Muon excess in ultra-high energy inclined EAS according to the NEVOD-DECOR data

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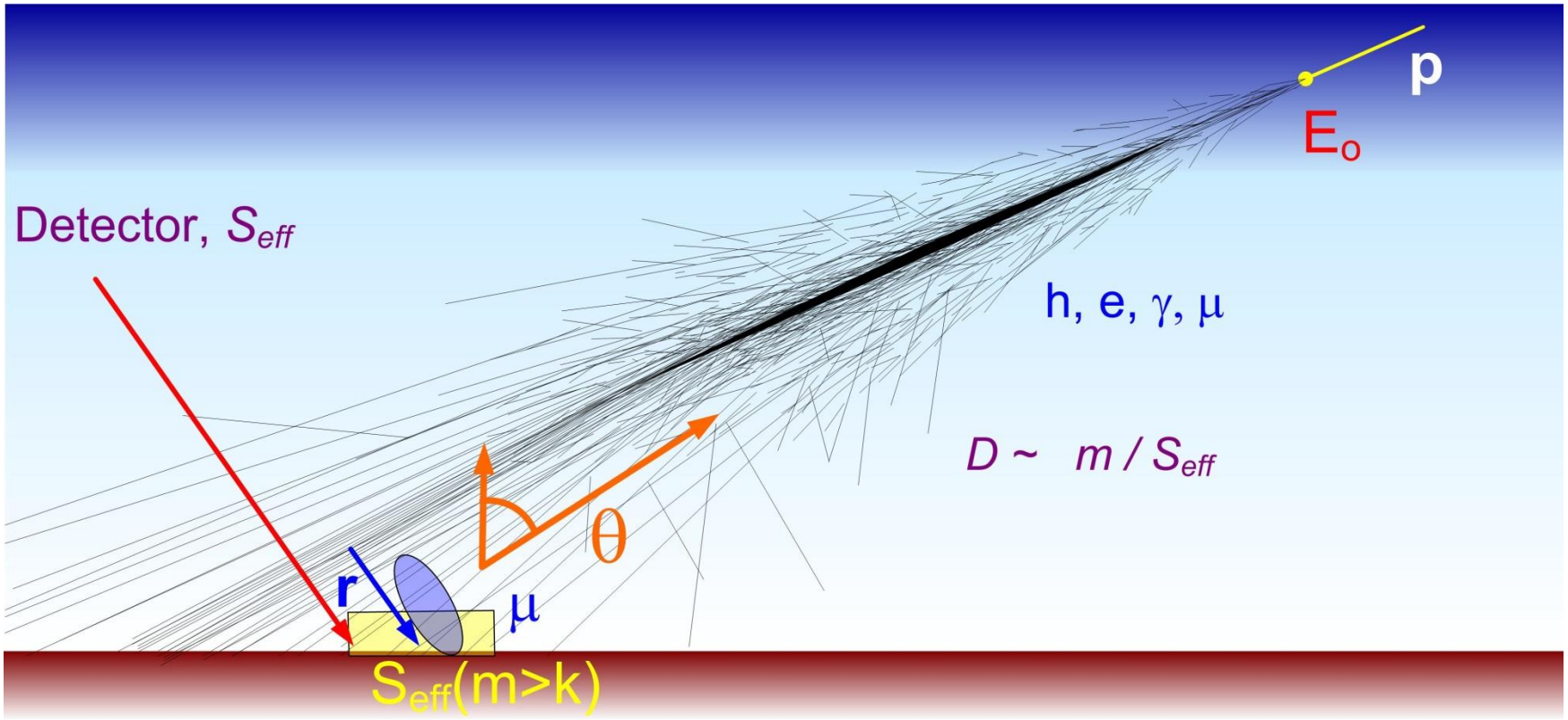
To analyze muon bundle data in inclined EAS, the phenomenology of Local Muon Density Spectra (LMDS) is used

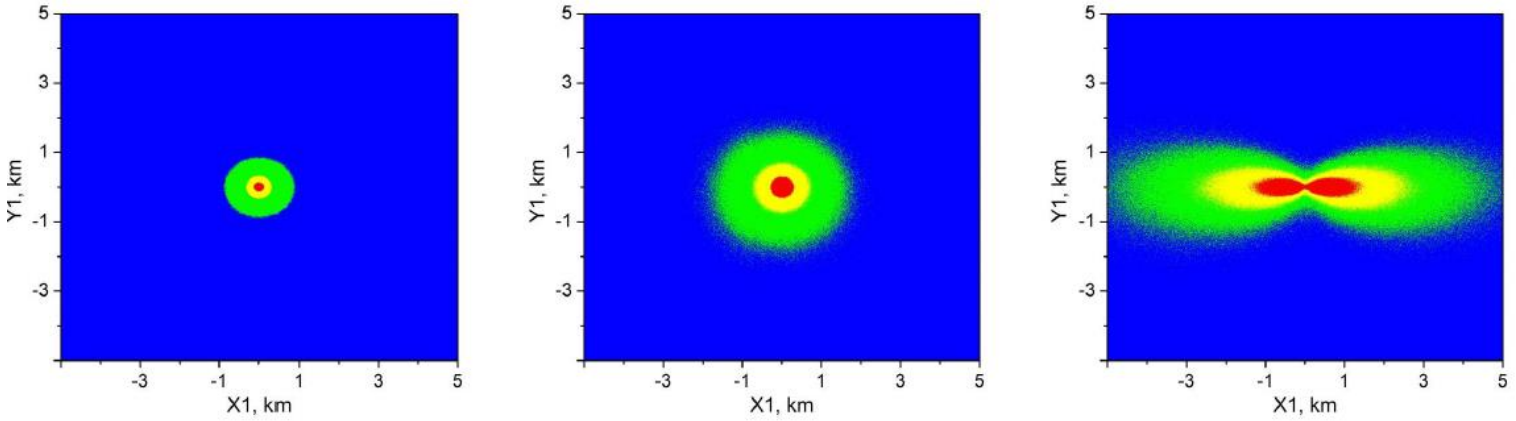


In an individual muon bundle event, a local muon density *D* at the observation point is measured. Distribution of events in the *D* estimate forms the LMDS.

EAS cross section in the muon component

EAS cross section (muon component)

Red, yellow, green contours contain 30, 60, 90% of EAS muons, respectively



35º without EMF | 80º without EMF | 80º with EMF

CORSIKA (SIBYLL+FLUKA), p, $E_0 = 10^{17}$ eV, 100 EAS, $E_\mu \geq 1$ 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.

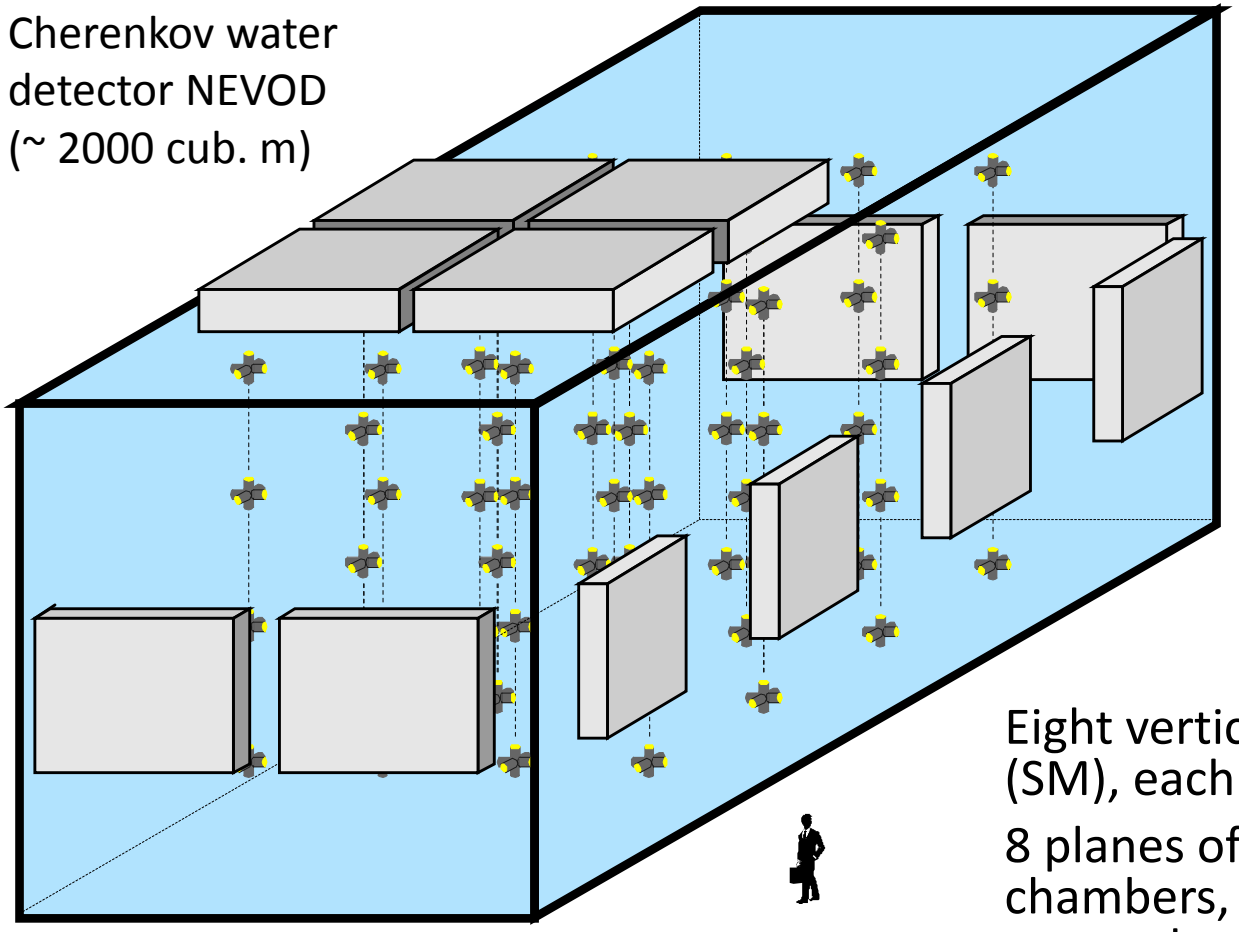
Important features of the method of the Local Muon Density Spectra

The event collection area is determined not by the detector size but by the EAS cross section in muon component which at large zenith angles reaches several square kilometers (sufficient to reach energies of 10^{18} eV and higher).

Simultaneous measurements of the LMDS at various zenith angles give the possibility of exploration of a very wide energy range in frame of a single experiment with a relatively small setup.

General layout of the NEVOD-DECOR complex

Cherenkov water detector NEVOD (~ 2000 cub. m)

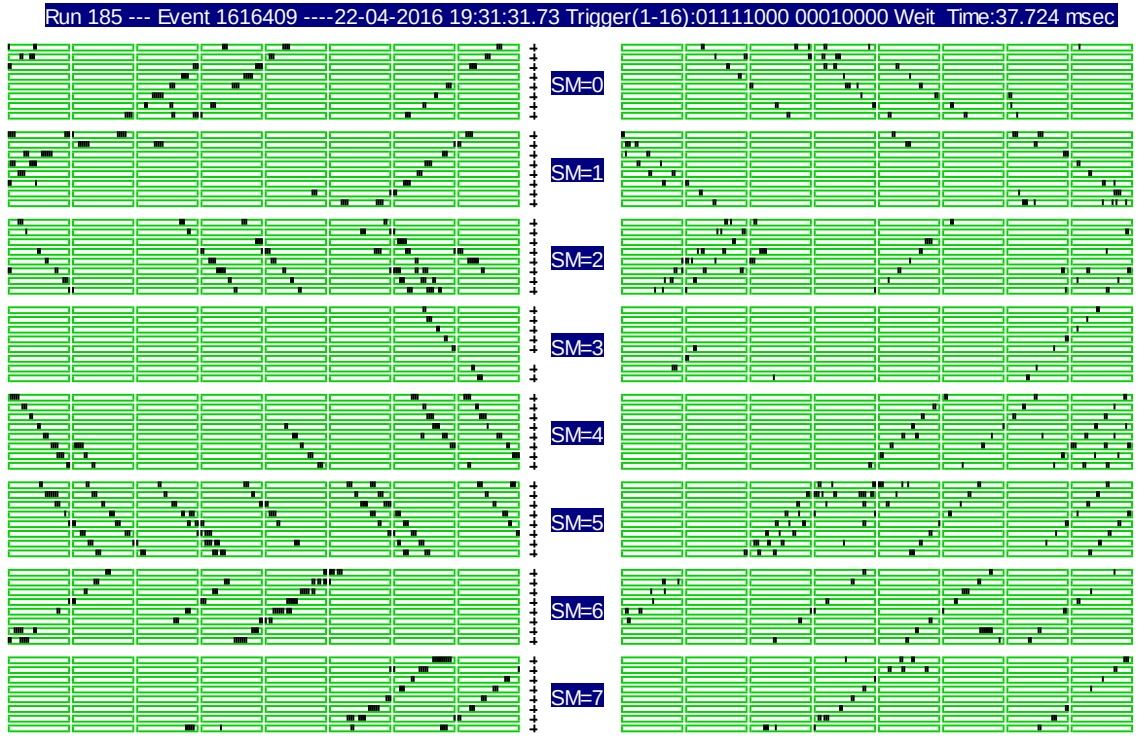


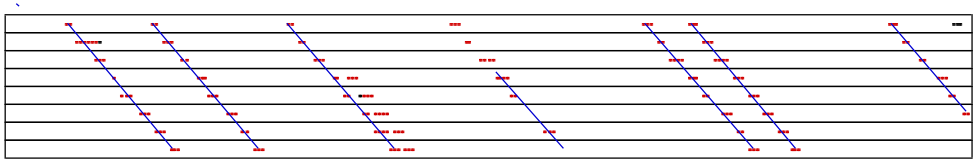
Side DECOR

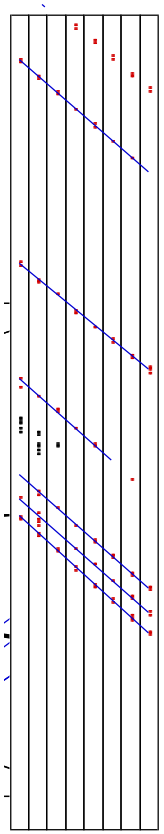
Eight vertical supermodules (SM), each with 8.4 sq. m area,

8 planes of plastic streamer tube chambers, with two-coordinate external strip readout.

The response of the coordinate-tracking detector DECOR for the event with a muon bundle







SM5: X-view, Y-view

New (updated) NEVOD-DECOR data on muon bundles

Four long-term series from May 2012 to March 2021

Live observation time: ~ 58,350 hours

Bundles $\theta \geq 55°$, $m \geq 5$: ~ 99.6 thousand events

Two 60° -wide sectors in azimuth

Threshold muon energy ~ 2 GeV

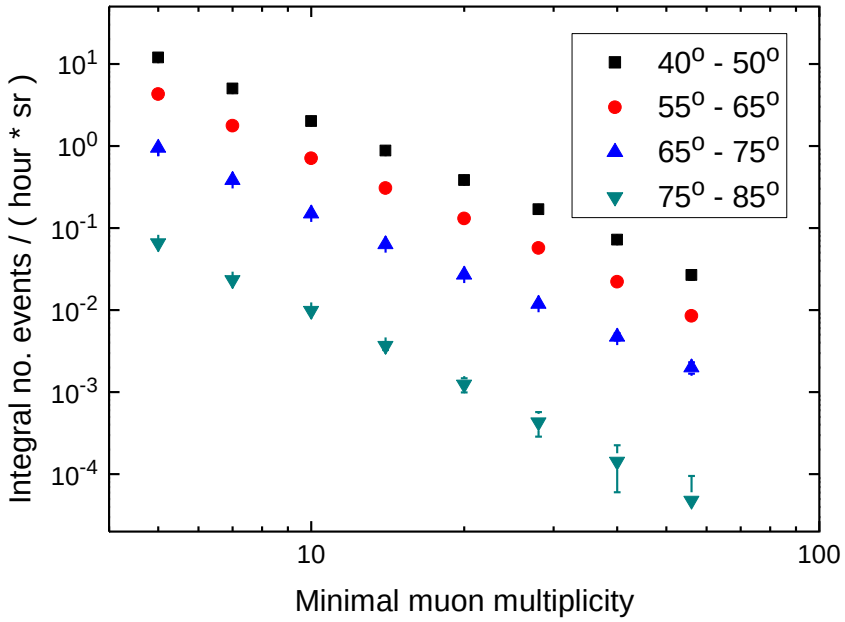
Additionally:

Live observation time: ~ 6,324 hours

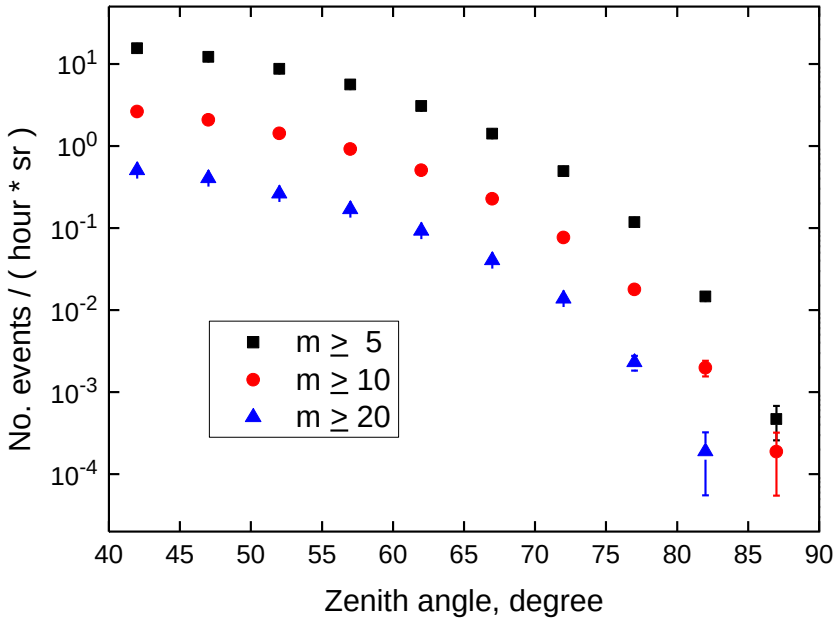
Bundles $40° \leq \theta < 55°$, $m \geq 5$: ~ 30.4 thousand events

NEVOD-DECOR 2021 Data Overview

Distribution in multiplicity



Distribution in zenith angle



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.

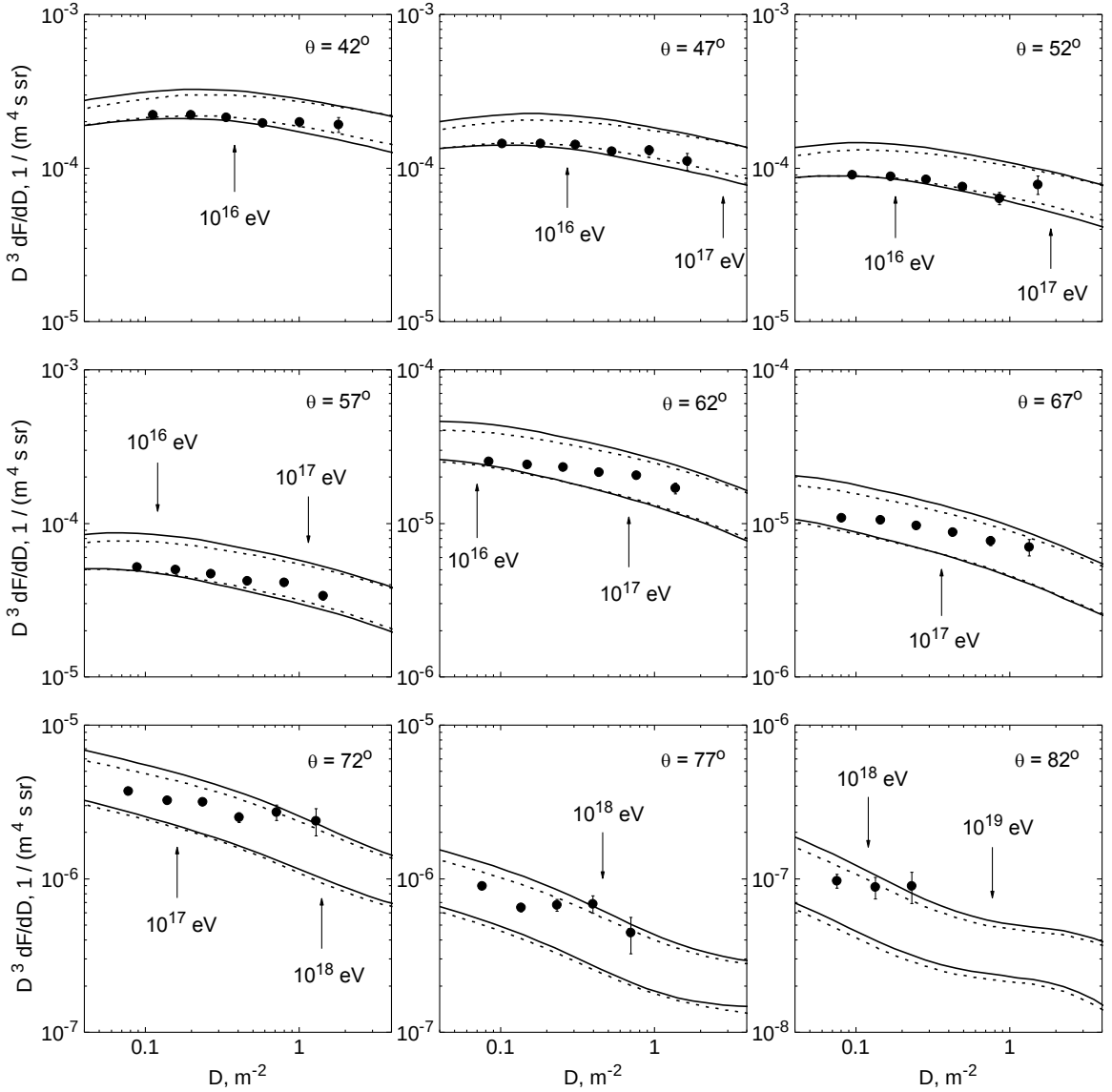
Local Muon Density Spectra (LMDS) - 2021

Points: experiment

Expectation:

1) Piece-wise power-law approximation of the all-particle primary spectrum.
2) Two composition assumptions: only protons and only iron.
3) Two models of hadronic interaction: QGSJET II-04 and SIBYLL 2.3c (solid and dashed curves).

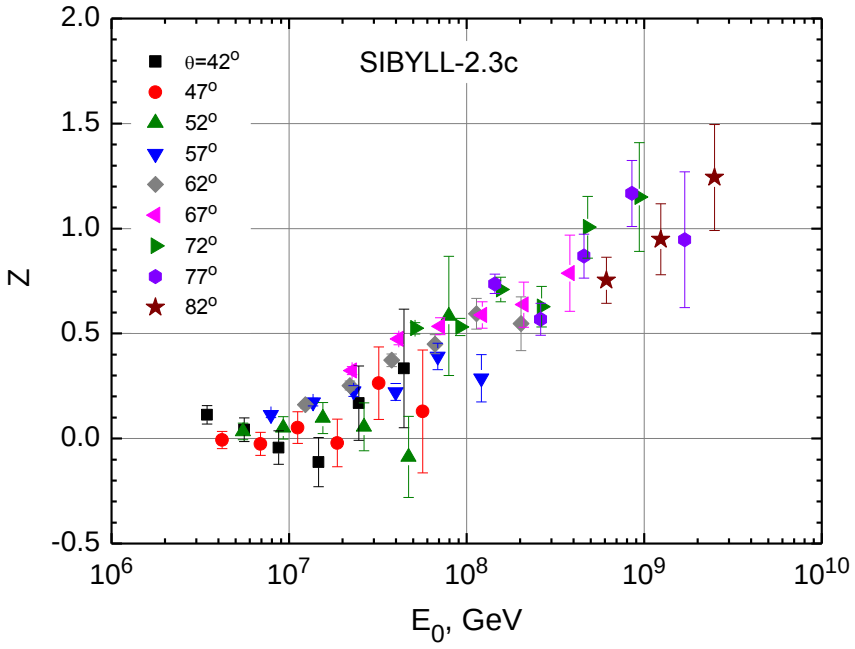
Arrows indicate typical energies of primary particles.

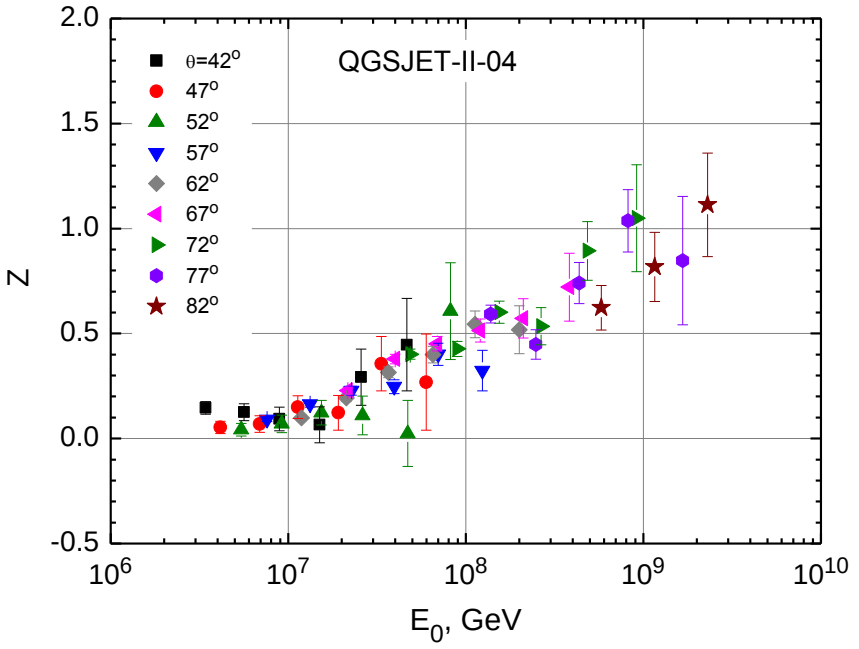


Comparison in z-scale (introduced by the WHISP group)

$$z = (\log F^{\mathrm{obs}} - \log F_{\mathrm{p}}^{\mathrm{sim}}) / (\log F_{\mathrm{Fe}}^{\mathrm{sim}} - \log F_{\mathrm{p}}^{\mathrm{sim}})$$

If protons, z = 0; if iron, z = 1.





Fast growth around 10^{17} eV and higher.

Z ~ 1 around 10^{18} eV (iron?) Contradiction with X_{max} measurements!

Conclusions

1) Local muon density spectra in the range of 40° - 85° zenith angles are reconstructed from the new (updated) NEVOD-DECOR data.
2) The reconstructed LMDS at different zenith angles are close to each other and embrace the primary energy range of about three orders of magnitude.
3) For the two considered hadronic interaction models: SIBYLL 2.3c and QGSJET II-04, a fast growth of the z-parameter at primary energies higher than 10^{17} eV is observed.
4) Around 10^{18} eV, the experimental points are close to the expectation for primary iron nuclei (z ~ 1).
5) Such an assumption contradicts the available fluorescence data on X_{max} which favor a light (predominantly proton) mass composition at these energies.
6) “Muon puzzle” is still waiting for its solution!

Thank you for your attention !