ENERGY ESTIMATION OF GIANT AIR SHOWERS

L. DEDENKO
M.V. Lomonosov Moscow State University

CONTENT

V. CONCLUSION

1. AT LEAST 4 SHOWER OBSERVED AT THE YAKUTSK ARRAY MAY HAVE ENERGIES ABOVE 10^{20} eV.

2. ENERGY OF ONE SHOWER HAS BEEN ESTIMATES AS $3 \cdot 10^{20}$ eV.

3. GIANT SHOWER INCLUDE MUONS – THE PRIMARY PROTONS?

4. NEW PHENOMENON – GIANT AIR SHOWERS WITH ENERGIES ABOVE 10^{20} eV HAS BEEN CONFIRMED

5. NEW CALCULATIONS SHOULD BE CARRIED OUT

DETECTOR READIGS should ~~be~~ interpreted

Acknowledgements. We wish to thank G.T. Zatsepin for useful discussions. The Russian National Fund for Fundamental Investigations is thanked for support (Grant 00-15-96632, scientific school of G.T. Zatsepin). Besides, we'd like to thank administrators of the computational cluster of RCC of the MSU for assistance and help during the work.

Direction of muon velocity $\vec{V}$ is defined by directional cosines:

$$\sin\Theta\cdot\cos\varphi\cdot\cos\alpha-\cos\Theta\cdot\cos\varphi\cdot\sin\alpha\cdot\cos\delta-\sin\varphi\cdot\sin\alpha\cdot\sin\delta;$$
$$\sin\Theta\cdot\sin\varphi\cdot\cos\alpha-\cos\Theta\cdot\sin\varphi\cdot\sin\alpha\cdot\cos\delta+\cos\varphi\cdot\sin\alpha\cdot\sin\delta;$$
$$-\cos\Theta\cdot\cos\alpha-\sin\Theta\cdot\sin\alpha\cdot\cos\delta$$

All muons are defined in groups with bins of energy $E_i \div E_i+\Delta E$; angles $\alpha_j \div \alpha_j+\Delta\alpha_j$, $\delta_m \div \delta_m+\Delta\delta_m$ and height production $h_k \div h_k+\Delta h_k$. The average values have been used: $\bar{E}$, $\bar{\alpha}_j$, $\bar{\delta}_m$ and $\bar{h}_k$. Number of muons ΔN^+_μ и ΔN^-_μ were regarded as some weights.

The relativistic equation:

$$\gamma m_\mu \frac{d\vec{V}}{dt}=e\vec{V}\times\vec{B},$$

here m_μ – muon mass; e – charge; γ – lorentz factor; t – time; $\vec{B}$ – geomagnetic field.

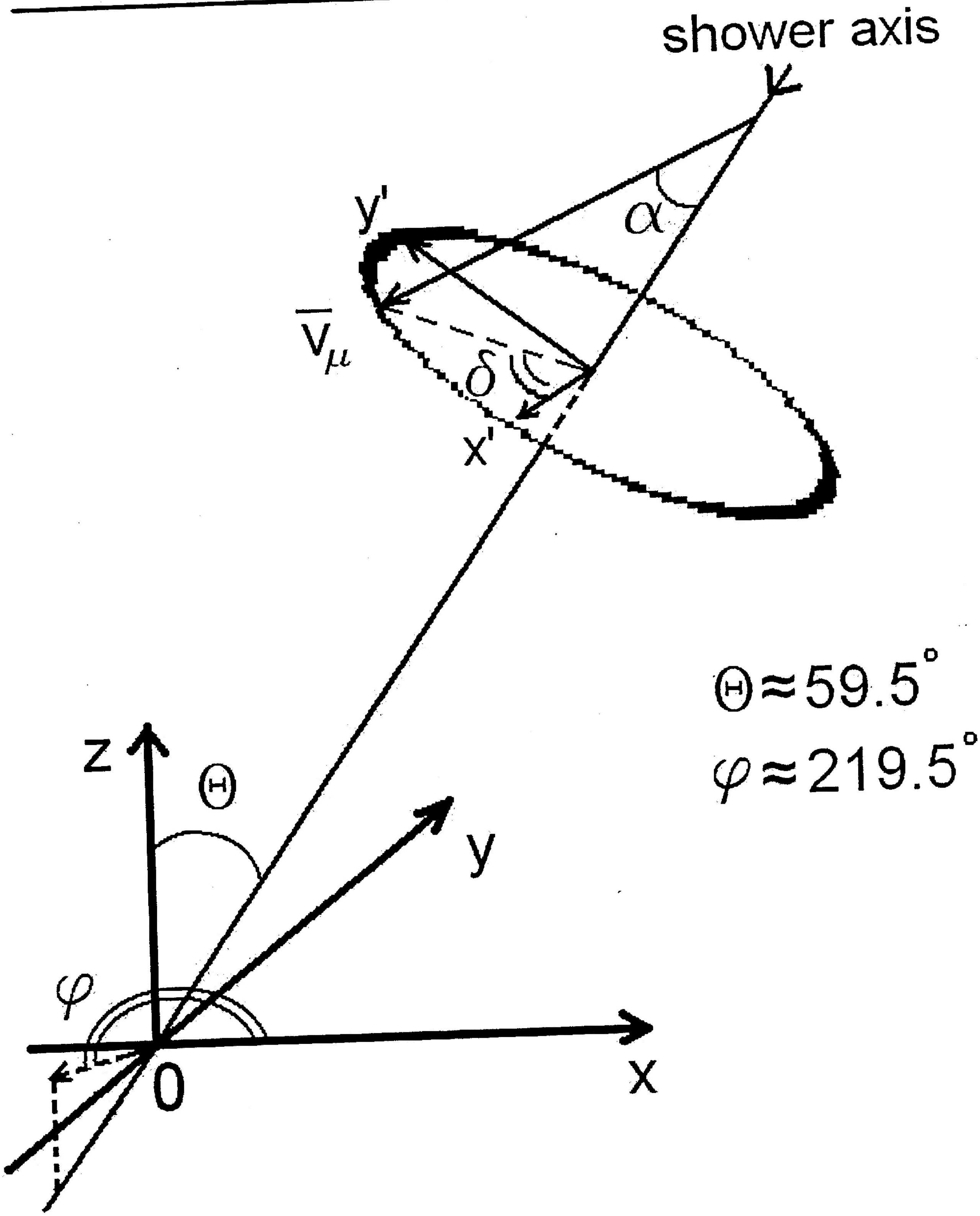
The explicit 2-d order scheme:

$$V_x^{n+1/2}=V_x^n+CHE^n(V_y^nB_z-V_z^nB_y)\cdot(0.5\cdot h_t); \qquad x^{n+1/2}=x^n+V_x^n\cdot(0.5\cdot h_t)$$
$$V_y^{n+1/2}=V_y^n+CHE^n(V_z^nB_x-V_x^nB_z)\cdot(0.5\cdot h_t); \qquad y^{n+1/2}=y^n+V_y^n\cdot(0.5\cdot h_t)$$
$$V_z^{n+1/2}=V_z^n+CHE^n(V_x^nB_y-V_y^nB_x)\cdot(0.5\cdot h_t); \qquad z^{n+1/2}=z^n+V_z^n\cdot(0.5\cdot h_t)$$

$$V_x^{n+1}=V_x^n+CHE^{n+1/2}(V_y^{n+1/2}B_z-V_z^{n+1/2}B_y)\cdot h_t; \qquad x^{n+1}=x^n+V_x^{n+1/2}\cdot h_t$$
$$V_y^{n+1}=V_y^n+CHE^{n+1/2}(V_z^{n+1/2}B_x-V_x^{n+1/2}B_z)\cdot h_t; \qquad y^{n+1}=y^n+V_y^{n+1/2}\cdot h_t$$
$$V_z^{n+1}=V_z^n+CHE^{n+1/2}(V_x^{n+1/2}B_y-V_y^{n+1/2}B_x)\cdot h_t; \qquad z^{n+1}=z^n+V_z^{n+1/2}\cdot h_t,$$

here $CHE=e\cdot(E_{thr}/E)$; E_{thr}, E – threshold energy and muon energy.

Direction of a muon velocity V_μ



$$E_0 = a \cdot \rho^b(0)$$, Hillas, 1971 (1)

$$\rho(0) = \rho(\theta) \cdot \exp\left(x_0(\sec\theta - 1)/\lambda\right)$$ (2)

Yakutsk : a=(4.8±1.6)·10[17], b=1.0±0.02

$$\lambda = 450 \pm 44 + (32 \pm 15) \cdot \lg \rho_{600}(0^\circ)\ g/cm^2$$ (3)

AGASA: a=2·10[18], b=1 ?

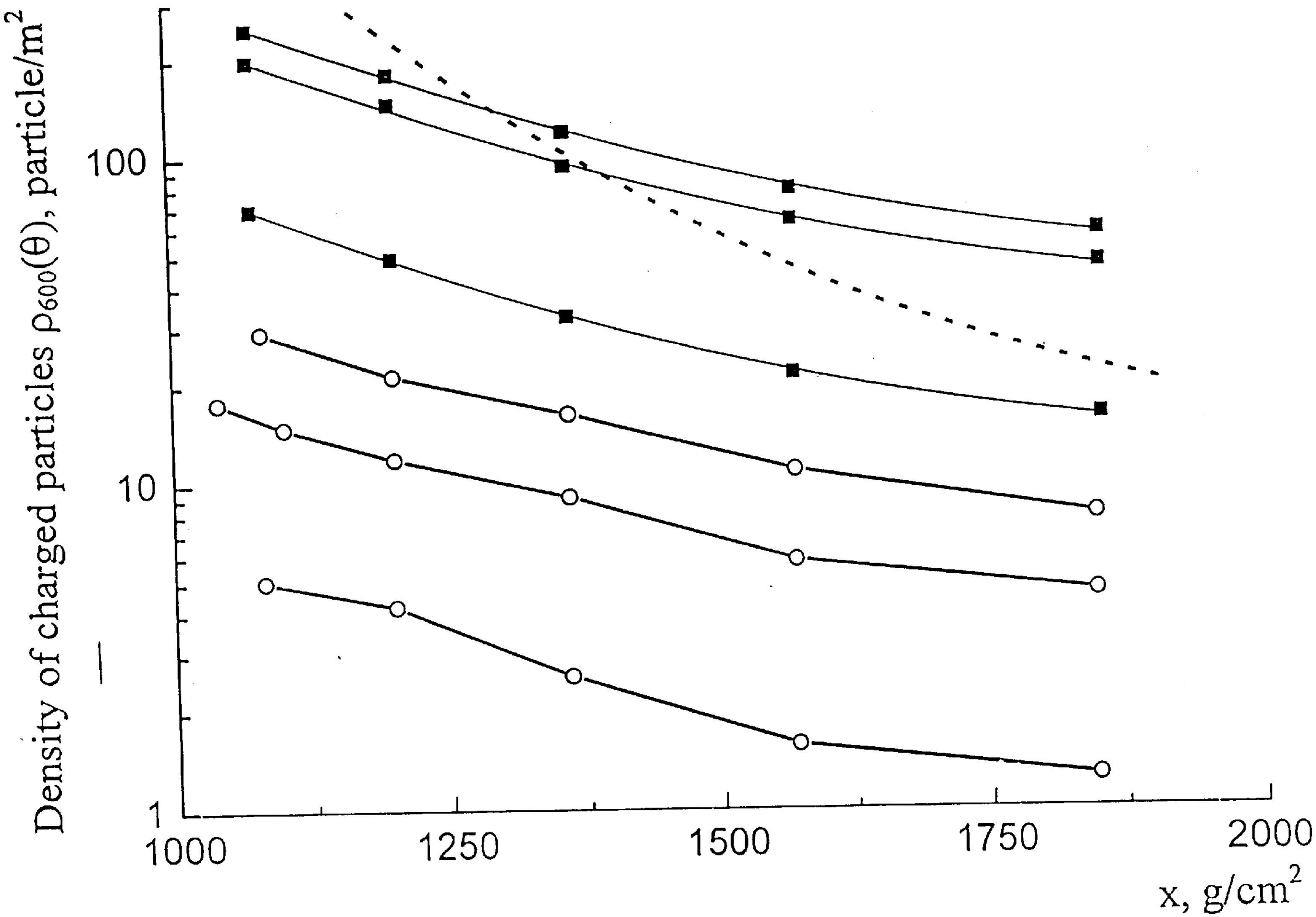
$$\lambda \cong 500\ g/cm^2$$ (4)

$$\lambda = x_0(\sec\theta - 1)/\ln(\rho(0)/\rho(\theta))$$ (5)

$$C(\rho_{600} > \rho_{threshold}) = \int_{\rho_{threshold}}^{\infty} C(\rho_{600})\, d\rho_{600}$$ (6)

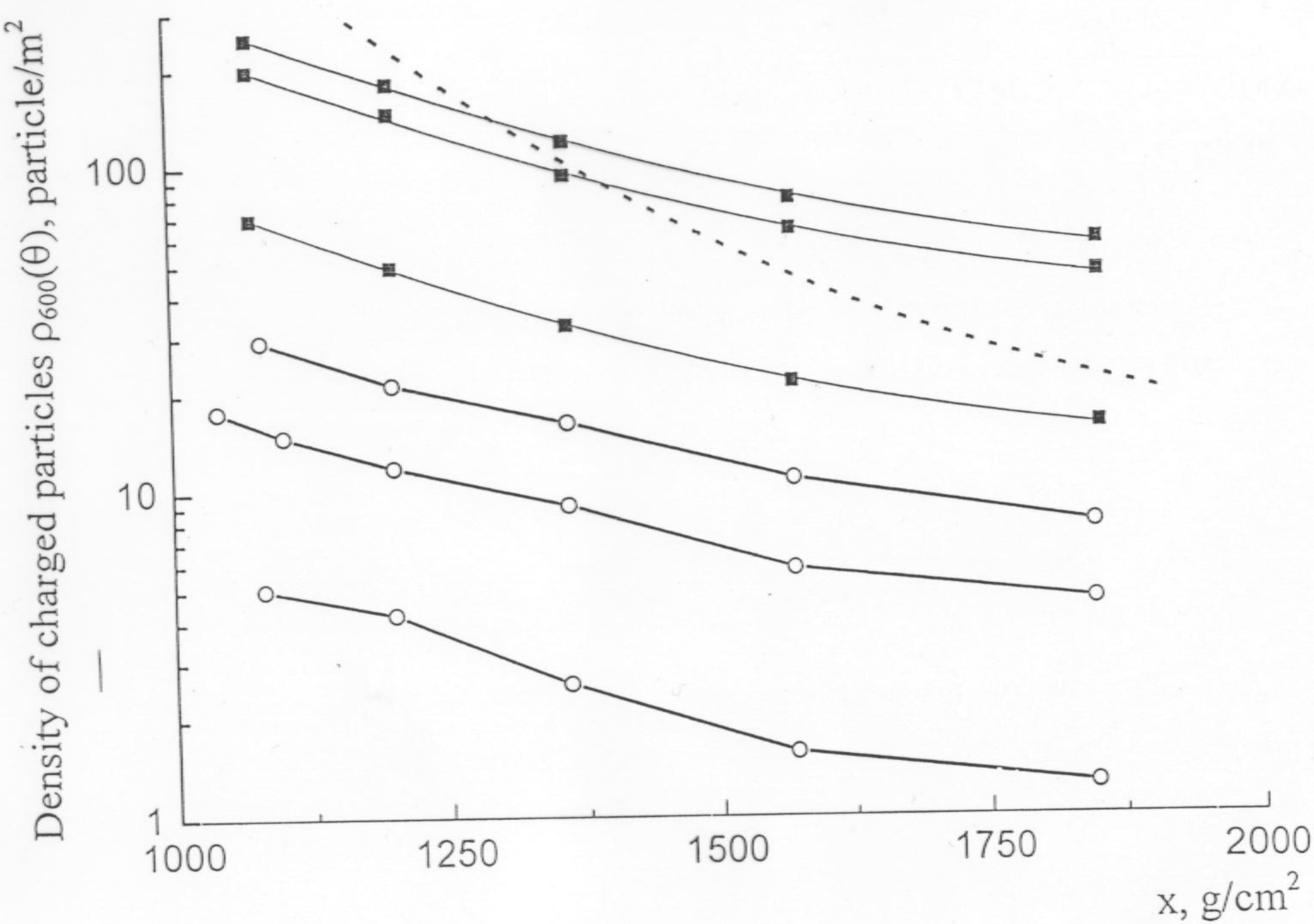
$$C(\rho_{600}(\theta)) = \\ = \int_{y_1}^{y_2} \exp(-\gamma y) dy \int_{\theta^i}^{\theta^{i+1}} d\theta_0 \int_{\theta_0 - 3\sigma}^{\theta_0 + 3\sigma} P(\rho_{600}(\theta) | \theta, y) \sin\theta \exp\left(-\frac{(\theta - \theta_0)^2}{2\sigma^2}\right) d\theta$$ (7)

y = 0.5



1.5

Fig. 3. Reconstructed cascade curves. Squares – simulations, circles – data [10], dotted curve – the mean cascade curve. – – – Λ ~ 350; —— Λ ~ 540 ± 60 gcm⁻²


Density of charged particles ρ600(θ), particle/m²
100
10
1
1000
1250
1500
1750
2000
x, g/cm²

A Fast Hybrid Approach to Air Shower Simulations and Applications

Hans-Joachim Drescher[1], Glennys Farrar[2], Marcus Bleicher[1], Manuel Reiter[1], Sven So.[1], Horst StËocker[1]
(1) Institut f¨ur Theoretische Physik, Johann Wolfgang Goethe Universit¨at, Robert-Mayer Str. 8-10, Frankfurt am Main, Germany
(2) Center for Cosmologie and Particle Physics, New York University, 4 Washington Place, NY 10003, USA

Hadronic Cascade Equations

$$\begin{aligned}\frac{\partial h_n(E,X)}{\partial X} &= -h_n(E,X)\left[\frac{1}{\lambda_n(E)}+\frac{B_n}{EX}\right] \\ &+\sum_m \int_E^{E_{\max}^{\mathrm{had}}} h_m(E',X)\left[\frac{W_{mn}(E',E)}{\lambda_m(E')}+\frac{B_m D_{mn}(E',E)}{E'X}\right] dE'\end{aligned}$$

Electromagnetic Cascading

$$g_i^n(X+\Delta X)=\sum_{m,j\geq i} g_j^m(X)V_{ji}^{mn}(\Delta X)\,.$$

Source Functions

$$\frac{\partial h_n^{\mathrm{source}}(E,X)}{\partial X} = \sum_m \int_{E_{\min}^{\mathrm{had}}}^{E_{\max}^{\mathrm{had}}} h_m(E',X)\left[\frac{W_{mn}(E',E)}{\lambda_m(E')}+\frac{B_m D_{mn}(E',E)}{E'X}\right] \mathrm{d}E'\,.$$

One-dimensional Hybrid Simulation of EAS Using Cascade Equations

N.N. Kalmykov[1], M.K. Alekseeva[1], T. Bergmann[2], V. Chernatkin[4], R. Engel[2], D. Heck[2], J. Moyon[4], S.S. Ostapchenko[3,1], T. Pierog[2], T. Thouw[2], and K. Werner[4]
(1) Skobeltsyn Institute of Nuclear Physics, Moscow State University, Leninskie Gory 1, 119992, Moscow, Russia
(2) Forschungszentrum Karlsruhe, Institut f¨ur Kernphysik, Postfach 3640, 76021 Karlsruhe, Germany
(3) Institut f¨ur Experimentelle Kernphysik, University of Karlsruhe, 76021 Karlsruhe, Germany
(4) SUBATECH, Universite de Nantes, EMN, IN2P2/CNRS, Nantes, France

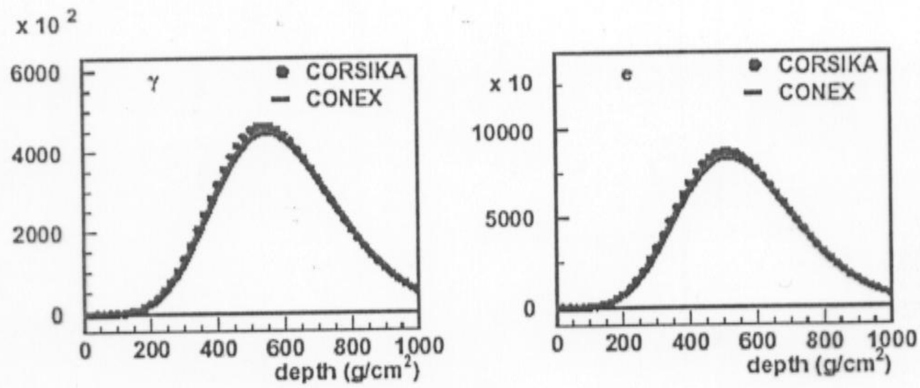


Fig. 1. Number of photons (left) and electrons/positrons (right) as function of slant depth for photon-induced showers of 10^{14} eV. Only particles with kinetic energy greater than 1 MeV are considered.

III. NEW SUGGESTION

1. THE NORMALISED MODEL SHOULD BE USED.
   - THE CALORIMETRY METHOD
   - THE FLY'S EYE DATA ON THE LONGITUDINAL DEVELOPMENT
   - μ / e RATIO

2. ARRIVAL DIRECTION IN TERMS OF CALCULATED TIME FRONT

3. INTERPRETING OF DETECTOR READINGS IN THE ARRAY PLANE

$$\chi^2_{N-3} = \sum_{i=1}^{N} \left(\frac{\rho_{th} - \rho_{\exp}}{\sigma} \right)^2$$

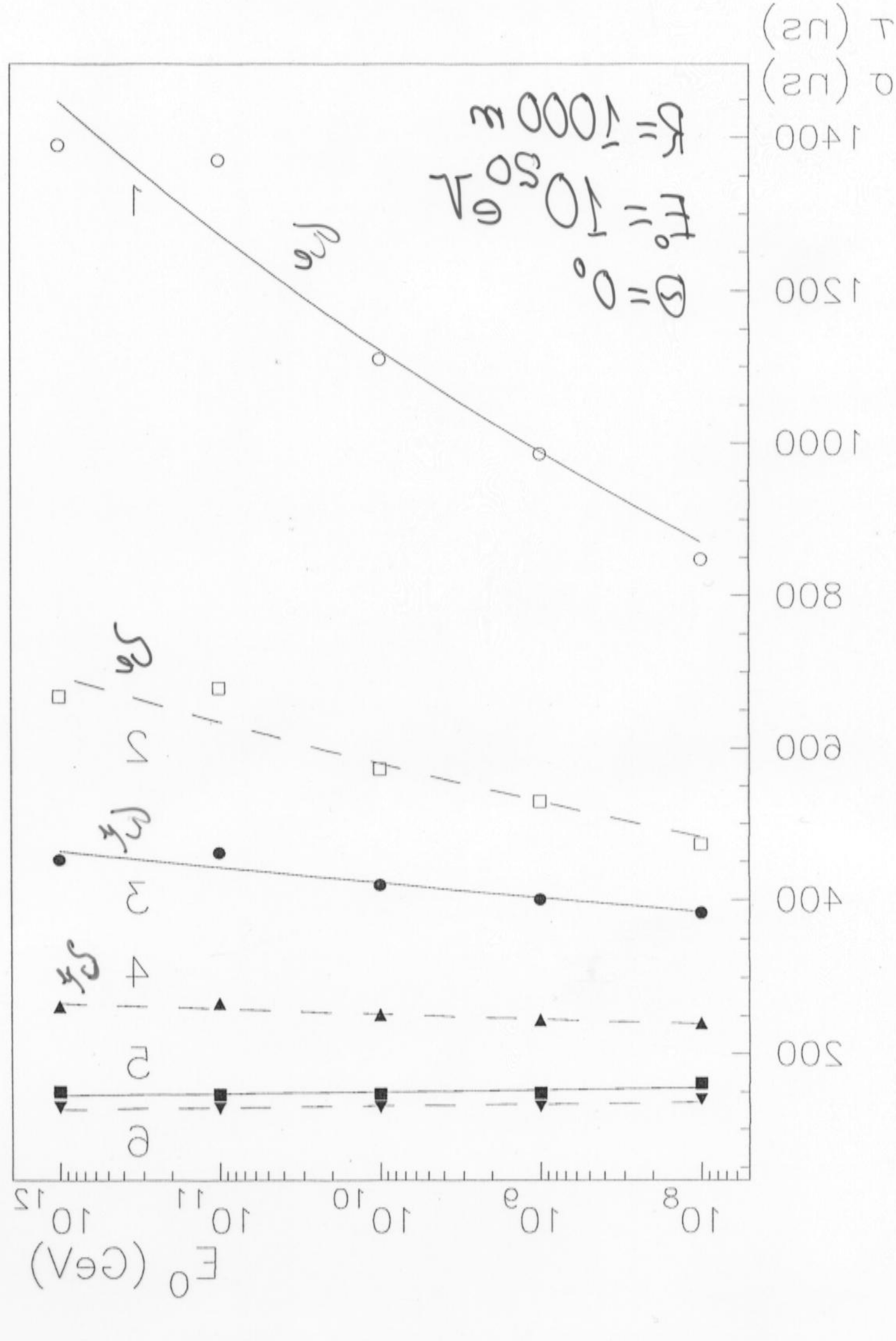
Eo, X, Y ARE ESTIMATED

OR $\quad \min \chi^2 : \; lg\rho = k\,(lgR)^{2.2} + b$

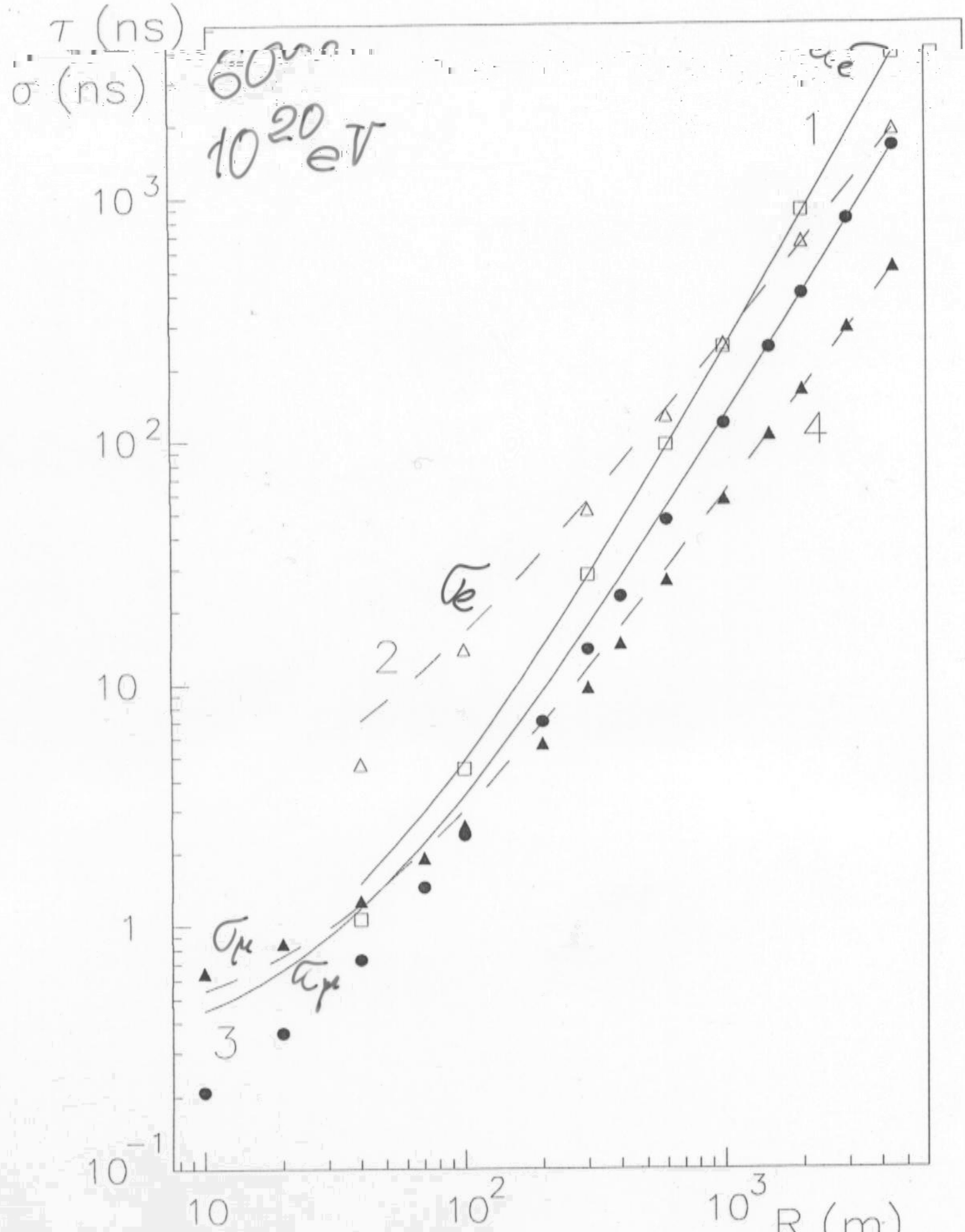
$$k = k(E, \theta)$$

$$b = b(E, \theta)$$

4. FOR INCLINED SHOWERS THE GEOMAGNETIC FIELD SHOULD BE TAKEN INTO ACCOUNT.



τ (ns)
σ (ns)
E0 (GeV)
1
2
3
4
5
6


τ (ns)
σ (ns)
60°
10^20 eV
τe
σe
1
2
3
4
σμ
τμ
10^3
10^2
10
1
10^-1
10
10^2
10^3
R (m)

5 – LEVEL SIMULATION OF THE GIANT AIR SHOWERS:

1. MONTE-CARLO CALCULATIONS FOR HIGH-ENERGY HADRONS,
2. CASCADE EQUATIONS FOR NUMEROUS SECONDARY HADRONS,
3. CASCADE EQUATIONS FOR HIGH- ENERGY ELECTRONS AND PHOTONS (UP TO NEARLY 10 GeV),
4. MONTE-CARLO SIMULATIONS OF THE ELECTRON-PHOTON CASCADES WITH ENERGIES UNDER 10 GeV,
5. USING GEANT TO PRODUCE THE RESPONCE OF A DETECTOR.

POSSIBILITY THEORY SHOULD BE USED TO INTERPRET DATA

A MODEL USED SHOULD BE CHECKED BY THE DATA (MU/E RATIO, CHERENKOV LIGHT AND etc.)

$$E_0=E_{ion}+E_{e\text{-}ph}+E_{mu,nu}+E_d$$

CALCULATION:	77,	13,	9,	1 %
DATA:	79+-2,	7.+-2,	8,	5

Transport equation for hadrons:

$$\frac{\partial P_k(E,x)}{\partial x} = -P_k(E,x)/\lambda_k(E) - B_k P_k(E,x)/(E\cdot x) + \sum_{i=1}^{m}\int dE' P_i(E',x) W_{ik}(E',E)/\lambda_i(E'),$$

here $k=1,2,....m$ – number of hadron types; $P_k(E,x)dEdx$ –number of hadrons k in bin $E\div E+dE$ and depth bin $x\div x+dx$; $\lambda_k(E)$ – interaction length; B_k – decay constant ($m_k c z_o/\tau_k$); $W_{ik}(E',E)$ – energy spectra of hadrons.

The integral form:

$$P(E,x) = P_b(E,x_b)\cdot \exp(-(x-x_b)/\lambda(E) - (B/E)\ln(x/x_b)) +$$
$$+ \int_{x_b}^{x} d\xi \cdot \exp(-(x-\xi)/\lambda(E) - (B/E)\ln(x/\xi))\cdot f(E,\xi),$$

here $f(E,\xi) = \int_{E}^{E_0} dE' P(E',\xi) W(E',E)/\lambda(E')$; E_0 – energy of the primary particle; $P_b(E,x_b)$ – boundary condition; x_b – point of interaction of the primary particle.

The basic cascade equations for electrons and photons can be written as follows:

$$\partial P / \partial t = -\mu_e P + \beta \partial P / \partial E + S_e + \int P W_b dE' + \int \Gamma W_p dE'$$

$$\partial \Gamma / \partial t = -\mu_\gamma \Gamma + S_\gamma + \int P W_b dE',$$

where $\Gamma(E,t)$, $P(E,t)$ – the energy spectra of photons and electrons at the depth t; β – the ionization losses; μ_e, μ_γ – the absorption coefficients; W_b, W_p – the bremsstrahlung and the pair production cross-sections; S_e, S_γ – the source terms for electrons and photons.

The integral form:

$$P(E,t) = P[E + \beta(t - t_0), t_0]\exp(-\int_{t_0}^{t} \mu_e[E + \beta(t - \xi)]d\xi) +$$

$$+ \int_{t_0}^{t} d\xi \exp(-\int_{\xi}^{t} \mu_e[E + \beta(t - t')]dt'[S_e[E + \beta(t - \xi), \xi] + A_e + B_e]$$

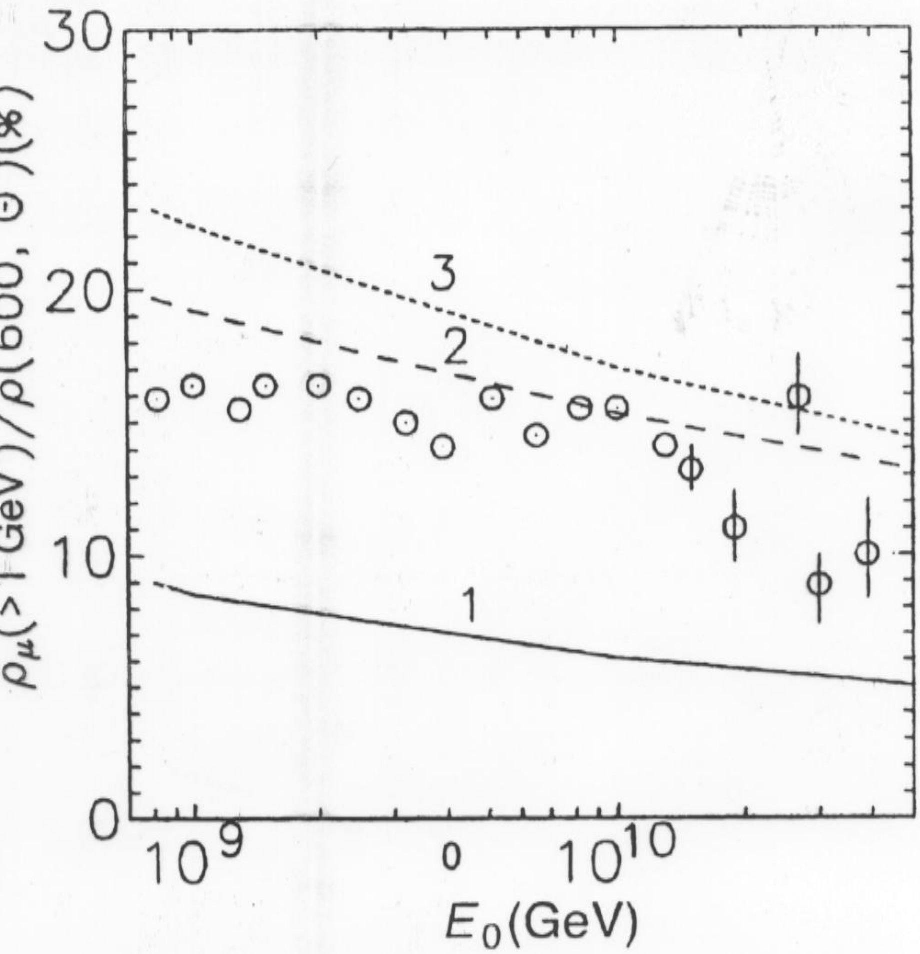
$$\Gamma(E,t) = \Gamma(E,t_0)\exp(-\mu_\gamma(E)(t - t_0)] +$$

$$+ \int_{t_0}^{t} d\xi \exp[-\mu_\gamma(E)(t - \xi)][S_\gamma(E,\xi) + \int dE' P(E',\xi) W_b],$$

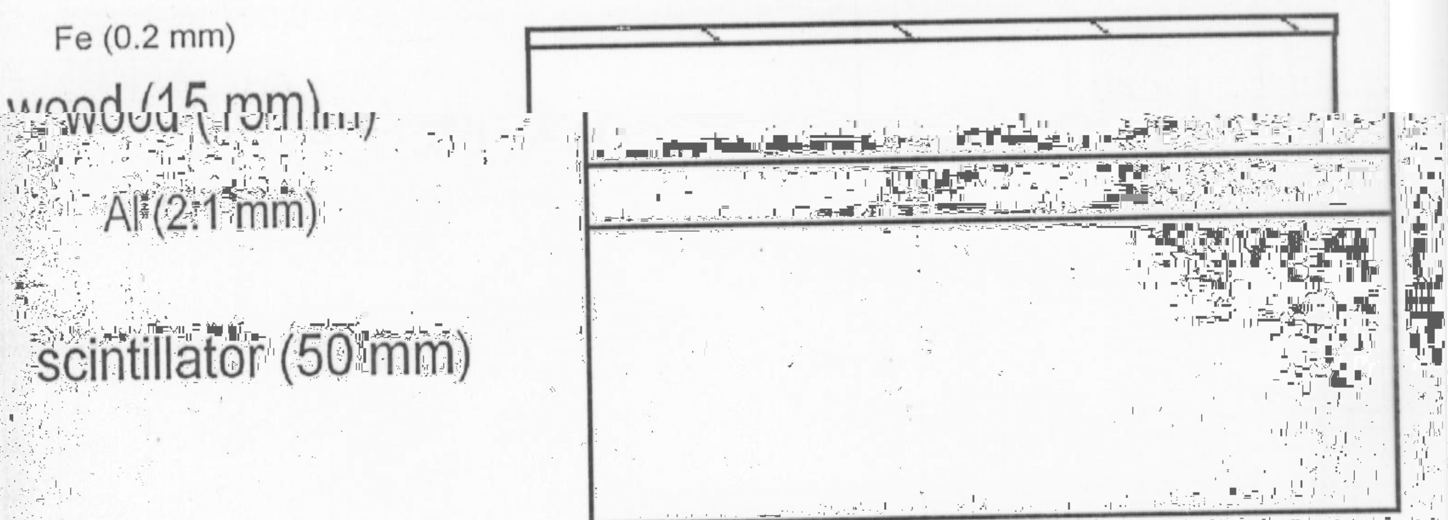
where

$$A_e = \int P(E',\xi) W_b[E', E + \beta(t - \xi)]dE', \qquad B_e = \int \Gamma(E',\xi) W_p[E', E + \beta(t - \xi)]dE'$$

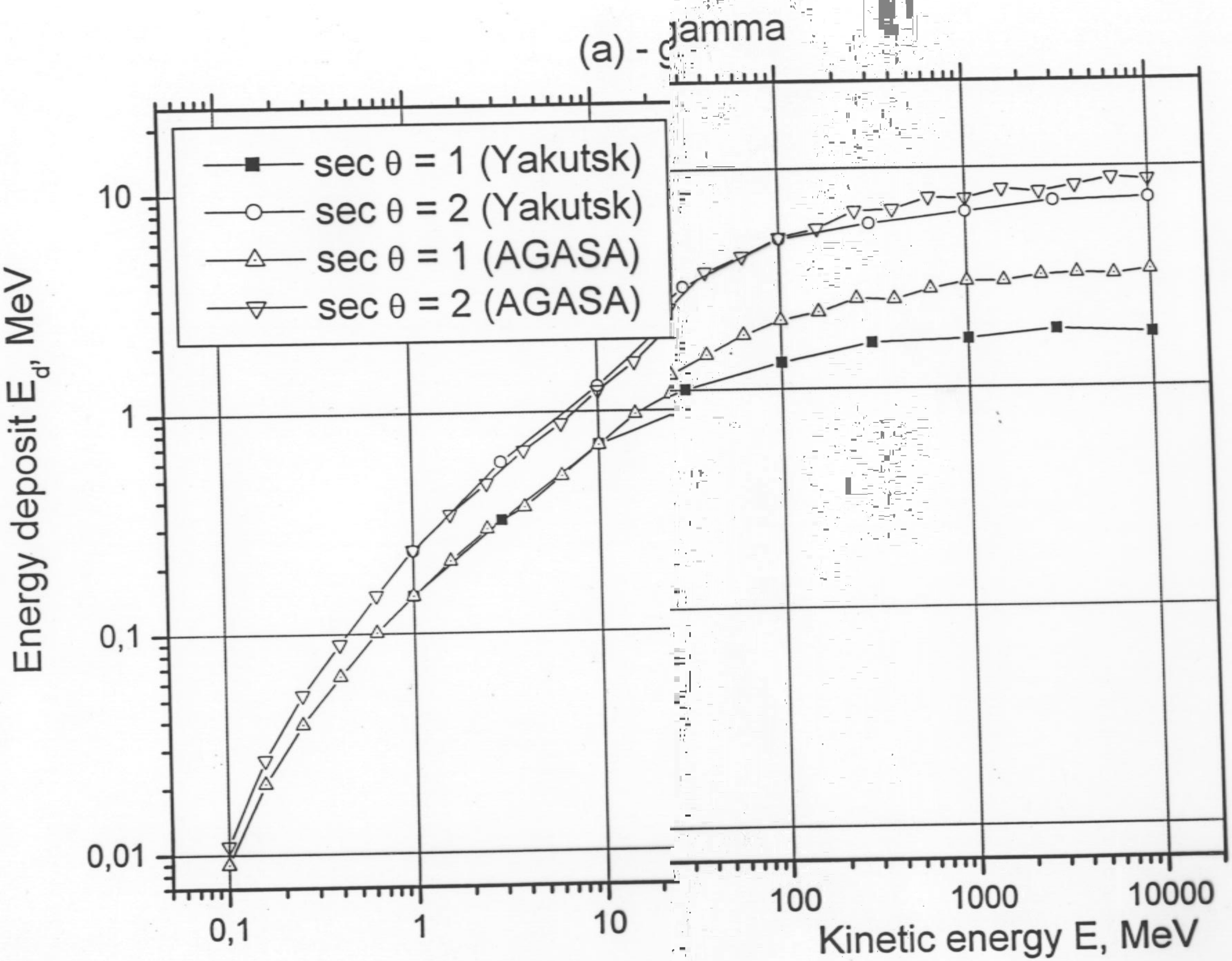
At last the solution of equations can be found by the method of subsequent approximations. It is possible to take into account the Compton effect and other physical processes.

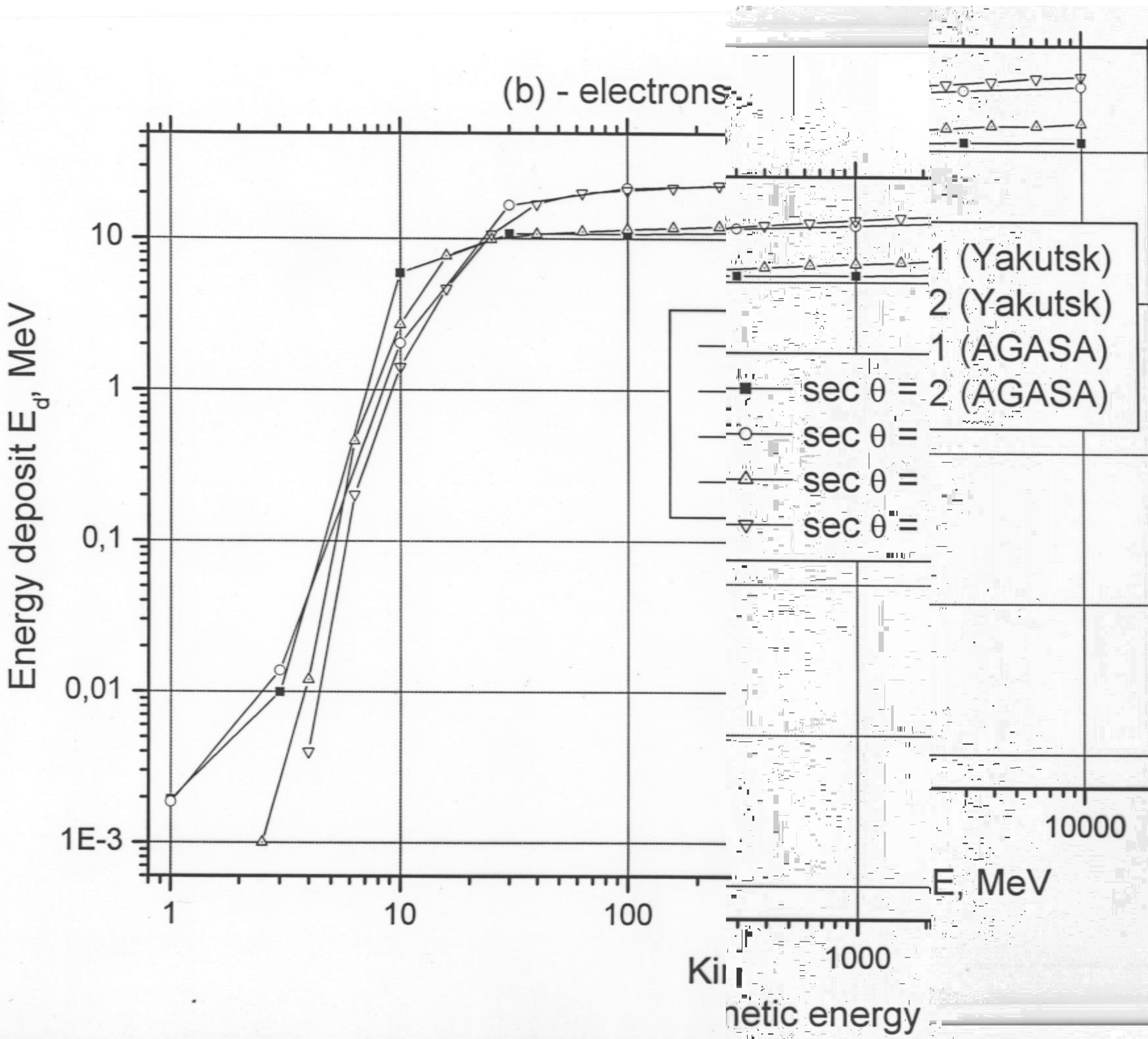


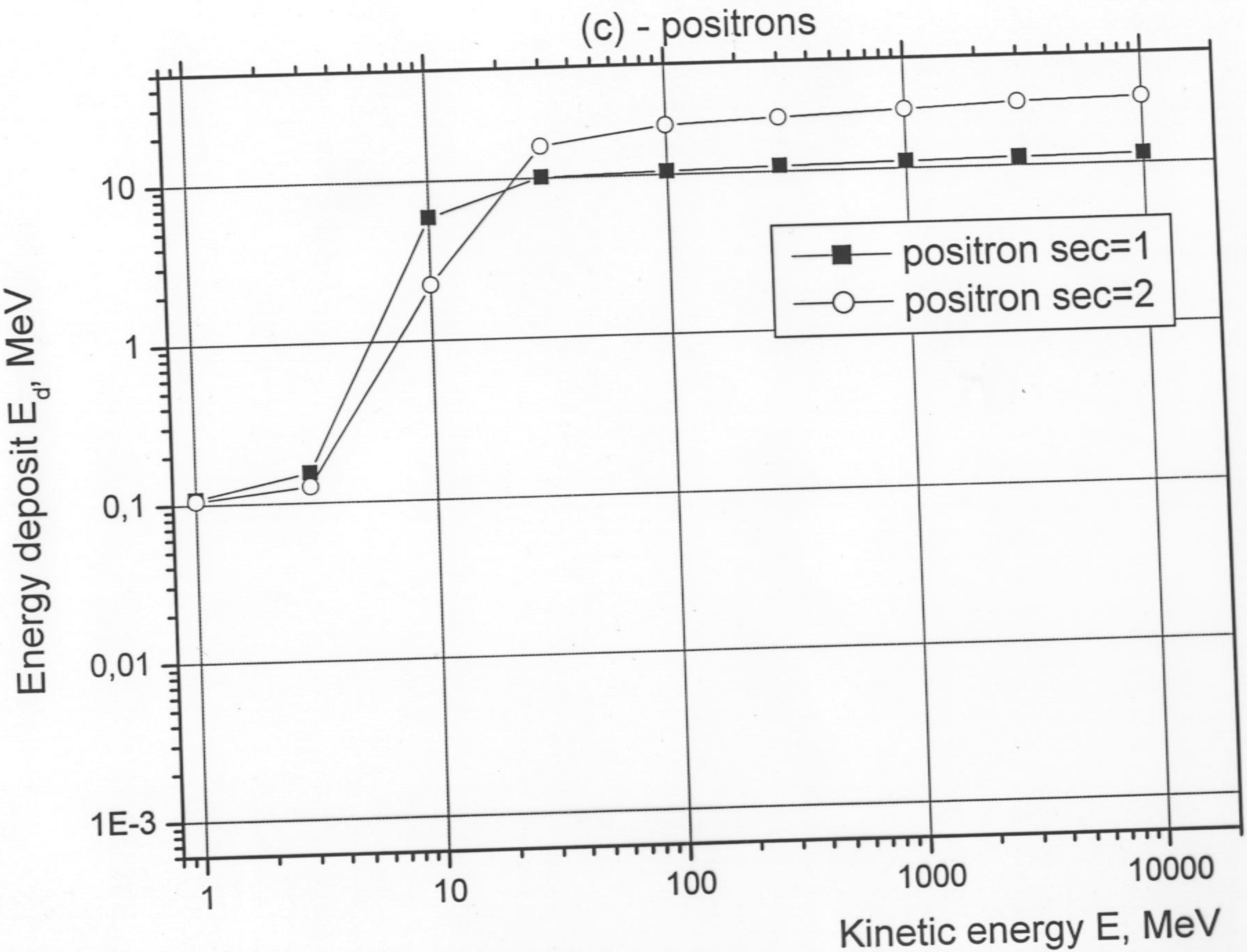
Fraction of muons with energy $E\mu$>1 GeV
600 m from the shower axis as function of Eo

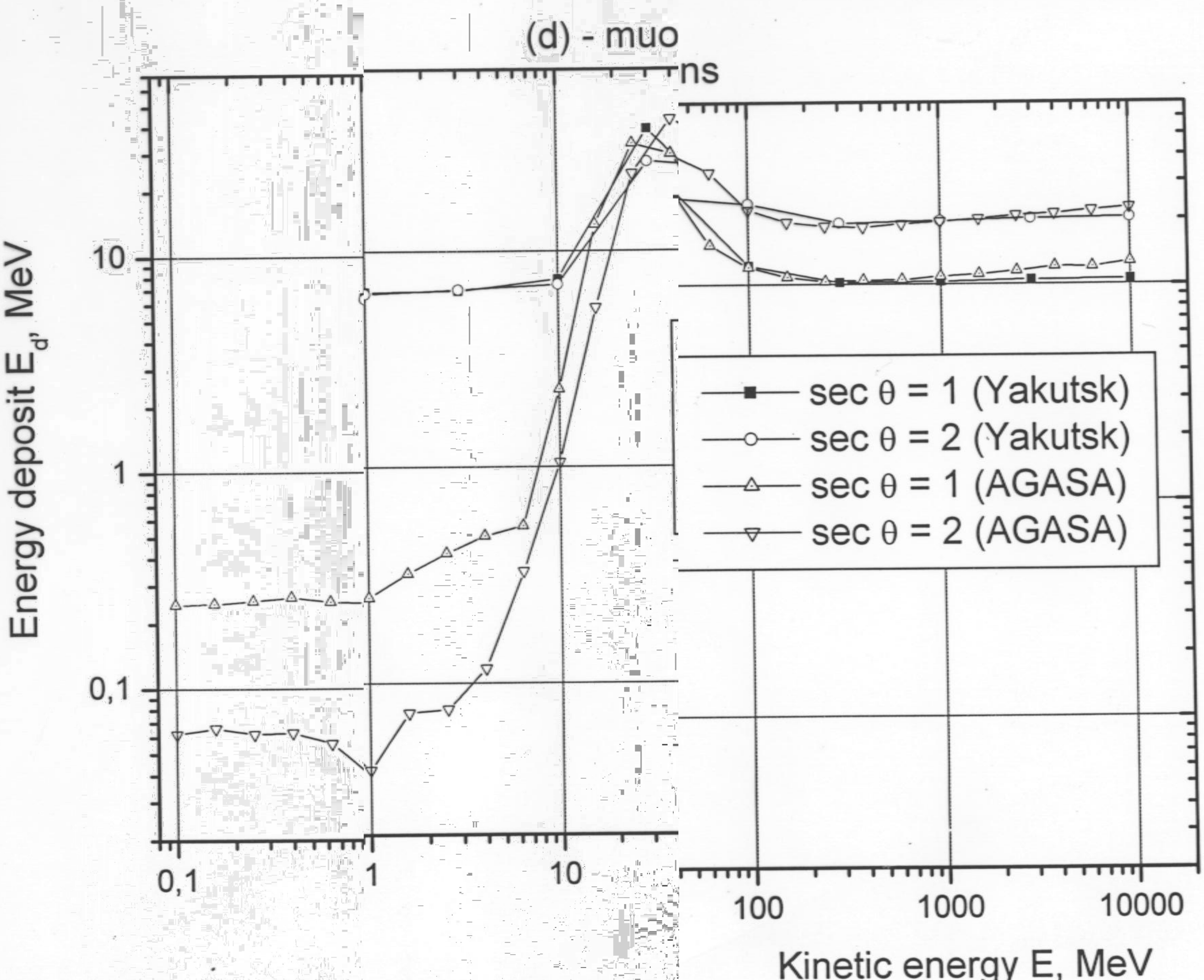


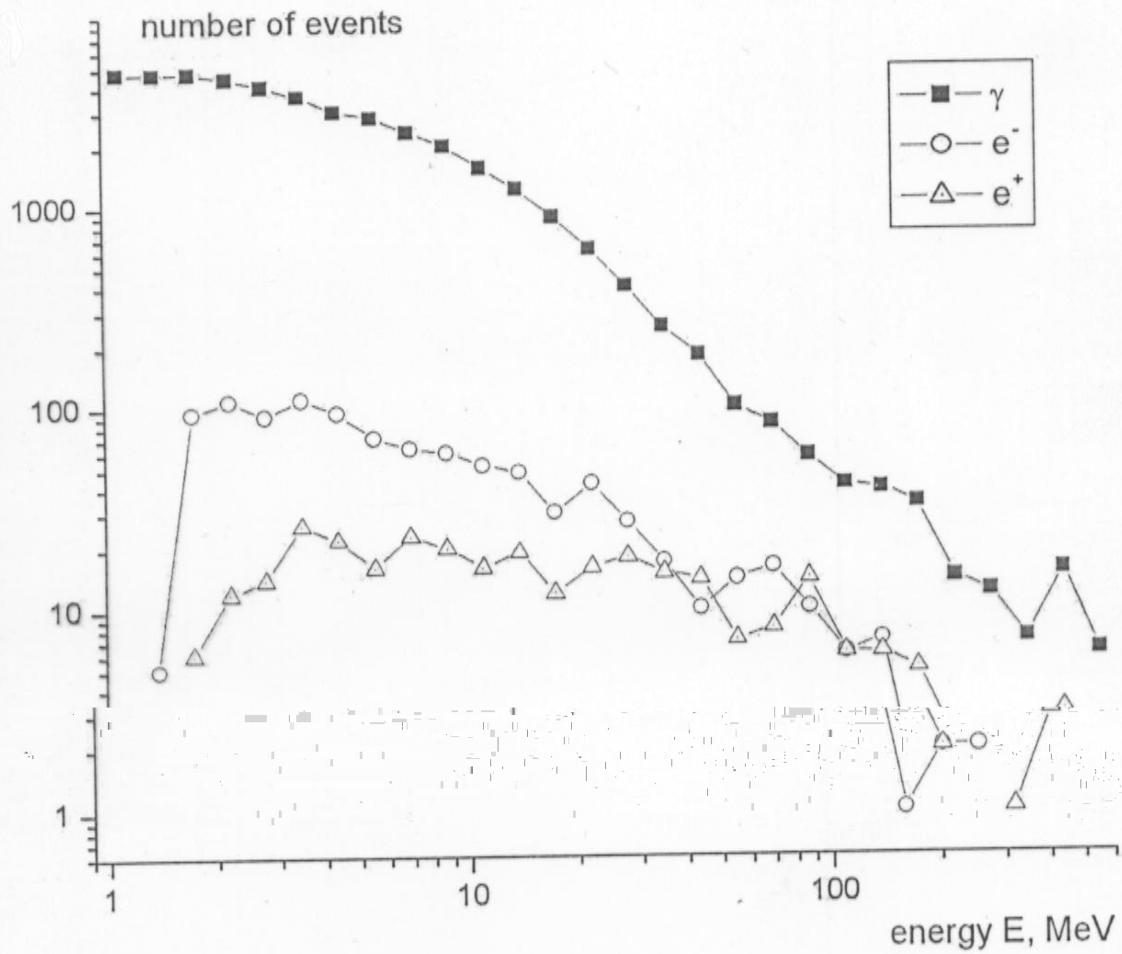
Fe (0.2 mm)
wood (15 mm)
Al (2.1 mm)
scintillator (50 mm)


(a) - gamma
sec θ = 1 (Yakutsk)
sec θ = 2 (Yakutsk)
sec θ = 1 (AGASA)
sec θ = 2 (AGASA)
Energy deposit E_d, MeV
10
1
0,1
0,01
0,1
1
10
100
1000
10000
Kinetic energy E, MeV

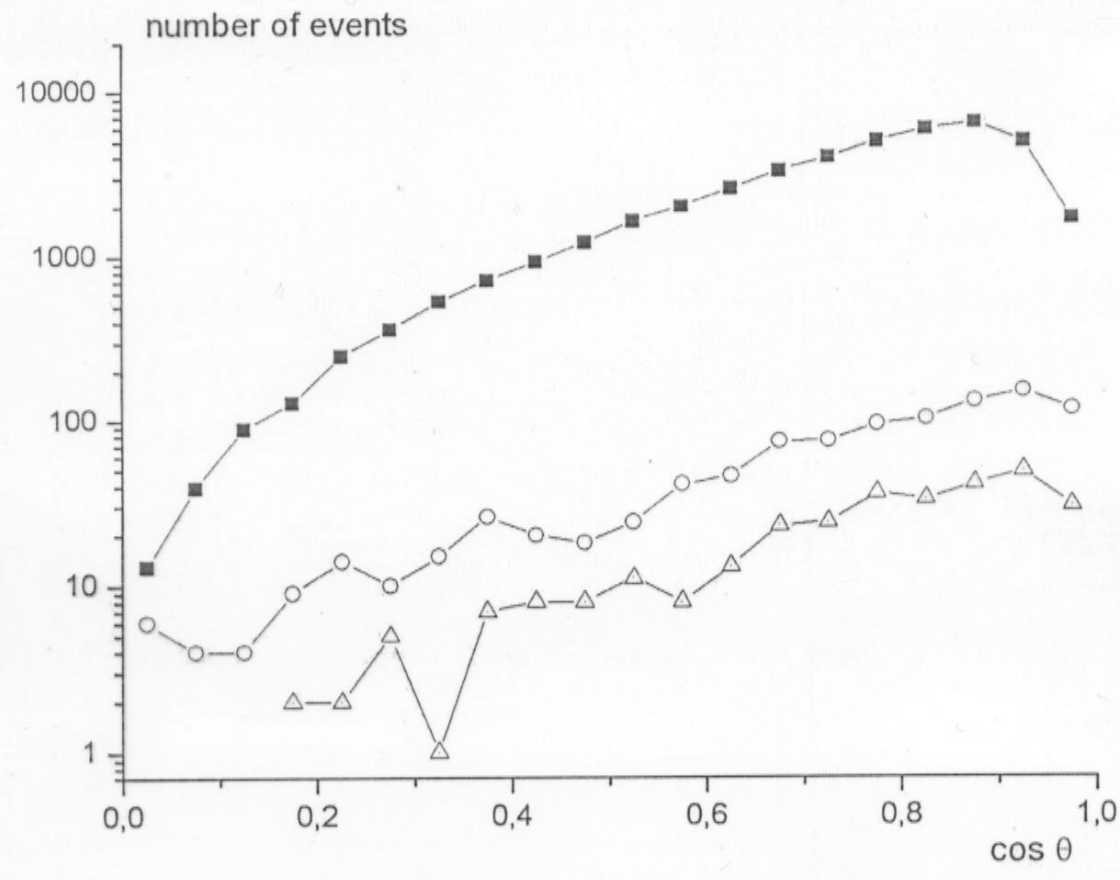

(b) - electrons
Energy deposit E_d, MeV
10
1
0,1
0,01
1E-3
1
10
100
1000
10000
Kinetic energy E, MeV
sec θ = 1 (Yakutsk)
sec θ = 2 (Yakutsk)
sec θ = 1 (AGASA)
sec θ = 2 (AGASA)

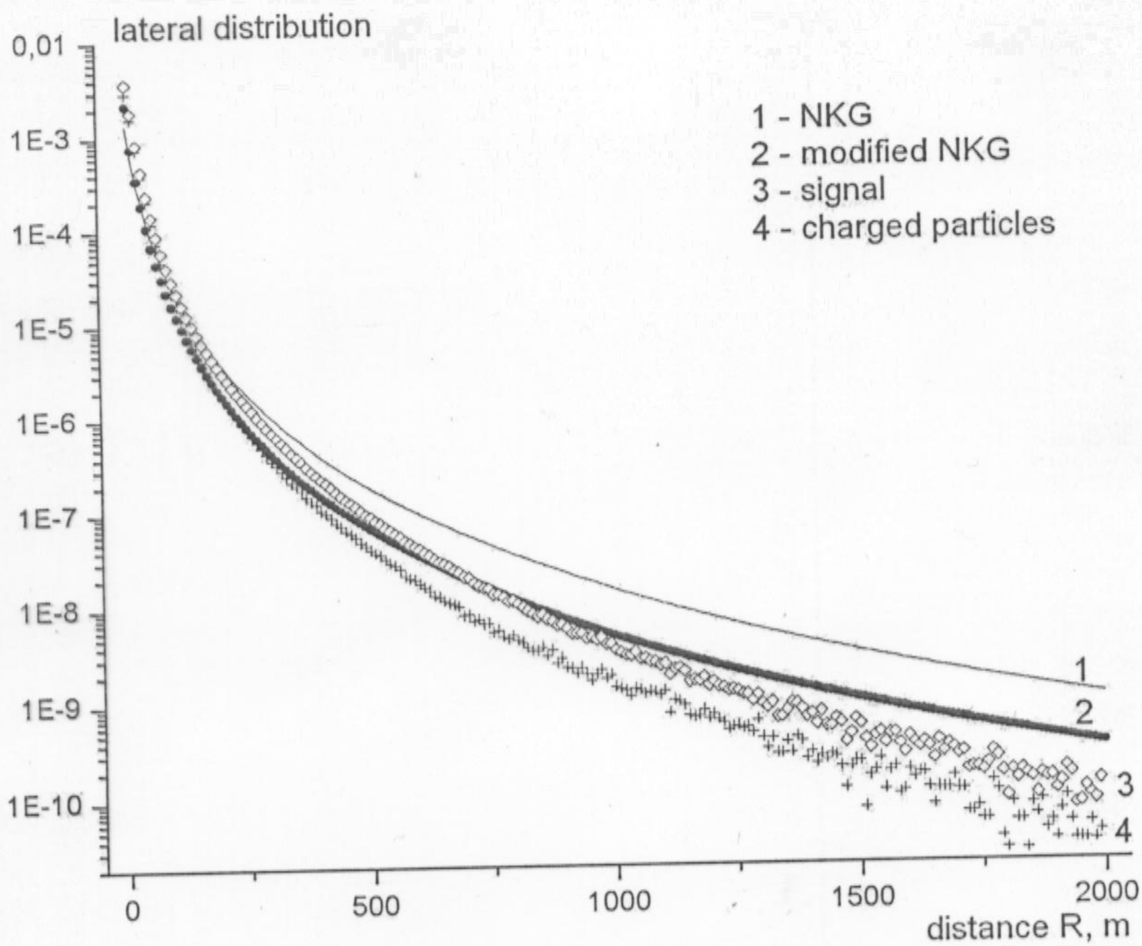

(c) - positrons
positron sec=1
positron sec=2
Energy deposit E_d, MeV
10
1
0,1
0,01
1E-3
1
10
100
1000
10000
Kinetic energy E, MeV

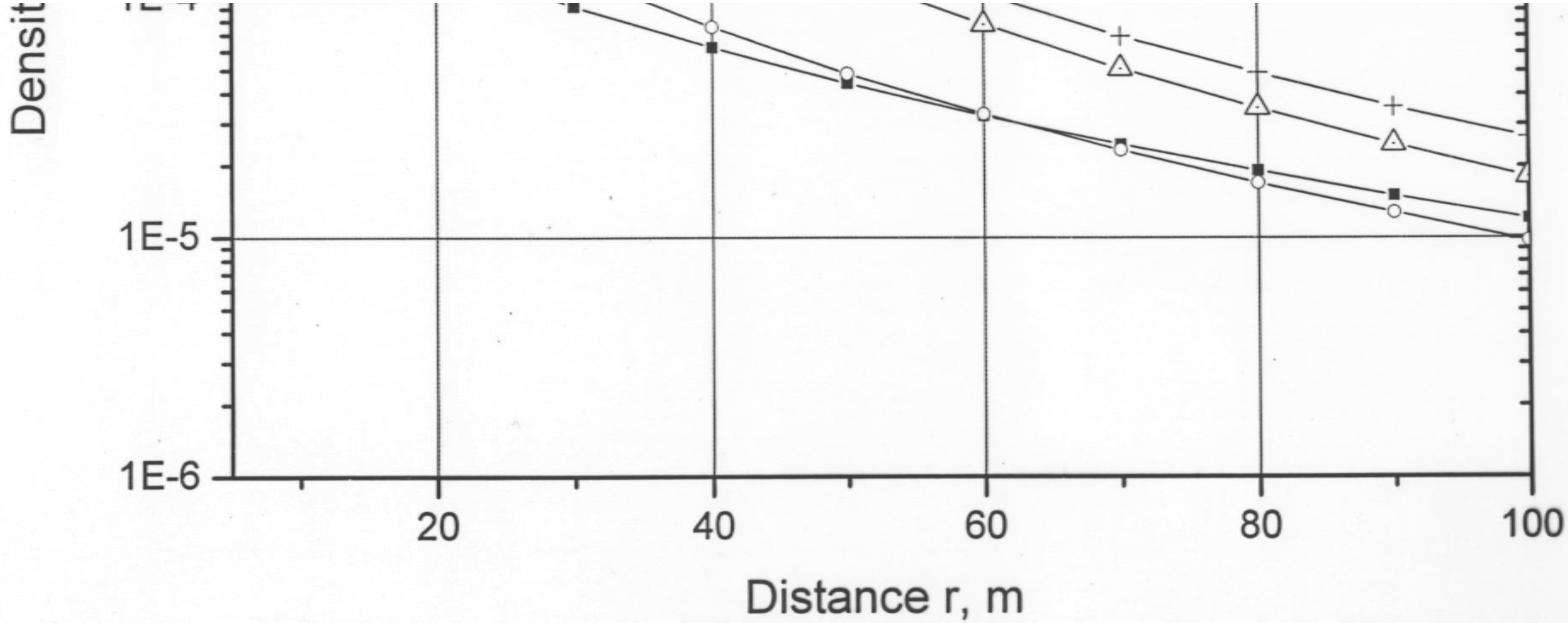

(d) - muo ns
Energy deposit E_d, MeV
10
1
0,1
0,1
1
10
100
1000
10000
Kinetic energy E, MeV
sec θ = 1 (Yakutsk)
sec θ = 2 (Yakutsk)
sec θ = 1 (AGASA)
sec θ = 2 (AGASA)

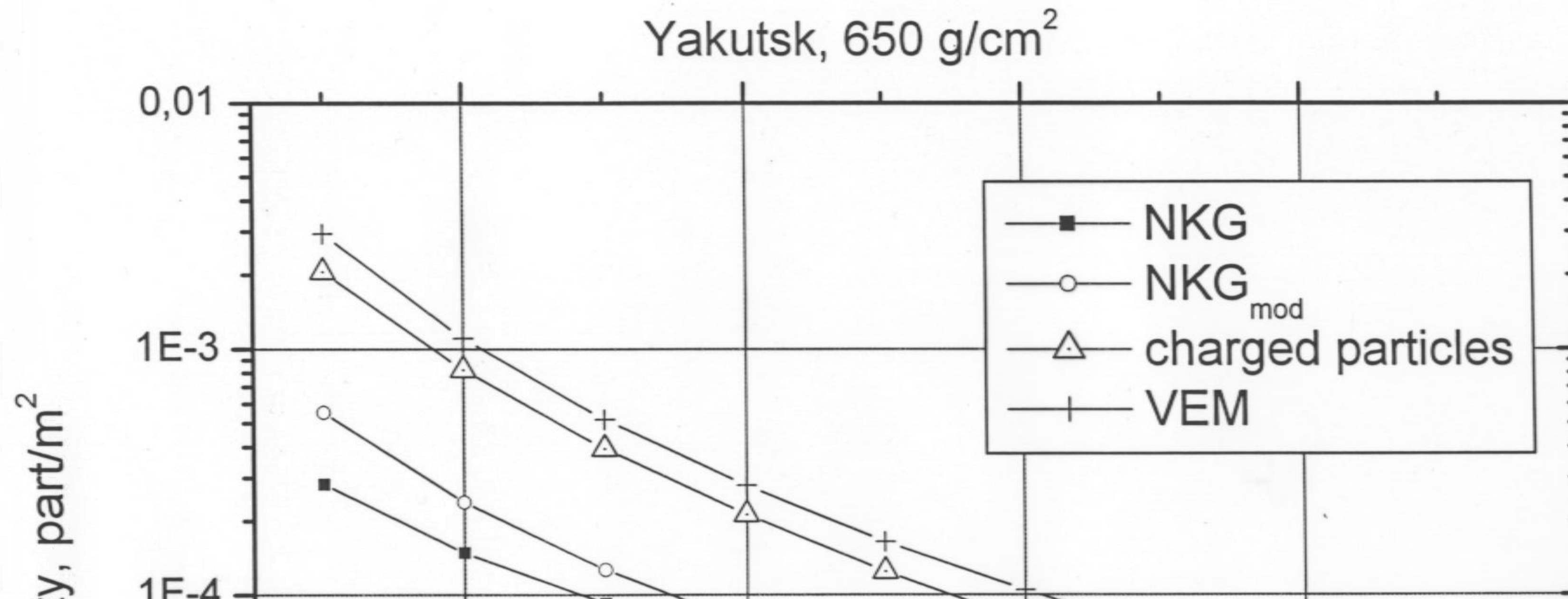


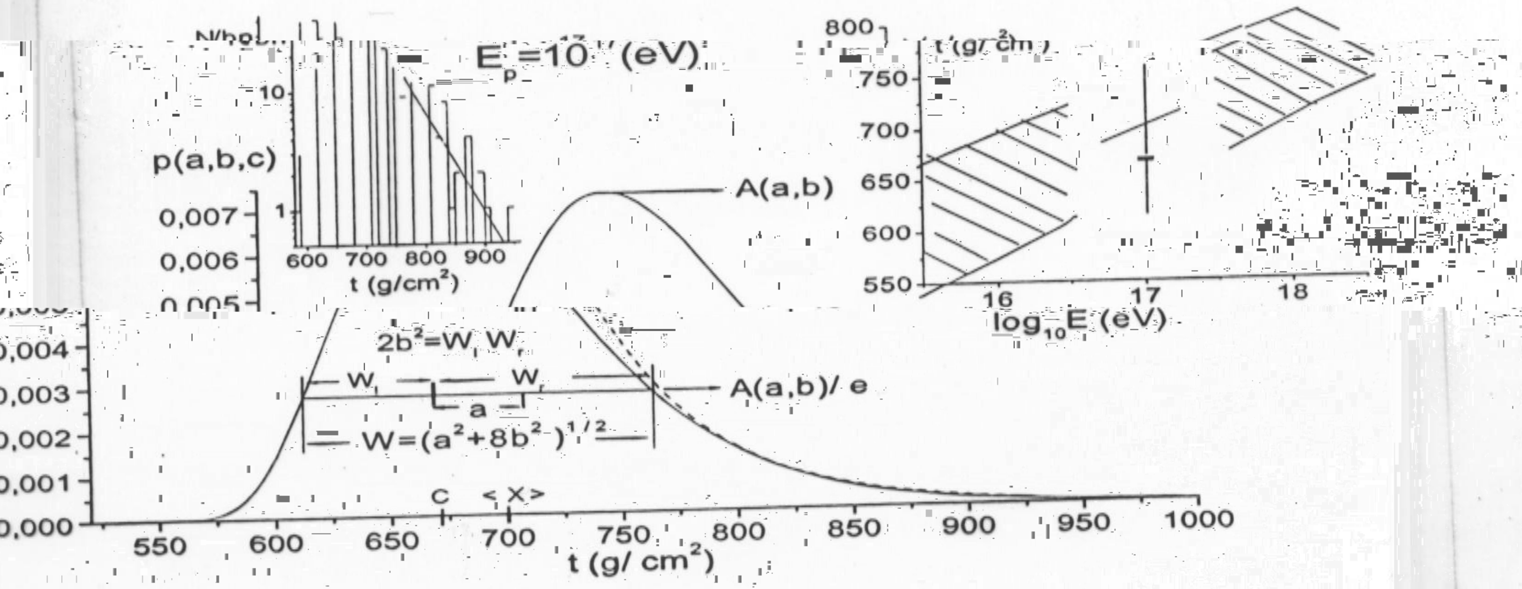
number of events
γ
e⁻
e⁺
1000
100
10
1
1
10
100
energy E, MeV


number of events
10000
1000
100
10
1
0,0
0,2
0,4
0,6
0,8
1,0
cos θ


lateral distribution
0,01
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1 - NKG
2 - modified NKG
3 - signal
4 - charged particles
1
2
3
4
0
500
1000
1500
2000
distance R, m


Densit
1E-5
1E-6
20
40
60
80
100
Distance r, m


Yakutsk, 650 g/cm2
0,01
1E-3
1E-4
y, part/m2
NKG
NKGmod
charged particles
VEM



1. Example of using of distribution with density $(a,b)exp(-(x-c)^2/(a(x-c)+2b^2))$ and interpretation of its parameters.

ig.

A(

Number of muons in a group with $h_k(x_k)$ and E_i :

$$\Delta N_\mu = \int_{x_k}^{x_{k+1}} \frac{dx}{x} \int_{E_i}^{E_{i+1}} dE_\mu W(E_\mu, E_{thr}, x, x_0) \int_{E_{\min}(E_\mu)}^{E_{\max}(E_\mu)} \frac{dE}{E} D(E, E_\mu) P(E, x),$$

here $P(E,x)$ from equations for hadrons; $D(E,E_\mu)$ – decay function; limits $E_{min}(E_\mu)$, $E_{max}(E_\mu)$; $W(E_\mu, E_{thr}, x, x_0)$ – probability to survive.

Transverse impulse distribution:

$$f(p_\perp)dp_\perp = p_\perp \exp(-p_\perp / p_0) dp_\perp / p_0^2,$$

here p_0=0.2 ГэВ/c.

The angle α:

$$tg\alpha_j = r_j / h_k = cp_\perp / E,$$

here $h_k = h_k(x_k)$ – production height for hadrons.

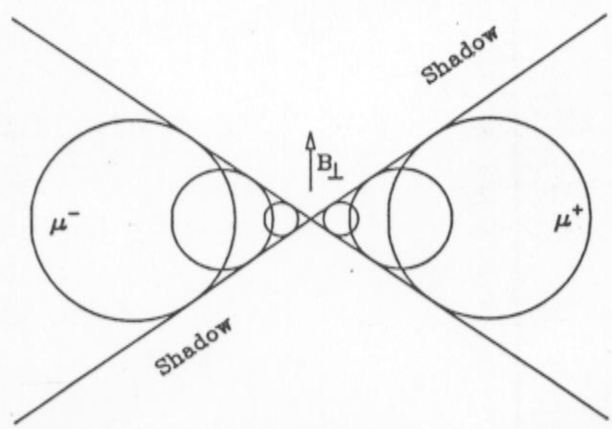
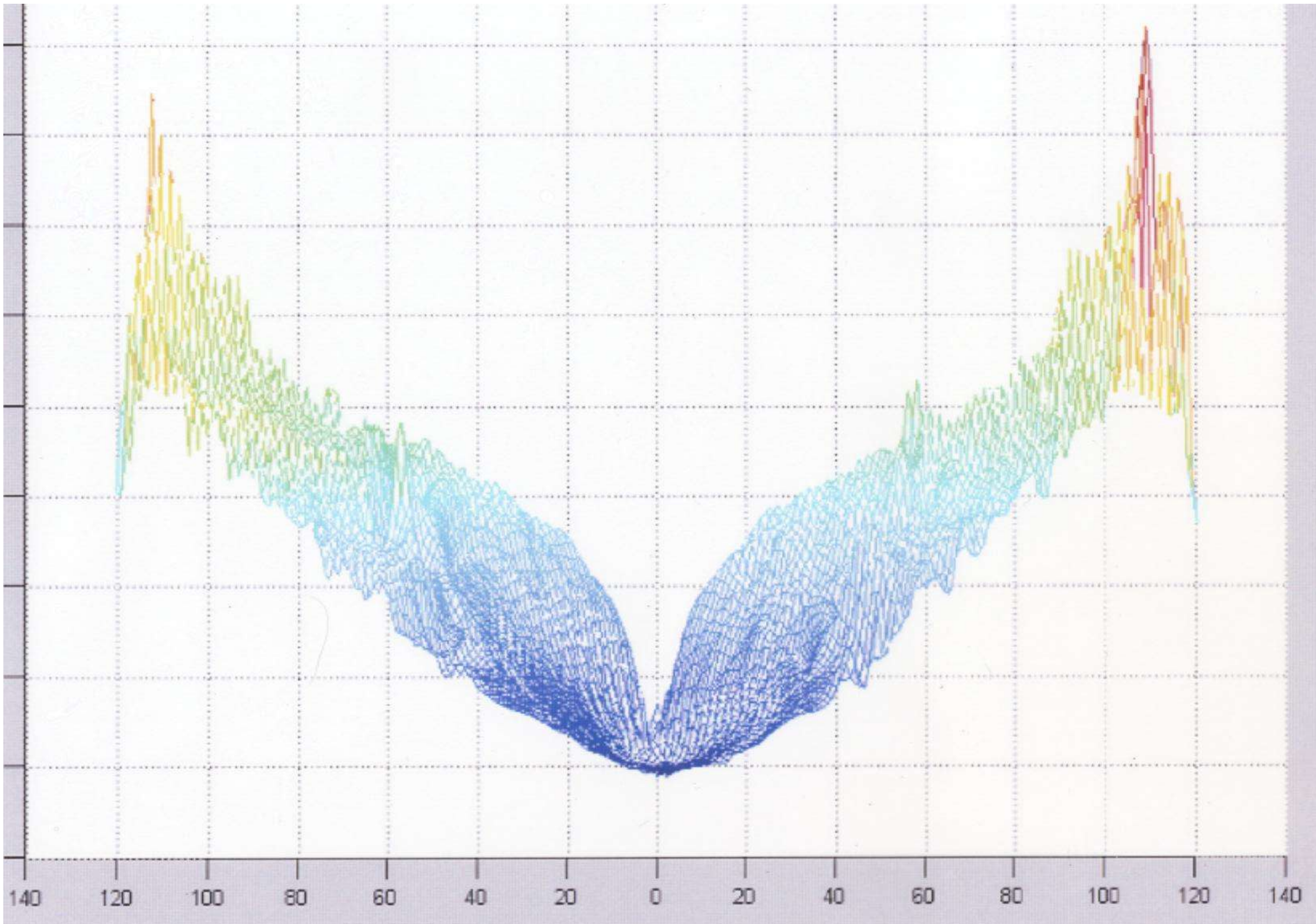
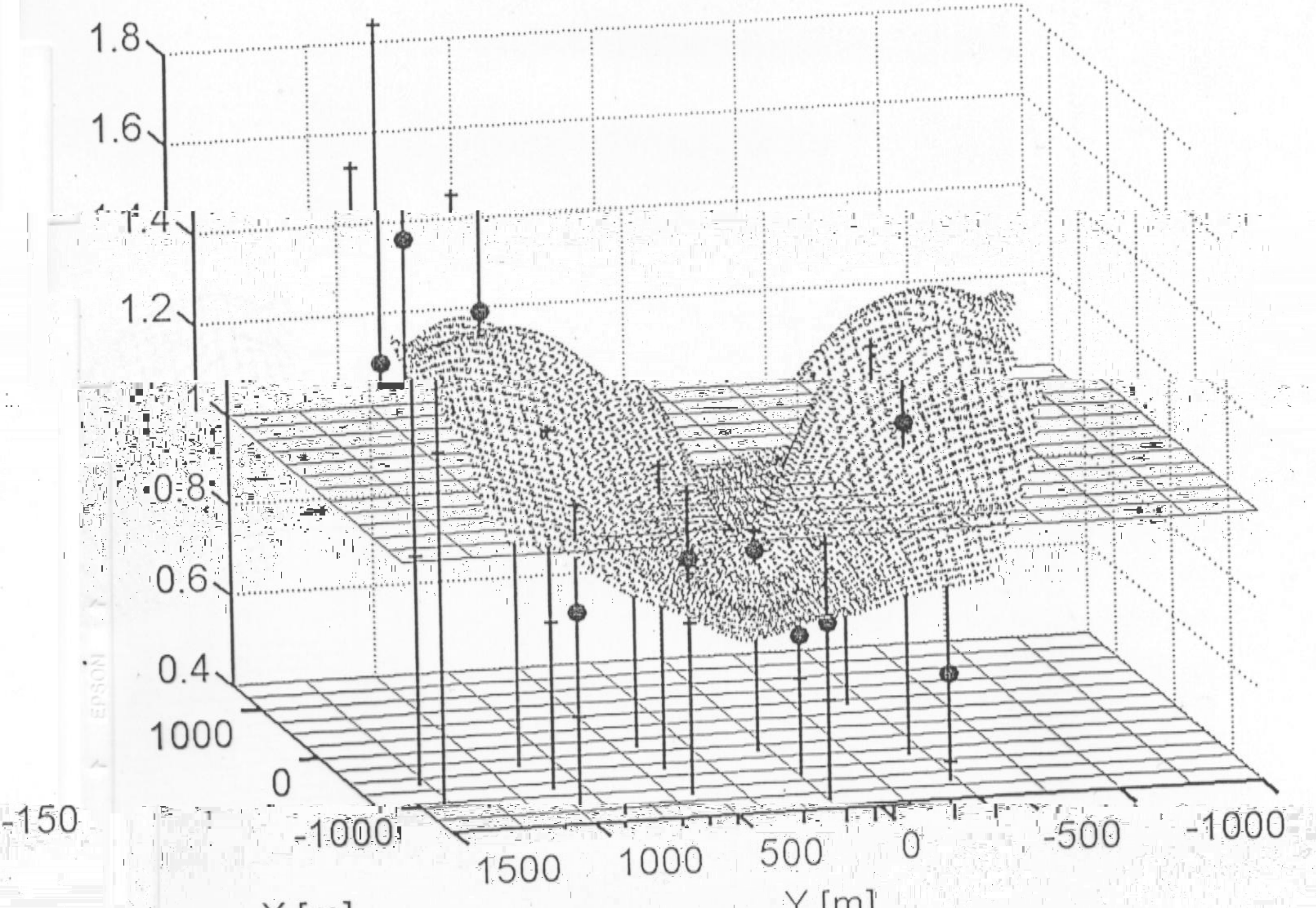


Fig. 9. Toy model magnetic deviations in the transverse plane associated to muons of different energies (and different radii), illustrating the origin of the *shadow* regions in which no muons are expected. The geometrical construction is identical to the two-dimensional plot typically used to explain Cherenkov radiation.



140
120
100
80
60
40
20
0
20
40
60
80
100
120
140


1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
1000
0
-1000
1500
1000
500
0
-500
-1000
Y [m]

A Study Of Very Inclined Showers In The Pierre Auger Observatory

M. Ave [1], for the Pierre Auger Collaboration
... (1) *Center for Cosmological Physics, University of Chicago, 933 S. Ellis Av, Chicago 60637, USA*

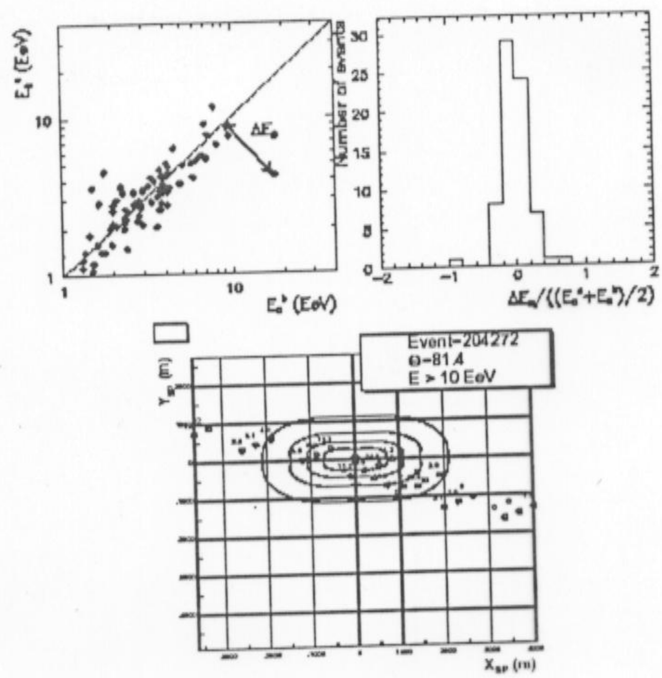
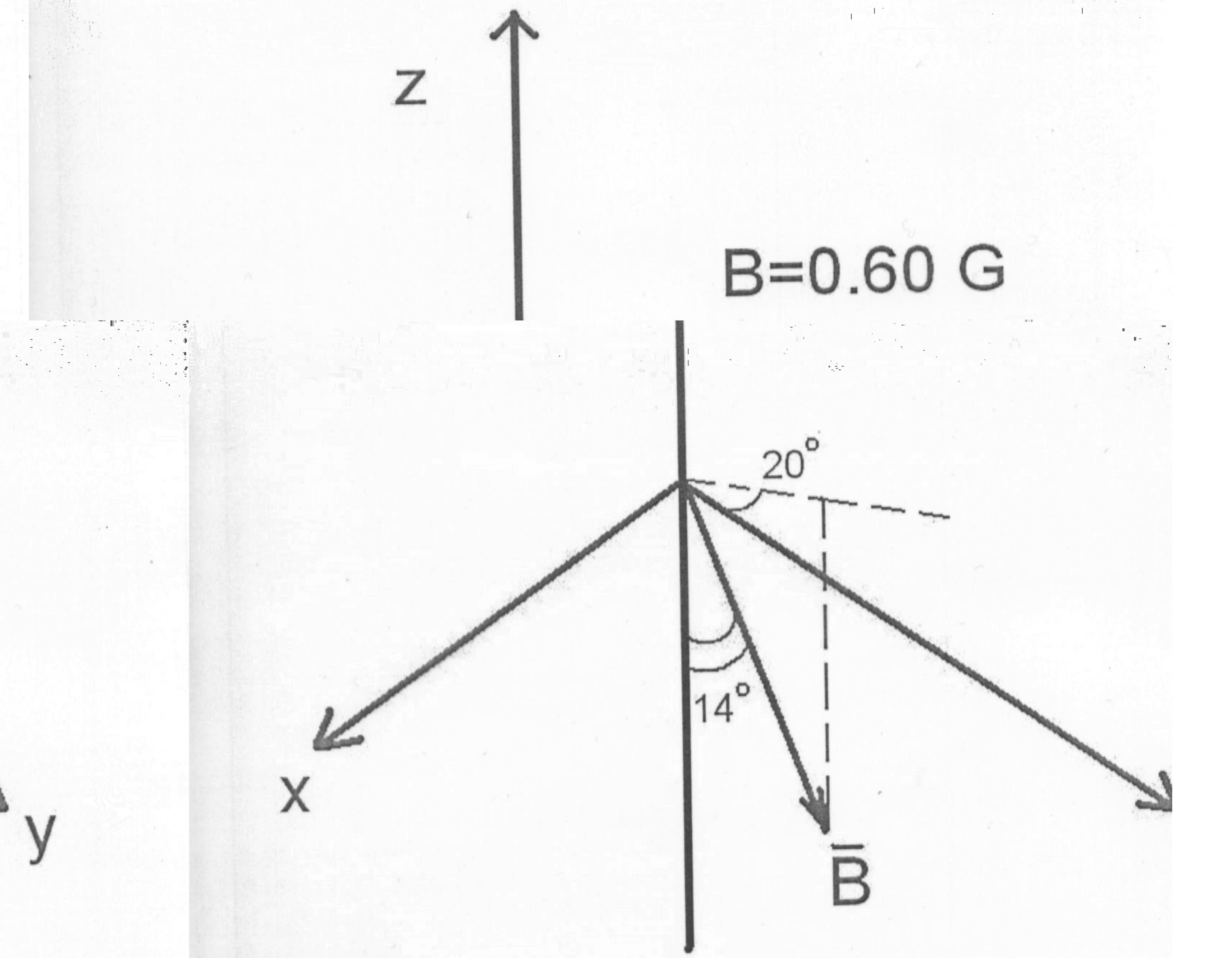
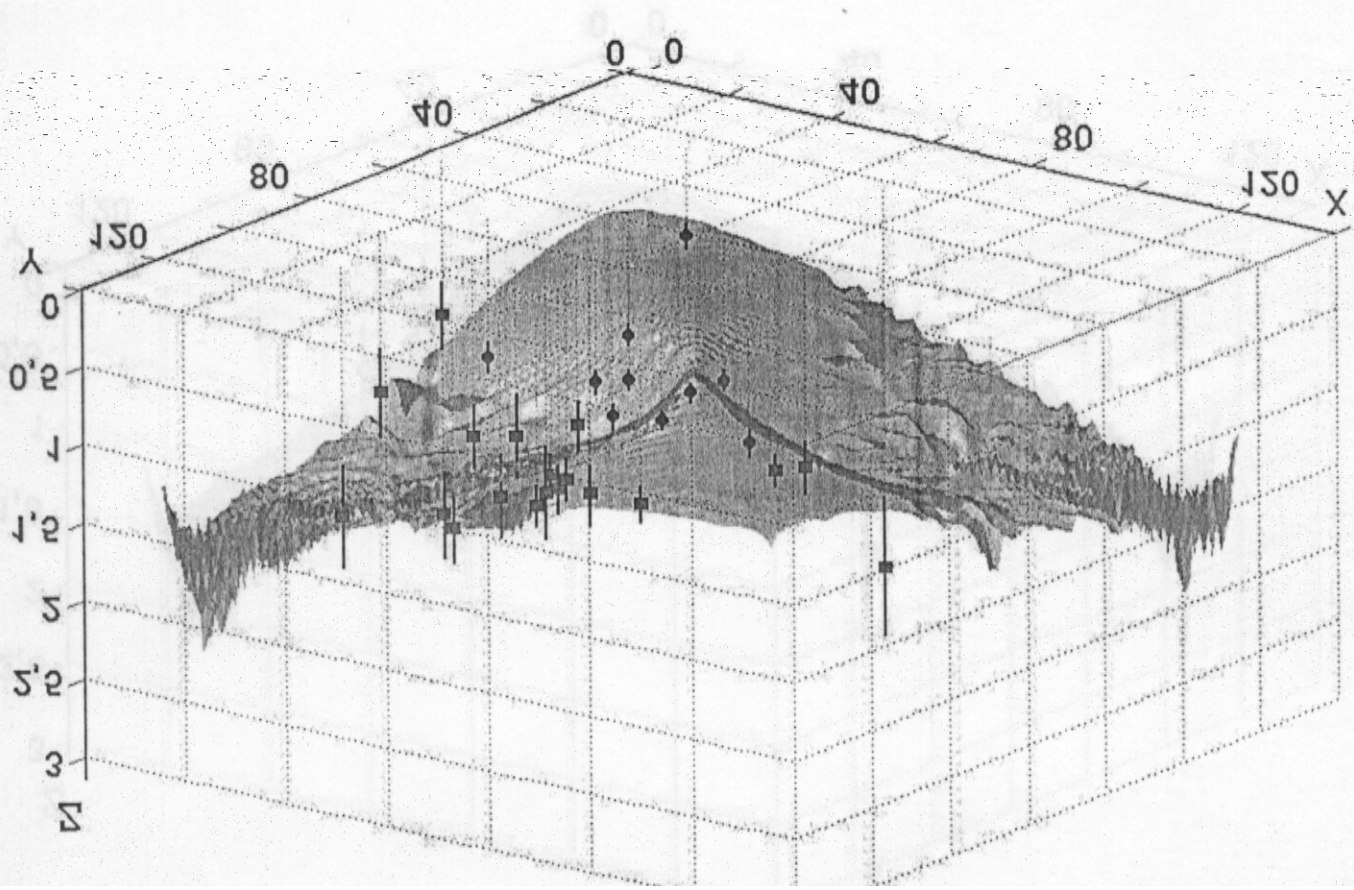


Fig. 1. Top left panel: Correlation of the reconstructed energy by two different algorithms, see text. Top right panel: Distribution of ΔE_0 to the mean energy reconstructed by the two algorithms, see text. Bottom panel:Density map of an event, see text.

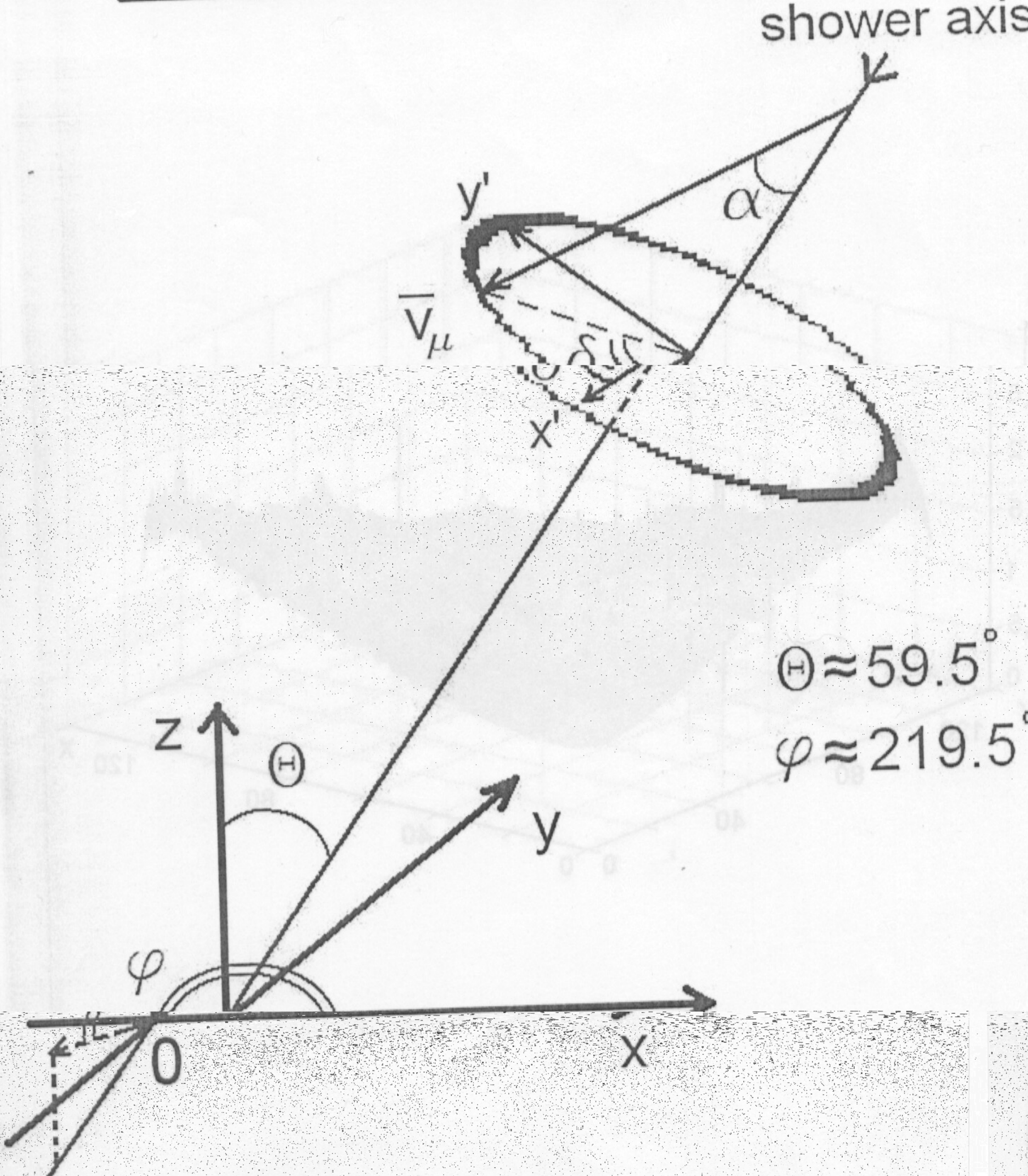
Magnetic field $\bar{B}$ at Yakutsk





X
Y
Z
0
40
80
120
0
40
80
120
0
0,5
1
1,5
2
2,5
3

Direction of a muon velocity V_μ



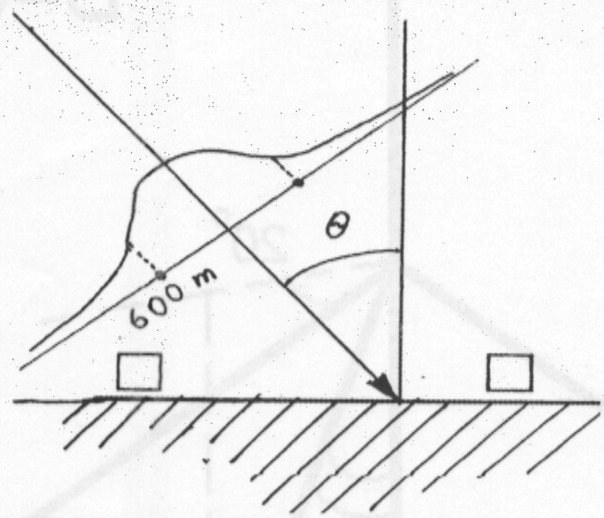
II. STANDARD PROCEDURE

GIANT AIR SHOWER'S PROBLEM: DATA →

- COMPOSITION
- ARRIVAL DIRECTION
- ENERGY
- MODEL

1. ARRIVAL DIRECTION
   - LINSLEY MODEL
   - FLAT FRONT MODEL

2. DENSITY OF CHARGED PARTICLES AT SPECIFIC DISTANCE FROM THE SHOWER AXIS ($\rho_{ch}(600)$ – M. HILLAS(1971)) IN THE SHOWER PLANE IN TERMS OF SOME SYMMMETRICAL FUNCTIONS OF PARTICLE LATERAL DISTRIBUTION.



AND COORDINATES X, Y WHERE SHOWER AXIS HITS THE DETECTOR PLANE

- READINGS OF ALL DETECTORS IN THE ARRAY PLANE
- GEOMAGNETIC FIELD MAY DISTURBE THE SYMMETRY

3. CONVERSION TO THE VERTICAL DIRECTION

$\rho_{ch}(600, \theta) \rightarrow \rho_{ch}(600, 0°)$

- EXPONENTIAL
- ELECTRONS, MUONS

4. SOME ESTIMATES OF ENERGY E.

- THE CALORIMETRY METHOD (YAKUTSK)
- RESULTS OF SIMULATIONS (AGASA) IN TERMS OF ANY MODEL