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PARTICLE BEAM EXPERIMENTS IN COSMIC RAYS. STRONG INTERACTION PARAMETERS DETERMINATION BY STATISTICAL PATTERN RECOGNITION

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ЭКСПЕРИМЕНТЫ С ПУЧКАМИ ЧАСТИЦ В КОСМИЧЕСКИХ ЛУЧАХ. ОПРЕДЕЛЕНИЕ ПАРАМЕТРОВ СИЛЬНЫХ ВЗАИМОДЕЙСТВИЙ МЕТОДАМИ ТЕОРИИ РАСПОЗНАВАНИЯ ОБРАЗОВ.

В работе предложен метод совместного анализа модельных и экспериментальных данных в многомерном пространстве измеряемых признаков ШАЛ, позволяющий, путем решения обратной задачи, определить сорт и энергию первичной частицы и оценить некоторые параметры взаимодействия протонов и ядер с ядрами атомов воздуха. В частности, обсуждается возможность оценки неупругого сечения взаимодействия протонов с атомами воздуха и коэффициентов неупругости в РА-взаимодействиях. Эти результаты, полученные с помощью анализа модельных выборок, позволяют надеяться на то, что возможна постановка аналога мишенного эксперимента в космических лучах и исследование характеристик РА- и АА-взаимодействий в области энергий 10^{15}-10^{17} эВ.

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1. INTRODUCTION

In the cosmic ray physics the main technique of solving the incorrect problem of determination of initial physical parameters (such as mass composition and energy spectrum of P strong interaction characteristics, etc.) by the measurable EAS characteristics is the direct problem solution with detailed simulation of the traversal of the atmosphere and the experimental installation by PCR with a following comparison of the multivariate simulation and experimental data. Actually, an algorithm is constructed, which describes EAS development and registration of its different components on the observation level, which is based on a certain model of the process investigated, i.e. the set of the parameters that characterize the PCR flux and interaction of hadrons and nuclei with the air nuclei.

By simulations with different models and comparing the experimental and model data, a class of models is selected, which describes the experimental data satisfactorily. Such an approach allows us to discard a certain class of n satisfactory models, but the available experimental data do not allow one to select the only model among the many proposed, as the mass composition and energy spectrum of PCR and the characteristics of hadron-nucleus interactions at E> 1000TeV are unknown. So, our task was to divide the problem of model selection into separate stages. First we determine the type of the primary nucleus, then the energy, and after that, having obtained the proton and nuclear "beams" with a known energy, we consider the possibility of estimating the parameters of th first interaction.

A method based on the statistical pattern recognition is proposed in Refs.[1-3], which allows us to determine the type of the primary particle with an efficiency of ~70-80% and estimate its energy with an accuracy of ~25% for each individual event, this allowing us to carry out experiments with cosmic-ray particle beams of certain type and energy and study the hadron-nuclear interactions at superaccelerator energies.

In this work is investigated the third stage of t[illegible] program - estimation of some parameters of hadron-nuclear interactions, provided the type and energy of the primaries are known. In particular, the possibility of estimating the inelastic cross section of interaction of protons with air nuclei and the PA interaction inelasticity coefficients is considered.

2. DETERMINATION OF THE TYPE AND ESTIMATION OF THE ENERGY OF PRIMARY PARTICLE

The method of EAS classification by the multivariate features is described in details in Refs.[1,2]. The parameters used at event simulation are also presented. The classification method is based on the Bayes decision rules with non-parametric estimation of the multivariate probability density function, which provide a complete account of a priori information obtained by simulation.

The events were classified by the total number of electrons N_e and muons N_μ with $E_\mu > 5GeV$. To test the influence of strong interaction parameters on the results of the event classification, we investigated the correlation of the total number of electrons and muons with the total number of charged hadrons N_{ch}, the mean transeverse momentum $\langle P_t \rangle_{ch}$, the total energy ΣE_{ch} of the charged hadrons produced in the first act of strong interaction, the first interaction depth z, and the initial energy E_0. Table 1 presents the corresponding correlation coefficients. As is seen from Table 1, N_e and N_μ do not practically correlate with N_{ch}, $\langle P_t \rangle_{ch}$, z and are in a strong dependence with the initial energy E_0 and ΣE_{ch}.

As far as N_e and N_μ are mainly determined by the third-fourth-generation hadrons, the energy of which is comparable with that of modern accelerators where the characteristics of strong interactions are studied well, then, by event selection in a narrow energy range (e.g., over N_e and N_μ), one may expect that the effect of the chosen model of strong interactions in the superaccelerator energy range on the results of classification by different nuclear groups will be weak. The Bayes error matrix $1 \cdot 10^5 > N_e > 2 \cdot 10^5$ is given below:

	P	CHO	H	VH
P	0.798	0.102	0.067	0.033
CNO	0.127	0.688	0.105	0.080
H	0.072	0.113	0.691	0.124
VH	0.034	0.090	0.150	0.726

The diagonal elements of this matrix show the probability for a correct classification of the events that correspond to four nuclear groups: P, CNO, H, VH (the protons and α-particles are included in a group). The non-diagonal elements show the misclassification probability. It is seen, that the event classification accuracy is 70-80%, this giving us a hope for a reliable selection of the events initiated by a certain primary from the total number of the showers registered.

Note that in this work the simulated showers have been generated at zenith angles $0\le\theta\le45^{\circ}$, and the event selection in a narrow interval of zenith angles can improve the efficiency of classification.

The strong correlation of N_e and N_{μ} with the initial energy allows one to estimate, according to these EAS characteristics, the primary particle energy for the events related to one of the nuclear groups. It is shown in Ref.[3], that the non-parametric regression method [4] permits to estimate the primary particle energy with an accuracy of ~25%. This method is based on the simple fact, that the events that are close in a metrics in the space of the features measured, have similar initial parameters (e.g., energy).

The events were simulated for primary protons and nuclei with $A\ge24$, the initial energy being uniformly simulated within the range of $100\le E_0\le10^4$ TeV.

An analog of an experimental data (control sample) was obtained by employing the method of [1,2] to the simulated showers generated according to the model of quark-gluon strings [5], in an assumption of a mixed composition and a power-law energy spectrum of PCR [6]. Below are presented the relative r.m.s. errors of estimation of the energy of the "pseudoexperimental" events initiated by the protons and nuclei with $A>24$, as well as the volumes of the simulation and control samples, by which the energy was estimated.

$\langle N_e\rangle/10^5$	0.66±0.196	1.404±0.281	2.716±0.534	9.758±1.079
$\langle N_{\mu}\rangle/10^3$	2.74±0.258	3.839±0.335	5.881±0.667	14.545±1.01
N^P_{TS}	864	913	484	402
N^P_{exp}	439	465	256	216
CKO^P, %	20	24.3	25	25
N^A_{TS}	377	357	184	128
N^A_{exp}	184	225	102	73
CKO^A, %	10.1	10.6	9.7	10.6

Note that the non-parametric regression method is, in fact, a generalization of the classification method in the occasion of an infinite number of classes that differ by the continuously varying parameters (energy, cross section of interaction, mean multiplicity, etc.). Thus, making use of the methods based on the statistical pattern recognition, we can determine, with a good accuracy, the type and energy of the primaries, regardless the model of strong interactions, this giving us a hope for studying the different components of EAS to turn to the investigation of the characteristics of hadron-nuclear interactions at superaccelerator energies.

3. THE POSSIBILITY OF INVESTIGATION OF THE STRONG INTERACTION PARAMETERS BY THE DATA FROM EXPERIMENTAL COMPLEXES

Having the purpose to investigate the possibility of determination of the parameters of the strong interaction of the protons with the air nuclei by the data from experimental complexes (provided, that the type and energy of the primary particle are determined), we simulated showers initiated by primary protons with E_0=1000TeV and calculated the coefficients of correlation of different measurable features of the shower with the parameters of the first interaction. The following parameters of the first interaction were considered: z-depth; N_{ch}-the number of charged hadrons; ΣE_{ch}-the total energy of charged hadrons; ΣE_{ch-p}- the total energy of charged hadrons, excluding the protons; $\Sigma E_{ch\pi}$- the energy of charged pions; $\langle P_t \rangle_{ch}$-the mean transverse momentum of the charged hadrons.

Table 2 presents the coefficients of the correlation of these parameters of the first interaction with N_e and N_μ and with the momenta of the spatial and energy distribution functions of the muons with $E_\mu \geq 200$GeV (the average distance to the shower core $\langle R_\mu \rangle$, the mean muon energy $\langle E_\mu \rangle$, the variance of the spatial and energy distributions $C^\mu_{R,E}$). It follows from Table 2, that N_e and N_μ correlate quite strongly with the energy characteristics of the first interaction (ΣE_{ch}, ΣE_{ch-p}, $\Sigma E_{ch\pi}$), and the spatial distribution functions of the high-energy muons depend on the depth z of the first interaction. This is also affirmed by Figs.1-4 which show the scattering diagrams of the parameters of the first interaction and of the EAS characteristics measured. Thus, the inelasticity coefficients can be estimated by N_e and N_μ. The depth of the first interaction and hence, the cross section of the interaction of protons with the air nuclei can be determined by the shape of the spatial distribution of high-energy muons.

The statistical independence of these EAS characteristics on the other parameters of the first interaction, as is seen from Table 2, indicates a certain model independence of the estimation of the corresponding values.

In this paper the method of non-parametric regression is used to estimate the inelasticity coefficients and the

inelastic cross section of the protons interaction with the air atom nuclei at E_0=1000TeV. In this method the object of the analysis is each individual event (a point in the multidimensional space of the features measured).

As far as both the hadron-nucleus interaction and the nuclear-electron cascade development in the atmosphere have a probabilistic character, then each individual event may correspond with a certain probability to any model, and the task of the analysis is to select the most probable model for each event, according to the measured characteristics.

When generating showers of higher than 100TeV particles, the model parameters of strong interaction, such as mean multiplicity, the cross section, the mean transeverse momentum, the inelasticity coefficient, were uniformly simulated in a wide interval. At energies lower than 100TeV, the simulation was performed according to the quark-gluon string model. Note, that with variation of the mean multiplicity at a fixed energy the inclusive spectrum is also changed. Thus, we get a bank of possible models. The simulated events correspond to different models, and all the events enter the model bank with equal probability.

Further, to test the technique stated, we chose the problem of the primary proton "beam" interaction with the atmosphere. The proton energy was simulated using a normal distribution with a mean energy of 1000TeV and a 20% variance. The EAS were further simulated using the characteristics of a definite model from the bank of possible models.

For each control event x there were determined its nearest neighbors from the bank of possible models (3 to 7 neighbors) in the space of the prechosen best EAS characteristics. Naturally, for each particular problem these characteristics will be different. The corresponding characteristics of the first interaction are defined as

$$\hat{E}(x) = \sum_{i=1}^{K} C_i E_{[i]}(x), \quad \sum C_i = 1 \ .$$

where K is the number of the nearest neighbors, $E_{[i]}$ is the value of the characteristics of the interaction (path, inelasticity coefficient, etc.) of that model event, which is the i-th nearest neighbor of the experimental event x. The weight coefficients C_i are inversely proportional to the distance.

Such formulation of the problem allows us to estimate the accuracy of the method used, as far as we forget, for a while, about the characteristics put into a definite model, then, after their reconstruction, we calculate the distribution of relative errors.

The results of the simulations as well as the values of the relevant parameters of the strong interaction of the protons with the air nuclei, which were used in the control shower simulation, are presented in Table 3. It is seen from Table 3, that the true and the estimated values of the mean path and the inelasticity coefficients are in a good agreement.

The comparison of the true and estimated integral distributions of the depth of the first interaction is shown in Fig.5. It is seen, that these distributions coincide within the statistical errors, although the estimated distribution is somewhat steeper. Fig.6 shows the distribution of the relative errors of the inelasticity coefficient estimation:

$$D = \{{\Sigma\!\!\!E}^{est}_{ch} - {\Sigma\!\!\!E}^{tr}_{ch}\} \,/\, {\Sigma\!\!\!E}^{tr}_{ch} \ .$$

As is seen from Fig.6, the estimate of the inelasticity coefficient is not biased, and the accuracy of measurement of K_{ch} in each individual event is ~35%.

Thus, the results of the simulation show, that by the characteristics of the electron-photon and muon components of EAS, one can estimate with a good accuracy the inelastic cross section and the inelasticity coefficients of the proton-nuclear interactions at superaccelerator energies.

Note, that the obtained results are not based on using a certain strong-interaction model with fixed parameters (at superaccelerator energies).

4. CONCLUSION

The proposed approach of combined analysis of simulated and experimental data, which is based on the methods developed in the frames of the statistical pattern recognition allows us to find the unique model from the bank of possible models, as well as:

a) to determine with 70-80% efficiency the type of the primary and to estimate its energy with an accuracy of ~25%. The results of classification are practically independent of the parameters of the hadron-nuclear interactions at superaccelerator energies;

b) to obtain model-independent estimates of some parameters of the strong interaction at superaccelerator energies by the characteristics of the electron-photon and the muon component of EAS.

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Table 1

The coefficients of the correlation of N_e and N_μ with the first interaction parameters.

	N_{ch}	ΣE_{ch}	Z	$\langle P_t \rangle_{ch}$	E_o
N	0.076	0.650	0.230	0.035	0.830
N	0.270	0.830	-0.029	0.047	0.910

Table 2

The coefficients of the correlation of the first interaction with the values measured

	N_{ch}	ΣE_{ch}	ΣE_{ch-p}	$\Sigma E_{ch\pi}$	Z	$\langle P_t \rangle_{ch}$
$\langle R_\mu \rangle$	0.167	-0.145	-0.087	-0.084	-0.615	0.056
σ^μ_R	0.150	-0.100	-0.052	-0.049	-0.590	0.012
$\langle E_\mu \rangle$	0.035	-0.044	-0.011	-0.006	-0.210	0.042
σ^μ_E	0.030	0.040	0.053	0.057	-0.120	0.032
N_e	0.076	0.652	0.549	0.537	0.230	0.035
N_μ	0.270	0.831	0.735	0713	-0.029	0.047

Table 3

The true and estimated values of the mean path and inelasticity coefficients

	true	estim
$\langle \Sigma E_{ch} \rangle$	612 ± .5	628.3 ± 15.9
$\langle \Sigma E_{ch-p}$	411 ± 9	421 ± 12
$\langle \Sigma E_{ch\pi}$	361 ± 3	368 ± 12.3
$\langle Z \rangle$	55.4 2.4	52.7 ± 3.2

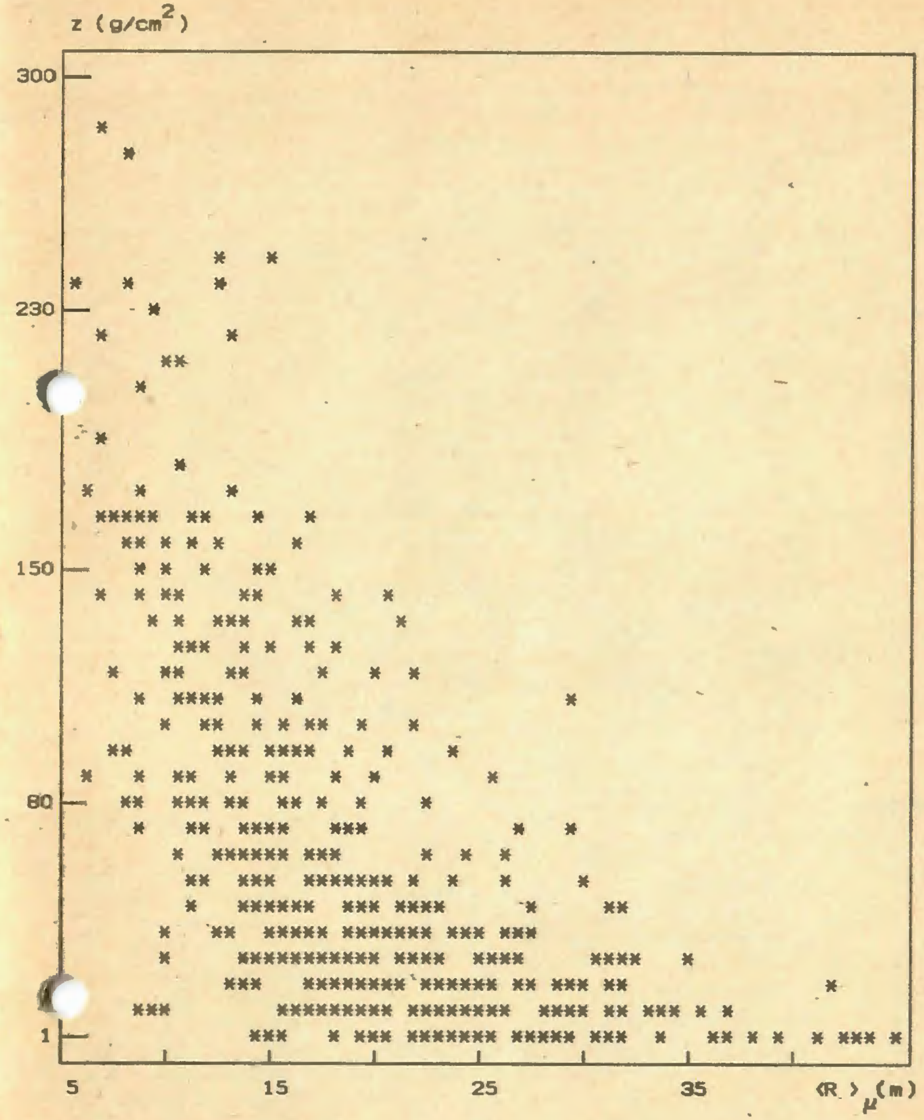

Fig.1 The average distance to the shower core for the muons with E>200GeV as a function of the free path.

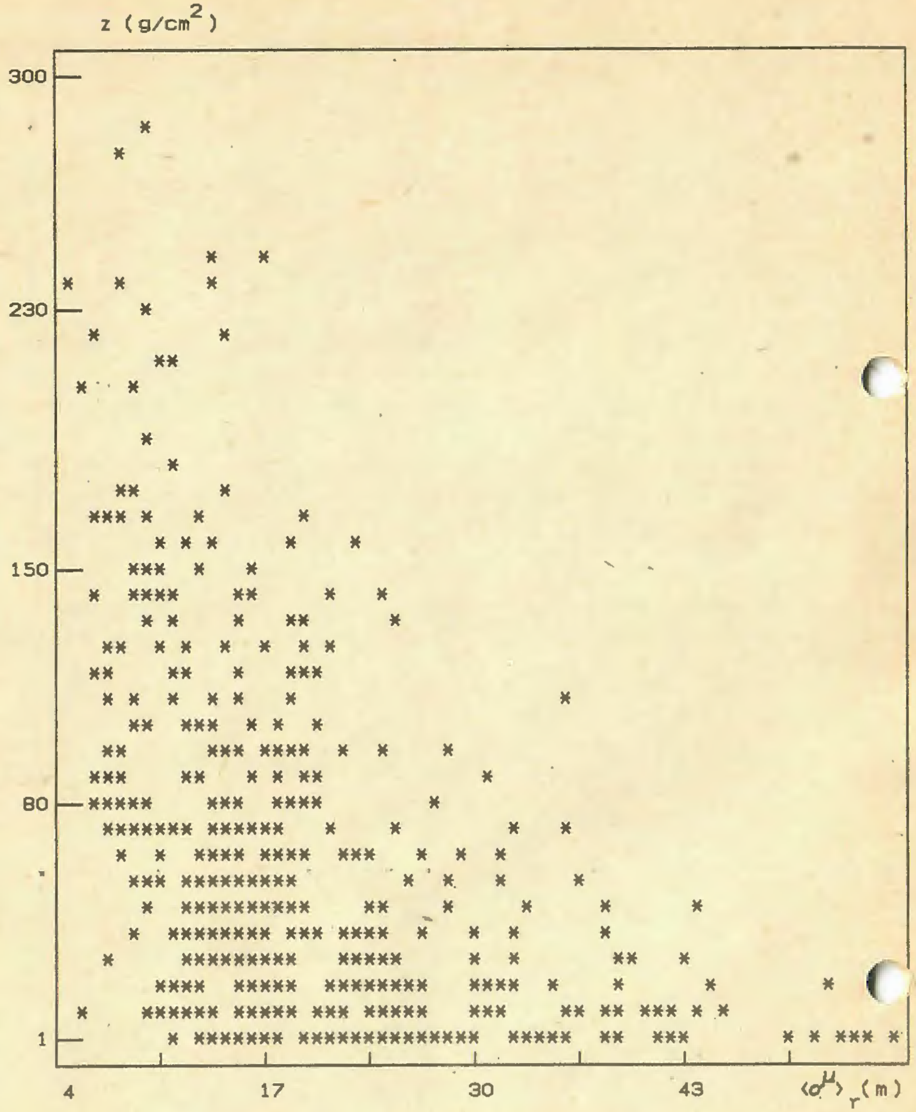

Fig.2 The variance of the spatial distribution of E>200GeV muons as a function of the free path.

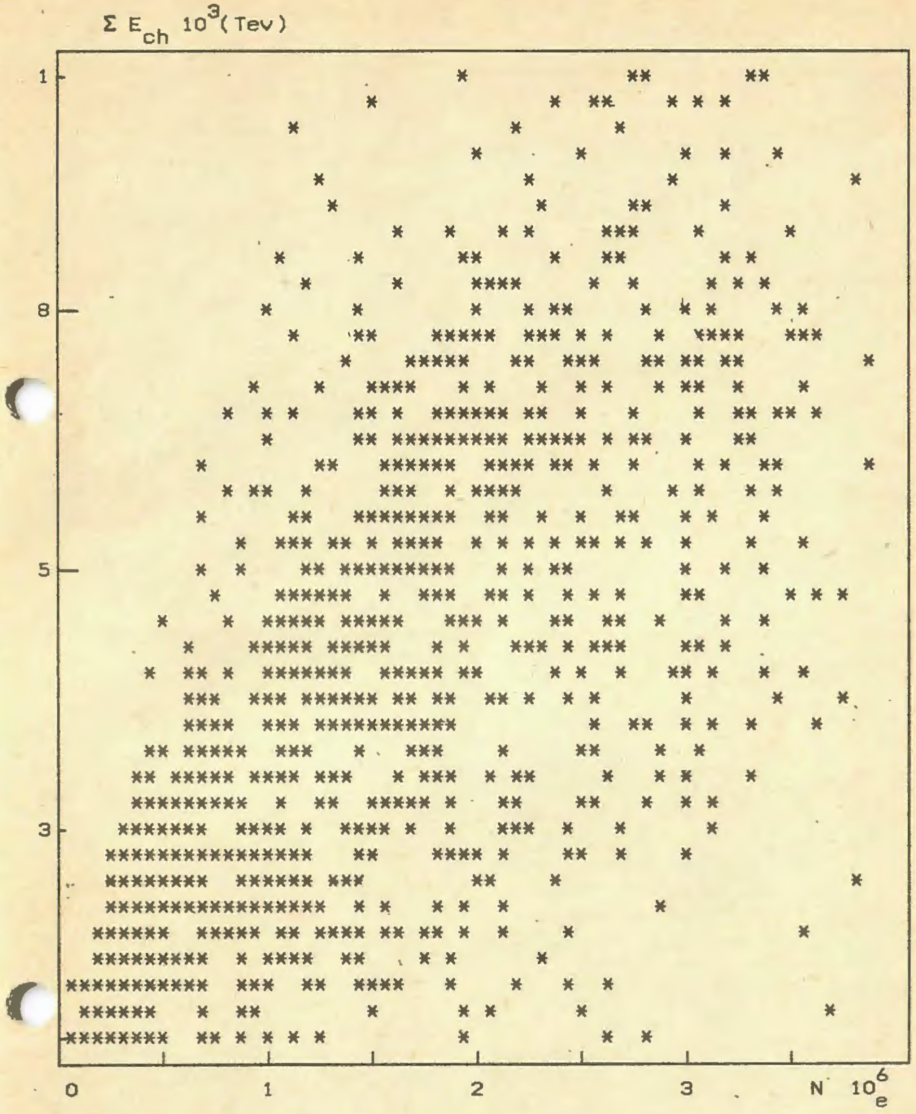

Fig.3 The total number of electrons as a function of the energy of the charged hadrons produced in the first interaction.

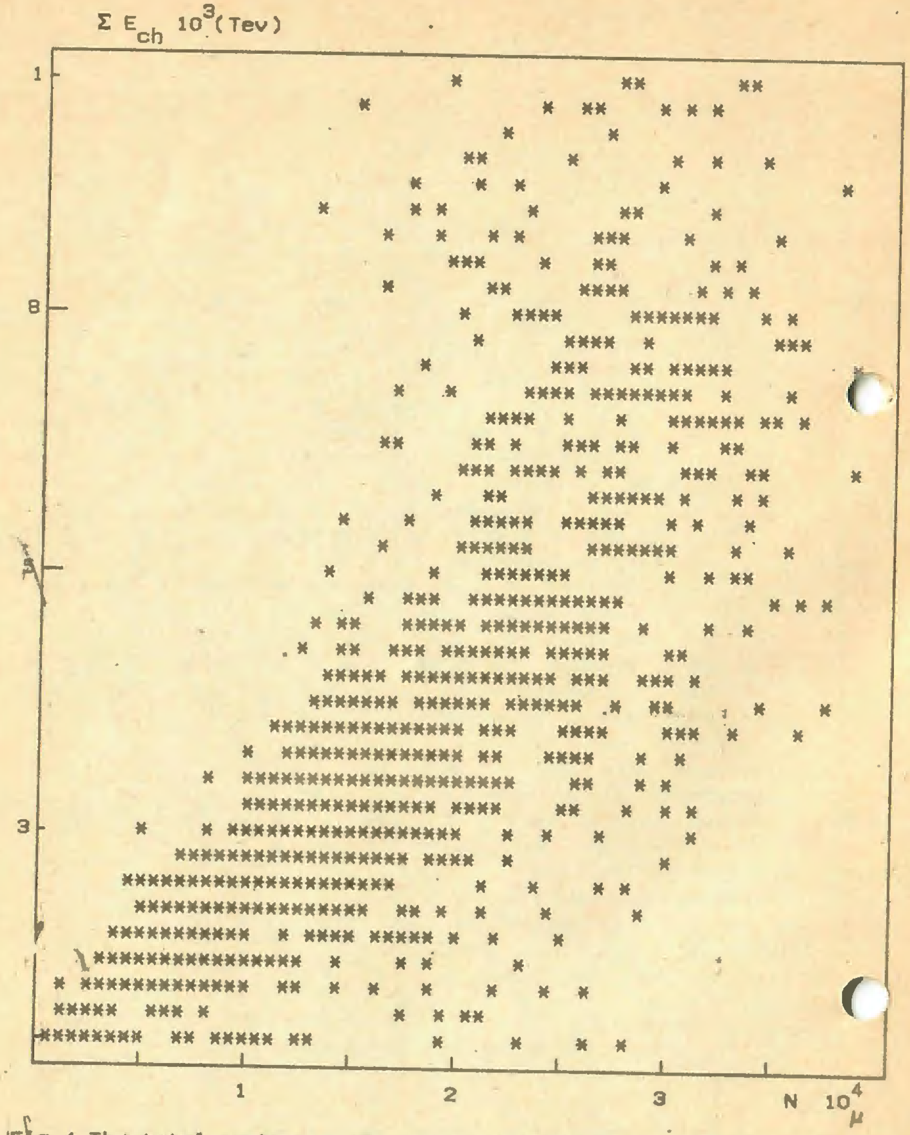

Fig.4 The total number of the muons with E>5GeV as a function of the energy of the charged hadrons produced in the first interaction.

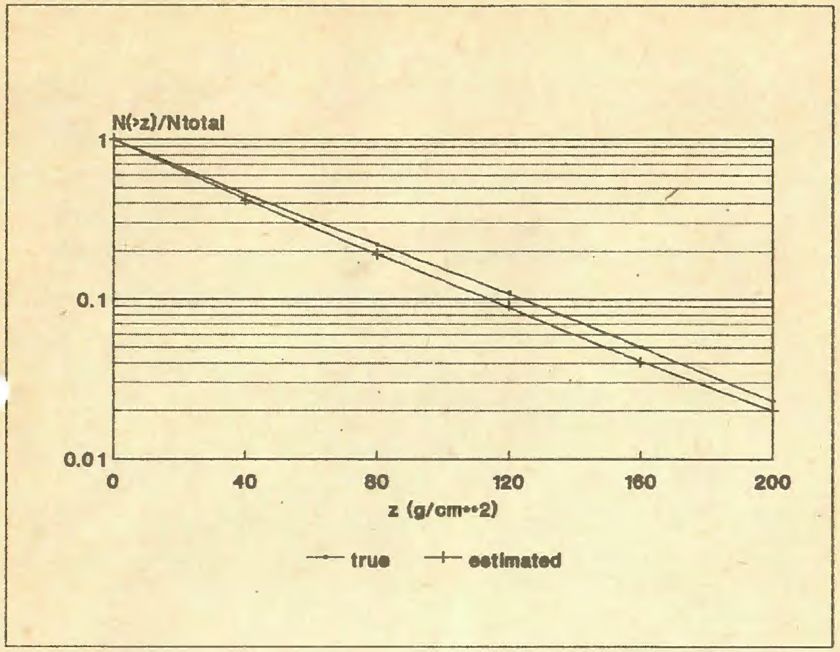

Fig.5 The integral distribution of the depth of first interaction

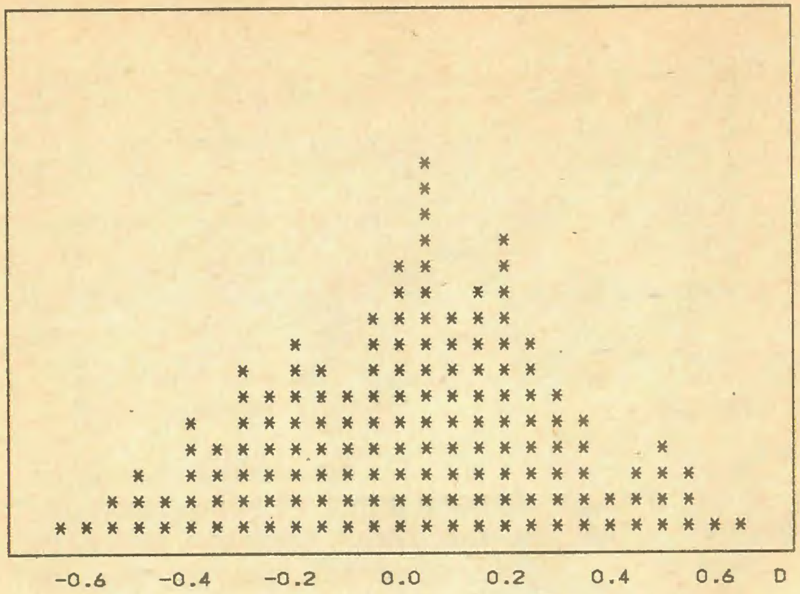

Fig.6 The inelasticity coefficient estimation relative error repetition histogram.

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