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Muon puzzle in cosmic rays according to data of NEVOD-DECOR experiment

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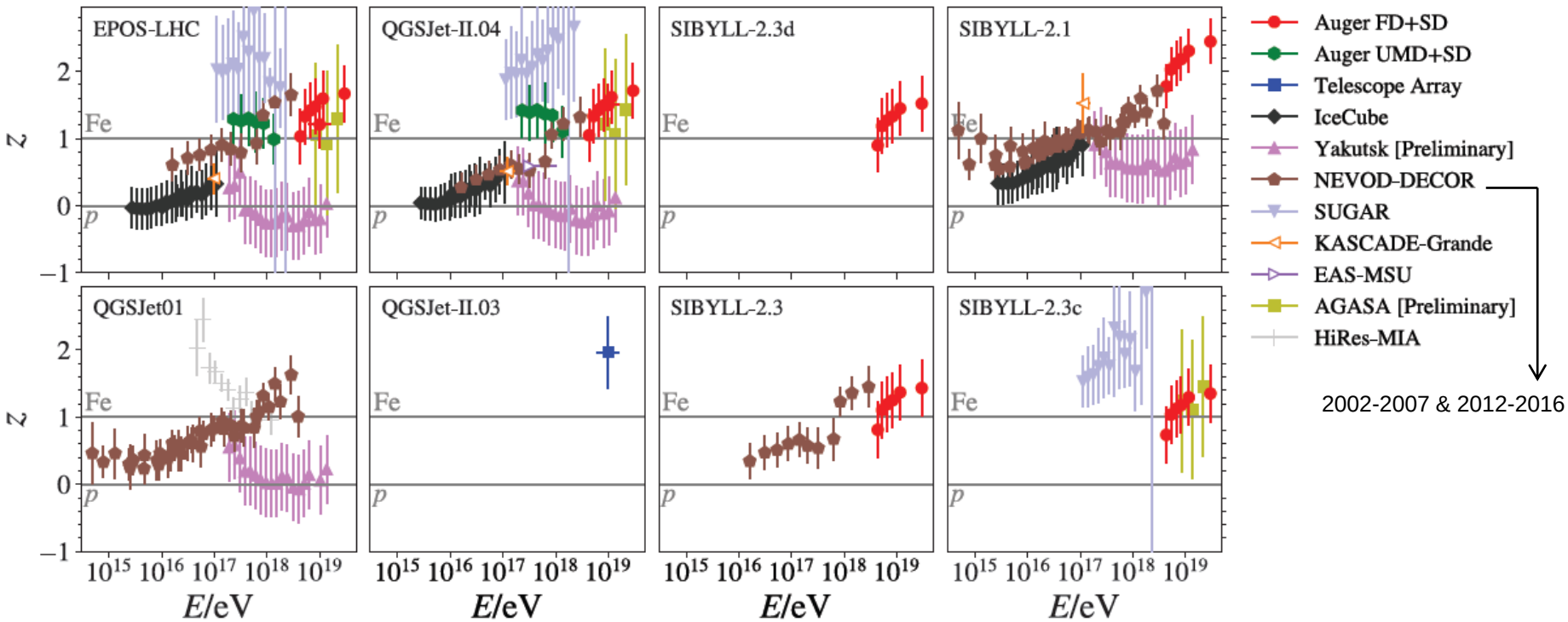
Introduction

Primary cosmic rays (CR), predominantly protons and nuclei, carry important information about the physical processes occurring in our Galaxy and the Universe. At energies above 10^{15} eV, the only way to study the main properties of primary CR flux (energy spectrum, mass composition, anisotropy) is the registration of extensive air showers (EAS) on the surface of the Earth. EAS is a nuclear-electromagnetic cascade initiated by an interaction of primary CR with the nuclei in the atmosphere.

The EAS muon component is formed mainly as a result of the decays of pions and kaons produced in numerous interactions of hadrons in the atmosphere and is often used to obtain information on the mass composition of primary CR and to check hadronic interaction models.

Combined Muon Measurements

- Muon lateral density in EAS as reported by 9 (10) experiments

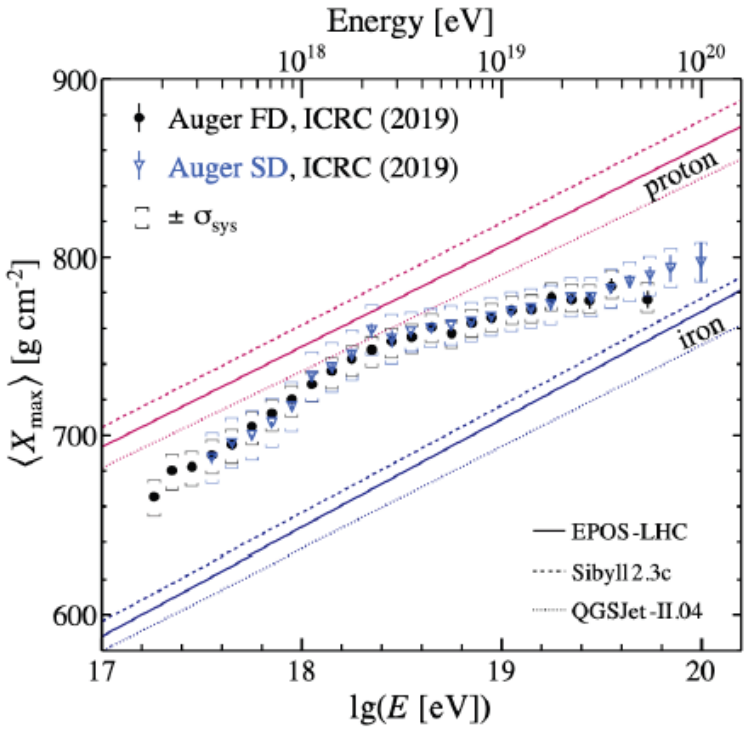


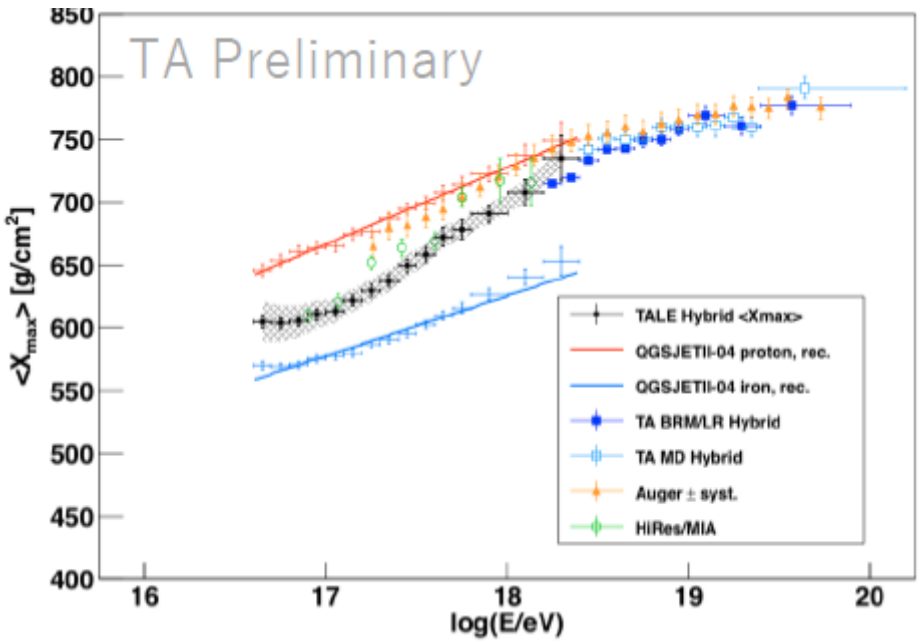
[D. Soldin et al., PoS ICRC2021 (2021) 349]

$$Z = \frac{\ln(N_\mu^{\mathrm{det}}) - \ln(N_\mu^{\mathrm{p\,sim}})}{\ln(N_\mu^{\mathrm{Fe\,sim}}) - \ln(N_\mu^{\mathrm{p\,sim}})}$$

N_μ^{det} is the observed value (muon density, number of muons, intensity of muon bundles, etc.), $N_\mu^{p\,sim}$ and $N_\mu^{Fe\,sim}$ are the calculated estimates of this value for air showers initiated by primary protons and iron nuclei; $Z = 0$ corresponds to pure proton mass composition and $Z = 1$ to pure iron one.

Measurements of the development maximum X_{max} of air showers by the fluorescence method (electron-photon component)



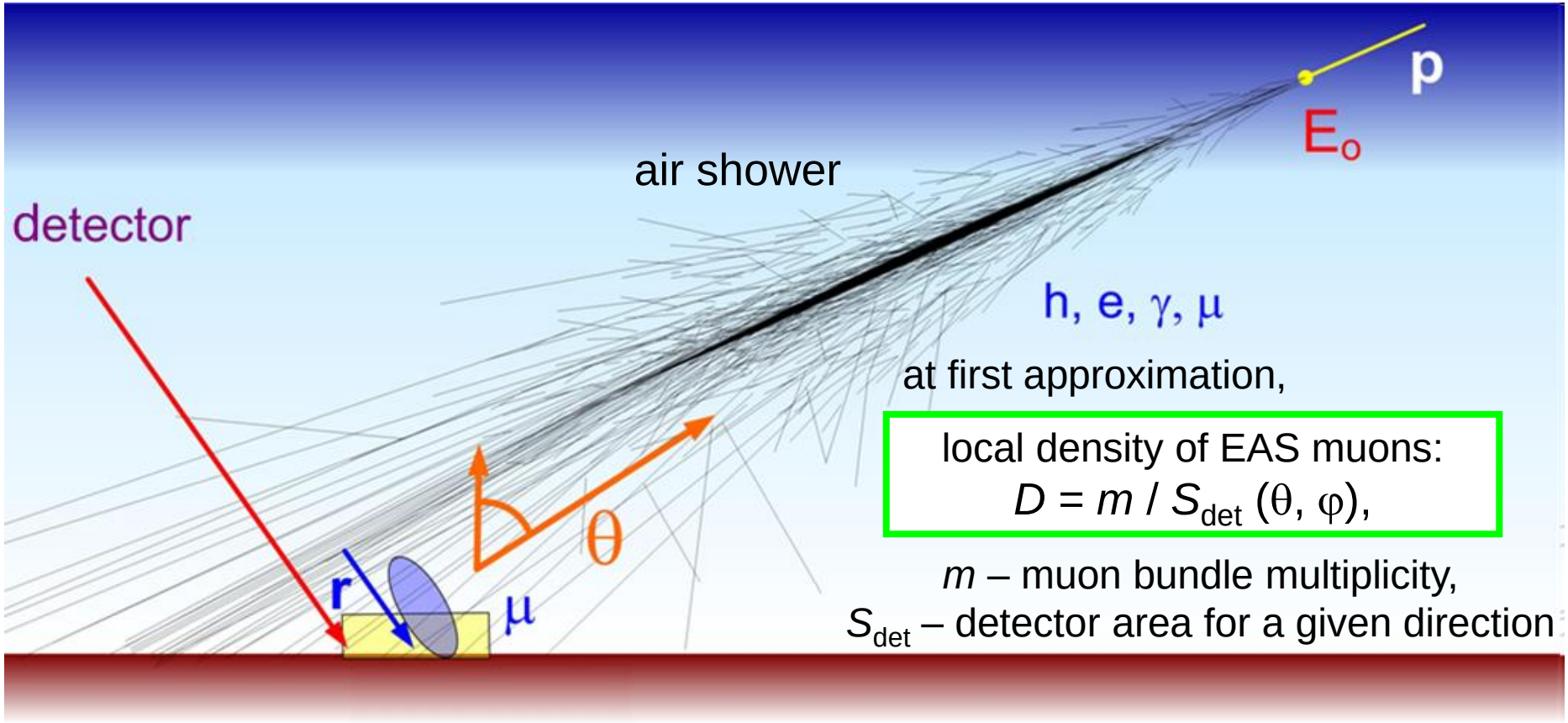


Antonella Castellina, for the Pierre Auger Collaboration, ISVHECRI-2022

Hiroyuki Sagawa, on behalf of Telescope Array Collaboration, ISVHECRI-2022

Data of experiments on investigations of muon content in air showers at ultra-high energies (heavy mass composition) contradicts the fluorescence data on X_{max} which favor a light mass composition of primary cosmic rays at the energies around 10^{18} eV.

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



In an individual muon bundle event, local muon density *D* (at the observation point) is measured, as dimensions of the air shower in muon component are much larger than the size of the NEVOD-DECOR setup. Distribution of events in muon density *D* forms the LMDS.

At the same muon density, different zenith angles correspond to substantially different (by the orders of magnitude) characteristic energies of primary cosmic ray particles contributing to the selected events, as the lateral spread of muons in bundles increases with zenith angle.

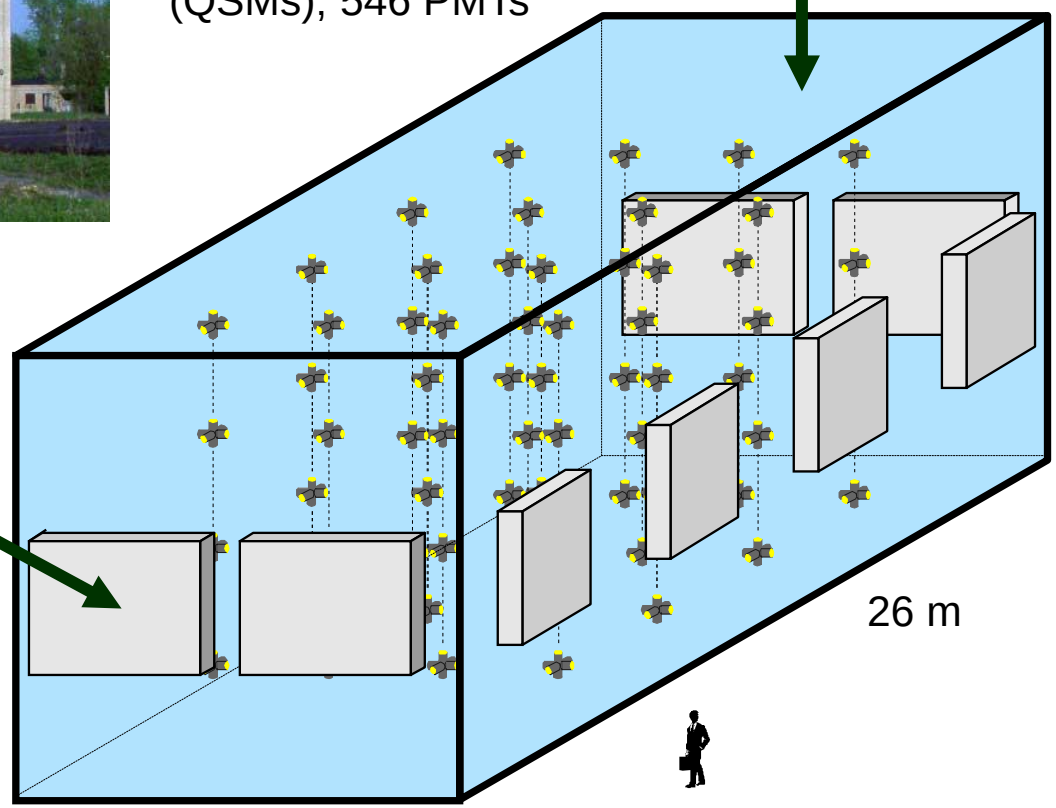
General view of the NEVOD-DECOR setup

Cherenkov water detector NEVOD (volume 2000 m^3)

spatial lattice of 91 quasi-spherical measuring modules (QSMs); 546 PMTs

Coordinate-tracking detector DECOR (total area 70 m^2)

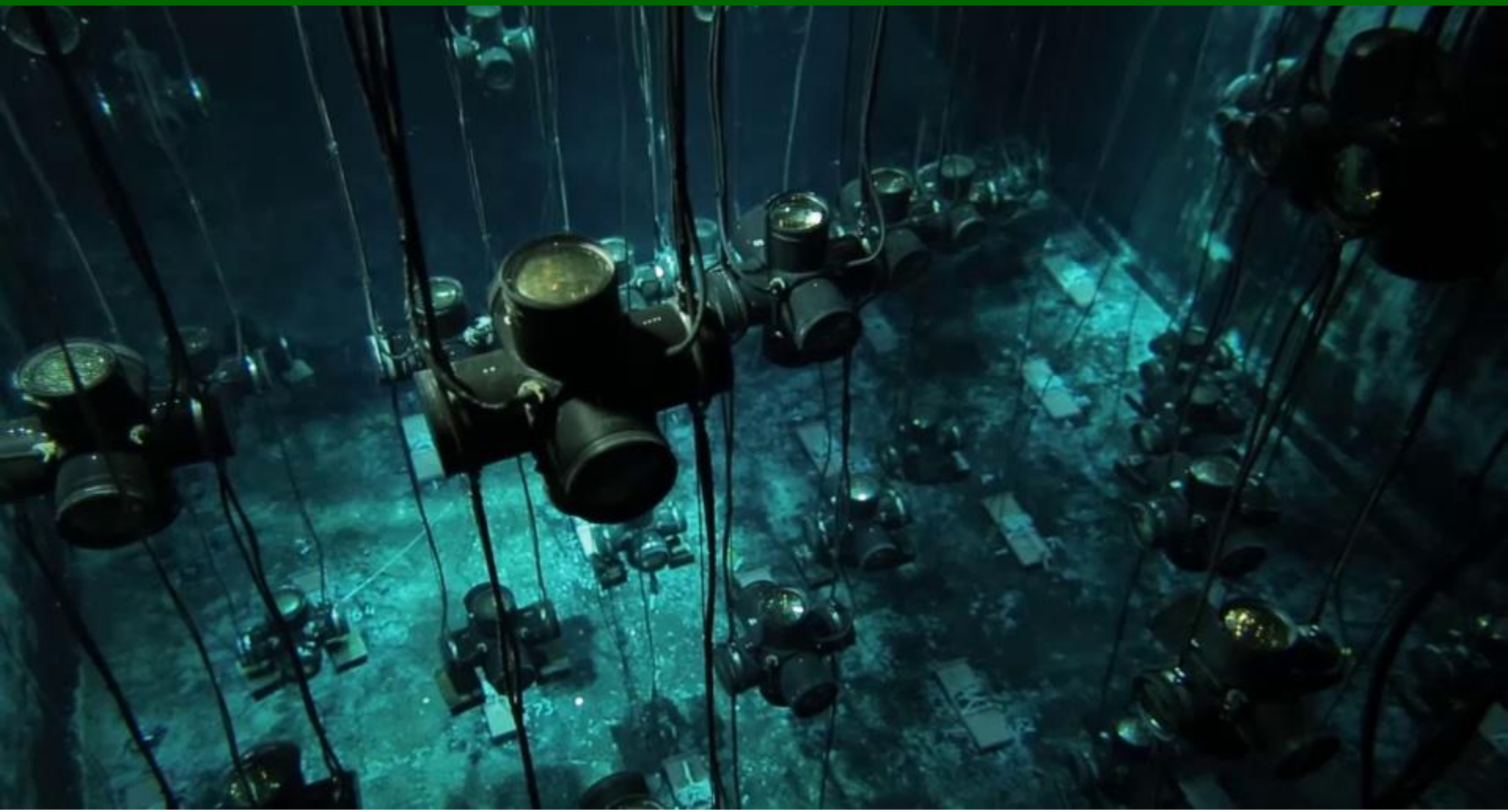
8 vertical supermodules (SMs) of streamer tube chambers



DECOR supermodules 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.

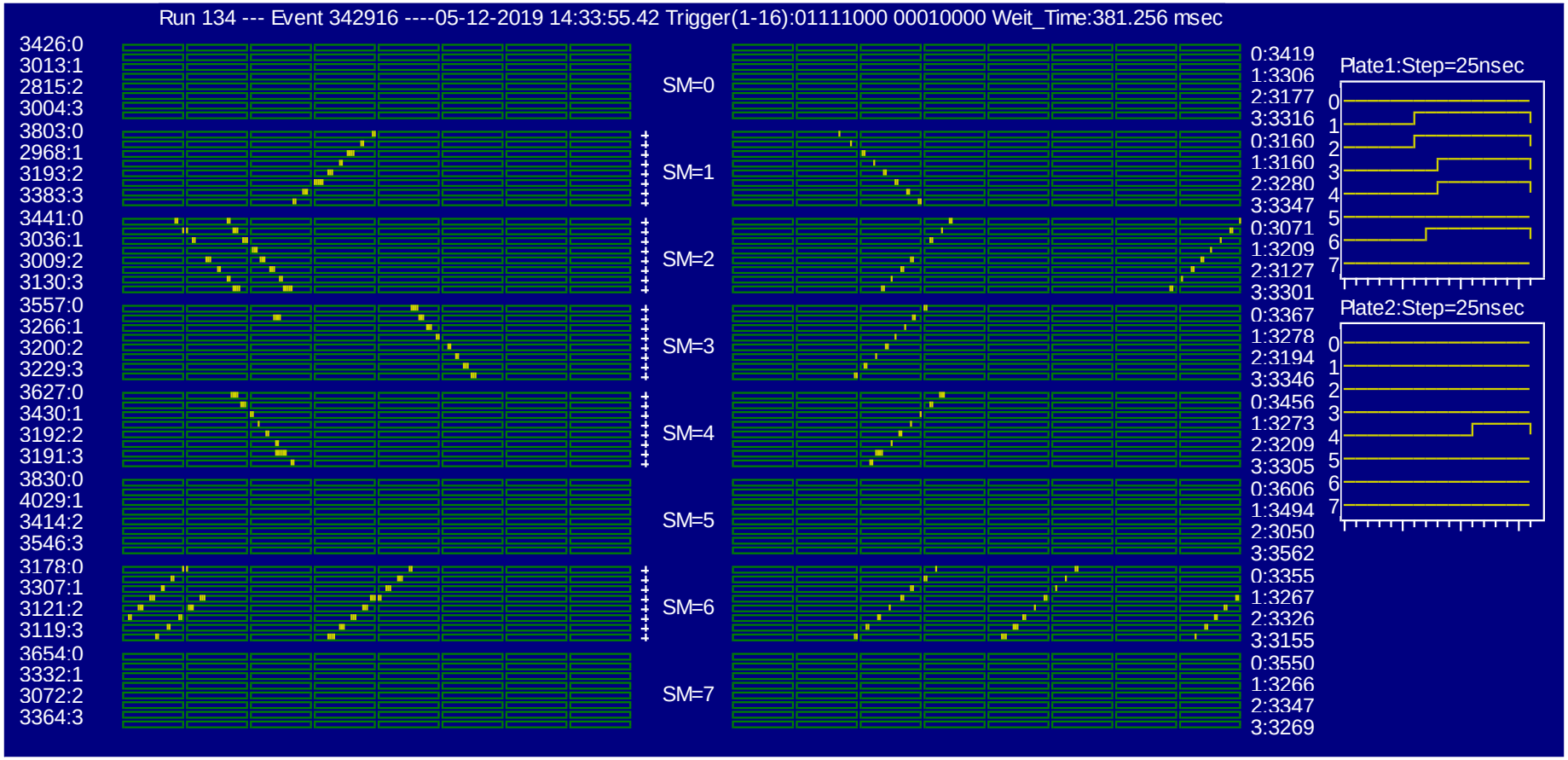
Detecting system of Cherenkov water calorimeter NEVOD



91 QSMs are arranged in an array of 25 vertical strings. Each QSM consists of 6 low-noise 12-dynode FEU-200 photomultipliers with flat 15 cm diameter photocathodes directed along rectangular coordinate axes. A wide dynamic range (1 – 10^5 photoelectrons) is provided due to 2-dynode signal readout and allows to measure energy deposit of muon bundles.

Muon bundle event in DECOR supermodules

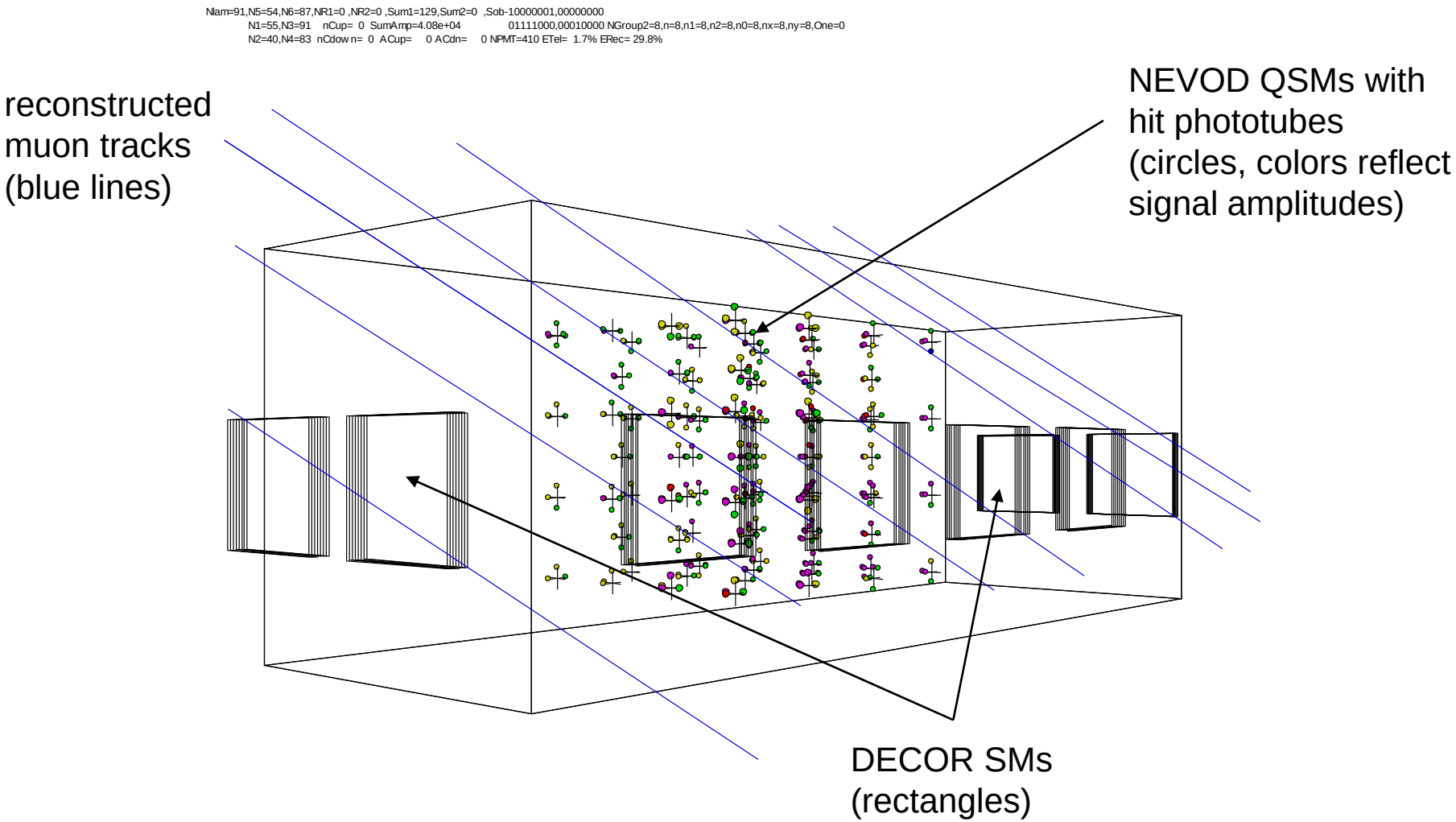
multiplicity m = 8 particles, zenith angle $\theta \approx 57°$



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

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

An example of geometry reconstruction of muon bundle event detected by the NEVOD-DECOR setup



NEVOD-DECOR experimental data and simulation results

NEVOD-DECOR is the unique experiment where long-term systematic studies of cosmic ray muon bundles in a wide range of zenith angles are carried out.

Experimental data accumulated from **May 2012** to **March 2022** are used:

Multiplicity $\boldsymbol{m} \geq \mathbf{5}$ and zenith angles $\theta \geq \mathbf{55°}$ – **112.4 thousand events** ("live" observation time is 65 705 h);

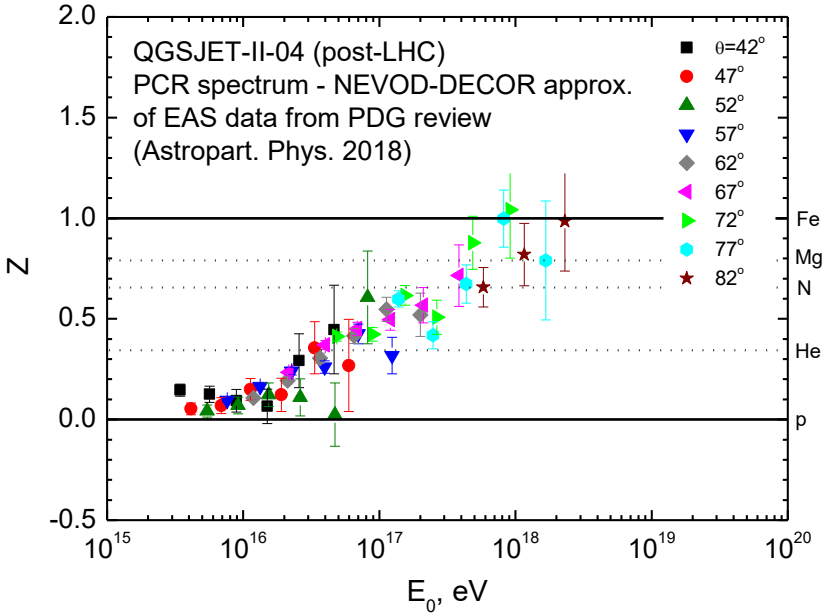
and **additionally,**

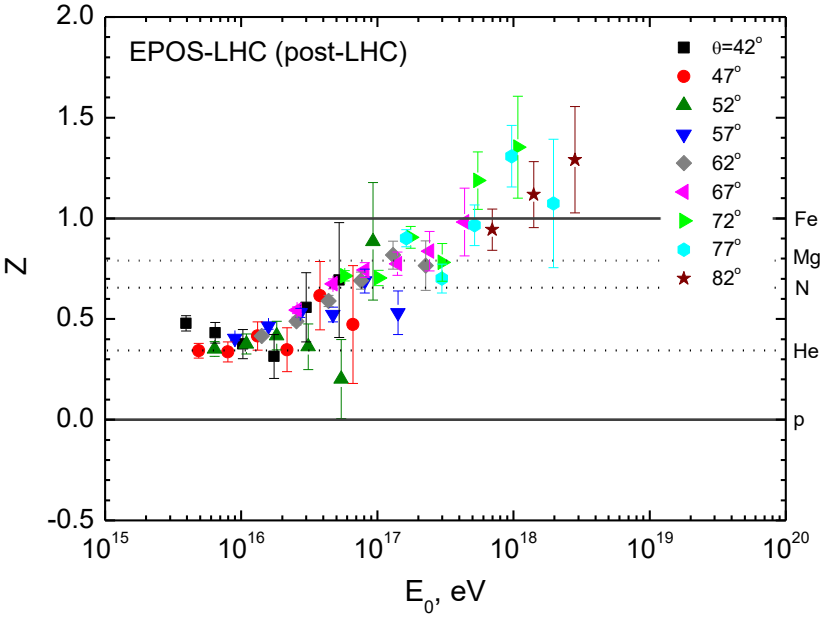
$\boldsymbol{m} \geq \mathbf{5}$ and, $\mathbf{40°} \leq \theta < \mathbf{55°}$ – **30.4 thousand events** ("live" time is 6 324 h).

Experimental LMDS are obtained from experimental distributions of event characteristics $N\,(m,\theta,\varphi)$ in a "detector-independent" form.

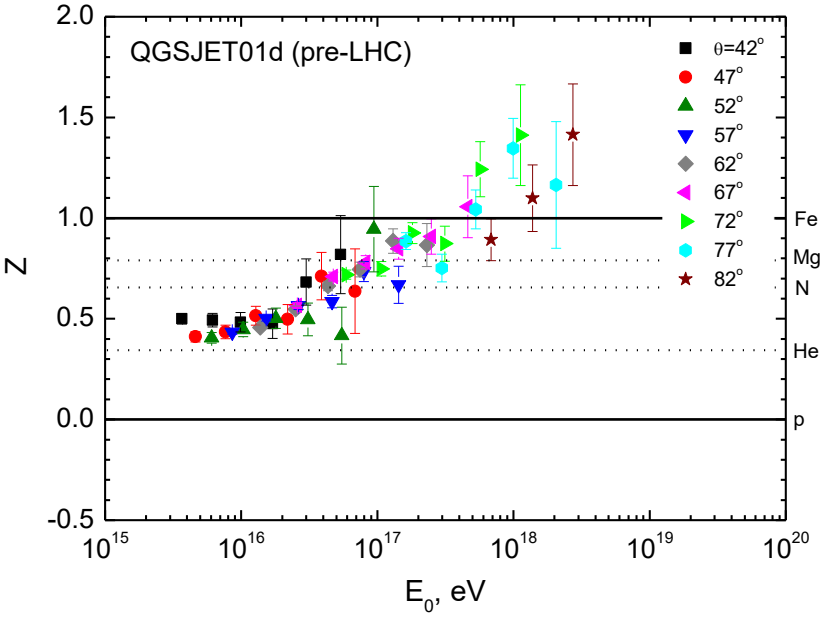
Expected LMDS are calculated using CORSIKA-based simulation of the EAS muon component and depend on: hadronic interaction model, primary mass composition, primary all-particle energy spectrum assumptions.

Comparison of LMDS at different θ angles by means of Z-scale (effect of the hadronic interaction model)





$$Z = \frac{\ln(N_\mu^{\mathrm{det}}) - \ln(N_\mu^{\mathrm{p\,sim}})}{\ln(N_\mu^{\mathrm{Fe\,sim}}) - \ln(N_\mu^{\mathrm{p\,sim}})}$$



Values of the *Z*-parameter obtained in different ranges of zenith angles from 40 to 90° overlap and are in good agreement with each other.

Fast increase in *Z*-parameter at the energies above 10^{17} eV is observed for all 3 models.

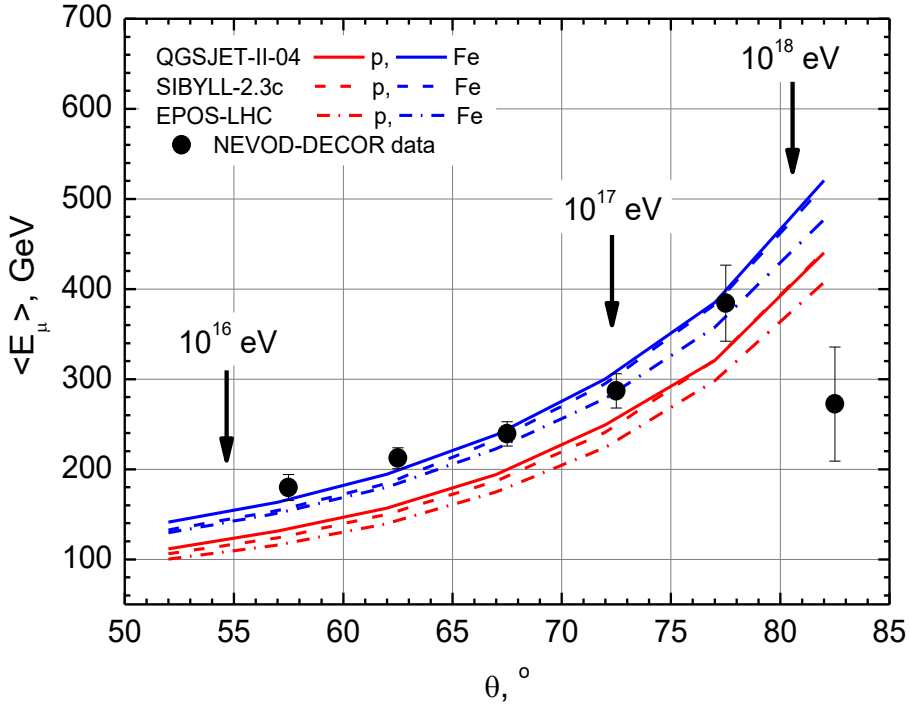
A possible approach to “muon puzzle” solution

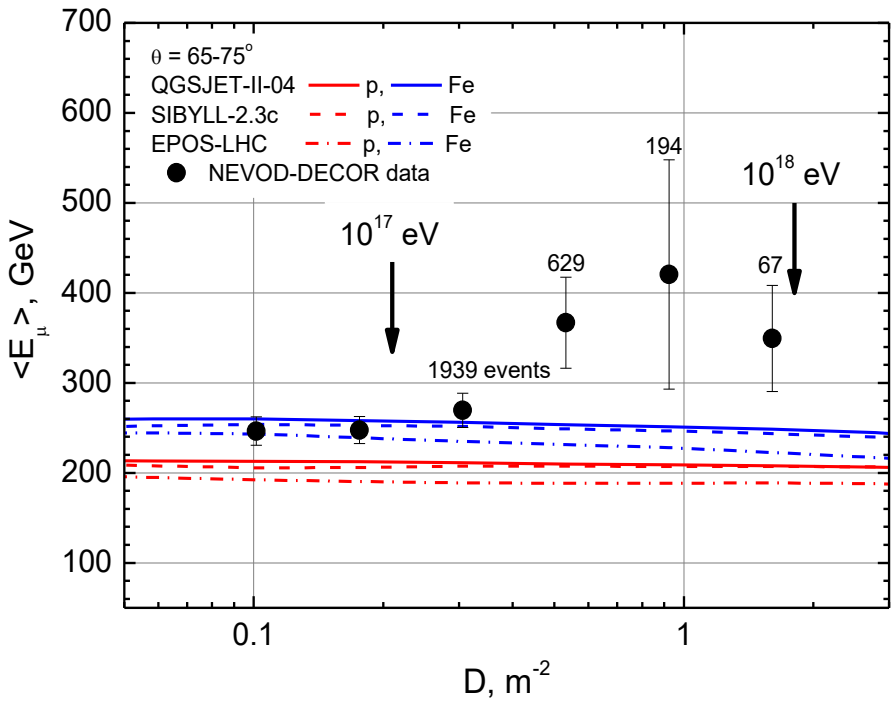
The key to the muon excess solution can be the study of the energy characteristics of the EAS muon component and their changes with increasing energy of primary cosmic rays.

One of the possible approaches is to measure the energy deposit of muon bundles in the Cherenkov water calorimeter, since muon energy loss in the matter almost linearly depends on their energy: $dE/dX \sim a + bE$

However, the energy deposit depends on the characteristics of the detector. In order to move to physical quantities, for example, muon energy losses, it is necessary to find their relationship with the yield of Cherenkov light (signals of the PMTs). For this purpose, a mathematical model of the NEVOD-DECOR setup was developed based on the Geant4 software package.

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





The average muon energy increases with zenith angle. The experimental data are in a good agreement with the expectation.

For large muon densities, corresponding to primary particles energies greater than 10^{17} eV, an increase in the average energy of muons in the bundles in comparison with the calculation results is observed (4.2-4.8 σ over calculation for primary protons and 3.1-3.7σ for iron nuclei).

Conclusions

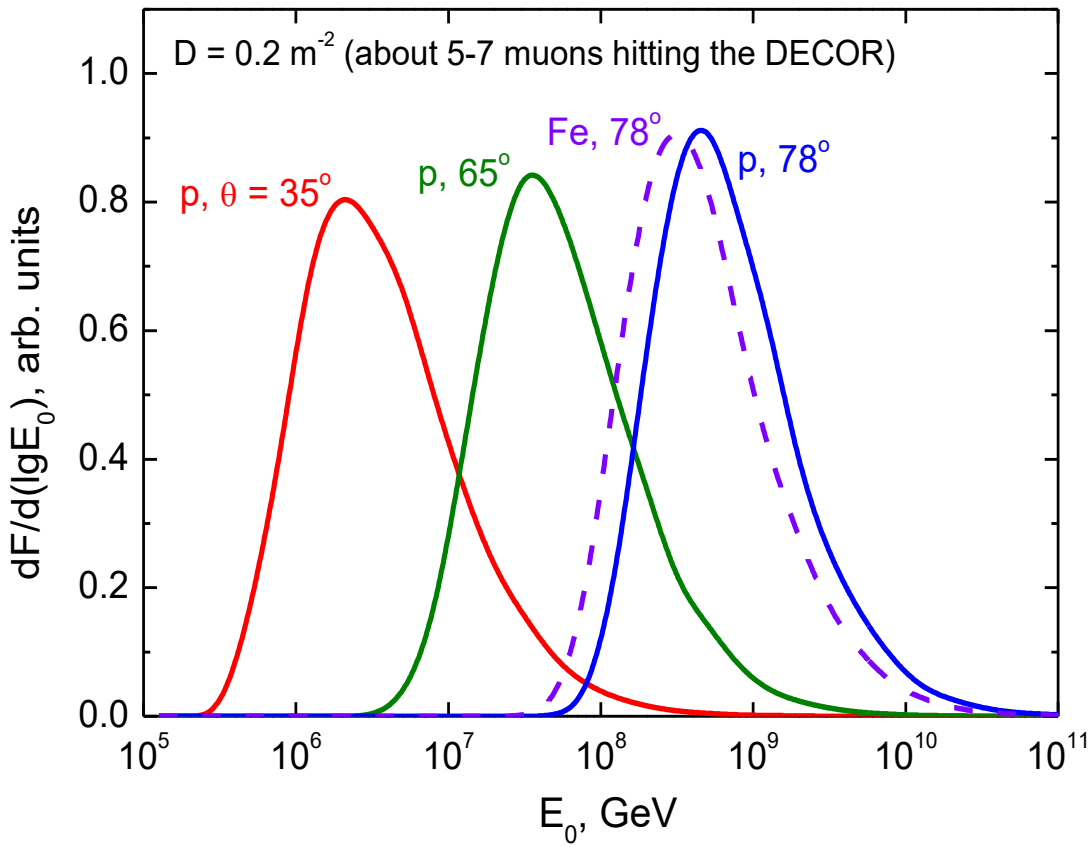
- The present NEVOD-DECOR data are only compatible with calculations if we assume extremely heavy mass composition at energies of primary particles about 10^{18} eV. It is consistent with data of several experiments on investigations of muon content in air showers.

- Moreover, an increase in the average energy of muons in the bundles is observed in comparison with the expected one for primary cosmic ray energies above 10^{17} eV.

- It gives reason to believe that a new physical features may emerge, which are not taken into account in modern hadronic interaction models, e.g. inclusion of a new mechanism of generation of high-energy muons.

Thank you for your attention!

Distribution of primary cosmic ray particle energies contributing to events with a fixed muon density at different zenith angles



$$D, \theta \rightarrow E_0$$

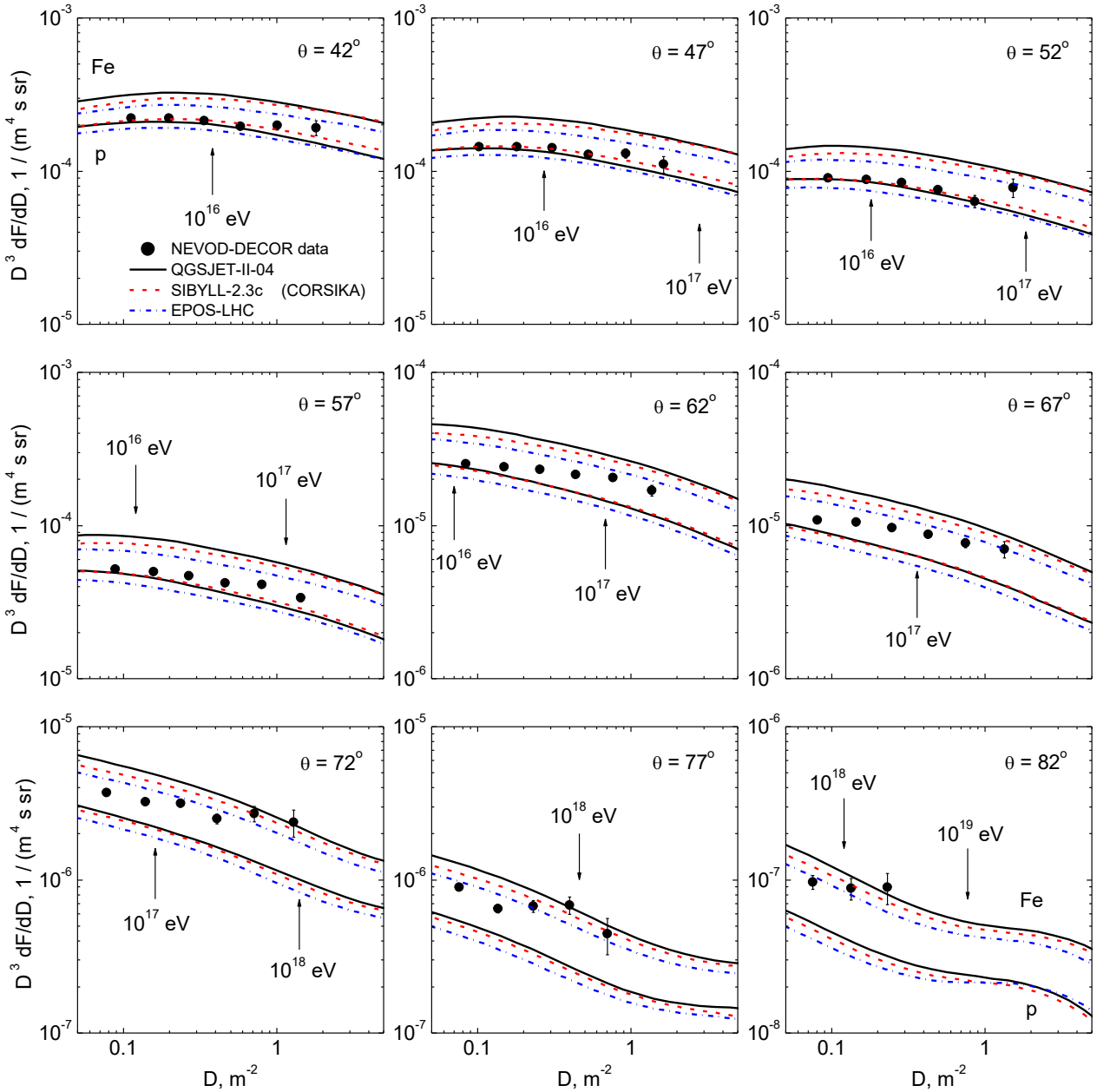
Contribution to events with a fixed local muon density *D* give showers with different primary energies, detected at random distances from the axis.

It is important to emphasize that at the same local density, muon bundles arriving at larger zenith angles will be associated with air showers from primary particles with higher energies (lateral spread of muons in the bundles increases).

Differential local muon density spectra for different zenith angles

At the energies ~ 10^{16} eV experimental points are close to the results of the calculations for a light mass composition.

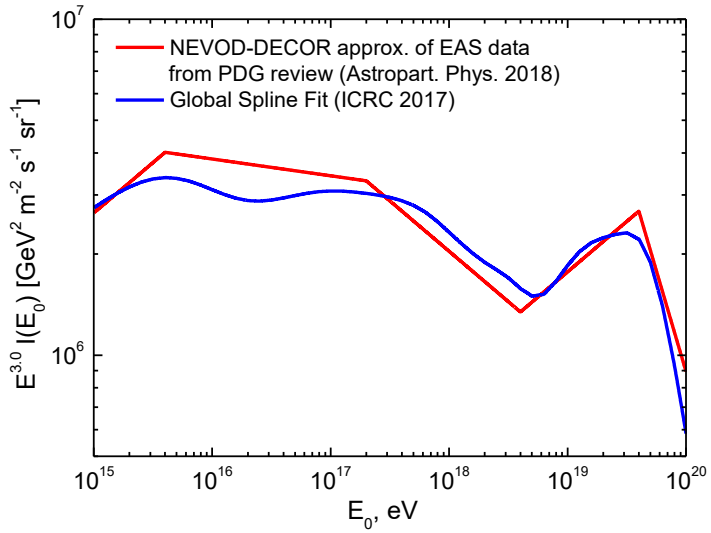
At the energy ~ 10^{18} eV, NEVOD-DECOR data and calculations are compatible only under the assumption of an extremely heavy mass composition.

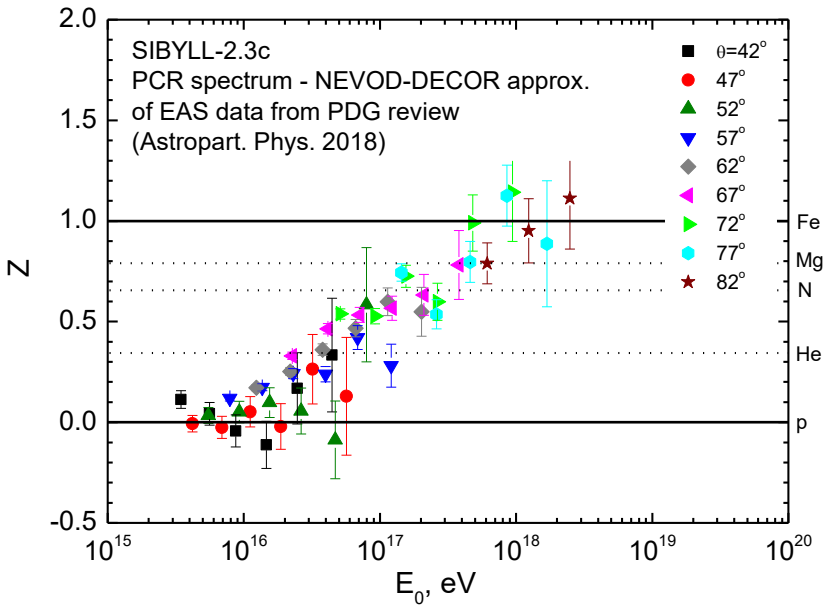


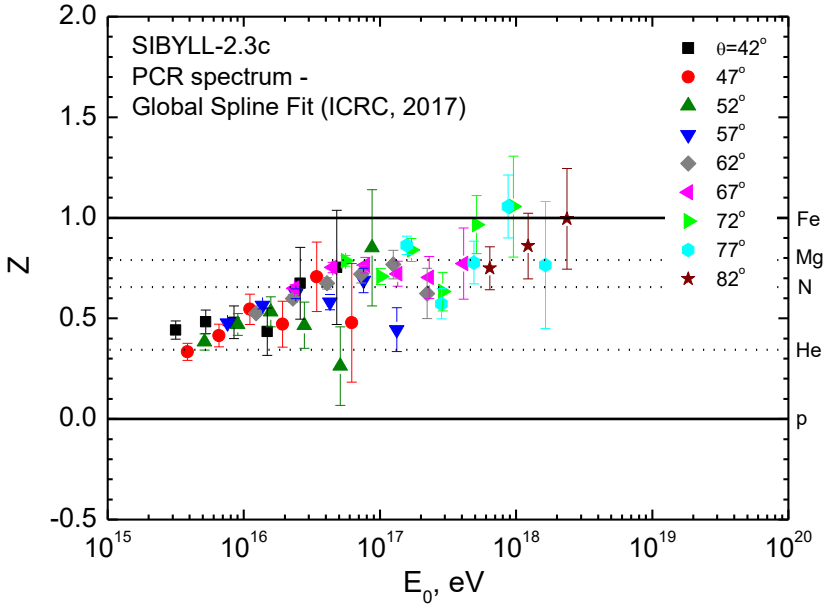
Comparison of LMDS at different θ angles by means of Z-scale (effect of the model of primary cosmic ray energy spectrum)

Two approximations of the all-particle primary energy spectrum were used: based on a PDG review of EAS data (NEVOD-DECOR) and Global Spline Fit model (WHISP).
Their differences is not large, but appreciable around 10-100 PeV.

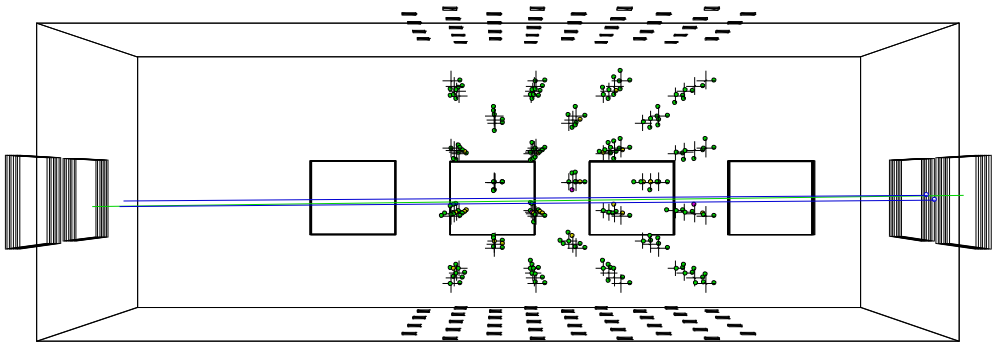
Intensity of muon bundles is compatible with calculations only assuming a heavy primary CR mass composition in the energy region ~ 10^{18} eV.



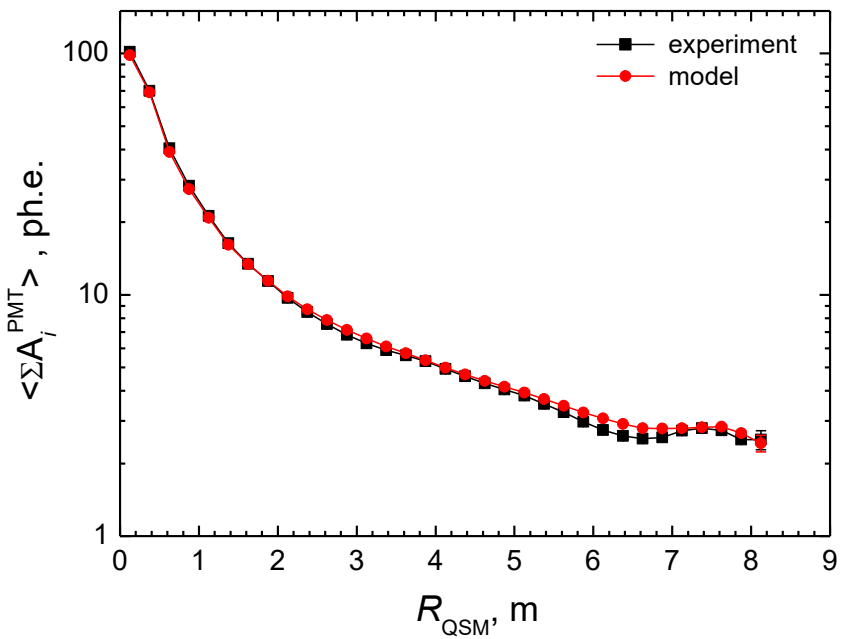




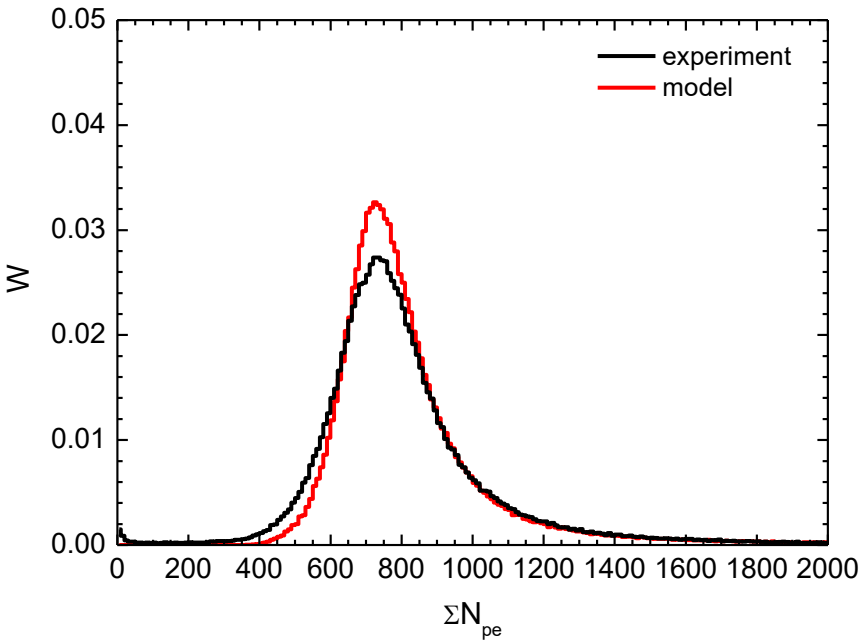
Calibration of the Cherenkov NEVOD detector model by the response to single near-horizontal muons



An example of the event with a single near-horizontal muon (average energy is about 100 GeV)



Dependence of the average response of QSM (6 PMTs) on the distance to muon track

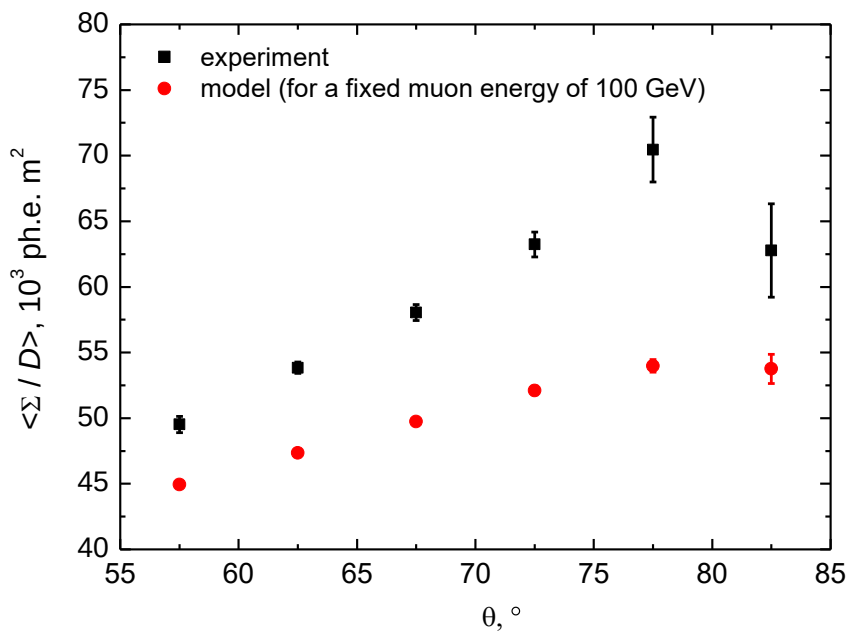


Distribution of events in the total number of photoelectrons

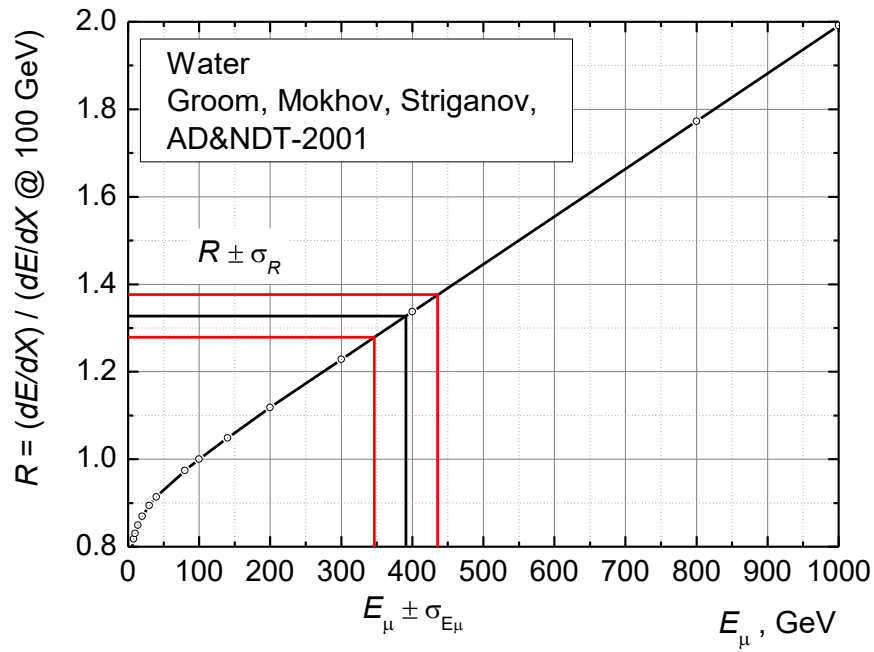
Transition from the average muon bundle specific energy deposit to the average energy of muons in the bundles

The ratio of the experimental values of the average specific energy deposit to the simulated ones for fixed muon energies of 100 GeV

$$R = (\Sigma / D)^{\exp} \Big/ (\Sigma / D)^{\mathrm{mod}}_{100\ \mathrm{GeV}}$$



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



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

NEVOD-DECOR experimental data

The method of identifying muon bundles of atmospheric origin in a coordinate detector is based on the parallelism of particle tracks (within 5° cone) recorded by the setup.

The event selection procedure consists of several stages:

- hardware level (3-fold coincidence of the signals from different SMs within the time gate of 250 ns);
- program reconstruction and selection;
- final classification of events and counting of tracks by several operators.

Special attention was paid to identifying possible systematic distortions that could affect the measurement results. The influence of such factors as residual contribution of the electron-photon and hadron components of the EAS to the response of the detector NEVOD, under-estimation of the response due to the digitization threshold, some changes of the registration conditions in different measurement series, efficiency of the DECOR response, masking of tracks, etc. were taken into account.