INTERNATIONAL ATOMIC ENERGY AGENCY
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SCHOOL ON
NON-ACCELERATOR PHYSICS
25 April - 6 May 1988

BACKGROUND RADIATION in DEEP UNDERGROUND LABORATORIES

by

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Background Radiation in Deep Underground Laboratories

- high energy muons
- neutrinos
- γ-rays and neutrons from natural radioactive nuclei

Primary cosmic rays

Energy (power law) $N(E>E_0) = K\, E_0^{-\gamma}$

K depends on chemical nature of p.c.r.

$\gamma \sim 1.7$

⋮

Chemical composition:

H, He, C, N, O, ... Fe ...

At sea level

$\phi \simeq 10^{-2}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{str}^{-1}$

(mainly μ's $\langle E_\mu \rangle \sim 2$ GeV)

Very high energy c.r.'s generate

- hadronic cascades $\longrightarrow$ μ's and ν's
- e.m. showers

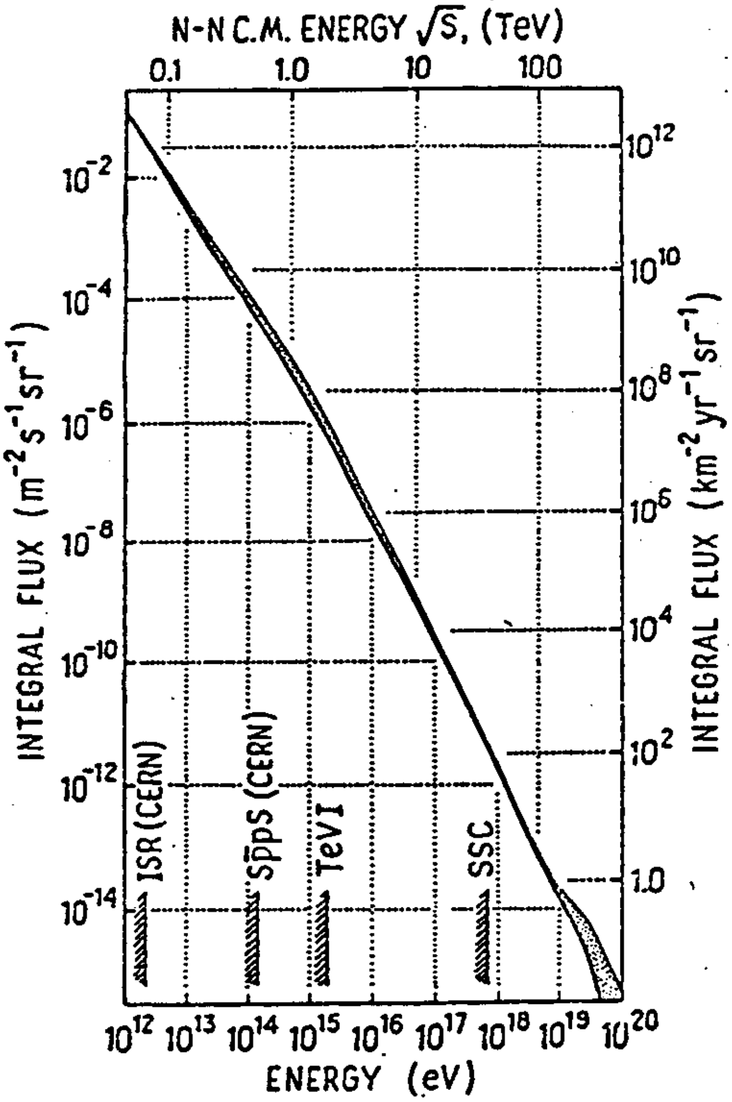


Figure 1. Cosmic ray primary integral flux spectrum vs. energy, with energies of nucleon-nucleon colliders indicated on the abscissa.

From L.W. Jones in Proc. 19th ICRC

La Jolla - USA Aug. 11-23 (1985), vol. 9

pag. 324

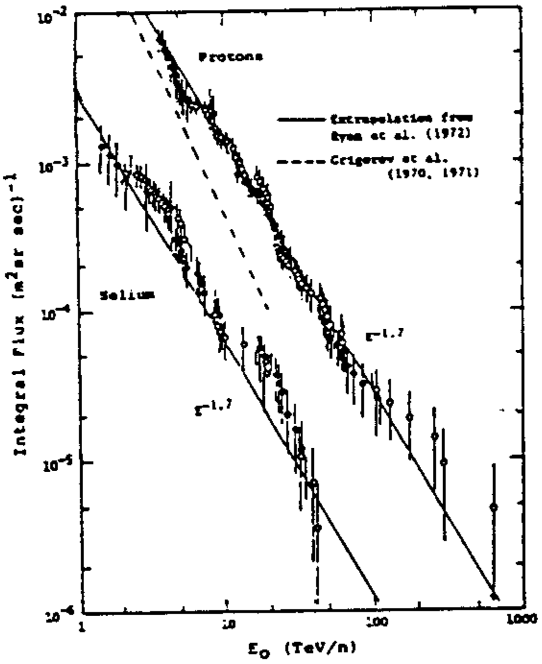


Fig. 2 Proton and helium ~~ar~~ flux as a function of energy ; note that the energy scale is in TeV / nucleon

[JACEE coll.
T. H. Burnett et al. Proc. 20th ICRC, vol 1, pag. 375
Moscow ~~ze~~ August 2-15 (1987)

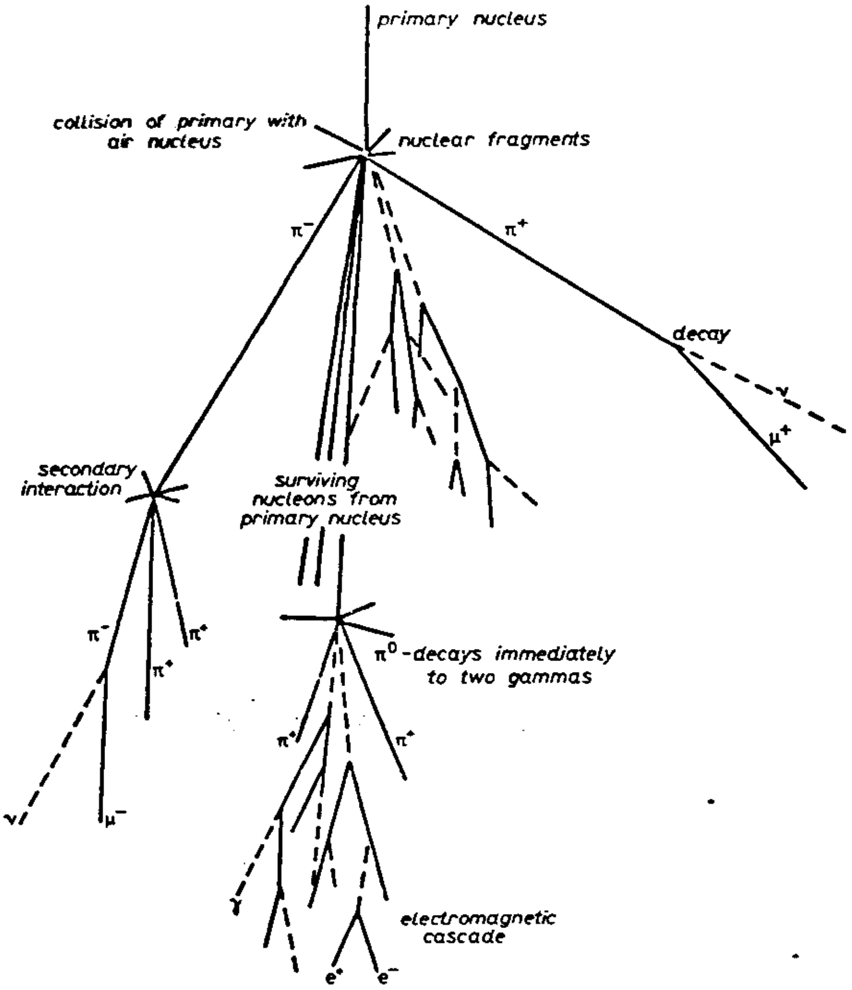


Fig. 3. – Schematic representation of the development of an extensive air shower.

vertical intensity: $I(h) = A\, e^{-h/B}$ $cm^{-2}\, s^{-1}\, str^{-1}$

h = hgr/cm^2 standard rock ($A = 22$, $Z = 11$)

at M.nt Blanc:

$$A = (0.76 \pm 0.05)\, 10^{-6} \quad cm^{-2}\, s^{-1}\, str^{-1}$$

$$B = 810 \pm 1 \quad hgr/cm^2$$

[C. Castagnoli and O. Saavedra N.C. 9C, 111 (1986)]

h (hgr/cm^2)	ϕ ($m^{-2}\, h^{-1}\, str^{-1}$)
3000	$6.7\ 10^{-1}$
5000	$5.7\ 10^{-2}$
7000	$4.8\ 10^{-3}$
9000	$4.1\ 10^{-4}$

To compute the total flux

$$I(h,\theta) = \underbrace{I_{\pi,K}(h)\sec\theta}_{\text{"Secant law"}} + \underbrace{I_x(h)}_{\text{prompt } \mu\text{'s } (\sim \text{negligible})}$$

- shape of overburden complicated

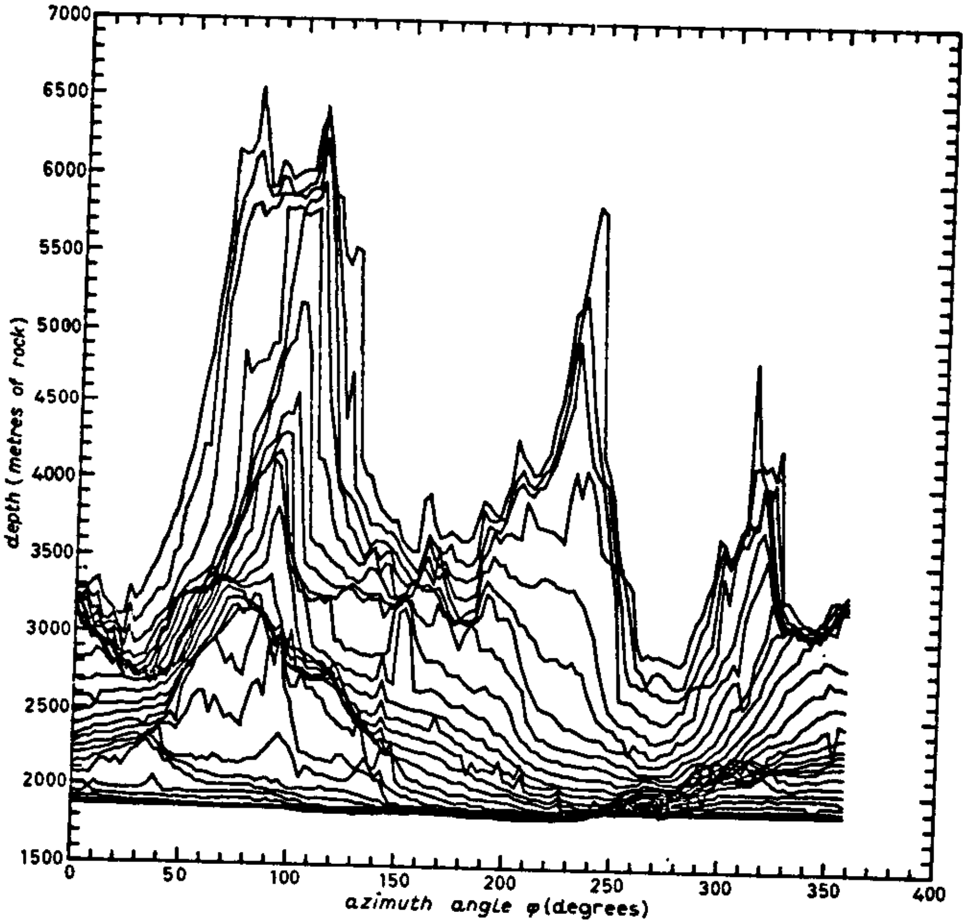


Fig. 2. – The slant depths, in metres of rock as a function of azimuthal angle φ at steps of $\Delta\theta = 2.5°$ of zenithal angle, pointed at the NUSEX Laboratory.

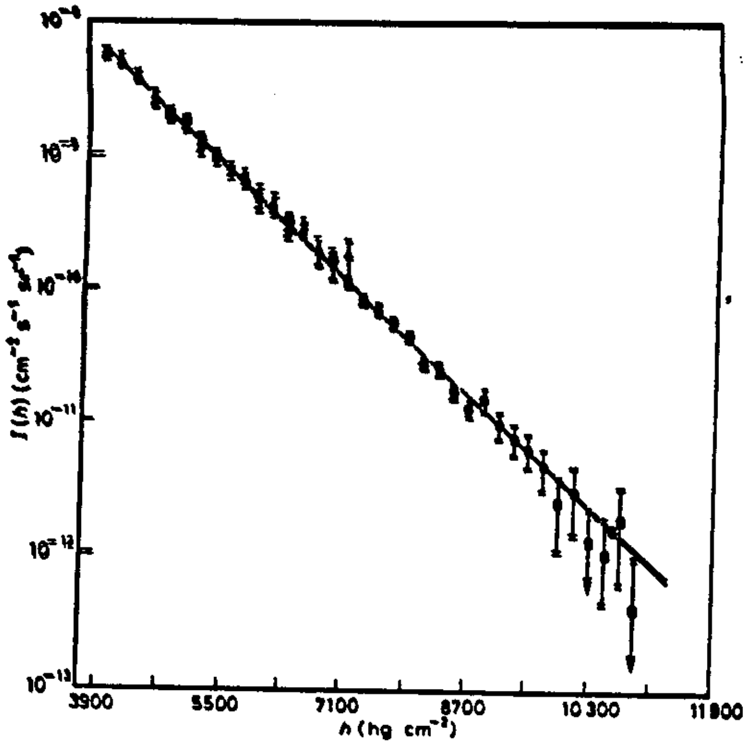


Fig. 4 – Vertical-depth-intensity relation as measured by SCE (▲) and NUSEX (•) experiments. The full line is the best fit to both experiments and it is given in the text.

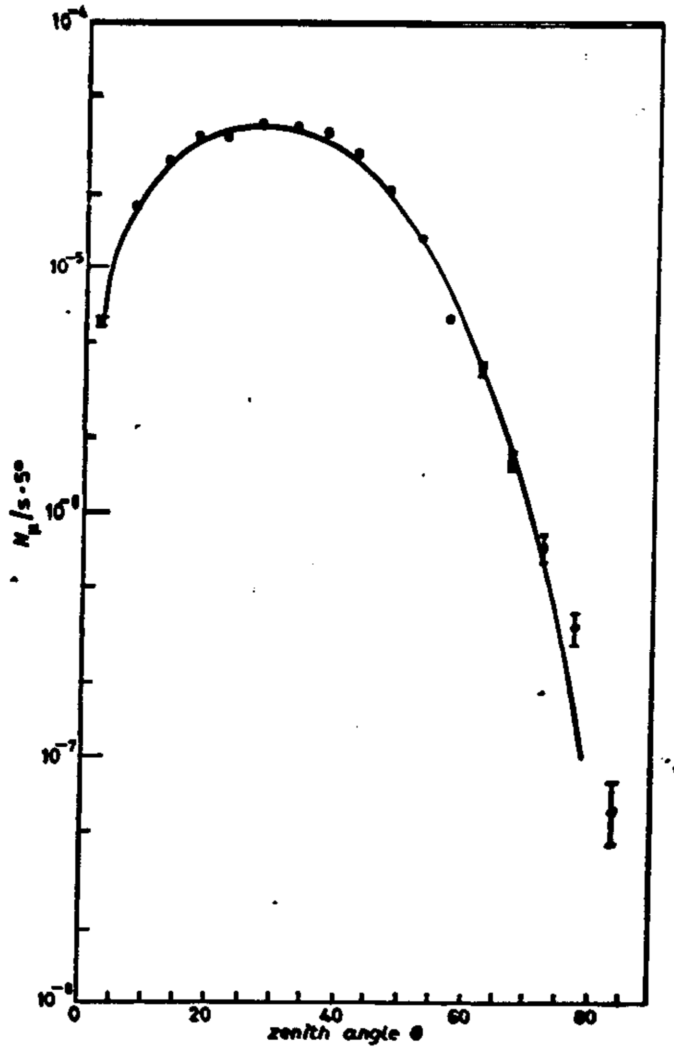


Fig. 5 – The angular distribution of penetrating particles at NUSEX 5000 hg/cm². The points shows the experimental data in 5° bins intervals. The errors are purely statistical. The solid curve is the expected atmospheric muon distribution.

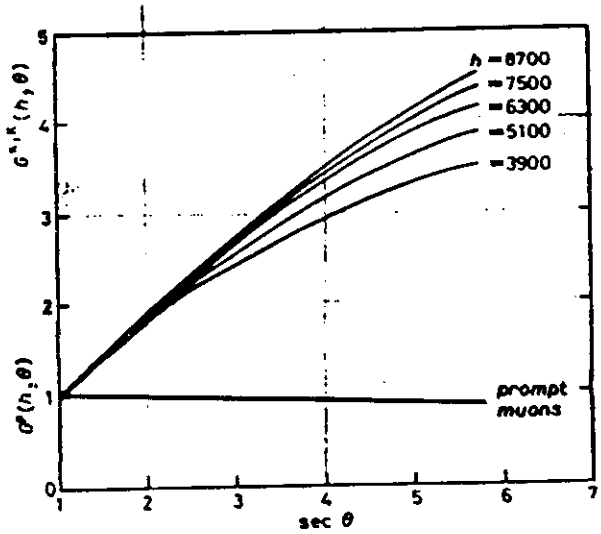


Fig. X. – Angular enhancement of underground intensities of conventional and prompt muons.

From NUSEX collaboration - N.C. Vol 9C, 198 (1986)

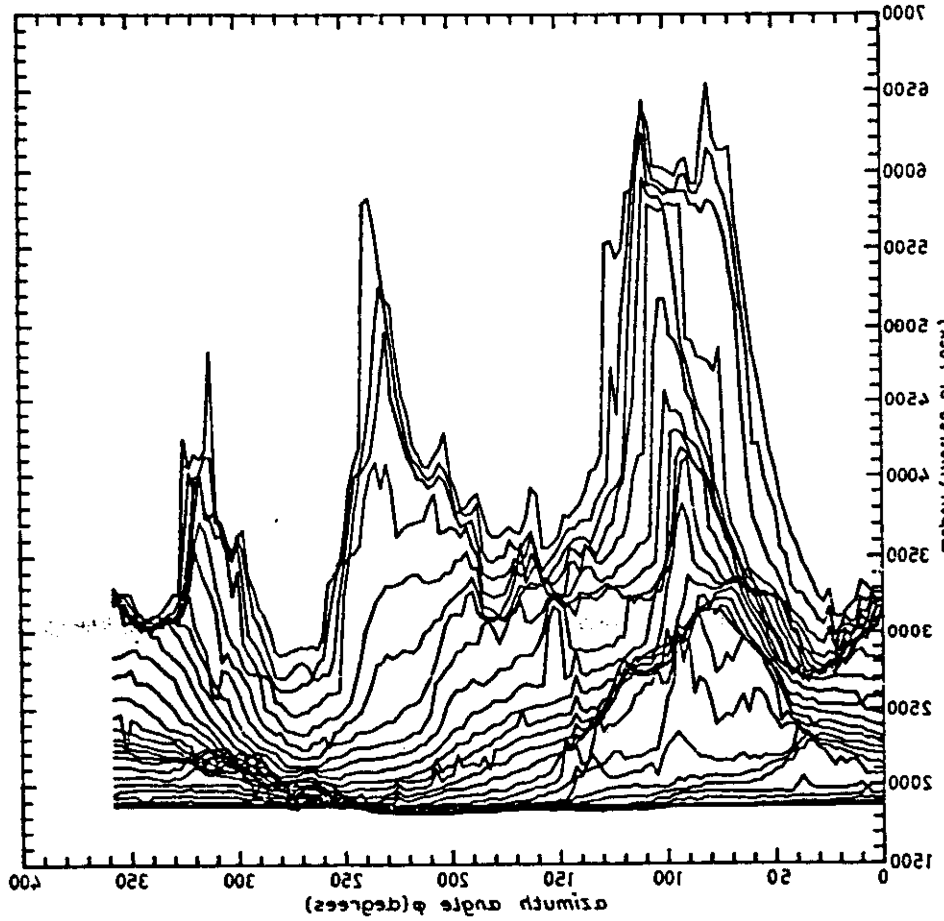


Fig. 2. – The slant depths, in metres of rock as a function of azimuthal angle φ at steps of $\Delta\theta = 2.5°$ of zenithal angle, pointed at the NUSEX Laboratory.

Parallel muons

Interesting to study the chemical composition of p.c.r.

Interacting muons

$$1\ \mathrm{TeV}\left\{\begin{array}{lll} \text{ionization} & \sim 2.5\ \mathrm{MeV}/(\mathrm{g/cm^2}) & \frac{dE}{dx} \sim \text{const.} \\ \text{pair production} & \sim 1.5\ \text{"} & \\ \text{bremsstrahlung} & \sim 1.0\ \text{"} & \\ \text{nuclear int.} & \sim 0.5\ \text{"} & \end{array}\right. \quad \left.\begin{array}{l}\\ \\ \end{array}\right\} \frac{dE}{dx} \sim E$$

Stopping muons

$$\mu^-(A,Z) \to \nu_\mu\ (A, Z-1)^*$$
$$\hookrightarrow (A', Z') + p, n, \alpha \ldots$$

e.g. $\mu^-\ {}^{16}O \to \nu_\mu\ {}^{16}N^*$

$\quad \to {}^{16}O + e^- + \bar{\nu}_e \quad \tau_{1/2} \sim 7\,s$, $T_e \sim 10\ \mathrm{MeV}$

$\quad \to {}^{12}B^* + \alpha$

$\qquad \hookrightarrow {}^{12}C + e^- + \bar{\nu}_e \quad \tau_{1/2} \sim 20\ \mathrm{ms}$

high energy muons and stopping μ's produce

${}^{12}B,\ {}^{12}Li,\ {}^{8}B,\ {}^{16}N \ldots$

(Kamiokande)

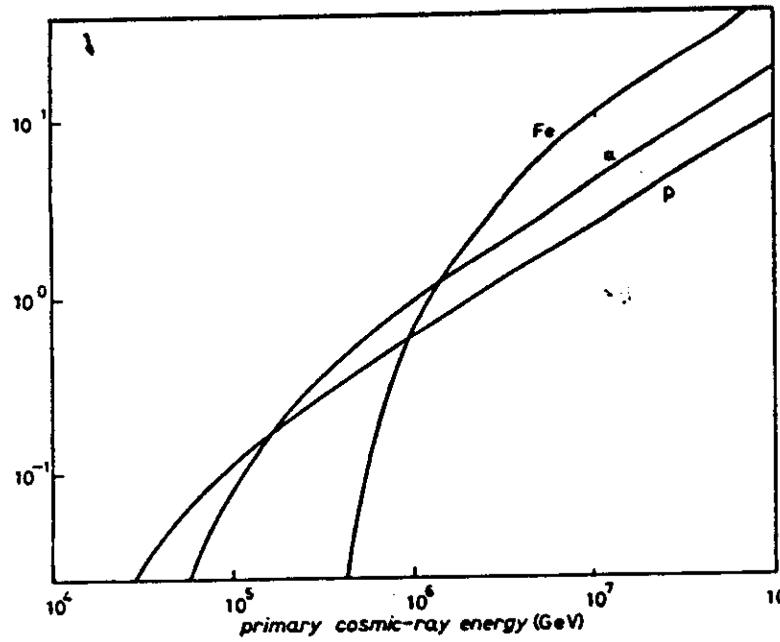


Fig. 6. – Expected mean number of muons at the depth of the underground laboratory for different primary nuclei, as a function of primary energy (vertical direction).

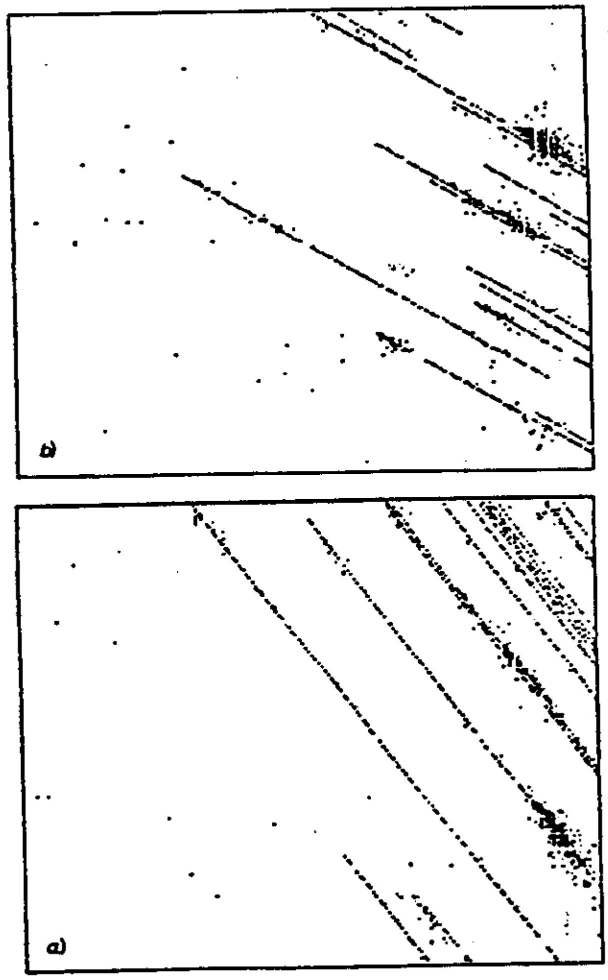
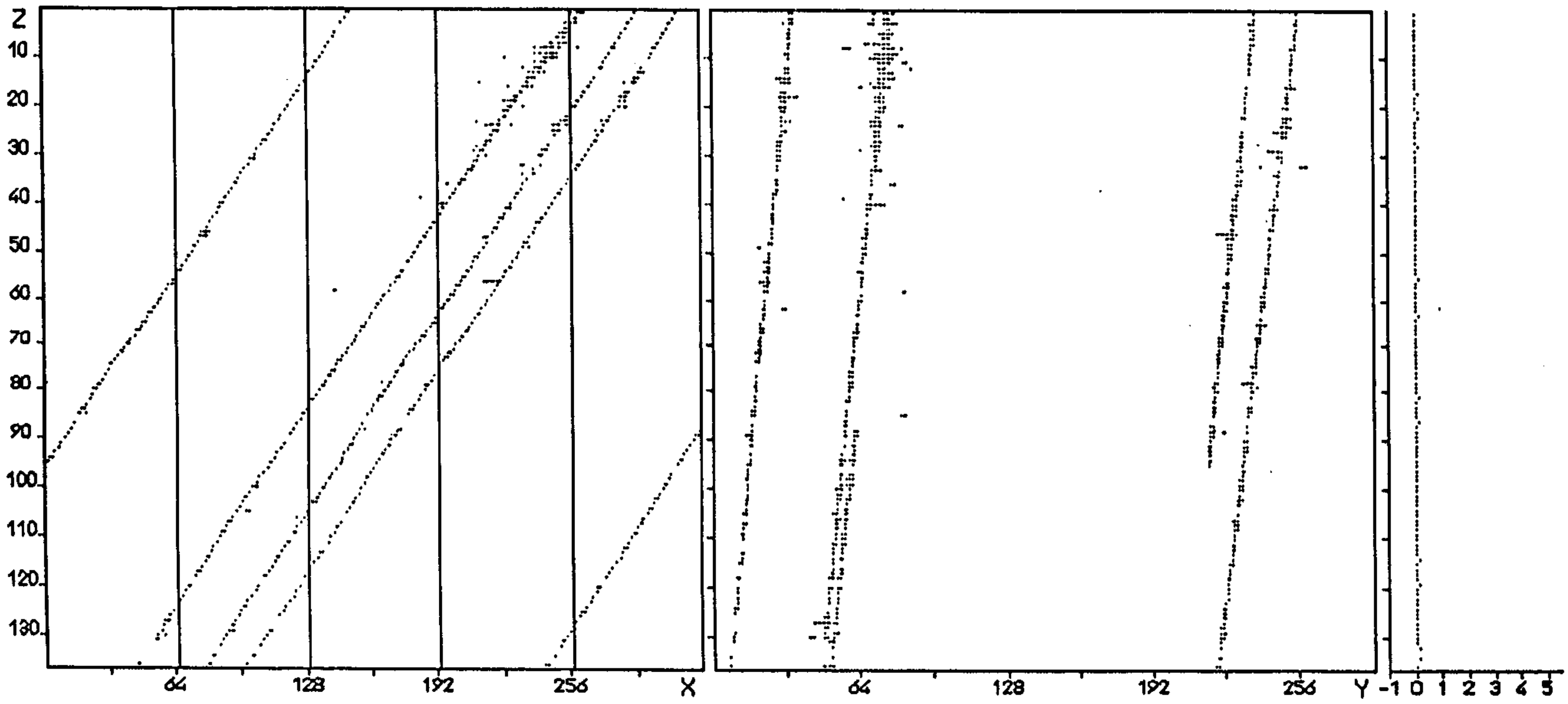


Fig. 2. – A bundle of 15 muons observed in the Fréjus detector: *a*) side view, 3199 flashes, 309 geigers; *b*) top view, 2688 flashes, 271 geigers).

NUSEX 134 PIANI

RUN # 1392 EVENT # 394 30/ 6/84 6:48:22



Atmospheric neutrinos

$\pi, K, \mu \ldots$ produce $\nu_\mu (\bar{\nu}_\mu)$, $\nu_e (\bar{\nu}_e)$

$$\nu_e \sim \frac{1}{3} \nu_\mu$$

$\nu_\mu (n) \to \mu^- p$ at large zenith angles

- Reines
- p-decay experiments

ν flux $\sim$ 10 GeV proton - bore ν beam
accelerator $\nu_\mu, \bar{\nu}_\mu$
but
atmospheric $\nu_\mu, \nu_e \ldots$

(ϕ_ν depends on latitude!)

expected rate: $\sim$ 150 events / (kton × year)
($E > 300$ MeV)

ultimate background in p-decay exp.

" in ν point source

M.F. Crouch et al - Phys. Rev 18 D, 2239 (1978)

(16

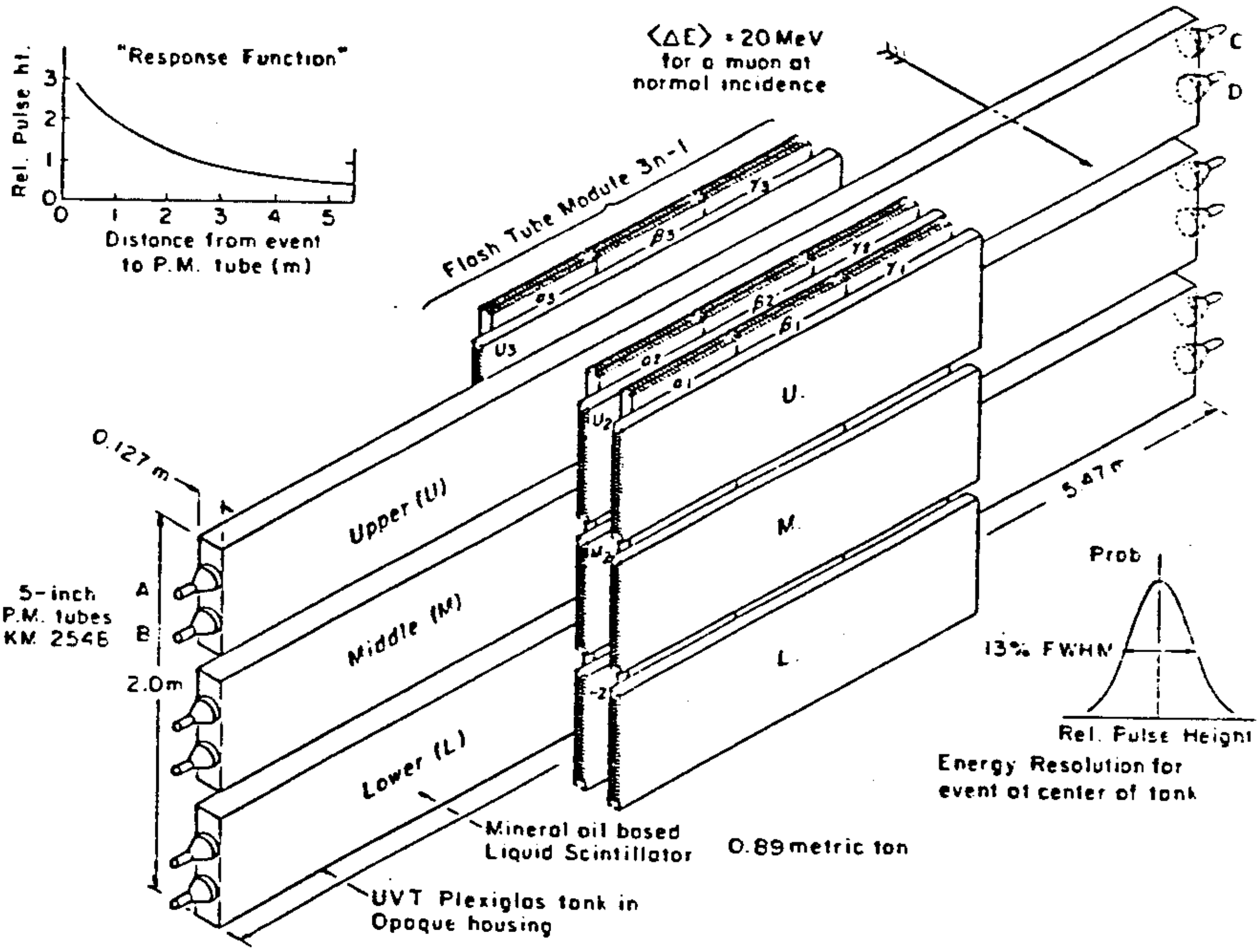


FIG. 2. Details of the nth scintillator bay and the (3n − 1)st flash-tube module.

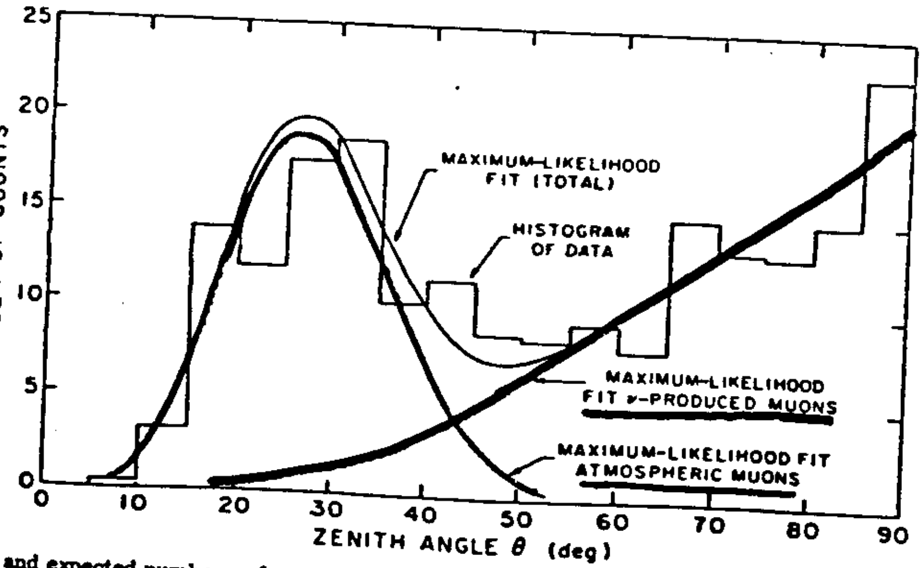
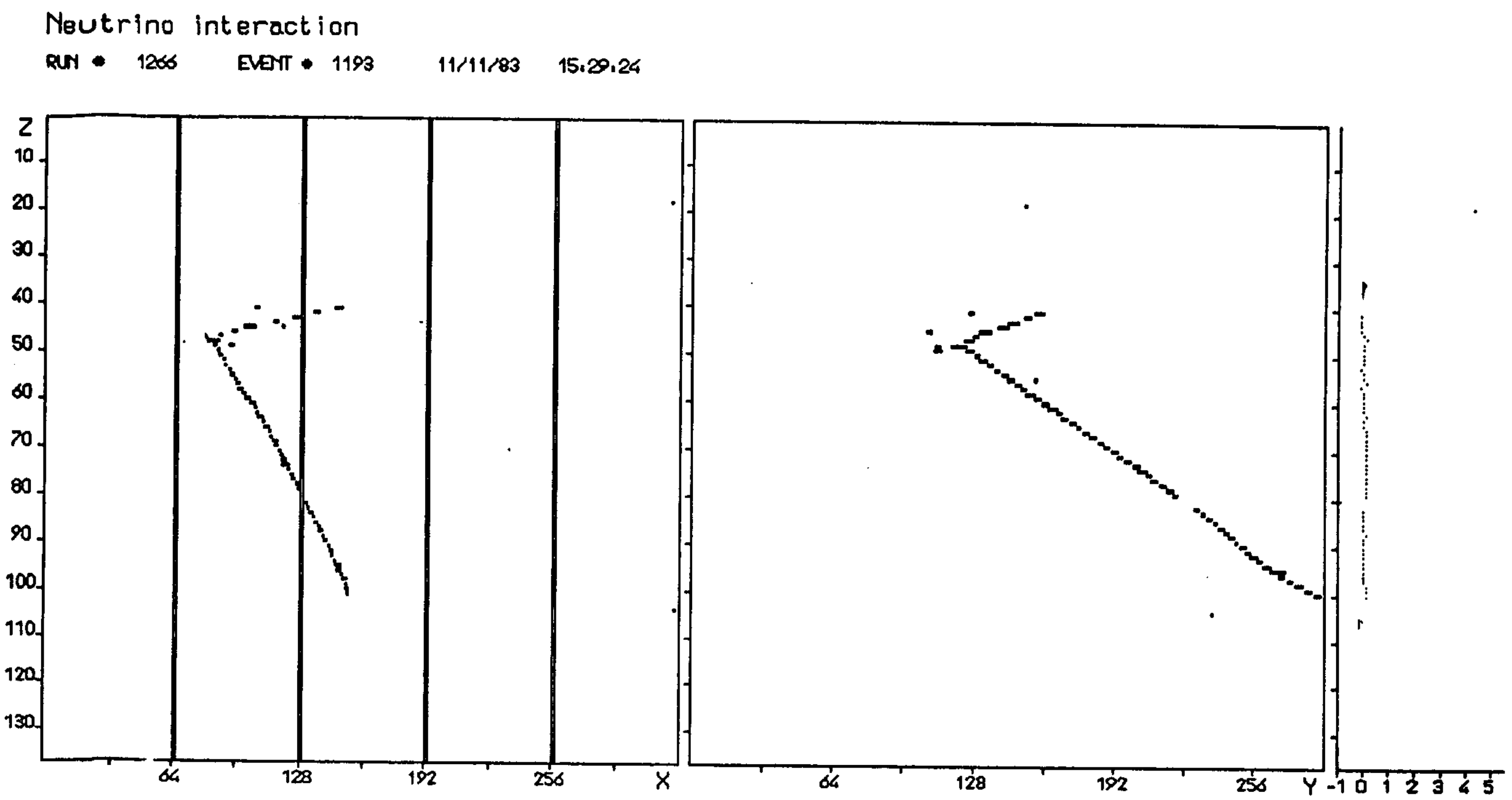
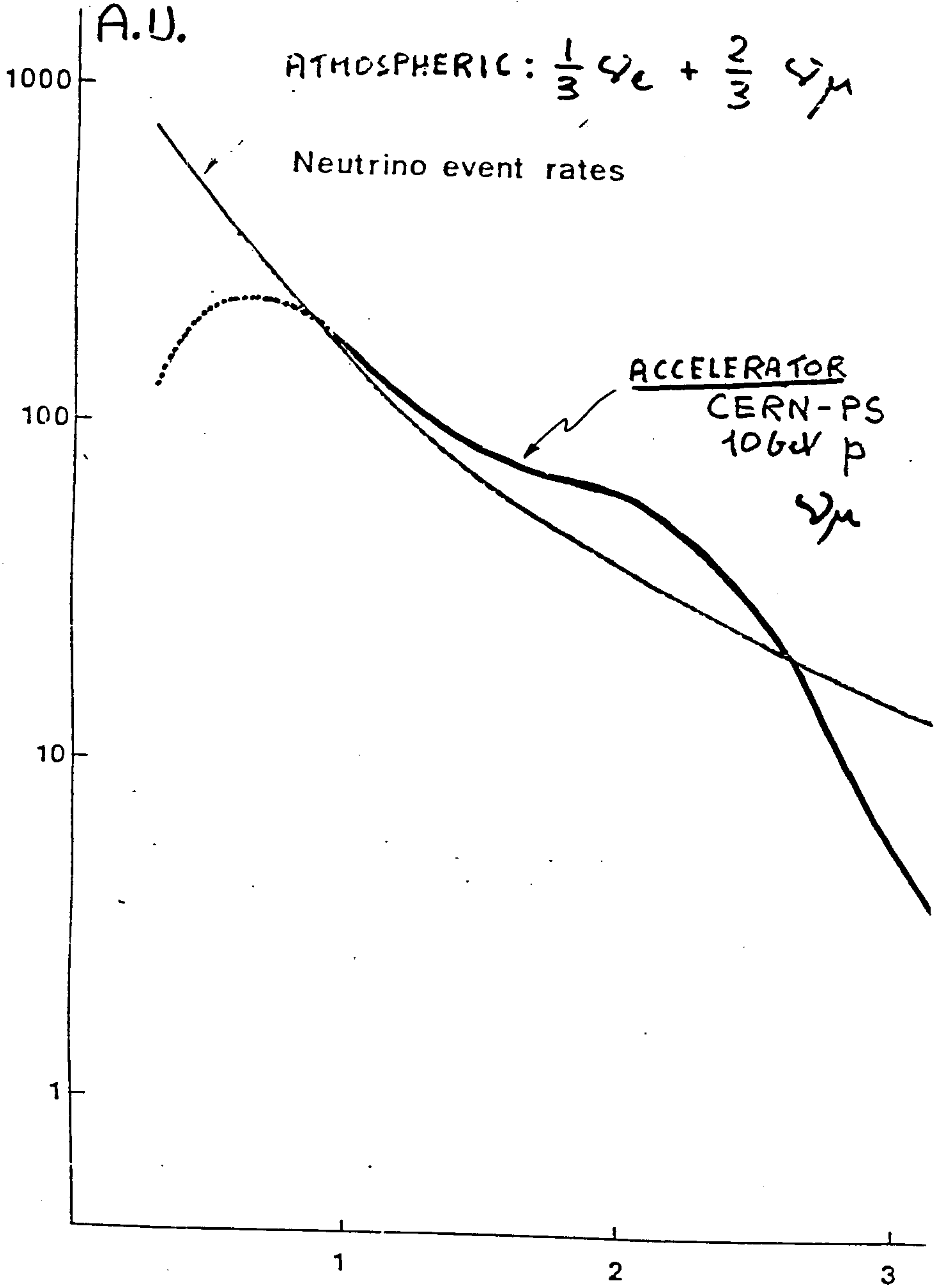


FIG. 8. Observed and expected numbers of counts vs zenith angle for events in which zenith angle is determined.


Neutrino interaction
RUN * 1266
EVENT * 1193
11/11/83
15:29:24
Z
10
20
30
40
50
60
70
80
90
100
110
120
130
64
128
192
256
X
64
128
192
256
Y
-1 0 1 2 3 4 5

(15


A.U.
ATMOSPHERIC: $\frac{1}{3}\nu_e + \frac{2}{3}\nu_\mu$
Neutrino event rates
1000
100
10
1
ACCELERATOR
CERN-PS
10 GeV p
ν_μ
1
2
3
E_ν, GeV

Reactor antineutrinos

[P.O. Lagage - Nature 316, 420 (1985)]

Power plant ~ 2.5 GW (thermal)

at 10 m $\phi = 2\ 10^{13}\ \bar{\nu}_e$'s /(cm^2·s)

> 1 MeV	50 %
> 3 MeV	10 %
> 5 MeV	1 %

Frejus	$3\ 10^{6}$
M.nt Blanc	$3\ 10^{6}$
Gran Sasso	$4.5\ 10^{5}$
Fairport Harbor	$1.3\ 10^{6} \rightarrow 4.7\ 10^{7}$
Kolar Gold Field	$4\ 10^{4}$

Bg Earth $\bar{\nu}_e$

Diffuse SN $\bar{\nu}_e$

(Solar ν_e)