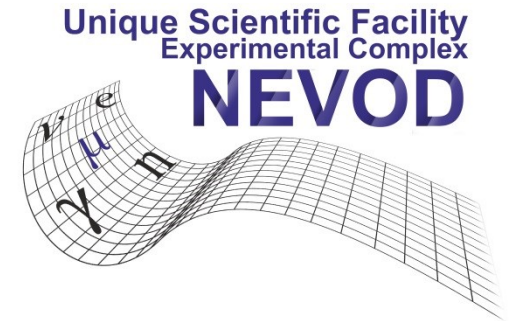




ISCRA-2017



Spatial distribution of Cherenkov light from cascades in water as a basis of methods for selecting cascades and reconstructing their parameters

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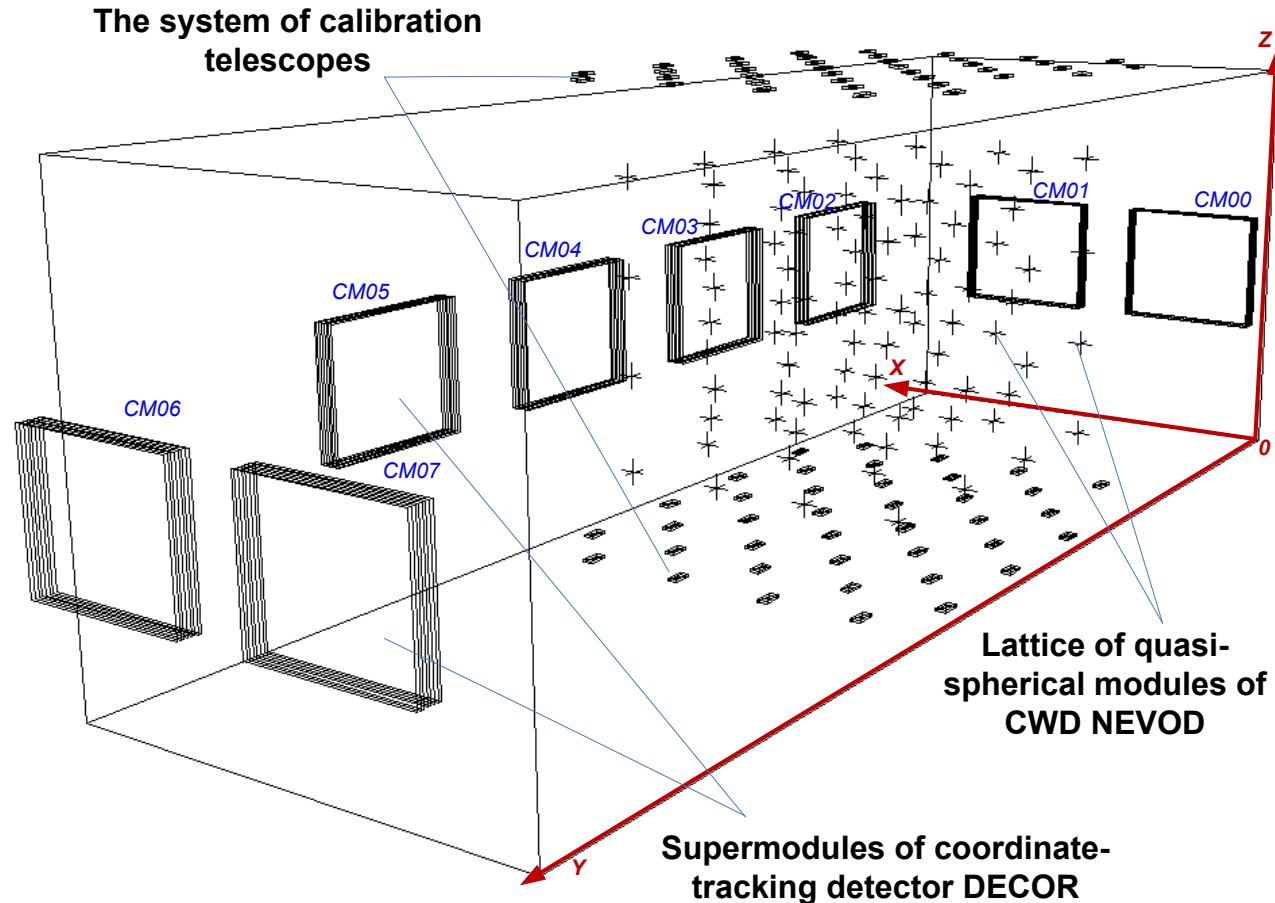
Introduction

- Cherenkov water detectors are widely used for investigating the ultrahigh-energy muons and neutrinos ([IceCube](#), [ANTARES](#), [Baikal](#));
- The energy of these particles is estimated through cascade showers;
- The topical experimental task is to investigate the distribution of the Cherenkov light from cascade showers in water;
- Large-scale detectors with long distances between the measuring modules are limited to obtain the detailed picture of light;
- In the present work, the light distribution from cascades is studied with the Cherenkov detector having the dense lattice of detecting modules.

Experimental complex NEVOD

- 2000 m³ volume.
- spatial lattice: 91 quasi-spherical modules (QSM) (step 2 x 2 x 2.5 m³).
- each QSM has six PMTs with flat cathodes
- the dynamic range for each PMT is 1–10⁵ ph.e.

The small step of the spatial lattice and the wide dynamic range allow the detector to work as a calorimeter and measure the full cascade curve in individual events



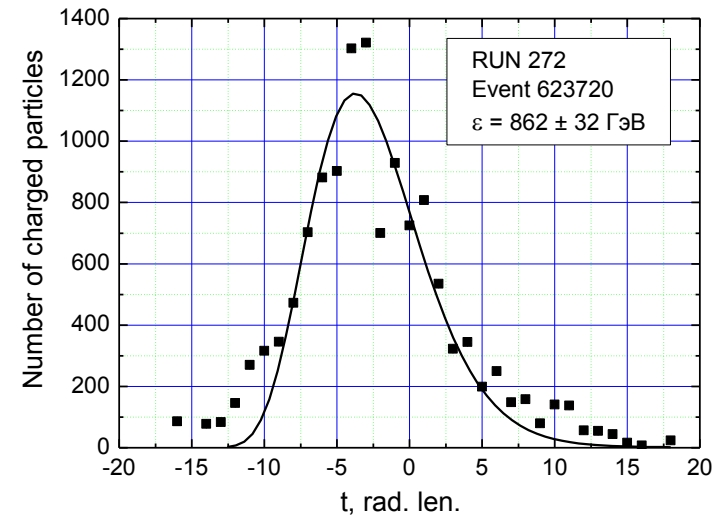
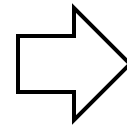
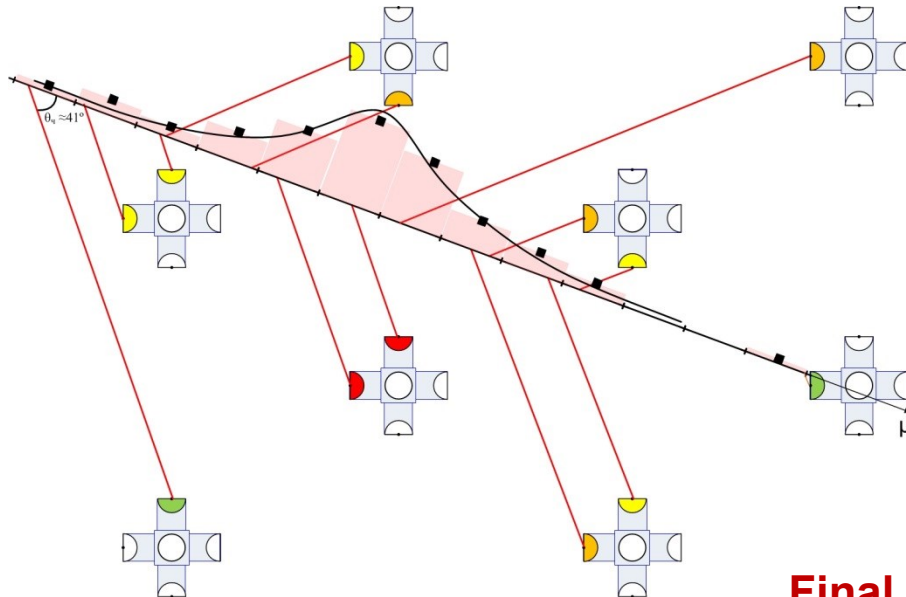
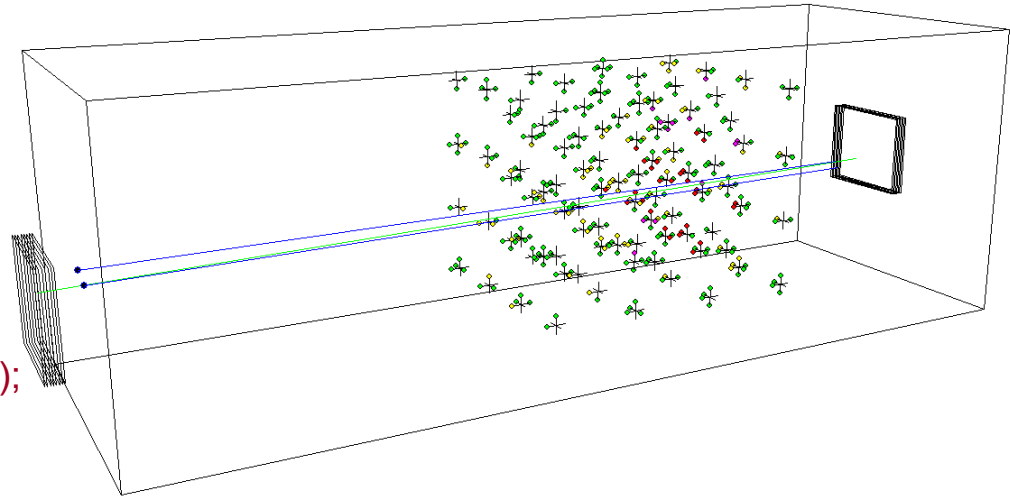
Analyzed data: **11 897 hours of «live time»**
(16 July 2013 - 8 April 2015)

Cascade showers with known axes and reconstruction of their parameters

The cascades produced by nearly horizontal muons were investigated (zenith angles are $85^\circ \div 90^\circ$).

The tracks were reconstructed by means of coordinate detector DECOR.

O.Saavedra et al., J. Phys.: Conf. Ser. 409 (2013);
S.S.Khokhlov et al., Bull. RAS. Phys. 77 (2013).



**Final sample: 522 cascade showers with
reconstructed energies from 100-500 GeV**

Distribution of light from the cascade showers

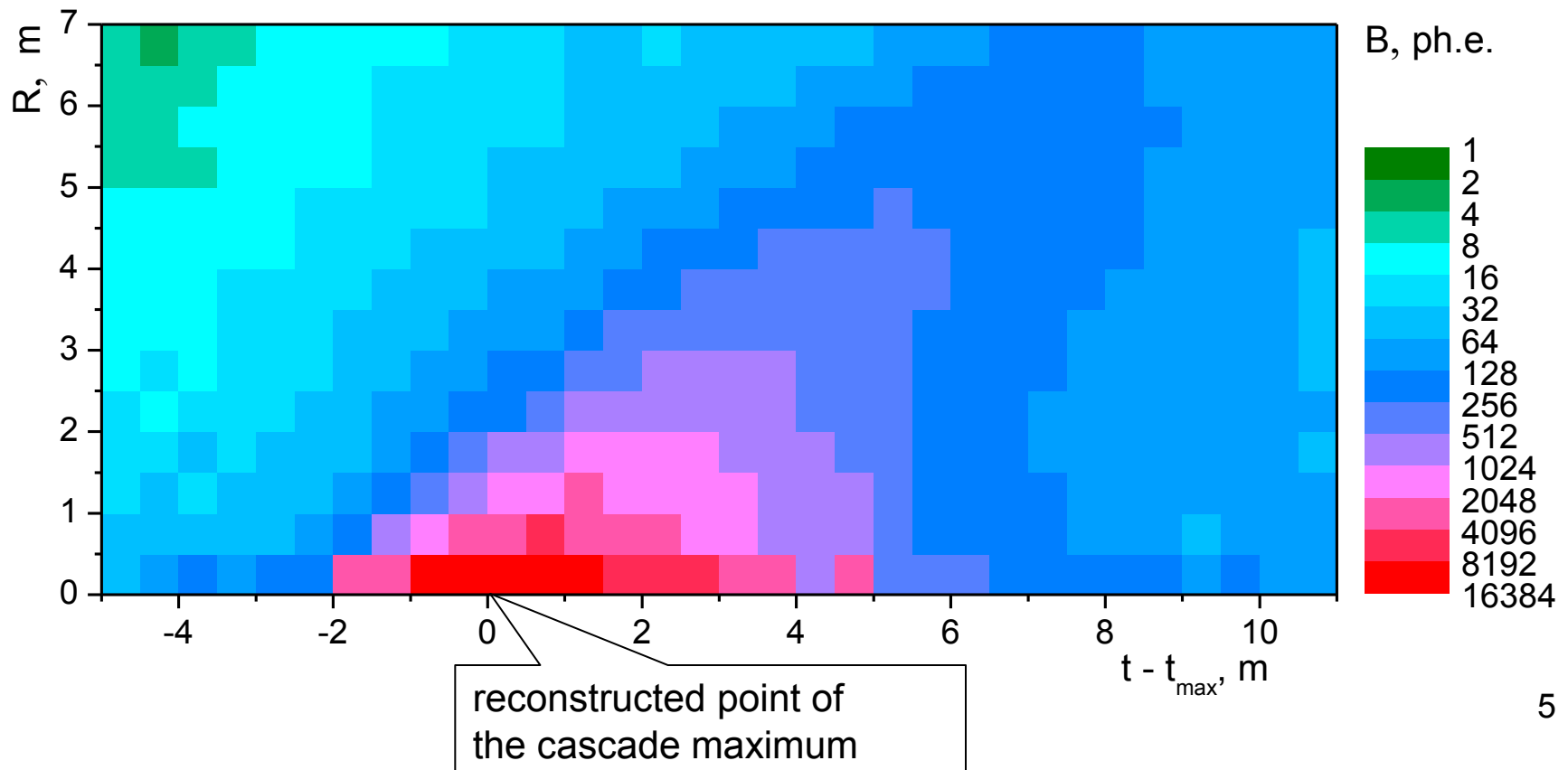
The responses of the modules in all events are normalized to reconstructed energy values:

$$B = \frac{\varepsilon_0}{\varepsilon} \sqrt{\sum_{i=1}^6 A_i^2}$$

where ε_0 is the normalizing energy of 200 GeV (close to the average energy of showers in the sample);

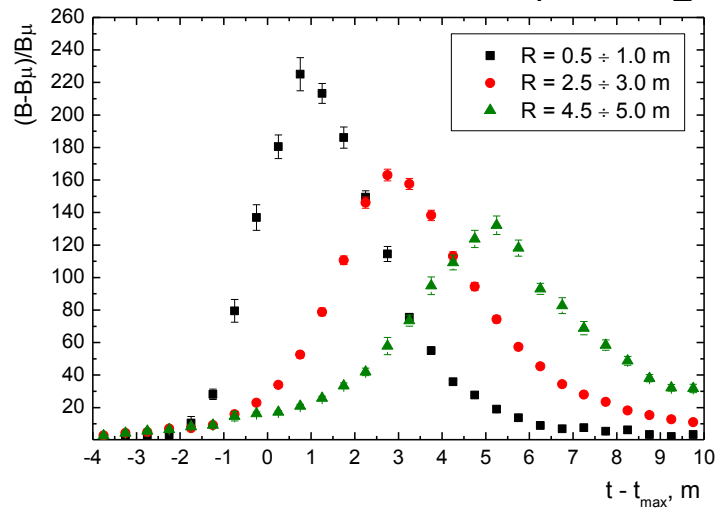
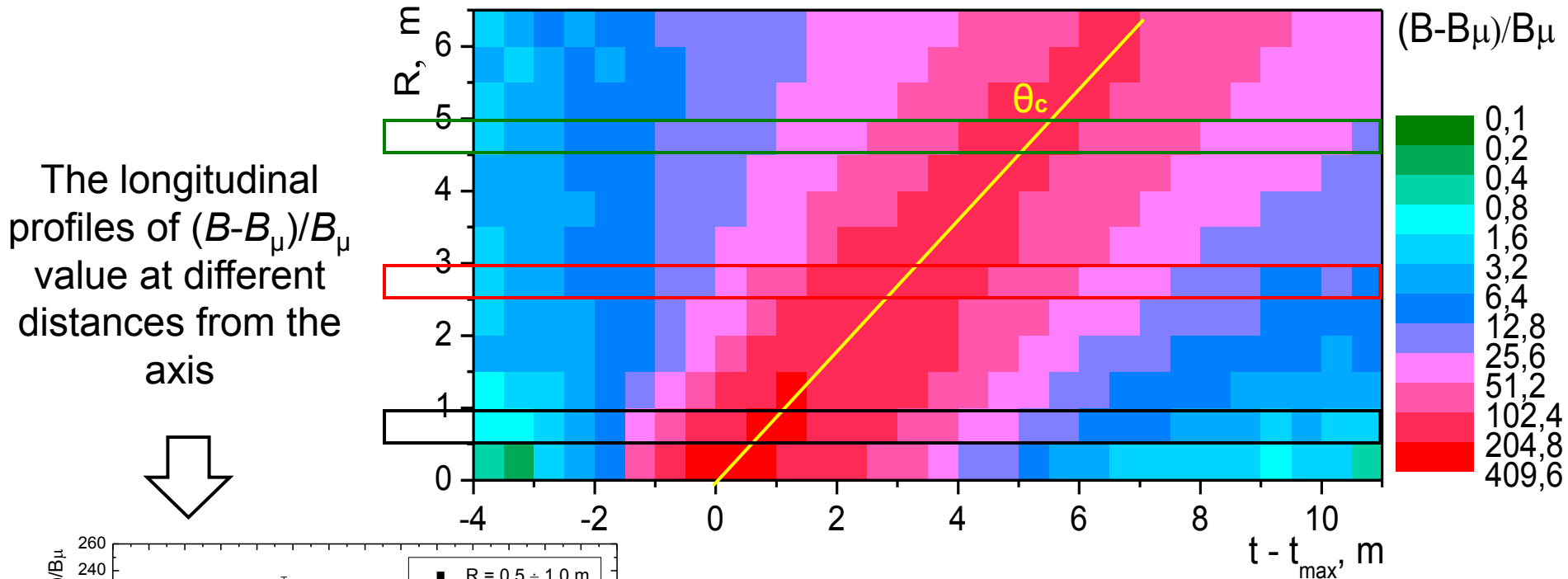
ε is the reconstructed energy of the shower in the event;

A_i is the amplitude of i-th PMT in QSM (in photoelectrons, ph.e.).



Compensation of light attenuation

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_μ):



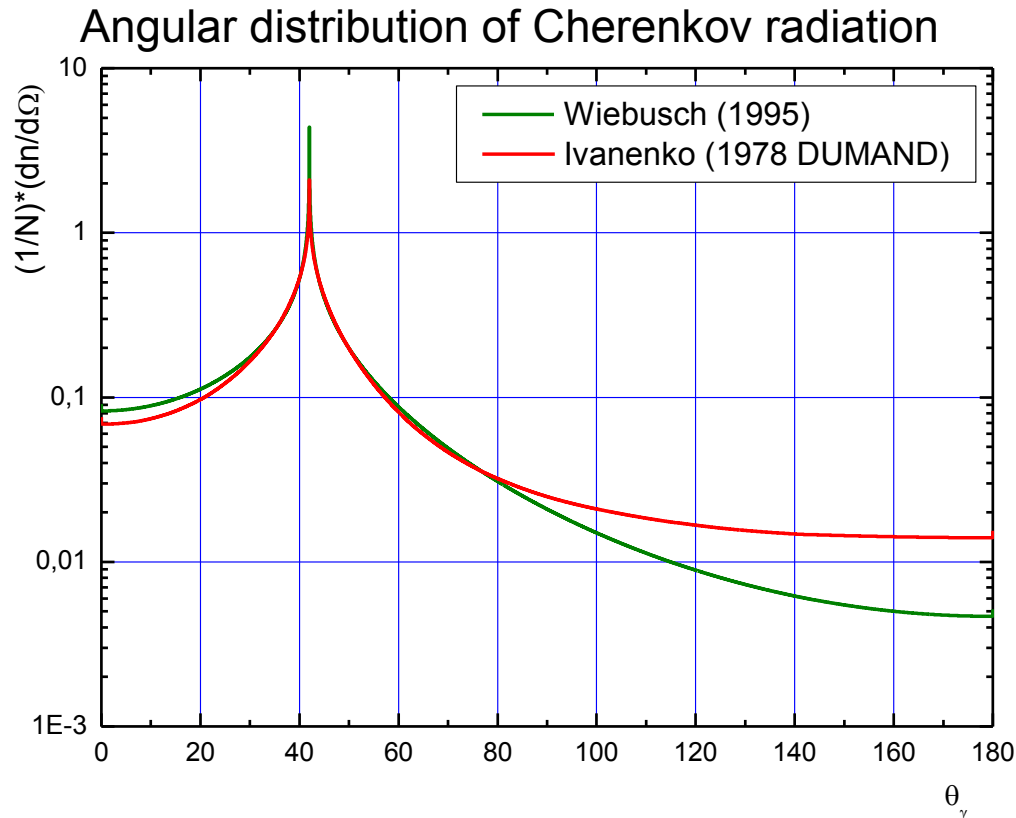
The width of the profile increases with distance from the axis of the shower

Models of scattering of cascade particles

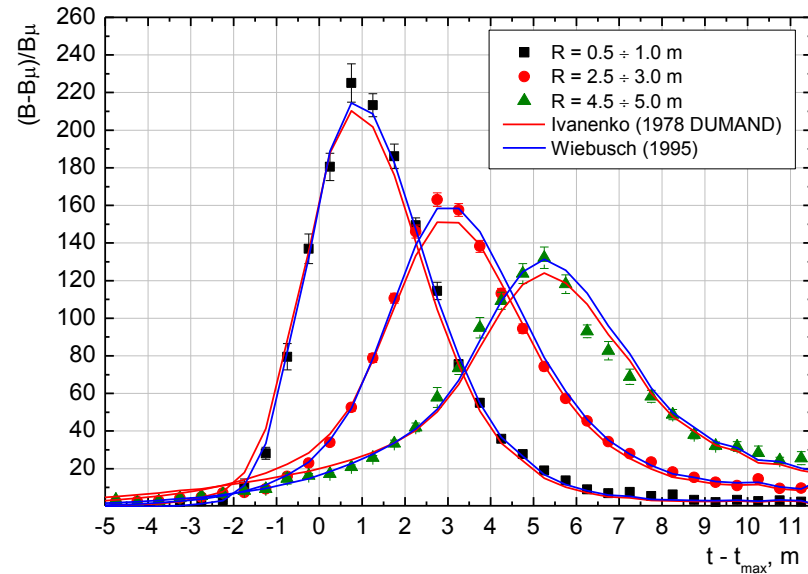
1. Analytical solution of cascade equations

(*I.P. Ivanenko et al. / Proc. of the 1978 DUMAND Summer Workshop*).

2. Approximation (*M.G. Aarsten et al. / Nucl. Instr. and Meth. in Phys. Res. A711, 2013*) of results of modelling in GEANT 3 (*C.H. Wiebusch / Ph.D. Thesis, Physikalische Institute, RWTH Aachen, 1995*).

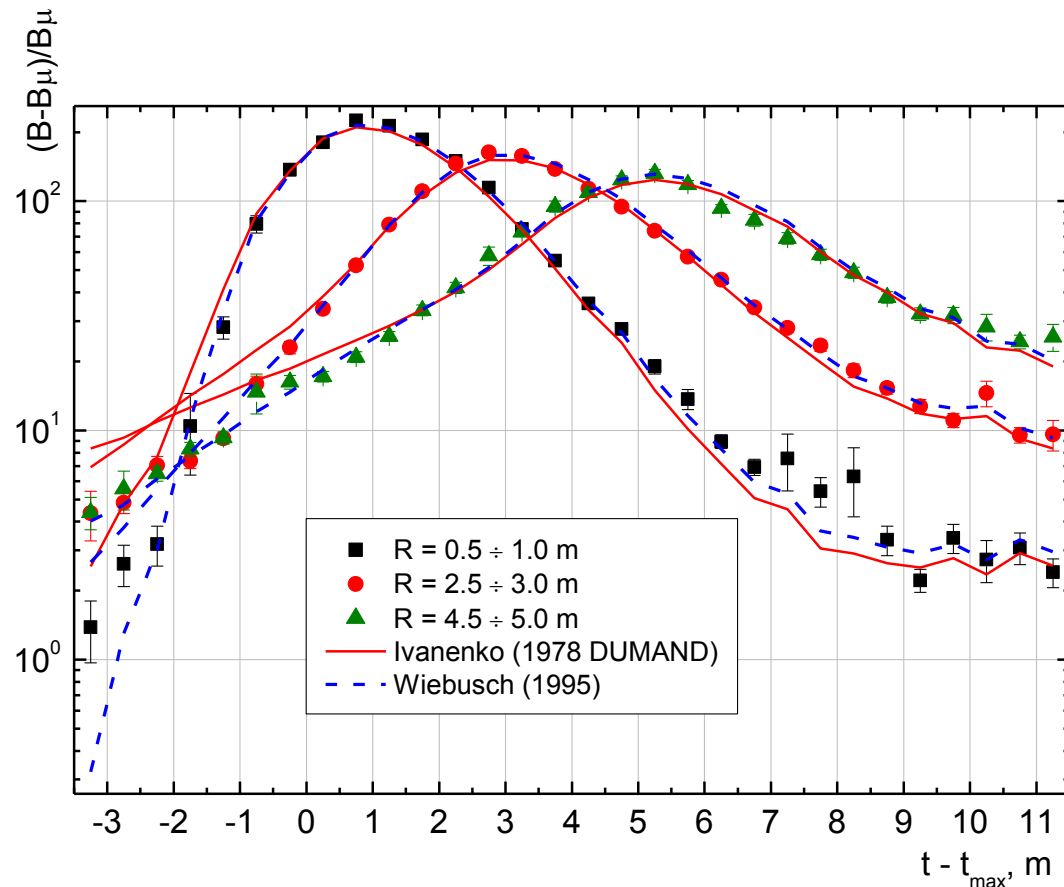


Comparison between experimental data and calculations



In the area of cascade maximum both models are in satisfactory agreement with experiment.

On the rising part of the profile (distribution of light in the back hemisphere) the model of Wiebusch is preferable.



Method of reconstruction of parameters of cascade showers

Reconstruction procedure:

- least square method;
- Iterative search with 6 parameters
- 30 QSM with maximum responses are used.

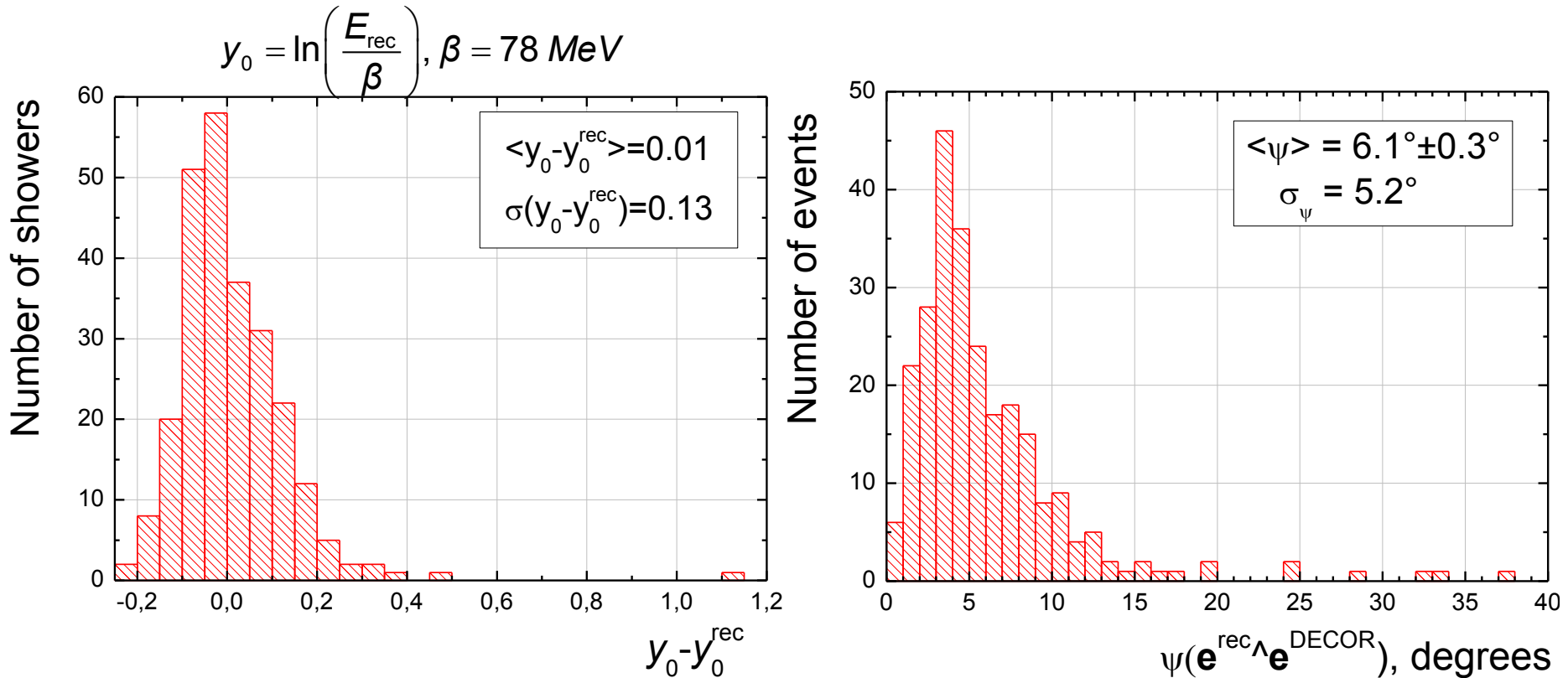
Initial estimations (based on data of QSMs with maximum responses):

- energy – based on summary response of group of such QSMs;
- position – the center of gravity of group of QSMs (weighted with responses);
- Direction of axis – based on the responses of PMTs on such group of QSMs.

Calculation of QSM response:

- Number of cascade particles on the depth of shower – **Greizen approximation** in approach B;
- Angular distribution of cascade particles – **Wiebusch model**;
- Response of QSM on the single muon – **based on experimental data**.

The accuracy of reconstruction (on the basis of cascades with known axes)

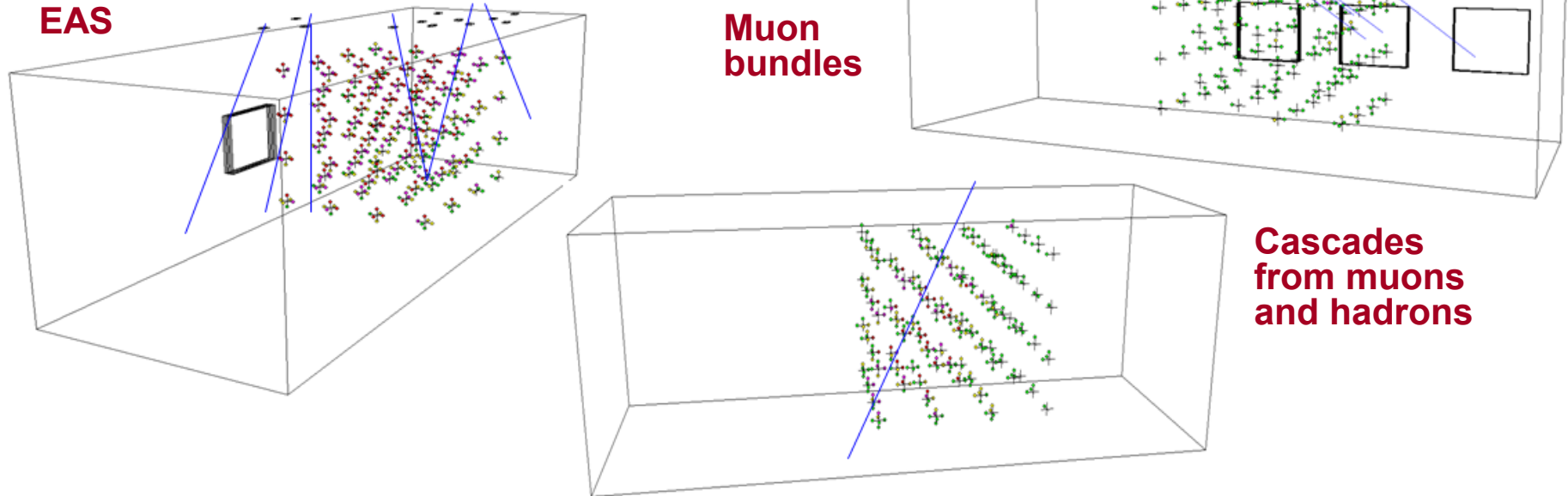


Estimated errors of the reconstructed parameters are:

- about 6° for direction of axis of cascade shower;
- about 13% for energy ($\varepsilon > 100 \text{ GeV}$)

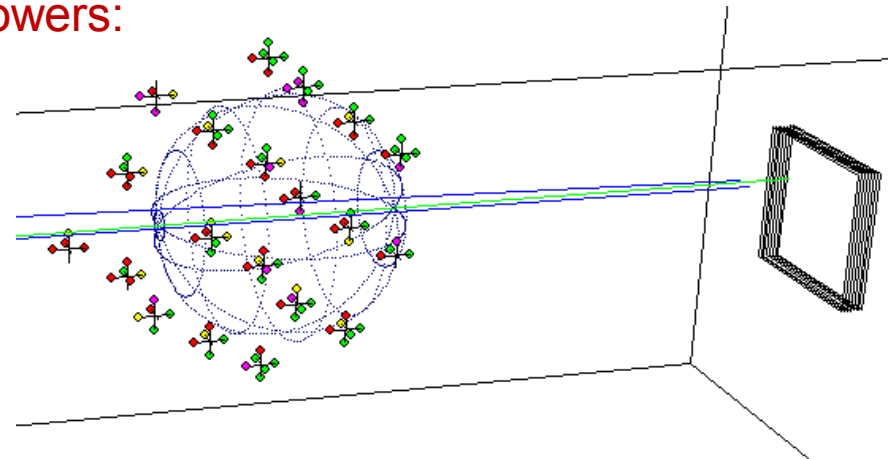
Events with high energy deposit in the lattice of CWD

Trigger « $\geq 60C$ ». Such events include:



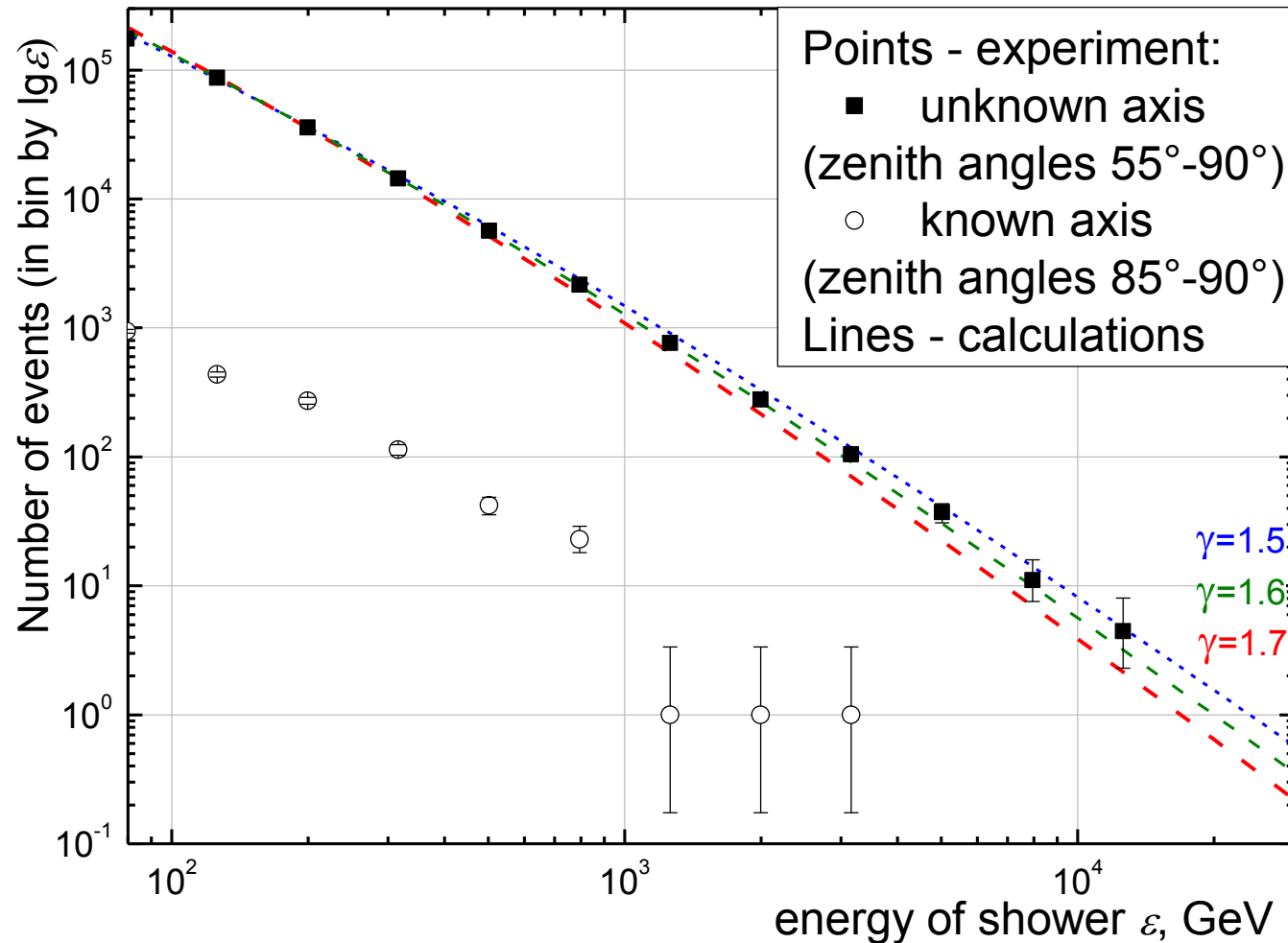
Main criterion for selection of cascade showers:

Compactness of cluster of QSMs with maximum responses
(the root mean square radius of such cluster < 2.35 m).



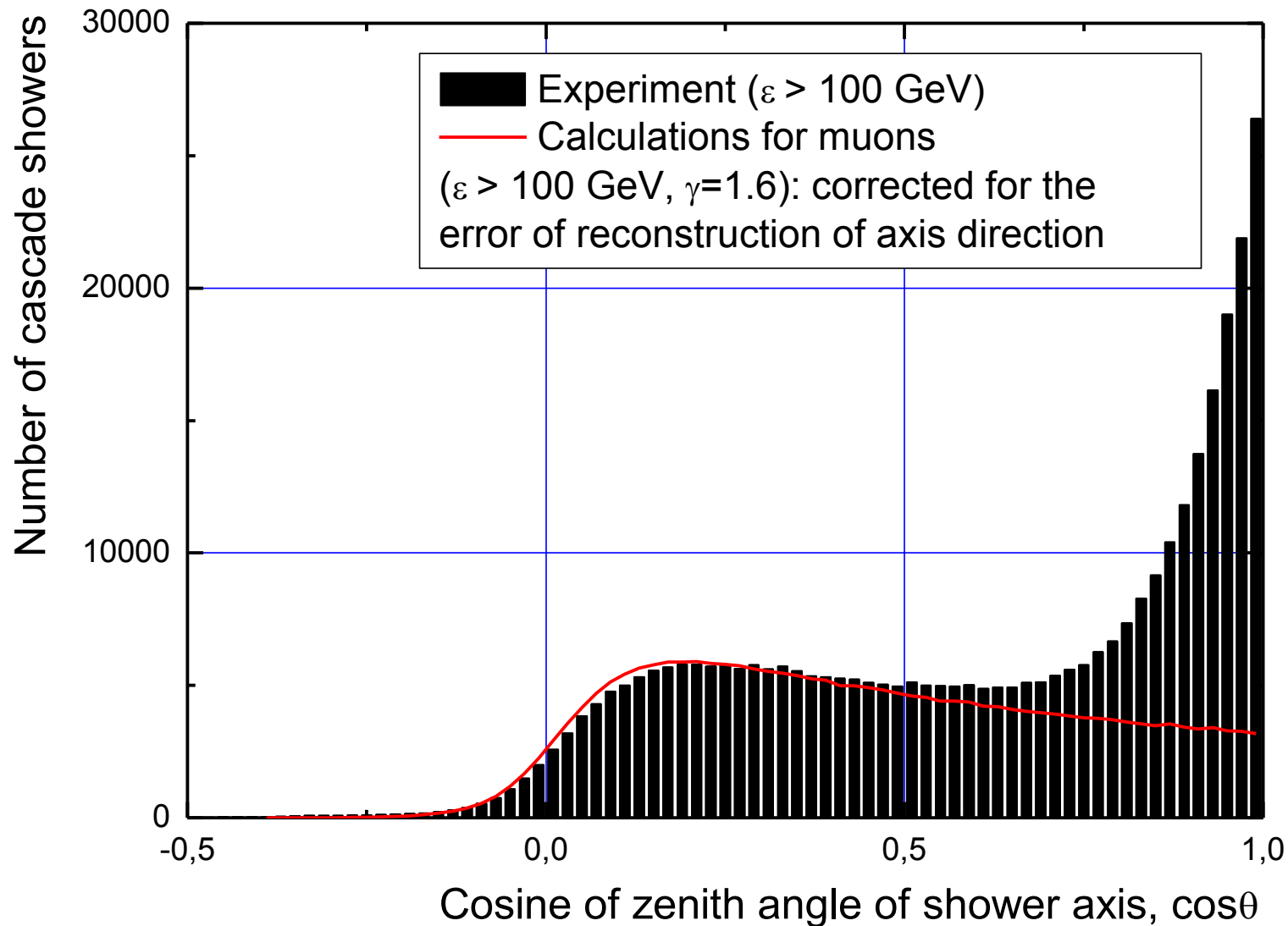
Differential energy spectrum of cascade showers with energies greater than 100 GeV

About 150 thous. of events with reconstructed energy > 100 GeV

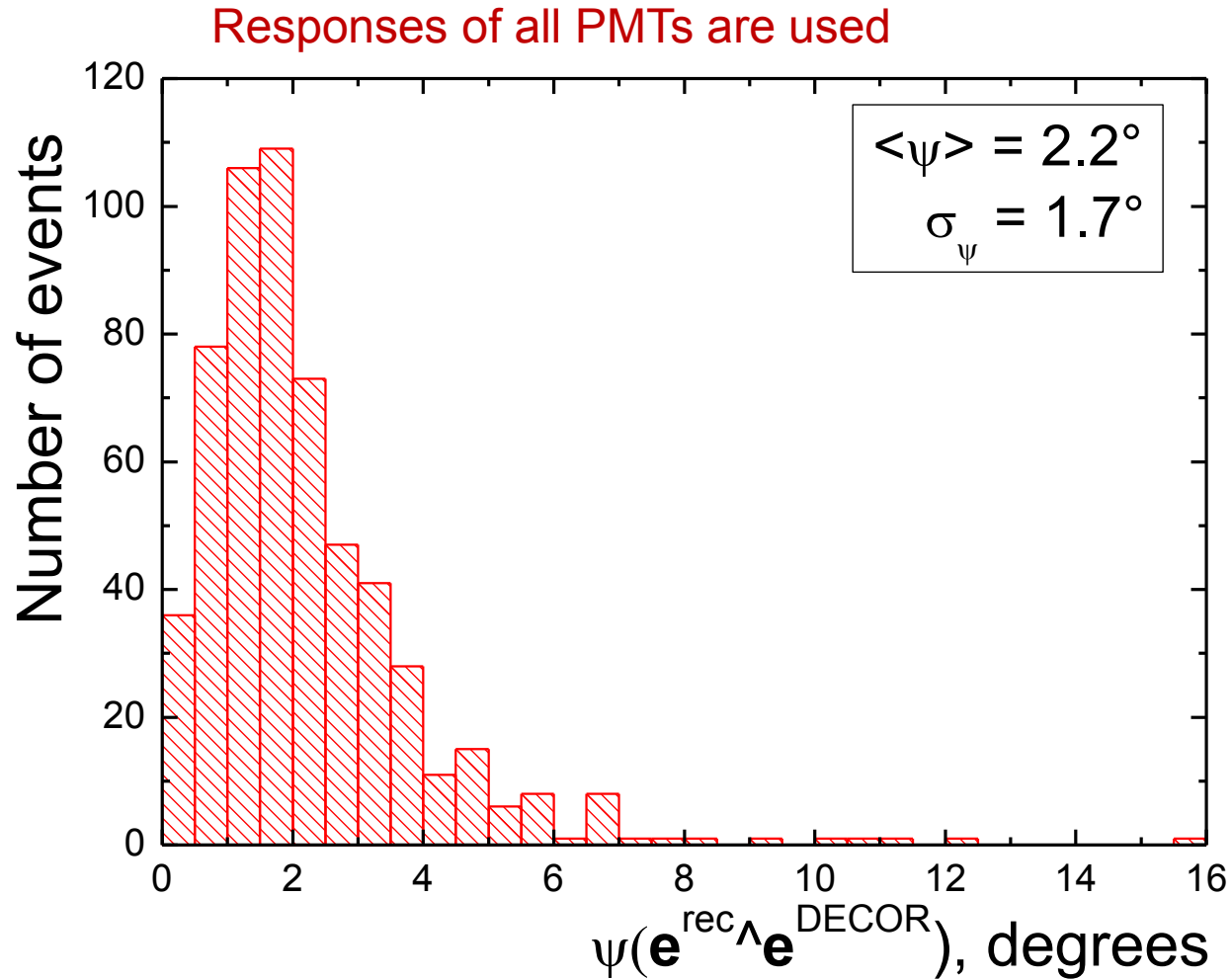


Estimated value of degree of integral spectrum of generation of pions and kaons $\gamma \sim 1.6$

Zenith angular distribution of experimental events with cascade showers



Improved reconstruction of axis of the cascade shower



Conclusions

- For the first time, the spatial distribution of Cherenkov light from cascade showers generated by muons in water has been experimentally measured at NEVOD CWD with a dense lattice of measuring modules.
- The models of angular distribution of the cascade particles are verified experimentally.
- Obtained results are used for development of criteria of selection of cascade showers in Cherenkov water detectors and for reconstruction of their parameters.

Thank you for your attention!

