F = 0$ then it would have in laboratory reference frame energy $E_\pi = \sqrt{E_{CR}/2\ GeV} \cdot m_\pi$, i.e. $E_\pi = 10$ GeV for $E_{CR} = 10$ TeV, or $E_\pi = 3$ GeV for $E_{CR} = 1$ TeV. So energetic muons are decay products of mesons produced in forward cone ($x_F > 0$) in first and subsequent interactions.

– When the primary CR particle is an E–M one (i.e. e^+, e^- or γ), muons can be produced via photoproduction of hadrons. The cross section for such a process is $\sigma_{\gamma \to hadrons} \approx 100$ μbarn. However the hadron (and then muon) energies are naturally smaller, than in corresponding case when the primary CR particle is a hadron.

4

3   Monte–Carlo simulations.

The detailed analysis of the arrival time of Cherenkov light from E–M component and from muons was performed by Monte–Carlo simulations of EAS development in the atmosphere, light transmission, mirror reflection, photomultiplier efficiency and signal convolution.

To simulate EAS development in the atmosphere we used the CORSIKA code v. 4.50 [3, *Capdevielle et al., 1992*] [11, *Knapp and Heck, 1995*]. This is a current version of detailed simulation program for EAS developed in Forschungszentrum Karlsruhe (Germany). It uses FORTRAN77, and different CMZ [4, *CodeME. S.A.R.L., 1993*] selections give the versions for different computer systems (IBM M3090, VMS, DEC-Unix, APPLE Macintosh and transputers used in FZK). The DEC-Unix option has been adapted to Alpha XP computers using Digital FORTRAN at Perpignan, and GNU's f2c converter at Alpha XP, PC 486 with Linux, and PC 486 with DOS in Łódź. The CORSIKA program has been used to study different aspects of Cherenkov radiation in EAS. Results presented in this work are extracted for further processing from simulations of 10 showers generated by vertical 6 TeV CR gamma and 10 showers by 10 TeV CR proton. We used the program option with GHEISHA code for low energy interactions, EGS electromagnetic interaction code, the Cherenkov light 'bunch size' of 1 photon per bunch, and CORSIKA Coulomb scattering parameter STEPFC = 0.2. The primary CR particle energies had been selected to give similar Cherenkov photon (300–450 nm, no losses) densities at 50 m from EAS core, equal to about 1000 ph/m^2. The simulation time using Alpha XP 175 MHz station was about 60 min. per gamma shower and about 40 min. per proton shower. The total (10 EAS) CORSIKA output have more than 105 Mb (for gammas) and more than 80 Mb (for protons) (mostly due to Cherenkov photon information, despite the fact that only photons pointed to preselected detector areas, 729 m^2 in total, were memorized; 28 bytes per 'bunch').

The standard CORSIKA output for Cherenkov light contains seven 4–byte real numbers per registered Cherenkov light bunch. These provide information on number of Cherenkov photons in a bunch, x position of bunch at registration level, y position, direction cosine to the x–axis, direction cosine to the y–axis, altitude of bunch production, time of bunch arrival with respect to the time of the first interaction in the EAS. The program produces the bunch of Cherenkov photons, all in the same direction (on the cone surface), instead of generating each photon at the cone surface. The average bunch size can be selected as an input parameter. In the default the photons have wavelength range $300 - 450$ nm.

For further analysis we have prepared a system of relatively smaller programs for processing the Cherenkov light CORSIKA output. These programs rescale the photon wavelength range, apply the losses of photons in the atmosphere (which are wavelength, altitude and pathlength dependent; see [1, *Attallah et al., 1995*] for more details. These programs calculate the detector mirror reflection probability according to [15, *Riera and Espigat, 1994*] (for the THEMISTOCLE mirrors). The photomultiplier quantum efficiency for bialkali cathode was taken from [5, *Philips Handbook, 1990*] as for phototube PHILIPS XP2020.

The progams use HBOOK procedures of CERN's *packlib* [9] and program PAW [13] was used to make most of presented graphics.

4   Example.

To demonstrate the role of muons in Cherenkov light detection as result of Monte–Carlo simulations we present an example of one shower observed by one detector in one place. EASs almost never look 'the same' because of fluctuations in their development and stochastic nature of most of physical processes involved. Average, mean nor 'most probable' values do not describe well the situation we are going to present. Many features are detector dependent and full detailed analysis should be performed for specific experimental setup.

In our example we present result of Monte–Carlo simulation of EAS triggered by vertical CR proton with energy 10 TeV. The detector is at the 1650 m a.s.l., altitude of Themis site (French Pyrenees) or Baksan Neutrino Observatory (Russia), where the Karpet detector is now equipped with Cherenkov device. Our simulated detector is located in (x_d, y_d) position equal to (–50 m, 0 m). We will consider two detector areas: 3 m x 3 m and the circle of the area of 0.44 m^2 both centred at (x_d, y_d). 0.44 m^2 is the effective area of each of the THEMISTOCLE experiment detectors [2, *Baillon et al., 1993*], and heliostat mirrors in the CELESTE experiment would have effective area of ≈ 31 m^2 (of 54 m^2 for each
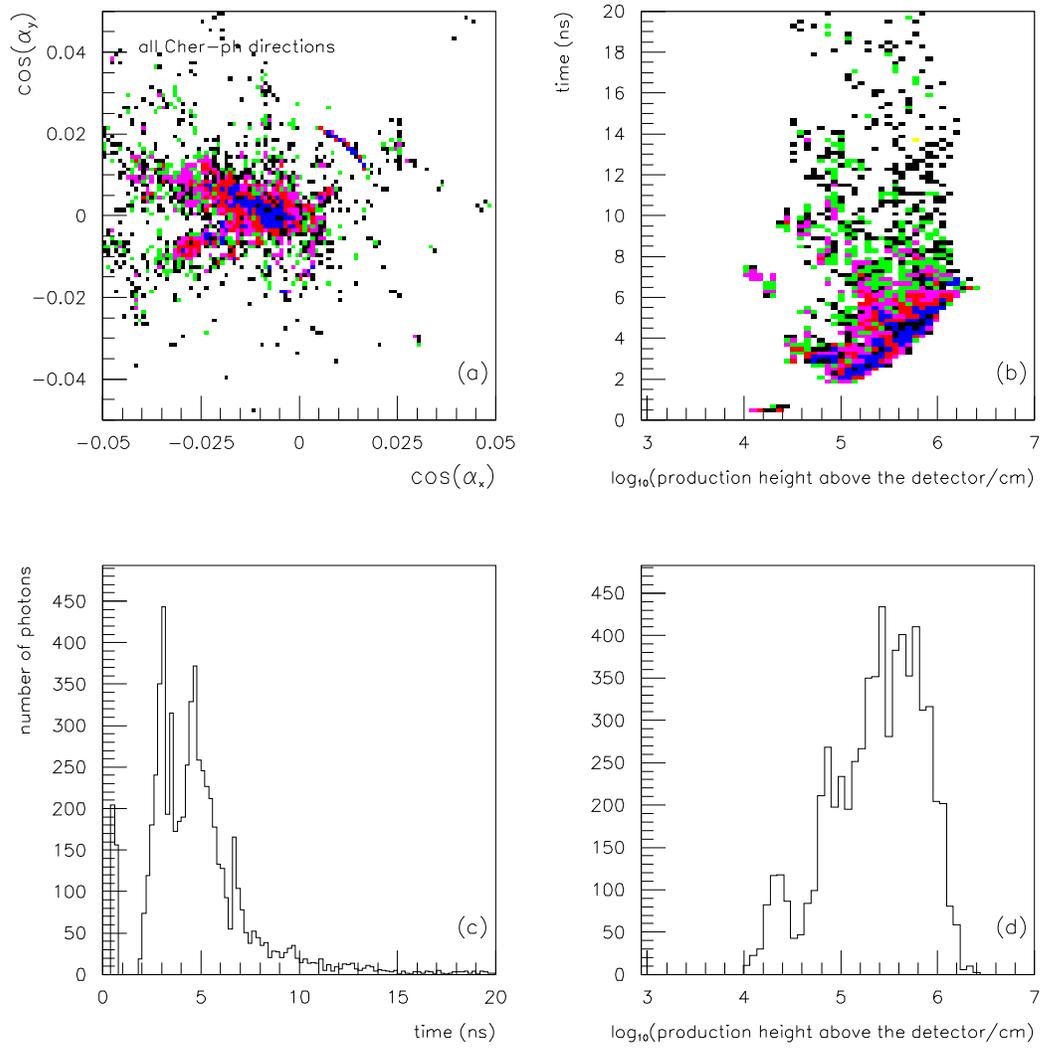
Figure 2: Arrival time and production height distributions and correlations for Cherenkov photons produced (no absorption) in 10 TeV proton EAS (photons on 3 m x 3 m area 50 m away from EAS core). See text for more comments and explanations.

mirror) [6, *Dumora et al., 1996*]).

The muon of energy 88.52 GeV has been found at position (−53.07 m, −3.59 m), with direction cosines $(\cos(\alpha_x),\cos(\alpha_y))$ equal to (−0.00196,0.00088) at $\Delta t_\mu = 0.3$ nsec.

In the Figure 2a we present the angular distribution of Cherenkov photons which fall on the area 3 m x 3 m centred at (−50 m, 0 m) and are produced in the EAS described above. This is a 2−dimensional distribution for $\cos(\alpha_x)$ and $\cos(\alpha_y)$ at the axes and grey scale corresponding to the decimal logarithm of the number of photons in the pixel (0.001 mrad x 0.001 mrad). White colour indicates no photons in the pixel. We have $\theta_x = \pi/2 - \alpha_x$ and $\theta_y = \pi/2 - \alpha_y$. For small zenith angle θ, $\cos(\alpha_x)$ and $\cos(\alpha_y)$ approximately correspond to θ_x and θ_y in radians, the axes limits are from −50 mrad to +50 mrad in x and y directions.
The result shown in the Figure 2a corresponds to the theoretical registration of all photons produced in EAS by the imaging Cherenkov device at 50 m away from the EAS core. The main pattern has an assymetry which corresponds to the fact that most of photons are coming from the direction of the EAS axis (negative $\cos(\alpha_x)$ values). The perpendicular spread of photon directions (in this case along $\cos(\alpha_y)$ axis) is quite large, and this fact is often used to discriminate between gamma and hadron primary particle.

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Around the point (0.015,0.015) there is an arc of Cherenkov photons produced by the muon. The angular radius of the arc is about 20 mrad which indicates the relativistic particle, the centre of arc points to the direction of the muon mentioned above (-0.00196,0.00088).

In the Figure 2b we present the distribution of Cherenkov photons in 2–dimensional space of arrival time vs. height of photon emission (these are the same photons as in the Figure 2a). Most of photons are produced 600 m above the detector level or higher and arrive with $\Delta t > 2$ ns. The small spot at place $\Delta t = 0.5 - 1$ ns and production height 120 –200 m corresponds to the Cherenkov light emitted by the energetic muon. The isolated spot with $\Delta t = 6 - 7$ ns and production height $120 - 200$ m corresponds to another, not very fast muon.

In the Figure 2c we show the arrival time distribution (projection of the Figure 2b on the time axis) The first peak in the histogram represents Cherenkov photons emitted by the energetic muon.
In the Figure 2d there is production height distribution (projection of the Figure 2b on the height axis). The bump around $4.3 \approx \log_{10}(200 \text{ m})$ is due to the accumulated signals from muons. From all charged
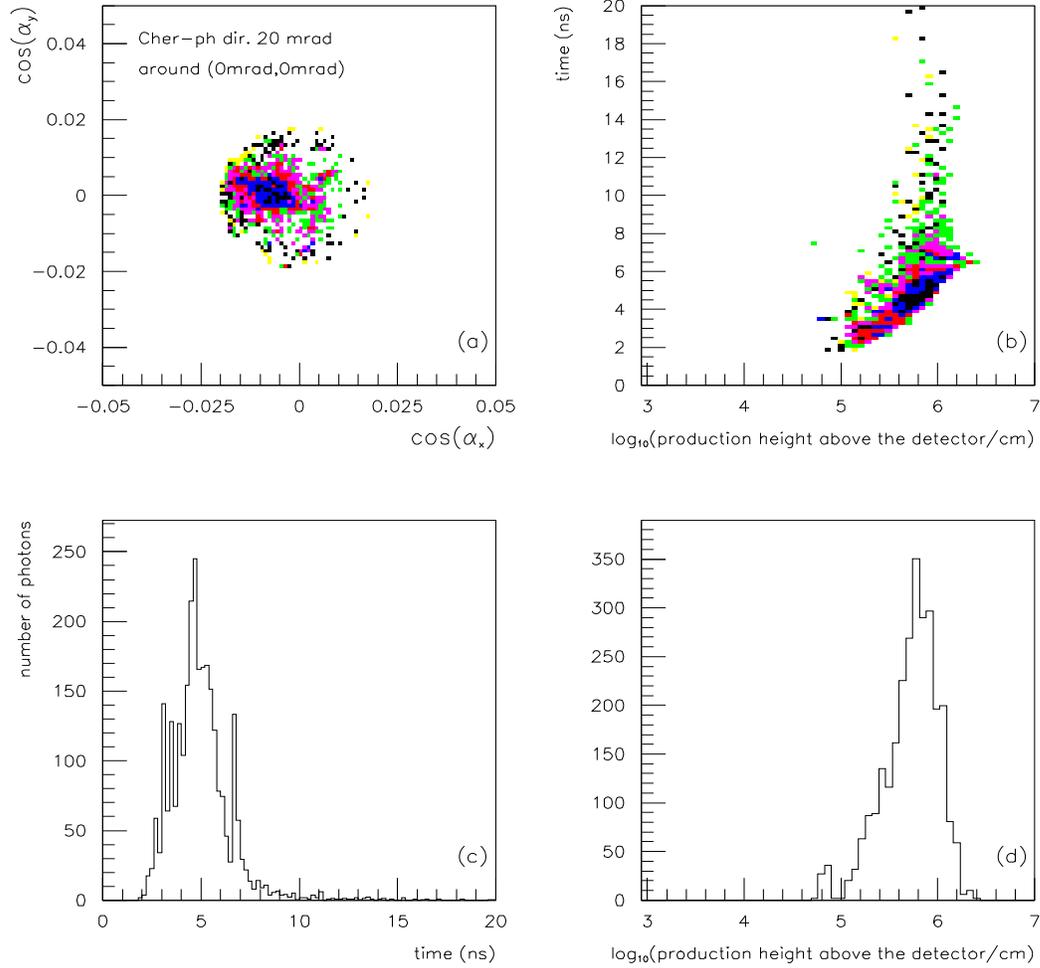

Figure 3: Similar to Figure 2 but only photons within 20 mrad from vertical direction. Arrival time and production height distributions and correlations for Cherenkov photons produced (no absorption) in 10 TeV proton EAS (photons on 3 m x 3 m area 50 m away from EAS core). See text for more comments and explanations.

particles of 10 TeV proton EAS only muons can get down below 2 km a.s.l. (i.e. around 200 m above the detector placed at altitude 1650 m a.s.l.).

Let us demonstrate a role of angular acceptance of each detector. This means that not all Cherenkov photons which are reflected from the mirros, fall onto the cathode of the phototube. In the case of the THEMISTO-CLE heliostat the angular acceptance can be described as a probability function $P(\gamma)$, where γ is the angular difference between the direction of photon and optical axis of the mirror:

$$P(\gamma) = \begin{cases} 1 & \text{if } \gamma < 10 \text{ mrad} \\ 2 - \dfrac{\gamma}{10 \text{ mrad}} & \text{if } 10 \text{ mrad} < \gamma < 20 \text{ mrad} \\ 0 & \text{if } \gamma > 20 \text{ mrad} \end{cases}$$
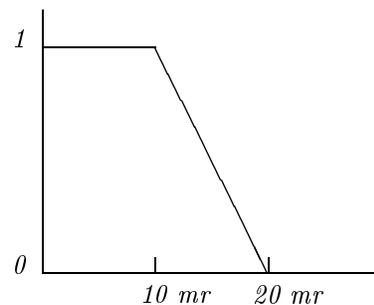

Figure 4: Approximate THEMISTO-CLE experiment detector acceptance angle distribution (P. Espigat, 1995, private communication)
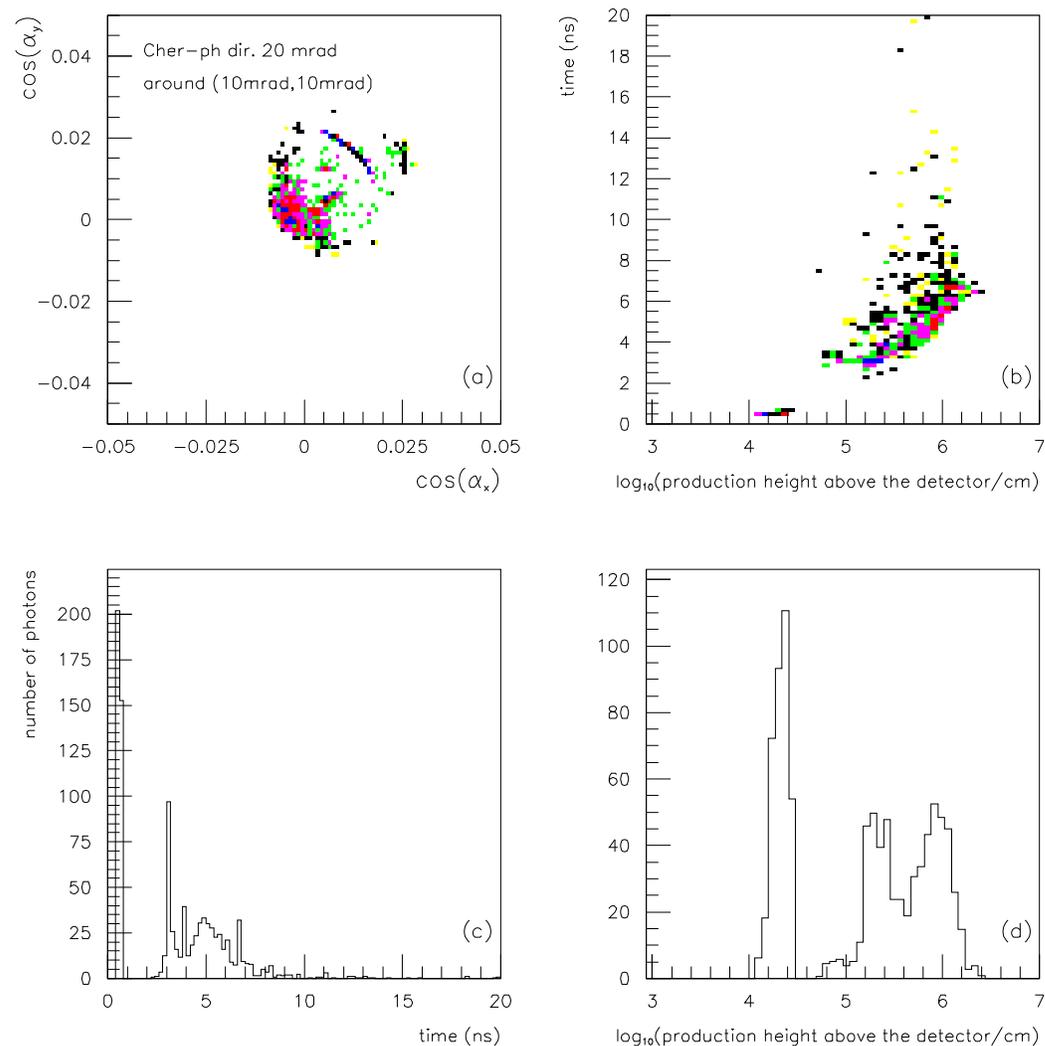

Figure 5: Similar to Figure 2 but only photons within 20 mrad around the direction (θ_x, θ_y) equal to (10 mrad, 10 mrad). Arrival time and production height distributions and correlations for Cherenkov photons produced (no absorption) in 10 TeV proton EAS (photons on 3 m x 3 m area 50 m away from EAS core). This time the muon signal is clearly seen. See text for more comments and explanations.
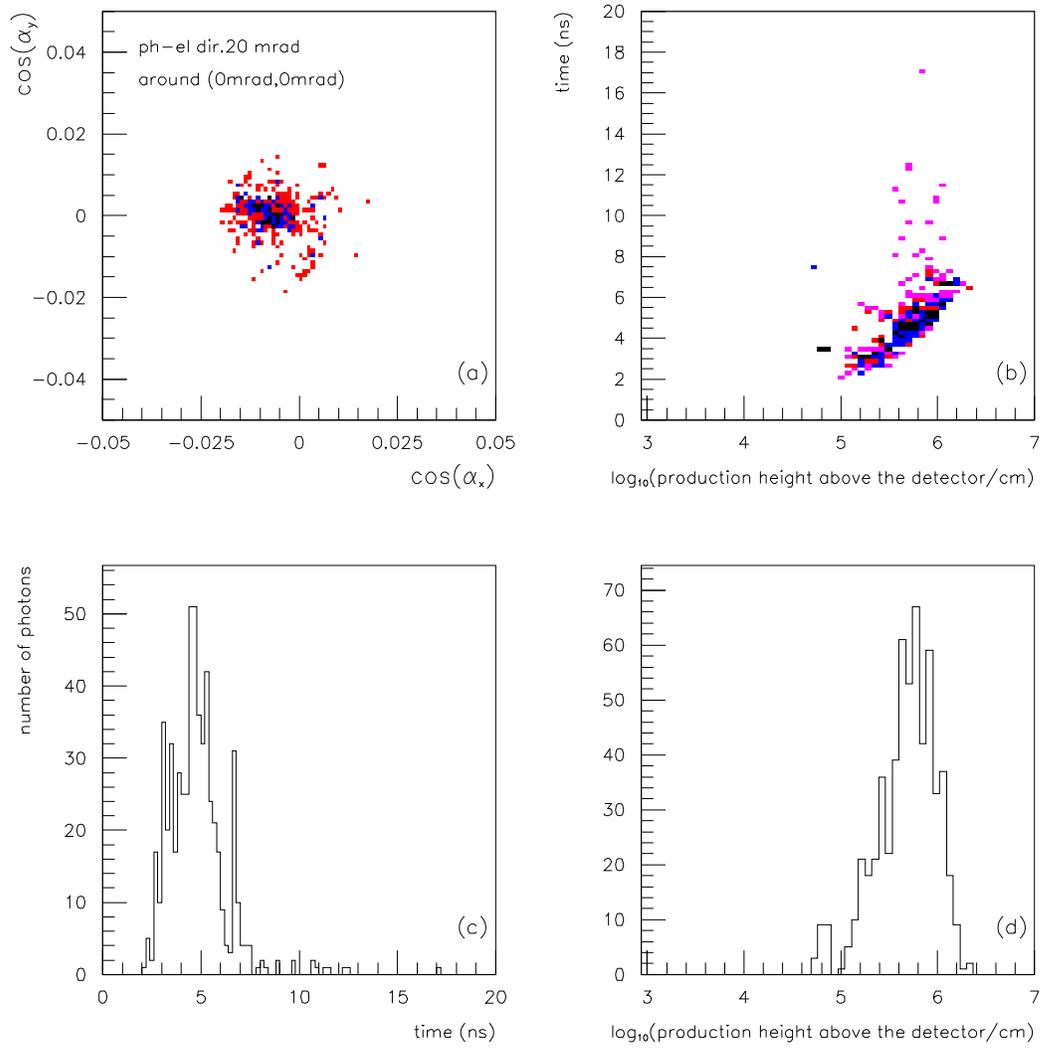
Figure 6: Similar to Figure 3 but for photo–electrons (and corresponding photons); only ph–el from photons within 20 mrad around the vertical direction. Arrival time of ph–el and production height distributions and correlations for related Cherenkov photons in 10 TeV proton EAS (detector area of 3 m x 3 m, 50 m away from EAS core). See text for more comments and explanations.

In the Figure 3 we present a 'subset' of photons shown in the Figure 2 taking into account the THEMIS-TOCLE mirror acceptance for the mirror optical axis in the direction of EAS, i.e. directional cosines (0.,0.). Since the muon direction was nearly vertical, the muon pattern shown in the Figure 2a disappeared in the Figure 3a (the Cherenkov cone angle is just 20 mrad). The muon signal is absent in the Figure 3b; we have only Cherenkov light from the E–M component of EAS present. The fastest photons arrive with $\Delta t \approx 2$ ns and the 'advanced' peak disappeared from the Figure 3c. The small bump seen in Figure 3d at 800 m above the observation level ($\log_{10}$(height/cm) ≈ 4.8) is probably due to another muon which produced Cherenkov photons with $\Delta t \approx 4$ ns (see Figure 3b).

In the Figure 5 we present another 'subset' of photons shown in the Figure 2. This time the mirror 'points' to the direction (10 mrad, 10 mrad) relative to the EAS direction. This direction has been selected to present clearly the signal of muon. The area of the detector is still 3 m x 3 m.
In the Figure 5a the arc of Cherenkov photons generated by muon is clearly seen. The muon signal is also exposed on other Figures 5b, c and d. We would pay special attention to the Figure 5c which presents Δt distribution, since it is potentially possible to be measured.

In the real case we need to consider the photo–electrons from the photomultiplier cathode instead of
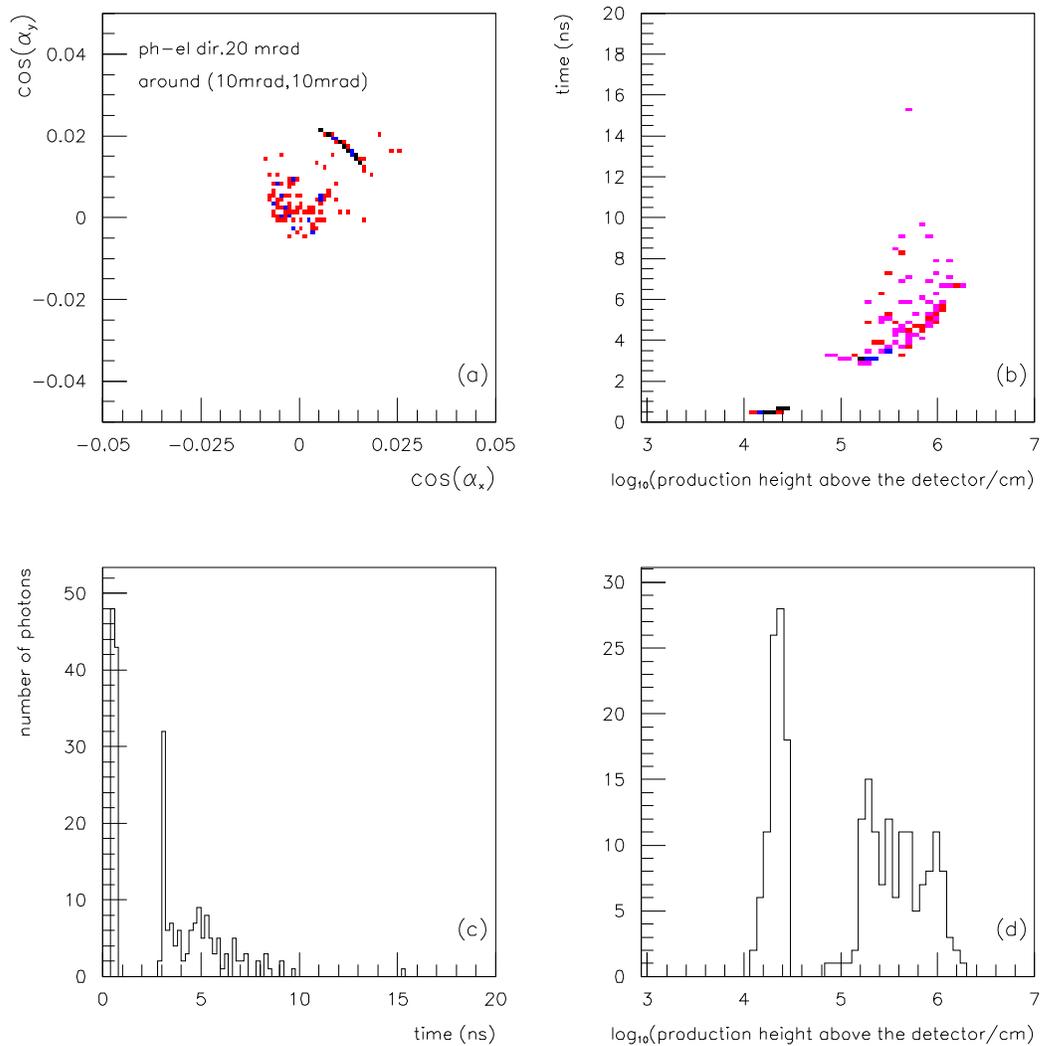
Figure 7: Similar to Figure 5 but for photo–electrons (and corresponding photons); only ph–el from photons within 20 mrad around the direction (10 mrad, 10 mrad). Arrival time of ph–el and production height distributions and correlations for related Cherenkov photons in 10 TeV proton EAS (detector area of 3 m x 3 m, 50 m away from EAS core). This time the muon signal is clearly seen. See text for more comments and explanations.

Cherenkov photons produced. The processes of photon absorption, mirror reflection and photomultiplier quantum efficiency were included in the Monte–Carlo program [1, *Attallah et al., 1995*], which processed the results of CORSIKA program (Cherenkov photons in 300–450 nm). In the Figure 6 we show time distributions of photo–electrons and angular and production height distributions of photons corresponding to photo–electrons for the 3 m x 3 m detector at (−50 m, 0 m) pointing vertically with angular acceptance within 20 mrad (related to the Figure 3). The difference due to transition from the 'emitted photon' case to the 'photo–electron' case can be seen by comparison of ordinate axes between Figures 3 and 6 for c) and d) histograms.

In the Figure 7 we present the photo–electron distributions for detector pointing to (10 mrad, 10 mrad) direction to the EAS direction and including the muon signal (related to the Figure 5). For the discussed problem of Cherenkov light from fast muons the 2 ns gap seen in the Figure 7c is very important.

The Figures 6c and 7c (Δt distributions for photo–electrons) differ quite significantly. However, photomultiplier anode signal does not reproduce these patterns accurately. Here we present results of signal convolution for two photomultipliers: PHILIPS XP2020 and Hamamatsu H2083. (The XP2020 data

after [5, *Philips Handbook, 1990*] and Hamamatsu H2083 after [15, *Riera and Espigat, 1994*]). We use following parametrization of the anode impulse corresponding to one photo–electron [14, *PHILIPS Composants, 1990*]:

$$R_\delta(t) = G \cdot \frac{\sqrt{m+1}}{m!\,\sigma_R} \cdot \left(\frac{\sqrt{m+1}}{m!\,\sigma_R} \cdot t\right)^m \cdot exp\left(-\frac{\sqrt{m+1}}{m!\,\sigma_R} \cdot t\right) \tag{1}$$

where $R_\delta(t)$ is the time dependent (negative) anode signal corresponding to δ impulse – one photo–electron, G is the actual gain (current amplification), t is time (see below for more details), m, σ_R are parameters related to the pulse shape. The $R_\delta(t)$ has following properties:

$$\int_0^\infty R_\delta(t)\,dt = G$$

$$t_{max} = \frac{m\,\sigma_R}{\sqrt{m+1}}$$

$$R_{max} = R_\delta(t_{max}) = G \cdot \frac{\sqrt{m+1}}{m!\,\sigma_R} \cdot m^m \cdot e^{-m}$$

The time between the photo–electron emission from the cathode and time of the maximum of signal t_{max} is called the transit time and its average value depends on photomultiplier, high voltage and divider. In this calculation we set the average transit time to be 30 ns for both photomultipliers (although it is different in the real case, e.g. about 39 ns for XP2020). Jitter is the variability of that time. Jitter has the Gaussian distribution with $\sigma_{t\_jitter} = 0.25$ ns. We assume another fluctuation of transit time due to the different photo–electron emission place in the cathode to be of Gaussian shape with $\sigma_{t\_cat} = 0.25$ ns.

	voltage	Gain	σ_{Gain}	FWHM	rise time	m	σ_R
XP2020	1800 V	$2 \cdot 10^4$	$0.35 \cdot Gain$	3.4 nsec	2.1 nsec	50	1.44
Hamamatsu H2083	3000 V	10^6	$0.4 \cdot Gain$	1.2 nsec	0.6 nsec	7	0.55

where rise time is the time between 10% and 90% of maximum value, m and σ_R are parameters of equation 1.

In the Figure 8 we present the simulated shapes of anode signals (reversed to positive) for photomultipliers PHILIPS XP2020 and Hamamatsu H2083 for input photo–electron distributions presented in the Figures 6c and 7c. Units are arbitrary, since, effectively, this is further electronics dependent. One can notice that at low discrimination level the signals with muon and E–M Cherenkov light last longer than signals without muon. In both cases (i.e. XP2020 and Hamamatsu H2083) the signal for the case with the fast muon in the field of view starts 2 ns earlier than the signal form E–M Cherenkov light.

This fact (time of start of the signal in one detector) does not discriminate between the no–muon and muon cases. To see the effect of fast muon (examining the start time) it is necessary to examine the start time in a number of detectors for the same event. In most cases (also experimental) it is possible to find the position of the EAS core by imposing the requirement of the cone alignement of starting time for detectors placed at various distances (see Figure 1). (Such a method is used in the THEMISTOCLE experiment, [2, *Baillon et al., 1993*]. Since most of detectors do not have Cherenkov light from fast muon in the field of view the alignement is usually very good. Then one detector with starting time several nsec in advance to the alignement obtained from other detectors might indicate the presence of the fast muon in the EAS, and such an event is almost surely of primary CR hadronic origin. Viewing the THEMISTOCLE data such events have been found.

However there is a problem with the night sky noise background, which might mimic the signal due to fast muon. It is not very likely to get 3 or more photo-electrons due to the night sky background within the XP2020 pulse width in the THEMISTOCLE experiment. The night sky background is about 1300 ph/(nsec m^2 sr) (330–550 nm) [6, *Dumora et al., 1996*], which produce on average ~ 0.04 ph–el/nsec in one THEMISTOCLE detector, or 2 ph–el within 3 nsec every ~ 200 nsec. The timing electronics might (might not) indicate 2–3 ph–el as a beginning of the event, but this depends on the amplitude of forecoming main signal.
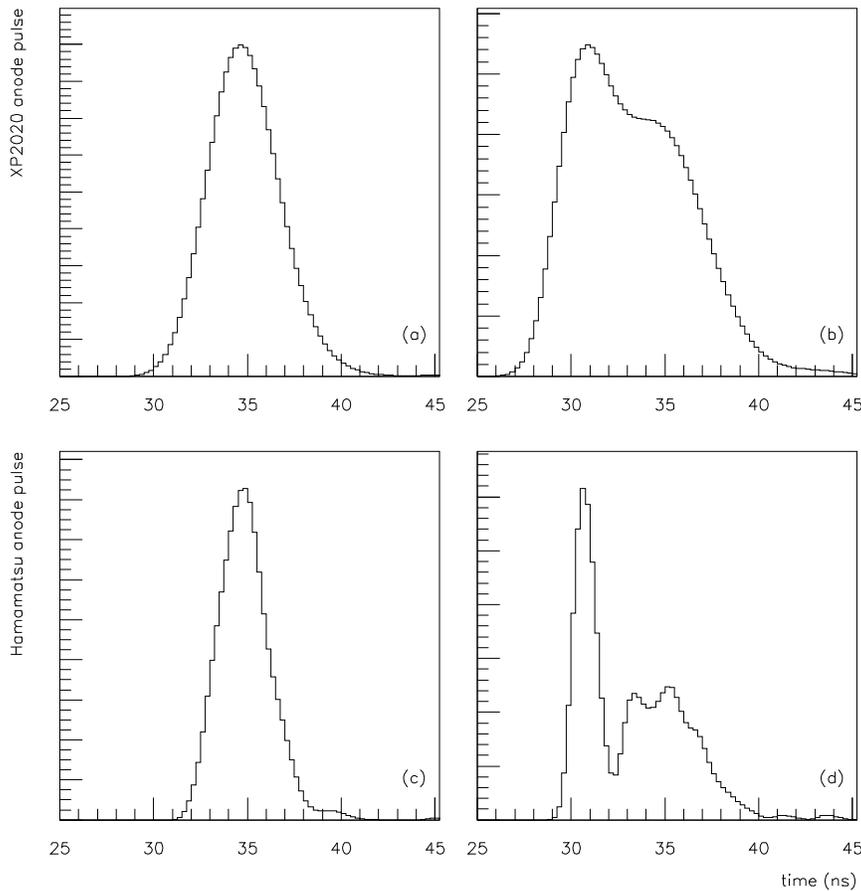
Figure 8: The anode signal (arbitrary units) for photomultipliers: PHILIPS XP2020 (a and b at the top) and Hamamatsu H2083 (c and d at the bottom) for 3 m x 3 m detector at 50 m away from the EAS core. Left figures (a and c) correspond to photo–electron distribution shown in the Figure 6 (no muon signal), right figures (b and d) to the Figure 7 with Cherenkov light from the muon $\sim$ 2 ns before the E–M Cherenkov light signal.

One of the possible solutions of the identification problem is to use fast Flash ADC. Such a device would allow to sample the anode amplitude every nsec. Using Hamamatsu H2083 and Flash ADC one would expect to have information similar to that shown in the Figures 8c and d. It would be possible to fit a cone timing shape to all detectors and to see the structure of the signal from the detector starting several nanoseconds earlier relatively to its distance to the EAS core.

Similar registrations have been performed for THEMISTOCLE experiment with one extra detector with Hamamatsu H2083 and Flash ADC (*P. Espigat, private communication, 1996*). In the CELESTE experiment all fast photomultipliers would be equipped with the Flash ADC.

5 Muons in TeV EAS.

Muons in EAS are decay products of pion and kaons. The probability of decay depends on the lifetime of hadron, its energy/mass ratio (factor γ) and the density of the atmosphere (hadrons might interact or decay). When the primary CR particle is a proton or nucleus then hadron production is a natural consequence of its inelastic interaction while passing through the atmosphere. When the primary CR particle is of E–M type (i.e. e^+, e^- or γ) then hadrons are produced due to photoproduction process.

Here we present the average distribution of muons produced in 10 TeV proton EAS and 6 TeV γ
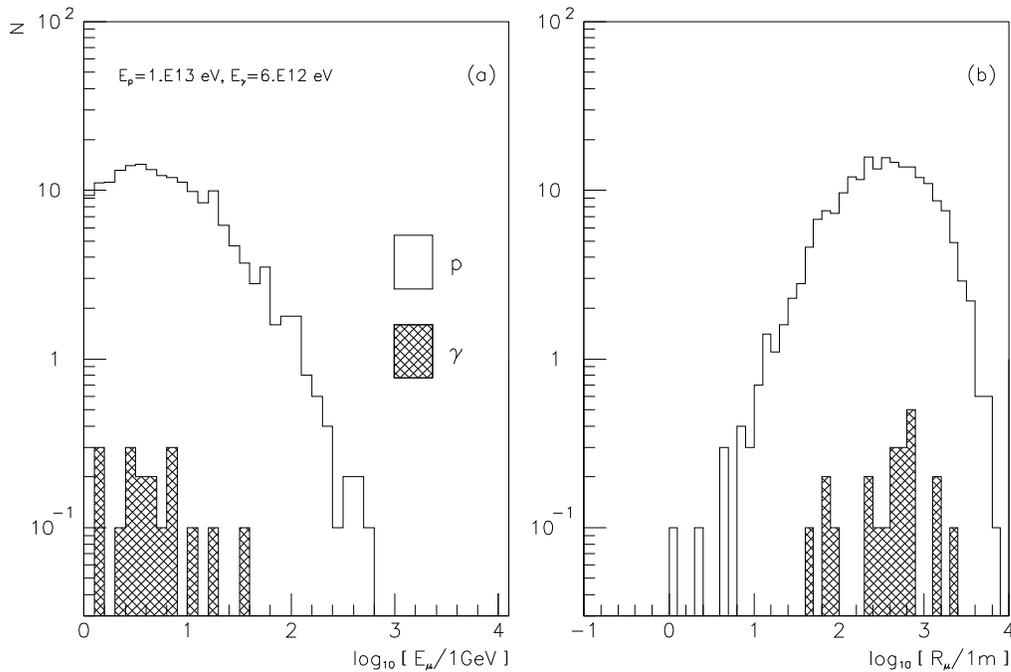
Figure 9: The average muon energy and lateral distributions for 10 vertical EAS produced by 10 TeV CR protons and 6 TeV CR γ's as seen at altitude 1750 m a.s.l. (860 g/cm^2).

EAS both from vertical direction. The energies of primary particles were selected to produce similar Cherenkov photon densities at 50 m from the EAS core. In the Figure 9a we present average energy distribution (i.e. $dN_\mu/d(log_{10}(E_\mu/GeV))$). For primary CR proton the number of muons with energy above 1 GeV is $\approx$ 120, above 5 GeV is $\approx$ 40 (they do produce Cherenkov light), and above 10 GeV is $\approx$ 20 per 1 EAS. For primary CR γ the number of muons is approximately 100 times lower.

The average lateral distribution of muons (Figure 9b) shows that the muon density is nearly constant till 100 m away from the EAS core (the $dN_\mu/d(log_{10}(R/1\ m))$ has a power law dependence with exponent nearly equal to 2). Muons which origin near the EAS core on $\sim$10 km and come about 100 m from the EAS core on the ground are inclined by $\sim$10 mrad. Since the Cherenkov cone is $\sim$20 mrad near the ground, part of the Cherenkov light produced by them would be registered when EAS come from the observation direction.

6 Conclusions.

In this paper we have discussed the possibility to distinguish between electromagnetic EAS and hadronic EAS in 'wavefront sampling' Cherenkov light measurements of TeV cosmic rays. The main target of those experiments is to identify and measure TeV γ flux from selected sources. The positive measurements would increase our knowledge about nature of high energy particle sources.

Positive results obtained so far identify the excess of source DC flux by comparison with the 'off source' measurements. For example, in the THEMISTOCLE experiment [2, *Baillon et al., 1993*] the observation of Crab nebula gained about 1440 events localized within 5 mrad from the Crab pulsar direction. From 'off source' observation the expected background within 5 mrad was estimated. The excess $\approx$ 260 events are the Crab nebula DC signal. The rest of $\approx$ 1180 events are mostly due to hadronic EAS background.

Using any other method of identifying the hadronic nature of observed event it would be possible to increase signal to noise ratio and add the strength to the result observed so far. We presented here some details of differences between E–M EAS and hadronic EAS due to the presence of fast muons and Cherenkov light produced by them.

It is very difficult to give a quantitative calculated prediction about the efficiency of this method. There are many problems and only some of them were addressed here. We hope that examining carefully

already existing experimental data one would be able to see a muon signal and then estimate the efficiency of the method in the specific experimental conditions.

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