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Investigations of very high energy cosmic rays by means of inclined muon bundles

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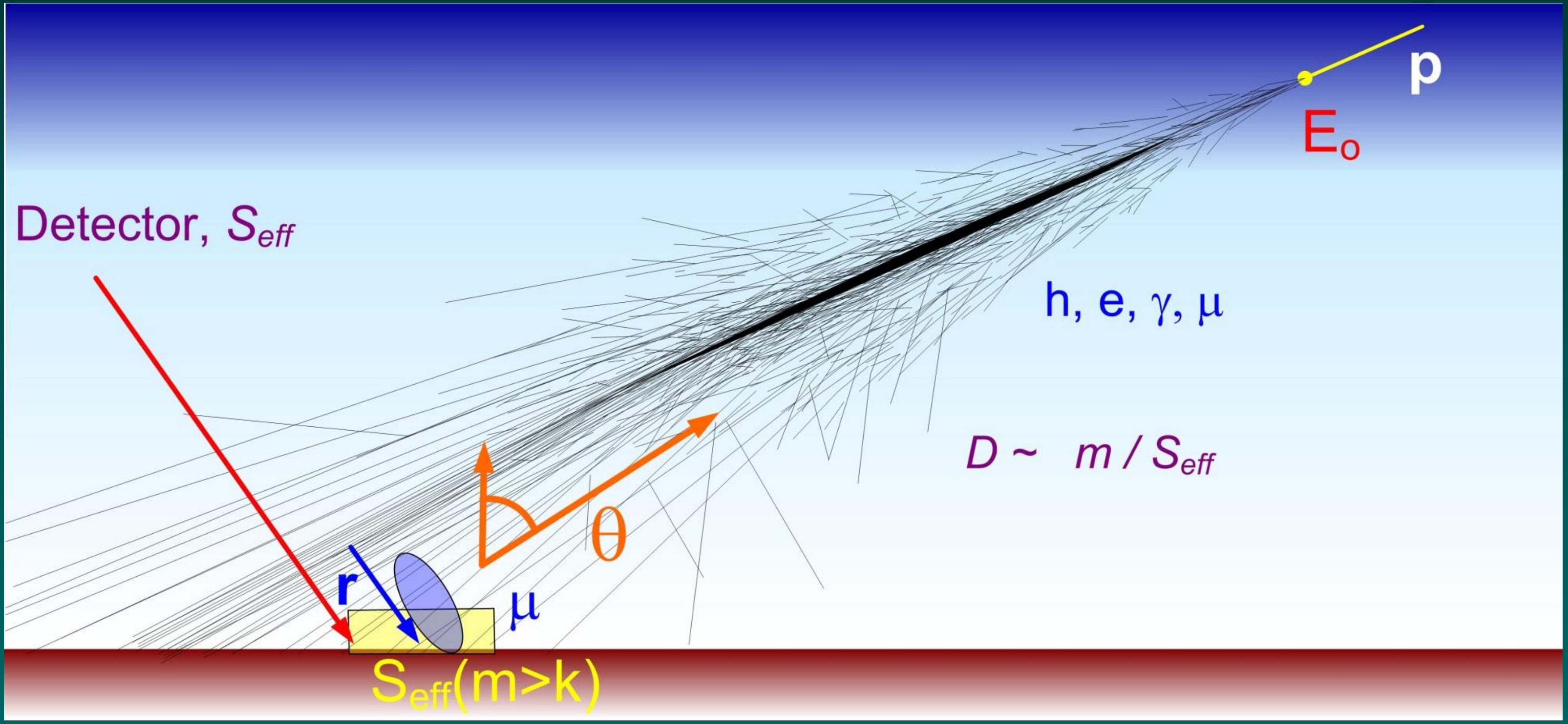
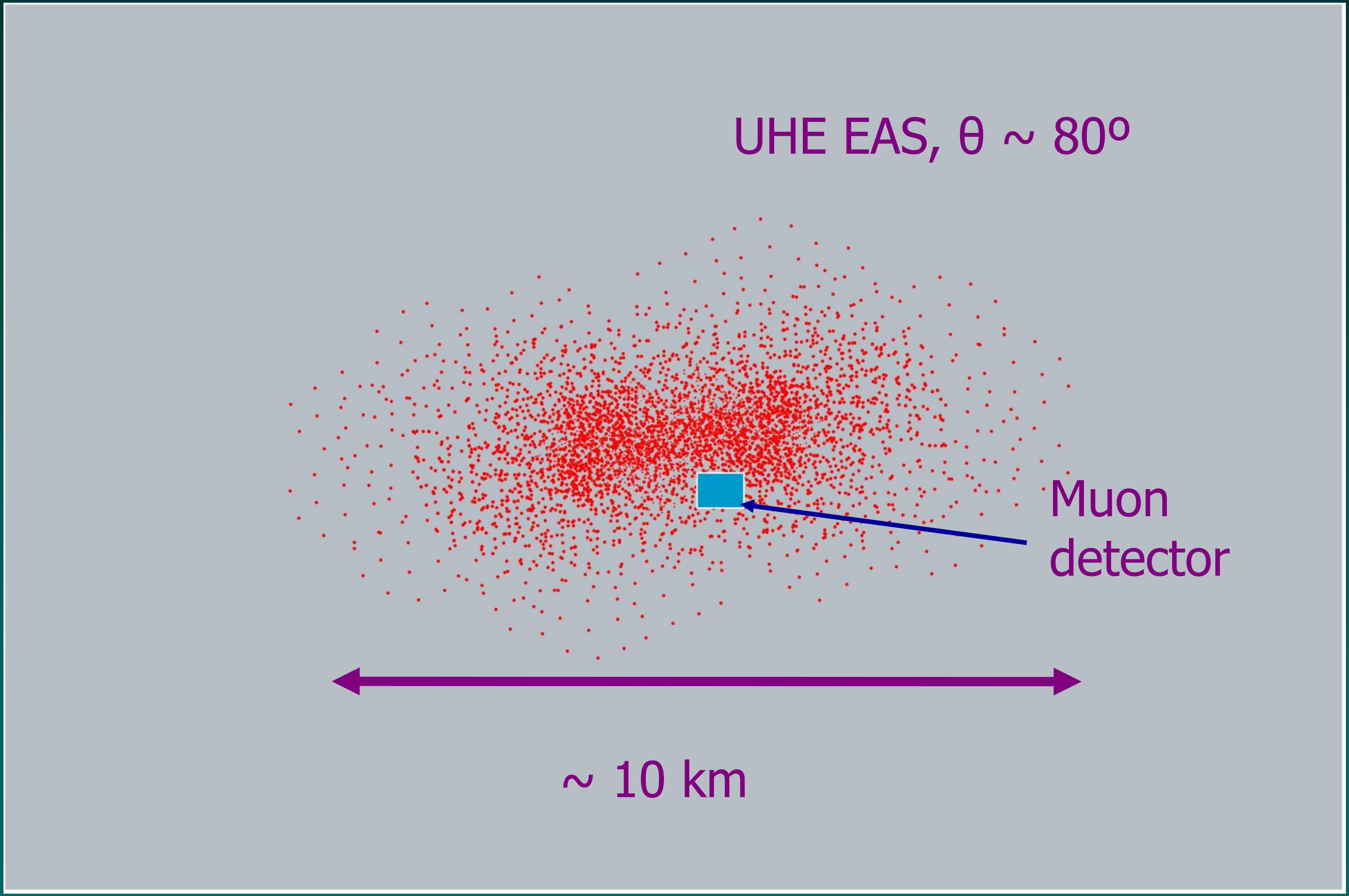
Novel approach to the analysis of muon bundles: method of Local Muon Density Spectra (LMDS)

A.G. Bogdanov et al., Phys. Atom. Nucl. 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 estimated muon density *D* forms the LMDS.

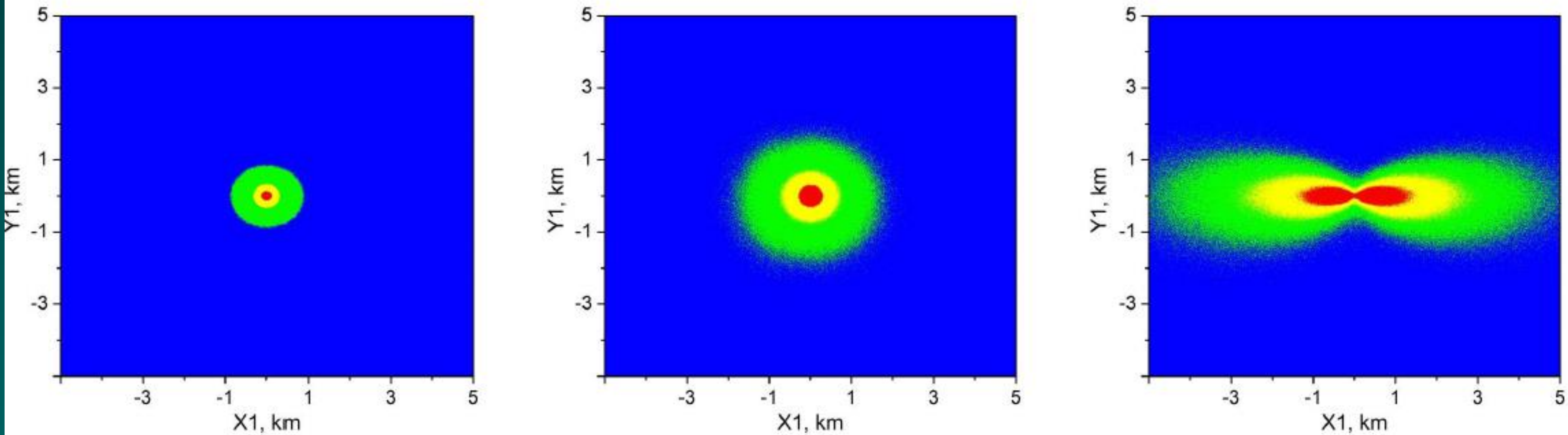
Local Muon Density Spectra detection technique



EAS cross section in muon component

EAS cross section (muon component)

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



35° without EMF

80° without EMF

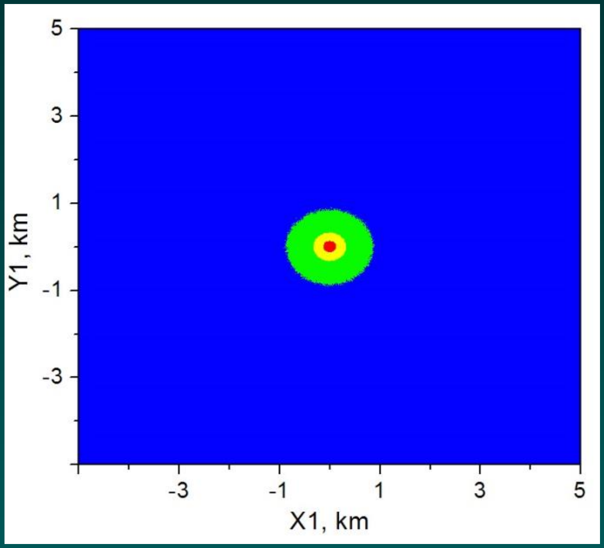
80° with EMF

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

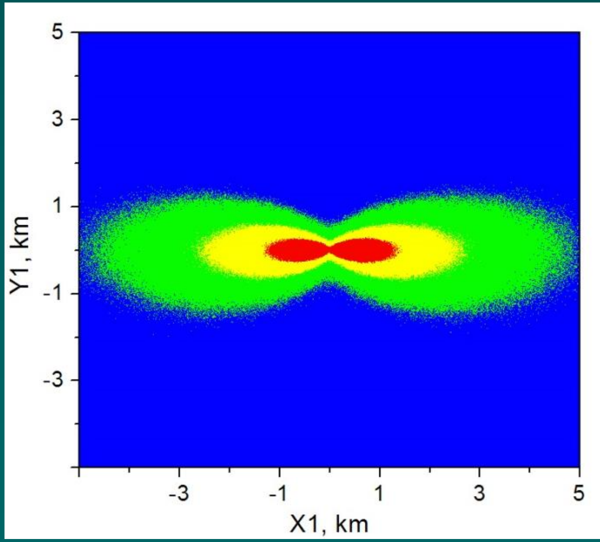
EAS collection area in LMDS method

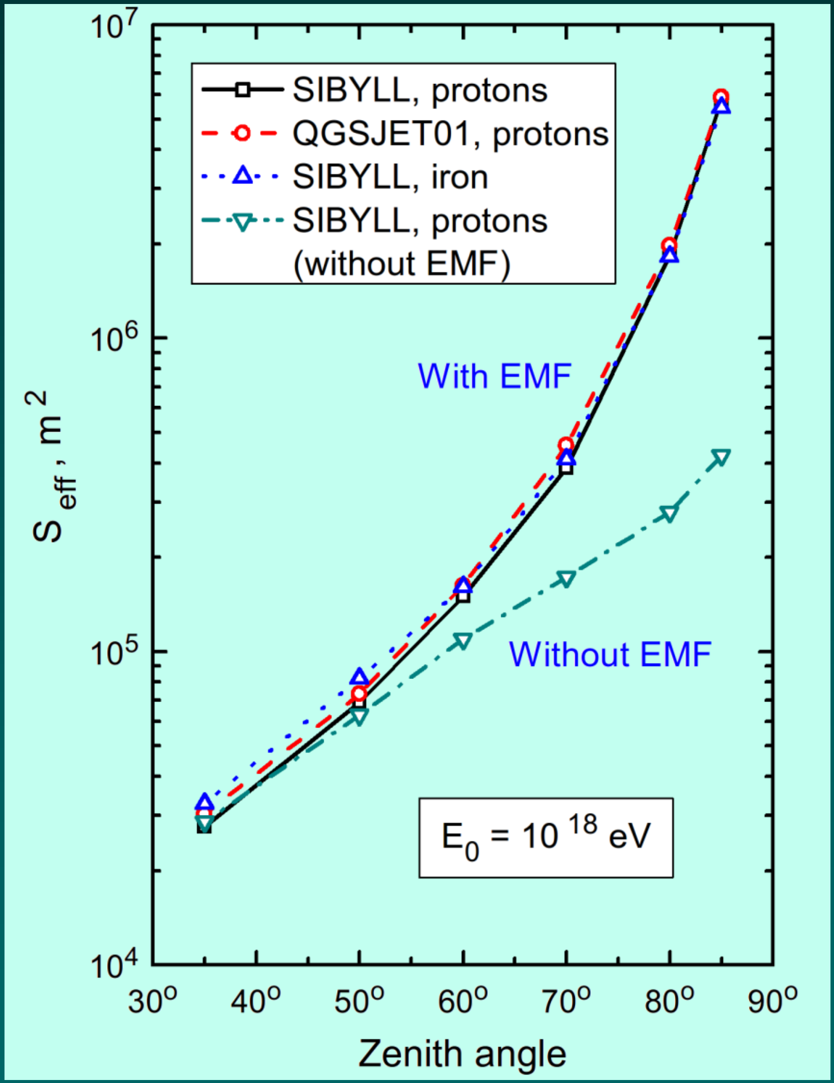
EAS cross section in muons

θ = 35º

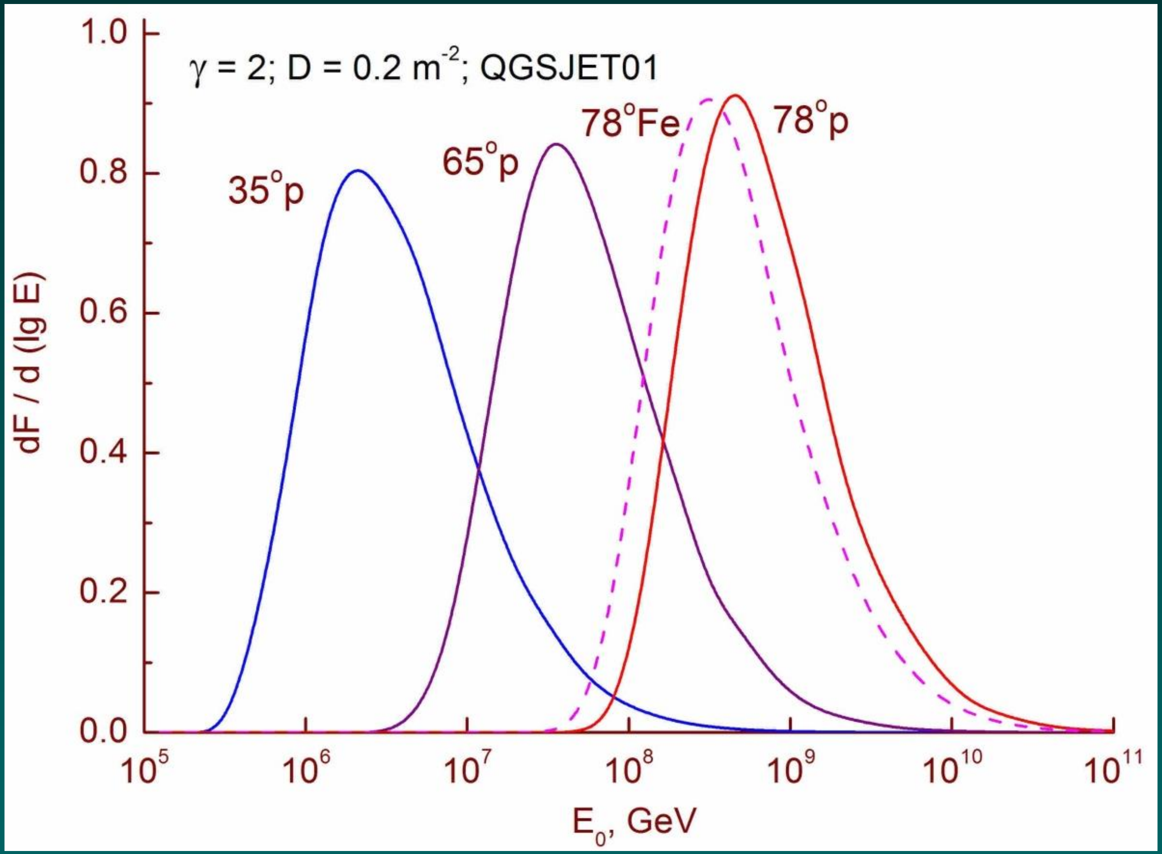


θ = 80º (with EMF)





Distribution of energies of primary particles contributing to events with a fixed local muon density



Different zenith angles correspond to different EAS energies:
very wide range of primary particle energies is accesssible.

Important features of the Local Muon Density Spectrum approach

Event collection area is determined not by the detector size, but by the shower transverse cross section which reaches several square kilometers near horizon (sufficient to reach energies of 10^{18} eV and higher).

Simultaneous measurements of LMDS at various zenith angles allows exploration of a very wide energy range in frame of a single experiment with a relatively compact setup.

Brief history of the DECOR collaboration

26 years ago (1 June 1992), the first cooperation agreement between MEPhI and Torino group (ICGF, TU) was signed.

The main purpose was the creation of the coordinate detector DECOR around the Cherenkov water calorimeter NEVOD for investigations of multi-particle events in cosmic rays at large zenith angles.

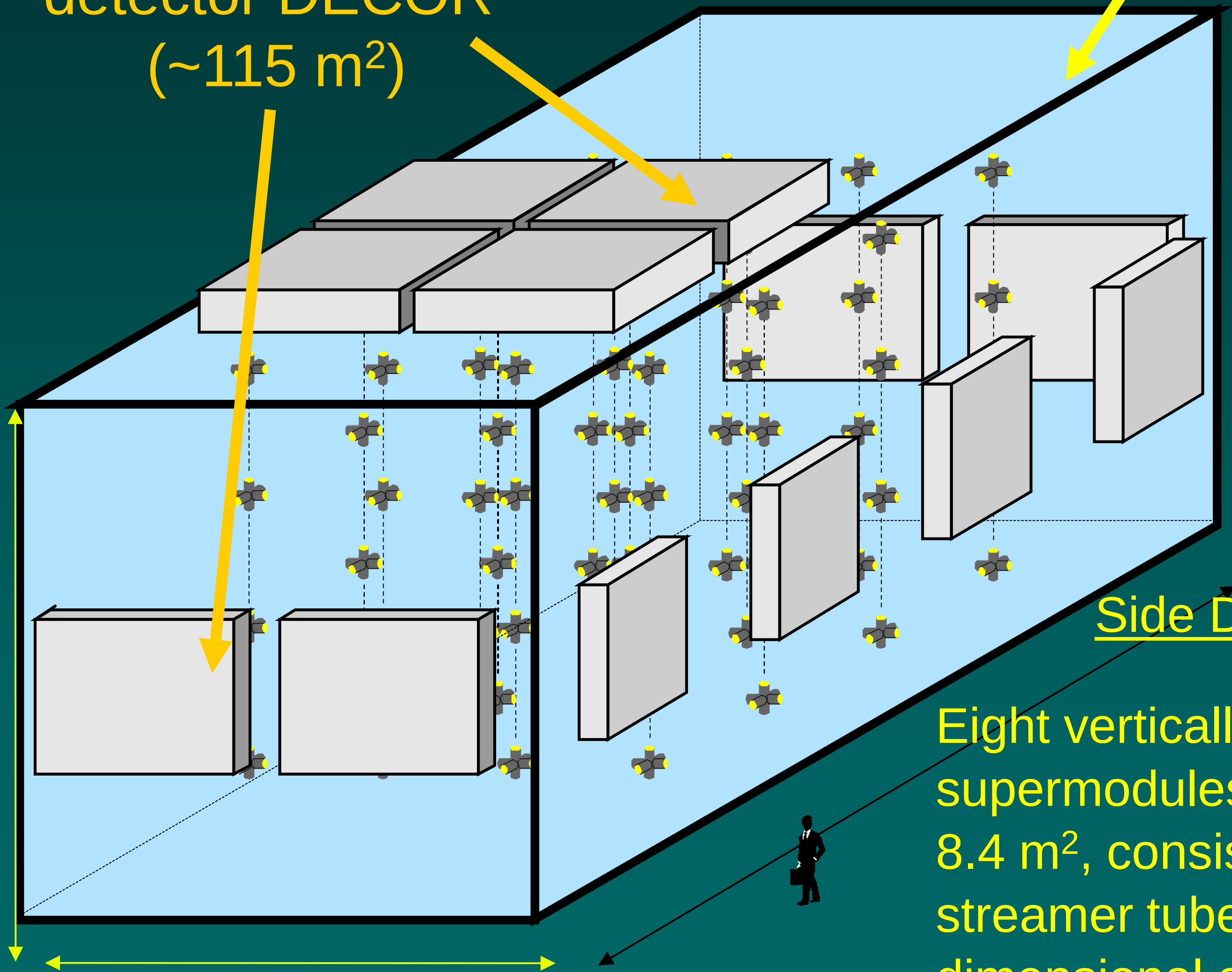
The first supermodules of the detector were put into operation in 1998. In 2001, the construction of the DECOR was completed.

Long-term experiments (about 50,000 h net operation time) on detection of muon bundles with NEVOD-DECOR complex were conducted in 2002-2007 and 2012-2018.

General view of NEVOD-DECOR complex

Coordinate-tracking detector DECOR (~115 m²)

Cherenkov water detector NEVOD (2000 m³)



$\sigma_X \sim 1$cm;
$\sigma_\psi < 1°$

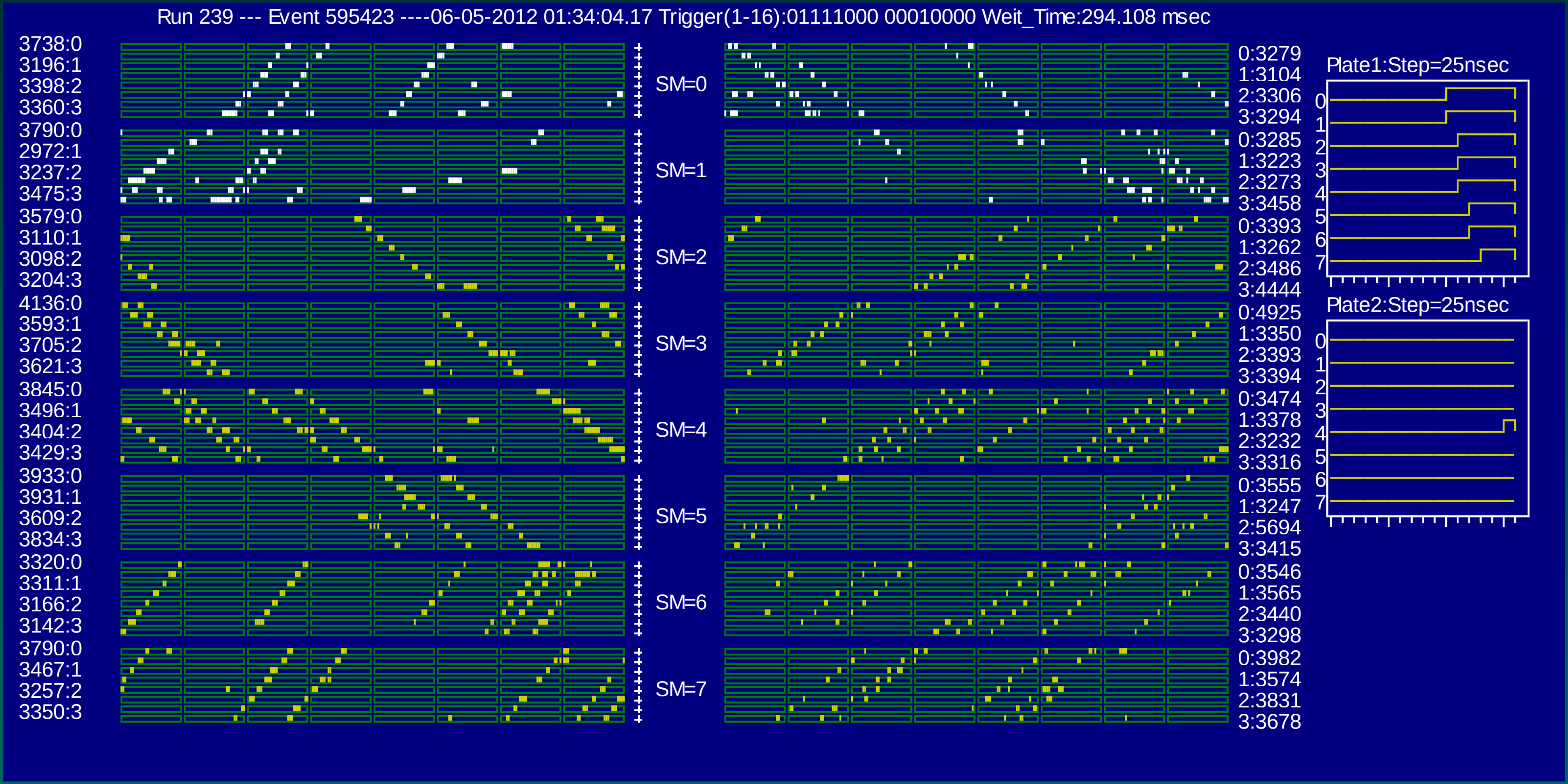
Side DECOR:

Eight vertically suspended supermodules, each with area 8.4 m², consisting of 8 planes of streamer tubes with two-dimensional external strip readout.

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

Muon bundle event in DECOR SMs

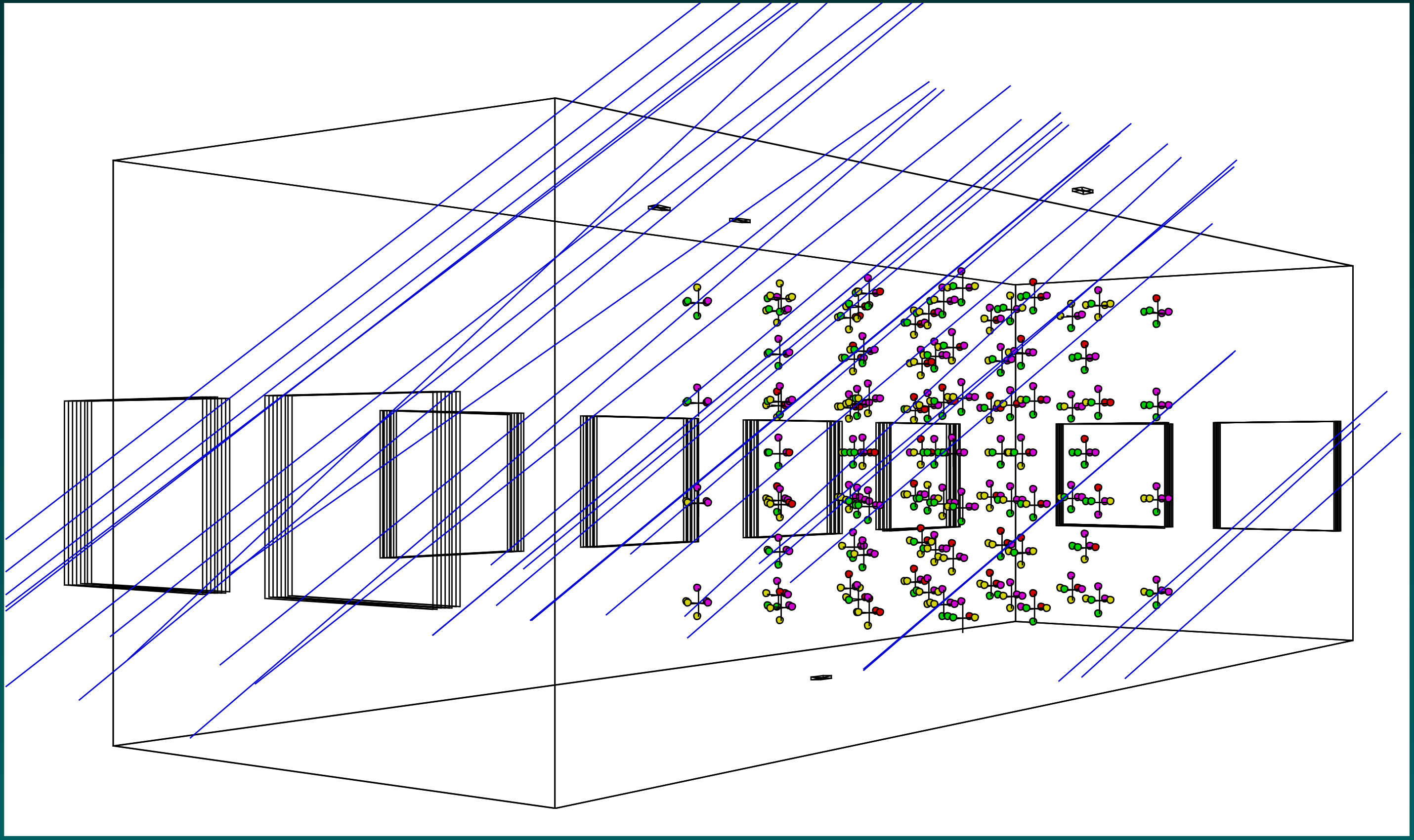
multiplicity m = 29 particles, zenith angle θ = 49°



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.

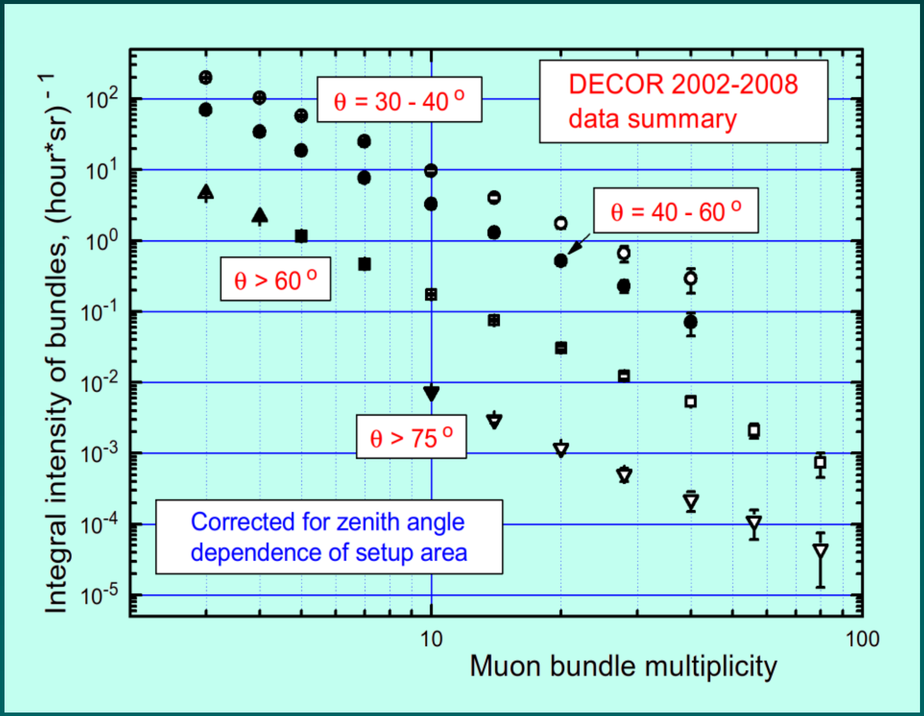
Geometry reconstruction of the muon bundle event in NEVOD-DECOR

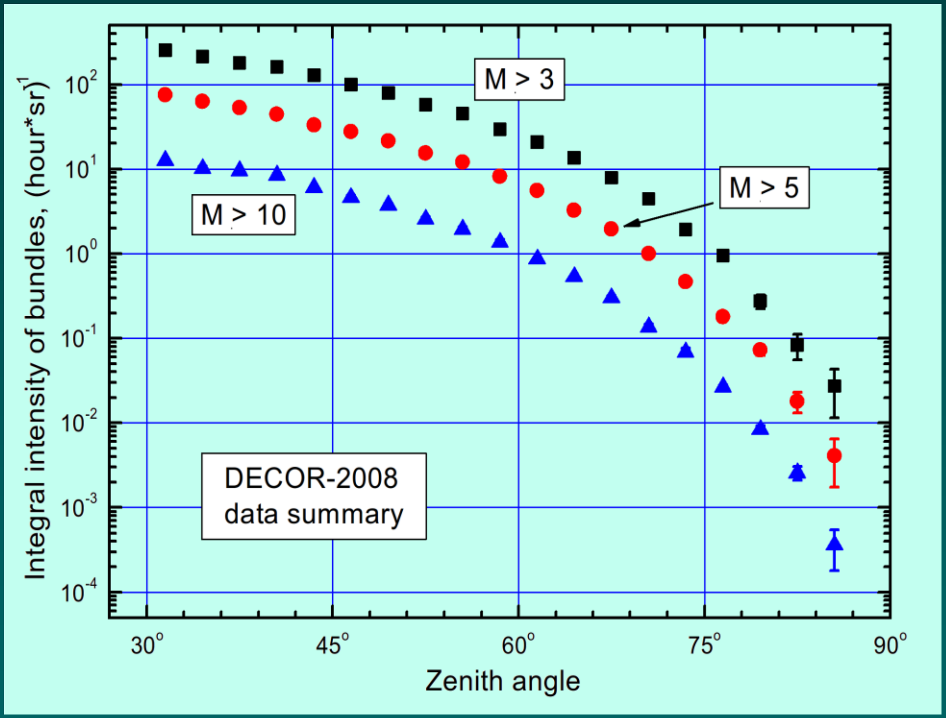


Lines – muon tracks reconstructed from DECOR data;
Circles – hit phototubes in CWD (colors reflect signal amplitudes);
Small rectangles – hit counters of the calibration telescope system.

Multiplicity and angular distributions

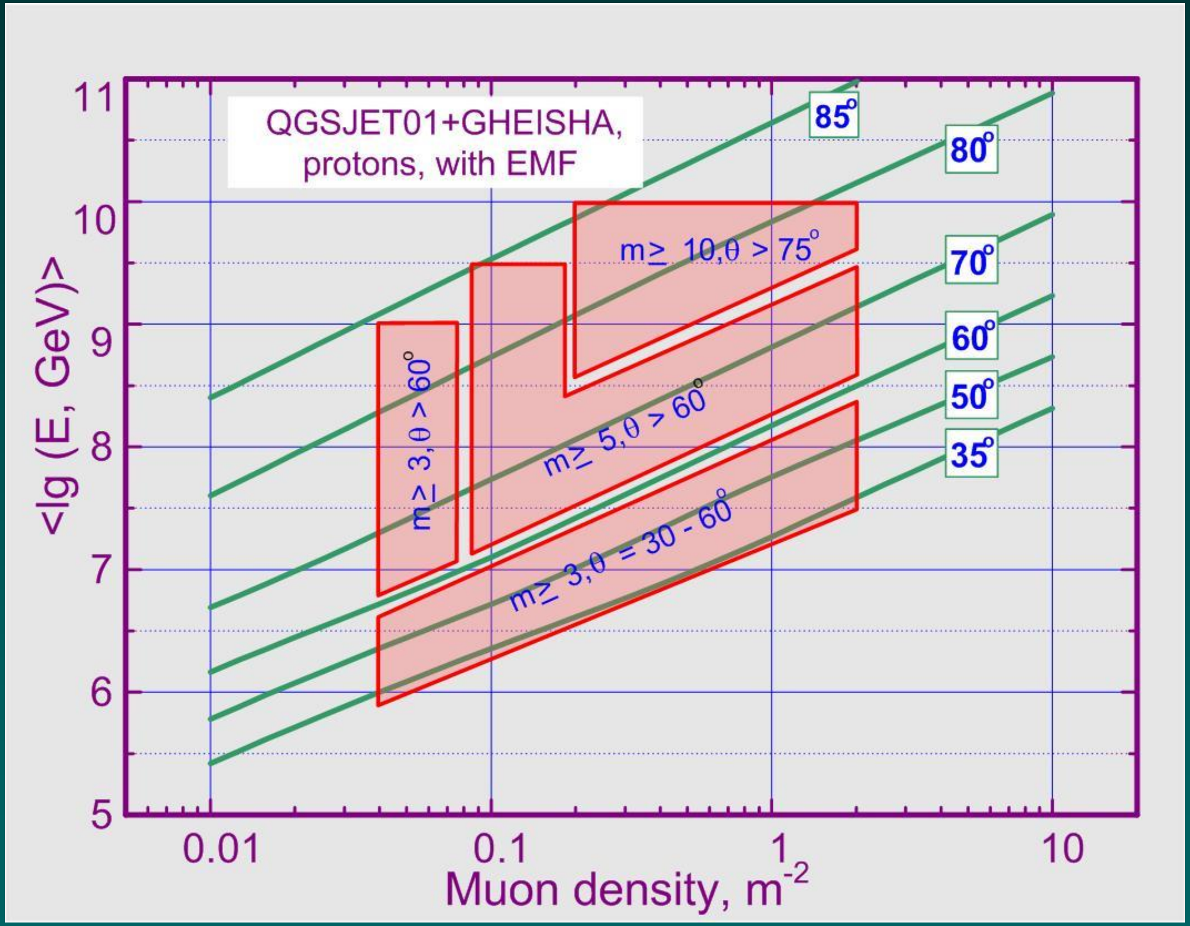
Over 40 thousand muon bundles with various multiplicities and zenith angles were selected from experimental data accumulated in 2002-2007 and 2012-2016.





NB: 6 – 7 orders of magnitude in the event intensity !!!

Mean logarithmic energies of primary particles for events with different muon multiplicities and various zenith angles

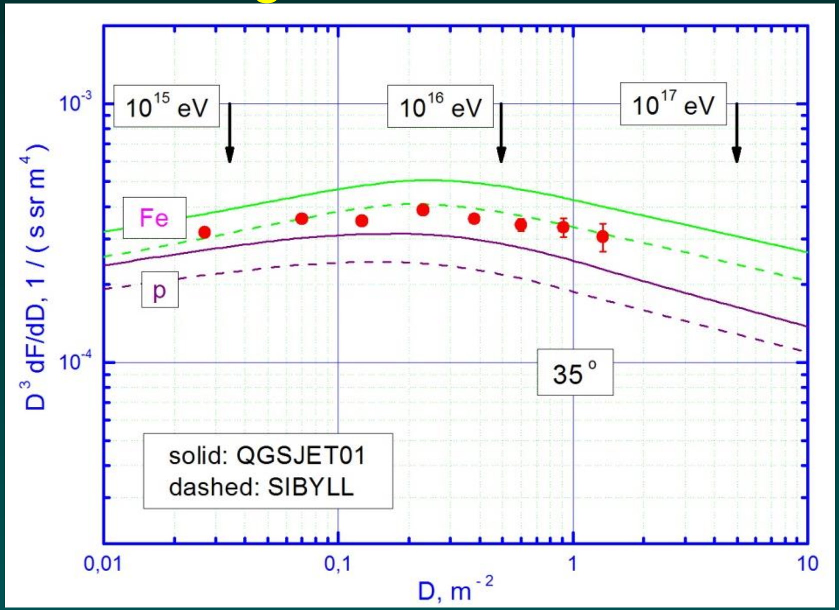


Lower limit ~ 10^{15} eV (limited by DECOR area).

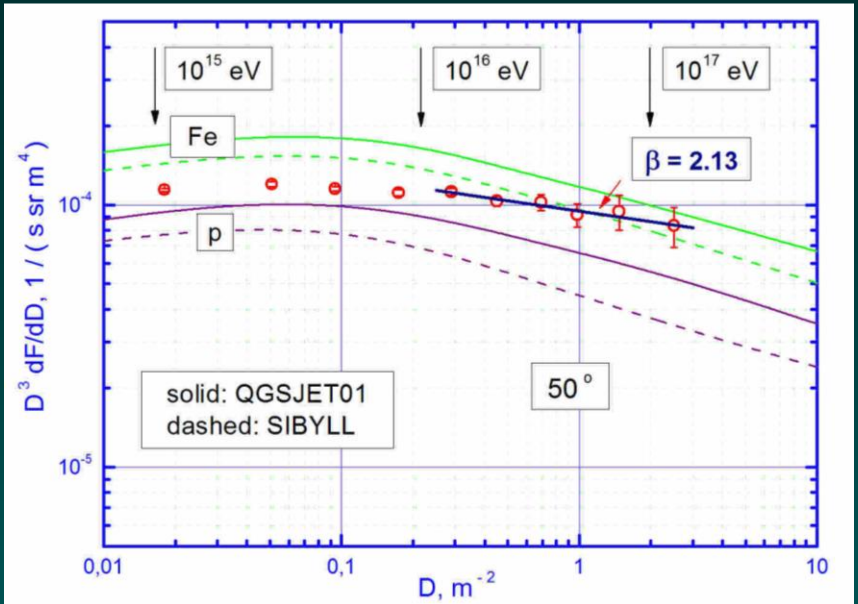
Upper limit ~ 10^{19} eV (limited by statistics).

Experimental Local Muon Density Spectra (2002-2007)

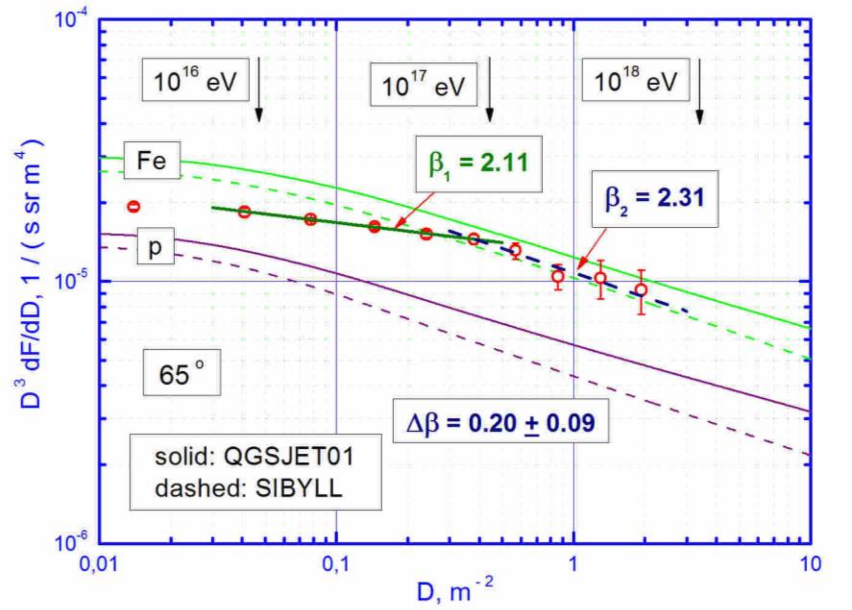
Low angles: around the "knee"



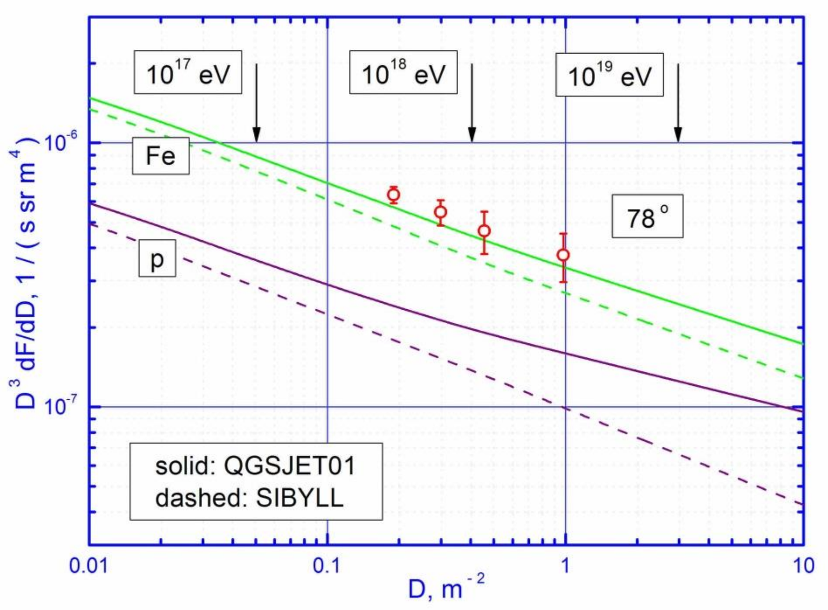
θ = 50° : 10^{15} – 10^{17} eV



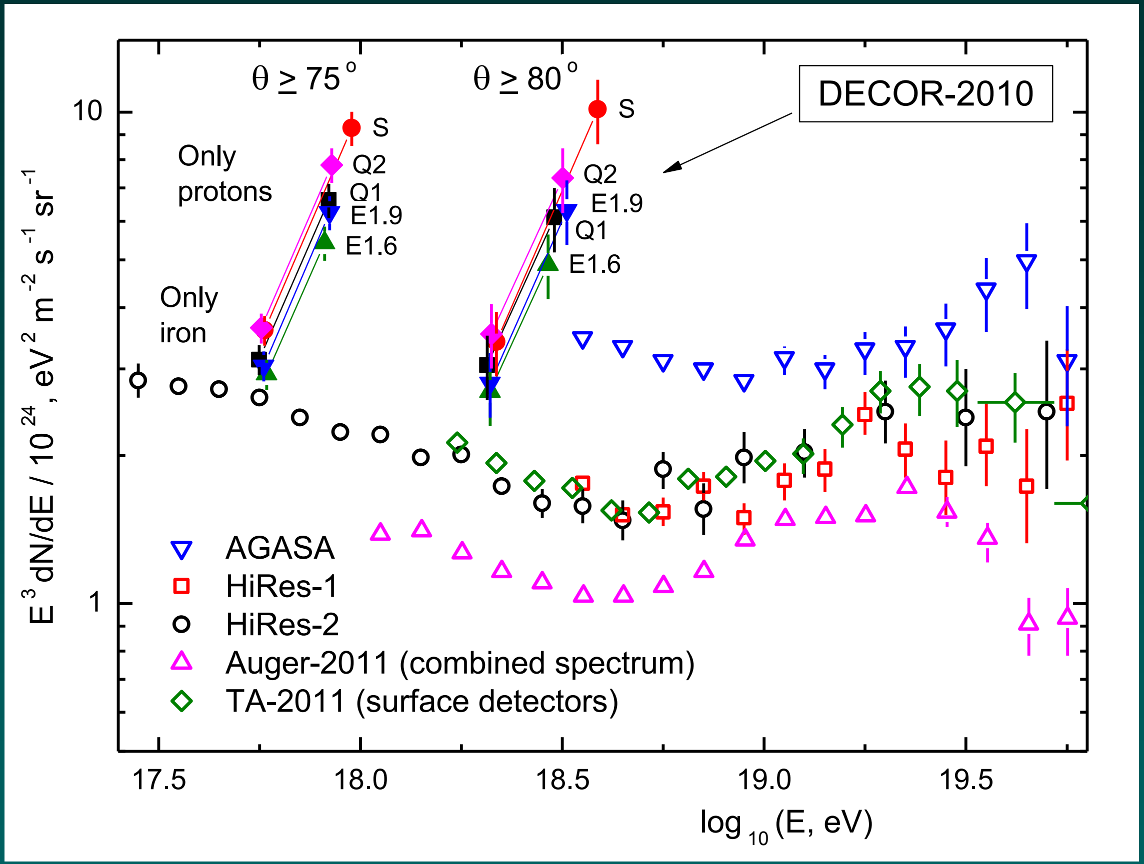
θ = 65° : 10^{16} – 10^{18} eV



Large angles: around 10^{18} eV



Comparison of UHECR energy spectrum derived from muon bundles with other data

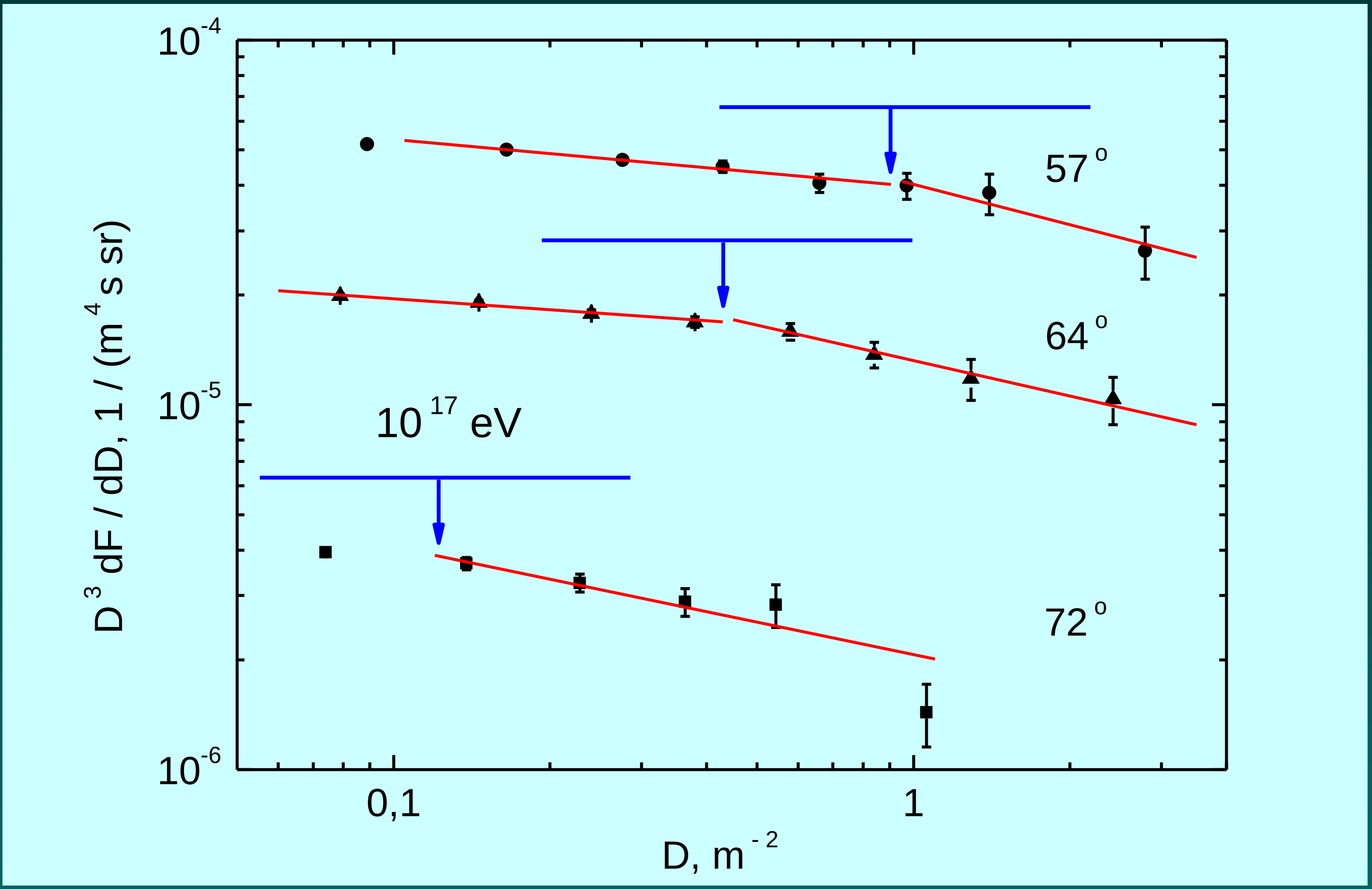


R. Kokoulin et al. , ISVHECRI 2008. Nucl.Phys. B (Proc. Suppl.). 196 (2009)106

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 (iron) primary composition. More muons in simulation is needed.

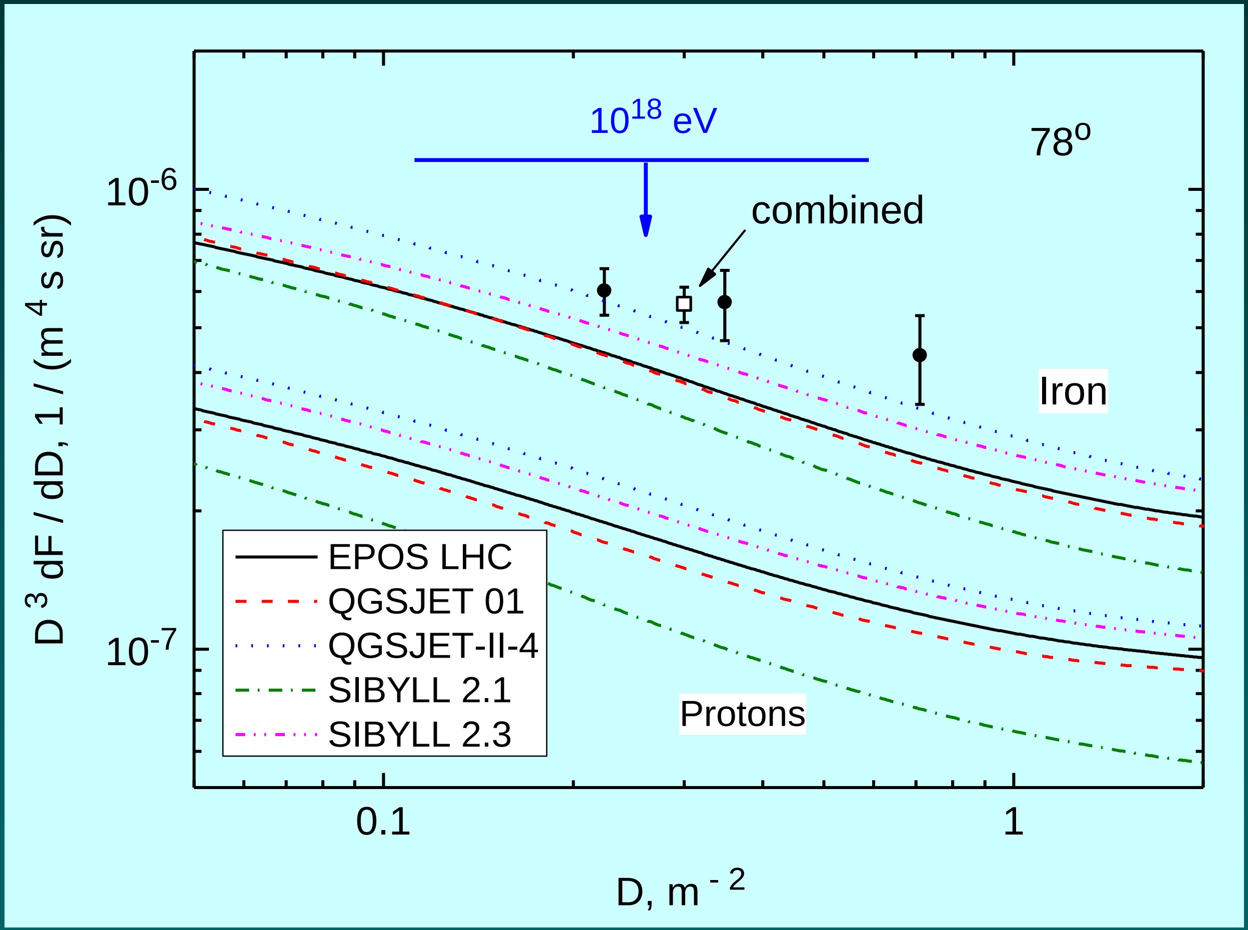
The 2nd knee observed in Local Muon Density Spectra (combined statistics of 2002-2007 and 2012-2016)

Astropart. Phys. 98 (2018) 13–20 https://doi.org/10.1016/j.astropartphys.2018.01.003



$\Delta\beta = 0.202 \pm 0.054$ (~ 3.7 σ)

Measured muon bundle intensity versus expectation from various interaction models for proton and iron composition assumptions (around 10^{18} eV primary energy)



Data are only compatible with extremely heavy composition (iron group nuclei) and recent LHC-adjusted interaction models (SIBYLL 2.3 and QGSJet II-4).

Results of LMDS studies in NEVOD-DECOR experiment

LMDS measurements gave possibility to obtain information on primary flux and interaction characteristics in a record wide energy range from 10^{15} to more than 10^{18} eV and to reveal the following basic features:

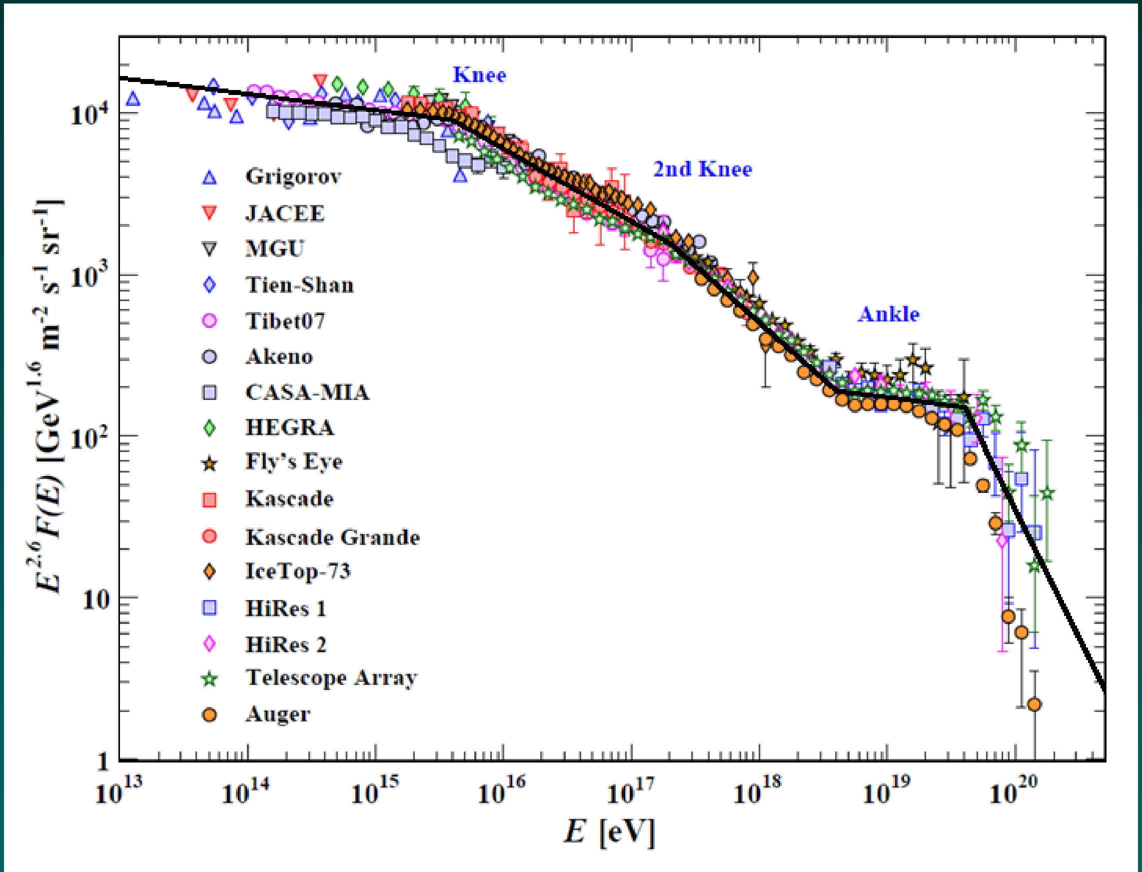
- Increase of LMDS slope at PeV energies (the first knee);
- Relative increase of muon bundle intensity which may be interpreted as a trend to a heavier mass composition above the knee, in the range 10^{16} – 10^{17} eV;
- Increase of LMDS slope near 10^{17} eV (the first 'second' knee observation in muon component);
- Excess of muon bundles in comparison with expectations based on independent estimates of UHE primary spectrum and widely used hadronic interaction models.

Thank you for your attention!

Backup Slides

Primary spectrum approximation

Astropart. Phys. 98 (2018) 13–20 https://doi.org/10.1016/j.astropartphys.2018.01.003



The all-particle primary energy spectrum (in energy-per-nucleus) from various air shower measurements presented in a recent review [C. Patrignani et al. PDG, 2016]. Broken line: piece-wise power function approximation.

Local muon density spectra (basic relations)

Without considering fluctuations, spectrum of events in local density may be written as [R.P. Kokoulin at al., 2005]

$$F(\geq D) = \int N\left(\geq E\left(\vec{r}, D\right)\right) dS, \quad \text{[events / (s·sr)]}$$

$$dF / dD = \int (dN / dE) dS / \left[d\rho(E, \vec{r}) / dE \right]$$

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

$$\rho\left(E, \vec{r}\right) = D$$

For a nearly scaling LDF around some primary energy E_0

$$\rho\left(E, \vec{r}\right) = \left(E/E_0\right)^{\kappa} \cdot \rho\left(E_0, \vec{r}\right), \kappa \approx 0.9$$

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

$$F\left(\geq D\right) = AD^{-\beta} \int \left[\rho\left(E_0, \vec{r}\right)\right]^{\beta} dS, \quad \beta = \gamma / \kappa \sim 2$$