NPA/Int. 68-18
25.7.1968

SOME CONSIDERATIONS ON HIGH ENERGY NEUTRINO EXPERIMENTS WITH A 76 GeV ACCELERATOR

This report is the result of a series of discussions among colleagues concerned with various aspects of high energy neutrino experiments.

Those participating in the discussions, which took place during the first half of 1968, were :

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CONTENTS

1. The Rôle of Serpukhov in Future Neutrino Experiments

One of the consequences of the operation of the new proton accelerator at Serpukhov is that neutrino experiments at higher energies and with more intense fluxes are now feasible. In response to an invitation from our colleagues at Serpukhov, we have assembled some scientific and technical data which are relevant to the planning of a neutrino facility and its experimental programme. We have concluded, from the considerations in the pages which follow, that neutrino experiments at the 76 GeV accelerator will make unique and decisive contributions in the field of the weak interactions.

Interactions of high energy neutrinos have been studied at Brookhaven,(1) CERN(2,3) and Argonne(4) with installations having the spectra shown in Fig. 1. A few tens of events per day have been obtained in bubble chambers and a few hundreds per day in spark chambers. Preliminary estimates of event rates at Serpukhov(5,6) and, for comparison, from a 300 GeV(7) accelerator, are also shown in Fig. 1, together with improvements which will come, over the next few years, from new power supplies and injectors for the present accelerators.(8)

It is clear from Fig. 1 and also from Fig. 2, which depicts event rates for various detectors, that a neutrino programme starting in 1972 could not be markedly superior to the programmes at CERN and Brookhaven in the energy region below 5 GeV. These laboratories either have already, or in an advanced stage of construction, neutrino beam installations, machine intensity improvement programmes and giant bubble chamber detectors. During the next four years they will have accumulated a substantial body of data on the more common reactions of neutrinos and antineutrinos on nucleons for which the cross-sections reach their asymptotic limits below 5 GeV.

The essential justification for a neutrino installation at the 76 GeV accelerator must therefore rest on the assessment of the physics programme possible with neutrino energies above 10 GeV.

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It is our opinion that this programme is of fundamental importance. Possible experiments which will be described in outline in this report, and which are oriented specifically to high neutrino energies, may be summarized briefly as follows :

(1) Experiments having as their aim the extension of the studies of neutrino processes which have been made at existing accelerators. An important example is the investigation of total and differential cross-sections on nucleons in the high-energy region. The behaviour of these cross-sections is crucial for the detection of the expected breakdown of the local current-current hypothesis. Neutrino experiments at Serpukhov would extend the range of such measurements from the region of up to 10 GeV, accessible today, to 40 or 50 GeV.

(2) A neutrino installation at Serpukhov would allow the study of interactions whose thresholds were not previously attainable. As examples of this type of experiment, we mention the elastic scattering of muon neutrinos by electrons which has a threshold energy of 10 GeV, and the certainty of producing and detecting the intermediate boson W, if its mass is less than 5 GeV. This latter possibility is still perhaps the most urgent of all neutrino experiments,(*) especially in view of several recent theoretical speculations(9) suggesting a W mass in the region of a few GeV.

(3) In discussing the justification of a higher-energy facility, the possibility of the discovery of new and unexpected phenomena must be borne in mind. Some of the many possibilities which have been discussed in theoretical studies in this field are mentioned later.

(*) " In any event, experimental studies of weak interactions at high energies and especially the search for W quanta, constitute some of the most important future problems (of particle physics)" A. Pais - Physics Today 21, 25, 1968.

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(4) Finally, experiments at Serpukhov, even if oriented to high energy, will yield of course many lower energy events which will result in invaluable and independent contributions to the study of amplitudes and form-factors for the common transitions. They will provide an assured programme of research because of the great wealth of data which will be obtainable, but as we have stated already, we do not maintain that they are a primary justification for the neutrino programme.

Both wide and narrow band neutrino beams have been considered.(6) The wide-band system optimized for the neutrino flux above 10 GeV seems to be superior for the type of programme envisaged, since practically all experiments require a wide range of neutrino energy with the maximum possible flux. Detailed calculations based on a scaled-up version of focusing element parameters, shielding requirements and fluxes of the present CERN system have been carried out.

It has been assumed that the neutrino interactions would be detected in large bubble chambers like SKAT or MIRABELLE and also, for selected processes, in massive spark chamber arrays. The expected numbers of events have been computed for an experiment using 3×10^{18} protons on the target of the magnetic horn, probably about 1 million pulses with the accelerator intensity then available. They are listed in the following pages, but it is useful to summarize some of them here :

(a) A search for the intermediate boson could usefully be carried out with both bubble chambers and spark chambers. For $M_W = 4$ GeV, about 600 events would be expected in SKAT filled with CF_3Br. The corresponding number for $M_W = 6$ GeV is 10 events. For such masses, the pionic decay mode of the W would probably dominate, and certainly for $M_W \lesssim 5$ GeV, such boson events would be readily detectable against the general inelastic background.

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(b) With a massive spark chamber, the leptonic decay mode of W would be detectable in much more certain conditions than were possible in the CERN and Brookhaven experiments. For $M_W = 4$ GeV, there would be 70 identifiable events per 100 tons of spark chamber, assuming a leptonic branching ratio of only 1%. For $M_W > 5$ GeV, background effects from direct lepton pair production, itself of great intrinsic interest, become important.

(c) Bubble chambers, both hydrogen and heavy-liquid, are especially suitable for studies of high-energy neutrino-nucleon cross-sections. In general such interactions are of high multiplicity and might be best studied using SKAT filled with freon and possibly also equipped with plates. This would ensure good identification of the outgoing lepton, which is essential. Some 500 events for a neutrino energy above 30 GeV would be obtained in such an exposure. Hydrogen or deuterium chambers would be more suitable for investigating the detailed energy dependence of cross-sections in the simpler channels of elastic reactions and single pion production.

(d) It is feasible to attempt to detect at Serpukhov, for the first time, examples of neutrino-electron elastic scattering with a massive spark chamber array. Such experiments would give more information on the four lepton interaction than can be obtained from muon decay, the only process of this type experimentally accessible at present. For the inverse reaction $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$, about 100 events could be obtained per 100 tons of detector. These events would have a very characteristic appearance; just a single muon of energy above 20 GeV which would be within an angle of less than 7 mrad to the neutrino direction. The problems of background are considerable, but not insurmountable.

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During our studies, we have become increasingly aware that by their very nature, higher energy neutrino experiments will be more difficult than all previous neutrino experiments. For example, many of the experiments described below, depend much more critically on a reliable determination of the neutrino flux than any previous ones. They will demand extremely careful preparations, from the choice of the scientific aim to the construction of the apparatus and the operation and analysis of the experiment. The host of problems which will arise will provide many stimulating challenges to experimentalists; their solution is also an essential stage in the evolution of neutrino experiments which are again considered as a fundamental justification for the 300 GeV and other future accelerators.

We are of the opinion that it is completely justified to devote the intellectual and material scientific effort which is essential to this field of research. High energy neutrino experiments are the only means by which the phenomena of weak interactions can be studied over an extensive range in energy and momentum transfer. Neutrino experiments with a 76 GeV accelerator give the only possibility, during the next decade, of investigating many of the most fundamental problems of the weak interactions.

2. OUTLINE OF A POSSIBLE PHYSICS PROGRAMME

2.1. Search for the Intermediate Vector Boson W.

The neutrino experiments performed at CERN(10) and Brookhaven(11) have put a lower limit of about 2 GeV/c^2 on the mass of the intermediate vector boson. It has been clear for some time that a large increase in the lower limit for the mass cannot be obtained merely by increases in flux or detector size at existing accelerators. This is not simply because the boson yield falls off sharply with increasing mass, but rather that once a low value of the boson production cross-sections is reached, background contributions from other processes become overwhelming. Thus, any substantial increase in the limit on M_W can only come from the use of higher energy neutrino beams.

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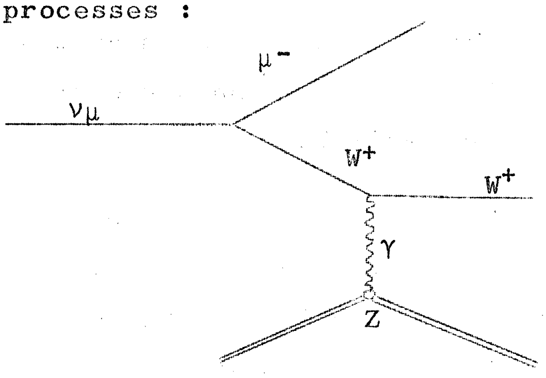
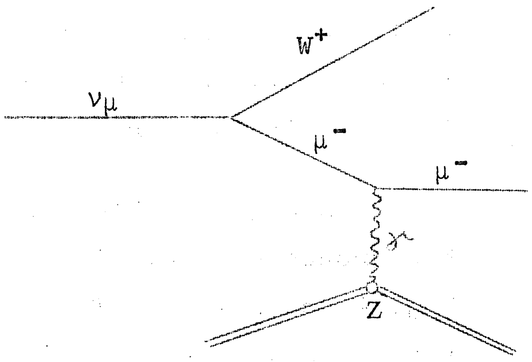
(A). Production and Decay of W - Boson

Wu et al.(12) have considered elastic W production by the processes :





where Z represents either a nucleus or a single nucleon. Cross-sections were calculated up to $M_w = 2.5$ GeV/c^2 and neutrino energy of 20 GeV. These cross-sections have been extrapolated to $M_w \sim 4$ GeV and $E_\nu \sim 40$ GeV; the errors from the extrapolation should not exceed a factor of 2. Fig. 3 shows the integral rate as a function of M_w for various spectra.

For W-bosons of mass greater than 2 GeV/c^2, many decay modes are possible. e.g.:

$W^+ \rightarrow \mu^+ + \nu_\mu$ (a)

$e^+ + \nu_e$ (b)

$\pi^+ + \pi^o$ (c)

$K^+ + \pi^o$ (d)

$p + \bar{n}$ (e) etc...

The decay rates for (a) and (b) can be estimated reliably and for $M_w > 2$ GeV/c^2 they put an upper limit on the mean life of the W-boson of 10^{-19} sec. The decay rates for processes (c), (d), (e) etc., are difficult to estimate, however Yamaguchi(13) has argued that the branching ratio into modes (a) and (b) should tend to $\sim 1/10$ as $M_w \rightarrow \infty$.

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(B). Detection of Pionic Decays of the W-Boson

An exposure of the heavy liquid chamber SKAT in a neutrino beam would be an excellent means of studying the pionic decay modes. It would be necessary to identify the negative muon among the many mesons in an event. For this purpose a plate system in the chamber would increase the number of interaction lengths available.

A major problem would be to distinguish boson events from the background of inelastic interactions not involving real bosons. Fig. 4 shows the differential boson rate as a function of E_ν for various M_W. For comparison, the inelastic rate is shown for a cross-section of the form $\sigma = 0.6 \times 10^{-38}\ E_\nu$ cm^2/nucleon, suggested by the early CERN experiments.(14) The boson rate for $M_W \sim 4$ GeV would be more than 12% of the total rate for neutrino energies well above the threshold.

To identify the boson events, the following criteria could be applied :

a) A cut in E_ν to select candidates well above the W-threshold. For $M_W \sim 4$ GeV, the cut could be $E_\nu > 20$ GeV, so that the inelastic background would be reduced.

b) A cut in E_{μ^-}. For $M_W > 2$ GeV, the accompanying μ^- will have momentum less than 20% of the neutrino momentum, since the W and the μ^- will have low relative momentum in their centre of mass system. A cut $E_{\mu^-} < 0.2 E_\nu$ might eliminate 75% of the inelastic events, without removing many boson events.

With these criteria, and for $M_W \sim 4$ GeV/c^2, boson candidates should show a signal to noise ratio of $\sim$ 1:1 in the pion invariant mass distribution.

From Fig. 4 it can be seen that a 1 million pulse exposure could extend the boson search to a mass $\gtrsim 4$ GeV/c^2 if the pionic branching ratio were ~ 0.5.

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(C). Detection of the Leptonic Decays of the W-Boson

The exposure of SKAT considered above would also yield excellent data on the decay mode $W^+ \rightarrow e^+ + \nu_e$. There is very little background in this mode ($\leqslant$ 1 event in 450 in the CERN experiment$^{(14)}$). If the branching ratio for leptonic modes were > 0.1, then a lower limit of 4 GeV/c^2 could be placed on the mass of the W.

The decay mode $W^+ \rightarrow \mu^+ + \nu_\mu$ would also be observed in the bubble chamber, but since the detection depends on the identification of muon pairs by their penetration, a better method would be to use a large spark chamber assembly, where more interaction lengths are available. Boson production by the high average neutrino energy at Serpukhov would yield higher energy muon pairs than in all preceding experiments. Their greater range would permit a much better discrimination of muons from pions, which is a difficulty in certain aspects of earlier work. The use of spark chambers with iron plates up to 50 cm thick would be feasible and would yield some 7000 events per 100 tons for $M_W \sim 4$ GeV and 3.10^{18} protons on the horn target. Even for a branching ratio $W^+ \rightarrow \mu^+ + \nu$ of only 1%, a boson could be detected up to the limit $M_W \sim 5$ GeV, at which stage the alternative mechanisms of muon pair production become important.

Recently, several theoretical papers have appeared giving estimates of the boson mass. A value of order 8 GeV is obtained from current algebra predictions in $K \rightarrow 2\pi$$^{(15)}$ and of order 4 GeV from perturbation theory and the observed $K_L - K_S$ mass difference.$^{(9)}$

2.2. Direct Lepton Pair Production

Cross-sections for processes of the type :
$\nu_\mu + Z \rightarrow \nu_\mu + \mu^+ + \mu^- + Z$, have been calculated by Czyz, Sheppey and Walecka,$^{(16)}$ who considered the following diagrams :

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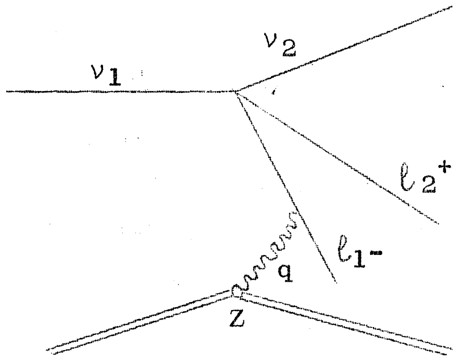

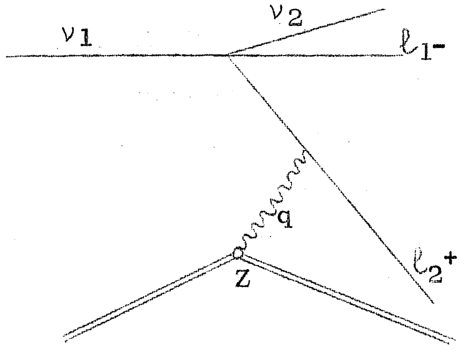

Their results are shown in Fig. 5.

If the search for muonic decays of the W-boson showed that its mass > 5 GeV/c^2 and that backgrounds were sufficiently low, one could envisage the construction of a larger detector in order to study the process. For example, an exposure of an iron plate spark chamber to 3×10^{18} protons on the horn target would yield ~ 10 events of this type per 100 tons of detector.

2.3. Cross-Sections in the Very High Energy Region

The concept of the four-fermion point weak interaction gives an excellent account of muon decay and other low-energy weak interactions but extrapolates to impossible results at very high energies. For example, s-wave e-ν scattering would lead to a cross-section violating the wave-theory limit $(\frac{\pi \bar{\lambda}^2}{2})$ at a centre of mass energy of 300 GeV. In a correct theory, such difficulties would presumably be removed by introducing non-localities in the form of a mediating boson and contributions from higher order graphs. However, attempts to take into account higher order processes in general lead to divergences. It is well to remember that the only known second-order weak interaction is the $K - \bar{K}$ transition with $\Delta S = 2$, the resulting $K_L - K_S$ mass difference yielding a finite experimental result. This has been interpreted in terms of cut-offs, or a finite boson mass of under 4 GeV.

Lee and Yang$^{(17)}$ assuming only the local current-current interaction hypothesis, have expressed the differential cross-section for the process $\nu + N \rightarrow \mu + N^*$ in the form :

$$\frac{d^2\sigma}{dq^2 dM^{*2}} = \frac{A(q^2, M^{*2})}{E_\nu^{\ 2}} + \frac{B(q^2, M^{*2})}{E_\nu} + C(q^2, M^{*2})$$

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where M* is the mass of the hadronic final state and A, B and C are structure factors. This simple quadratic form follows directly from the local current assumption. If this assumption were invalid, one would in general expect a much more complicated dependence of the cross-section with, for example, terms depending on the differences of lepton energies. If non-local effects occur at high q^2 and at high E_ν, then they may be detectable at Serpukhov, where it will be possible to have access to a completely unexplored region of momentum transfer and centre of mass energy several orders of magnitude above the values where the conventional theory is known to hold rigorously.

If an anti-neutrino run were also performed, then it would be possible to test the "sum rules" by the method proposed by Adler,(18) which is to investigate whether $\frac{d\sigma^{\nu}}{dq^2} - \frac{d\sigma^{\bar{\nu}}}{dq^2}$ tends to a constant value.

The Pomeranchuk theorem leads to equality of the asymptotic total cross-section for particle and anti-particle interactions. Further detailed considerations of dispersion relations(19) have led to asymptotic relations for cross-sections for strangeness non-changing processes which could be tested in neutrino and anti-neutrino experiments. The relations are :

$$\frac{d^2\sigma\,(\nu p)}{dq^2 dM^{*2}} = \frac{d^2\sigma(\bar{\nu} n)}{dq^2 dM^{*2}} \quad : \quad \frac{d^2\sigma(\bar{\nu} p)}{dq^2 dM^{*2}} = \frac{d^2\sigma(\nu n)}{dq^2 dM^{*2}}$$

where the cross-sections are integrated over all combinations of hadrons. As with all studies involving the energy dependence of cross-sections, the higher neutrino energy at Serpukhov is advantageous. The rates of elastic and inelastic neutrino interactions to be expected in various detectors at Serpukhov are given in Table 1.

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2.4. Neutrino-Electron Scattering

Neutrino-electron elastic scattering is in principle the best way to investigate the behaviour of weak interactions at high energy and high momentum transfer without complications from strong interaction structure. Unfortunately the range of momentum transfer available with a 76 GeV machine is only of the same order as that in muon decay, so that deviations from the classical four-fermion point interaction are likely to be negligible. Nevertheless, it is most important to demonstrate this interaction with free neutrinos, with all the flexibility and choice of variables which collision processes permit, in contrast to decay processes.

The reactions which can occur are :

Reaction	Threshold Energy	Cms. angular distribution of charged lepton	Approximate Cross-Section Dependence
1) $\nu_\mu + e^- \to \mu^- + \nu_e$	10.8 GeV	isotropic	$\frac{G^2}{\pi} \quad \frac{(2mE_\nu - M_\mu^2)^2}{2mE_\nu}$
2) $\nu_e + e^- \to e^- + \nu_e$	0	isotropic	$\frac{G^2}{\pi} \cdot 2mE_\nu$
3) $\bar{\nu}_e + e^- \to e^- + \bar{\nu}_e$	0	$(1-\cos\theta^*)^2$	$\frac{1}{3} \quad \frac{G^2}{\pi} \cdot 2mE_\nu$
4) $\bar{\nu}_e + e^- \to \mu^- + \bar{\nu}_\mu$	10.8 GeV	$(1-\cos\theta^*)^2$	$\frac{1}{3} \quad \frac{G^2}{\pi} \, \frac{(2mE_\nu - M_\mu^2)^2}{2mE_\nu}$

The reactions (1) and (2) show strong forward peaking of the charged lepton in the laboratory system, $\theta \sim \sqrt{\frac{2m_e}{E}} \sim \frac{1}{\sqrt{1000\ E_\nu\ (\mathrm{GeV})}}$

The forward cross-section $\left(\frac{d\sigma}{d\Omega}\right)_{0^\circ} \sim \frac{G^2E^2}{\pi^2}$ has the same value as for the reaction $\nu_\mu + n \to \mu^- + p$ on a free neutron target. For the antineutrino reactions, the forward amplitude is zero, the overall distribution is consequently broader, and the cross-sections reduced by a factor 3. The neutrino cross sections (1) and (2) are more

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favourable for measurement, especially as the anti-neutrino beam is intrinsically less intense than the neutrino beam.

The cross-sections for these processes are indicated in Fig. 6 and are of order 10^{-2} of the asymptotic elastic cross-section $\nu_\mu + n \rightarrow \mu^- + p$; in the region above the threshold of reaction (1), they are about 10^{-3} of the total cross-section. Since the ν_e flux is only about 1% of the ν_μ flux, the rate of (2) will be of order 10^{-5} of the total neutrino event rate. Thus, it seems that reaction (2) could only be studied, if at all, with massive spark-chamber detectors.

In the (ν,e) scattering reactions, the charged lepton is emitted very near to the incident neutrino direction and with about the full neutrino energy (e.g. at 20 GeV, $\theta < 7$ mrad). This aspect could be used in principle to identify the reaction. However, the deflection of the secondary electron through radiation losses, would inhibit the identification of reaction (2) in a spark chamber and therefore the inverse muon decay reaction (1) seems the only feasible study at present. The ν_μ flux above the threshold for this interaction is only a few per cent of the total flux.

Fig. 7 shows the relative event rates for reaction (1) at Serpukhov and CERN per incident proton; the 76 GeV machine yields an integrated rate almost exactly 100 times that of a 25 GeV machine. Evidently, even with this situation, which corresponds to 10^{-4} of the total ν-event rate, rather than 10^{-6}, such an experiment would still be extremely difficult, although it is likely that neutrino-electron scattering processes will account for 1% of all muons more energetic than 20 GeV.

The numbers of events in a 100 ton detector of radius 0.7 m, with 3.10^{18} protons on the target, are as follows :-

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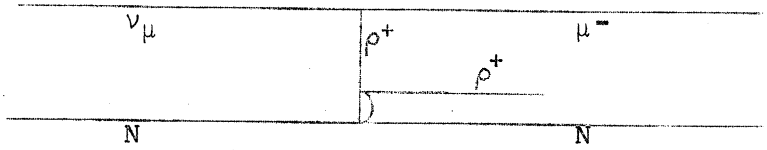
E_ν GeV	CERN (25 GeV)	Serpukhov (76 GeV)
10 - 15	0.39	6
15 - 20	0.44	23
20 - 25	-	26
25 - 30	-	22
30 - 35	-	16
35 - 40	-	8
Total < 40 GeV	0.8	101

2.5. Direct Meson Production, Tests, etc.,

The investigation of the direct production of mesons by neutrinos is the only way of investigating the weak interaction properties of these particles. The cross-section for diffraction production of ρ^+ mesons by the process :



has been estimated$^{(20)}$ to be $\sim 10^{-39}$cm^2 at 4 - 6 GeV neutrino energy. For heavier mesons such as the A_1, higher energies are needed to obtain the same cross-sections. This type of study lends itself well to the Serpukhov accelerator.

The tests of CVC and PCAC can also be studied with advantage at Serpukhov. It is predicted that the studies of the variation of cross-sections with $A^{2/3}$ would be improved by the availability of higher energy neutrinos.$^{(21)}$

2.6. New Particles

There are many postulates of possible new particles which might be detected in neutrino experiments. In addition to the W already discussed, we select the following three types of particles as subjects of typically feasible experiments.

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a) The scalar boson proposed by Kinoshita(22) would have a cross-section of $\sim 10^{-34}\,\mathrm{cm}^2$ for neutrino interactions on complex nuclei. In the 1963-65 CERN experiments, a lower limit to its mass was set at 4 GeV. An experiment at Serpukhov could set a lower limit of ~ 8 GeV.

b) Ericson and Glashow(23) and more recently Callan(24) have proposed that vector bosons have strong quadratic coupling. Such particles could be produced in pairs in strong interactions, or singly, via intermediate coupling, by neutrino beams. Existing experiments set a lower limit of 3 - 4 GeV for the mass. Experiments at Serpukhov would raise this limit to 7 or 8 GeV.

An interesting feature of such a boson theory is that neutral and charge-changing currents have equal coupling, except that crossing symmetry forbids neutral couplings at low q^2 (as observed). For a massive boson, the ratio $d\sigma(\nu + p \rightarrow \nu + p) / d\sigma(\nu + n \rightarrow \mu + p)$ is of order $R = \frac{E_\nu}{M_p} \frac{q^2}{M_W{}^2}$, instead of the value $\alpha^2 \sim 10^{-4}$ expected for electromagnetic neutrino scattering in the usual theory. A search at Serpukhov for $\nu + p \rightarrow \nu + p$ events of high E_ν and q^2 in a hydrogen chamber could certainly set a limit for $R < 10^{-2}$ (depending on neutron background) and thus, $M_W > 20$ GeV.

c) Lifetimes and decay modes of a group of heavy leptons which could participate together with ν_μ and ν_e in the leptonic current have been calculated by S. Gerstein and V. Folomeshkin.(25) These particles could have the same or different quantum numbers as the known leptons and might be produced by the reaction:

$\nu_\mu + n \rightarrow \mu^{*}_{\pm} + p$

$\mu^{*}_{-} \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\mu,\ e^- + \bar{\nu}_e + \nu_\mu,\ \pi^- + \nu_\mu,\ K^{\mp}\,\nu_\mu,\ n\pi + \nu_\mu$ etc.

Lifetimes have been estimated to be 10^{-11} to 10^{-13} secs., for masses between 1 and 2 GeV. The CERN results set lower limits to the masses at about 1 GeV, the Serpukhov facility could extend this to about 2 GeV.

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d) S. Gerstein and Folomeshkin (25) have also considered a heavy lepton λ with its own lepton number and which could be produced in the decay $W^+ \rightarrow \lambda^+ + \nu_\lambda$ for $m_\lambda = \frac{m_W}{2}$:

$$\frac{W^+ \rightarrow \lambda^+ + \nu_\lambda}{W^+ \rightarrow \mu^+ + \nu_\mu} \sim 0.6.$$

3. A POSSIBLE EXPERIMENTAL LAYOUT

The actual design of an optimized installation for a neutrino experiment at Serpukhov would take considerable time. We have not made this detailed study, instead we have considered an extrapolation of the CERN installation, a procedure which will give realistic results but which certainly could be improved in an actual design study.

The neutrino installation considered here has the following features : (see Fig. 8)

1) The focusing system would be a scaled-up version of the present CERN system.

2) The muon shield has been designed so that the amount of iron is minimum, ($\sim$3000 t in the neutrino filter, $\sim$1000 t in the decay tunnel wall, $\sim$500 t around the target and R_1).

3) The detectors would be one or more of those available at Serpukhov: SKAT, MIRABELLE, spark chambers and later perhaps the 60 m^3 hydrogen bubble chamber.

4) A built-in muon flux measuring system to determine the neutrino spectrum.

3.1. Neutrino Beam :

(A). Extrapolation of the CERN Focusing System

The present CERN system is designed to maximize the neutrino yield from pions and kaons in the energy range of 3 to 10 GeV. It has been assumed that the momentum spectrum of the secondary particles at Serpukhov will be broadly similar to that at CERN, but scaled up in energy by about a factor of three, corresponding to the increased proton energy. The neutrino yield for the extrapolated

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system at Serpukhov has been maximized for parents in the energy band of 10 to 40 GeV, giving neutrinos from pions (ν_π) of between 4 and 16 GeV and neutrinos from kaons (ν_K) up to 40 GeV.

For approximately the same radial dimensions as previously for the proton beam, the target, the focusing elements and the detector, all linear dimensions parallel to the beam axis have been trebled except those of the focusing elements themselves and the first focusing element, whose entry surface requires modification to cope with the longer target.

(B). Computational Results

A beam design with these principles has been tested by computer calculations. The pion spectrum used was that deduced according to a modification by Perkins,(26) of the Cocconi-Koester-Perkins formula and is shown in **Fig.** 9. The K^+/π^+ ratio was assumed to be 0.15. The basic parameters used are as follows :

Decay path $D = 210$ m
Shield length $S = 55$ m
Target : Length $l = 2.5$ m
Radius $r = 2$ mm
Proton interaction Length $\lambda_p = 0.9$ m
Detector radius $R = 0.70$ m

The entry surface of the horn was adjusted to maximize the neutrino flux. The absorption length in the target of the secondary particles (λ_s) was assumed equal to the interaction length for the primary protons (λ_p). The ν spectrum calculated for these conditions is shown in Fig. 10. The calculated neutrino spectrum for a single focusing element is in agreement with that of Alekseev et al.(5) using the same input conditions.

The "perfect focusing" curves correspond to the parameters of Table 2 and a limiting assumption that any particle entering the field of a focusing element emerges along the beam axis. Target

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inefficiency and reabsorption in the target and the entry surface of the horn are therefore included in the "perfect focusing" curve.

The flux appears to be substantially higher than that from the previously proposed single element system and is within a factor 2 of that obtained from "perfect focusing" throughout the energy range chosen. The potential gain achievable by adopting some radically different focusing system would at first sight appear to be fairly small, but it must not be overlooked that the "perfect focusing" curve itself will change if any of the parameters in Table 2 are changed. It must be appreciated therefore that this data cannot exclude that further substantial improvements might be made by changing these parameters. Significant improvements may come also from a refined study of the target design.

The dimensions of the focusing devices R_1, R_2, R_3, and their power supplies are shown in table 2. The requirement to focus the fast ejected protons onto a 4 mm diameter target is feasible for a beam transport system.

3.2. Shielding

Shielding accounts for an important part of the cost of neutrino experiments. The size of the shielding should be kept as small as possible, not only because of the expense of shielding material, but also because of the loss of neutrino flux density due to the reduction in solid angle or decay path length. A thickness of about 50 m of iron would reduce the muon flux at the detector to less than 1 per m^2 and 10^{12} protons, as can be seen from the muon attenuation curve in Fig. 11. This filter thickness could be adjusted as soon as the results of the particle production experiments are available.

Table 3 illustrates the gain in neutrino flux, in a given layout, for a filter of half the thickness required if it were iron. Such a thin shielding would be sufficient if the central core consisted of uranium (~ 840 t) or if it were magnetized. The feasibility of magnetizing the neutrino filter and the corresponding muon flux distribution will be studied further in detail.

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In the layout sketched in Fig. 8, the decay tunnel and the 50 m iron filter are designed so that a detector area of 6 m width and 6 m height is kept free from muons. Due to the narrow decay tunnel, the actual iron filter need not be wider than 2.5 m, the rest of the detector surface is shielded by the side walls consisting of ~ 25000 t of concrete and ~ 700 t of iron. The reduction in neutrino flux above 5 GeV is only a few percent, as long as the decay tunnel width is not smaller than the detector diameter. The muon flux distribution calculated for a homogeneous iron filter is shown in Fig. 12. Further studies are needed on the modification due to the concrete walls.

To measure the muon flux distribution (§ 3.4) transverse gaps or channels must be foreseen. As in the present CERN layout, a mercury-filled pipe on the axis of the shielding could give a muon test beam for the neutrino detectors.

3.3. Detectors

Due to the low cross-section of neutrino interactions, a detector containing a large mass of target material is needed. The detector finally chosen should be determined by the type of reaction of interest and the methods of their identification.

We consider three large bubble chambers : SKAT, MIRABELLE and the 60m^3 hydrogen bubble chamber project of Dubna, and for a comparison, a spark chamber with 100 tons of iron plates, which is an approximate scaling for the Serpukhov energies of earlier spark chamber neutrino experiments of BNL and CERN.

In table 1, the expected numbers of elastic and inelastic events are presented for these detectors.

3.4. Experimental Spectrum Determination

During the last CERN neutrino experiments, the muon flux in the neutrino filter has been used to determine the neutrino spectrum. This is possible since the muon flux within about 70 cm of the axis of the shielding comes mainly from pion decay; there is only a small

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contribution of kaon decay muons. This separation is due to the fact that the pions and kaons are well collimated, and to the larger energy released in the kaon decay. Hence the muon flux as a function of the filter depth is a measure of the momentum spectrum of pion neutrinos. The high energy part of the neutrino spectrum, due to the kaons, must be deduced from the experimental K/π production ratio.

From detailed calculations of both the neutrino spectrum in the detector plane and the muon flux at several depths in the filter, one finds that the correlation between muon and neutrino fluxes is strongest for $p_\nu \lesssim p_{\mu\,\mathrm{min}} \lesssim 1.5\, p_\nu$ where $p_{\mu\,\mathrm{min}}$ is the lowest momentum of muons which can reach the point of observation in the filter. In order to obtain the neutrino spectrum between 4 and 14 GeV/c for the layout of Fig. 8, it is necessary to measure the muon flux for at least 6 filter depths; as an example, the following table shows for a certain choice of measurement planes, how the pion neutrino spectrum can be derived from the number of muons traversing these measurement planes :

measurement plane at iron depth	3.3	4.5	6.9	9.3	10.5	12.9	m
corresponding $p_{\mu\,\mathrm{min}}$	4.25	5.9	9.3	12.8	14.5	18	GeV/c
Effective neutrino momentum	4	6	8	10	12	14	GeV/c
Neutrinos per m^2 per GeV, averaged over 70 cm radius detector, per muon observed	.0268	.0254	.0184	.0155	.0108	.0123	

The detailed relationships depend on the focusing currents and on the detector size. Proton intensity and focusing current monitors must be operated continuously during a neutrino experiment. If the pion spectrum is not known, a differential fit to the muon flux distribution must be made varying the parameters in one of the empirical

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pion production formulae. By measuring the muon flux during the whole neutrino experiment, the corresponding absolute neutrino spectrum can be determined to about 10% up to 14 GeV/c. The accuracy above 14 GeV/c depends on the knowledge of the $K/_{\pi}$ production ratio. The errors are unlikely to exceed 15%, the overall precision of course depends strongly on the homogeneity of the iron filter.

4. CONCLUSIONS

This report is not intended as a presentation of specific proposals for neutrino experiments, but rather to illustrate the type of programme which we consider feasible for the next phase of higher energy neutrino experiments.

The general conclusions are :

1) Neutrino beams offer the only possibility of studying many of the most fundamental problems of weak interactions, especially those concerned with high momentum and energy transfer. A neutrino installation at Serpukhov, aimed specifically at neutrino energies above 10 GeV, would make a decisive and unique contribution in this field, and study a wide range of problems not otherwise accessible.

2) Higher energy neutrino experiments will be technically complex and difficult, requiring not only large detectors and long running time, but very careful planning, especially in regard to monitoring of neutrino fluxes over a wide energy range. We believe these technical problems are soluble, and that the effort required is justified in relation to the scientific interest of the subject.

3) The neutrino processes we have considered could not possibly all be studied by one type of detector alone. A giant hydrogen chamber would be the only satisfactory instrument for detailed investigation of the energy dependence of elastic and single-pion cross-sections and neutral currents. The same chamber, using neon, or a heavy liquid chamber, would be necessary for

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evaluation of complex inelastic processes up to very high energies (~ 50 GeV). A massive spark chamber array is the only conceivable instrument for study of neutrino-electron scattering. It is clear that the question of suitable detectors is related very closely to the priorities in the physics programme envisaged.

4) A simple sacling-up of the existing CERN neutrino beam system could provide fluxes which would be comparable to existing installations at neutrino energies below 5 GeV and much more intense above. A more refined study should still further improve this situation.

ACKNOWLEDGEMENTS

We record our appreciation of the invitation by our colleagues from Serpukhov to prepare this report. Our thanks are due to many of our other colleagues also for individual and enlightening exchanges of view; especially J.S. Bell, C. Franzinetti, T.B. Novey, R. Palmer, T. Rijken, B. Roe and H. Yoshiki.

We thank Mme Cabel and Miss Sleap for their help in the preparation of the text and diagrams.

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TABLE 1

A) INELASTIC NEUTRINO EVENTS

($\sigma = 0.6\ E_\nu \times 10^{-38}\,\mathrm{cm}^2$ per nucleon)

E_ν	SKAT + CF_3Br ($1\,m^2 \times 4\,m$)	$60\,m^3$ HBC ($6\,m^2 \times 4.5\,m$)
10 - 20 GeV	2.8×10^4	4.7×10^3
20 - 30 "	1.0×10^4	1.6×10^3
30 - 40 "	2.8×10^3	470
40 - 50 "	510	80

B) ELASTIC EVENTS $\nu + n \rightarrow \mu^- + p$

($\sigma = 0.75 \times 10^{-38}\,\mathrm{cm}^2$ per neutron)

	MIRABELLE D_2 ($1\,m^2 \times 3\,m$)	$60\,m^3$ HBC ($6\,m^2 \times 4.5\,m$)
5 - 10	660	4000
10 - 20	107	640
20 - 30	20	120
> 30	5	30

The estimates assume the spectrum of Fig.10 and 3×10^{18} protons on the target of the magnetic horn.

For elastic antineutrino events $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ in H_2 or D_2, divide above numbers by ~ 3.

For elastic hyperon events $\bar{\nu}_\mu + p, n \rightarrow \mu^+ + \Lambda, \Sigma$, in H_2 or D_2, divide above numbers by ~ 30.

A heavy liquid chamber is probably not suitable for precise measurements of elastic cross-sections at high energy, because of the lack of kinematic constraints and the ensuing energy - dependent background problems.

TABLE 2

TABLE OF PARAMETERS OF EXCITATION OF NEUTRINO FOCUSING DEVICES :

	R_1	R_2	R_3
Location from target (m) :	0	40	120
Peak current (kA) :	400	500	500
Energy of storage capacitor (kJ) :	200	200	150
Capacitor voltage (kV) :	12	12	12
Pulse duration (μs) :	200	200	150

TABLE 3

CALCULATED GAIN IN NEUTRINO FLUXES FOR A MODIFICATION
OF THE DECAY LENGTH FROM 200 m to 225 m AND
OF THE SHIELD LENGTH FROM 50 m to 25 m
(TUNNEL WIDTH 3m, DETECTOR RADIUS 1 m)

E_ν (GeV)	2	3	5	7	10	15	20	25	30
ν_π	1.38	1.25	1.15	1.12	1.12	1.12	1.11		
ν_K			1.26	1.38	1.39	1.36	1.17	1.15	1.13

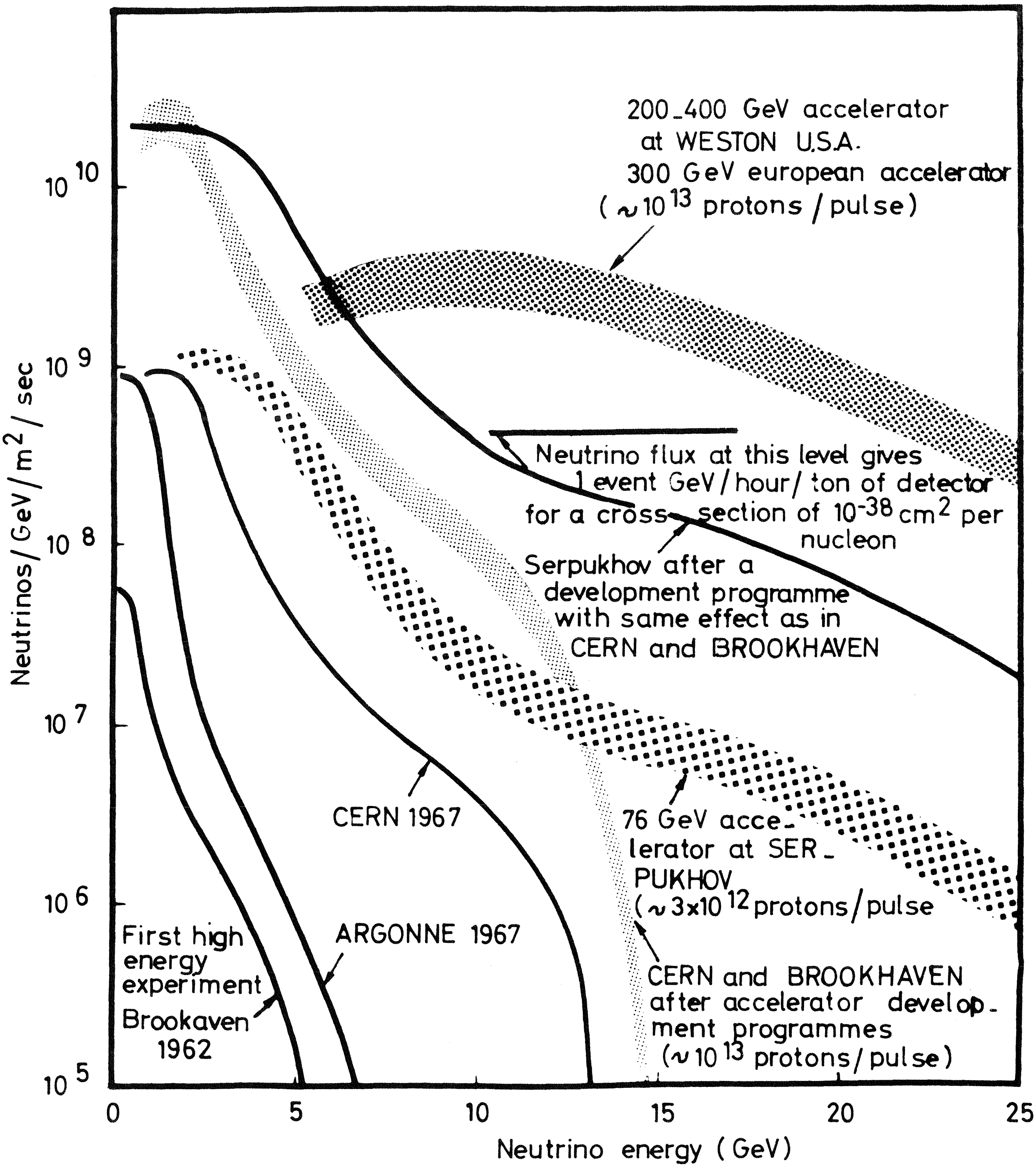


FIG. 1. Estimated development of neutrino fluxes at the large accelerators

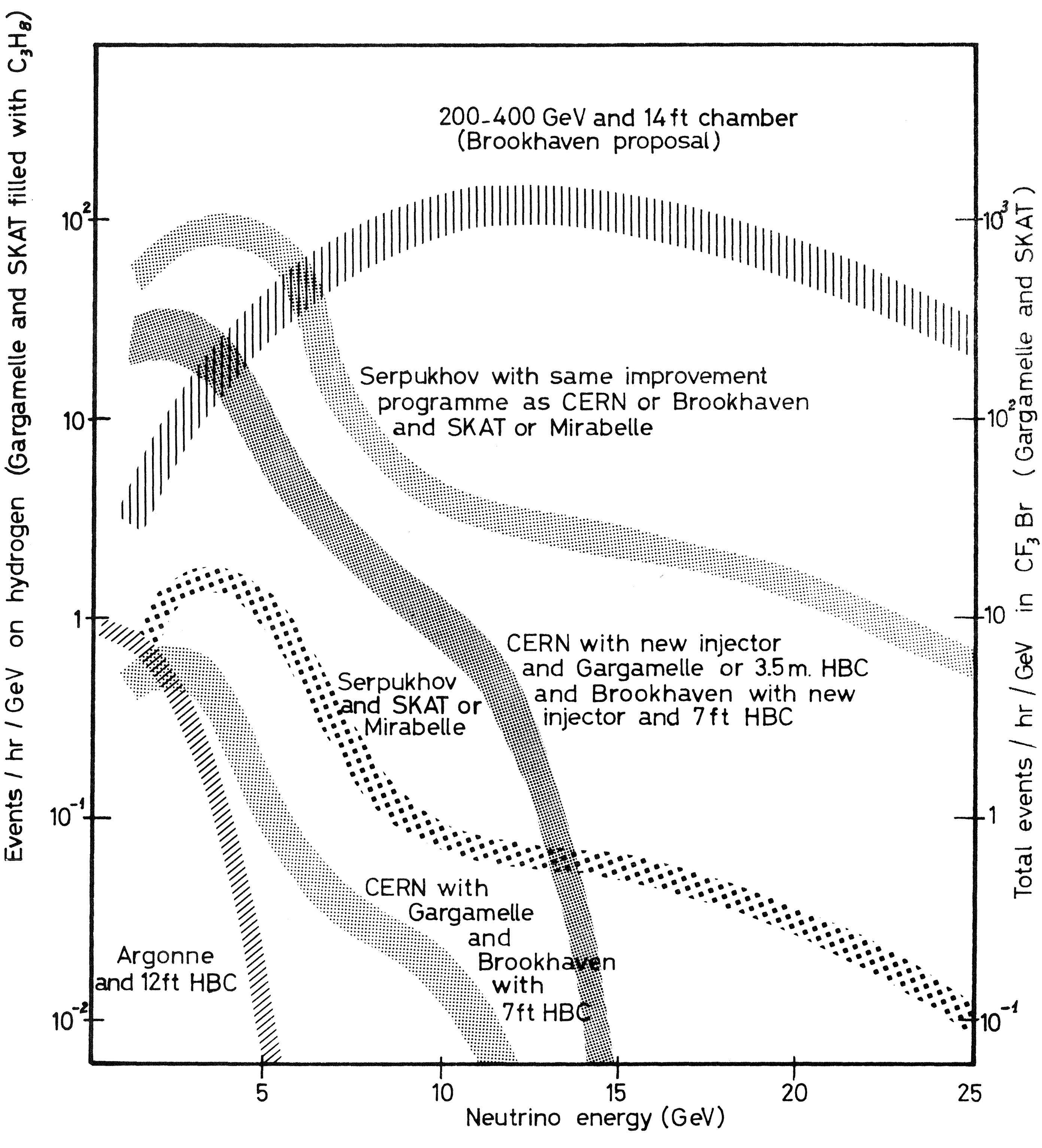


Fig. 2 Estimated neutrino event rates

($\sigma = 0.6 \times 10^{-38}\,\mathrm{cm}^2 \times E_\nu$)

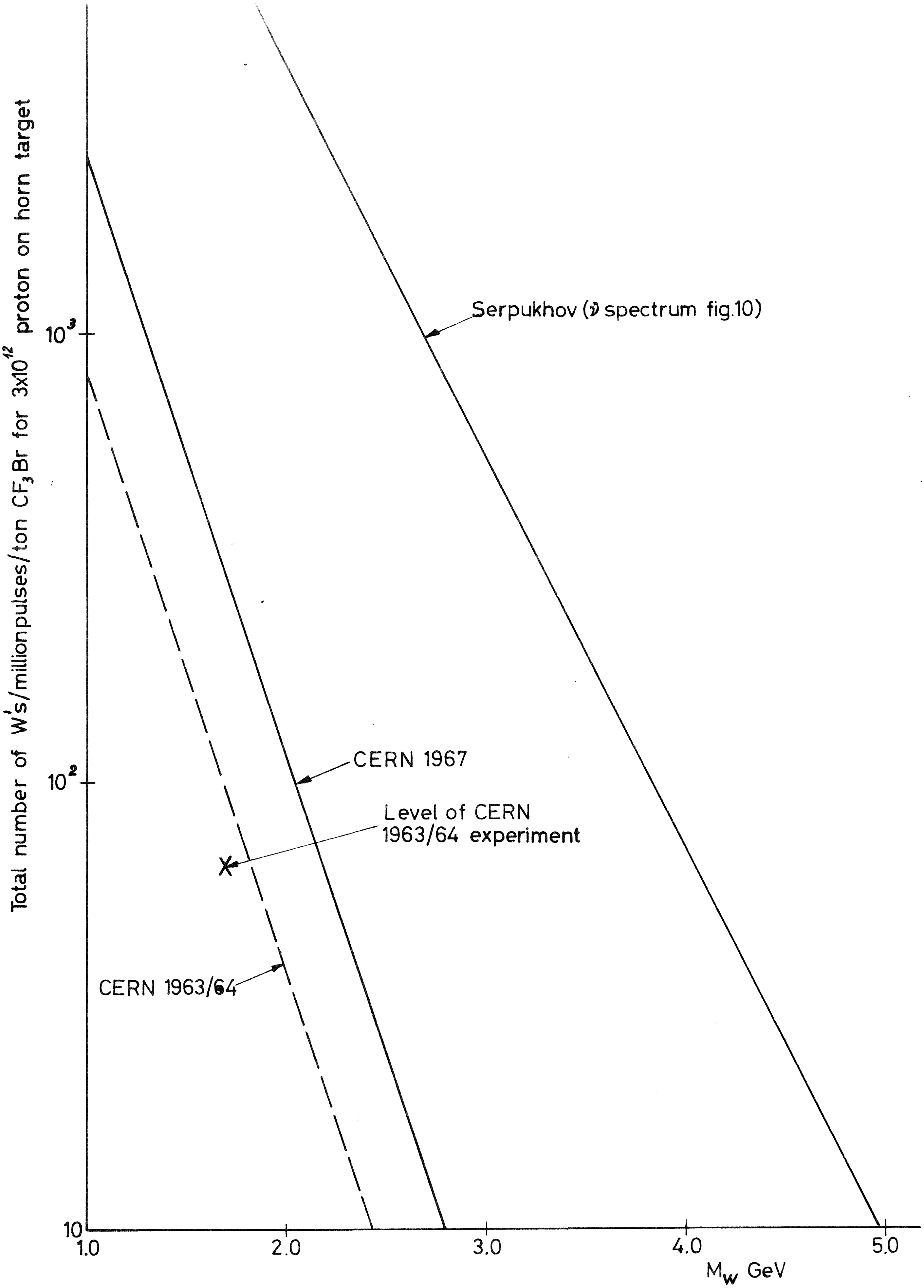


Fig. 3 Boson production rates at Serpukhov and CERN (extrapolation of W_u et al. from $M_W = 2.5$ to 4.0 GeV)

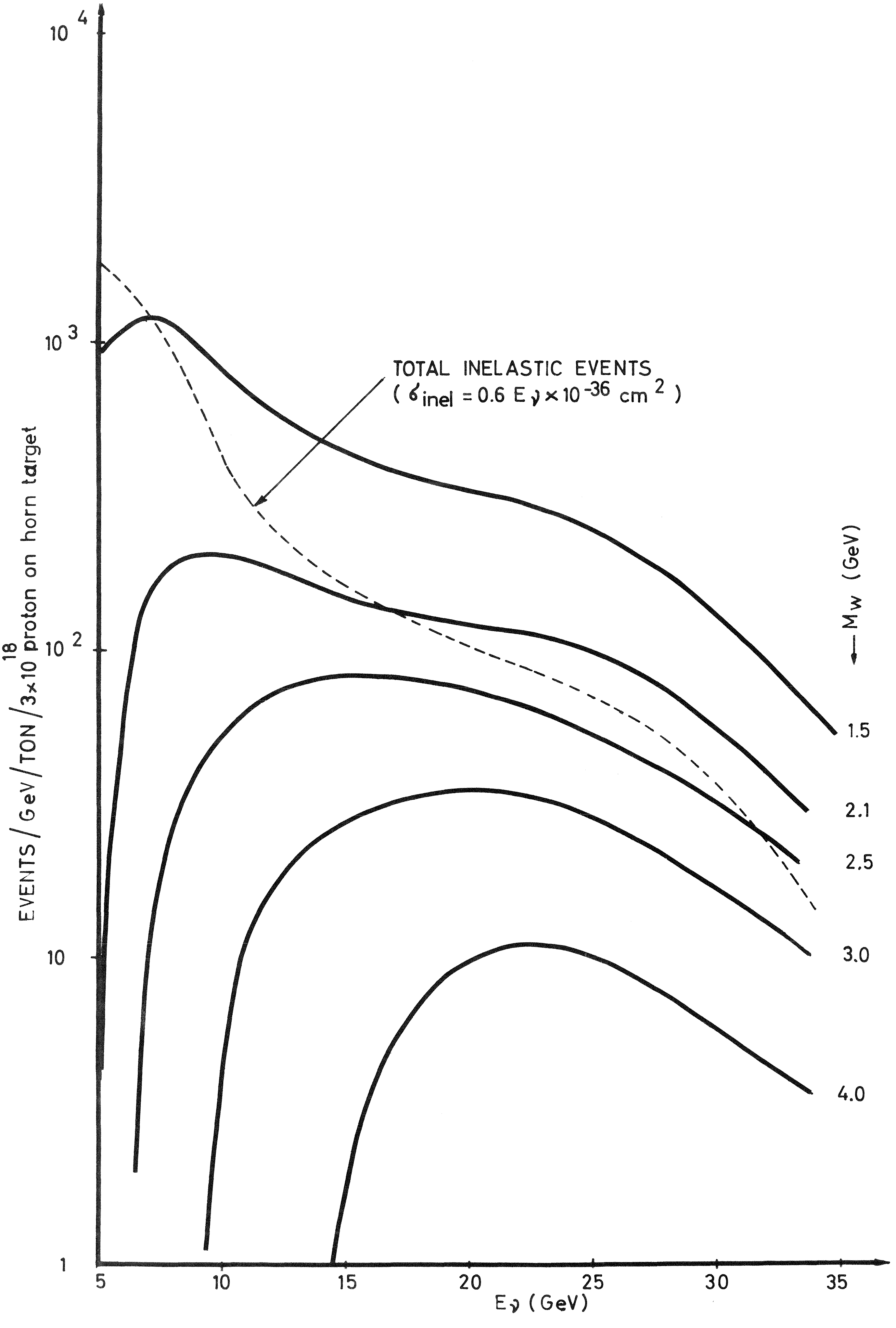


FIG.4 _ W_ BOSON PRODUCTION AT SERPUKHOV

$(\nu_\mu + Z \rightarrow \mu^- + W^+ + Z)$

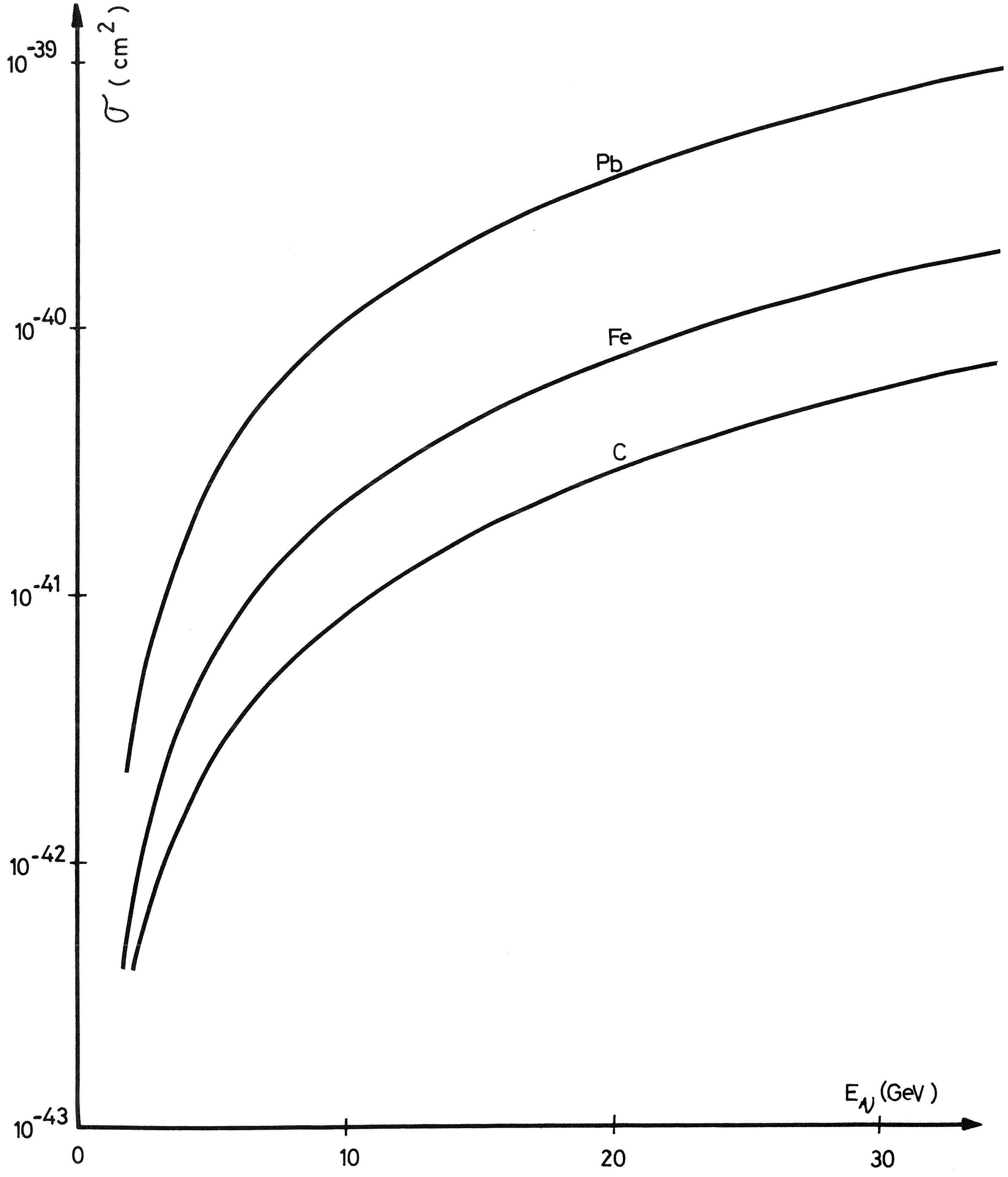


Fig. 5 Cross-sections for lepton pair production

($\nu_\mu + Z \rightarrow \nu_\mu + \mu^- + \mu^+ + Z$)

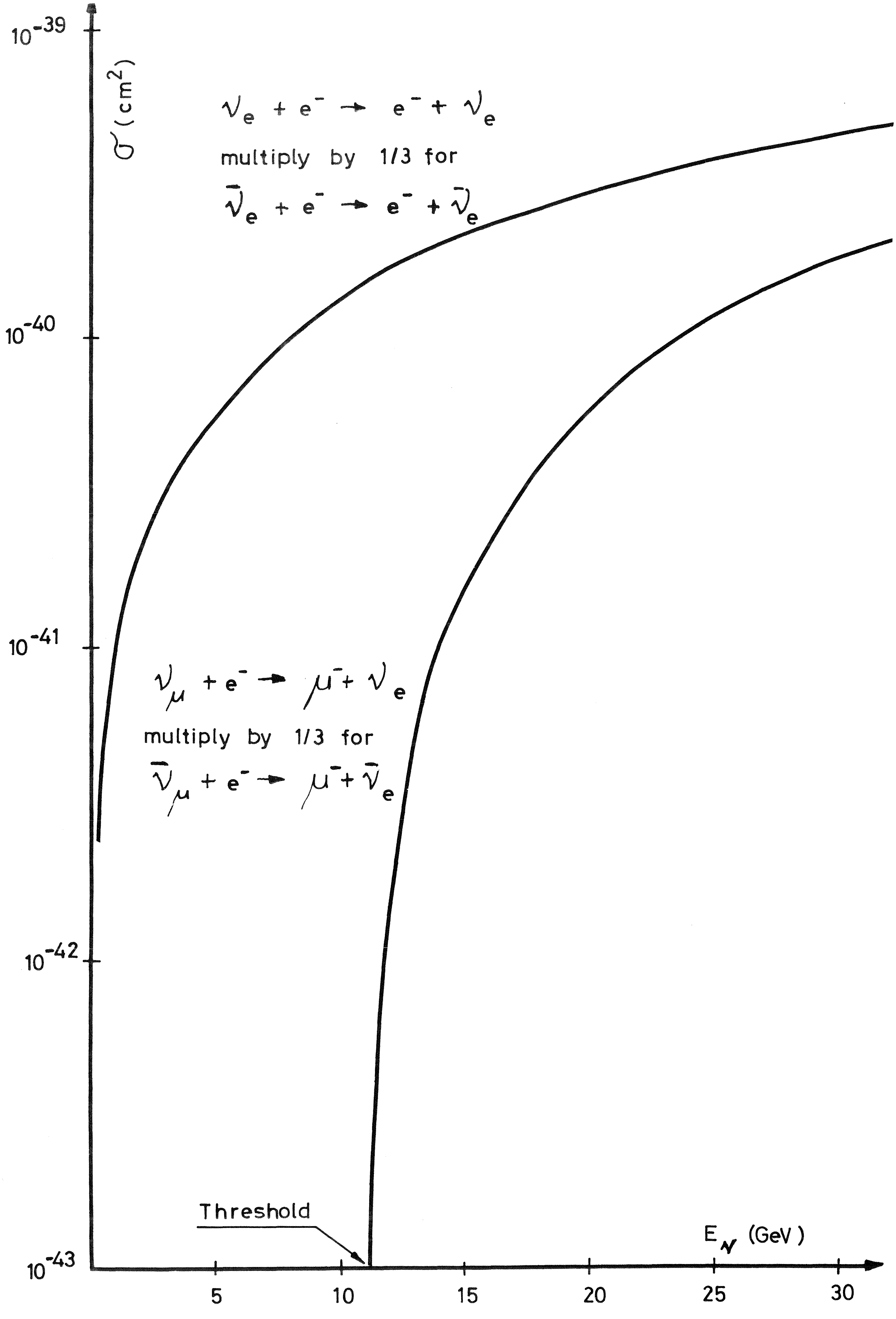


Fig. 6 Neutrino-electron scatering cross-sections

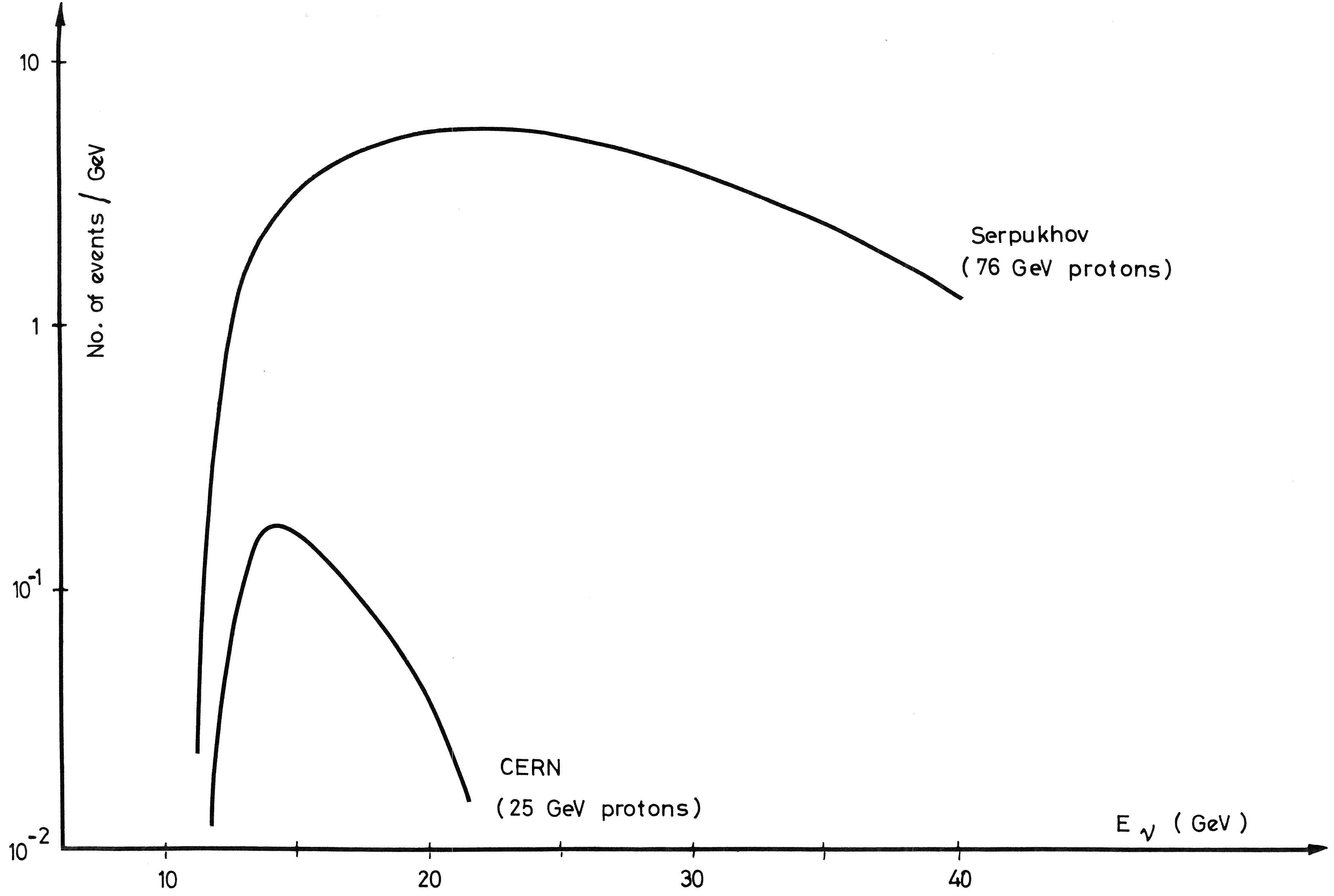


Fig. 7 Neutrino - electron scattering event rates

$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$$

(Per 100 tons of detector per 3.10^{18} protons on the horn target)

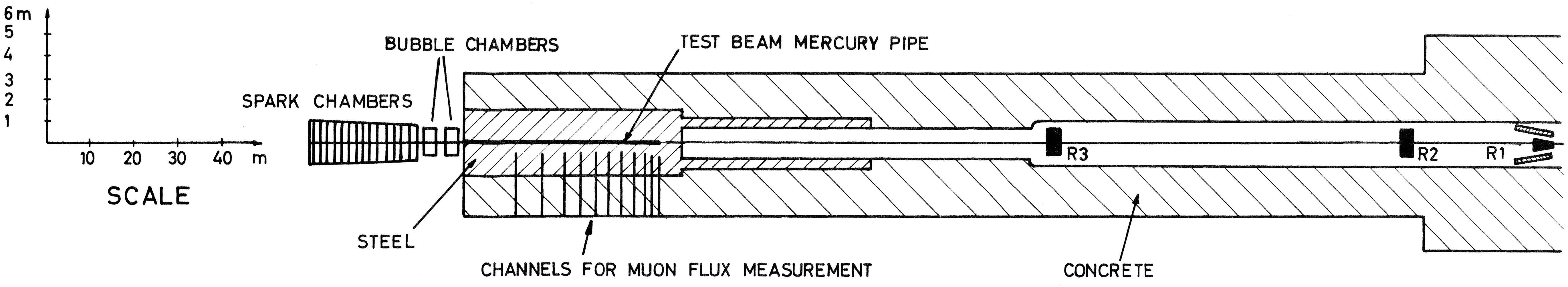


FIG. 8a. Schematic layout of a neutrino experiment at 76 GeV

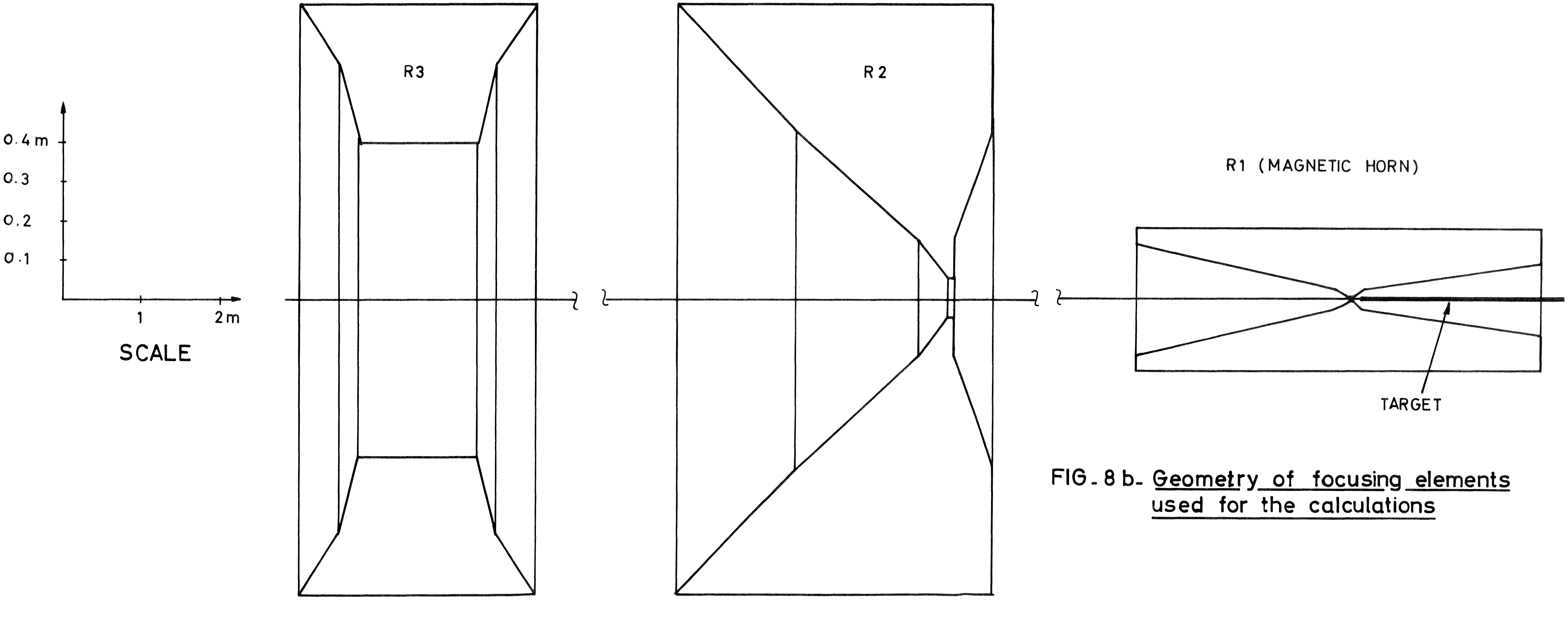


FIG. 8 b. Geometry of focusing elements used for the calculations

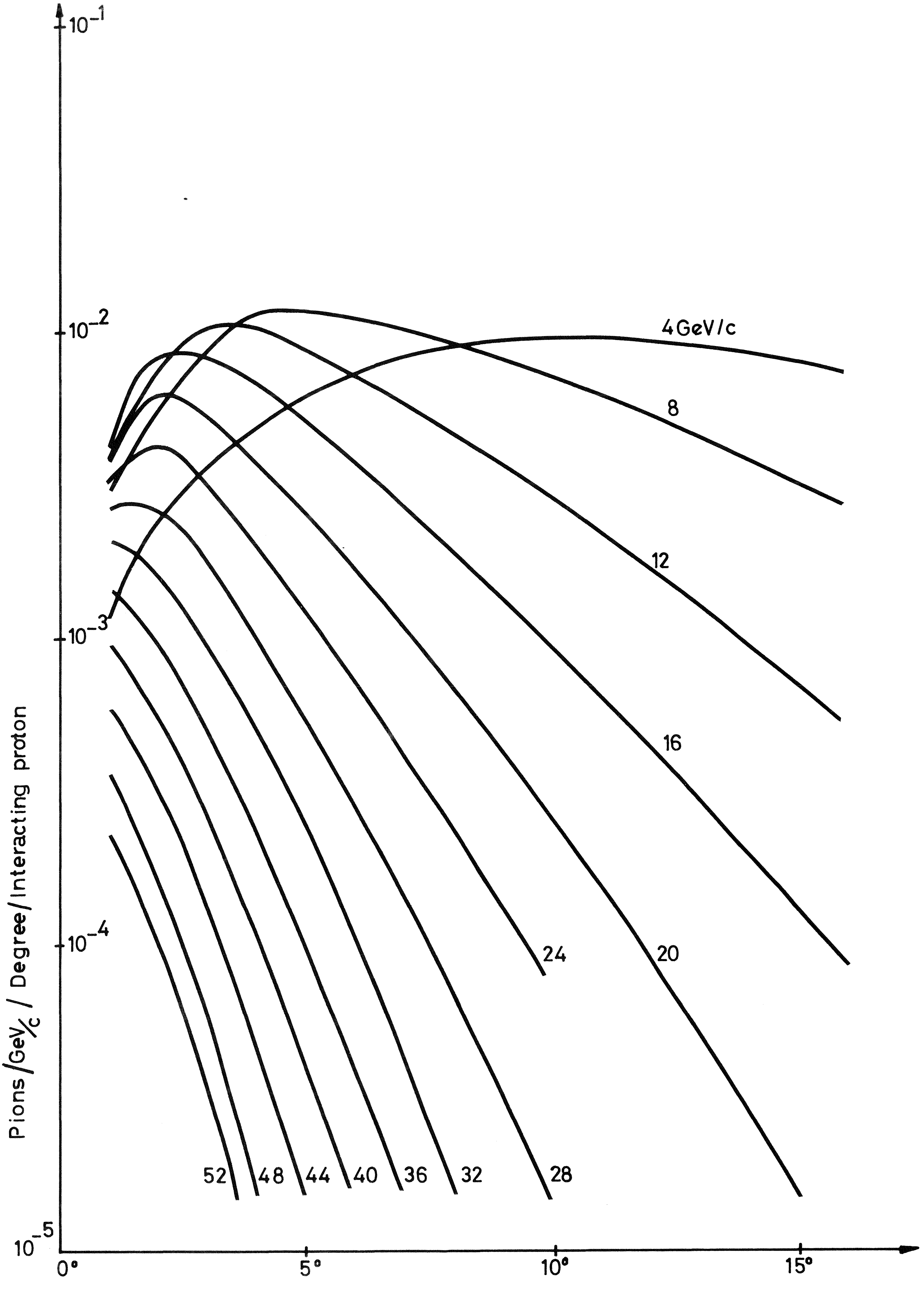
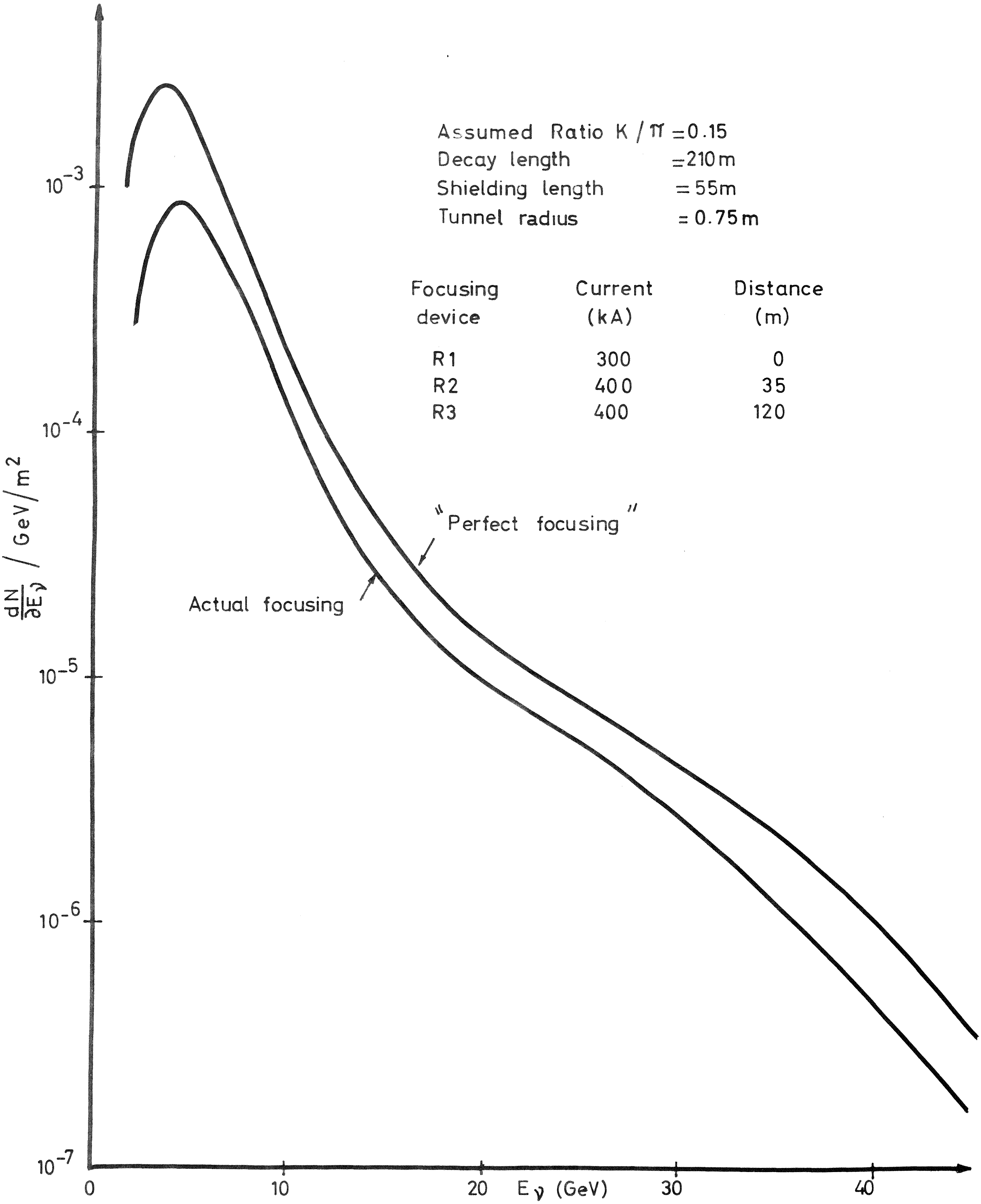


Fig.9 Pion spectrum estimated for 76 GeV (p, Be) collisions



Assumed Ratio $K/\pi = 0.15$
Decay length = 210 m
Shielding length = 55 m
Tunnel radius = 0.75 m

Focusing device	Current (kA)	Distance (m)
R1	300	0
R2	400	35
R3	400	120

FIG-10 - Neutrino spectrum for 76 GeV protons using the pion production spectrum shown in fig 9.

(Neutrinos averaged over a detector of 70 cm radius per proton on the Horn Target)

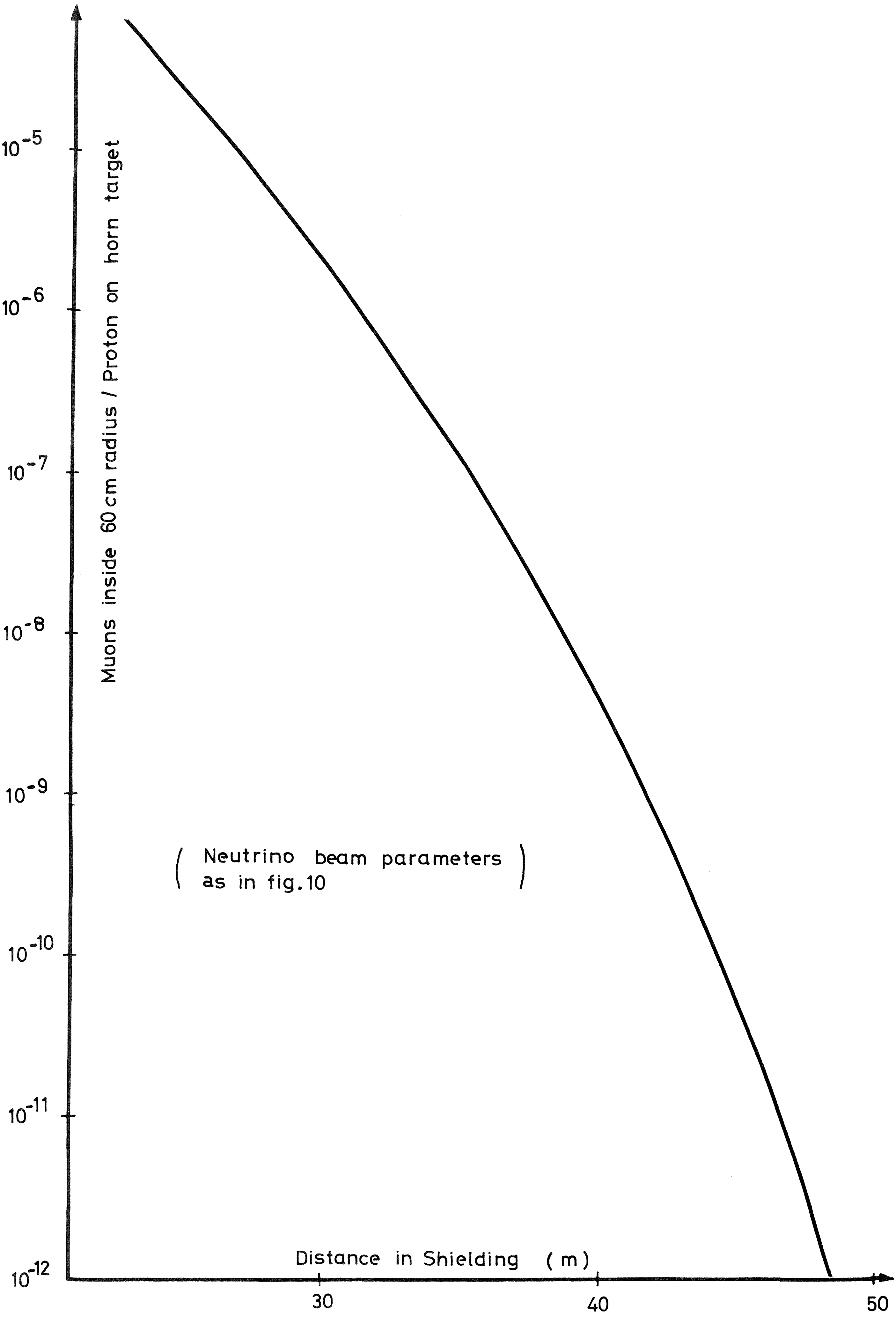


Fig. 11 Muon flux attenuation estimated for 76 GeV protons

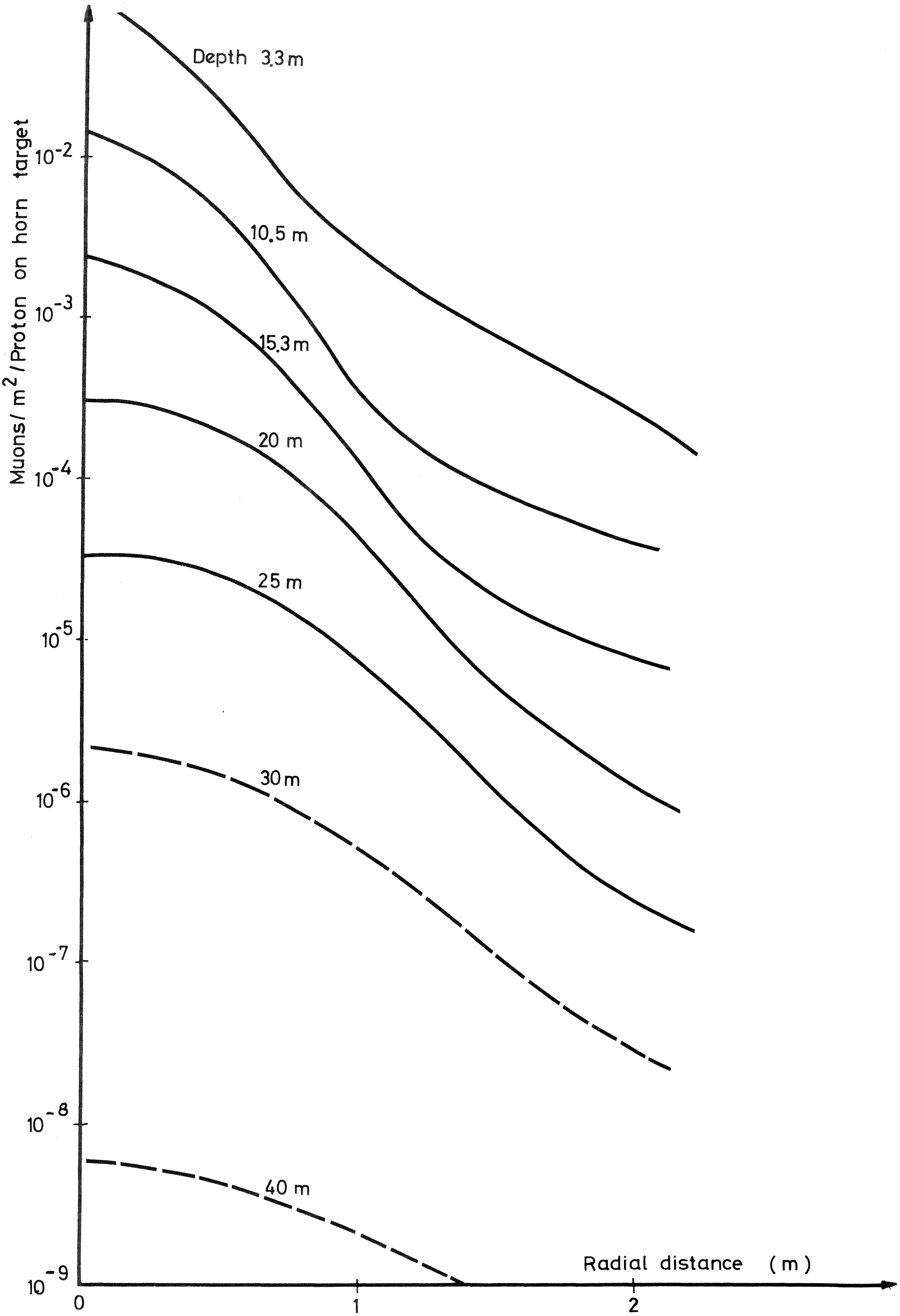


Fig.12 Muon flux distribution in neutrino shielding (ρ = 7.5gm cm^{-3})