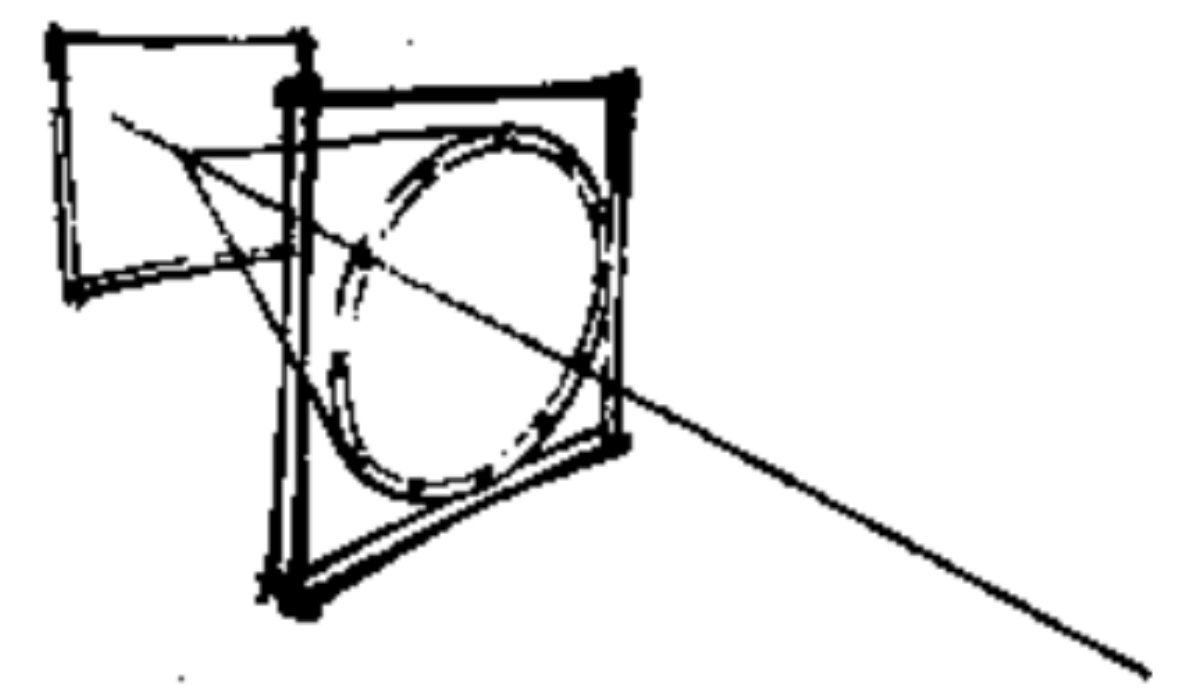


# Cascade showers in the Cherenkov light in water

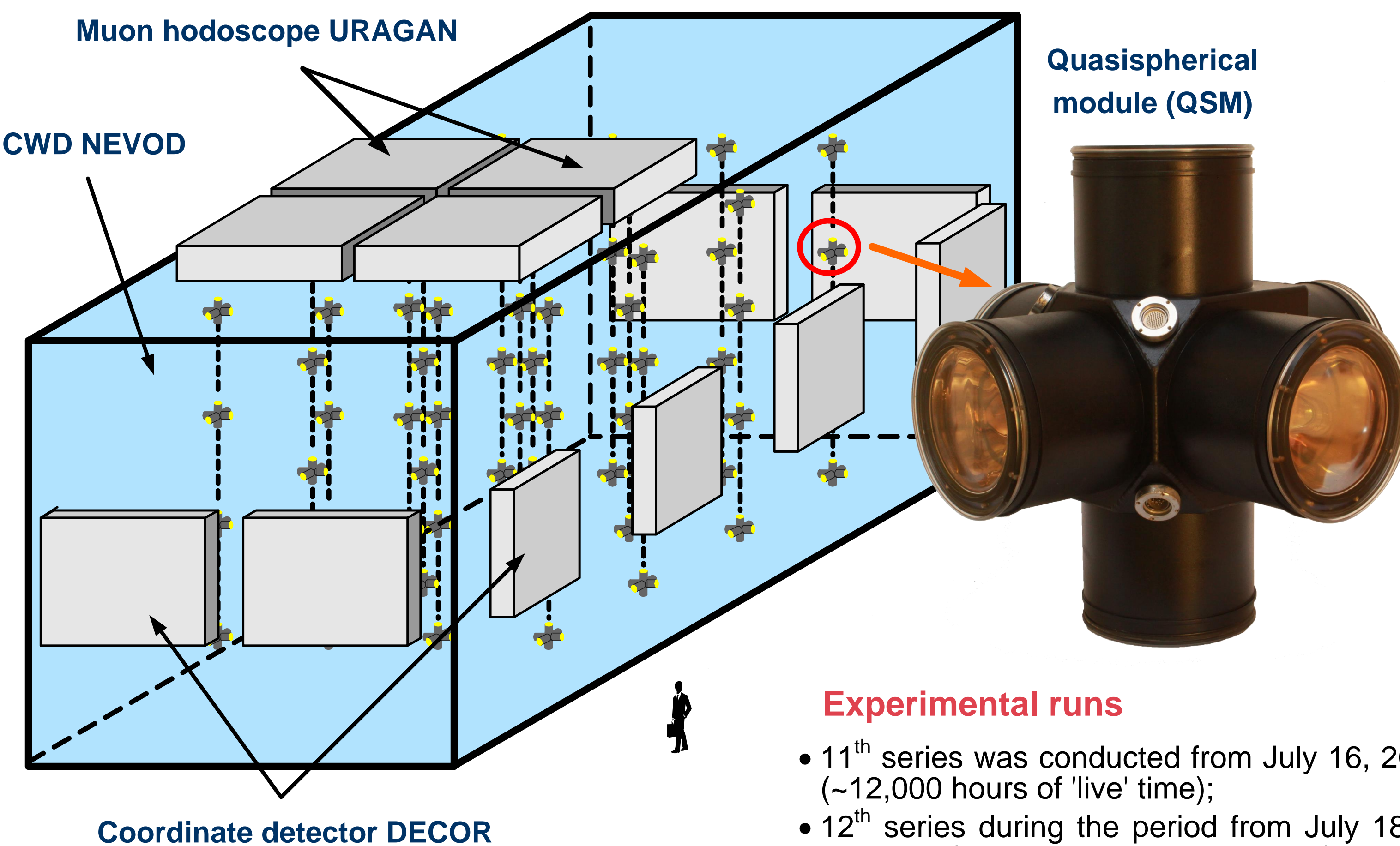


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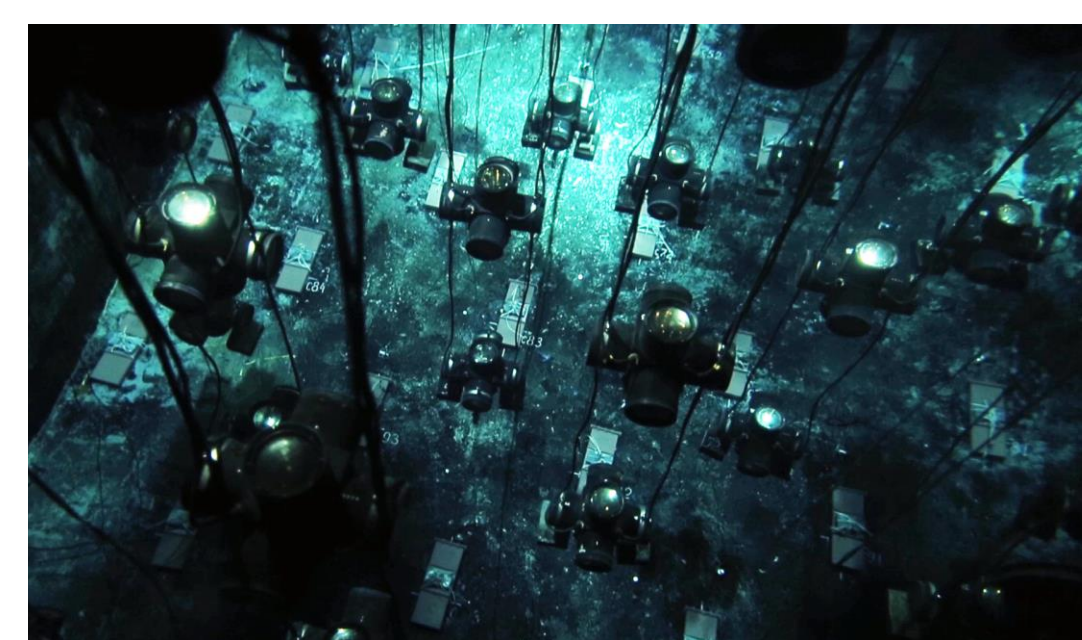
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Russian Academy of Sciences  
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## Experimental complex NEVOD

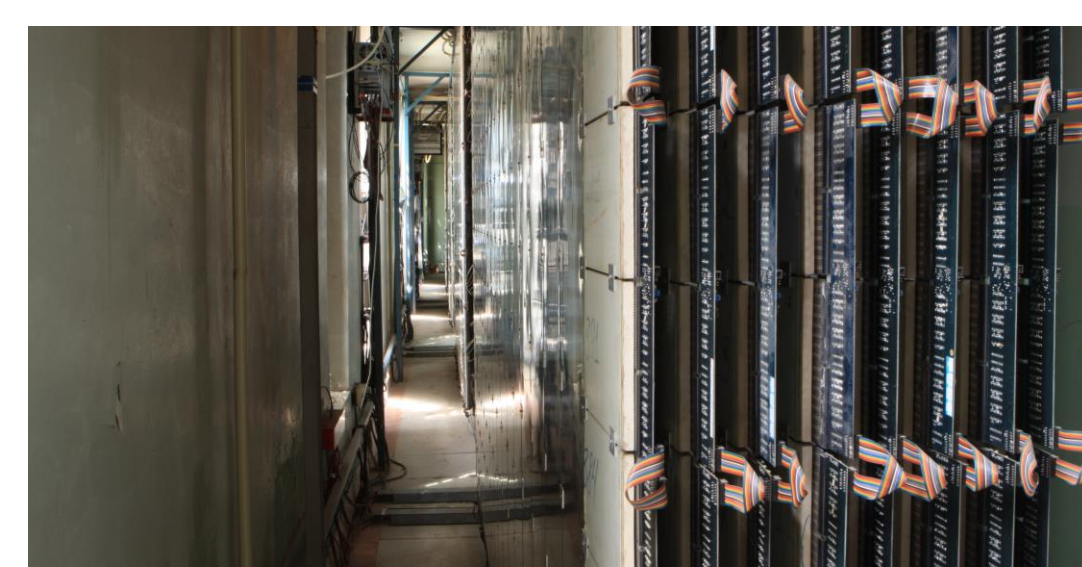


### Cherenkov water calorimeter NEVOD



- detector volume - 2000 m<sup>3</sup> of purified water;
- quasi-spherical modules (QSM) have an equal sensitivity to any direction of Cherenkov light;
- 91 QSM in 25 strings (clusters);
- 546 low-noise 12-dynode photomultipliers FEU-200 (Russia) (15 cm diameter);
- dynamic range of PMT signals: from 1 to 10<sup>5</sup> photoelectrons;
- 1092 spectrometric channels.

### Coordinate-tracking detector DECOR



- 8 vertically suspended 8-layer supermodules of plastic streamer tube chambers with resistive cathode coating;
- total sensitive area ~70 m<sup>2</sup>;
- chamber planes are equipped with two-coordinate external strip readout system;
- measurement accuracy - about 1 cm in both coordinates;
- angular accuracy of muon track reconstruction is better than 1°.

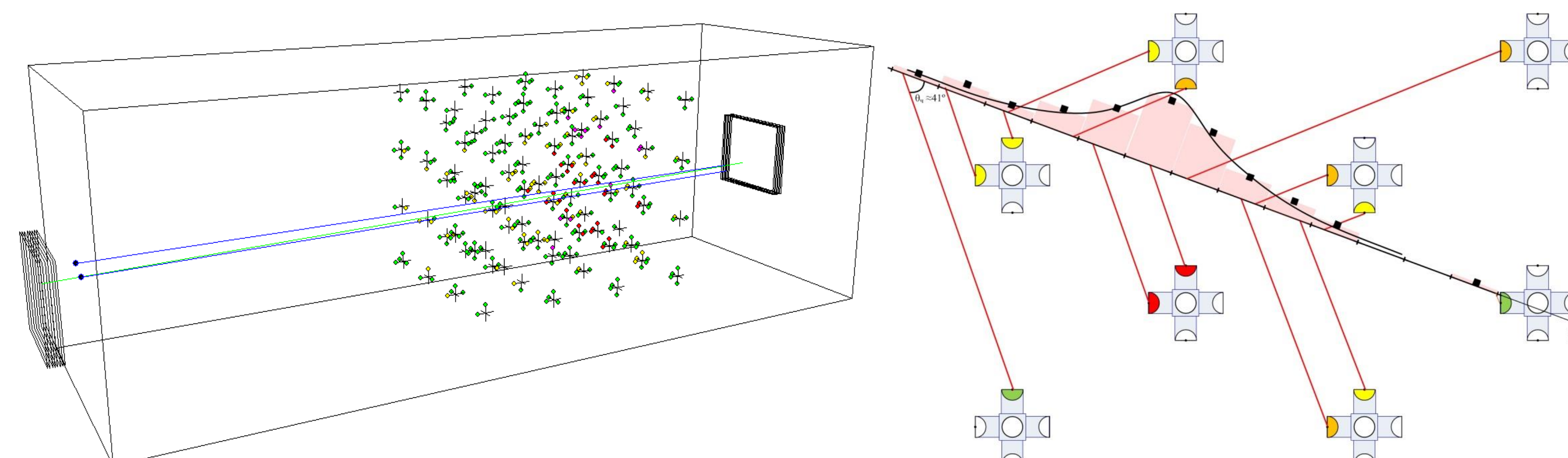
### Experimental runs

- 11<sup>th</sup> series was conducted from July 16, 2013 to April 08, 2015 (~12,000 hours of 'live' time);
- 12<sup>th</sup> series during the period from July 18, 2015 to December 13, 2017 (~17,000 hours of 'live' time);
- 413 million events with big energy deposit have been registered with a special trigger "60c" (more than 60 hit QSMs);
- 6 million events with single near-horizontal muons.

### Single near-horizontal muons

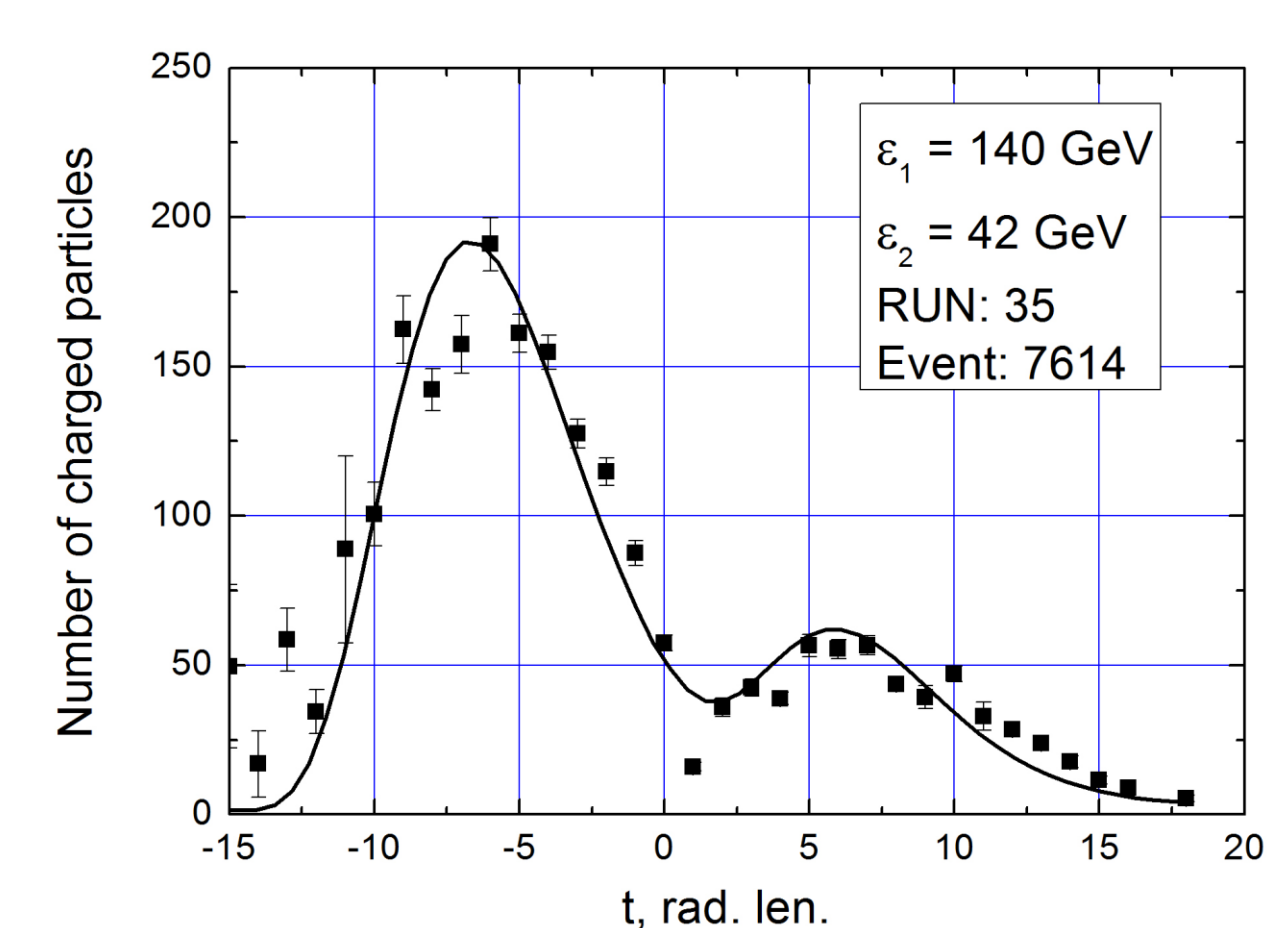
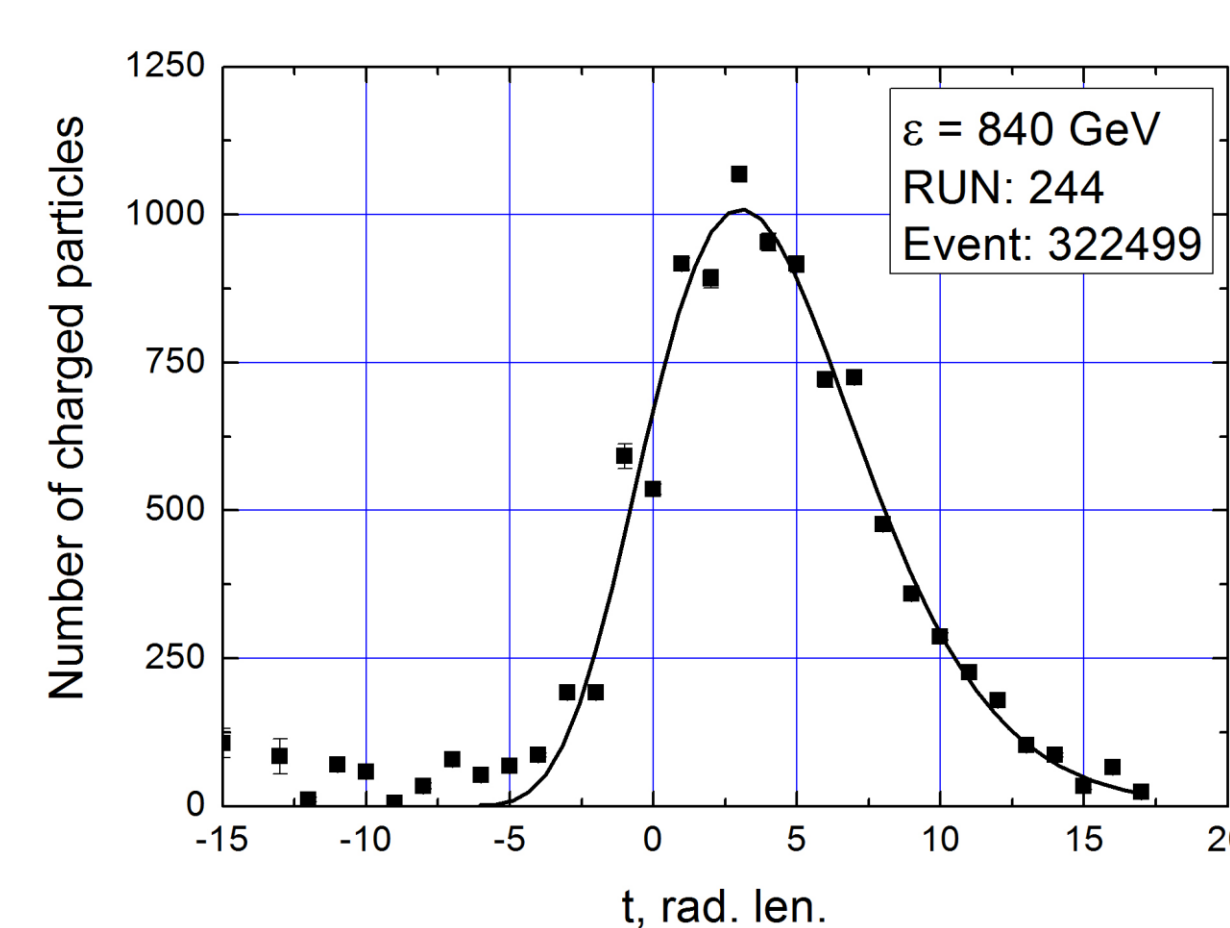
- two SMs of DECOR located at opposite short sides of the tank are triggered;
- tracks reconstructed on the basis of individual supermodule responses are within a cone of angles less than 5°;
- line connecting midpoints of tracks in SMs is taken as a track of the muon;
- muons in the range of zenith angle from 84° to 90° are selected;
- mean energy of muon E = 100 GeV;
- significant part of muons generate cascades in the detector water.

## Selection of cascade showers with known axis and reconstruction of their parameters



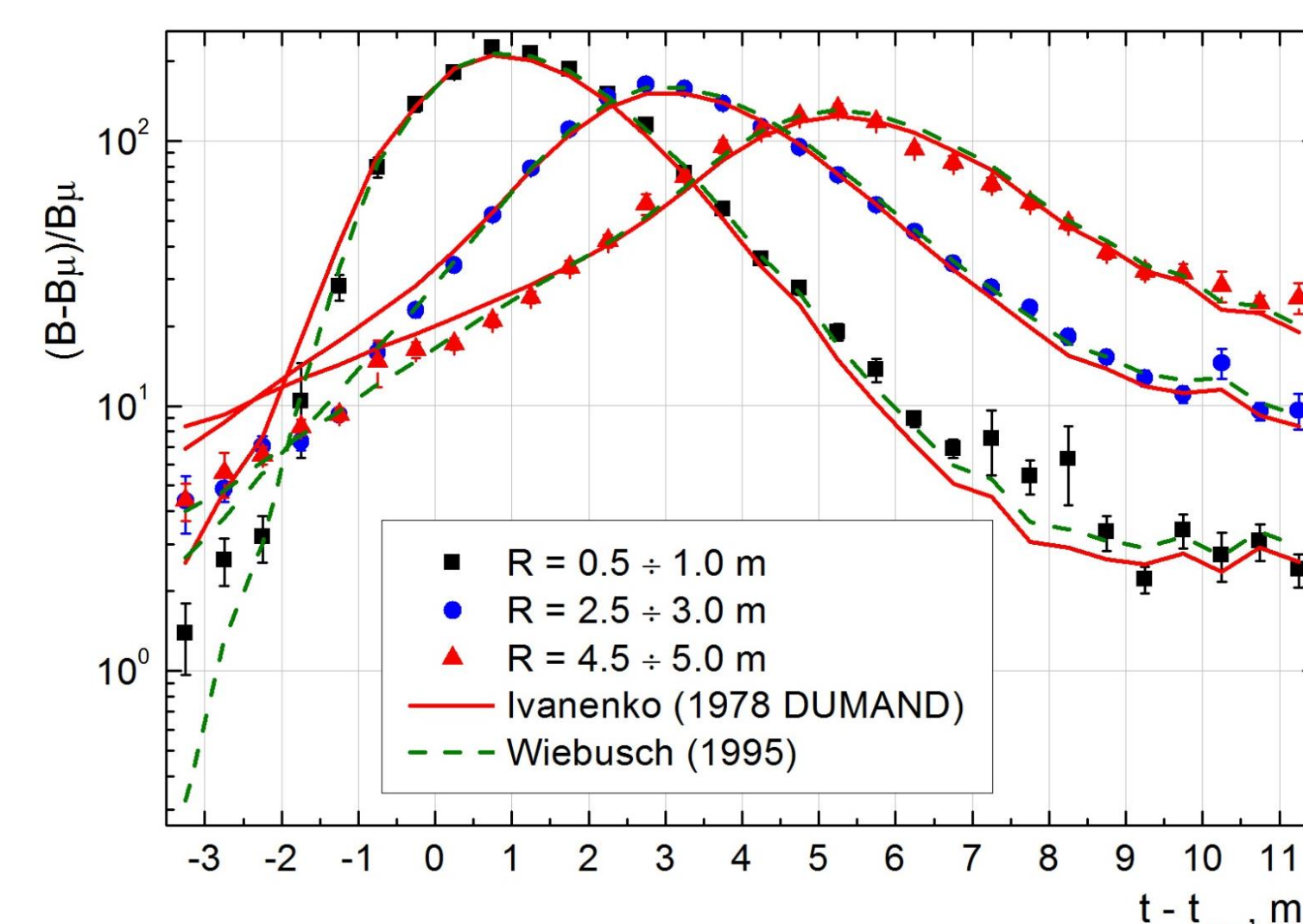
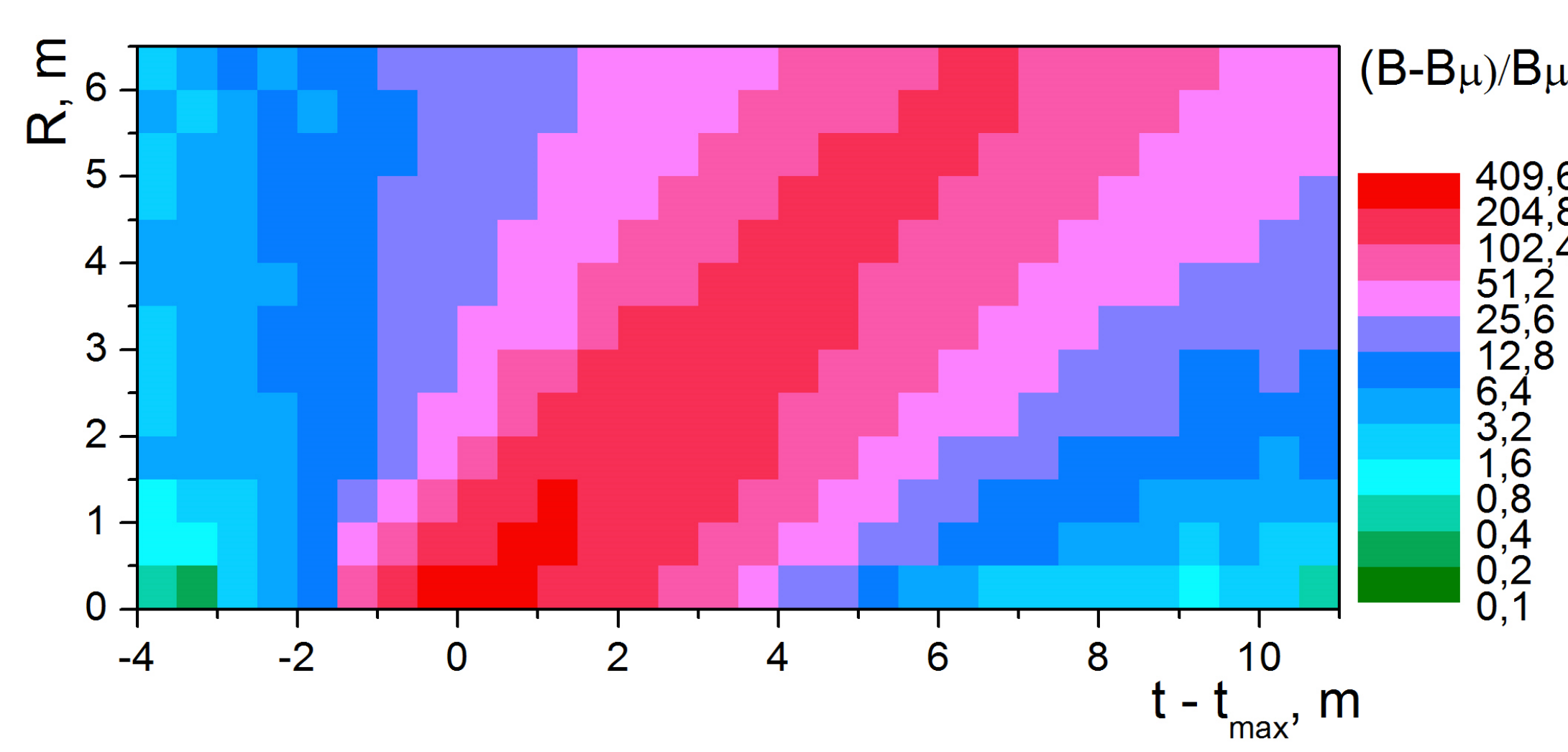
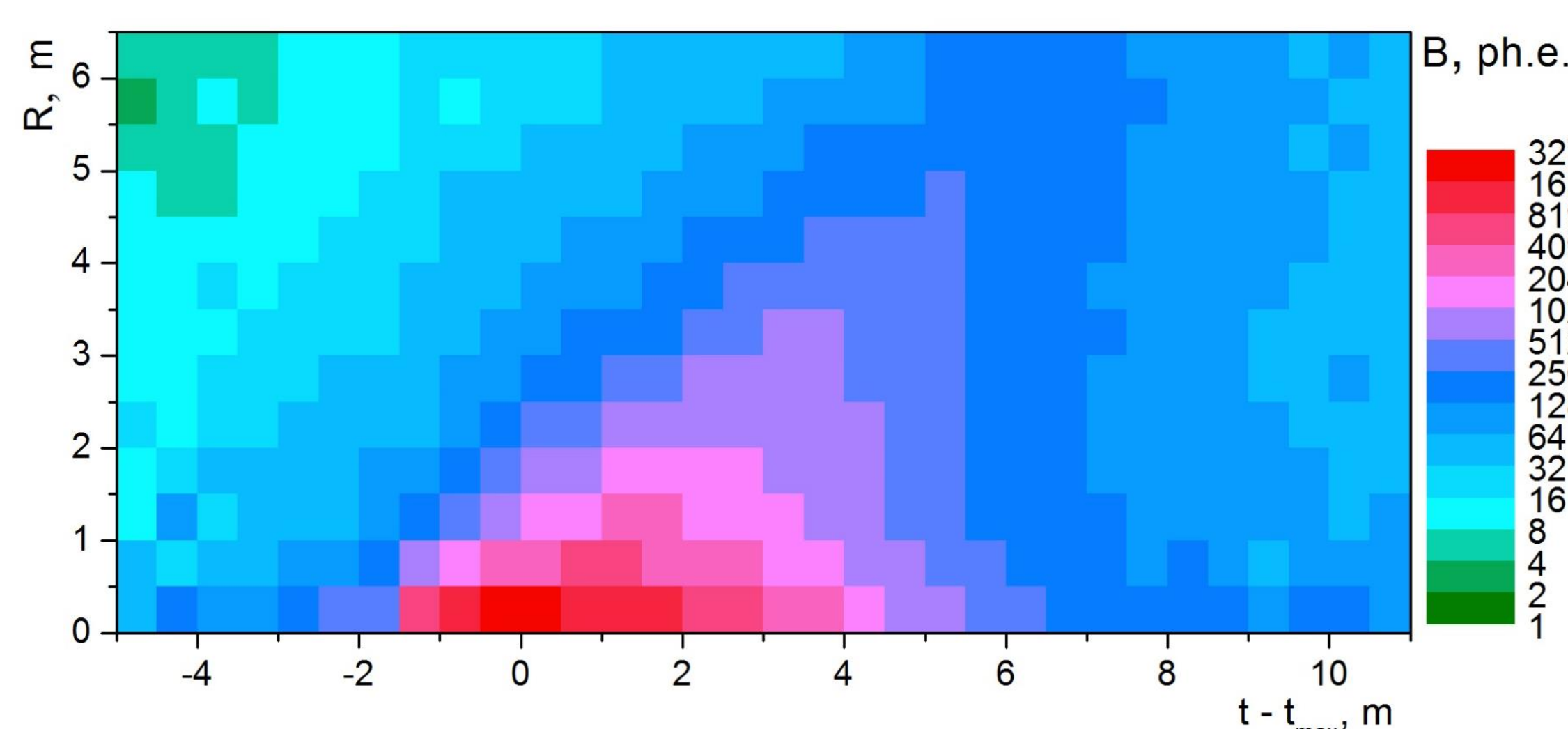
High granularity of optical module lattice allows to measure the distribution of Cherenkov light from the cascade. The cascades produced by nearly horizontal muons were investigated. We assumed that the axis of the cascade coincides with muon track.

### Examples of experimental cascade curves



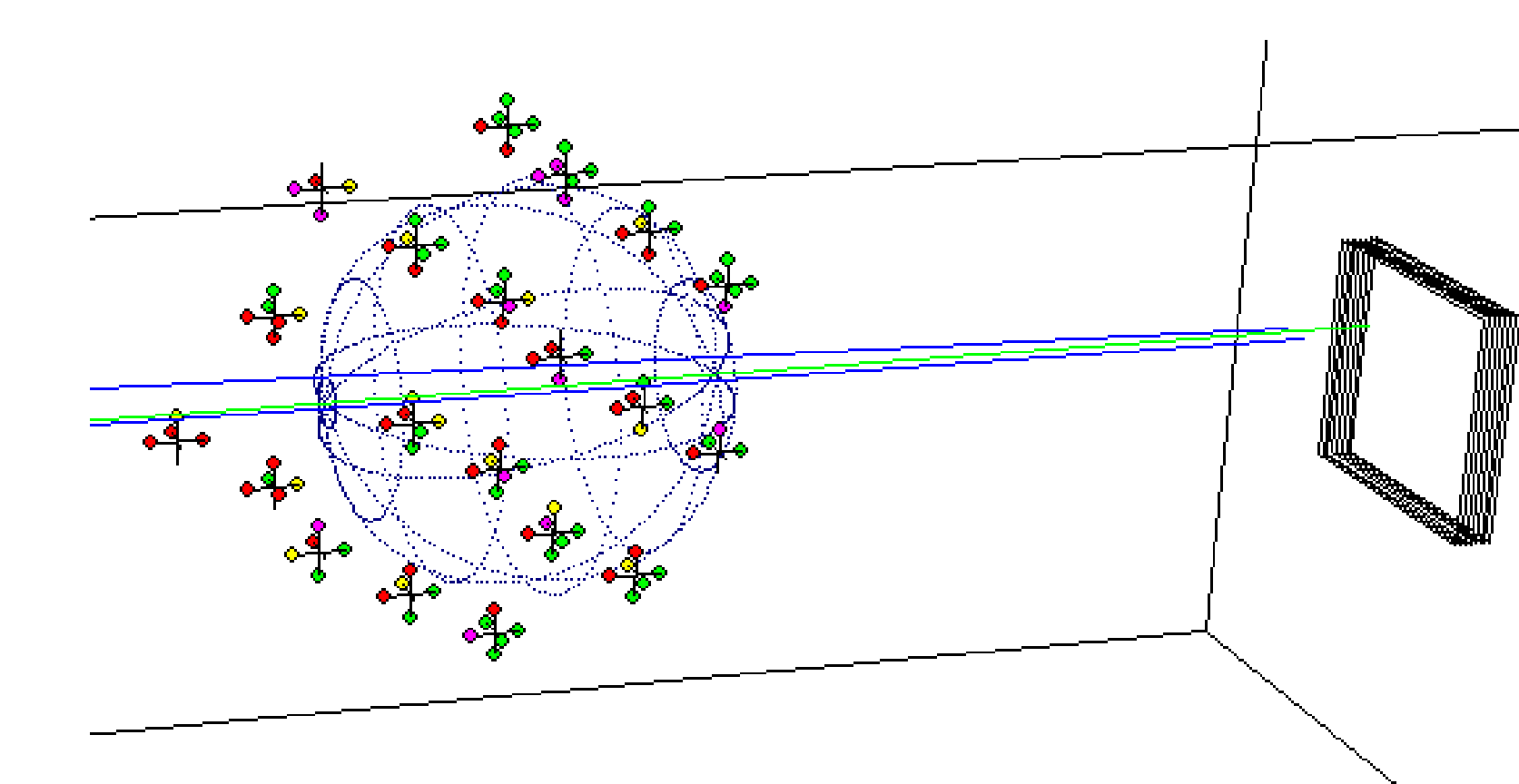
In the first approximation we assumed that all Cherenkov photons are emitted and propagate under the same angle  $\theta = 42^\circ$ . It allows to reconstruct the cascade curve (dependence of the number of charged particles on cascade depth) and to estimate the energy of cascade and the point of generation.

## Distribution of Cherenkov light from the cascade showers



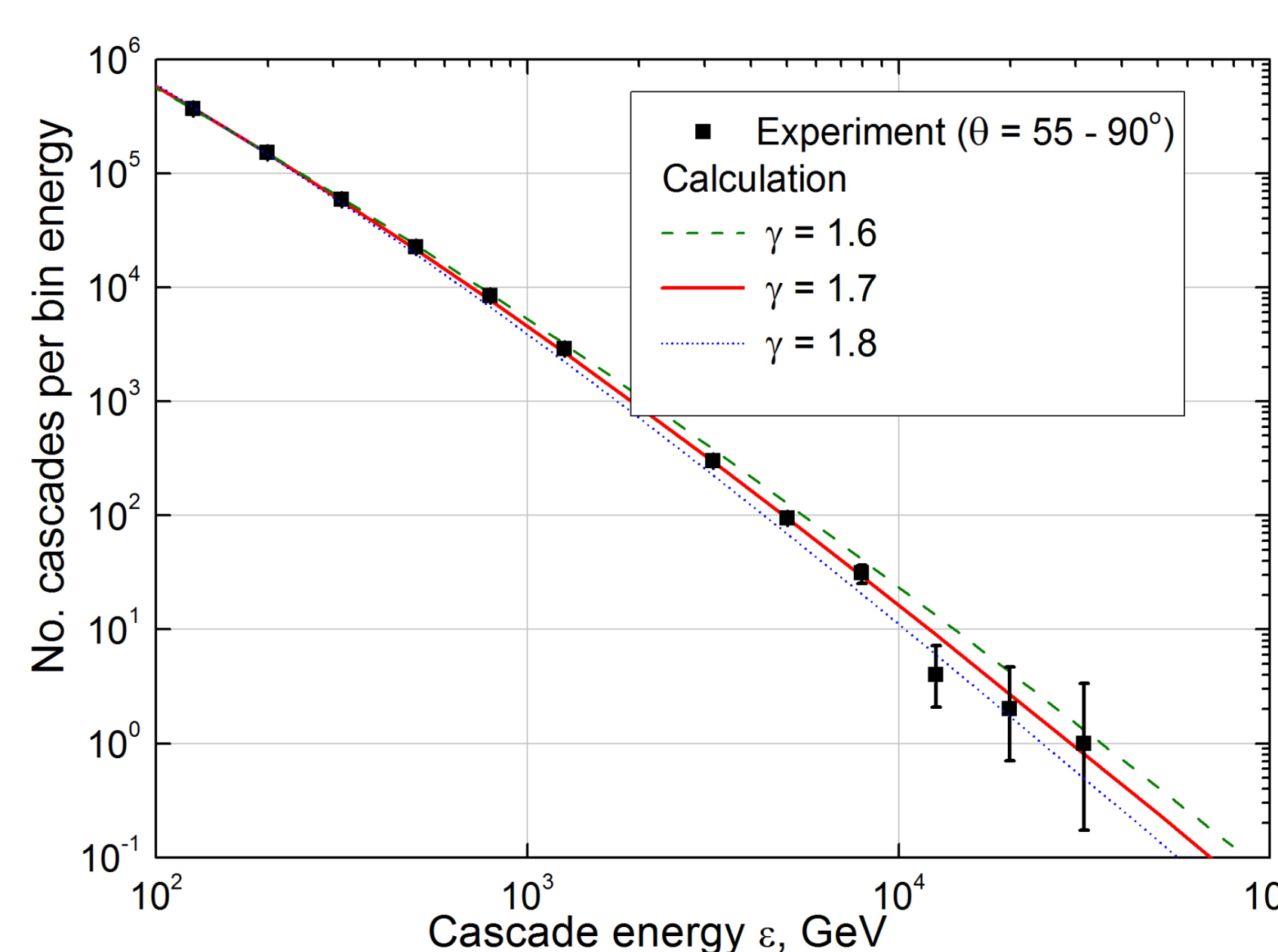
Distribution of light from cascade showers with energies 100-500 GeV has been measured. Since the parameters of the light attenuation are the same for cascades and for single muons, it is reasonable to consider the ratio of light intensity for cascades (B) to the intensity measured for events with single muons ( $B_\mu$ ). The comparison shows a good agreement of experimental data with two models of cascade electron scattering: analytical solution of cascade equations (I.P. Ivanenko et al. / Proc. 1978 DUMAND Summer Workshop) and approximation (M.G. Aarsten et al. / Nucl. Instr. Meth. in Phys. Res. A711, 2013) of MC simulation with GEANT 3 (C.H. Wiebusch / Ph.D. Thesis, Physikalische Institute, RWTH Aachen, 1995).

## Reconstruction of cascades with unknown axis



Selection of cascade is based on the compactness of the cluster of QSMs with most powerful responses. Reconstruction of parameters is based on  $\chi^2$ -comparison of experimental and expected PMT responses. The technique has been tested on the cascades with the known axis.

The cascade reconstruction accuracy is better than 0.2 m for cascade maximum position, about 2° for the axis direction, and better than 15 % for the cascade energy.



The likelihood estimate of the index of pion and kaon integral generation spectrum is  $\gamma = 1.65 \pm 0.01$ .

## Conclusion

For the first time, the spatial distribution of Cherenkov light from high energy cascades in water has been measured at NEVOD CWD with a dense lattice of measuring modules.

The differential energy spectrum of cascades generated by muons has been measured in the energy range of  $\varepsilon = 0.1 - 10$  TeV, and the value of the index of pion and kaon integral generation spectrum was estimated ( $\gamma = 1.65 \pm 0.01$ ).

Obtained results may be used for verification and improvement of models of development of electromagnetic cascades in water, for development of criteria of selection of cascade showers in Cherenkov water detectors and for reconstruction of their parameters.

## Acknowledgements

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