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Studying muon bundles of inclined air showers in the NEVOD-DECOR experiment

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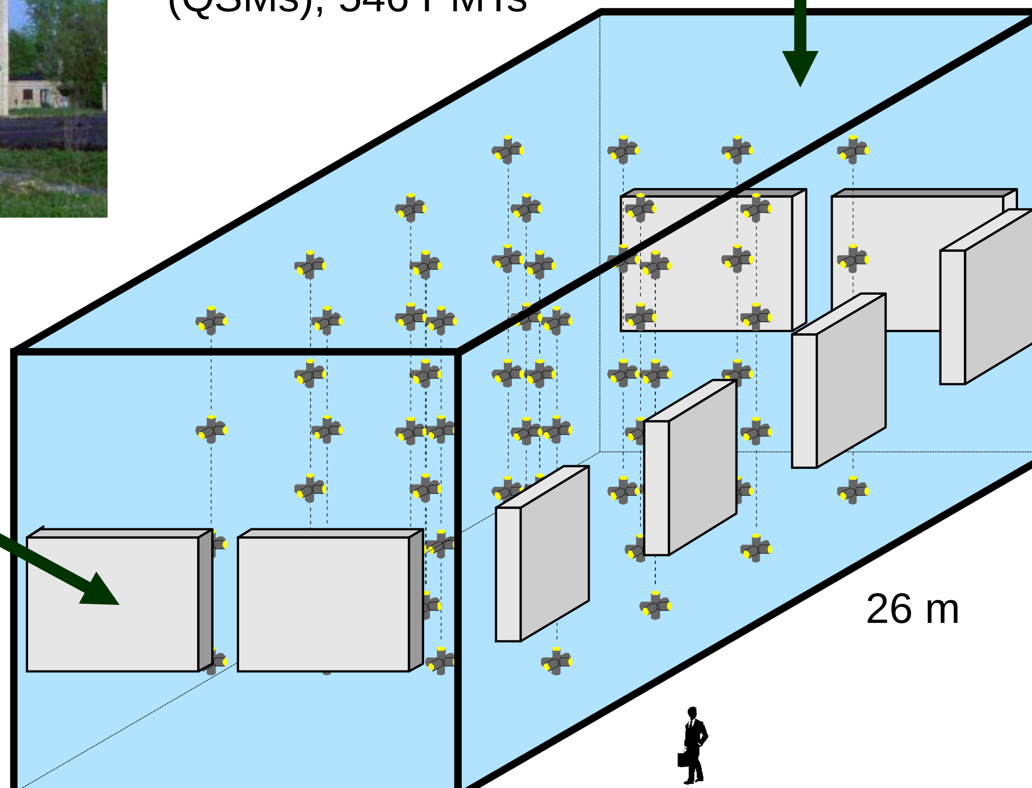
General view of the NEVOD-DECOR setup

Cherenkov water detector NEVOD (volume 2000 m³)

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

Coordinate-tracking detector DECOR (total area 70 m²)

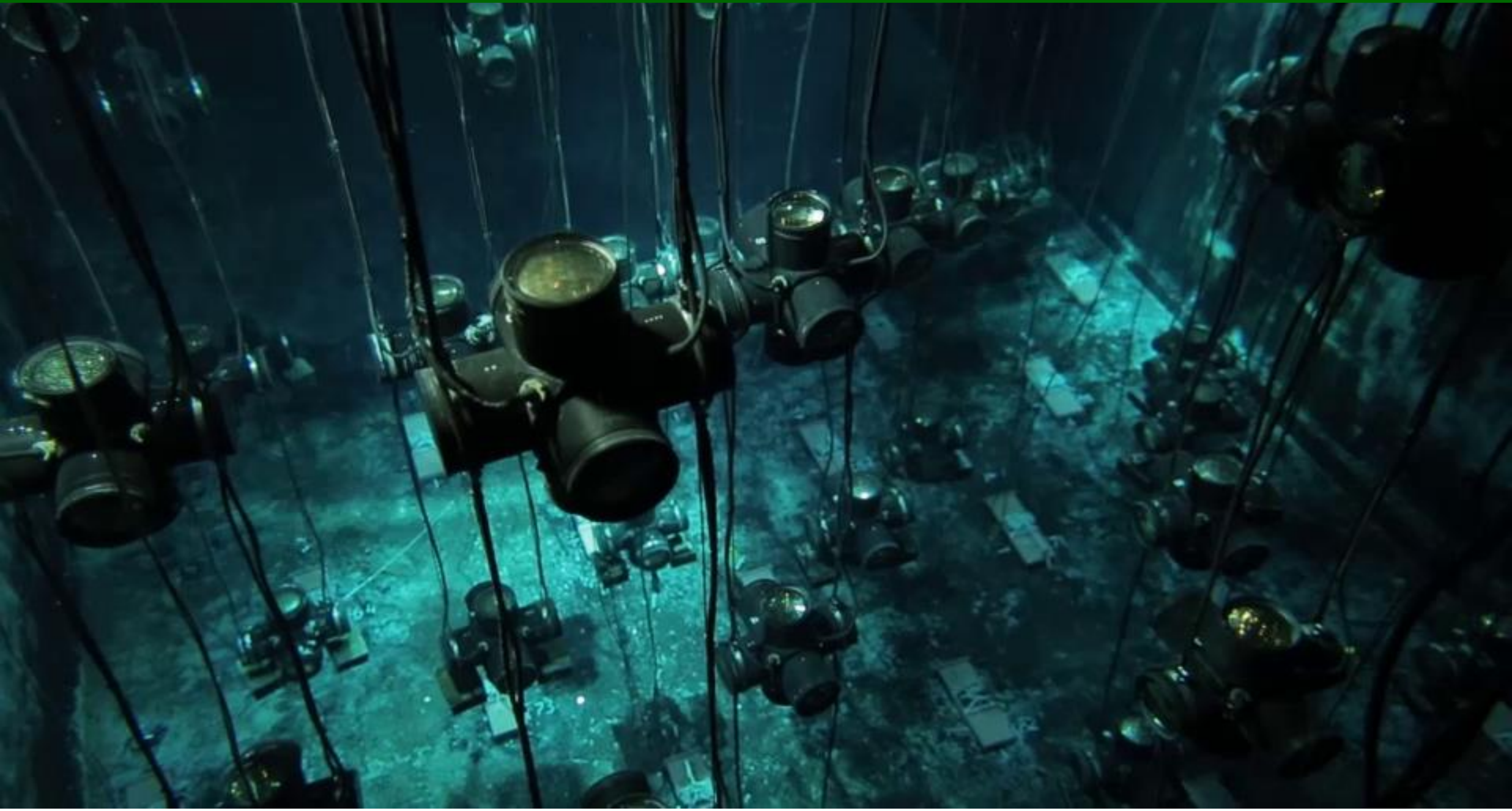
8 vertical supermodules (SMs) of streamer tube chambers



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.

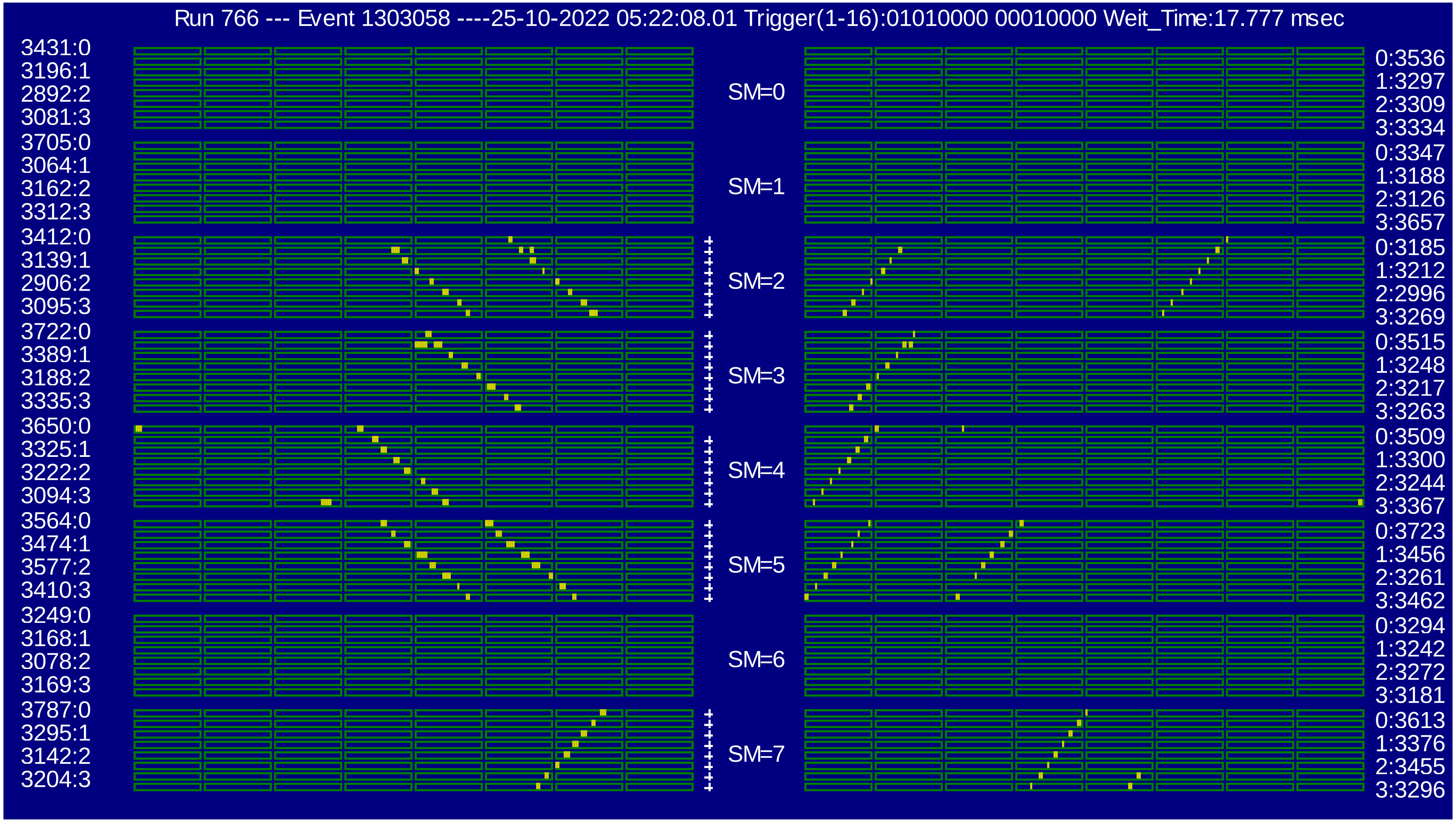
Detecting system of Cherenkov water calorimeter NEVOD



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

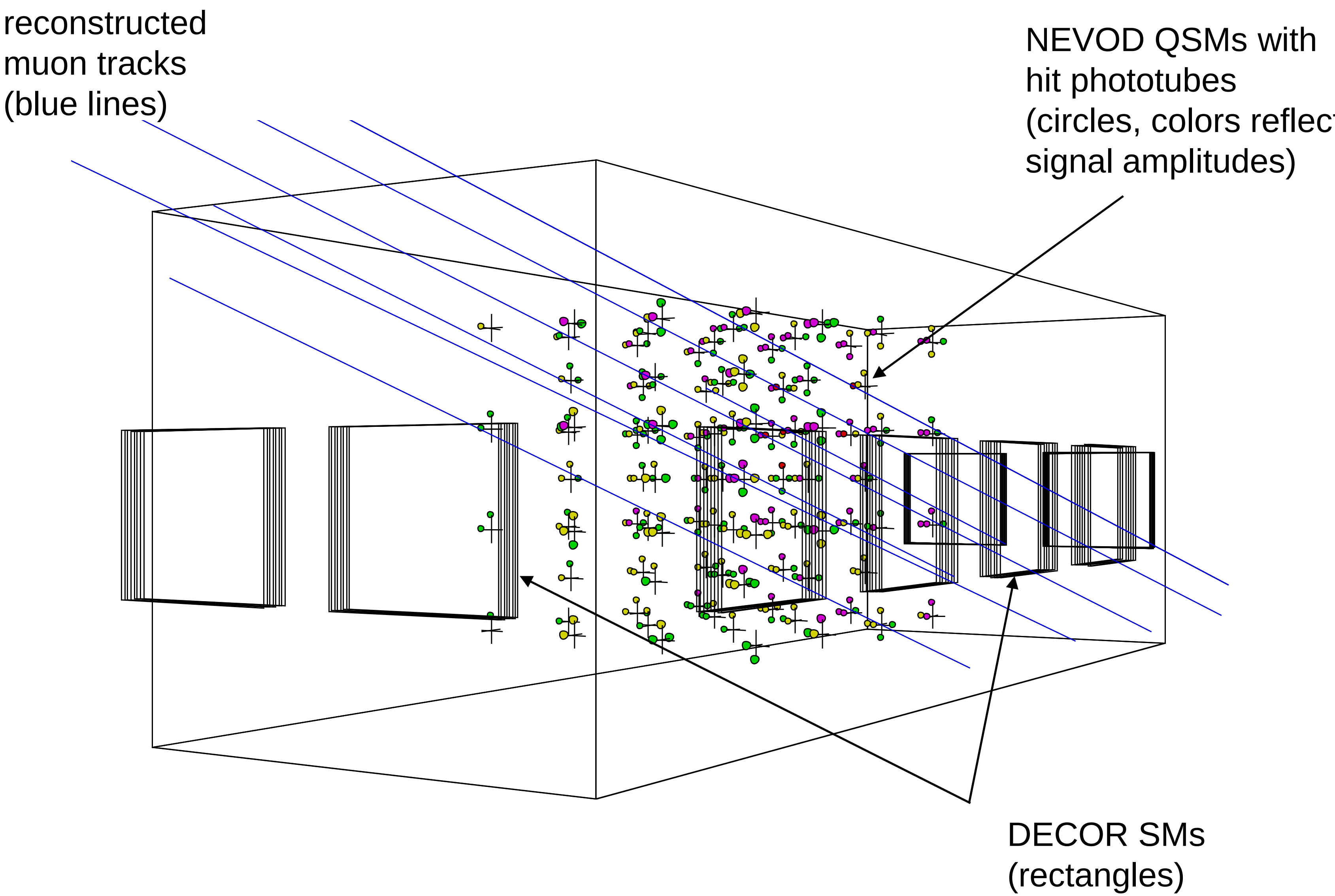
multiplicity m = 7 particles, zenith angle $\theta \approx 64^\circ$



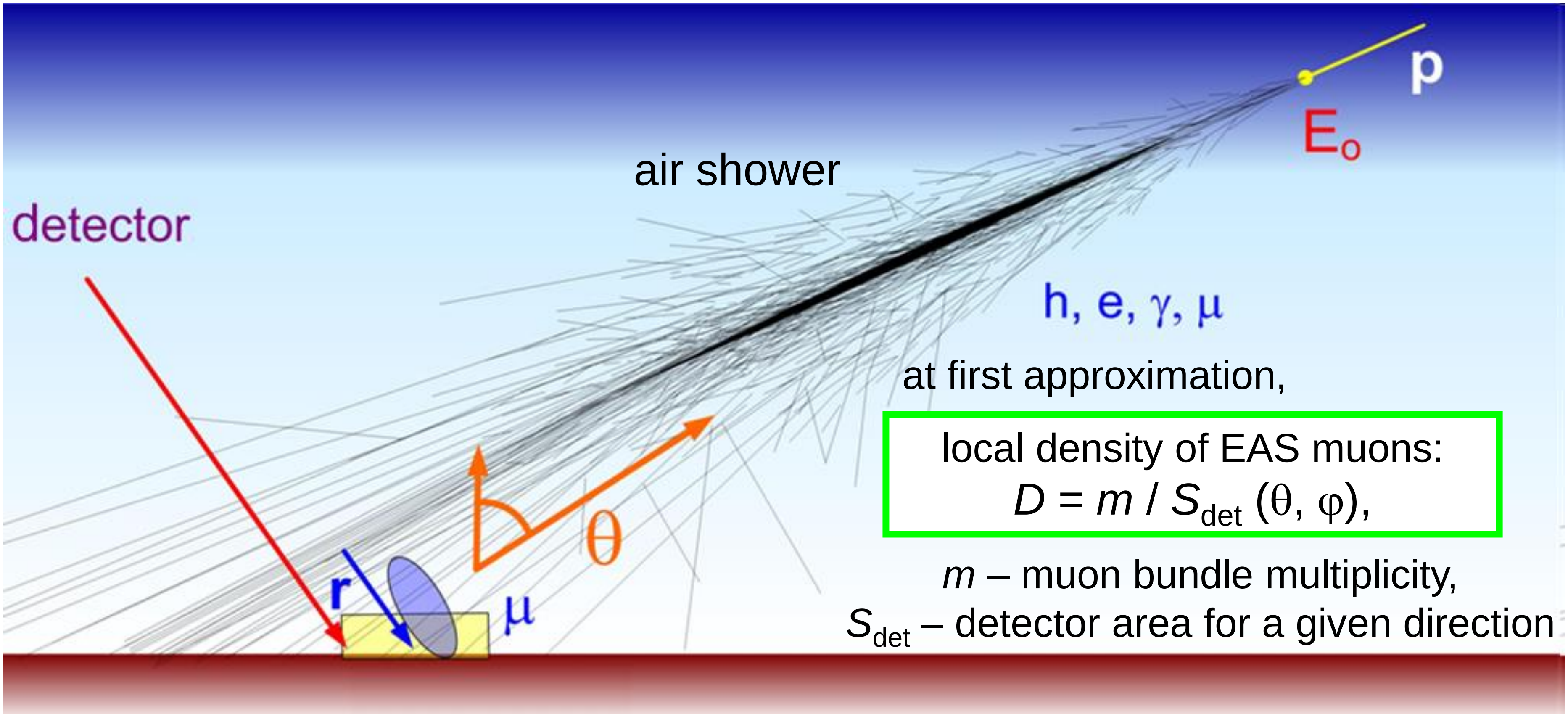
Y-coordinate (azimuth angle) *X-coordinate (projected zenith angle)*

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



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.

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 **December 2022** are used:

Multiplicity $\boldsymbol{m} \geq \mathbf{5}$ and zenith angles $\theta \geq \mathbf{55°}$ – **122133 events** (“live” observation time is 71 311 h);

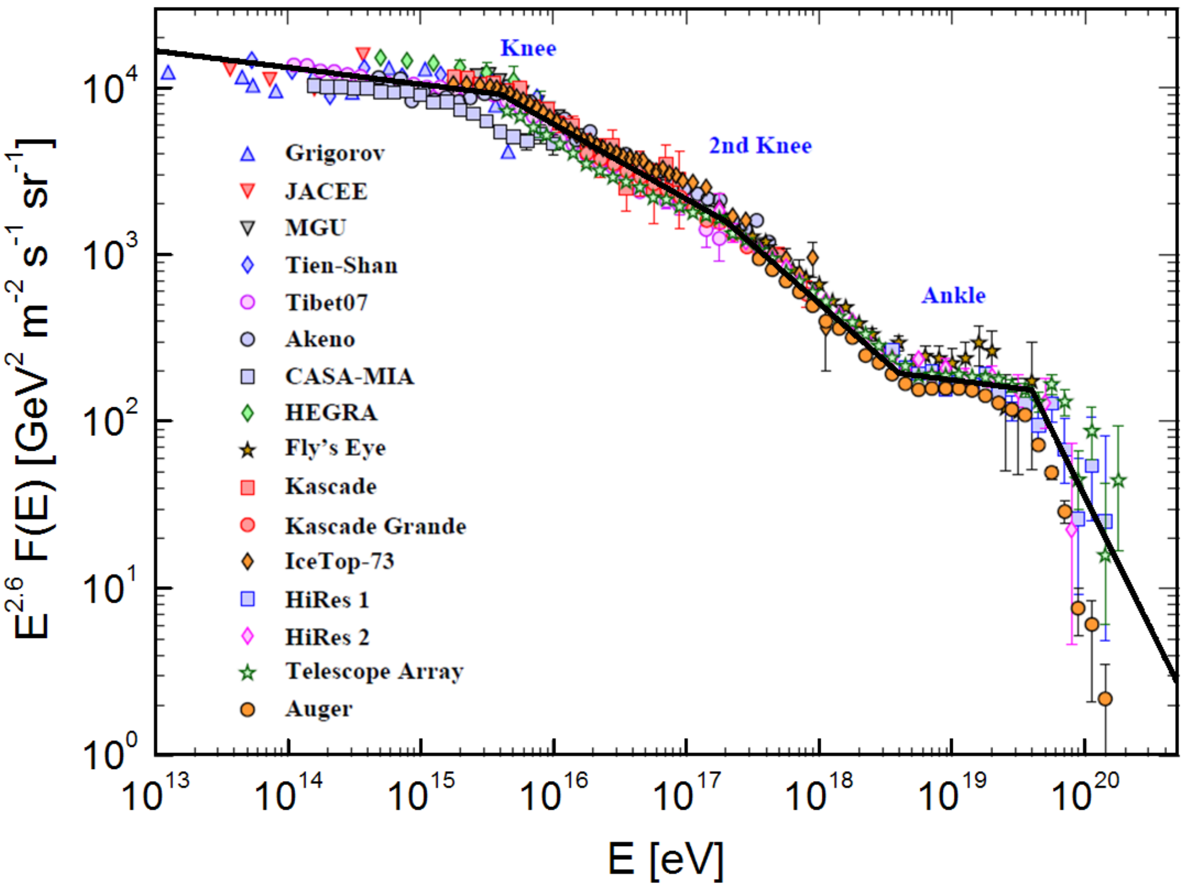
and **additionally,**

$\boldsymbol{m} \geq \mathbf{5}$, $\mathbf{40°} \leq \theta < \mathbf{55°}$ – **30 375 events** (“live” time is 6 324 h),
$\boldsymbol{m} = \mathbf{4}$, $\mathbf{40°} \leq \theta < \mathbf{55°}$ – **4 139 events** (“live” time is 1 043 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.

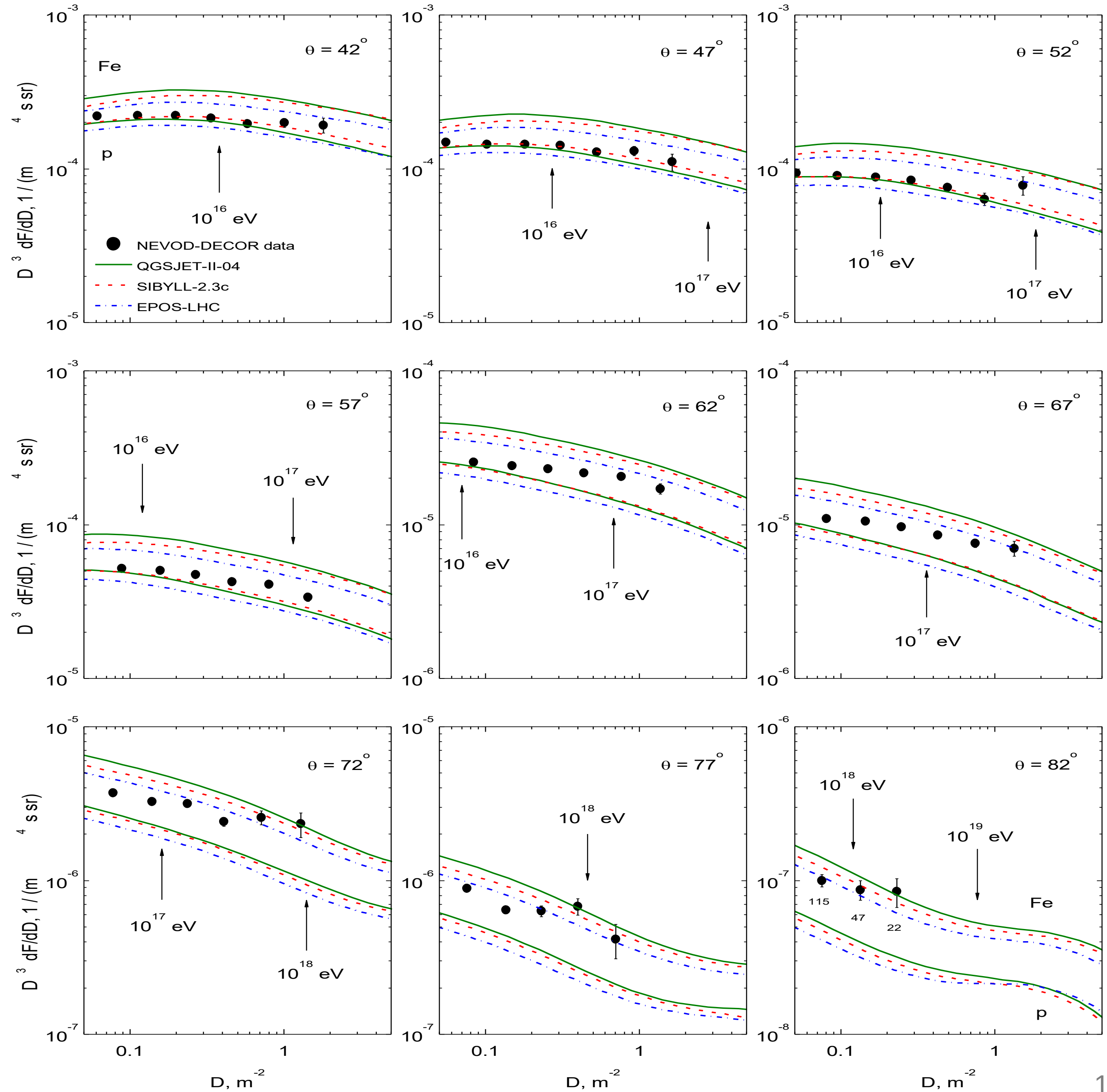
DECOR 2002-2007 + 2012-2016 // *Astropart. Phys. 98 (2018) 13*



The all-particle spectrum, PDG 2016

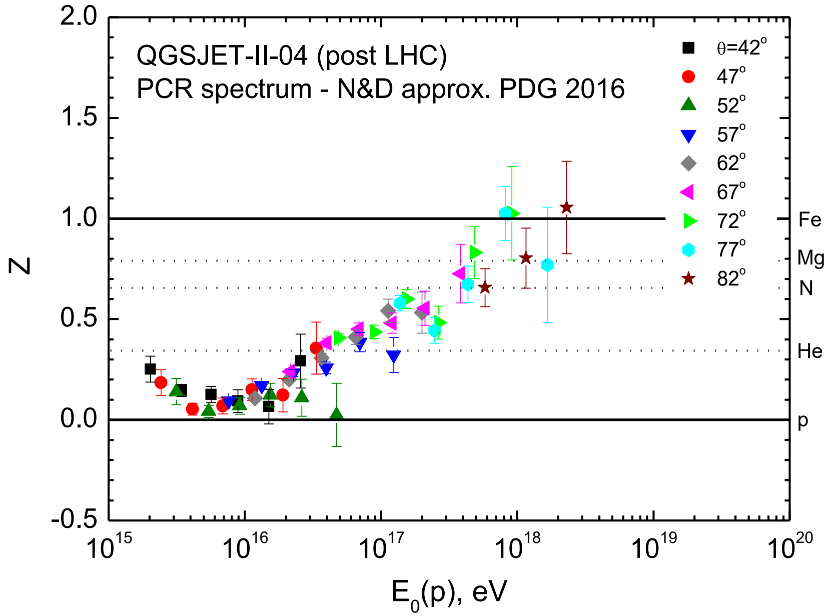
Differential local muon density spectra for different zenith angles

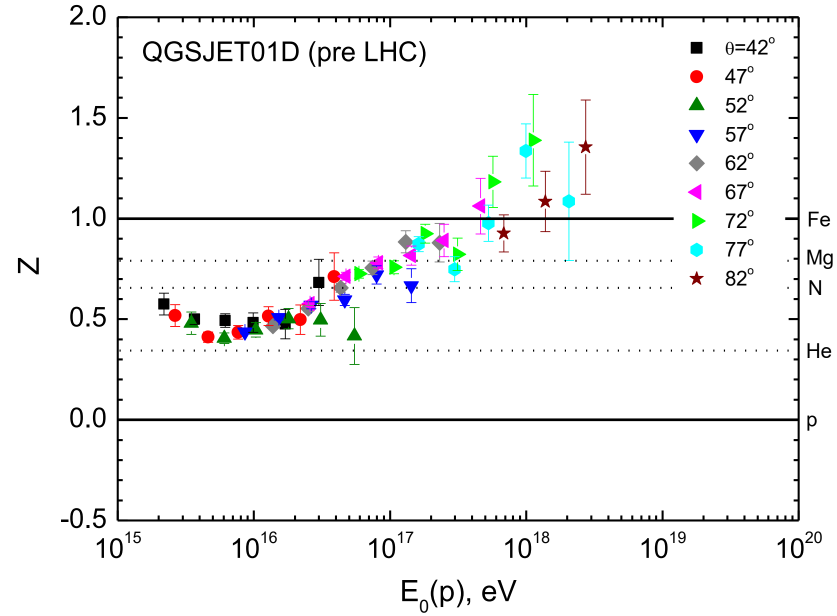
At the energies ~ 10^{16} eV experimental points are close to the results of the calculations for a light mass composition.



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 hadronic interaction model)

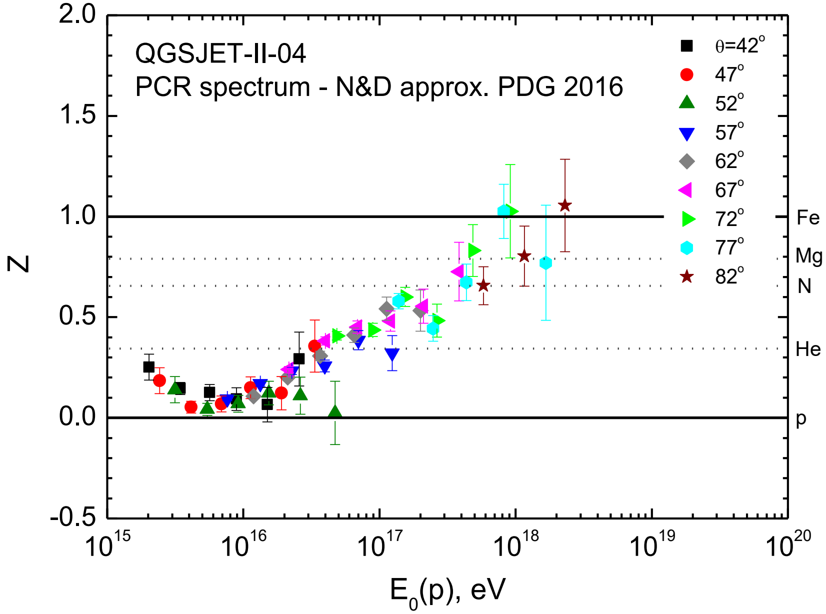


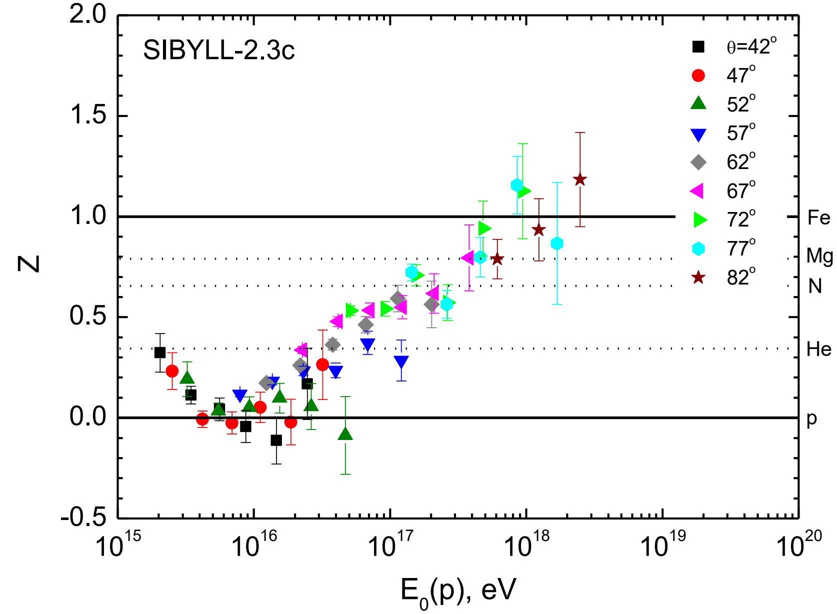


$$Z = \frac{\ln(N_\mu^{\mathrm{det}}) - \ln(N_\mu^{\mathrm{p\,sim}})}{\ln(N_\mu^{\mathrm{Fe\,sim}}) - \ln(N_\mu^{\mathrm{p\,sim}})}$$

N_μ^{det} is the observed value (number of muons, **local muon density spectrum**, etc.), $N_\mu^{\mathrm{p\,sim}}$ and $N_\mu^{\mathrm{Fe\,sim}}$ 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.

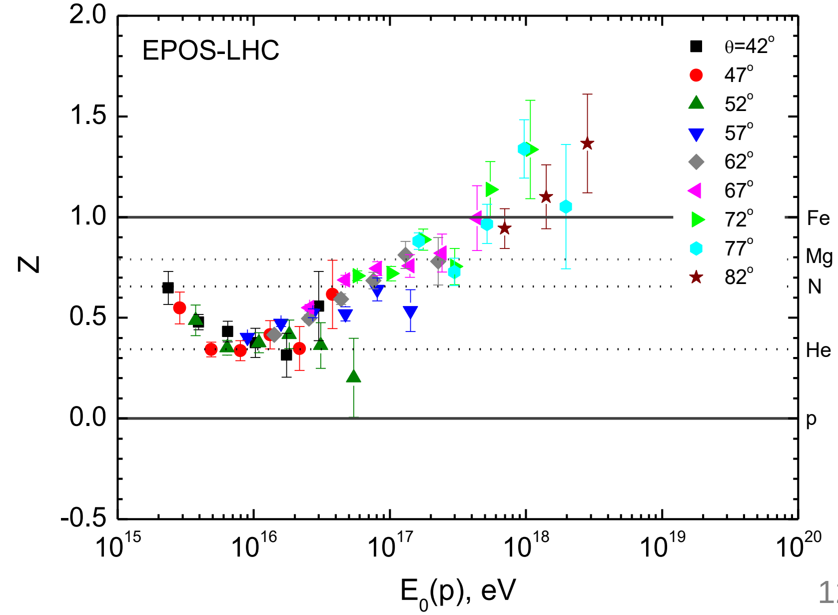
Comparison of LMDS at different θ angles by means of Z-scale (effect of the hadronic interaction model)



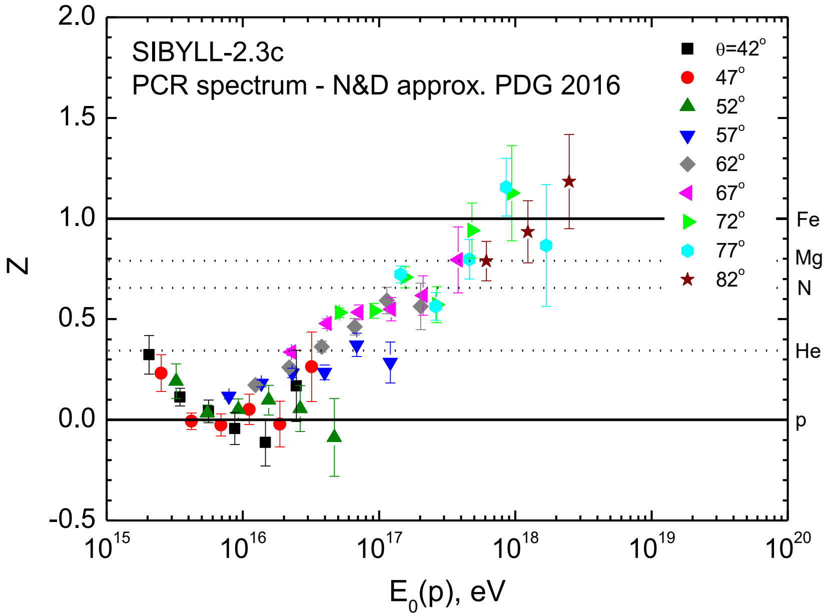


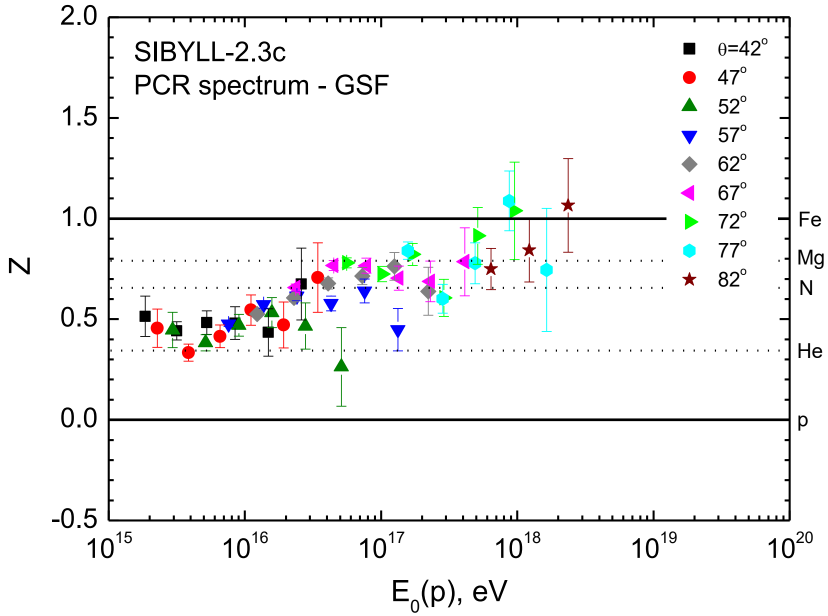
Values of the *Z*-parameter obtained in different ranges of zenith angles from 40 to 90° overlap and are in good agreement with each other.

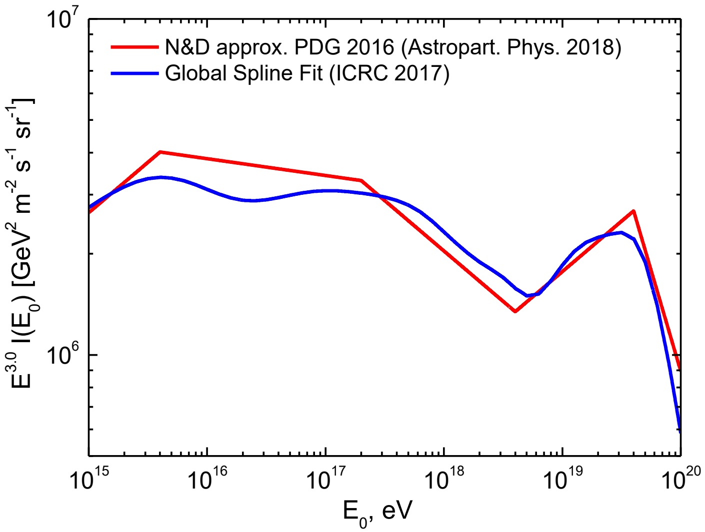
Fast increase in *Z*-parameter at the energies above 10^{17} eV is observed for all models.



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





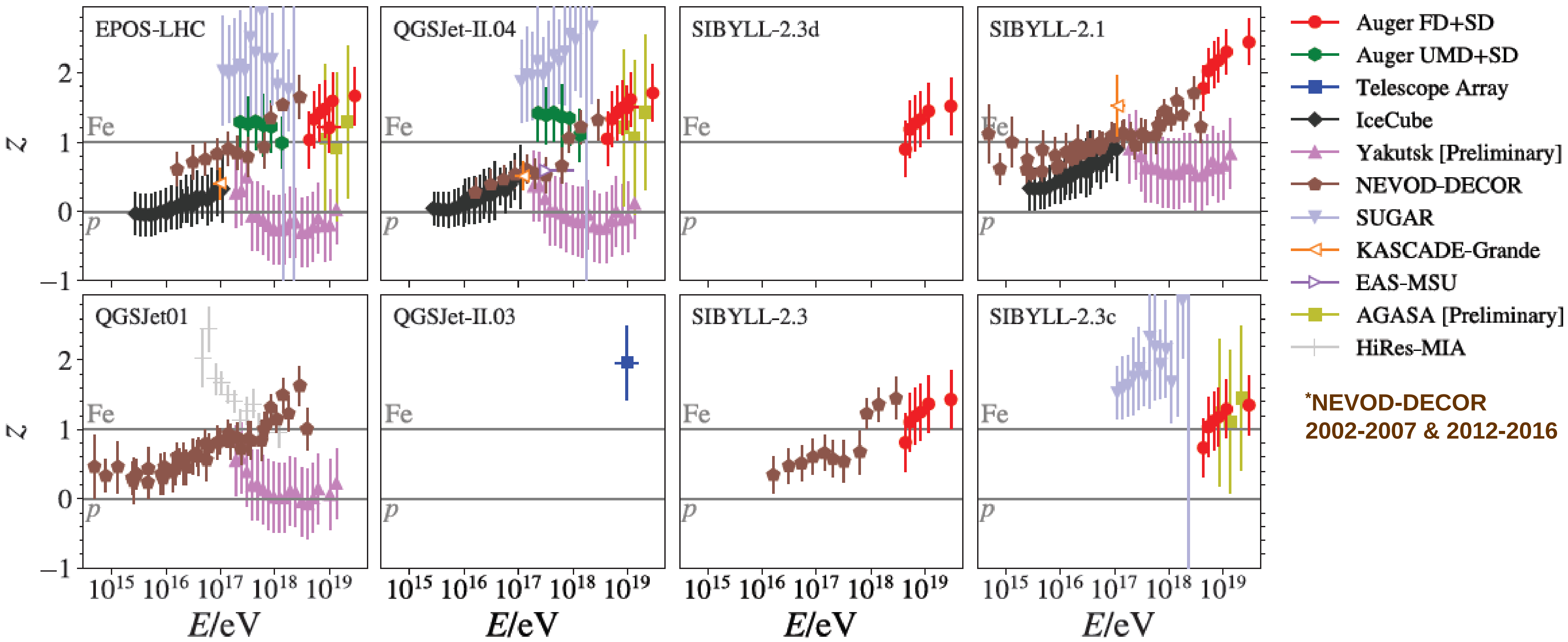


For interpretation of our data, assumption on the primary all-particle spectrum is necessary. We used an approximation of the all-particle primary energy spectrum which was based on a PDG review of EAS data.

Differences between our parameterization and Global Spline Fit is not large, but appreciable around 10-100 PeV.

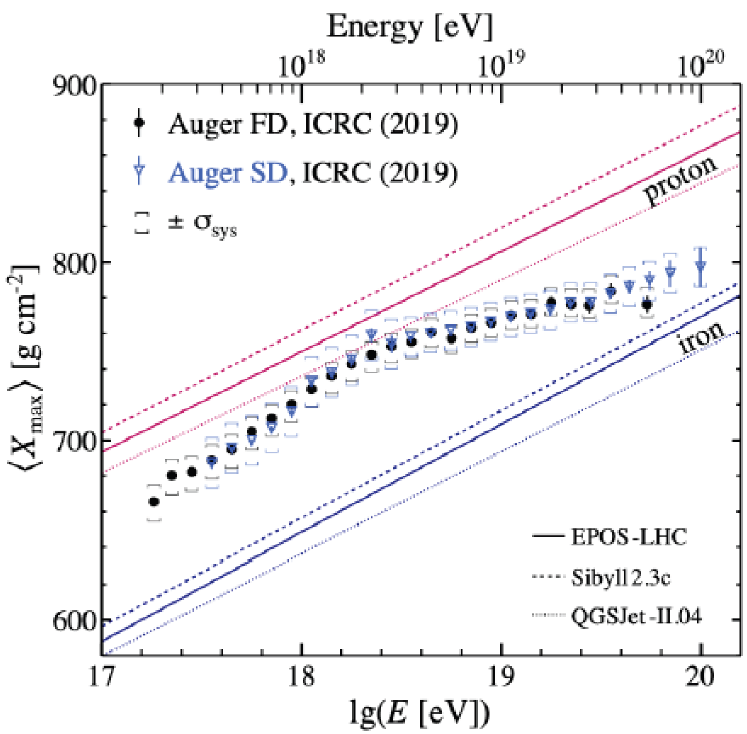
Combined Muon Measurements

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

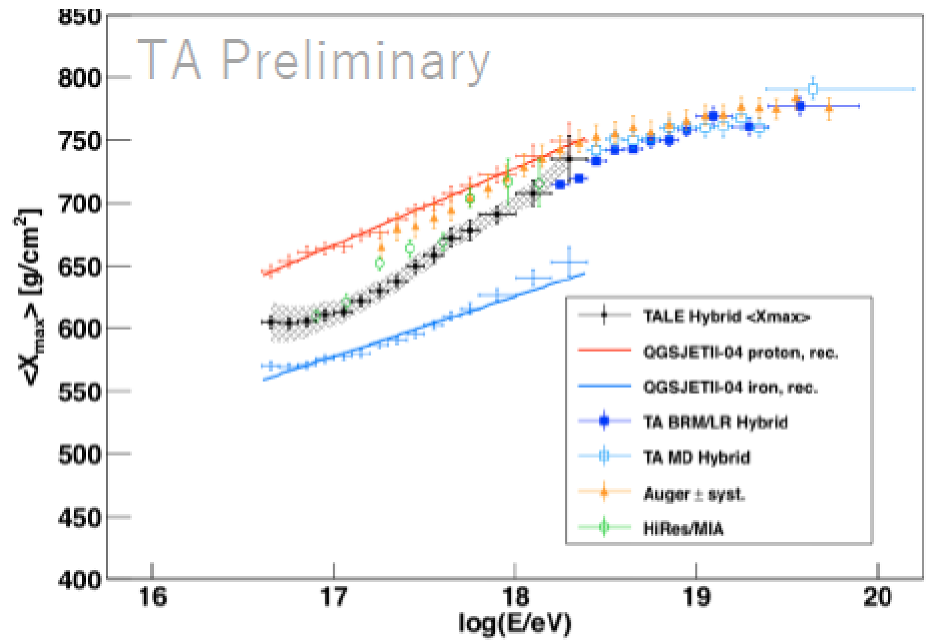


[D. Soldin et al., PoS ICRC2021 (2021) 349]

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



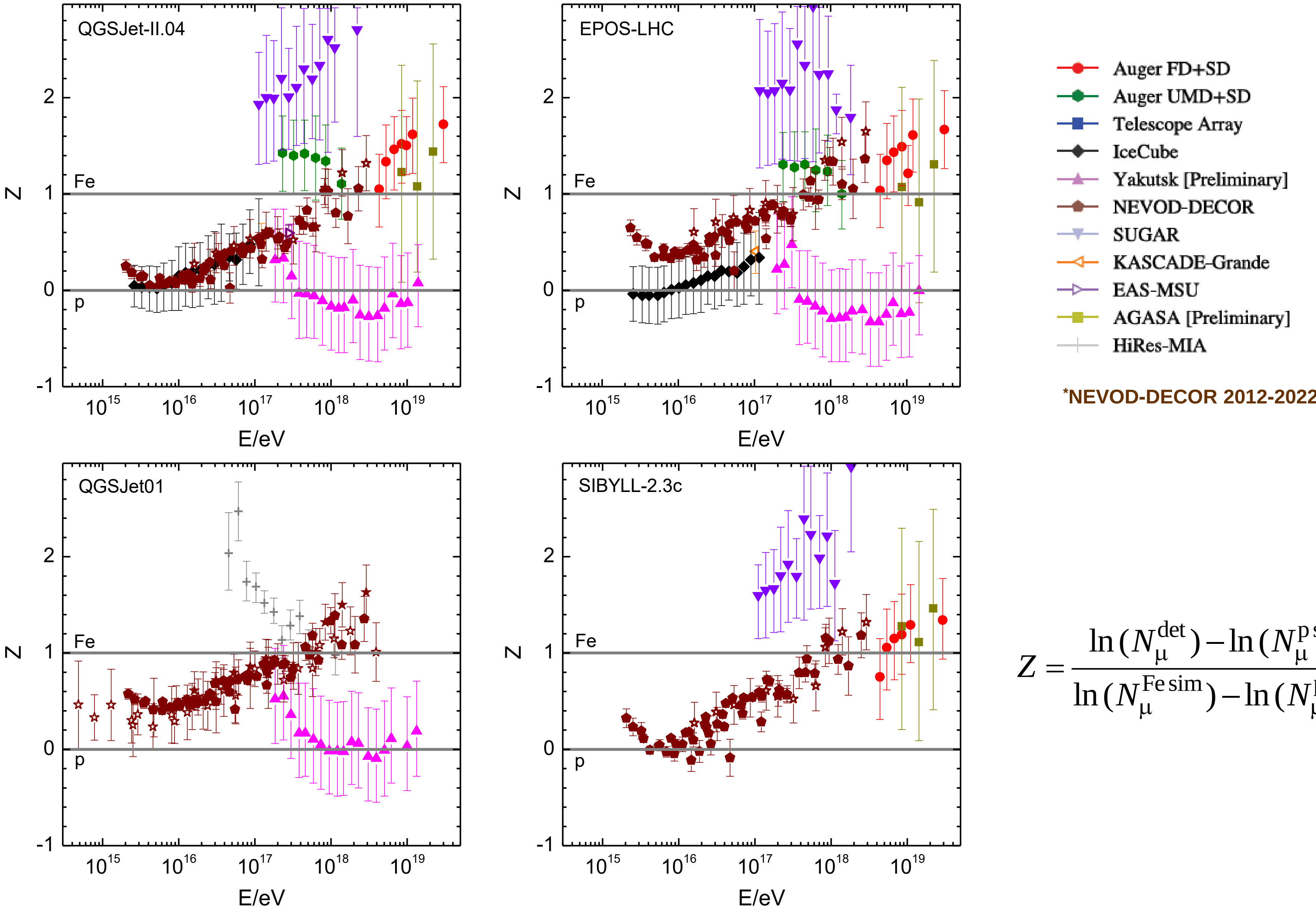
Antonella Castellina, for the Pierre Auger Collaboration, ISVHECRI-2022



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.

Comparison of new NEVOD-DECOR data by means of Z-scale with muon measurements from other air shower experiments



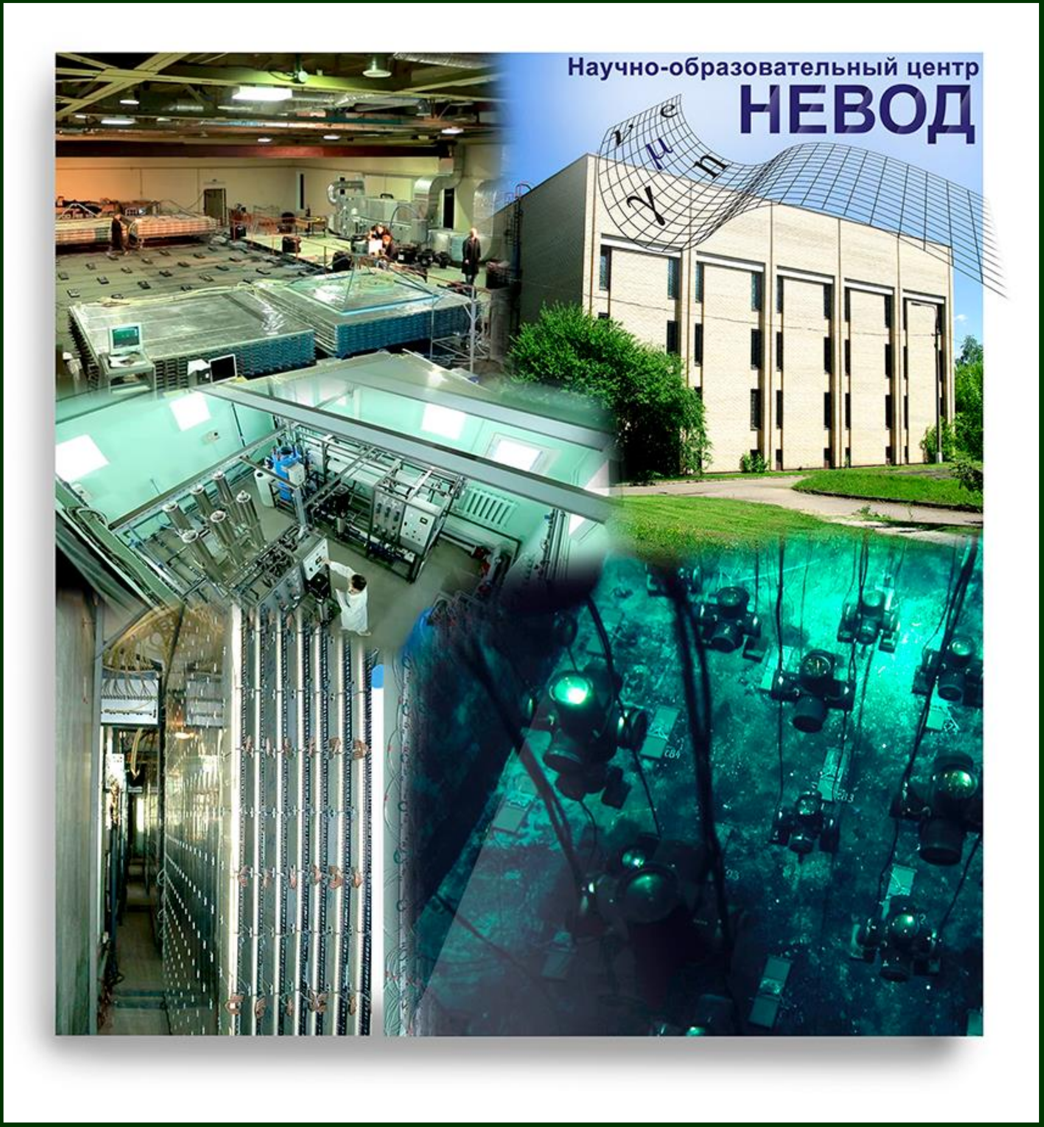
*NEVOD-DECOR 2012-2022

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

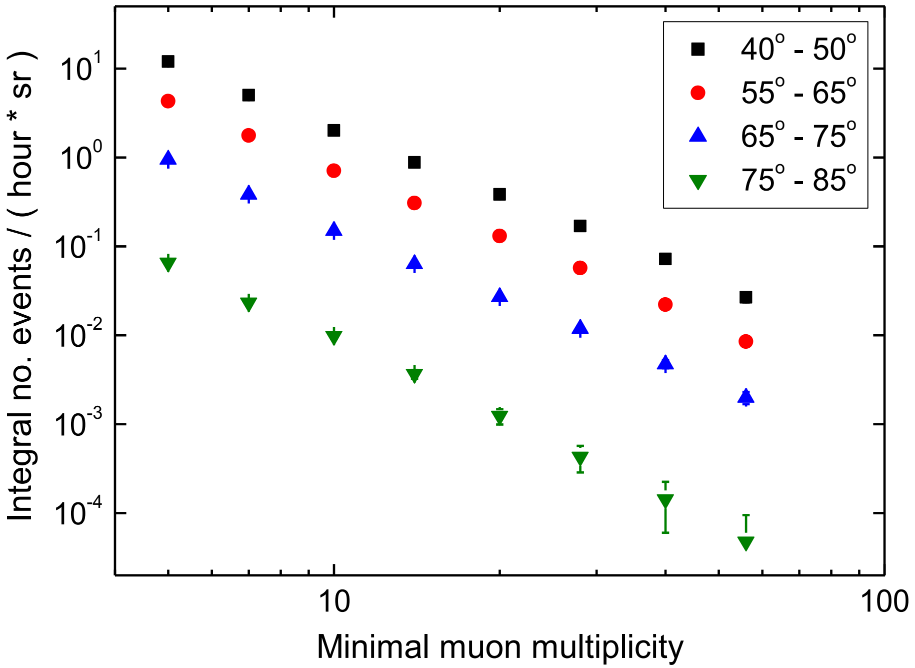
Conclusions

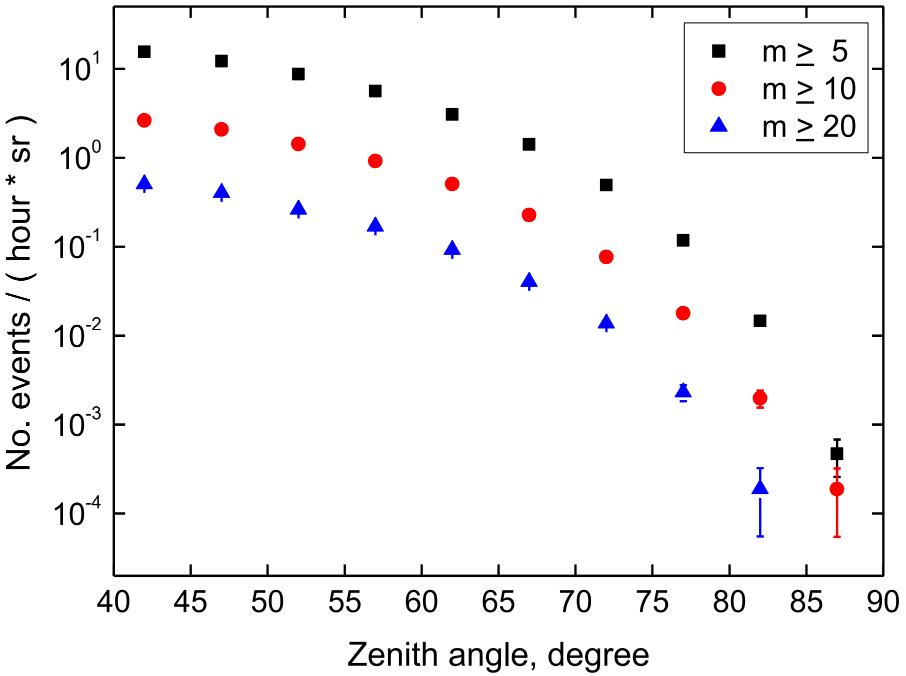
- The present NEVOD-DECOR data are only compatible with calculations if we assume extremely heavy mass composition at energies of primary particles about 10^{18} eV. It is consistent with data of several experiments on investigations of muon content in air showers.
- Moreover, an increase in the average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



Multiplicity and angular distributions of muon bundles

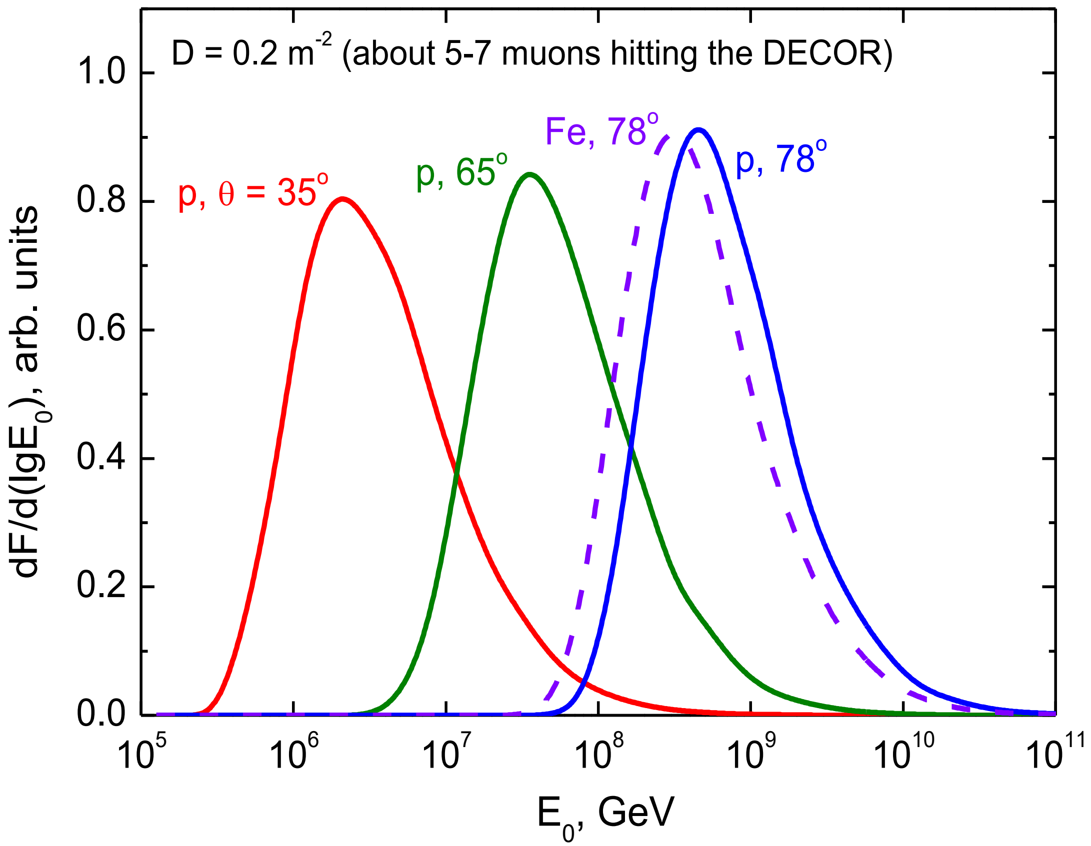




Data embrace the range of about 5 orders of magnitude in the event intensity.

From these data, local muon density spectra for nine intervals of zenith angles from 40° to 85° have been reconstructed.

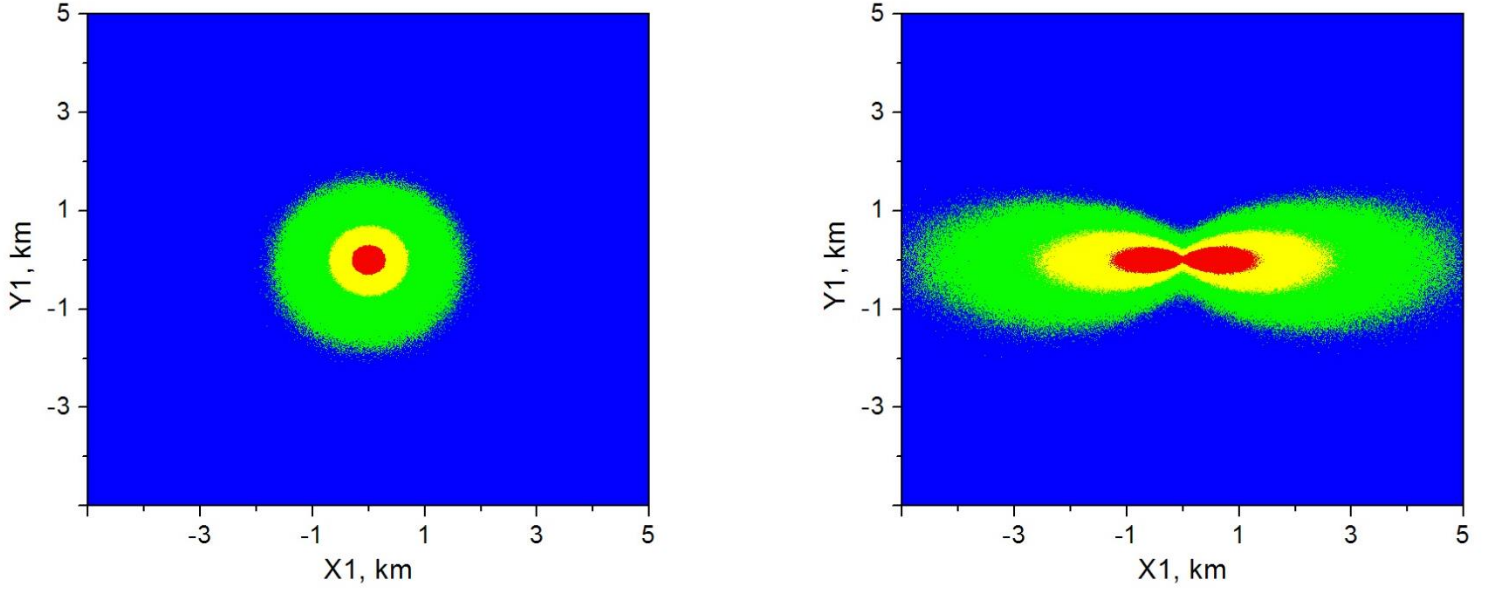
Distribution of primary cosmic ray particle energies contributing to events with a fixed muon density at different zenith angles



$$D, \theta \rightarrow E_0$$

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

Shower cross section in muons



$\theta = 80°$ (without EMF) $\theta = 80°$ (with EMF)

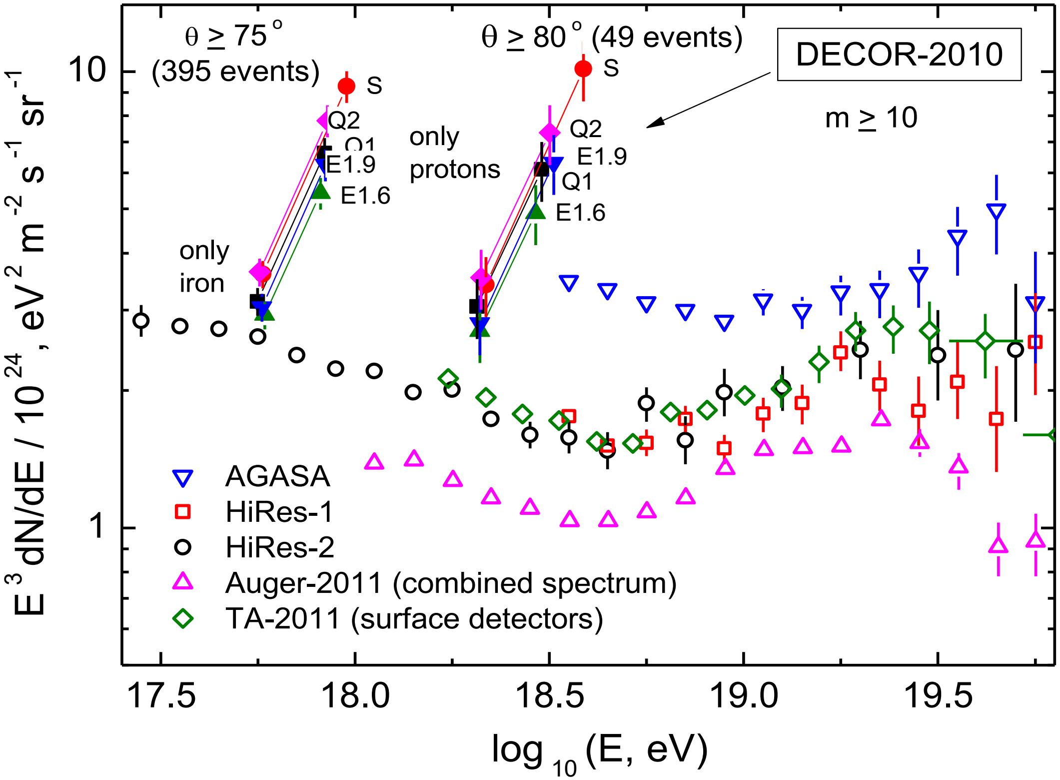
The content of particles in each of the colored area is 30% of the total number of muons

CORSIKA (100 EAS): proton, $E_0 = 10^{18}$ eV, $E_\mu \geq 1$ GeV

A muon detector with sizes of tens meters may be considered as a point-like probe in comparison with a shower dimension in muon component. A small fragment of the shower cross section is registered in the experiment.

Excess of muon bundles intensity from DECOR data 2002-2007

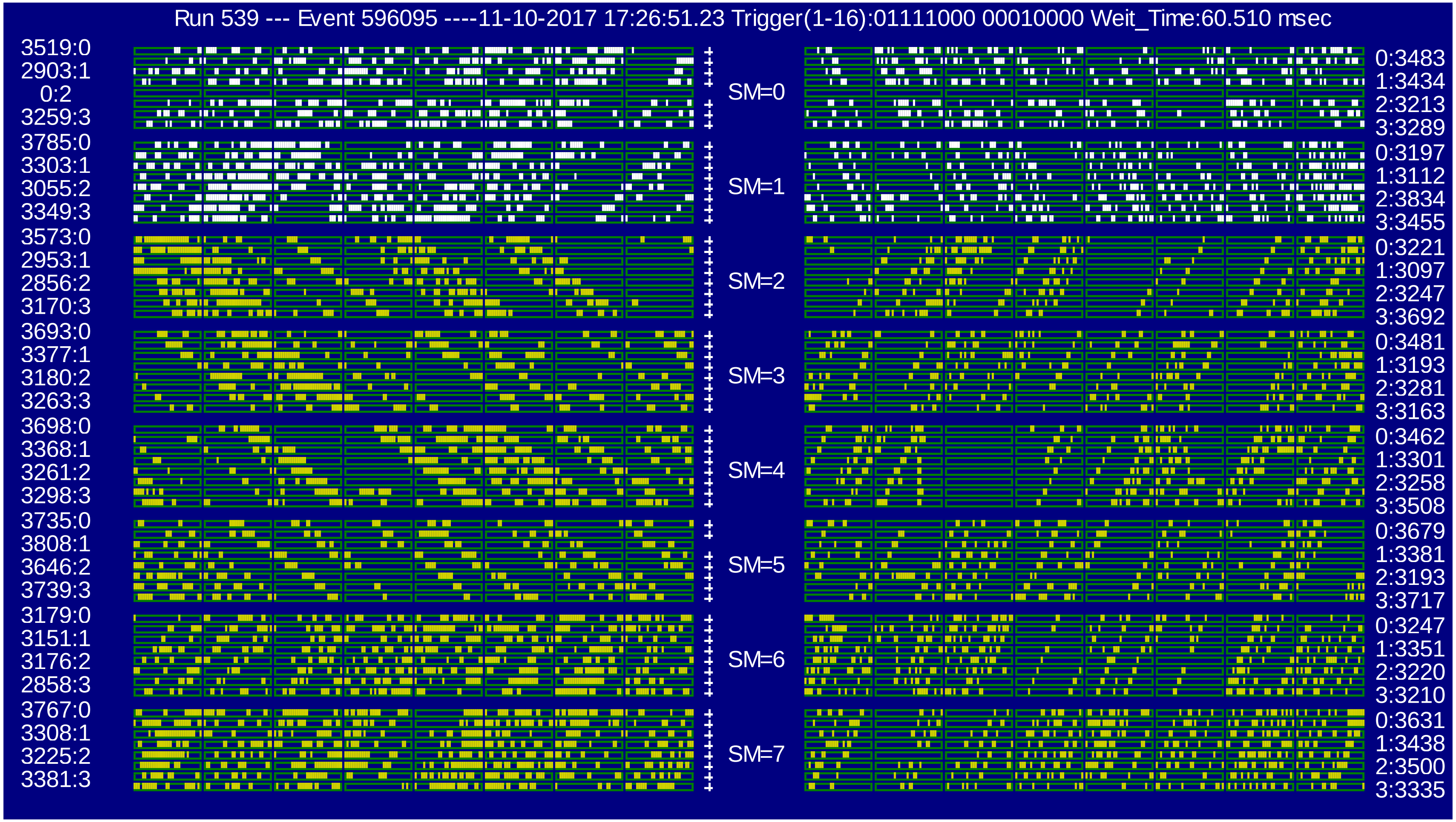
O. Saavedra et al., Journ. of Phys.: Conf. Ser. 409 (2013) 012009



Reconstructed energy spectrum of primary cosmic rays at ultra high energies

Muon bundle event in DECOR supermodules

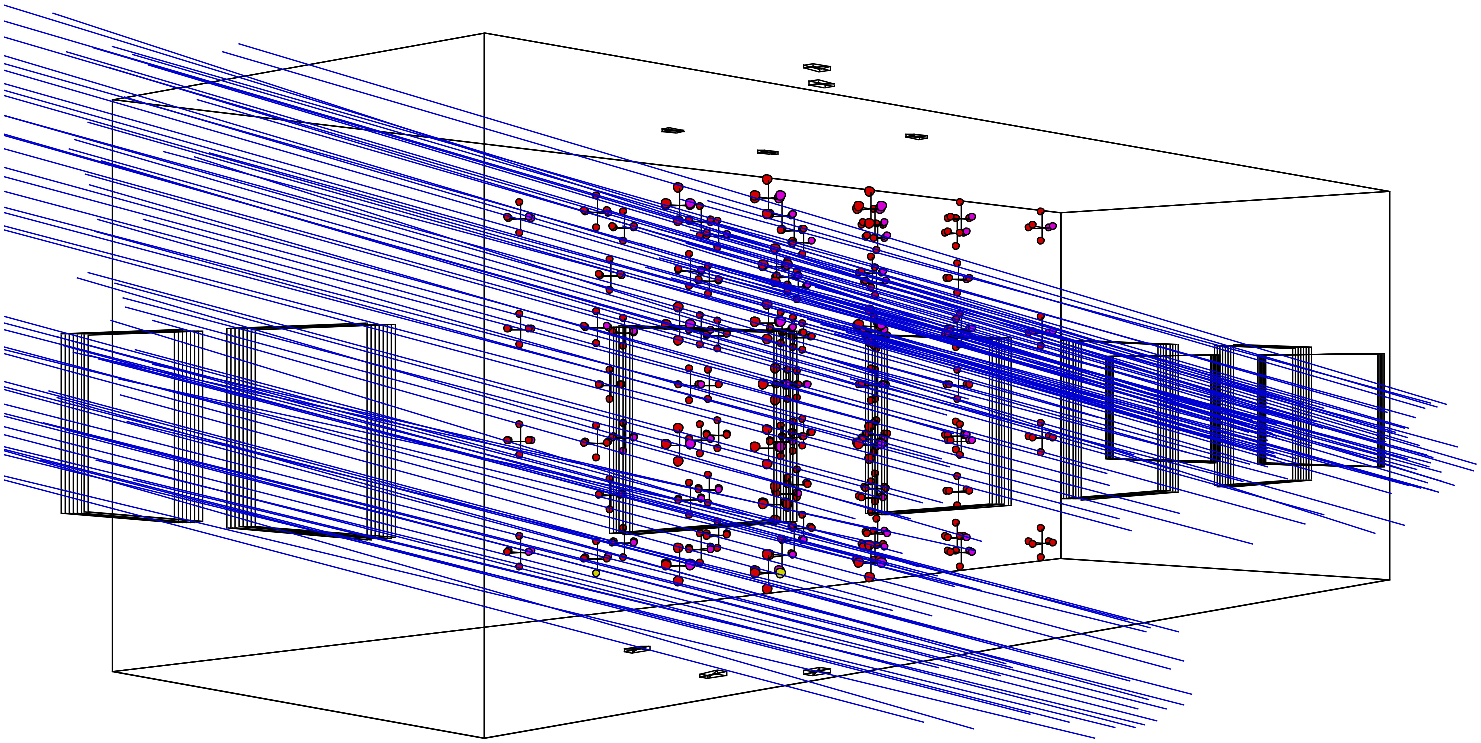
multiplicity m = 124 particles, zenith angle $\theta \approx 75°$



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

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

Nlam=91,N5=91,N6=91,NR1=0 ,NR2=0 ,Sum1=131,Sum2=7 ,Sob-11000001,11100000
N1=87,N3=91 nCup= 5 SumAmp=8.22e+05 01111000,00010000 NGroup2=129,n=129,n1=134,n2=151,n0=120,nx=151,ny=134,One=3
N2=91,N4=91 nCdow n= 3 ACup=1.14e+03 ACdn= 413 NPMT=542 ETel= 25.3% ERec= 43.4%



Date=11-10-17 17:26:51.023 Nrun=539 Nevent=596095 Group: fm=229.28 tm=75.09 Recon: fi=44.10 t=55.08 F= 0.0

DECOR 2002-2007 // *Phys. Atom. Nucl. 73 (2010) 1852*

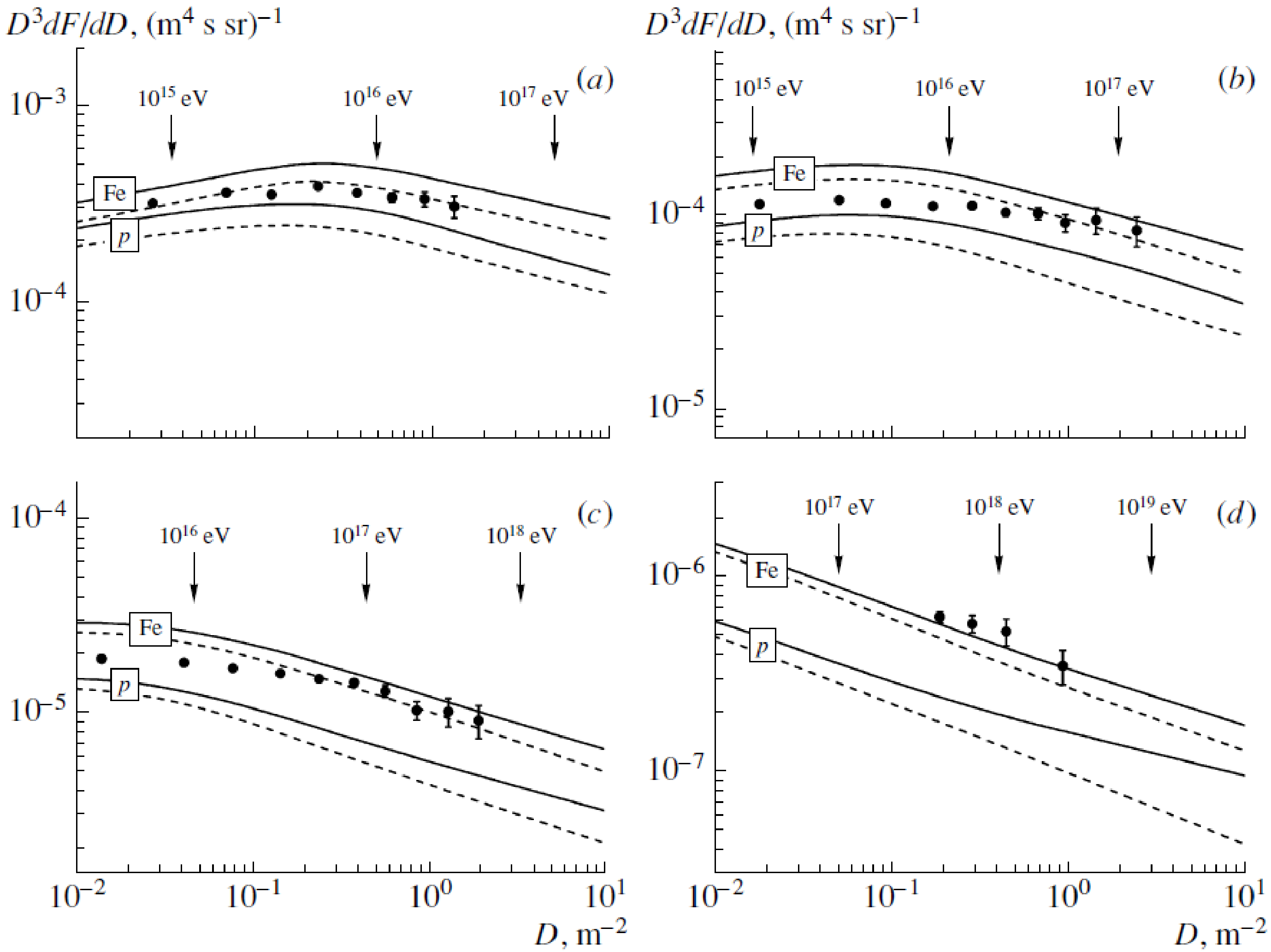
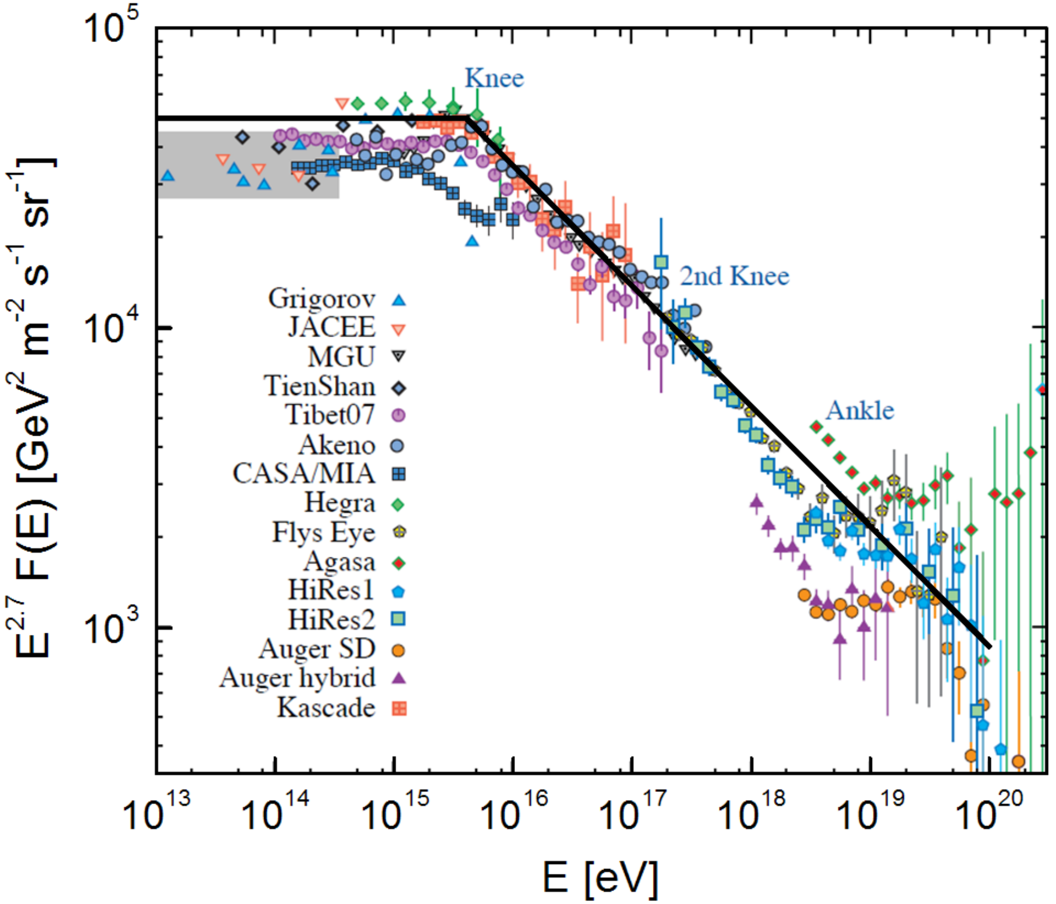


Fig. 9. Experimental and calculated differential spectra of the local muon density at the zenith angles of (a) 35°, (b) 50°, (c) 65°, and (d) 78°. The displayed points stand for experimental data, while the solid and dashed curves represent the results of the calculations performed by using the QGSJET01 and SIBYLL 2.1 models, respectively. In each panel, the lower pair of curves corresponds to primary protons, while the upper pair corresponds to iron nuclei.

DECOR 2002-2007 // *Phys. Atom. Nucl. 73 (2010) 1852*



The all-particle spectrum, PDG 2008

DECOR 2002-2007 + 2012-2016 // *Astropart. Phys. 98 (2018) 13*

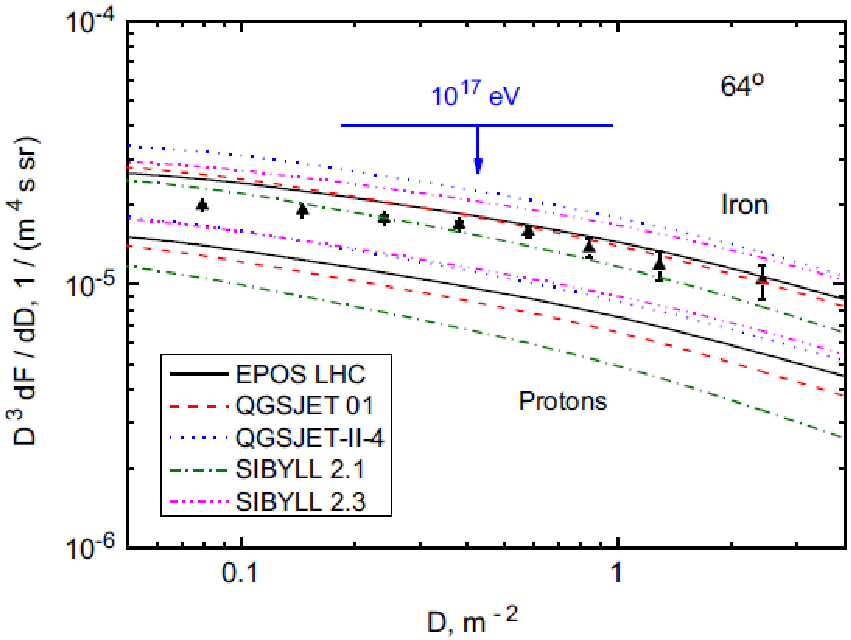


Fig. 8. Reconstructed local muon density spectrum at 64° zenith angle (dark triangles) and expected spectra calculated for protons and iron nuclei as primary particles (lower and upper groups of the curves respectively) with five different hadron interaction models. Arrow indicates the position of the effective 10^{17} eV primary particle energy.

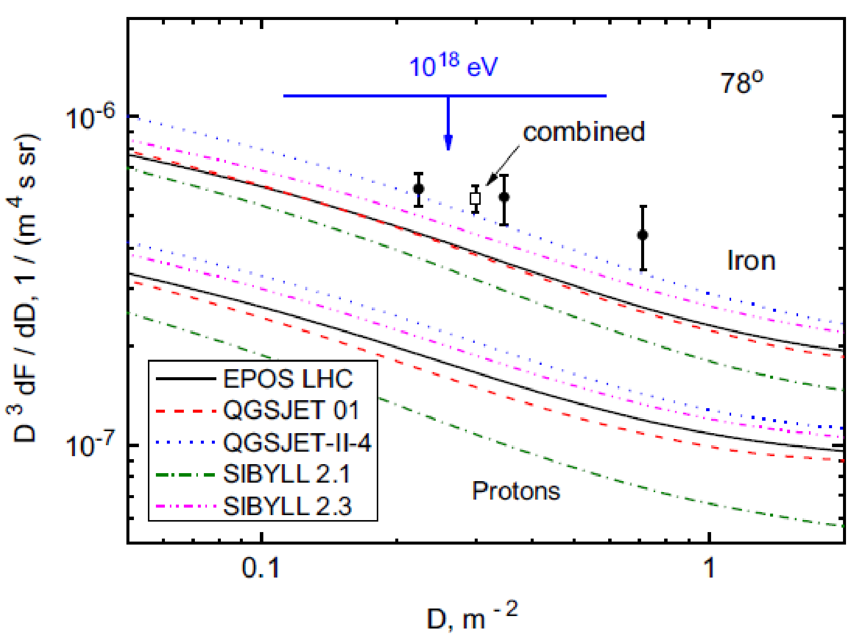
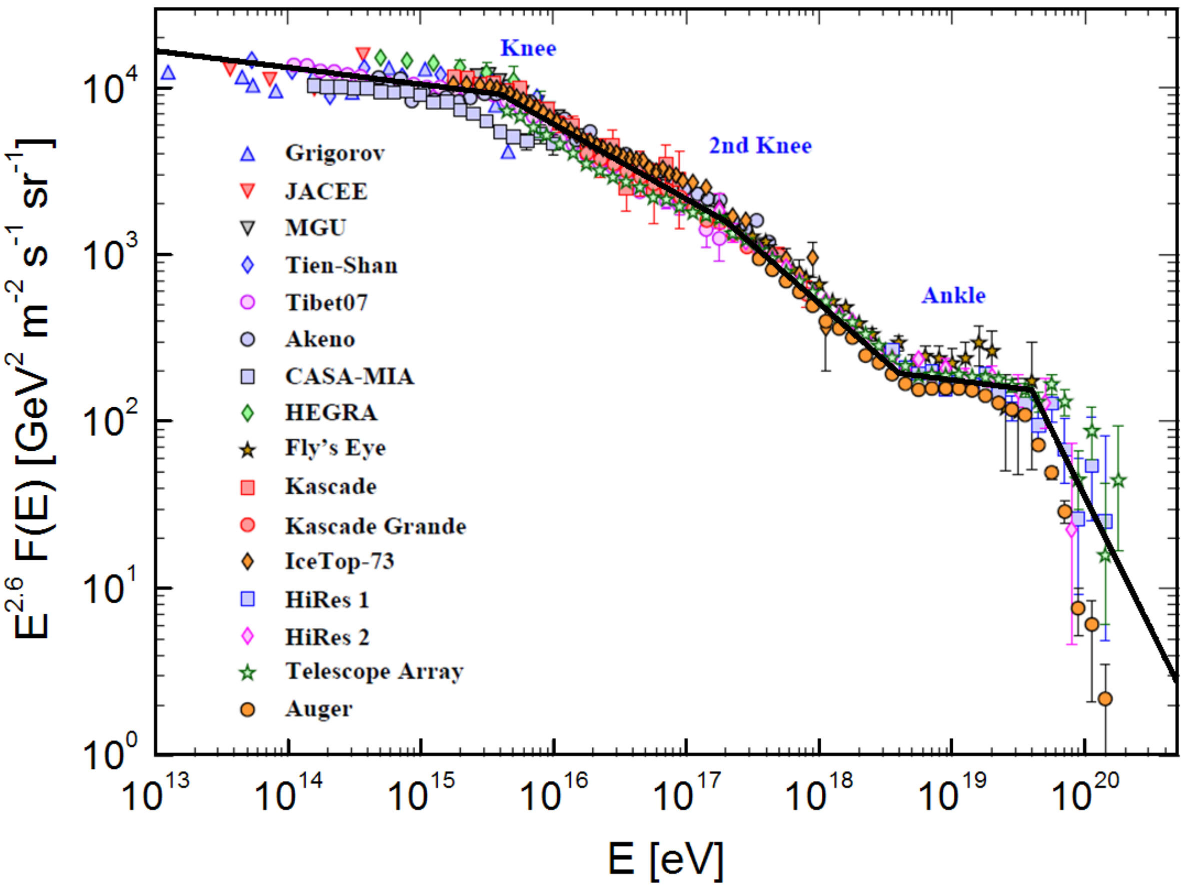


Fig. 9. Reconstructed muon density spectrum at 78° zenith angle (dark circles) and expected spectra calculated for protons and iron nuclei as primary particles (lower and upper groups of the curves respectively) with five different hadron interaction models. The open square represents a combined estimate based on all events with muon multiplicity $m \geq 10$ in the respective angular bin. The arrow indicates the position of 10^{18} eV effective primary energy.

DECOR 2002-2007 + 2012-2016 // *Astropart. Phys. 98 (2018) 13*



The all-particle spectrum, PDG 2016

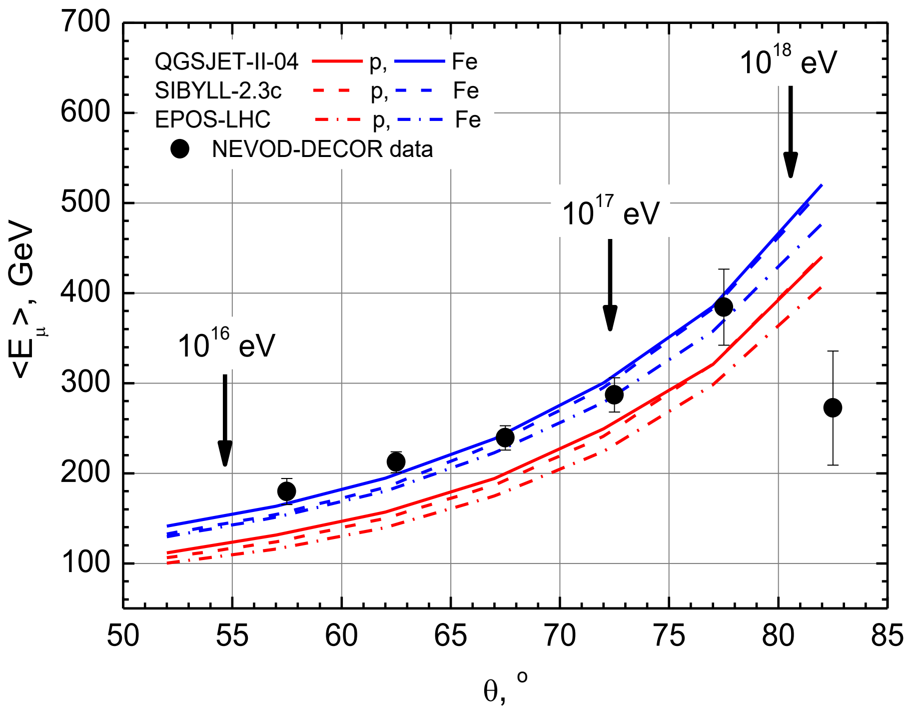
A possible approach to "muon puzzle" solution

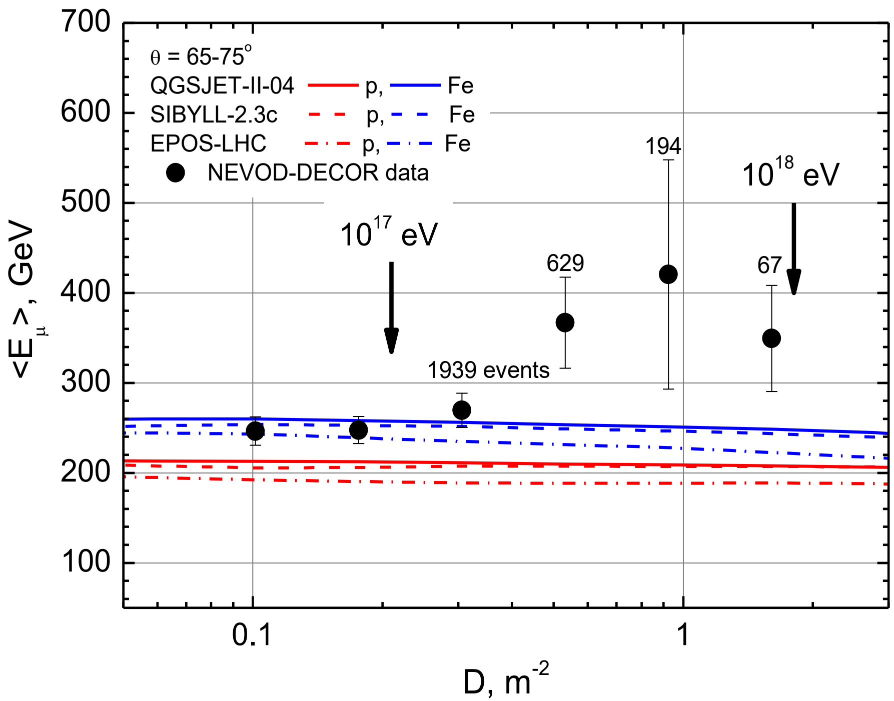
The key to the muon excess solution can be the study of the energy characteristics of the EAS muon component and their changes with increasing energy of primary cosmic rays.

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).