Muon with threshold 1 GeV in extensive air showers with energy greater than 5 EeV

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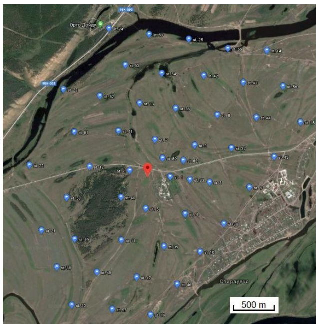
Abstract. The paper presents an analysis of the characteristics of muons with a threshold greater than 1 GeV in showers with energies greater than 5 EeV and zenith angles less than 60 degrees. The analysis is based on the registration data of extensive air showers of the Yakutsk array. Estimation of muons at different distances from the shower core, fraction of muons $\rho_\mu/\rho_{\mu+e}$ at a distance of 600 m are obtained. An empirical relationship is found between the fraction of muons and longitudinal development – the depth of the maximum development of the air shower X_{max}. Calculations of the fraction of muons are performed using the QGSjetII-04 hadronic interaction model for different primary nuclei, and compared with the data. Mass composition of primary particles is estimated by muon component. Severl showers were found in the sample, with a low content of muons, which possibly is produced by ultra-high energy gammara rays.

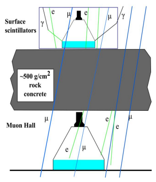
Yakutsk Array

Location: *61°42' N, 129°24' E*; Height: *110 m*
Area of the array: ~*8 km²*; Energy range: *10^{15}≤E≤10^{20} eV*
58 stations with 120 scintillation detectors $\varepsilon_{thr} \geq$ 10 MeV
Spacing: *500 m*
Yakutsk array measures: charged component; muon component; Cherenkov light. radio emission



Muon detectors

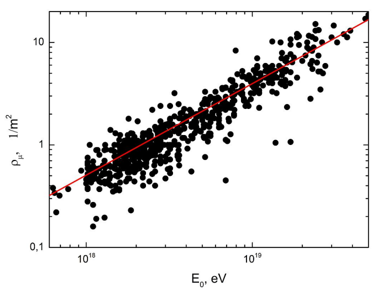
1 Muon detector with S = 190 m²
6 Muon detectors with S= 16-20 m²
3 Muon telescopes with S = 2m²



Air shower statistics registered at the Yakutsk array

Year	Obs. time	N	Data proc.	N_{muon}	N_{ch}	Cherenkov obs. time	Events E≥10EeV
09-10	6154	113138	87%	60618	9897	622	10
10-11	6455	137830	89%	56130	8611	508	15
11-12	6534	155351	91%	54559	9227	482	15
12-13	6515	149381	92%	89430	10219	592	17
13-14	6446	147589	91%	72110	7164	396	15
14-15	6365	140101	72%	82392	7838	429	15

In the table as an example, a part of the data is shown – 2009-2015. It shows observation time, statistics of registered air showers, fraction of analyzed showers, number of showers with registered muons and Cherenkov light and the number of showers with E >10 EeV. N – total number of air showers, N_{muon} – air showers registered by muon detectors, N_{ch} – air showers registered by Cherenkov light detectors.

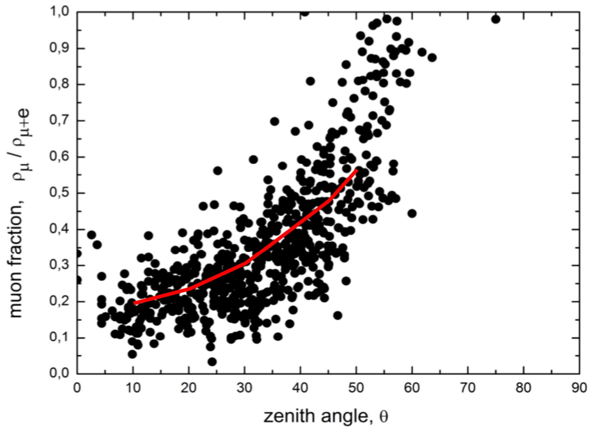


Correlation of classification parameter ρ_μ and air shower energy E_0. Here, E_0 is determined by a method of balancing all components energies of air showers, and ρ_μ determined by formula:

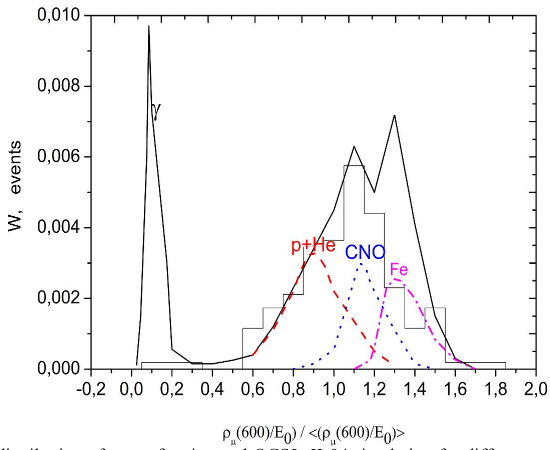
$$\log_{10} E_\mu = 18.33 + 1.12 \cdot \log_{10} \rho_\mu$$

with no conversion to vertical

Dependence of muon fraction on zenith angle



Distribution of muon numbers in showers with energy 5-50 EeV and zenith angle ≤ 60°



In the fig. distribution of muon fraction and QGSJetII-04 simulation for different primaries are shown. Experimental data are converted to vertical and normalized to shower energy for comparison with simulations. As one can see there are some vaguely distinguished maxima, which are – according to simulations – shaped by different primaries. By comparing simulation with experimental data one can distinguish group of showers with small number of muons (0-0.3), group with (0.4-1.3), which is possibly produced by light nuclei like protons and helium nuclei, group with (0.8-2.0) produced by CNO and Fe nuclei.

Summary

By measurements of muon with threshold > 1 GeV at the Yakutsk array correlation of ρ_μ(600) with energy was established. Dependence of muon fraction ρ_μ/ $\rho_{\mu+e}$ on zenith angles was found. Distribution of muon fraction has several maxima shaped by particles with different atomic weights. Quantitate comparison of the experimental data with simulations shown that 40-50% of air shower with energies 5-50 EeV in the sample is produced by p and He, 1-2% of air showers are possibly produced by primary gamma-ray, rest of air shower are produced by heavier nuclei CNO and Fe.

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