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Energy spectrum and mass composition of the primary cosmic rays based on the intensity of muon bundles detected in the NEVOD-DECOR experiment

A.G. Bogdanov[1], A. Chiavassa[2,3], D.M. Gromushkin[1], S.S. Khokhlov[1], V.V. Kindin[1], K.G. Kompaniets[1], A.Yu. Konovalova[1], K.I. Mannanova[1], G. Mannocchi[4], A.A. Petrukhin[1], G. Trinchero[3,4], I.Yu. Troshin[1], I.A. Shulzhenko[1], V.V. Shutenko[1], V.S. Vorobev[1], I.I. Yashin[1], E.A. Yurina[1]

[1] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Russia
[2] Dipartimento di Fisica Dell' Universit'a Degli Studi di Torino, Italy
[3] Sezione di Torino Dell' Istituto Nazionale di Fisica Nucleare – INFN, Italy
[4] Osservatorio Astrofisico di Torino – INAF, Italy

E-mail: agbogdanov@mephi.ru

Annotation

The results of the analysis of the NEVOD-DECOR data on the study of inclined muon bundles ($\theta = 40° - 85°$) of cosmic rays for the period from 2012 to 2023 are presented.

The estimates of the energy spectrum and the behavior of the mass composition of primary cosmic rays in a wide energy range from 2×10^{15} eV to 3×10^{18} eV were obtained. They are compared with the data of other experiments.

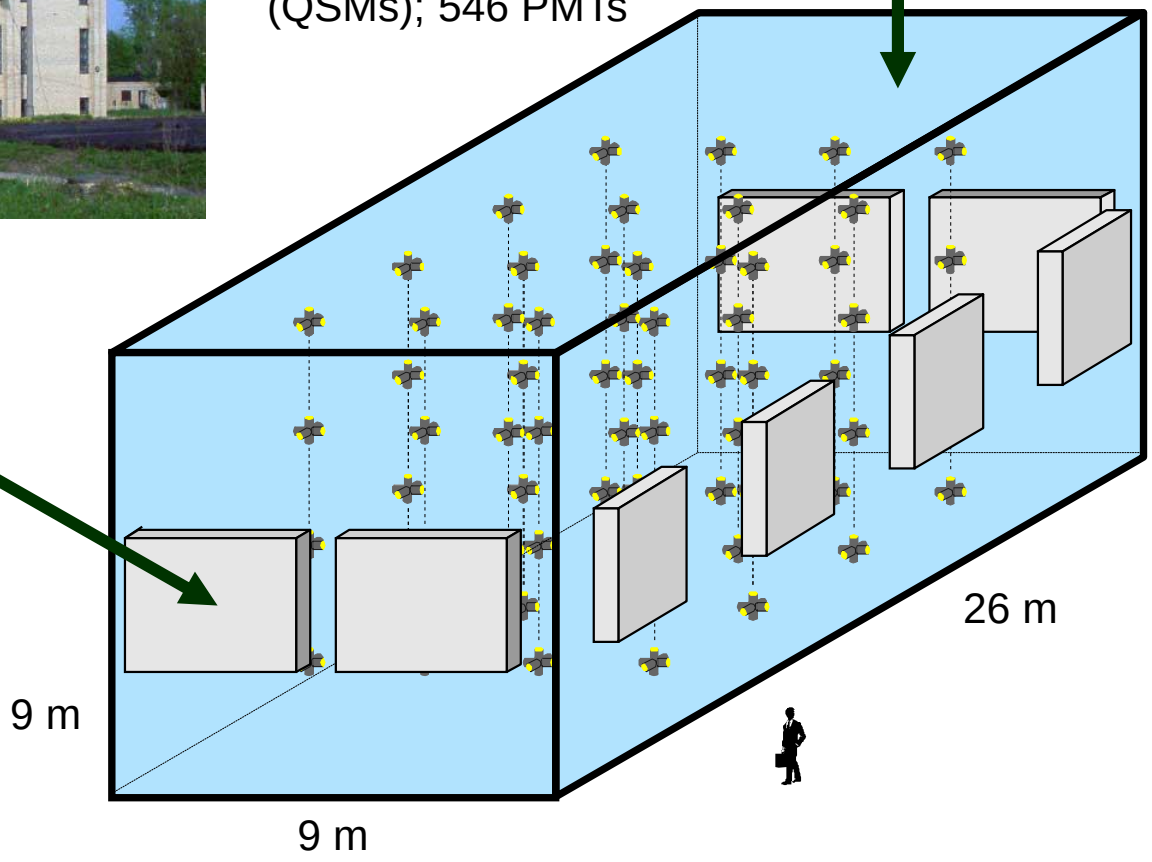
General view of the NEVOD-DECOR setup

Cherenkov water detector NEVOD (volume 2000 m³)

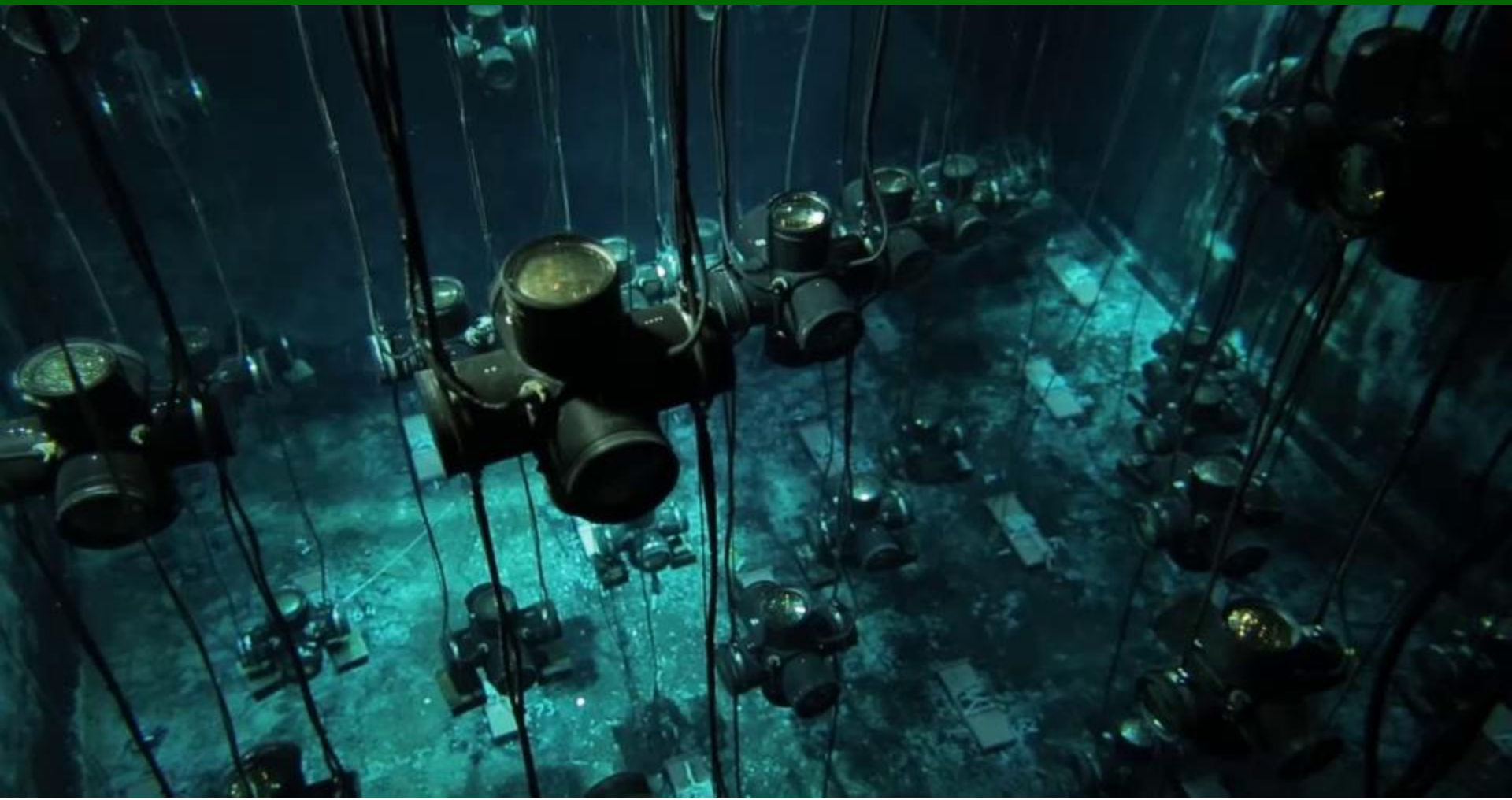
spatial lattice of 91 quasi-spherical measuring modules (QSMs); 546 PMTs

Coordinate-tracking detector DECOR (total area 70 m²)

8 vertical supermodules (SMs) of streamer tube chambers



Detecting system of Cherenkov water calorimeter NEVOD



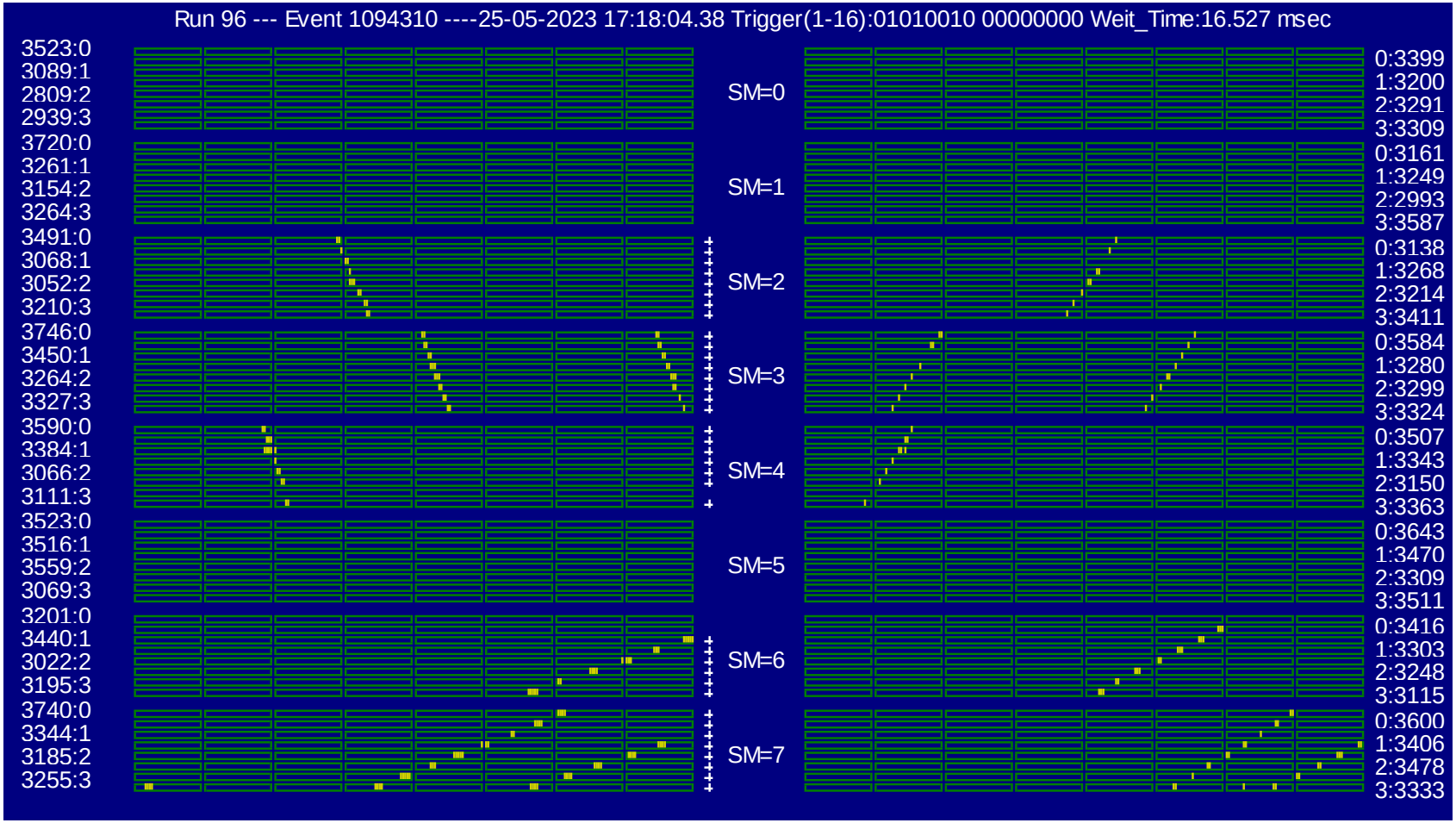
91 QSMs are arranged in an array of 25 vertical strings. Each QSM consists of 6 PMTs with flat photocathode directed along rectangular coordinate axes. A wide dynamic range (1 – 10^5 photoelectrons) allows to measure energy deposit of muon bundles.

DECOR SMs in the galleries around the NEVOD water tank

Each SM has an effective area 8.4 m^2 and consists of 8 vertical 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.

Typical event with muon bundle in DECOR supermodules

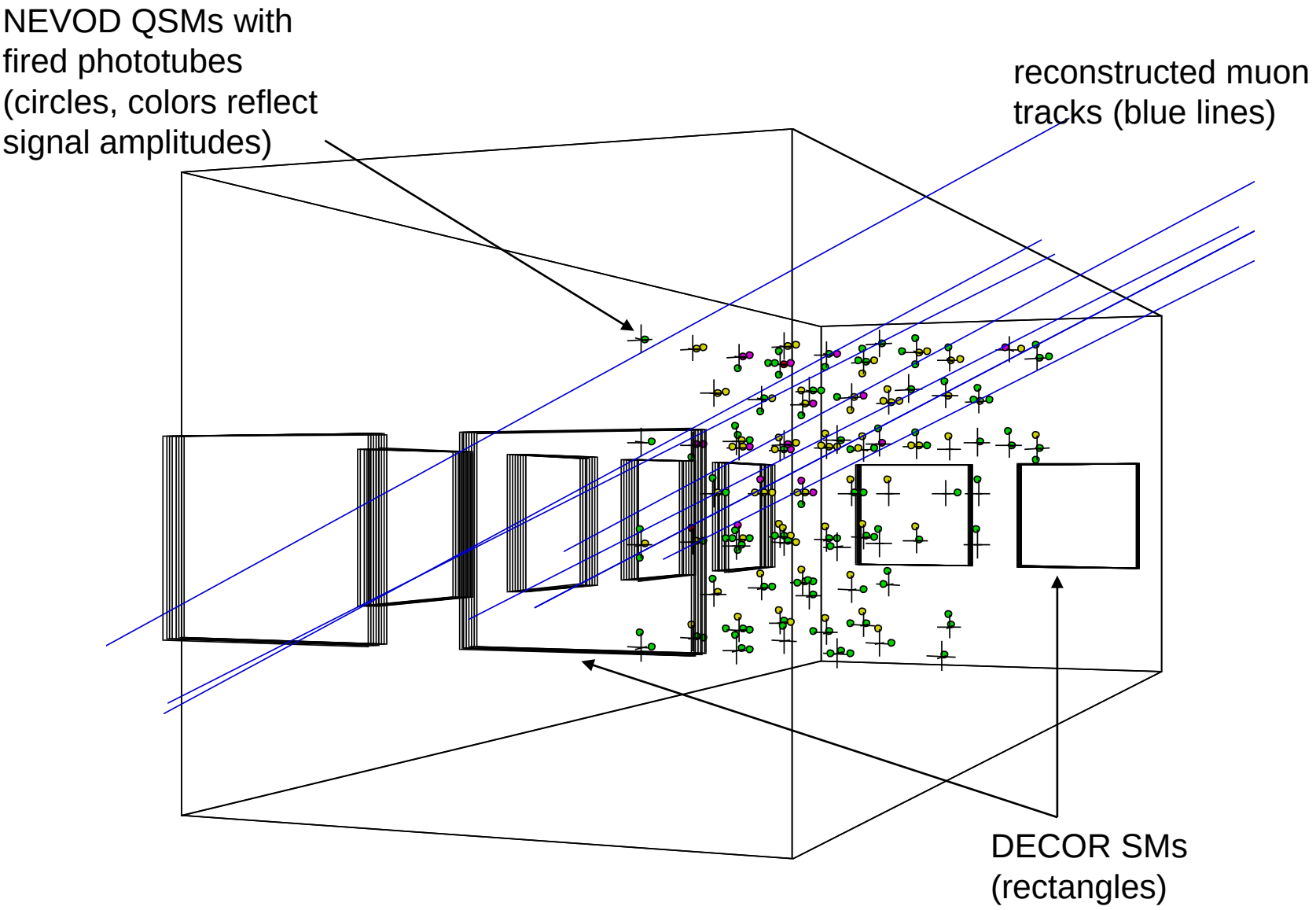
multiplicity m = 7 particles, zenith angle $\theta \approx 62°$



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

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

An example of geometry reconstruction of muon bundle event detected by the NEVOD-DECOR setup



NEVOD-DECOR experimental data

Experimental data accumulated from **May 2012** to **July 2023** are used:

multiplicity ***m*** ≥ **5** and zenith angles θ ≥ **55°** – **129173 events**
(“live” observation time is 75 238 h);

and **additionally,**

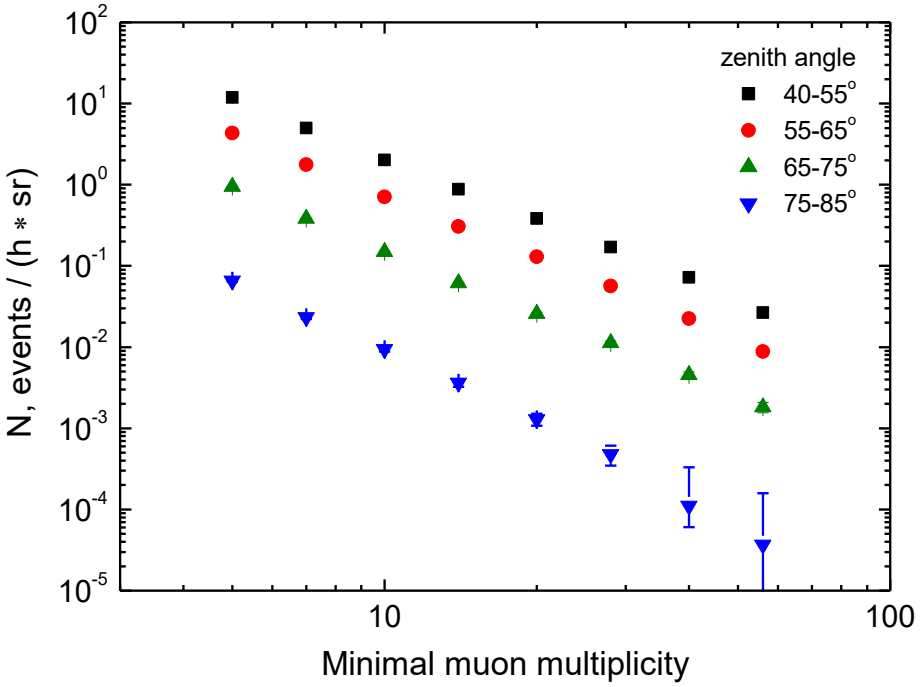
m ≥ **5**, **40°** ≤ θ < **55°** – **30 375 events** (“live” time is 6 324 h),
m = **4**, **40°** ≤ θ < **55°** – **4 130 events** (“live” time is 1 043 h).

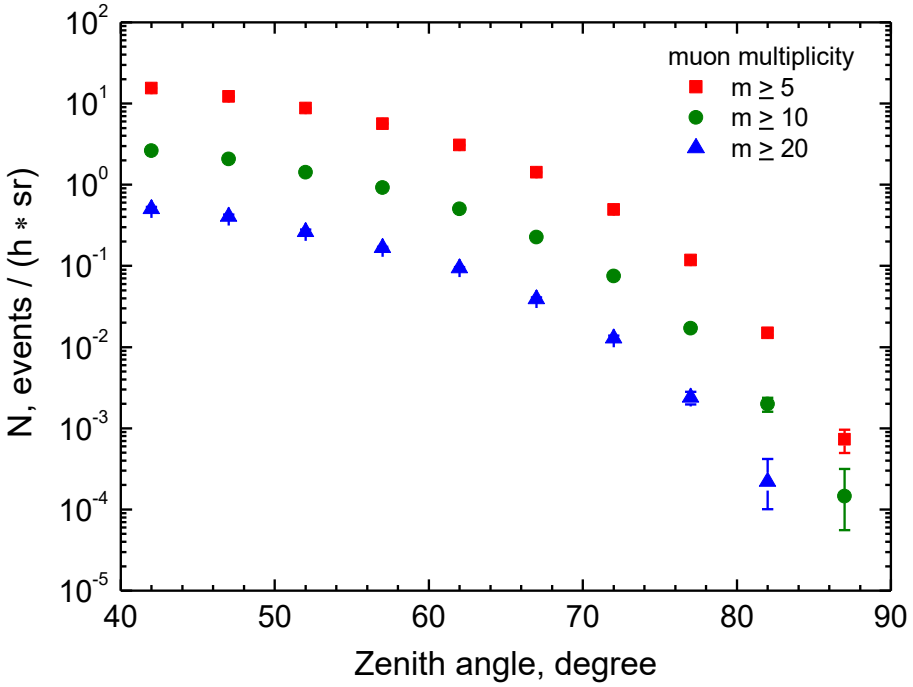
two sectors of azimuthal angles are used (φ = 105-165° and φ = 195-255°) – six of the eight DECOR SMs are shielded by the water volume of the NEVOD

The procedure for selecting events:

- hardware selection of 3-fold coincidences of signals from different SMs within a time gate of 250 ns;
- software selection and reconstruction of candidate events containing quasi-parallel tracks within a 5° cone;
- final classification of events and visual track counting by several operators.

Multiplicity and angular distributions of muon bundles

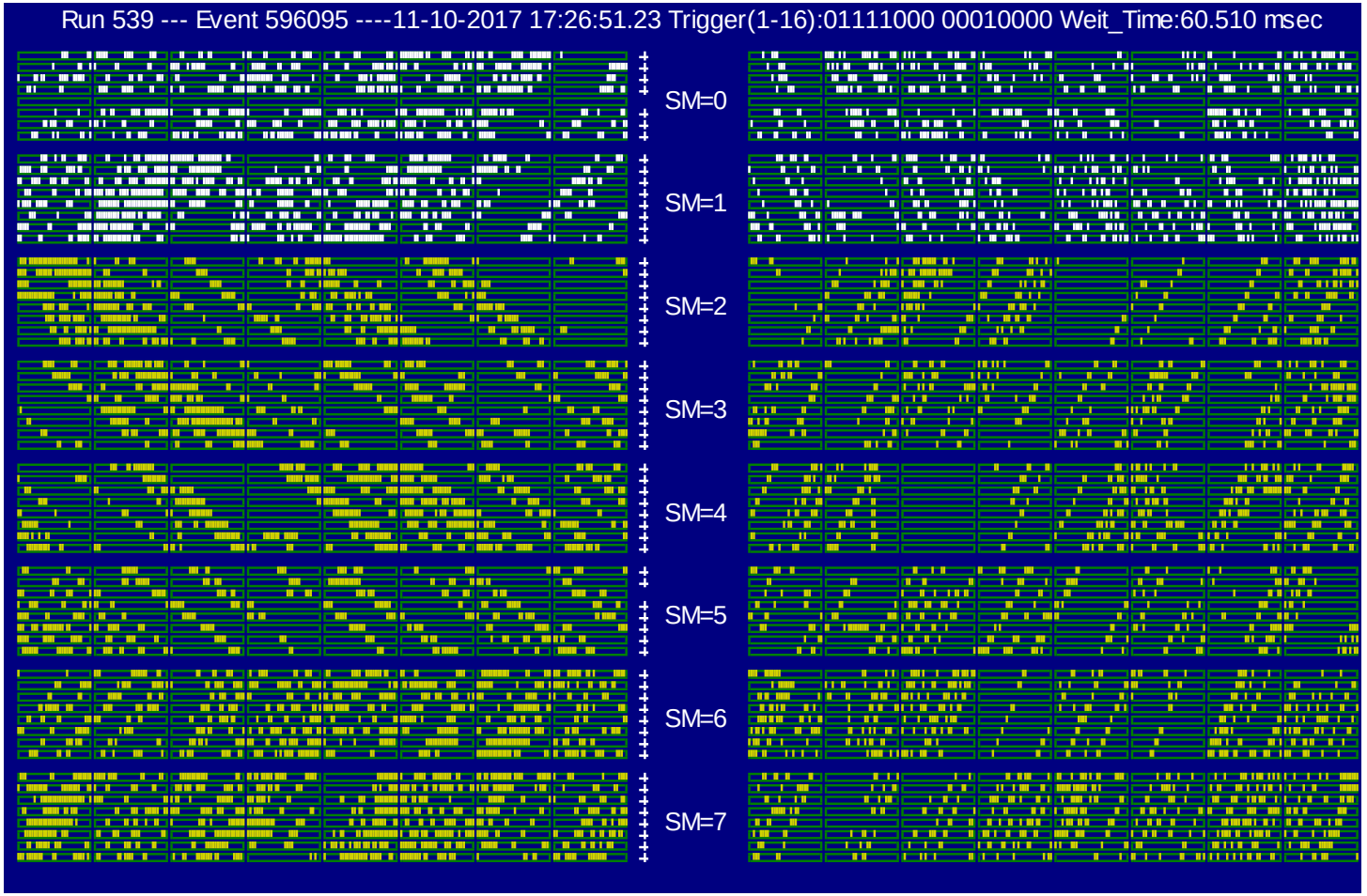




Data embrace the range of about 5 orders of magnitude in the event intensity.
From these data, local muon density spectra have been reconstructed.

Record-breaking multi-muon event (with large multiplicity) detected by the NEVOD-DECOR setup

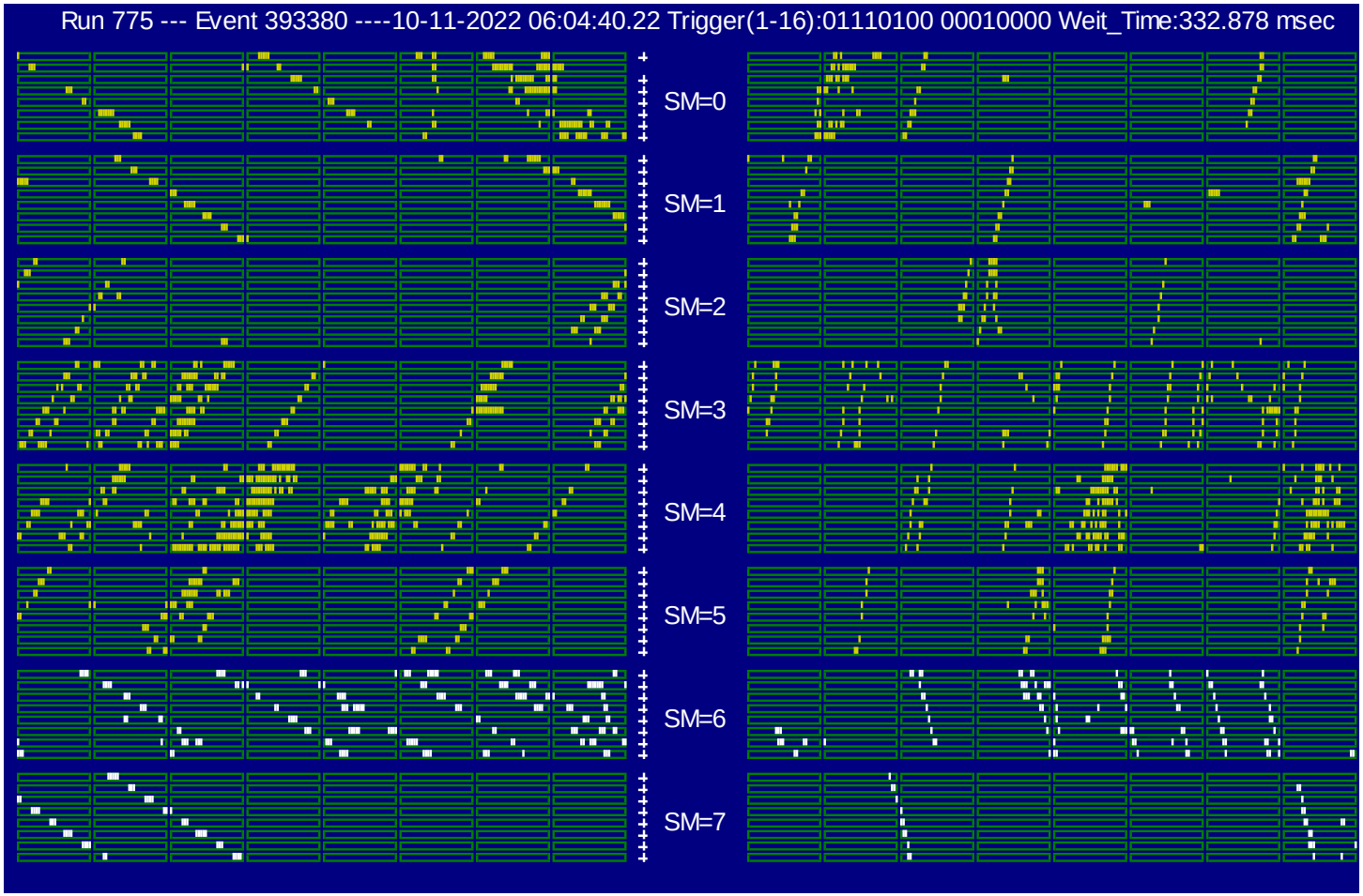
multiplicity m = 124 particles, zenith angle $\theta \approx 75°$, $E_0 \approx 7 \times 10^{18}$ eV



Y-coordinate *X-coordinate*

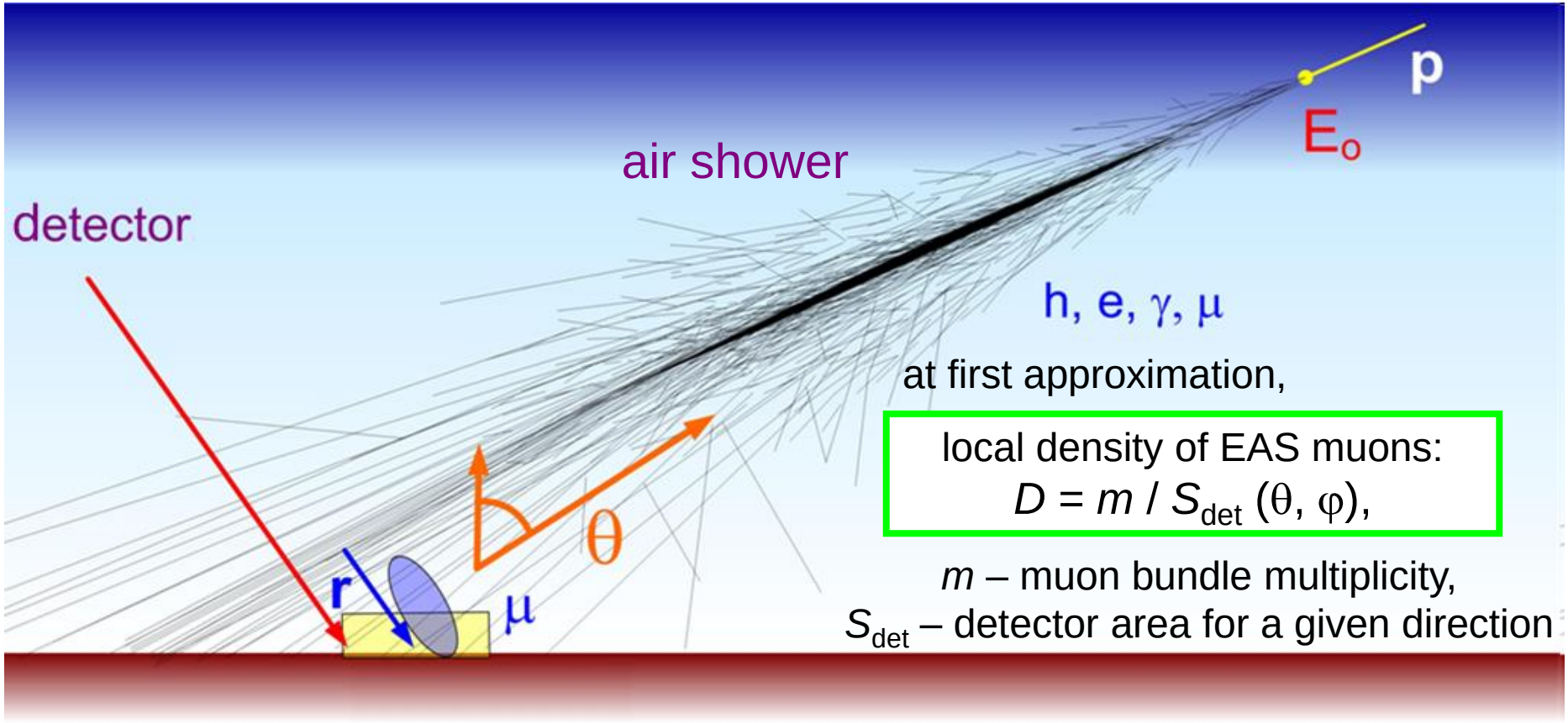
Record-breaking multi-muon event (with large zenith angle) detected by the NEVOD-DECOR setup

multiplicity m = 33 particles, zenith angle $\theta \approx 84°$, $E_0 \approx 4 \times 10^{19}$ eV



Y-coordinate *X-coordinate*

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



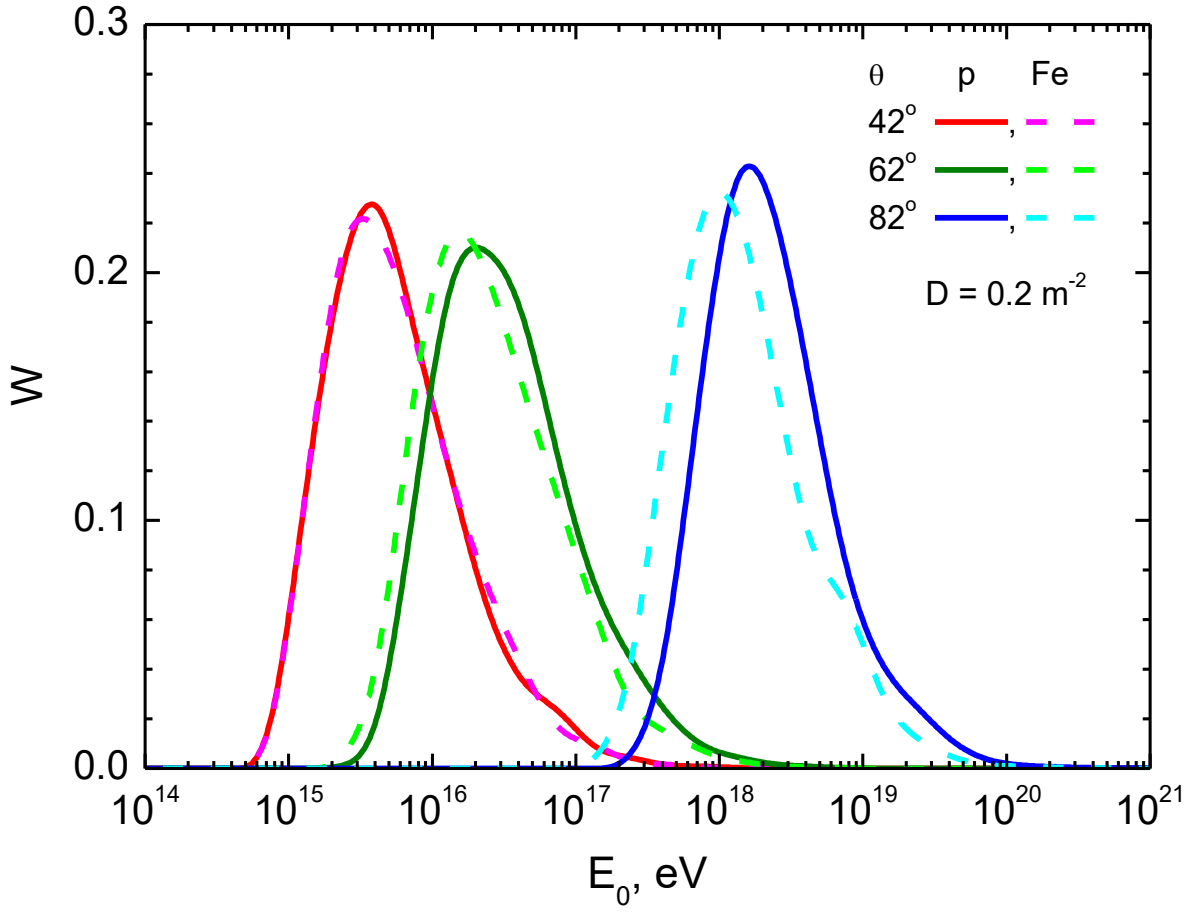
at first approximation,

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.

Distribution of primary cosmic ray particle energies contributing to events with a fixed muon density at different zenith angles



At the same muon density, different zenith angles correspond to substantially different (by the orders of magnitude) characteristic energies of primary cosmic ray particles contributing to the selected events, as the lateral spread of muons in bundles increases with zenith angle.

Этапы анализа данных по локальной плотности мюонов

Восстановление экспериментальных СЛПМ $dF(D,\theta)/dD$ из измеренных распределений характеристик событий $N(m,\theta,\varphi)$ с учетом геометрии, флуктуаций, эффективности регистрации, триггерных условий и т. д.

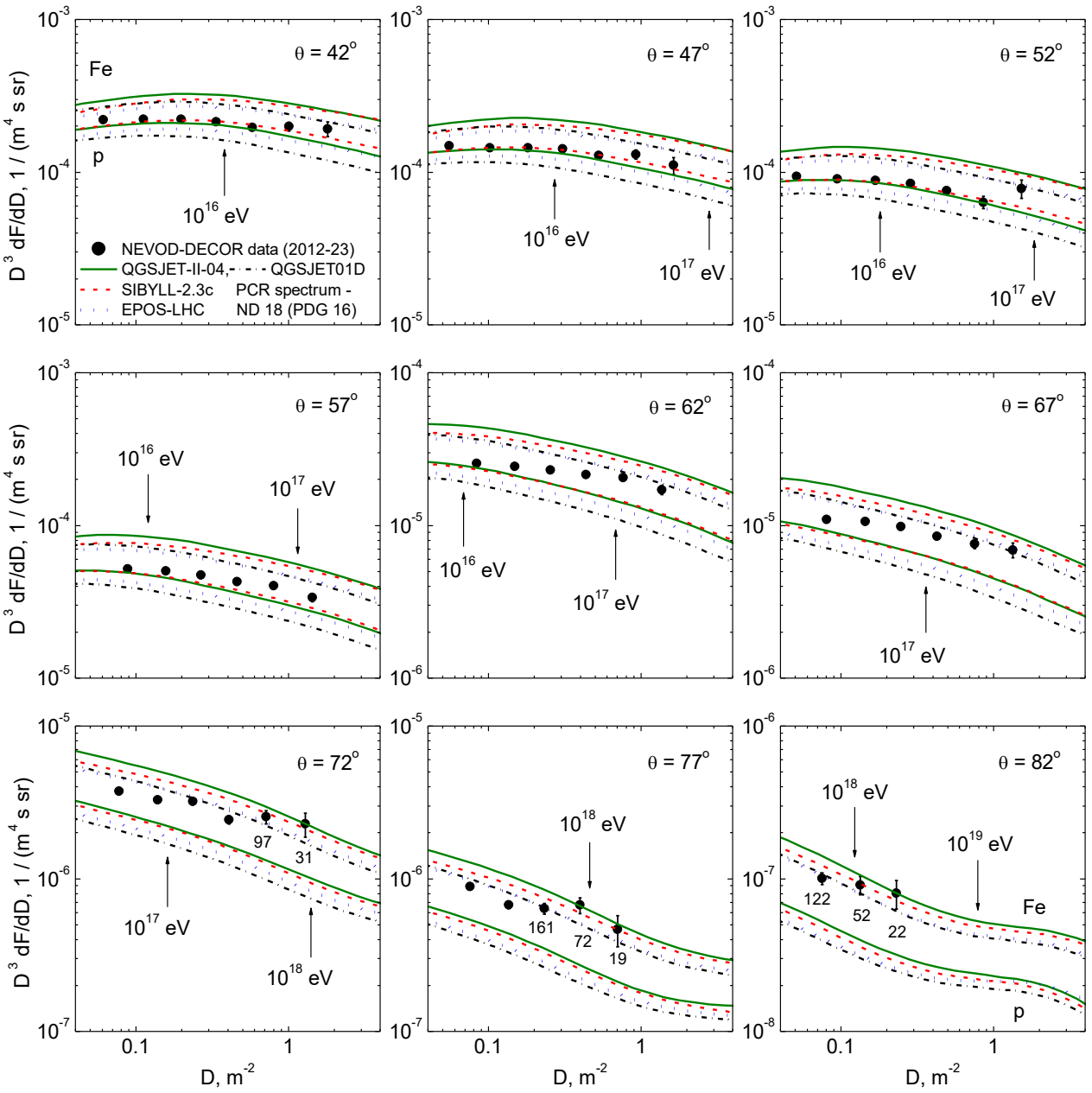
Получение расчетных СЛПМ в виде свертки модели энергетического спектра ПКЛ и функций пространственного распределения (ФПР) мюонов, которые вычисляются на основе моделирования ШАЛ с помощью программы CORSIKA для заданных энергий, зенитных углов, моделей адронных взаимодействий: EPOS-LHC, QGSJET-II-04, SIBYLL-2.3c (post-LHC) и QGSJET01D (pre-LHC) и предположений о массовом составе ПКЛ (p, Fe).

Сопоставление экспериментальных и расчетных СЛПМ.

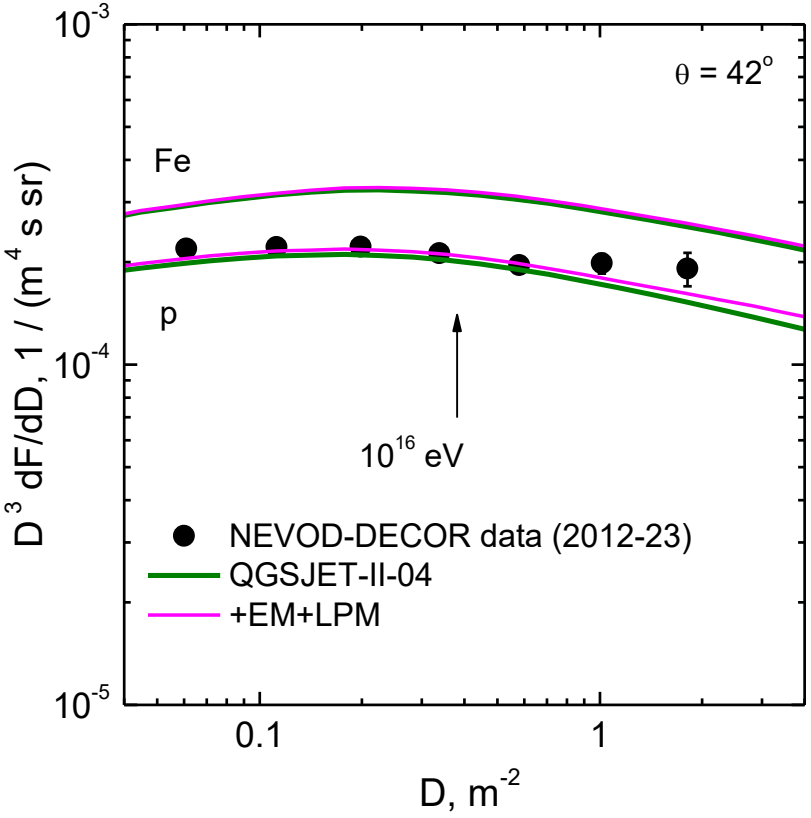
Differential local muon density spectra for different zenith angles

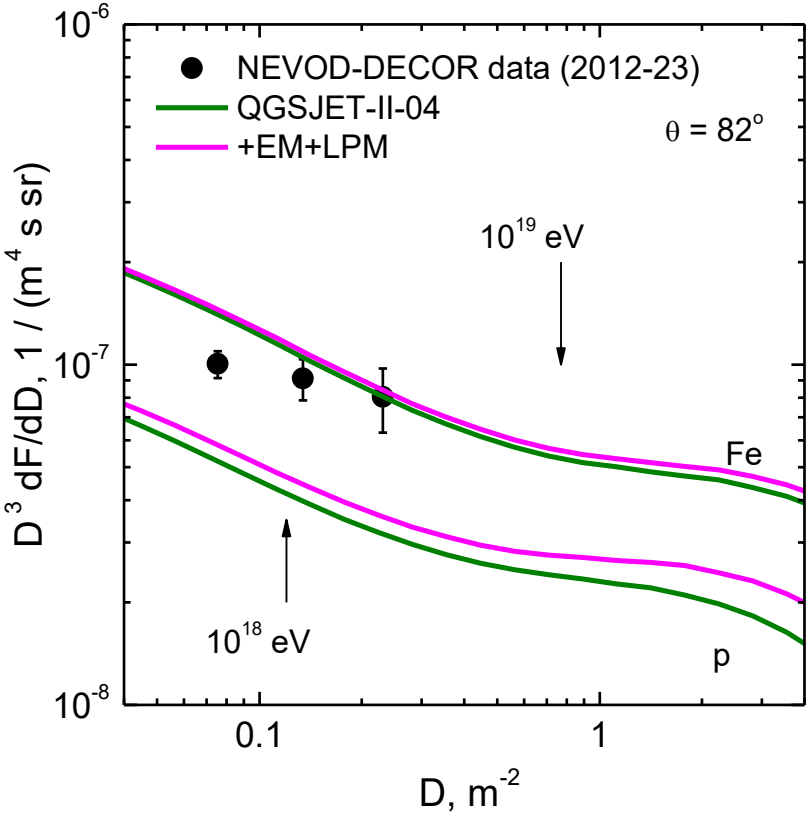
At the energies ~ 10^{16} eV experimental points are close to the results of the calculations for a light mass composition.

At the energy ~ 10^{18} eV, NEVOD-DECOR data and calculations are compatible only under the assumption of an extremely heavy mass composition.

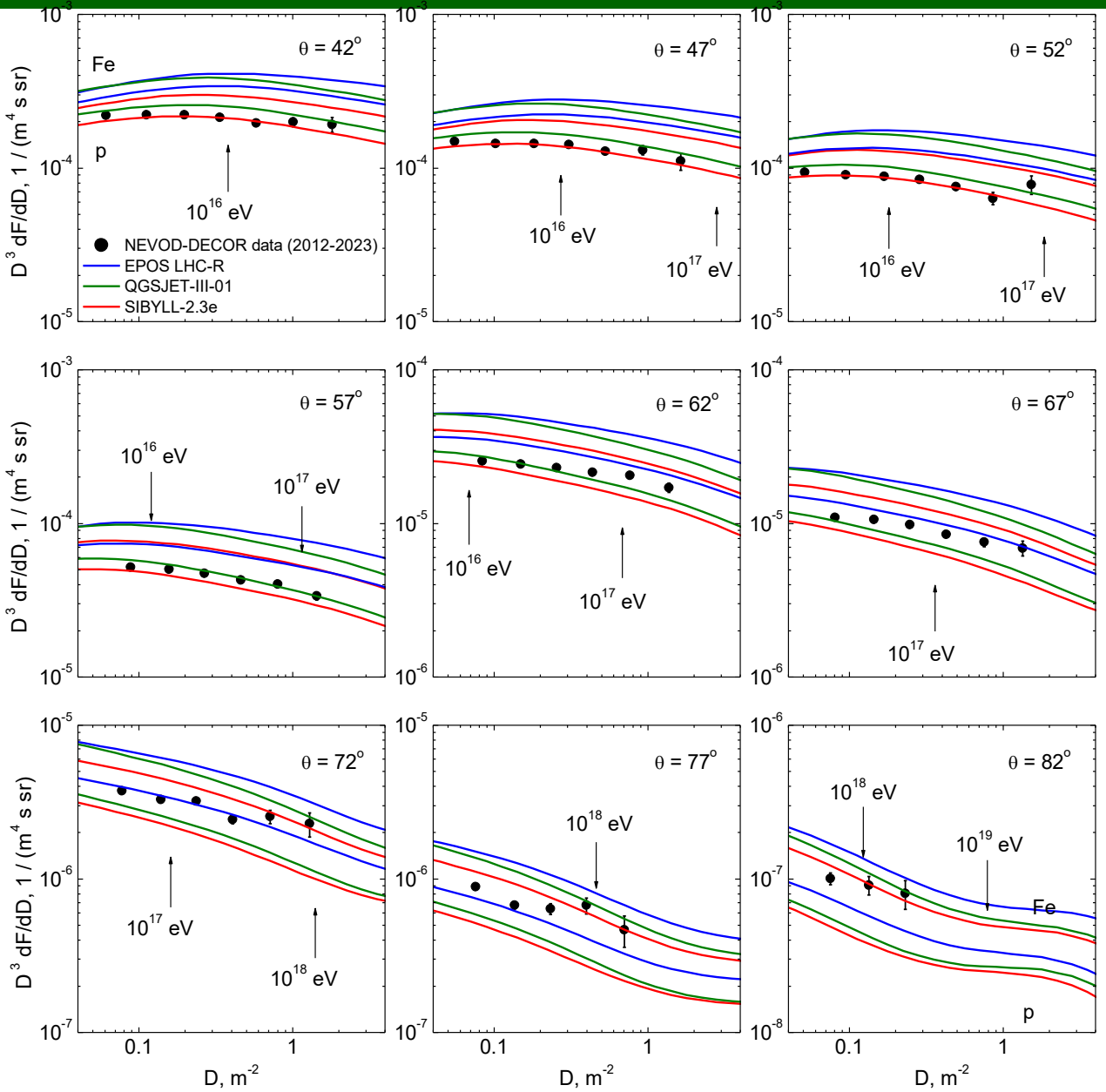


Влияние электронно-фотонной компоненты ШАЛ на СЛПМ





Экспериментальные СЛПМ и новые (2025) модели адронных взаимодействий (EPOS LHC-R, QGSJET-III, SIBYLL-2.3e)



Estimates of the primary cosmic ray energy spectrum

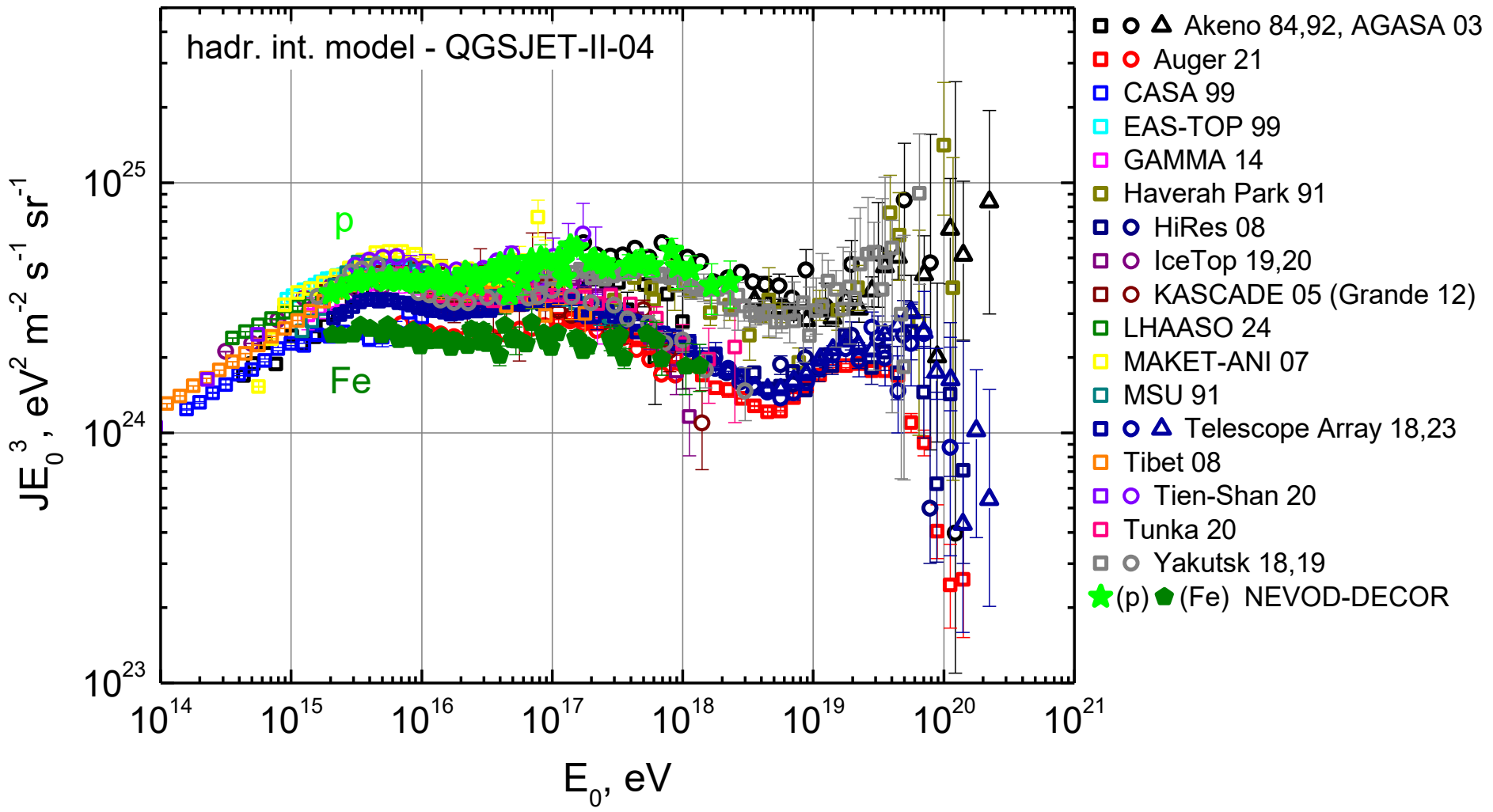
Muon bundles are part of the muon component of air showers, so their intensity can be directly recalculated to the intensity of the primary CR flux, but under certain assumptions about the mass composition and the hadronic interaction model.

Reconstruction of the differential CR energy spectrum from the experimental LMDS (for each zenith angle interval):

$$dJ/dE_0 = \left(dN/dE_0\right)_{\mathrm{mod}} \times \left[\left(dF/dD\right)_{\mathrm{obs}} / \left(dF/dD\right)_{\mathrm{sim}}\right]$$

where $(dN / dE_0)_{\mathrm{mod}}$ is the model of the CR spectrum,
$(dF / dD)_{\mathrm{obs}}$ is the experimental LMDS,
$(dF / dD)_{\mathrm{sim}}$ is the theoretical LMDS
(convolution of the muon LDF with the spectrum model).

The differential energy spectra of the primary CRs obtained from the intensity of muon bundles detected at the NEVOD-DECOR



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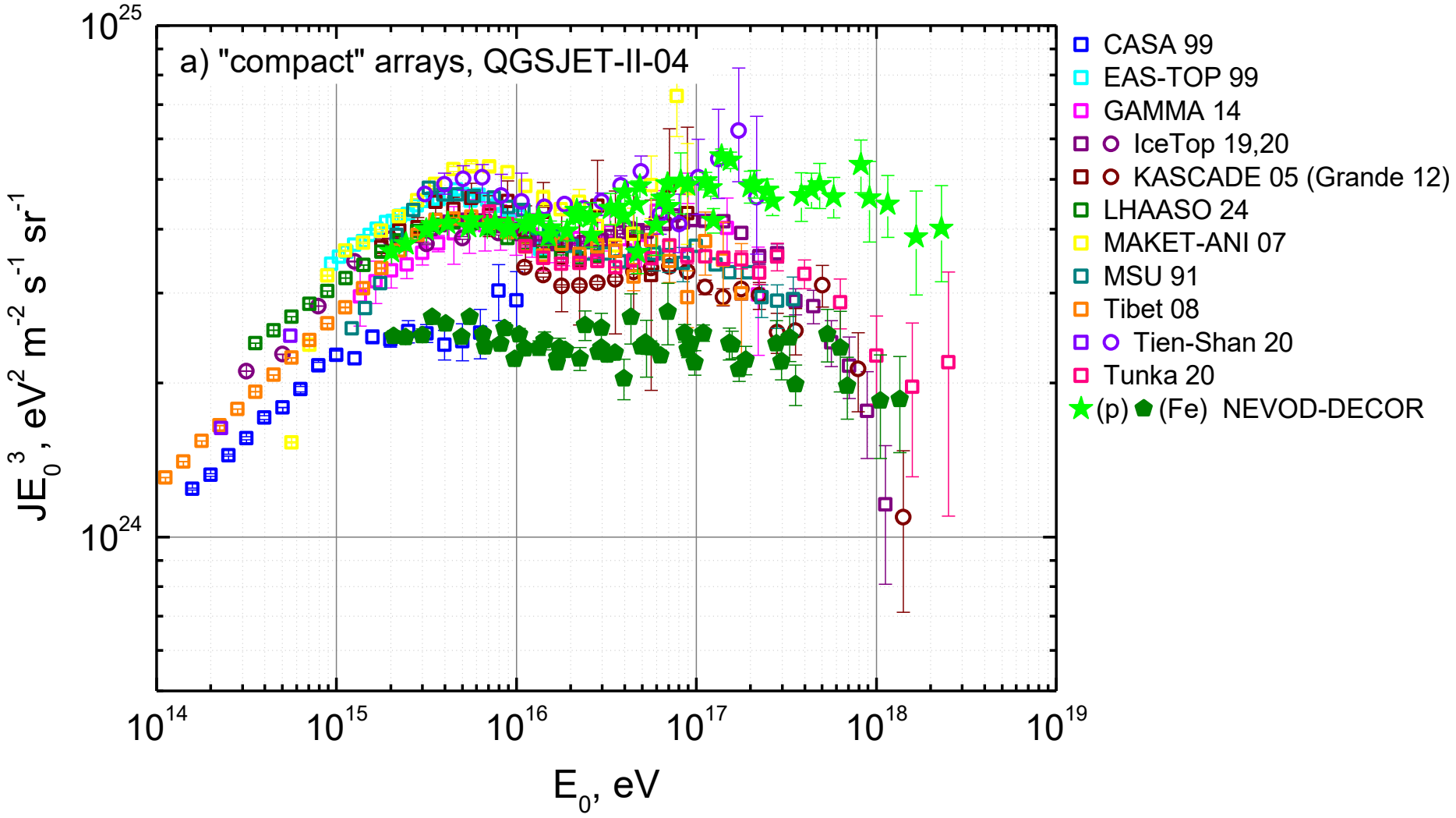

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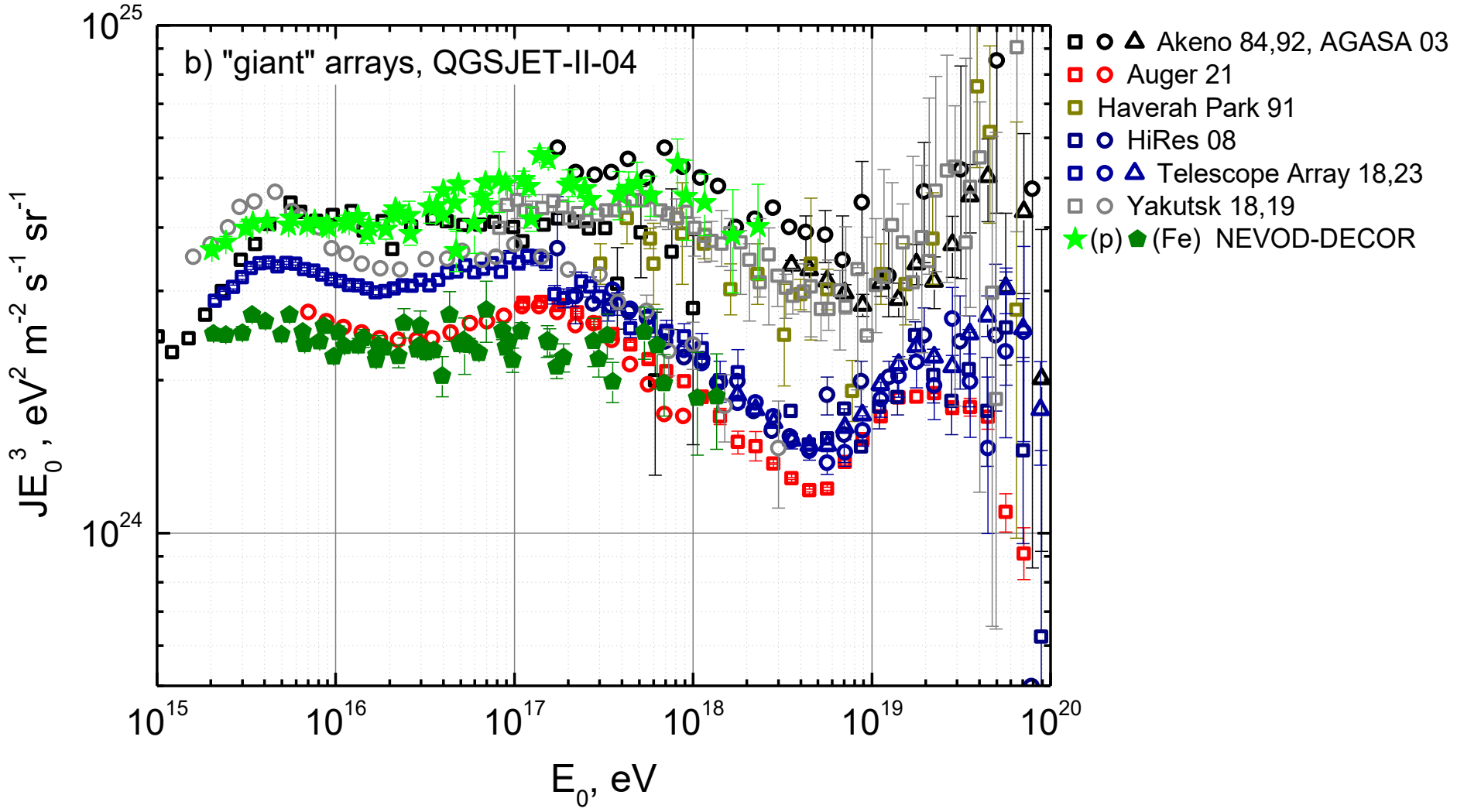
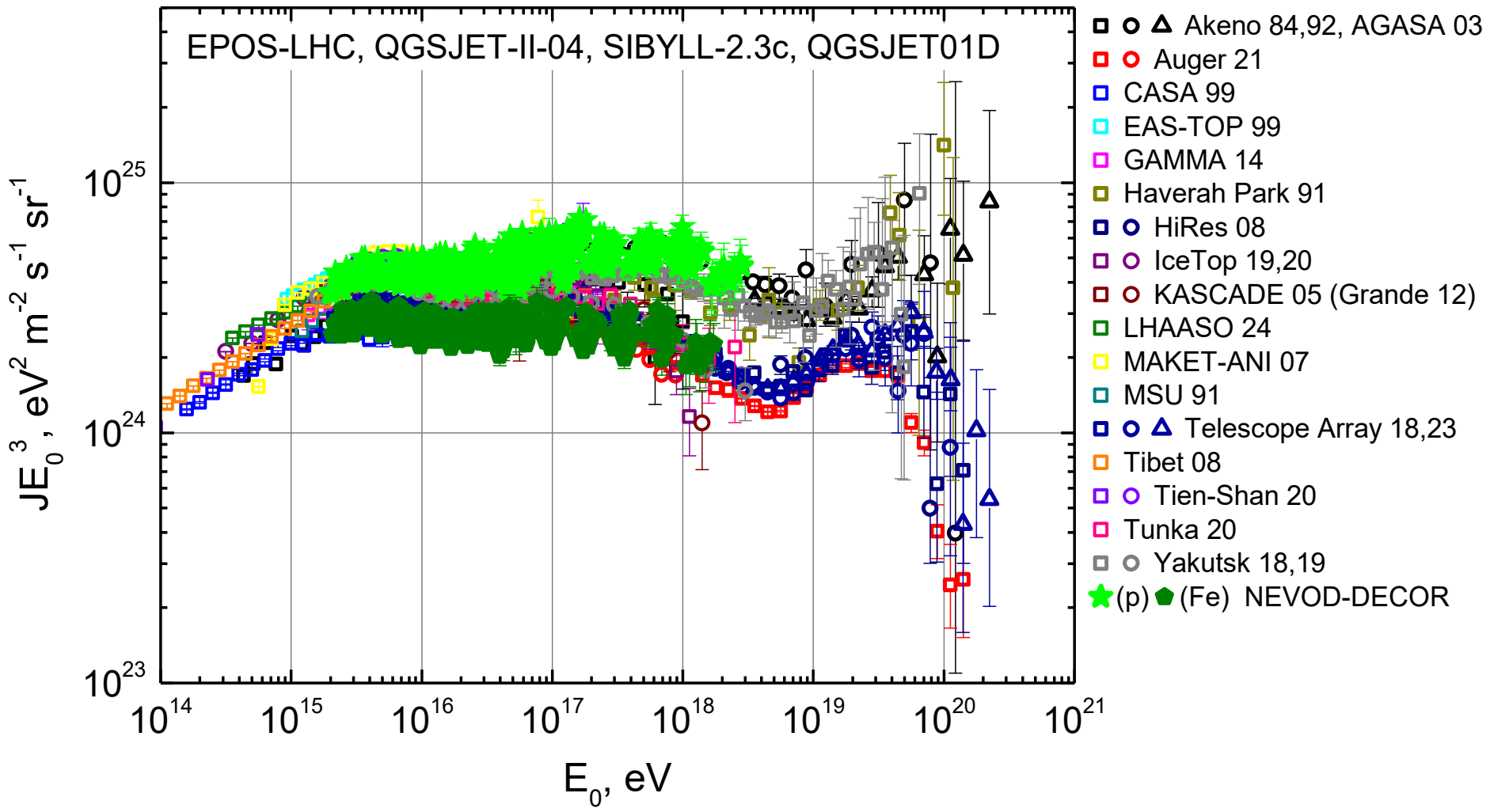


The differential energy spectra of the primary CRs obtained from the intensity of muon bundles detected at the NEVOD-DECOR



Behavior of the prinary cosmic ray mass composition

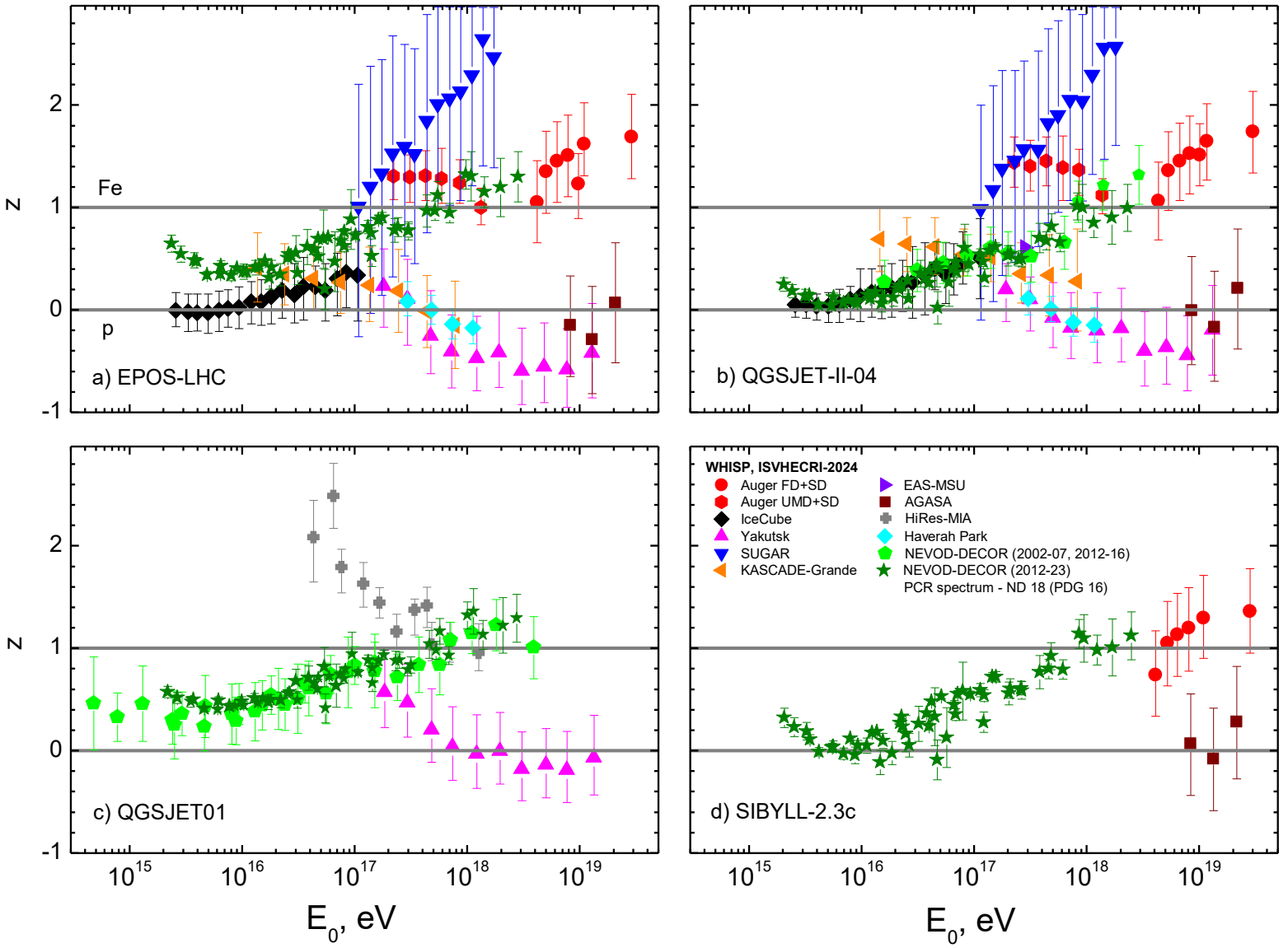
It is possible to estimate the behavior of the mass composition with a change of the primary CR energy using the NEVOD-DECOR data in the case of an a priori choice of a certain hadronic interaction model and energy spectrum model.

A convenient value that allows obtaining such estimates is the *z*-scale, which was proposed by WHISP:

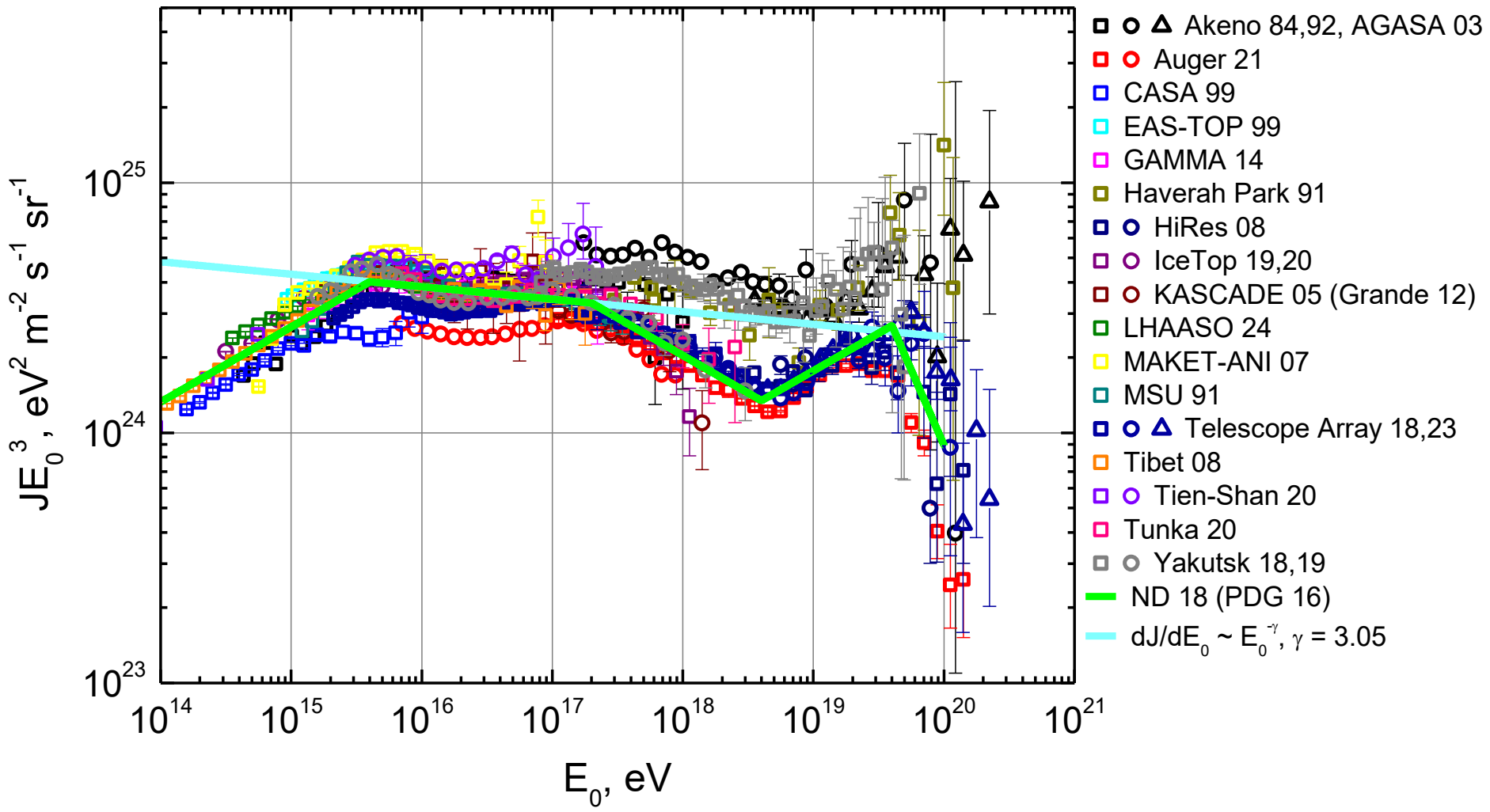
$$z = \left[\ln\left(N_{\mu}^{\text{det}} \right) - \ln\left(N_{\mu}^{\text{p sim}} \right) \right] \Big/ \left[\ln\left(N_{\mu}^{\text{Fe sim}} \right) - \ln\left(N_{\mu}^{\text{p sim}} \right) \right]$$

where N_{μ} is the observed value
(muon density, muon number, in our case LMDS, etc.),
$N_{\mu}^{\text{p sim}}$ and $N_{\mu}^{\text{Fe sim}}$ are the calculated estimates of this value for EAS formed by primary protons and iron nuclei
(z = 0 – only of protons, z = 1 – only iron nuclei).

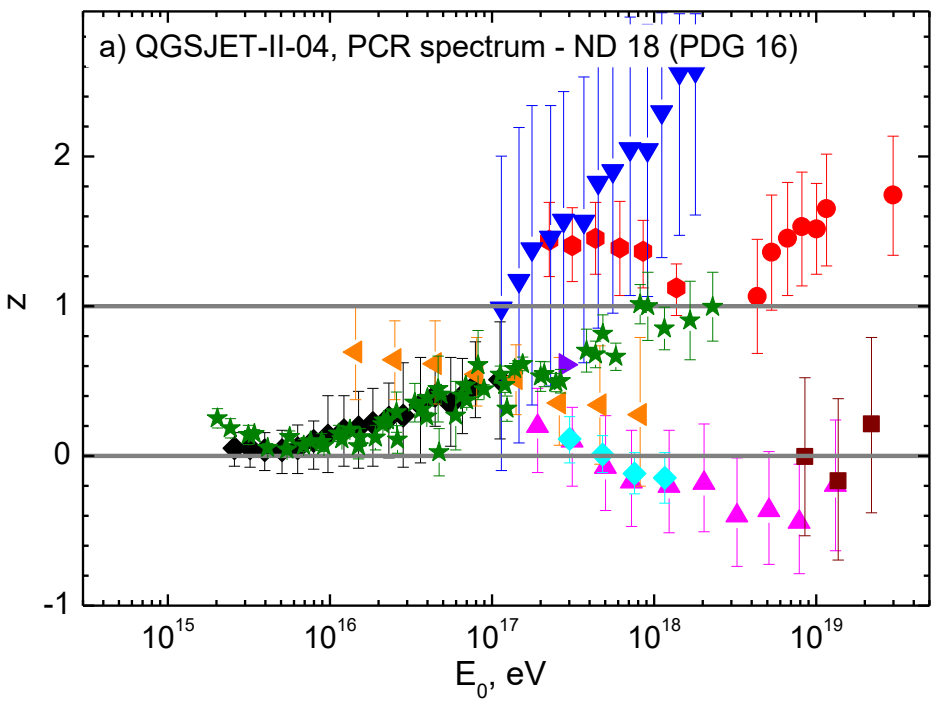
Comparison of new NEVOD-DECOR data by means of z-scale with muon measurements from other air shower experiments

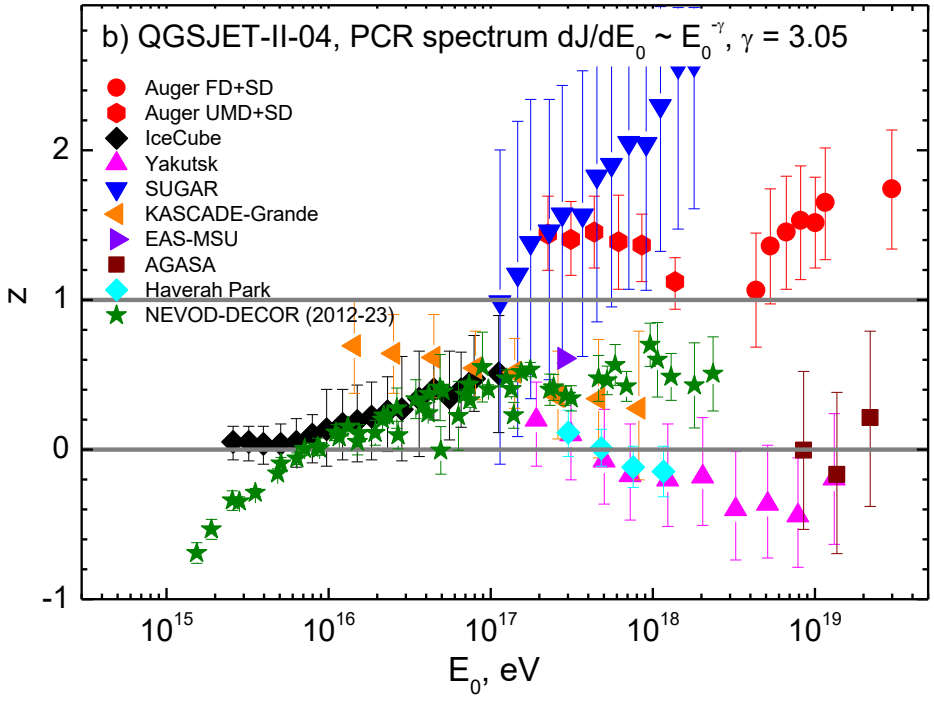


The all-particle spectrum (experiments and models)



Comparison of new NEVOD-DECOR data by means of z-scale with muon measurements from other air shower experiments





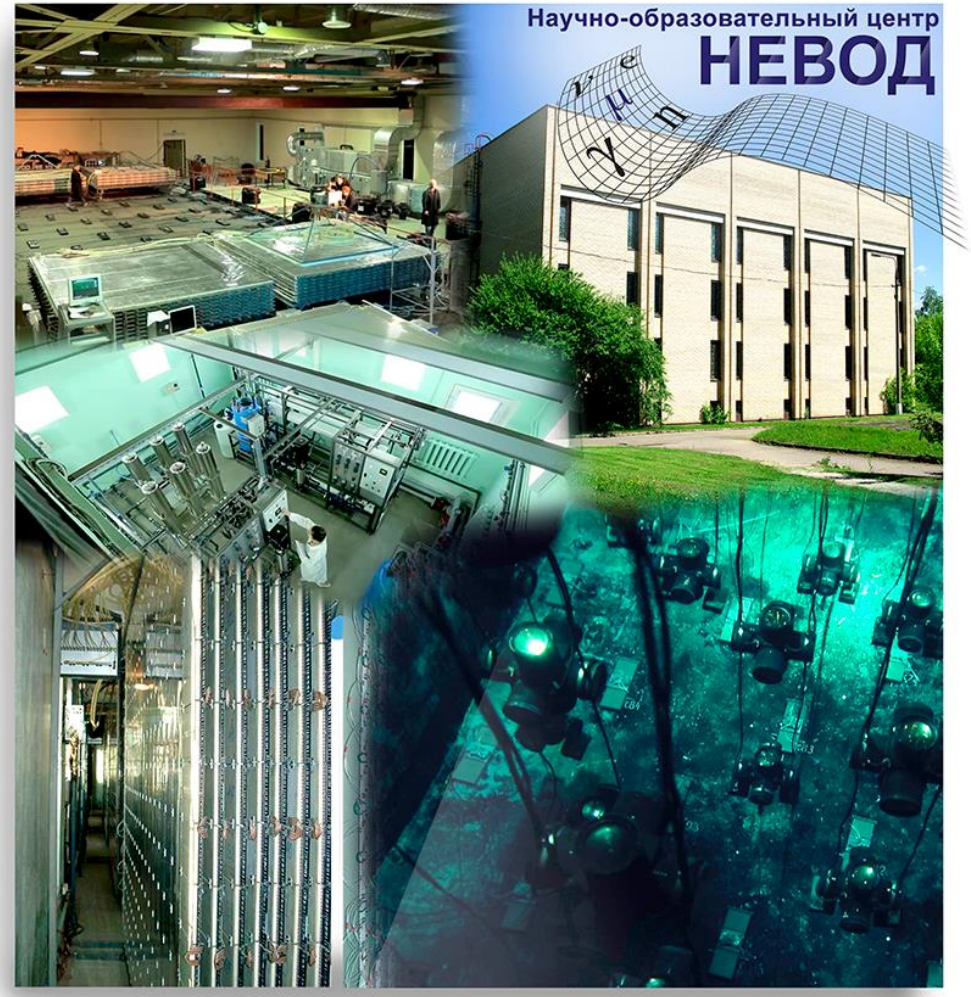
For interpretation of our data, assumption on the primary all-particle spectrum is necessary.

Conclusions

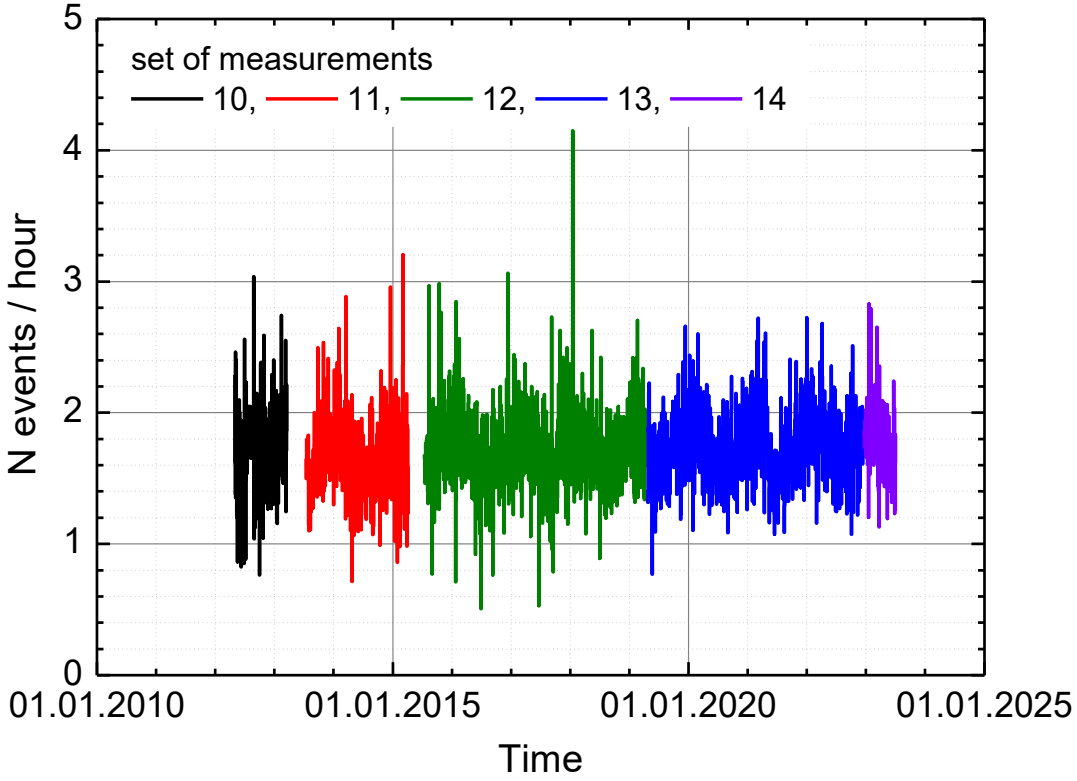
- A long-term experiment on the systematic study of muon bundles in a wide range of zenith angles in extensive air showers generated by primary cosmic rays with energies of 10^{15} – 10^{19} eV is being conducted at the NEVOD-DECOR setup. The mean energies of muons in bundles are hundreds of GeV.

- The experimental data on the muon bundles intensity allow us, within the LMDS method, to obtain estimates of the primary CR energy spectrum, making certain assumptions about the mass composition and the characteristics of hadronic interactions, as well as to study the behavior of the CR mass composition using the models of the energy spectrum and hadronic interactions.

Thank you for your attention!

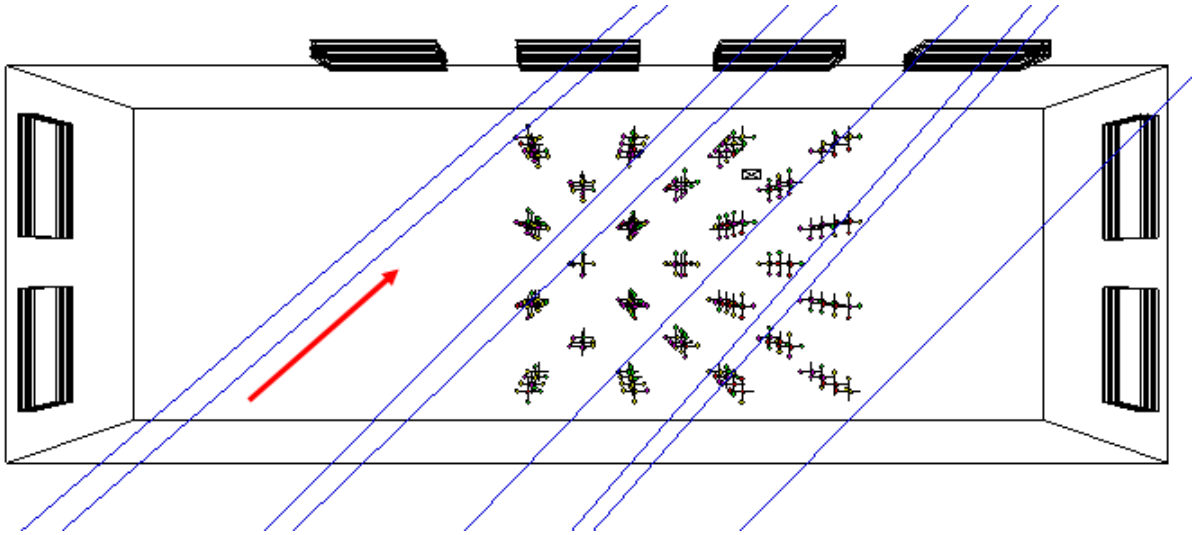


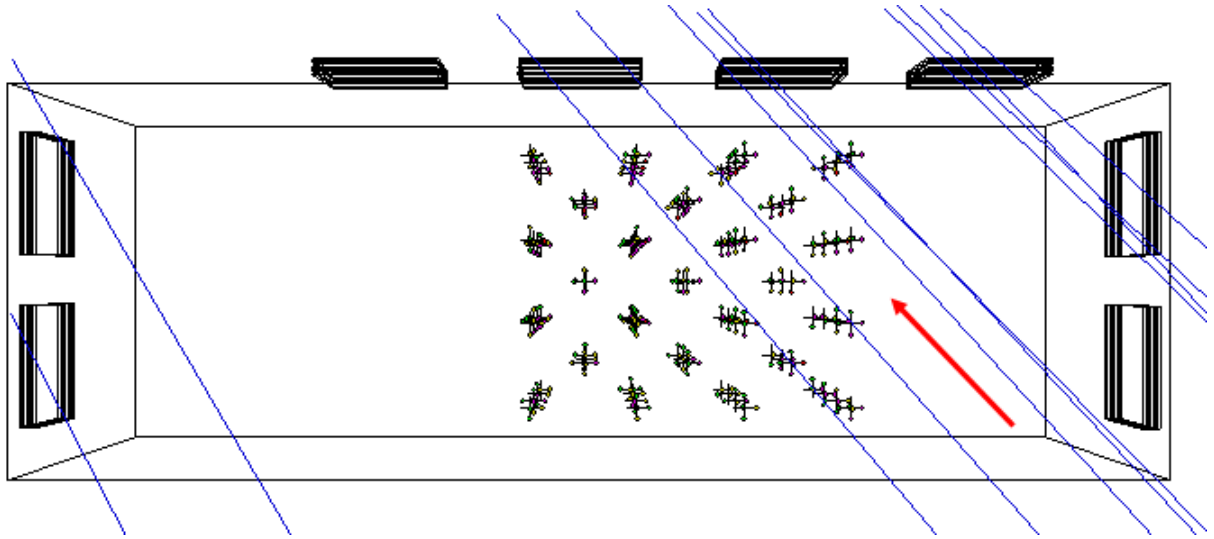
Частота регистрации групп мюонов



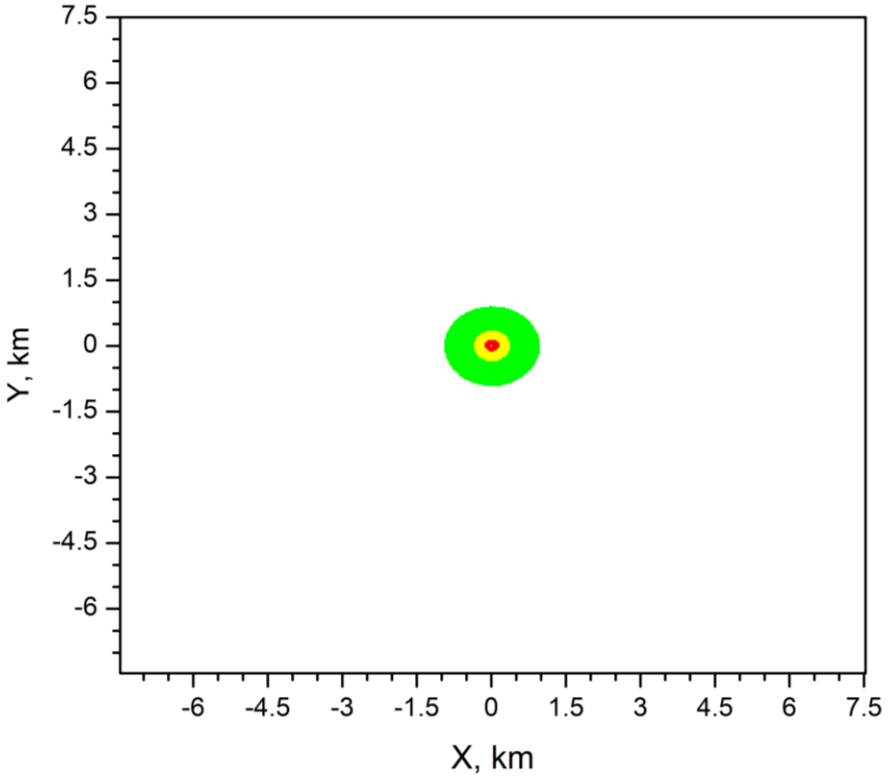
серия	период измерений	“живое” время, ч	число событий
10	май 2012 – март 2013	5541.8	9412
11	июль 2013 – апрель 2015	11897.5	19923
12	июль 2015 – апрель 2019	27269.3	46708
13	апрель 2019 – декабрь 2022	26602.6	46090
14	декабрь 2022 – июль 2023	3927.4	7040
итого:	май 2012 - июль 2023	75238.6	129173

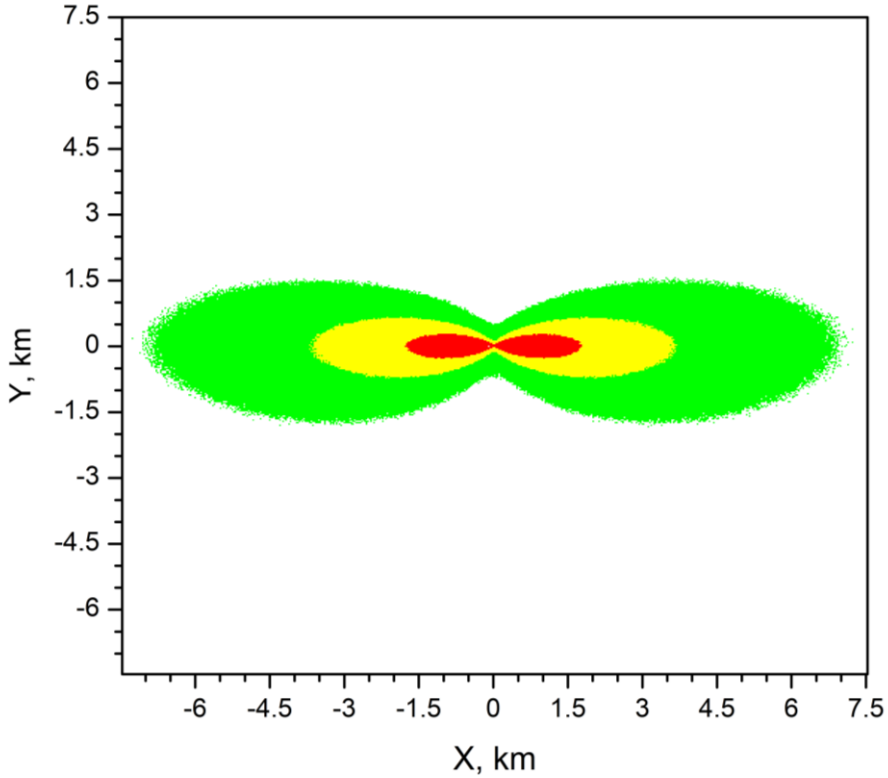
Отбор событий в двух 60° секторах азимутальных углов





Shower cross section in muons





$\theta = 42°$ (with EMF)

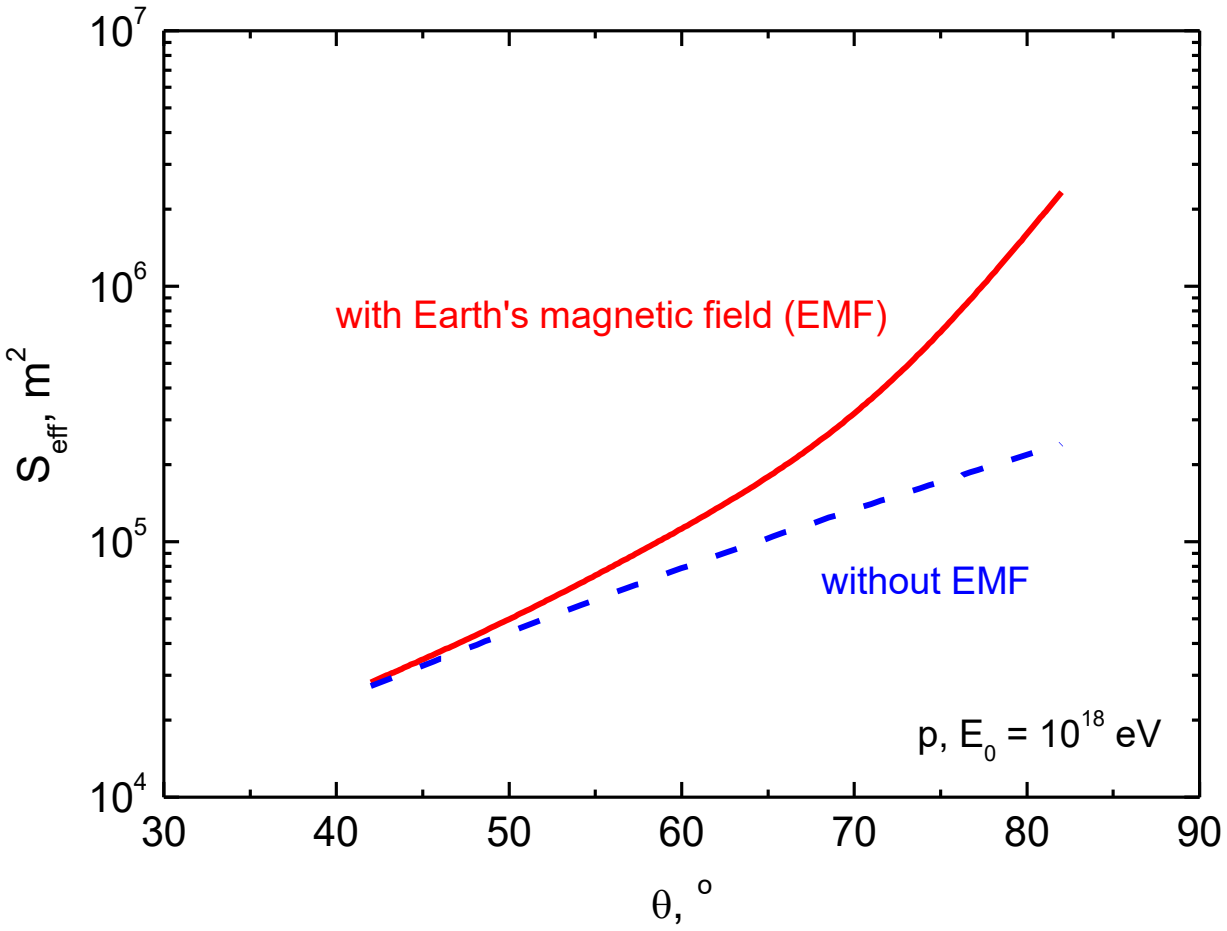
$\theta = 82°$ (with EMF)

p, $E_0 = 10^{18}$ eV, $E_\mu \geq 1$ GeV

The muon content in each colored area is about 30% of the total number.

A muon detector with sizes of tens meters may be considered as a point-like probe in comparison with a shower dimension in muon component. A small fragment of the shower cross section is registered in the experiment.

Эффективная площадь собирания событий для метода СЛПМ



Экспериментальные оценки СЛПМ в независимом от детектора виде

$$dF/dD = dF_0/dD \times \left[\Delta N_{\text{obs}}(\Delta D, \Delta\theta)\right] / \left[\Delta N_{\text{exp}}(\Delta D, \Delta\theta)\right]$$

“опорная” модель: $dF_0/dD = CD^{-(\beta+1)}\cos^{\alpha}\theta$ $C = 7\times10^{-4}$, $\alpha = 4.7$ и $\beta = 2.1$

$$D^3\, dF/dD = [N_{\text{obs}}(\Delta D, \Delta\theta)/N_{\text{exp}}(\Delta D, \Delta\theta)]\, CD^{2-\beta}\cos^{\alpha}\theta$$

Расчеты СЛПМ

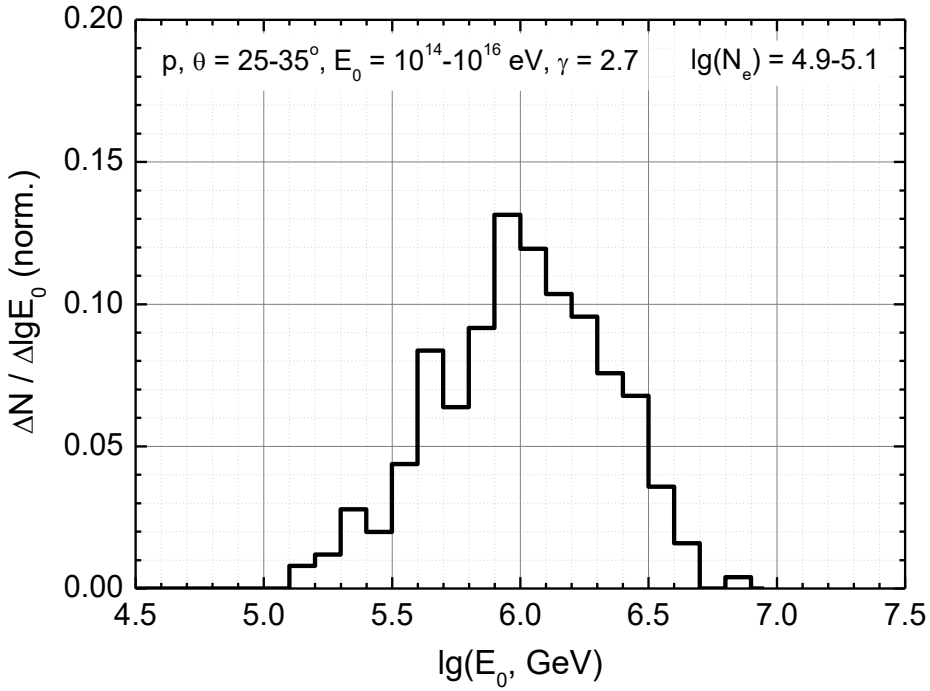
Интегральный СЛПМ: $F\left(\geq D\right)=\int N\left(\geq E_0\left(\mathbf{r},D\right)\right)dS$ событий / (с ср)

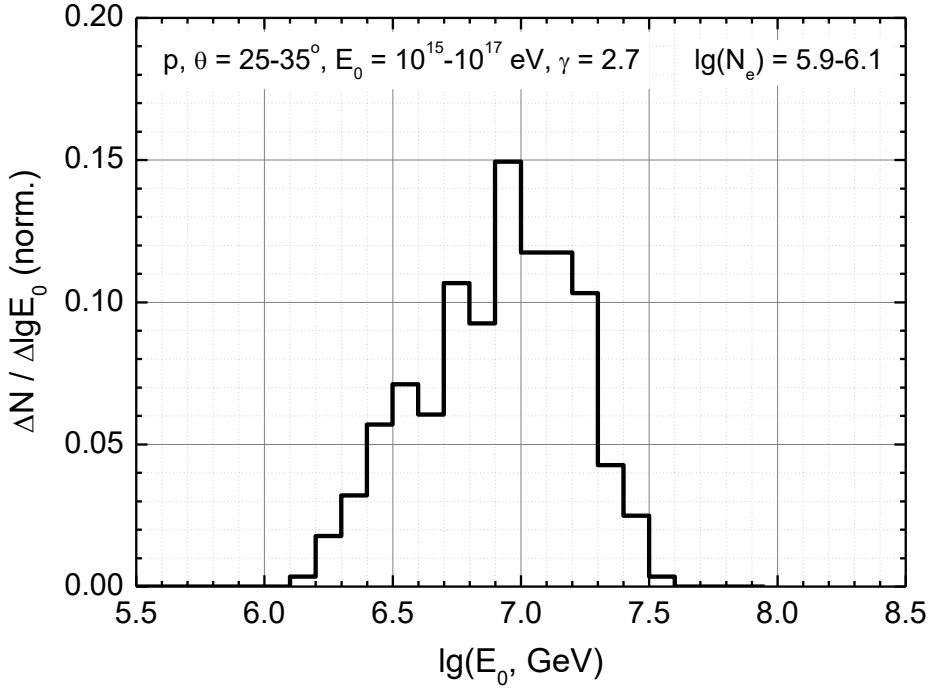
$N\ (\geq E_0)$ – энергетический спектр ПКЛ

E_0 определяется уравнением: $\rho\left(E_0,\mathbf{r}\right)=D$

Дифференциальный СЛПМ: $dF/dD=\int\left(dN/dE_0\right)\Big/\left[d\rho\left(E_0,\mathbf{r}\right)/dE_0\right]dS$

Распределение первичных частиц по энергиям E_0, которые дают вклад в ШАЛ с заданным числом частиц N_e



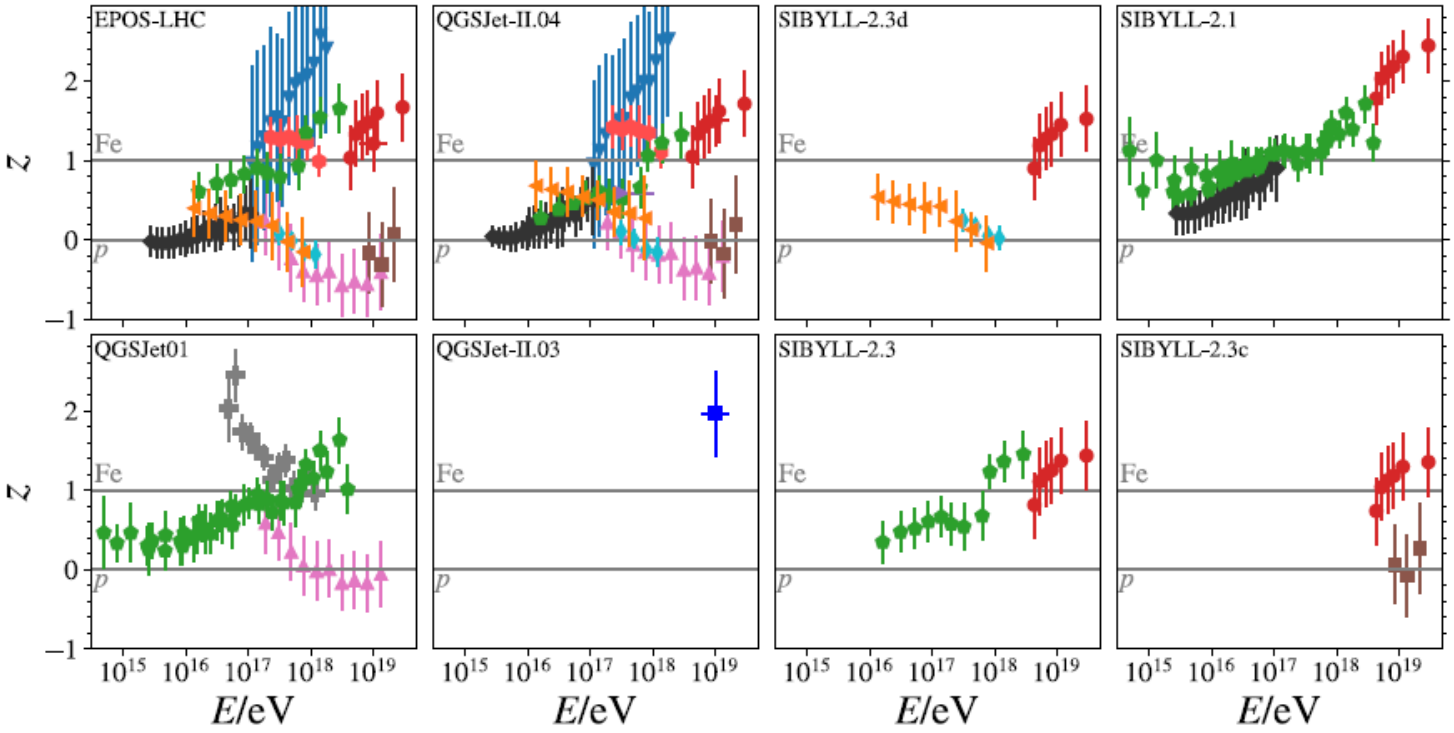


Изучение мюонной компоненты ШАЛ на разных установках

4) Combined analysis

ISVHECRI 2024

Preliminary



$$z = \frac{\ln\langle N_\mu^{\rm det}\rangle - \ln\langle N_{\mu,\rm p}^{\rm det}\rangle}{\ln\langle N_{\mu,\rm Fe}^{\rm det}\rangle - \ln\langle N_{\mu,\rm p}^{\rm det}\rangle}$$

J.C. Arteaga-WHISP's combined analysis of μ data ISVHECRI 2024, Puerto Vallarta, Mx 10

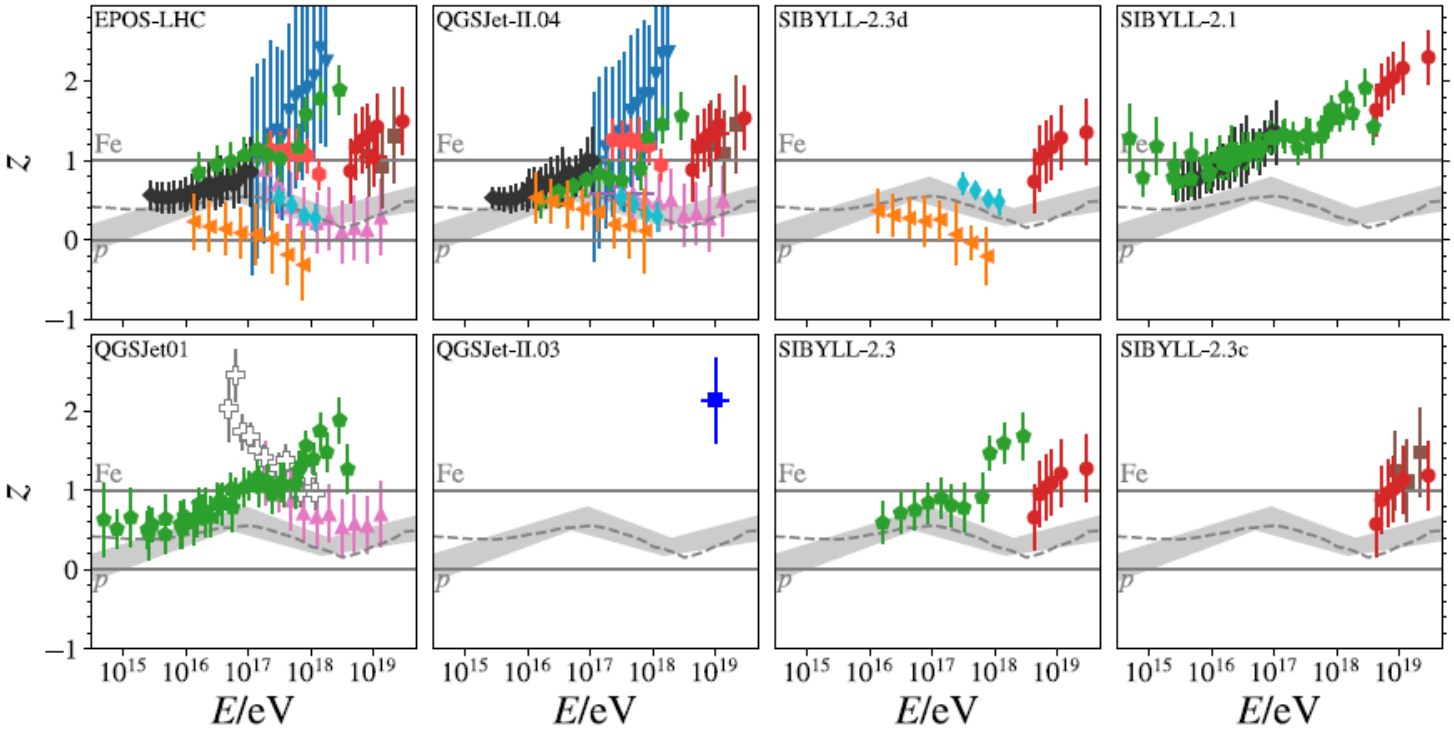
J.C. Arteaga-Velázquez, A combined analysis from the **WHISP** working group on the muon data from ten extensive air shower experiments

4) Combined analysis

ISVHECRI 2024

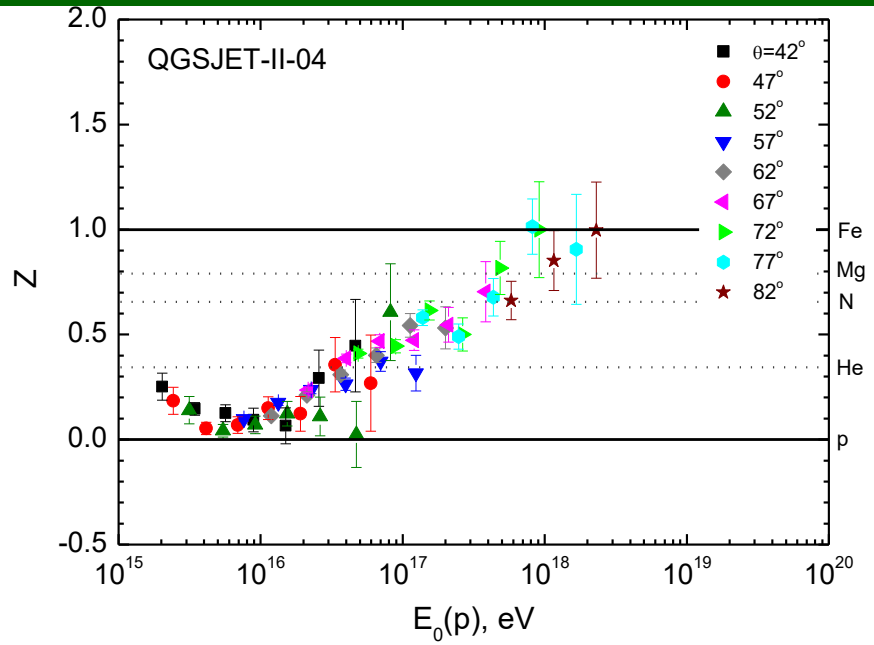
- The z-scale after applying the energy shifts for common energy calibration.

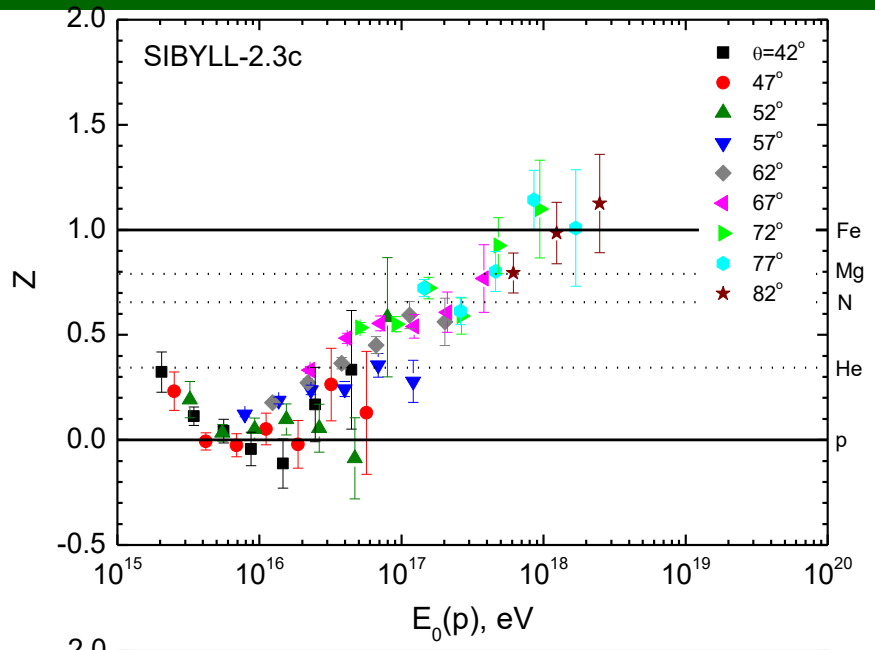
Preliminary

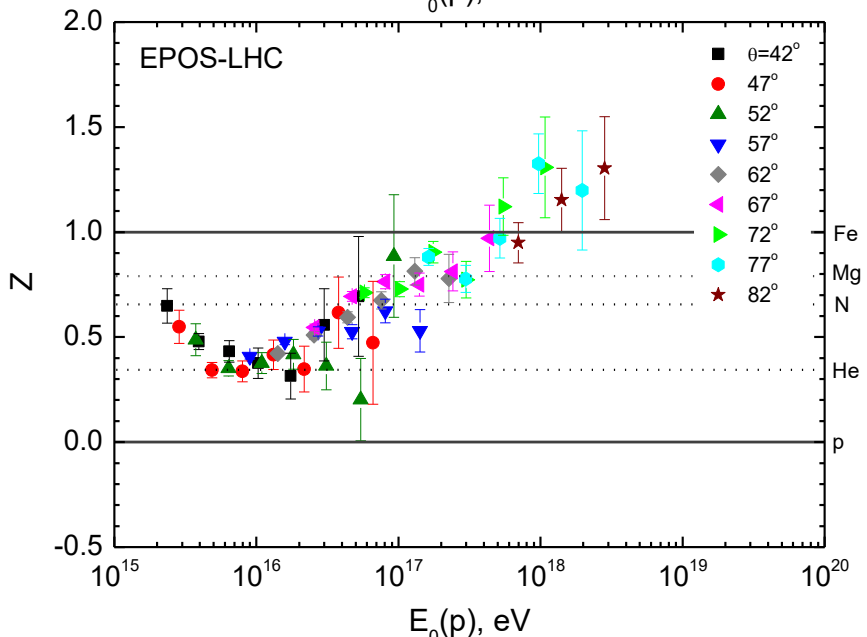


$$z = \frac{\ln\langle N_{\mu}^{\det}\rangle - \ln\langle N_{\mu,\mathrm{p}}^{\det}\rangle}{\ln\langle N_{\mu,\mathrm{Fe}}^{\det}\rangle - \ln\langle N_{\mu,\mathrm{p}}^{\det}\rangle}$$

Сопоставление СЛПМ для различных зенитных углов (влияние выбора модели адронных взаимодействий)







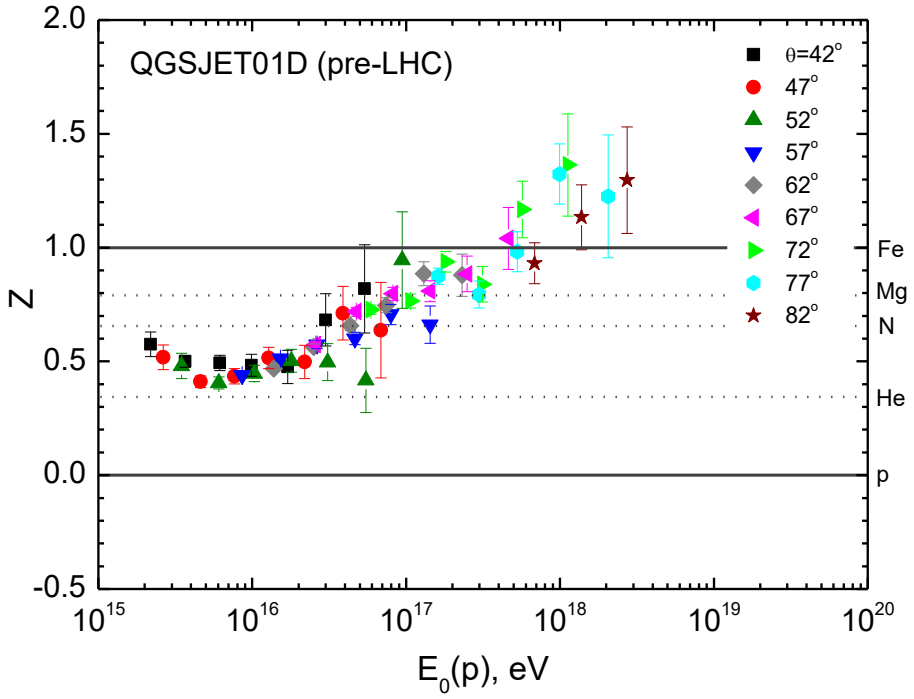
$$Z = \frac{\ln(N_\mu^{\text{det}}) - \ln(N_\mu^{\text{p sim}})}{\ln(N_\mu^{\text{Fe sim}}) - \ln(N_\mu^{\text{p sim}})}$$

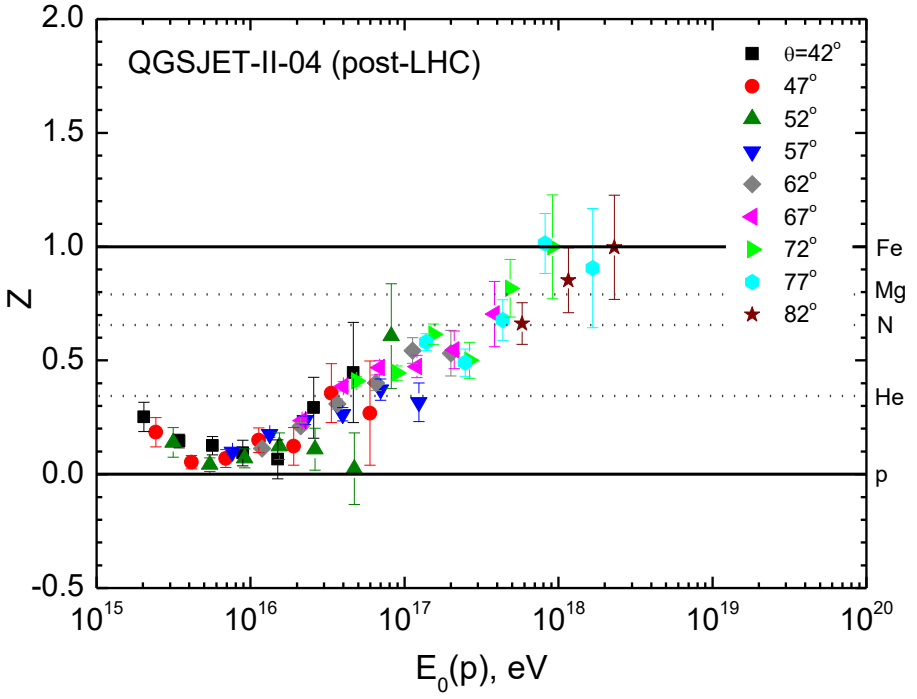
N_μ^{det} – экспериментальная оценка числа мюонов (плотности, СЛПМ, …) в детекторе,

$N_\mu^{\text{p sim}}$ и $N_\mu^{\text{Fe sim}}$ – расчетные оценки для ШАЛ, образованных протонами и ядрами железа;

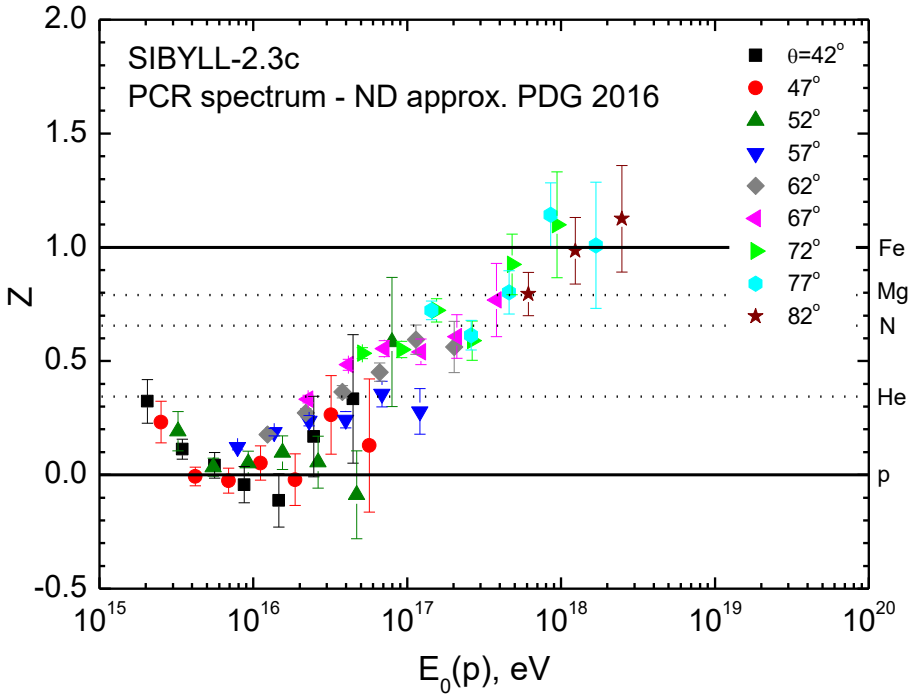
$Z = 0$ соответствует ШАЛ от протонов,
$Z = 1$ – ШАЛ от ядер железа.

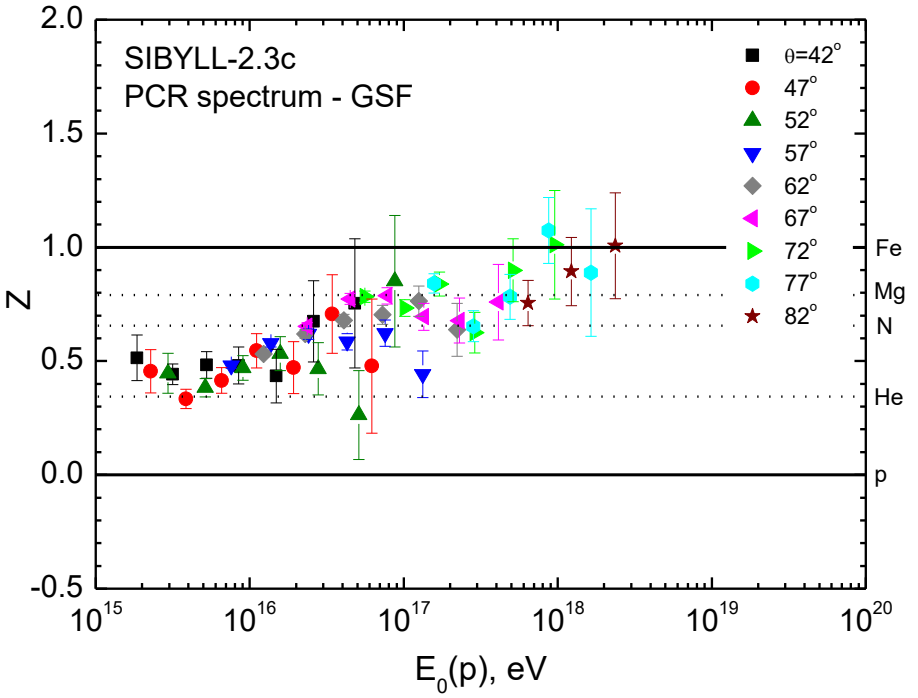
Сопоставление СЛПМ для различных зенитных углов (влияние выбора модели адронных взаимодействий)

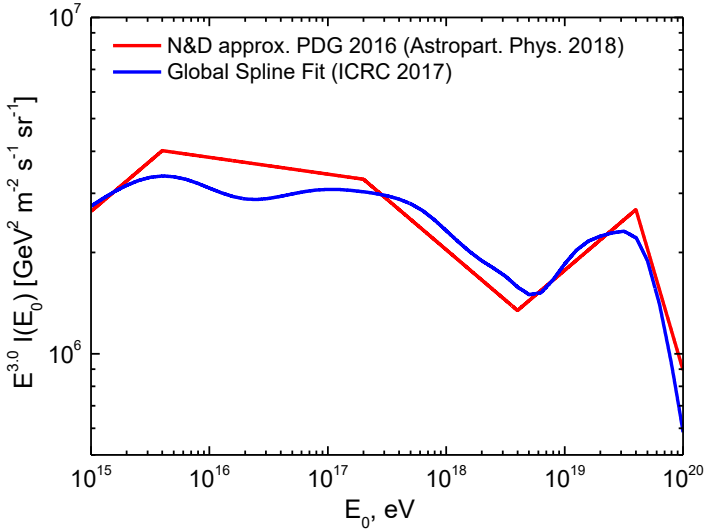




Сопоставление СЛПМ для различных зенитных углов (влияние выбора энергетического спектра ПКЛ)

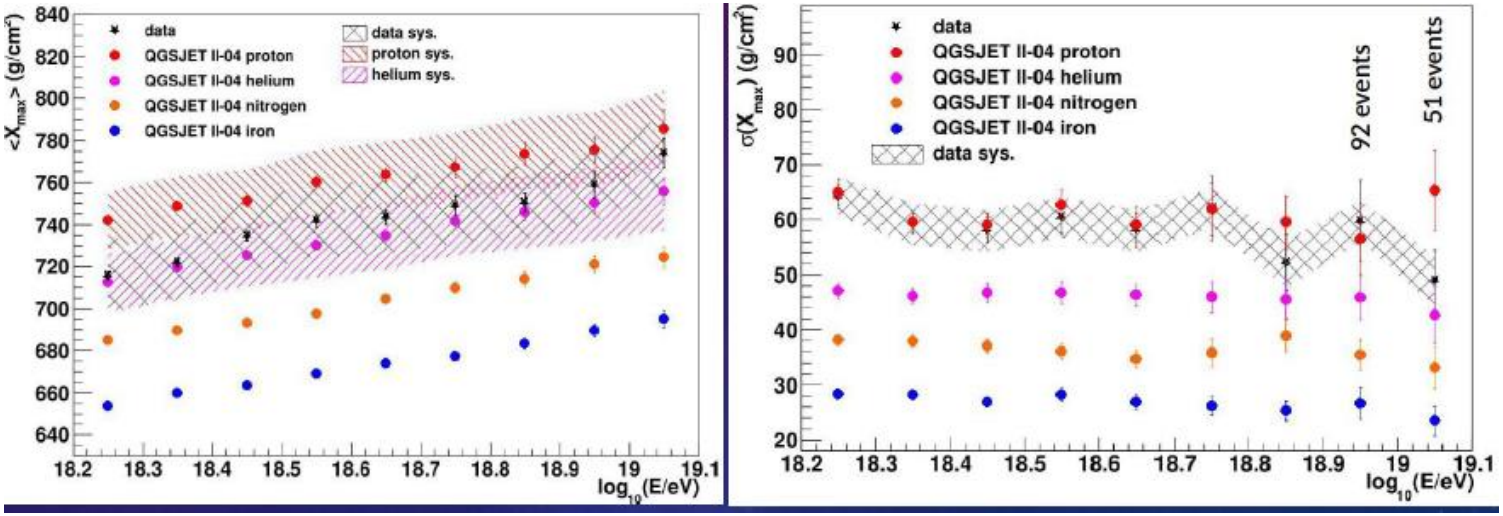




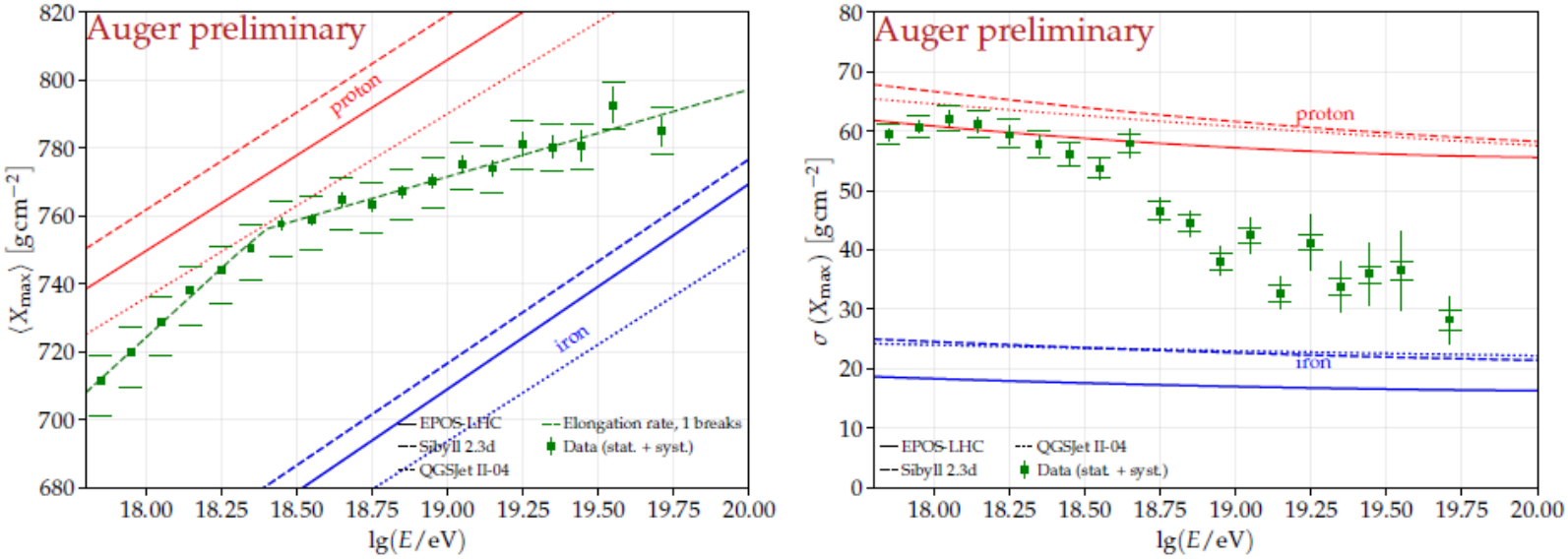


Измерения глубины максимума развития ШАЛ X_{max} флуоресцентным методом

John Matthews, Telescope Array Collaboration, ISVHECRI-2024



Thomas Fitoussi, Pierre Auger Collaboration, UHECR-2022



ДЕКОР (2002-2007) // *Ядерная физика, 73 (2010) 1904*

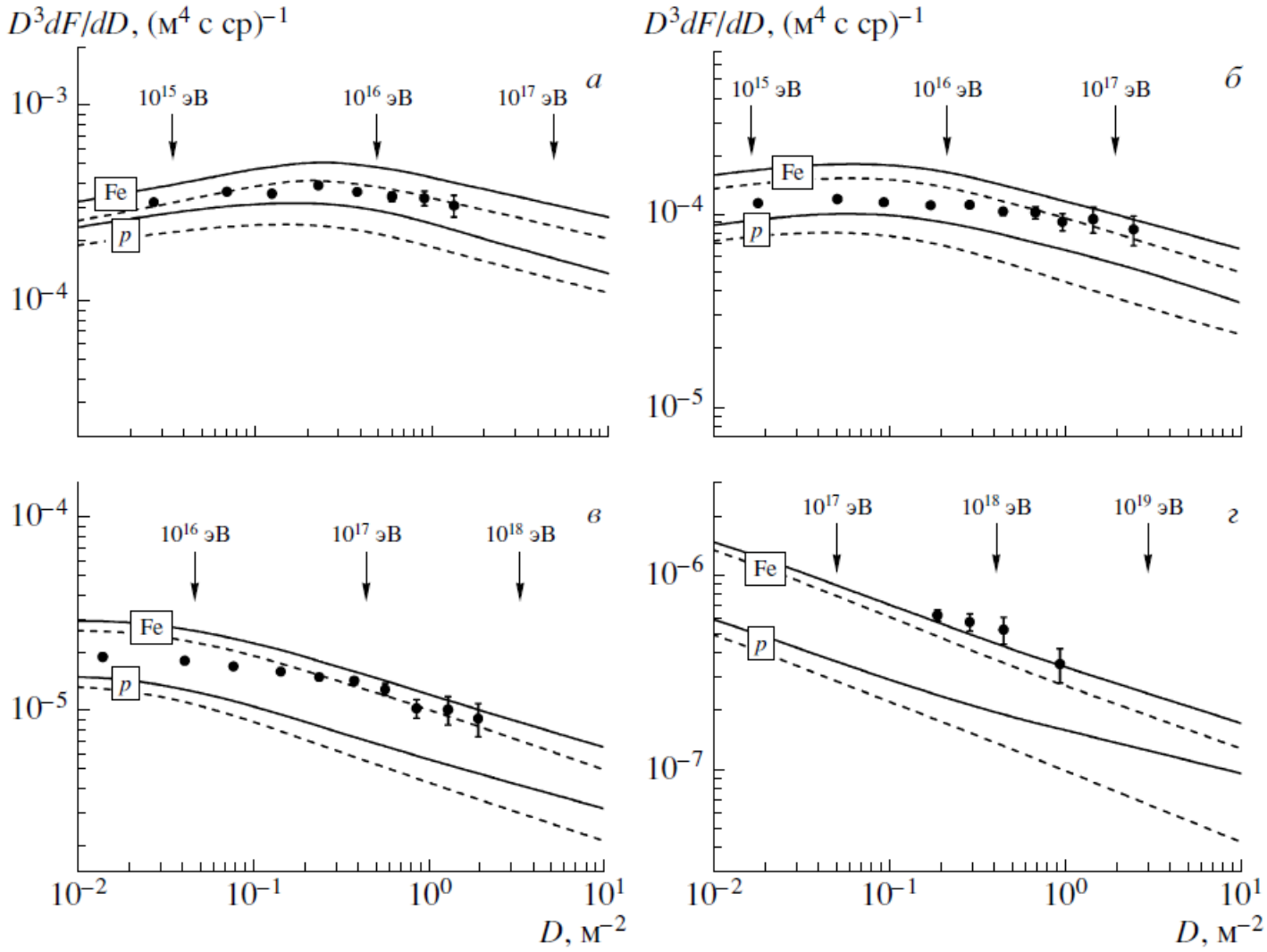
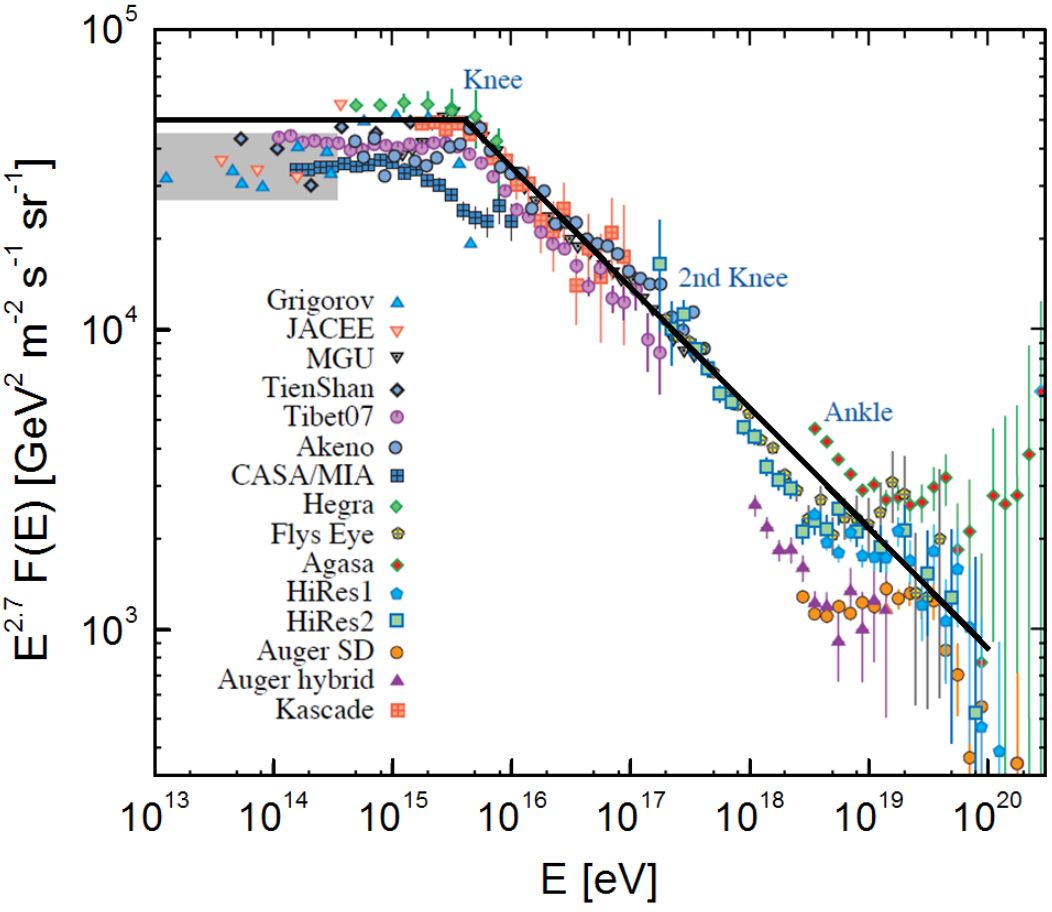


Рис. 9. Экспериментальные и расчетные дифференциальные спектры локальной плотности мюонов для зенитных углов 35° (*а*), 50° (*б*), 65° (*в*) и 78° (*г*). Точки — экспериментальные данные; сплошные и штриховые кривые — расчет с моделями QGSJET01 и SIBYLL 2.1 соответственно. Нижние пары кривых на каждом рисунке — первичные протоны, верхние — ядра железа.

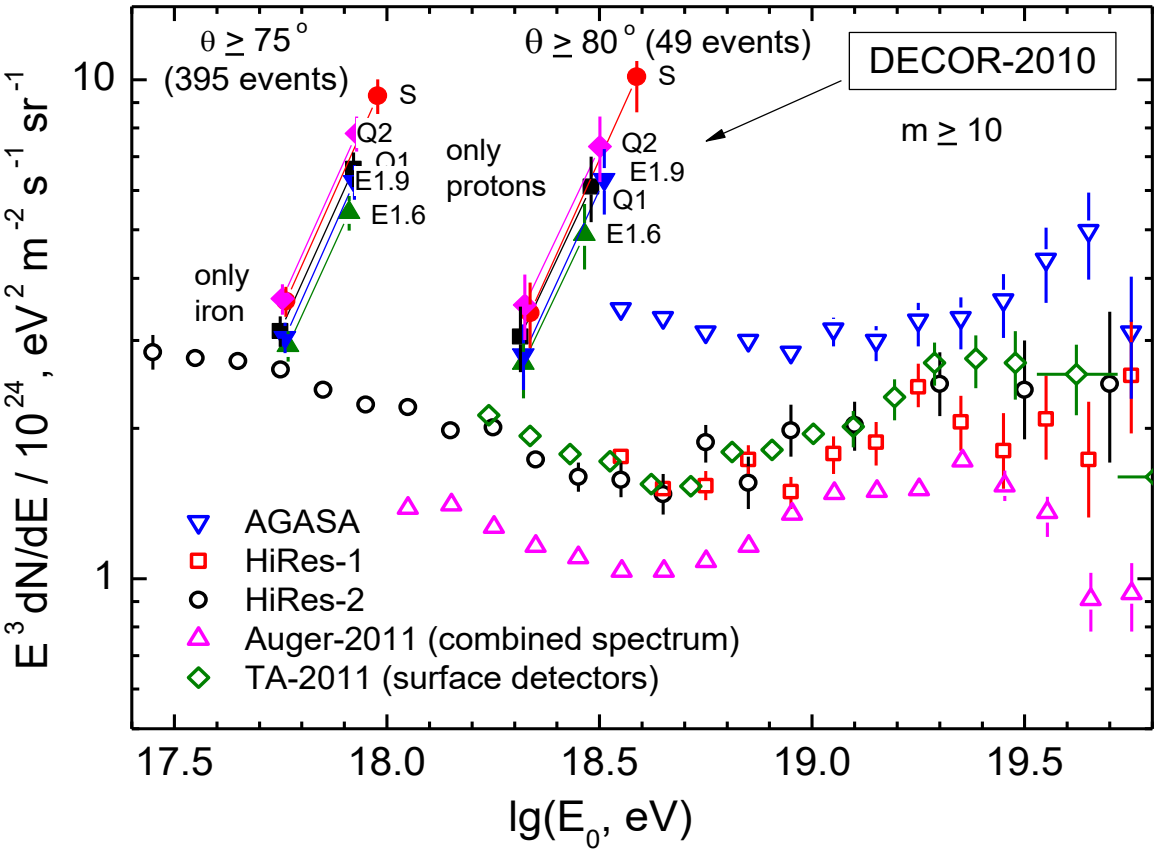
DECOR 2002-2007 // *Phys. Atom. Nucl. 73 (2010) 1852*



The all-particle spectrum, PDG 2008

Энергетический спектр ПКЛ при сверхвысоких энергиях

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



Оценки спектра ПКИ, основанные на данных ДЕКОР по группам мюонов при больших зенитных углах, оказываются плохо совместимы (даже в предположении тяжелого массового состава) с данными установок HiRes, PAO, TA. Это противоречие становится еще более значимым, если принять во внимание, что данные флуоресцентных детекторов указывают на доминирование легких ядер в области энергий ~ 10^{18} эВ.

DECOR 2002-2007 + 2012-2016 // *Astropart. Phys. 98 (2018) 13*

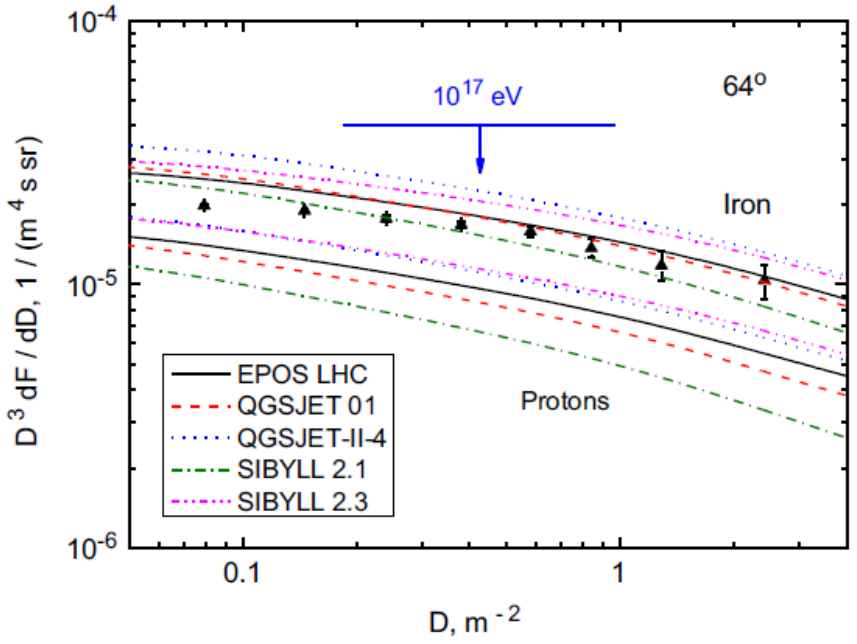


Fig. 8. Reconstructed local muon density spectrum at 64° zenith angle (dark triangles) and expected spectra calculated for protons and iron nuclei as primary particles (lower and upper groups of the curves respectively) with five different hadron interaction models. Arrow indicates the position of the effective 10^{17} eV primary particle energy.

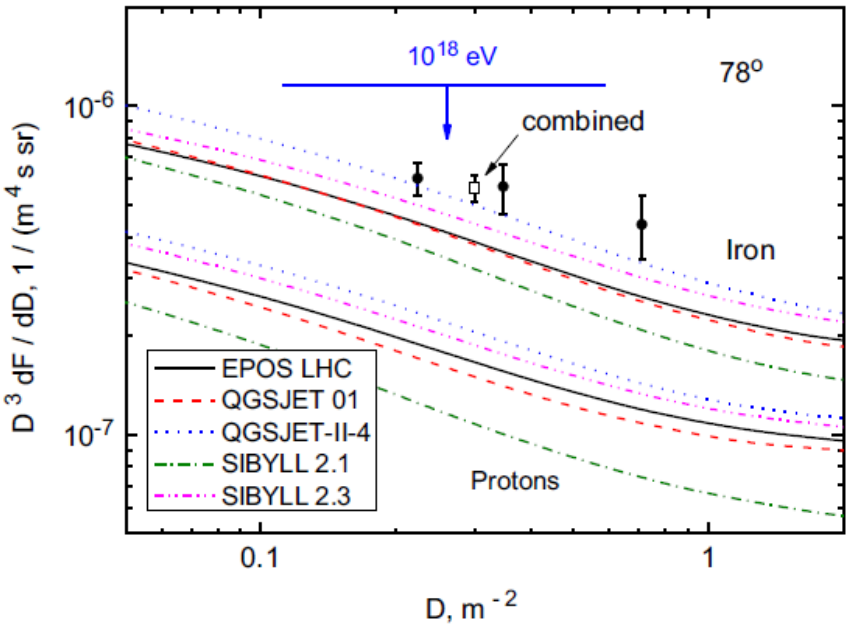
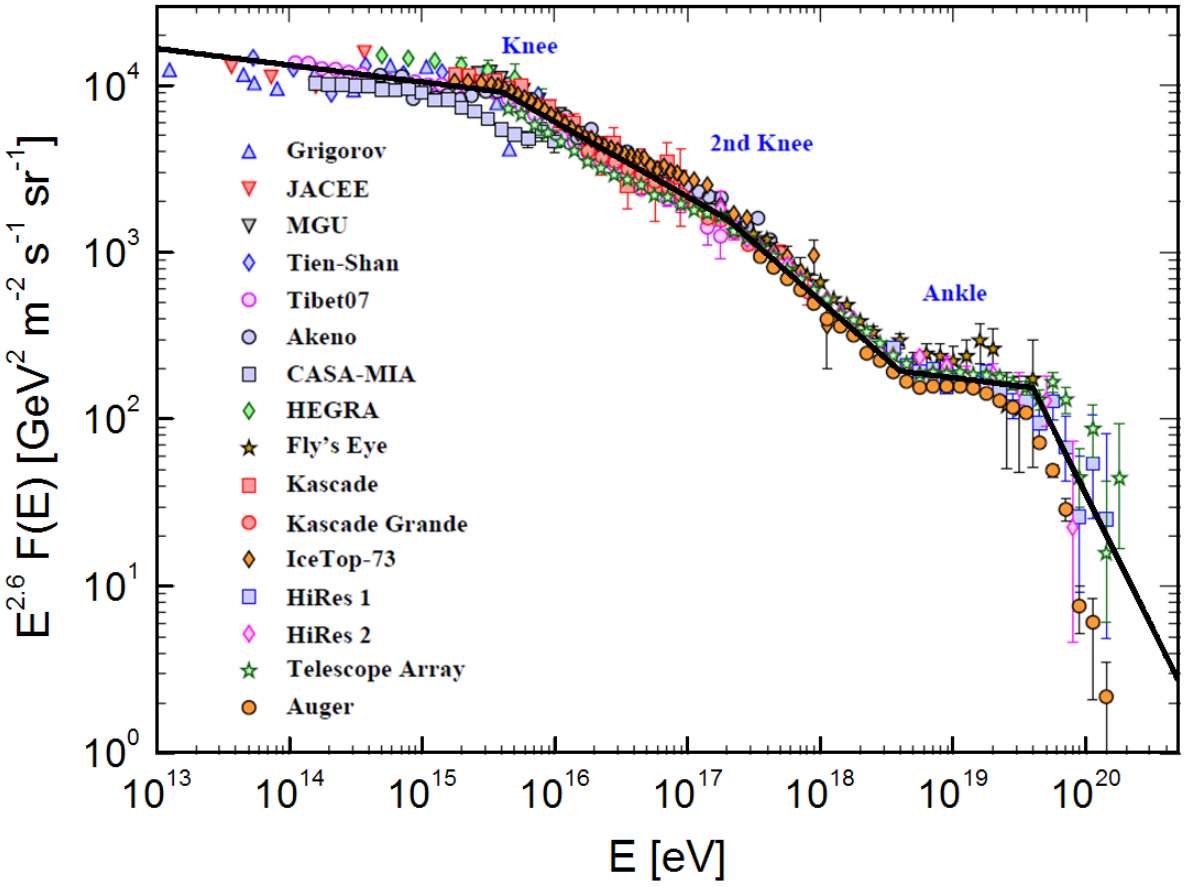


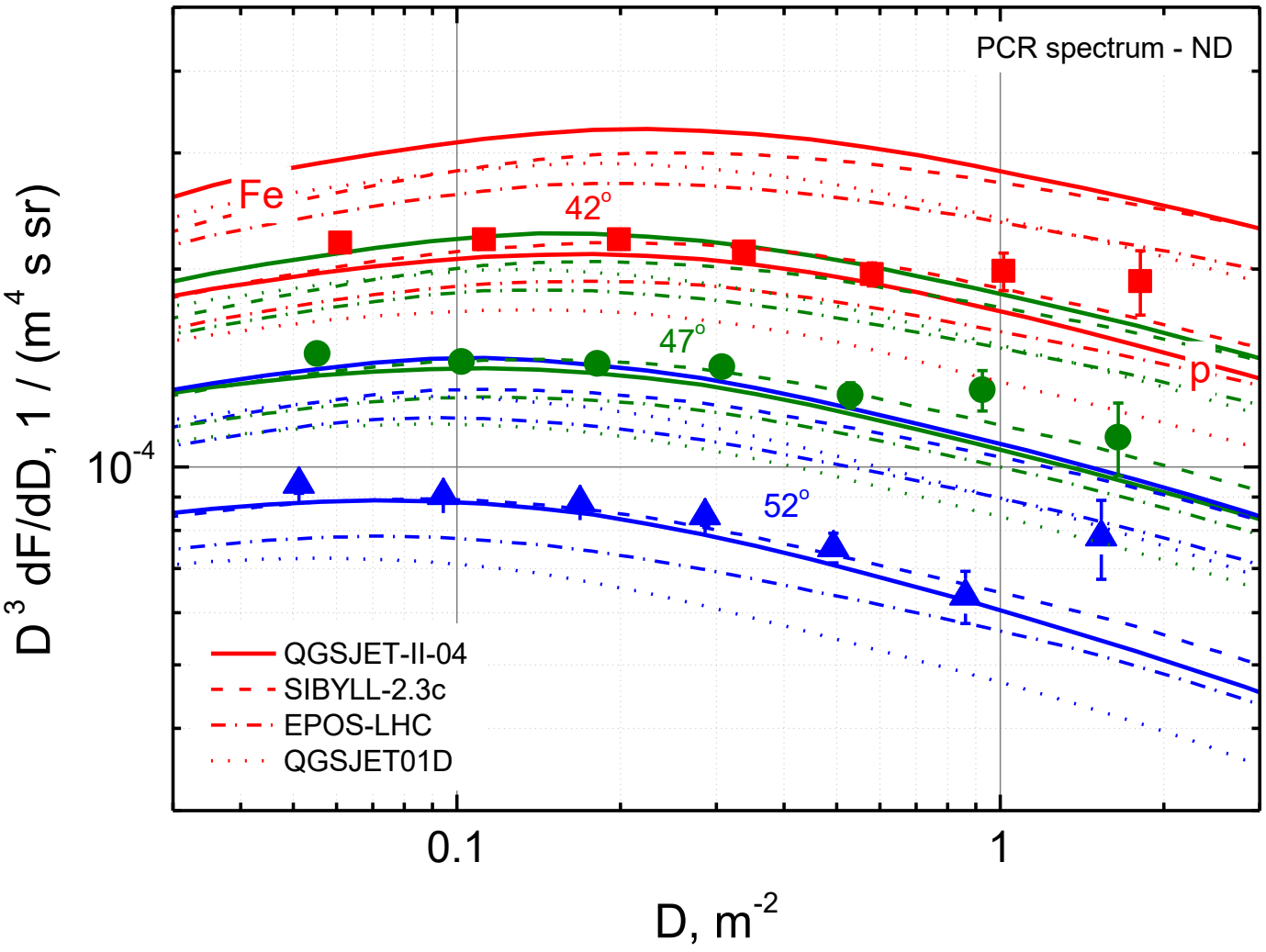
Fig. 9. Reconstructed muon density spectrum at 78° zenith angle (dark circles) and expected spectra calculated for protons and iron nuclei as primary particles (lower and upper groups of the curves respectively) with five different hadron interaction models. The open square represents a combined estimate based on all events with muon multiplicity $m \geq 10$ in the respective angular bin. The arrow indicates the position of 10^{18} eV effective primary energy.

DECOR 2002-2007 + 2012-2016 // *Astropart. Phys. 98 (2018) 13*

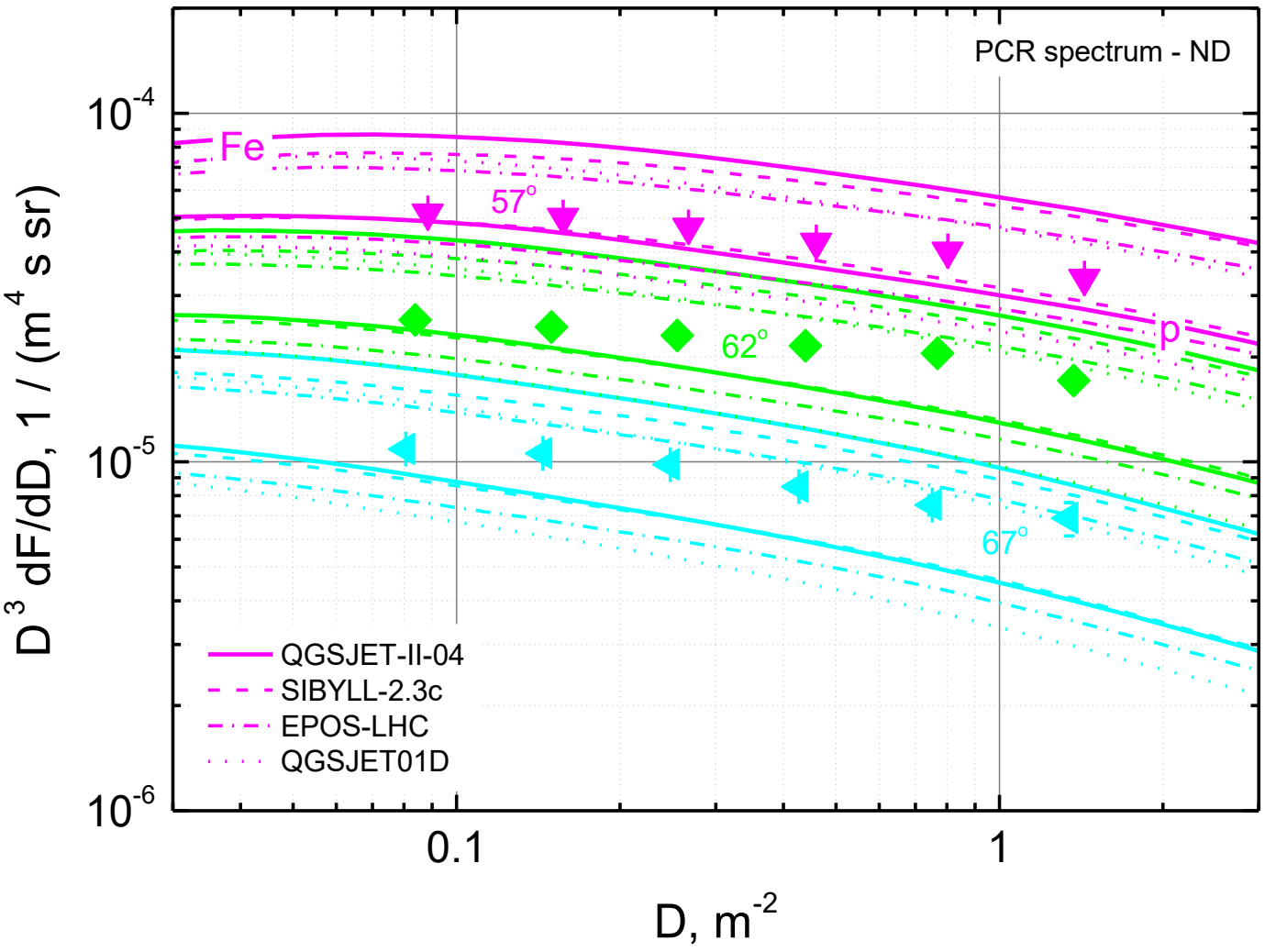


The all-particle spectrum, PDG 2016

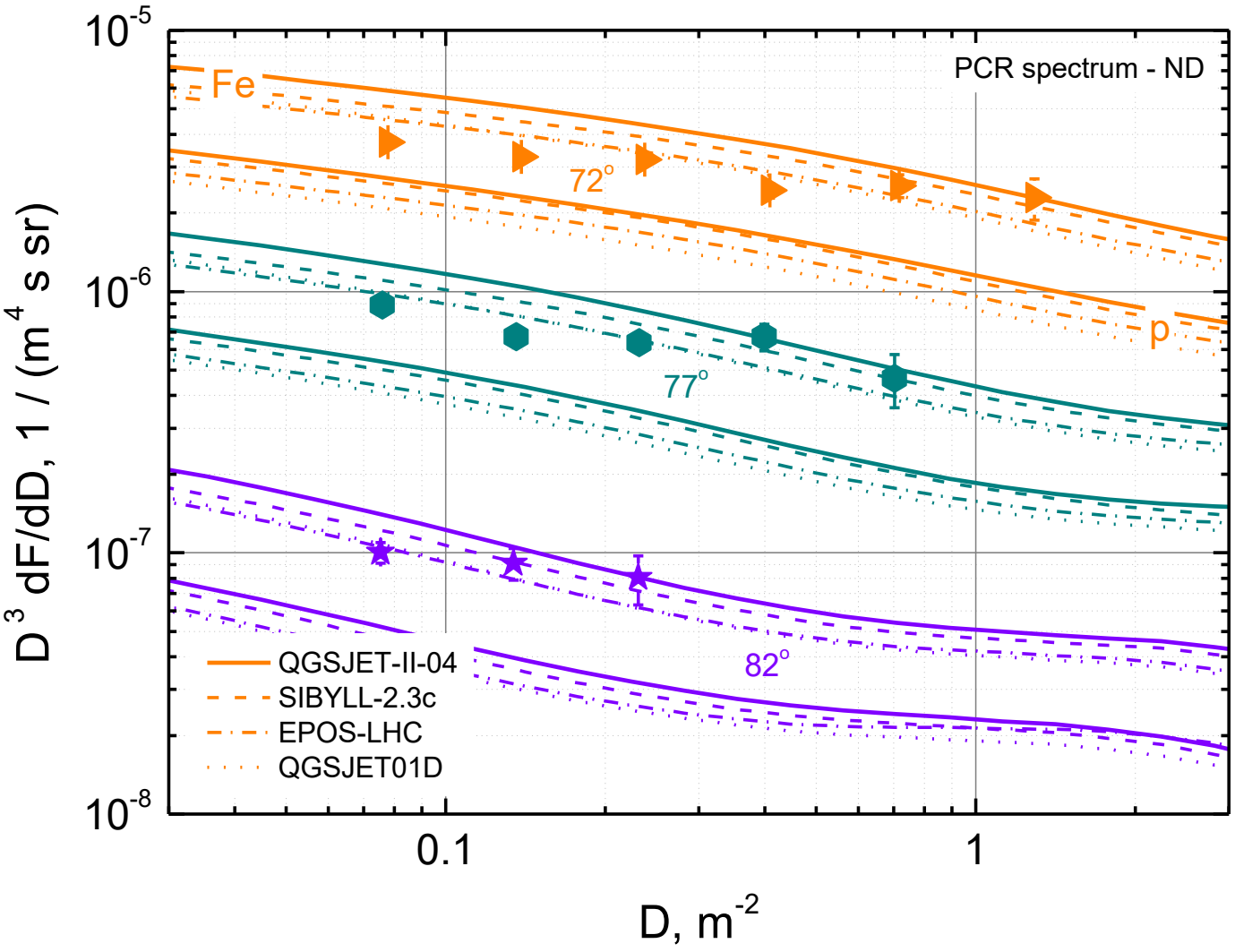
LMDS for different zenith angles (42 – 52°), ND



LMDS for different zenith angles (57 – 67°), ND

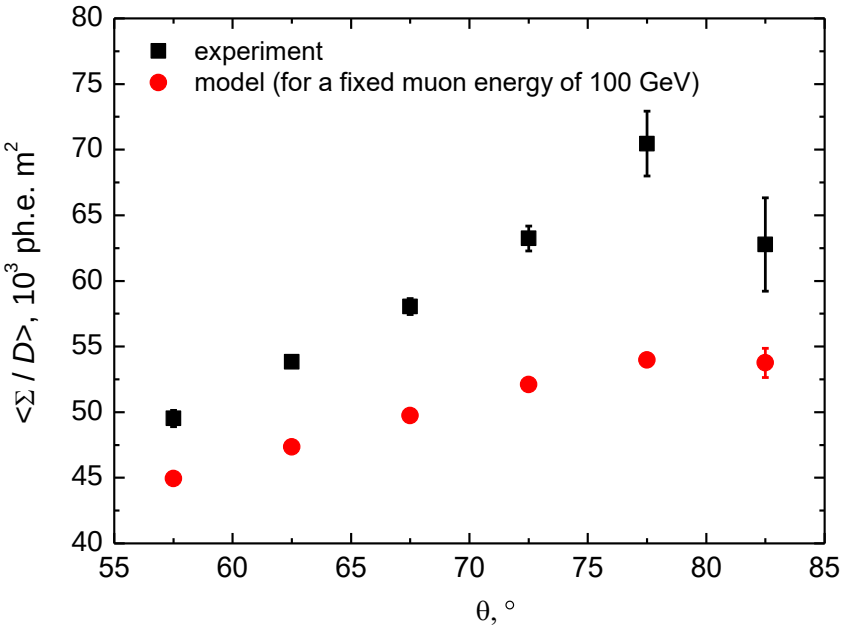


LMDS for different zenith angles (72 – 82°), ND

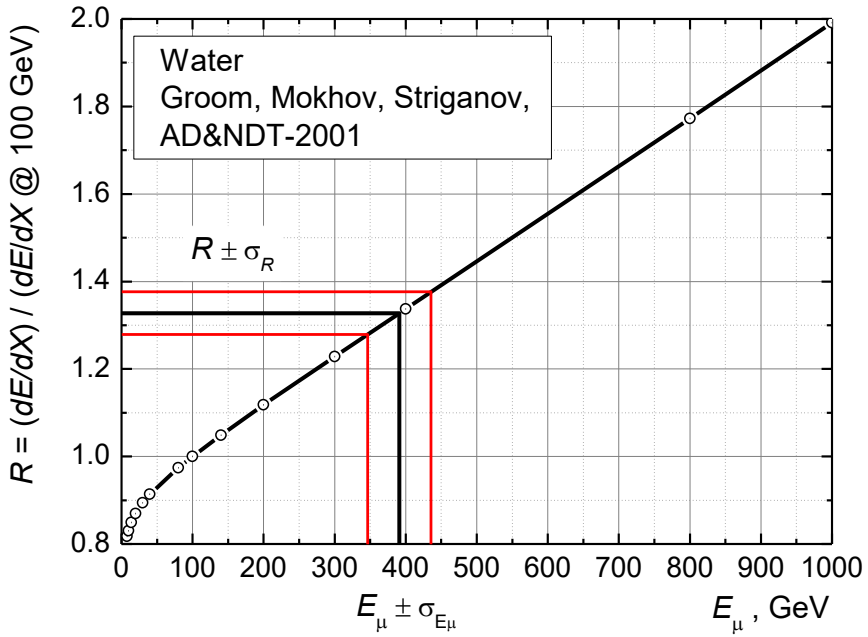


Переход от средних удельных энерговыделений к средним энергиям мюонов в группах

$$R = \left(\Sigma / D\right)^{\exp} \Big/ \left(\Sigma / D\right)^{\mathrm{mod}}_{100\ \mathrm{GeV}}$$

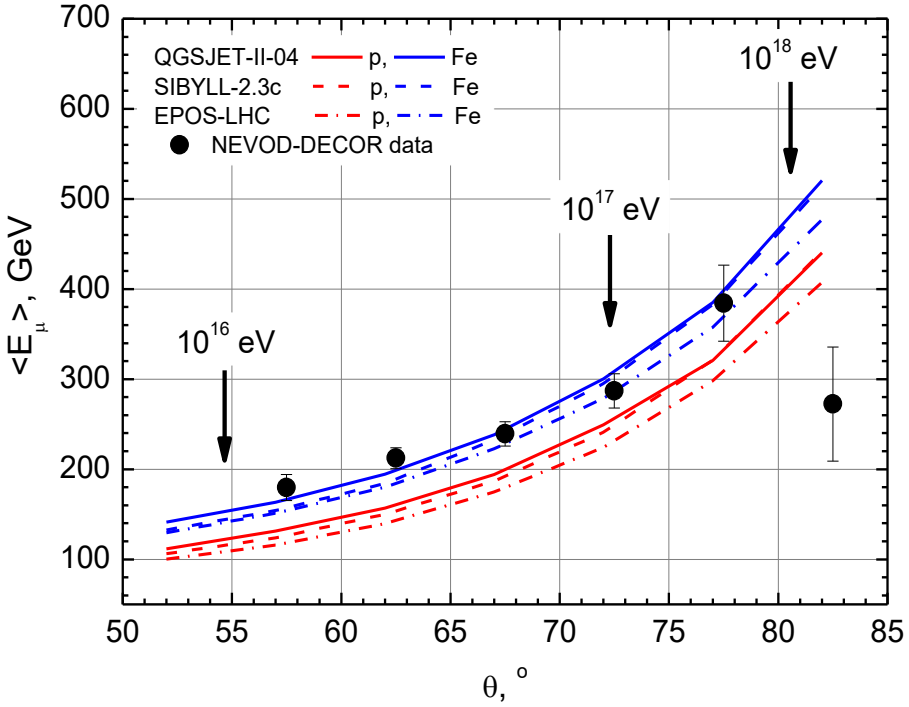


Зависимость среднего удельного энерговыделения групп мюонов от зенитного угла

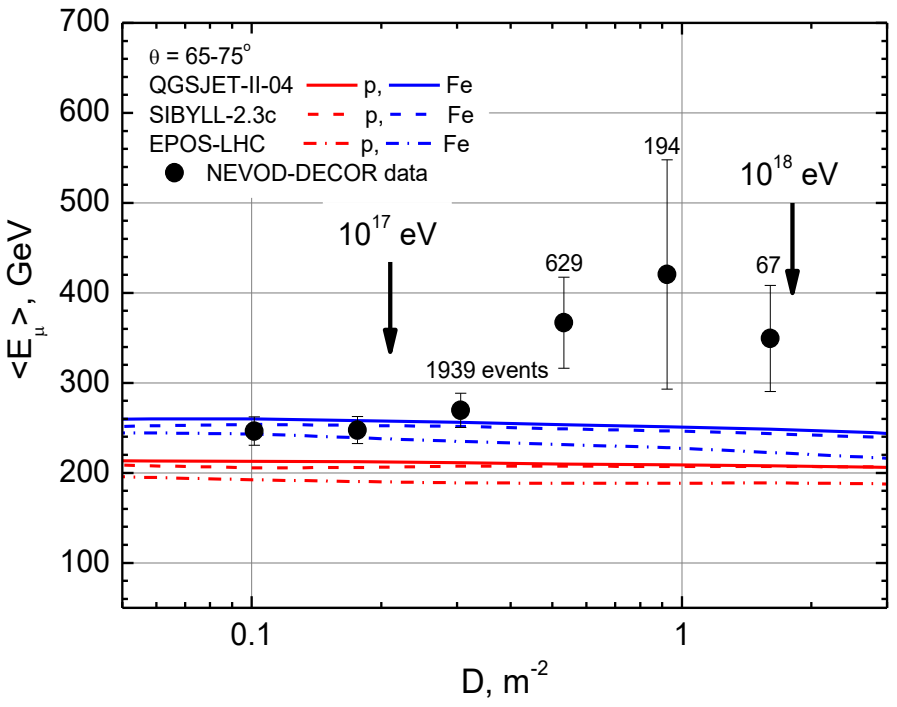


Средние удельные потери мюонов, нормированные на потери при энергии 100 ГэВ

Зависимости средней энергии мюонов в группах от зенитного угла и локальной плотности мюонов



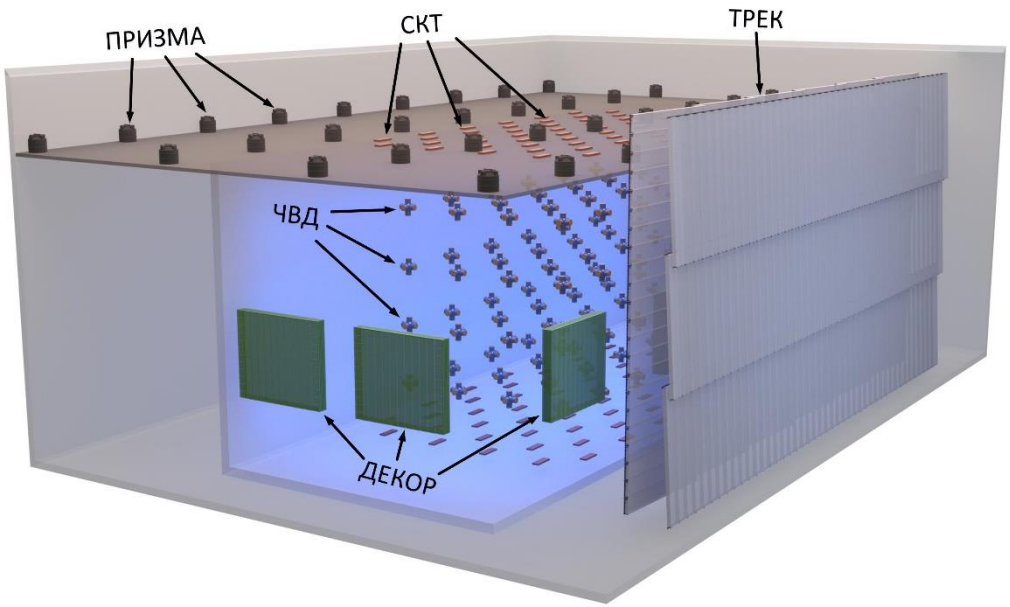
Зависимость средней энергии мюонов в группах от зенитного угла

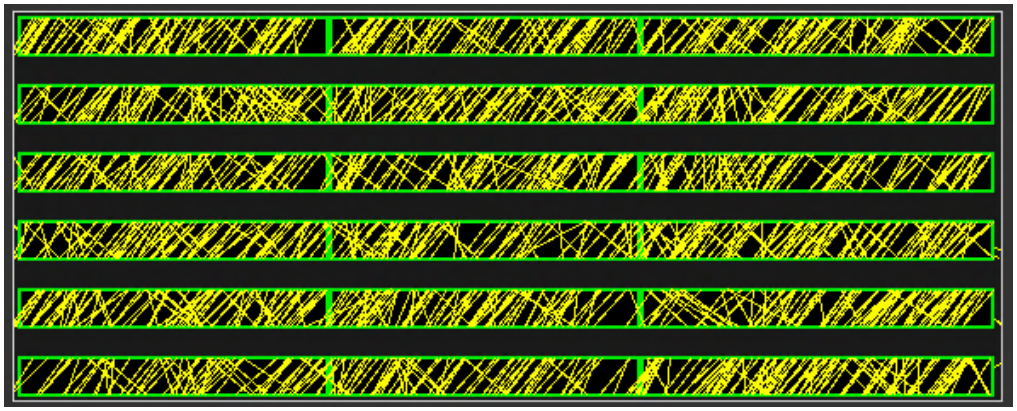


Зависимость средней энергии мюонов в группах от локальной плотности мюонов

Для больших плотностей, соответствующих энергиям ПКЛ $> 10^{17}$ эВ, превышение экспериментальных оценок средней энергии мюонов над расчетными: для p на 4.2 – 4.8σ, для ядер Fe на 3.1 – 3.7σ.

Развитие ЭК НЕВОД – детектор ТРЕК





отклик детектора ТРЕК на прохождение группы мюонов

264 дрейфовые камеры (ИФВЭ),

2 плоскости площадью ≈ 250 м^2,

разрешение двух треков ≈ 3 мм