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Intensity of muon bundles according to the NEVOD-DECOR cosmic ray experiment

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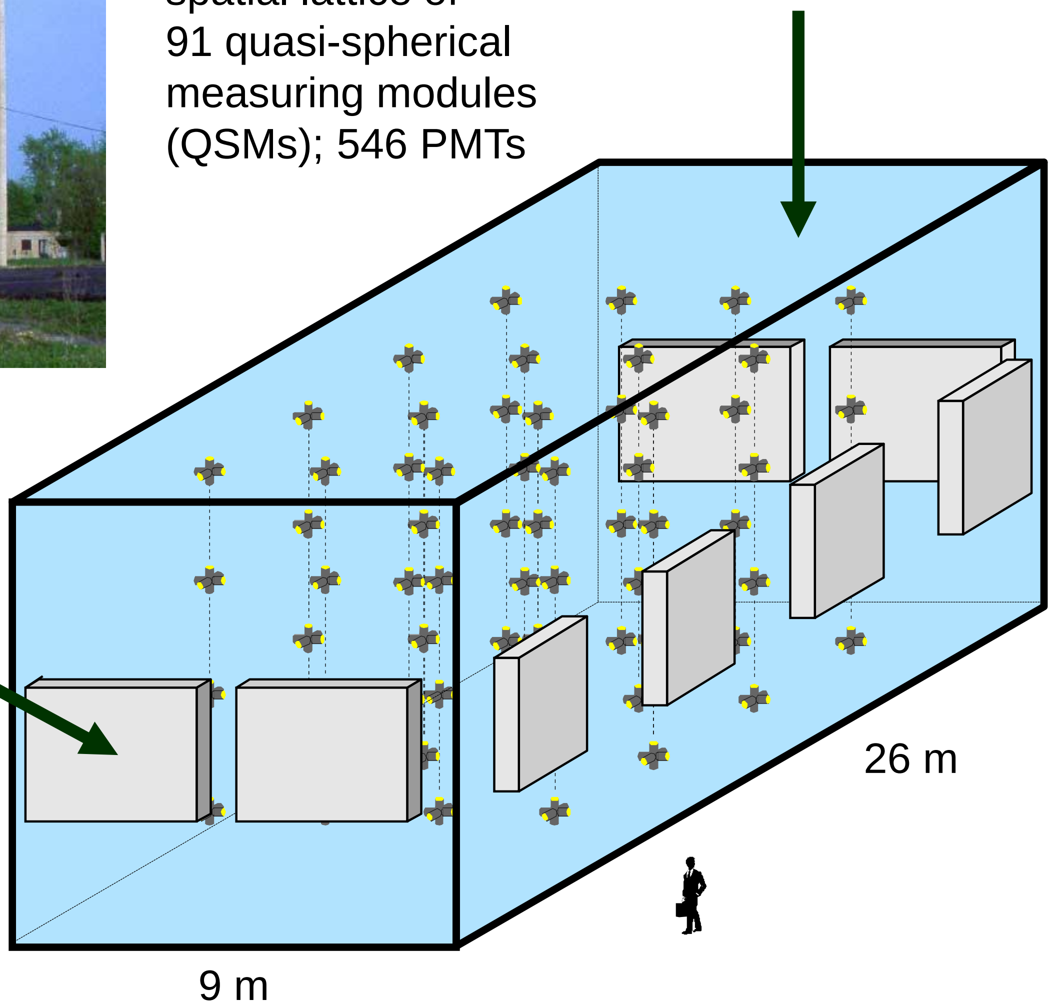
Introduction

Investigations of muon component of extensive air showers (EAS) allow us to obtain information about primary energy spectrum, mass composition and the features of hadronic interaction at ultra-high energies.

Of particular interest are events with muon bundles caused by the simultaneous (within tens of nanoseconds) passage through the detector of genetically related penetrating particles with almost parallel trajectories.

To date, NEVOD-DECOR is the only experiment where long-term systematic studies of muon bundles in a wide range of zenith angles are carried out.

General view of the NEVOD-DECOR setup

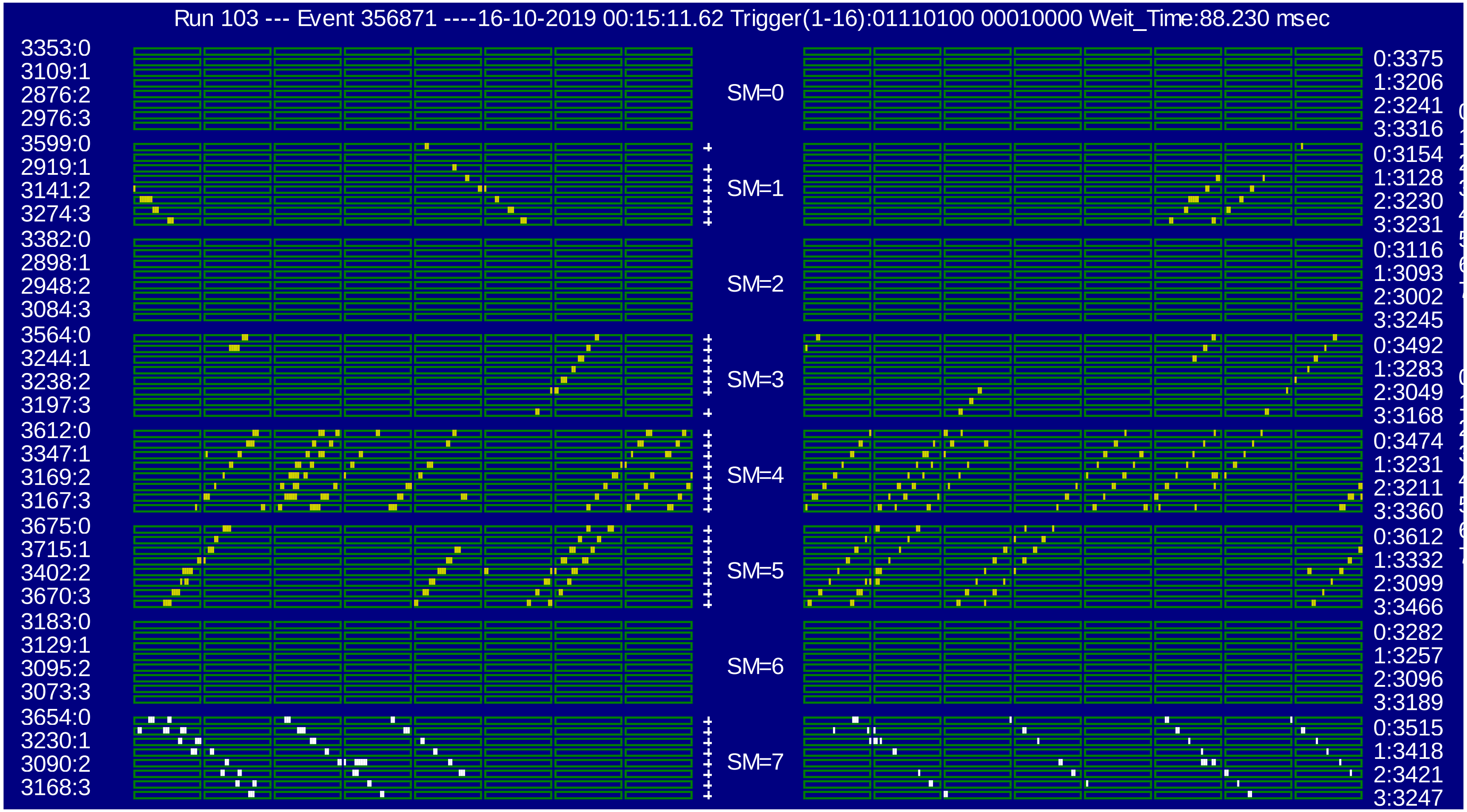


DECOR supermodules (SMs) in the galleries around the NEVOD water tank


Each SM has an effective area 8.4 m^2 and consists of 8 vertical planes of streamer tube chambers. The length of the chambers is 3.5 m, inner tube cross section is 9×9 mm^2. The planes of the chambers are equipped with a two-dimensional system of external readout strips.

Muon bundle event in the DECOR SMs

multiplicity *m* = 20 particles, zenith angle $\theta \approx 59^\circ$



Y-coordinate (azimuth angle) *X-coordinate (projected zenith angle)*

Spatial and angular accuracy of muon track location in the supermodule is better than 1 cm and 1°, respectively.

NEVOD-DECOR experimental data

In the present analysis the data accumulated over the period from May 2012 to May 2020 are used ("live" observation time is 52478.4 h)

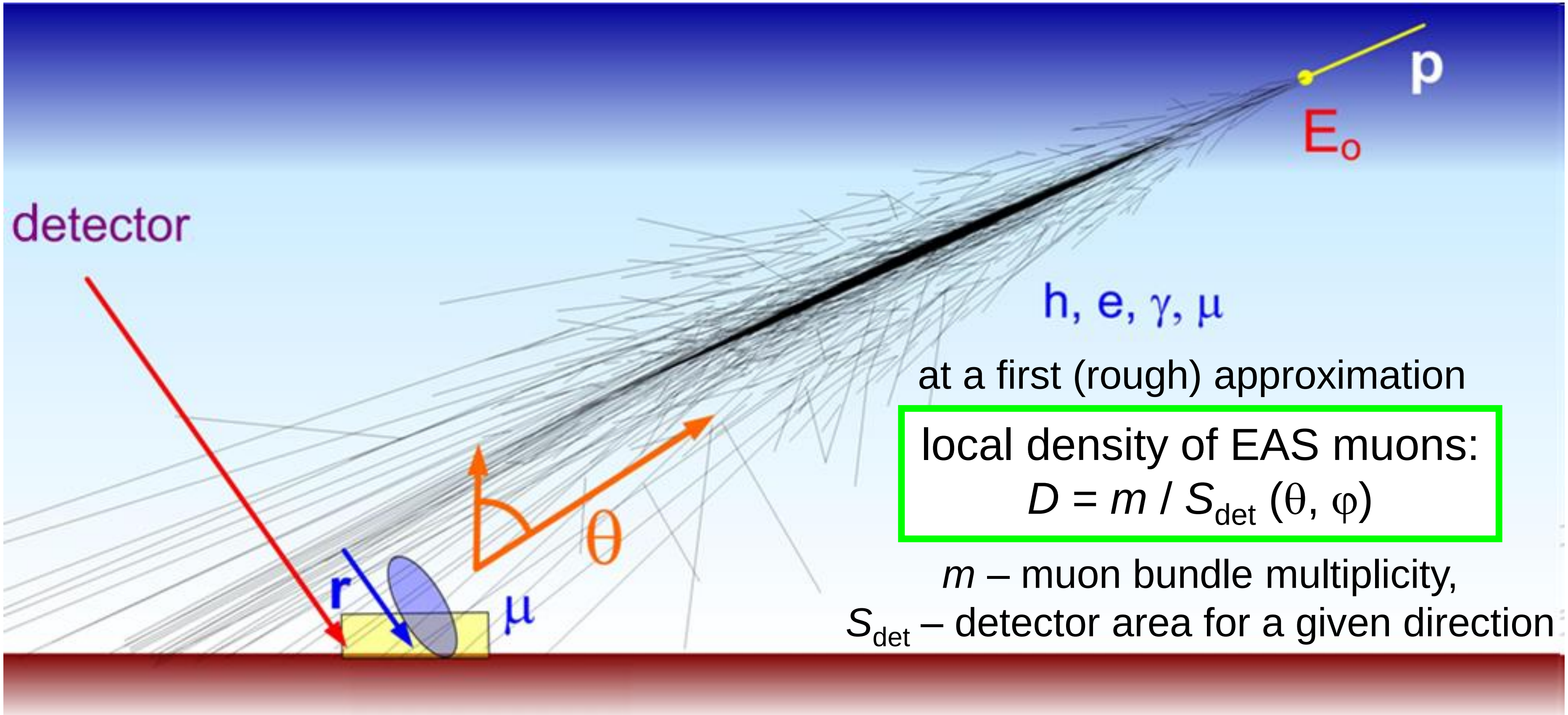
89551 events with muon multiplicity $m \geq 5$ and zenith angles $\theta \geq 55°$ and additionally 30375 events in the range of zenith angles from 40 to 55° have been selected.

In order to improve muon identification, only events in two 60°-wide sectors of azimuth angles are analyzed, where most of DECOR SMs (six of eight) are screened by the water volume of the NEVOD detector.

Muon bundles have a very bright signature in the DECOR response and cannot be confused with other multi-particle events.

Novel approach to the analysis of data on muon bundles: method of Local Muon Density Spectra (LMDS)

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



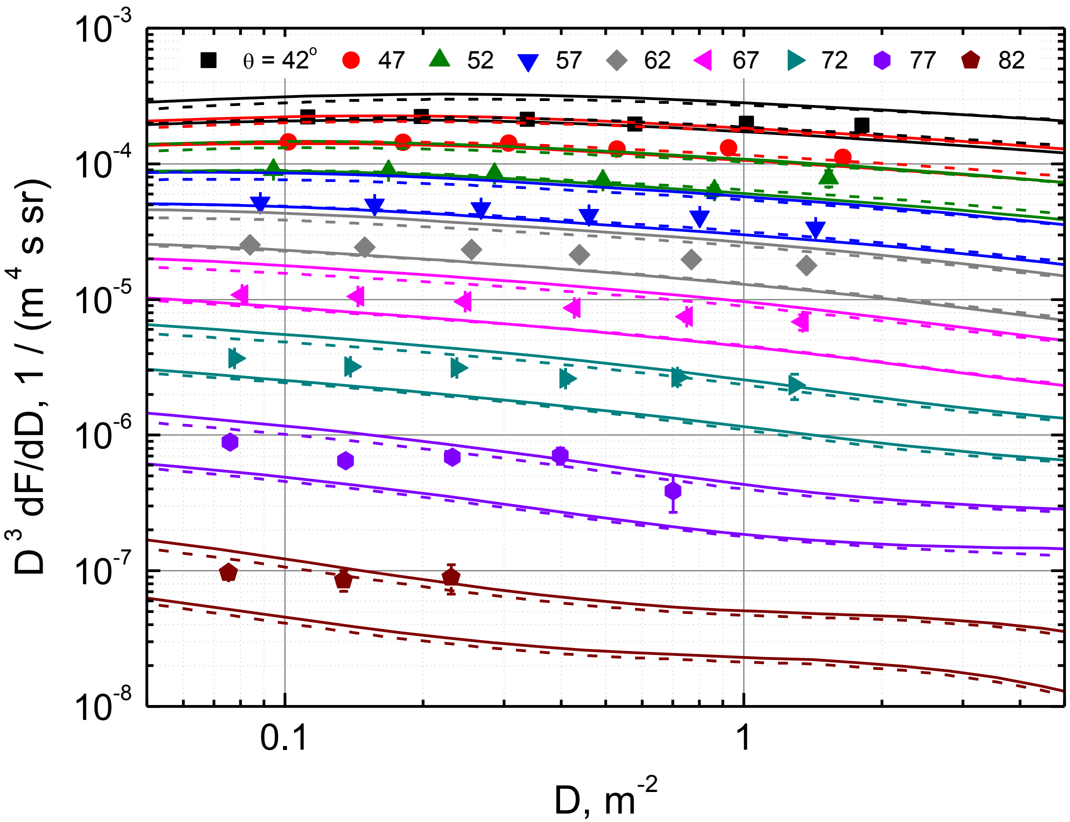
at a first (rough) approximation

local density of EAS muons:
$D = m / S_{det}(\theta, \varphi)$

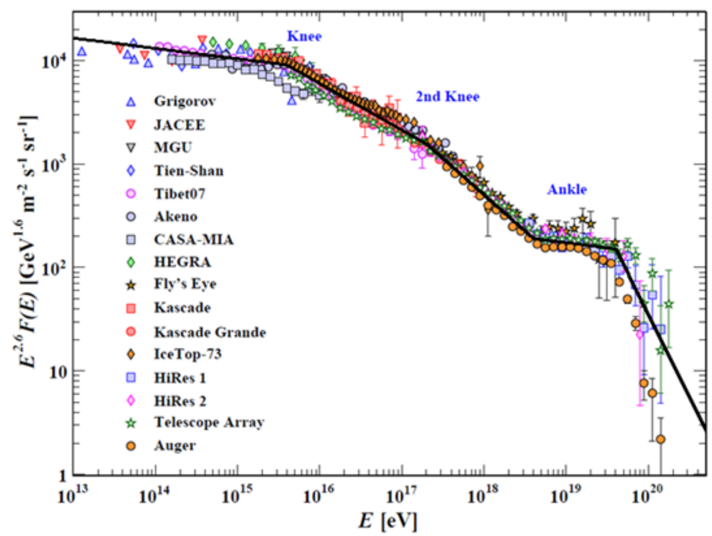
m – muon bundle multiplicity,
S_{det} – detector area for a given direction

In an individual muon bundle event, local muon density D (at the observation point) is measured. Distribution of events in muon density D forms the LMDS. Measurements of LMDS at various zenith angles allows exploration of a very wide energy range in frame of a single experiment with a relatively compact setup.

Differential local muon density spectra for different zenith angles



C. Patrignani et al. Particle data group,
Rev. Particle Phys. Chin. Phys. C 40 (2016) 100001.



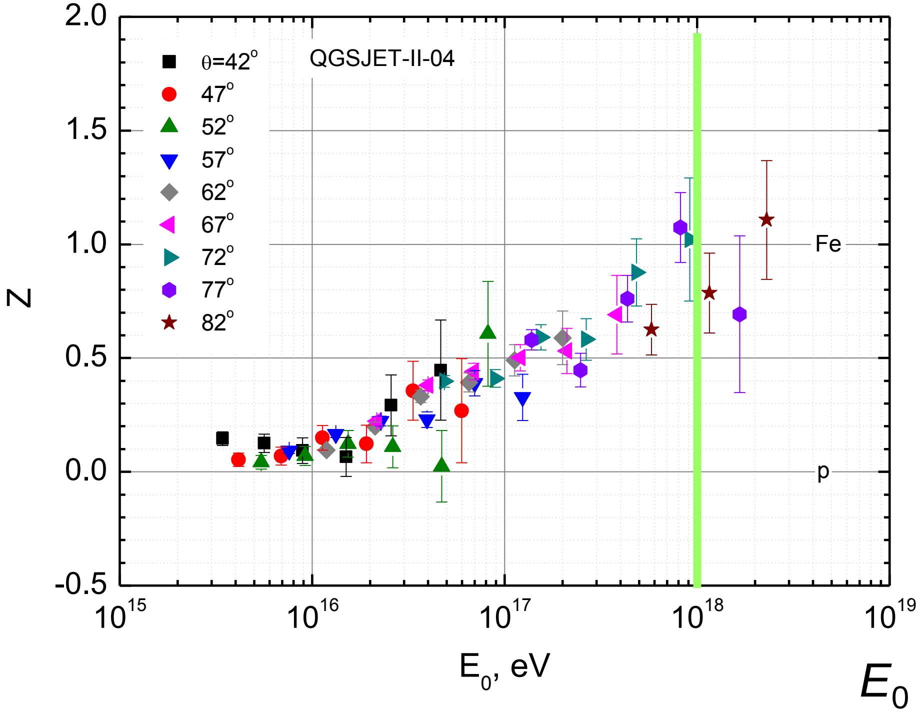
Experimental data NEVOD-DECOR are shown by symbols. Dashed and solid curves represent the results of the CORSIKA-based calculations using two actual (post-LHC) hadron interaction models SIBYLL-2.3c and QGSJET-II-04, respectively. Two limiting cases of the mass composition (only protons and only iron nuclei) were considered. As a reference model for the energy spectrum of primary CR, we employed a piece-wise power law function for several energy intervals.

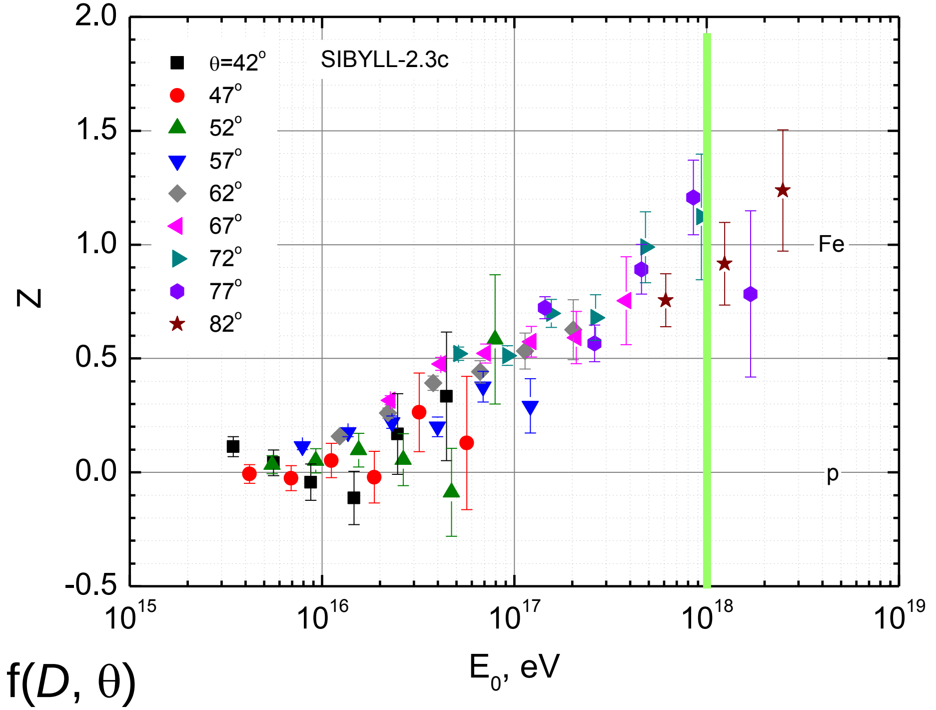
Comparison of LMDS at different θ angles by means of *Z*-scale

$$Z = \frac{\ln\left(N_{\mu}^{obs}\right) - \ln\left(N_{\mu p}^{sim}\right)}{\ln\left(N_{\mu Fe}^{sim}\right) - \ln\left(N_{\mu p}^{sim}\right)}$$

WHISP: Working group in Hadronic Interactions and Shower Physics
H.P. Dembinski et al. EPJ Web of Conferences 210 (2019) 02004

where N_{μ}^{obs} is the muon density estimate as seen in the detector, while $N_{\mu p}^{sim}$ and $N_{\mu Fe}^{sim}$ are the simulated muon density estimates for proton and iron showers after full detector simulation;
Z = 0 corresponds to pure proton showers and *Z* = 1 corresponds to pure iron showers.





$E_0 = f(D, \theta)$

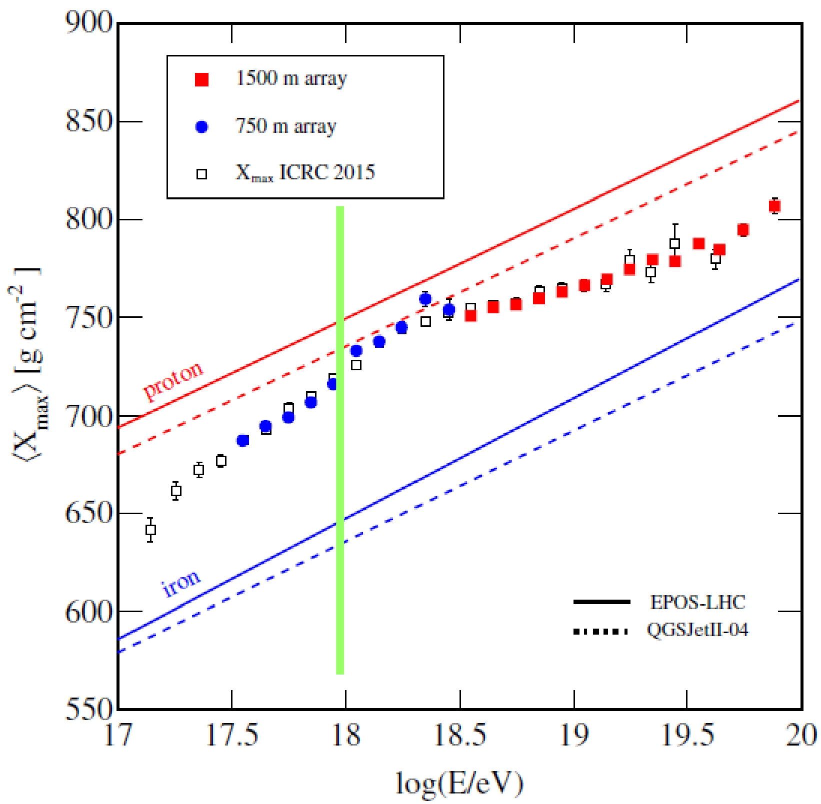
At 10^{16} eV experimental points are close to the results of the calculations for a light mass composition of primary CR. At higher energies relative increase of muon bundle intensity may be interpreted as a trend to a heavier mass composition. But at the energy about of 10^{18} eV, data of NEVOD-DECOR and models are only compatible for iron assumption.

Cosmic ray mass composition from X_{max} measurements

At the same time, measurements of the depth of the shower maximum X_{max} in the atmosphere (electromagnetic component) in the experiments using air fluorescence technique (Pierre Auger Observatory, Telescope Array, HiRes), on the contrary, favor a light (predominantly proton) mass composition of primary CR at ~ 10^{18} eV.

This problem in the study of cosmic rays has been called the “muon puzzle”. One of the possible ways to solve it is to measure the energy characteristics of the muon component of an EAS.

A. Aab et al. Phys. Rev. D 96 (2017) 122003



Evolution of <X_{max}> as a function of energy. The figure compares the mean values of the X_{max} distributions measured by the fluorescence and surface detectors of the Pierre Auger Observatory.

Conclusion

- The experiment on the investigation of inclined muon bundles formed as a result of interactions of primary cosmic ray particles with energies 10^{16} – 10^{18} eV is being conducted at the NEVOD-DECOR setup.
- Accumulation of experimental data, their processing and analysis are being continued. The addition of the detector TREK based on drift chambers to the complex NEVOD will expand the energy range.
- The present data are only compatible with calculations if we assume extremely heavy (iron group nuclei) primary composition at 10^{18} eV energy. This conclusion is consistent with data on multi-muon events obtained in a number of other experiments. However, such an assumption is in a strong contradiction with the results of X_{max} measurements of electromagnetic component of the EAS.
- It seems that the solution of the “muon puzzle” requires the introduction of serious changes in existing hadron interaction models, which could change the balance between muon and electron-photon EAS components in favor of muons.

Thank you for your attention!