International Symposium on Cosmic Rays and Astrophysics

INVESTIGATION OF THE ENERGY LOSS OF MUON BUNDLES IN THE CHERENKOV WATER CALORIMETER

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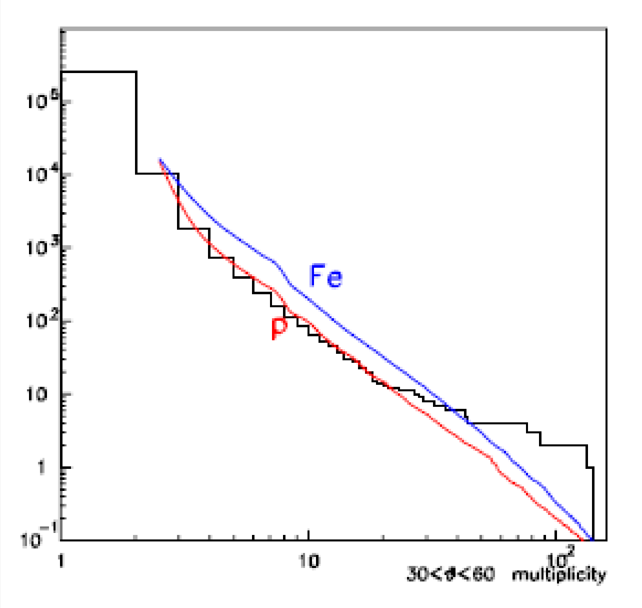
OVERVIEW

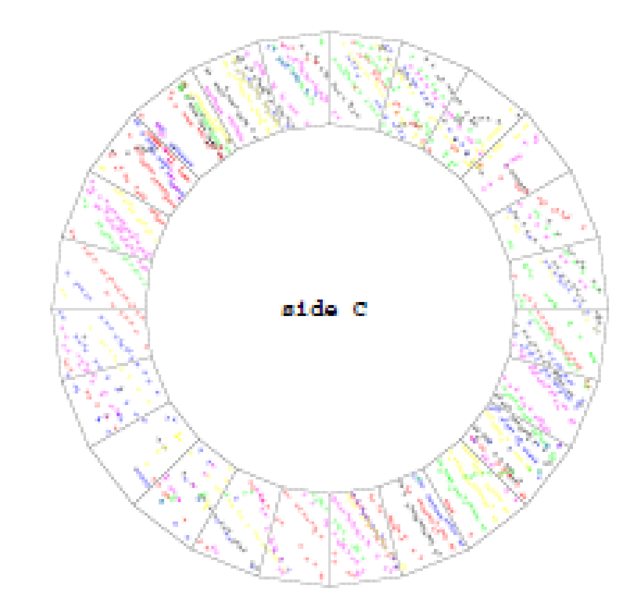
- Excess of muons in experiments
- A possible approach to solve "muon puzzle"
- Experimental data 2012-2013 and preliminary results
- Experimental data 2013-2018 (new statistics) and results of analysis
- Conclusion

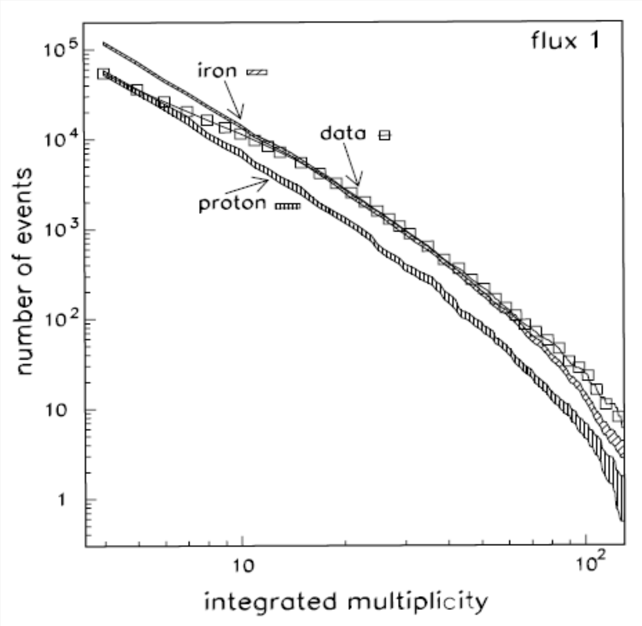
Muon puzzle in cosmic rays



ALEPH

C. Grupen et al., Nucl. Phys. B (Proc. Suppl.) 175-176 (2008) 286





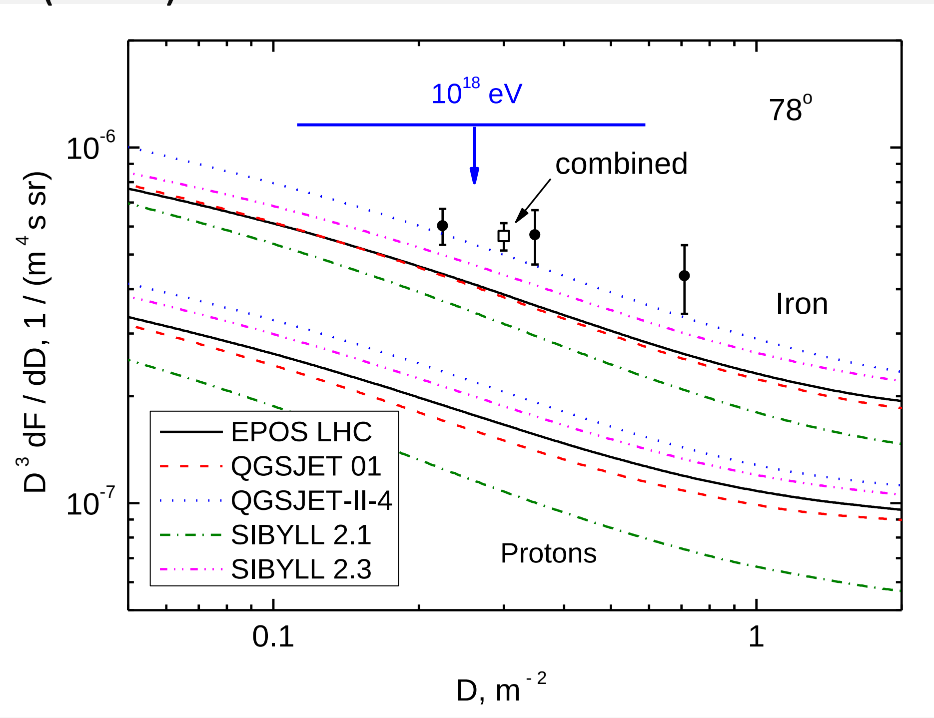
DELPHI

J. Abdallah et al., Astroparticle Physics 28 (2007) 273

Muon puzzle in cosmic rays

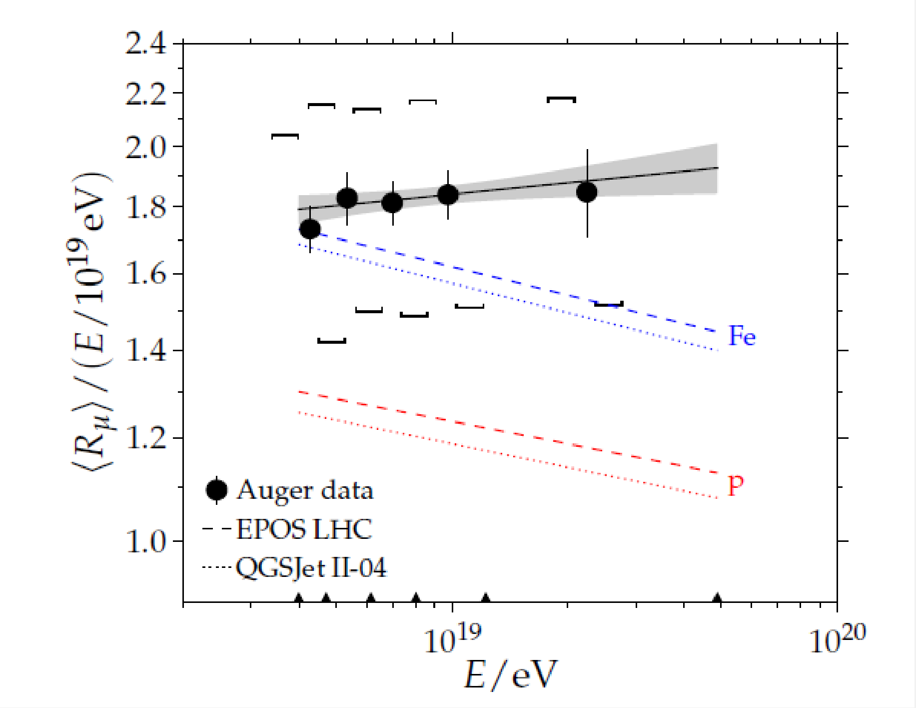
DECOR data 2002-2016

A. G. Bogdanov Astropart. Phys., 98 (2018) 13–20



Pierre Auger Observatory

A. Aab et al. Phys. Rev. D 91, 032003 (2015)

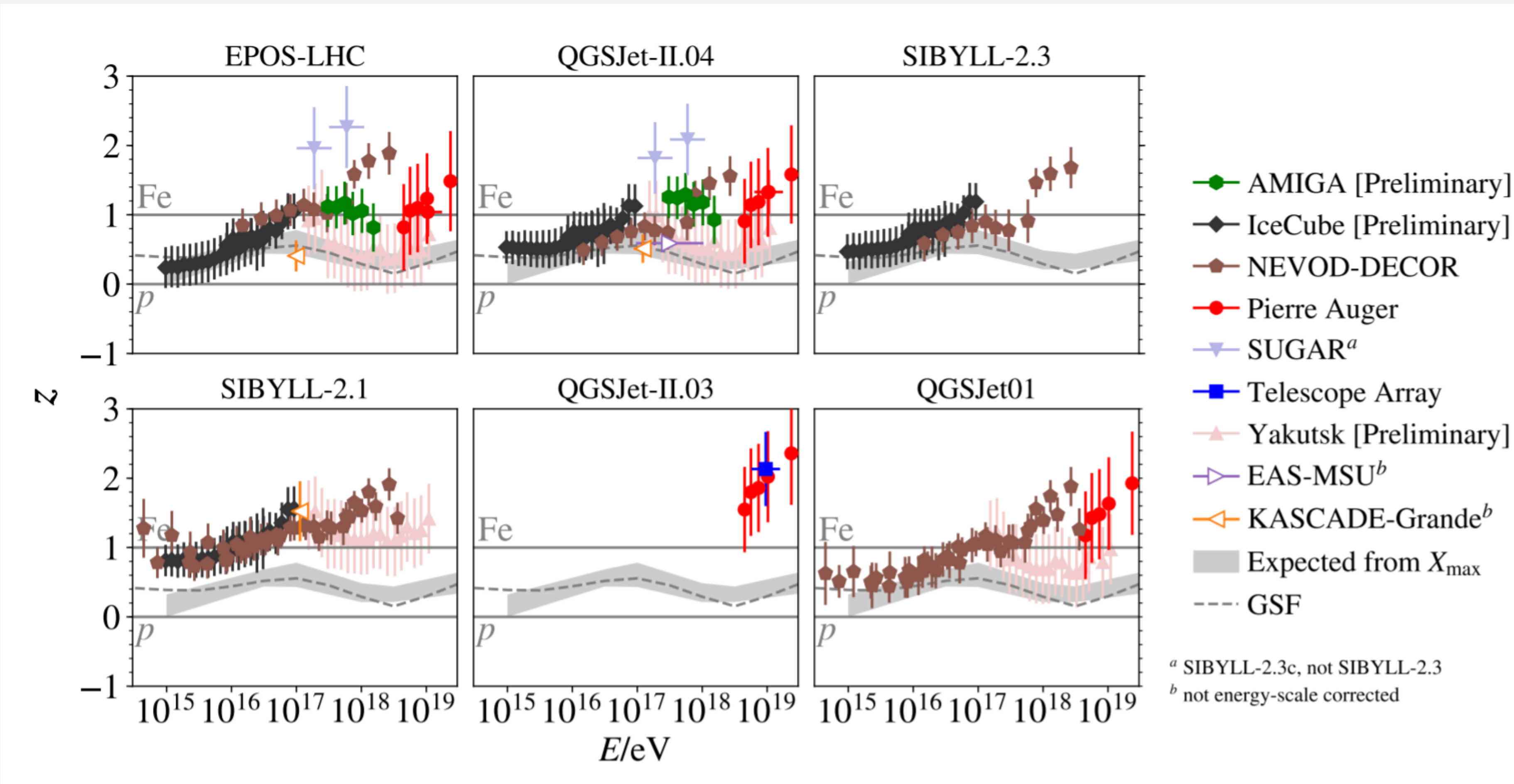


Muon puzzle in cosmic rays

Combining muon measurements

$$z = \frac{\ln(N_{\mu}^{det}) - \ln(N_{\mu p}^{det})}{\ln(N_{\mu Fe}^{det}) - \ln(N_{\mu p}^{det})}$$

Dembinski H.P. et al. https://arxiv.org/pdf/1902.08124.pdf

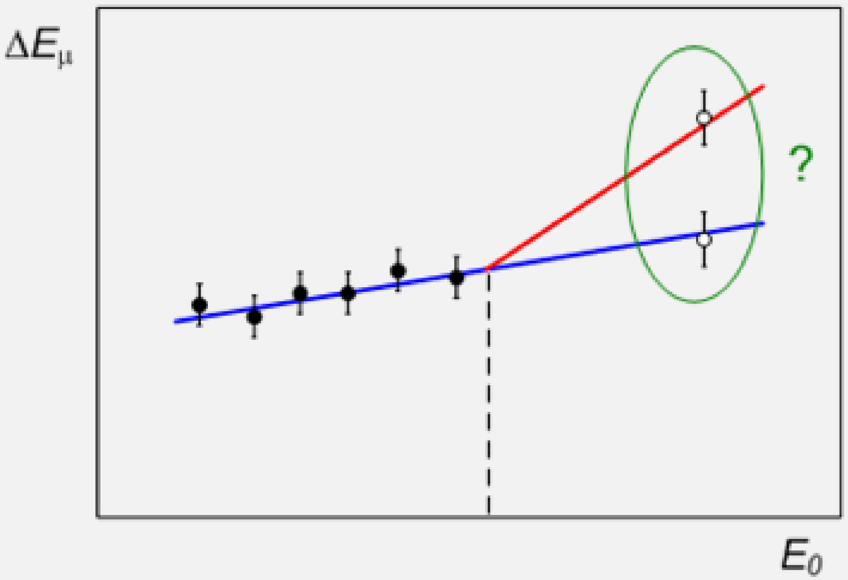


Approach to solve muon puzzle

In a number of UHE experiments, excess of muons in comparison with calculations (even for heavy composition) is observed.

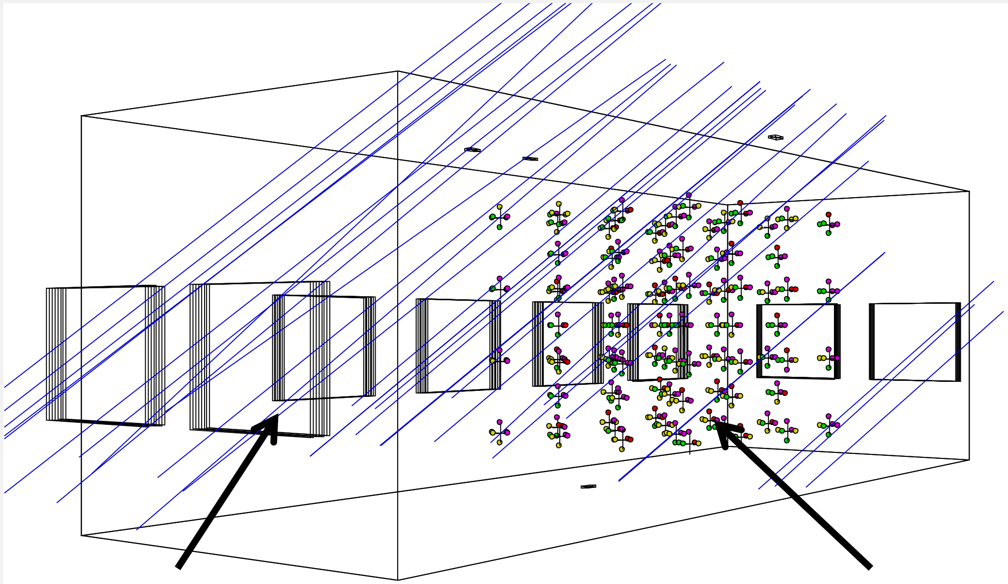
In order to solve this so-called "muon puzzle", measurements of muon component energy characteristics are necessary. A possible approach: measurement of muon bundle energy deposit in the detector material.
The average energy loss of muons in matter almost linearly depends on the muon energy:

$$dE_\mu/dX \sim a + bE_\mu.$$

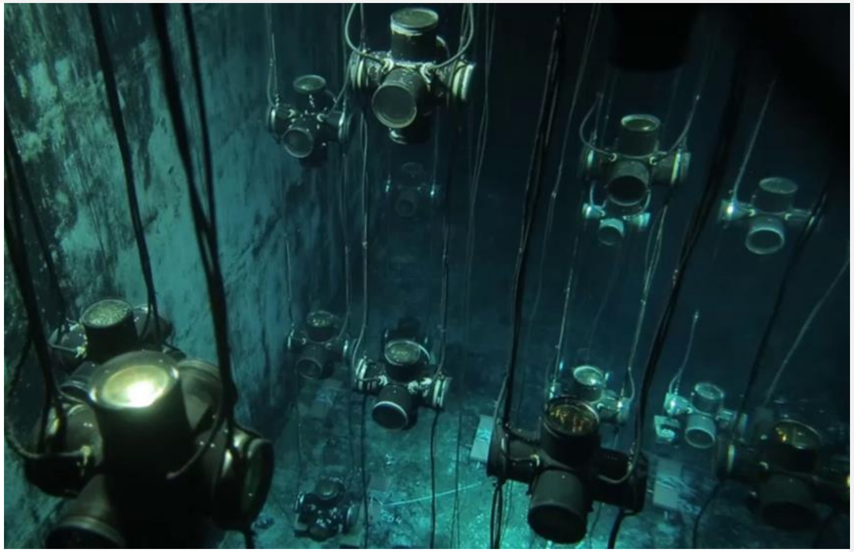


If some excess of high-energy muons appears, it should be reflected in the dependence of the energy deposit on the primary particle energy.

Experimental setup



Coordinate-tracking detector DECOR

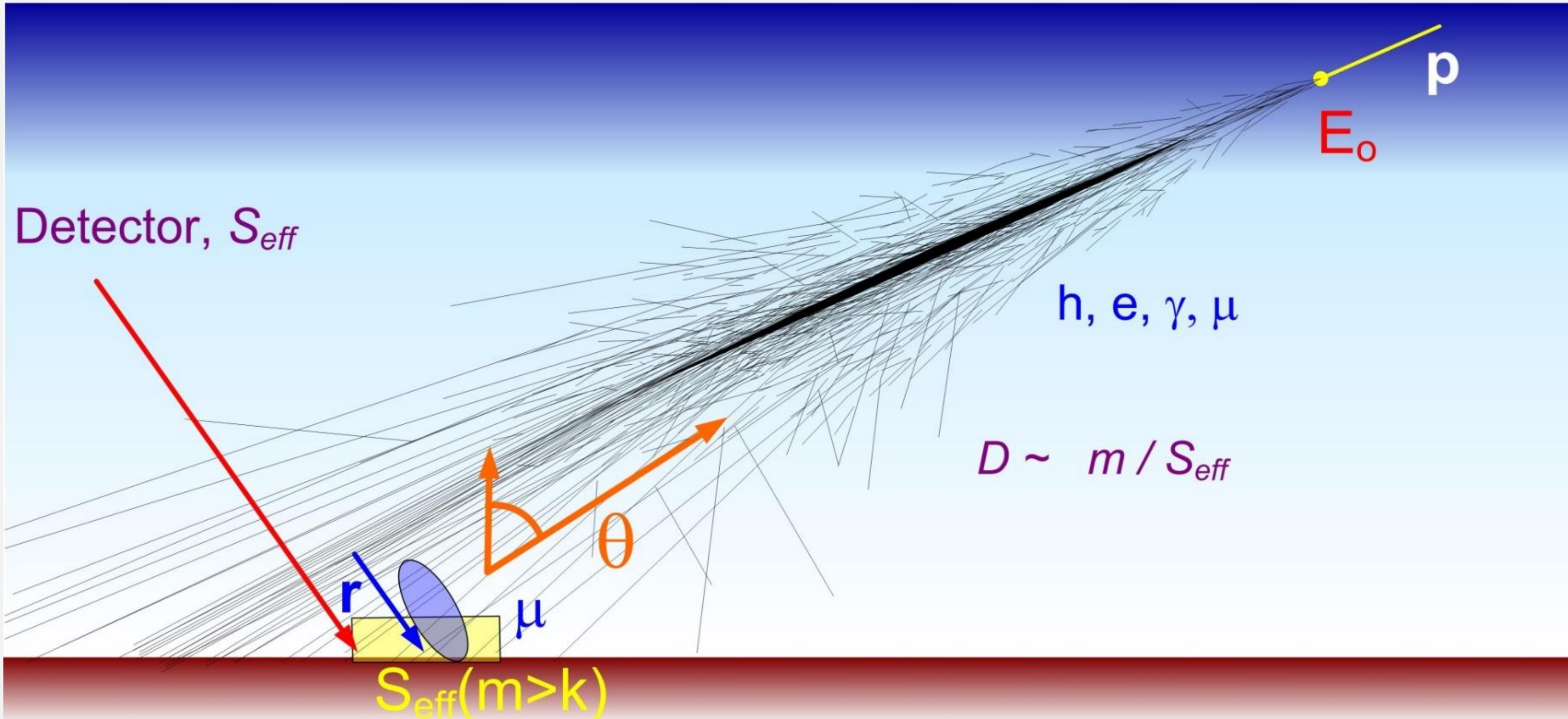


Cherenkov water calorimeter NEVOD (2000 m^3)

Local muon density in the event and EAS arrival direction are estimated from DECOR data; the energy deposit is measured in the Cherenkov water calorimeter NEVOD.

Approach to the analysis of muon bundle: method of Local Muon Density Spectra

A.G. Bogdanov et al., Physics of Atomic Nuclei. 2010. V. 73. N 11. P. 1852



In an individual muon bundle event, local muon density *D* (at the observation point) is measured. Distribution of events in estimated muon density *D* forms the LMDS.

Data of the first experimental series (2012-2013)

03.05.2012 – 20.03.2013; live time: 5542 h

m ≥ 5, θ ≥ 40°, two 60°-wide sectors in φ – 24496 events.

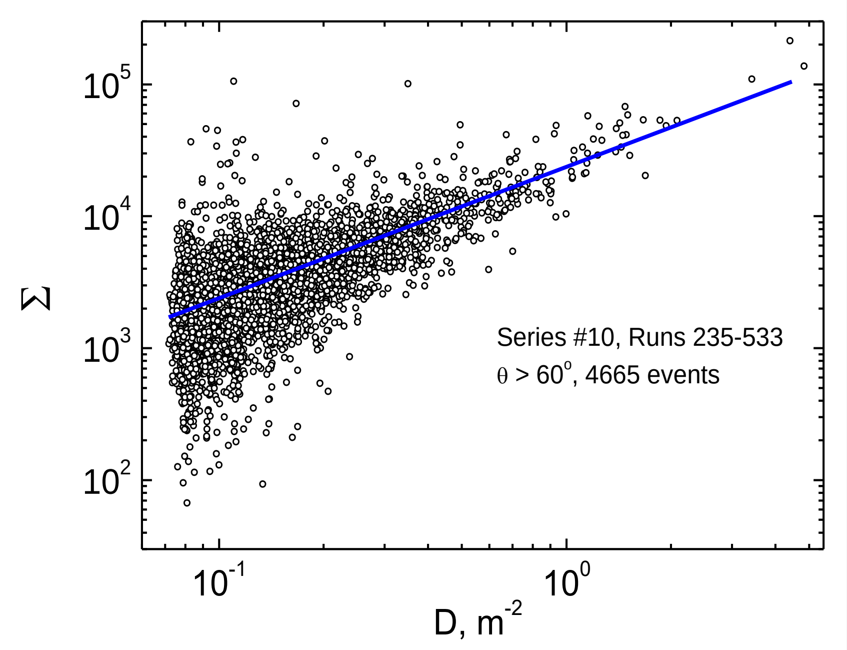
Local muon density is calculated as:

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

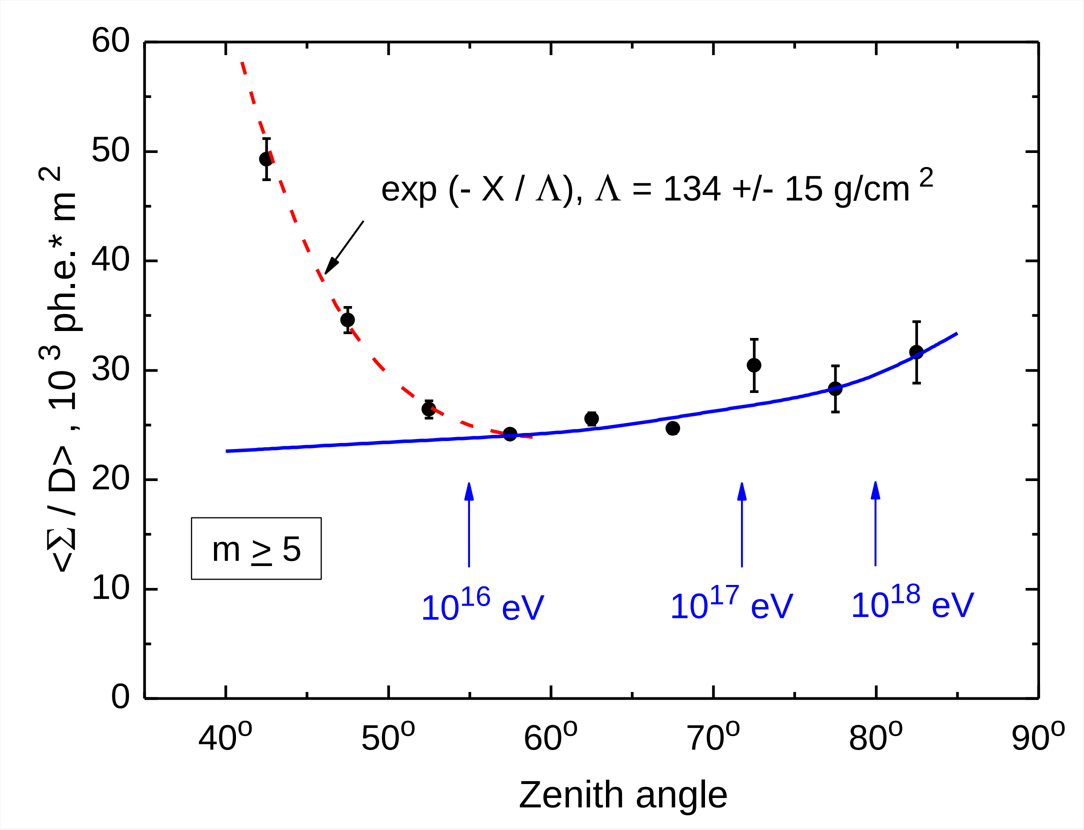
where m is the number of muons, $\beta \approx 2.1$ is the integral LMDS slope, S_{det} is the effective area of DECOR SMs for a given direction of muon bundle arrival.

The total energy deposit (sum of the signals of all PMTs Σ, photoelectrons) is proportional to muon density in the event. Therefore, in the further analysis we use the specific energy deposit $\langle\Sigma/D\rangle$ (response normalized to the muon density).

Correlation of the total CWD response with the local muon density



Dependence of the muon bundle average specific energy deposit on zenith angle (data 2012-2013)



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

Experimental data 2013-2018 (new statistics)

Two series of measurements:
16.07.2013 – 08.04.2015, 11897 h
17.07.2015 – 13.12.2018, 18791 h
Total: 36780 hours live time:
$m \geq 5$, $\theta \geq 55°$, two 60°-wide sectors in φ : 62298 events

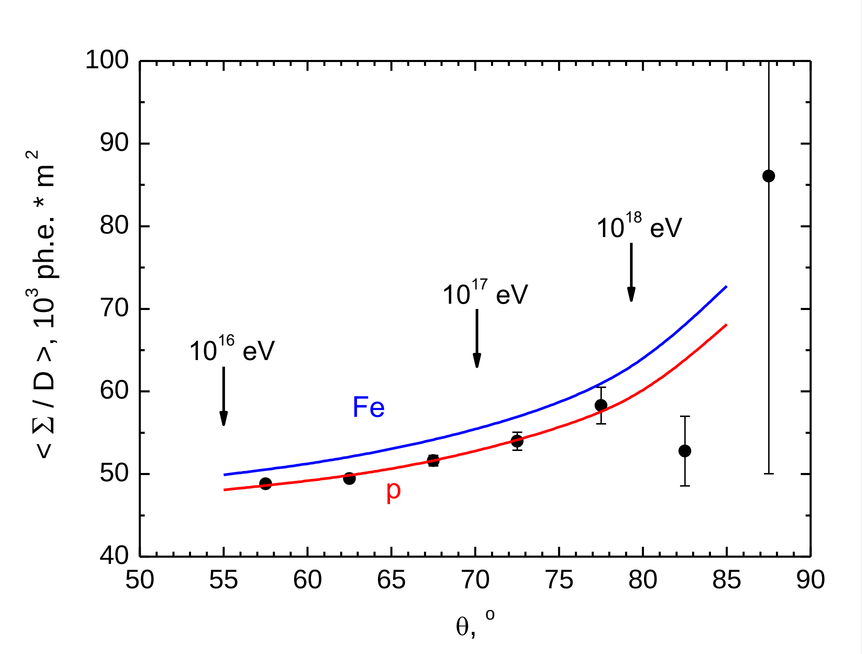
New water purification system: absorption length of Cherenkov light increased several times and reached about 10 m (more than the transverse size of the water tank). As a result:

- 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 the CWD) became important.

Dependence of the muon bundle average specific energy deposit on zenith angle (data 2013-2018)

The curves represent the expected dependence of the mean energy loss of muons in the bundles on the zenith angle (CORSIKA, QGSJet II-4 + FLUKA). The proton curve is normalized to the data between 55° - 65° zenith angle.

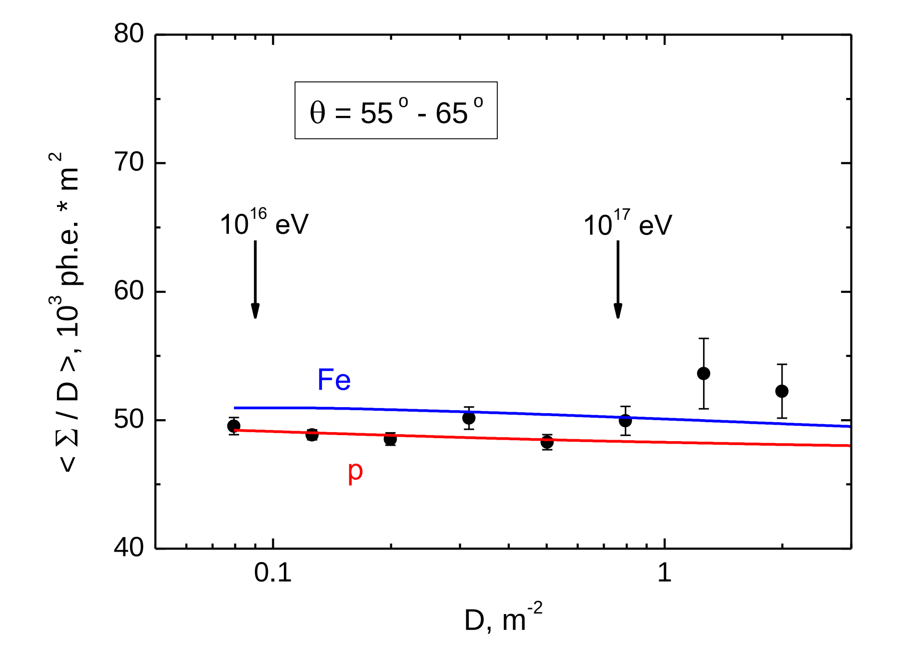
Data points are corrected for the contribution of the light reflected from the water surface (on the basis of Geant4 simulation).

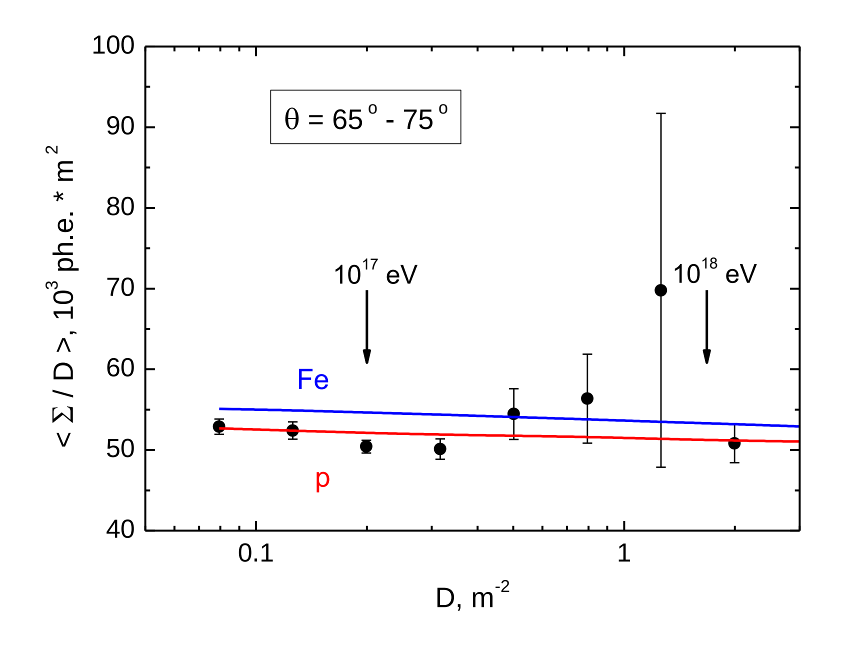


The increase of the energy deposit with zenith angle reflects the increase of the average muon energy in the bundles.

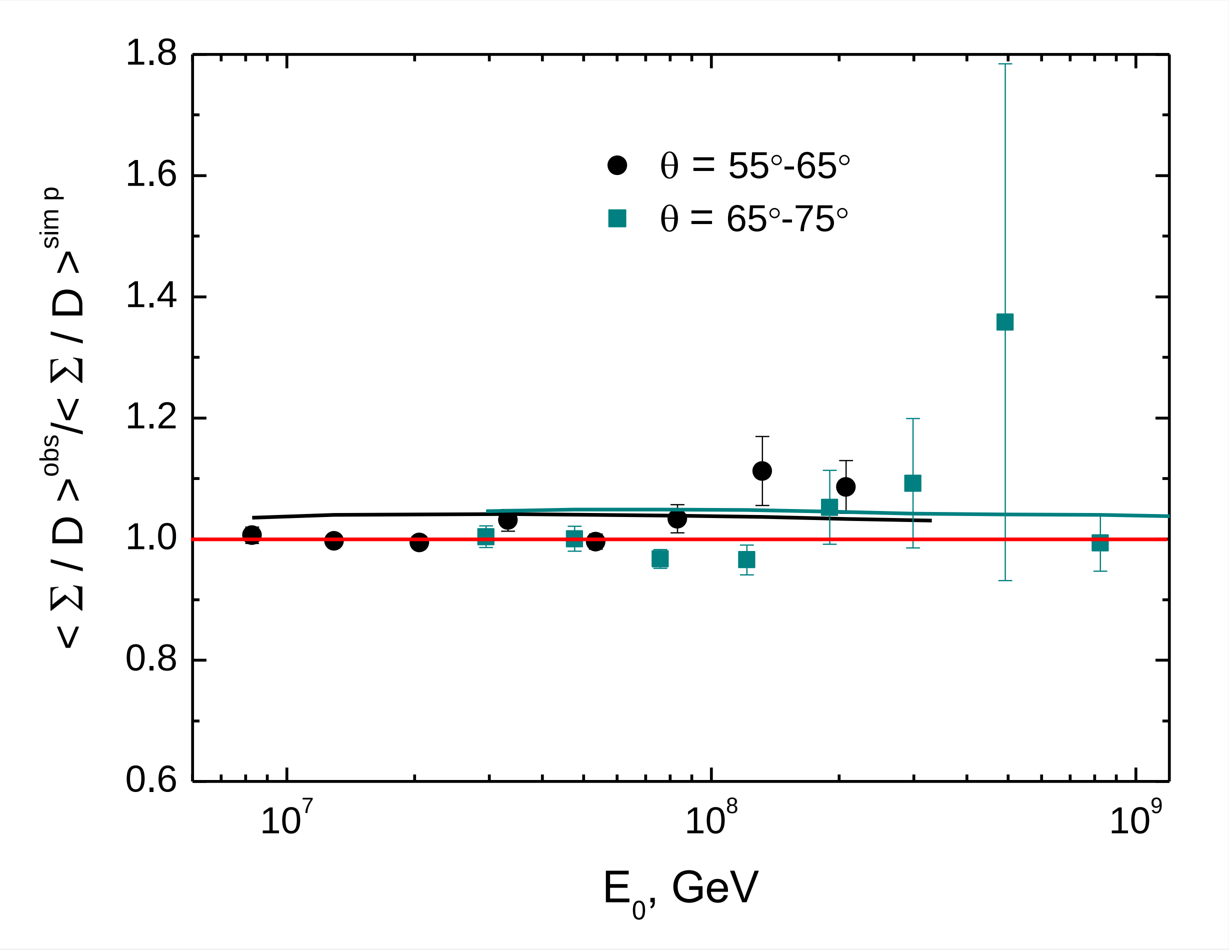
Dependence of the muon bundle average specific energy deposit on local muon density (data 2013-2018)

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).





Dependence of the ratio of the measured specific energy deposit to simulated energy deposit for primary protons on primary particle energy



Conclusion

1. Measurements of the energy characteristics of muon bundles generated by primary particles of cosmic rays in the energy range 10^{16}-10^{18} eV are carried out at the NEVOD-DECOR complex.

2. An appreciable dependence of the mean specific energy deposit (normalized to the muon density) on the zenith angle was found. This dependence is in a good agreement with the results of the simulation based on the CORSIKA program.

3. An indication of an increase in the average energy of muons in bundles in comparation with the expectation at primary energies between 10^{17} and 10^{18} eV was found.

Thank you for attention!