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Local muon density spectra at various zenith angles measured with NEVOD-DECOR

R. P. Kokoulin

for the DECOR Collaboration

National Research Nuclear University MEPhI, Moscow, Russia
Dipartimento di Fisica dell' Universita di Torino, Italy
Istituto Nazionale di Astrofisica, Torino, Italy

Introduction

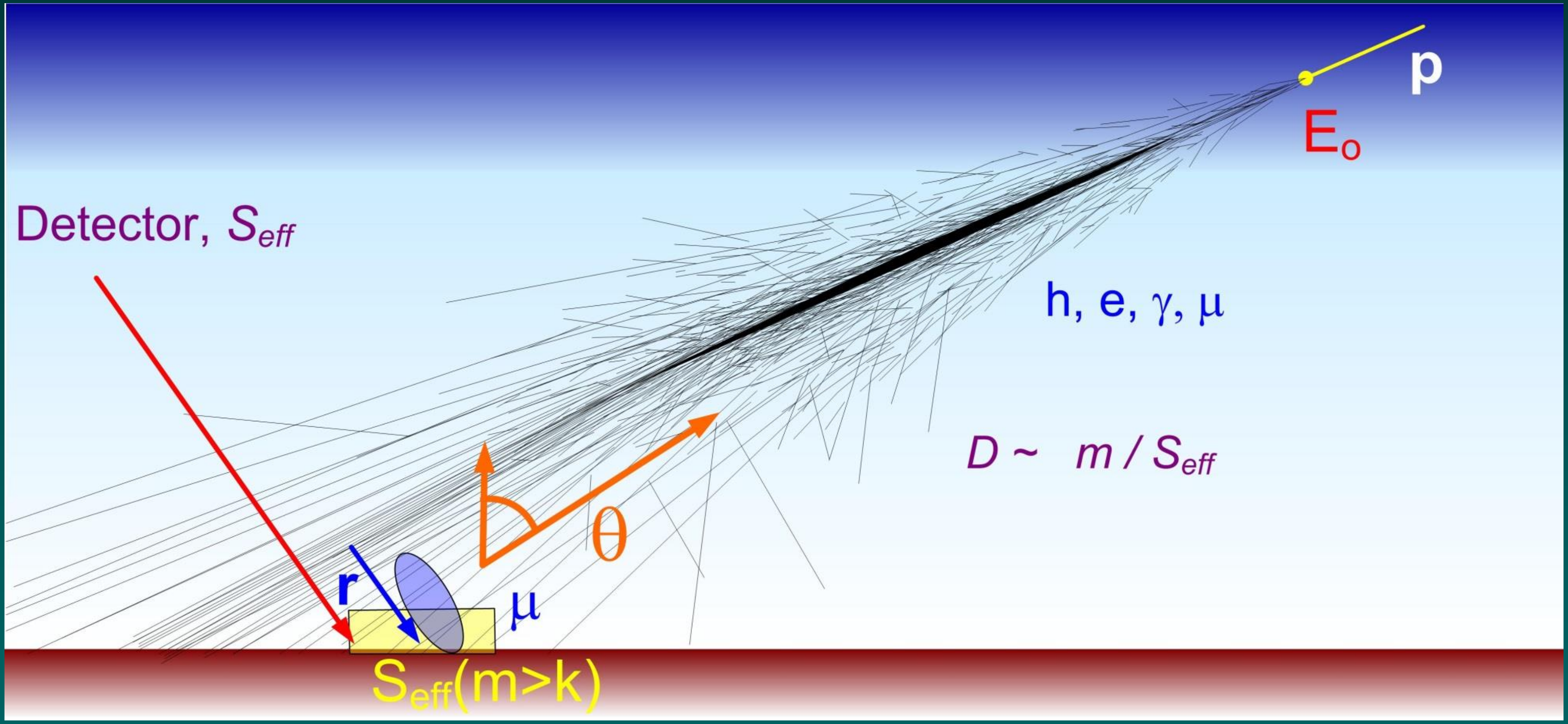
Investigations of muon component of extensive air showers (EAS) allow us to obtain information about primary energy spectrum, mass composition and the features of hadronic interaction at ultra-high energies.

Though the experimental situation with muon content in EAS is somewhat controversial, a recent comparative analysis showed that most of the experiments indicate for an increasing excess of multi-muon events in comparison with the expectation at energies around and above 10^{18} eV.

One of the approaches to study EAS muon component in a wide range of primary energies is the measurement of local muon density spectra (LMDS) at various zenith angles.

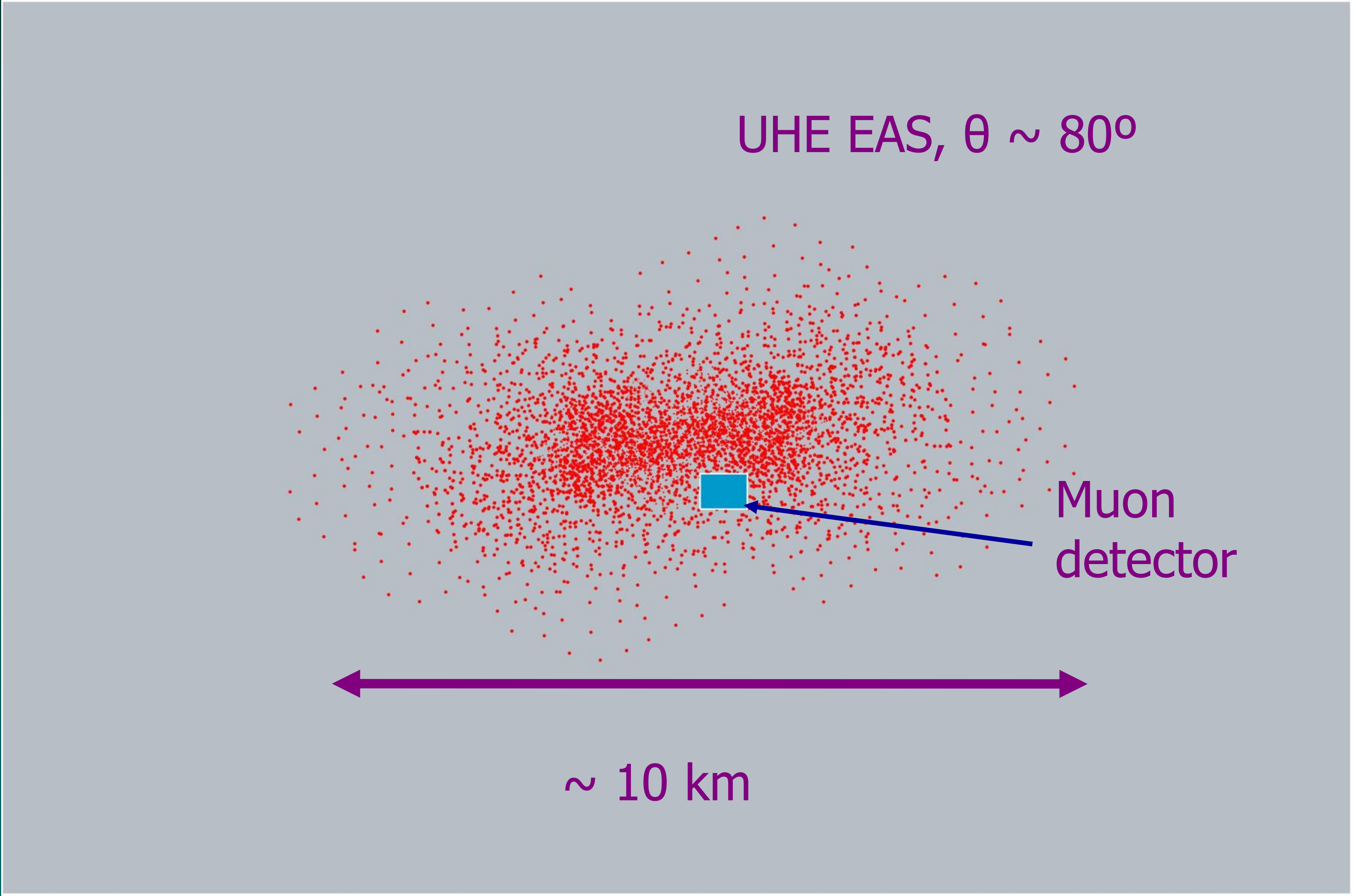
Novel approach to the analysis of muon bundles: method of Local Muon Density Spectra (LMDS)

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.

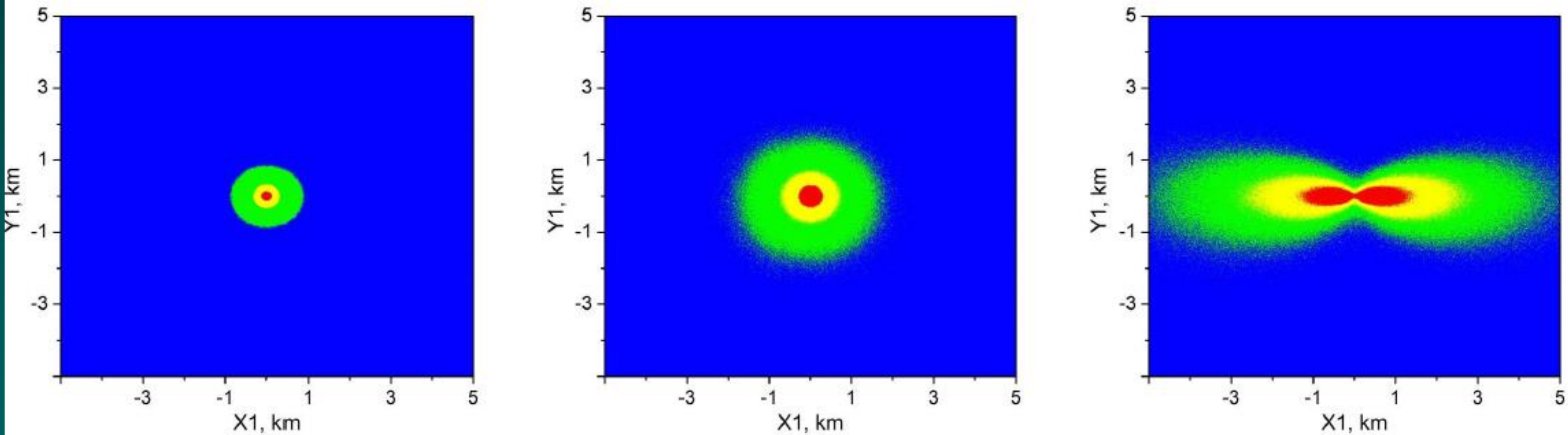
Local Muon Density Spectra detection technique



EAS cross section in muon component

EAS cross section (muon component)

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



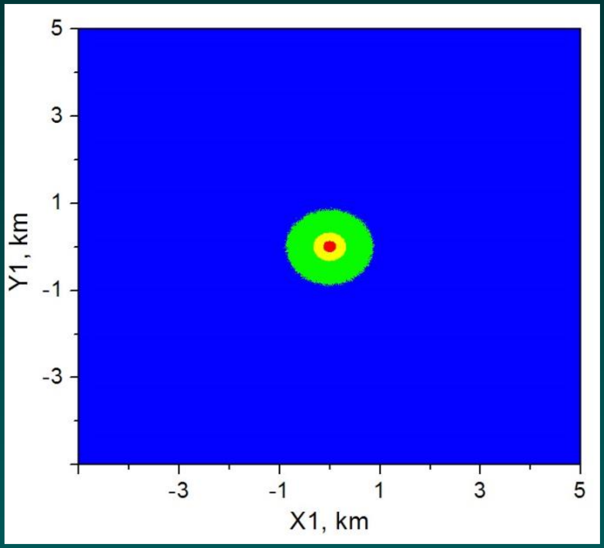
35° without EMF | 80° without EMF | 80° with EMF

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

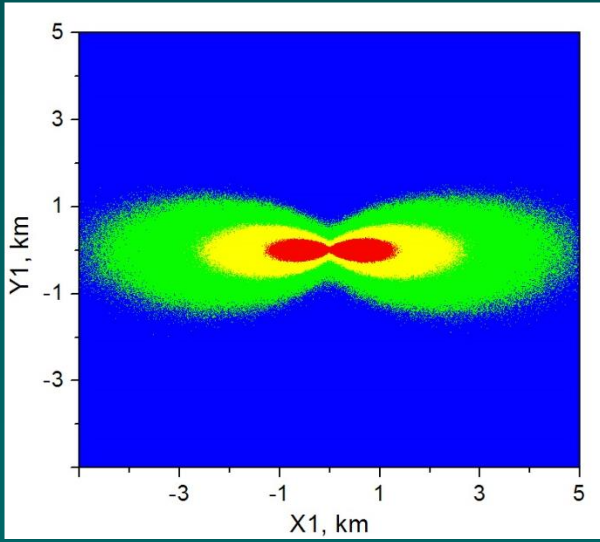
EAS collection area in LMDS method

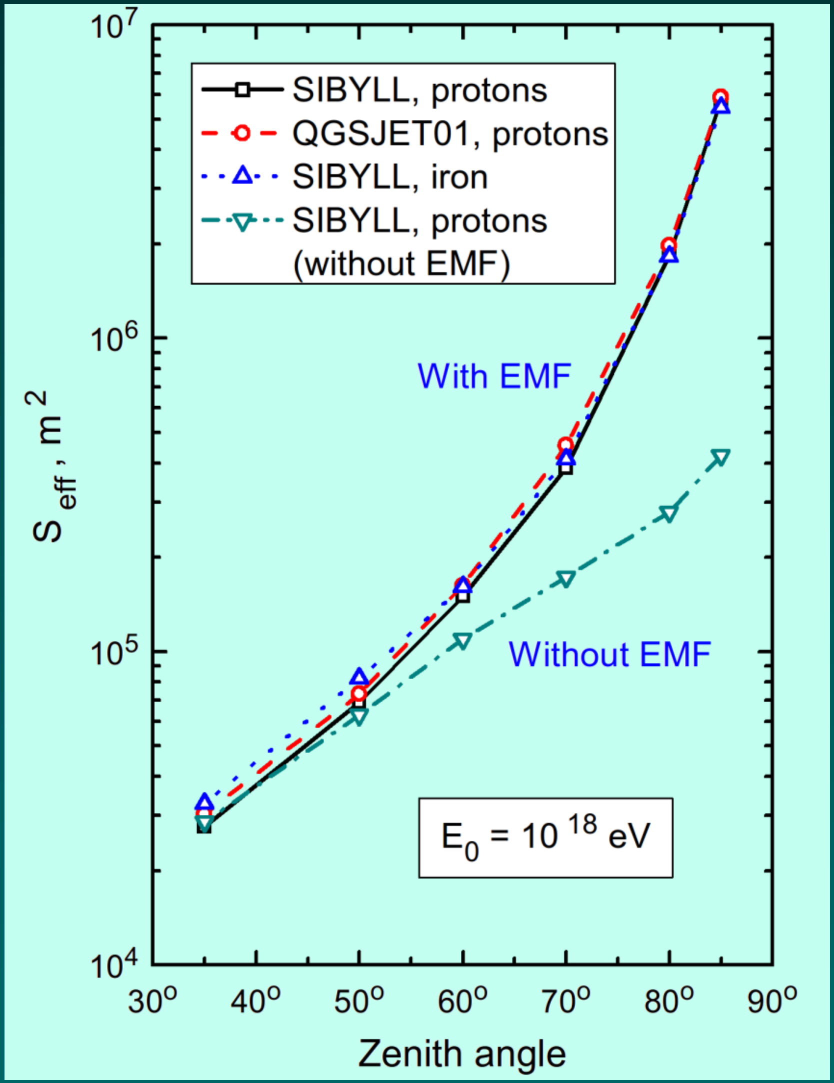
EAS cross section in muons

θ = 35º

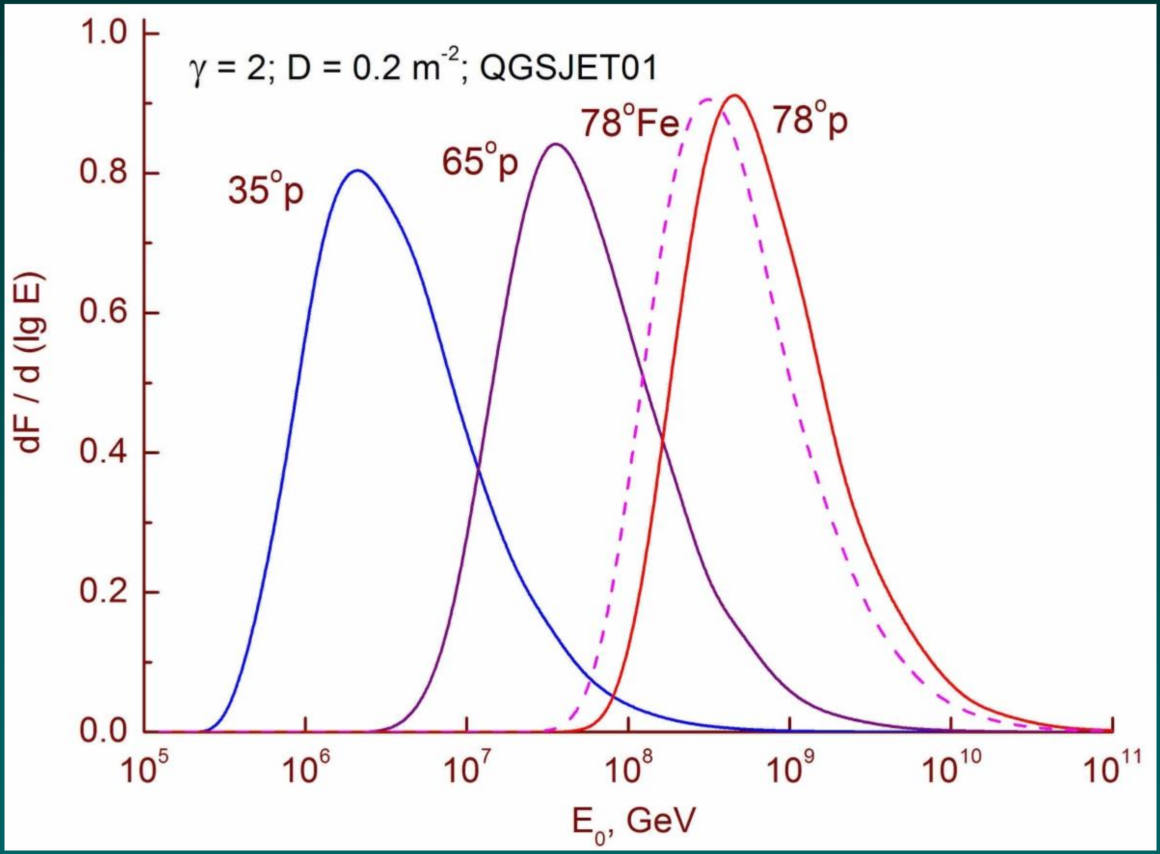


θ = 80º (with EMF)





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 accessible.

Important features of the Local Muon Density Spectrum (LMDS) approach

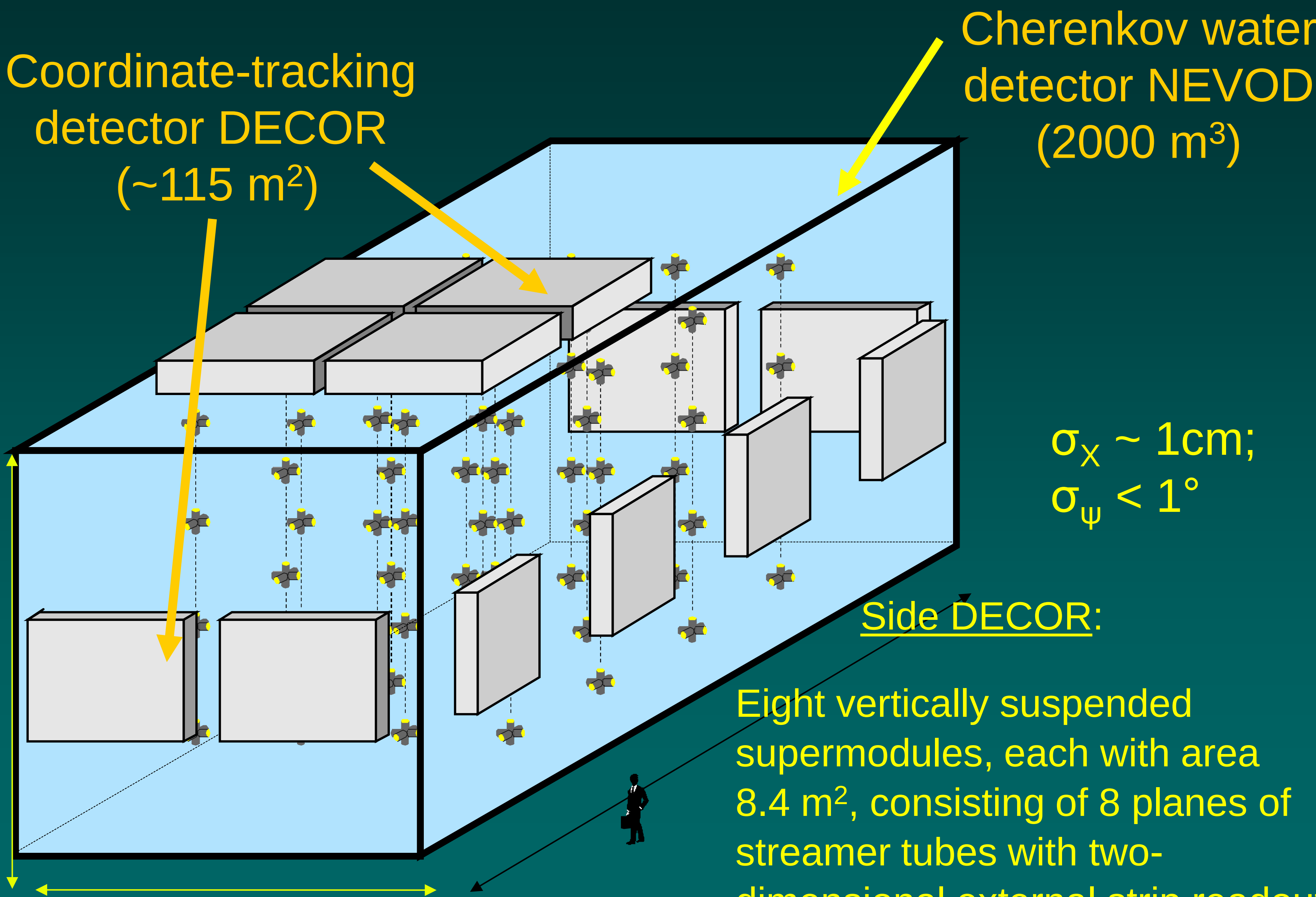
Event collection area is determined not by the detector size, but by the shower cross section which reaches square kilometers near horizon (sufficient to reach 10^{18} eV and higher).

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.

Similar to the EAS spectrum in the total number of muons, for a power-type primary spectrum with the slope γ, the LMDS also has power form with somewhat steeper slope $\beta = \gamma / \kappa$, $\kappa \sim 0.9$.

A drawback of LMDS method is a relatively poor energy resolution: for a fixed D, sigma ($\log E_0$) ~ 0.4.

General view of NEVOD-DECOR complex



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

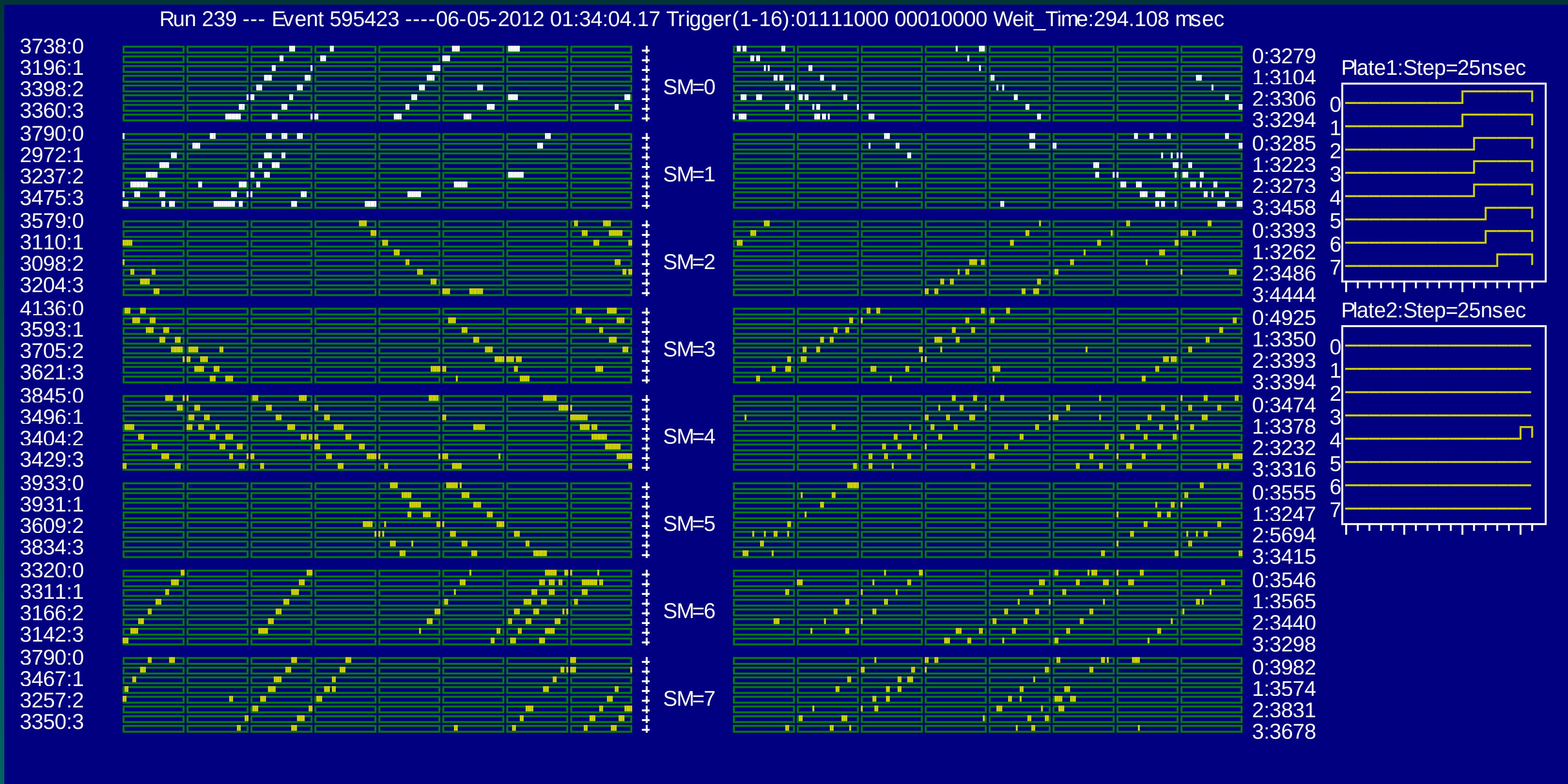
Side DECOR:

Eight vertically suspended supermodules, each with area 8.4 m^2, 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

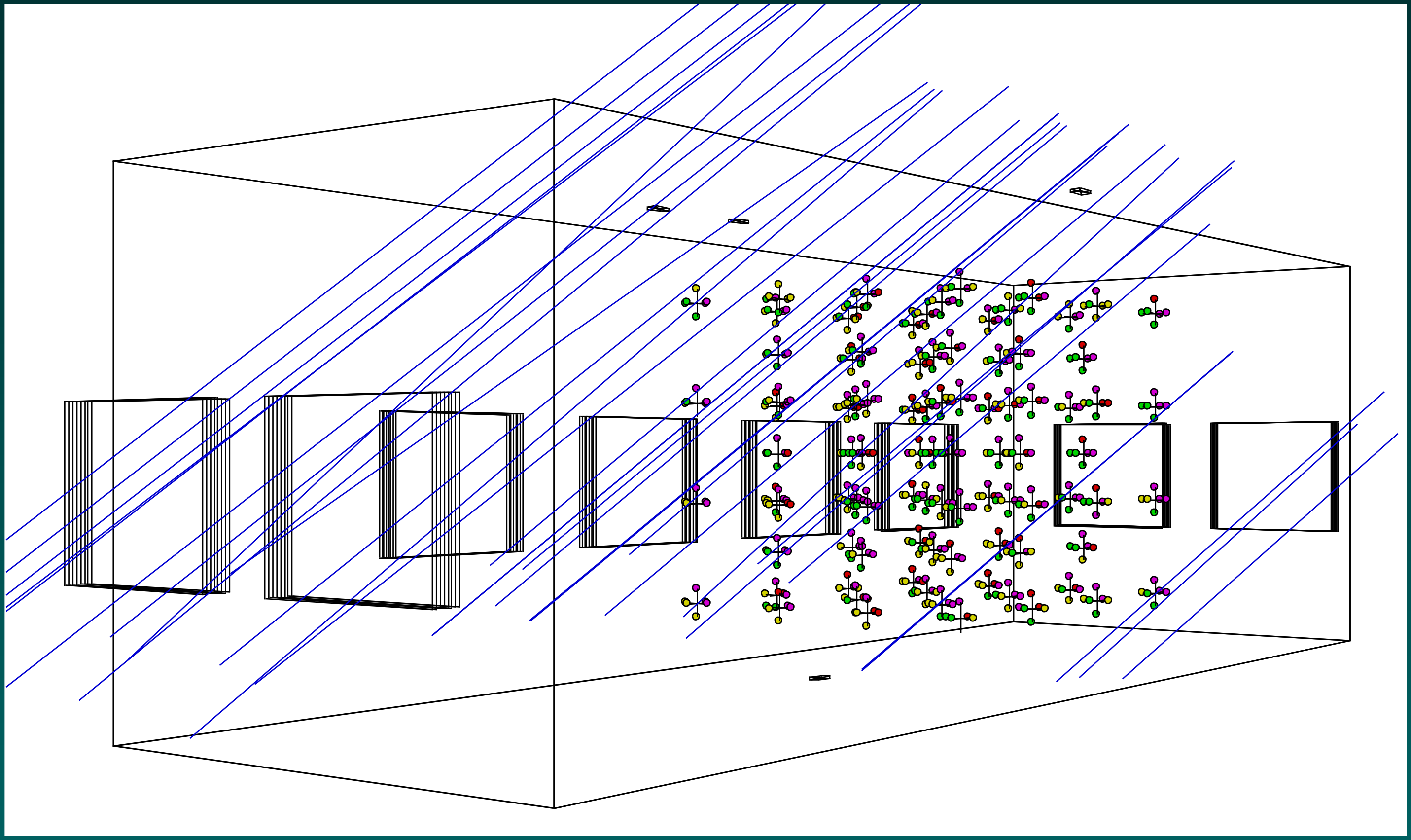
multiplicity m = 29 particles, zenith angle θ = 49°



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.

Experimental data on muon bundles

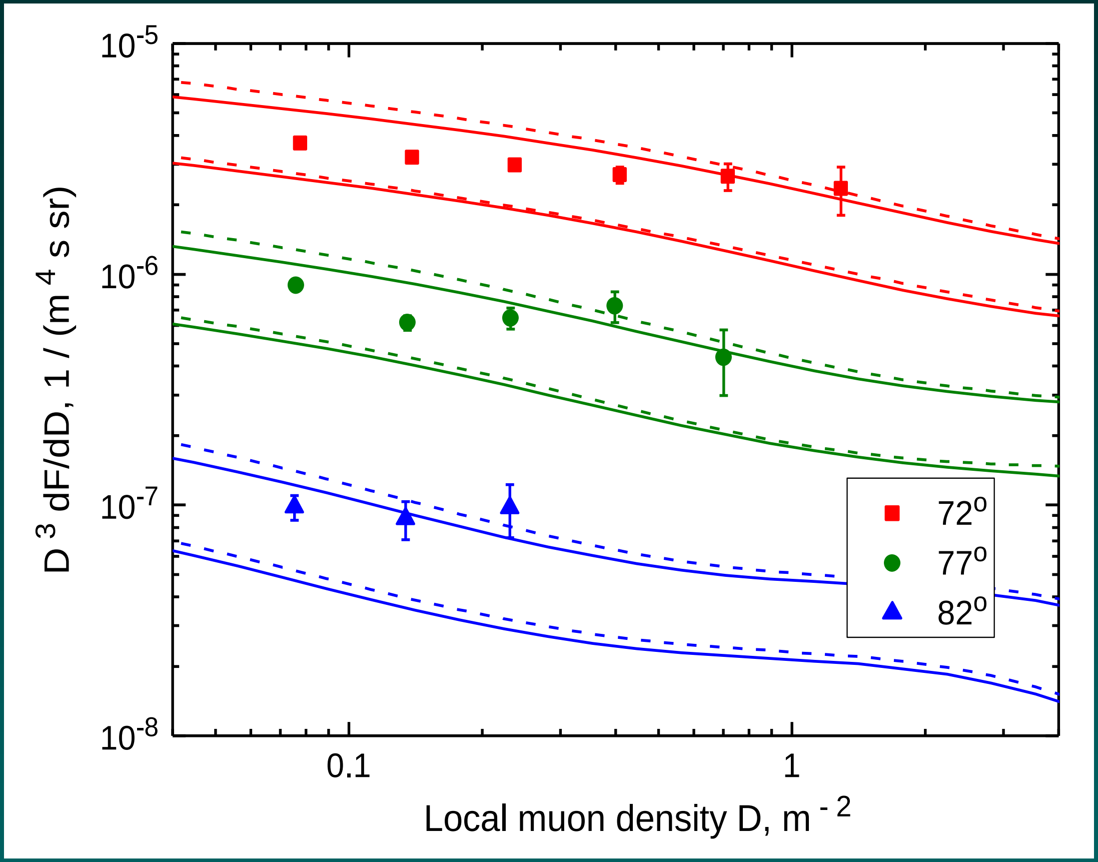
Data accumulated over the period from May 2012 to December 2018 are used.

Live observation time ~ 42.4 thousand hours .

About 71.8 thousand muon bundle events with muon multiplicity ≥ 5 and zenith angles ≥ 55° have been selected.

In comparison with our preceding analysis [A.G.Bogdanov et al., Astropart. Phys., 2018], event statistics has been increased ~ 1.9 times.

Measured and expected LMDS



<u>Expectation</u>:

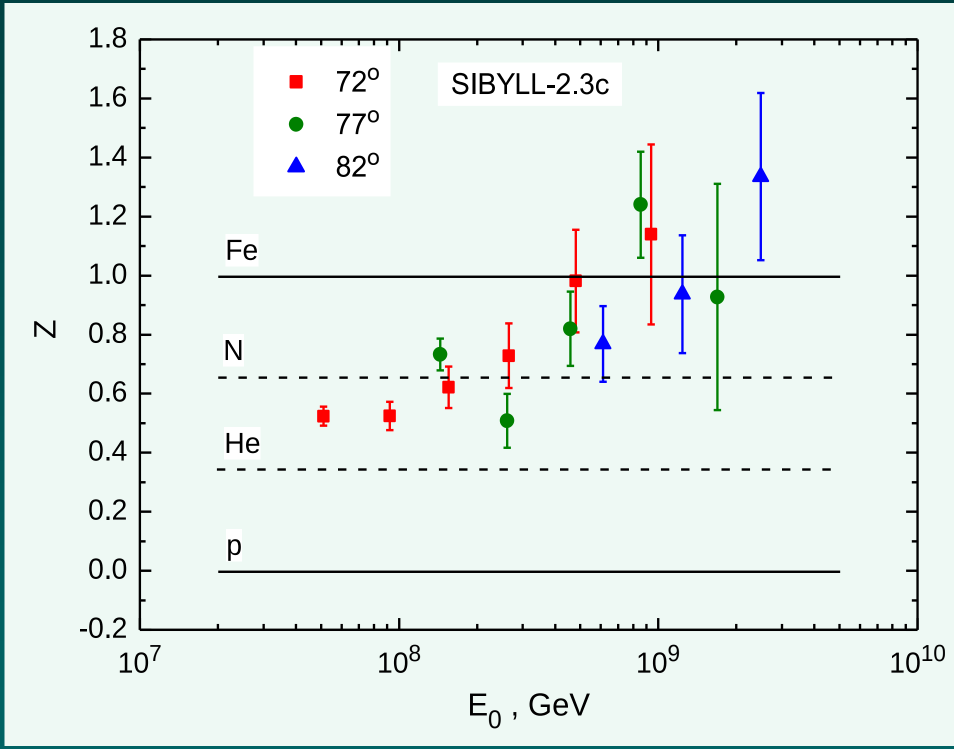
Primary all-particle spectrum parameterization (Astropart. Phys. 2018);
Two extreme assumptions on the composition (protons and iron);
Two post-LHC interaction models: SIBYLL-2.3c and QGSJet-II-4.

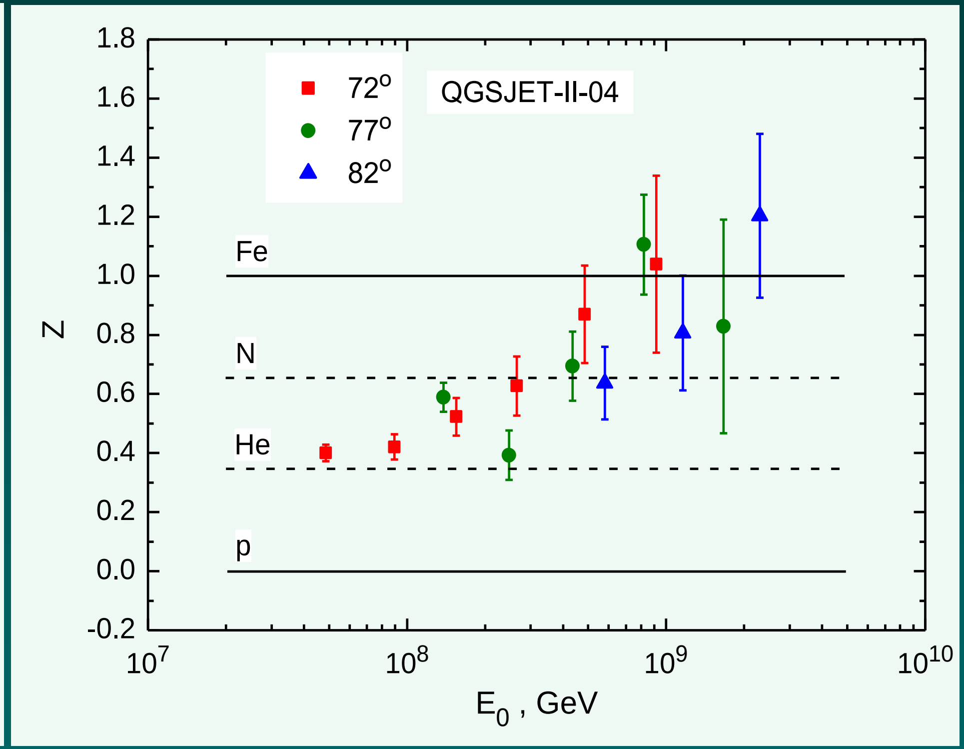
Comparison with models (different angles)

Z-factor: H. P. Dembinski et al. arXiv:1902.08124v1 [astro-ph.HE].

$$Z = (\log F^{obs} - \log F^{mod}(p)) / (\log F^{mod}(Fe) - \log F^{mod}(p))$$

(Z = 0 for protons; Z = 1 for iron).





Fast increase of the Z-factor around 1 EeV.

At 10^{18} eV, data and models are only compatible for iron assumption.

Discussion

How to explain the increasing with energy excessive amount of muon bundles?

Primary heavy nuclei near EeV? Contradicts to X_{max} measurements (PAO, TA).

Flatter primary spectrum between 10^{17} - 3×10^{18} ?
Contradicts the absolute intensity near the ankle inferred from fluorescence measurements (PAO,TA).

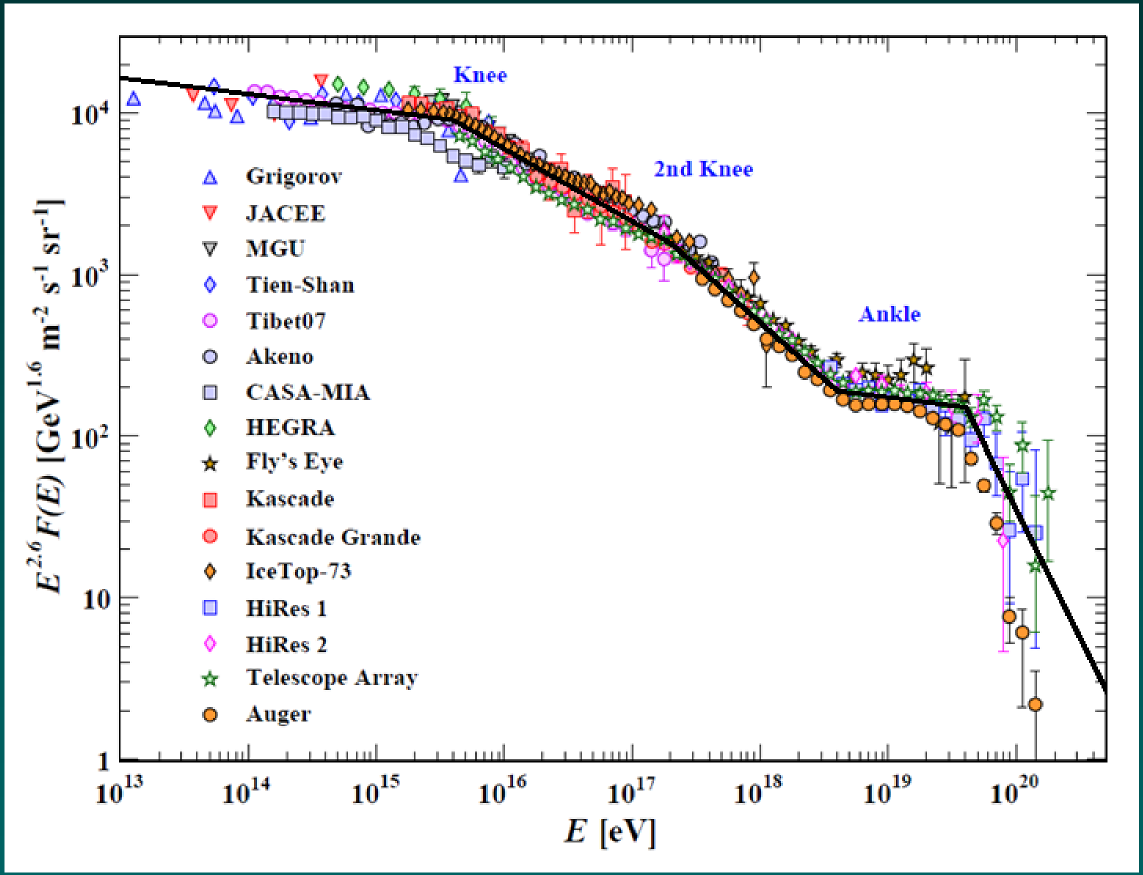
It seems ‘highly likely’ that the solution of the muon puzzle requires the introduction of serious changes in existing hadron interaction models, which could change the balance between muon and electron-photon EAS components in favor of muons.

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 $N\left(\geq E\right) = A\left(E / E_0\right)^{-\gamma}$,

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