Lateral distribution functions of signals in surface scintillation detectors of the Yakutsk Array and new energy estimates of extensive air showers and the energy spectrum of the primary cosmic radiation at energies ~ $10^{17} – 10^{19}$ eV

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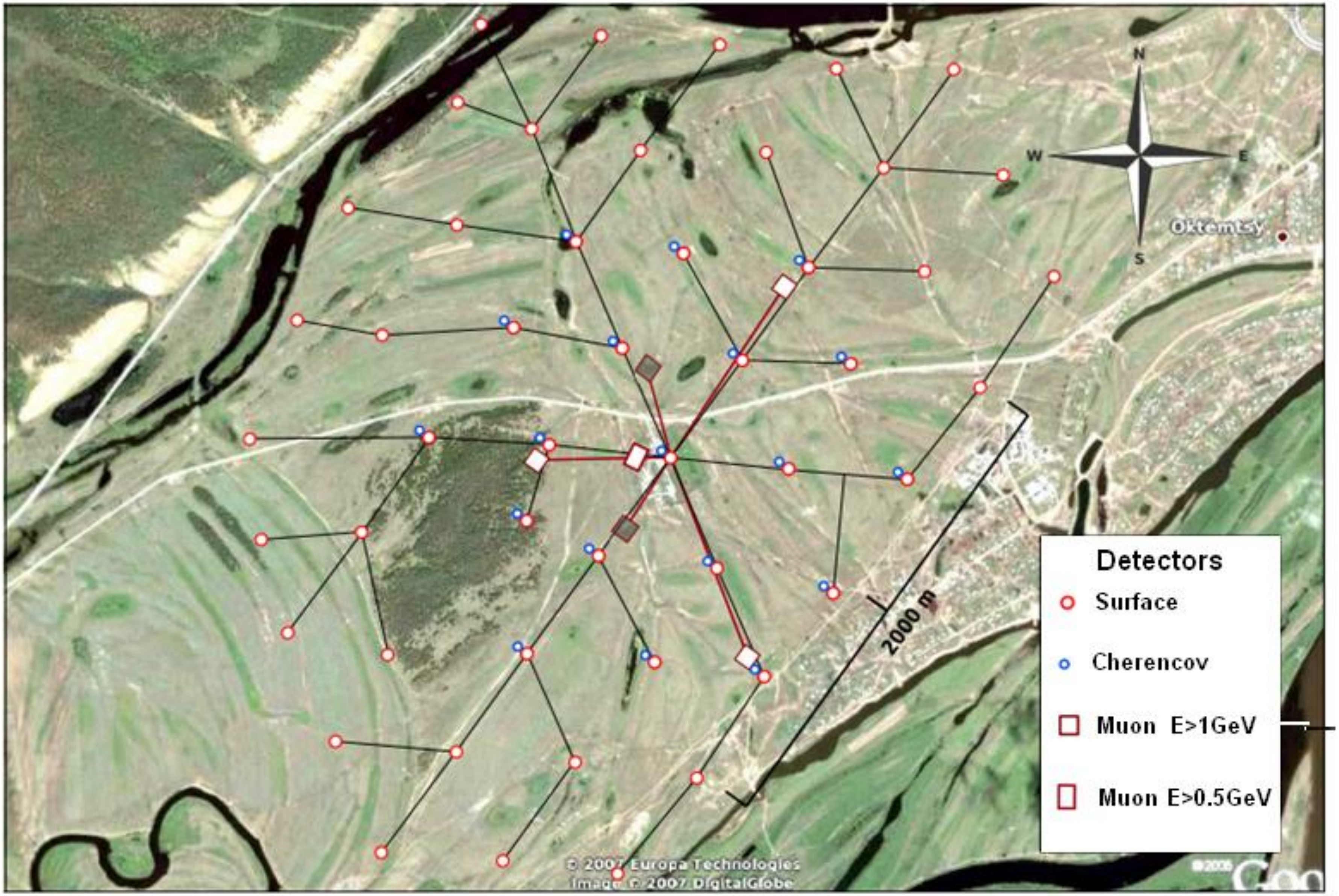
The Yakutsk array

- Oktemtsy village, 50 km south of Yakutsk near Lena river.
- Area: ~8 km^2
- ~58 surface scintillation detectors
- ~6 underground scintillation detectors
- ~48 detectors of the Vavilov-Cherenkov Radiation

250, 500, 1000 m between detectors

River LENA



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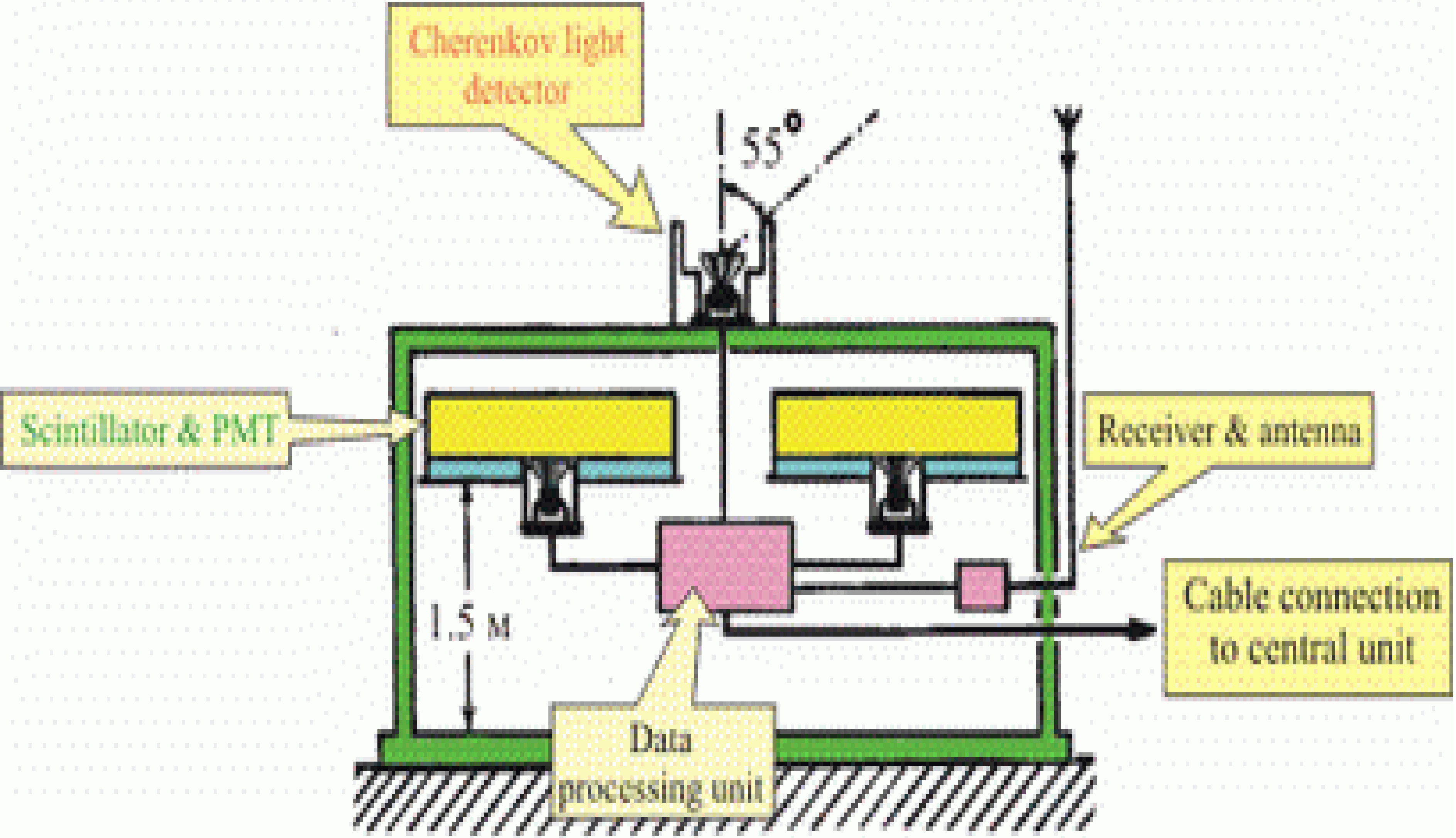
The Yakutsk Array

Detectors arrangement in a station



Cherenkov light detector

Scintillator & PMT

Receiver & antenna

Cable connection to central unit

Data processing unit

OUTLINE

- 1. Lateral Distribution Function (LDF)
- NEW APPROXIMATION
- 2. New energy estimate
- NEW METHOD OF SIGNAL SIMULATION
- 3. New energy spectrum
- NEW ENERGY ESTIMATES USED
- 4. Fluctuations and energy estimates
- REAL UNCERTAINITIES OF ENERGY ARE LARGE FOR THE ONE DETECTOR

Signals in scintillation detectors

J. Linsley

Lateral Distribution Function (LDF)

- Parabolic approximation
- of LDF
- for individual showers have been suggested to take into account fluctuations

Nichimura-Kamata-Greisen function

- Nichimura-Kamata-Greisen function for fitting average lateral distributions of charged particles in the electron-photon cascades:
- $f(r) = C(s)\,(r/r_M)^{s-2}(1+(r/r_M))^{s-4.5}$.
- Here a value $s < 2$ has a sense of the “age” parameter and r_M is the Moulier radius of lateral displacement due to the Coulomb scattering.

J. Linsley′s function

- J. Linsley suggested a function practically of the same type :
- $f(r) = C\,(r/r_M)^{-a}\,(1 + (r/r_M))^{a-b}$
- for lateral displacement of signals in scintillation detectors at the Volcano Ranch array.
- In scintillation detectors gamma-quanta produce a main contribution to a signal.
- A. Watson suggested to measure such signals in some experimental units called VEM (Vertical Equivalent Muon).
- *So, some conditional (not real) particles were introduced.*

Conditional particles

- The energy deposits to total signal in detector (mainly by gammas) are considered as conditional particles which look like muons with energies 10.8 MeV (1 VEM for the Yakutsk detector) due to a suggestion by A. Watson.
- They are not real particles

Fractions of energy deposit to total signal s *in detector* by γ, e^+, e^-, $\mu^\pm$ in the shower with $E=10^9$ GeV

r, m	$s(r, 0)$, MeV·m^{-2}	γ	e^+	e^-	$\mu^\pm$
300	$4{,}00\times10^2$	0,64	0,09	0,17	0,10
600	$3{,}85\times10^1$	0,58	0,08	0,13	0,19
1000	$5{,}63\times10^0$	0,47	0,08	0,12	0,33

17

AGASA lateral distribution

- At the AGASA array the lateral distribution function:
- $f(r) = C\,(r/r_M)^{-1.2}\,(1+(r/r_M))^{1.2-\eta}(1+(r/r_0)^2)^{-0.6}$.
- Here $r_M = 125\,m$, $r_0 = 1000\,m$, and parameter $\eta = 3.97 - 1.79(sec\theta - 1)$ was a simple function of the zenith angle θ.

Yakutsk array function

- At the Yakutsk array the Linsley's function was used:
  - $f(r) = C\,(r/r_M)^{-1}\,(1+(r/r_M))^{1-b}$.
- Here $r_M = 79\,m$

Parabolic approximation of LDF

- Variables: $x=\lg(r/1\text{ m})$, $y=\lg(s(r,\theta)/1\text{ VEM})$,
- The unit to measure signal is
- 1 VEM=10.8 MeV for ALL inclined showers. Signals $s(r,\theta)$ in detectors for inclined showers were calibrated by GEANT4.

Approximation

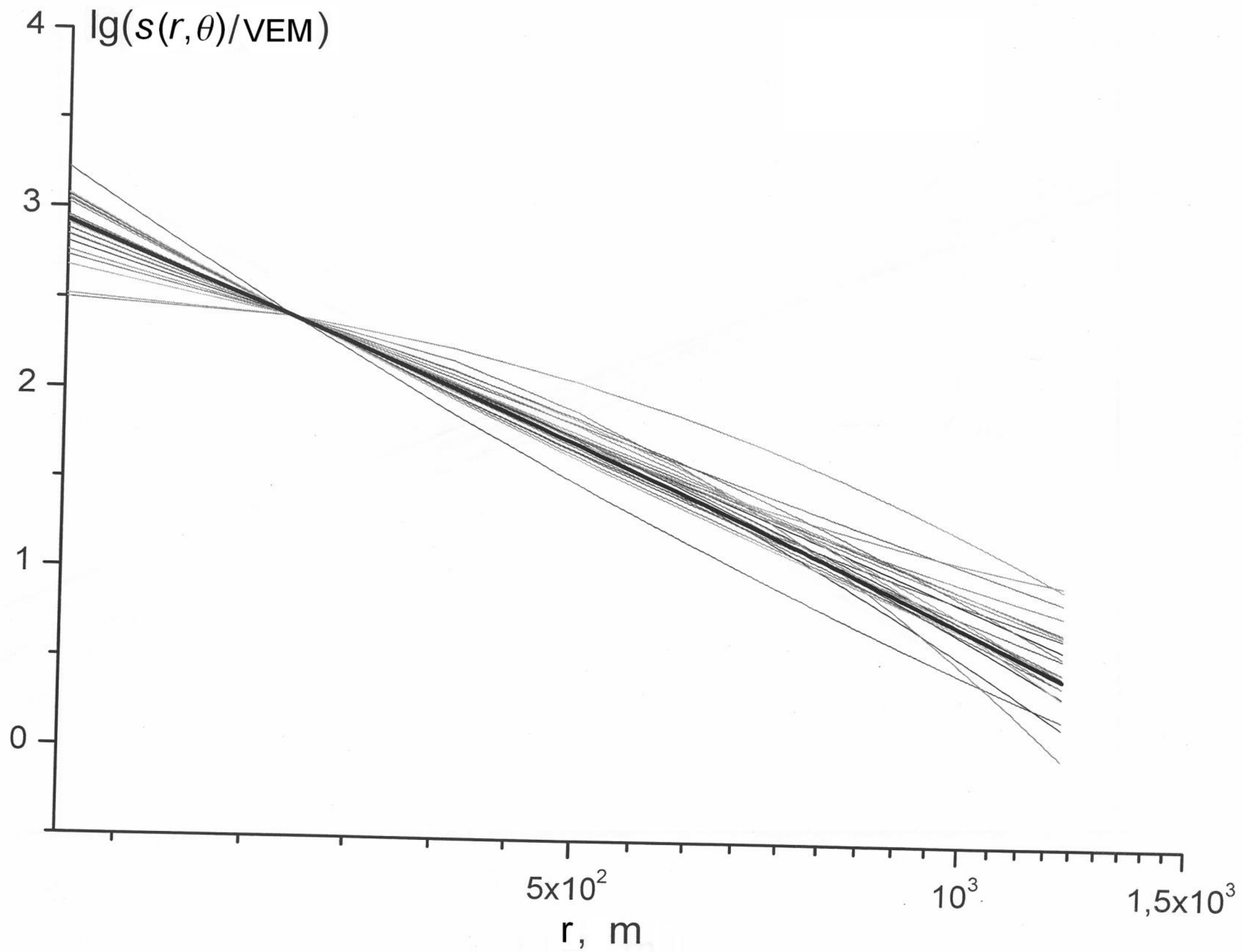
- $y=a+bx+cx^2$

- The LEAST SQUARE METHOD was used to estimate a, b, c.

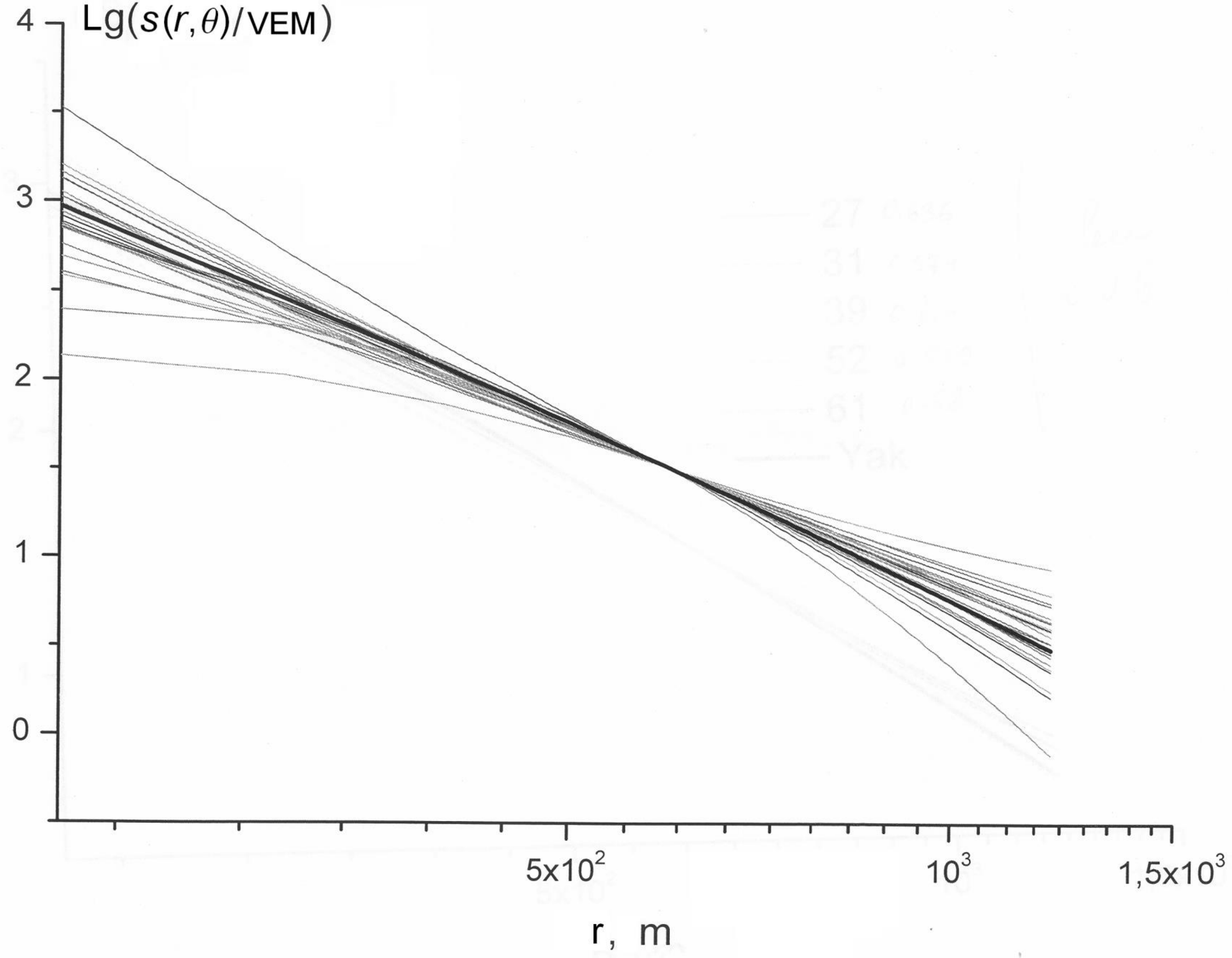
Some examples

- FLUCTUATIONS in REAL SHOWERS
- Thin lines – individual showers
- Thick line – Linsley function

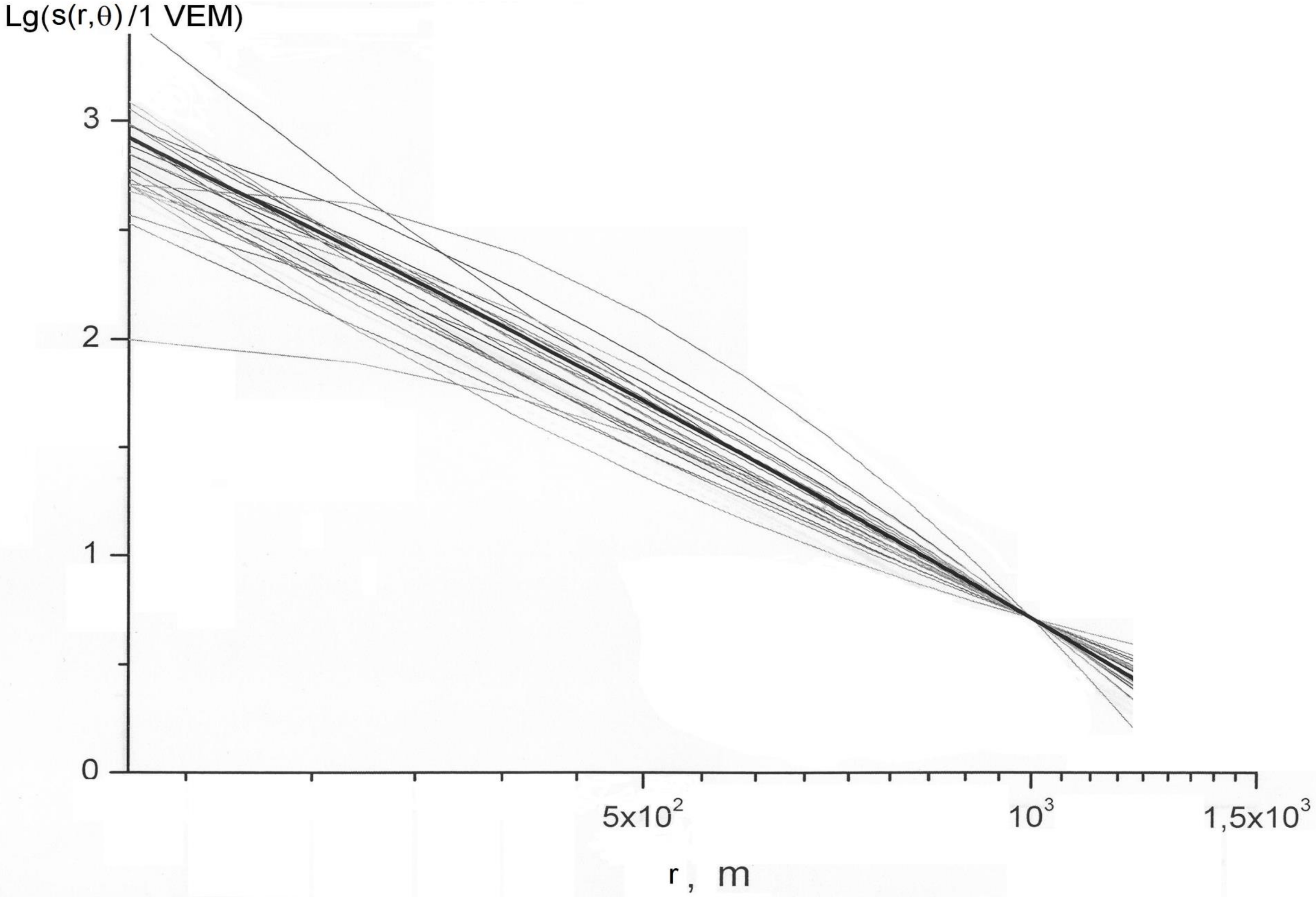
Yakutsk data. LDF normalized at 300 m



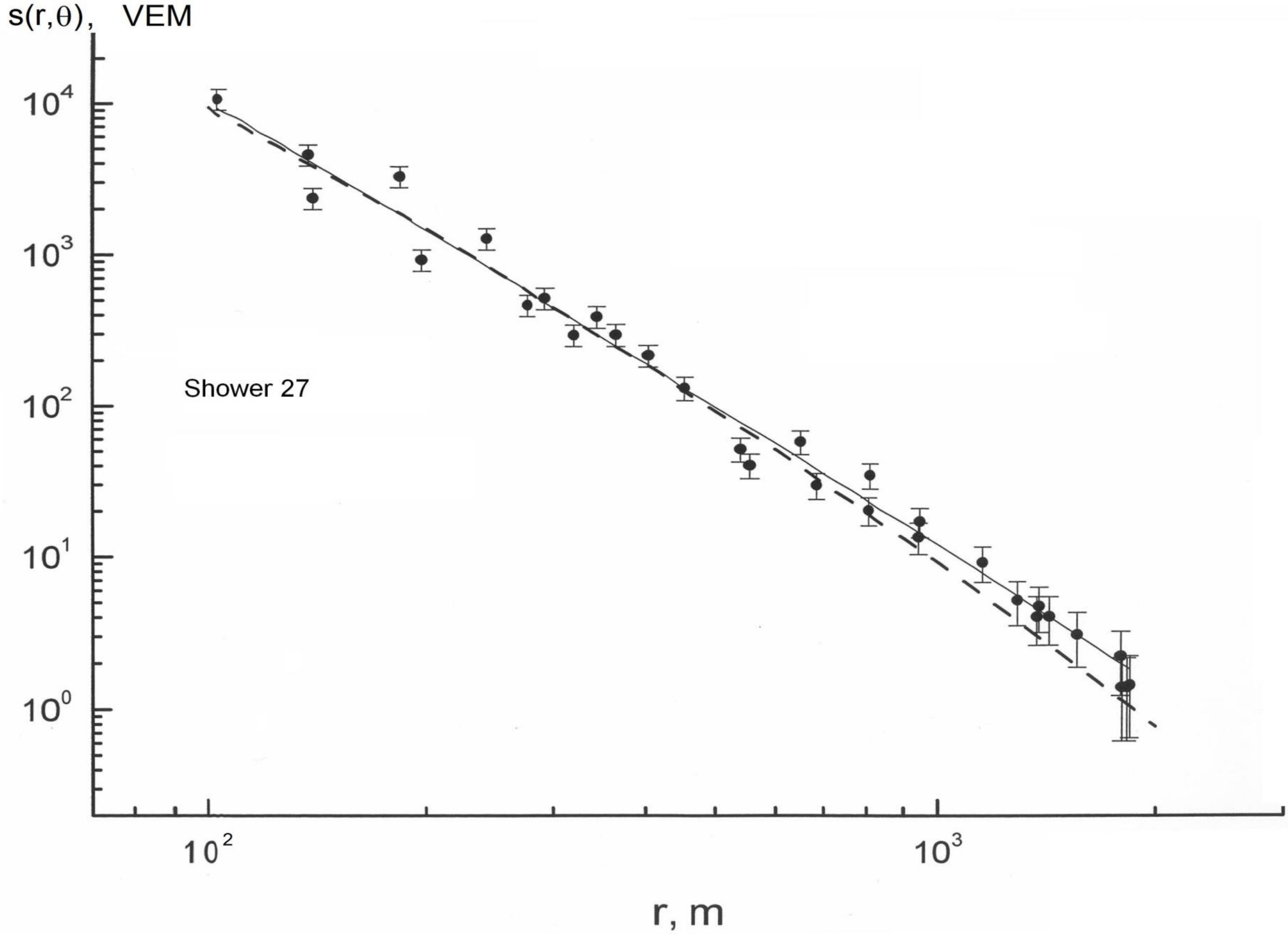
Yakutsk data. LDF normalized 600 m



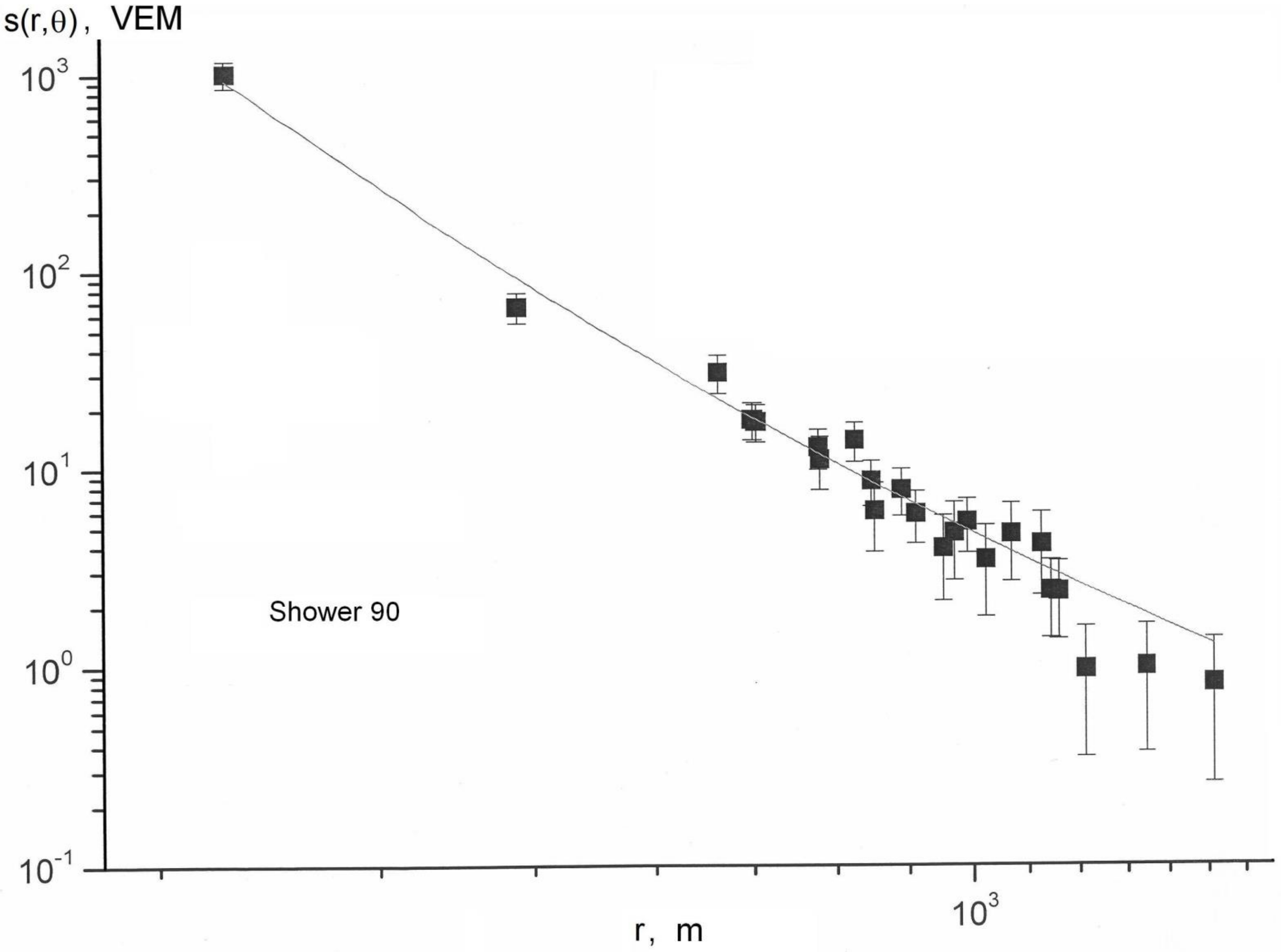
Yakutsk data. LDF normalized at 1000 m



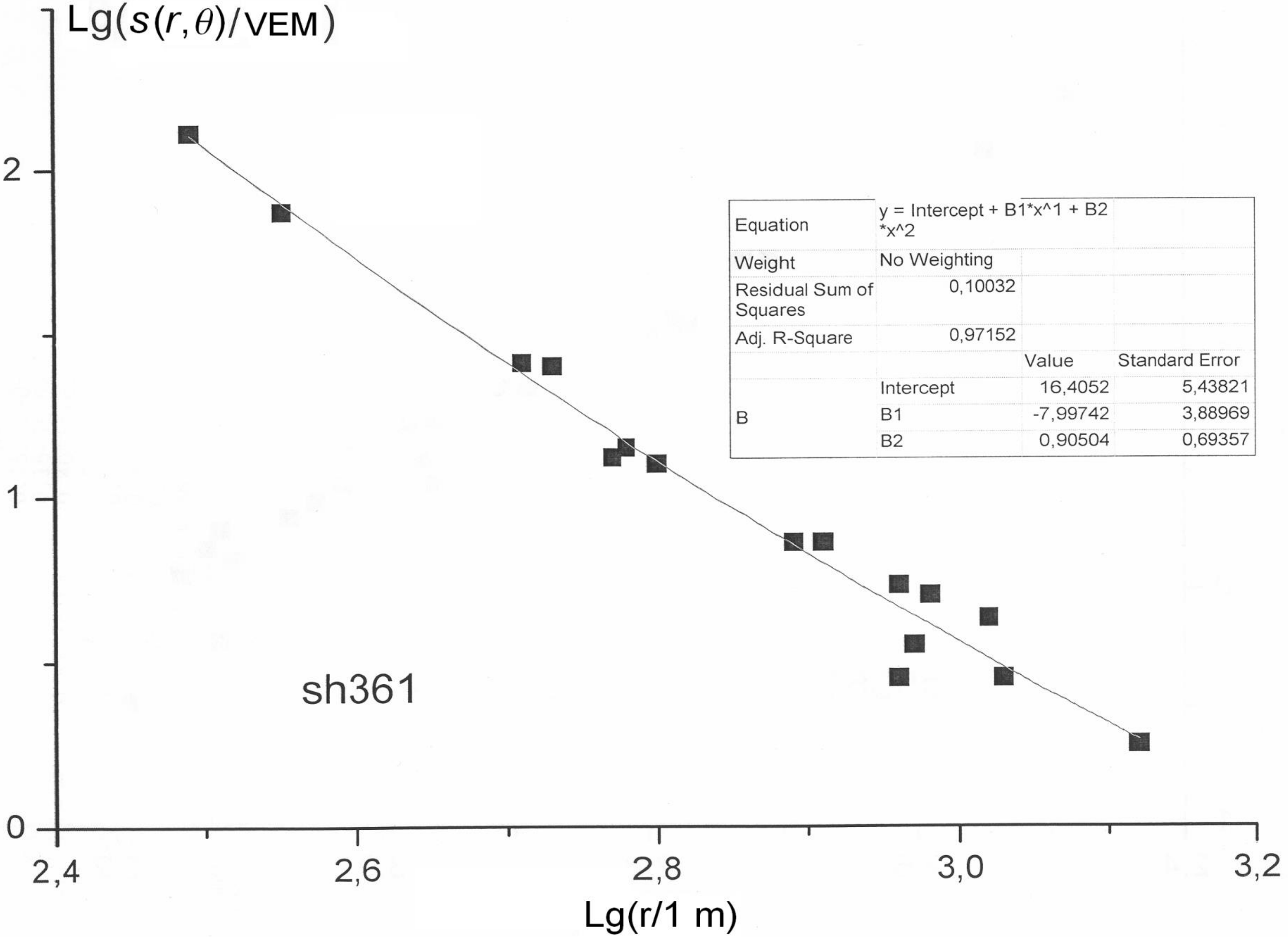
LDF for shower N27, ●-Yakutsk data, —parabolic ---Linsley's type



LDF, ■ -Yakutsk data, — - parabolic approximation

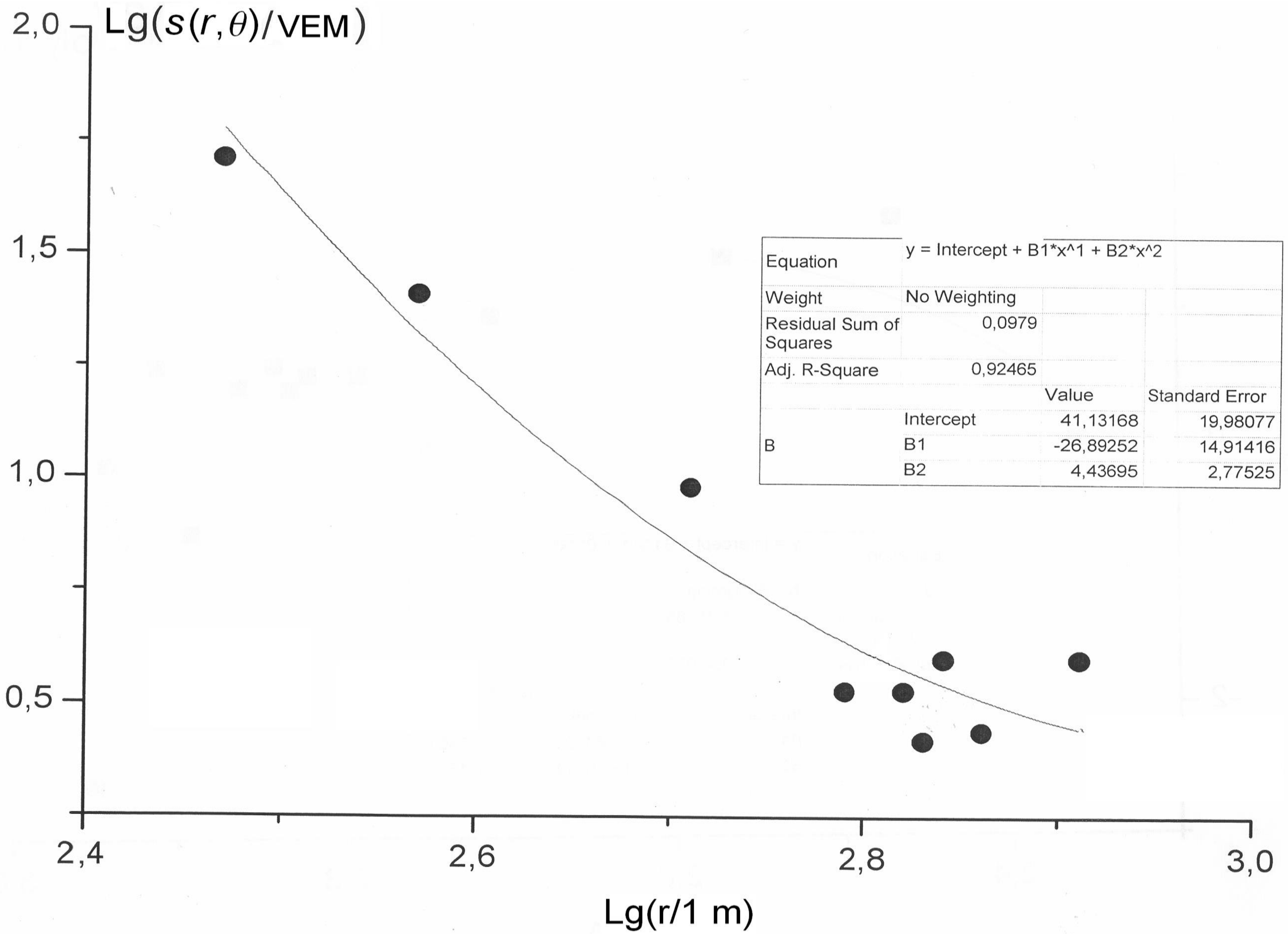


LDF, ■ -Yakutsk data, — - parabolic approximation



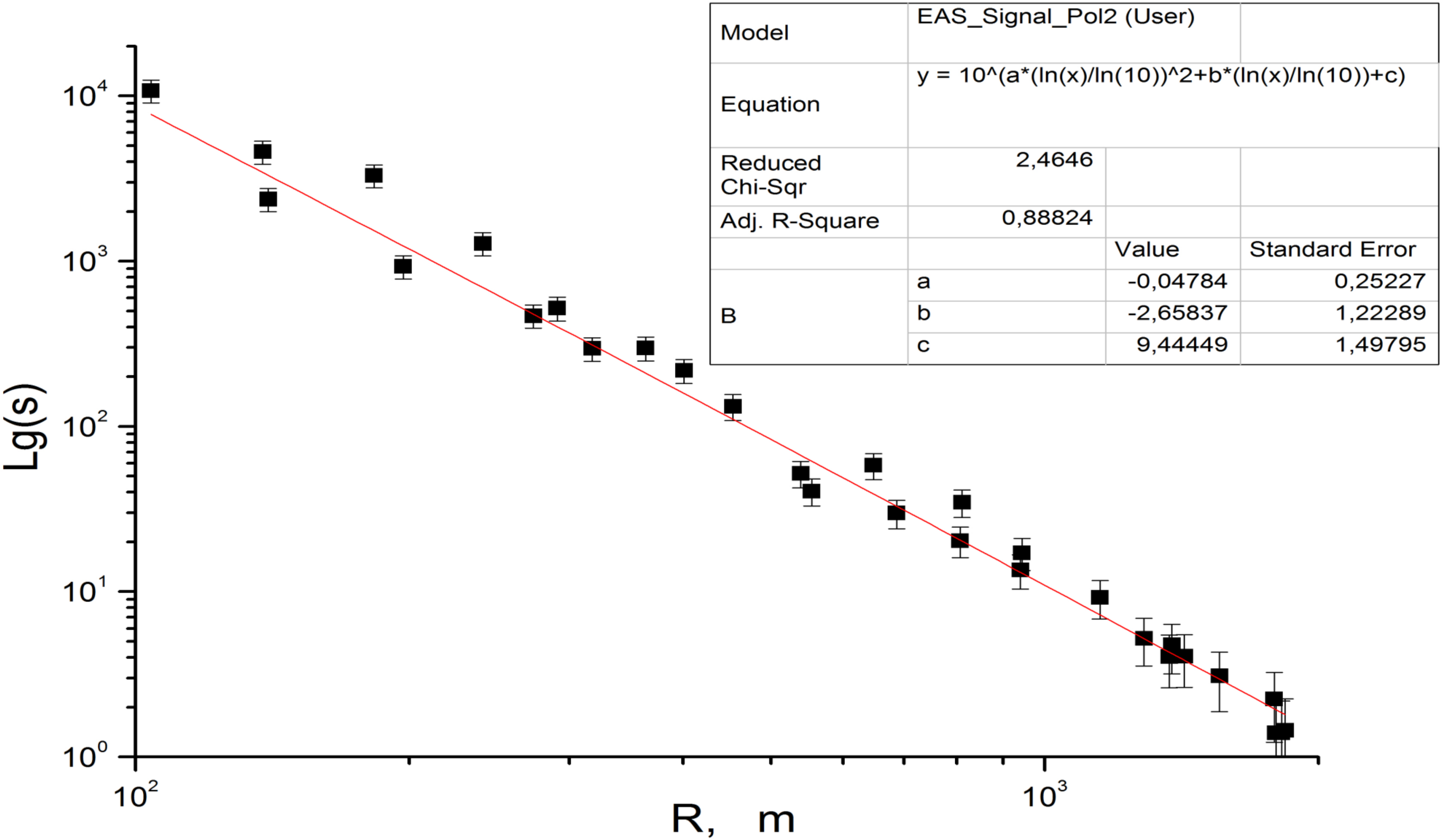
Equation	y = Intercept + B1*x^1 + B2 *x^2		
Weight	No Weighting		
Residual Sum of Squares	0,10032		
Adj. R-Square	0,97152		
		Value	Standard Error
B	Intercept	16,4052	5,43821
	B1	-7,99742	3,88969
	B2	0,90504	0,69357

Yakutsk data. LDF. Parabolic approximation.



Equation	y = Intercept + B1*x^1 + B2*x^2		
Weight	No Weighting		
Residual Sum of Squares	0,0979		
Adj. R-Square	0,92465		
		Value	Standard Error
	Intercept	41,13168	19,98077
B	B1	-26,89252	14,91416
	B2	4,43695	2,77525

Yakutsk data. LDF N27. Parabolic approximation

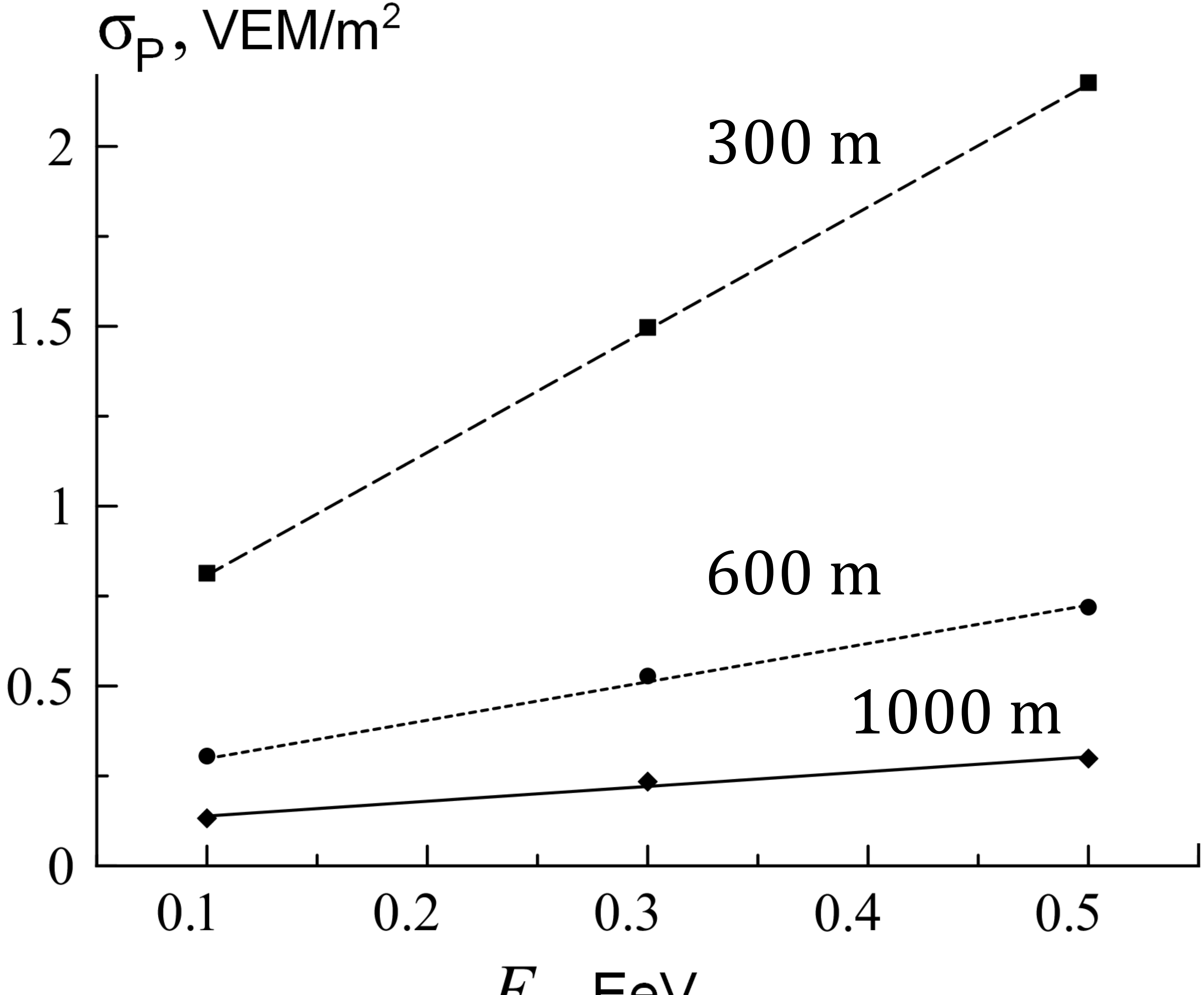


Model	EAS_Signal_Pol2 (User)		
Equation	y = 10^(a*(ln(x)/ln(10))^2+b*(ln(x)/ln(10))+c)		
Reduced Chi-Sqr	2,4646		
Adj. R-Square	0,88824		
		Value	Standard Error
B	a	-0,04784	0,25227
	b	-2,65837	1,22289
	c	9,44449	1,49795

Fluctuations of signals

- Estimates of the Poisson fluctuations
- Real simulations without thinning

Poisson deviation σ_P of signals s in surface detectors



Relative fluctuations σ_P/s

E, EeV	300 m	600 m	1000 m
0.1	0.242	0.849	2.32
0.3	0.141	0.503	1.48
0.5	0.124	0.402	1.11

NEW energy estimates

- 1. For each inclined shower
- with the zenith angle *θ* detectors placed in the array plane have different characteristics .
- 2. The signals in such detectors should be simulated with the help of the GEANT4 and the CORSIKA packages.

CORSIKA – secondary particles from a shower

GEANT4 – signals in detectors from these secondary particles

New energy estimates of inclined showers

- $E_n = a(\theta) \cdot s(600,\theta), \cdot \mathrm{EeV}$
- $a(\theta) = a_0 + a_1 \cdot (\sec\theta - 1) + a_2 \cdot (\sec\theta - 1)^2$
- The zenith angle θ.
  - Signals $s(600,\theta)$ at distance 600 m
  - from the shower core are expressed
  - in units E_{VEM}=10.8 MeV.
- Coefficients $a(\theta)$ were calculated for showers with $\theta = 0^o, 15^o, 30^o$ and 45^o and then values of a_0, a_1, a_2 were estimated.

Coefficients a_i , EeV/VEM

Model	a_0	a_1	a_2
QGSJETII-04	0.289	0.051	1.34
EPOS LHC	0.269	0.0347	1.03

Model calibration

QGSJETII-04, EPOS LHC

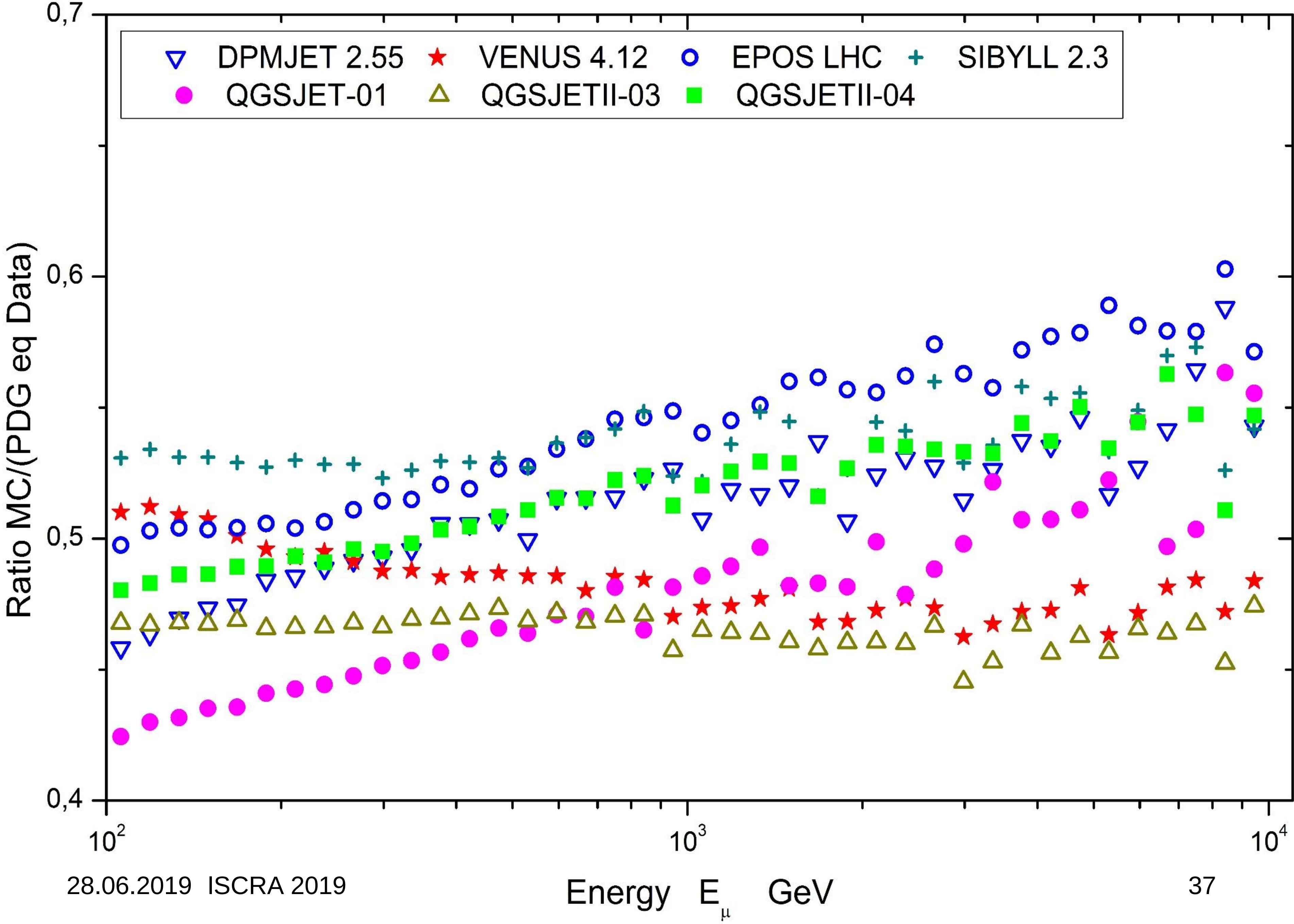
and 6 other models

had been calibrated with the help of the

atmospheric vertical muon energy spectrum.

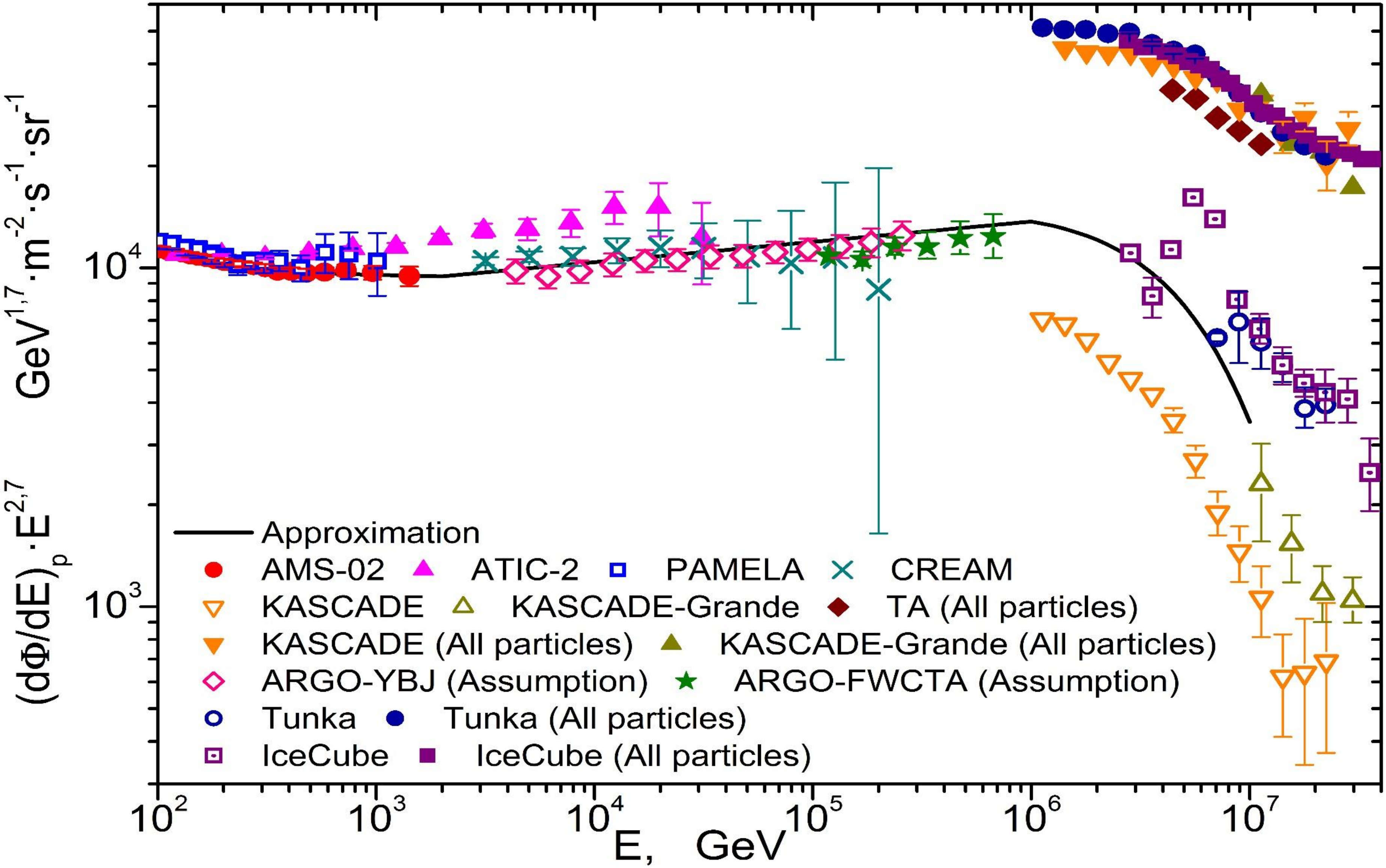
Simulations and Calibration with

PPhDATA.

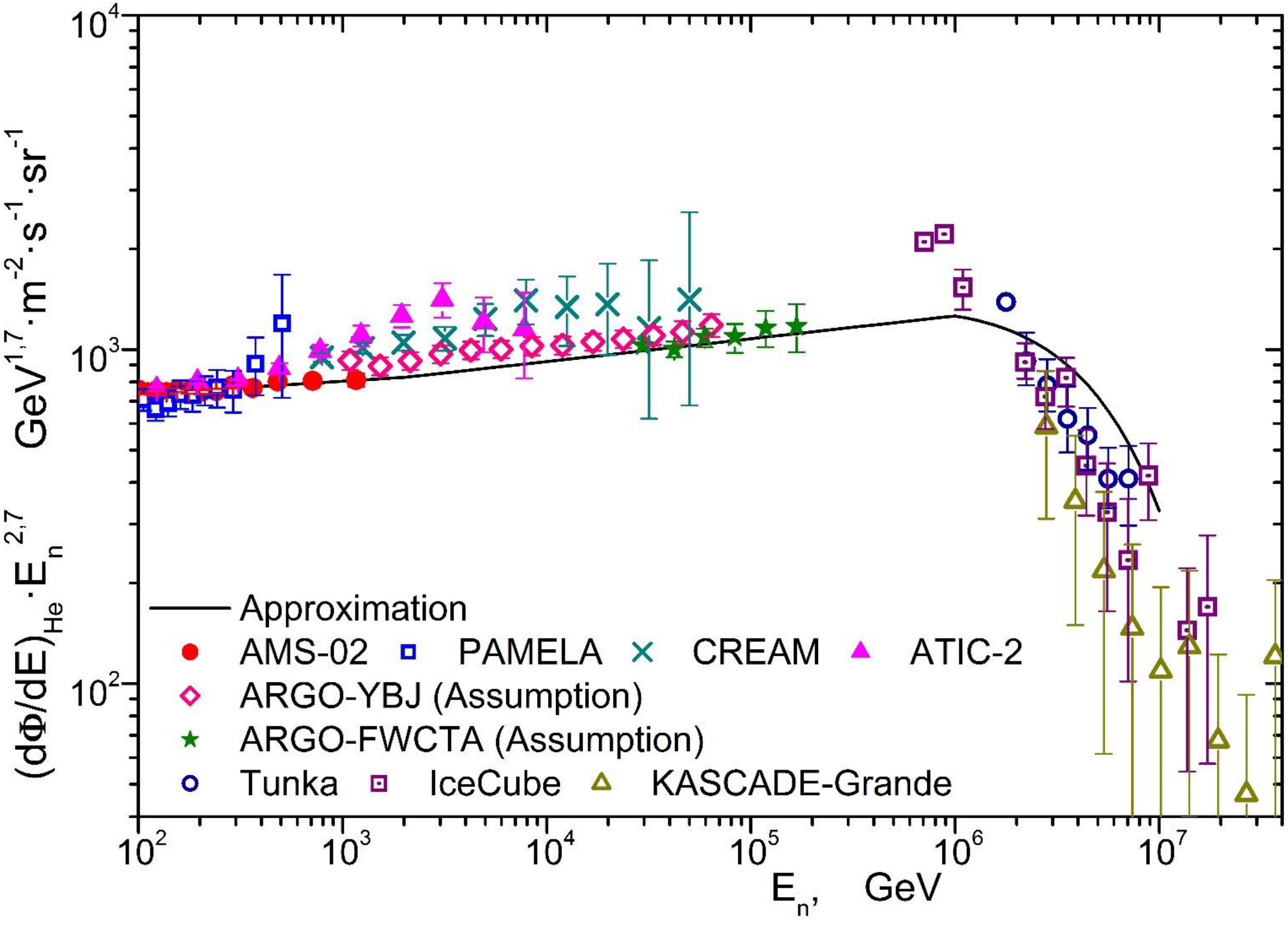


DPMJET 2.55
VENUS 4.12
EPOS LHC
SIBYLL 2.3
QGSJET-01
QGSJETII-03
QGSJETII-04
Ratio MC/(PDG eq Data)
0,7
0,6
0,5
0,4
10^2
10^3
10^4
Energy E_μ GeV

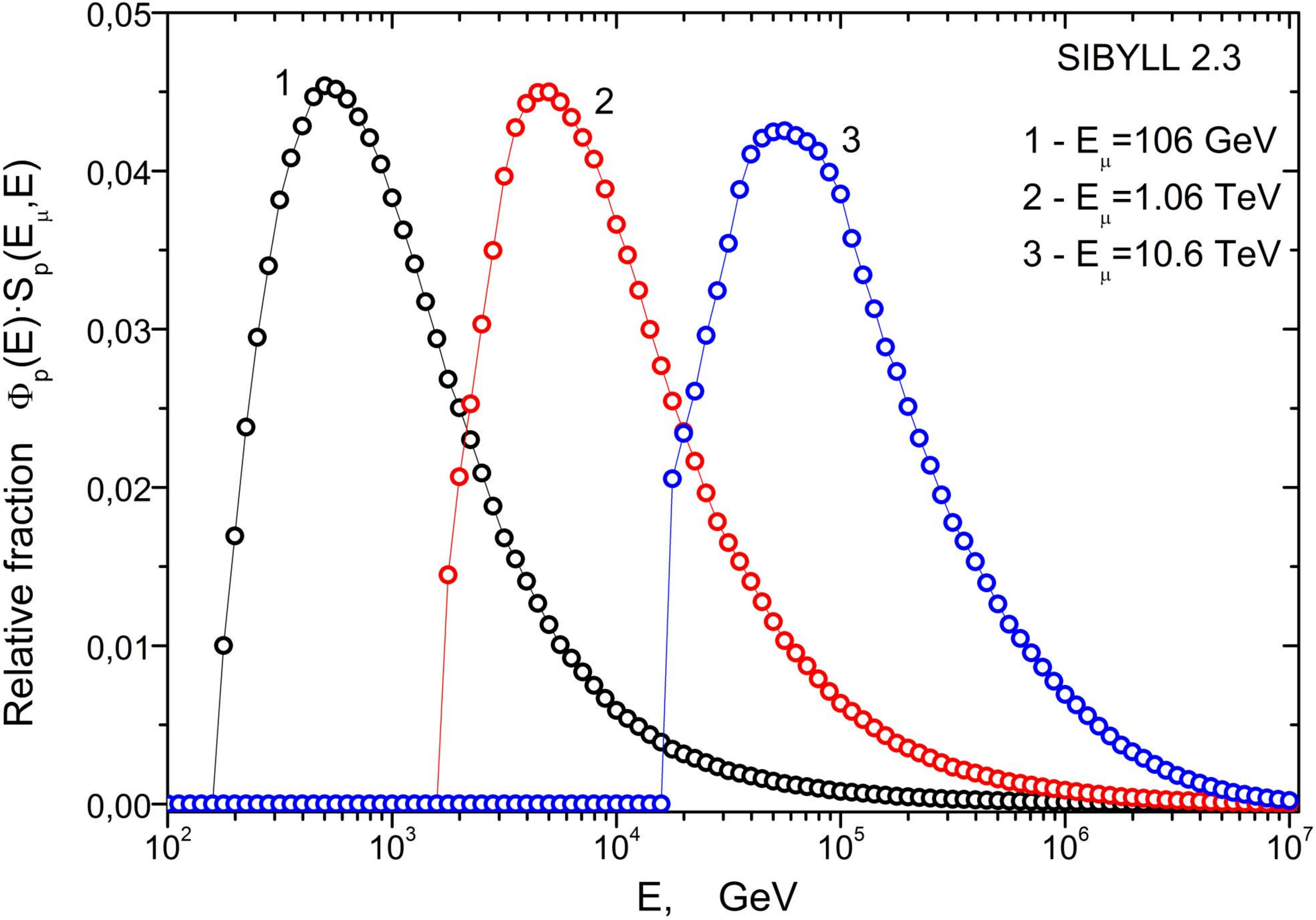
The primary proton spectrum



The primary He spectrum



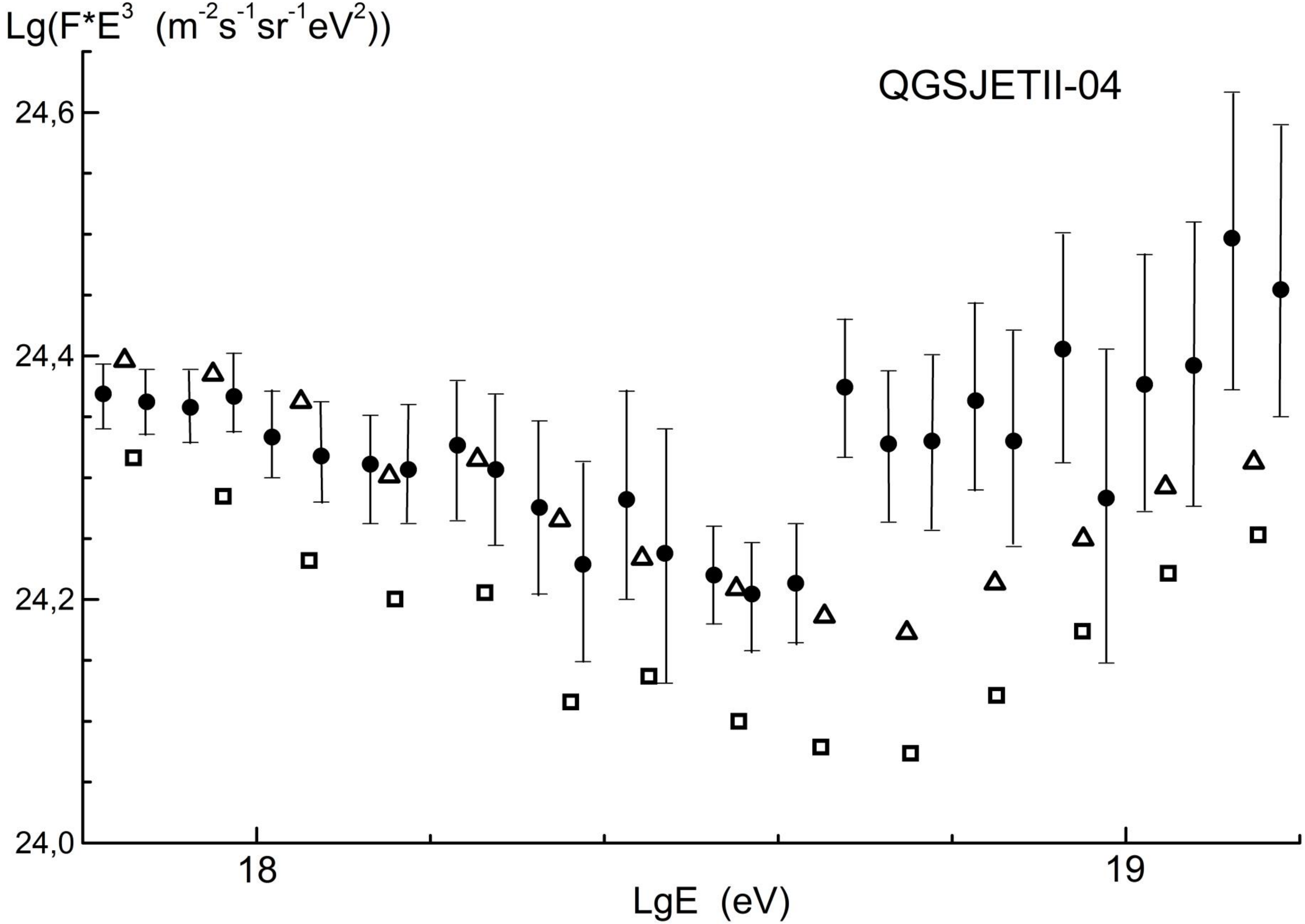
Energy distributions of the primary protons for 3 bins of muon energy spectrum



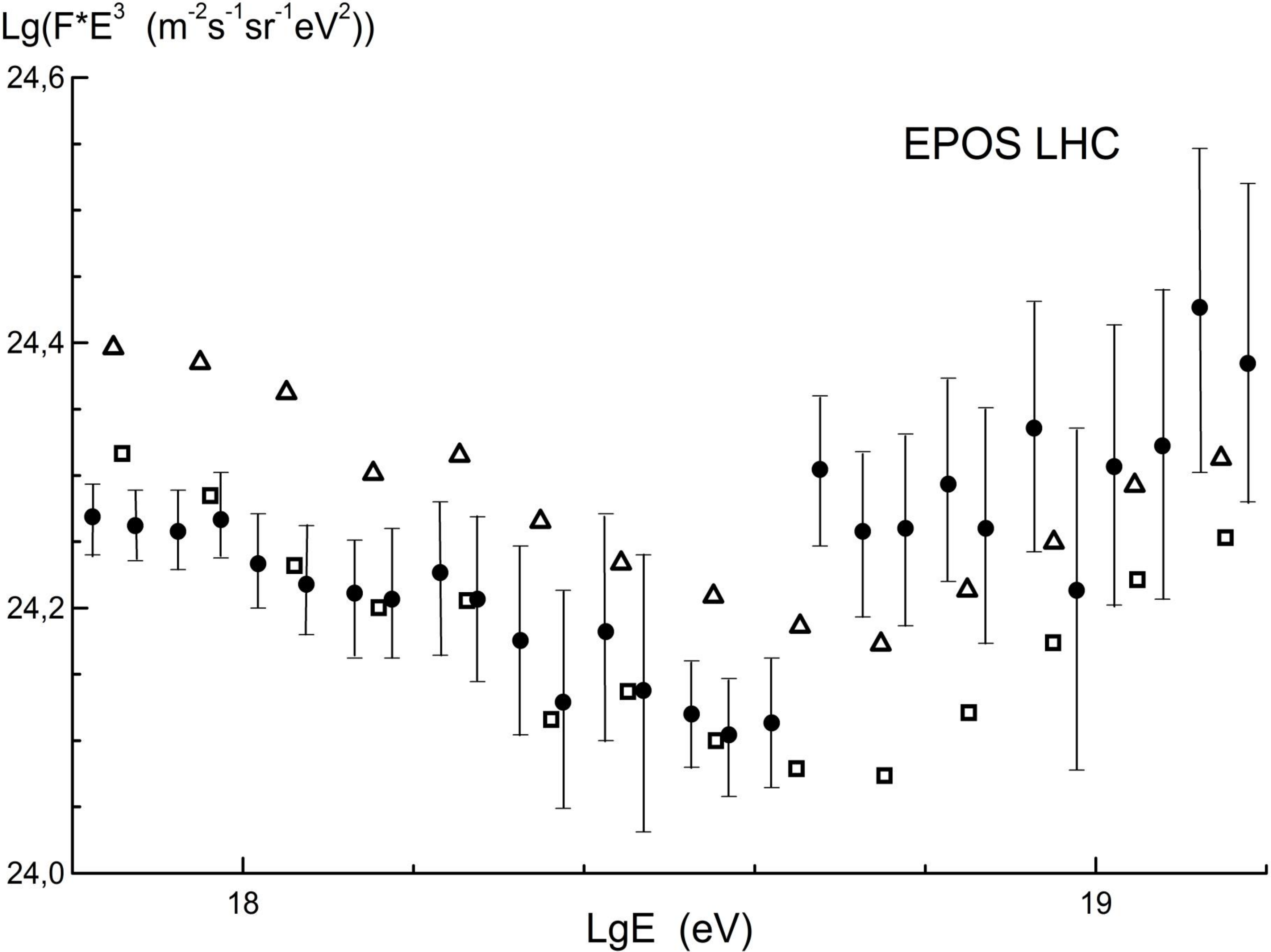
The Yakutsk energy spectrum

- NEW energy estimates had been used to simulate
- the new Yakutsk energy spectrum.

Energy spectra. ●-Yakutsk, △-TA, □- PAO



Energy spectra. ●-Yakutsk, △-TA, □- PAO



The energy uncertainties

- Normal distribution of signals *s* at fixed energy *E*

$$f(s \mid E) = (1/\sqrt{2\pi}\,\sigma)\exp(-(s - < s(E) >)^2/2\sigma^2)$$

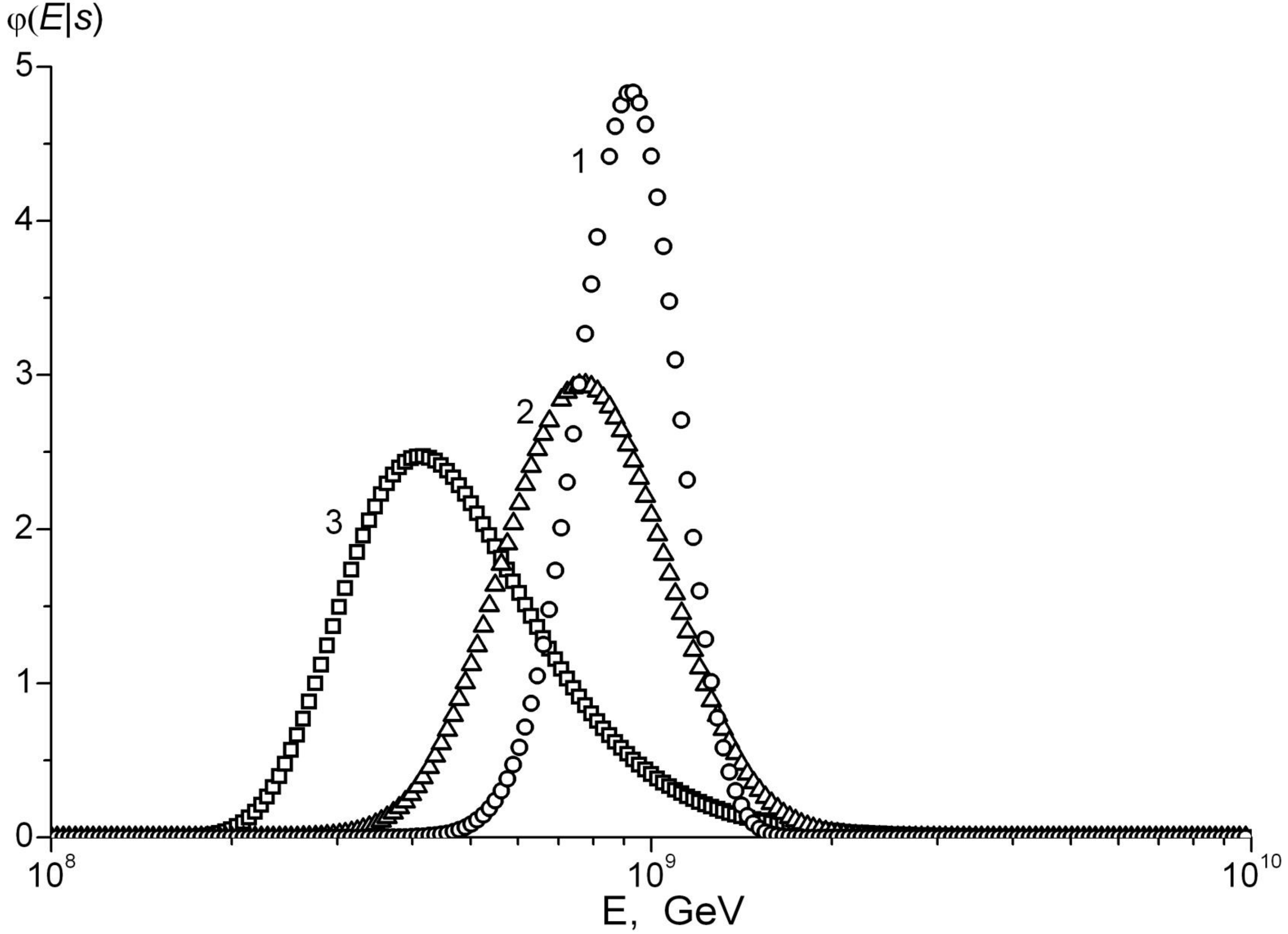
- Conditional distribution of energy *E* at fixed signal *s*

- $\varphi(E \mid s) = F(E)f(s \mid E) \Big/ \int F(E)f(s \mid E)dE$

- $F(E)$ – the energy spectrum of the primary particles

Conditional distributions of energy *E* at fixed signal *s*.

1 – 0.5σ, 2 – σ, 3 - 2σ



CONCLUSION

FOR THE FIRST TIME IT WAS SHOWN THAT

THE YAKUTSK ENERGY SPECTRUM

IS COMPATIBLE WITH THE WORLD DATA

(TA and PAO)

ACKNOWLEDGMENTS

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- *Thanks*
- *for kind*
- *attention*