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Measurements of the average muon energy in inclined muon bundles in the NEVOD-DECOR experiment

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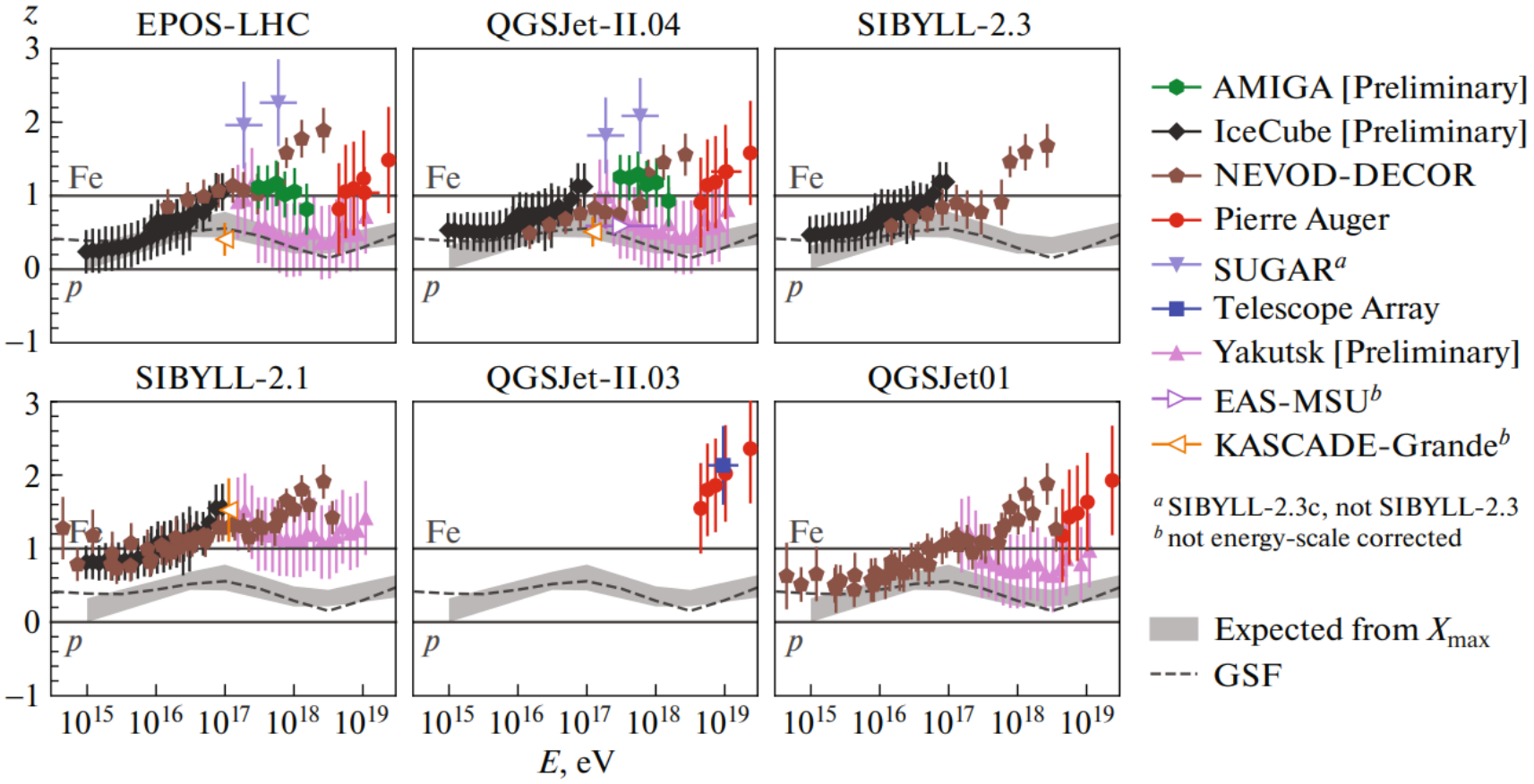
Muon puzzle in cosmic ray

"Muon puzzle" is the excess of multi-muon events in extensive air showers in comparison with calculations.

Combining the results of measurements of the EAS muon component

H.P. Dembinski et al. *EPJ Web Conf*. **210**. 02004 (2019).



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

z = 0 for protons;

z = 1 for iron nuclei.

An approach to “muon puzzle” investigation

The key to the muon excess solution can be the study of the energy characteristics of the EAS muon component and their changes with increasing energy of primary particles. A possible approach to such investigations is the measurement of the energy deposit of muon bundles in the detector material.

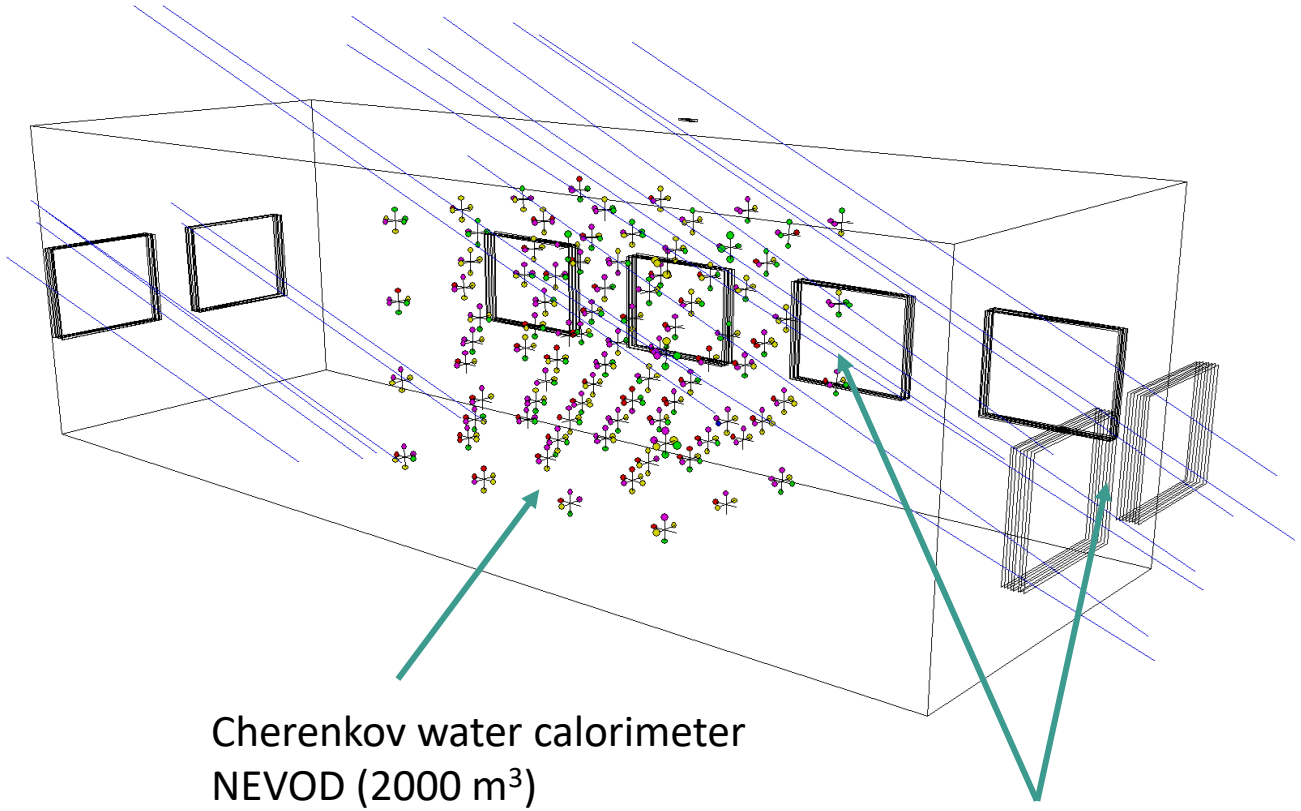
Different mechanisms for the appearance of an excess of multi-muon events (of cosmophysical or nuclear-physical nature) should have different effects on the muon energy.

The average energy loss of muons in matter 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 muon bundle energy deposit on the primary particle energy.

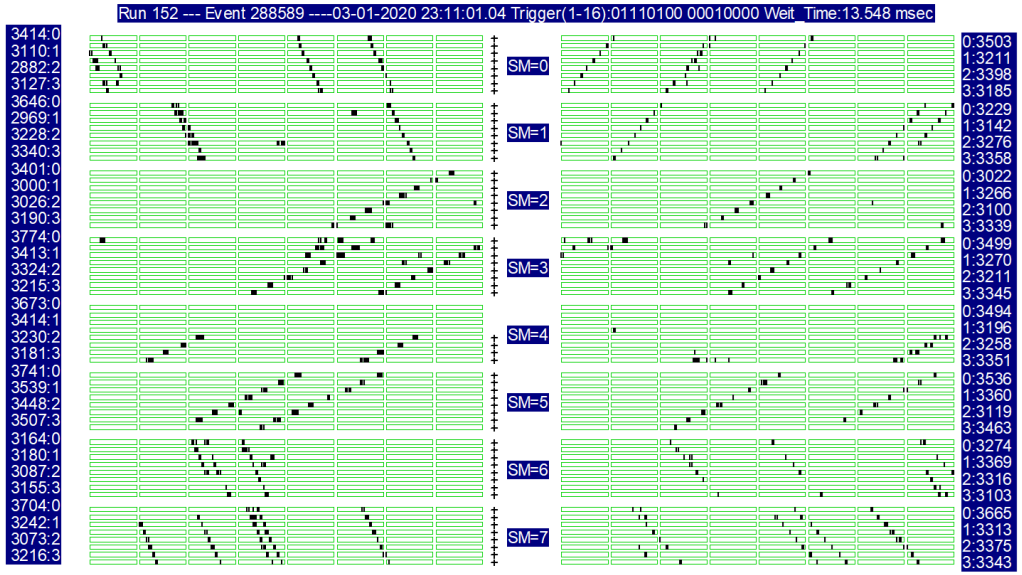
Experimental setup and an event with a muon bundle



Cherenkov water calorimeter
NEVOD (2000 m^3)

DECOR supermodules (70 m^2)

Muon bundle in DECOR supermodules
Left – *Y*-projection, azimuth angle,
Right – *X*-projection, projected zenith angle.



Experimental data

The local density of muons in the event and the direction of their arrival are measured according to the DECOR data. These quantities allow to estimate the energy of the primary particle.

The local muon density is estimated 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 the Cherenkov water calorimeter NEVOD.

On the average, energy deposit is nearly 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).

Three series of the measurements (from July 2013 to March 2021).
Selection criteria: **m ≥ 5, θ ≥ 55°, two 60-degree sectors of azimuth angle.**

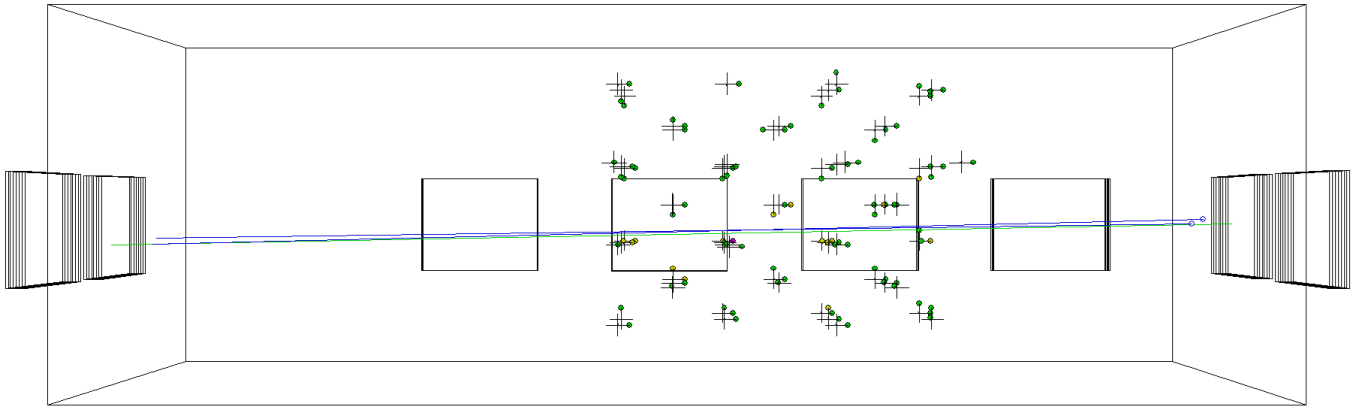
Series	Number of events	"Live" time, h (counting rate, event/h)
11th (026-455)	19,923	11,897 (1.67)
12th (001-884)	46,647	27,234 (1.71)
13th (000-233)	23,595	13,642 (1.73)
Sum	90,165	52,773 (1.71)

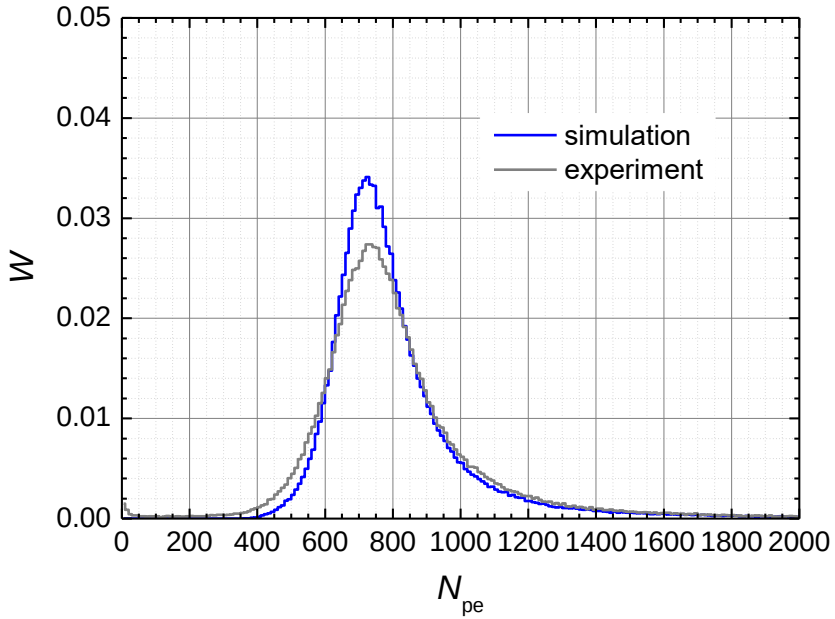
Simulation of the NEVOD-DECOR response to the muon bundles

The energy deposit of muon bundles with fixed muon energies of 100 GeV was simulated for the NEVOD-DECOR setups. The model of the CWC NEVOD was tested and calibrated by the response to single near-horizontal muons.

1. Events with bundles were simulated according to the local muon density spectrum with a slope close to the experimental one.
2. The simulation takes into account the physical features of the setups and the conditions of selection of events with muon bundles.
3. For events satisfying the selection conditions, the response of the Cherenkov water calorimeter NEVOD was calculated using the Geant4 package.

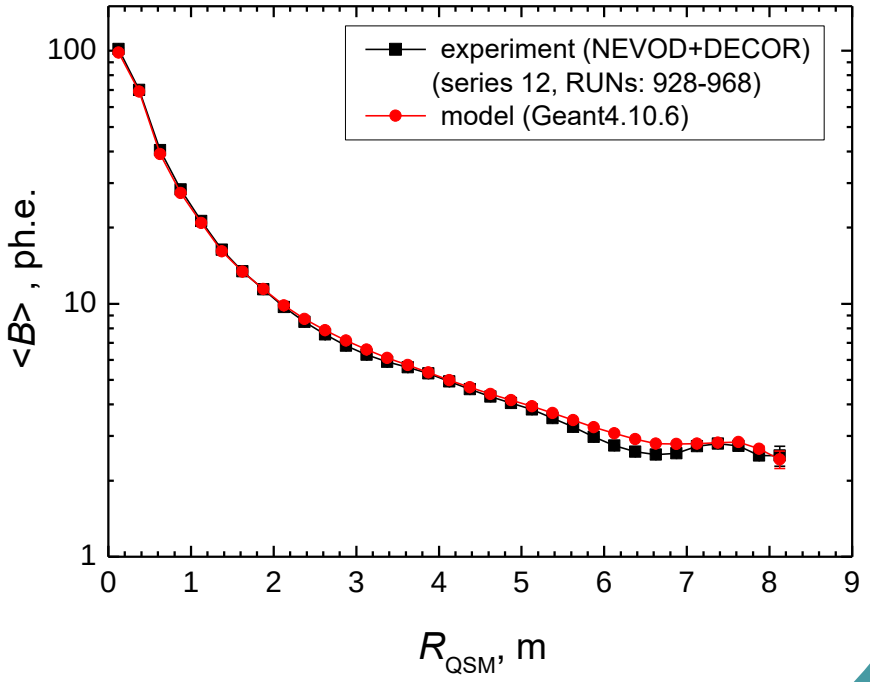
Calibration of the CWC NEVOD model by the response to single near-horizontal muons





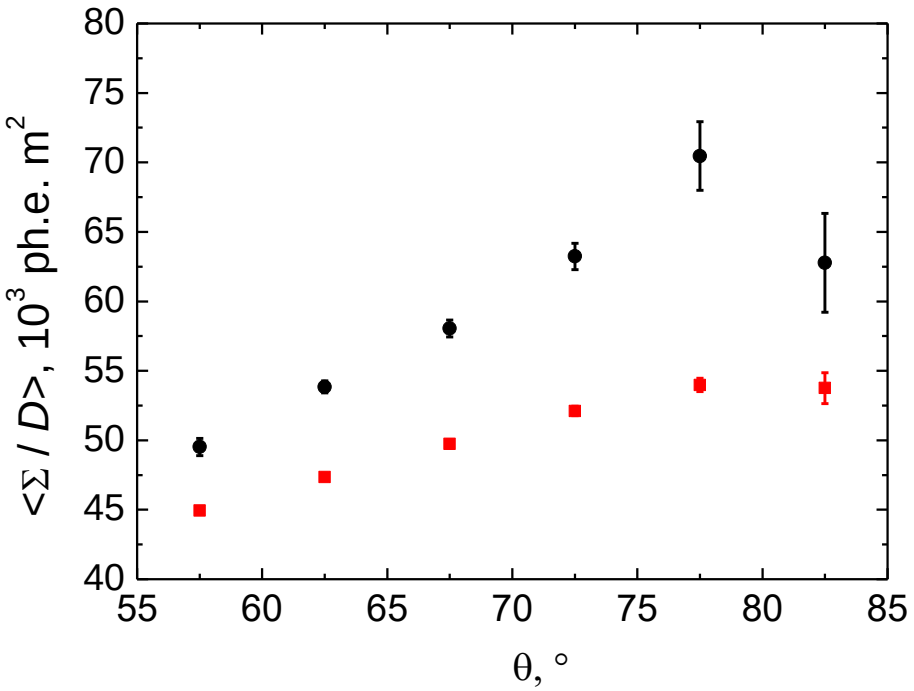
Distribution of events in the total number of photoelectrons

Dependence of the average response of QSM on the distance to muon track



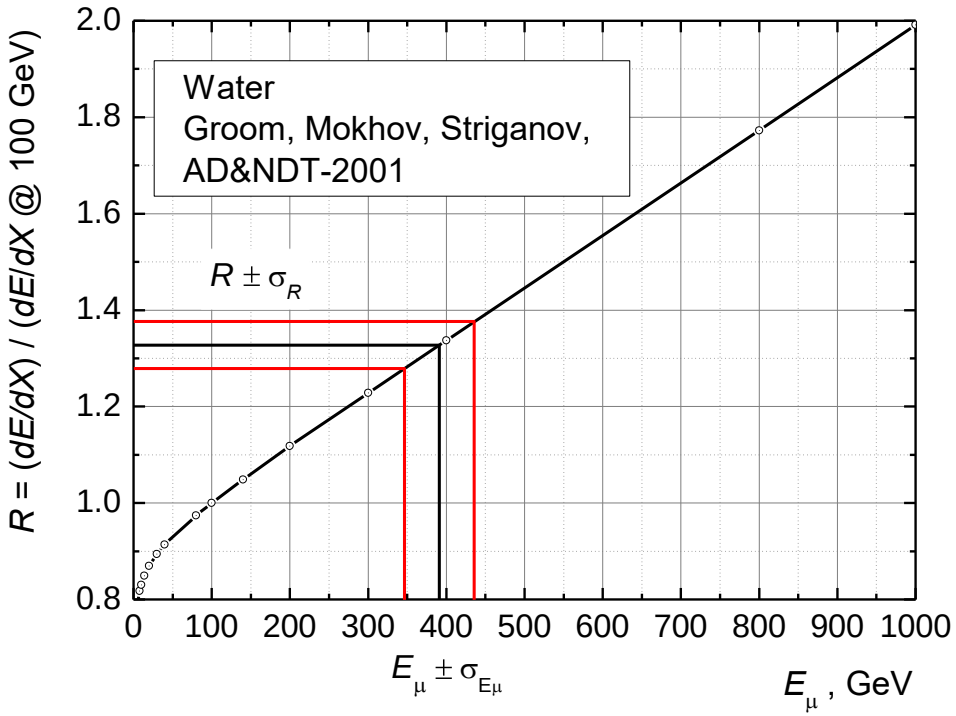
Transition from the average muon bundle specific energy deposit to the average energy of muons in the bundles

Black circles are experimental data, red squares are simulation results (for a fixed muon energy of 100 GeV)



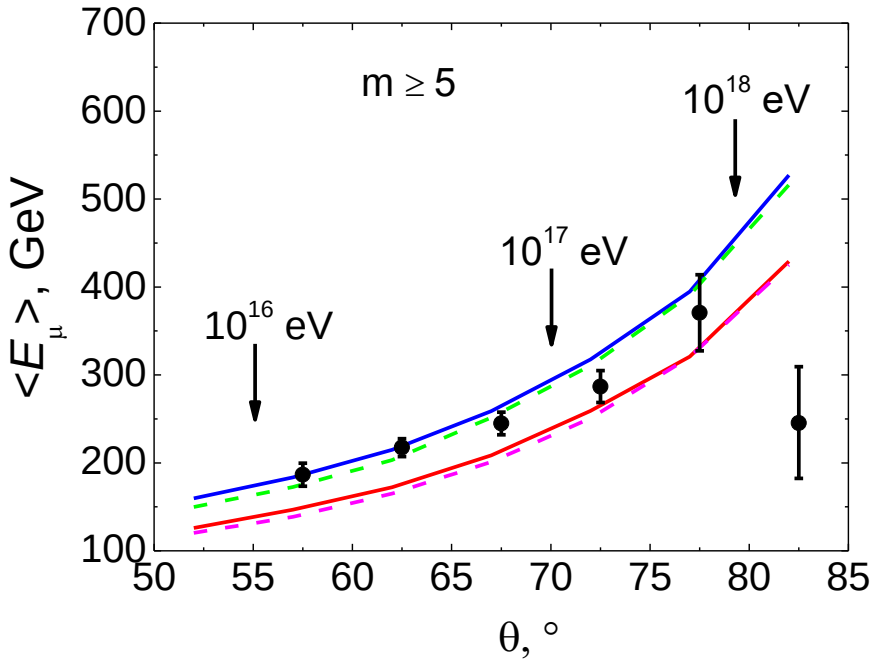
$$R = \frac{\langle \Sigma / D \rangle^{obs}}{\langle \Sigma / D \rangle^{sim}_{100\ GeV}}$$

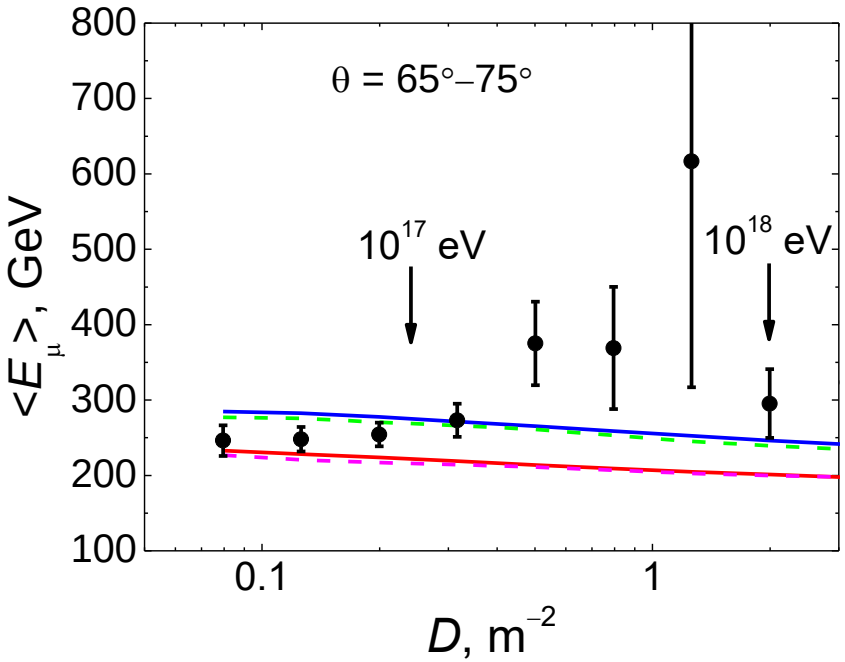
Average specific loss of muons normalized to a loss at an energy of 100 GeV



Dependences of the average energy of muons in the bundles on the zenith angle and local muon density for θ = 65°–75°

The curves were obtained by simulation of the muon component of EAS formed by primary protons (bottom pairs of curves) and iron nuclei (top pairs of curves) in the CORSIKA software package for two models of hadronic interactions: QGSJET-II-04 (solid lines) and SIBYLL-2.3c (dashed lines).





Conclusion

1. Experimental statistics of muon bundles for more than 7 years observations (53 thousand hours “live” time, 90 thousand events) was accumulated.
2. A transition has been made from the average specific energy deposit to the average energy of muons in the bundles.
3. The dependences of the average energy of muons in the bundles on the zenith angle and local density in the region corresponding to the energies of primary particles 10 - 1000 PeV have been obtained. The obtained dependences have been compared with the expected one using the CORSIKA program with two models of hadron interactions: QGSJET-II-04 and SIBYLL-2.3c.
4. In the dependence of the average energy of muons on their local density, an increase in the average energy of muons in the bundles is observed in comparison with the expected one for primary energies greater than 10^{17} eV.
5. Accumulation of the experimental data and analysis of possible systematic errors are being continued.

Thank you for attention!