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Different Aspects of the FNC Simulation in the Framework of H1SIM

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Abstract

This note presents the results of simulation of new upgraded in 2000 Forward Neutron Calorimeter obtained with Monte Carlo program implemented in H1SIM. The simulation of the response of the FNC calorimeter is compared in detailed and fast modes. The results are presented for electrons and hadrons in the energy range 120 $GeV \div 900\ GeV$. The good quality of the simulation is demonstrated in distributions like deposited energy, longitudinal and transverse profiles.

Contents

1 Introduction

In 1996, the H1 Collaboration has installed the first lead/scintillator forward neutron calorimeter (FNC) of "spacal" type [1, 2] with aim to provide the calorimetry of neutrons in a very forward region at energies $100\,GeV \div 900\,GeV$. This calorimeter in conjunction with H1 experiment at HERA was used to study $ep \longrightarrow e'nX$ reaction.

In 1998 the new "sandwich" type preshower was installed in front of the main calorimeter which has allowed better separation of the neutrons from the electromagnetic showers and improvement of the energy and space resolution.

The acceptance and the energy response of the FNC were simulated by tracking neutrons through the H1 beam line and by smearing the energy according to the resolution of the calorimeter determined in testbeam and simulated by stand-alone program in framework of GEANT [3, 4]. Using data obtained with the FNC the different physics topics have been studied, for example, the triple differential cross section $d\sigma/(dxdQ^2dz)$ has been measured [5].

With a time, an energy response of FNC calorimeter has been significantly deteriorated. Therefore, it was decided to replace the main FNC calorimeter with a new calorimeter as a part of a large HERA and H1 upgrade program in 2000 [6].

The technology for new FNC calorimeter is based on a sampling technique using lead absorber material and scintillating plates readout by wavelength shifting fibers and photo-multiplier tubes. Such type of lead - scintillator sandwich calorimeters provides e/π ratio close to unity [7] and allows to achieve good energy resolution for hadrons.

The reliable simulation of FNC together with the simulation of all other H1 subdetectors is essential for the analysis and study of many physics topics where the scattered neutral particles are produced in proton direction and can be measured by the FNC calorimeter.

There exist two packages for simulation of hadronic showers: GEISHA - which is default mode in H1SIM and FLUKA - the MC package used for detailed simulation of high energy hadrons. Different energy distributions for electrons and pions in the energy range $10\ GeV \div 80\ GeV$ can be well described by GEISHA and FLUKA both [8]. One of the interesting points to be performed in the simulation analysis with new FNC is the comparison of results for high energetic hadrons obtained with two packages.

A complete simulation for the new FNC in framework of H1SIM includes detailed and fast modes both with the standard GEISHA interface for simulation of hadronic showers and the FLUKA interface.

The main calorimetric characteristics: linearity, energy and space resolution, e/π ratio, longitudinal and transversal profiles, energy response in different partitions of FNC were investigated with this MC.

2 Description of the simulation

The pre-upgrade FNC calorimeter was presented in framework of H1SIM as a piece of dead material only. The FNC simulation is implemented now in H1SIM to provide the easy access for everybody in H1 to simulate the FNC response and response of any H1 subdetector in any sort of events. The current version of simulation for new calorimeter includes the detailed and fast simulation modes to be used both for MC tuning and comparison with test data. Due to a very large number of particles involved in the development of electromagnetic showers in the calorimeter the full detailed simulation is rather slow. The typical simulation time for hadrons is ~ 30 sec/100GeV on 600MHz Linux PC. The cpu time with fast mode of the simulation is expected to be reasonable for producing of high statistics MC event samples. The typical timing for hadrons is ~ 0.5 sec/100GeV. The 100.000 events of 700 GeV neutrons, for instance, could be produced in 4 days.

2.1 Implementation of new FNC into H1SIM

The FNC simulation within H1SIM is possible either in fast or detailed modes.

Detailed mode

The detailed mode imply the use of complete tracking of the particles in detailed geometry. The detailed geometry description takes into account all essential features of calorimeter construction [6]. The FNC volume contains the main FNC volume and the preshower volume. The main FNC volume is composed of four module volumes, each spanning 50 cm in the axial (Z) direction and with a front face of 60 x 60 cm^2. Each module volume includes 6 towers with size 20 x 20 cm^2 and 2 towers with size 26 x 20 cm^2. The volumes of the towers and preshower are divided on the layers which are filled by certain volumes of lead, scintillator, stainless steel and Tyvec-paper with sizes as in real detectors. All towers are located inside an aluminum roofing volume. The support structure of the calorimeter is also implemented into the H1SIM geometry description of the FNC.

Fast mode

In the fast simulation, the complicated sampling structure of FNC medium is described by homogeneous volumes filled with a mixture of lead, scintillator, stainless steel and so on. The filling of volumes in that case does not have division on layers inside ones. Three types of mixed material in the calorimeter are used for main FNC towers, electromagnetic and hadronic compartments of the preshower. The description of the dead material remains the same as in detailed mode.

The tracking in fast mode of simulation implies the parameterization of shower evolution of electromagnetic particles and the complex simulation for hadrons. The shower evolution of electromagnetic particles is fully parameterized if shower is contained in the homogeneous medium. If shower extends over the dead material inside the calorimeter, the detailed simulation is kept. For hadrons, the situation is more complex since a lot of processes are involved and in this case the hadrons are tracked by the GEANT program through the calorimeter. Neutral pions decay into two γ's and their energy deposition is parameterized in the same way as for electromagnetic showers.

2.2 Special effects

Signal recombination effects in FNC scintillator, described by Birk's Law, were handled with standard GEANT package in detailed simulation mode. Special correction coefficients were implemented into H1SIM in the fast mode for the FNC to take into account the effect of signal attenuation. The deposited energy in dependence of particle energy and its type was corrected by this coefficients.

The noise signal was not added for each read-out channel due to rather small effect seen in the real DATA.

2.2.1 Homogeneity

Due to a special construction of readout channels in FNC towers with the wavelength shifter fibers grooved on the surface of scintillator plates, a non-homogeneity of signal is possible. A special tests and MC study were carried out in Institute for Theoretical and Experimental Physics, Moscow (ITEP) to understand the level of possible non-homogeneity of signal response. The central FNC tower was scanned in x and y directions uniformly at 64 points, from the front face with radioactive β - source. Similar test was done in framework of MC simulation of light collection passing particles through the scintillating plate. The mean value of signal response in central FNC tower measured as a function of the beam impact point is shown in figure 1 for tests with β - source and MC simulation both. This distributions of signal amplitude and layout of fibers in the scintillators for all FNC towers were taken into account in description of the simulation for main FNC calorimeter.

2.2.2 The cross talk

The light cross talk (LCT) between adjacent X(Y) strips of the preshower has a heavy impact on the space resolution, cluster radius, second moment. The LCT is caused by deposited in one channel light transmitting not only into appropriate photo-diode but into several others adjacent strips. Without taking this feature into account the distributions of electron energy in preshower strips are different in DATA and MC. To make the simulation in better agreement with DATA one can find the function to be applied to MC to spread the light in strips. The distributions of energy portions in 9 X and 9 Y strips for DATA and MC are shown in figure 2a for electrons shooting in the center of the preshower. The shape of this distributions depends slightly on beam energy of 120 $GeV \div 350$ GeV. Full error of each point is

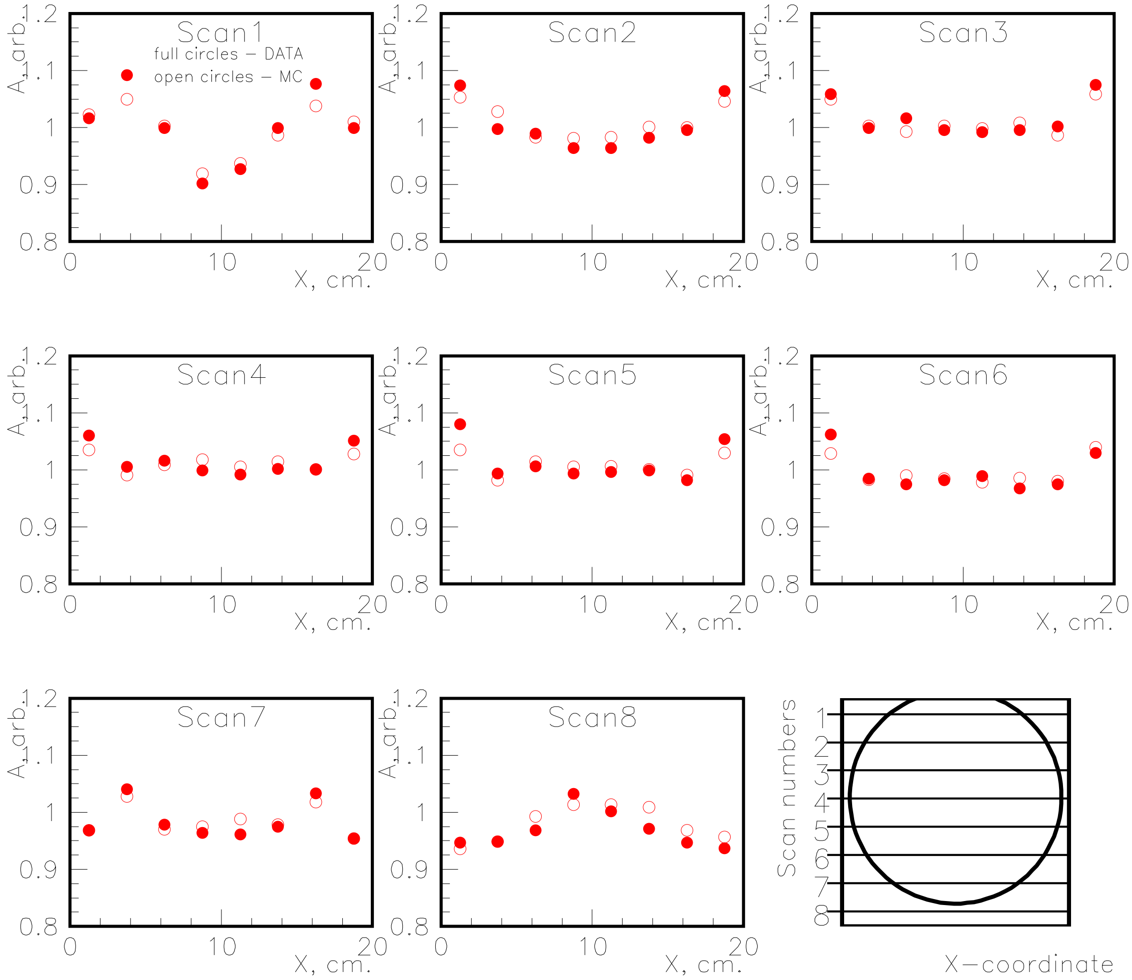

Figure 1: The signal amplitude (A) dependence versus coordinate in scan over the main FNC tower face space.
The open points - MC calculations (see text).
The full points - results obtained with radioactive β - source.
The correspondence of plots to scan lines is shown in the lower right corner.

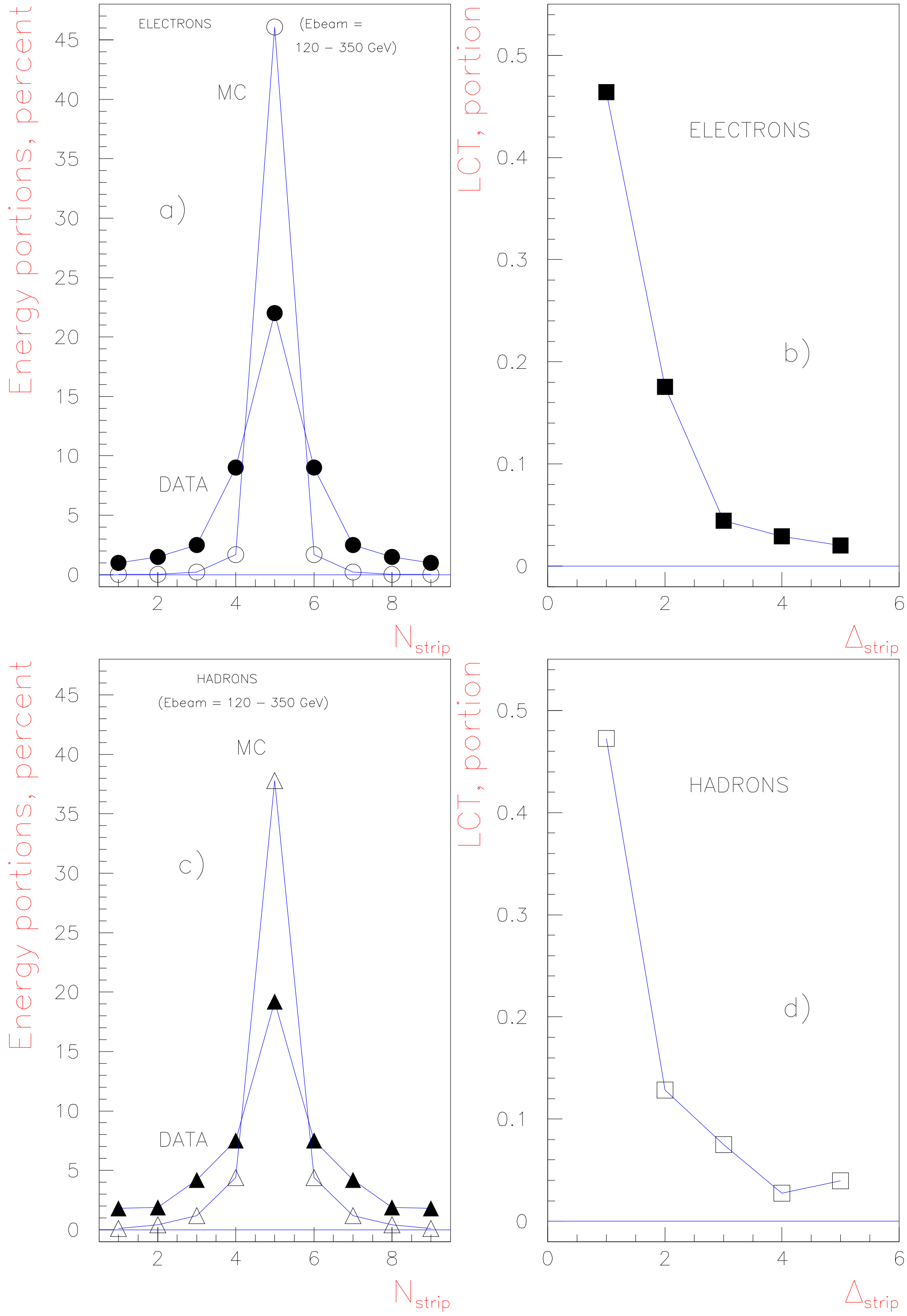

Figure 2: Portions of energy deposited in strips for electron beam(a) and hadron beam(c), shooting to center of the preshower;
LCT function(see text) obtained with electrons to be applied in MC(b)
and LCT function obtained with hadrons(d);
DATA - full points, MC - open points.

estimated to be better 4 % in DATA and MC both. Using this plots the smearing function A_m can be found for light deposited in strip i , where m to be changing between 1 and 9: $m = |i - j| + 1$ and j - is a number for strip with smeared energy.

The smearing function, the measured and MC energies can be regarded as the following equation system:

$E_1^{mc} A_1 + E_2^{mc} A_2 + E_3^{mc} A_3 + E_4^{mc} A_4 + E_5^{mc} A_5 + E_6^{mc} A_6 + E_7^{mc} A_7 + E_8^{mc} A_8 + E_9^{mc} A_9 = E_1^{data}$

$E_2^{mc} A_1 + (E_3^{mc} + E_1^{mc}) A_2 + E_4^{mc} A_3 + E_5^{mc} A_4 + E_6^{mc} A_5 + E_7^{mc} A_6 + E_8^{mc} A_7 + E_9^{mc} A_8 = E_2^{data}$

....

$E_5^{mc} A_1 + (E_6^{mc} + E_4^{mc}) A_2 + (E_7^{mc} + E_3^{mc}) A_3 + (E_8^{mc} + E_2^{mc}) A_4 + (E_9^{mc} + E_1^{mc}) A_5 = E_5^{data}$

....

$E_9^{mc} A_1 + E_8^{mc} A_2 + E_7^{mc} A_3 + E_6^{mc} A_4 + E_5^{mc} A_5 + E_4^{mc} A_6 + E_3^{mc} A_7 + E_2^{mc} A_8 + E_1^{mc} A_9 = E_9^{data}$,

which can be written in more general form:

$$\hat{E}_{mc} \cdot \hat{A} = \hat{E}_{data}, \tag{1}$$

where $\hat{E}_{data}$ - the matrix of measured energies E_i^{data} and $\hat{E}_{mc}$ - the matrix with elements which consists of linear combinations of the MC energies E_i^{mc}.

In general case, the $\hat{E}_{mc}$ is the 9×9 matrix. Assuming the $A_6 \div A_9$ to be small one can reduce the order of matrixes up to 5, keeping under control the sum combination of smearing coefficients:

$$A_1 + 2 * A_2 + 2 * A_3 + 2 * A_4 + 2 * A_5 \ \simeq \ 1 \tag{2}$$

The expression (2) follows from the conservation of deposited and smeared energies. So, one can resolve the equation system (1) and find $\hat{A}$ matrix. The LCT function plotted versus strip number difference m is shown in figure 2b. This smearing function obtained with electrons was chosen to be applied in MC. The precision of such a procedure estimated with (2) is equals 0.2 % for electrons and 1.2 % for hadrons. The similar plots for hadrons are shown in figure 2c and figure 2d. The results have some difference due to the bigger lateral leakage for hadrons.

2.2.3 Light losses in hadronic preshower

The preshower consists of two parts: electromagnetic and hadronic. The energy of hadrons on electromagnetic scale in preshower can be written as follows:

$$E_{presh}^{elm} = \frac{E_1^{v.h.}}{s_1} + \frac{E_2^{v.h.}}{s_2} \tag{3}$$

where $E_1^{v.h.}$ and $E_2^{v.h.}$ are the visible energies deposited by hadrons in electromagnetic and hadronic compartments of preshower respectively; s_1 and s_2 - sampling fractions of the two parts. The two parts of real preshower are not separated in readout and for this reason, the value proportional to $(E_1^{v.h.} + E_2^{v.h.})$ can only be measured. Besides, the sampling fraction s of the preshower can be found from tests with electrons of known energy E_0 shooting in the preshower center:

$$E^{vis} = E_0 * s, \tag{4}$$

where E_{vis} is the visible energy deposited in active material (proportional to measured energy). The sampling fraction s is really the sampling fraction s_1 because electrons deposit full its energy in electromagnetic compartment. So, the hadronic energy on electromagnetic scale can be expressed via the visible energy of preshower and sampling fraction of electromagnetic compartment:

$$E_{presh}^{elm} = \frac{E_{presh}^{v.h.}}{(k * s_1)} = \frac{(E_1^{v.h.} + E_2^{v.h.})}{(k * s_1)} \tag{5}$$

The sampling fraction s_2 of hadronic compartment of preshower is not used in equation (5) and because of that, the coefficient k is added there. Combining (3) and (5), k can be defined as

$$k = \frac{(E_1^{v.h.} + E_2^{v.h.}) * s_2}{E_1^{v.h.} * s_2 + E_2^{v.h.} * s_1} \tag{6}$$

It is assumed that $s_1 = s_2$ in the preshower due to the same constructive structure of two compartments (just double longitudinal sizes of hadronic part with respect to electromagnetic part). In this case $k = 1$ as it follows from (6). Therefore, energy of hadrons on electromagnetic scale can be restored (see (5)) using visible energy of the preshower and sampling fraction s_1.

It was confirmed by the MC that $s_1 = s_2$ (≈ 0.027). Nevertheless, it is important to check this equality for real preshower. In hadronic compartment of the preshower each layer contains two adjoined scintillator plates. One can expect the increasing of light with respect to the electromagnetic compartment with one scintillator plate only by factor 2.0 . But, this factor obtained from measurements is 1.46. The possible reason is the losses of light in space between two plates. So, there is reducing of signal by factor $a = 1.46 : 2.0 = 0.73$. In this case the $E_2^{v.h.}$ and s_2 both in expression (6) should be multiplied by factor a, and equation (6) can be rewritten as:

$$k = \frac{(E_1^{v.h.} + a * E_2^{v.h.})}{E_1^{v.h.} + E_2^{v.h.}} \tag{7}$$

Using the visible hadronic energies $E_1^{v.h.}$ and $E_2^{v.h.}$ from MC, the obtained value of k is equals 0.77 independent on beam energy. From CERN TESTs data the same factor was obtained for different beam energies using optimization of hadronic energy resolution applied for full calorimeter.

So, to restore in preshower the energy of hadrons on electromagnetic scale using sampling fraction of electromagnetic compartment only (see (5)), the obtained energy has to be increased by factor $1./0.77 = 1.3$.

2.3 Digitization

Two output simulation banks FRCE and FRCX provide FNC information for H1REC. The FRCE bank contains visible energy and corresponding channel numbers, the FRCX bank - relations between simulated tracks and digits.

For correct use of this information the special effects present in real calorimeter and implemented in MC (see section 2.2) have to be taken into account. Due to some inhomogeneity there is slightly different (see section 2.2.1) energy response of each FNC tower to electrons of the same initial energy shooting in the tower center. The energy response of each preshower strip is also different due to LCT effect (see section 2.2.3) and lateral losses of light in scintillator plates.

The difference of energy response of FNC channels to the same initial electron energy has been taken into account to provide the inter-calibration of all FNC cells and to get electromagnetic energy scale. This scale, in particular, was used in MC investigation of main FNC characteristics performed in this note (see section 3).

2.4 Steering

To simulate full H1 detector including FNC in post-upgrade configuration, some parameters have to be changed in steering banks of H1SIM simulation.

The flag of configuration setup in 'OSGO' bank has to be set to value ≥ 10.

The steering of the FNC area is derived via 'FWFE' subdetector column in 'OSGD' bank. The selection of the desired granularity and tracking can be done there. This steering is applied to preshower and main FNC calorimeter simultaneously.

The default setting in upgrade simulation is the medium granularity and fast tracking with flags 2 and 3 respectively.

The 'FWFE' column is related also to other forward detectors, but they are always simulated with fine granularity and tracking.

3 Simulation results

3.1 Linearity and resolution for electrons

The calorimeter response to electrons and photons was studied with simulation using the generated electrons. The beams have shot in the center of the preshower or in the center of central FNC tower in the configuration of set-up without preshower. The electrons of different initial energies ($1\ GeV \div 700\ GeV$) were generated in front of the corresponding set-up.

Linearity

The energy linearity for electrons is shown in the figure 3 as function of the visible in calorimeter energy E_{vis} versus beam energy E_{beam}. The two sets of points related to preshower and main calorimeter can be very well described by straight lines going through zero. The second parameter in every fit is the sampling energy fraction - portion of initial energy deposited in active material of the calorimeter. The sampling energy fraction is the constant value for calorimeter of definite type and allows to get electromagnetic energy scale. The sampling fraction for preshower is $\sim$ 2.7 %, for main FNC calorimeter - $\sim$ 1.5 % as seen in figure 3. The linearity of energy response for preshower and main FNC calorimeter is better than 1 %. The value of energy leakage for electrons in preshower is $\sim$ 0.3 %, in main FNC calorimeter - $\sim$ 0.4 %.

Energy resolution

The physical processes of particle energy losses in the material are of a statistical nature. Discrete sandwich structure of calorimeter cause fluctuations in the number of shower particles that intersect the sensitive space of the detector. For this reason the deposited energy fluctuates and causes errors of energy measurement. The magnitude of the error is a function of the construction features and of the initial particle energy ($\sim 1/\sqrt{E}$). The relative energy resolution σ_E/E as a function of incident energy E_{beam} for electrons was fitted to a function including a sampling term $(1/\sqrt{E})$ and a constant term added in quadrature. The fits yield for preshower and main calorimeter respectively:

$$\sigma_E/E = \left(\frac{18.3 \pm 0.2}{\sqrt{E[GeV]}} \oplus (0.5 \pm 0.0)\right)\%. \tag{8}$$

$$\sigma_E/E = \left(\frac{26.2 \pm 0.2}{\sqrt{E[GeV]}} \oplus (0.1 \pm 0.0)\right)\%. \tag{9}$$

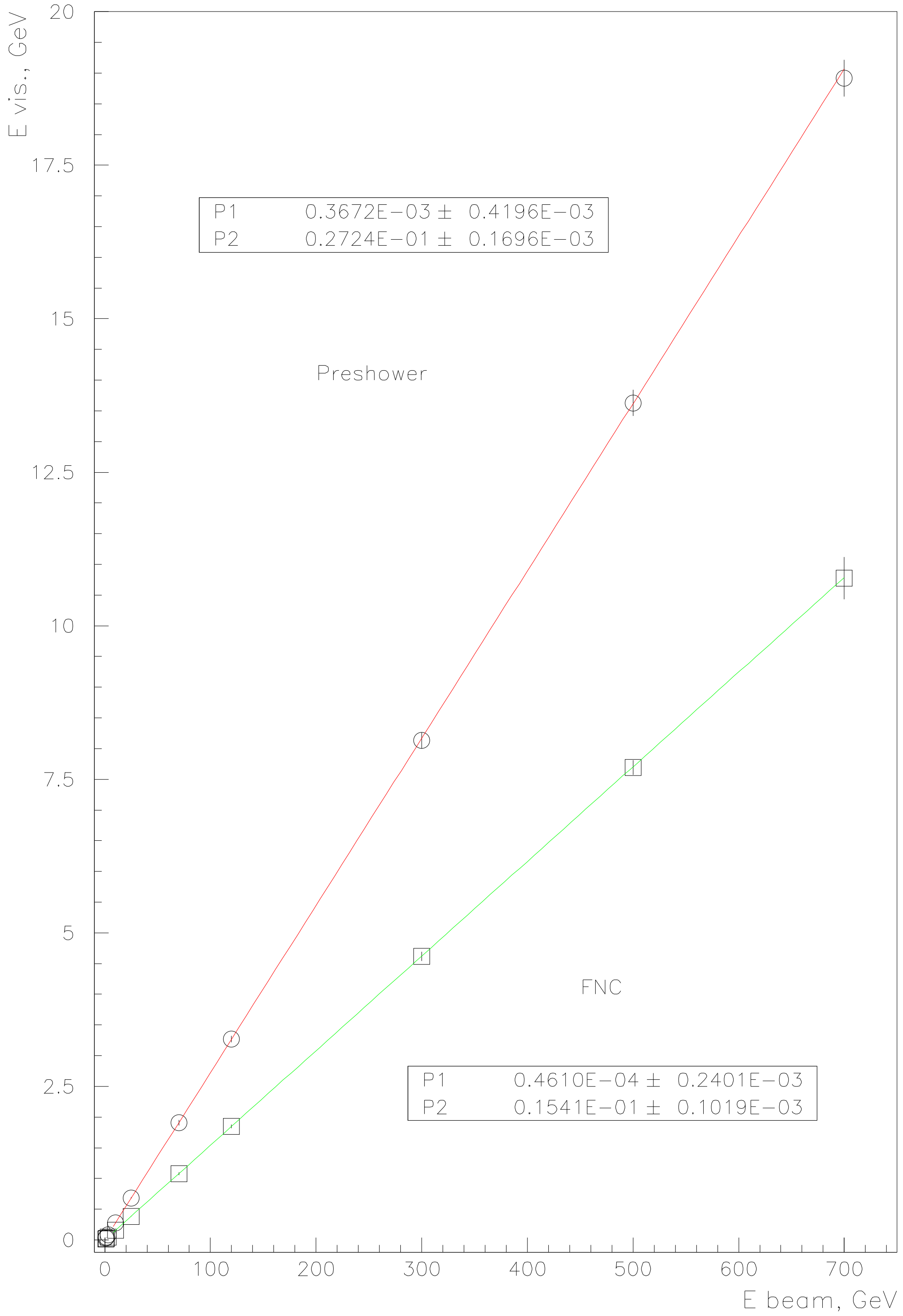

Figure 3: The visible energy versus electron beam energy for the preshower(circles) and the main FNC calorimeter(boxes).

3.2 Hadronic response in the calorimeter

The FNC simulation in two configurations of the set-up with and without preshower was used to study a calorimeter response to hadrons. The generated in front of the corresponding set-up hadrons of different initial energy in range 120 $GeV \div 900$ GeV have shot in the centers of the preshower or central FNC tower.

3.2.1 GEISHA - FLUKA comparison

The MC program FLUKA [11] which simulates the development of hadron-induced cascades is a stand-alone code. FLUKA takes care to describe at high energies the following aspects of direct relevance for calorimetry: electromagnetic energy fraction (π^0 and γ production including γ's produced by slow neutrons), energy spent in "heavy" recoils and fission fragments, binding energy losses, the transport of low energy neutrons, multiplicity distributions of relativistic particles and so on.

FLUKA is able to simulate inelastic nuclear collisions in details, in an energy range from several TeV down to 20 MeV.

The level of accuracy that can be reached with FLUKA concerning the spatial distributions of energy deposition in cascades induced by high-energy hadrons is close to the best level that can be tested by several CERN experiments [10].

Since version 3.15, GEANT includes an interface with some FLUKA routines, mainly the ones, dealing with hadronic elastic and inelastic interactions.

The MC study of hadronic response in the FNC was carried out in framework of H1SIM with usage of FLUKA and GEISHA modes for simulation of hadronic interactions.

It is known that the simulation with GEISHA can describe the hadronic showers at energies < 100 GeV only [8], and for that reason the simulation results at higher energies obtained with GEISHA will be shown for comparison only.

To obtain accurate results, the MC program was run with cutoff values that are sufficiently low to correctly describe the peculiarities of the energy deposition by the soft component. The essential cut off parameters E_γ, E_e for γ' s and electrons are 10 KeV .

Leakage and energy components

Due to limited sizes of the FNC one important question concerns the hadronic energy leakage. In the figure 4a the energy beam dependence of leakage is shown as calculated in FLUKA and GEISHA. The average leakage for FLUKA over energy range 120 $GeV \div 900$ GeV is equal to $(5.2 \pm 0.1)\%$. This value is bigger than $(3.2 \pm 0.1)\%$ for GEISHA.

The hadronic shower development includes many different processes of strong interactions. Hadronic shower have two basic components: electromagnetic and pure hadronic. Electromagnetic component is related to the produced in the shower π^0's

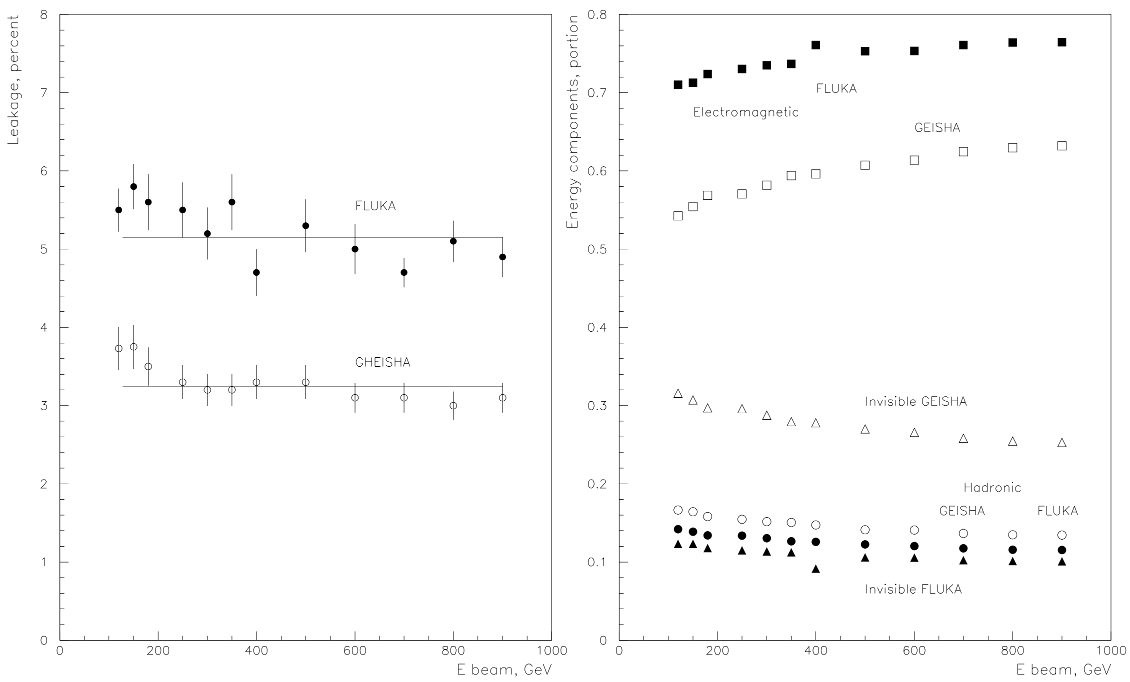

Figure 4: GEISHA(open points) and FLUKA(full points) results for hadrons plotted versus beam energy: a) Leakage of total energy, b) portions of electromagnetic, hadronic and invisible energy components.

and η's which decay into γ's. In the pure hadronic component, some fraction of energy disappear without contributing to calorimeter signal and is invisible: neutrinos, muons which escape from the detector, a certain fraction of the neutrons produced in the nuclear reactions and, finally, the energy spent in breaking up the nuclei in these reactions. So, energy deposited in the calorimeter by high-energy hadrons contains electromagnetic, hadronic and invisible portions.

The portions of electromagnetic, hadronic and invisible energies to total deposited energy are shown in figure 4b. The invisible component is very large in GEISHA ($\sim$ 30 %) while in FLUKA it is much smaller ($\sim$ 10 %). In the contrary, the contribution of electromagnetic energy component in FLUKA is larger by 20%. These differences can clarify the difference between FLUKA and GEISHA in energy leakage distribution (figure 4a: the more visible energy the more leakage).

e/π ratio

The energy responses obtained for electrons and pions give the possibility to determine the e/π ratio which characterize non-compensation of a calorimeter. For the calorimeters with similar to FNC relation of active and dead materials, the e/π ratio is close to 1 [7]. The figure 5a shows these ratios for FNC obtained with GEISHA and FLUKA. For GEISHA the e/π ratio shows some energy dependence and value of this ratio is $\sim$ 1.15 in average. The e/π ratio for FLUKA is close to unity and as a consequence, this ratio is energy independent [9]. The average value is about 0.94. It means that FNC is slightly over-compensating.

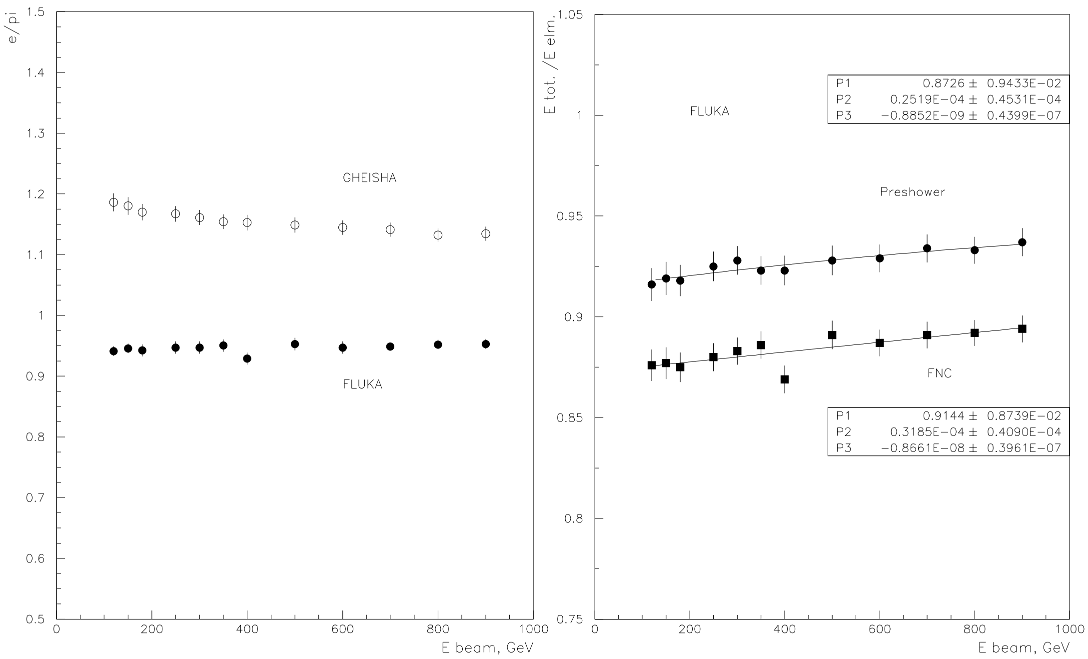

Figure 5: GEISHA(open points) and FLUKA(full points) results for hadrons plotted versus beam energy: a) The e/π ratio, b) The ratio of total deposited hadronic energy to electromagnetic scale energy for the preshower and the main FNC calorimeter.

Energy scales

In order to measure the energy of hadrons in calorimeter one needs to know the electromagnetic scale energy. This scale relates the measured charge (or visible energy in MC) to the known initial energy of electron beam. The energy of hadrons on electromagnetic scale is often named as electromagnetic energy (do not mix up with electromagnetic fraction of deposited energy in figure 4b).

To restore the full energy of hadrons one needs to know the calibration function which relates electromagnetic and total deposited energies. The correction function can be calculated in simulation where all scales of energy are known.

The ratio of total deposited hadronic energy to energy on electromagnetic scale is shown in figure 5b in the large range of beam energies for the preshower and the main FNC calorimeter. The fitting results with second order polynomial function are plotted to get the correction functions.

Portions of deposited energy

It is important to know the average energy deposited in different compartments of the FNC set-up. The figure 6 shows the energy portions deposited in the preshower and four FNC modules calculated with FLUKA and GEISHA as function of beam energy. There are certain differences between GEISHA and FLUKA calculations. It is seen also that in average ~ 90 % of all energy is deposited in the preshower and two modules of main calorimeter.

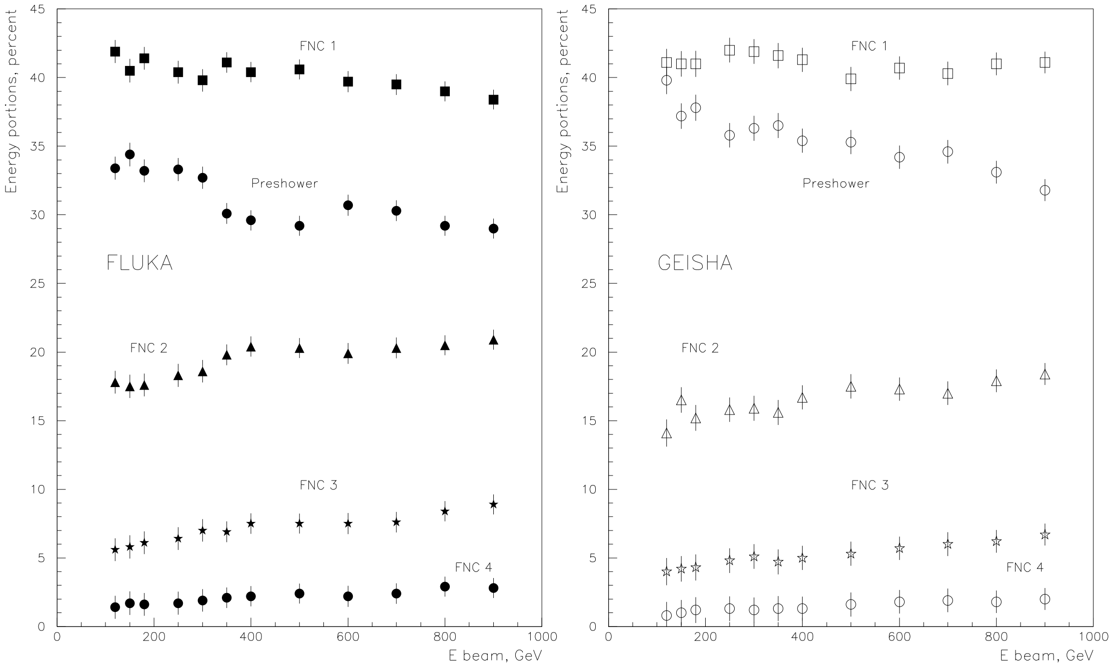

Figure 6: The portions of deposited energy in the preshower and four FNC modules as function of hadronic beam energy.
a) FLUKA calculations. b) The results with GEISHA.

Linearity

The linearity of energy response for hadrons in the FNC is shown in the figure 7a as dependence of electromagnetic scale energy $E_{elm.}$ versus beam energy E_{beam}. The two sets of points related to FLUKA and GEISHA simulation can be very well described by straight lines going through zero. The slope obtained in the fit for FLUKA is equal $\simeq 1.052$. The value of this slope defines the relation between electromagnetic scale energy of hadrons $E_{elm.}$ and their total, initial beam energy E_{beam}. One can estimate the value of this relation using known from figure 4a the average value $\simeq 0.95$ of leakage, i.e.

$$E_{dep.} = 0.95\ E_{beam}, \tag{10}$$

where $E_{dep.}$ is total deposited energy in the calorimeter. One need to use also the correlation between this $E_{dep.}$ and $E_{elm.}$ which can be found from figure 5b. The average value in this proportion is ~ 0.90, i.e.

$$E_{dep.} = 0.90\ E_{elm.}. \tag{11}$$

So, from expressions (10) and (11) the relation

$$E_{elm.} = (0.95/0.90)\ E_{beam} = 1.056\ E_{beam} \tag{12}$$

is obtained, with coefficient 1.056 very close to the one obtained in the fit.

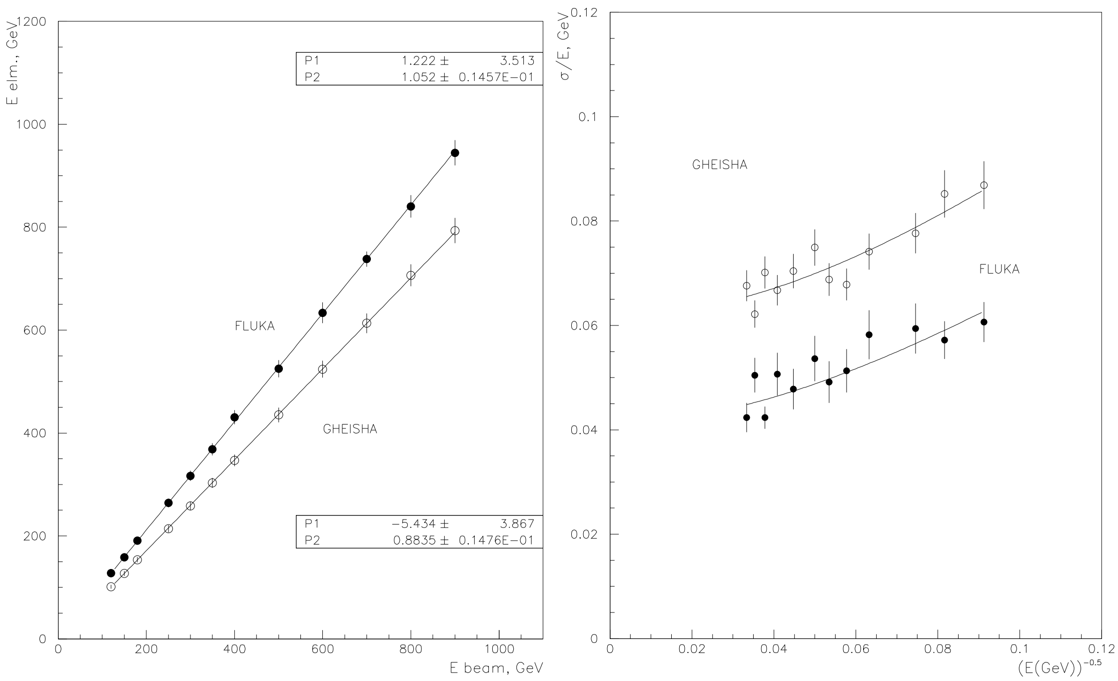

Figure 7: GEISHA(open points) - FLUKA(full points) results for hadrons plotted versus beam energy:
a) Energy in calorimeter (electromagnetic scale), b) Hadronic energy resolution.

Energy resolution

The relative energy resolution σ_E/E as a function of incident energy E_{beam} for hadrons in the FNC is shown in the figure 7b. The fit including the sampling and a constant terms added in quadrature for GEISHA points yields:

$$\sigma_E/E = \left(\frac{65.6 \pm 5.9}{\sqrt{E[GeV]}} \oplus (6.2 \pm 0.2) \right) \%, \tag{13}$$

The energy resolution in FLUKA case is better:

$$\sigma_E/E = \left(\frac{51.6 \pm 6.3}{\sqrt{E[GeV]}} \oplus (4.1 \pm 0.3) \right) \%. \tag{14}$$

The level of hadronic energy resolution with FLUKA for the FNC calorimeter is comparable with other results obtained for Pb/plastic-scintillator calorimeters [9].

3.2.2 The tuning of H1FAST

The results of detailed simulation based on FLUKA were used for the tuning the fast mode of H1SIM program. In H1FAST module the inelastic interactions and their products are determined at each step of the hadronic shower evolution via the GHEISHA interface.

The response of the calorimeter in the fast mode of the simulation is defined by the properties of material mixture and by the tuning parameters defined in 'GFC0' bank. The bank 'GFC0' is a new bank instead of 'GFC5' since upgrade 2001. Columns 'FNCA' and 'FNPR' in this bank are related to the main FNC calorimeter and preshower respectively.

For tuning the fast FNC simulation, several characteristics of the energy response in the preshower and FNC modules were used in comparison with detailed FLUKA simulation, in particular, the position and width of electron and hadron peaks. In figure 8 the distributions of the energy deposited in the preshower, the main FNC calorimeter and in four its modules for 350 GeV hadrons are shown with rather reasonable agreement between the fast and detailed simulations. The MC results are compared on the electromagnetic scale energy.

The comparison of the transversal and longitudinal profiles were also used for tuning the fast FNC simulation. This profiles were obtained using the MC information about the coordinates and the energies of the simulated hits to calculate averaged in hits in a given read-out channel the X, Y and Z coordinates and energy.

Figure 9 represents the X, Y - coordinate profiles of energy deposited by 350 GeV hadrons in preshower channels for detailed and fast simulation. Longitudinal profiles for preshower are shown in figure 10a. The profiles obtained with detailed FLUKA simulation are in reasonable agreement with the results of fast simulation except some regions with very small energy deposition.

For the main FNC calorimeter the longitudinal and lateral in radius profiles of energy deposited by 350 GeV hadrons are shown in figures 10b and 10c respectively. In general, the plots also show rather good agreement between the detailed and the fast simulation.

The attempts to improve this agreement using only tuning parameters of 'GFC0' bank were unsuccessful. Main reason for that is the use in the fast mode the GEISHA interface for simulation of hadronic showers. One can improve the agreement using instead the FLUKA interface. Nevertheless, since the GEISHA interface is used for simulation of all other H1 subdetectors this interface was chosen for FNC simulation as well.

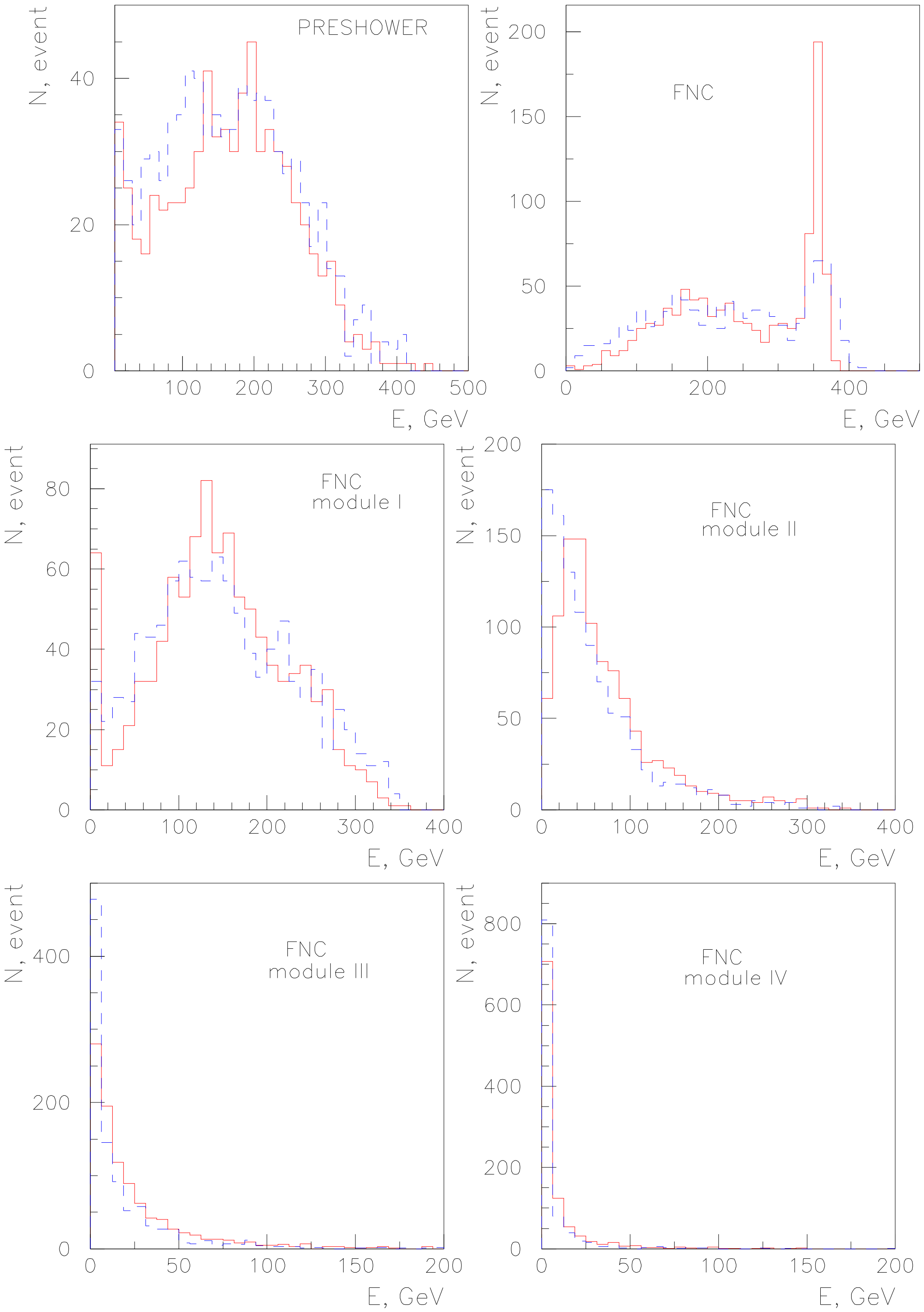

Figure 8: The distributions of energy (electromagnetic scale) deposited in the preshower, the main FNC calorimeter and in four its modules for 350 GeV hadrons. Solid lines - detailed simulation with FLUKA, dash lines - H1FAST simulation.

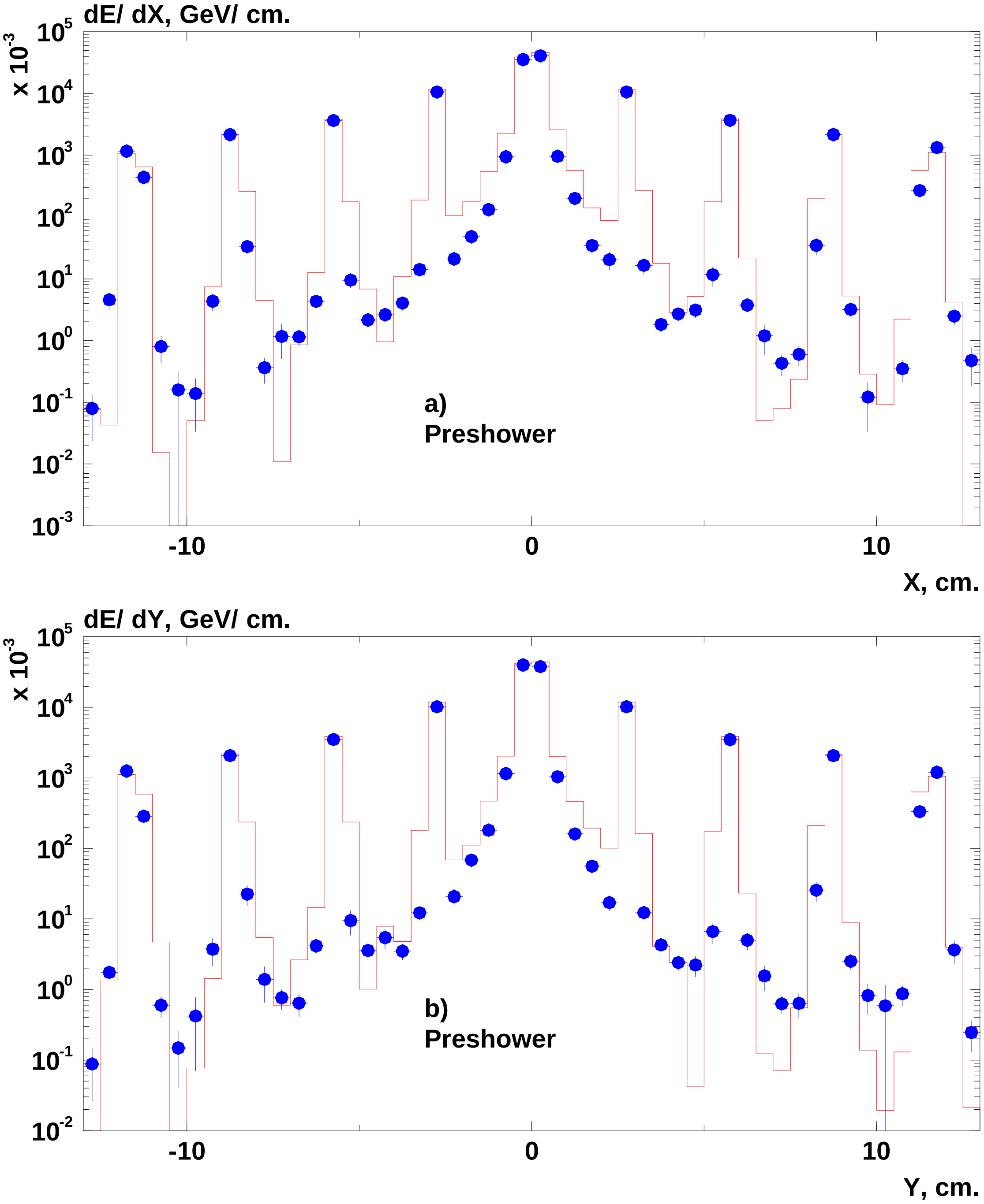

Figure 9: The lateral X(a) and Y(b) profiles of deposited in the preshower energy for 350 GeV hadrons for detailed (solid lines) and fast (points) simulation.

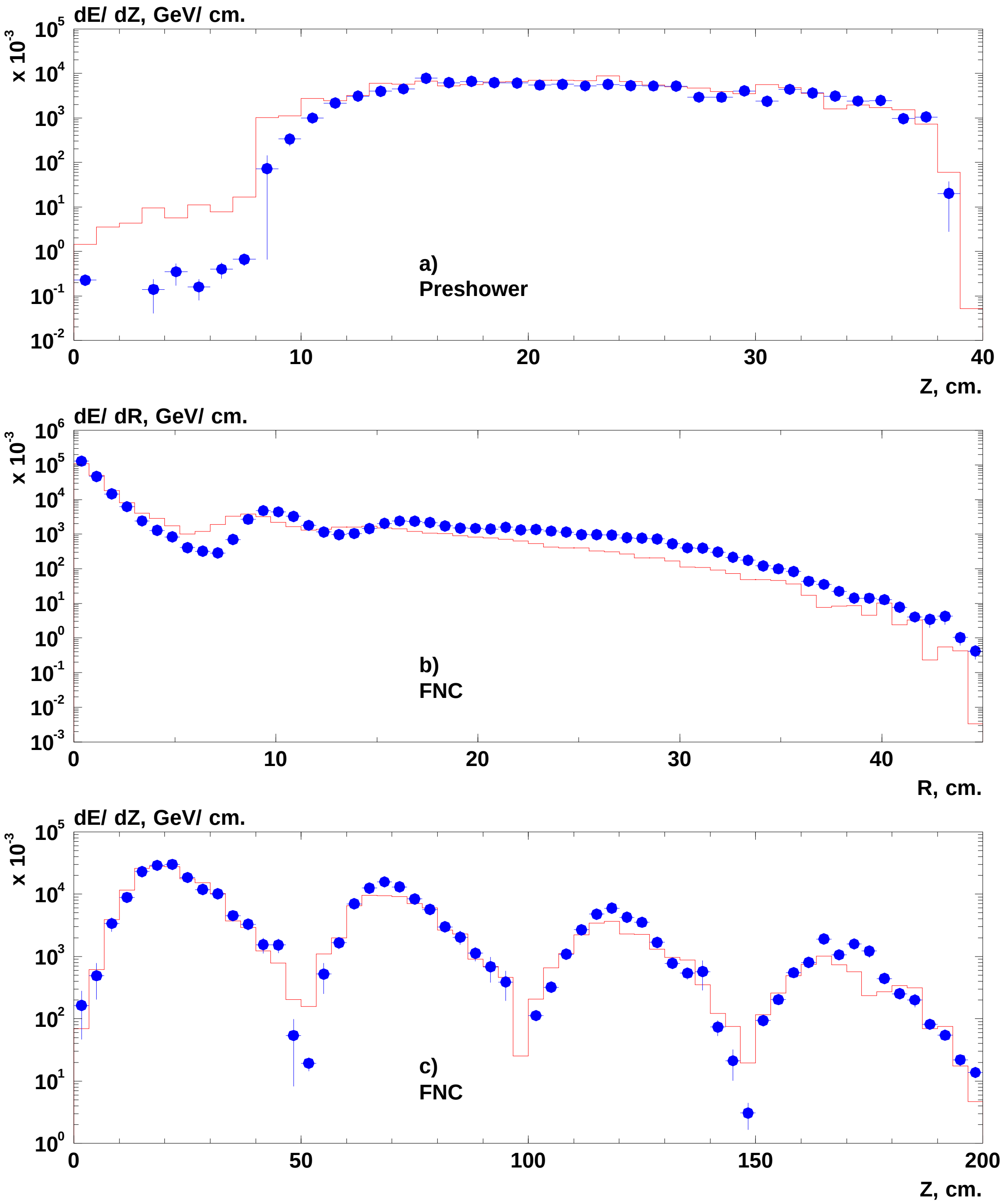

Figure 10: The longitudinal profiles in the preshower(a), the main FNC calorimeter(c) and lateral in radius profile(b) of deposited energy for 350 GeV hadrons for detailed (solid lines) and fast (points) simulation.

3.2.3 Spatial resolution

The calculations of spatial resolution of the preshower and main FNC calorimeter are based on different methods of cluster coordinate determination.

Coordinate calculations

The coordinate of cluster center in X-Y plane can be determined more precisely in the preshower compared to the main FNC calorimeter due to the significantly smaller cell size in preshower (2.9 cm w.r.t. 20. cm). The algorithms of coordinate calculations imply the usage of the deposited in cells energy. For this reason if energy in preshower is rather small and distributed in 1-2 strips, the calculation of coordinates can not be reliable. However, the ~ 30 % of particles penetrate through the preshower as minimum ionizing particle (MIP). In this case one should rely on coordinate calculations based on use of information from FNC towers. In choice of energy cuts to define a relevant part of the calorimeter to be used for coordinates determination, the table 1 can be used. In this table the deposited energies on electromagnetic scale in the preshower and the main FNC calorimeter are shown for initial muons energies of 120 GeV and 350 GeV.

beam energy	preshower	main FNC
120 GeV	1.29	5.60
350 GeV	2.48	10.24

Table 1: The FNC energy response(electromagnetic scale in GeV) to muons.

The few methods can be used for X(Y) coordinate calculation of the impact point of an incident particle. The well known center of gravity method (c.o.g.) with linear energy weighting have the form:

$$X_{rec}^{c.o.g.} = \frac{\sum_{i=1}^{N_{cells}} x_i E_i}{\sum_{i=1}^{N_{cells}} E_i} \tag{15}$$

where x_i is the cell center coordinate and E_i - the deposited cell energy.
This method is used for comparison with others, so called, ratio of energy methods (r.o.e.) defined for preshower and main FNC calorimeter as follows.
For preshower

$$X_{preshower}^{r.o.e.} = X_{max} + C_1 \ln(\frac{E_{right}}{E_{left}}), \tag{16}$$

where X_{max} is the coordinate of center of the strip with maximal energy, E_{right} - the energy in all strips from right side of the strip with maximal energy, E_{left} - the same for the left side and C_1 - the known coefficient.

For main FNC calorimeter the similar expression is

$$X_{FNC}^{r.o.e.} = C_1 + C_2 \ln(\frac{E_{left}}{E_{right}}), \tag{17}$$

where $E_{left}(E_{right})$ are the energies in all left(right) FNC towers and C_1, C_2 - the known coefficients. For Y coordinates in similar expressions (15)- (16), the E_{right} variable have to be changed by the energy in upper side E_{up} and E_{left} variable - by energy in lower side E_{down}.

The correlations between the measured and the true space coordinates of the impact point of an incident particle were obtained by the Monte Carlo simulation in framework of H1SIM.

The electrons and neutrons of different energies 120 $GeV \div 900$ GeV were generated in front of the preshower over the full its X-Y space with theta angles < 0.5 mrad. The c.o.g. calculations based on the hit information were used as a true X(Y) coordinates.

$$X_{true} = \frac{\sum_{j=1}^{N_{hits}} x_j E_j}{\sum_{j=1}^{N_{hits}} E_j} \tag{18}$$

The dependences of the true coordinates $X(Y)_{true}$ versus the reconstructed by c.o.g. method $X(Y)_{rec}^{c.o.g.}$ coordinates in preshower are shown in upper part of figure 11.

This dependences were described inside every strip by function:

$$C_1 + C_2 \arctan(C_3(X_{rec}^{c.o.g.} - C_4)) \tag{19}$$

and coefficients C_1 - C_4 were defined to be $0.008cm,\ 1.256cm,\ 1.223cm^{-1},\ 0.0055cm$ respectively.

In the lower part of figure 11 the coordinate dependences $X((Y)_{true} - X(Y)_{max})$ versus logarithm of measured energy ratio from expression (16) are shown. The value of coefficient C_1 obtained from the fit by straight line is 1.94 cm .

Resolution

The energy dependences (figure 12) of the hadronic spatial resolution for the preshower with c.o.g. method (15) using expression (19) and r.o.e. method (16) were respectively determined to be:

$$\sigma_{xy}^{had}(E) = \left(\frac{1.30 \pm 0.05}{\sqrt{E[GeV]}} + (0.20 \pm 0.00) \right) cm \tag{20}$$

$$\sigma_{xy}^{had}(E) = \left(\frac{1.11 \pm 0.05}{\sqrt{E[GeV]}} + (0.21 \pm 0.00) \right) cm \tag{21}$$

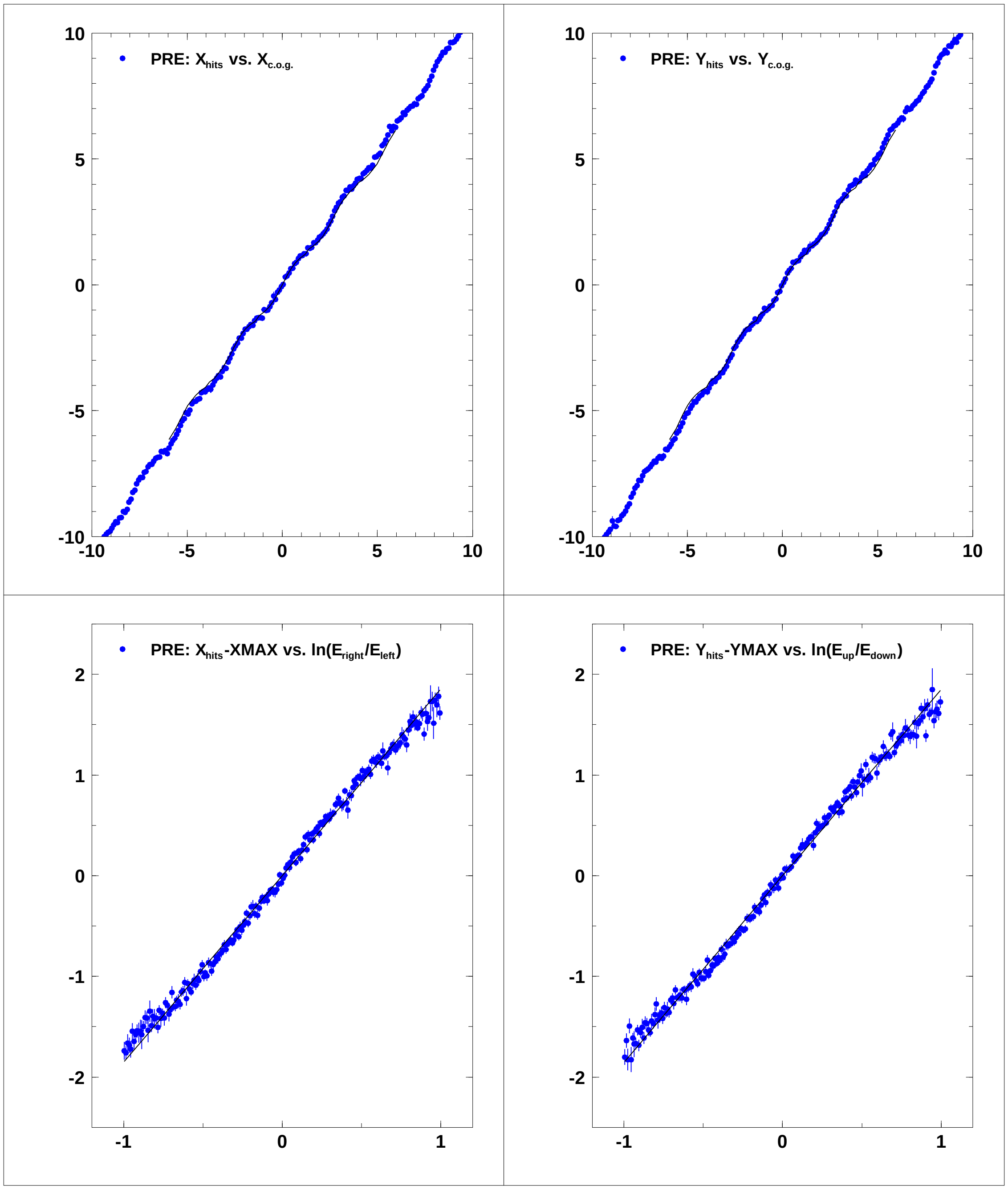

Figure 11: For neutrons in the preshower, the correlation between the X(Y) coordinates of the impact point measured with c.o.g. method and true coordinates $[cm]$ (upper plots), and the correlation between the *logarithm* of measured energy ratio and true coordinates $(X(Y)_{true} - X(Y)_{max})$ $[cm]$ of the impact point (lower plots). Left plots related to X coordinates, right plots - to Y coordinates.

The hadronic spatial resolution can be compared with similar resolution for electrons and photons in preshower:

$$\sigma_{xy}^{elm}(E) = \left(\frac{2.2 \pm 0.2}{\sqrt{E[GeV]}} + 0.0 \right) mm \tag{22}$$

In the upper part of figure 13 the dependences are shown of true coordinates $X(Y)_{true}$ from the reconstructed by c.o.g. method $X(Y)_{rec}^{c.o.g.}$ in main FNC calorimeter. Due to some asymmetry of tower centers with respect to the center of central tower one can expect slight difference in curves behavior for X and Y coordinates. In fitting by function (19) the obtained coefficients for X coordinates are $C_1 = -0.14cm,\ C_2 = 6.95cm,\ C_3 = 0.51cm^{-1},\ C_4 = -0.037cm$, for Y coordinates are $C_1 = -0.14cm,\ C_2 = 6.68cm,\ C_3 = 0.63cm^{-1},\ C_4 = -0.050cm$.

In the lower part of figure 13 there are the coordinate dependences $X(Y)_{true}$ versus the logarithm of measured energy ratio from expression (17). From the fit by straight line the coefficients for X coordinate are $C_1 = 0.149cm,\ C_2 = -2.538cm$, for Y coordinate - $C_1 = 0.335cm,\ C_2 = -2.190cm$.

The hadronic X, Y spatial resolutions for main FNC calorimeter (figure 12) with c.o.g. and r.o.e. methods were respectively determined to be:

$$\sigma_x(E) = \sigma_y(E) = \left(\frac{9.91 \pm 0.22}{\sqrt{E[GeV]}} + (0.60 \pm 0.01) \right) cm \tag{23}$$

$$\begin{cases} \sigma_x(E) = \left(\frac{10.57 \pm 0.23}{\sqrt{E[GeV]}} + (0.64 \pm 0.01) \right) cm \\ \sigma_y(E) = \left(\frac{12.04 \pm 0.28}{\sqrt{E[GeV]}} + (0.80 \pm 0.02) \right) cm \end{cases} \tag{24}$$

So, one can conclude that a precise determination of neutron impact point on the preshower face space can be achieved with c.o.g. and r.o.e. methods both. The spatial resolution for hadronic particles with energy 120 $GeV \div 900$ GeV is estimated to be better than 3 mm .

For the main FNC calorimeter the c.o.g. method allows to have better space resolution with respect to r.o.e. method and can be estimated to be at the order of 1 cm at 500 GeV neutron energy beam.

All obtained results are related to the study of properties of the FNC calorimeter. In this study the particles were generated over the full X-Y space of the preshower and central tower of main FNC calorimeter. The applied methods of cluster coordinate calculations in the FNC can be directly used in real conditions of H1 experiment if acceptance of the FNC corresponds the conditions of particles generation used in the study of spatial resolution.

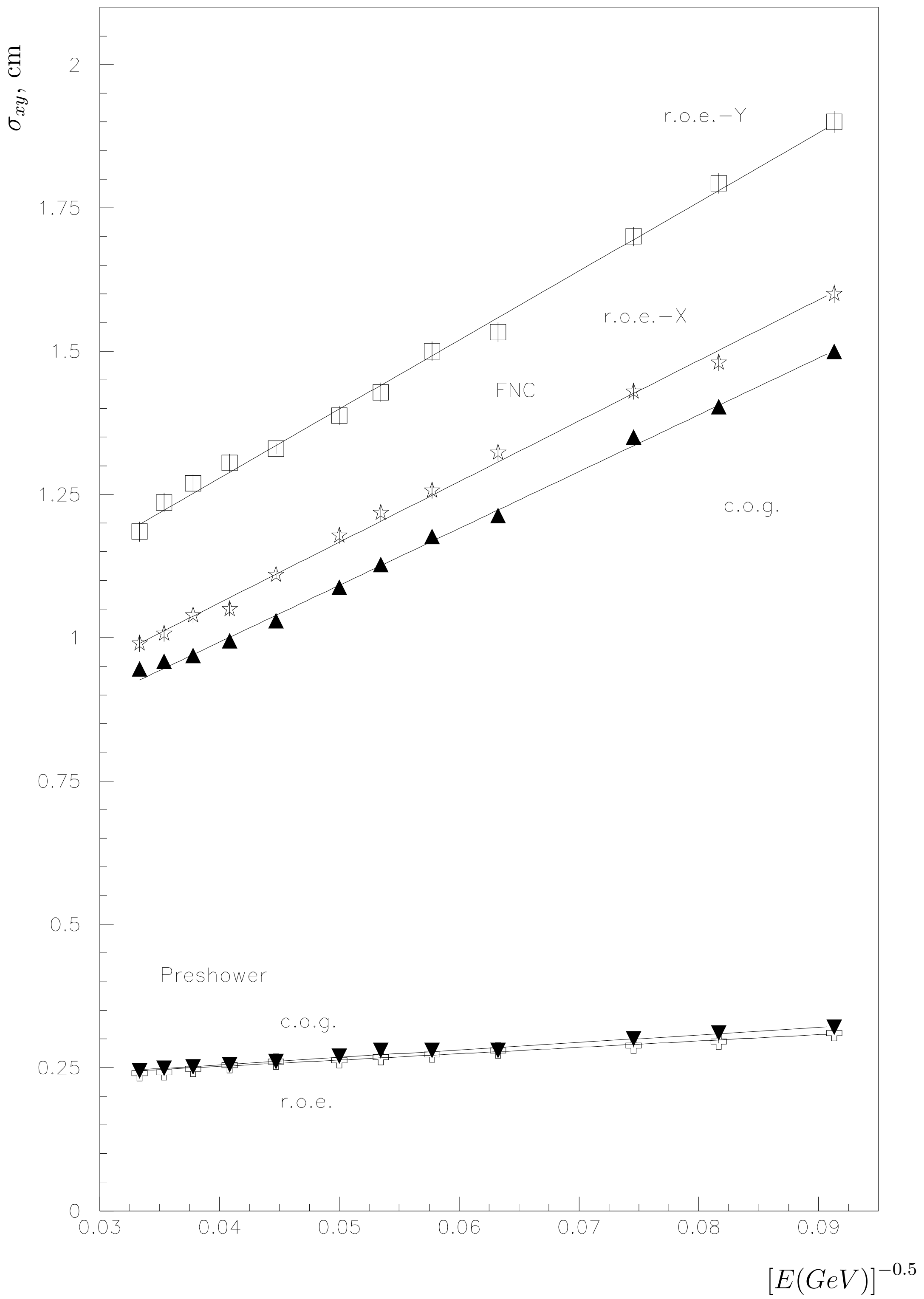

Figure 12: The hadronic spatial resolution for the preshower and the main FNC calorimeter with c.o.g. and r.o.e. methods. (see text)

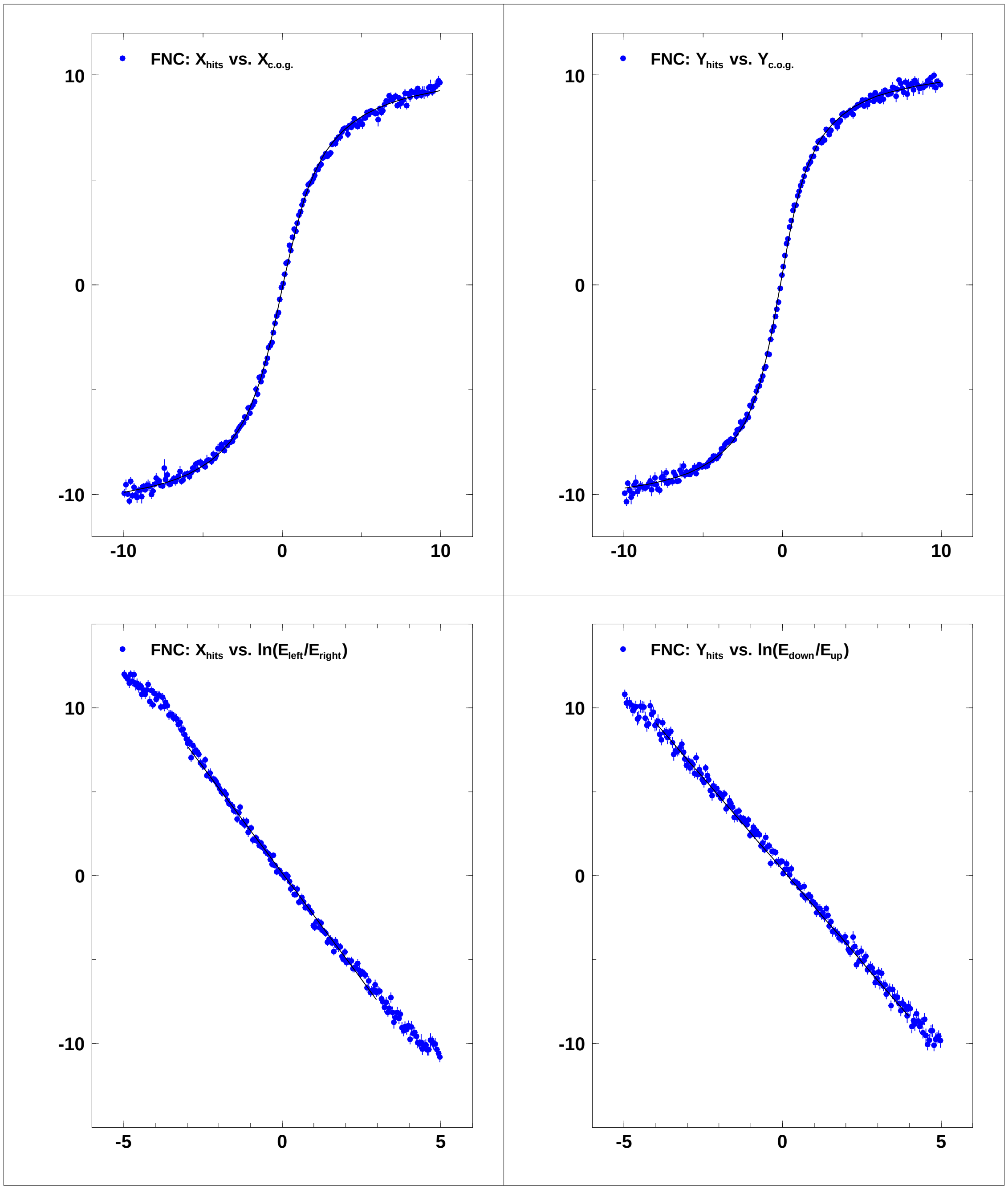

Figure 13: For neutrons in the main FNC calorimeter, the correlation between the X(Y) coordinates of the impact point measured with c.o.g. method and true coordinates $[cm]$ (upper plots), and the correlation between the *logarithm* of measured energy ratio and true coordinates $X(Y)_{true}$ $[cm]$ of the impact point (lower plots). Left plots related to X coordinates, right plots - to Y coordinates.

Acceptance

The geometrical acceptance of FNC is determined by the aperture of the forward beam line elements located between the H1 and the FNC. The upgraded for HERA-II, forward beam line description in framework of H1SIM was used in acceptance simulation. The acceptance was determined as ratio of well reconstructed in the FNC neutrons to number of generated neutrons. The neutrons of high energy 120 $GeV \div$ 920 GeV were generated at H1 interaction point corresponding to e^-p and e^+p collisions. The acceptance region of the FNC in X-Y plane is shown in figure 14. The coordinate system is related to H1 frame of reference.

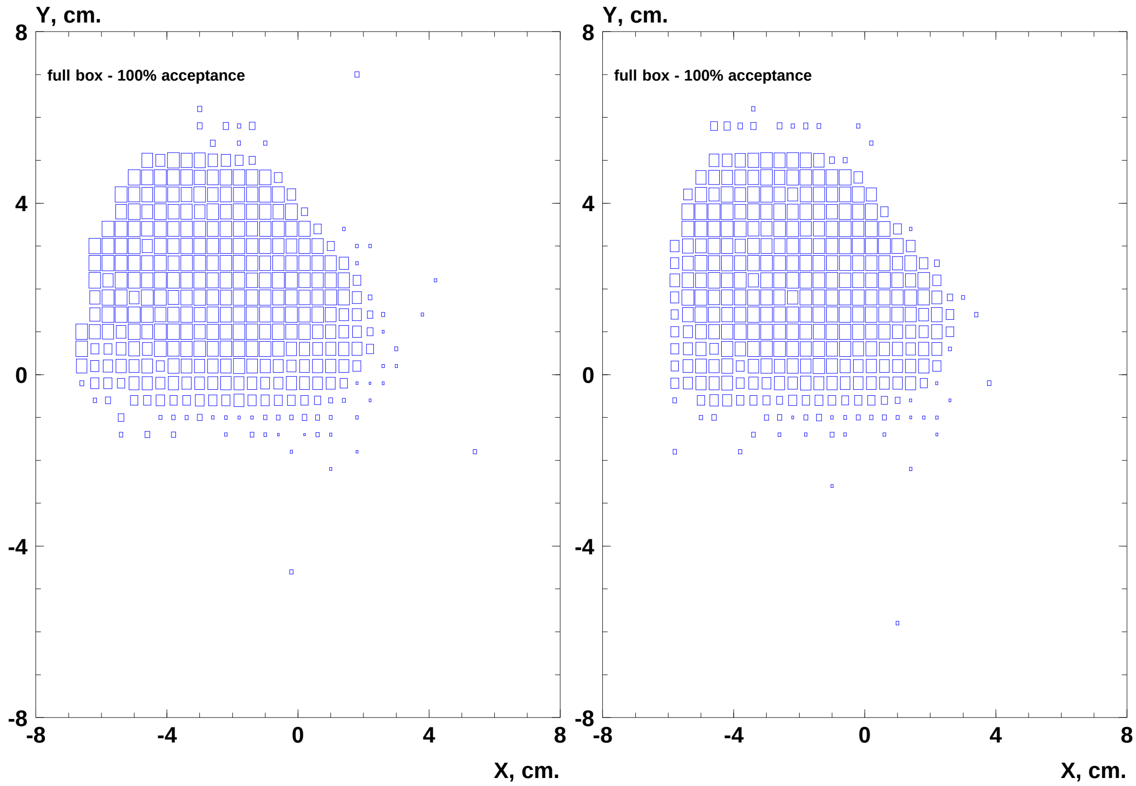

Figure 14: The FNC acceptance in X-Y plane for high energetic neutrons produced in e^-p (left) and e^+p (right) collisions.

The full boxes in two-dimensional bins on the plots correspond to 100 % acceptance. One can see in figure 14 that the events populate not full range of the preshower (2 $\div$ 3 strips only). The acceptance range in the face of main FNC calorimeter is even less than the size of one tower. Besides, the acceptance region is shifted with respect to centers of the preshower and central tower. For these reasons, the dependences shown in figure 11 and, especially, in figure 13 can be distorted.

4 Summary and Conclusion

- The simulation of the upgraded in 2000 Forward Neutron Calorimeter including the detailed and fast modes is implemented in H1SIM.
- Special effects present in the calorimeter were taken into account in the FNC simulation: signal attenuation in scintillator, homogeneity in main FNC towers, light cross talk in preshower strips, light losses in hadronic compartment of the preshower.
- The detailed analysis of the FNC behavior in framework of H1SIM simulation was performed.
- Electron energy response in detailed simulation mode for preshower and main FNC calorimeter can be reproduced by fast mode with good accuracy.
- The complete comparative analysis of the MC results for energetic hadrons based on detailed simulation with GEISHA and FLUKA in framework of H1SIM was presented. The following points were considered: e/π ratio, leakage of energy, contribution of different energy components in calorimeter, correction to electromagnetic scale energy to total deposited hadronic energy for preshower and main FNC calorimeter, energy linearity and resolution.
- Hadronic response of FLUKA is rather well reproduced by fast MC in comparison of mean values and resolution.
- The comparison of the energy profiles for hadrons between fast MC simulation and detailed FLUKA simulation shows rather good agreement over the full coordinate range of the FNC calorimeter.
- Consideration of few reconstruction algorithms of hadron impact point on the preshower face space leads to the conclusion that a precise determination can be achieved with c.o.g. and r.o.e. methods both. For the main FNC calorimeter the center of gravity method allows to have better space resolution with respect to ratio of energy method.
- The cpu time with fast simulation mode is reasonable for producing of high statistics MC event samples.

For the improvement of the simulation for FNC, any comments and suggestions are welcome.

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