Scientific & Educational Centre NEVOD

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# Energy characteristics of multi-muon events in a wide range of zenith angles

A.G. Bogdanov[1], N.S. Barbashina[1], D.V. Chernov[1], L.I. Dushkin[1], S.S. Khokhlov[1], V.A. Khomyakov[1], V.V. Kindin[1], R.P. Kokoulin[1], K.G. Kompaniets[1], G. Mannocchi[2], A.A. Petrukhin[1], O. Saavedra[3], G. Trinchero[2], V.V. Shutenko[1], I.I. Yashin[1], E.A. Yurina[1]

[1] *National Research Nuclear University MEPhI, Moscow, Russia*
[2] *Osservatorio Astrofisico di Torino, Torino, Italy*
[3] *Dipartimento di Fisica dell' Universita di Torino, Torino, Italy*

# “Muon puzzle” in cosmic ray experiments

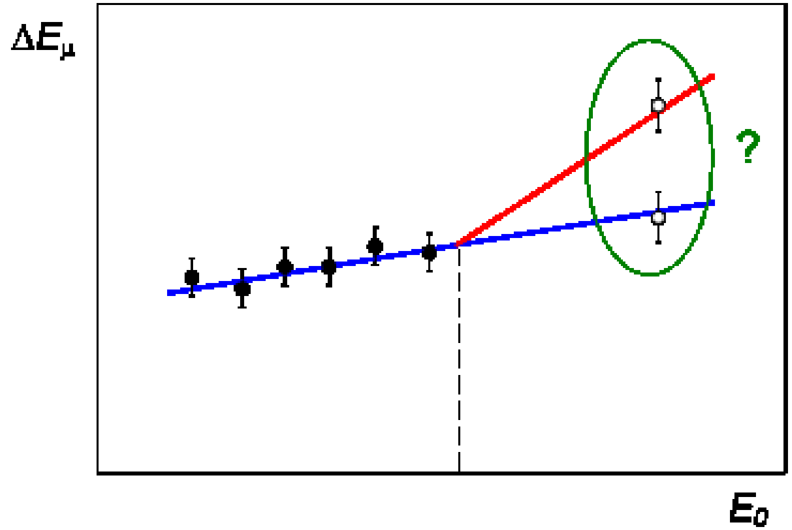
In a number of UHE cosmic ray experiments (HiRes/MIA, DECOR, Pierre Auger Observatory), excess of muons in comparison with calculations (even for extremely heavy composition) is observed.

Measurements of muon component energy characteristics are necessary. Possible approach: measurement of muon bundle energy deposit in the detector material.

The average specific energy loss of muons in matter almost linearly depends on the muon energy: $dE/dx \sim a + bE$.

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

The experiment on the study of the energy deposit of the muon bundles was started at the NEVOD-DECOR setup in 2012.




*Two possible scenarios of muon energy deposit measurements*

# General view of the NEVOD-DECOR setup

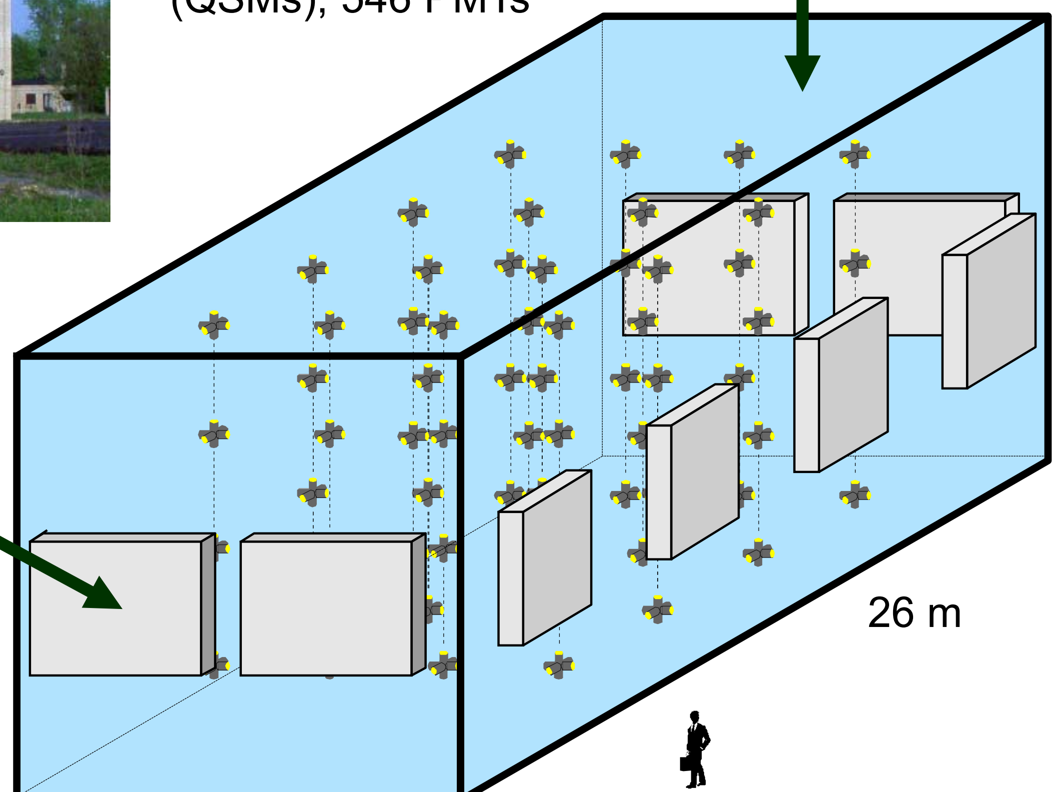
**Cherenkov water detector NEVOD (volume 2000 m$^3$)**

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

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

8 supermodules (SMs) of streamer tube chambers

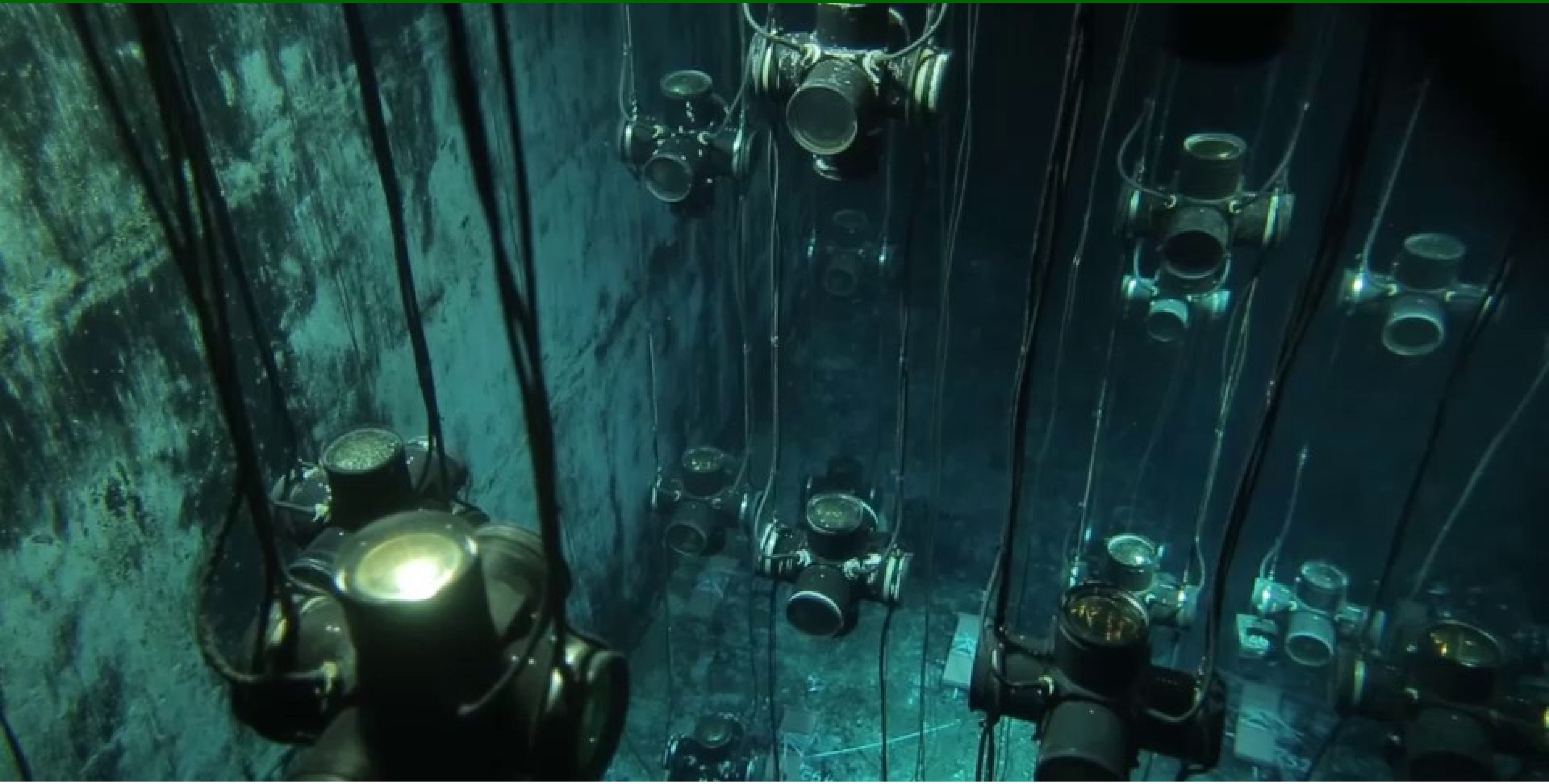
*these chambers were used earlier in the NUSEX experiment*




9 m

9 m

# Detecting system of Cherenkov water calorimeter NEVOD. Quasi-spherical measuring modules of the NEVOD detector



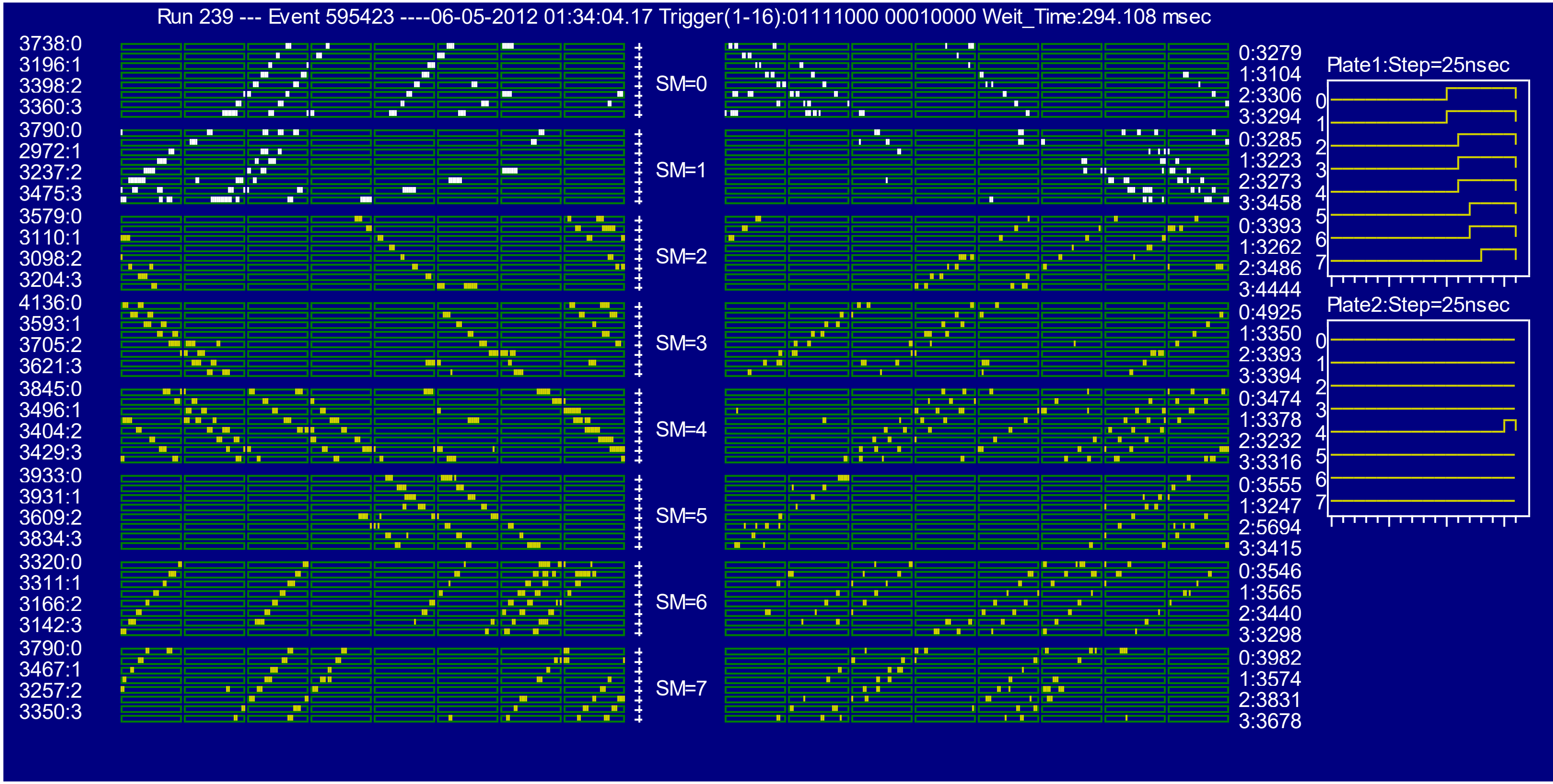
91 QSMs are arranged into an array of 25 vertical strings (9 strings × 3 QSM, 16 strings × 4 QSM). Each QSM consists of 6 low-noise 12-dynode photomultipliers FEU-200 with flat 15 cm diameter photocathodes directed along rectangular coordinate axes. A wide dynamic range ($1 - 10^5$ photoelectrons) is provided due to 2-dynode signal readout and allows to measure both high-energy cascades and energy deposit of muon bundles in the calorimeter.

# 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. 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 $m$ = 29 particles, zenith angle $\theta$ = 49°

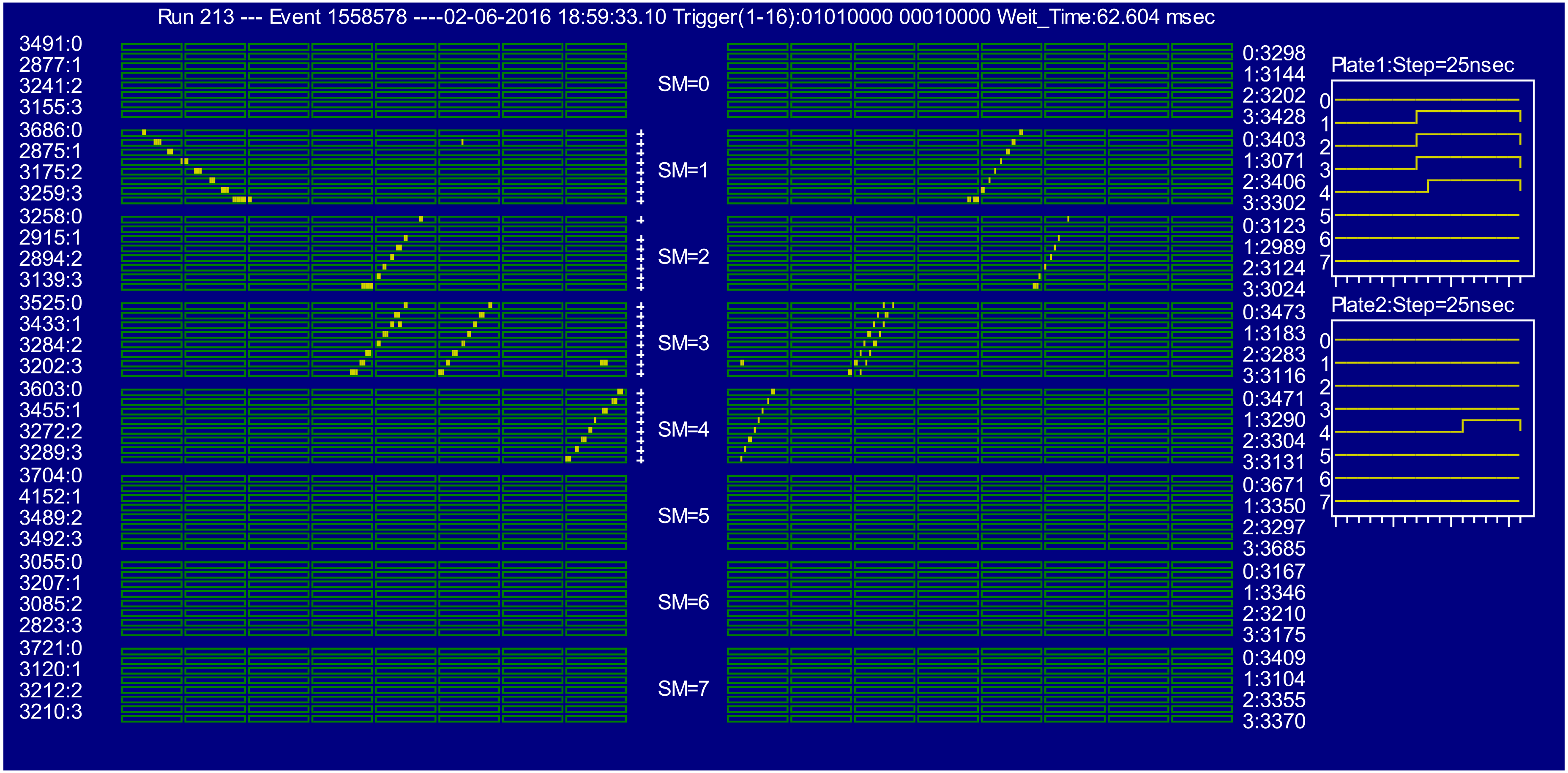



*Y-coordinate (azimuth angle)* *X-coordinate (projected zenith angle)*

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

# Muon bundle event in the DECOR SMs

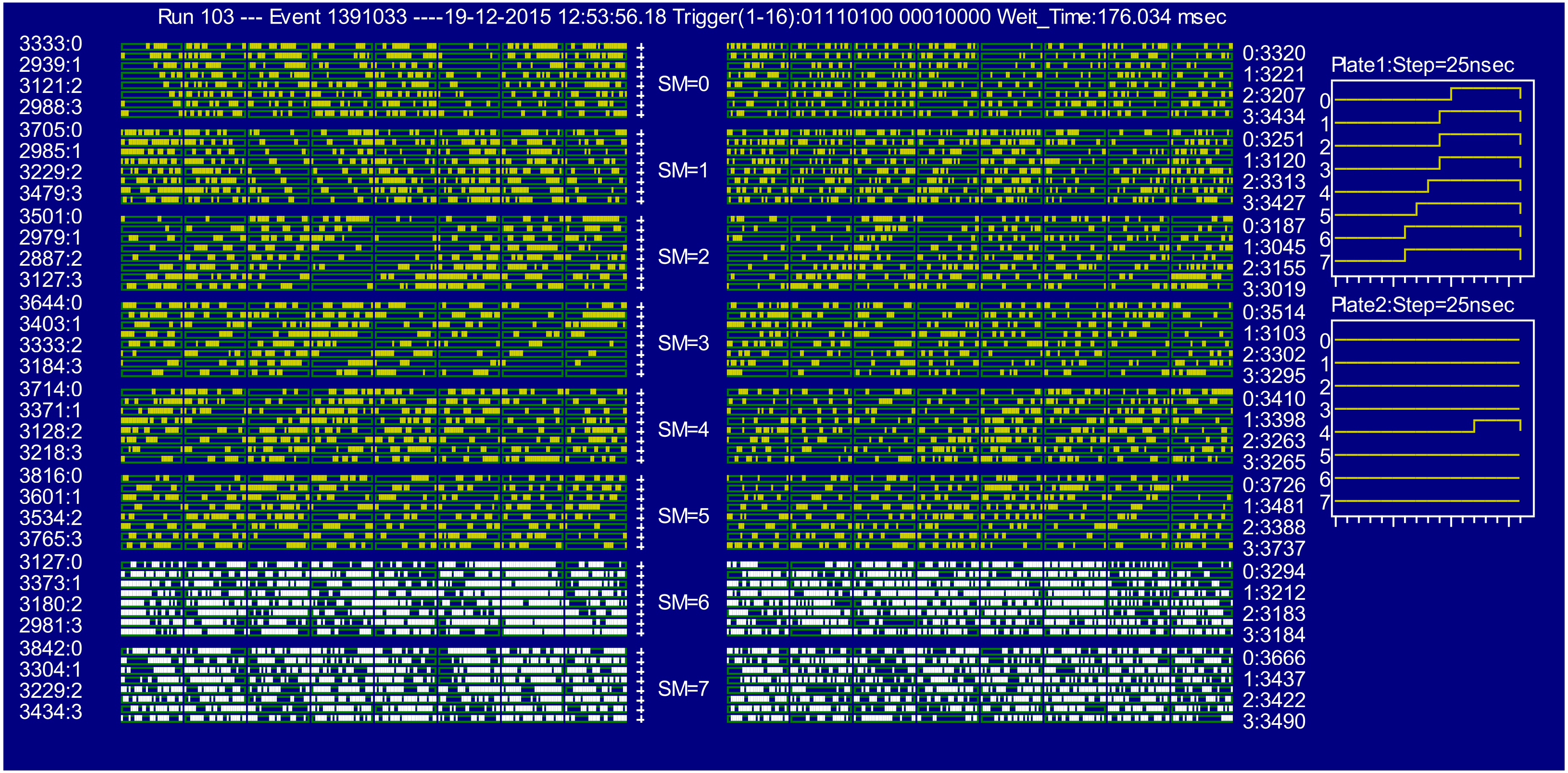
multiplicity $m$ = 5 particles, zenith angle $\theta$ = 72°




*Y-projection* *X-projection*

# Muon bundle event in the DECOR SMs

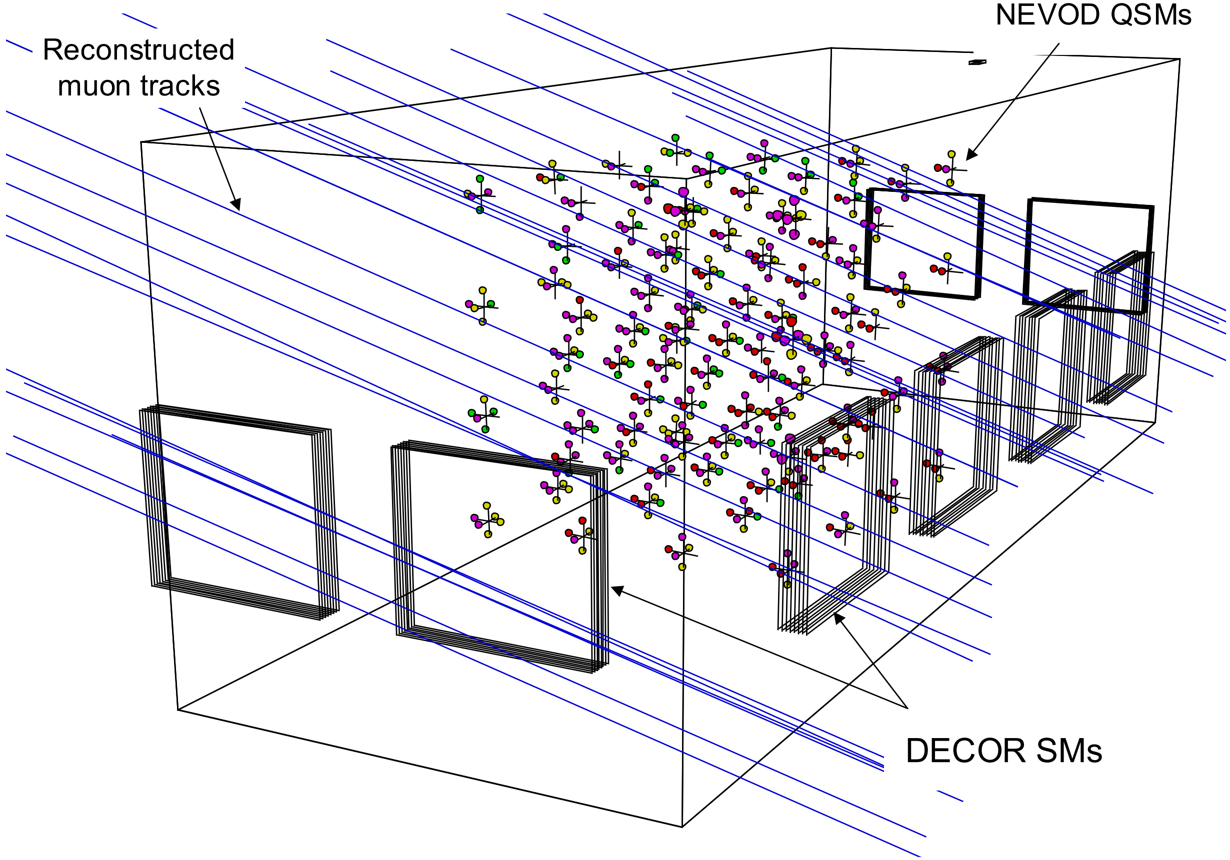
multiplicity $m$ = 144 particles, zenith angle $\theta$ = 57°




*Y-projection*

*X-projection*

# 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)*

Local muon density in the event and EAS arrival direction are estimated from DECOR data; the energy deposit is measured in the Cherenkov water calorimeter NEVOD.

# NEVOD-DECOR experimental data

Results of the analysis of the data on the energy deposit of inclined muon bundles accumulated during 3 measurement series:

03.05.2012 – 20.03.2013, 5542 h
16.07.2013 – 08.04.2015, 11897 h
16.07.2015 – 04.05.2016, 5776 h (is now continuing)

Total “live” observation time – 23215 h

$m$ (multiplicity) $\geq 5$ and $\theta$ (zenith angles) $\geq 55^\circ$ – 39542 events;

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

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

The selection procedure includes several stages:
trigger level (3-fold coincidence of signals from SMs, time gate = 250 ns);
program reconstruction and selection – quasiparallel tracks (5°-cone), ≥ 3 different SMs;
final event classification and track counting by the operators.

# Local muon density

Unbiased estimate (taking into account a steep muon density spectrum and Poisson fluctuations of the number of muons in the setup) of local muon density is calculated as:

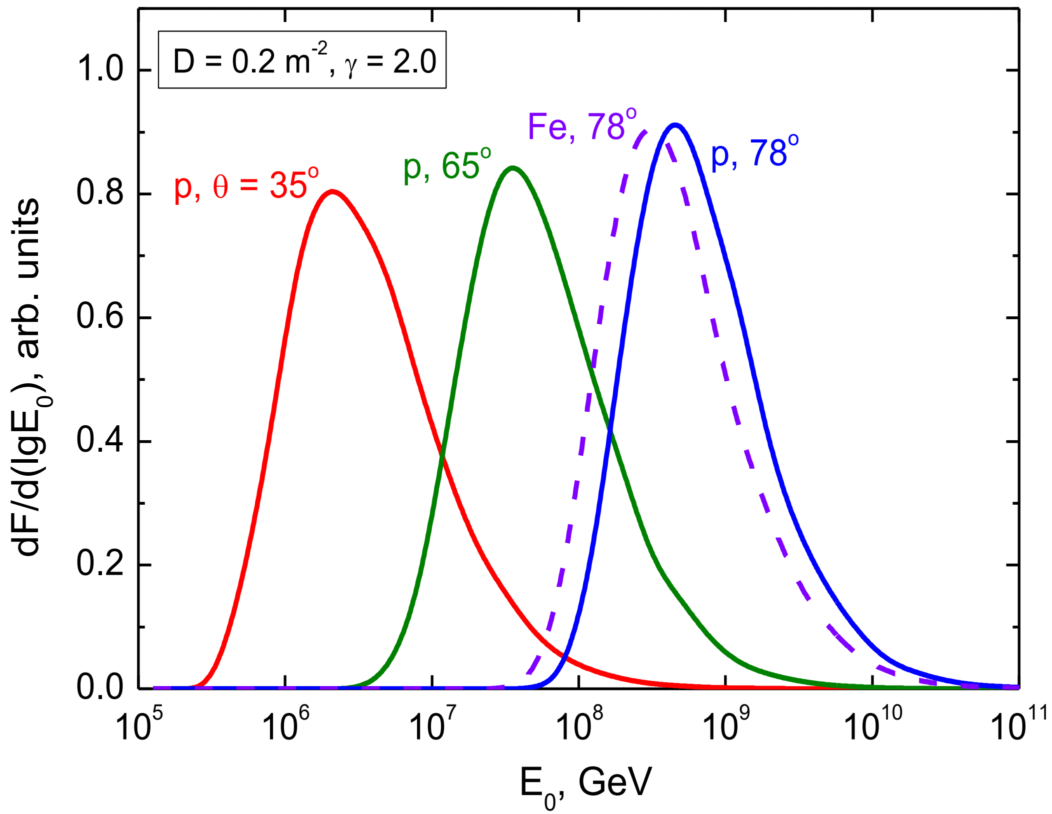
$$D = (m - \beta) / S_{det},$$

where $m$ is the number of muons, $\beta \approx 2.1$ is the integral LMDS slope, $S_{det}$ is the effective area of DECOR SMs for a given direction of muon bundle arrival.

The earlier developed method of EAS investigations by local muon density spectra (LMDS) allows to estimate the energy of the primary particles according to the DECOR data.

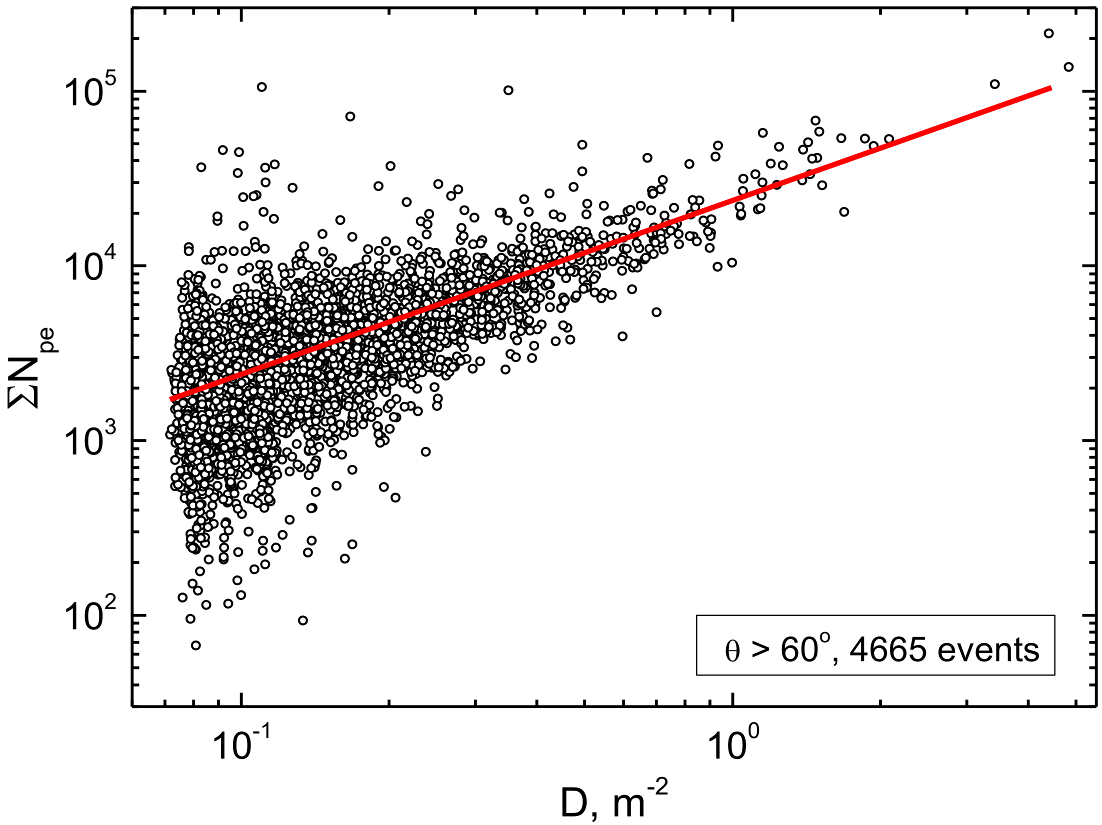
*Description of the phenomenology of the LMDS –*
*A.G. Bogdanov et al., Physics of Atomic Nuclei. 2010. V. 73. N 11. P. 1852.*

# Contribution of various primary particle energies to the formation of muon bundle events at different zenith angles (CORSIKA)




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.

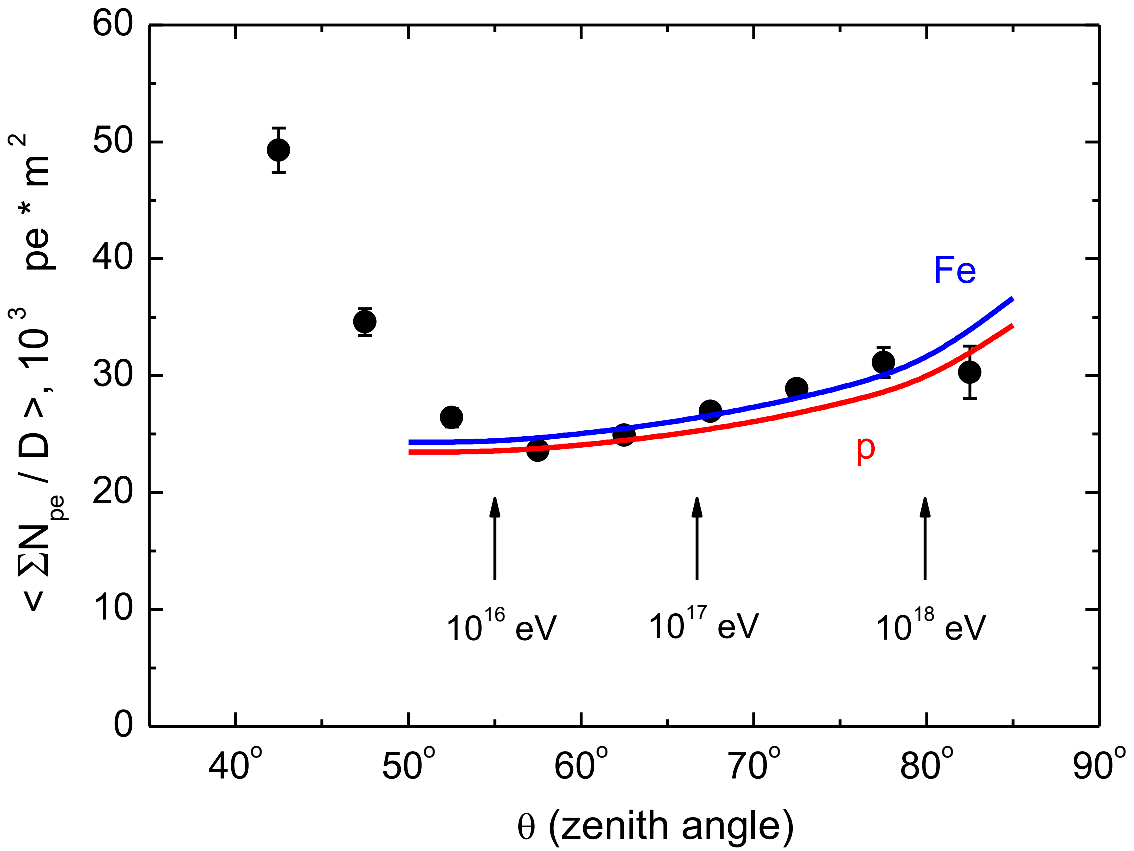
# Correlation of the total Cherenkov water detector response with the local muon density estimate




In a first approximation, the total energy deposit is proportional to muon density in the event. Therefore, in the further analysis we use the **specific energy deposition** $< \Sigma N_{pe} / D >$ (the response normalized to the muon density).

It was assumed that the number of Cherenkov photons is approximately proportional to the total muon energy loss in the detector.

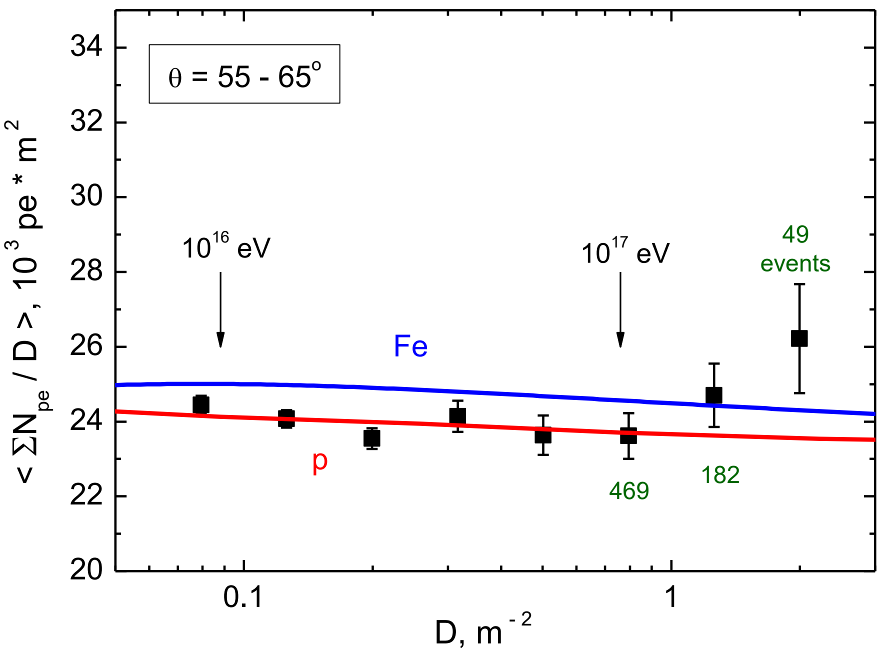
# Dependence of the muon bundle average specific energy deposit on zenith angle

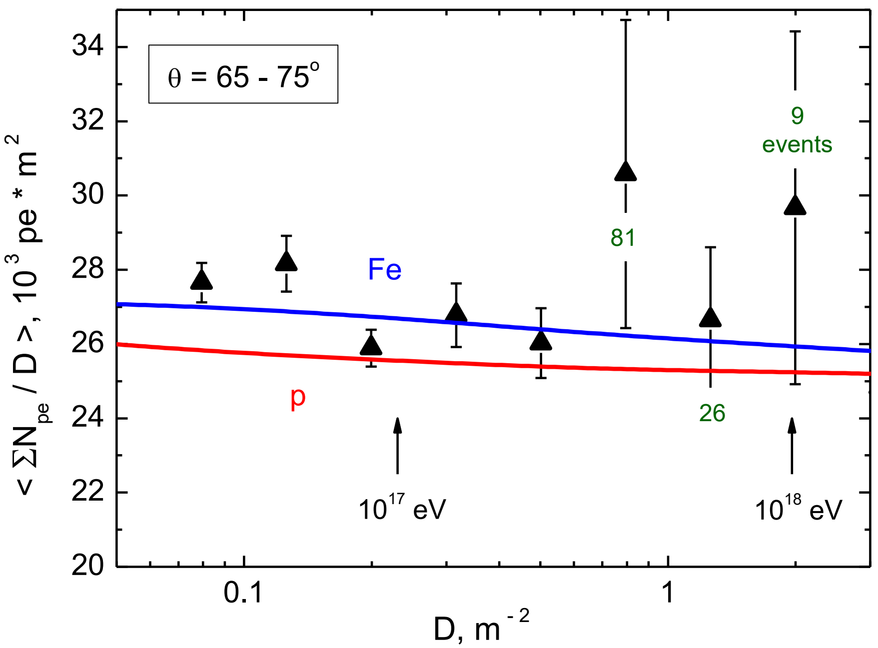



At moderate zenith angles, a residual contribution of electron-photon and hadron EAS components to the response of non-screened water calorimeter is significant. At $\theta \geq 55°$, practically pure muons remain. The increase of the energy deposit with zenith angle reflects the increase of the average muon energy in the bundles (up to 500 GeV near horizon).

# Dependence of average specific energy deposit on muon density for different zenith angles

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.




Simulation results show a tendency to a slow decrease of muon energy in the bundles with the increase of primary energy. In contrast, data indicate some increase of the average specific energy deposit at high muon densities (corresponding to effective primary particle energies more than $10^{17}$ eV).

# Conclusion

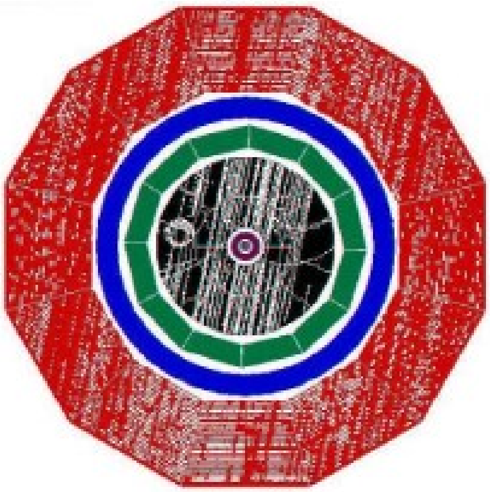
- The experiment on the investigation of the energy characteristics of inclined muon bundles formed as a result of interactions of primary cosmic ray particles with energies $10^{16}$ – $10^{18}$ eV is being conducted at the NEVOD-DECOR setup. For the moment, preliminary analysis of the data accumulated for 23.2 thousand hours observation time has been performed.
- The results of the measurements of zenith-angular dependence of the average specific energy deposit in the Cherenkov water detector are in a reasonable agreement with CORSIKA-based simulations of the EAS muon component and confirm the increase of the mean energy of muons in the bundles at large zenith angles.
- An indication for an increase of the average specific energy deposit compared to the expectation at primary particle energies above $10^{17}$ eV has been found. However, further increase of experimental statistics and a careful analysis of possible systematic effects are necessary.
- Accumulation of experimental data, their processing and analysis are being continued.

# Thank you for your attention!

# Grazie per la vostra attenzione!

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

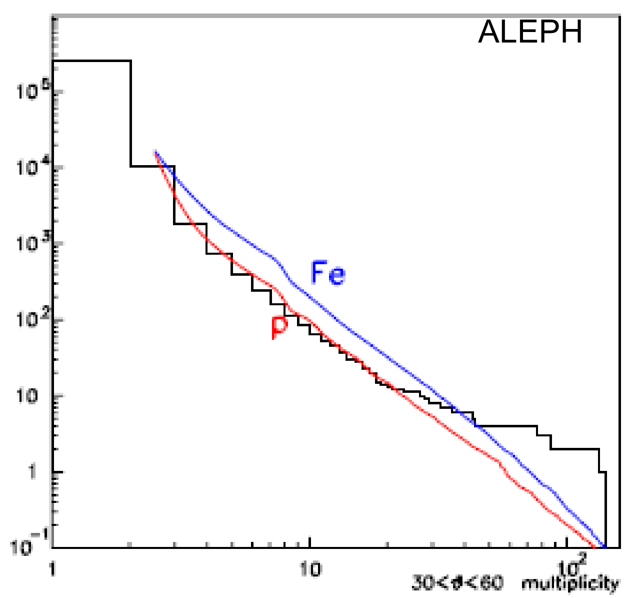
ALEPH

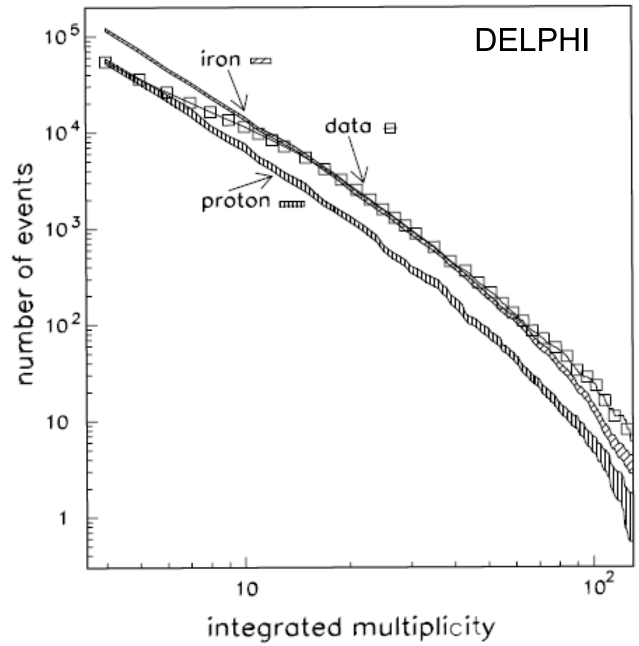



DELPHI

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

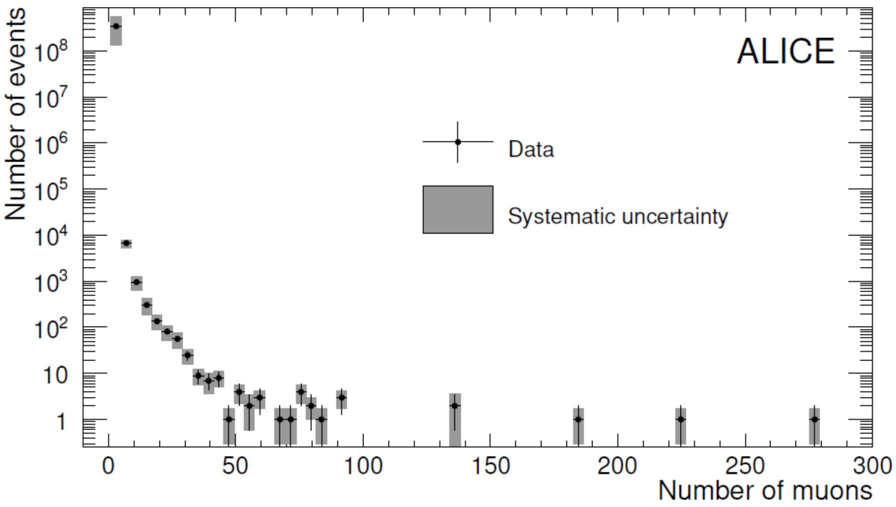
*J. Abdallah et al., Astroparticle Physics 28 (2007) 273*

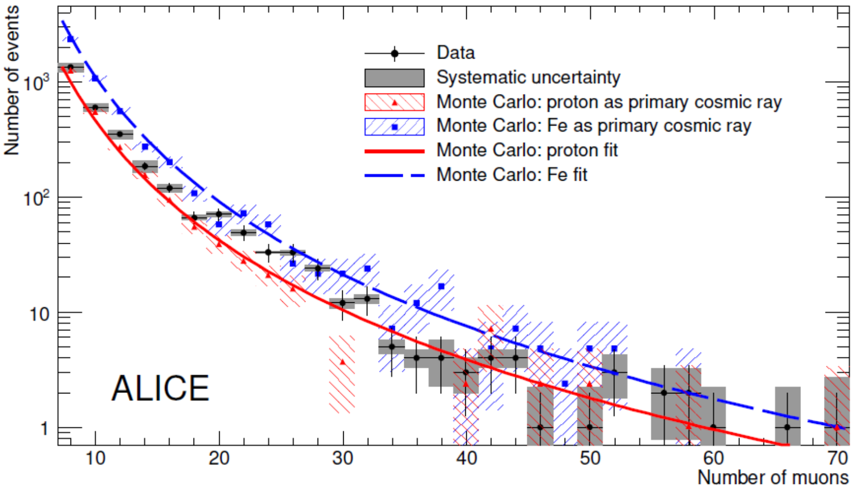


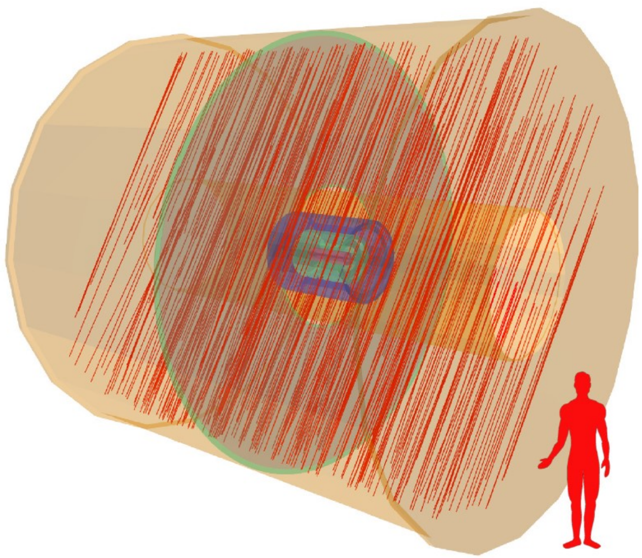



# Excess of muon bundles with high multiplicity from ALICE detector data (LHC, CERN)

*The ALICE collaboration, JCAP01 (2016) 032*

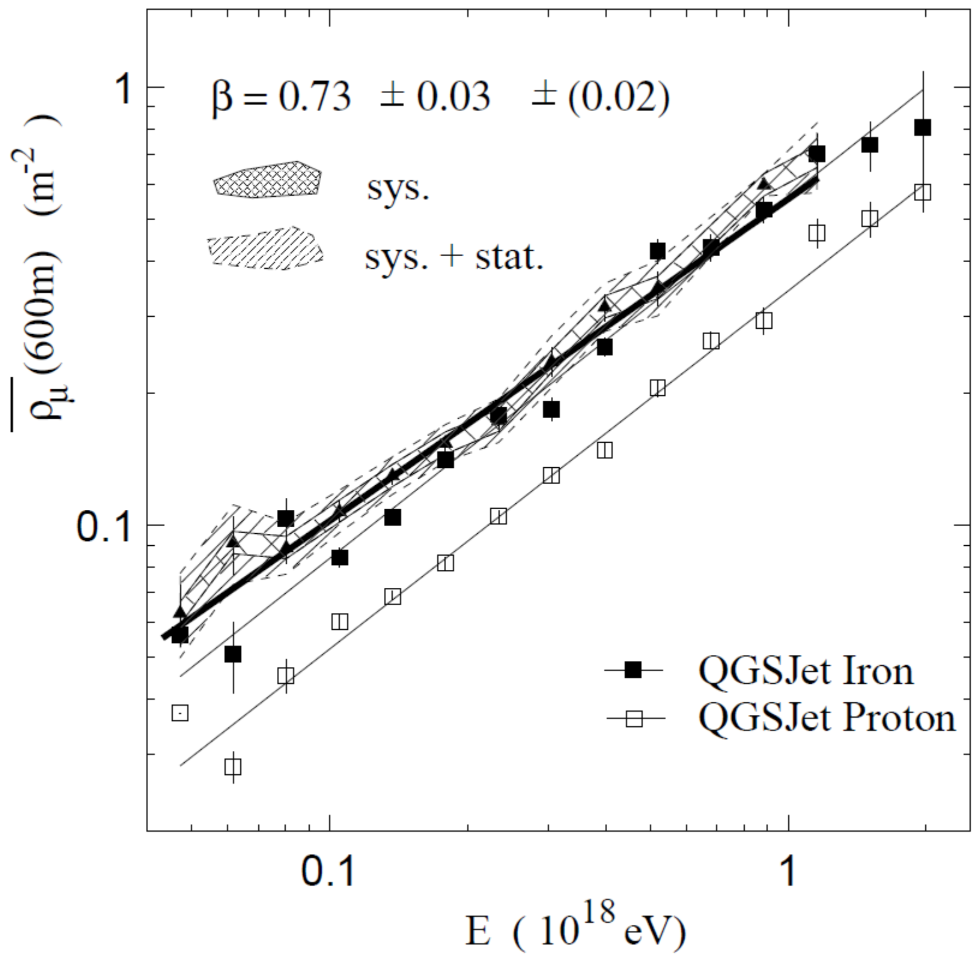


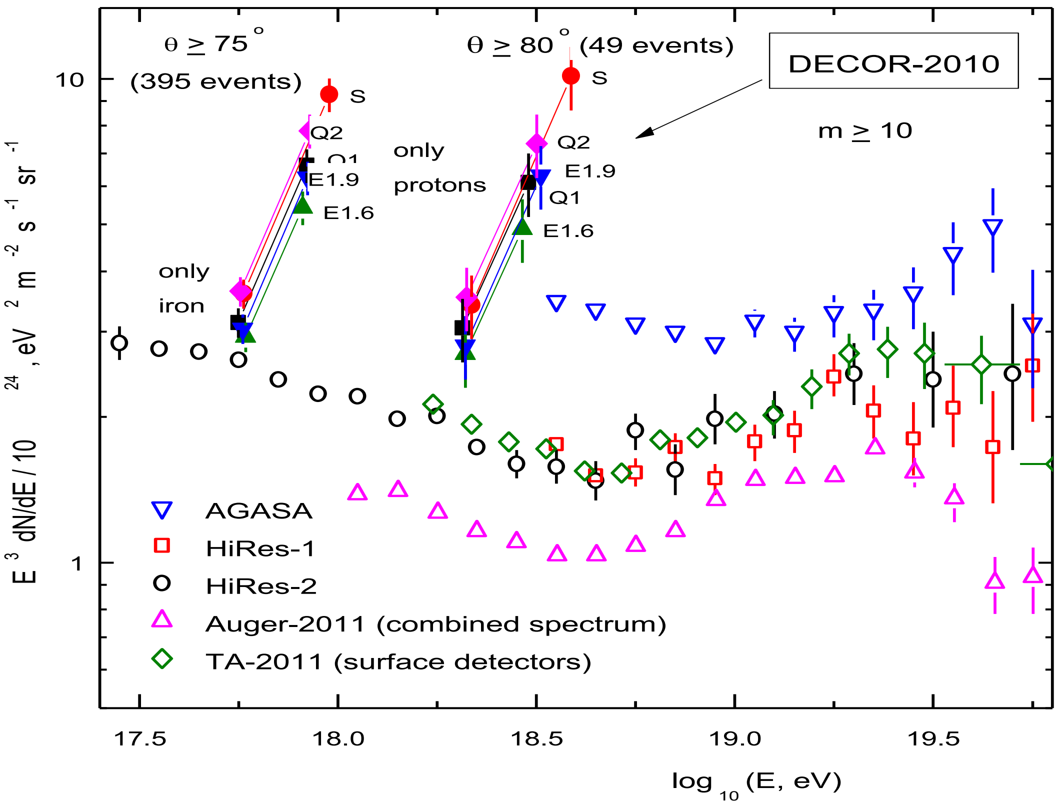
# Excess of the muons in HiRes/MIA data

*T. Abu-Zayyad et al., Phys. Rev. Letters 84 (2000) 4276*



# Excess of muon bundles intensity from DECOR data 2002-2007

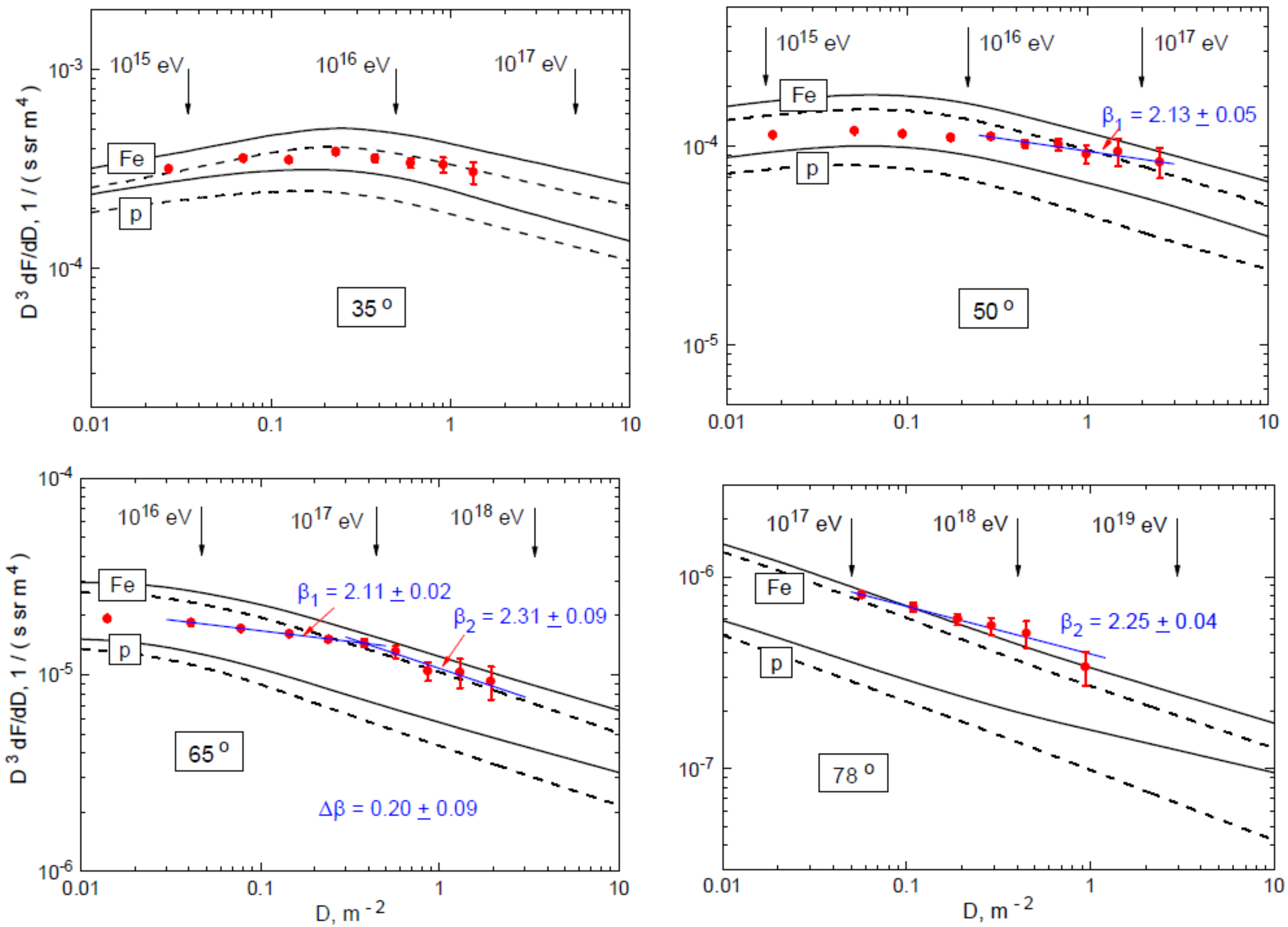
*R.P. Kokoulin et al., Nucl. Phys. B (Proc. Suppl.) 196 (2009) 106; O. Saavedra et al., Journ. of Phys.: Conf. Ser. 409 (2013) 012009*




*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.

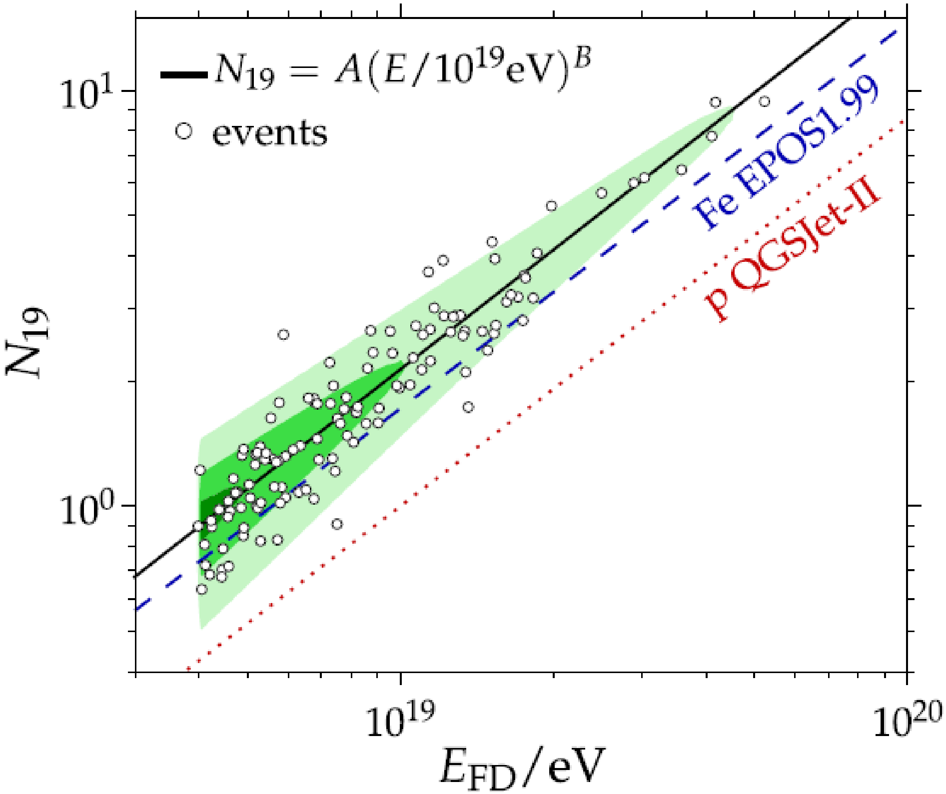
# Experimental LMDS (local muon density spectra) reconstructed from DECOR data on muon bundles



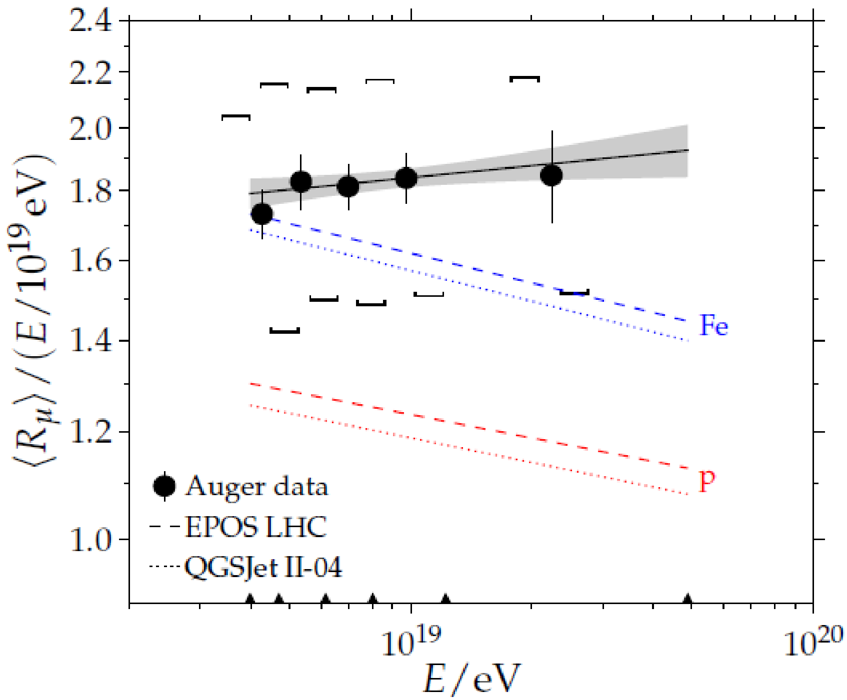

Measured (points) and calculated LMDS for 4 zenith angles (labels in the frames). Thin lines represent partial power fits of the data between $10^{16}$ and $10^{17}$ eV (integral spectrum slope $\beta_1$), and above $10^{17}$ primary energy ($\beta_2$). The solid and dashed curves represent the results 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 the number of muons in highly inclined EAS from Pierre Auger Observatory data

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

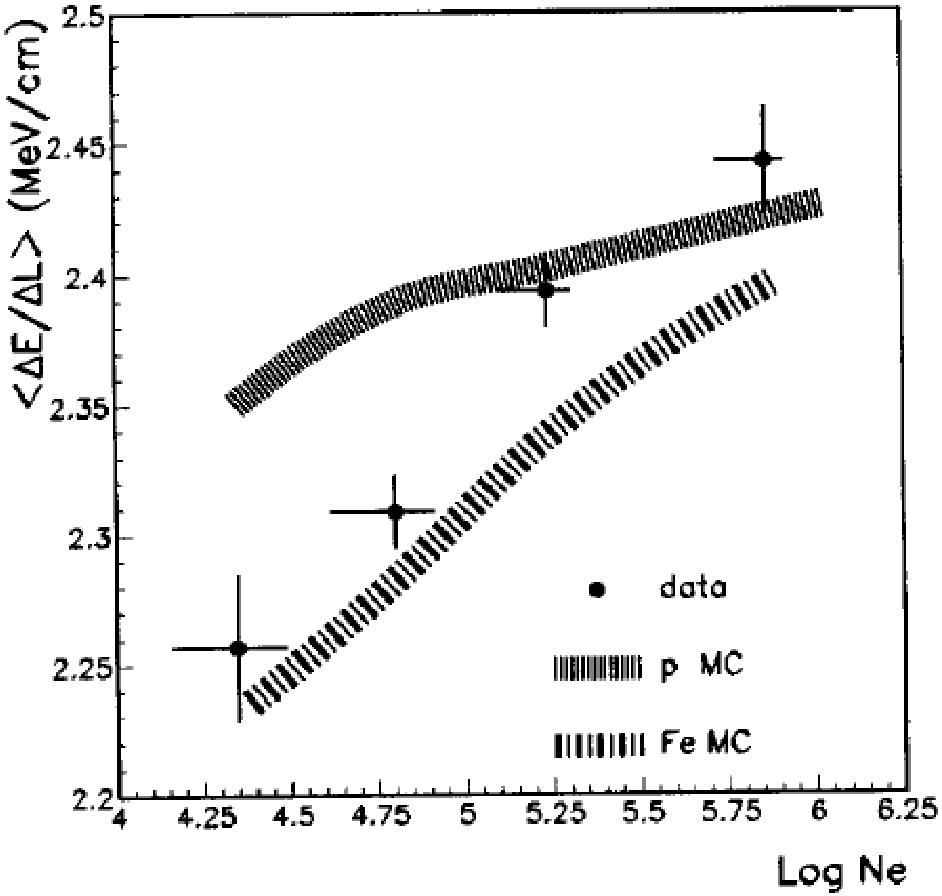



*A. Aab et al. Phys. Rev. D 91, 032003 (2015)*



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

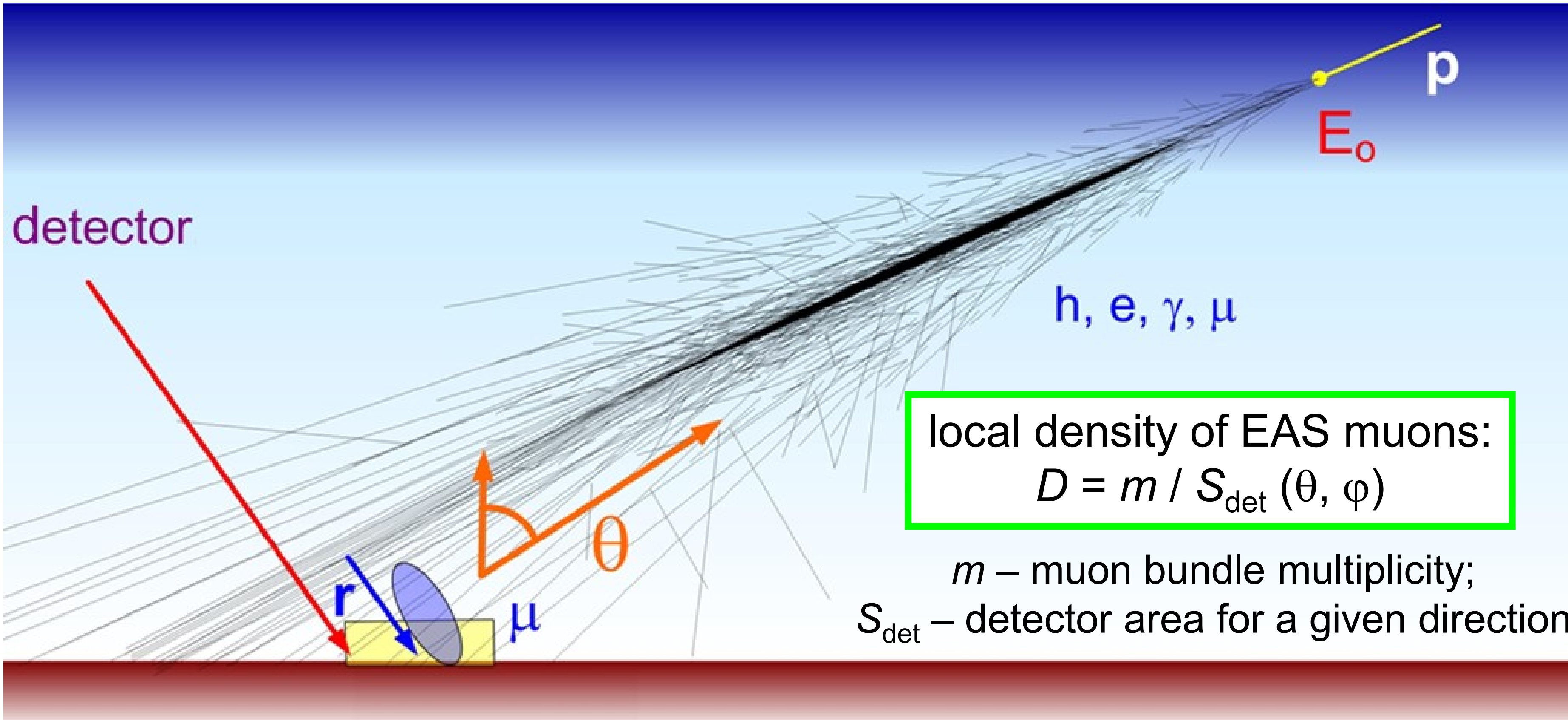
*M. Aglietta et al., Astroparticle Physics 9 (1998) 185*




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

# 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*




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.

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

# 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:

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

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

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

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

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

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

# Local muon density phenomenology

For a nearly scaling LDF around some energy $E_0$

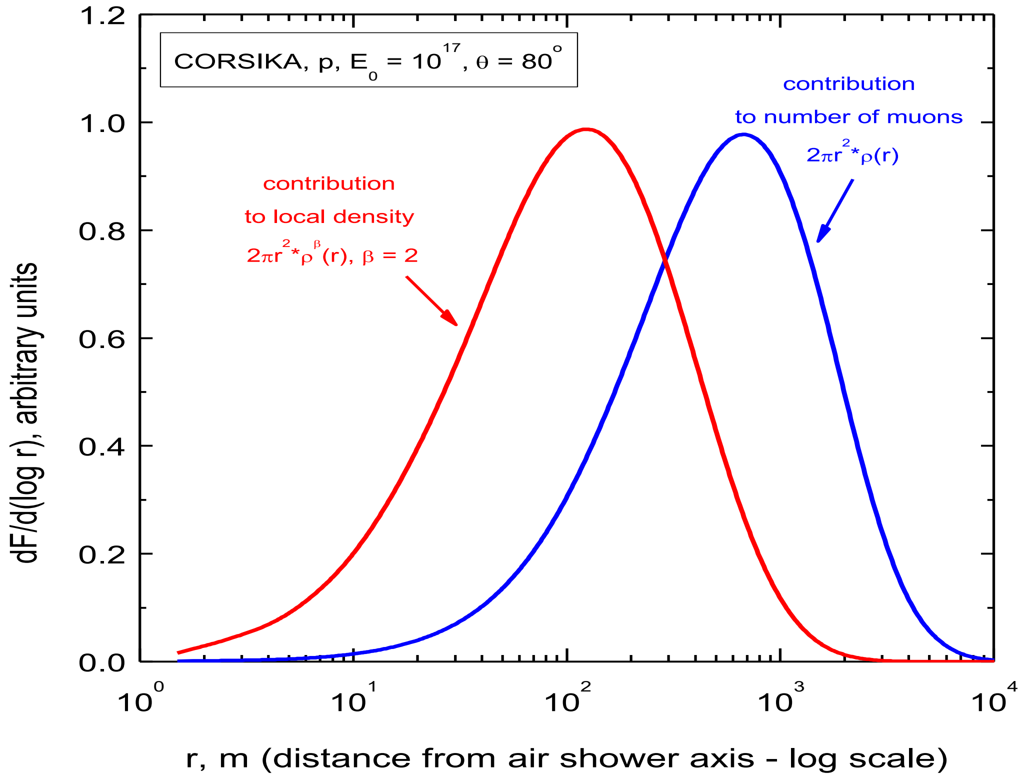
$$\rho(E,\mathbf{r}) = (E/E_0)^{\kappa} \times \rho(E_0,\mathbf{r}),\ \kappa \approx 0.9$$

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 ($\beta = \gamma / \kappa \approx 2$).

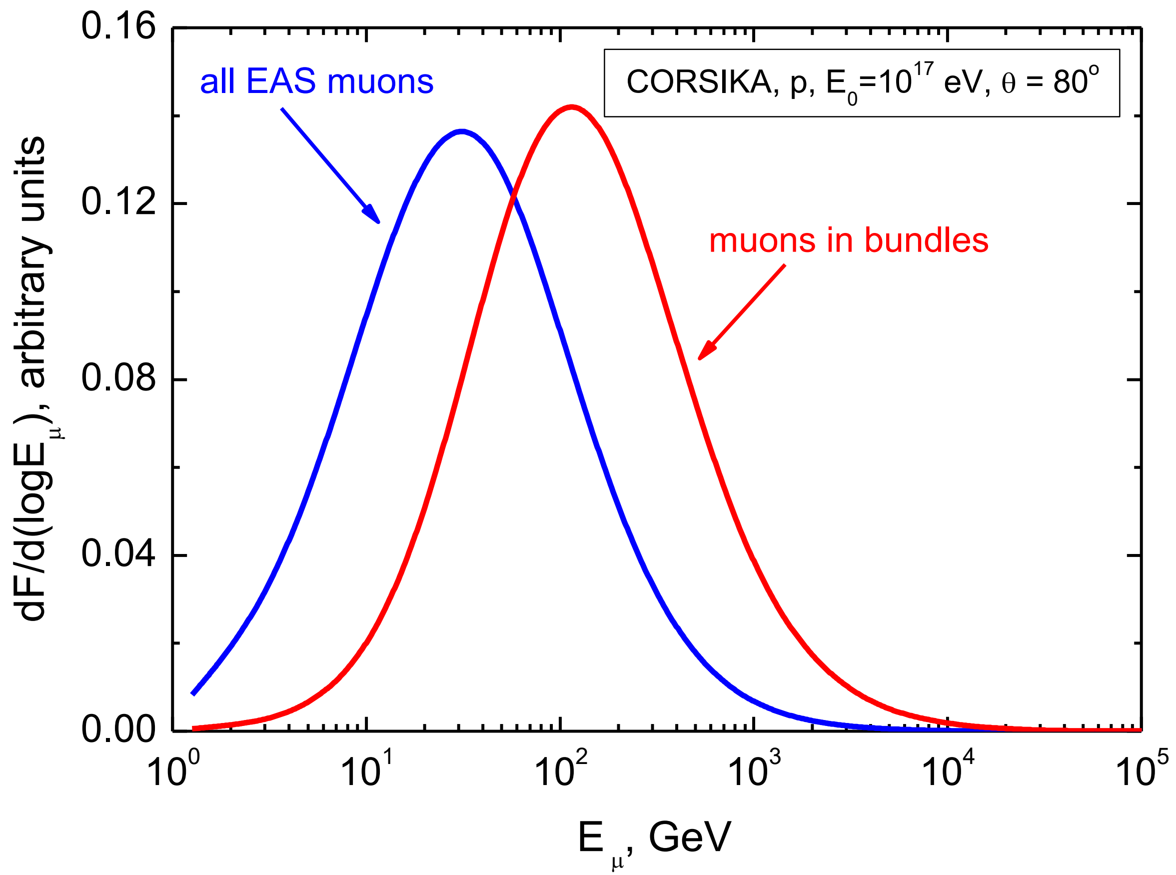
# Basic features of the LMDS technique




*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)

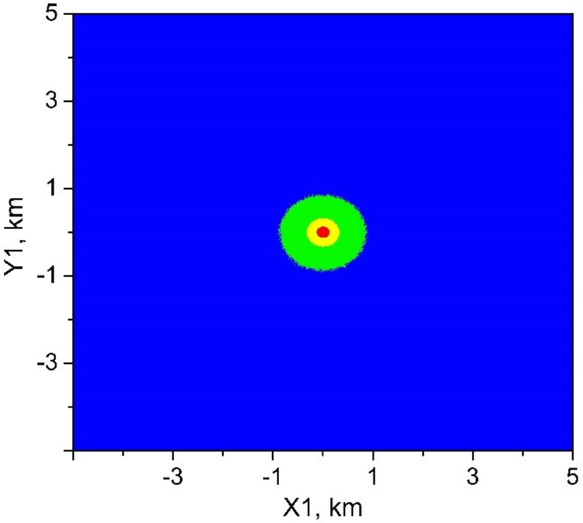
# Basic features of the LMDS technique



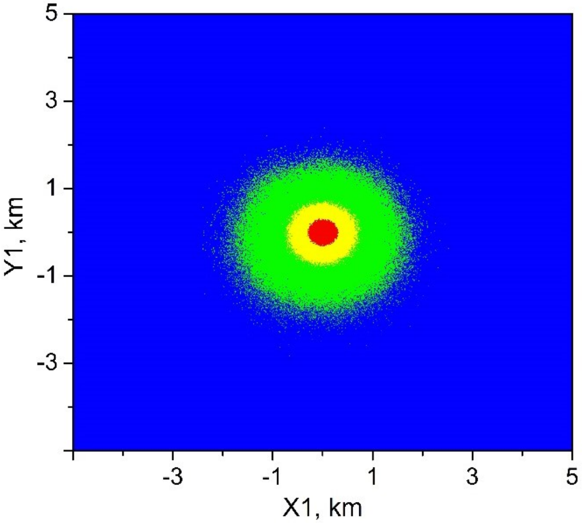

*Energy spectrum of muons in bundles (selection of events by muon density) and of all muons in EAS*

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

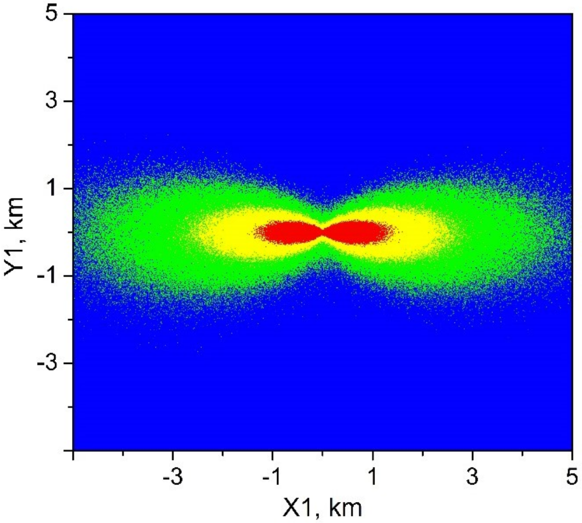
# Shower cross section in muons




$\theta = 35^\circ$



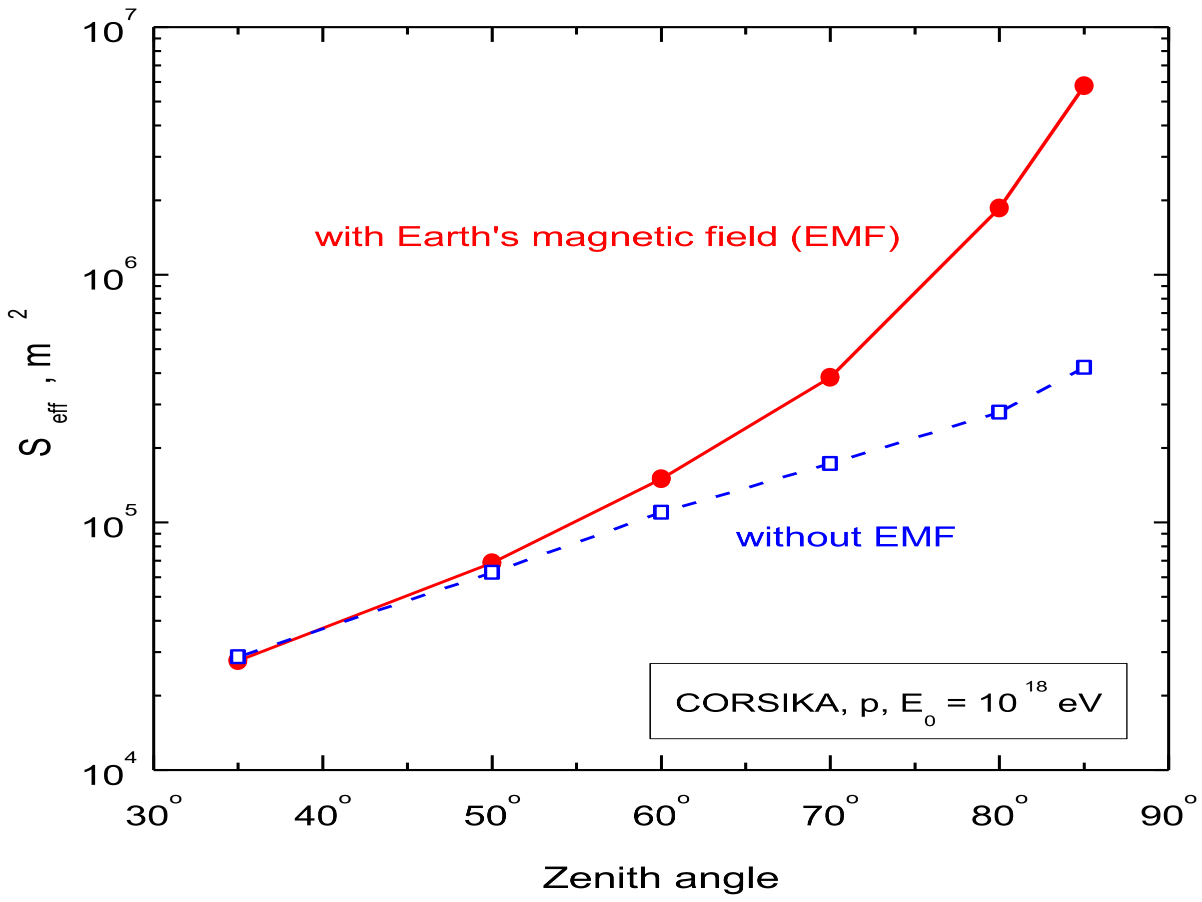

$\theta = 80^\circ$ (without EMF)



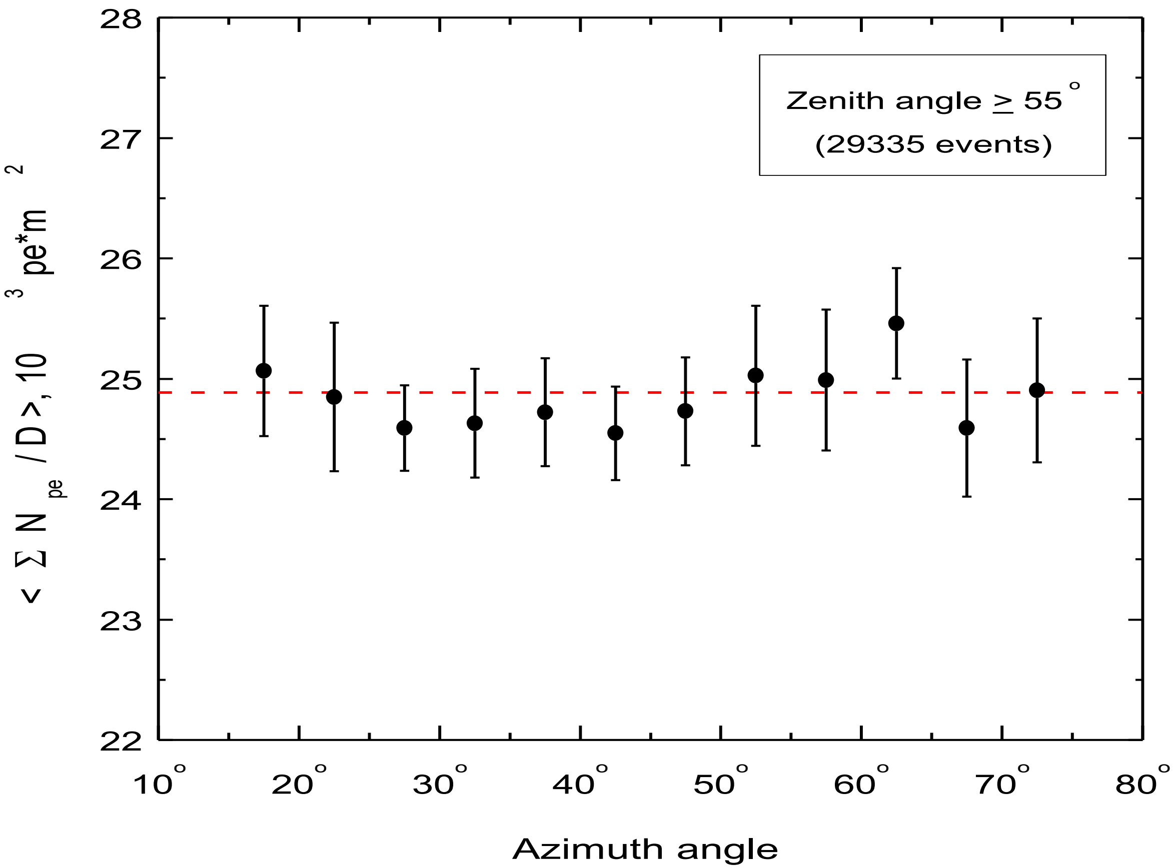

$\theta = 80^\circ$ with EMF

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



# 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.