Analysis of capability of detection of extensive air showers by simple scintillator detectors

Jerzy Pryga [1] Weronika Stanek [2]
on behalf of the CREDO Collaboration

[1]Jagiellonian University in Kraków

[2]AGH University of Science and Technology

07.2021

$\langle N|\widehat{K}|F\rangle$

CREDO
THE QUEST FOR THE UNEXPECTED

Introduction

High energy primary cosmic rays ($E \geq 1\ TeV$).

$\Downarrow$

Interaction with Earts's atmosphere.

$\Downarrow$

Cascade of secondary particles.

$\Downarrow$

Registration of particles on the ground.

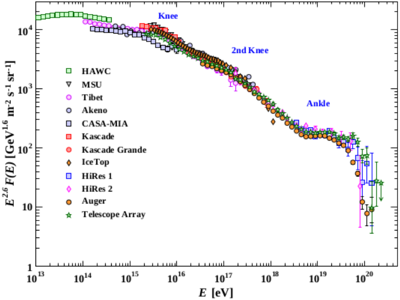

Figure: Primary cosmic-rays energy spectrum for all particles [1].

Motivation & method

Goal of CREDO project:
Confirmation of existence of Cosmic Rays Ensembles (CRE)

Requires:
Global infrastructure of detectors.

One of possible candidates:
System of several connected scintillator detectors (like Cosmic Watch [2])

Goal of this work:
Analysis of reliability and efficiency of such system.

CREDO
THE QUEST FOR THE UNEXPECTED

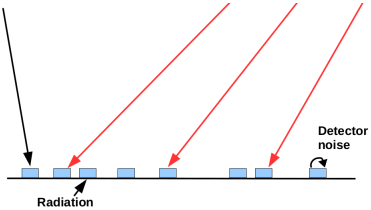

Figure: System scheme.

Assumptions

Assumptions about detectors:

- Each of n devices is identical.
- Detectors are placed close to each other (within meters).
- Flat devices $\Rightarrow$ detect particles from all directions.
- Small area of their surface A.

Assumptions about cascades:

- Symmetrical in azimuthal angle.
- Characterized by:
  - E - energy o primary particle,
  - θ - angle of incidence,
  - N_{part} - number of produced particles.
- Density ρ is a function of r - distance from cascade centre.

Simulations

Currently used:

- Showers simulated using CORSIKA software [3].
- Cascades from **protons**.
- 18 different energies between 1 TeV and 4000 TeV.
- From 500 to 10000 simulated cascades for each energy.
- Only particles with $E_{part} \geq 0.3\ GeV$ included.

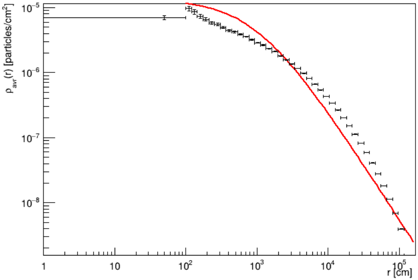

Figure: **Muon** density distribution $\rho_\mu(r)$ for proton with $E = 100\ TeV$ as a primary particle.

Methodology - background

Probability of a signal from the background:

$$P_{bg} = 1 - e^{-\delta T\left(\eta \cdot A \cdot I_{bg} + f_{bg}\right)} \quad (1)$$

- δT - coincidence time,
- η - detector's efficiency,
- I_{bg} - background particles flux,
- f_{bg} - frequency of non cosmic background signals.

Expected number of background events:

$$\langle N_{bg}\left(k\right)\rangle = Q\left(n, k, P_{bg}\right) \cdot \frac{T}{\delta T} \quad (2)$$

- $Q\left(n, k, P_{bg}\right)$ - probability of coincidence (binomial distribution),
- T - time of measurement.

Methodology - EAS parametrization

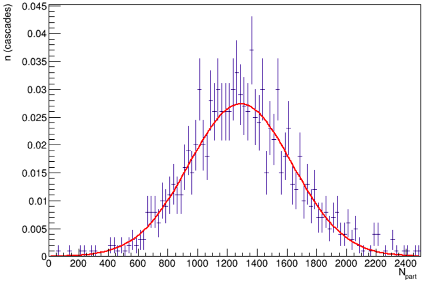

Figure: Number of cascades with certain number of produced **muons** for primary cosmic-ray proton with energy $E = 100\ TeV$ as a prime.

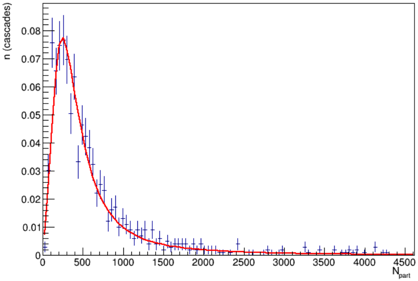

Figure: Number of cascades with certain number of produced **photons** for a proton with energy $E = 100\ TeV$.

Methodology - EAS parametrization

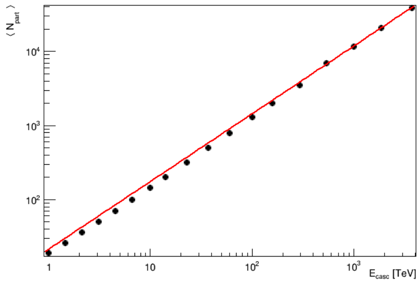

Figure: Average number of produced **muons** $\langle N_\mu \rangle (E)$ in cascades from cosmic-ray protons for different energies, presented with fitted function as red line.

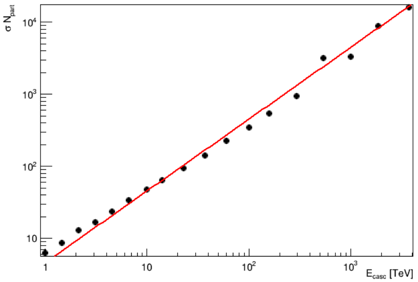

Figure: Standard deviation of the number of produced **muons** $\sigma_\mu (E)$ in cascades from cosmic-ray protons for different energies, presented with fitted function as red line.

Methodology - EAS parametrization

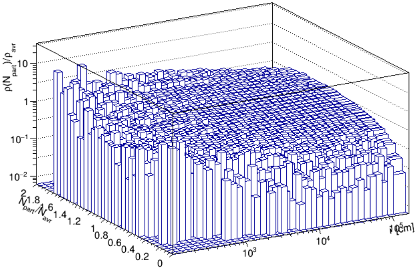

Figure: Normalised **muons** density distribution $\rho_\mu(r, N_\mu)$ for different number of produced particles.

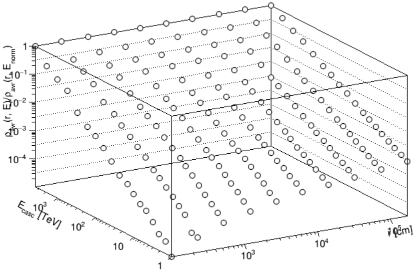

Figure: Normalised **muons** density distribution $\rho_\mu(r, E)$ for different energies of primary particle.

Methodology - EAS parametrization

Zenith angle distribution assumptions and simplifications:

- $\rho_{part}(\theta) \propto N_{part}(\theta)$.
- $\rho_{part}(\theta)$ the same for every energy.
- $\rho_{part}(\theta)$ does not depend on the distance from the centre of the shower r.

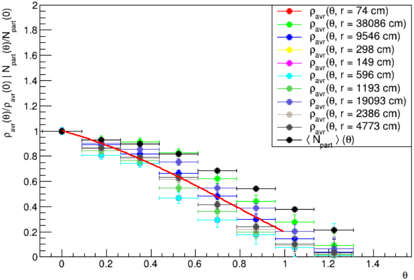

Figure: Normalised number of **muons** $\frac{\langle N_\mu(\theta)\rangle}{\langle N_0\rangle}$ produced for different angles of incidence of primary protons with energy $E = 100\ TeV$ with fitted function.

Methodology - EAS signals

Function of particles density $\rho(r, \theta, E, N_{part})$:

$$\rho\left(r, \theta, E, N_{part}\right) = \rho_{norm}\left(r\right) \cdot F_{\theta}\left(\theta\right) \cdot F_{E}\left(E, r\right) \cdot F_{N}\left(N_{part}, r\right) \quad (3)$$

- $\rho_{norm}\left(r\right)$ - average particles density for vertical cascade of given energy.
- $F_{\theta}\left(\theta\right)$ - scaling with angle.
- $F_{E}\left(E, r\right)$ - scaling with energy.
- $F_{N}\left(N_{part}, r\right)$ - scaling with total number of produced particles.

Methodology - EAS signals

An integral for expected number of events $\langle N(k) \rangle$:

$$\langle N(k) \rangle = \int_0^{r_{max}} \int_{E_{min}}^{E_{max}} \int_0^{\frac{\pi}{2}} Q(n, k, P)\, 2\pi r\, j(E)\, T\, d\Omega\, dE\, dr \quad (4)$$

- k - number of coincidences.
- n - number of devices in the system.
- r_{max} - maximal distance from the centre of the cascade (radius in which 95% of particles are contained).
- $j(E)$ - frequency of primary cosmic rays [4].
- $P = 1 - \exp(-\eta \cdot A \cdot \rho(r, \theta, E, N_{part}))$ - probability of a signal from EAS.

Results

Results for system of 4 Cosmic Watches with parameters:
$A = 25\ cm^2$, $\delta T = 200\ ms$, $\eta = 95\%$, $I_{bg} = 163$ particles $m^{-2}s^{-1}$, $f_{bg} = 0.1\ s^{-1}$ and $T = 7\ days$.

	Background		Analysis		Simpler method	
	Only μ	μ, $e^{\pm}$, γ	Only μ	μ, $e^{\pm}$, γ	Only μ	μ, $e^{\pm}$, γ
k	$\langle N(k)\rangle_{bg}$	$\langle N(k)\rangle_{bg}$	$\langle N(k)\rangle$	$\langle N(k)\rangle$	$\langle N(k)\rangle$	$\langle N(k)\rangle$
1	860000	$1.17 \cdot 10^6$	41000	64000	59000	178000
2	0.092	0.17	0.179	426	0.213	63
3	$\sim 10^{-9}$	$\sim 10^{-8}$	0.0182	31	0.003	0.406
4	$\sim 10^{-17}$	$\sim 10^{-16}$	0.0068	21	0.0006	0.143

Table: Results of the calculations for cascades and background signals.

Comparison with measurements

$\langle N(k) \rangle_{window}$ - only 30% of EAS with $\theta \geq 15^o$ have electromagnetic component included.

k	$\langle N(k) \rangle_{\mu}$	$\langle N(k) \rangle_{\mu,e,\gamma}$	$\langle N(k) \rangle_{window}$	$N_{data}(k)$
2	0.179	426	99.5	94
3	0.0182	31	5.9	2
4	0.0068	21	3.9	1

Table: Results of the calculations for cascades and background signals compared with measurements [5]

Important remark

Those are very early results and thus need to be treated with caution. After improvements in the analysis they may change significantly.

Possible energy estimation

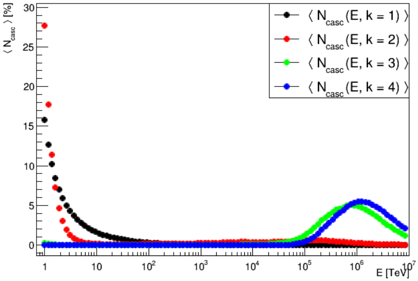

Figure: Expected number of coincidence signals for different energies $\langle N_{casc}(k, E) \rangle$ for analysed system (simpler method).

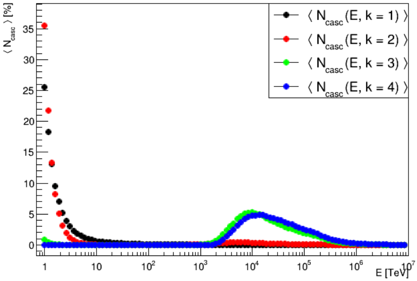

Figure: Expected number of coincidence signals for different energies $\langle N_{casc}(k, E) \rangle$ for analysed system (analysis).

Summary

Conclusions:

- Small detectors systems should be able to detect EAS with high reliability but rather low efficiency.
- More information about detectors is necessary.
- Conditions of measurement significantly impact results.
- Groups of heavier nuclei should be included in the analysis.
- Different energy thresholds for different particle types should be considered.
- It might be possible to estimate energy of cascades that caused signal.

Thank you for your attention!

References I

[1] P.D. Group et al., *Review of particle physics*, *The European Physical Journal C-Particles and Fields* **3** (1998) 1.

[2] T. Abu-Zayyad, R. Aida, M. Allen, R. Anderson, R. Azuma, E. Barcikowski et al., *The cosmic-ray energy spectrum observed with the surface detector of the telescope array experiment*, *The Astrophysical Journal Letters* **768** (2013) L1.

[3] D. Heck, G. Schatz, J. Knapp, T. Thouw and J. Capdevielle, *Corsika: A monte carlo code to simulate extensive air showers*, Tech. Rep. (1998).

[4] R. Abbasi, Y. Abdou, M. Ackermann, J. Adams, J. Aguilar, M. Ahlers et al., *Icetop: The surface component of icecube*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **700** (2013) 188.

References II

[5] M. Karbowiak, T. Wibig, D. Alvarez-Castillo, D. Beznosko, A.R. Duffy, D. Góra et al., *The first CREDO registration of extensive air shower*, *Physics Education* **55** (2020) 055021.