

Production and Transport of Hadrons Generated in Nuclear Cascades Initiated by Muons in the Rock (Exclusive Approach)

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Abstract

Monte Carlo calculation of differential distributions of hadrons going into LVD experimental hall from the rock was performed. Probability of energy transfer into nuclear cascade by muon is taken according to Bezrukov and Bugaev (1981) giving 9.45×10^{-6} inelastic muon-nucleus interactions per gram per year at the depth of Gran Sasso. Simulation of hadron cascades in the rock was made using the universal hadron transport code SHIELD. It allowed calculate transport of nucleons, pions, kaons, and antinucleons at energy up to 1 TeV. Exclusive simulation of nuclear reactions in the whole energy range is provided with known Russian hadron-nucleus codes included in the SHIELD. Differential distributions of neutrons, protons and charged pions are presented for the roof, walls and floor of the hall separately in absolute units. Total number of hadrons with energy above 15 MeV going into the hall is about 250 particles per m^2 per year. Number ingoing neutrons is in good agreement with measurement. The yield of high energy hadrons (> 1 GeV) in backward hemisphere is observed. Possible roland of neutral kaons as a source of background events in LVD is distinguished.

1 Introduction

As it is known hadrons generated in the ground by atmospheric muons can produce background events in deep underground installations. So it is of interest to know composition, total number and spectral- angular distributions of hadrons going into experimental hall from the rock.

Such kind of calculations is made in this work concerning LVD (Large Volume Detector) experimental hall. The task setting is the following (see fig.1):

Coordinates of the point of inelastic muon-nucleus interactions were supposed uniformly distributed inside rock volume. Direction of primary muon was sampled according to the measured angular distributions at the depth of LVD [1], see fig. 2b,c. Polar and azimuthal angles are noncorrelated. Events with muon trajectory crossing LVD immediately were rejected (fig.1), giving no contribution in hadron spectra.

Muon spectrum at Gran Sasso depth was taken in the view:

$$\frac{dN}{dE} = Const \times [E + (\gamma - 1) \times \bar{E}]^{-(\gamma+1)}$$

where $\gamma = 2.70$ – power index for atmospheric muon spectra, $\bar{E} = 280$ GeV – average muon energy at the given depth.

Fraction of energy transferred by muon to hadron cascade was calculated according to Bezrukov and Bugaev [2]. Spectrum of energy transferred to hadron cascade is presented in fig 1a. Absolute density of inelastic muon-nucleus interaction is 9.45×10^{-6} (1/g · year). This value is used further for normalization of hadron spectra.

As average energy transferred to hadron cascade is very high (about 80 GeV, see fig.1a) there is no matter what agent imports the energy into a nucleus. It can be for example photon or hadron. In present calculations we have used charged pion to realize the first inelastic nuclear interaction in the rock.

2 Method of calculation

The calculations were performed using universal Monte Carlo hadron transport code SHIELD [3,4]. The SHIELD code is dedicated to simulation of the interaction of high energy particles with complex macroscopic targets. It has been designed as an universal tool for wide field of studies. In the framework of a unified approach the SHIELD code provides a thorough calculation of the interaction process in full measure.

During 25-years lifetime the SHIELD code has been successfully applied to a number of problems, such as:

- Study of the spallation-process in heavy targets under proton beam irradiation including generation of neutrons, energy deposition in the target, and radionuclides production.
- Radiation damage of target materials under primary and secondary radiation fields.
- Radiation shielding of accelerators and in the Space.

- Simulation of background events in experimental installations on accelerators and for underground physics and so on.

Recent progress in the SHIELD code development [4] (and also in computer technic) made available detailed solving of tasks of cosmic rays and underground physic.

2.1 Transport part of the SHIELD code

At present the SHIELD code allows to simulate the nucleon, pion, kaon, antinucleon, and muon transfer in energy range up to 1000 GeV. The ionization energy loss for charged particles and straggling are taken into account. Main modes of 2- and 3-particles decays are simulated at transport of pions and kaons.

Geometric configuration of a target is an arbitrary combination of bodies bounded with second degree surfaces. Original geometric module GEMCA [5] is used.

Chemical composition of media in geometric zones of the target is arbitrary. Any elements from $Z = 1$ to transuraniums can be included. Any compounds, alloys and mixtures are foreseen. Natural isotope mixture for all elements is set up by default if user doesn't describe the special one.

At sampling of free pass of a particle to interaction point and the interaction type (elastic or inelastic) the total and inelastic hadron-nucleus cross sections are used. These cross sections are calculated on a basis of compilation [6].

Elastic nuclear scattering is described with a simple diffraction- like formula. Inelastic hadron-nucleus interaction is simulated in exclusive approach with the very advanced MSDM-generator (Many Stage Dynamical Model) described below in more detail.

During simulation of regular hadron cascade in the target the sources of γ , e^\pm , and neutrinos (as products of pion and kaon decays) are formed as well as the source of low energy ($E_n < 14.5$ MeV) neutrons. All these particles are stored in special source arrays with all their individual parameters. After simulation of the hadron cascade tree is finished the transfer starts of stored particles from the sources.

EM-cascades are simulated with the known EGS4 code which is connected to SHIELD by means of special elaborated interface which fits together, in particular, run of the geometric modules and descriptions of chemical composition.

Any neutron transport code can be, in principle, applied for transfer of neutrons from the source. We often use our original code LOENT (see below).

In the SHIELD code the complete storing of the hadron tree during its simulation is realized. The individual parameters of all particles for all generations are stored in special arrays as well as all events of fly out from the target, absorption, decay or interaction. All acts of elastic or inelastic interaction are presented with individual parameters of residual nuclei as well. This storing is made in connection to geometric structure of the target i.e. the energy, coordinates, etc. for any particle are fixed at intersection of the boundary of each geometric zone and so on.

As a result after the simulation of the hadron cascade is finished the cascade tree is fixed completely without any loss of physical information. Such organization of the calculations appears as very convenient and universal. It admits to set up uniformly the registration and output procedure of any results for each specific task without any

intervention into modeling part of the code. Additional possibilities are opened e.g. visualization of the tree or storing in magnetic media.

A payment for these advantages is the necessity to deal with arrays of relatively complex structure. Therefore a permanent output procedure for most essential parameters (e.g. energy deposition, yield of particles and nuclides etc.) is realized in the SHIELD code. It is enough for many task so the user is often saved from necessity to write additional output subroutines. During elaboration of SHIELD an opened code's architecture was foreseen to facilitate modifications and development of the code. In particular, inclusion of additional particles into transfer, upgrade of hadron-nucleus generator, increase of dimensions of inner arrays with growth of energy and complexity of the target, using of statistical weights etc. were foreseen. All these items have proved itself at the code operation.

2.2 Simulation of hadron-nucleus interactions

The capabilities of hadron transport code depends substantially on the hadron-nucleus generator used. In the SHIELD code the MSDM generator is employed. It includes known Russian nuclear codes.

Lacking a space let us restrict ourselves to listing only the nuclear models included in MSDM. It allows to simulate in the exclusive approach both hadron-nucleus and nucleus-nucleus interactions in energy range up to 1 TeV. Fast, cascade stage of the reaction below 600 MeV is treated according to Dubna Cascade Model (DCM) [7]. Above 10 GeV the Independent Quark-Gluon String Model (QGSM) is used [8] and in intermediate area 600 MeV ÷ 10 GeV – some extension of QGSM [9]. So self-consisted description of the cascade stage is provided over a whole energy range of primary hadrons up to 1 TeV.

Secondary nucleons which are close each to other in the momentum space can form complex particles H^2 , H^3 , He^3 , He^4 according to coalescence model [7]. Evolution of excited residual nucleus to equilibrium state is described in terms of the pre-equilibrium model based on Monte Carlo solution of corresponding master-equation [10].

Further equilibrium deexcitation of residual nucleus includes several mechanisms. For light nuclei ($A < 16$) the modified Fermi break up model [11] is used. Medium and heavy nuclei at moderate excitations ($E^* < 2$ MeV/nucleon) suffer evaporation process including fission competition for heavy nuclei [11,12]. Highly excited nuclei ($E^* > 2$ MeV/nucleon) can decay in several excited fragments according to Statistical Model of Multyfragmentation (SMM) [13] with consequent particles emission. The equilibrium deexcitation stage completes run of the MSDM generator.

2.3 Neutron transport with the code LOENT

Neutron transport code LOENT is based on 28-group neutron data system BNAB [14]. It is destined for Monte Carlo simulation of neutron transfer below 14.5 MeV. The LOENT code can be used independently as well as together with the SHIELD code having the same geometric module and some subroutines. The following neutron interactions are considered:

Elastic scattering (n,n). Neutron scattering angle is defined with a single parameter – average cosine – and sampled in the linear-anisotropic approximation. Neutron energy is calculated from two-particle kinematics.

Neutron capture (n,c) means the end of the neutron's history. The channel of reaction – (n,g), (n,p) or (n,a) – is not specified.

Inelastic scattering (n,n'). The group number of scattered neutron is sampled with the matrix of inelastic transitions. The uniform energy distribution inside this group is assumed. Angular distribution is isotropic in the lab. frame.

Reaction (n,2n) is described with the same matrix of inelastic transitions and competes with (n,n') scattering. Parameters of both secondary neutrons are sampled in the same way.

Fission (n,f). Using given average number of fissional neutrons the specific value of neutron number is sampled as one of two adjacent integers. Then each neutron gets its energy from fission spectrum. Angular distribution is isotropic in the lab. frame.

In our practice the LOENT code was employed mainly for deeply subcritical problems at hard evaporational spectra.

In conclusion let us say several words on further development of the SHIELD code. As the MSDM generator provides simulation of both hA- and AA-interactions there are all prerequisites to include in the transport calculations the nuclei (heavy ions) of arbitrary (A, Z) at energies up to 1 TeV/A. As far as we know this is not completely accomplished in any transport code. Other actual problem is increasing of the top energy limit of the SHIELD code.

3 Results

It is clear that number of hadrons going into the hall should depend on the thickness of the rock accepted for calculation (see fig.1). Very large thickness is too computer time consuming. Too small thickness (as compared to inelastic nuclear path) will underestimate particle yield due to undeveloped nuclear cascade.

So the first item is to find the optimal rock thickness. The dependence of total number of hadrons on the thickness of the ground is presented in fig.3-5 for different energy thresholds: above 14.5, 200, and 1000 MeV. As one can see the rock thickness 3 m is a good choice. This value was accepted for all calculations below.

The thickness dependence was fitted with function (see figs):

$$Y = Y_{max} \times \left[1 - e^{-\frac{x}{\lambda}} \right]$$

The fit constant λ is equal about two inelastic nuclear paths indicating that at least two hadron cascade generations give essential contribution to particle yield into the hall.

The total number of neutrons per m^2 per year is in very good agreement with previous experimental data [15] and with estimation [16].

It is interesting to compare the spectra of particles entering the hall in dependence on the depth of the muon-nucleus interaction point inside the rock. Fig.6 shows spectra of neutrons, protons and charged pions for two cases: if the point lies at the distance

less/more than 1 m from the hall surface (and summary total spectrum as well). As one can see there is a scaling: no significant differences in the spectra shapes is observed.

Fig.7 presents a comparison of total spectra of neutrons, protons and pions going into the hall. It is seen that neutron and proton spectra are asymptotically (at high energies) coincident. Charged pion spectra are more hard then proton's one.

Angular distributions of the particles were calculated for the roof, walls and floor of the hall separately (see fig.8-11) and for three different energy thresholds indicated in the figures.

Let us emphasize that there is the particle yield into back hemisphere even at high energies $E > 1$ GeV (fig.12). Total backward yield ($E > 1$ GeV) from the floor and walls per year per 1000 m^2 of the hall surface is the following (statistical accuracy is about $15 \div 20\%$):

Yield, $E > 1$ GeV	n	p	π^-	π^+
$1/(1000m^2 \cdot year)$	23.8	8.4	16.8	20.9

Fig.13,14 illustrate the shape of energy spectra of the particles entering the hall in different angular intervals: in forward direction, at 0 degree, and backward.

Let us note that neutral kaons can play sometime significant part in background events producing (possibly comparable with neutrons). In our calculations we observed events when K_S^0 meson gave clear response in the detector due to decay to π^-/π^+ pair in the core LVD posts. But the kaon contribution is the subject of future investigations.

Our exclusive (eventual) approach to simulation of LVD background events allows us also to study responses of separate posts, correlations between them, to estimate the efficiency of registration, to treat development of the event with time and so on.

Acknowledgments

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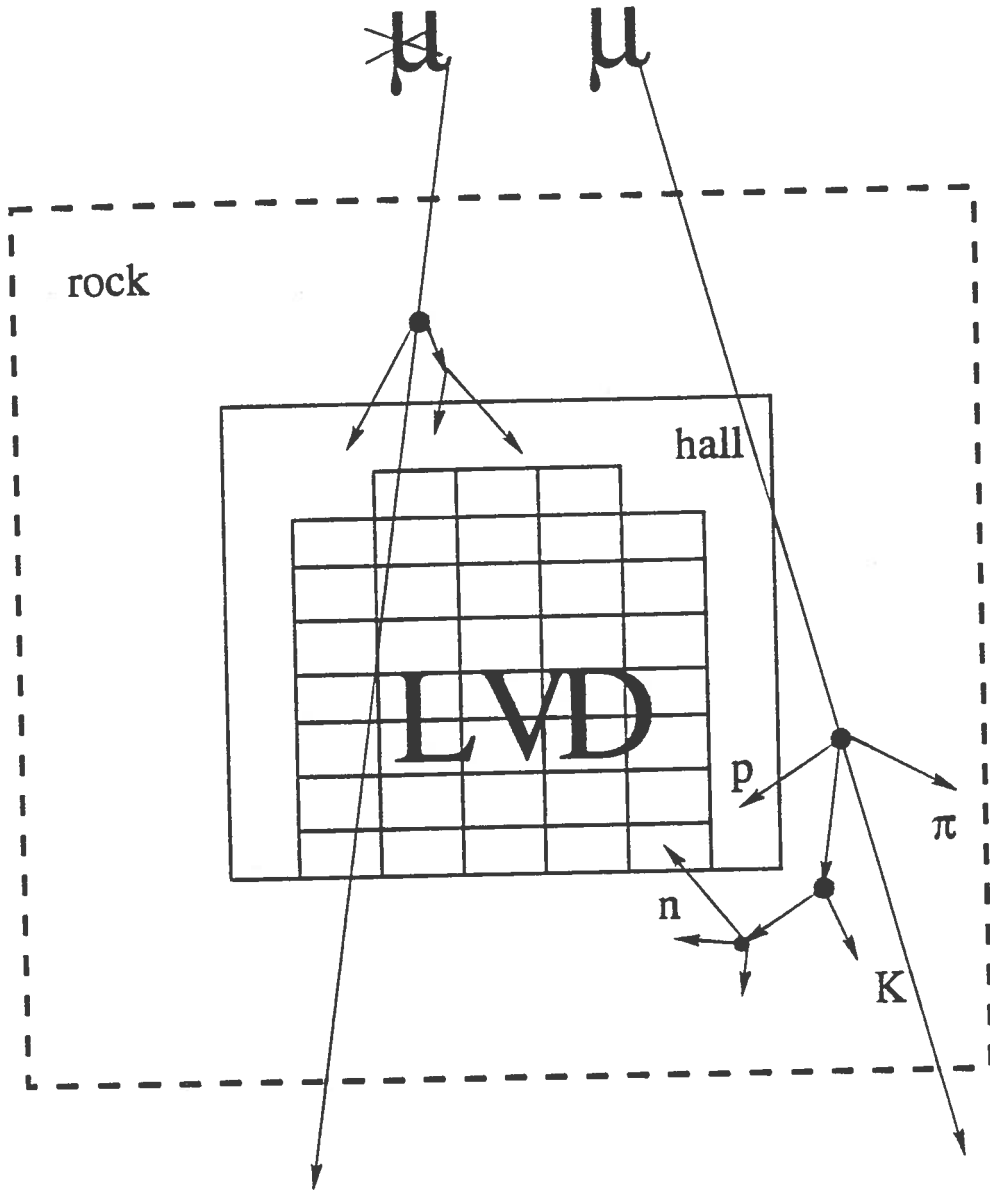


Figure 1: Illustration of task setting.

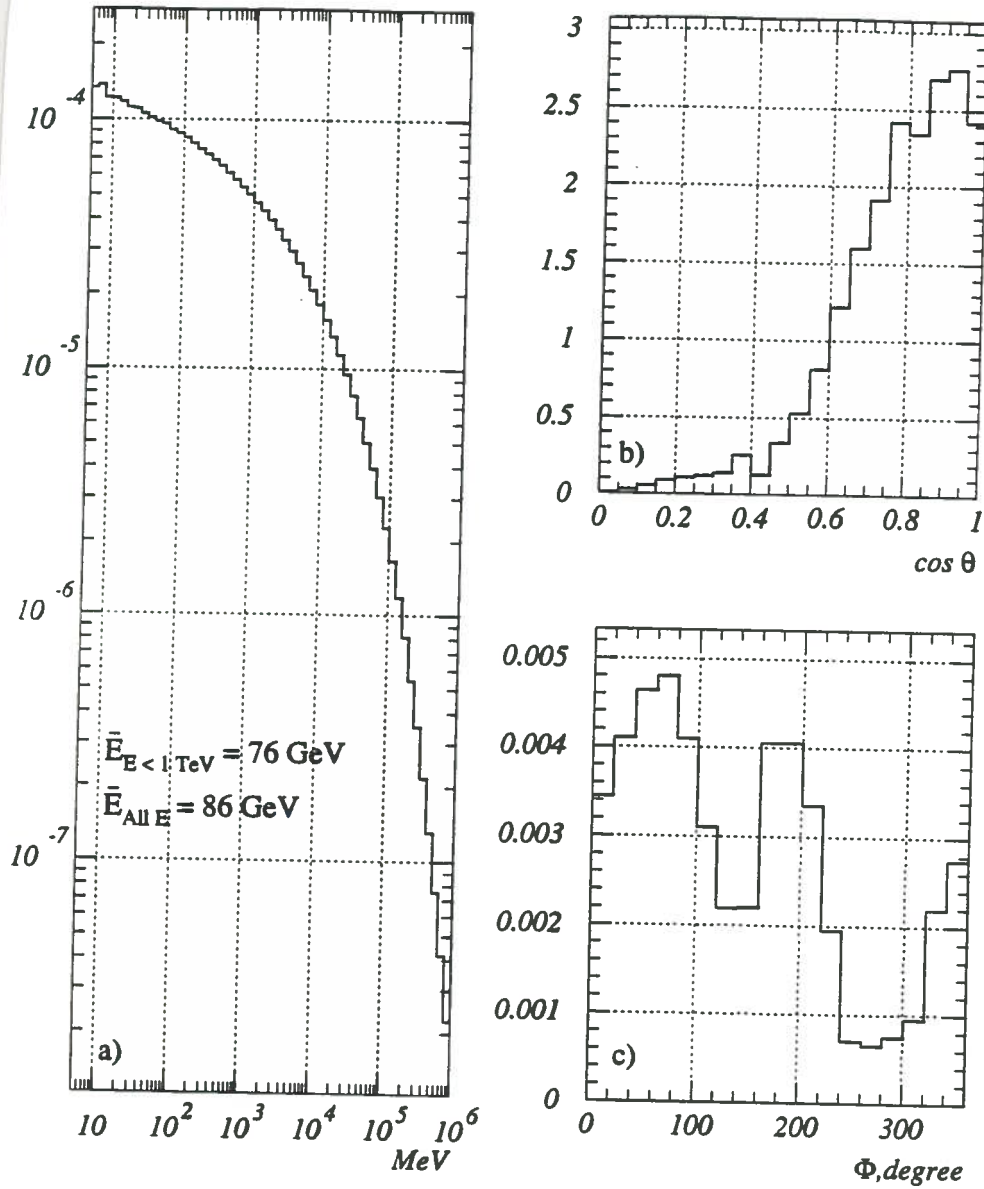


Figure 2:

Spectrum of energy,
transferred by muons
into hadron cascades
(normalized to unit area)

Angular distributions of
primary muons at LVD depth.
(LVD Collab., Nucl.Phys(Proc.Suppl.)
B35(1994)240, normalized
to unit area)

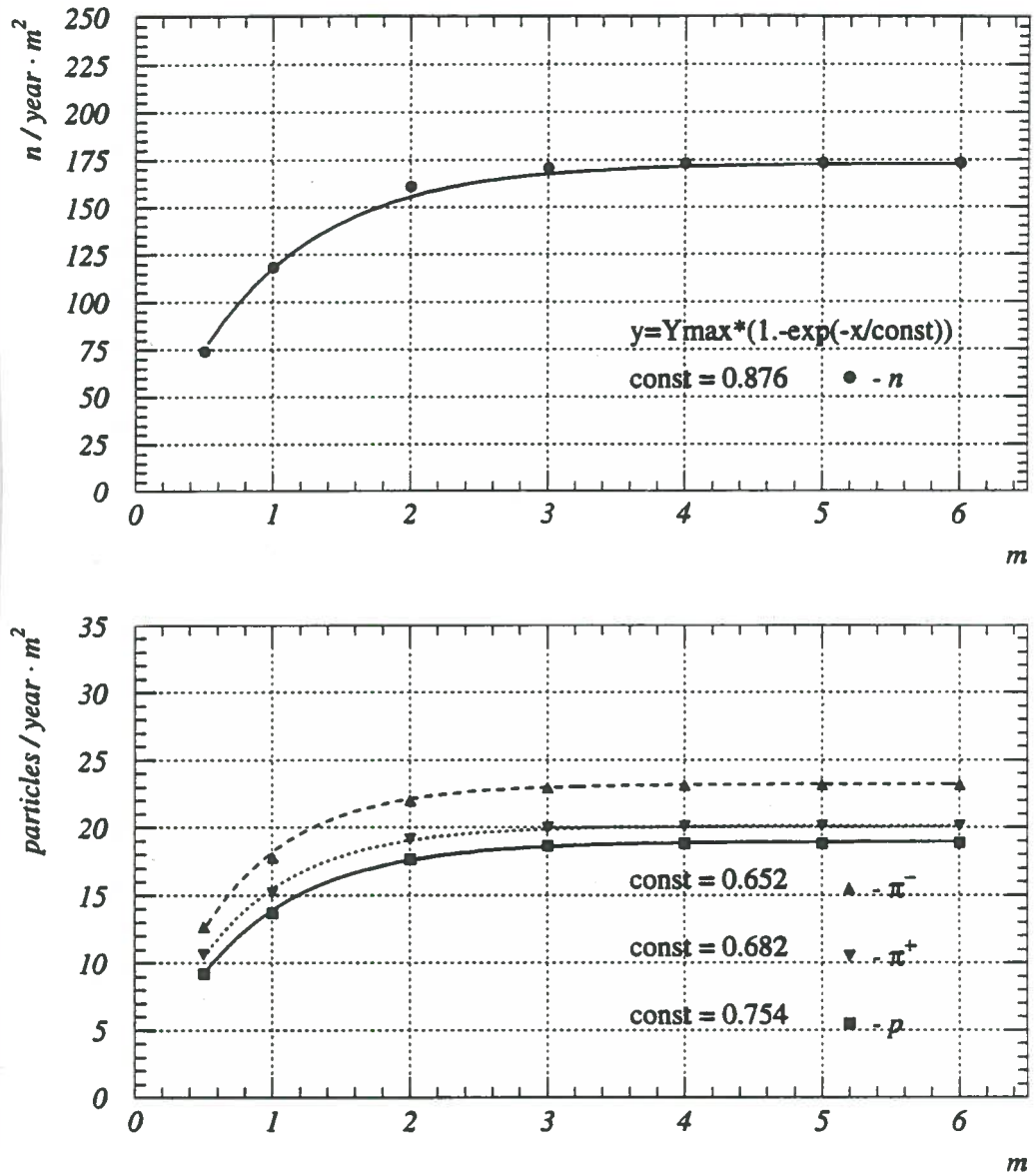


Figure 3: Number of particles (of all energies, $E_n > 14.5$ MeV) going into the hall as a function of rock thickness. Points – MC calculation, curves – fit.

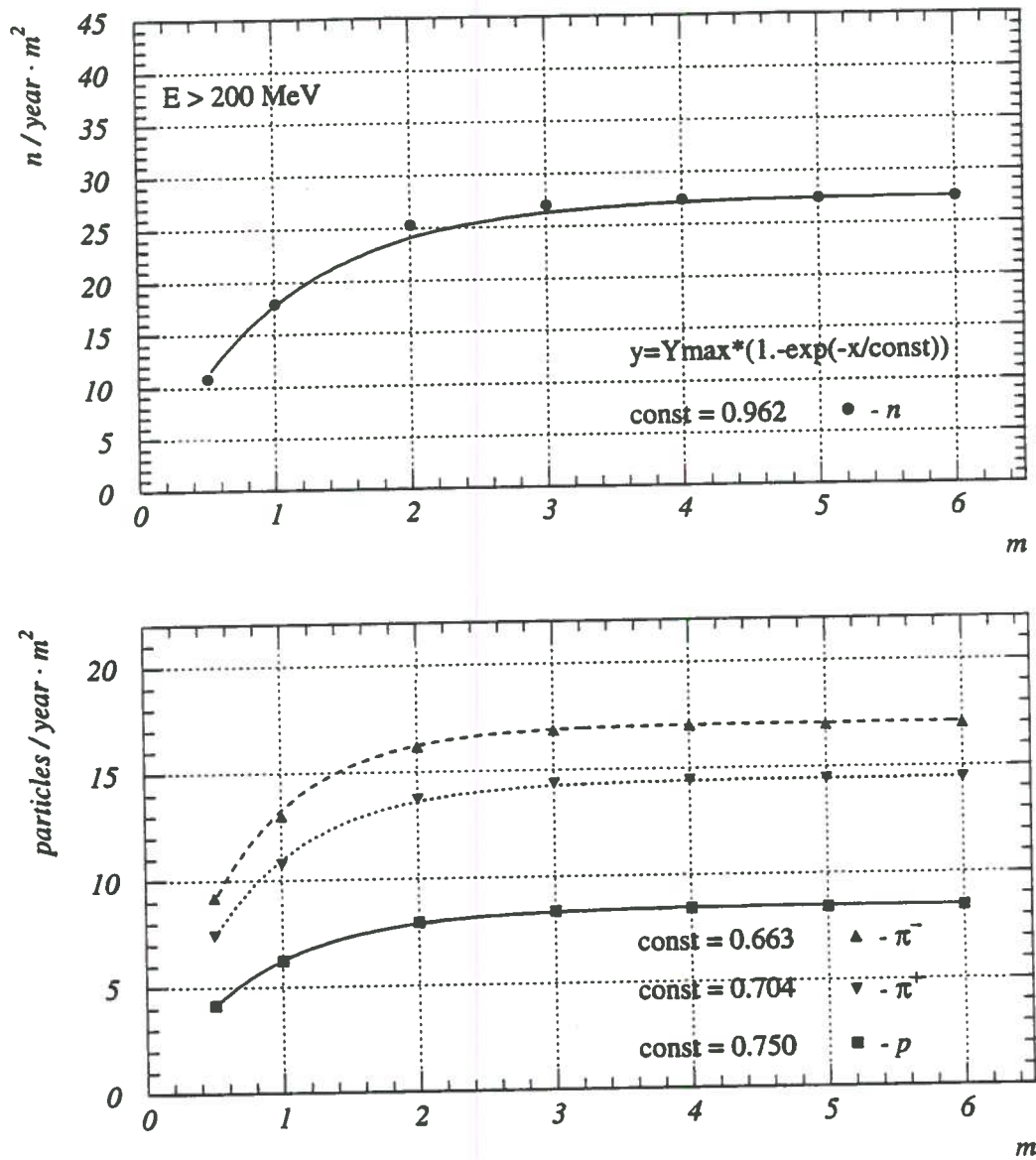


Figure 4: Number of particles (with E > 200 MeV) going into the hall as a function of rock thickness. Points - MC calculation, curves - fit.

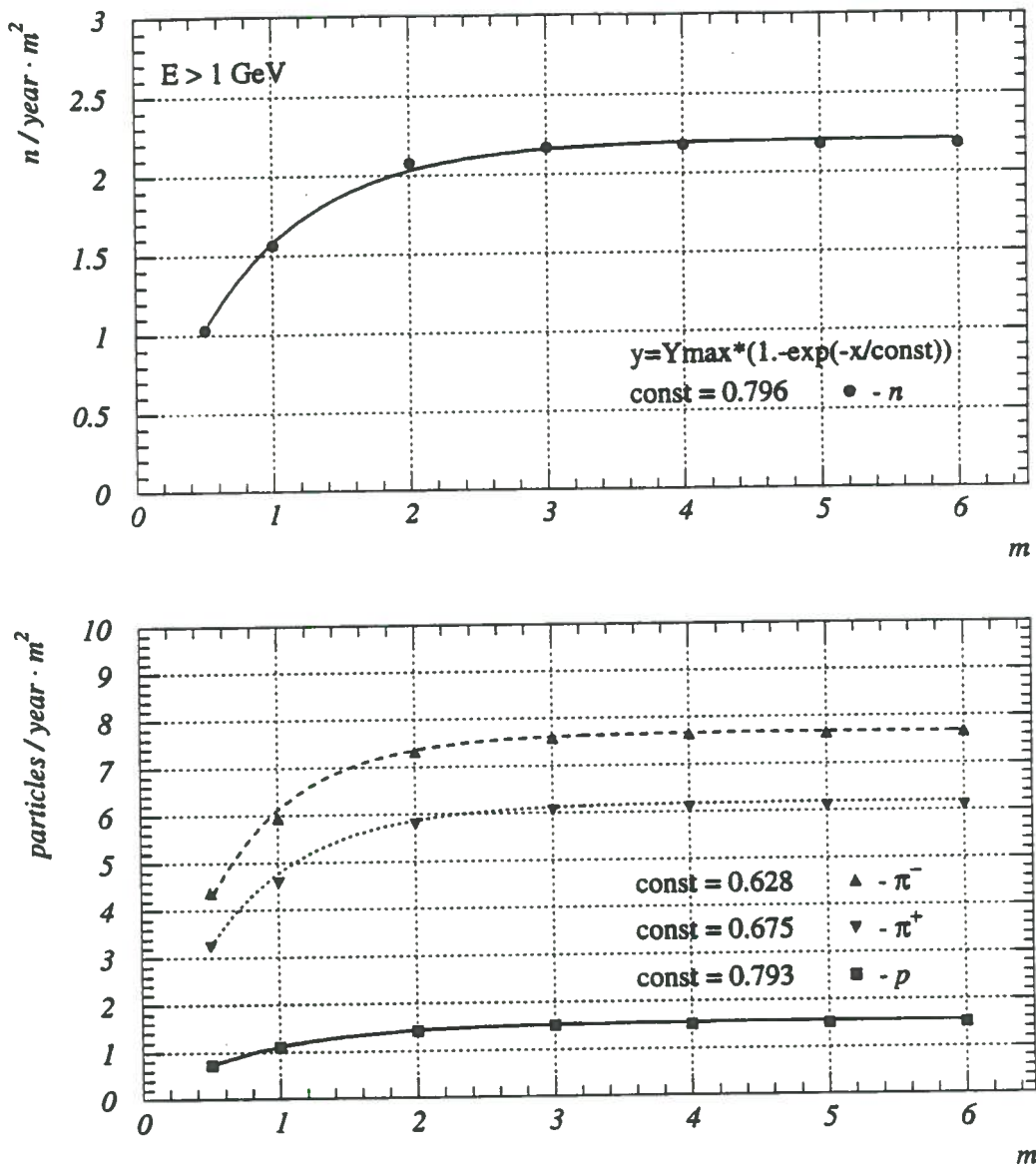


Figure 5: Number of particles (with $E > 1$ GeV) going into the hall as a function of rock thickness. Points - MC calculation, curves - fit.

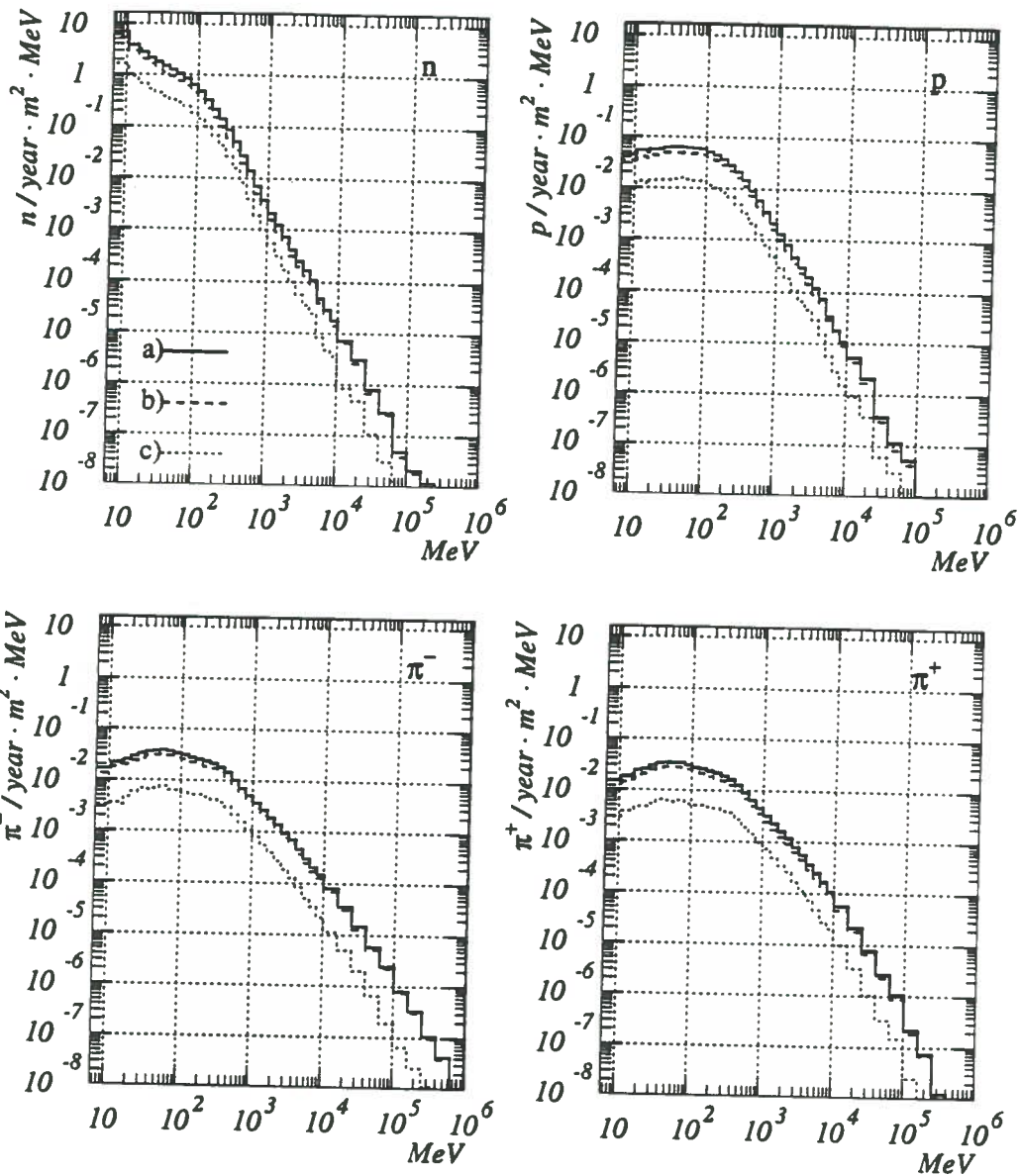


Figure 6: Energy spectra of particles going into the hall: a) total, b) μA interaction point is placed on distance $< 1\text{m}$ from hall walls, c) the same but distance $> 1\text{m}$.

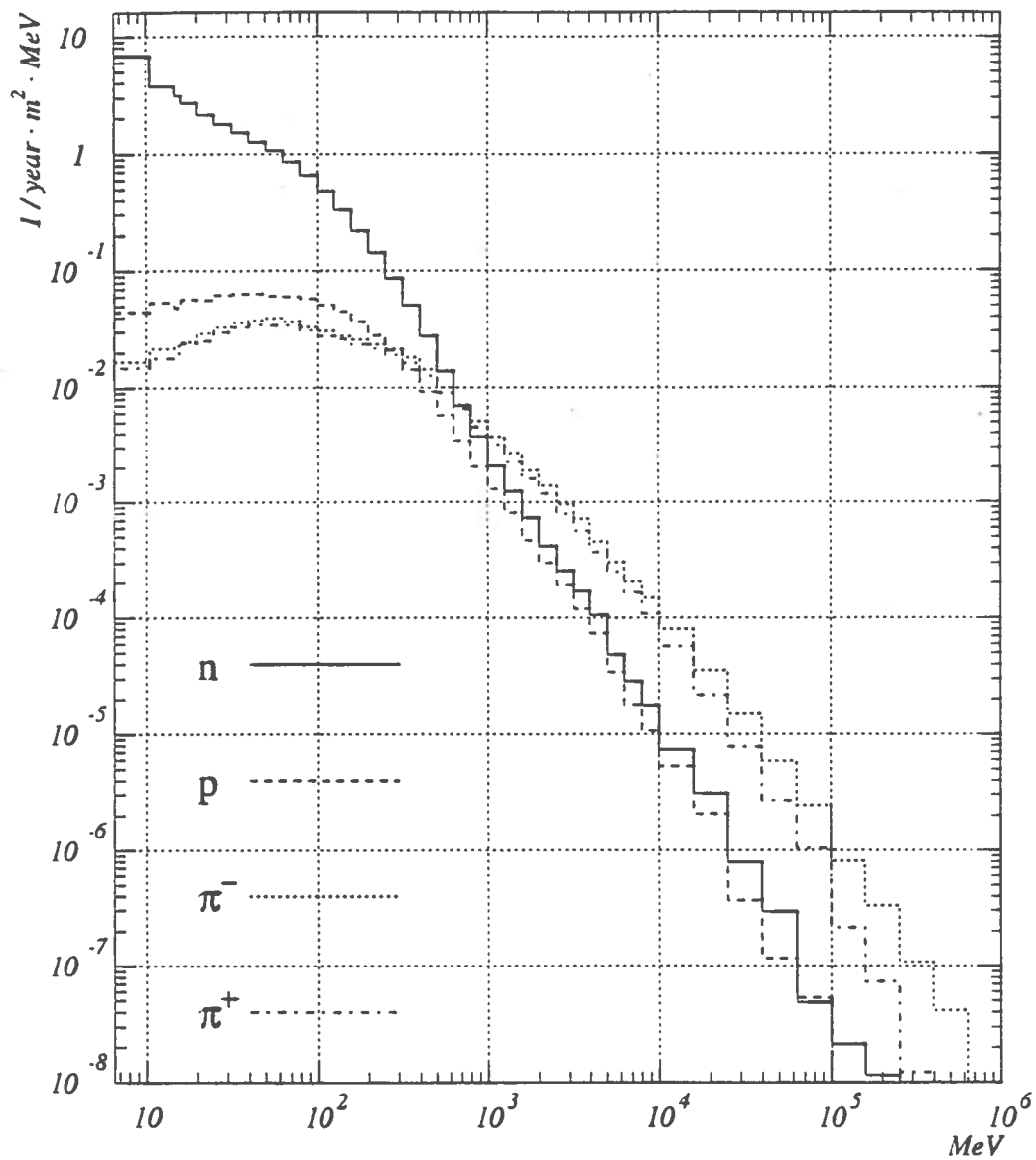


Figure 7: Comparison of n, p, π^- and π^+ spectra at entry into the hall.

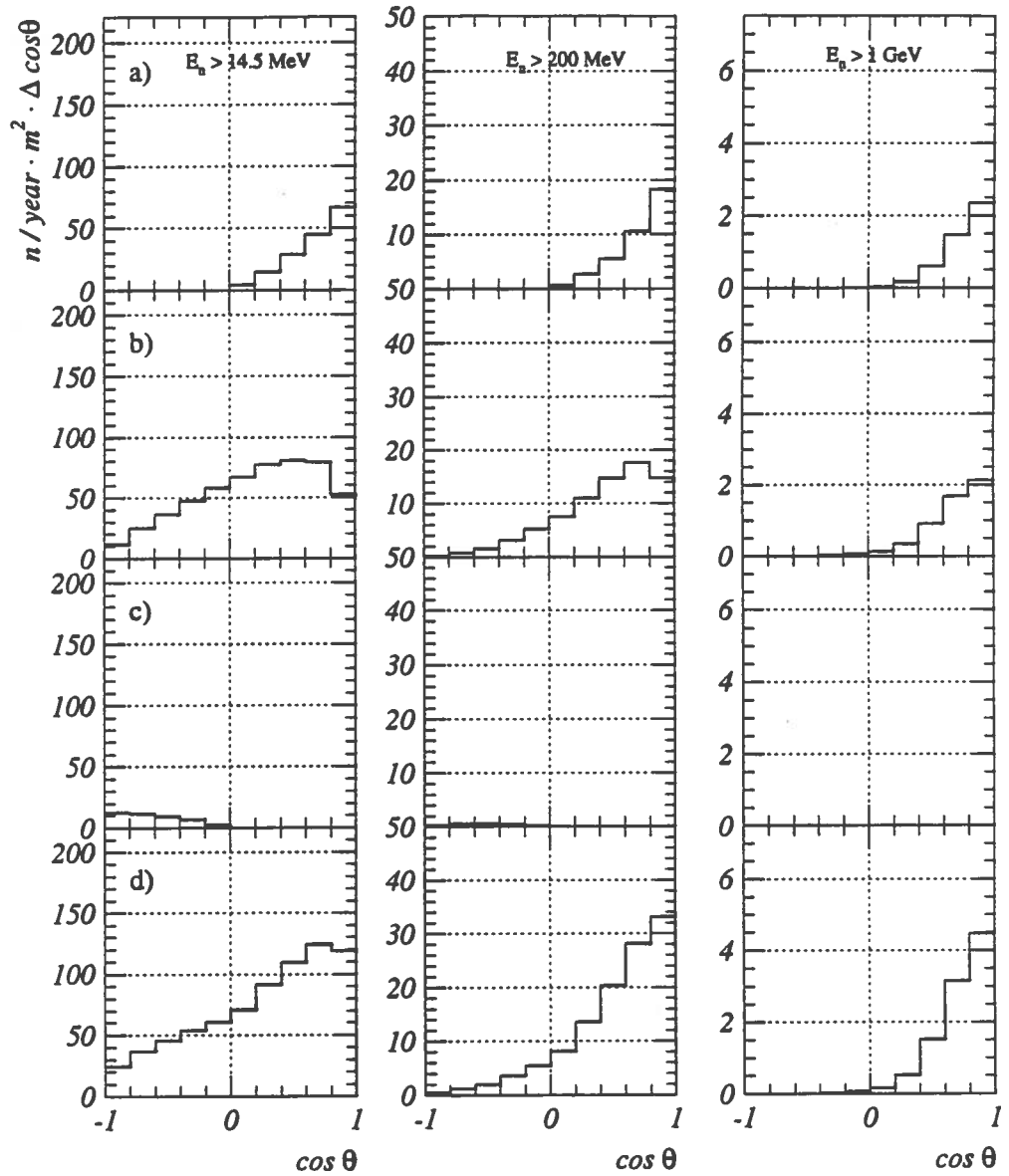


Figure 8: Angular distributions of neutrons going into the hall from: a) roof, b) walls, c) floor and d) sum, for three energy thresholds: 14.5, 200 and 1000 MeV.

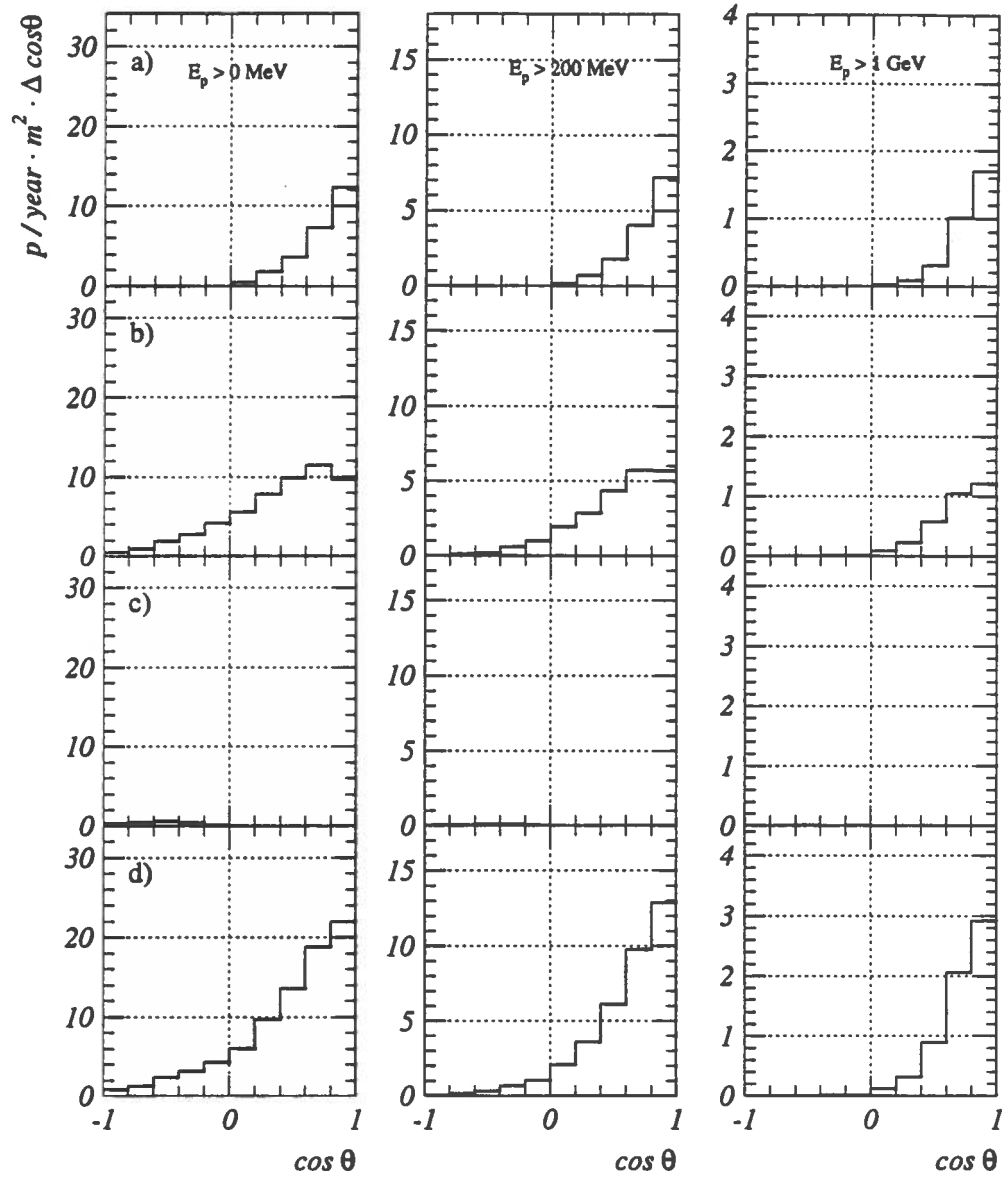


Figure 9: Angular distributions of protons going into the hall from: a) roof, b) walls, c) floor and d) sum, for three energy thresholds: 0, 200 and 1000 MeV.

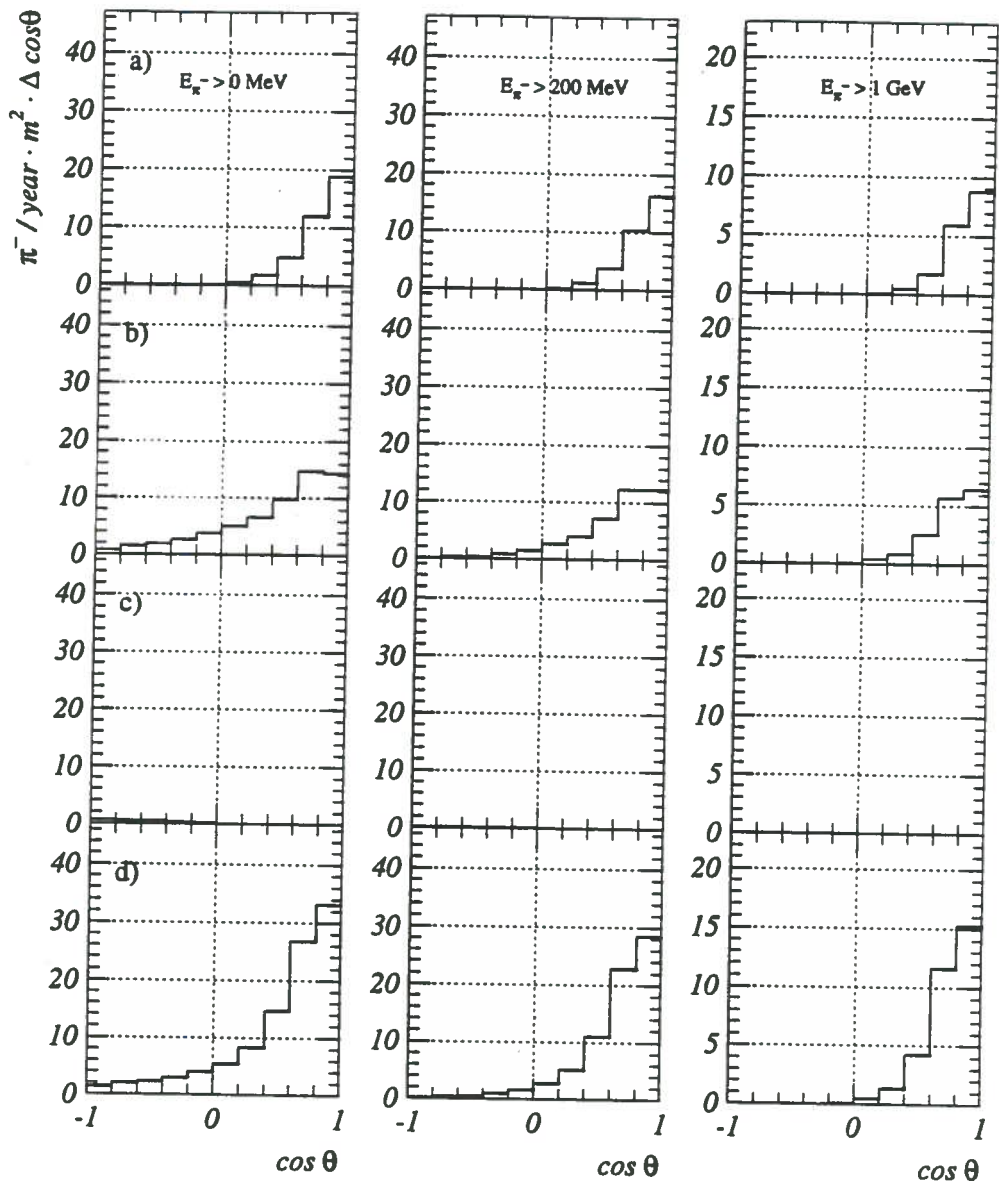


Figure 10: Angular distributions of π^- -mesons going into the hall from: a) roof, b) walls, c) floor and d) sum, for three energy thresholds: 0, 200 and 1000 MeV.

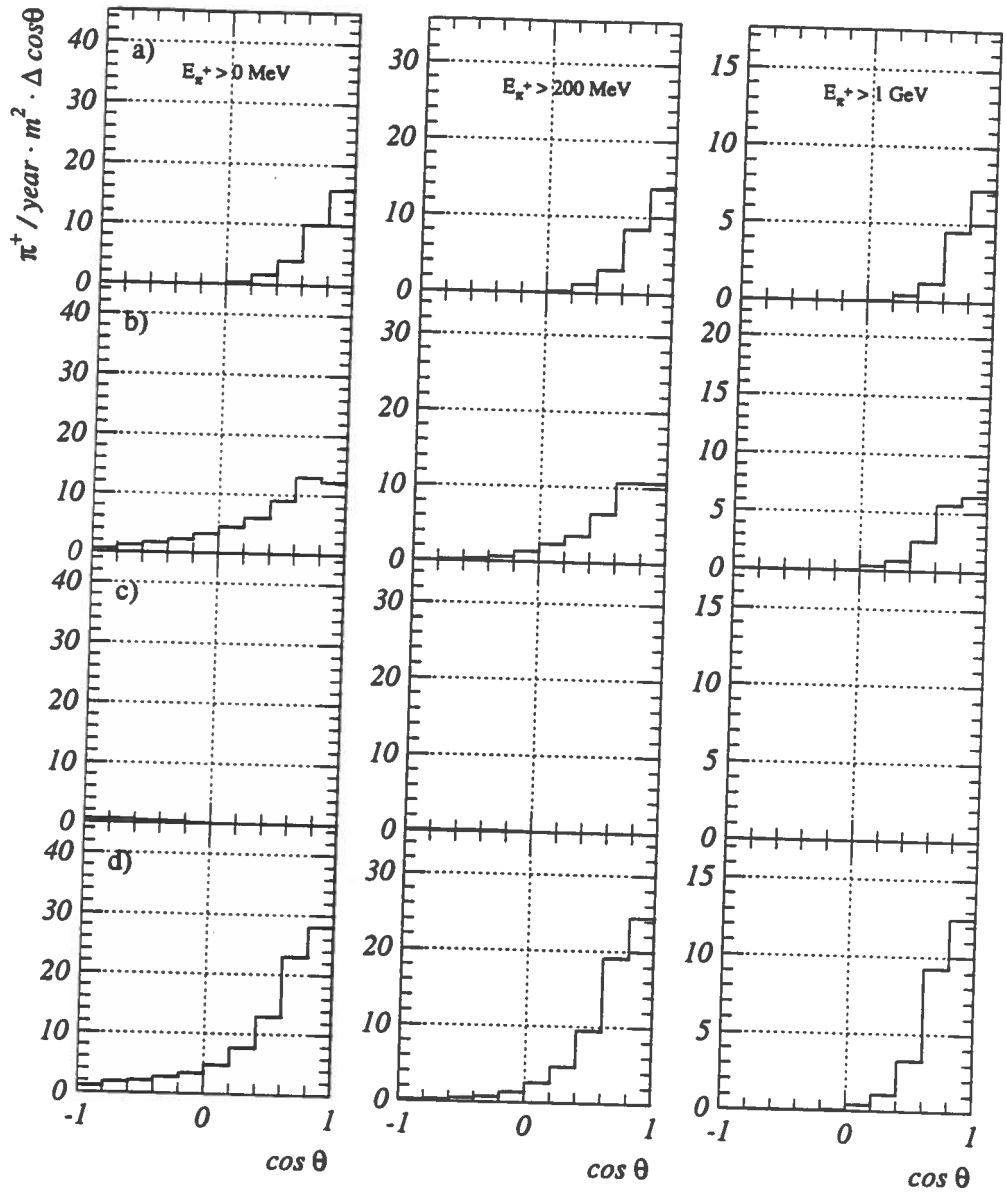


Figure 11: Angular distributions of π^+ -mesons going into the hall from: a) roof, b) walls, c) floor and d) sum, for three energy thresholds: 0, 200 and 1000 MeV.

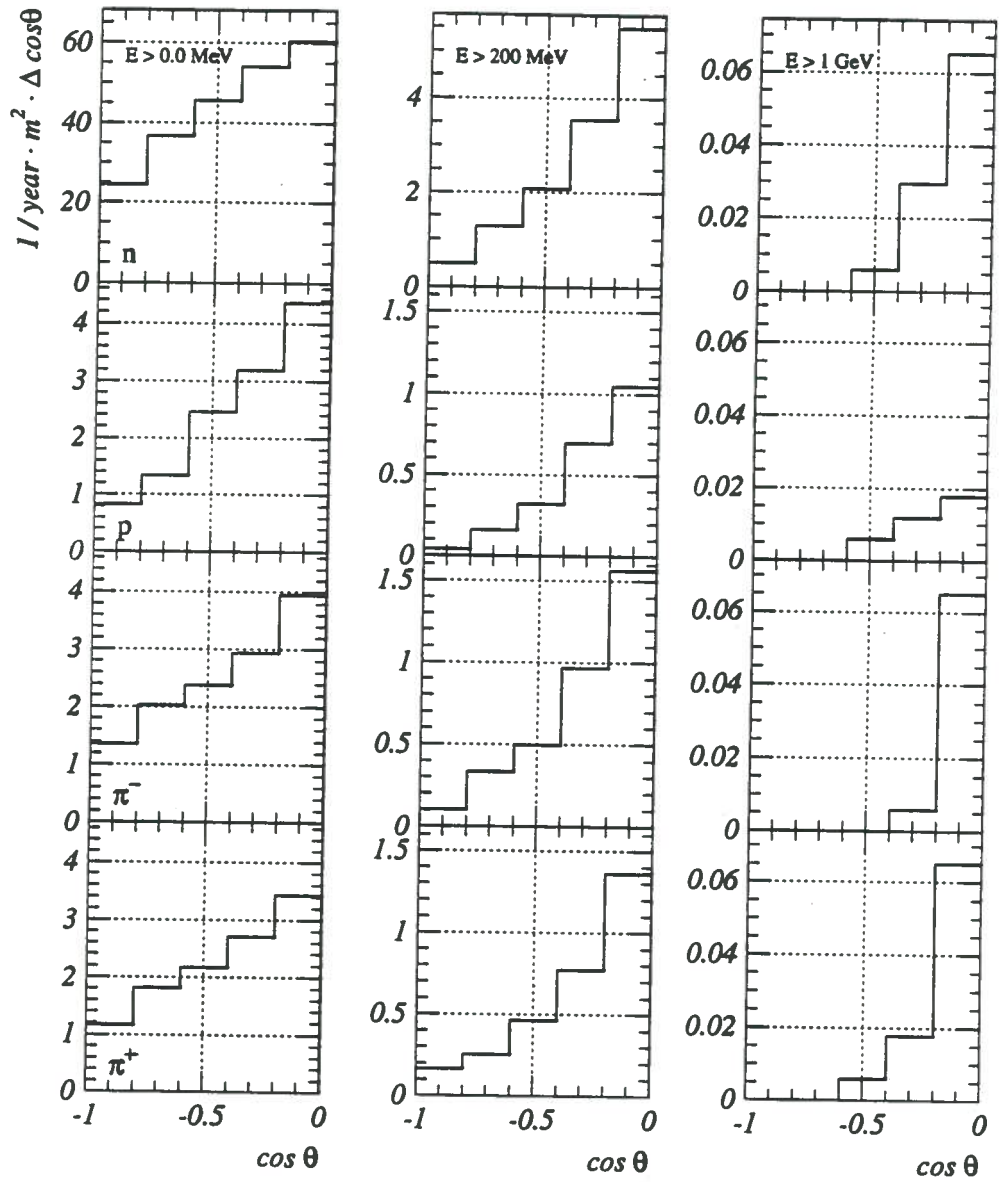


Figure 12: Yield into backward hemisphere from floor and walls.

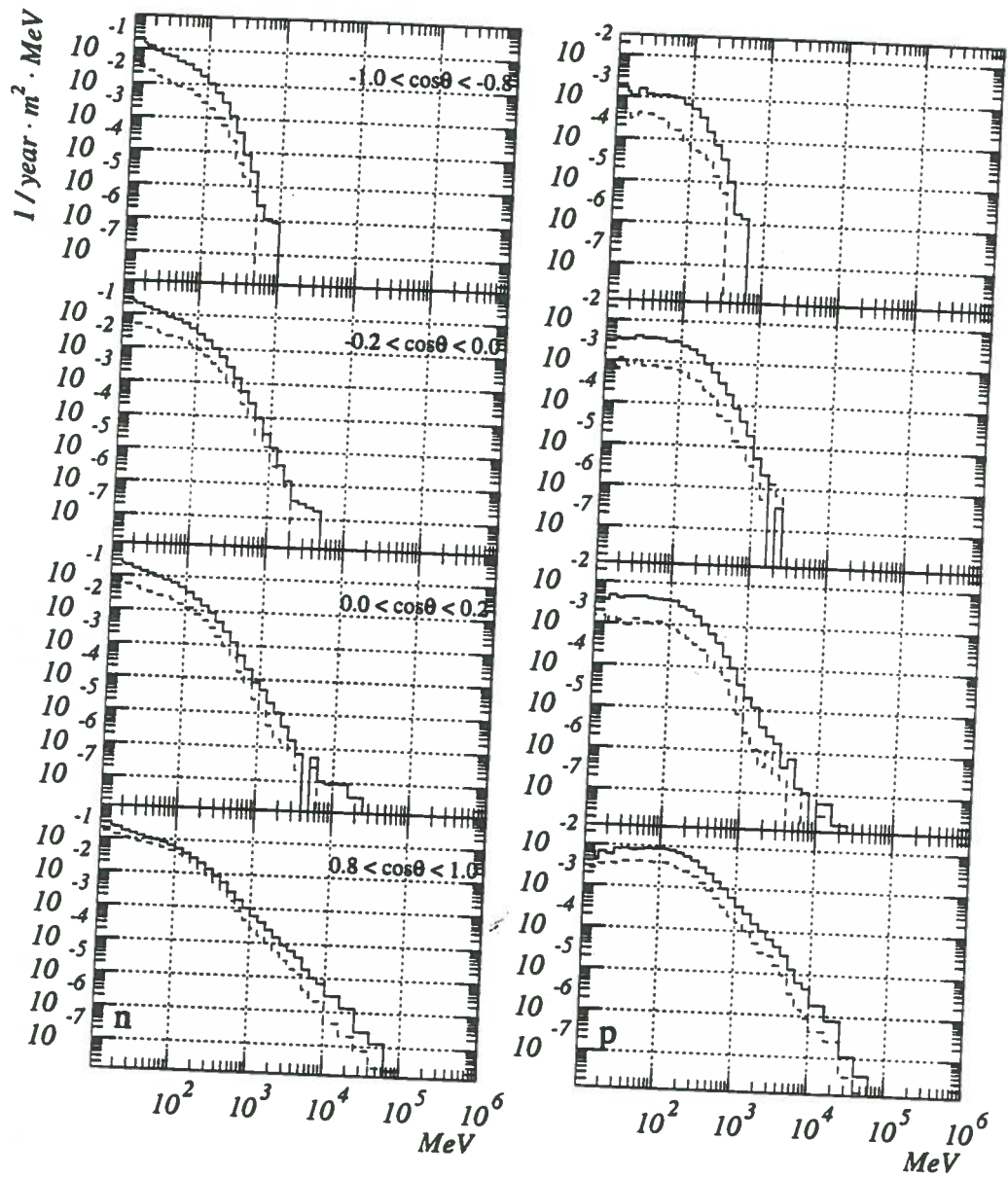


Figure 13: Spectra of neutrons and protons in different angular intervals from whole hall surface.

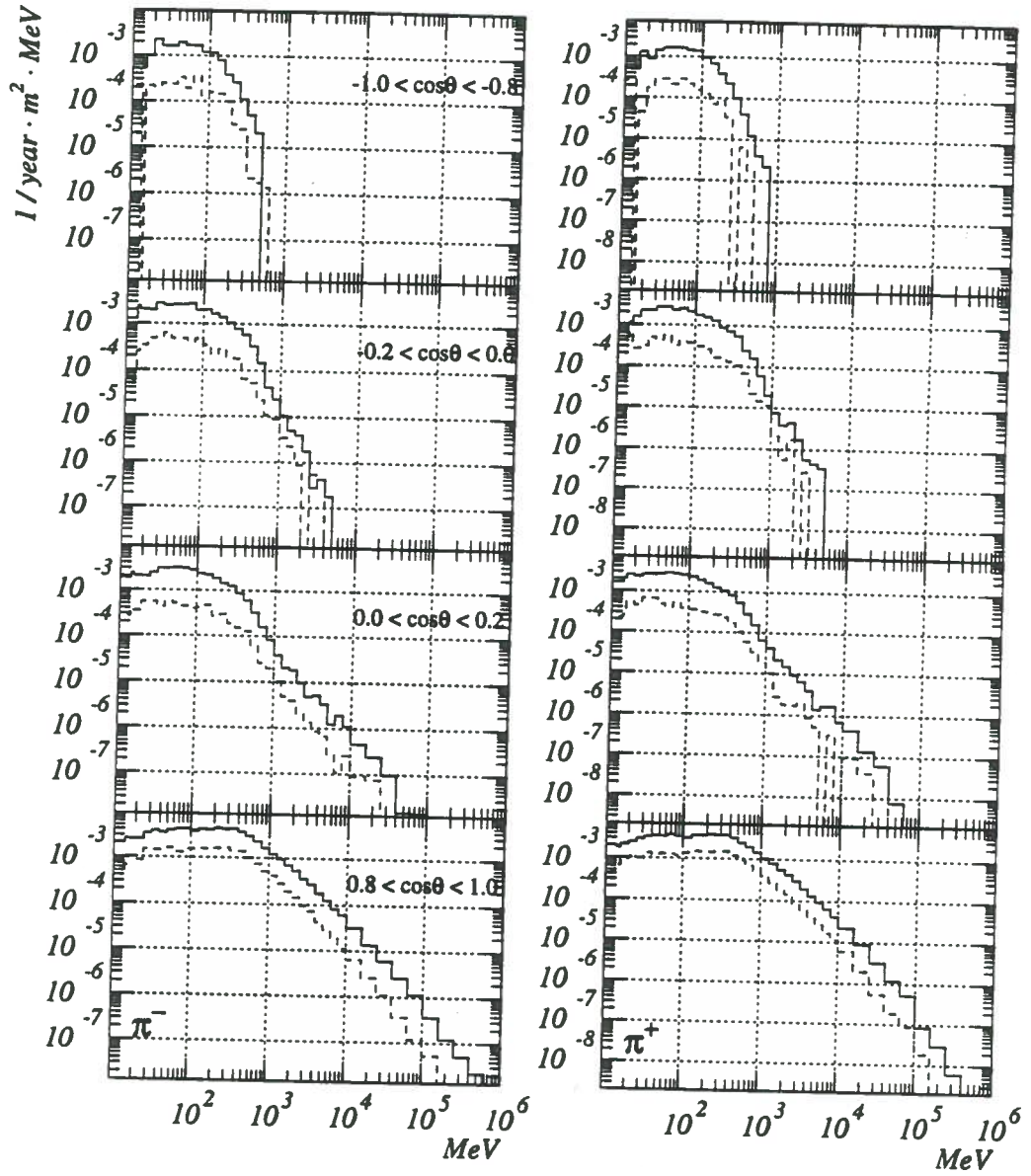


Figure 14: Spectra of π^- and π^+ mesons in different angular intervals from whole hall surface.