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Status of investigations of the energy deposit of cosmic ray muon bundles in the Cherenkov water calorimeter

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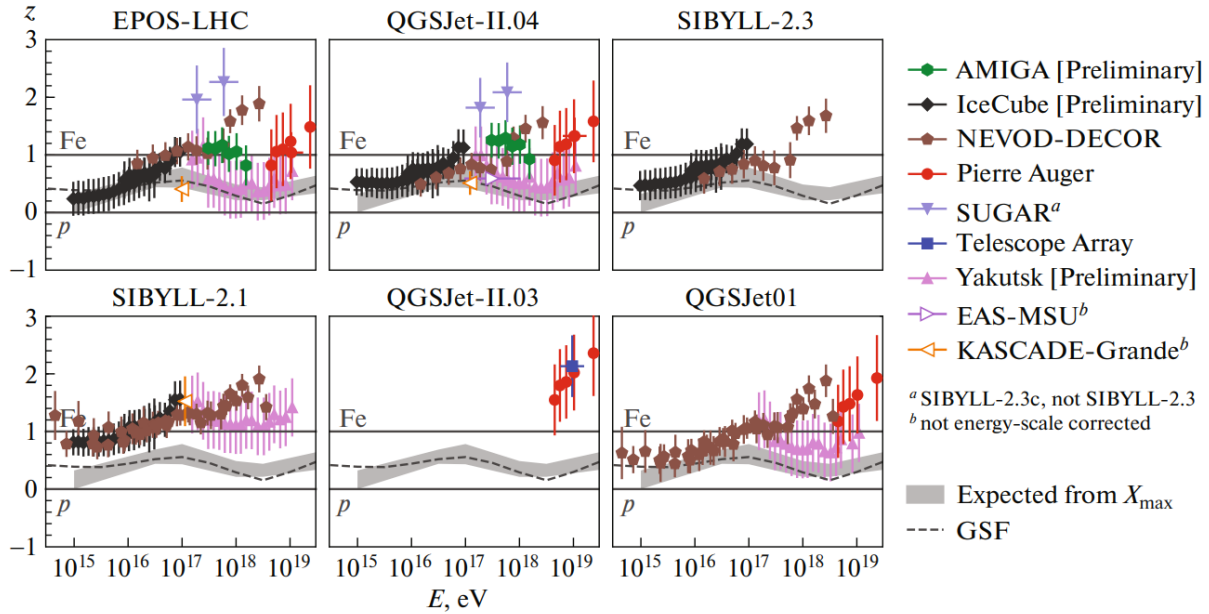
“Muon puzzle” in cosmic rays

Combining of the results of EAS muon component measurements

Dembinski H.P. et al. Physics of Atomic Nuclei, 2019, Vol. 82, No. 6, p. 644



$$z = \frac{\ln N_{\mu} - \ln N_{\mu p}^{sim}}{\ln N_{\mu Fe}^{sim} - \ln N_{\mu p}^{sim}}$$

z=0 for p; z=1 for Fe

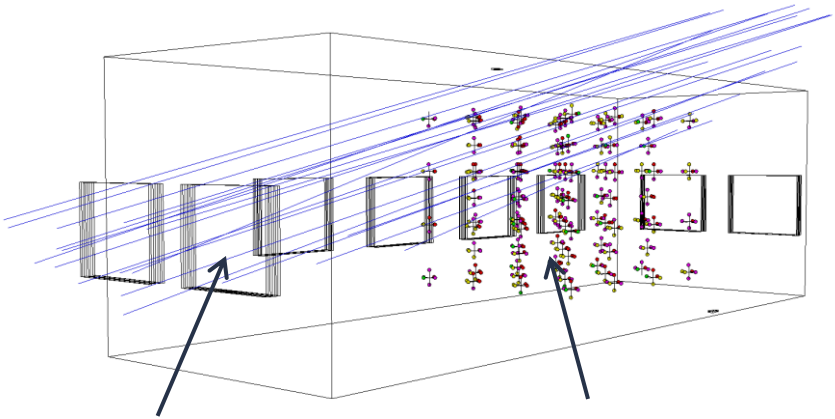
An approach to solving the "muon puzzle"

Since various mechanisms for the appearance of an excess of multi-muon events (cosmophysical or nuclear-physical nature) should have different effects on the muon energy, one of the possible approaches to solve the problem is to study the energy characteristics of the muon component of EAS. For this purpose, in the NEVOD-DECOR experiment, measurements of the energy deposit of muon bundles in the detector material are carried out. The average energy loss of muons in the material almost linearly depends on the energy of muons:

$$\mathrm{d}E_{\mu} / \mathrm{d}X \sim a + bE_{\mu} .$$

If some excess of high energy muons appears, it should be reflected in the dependence of the energy of muons on the primary particle energy.

Experimental setup



Coordinate-tracking detector DECOR (70 m^2)

Cherenkov water calorimeter NEVOD (2000 m^3)

Local muon density in the event and their arrival direction are measured from DECOR data. Energy of primary particles is estimated from these data.

Local muon density is calculated as:

$$D = (m - \beta) / S_{det},$$

where m is the number of muons in the bundle, $\beta = 2.1$ is the integral LMDS slope, S_{det} is the effective area of DECOR SMs for a given direction of muon bundle arrival.

Energy deposit of muon bundles (sum of the signals of all PMTs in photoelectrons) is measured in Cherenkov water calorimeter NEVOD.

The total energy deposit is proportional to muon density in the event. Therefore, in the further analysis we use the specific energy deposit Σ / D (CWC response normalized to the muon density).

Experimental data

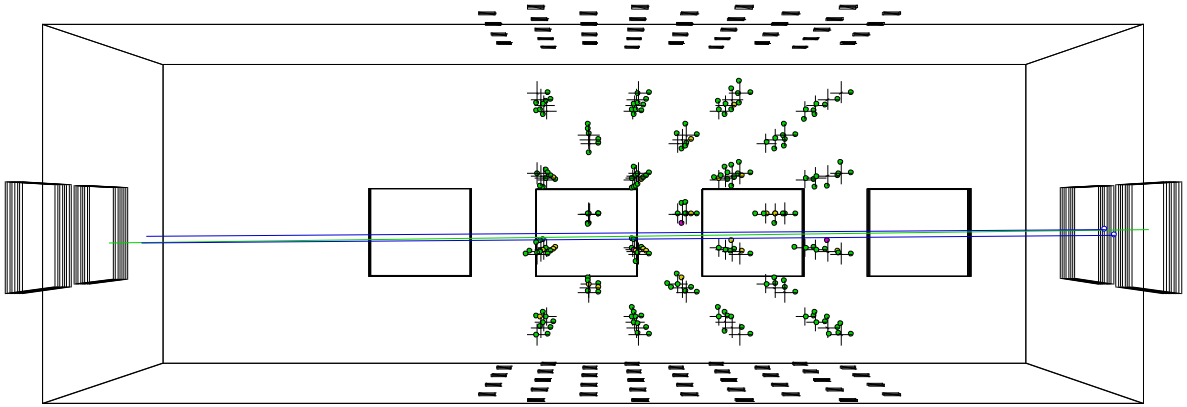
Three series of the measurements (from July 2013 to May 2020)
m ≥ 5, θ ≥ 55°, two 60-degree sectors of azimuth angle

Series	Number of events	"Live" time, h (counting rate, event/h)
11th (026-455)	19923	11897 (1.67)
12th (001-884)	46647	27234 (1.71)
13th (000-233)	13508	7770 (1.74)
Sum	80078	46901 (1.71)

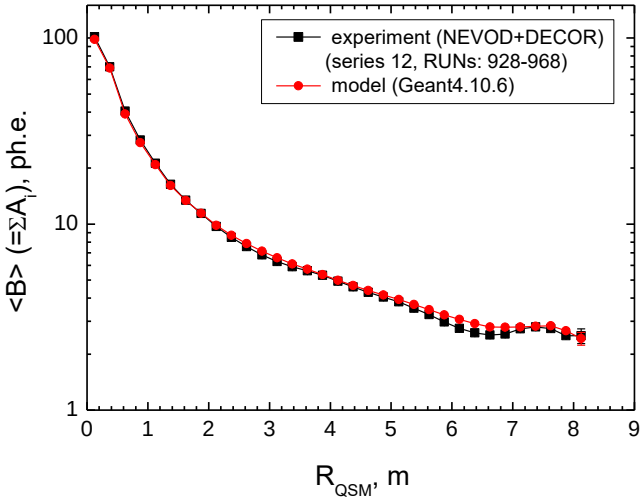
Simulation of the response of the NEVOD-DECOR setup

The energy deposit of muon bundles with fixed muon energies of 100 GeV was simulated at the NEVOD-DECOR setup. Events with the bundle were modeled according to the muon density spectrum with a slope close to the experimental one. The physical features of the setups, as well as hardware, software and operator conditions for muon bundle events selection were taken into account in the simulation. For events which satisfy the selection conditions, the response of the Cherenkov water calorimeter NEVOD was calculated using the Geant4 package. The model of the CWC NEVOD was tested and calibrated by the response to single near-horizontal muons.

Calibration of the CWC NEVOD model by the response to single near-horizontal muons

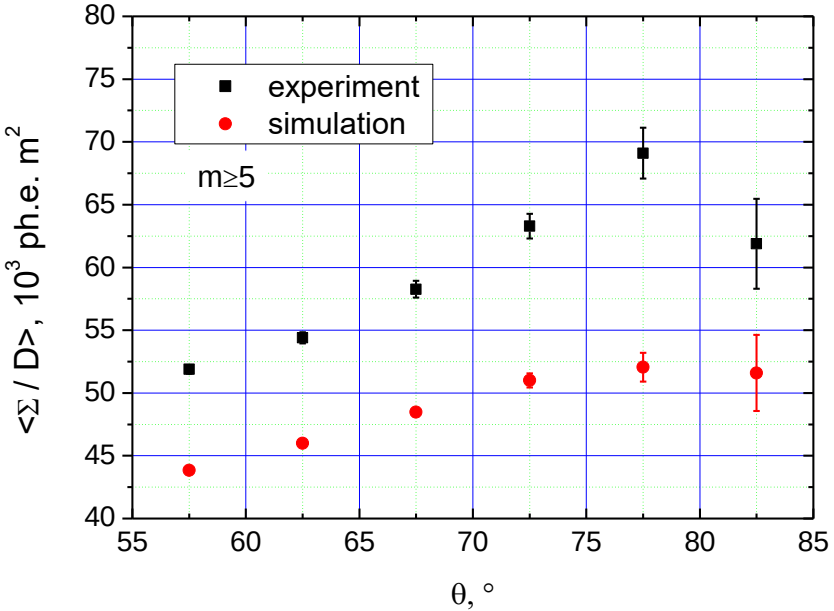


Dependence of the average response of QSM ($B = \Sigma A_i$) on the distance to muon track



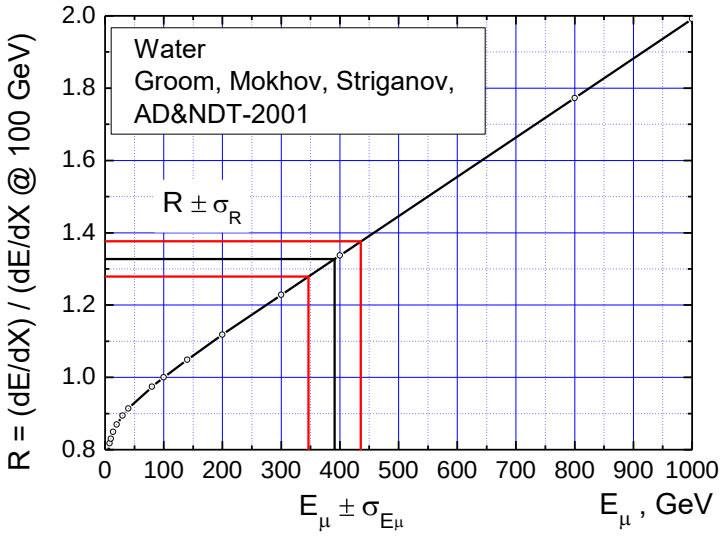
Dependence of the average specific energy deposit on the zenith angle

Black squares are experimental data. Red circles represent simulated specific energy deposit of muon bundles with the fixed muon energy 100 GeV.

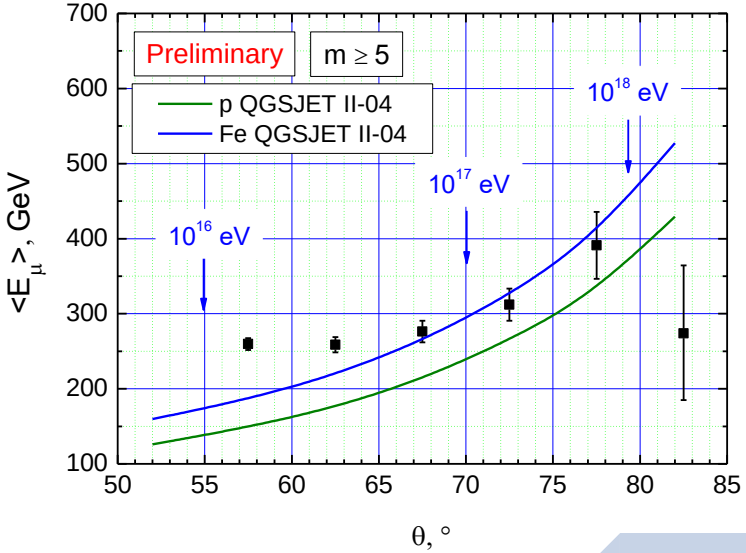


Transition from the average specific loss of muons in water to energy of muons in bundles

Average specific loss of muons normalized to loss for energy 100 GeV

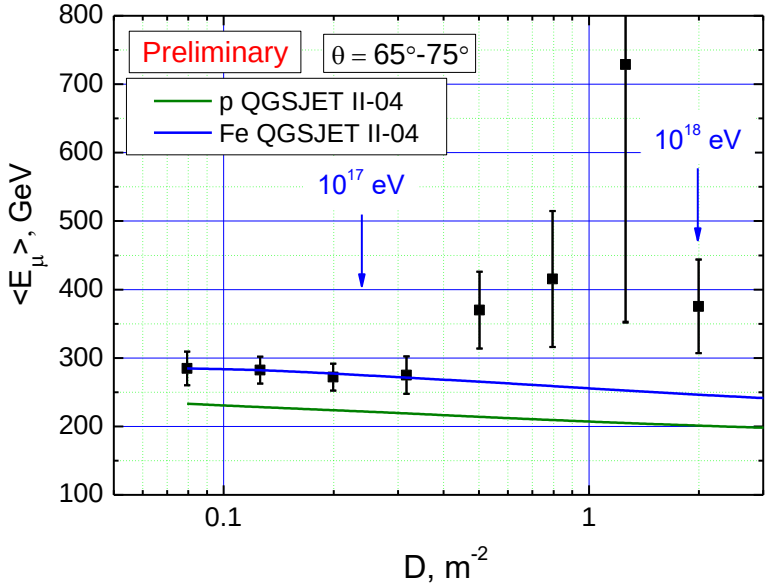


Dependence of the average energy of muons in bundles on the zenith angle



Dependence of the energy of muons in the bundles on the local muon density

The data indicate an increase in the average energy of muons in the bundles at high muon densities (which correspond to effective energies of primary particles above 10^{17} eV).



Conclusion

1. The experiment of the measurement of the energy deposit of inclined muon bundles from extensive air showers in a wide range of energies of primary particles 10^{16}-10^{18} eV is carried out at the NEVOD-DECOR setups. Experimental data collections and an increase in statistics from simulated data are continued. The search and analysis of possible systematic errors is continued.
2. For the first time, estimates of the average energy of muons in the bundles for different zenith angles were obtained. The zenith-angular dependence of the average muon energy reflects an increase of the average energy of muons in the bundles. In the dependence of the average energy of muons on their local density, an indication of the increase of the average energy of muons in the bundles for primary energies above 10^{17} eV was observed.

Thank you for attention!