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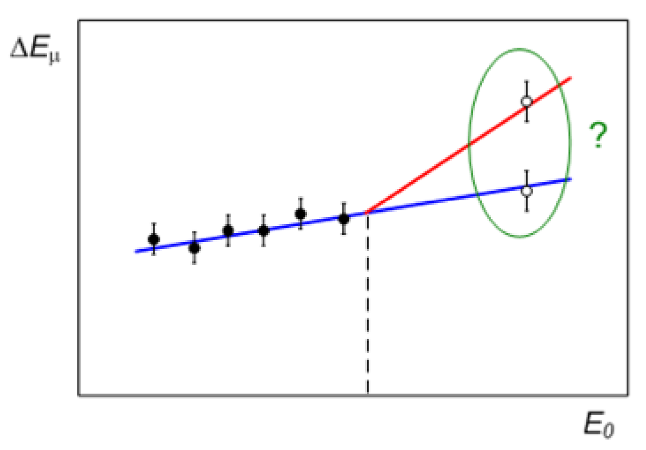
Measuring the Cherenkov light yield from cosmic ray muon bundles in the water detector

R.P. Kokoulin[1], N.S. Barbashina[1], A.G. Bogdanov[1], S.S. Khokhlov[1], V.A. Khomyakov[1], V.V. Kindin[1], K.G. Kompaniets[1], G. Mannocchi[2], A.A. Petrukhin[1], O. Saavedra[3], G. Trinchero[2], V.V. Shutenko[1], I.I Yashin[1], E.A. Yurina[1]

[1]National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russia
[2]Osservatorio Astrofisico di Torino – INAF, Torino, Italy
[3]Dipartimento di Fisica dell' Universita di Torino, Italy

Problem of muon excess in UHE experiments and the energy deposit measurements

In several UHE experiments (DELPHI, ALEPH, DECOR, PAO, and some others), an excess of muons in extensive air showers in comparison with calculations is observed. To find the reason, measurements of the muon component energy characteristics are required. A possible approach is the study of muon bundle energy deposit. Muon energy loss (at high muon energies):

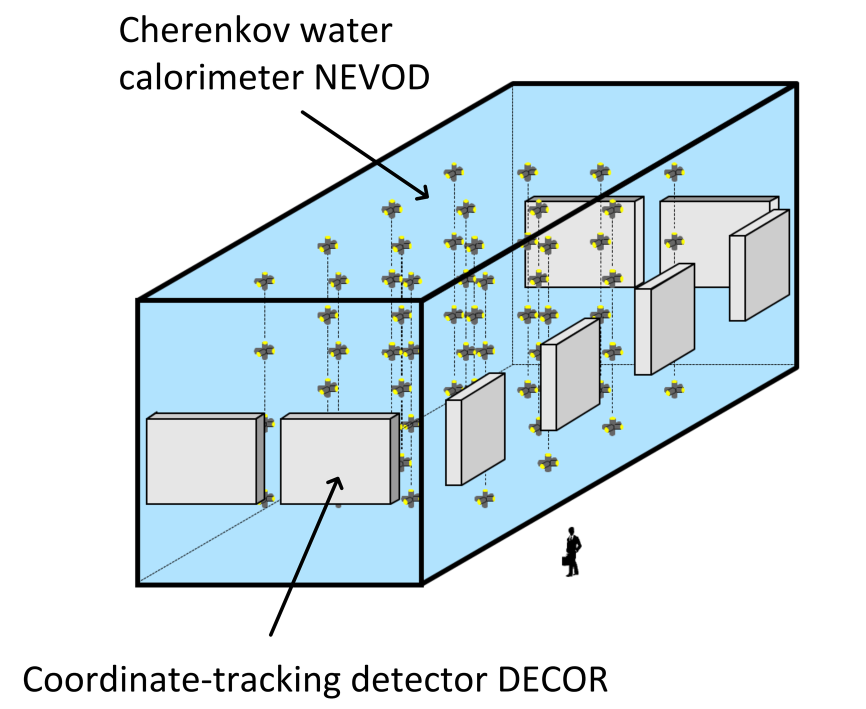


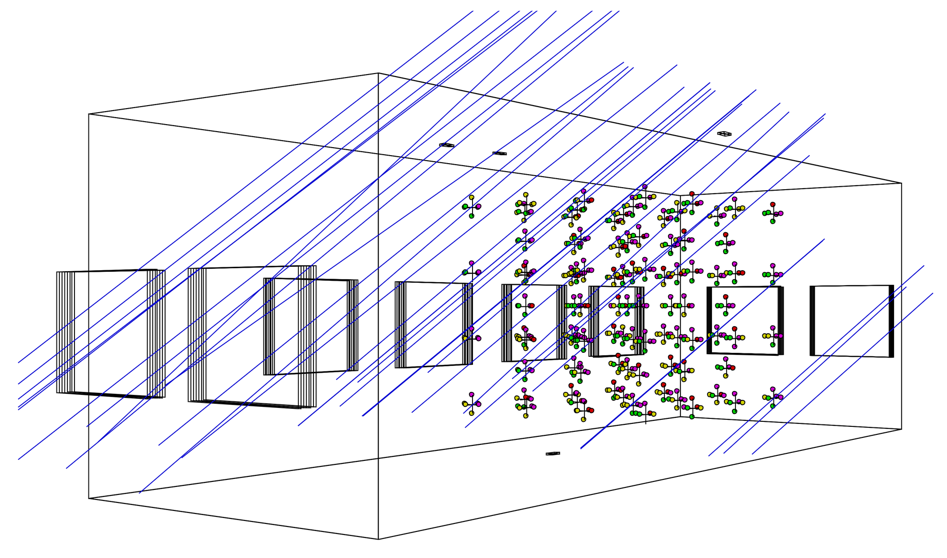
$$dE/dx = a + bE.$$

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

NEVOD-DECOR experimental complex

NEVOD: 9 x 9 x 26 m^3 volume; 91 quasi-spherical modules (QSMs); 546 PMTs.
DECOR: 8-layer supermodules of streamer tubes. Accuracy about 1 cm and better than 1°.

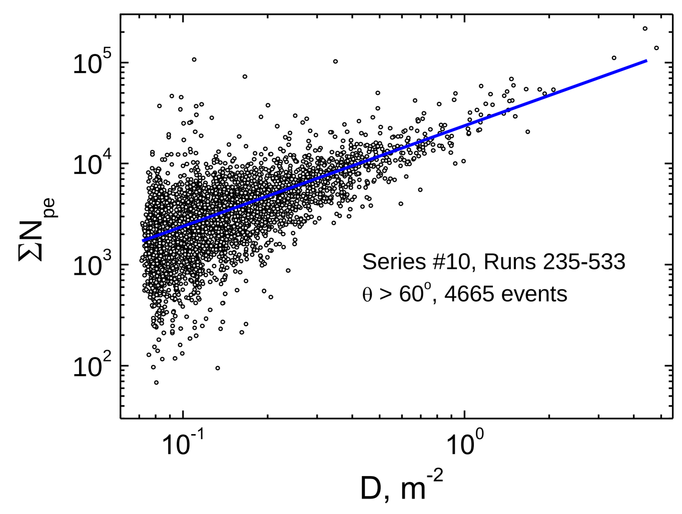




Example of muon bundle event in NEVOD-DECOR. Thin lines: reconstruction of muon tracks from DECOR data; circles: hit phototubes in Cherenkov water detector (colors reflect signal amplitudes).

Data of the first experimental series (2012-2013)

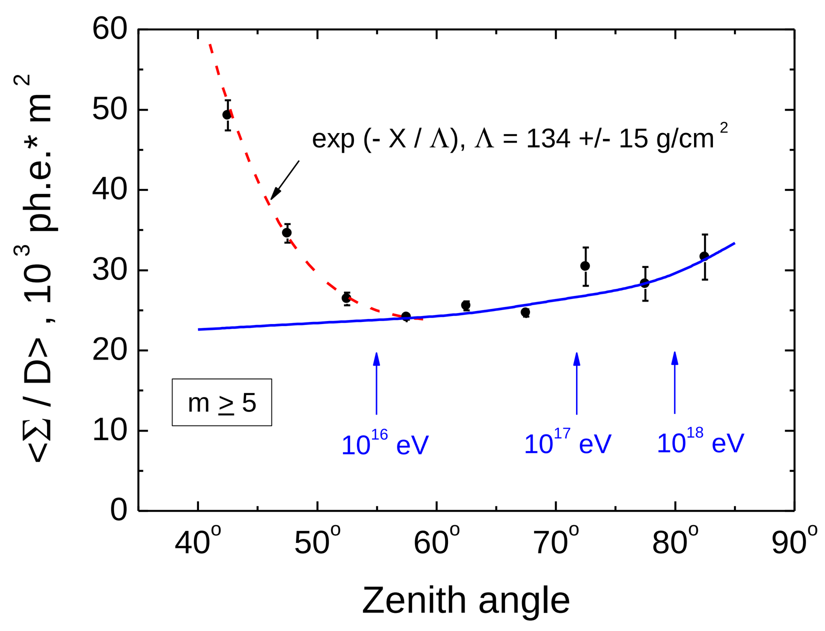
03.05.2012 – 20.03.2013; live time: 5542 h;
$m \geq 5$, $\theta \geq 40°$, two 60°-wide sectors in φ – 24496 events.
As a measure of the muon energy deposit in the CWD, the sum of the signals ΣN_{pe} of all PMTs of the NEVOD detector (in photoelectrons) was used.
Local muon density is calculated as: $D = (m - \beta) / S_{det}$,
where m is the number of muons, $\beta = 2.1$ is the integral LMDS slope, S_{det} is the effective area of DECOR SMs for a given direction of muon bundle arrival.



Correlation of the total CWD response with the local muon density.

The total energy deposit (sum of the signals of all PMTs) is proportional to the muon density in the event. Therefore, in the further analysis we use the specific energy deposit N_{pe} / D (i.e., the response normalized to the muon density).

At moderate zenith angles, a residual contribution of electron-photon and hadron EAS components to the response of the ground-based non-screened water calorimeter is significant. At $\theta \geq 55°$, practically pure muons remain.



Dependence of the muon bundle average specific energy deposit on zenith angle.

Experimental data 2013-2018 (new statistics)

Two series of measurements:
16.07.2013 – 08.04.2015, 11897 h
17.07.2015 – 15.02.2018, 18791 h (is continuing)
Total: 30688 hours live time;
$m \geq 5$, $\theta \geq 55°$, two 60°-wide sectors in φ : 52141 events.

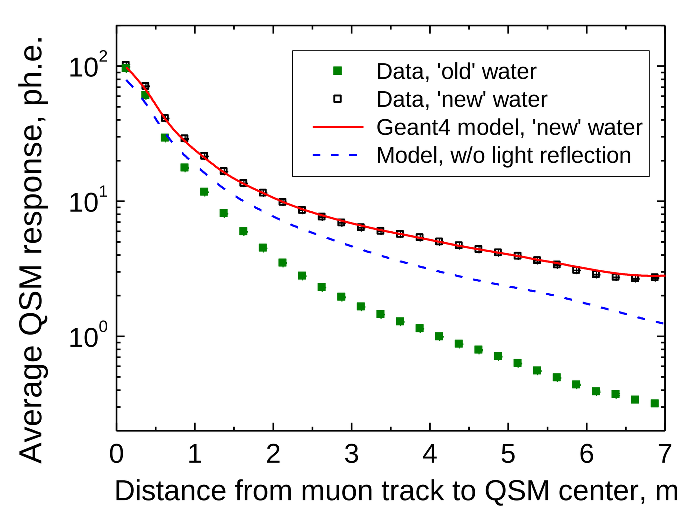
New water purification system: absorption length of Cherenkov light increased several times and reached about 10 m (more than the transverse size of the water tank). As a result:

The number of detected photoelectrons for single muons and muon bundles increased more than twice.

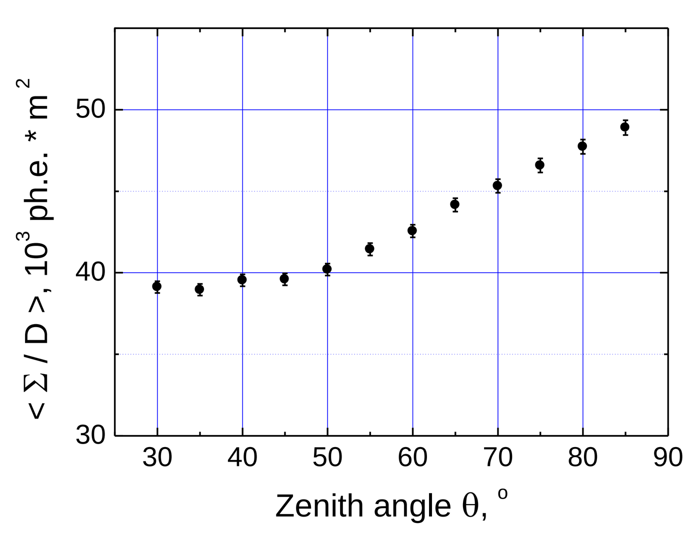
At the same time, some non-trivial effects (such as contribution of the light reflected from the surface of the water in CWD) became important.

Effect of improved water transparency

Average QSM response for single near-horizontal muons selected by means of DECOR was analyzed. Points correspond to experimental data of 2012-2013 (old water) and 2013-2018 (new water). The curves are obtained with Geant4 model of the CWD (with and without light reflection from the water surface).



Average specific energy deposit Σ/D for artificial muon bundles with a fixed density and fixed 100 GeV muon energy (simulation). An increase at zenith angles more than 50° due to the reflected light is clearly seen.



Conclusion

At NEVOD-DECOR complex, measurements of energy characteristics of muon bundles generated by cosmic ray primary particles in the energy range of 10^{16} - 10^{18} eV are being conducted. An indication for an increase of the energy deposit in comparison with expectation at primary energies higher than 10^{17} eV has been found.

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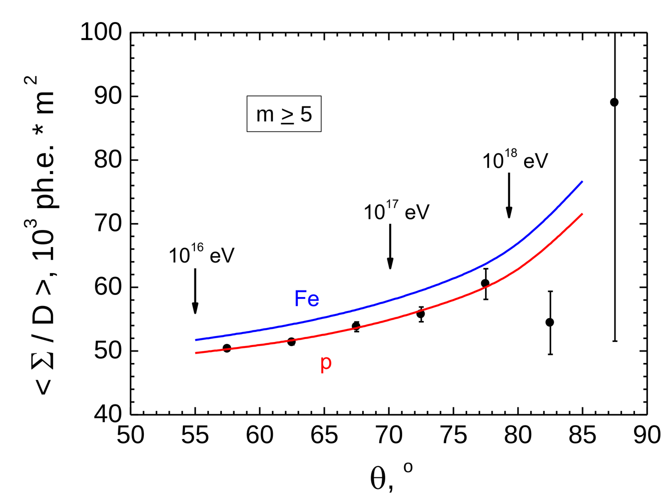
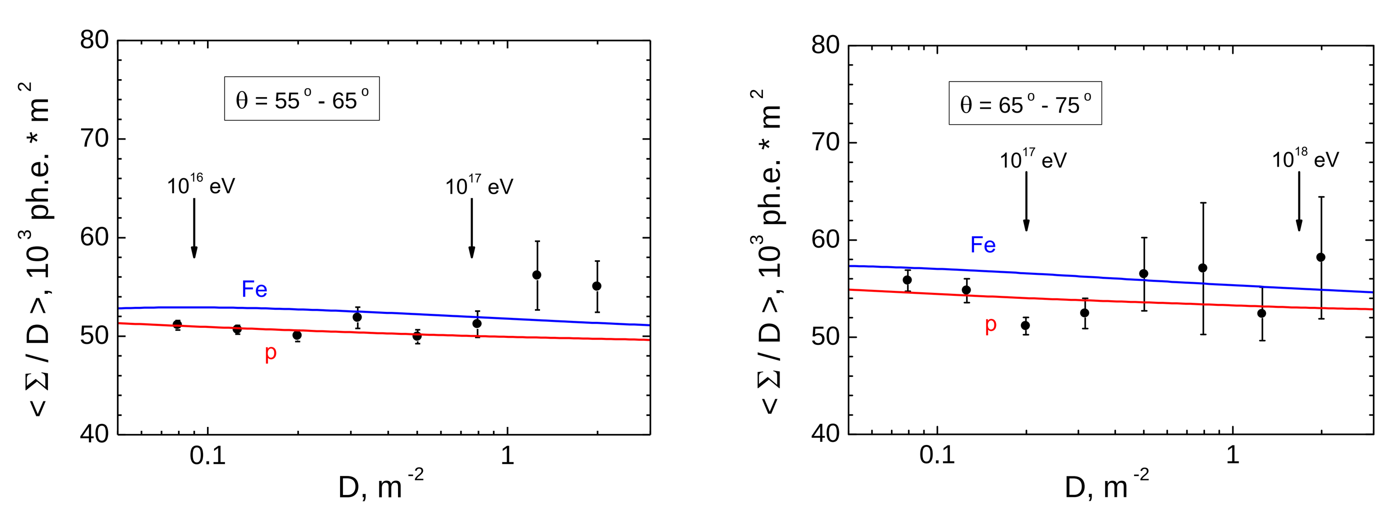
Results of 2013-2018 data analysis

The curves represent the expected dependence (CORSIKA, QGSJet II-4 + FLUKA). The proton curve is normalized to the data between 55° - 65° zenith angle. Data points are corrected for the contribution of the light reflected from the water surface (on the basis of Geant4 simulation).



The increase of the energy deposit with zenith angle reflects the increase of the average muon energy in the bundles.

Dependence of the muon bundle average specific energy deposit on zenith angle.



Dependence of the muon bundle average specific energy deposit on local muon density.

Simulation results show a tendency to a slow decrease of muon energy in the bundles with the increase of primary energy. In contrast, data indicate some increase of the average specific energy deposit at high muon densities (corresponding to effective primary particle energies more than 10^{17} eV).