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Study of the energy deposit of muon bundles in the NEVOD detector

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“Muon puzzle” in cosmic ray experiments

In several cosmic ray experiments at ultra-high energy of primary particles (NEVOD-DECOR, Pierre Auger Observatory), an excess of multi-muon events in comparison with simulation performed within the framework of commonly used hadron interaction models (even under assumption of heavy primaries - iron nuclei) has been revealed.

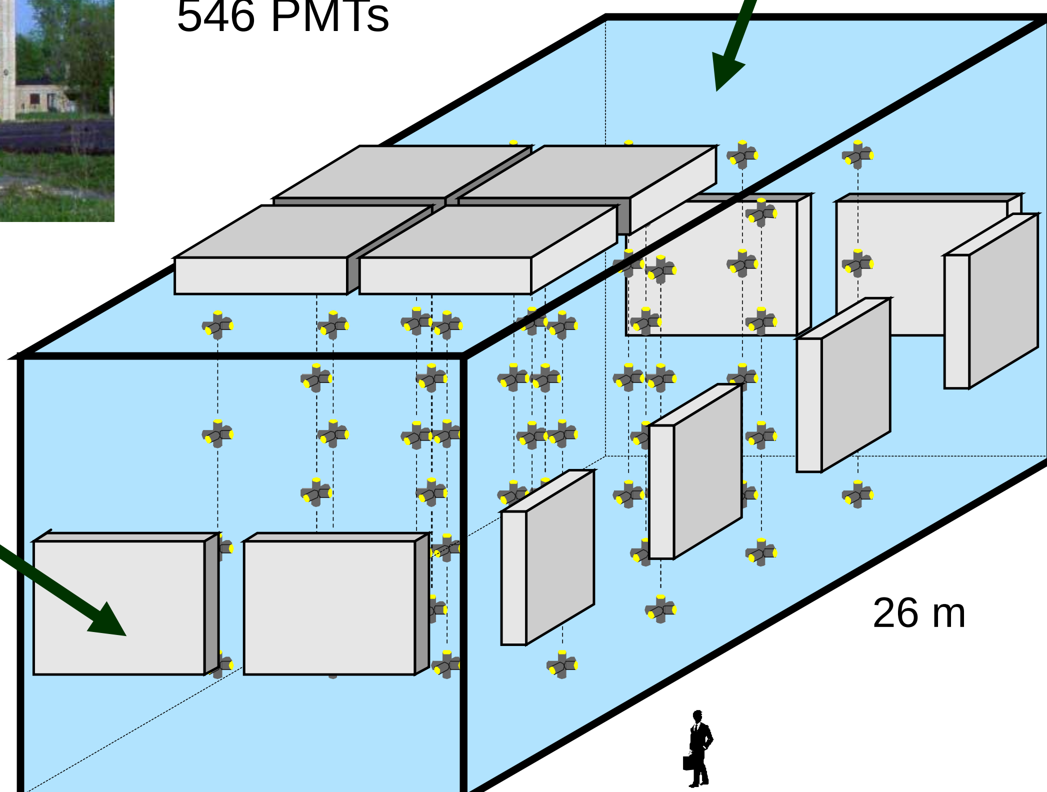
General view of NEVOD-DECOR complex

Cherenkov water detector NEVOD (volume 2000 m^3)

spatial lattice of 91 QSM (quasi-spherical optical modules); 546 PMTs

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

8 vertical SMs (supermodules) of streamer tube chambers

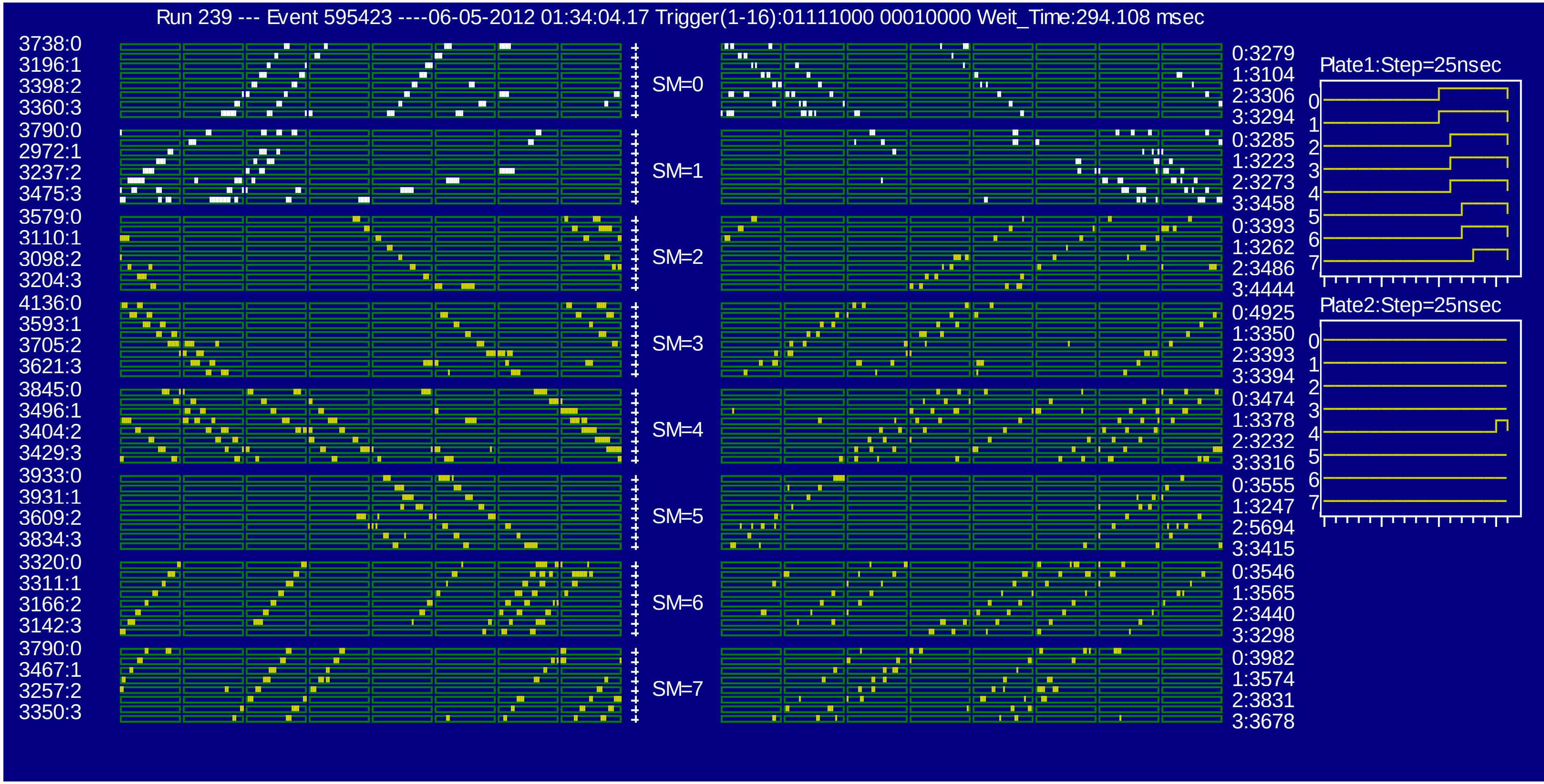


Side DECOR supermodules (SMs) in the galleries around the NEVOD water tank

Each SM has an effective area 8.4 m^2 and consists of 8 planes of streamer tube chambers with resistive cathode coating. 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 side DECOR SMs

multiplicity m = 29 particles, zenith angle θ = 49°

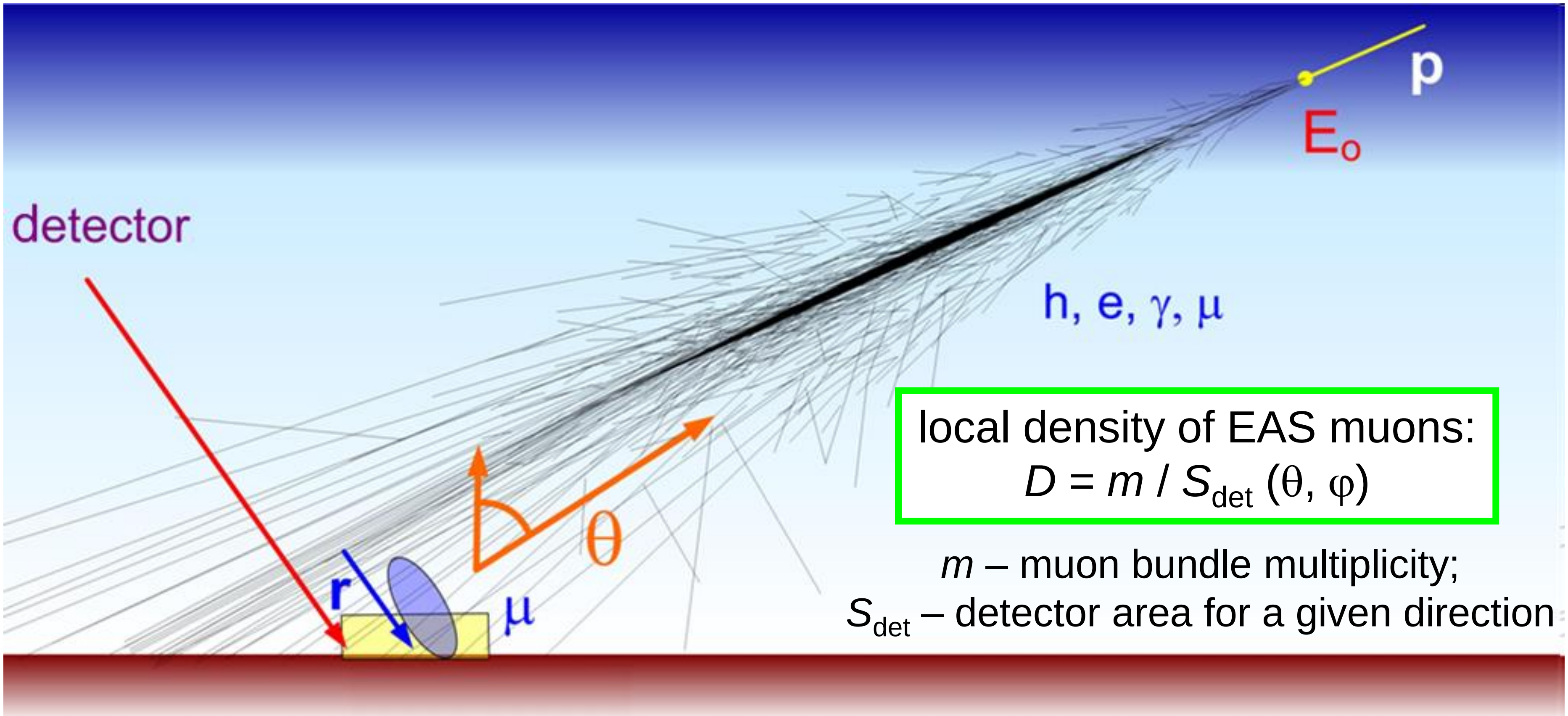


Y-coordinate (azimuth angle) *X-coordinate (projected zenith angle)*

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

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

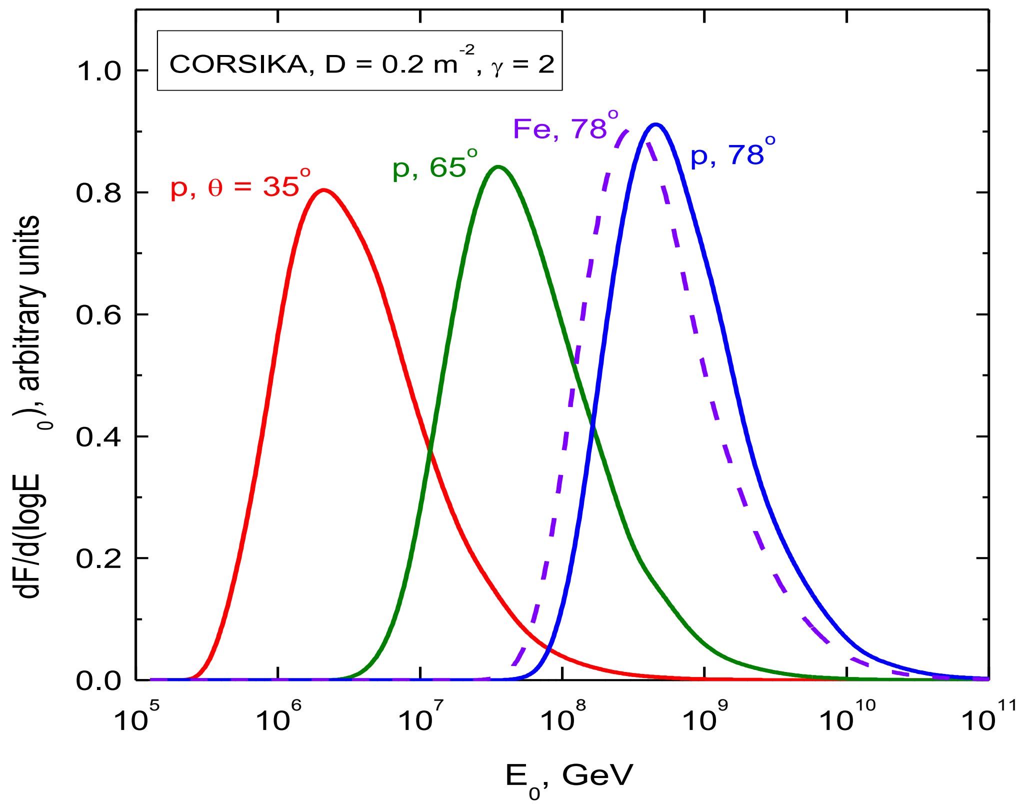
Description of the phenomenology of the LMDS – A.G. Bogdanov et al., Physics of Atomic Nuclei. 2010. V. 73. N 11. P. 1852



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

Event collection area is determined by transverse dimensions of the showers in muon component (up to several square kilometers at large zenith angles).

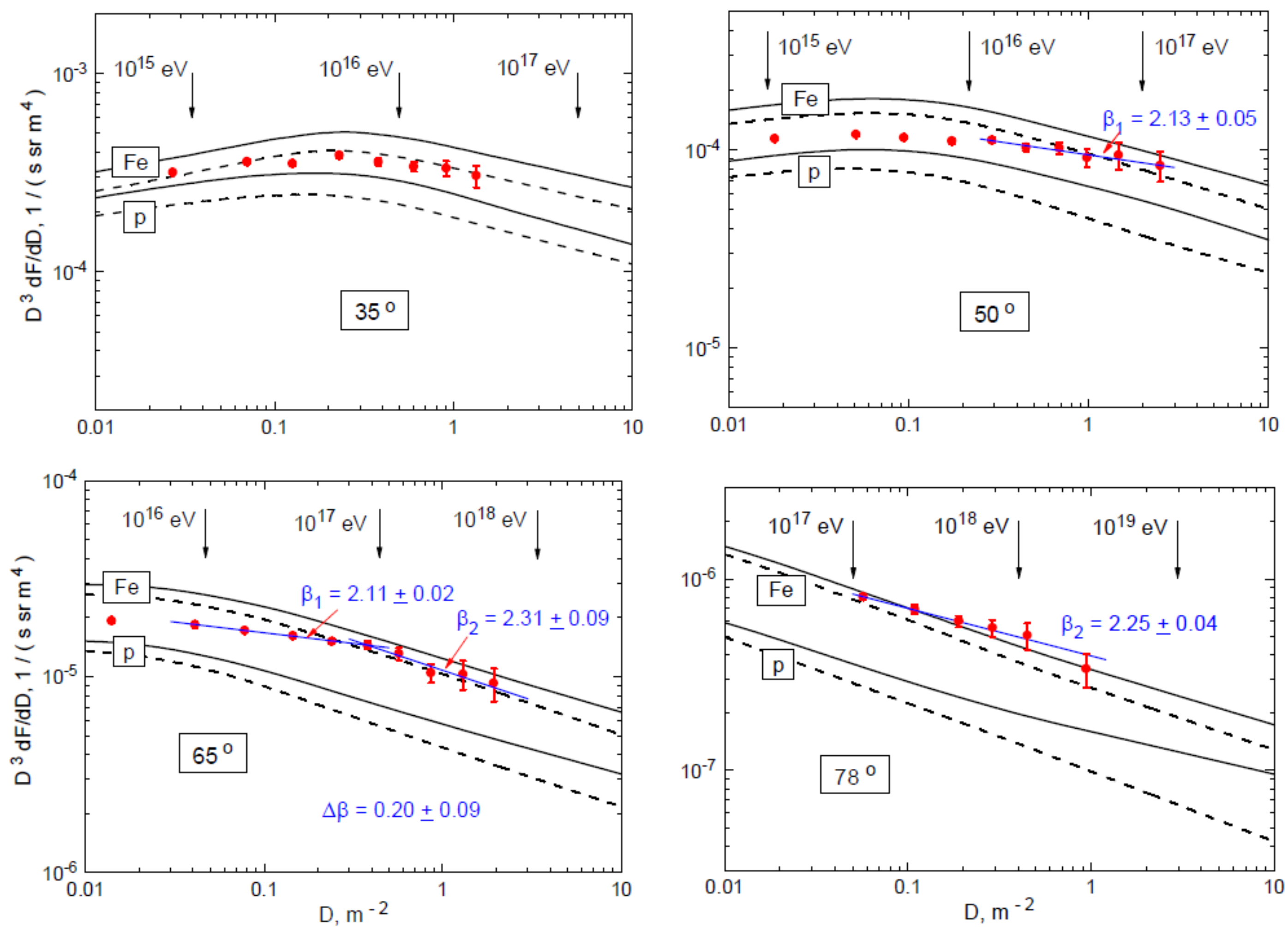
Distribution of primary cosmic ray particle energies contributing to events with a fixed muon density at different zenith angles



$D \sim E_0$!

Contribution to events with a certain muon density give showers with different primary energies, detected at random distances from the axis. However, due to a fast decrease of primary cosmic ray intensity with the increase of energy, the effective primary energy band appears relatively narrow. At different zenith angles, the events with a fixed muon density are formed by primary particles with substantially different energies.

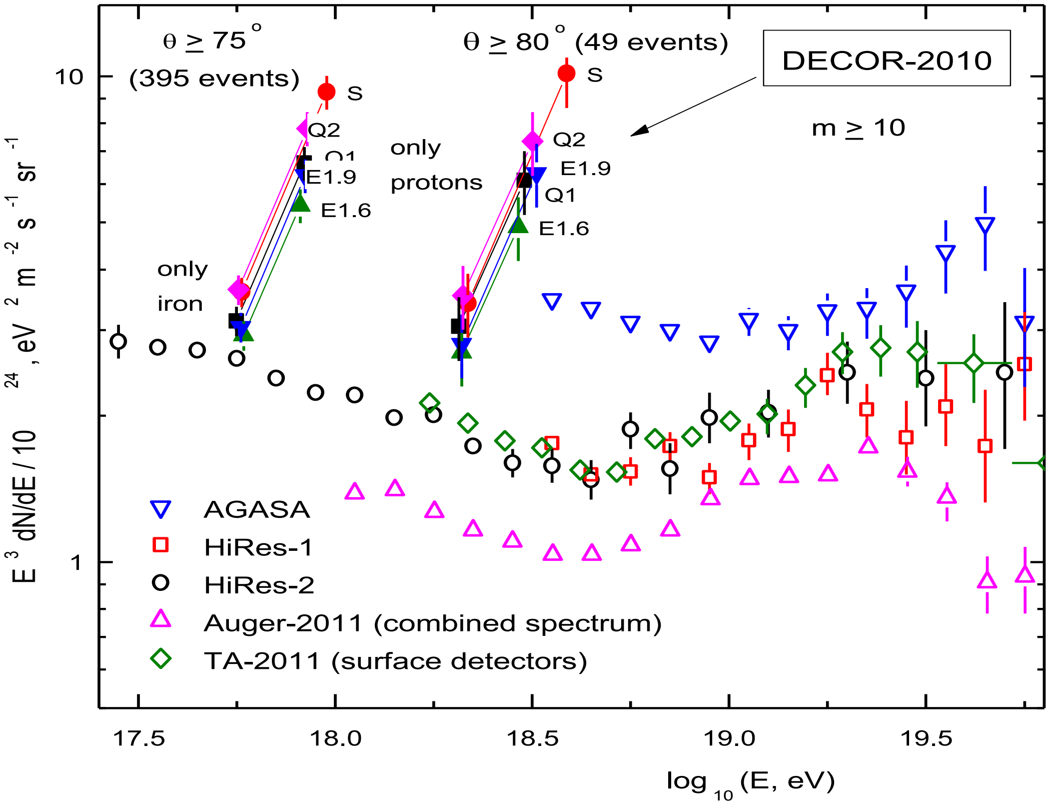
Experimental LMDS (local muon density spectra) reconstructed from DECOR data on muon bundles



Measured (points) and calculated LMDS for 4 zenith angles (labels in the frames). Thin lines represent partial power fits of the data between 10^{16} and 10^{17} eV (integral spectrum slope β_1), and above 10^{17} primary energy (β_2). The solid and dashed curves represent the results of the calculations performed by using the QGSJET01 and SIBYLL-2.1 models. The lower pair of curves corresponds to primary protons, upper pair – iron nuclei.

Excess of muon bundles intensity from DECOR data 2002-2007

R.P. Kokoulin et al., Nucl. Phys. B (Proc. Suppl.) 196 (2009) 106; O. Saavedra et al., Journ. of Phys.: Conf. Ser. 409 (2013) 012009



Reconstructed energy spectrum of primary cosmic rays at ultra high energies

At large zenith angles and high multiplicities, the measured muon bundle intensity is not compatible with fluorescence data for any interaction model, even under assumption of a heavy primary composition. This contradiction becomes even more significant, if one takes into account that fluorescence data favor a light (predominantly proton) composition near 1 EeV.

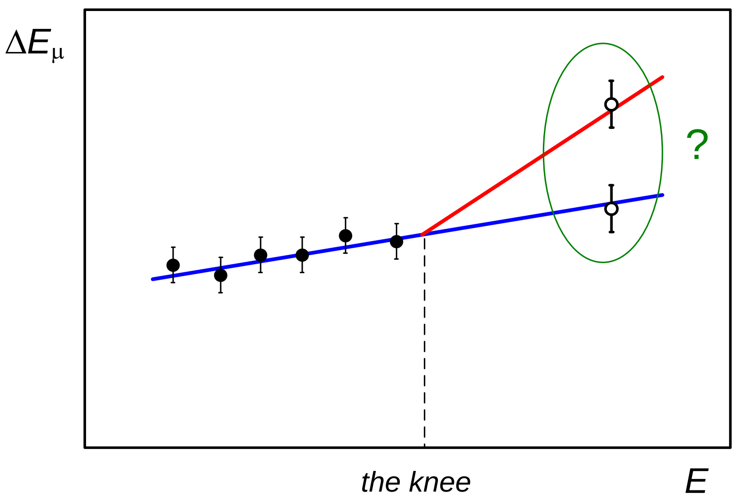
How to solve the “muon puzzle”?

In order to clarify the nature of the muon excess, investigation of energy characteristics of EAS muon component is necessary. A possible approach to the solution of this task is the measurement of muon energy deposit in the detector material. Such experiment has been started at NEVOD-DECOR complex in 2012 !

The total muon energy loss may be expressed as a function of the amount of matter traversed as

$$dE/dX \sim a + bE,$$

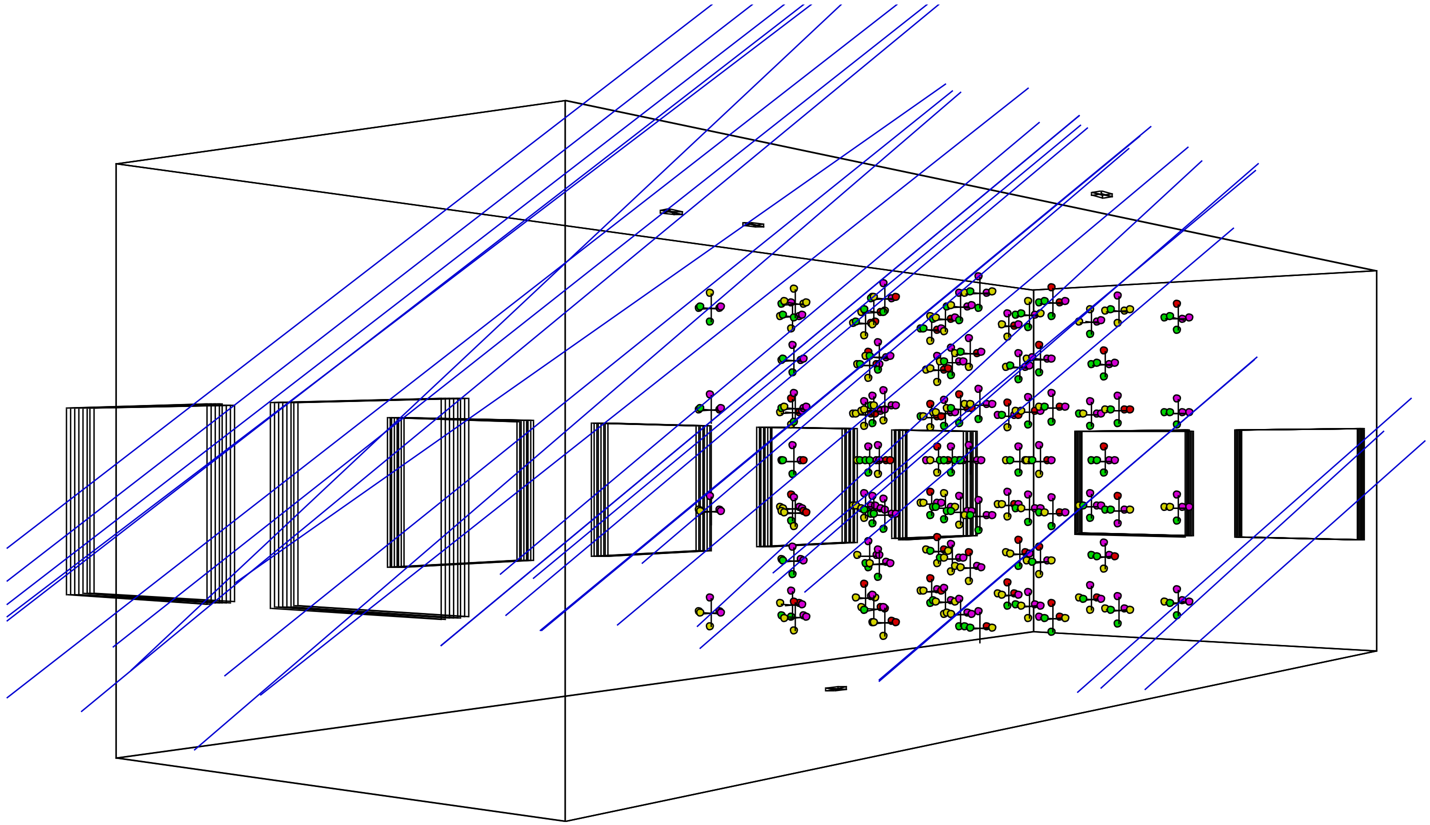
where *a* is the ionization loss and *b* is the fractional energy loss for radiation processes (both are slowly varying functions of energy).



Expected results of muon energy deposit measurements

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

An example of muon bundle event detected in NEVOD-DECOR



lines – reconstruction of muon tracks from DECOR data;
circles – hit phototubes in Cherenkov water detector (colors reflect signal amplitudes)

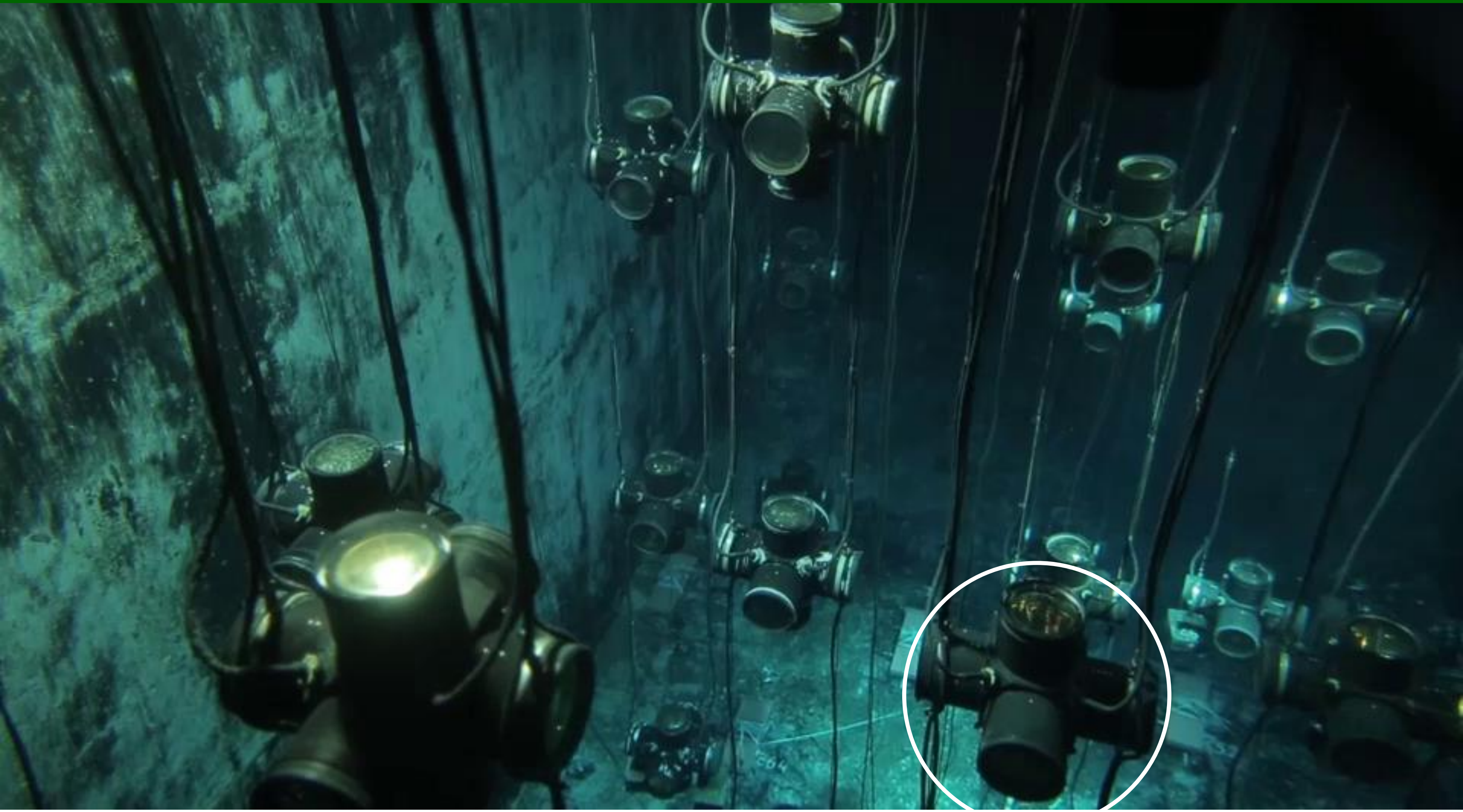
The density of muons is estimated according to the coordinate detector DECOR data; energy deposit of muon bundles is measured in the Cerenkov calorimeter NEVOD.

Detecting system of Cherenkov water calorimeter NEVOD (inner view)

video (in Russian) – http://youtu.be/dBLNU1SCeaA

91 QSMs are arranged into an array of 25 vertical strings (9 strings with 3 QSM and 16 strings with 4 QSM). NEVOD is equipped with the calibration telescope system: 40 scintillation counters (20×40 cm^2) are placed on the roof of the water tank, and 40 ones on the bottom.

Quasi-spherical measuring modules of the NEVOD detector



Each QSM consists of 6 low-noise 12-dynode photomultipliers FEU-200 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.

NEVOD-DECOR experimental data

Results of the analysis of the data on the energy deposit of inclined muon bundles accumulated during 2012, May – 2014, February.

Two series of measurements:

03.05.2012 – 20.03.2013 (5542 h)

16.07.2013 – 24.02.2014 (4131 h)

Total: 9673 h “live” time

$m \geq 5$ and $\theta \geq 55^\circ$ – 16415 events;

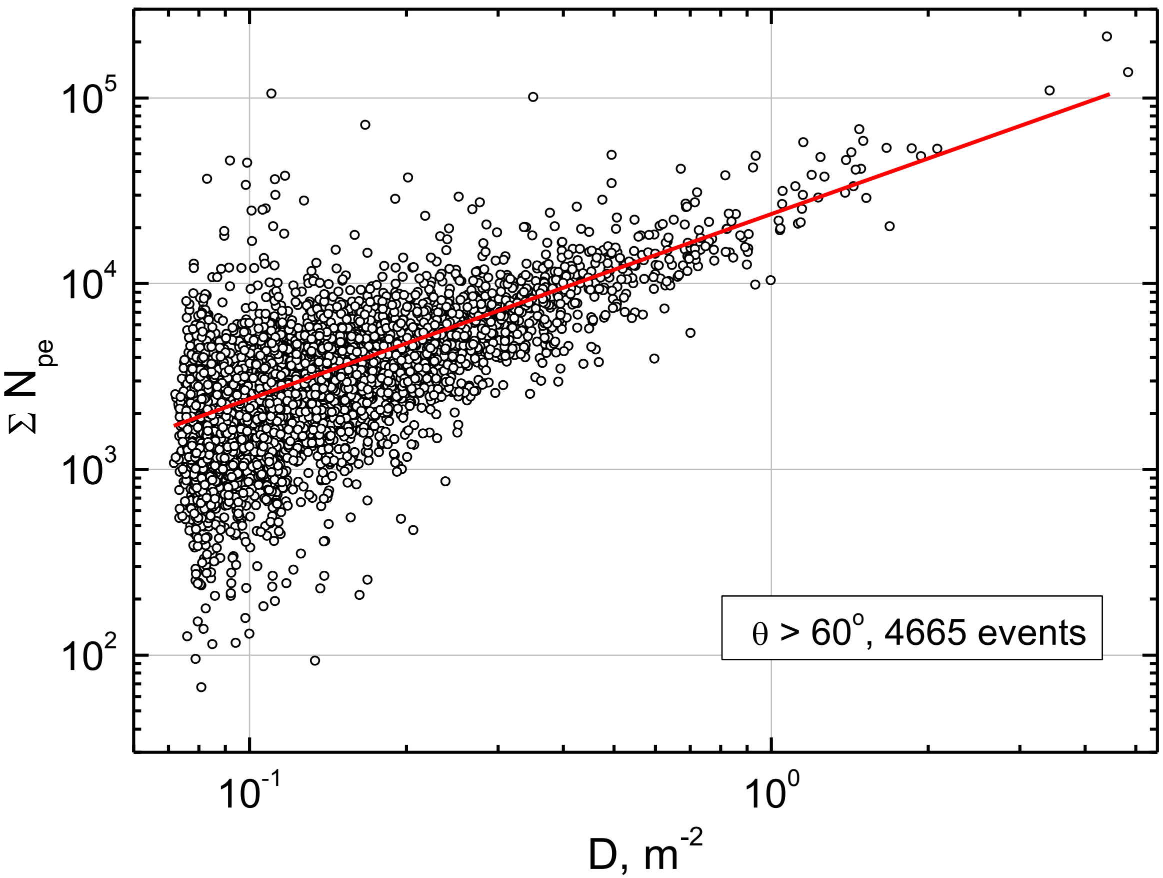
in addition: $40^\circ \leq \theta \leq 55^\circ$ – 15084 events (3253 h)

Multi-muon events were selected in two sectors of azimuth angle φ (60°), where most of DECOR SMs (six of eight) were screened with the NEVOD volume.

As a measure of the muon energy deposit, the sum of the signals of all PMTs – ΣN_{pe} (in photoelectrons) of the NEVOD detector was used.

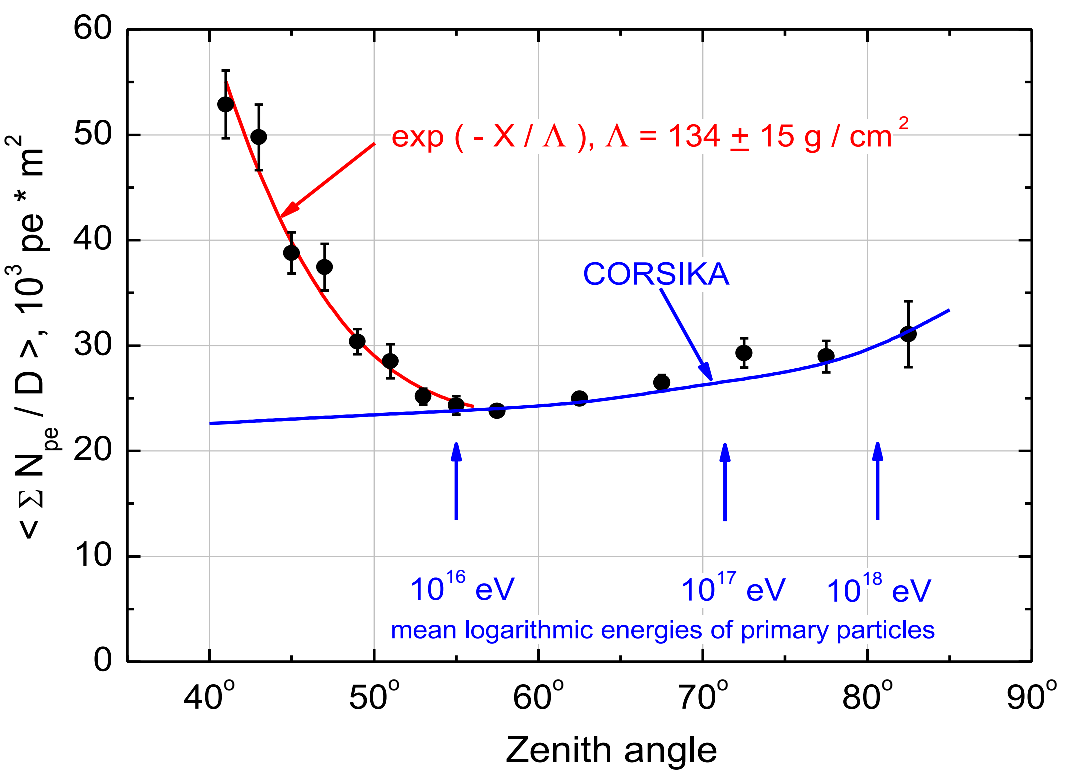
The estimate of the muon density in the event, taking into account the bias due to a steep muon density spectrum, was obtained as $(m - \beta) / S_{det}(\theta,\varphi)$, where $\beta \approx 2.1$ is the integral slope of the local muon density distribution.

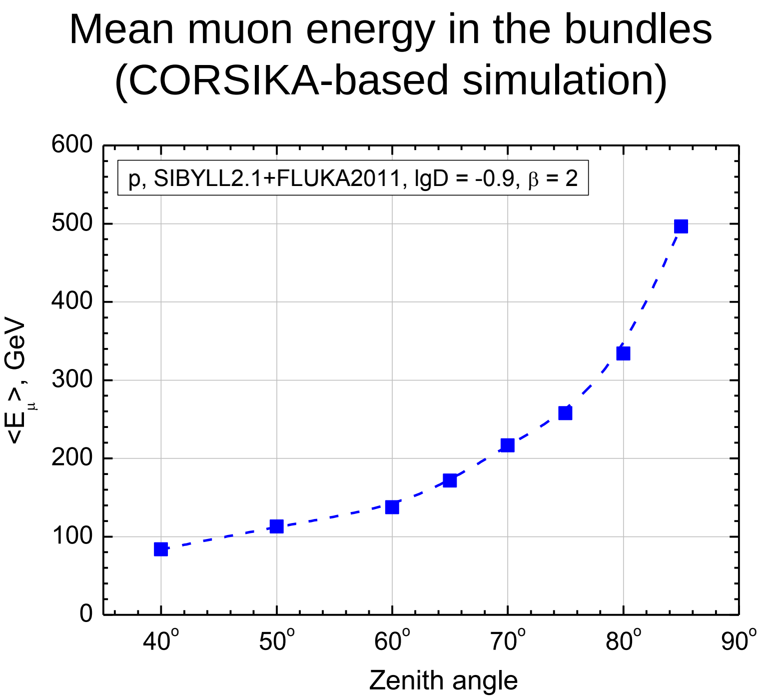
Correlation of the total Cherenkov water detector response with the local muon density estimate



As it might be expected, the energy deposit is proportional to the local density of muons. Therefore in the further analysis we use the specific energy deposition $< \Sigma N_{pe} / D >$ (the response normalized to the muon density estimate).

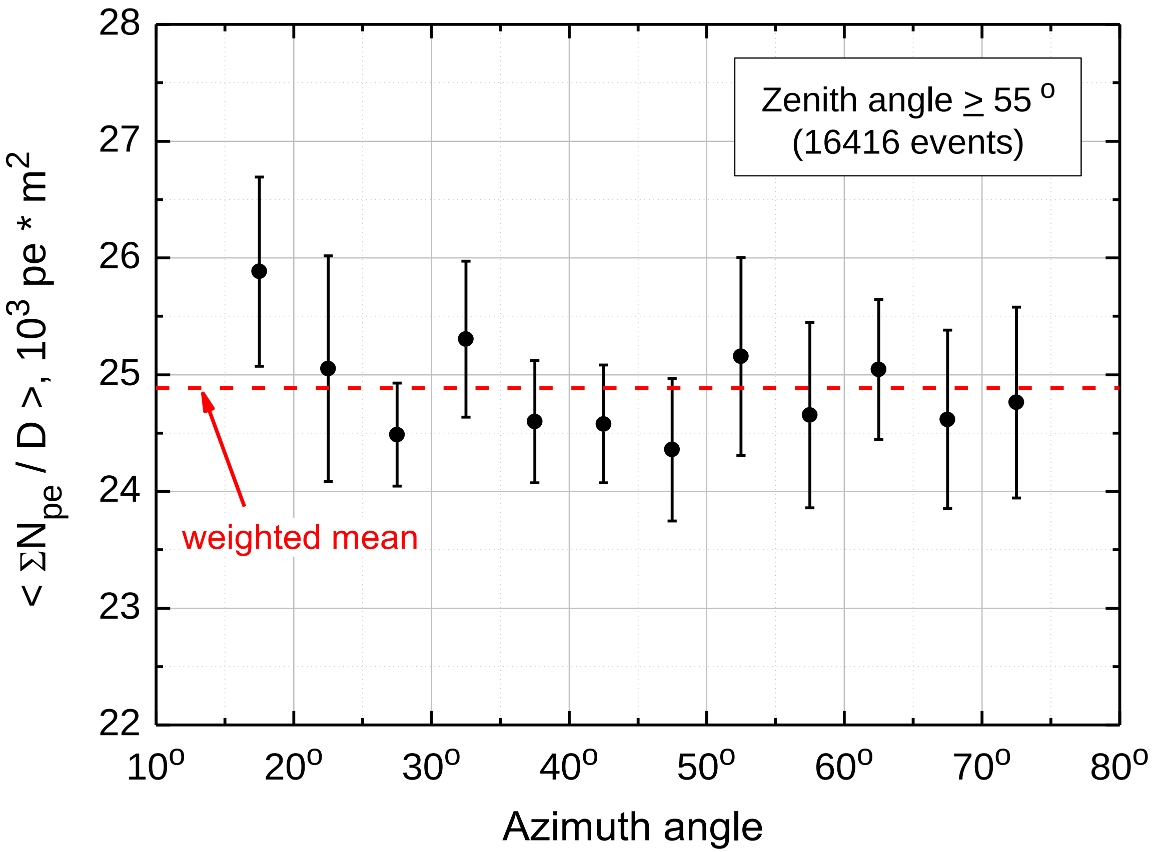
Zenith-angular dependence of the average specific energy deposit for muon bundles





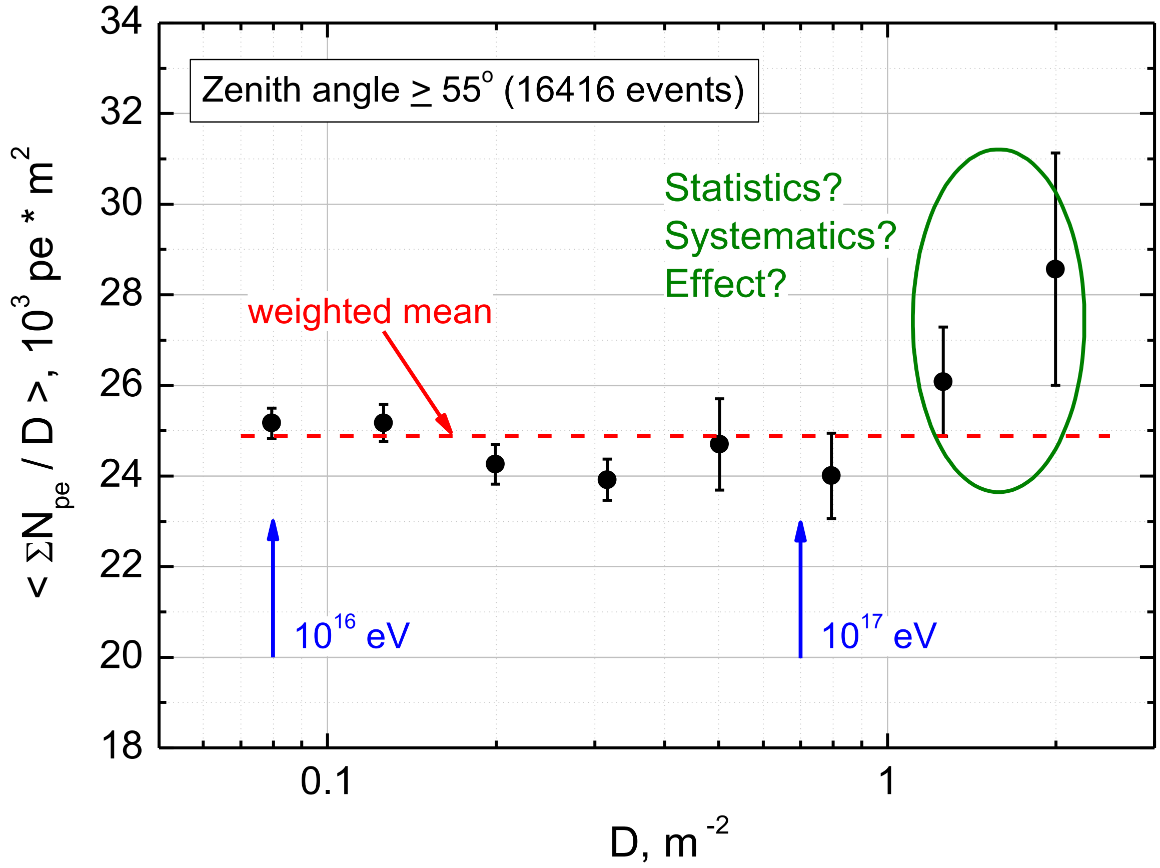
At moderate zenith angles, the average response falls off rapidly which can be explained as an atmospheric suppression of the residual contribution of electromagnetic and hadron EAS components. At larger zenith angles $\theta > 60^\circ$, the average specific energy deposit increases with θ, thus reflecting the increase of the average muon energy in the bundles.

Dependence of the average specific Cherenkov water detector response on the azimuth angle



The data exhibit a good uniformity (horizontal dashed line shows the weighted mean value). Thus, the structure of the measuring system NEVOD does not distort the results of the angular dependence measurements.

Average specific NEVOD response as a function of muon density



In fact (for a fixed range of zenith angles), this is a measurement of the dependence $<\Sigma N_{pe} / D>$ on the energy of primary particles. At present, within the measurement errors, no clear dependence of the response normalized to muon density is seen, at least for bulk data in a wide range of large zenith angles.

Conclusion

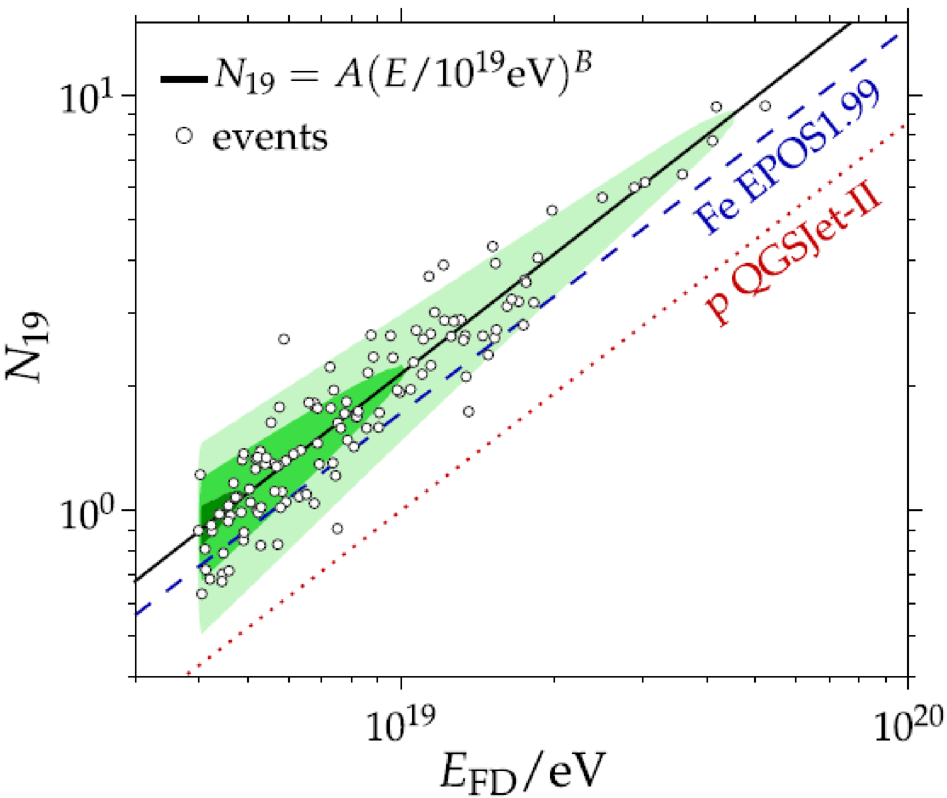
- An experiment on the measurements of the energy deposit of inclined muon bundles in the Cherenkov water detector is being conducted with the NEVOD-DECOR complex.
- As a result of the analysis of the data accumulated during first series of measurements (9673 h), a significant dependence of average specific energy deposit (normalized to the density of muons) on the zenith angle has been revealed.
- This dependence is explained by the increase of the average energy of muons in the bundles at large zenith angles and is in a good agreement with expectation based on CORSIKA simulations.
- Accumulation of data and their further analysis are in progress.

Thank you for your attention!

Backup Slides

Excess of the number of muons in highly inclined EAS from Pierre Auger Observatory data

G. Rodriguez, EPJ Web of Conf. 53 (2013) 07003



A. Aab et al., arXiv:1408.1421v2 [astro-ph.HE]

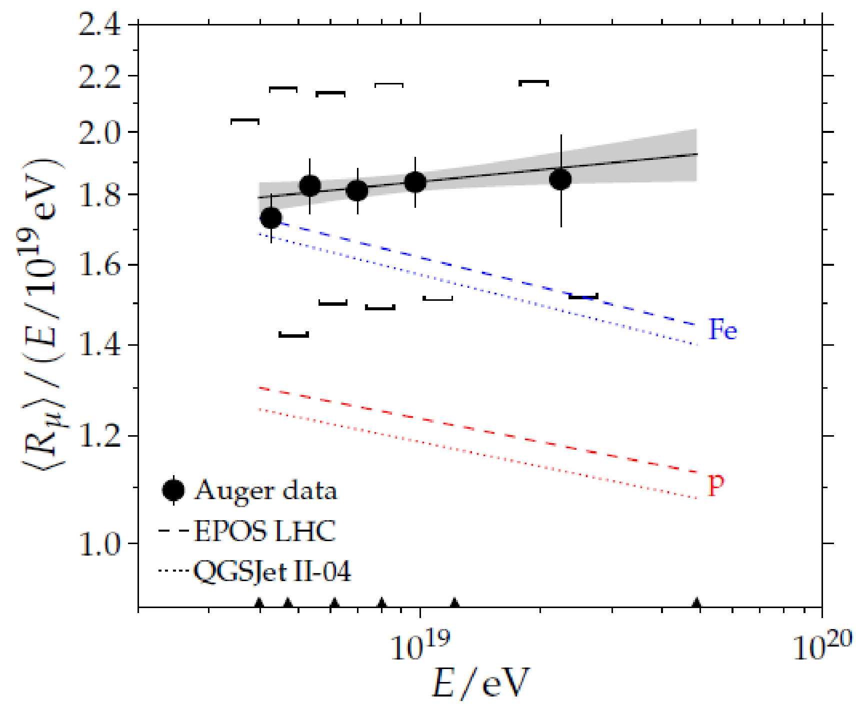


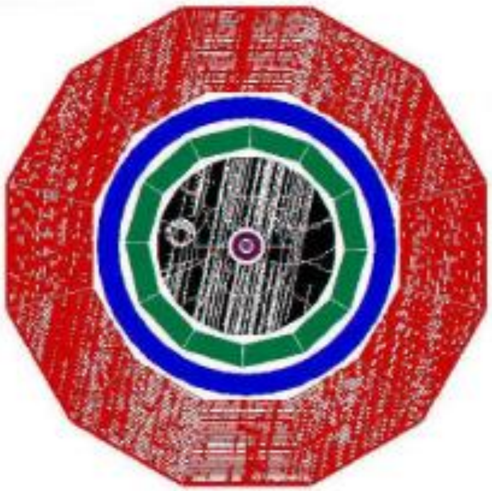
FIG. 4. Average muon content $\langle R_\mu \rangle$ per shower energy E as a function of the shower energy E in double logarithmic scale. Our data is shown bin-by-bin (circles) together with the fit discussed in the previous section (line). Square brackets

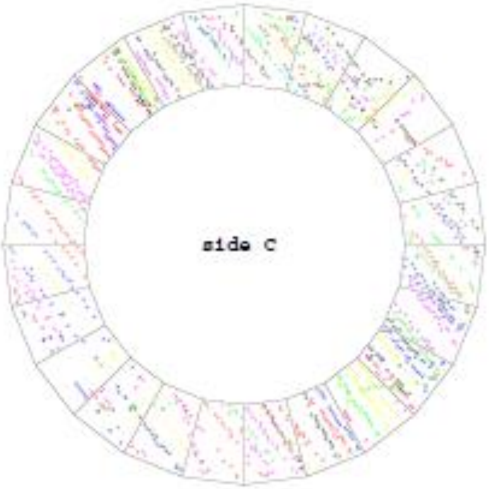
Summary: "We find that none of the current shower models, neither for proton nor for iron primaries, are able to predict as many muons as are observed".

Conclusion: "We observe a muon deficit in simulations of (30−80)% at 10^{19} eV, depending on the model".

Excess of muon bundles with high multiplicity from ALEPH and DELPHI detectors data (LEP, CERN)

ALEPH

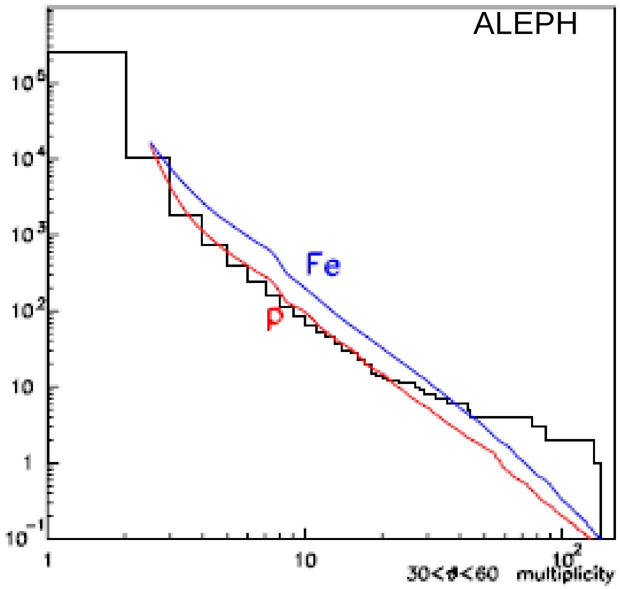


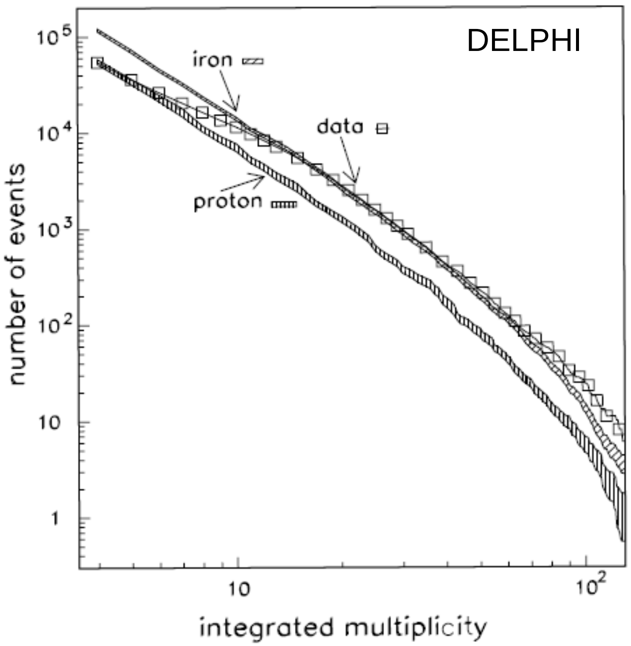


DELPHI

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

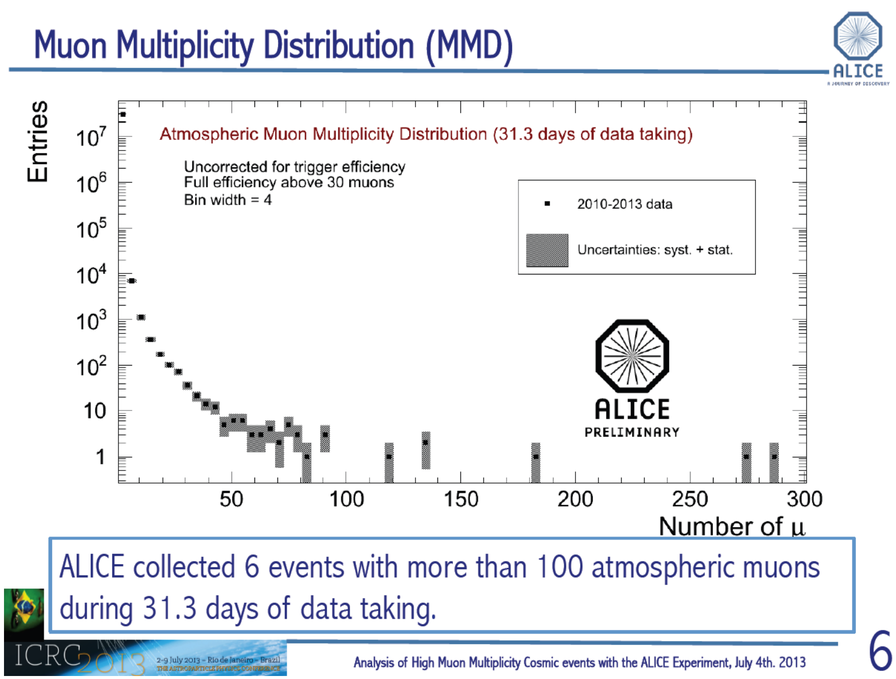
J. Abdallah et al., Astroparticle Physics 28 (2007) 273

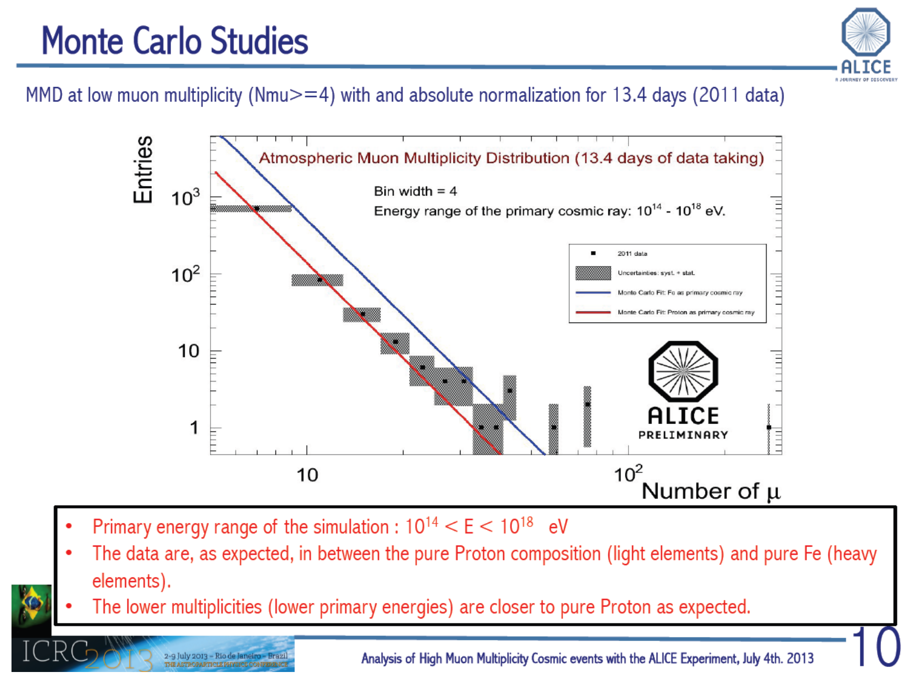


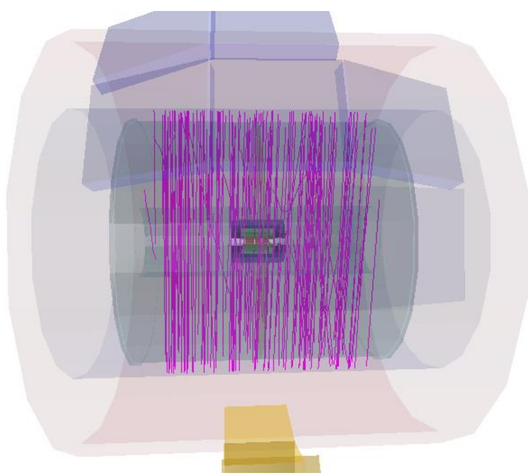


Excess of muon bundles with high multiplicity from ALICE detector data (LHC, CERN)

A. Fernandez, ICRC 2013



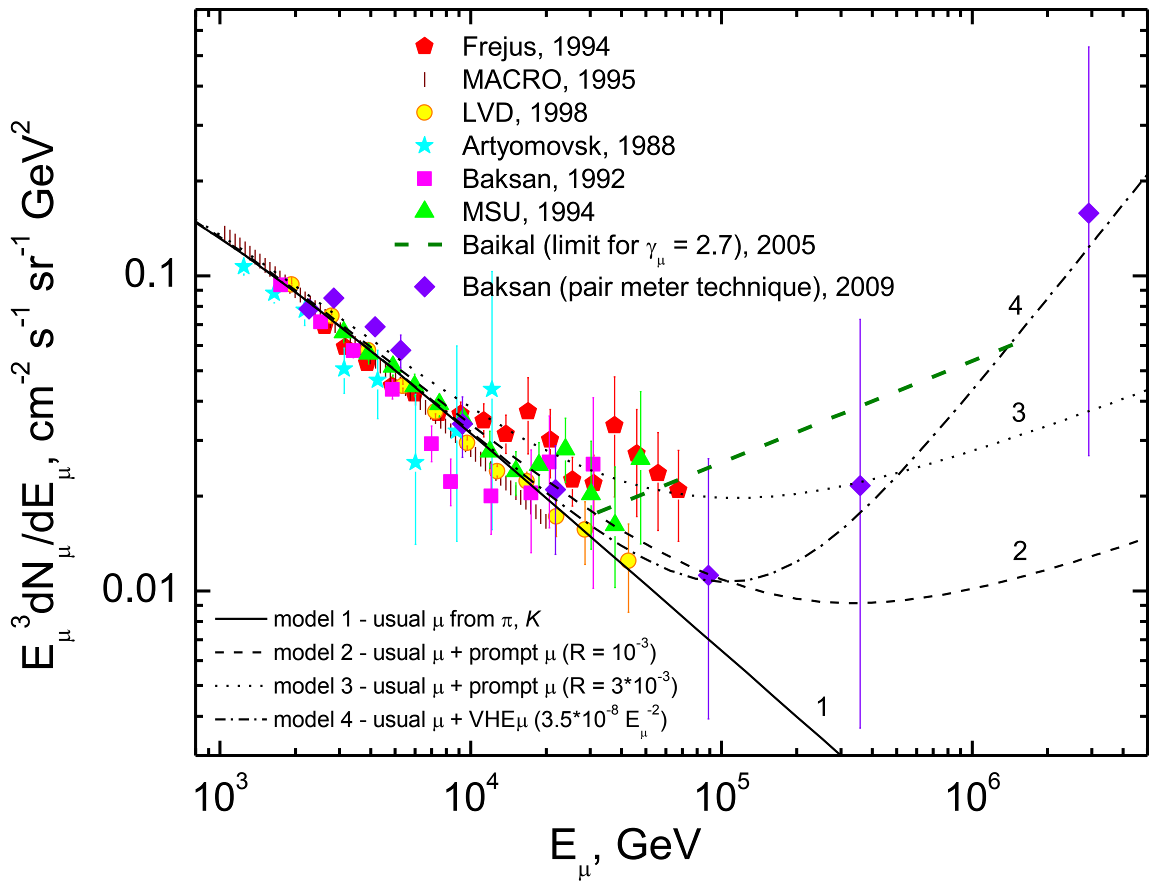




"… 5 events with more than 100 muons reconstructed in the TPC have been found. These events seem mostly due to iron or heavy nuclei with an energy greater than 10^{16} eV and a shower core located near ALICE …"

Excess of VHE muons from Baksan data

A.G. Bogdanov et al., Astroparticle Physics 36 (2012) 224



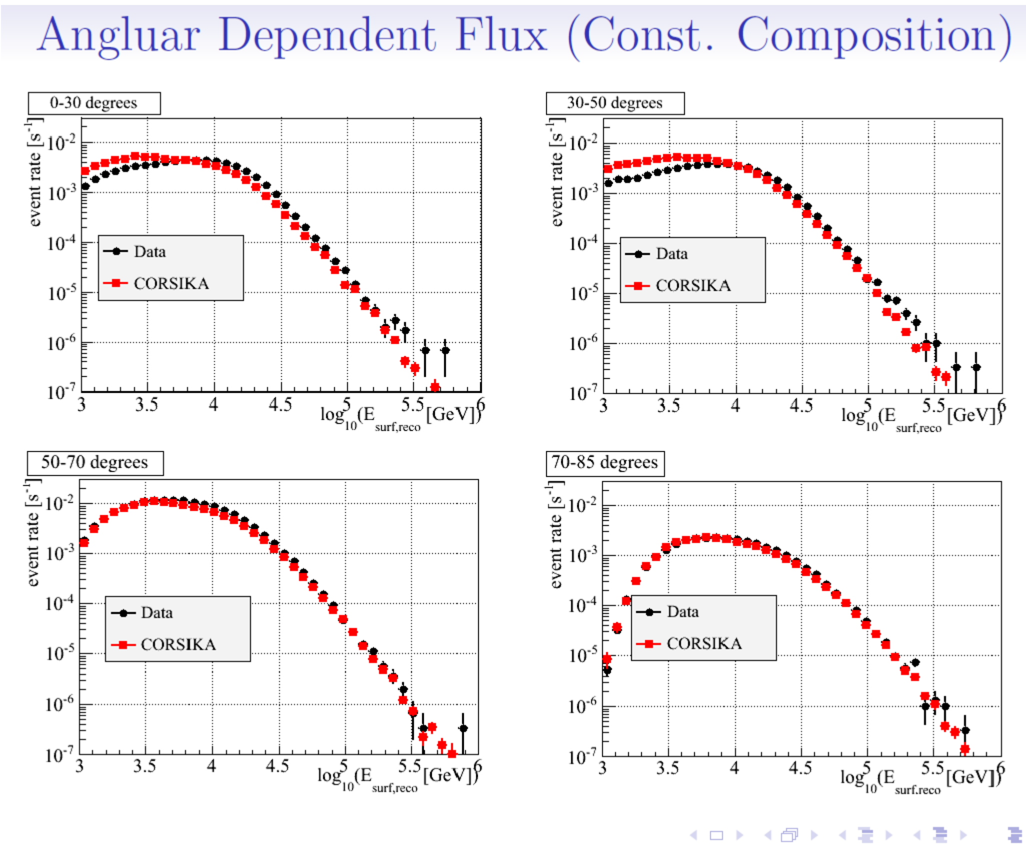
Differential muon energy spectra for vertical direction measured in various experiments

Depth intensity curve analysis and cascade shower spectrum measurements are shown. BUST results obtained by means of multiple interaction method are added (diamonds). The curves correspond to different spectrum models.

Excess of VHE muons from IceCube data

P. Berghaus, EPJ Web of Conferences 52 (2013) 09006

Berghaus P and Xu C, ICRC 2011



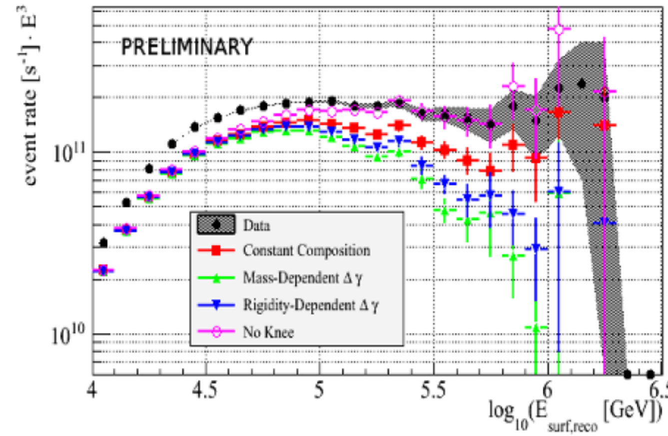


Figure 8. Experimentally measured single muon surface energy $E_{surf,reco}$ to simulation using data from the IceCube 59-string configuration [15]. The result is compared to three fluxes based on the Poly-Gonato model [11] and a toy model ignoring the cosmic ray knee. As only the conventional muon flux from light mesons was considered in the simulation, the lack of evidence for a cutoff in the spectrum could be due to an emerging prompt component. Errors are statistical only. As can be seen from the size of the error bars, availability of simulated events is a critical factor for the interpretation of the result.

"Even though the result is still preliminary, it seems difficult to explain the result with a purely conventional flux from a nucleon spectrum that cuts off at the Knee".

Local muon density phenomenology

For inclined EAS, the muon detector may be considered as a point-like probe. In a muon bundle event, the local muon density D (in a random point of the shower) is estimated:

$$D = \text{(number of muons) / (detector area)}; \quad [D] = \text{particles / m}^2.$$

Without considering fluctuations, spectrum of events in local density may be written as

$$F(\geq D) = \int N\left(\geq E(\mathbf{r}, D)\right) dS,$$

where $N(\geq E)$ - primary spectrum, E is defined by the equation:

$$\rho(E, \mathbf{r}) = D.$$

Dimension: $[F(\geq D)]$ = events / (s sr).

Local muon density phenomenology

For a nearly scaling LDF around some energy E_0

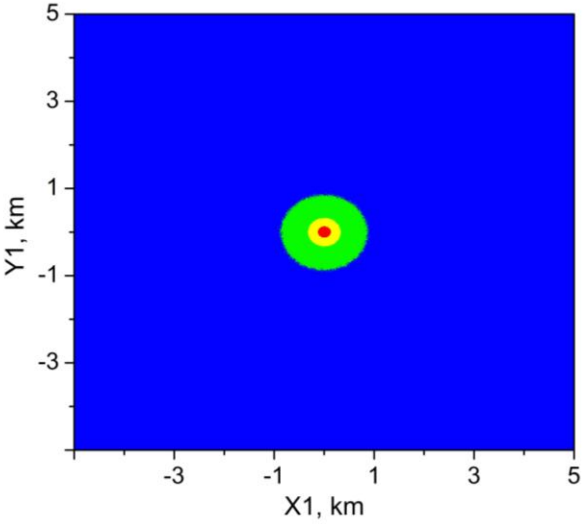
$$\rho(E,\mathbf{r}) = (E/E_0)^{\kappa} \times \rho(E_0,\mathbf{r}),\ \kappa \approx 0.9$$

and power type primary spectrum $N(\geq E) = A(E/E_0)^{-\gamma}$,

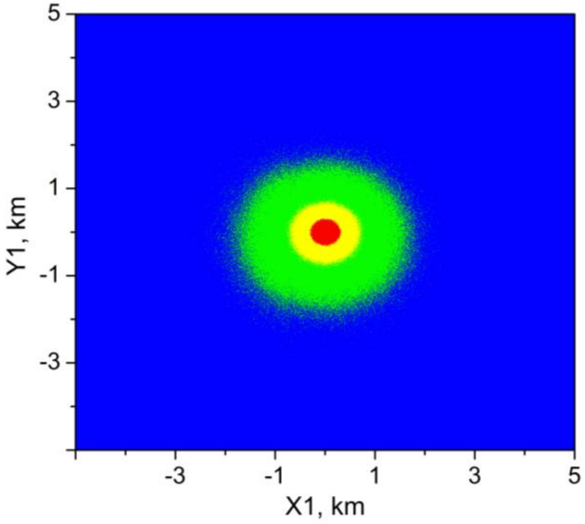
$$F(\geq D) = AD^{-\beta} \int \left[\rho(E_0,\mathbf{r})\right]^{\beta} dS$$

Power type spectrum of local density, a bit steeper than the primary one ($\beta = \gamma / \kappa \approx 2$).

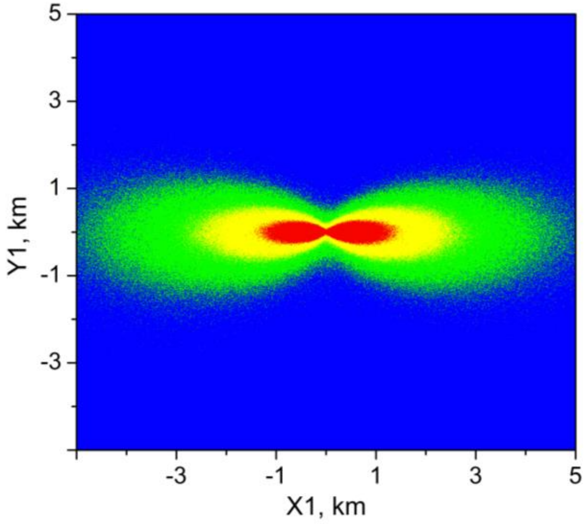
Shower cross section in muons



$\theta = 35^\circ$



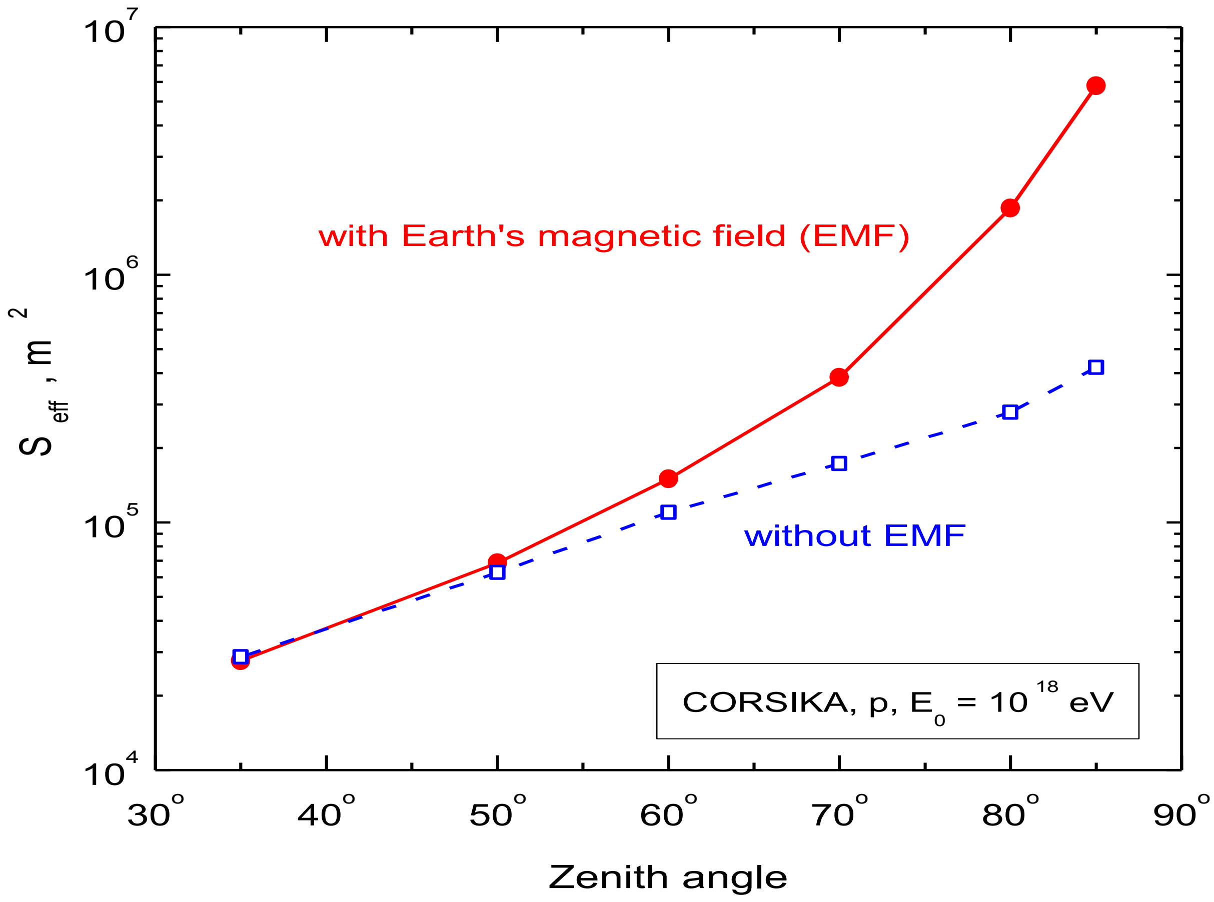
$\theta = 80^\circ$ (without EMF)



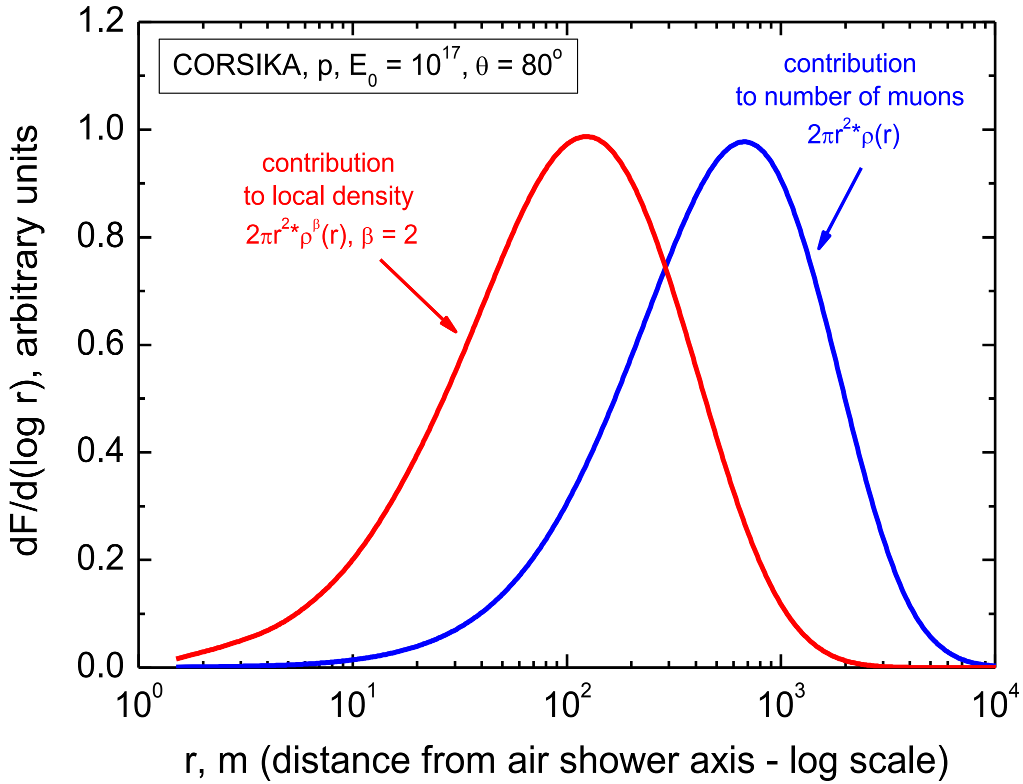
$\theta = 80^\circ$ with EMF

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

Dependence of the effective EAS collection area in theLMDS technique on zenith angle



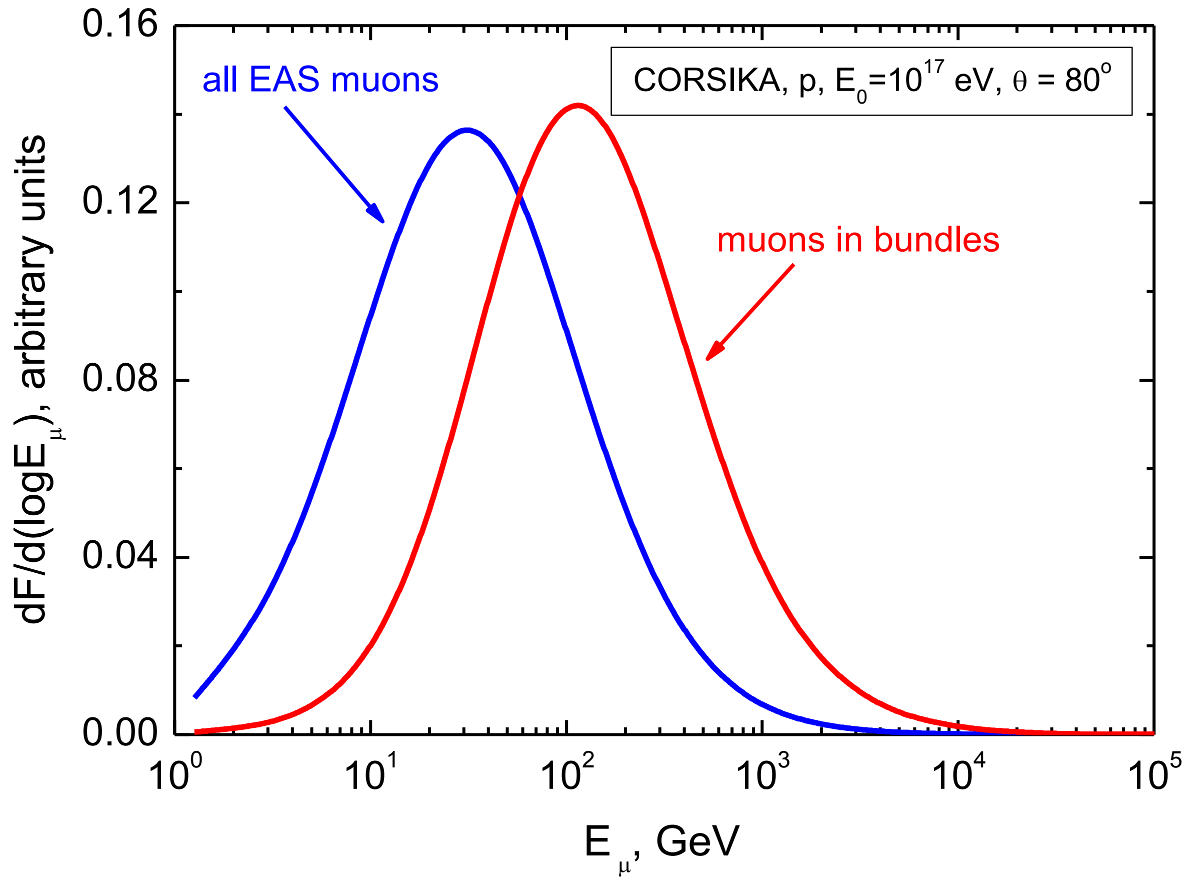
Basic features of the LMDS technique



Contribution of various distances from the shower axis to the total number of muons in EAS and to the local muon density spectrum

Selection of the events according to the muon density pre-determines an enhanced sensitivity to the central part of the shower (forward interaction region)

Basic features of the LMDS technique



Energy spectrum of muons in bundles (selection of events by muon density) and of all muons in EAS

Median muon energy in bundles is several times higher than in EAS as a whole.

Experimental observation of the effect of the Earth's magnetic field on the EAS muon component

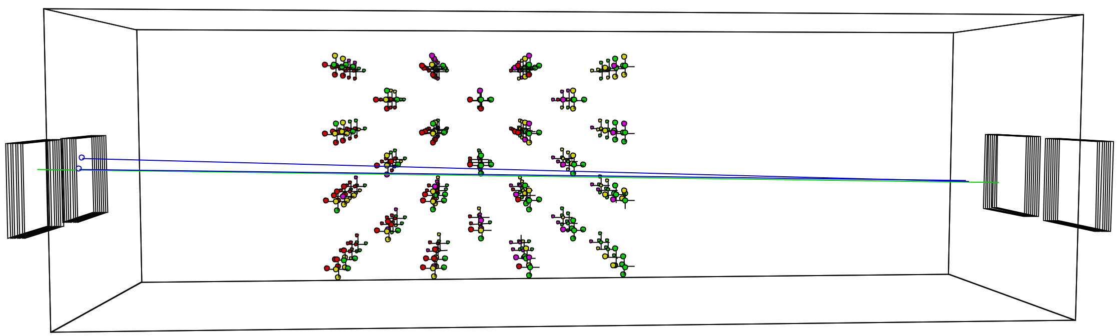
Influence of the Earth's magnetic field on EAS muon component was studied [A.G. Bogdanov et al., Bulletin of the Russian Academy of Sciences: Physics. 2007. V. 71. N 4. P. 528]. A serious non-uniformity of the azimuth dependence of muon bundle intensity was revealed; this non-uniformity being enhanced with the increase of zenith angle. This phenomenon is quantitatively explained by the distortion of the lateral distribution function of EAS muons by the geomagnetic field. A new effect – the presence of a coplanar component in the directions of muon tracks within a bundle in a plane determined by EAS direction and Lorentz force vector – was found.

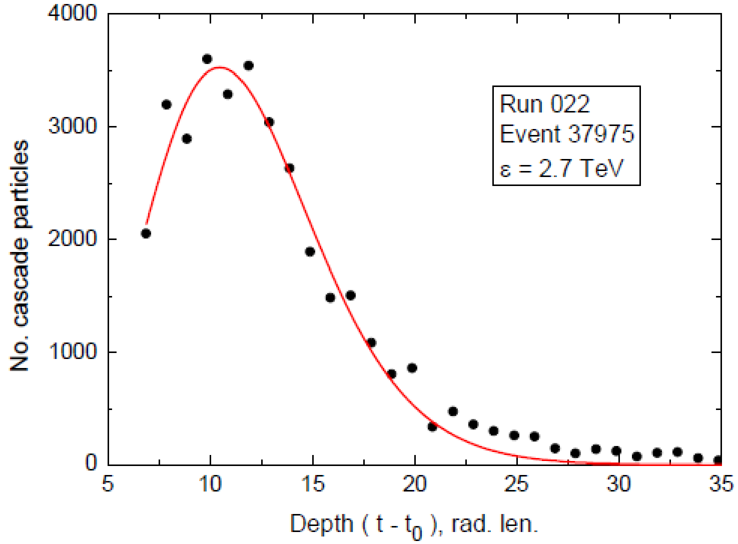
Meteorological effects in the intensity of muon groups

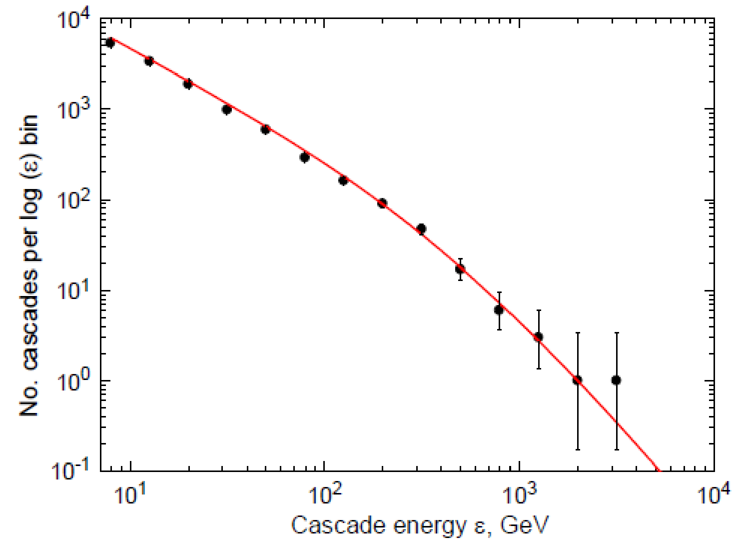
For the first time, experimental estimates of meteorological effects in the intensity of muon bundles detected at the ground surface were obtained [N.V. Tolkacheva et al. Bulletin of the Lebedev Physics Institute. 2010. V. 37. Issue 6, P. 173]. It was found that the frequency of registration of muon bundles was appreciably different during a year; in winter, the intensity was 10-15% higher than in summer. As a result of a more detailed study, the temperature and barometric coefficients for muon bundle intensity were estimated. It was shown that, similar to geomagnetic field effects, variations of the intensity of the bundles are caused by changes of muon LDF in the extensive air showers developing in a changeable atmosphere.

Energy spectrum of cascade showers from nearly horizontal muons: first results (NEVOD-DECOR)

O. Saavedra et al., Journal of Physics: Conference Series 409 (2013) 012009



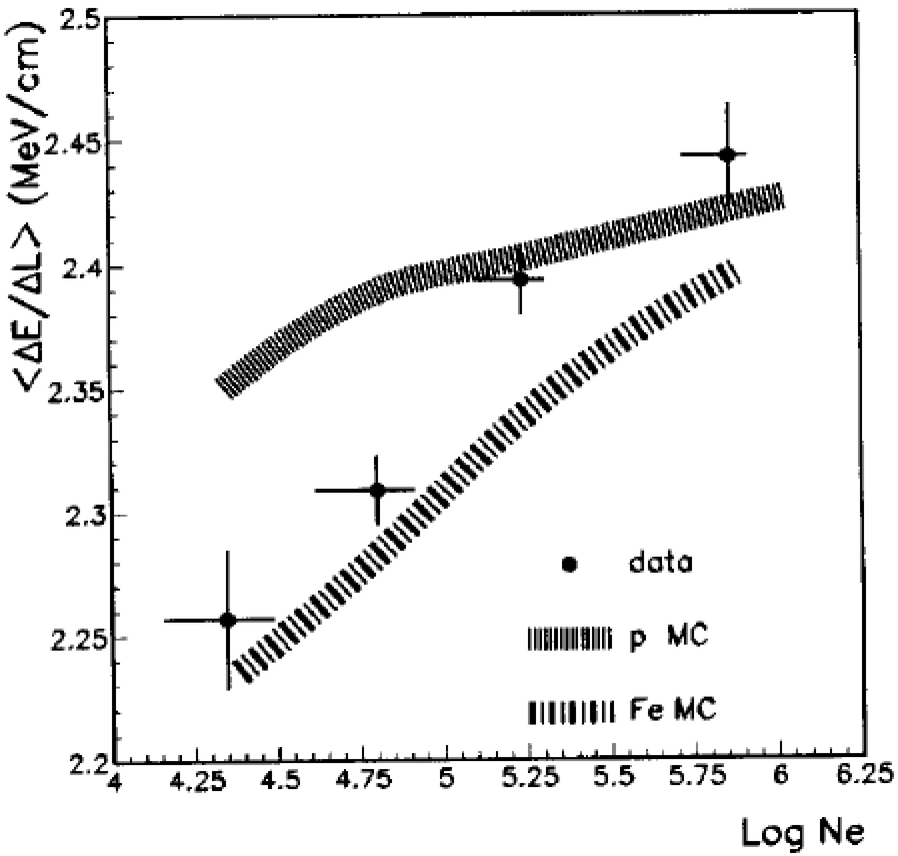




An example of the reconstruction of the individual cascade curve in the Cherenkov water detector (left) and the measured energy spectrum of cascade showers generated by muons in water (right).

LVD (muon energy loss) and EAS-TOP (air shower size) combined data analysis

M. Aglietta et al., Astroparticle Physics 9 (1998) 185



Mean energy depositions per unit track length inside LVD counters as function of shower size N_e of time correlated EAS-TOP events

“The present LVD-EAS-TOP combined data analysis shows that the mean muon energy loss in LVD per unit path length increases with shower size at $N_e \sim 10^5$, this is compatible with the expectations from a mixed cosmic ray composition …”