EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/PSCC 83-12
PSCC/P 67
25 February 1983

PROPOSAL

SEARCH FOR DECAYS OF HEAVY NEUTRINOS WITH THE PS BEAM

D. Perret-Gallix
LAPP, Annecy(*)

M. Ferro-Luzzi, J.M. Perreau and Ch. Peyrou
CERN European Organization for Nuclear Research, Geneva, Switzerland

T. Bacon, R. Campbell and E. Clayton
Imperial College, London, UK

J.M. Levy, Y. Pons, M. Rivoal and F. Vannucci
LPNHE, Paris, France(*)

Spokesman: F. Vannucci

(*) Subject to IN2P3 approval.

1. INTRODUCTION

The search for neutrino masses is fundamental to our understanding of the basic interactions of nature and very relevant for the unraveling of some astrophysical puzzles. The effects of massive neutrinos vary with the scale of these masses:

(a) In the range between 0.1 eV and 100 eV neutrino masses may give rise to measurable oscillations. Among others, a proposal exists to search for such a phenomenon in the SPS wideband beam [1].

(b) In the range between 1 and 100 MeV neutrinos may decay with lifetimes accessible to an experimental study. This phenomenon is what we wish to search for, using the PS neutrino beam and a detector similar to the one proposed for the oscillation experiment [1] but much reduced in size.

2. HEAVY NEUTRINO PHENOMENOLOGY

2.1 Limits on neutrino masses

If neutrinos are massive, the weak eigenstates ν_e, ν_μ, ν_τ, ... do not have definite mass but are linear combinations of the mass eigenstates ν_1, ν_2, ν_3, ... The problem of measuring the neutrino mass must then be re-examined because leptonic decays will consist of an incoherent sum of separate channels. For instance, the tritium experiment [2] should be analyzed in terms of

$$^3\mathrm{H} \to \sum_{i=1}^{n} {}^3\mathrm{He}^+ + e^- + \bar{\nu}_i \ .$$

The current mass limits [3]

$$m(\nu_\mu) < 520 \text{ keV} \ ,$$

$$m(\nu_\tau) < 250 \text{ MeV} \ .$$

leave open the possibility of substantial masses. Even the limit on $m(\nu_\mu)$ only applies to the dominantly coupled mass eigenstate (ν_2 ?) and does not forbid a much heavier component (ν_3 ...).

One way of searching for massive neutrinos is to look for peaks in the lepton spectrum of charged pseudoscalar meson decays [4]. This search has been performed on the easily accessible channels: $\pi \to \mu\nu$, $\pi \to e\nu$, $K \to \mu\nu$, $K \to e\nu$ [5]. The search is here limited by the experimental resolution and is rather weak near the dominant peak corresponding to $m(\nu) = 0$. Possible evidence has been found for the decay $\pi \to \mu\nu$ studied in an emulsion experiment [4]: eight events cluster at $m(\nu) = 12$ MeV with a branching ratio of a few 10^{-5}.

The existence of massive neutrinos would also upset the ratio

$$R = \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)}$$

changing its value from the R_0 corresponding to massless ν, because the helicity enhancement mainly increases the channel $e\nu$ which is no longer suppressed with respect to $\mu\nu$. The present experimental value of R/R_0 is 1.028 ± 0.019, compatible with a small contribution from a neutrino mass in the range from 10 to 100 MeV [4].

Finally, it has been speculated that the observed excess of prompt-muon over prompt-electron events in the CERN beam dump experiments could also be accounted for by sufficiently heavy neutrinos [6].

2.2 Decays of heavy neutrinos

If heavy neutrinos ν_H exist with a mass above 1 MeV they may decay into $e^+e^-\nu_e$. The corresponding diagram is shown in fig. 1(a). Other decay modes open up with increasing mass: $e\mu\nu$, πe, $\mu\mu\nu$, $\pi\mu$ etc. In the following we will concentrate on the first channel ($e^+e^-\nu_e$). The evaluation of this decay is similar to the evaluation of the μ lifetime, except for a coupling strength U_{He} which measures the overlap between ν_H and ν_e. The partial lifetime into this mode of a heavy neutrino of mass m_ν is, in seconds,

$$\tau = 2.2 \times 10^{-6} \left(\frac{m_\mu}{m_\nu}\right)^5 \frac{1}{|U_{He}|^2} .$$

The probability of decay over a path length L in meters is then given by

$$P = \frac{L}{8E_\nu} m_\nu^5 \, |U_{He}|^2 \, 10^{-12} ,$$

E_ν being the ν energy and m_ν its mass in MeV. Recent calculations [7] have shown that the decay $\nu_H \to \nu_e \gamma\gamma$, represented by the diagrams of fig. 1(b), is also experimentally accessible. In fact, the partial lifetime of this mode, in seconds, is

$$\tau = 7.1 \times 10^{10} \frac{1}{m_\nu^9} \frac{1}{|U_{He}|^2}$$

shorter than the previous lifetime for masses of neutrinos above $\sim$ 20 MeV.

We then plan to optimize a detector able to measure both decay modes simultaneously.

Experimentally, a huge neutrino flux is available at CERN for such an experiment. The number of potential decays, for neutrinos in the mass range considered here, could be larger than the number of interactions over the same length [6].

Because of the Lorentz boost such a search is best done at low energy, namely in the PS beam. Because the aim is to look for decays and not interactions, the detector will be somewhat different from that of a conventional neutrino experiment: it will have a long path length with very little matter on the way, followed by a calorimeter to identify electrons and photons.

3. THE NEUTRINO BEAM

Heavy neutrinos may have different origins: either via oscillation or by direct production.

3.1 Production by oscillation

Neutrino beams are mainly composed of ν_μ coming from $K \to \mu\nu$ or $\pi \to \mu\nu$ decays. The ν_μ may oscillate to a heavy neutrino ν_H. If we assume that the ν_μ-ν_H mass difference is in the MeV region, the oscillation length will be tiny and the overall effect of the oscillation will be to produce an admixture of ν_H in a predominantly ν_μ beam. The fluxes are in the ratio $|U_{H\mu}|^2:1$. Knowing the number of ν_μ in the PS beam, the number of ν_H

is in first approximation lower by $|U_{H\mu}|^2$. In fact, an extra factor is gained owing to the helicity argument but there will be a loss because of kinematics. This factor is given in Table 1 for different neutrino masses.

The other contribution coming from ν_e is now quite important. The channels $K \rightarrow e\nu_H$, $\pi \rightarrow e\nu_H$ are no longer suppressed with respect to $K \rightarrow \mu\nu_H$, $\pi \rightarrow \mu\nu_H$. In fact, the enhancement is such that, in the region kinematically interesting, it more than compensates for the helicity suppression of $\pi \rightarrow e\nu/\pi \rightarrow \mu\nu$ [4]. This second contribution is also given in table 1 relative to the contribution of the $\mu\nu$ mode.

3.2 Direct production

The present limit on the ν_τ mass makes it a candidate for a heavy neutrino. At SPS energies there is a direct production of ν_τ via F decays: $F \rightarrow \tau\nu_\tau$. Looking for possible decays of ν_τ the CHARM Collaboration have set a stringent limit on its mass vs $|U_{\tau e}|$ [8].

At low energy there are also direct sources of heavy neutrinos. If ν_H exist, namely if neutrinos have both right and left-handed helicities, the decays π^0, K^0, η, $\eta' \rightarrow \nu_H\bar{\nu}_H$ are allowed. Branching ratios are not totally negligible. In fact, we expect that

$$\Gamma(\pi^0 \rightarrow \nu_H\bar{\nu}_H)/\Gamma_t > 10^{-9}$$

for each family of ν_H in the mass region from 20 to 60 MeV. A beam dump type experiment with a very close detector could take advantage of this source. In the present proposal it appears that $\pi \rightarrow e\nu$ gives better limits, so this possibility is not considered further.

Fig. 2 gives the flux of ν_μ and $\bar{\nu}_\mu$ in the PS beam for 19 GeV protons, at 145 m from the target and at an angle of 35 mrad. These parameters will be explained later. The flux of ν's is obtained from these fluxes by taking into account the factors of table 1. These calculations correspond to the "bare" target beam presently in use. The "horn focused" beam gives larger fluxes, the gain being a factor 2 to 3. The calculated limits with this version of the beam are correspondingly better.

4. THE DETECTOR

The aim is to detect an e^+e^- or $\gamma\gamma$ pair originating from a point in an empty volume exposed to a flux of neutrinos. With this in view, the detector consists of a decay volume as large as possible and equipped with charged particle detectors followed by a calorimeter where e^+e^- and photons convert.

4.1 Position of the detector

One wants to be as close as possible to the production target. A practical position is shown in fig. 3. The experimental hall is the ISR Hall 181, where the ν-oscillation experiments [9] have installed their close-up detectors. The detector can be set up on top of the detectors for the oscillation experiments. Being off axis by 35 mrad is not a handicap: the flux is essentially unaffected. On the contrary, the momentum of the neutrinos is lower than on axis and this is a favourable point for an experiment studying decays. The total length available in the ISR hall up to the present concrete wall is ∿ 20 m. This could easily be enlarged to ∿ 50 m simply by opening the access door or removing the concrete shield when the ISR are no longer in operation. The exact location of the experiment depends on the scheduling of the PS beam (bare target or horn-focused). It also depends on the other detectors present at the time of data taking. It should be stressed that the final result will not depend critically on the detector position. The limits presented here have been computed for a decay length of 30 m.

4.2 The end calorimeter

This must convert and measure the energy of electrons and photons of a few 100 MeV. Eight radiation lengths are enough. It is proposed to use a calorimeter of the flash-tube-iron technique also envisaged for the Jura experiment [1] and which has been developed at Saclay for a very large proton-lifetime detector [10]. Details of this technique can be found in ref. [1].

The calorimeter will be made of one module 4.5 x 4.5 m^2 in cross section and eight radiation lengths thick. This corresponds to a total of

40 layers of 3 mm thick iron each. The overall thickness is 50 cm and the total number of channels is 30 720. The total iron weight is 20 t.

4.3 The decay volume

To avoid neutrino interactions (which will be responsible for the main background) the decay volume is filled with helium bags, each 5 m long, separated by planes which detect charged particles. This is shown in fig. 3. The detection of the tracks does not require a good spatial precision and the active planes will be made of the same flash-tube layers as in the calorimeter, a double layer giving the information in x and y. The cell size being 5 mm, this gives an angular uncertainty of 1 mrad, certainly good enough for our purpose. The vertex is reconstructed with a longitudinal uncertainty of a few centimeters. The corresponding number of channels is 7680 for 30 m of decay length (6 units).

The decay region starts with a plane of scintillator counters to tag all incoming charged particles. Another plane of scintillators is sandwiched into the calorimeter to give timing information.

5. PERFORMANCES OF THE DETECTOR

5.1 Trigger

The signature of an e^+e^- event is two charged tracks pointing to a vertex, at least one of them generating an electromagnetic shower when reaching the calorimeter. For the $\gamma\gamma$ events one requires two showers in the calorimeter. The events will be reconstructed from the data obtained using the following less restrictive trigger criteria:

(a) signals from at least one scintillator plane after four radiation lengths inside the calorimeter,

(b) veto of the front scintillator plane,

(c) occurrence within the beam gate which, for the PS beam, is 2 μs wide.

5.2 Energy resolution

Fig. 4 shows the display of an electromagnetic shower generated by 300 and 500 MeV electrons. The energy is measured by the number of tubes hit. This technique gives, for low energy showers, a resolution better than the usual calorimeter technique based on pulse-height measurements. This is shown in fig. 5. The energy resolution in the region that we probe is essentially $\Delta E/E \sim 10\%/\sqrt{E}$.

5.2 Detection efficiency

The trigger is based on a large amount of energy deposited in the end calorimeter. For the e^+e^- events only one electron out of the pair produced at the decay is required to reach the calorimeter. For the $\gamma\gamma$ events one requires both photons converted. With such topologies the detection efficiency for various masses of the ν_H is given in table 2: ε is the efficiency for detecting at least one shower, ε' both showers.

5.3 Background

Cosmic rays give a negligible trigger rate owing to the very narrow beam gate of 2 μs. Their contribution is at most one trigger every 150 pulses. The decision time of the flash tubes (after which the efficiency becomes small) is also a few microseconds. The second source of unwanted triggers comes from muons associated with the beam. A measurement done for the oscillation experiments gives an expected number of $\sim$ 2 such triggers per pulse. These events will cross the veto plane and they will only leave minimum ionizing tracks in the calorimeter. Even if some are superimposed over good events, they will be rejected off-line.

The main background comes from neutrino interactions in the detector. In the calorimeter itself we expect on the order of 1000 events for 10^{19} protons on target. These events do not fulfill our criteria of either: (i) two charged tracks in the decay volume at least one giving an electromagnetic shower, or (ii) two well separated electromagnetic showers in the end calorimeter. The flash tubes in the decay path are made of polypropylene, each double plane being 1 mm thick. Together with the thickness of the helium bags, they will generate, in well localized positions, a total of 50 events. These events do not affect the search because one can reconstruct the decay vertex and reject vertices pointing to a flash tube plane. The number of events generated in 30 m of helium is 5. They are of the charged-current ν_μ type which do not fulfill our criteria of generating an electromagnetic shower at the end of a charged track (this was also true for the events generated in the flash tubes). Events which would fake the correct signature are of the following type: charged current with an energetic π^0 accompanied by a charged π, neutral current with an energetic π^0 decaying very asymmetrically, ν_e charged current processes. The number of true charged-current events is so small that the number of the above events is negligible. The number of neutron generated events in the oscillation experiments is small with respect to neutrino events and so it cannot bother us.

6. LIMITS ON NEUTRINO MASSES

With the calculated flux of ν_H, knowing the decay probability and the detection efficiency, one can extract the 90% confidence level limits in the plot $m(\nu_H)$ vs $|U_{H\ell}|^2$ corresponding to no event being seen.

$|U_{H\ell}|^2$ has one contribution from the neutrino production and one from the neutrino decay. At production, it can be either $U_{H\mu}$ or U_{He}; at decay we consider here the cases $\nu_H \to e^+e^-\nu_e$ and $\nu_H \to \gamma\gamma\nu_e$ for which the coupling is U_{He}. It is to be noted that for high enough masses the coupling at decay can be $U_{H\mu}$, as for instance in $\nu_H \to \mu\pi$. In fact, the two-body decays $\nu_H \to \ell\pi$ are favoured as soon as they are kinematically allowed and the proposed detector is equally well suited for these decay modes.

Fig. 6 gives the limits which can be set by the experiment. These limits have to be compared with those obtained in the meson-decay search for secondary peaks, which have also been entered in fig. 6. These were delicate experiments needing very good resolution. The proposed search is complementary to these experiments; it is more powerful by several orders of magnitude and it searches in the four different neutrino production channels in a single experiment covering the whole region from 10 to 400 MeV.

Searching for heavy neutrinos with two different decay signatures, if signals were to be found, would give a measurement of the neutrino mass because the decay probability of $\nu_H \rightarrow \nu_e e^+e^-$ varies as m_ν^5 and the decay probability of $\nu_H \rightarrow \nu_e \gamma\gamma$ varies as m_ν^9.

When ν_H is produced together with an electron, the same coupling strength $|U_{He}|^2$ appears at production and at decay. In that case the previous limit can be directly translated into a limit on lifetime. This is shown in fig. 7. The lower limit on a massive neutrino lifetime can be compared with other typical lifetimes of particle decaying weakly: μ, π, K and τ, independently of any arbitrary coupling.

The experiment will also produce a limit on the decay mode $\nu_H \rightarrow \nu\gamma$. Candidates for such events will exhibit only one electromagnetic shower in the calorimeter, pointing to the beam direction. Here the interpretation is model dependent [11]. With some calculations [12] this search could give very interesting limits in the region from 100 keV to 10 MeV. Other exotics could also be looked for with this set-up: axions, anomalous μe, supersymmetric particles (such as U particles, photinos etc.).

7. CONCLUSIONS

Table 3 presents a breakdown of the equipment costs associated with the experiment. We reach a total cost of KSF 440.

The calorimeter will be built at Saclay; a rapid approval of the experiment would ensure its state of readiness by the beginning of 1984.

The items listed in the table are self-explanatory. Notice that price reductions may be applied on some of the costs depending on the availability of items which could be recuperated. For instance, we are presently investigating the possibility of using the old gas circulation system of the Omega spark chambers.

Finally, we stress that this is a parasitic experiment using the recently constructed neutrino beam which is very appropriate and convenient for our use.

TABLE 1

Helicity times phase space factor for the various ν_H production modes and several hypotheses of masses

m_ν (MeV)	$\pi \to \mu\nu_H$	$\pi \to e\nu_H$	$K \to \mu\nu_H$	$K \to e\nu_H$
20	1.	0.25		
25	0.90	0.35		
30	0.70	0.45		
40		0.60		
60		1.10		
80		1.40		
100		1.25	2.0	0.75
120		0.50	2.3	1.1
200			3.5	2.4
300			4.0	3.0
350			2.2	2.6
400				1.8
450				0.5

TABLE 2

Efficiency averaged over the decay length and the momentum spectrum for various hypotheses of neutrino masses. ε is the efficiency to detect at least one shower in the end calorimeter, ε' is the efficiency to detect both showers.

	from π decays			from K decays		
m_ν(MeV)	10	50	100	100	200	400
ε	0.99	0.83	0.64	0.97	0.85	0.72
ε'	0.82	0.42	0.20	0.78	0.45	0.30

TABLE 3

Costs

Item	Price (KSF)
Iron + flash tubes	30
HT system	10
Construction	40
Gas system	50
Read-out electronics	40
CAMAC control	50
Helium bags	10
Scintillators	80
PM tubes	30
Electronics	40
Supports	40
Transport, installation	20
Total	440

REFERENCES

[1] T.C. Bacon et al., Search for neutrino oscillations in a high energy long base line experiment, Proposal CERN/SPSC/P 178 (1982).

[2] V.A. Lyubimov et al., Phys. Lett. 94B (1980) 266.

[3] Particle Data Group Booklet, April 1982.

[4] R.E. Shrock, Phys. Rev. D24 (1981) 1232.

[5] R.S. Hayano et al., Phys. Rev. Lett. 49 (1982) 1305;
D.A. Bryman et al., TRIUMF prepring TRI-PP 82-43 (1982);
P. Kalyniak and J.N. Ng, TRIUMF prepring TRI-PP 82-48 (1982).

[6] M. Gronau, Haifa preprint TECHNION-PHYS-82-45 (1982).

[7] J. Nieves, Puerto Rico preprint PRE 26311 (1982);
R. Ghosh, Stony Brook preprint ITP-SB 82-42 (1982).

[8] CHARM Collaboration, Presentations by J. Aspiazu, G. Barbiellini and C. Santoni at the SPS Workshop, December 1982.

[9] CDHS Collaboration, Proposal CERN/PSCC 80-105/P30 (1980);
CHARM Collaboration, Proposal CERN/PSCC 81-8 (1981).

[10] Proposition d'une expérience pour l'étude de l'instabilité du nucléon au moyen d'un détecteur calorimétrique, Orsay-Palaiseau-Saclay Wuppertal Collaboration.

[11] A. de Rujula, MIT preprint, CTP 848 (1980).

[12] S. Eliezer and D.A. Ross, Phys. Rev. D10 (1974) 3088.

FIGURE CAPTIONS

Fig. 1 Heavy neutrino decay diagrams: (a) $\nu_H \rightarrow e^+e^-\nu_e$ and (b) $\nu_H \rightarrow \gamma\gamma\nu_e$.

Fig. 2 Neutrino spectrum for the "bare target" 19 GeV PS beam.

Fig. 3 Set up of the apparatus in the ISR Hall 181. The CHARM and CDHS close-up detectors are inside the pit.

Fig. 4 Calculation of the expected shower spread in the calorimeter for two electron energies.

Fig. 5 Energy resolution expected from the number of tubes hit in the calorimeter.

Fig. 6 Upper limits on the ν_H decay and production matrix elements expected from the experiment as a function of the ν_H mass. Solid lines refer to the $e^+e^-\nu_e$ decay mode, dash-dotted lines to the $\gamma\gamma\nu_e$ decay mode. Results from earlier experiments are also shown. Notice that the existing limits for very small masses are off the scale in the upper left corner of the graph.

Fig. 7 Lower limits expected from the experiment on the lifetime of a ν_H produced in association with an electron and decaying via $e^+e^-\nu_e$.

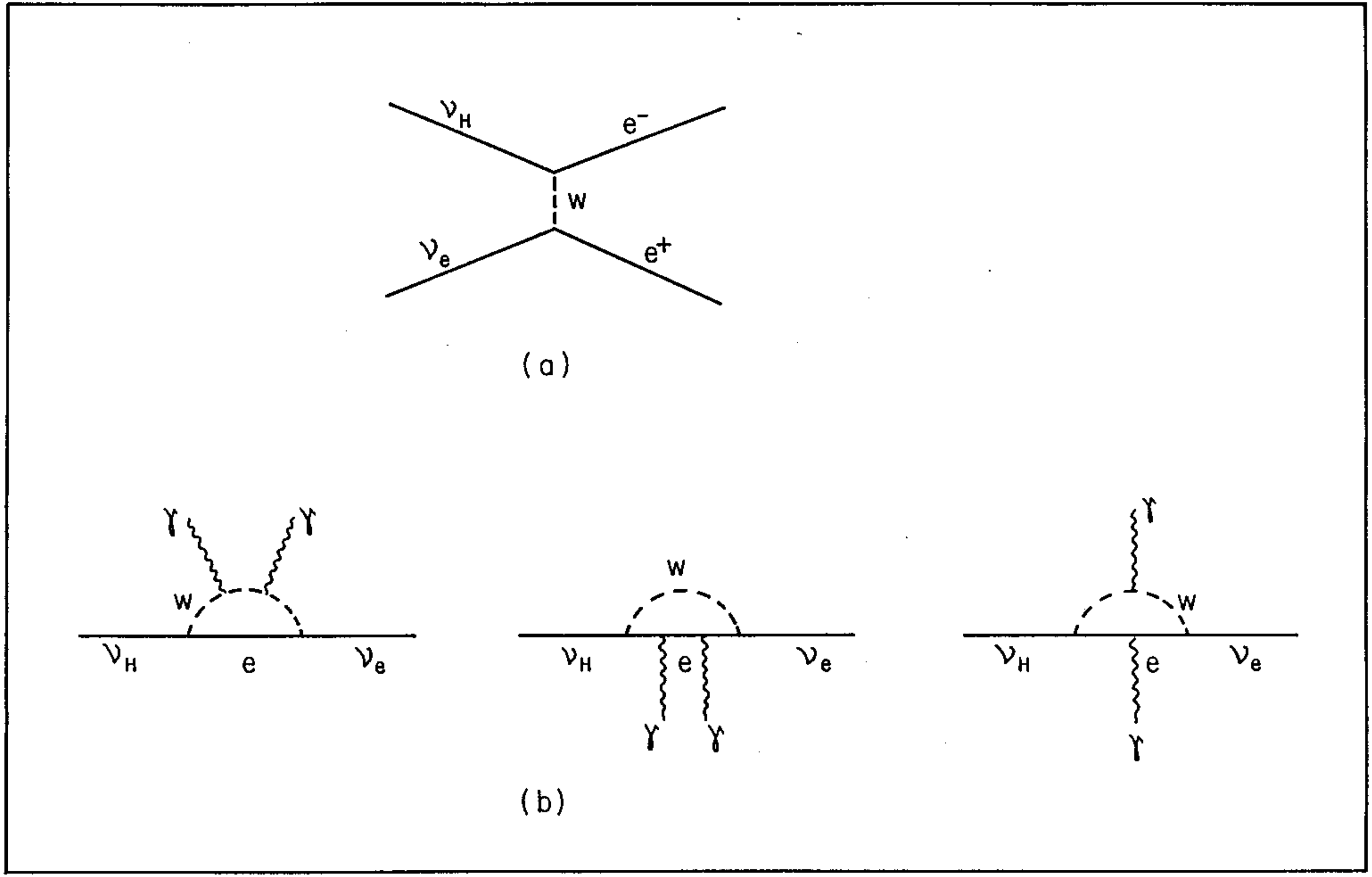


Fig. 1

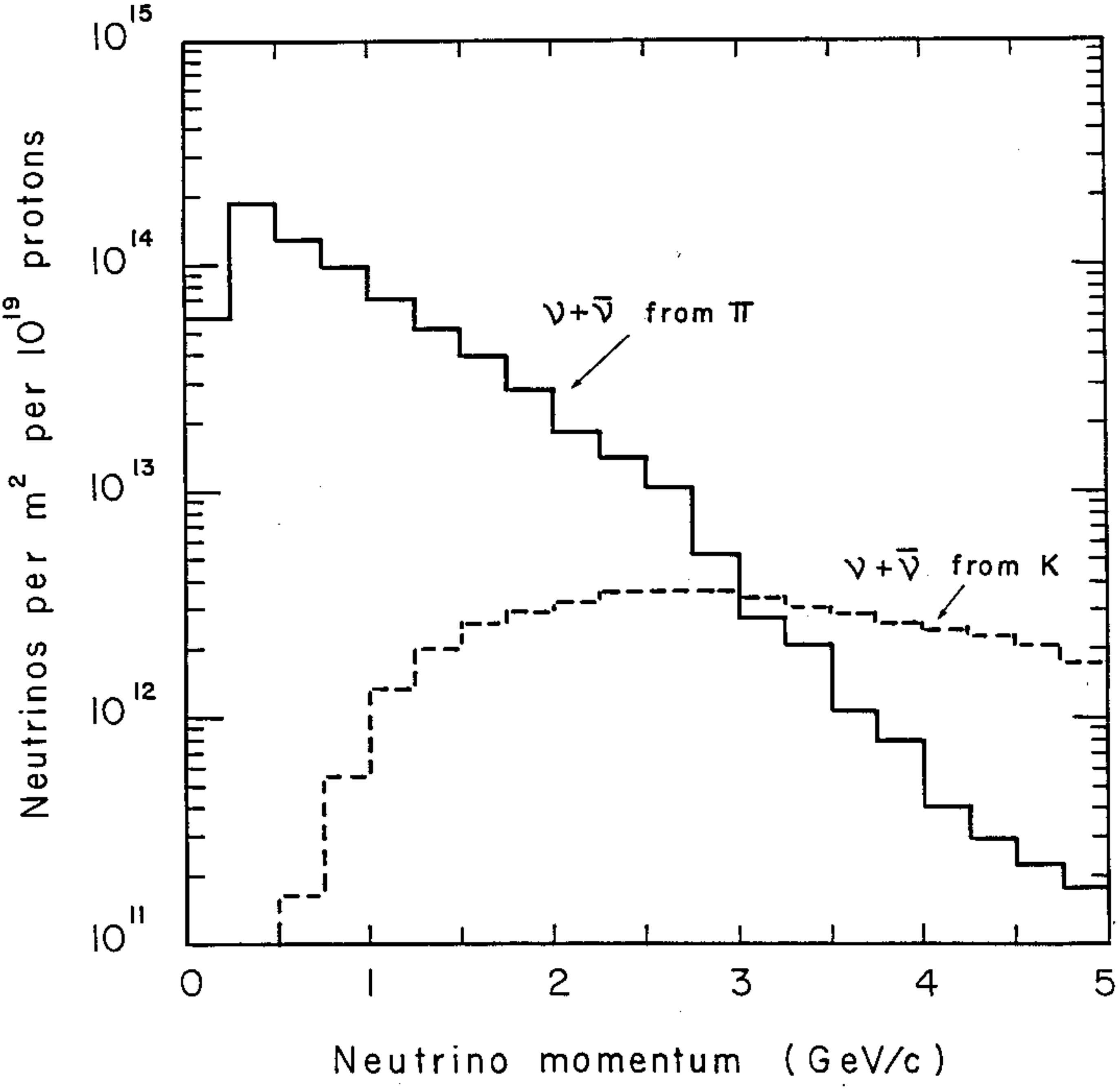

10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
Neutrinos per m^2 per 10^{19} protons
$\nu+\bar{\nu}$ from π
$\nu+\bar{\nu}$ from K
0
1
2
3
4
5
Neutrino momentum (GeV/c)

Fig. 2

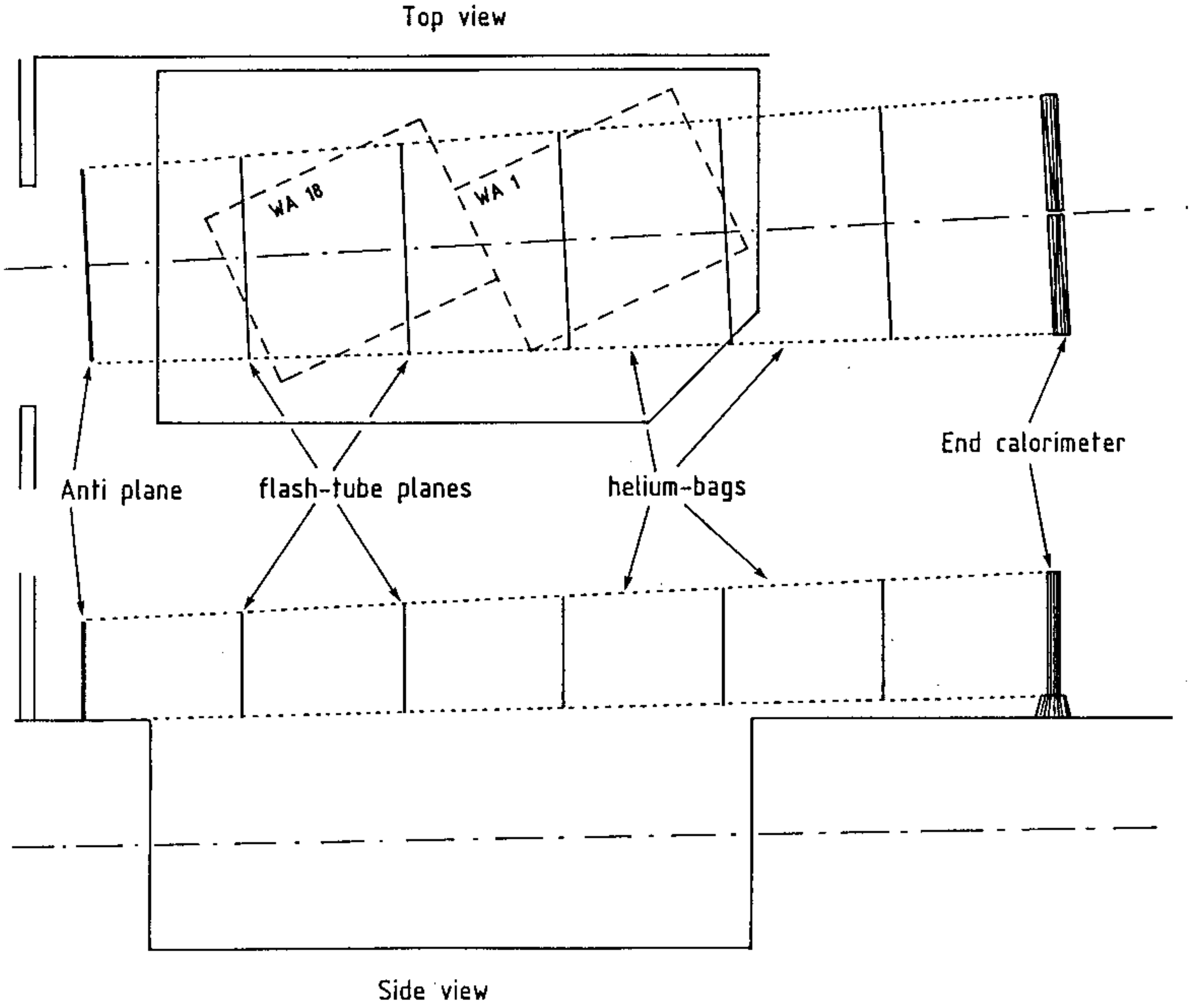

Top view
WA 18
WA 1
Anti plane
flash-tube planes
helium-bags
End calorimeter
Side view

Fig. 3

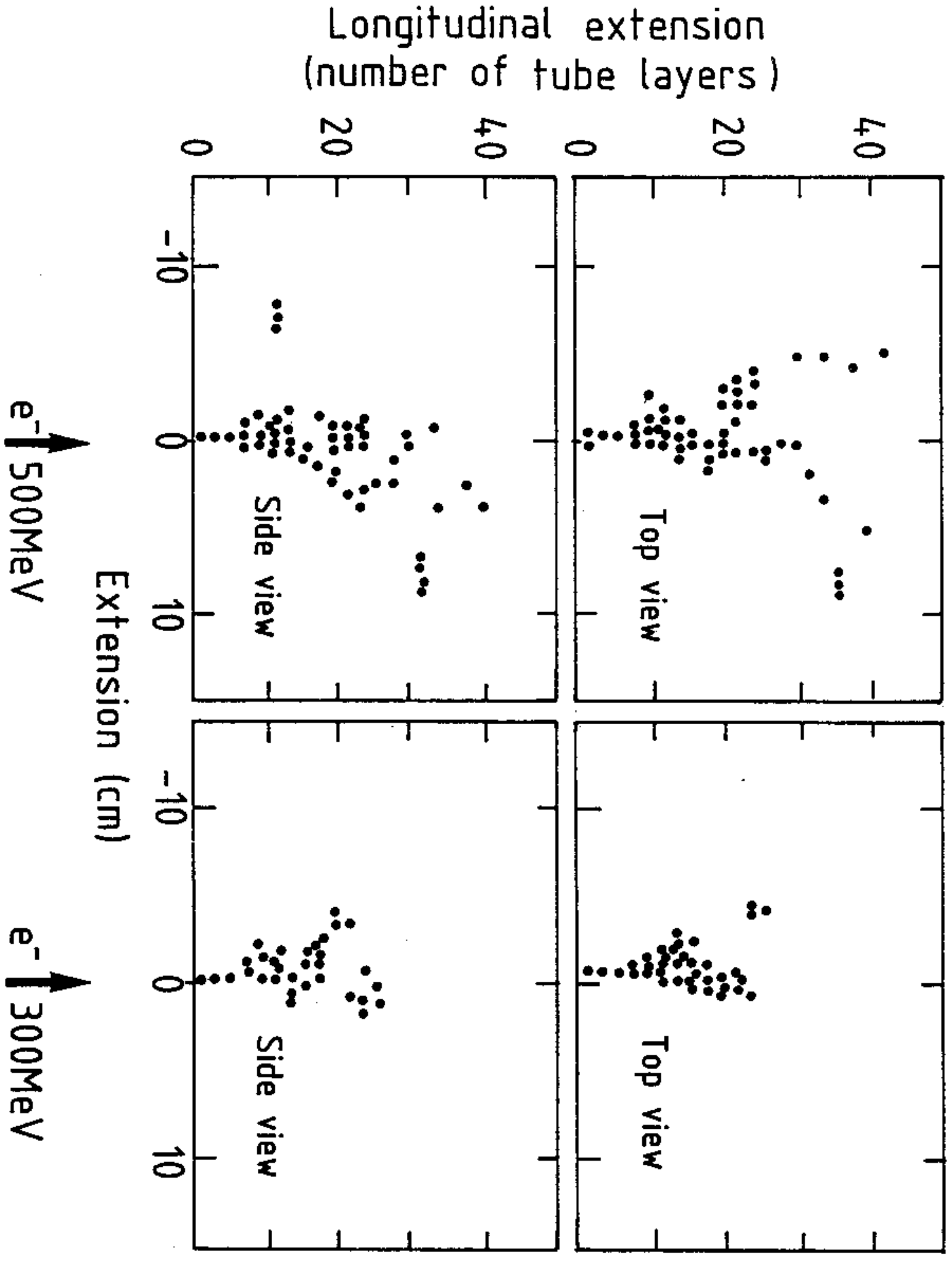

Longitudinal extension
(number of tube layers)
0
20
40
-10
0
10
Top view
Side view
Extension (cm)
e^- 500MeV
e^- 300MeV

Fig. 4

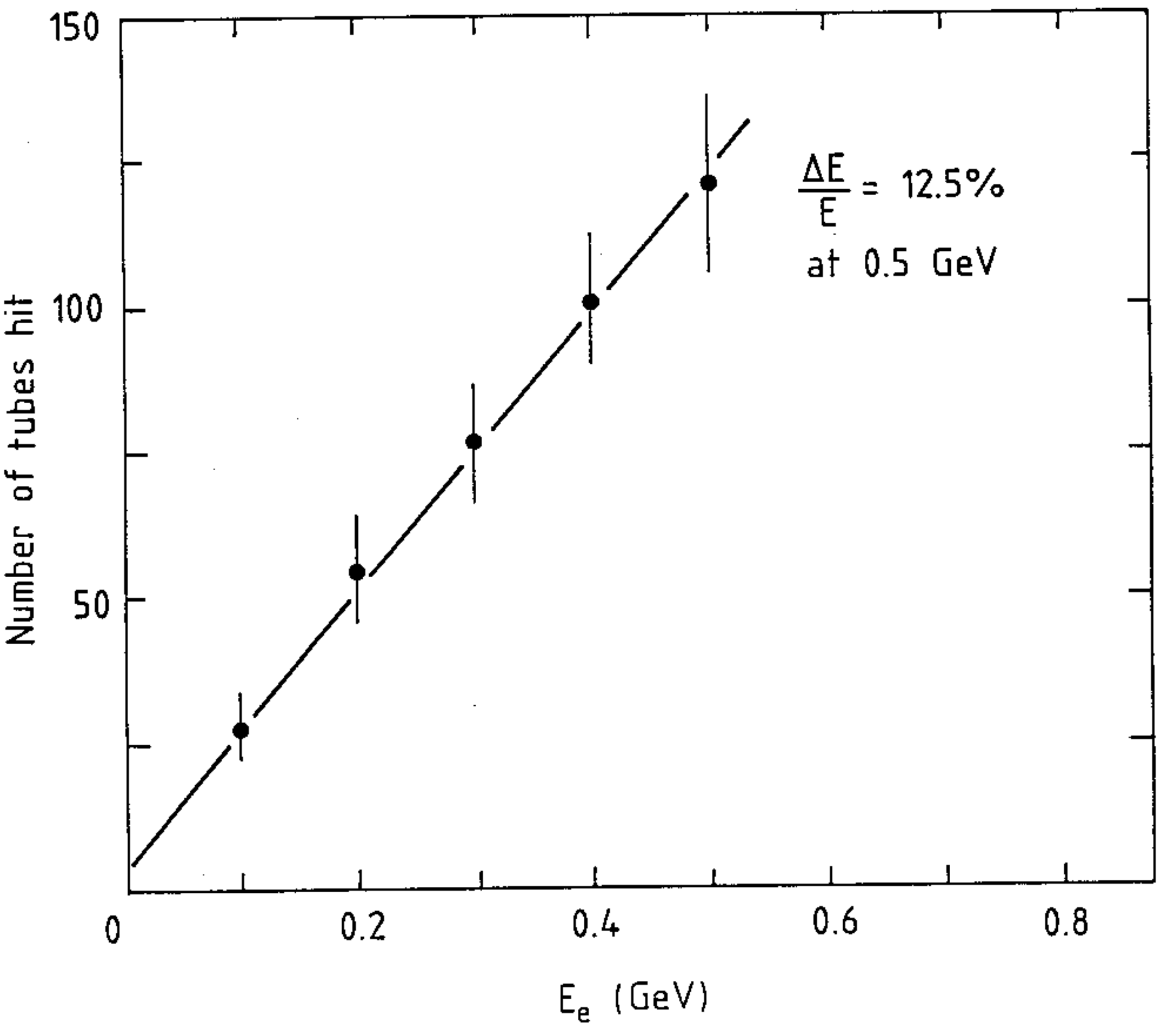
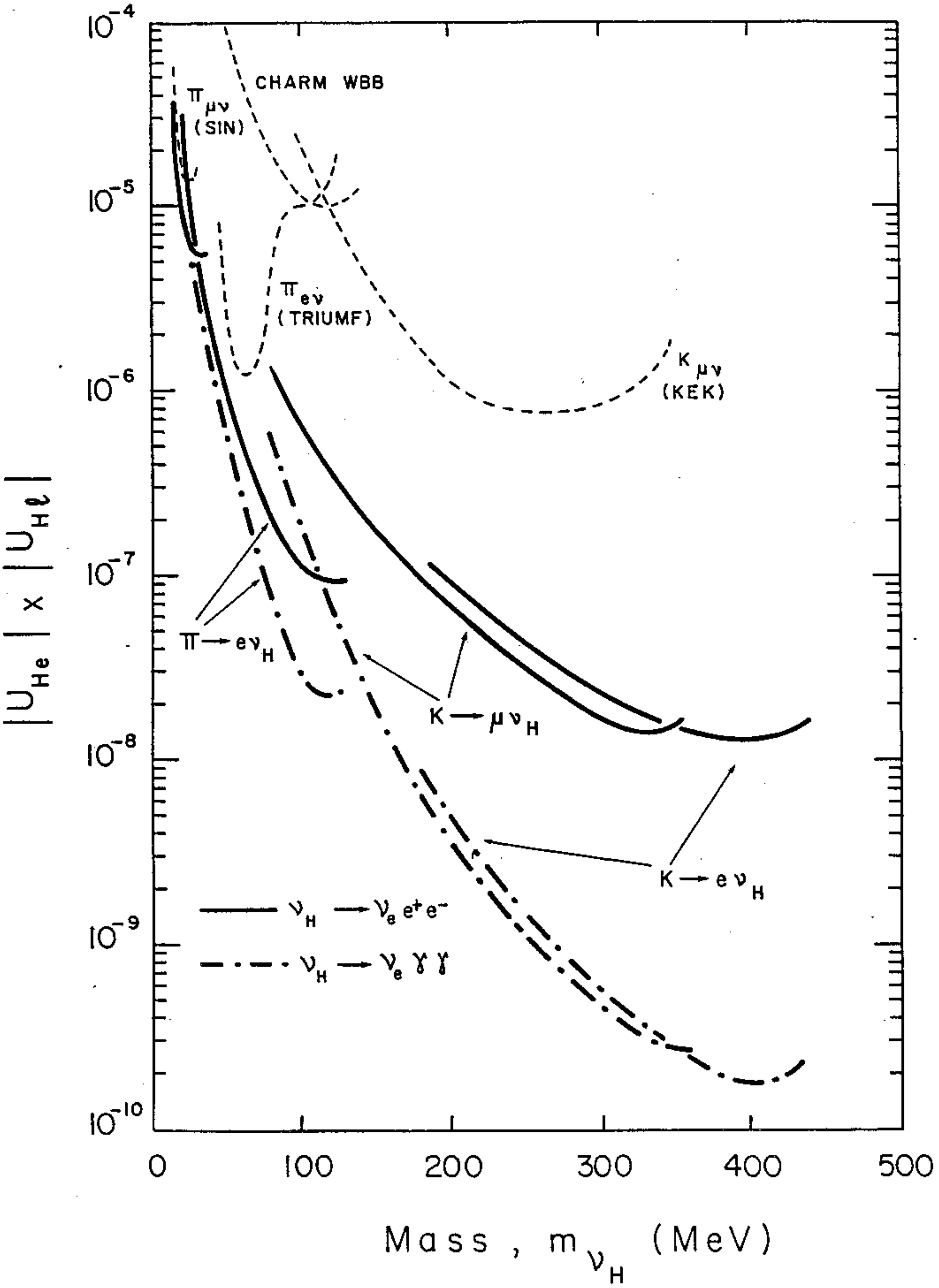

150
100
50
0
0.2
0.4
0.6
0.8
Number of tubes hit
E_e (GeV)
$\frac{\Delta E}{E}$ = 12.5%
at 0.5 GeV

Fig. 5


10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
CHARM WBB
$\pi_{\mu\nu}$ (SIN)
$\pi_{e\nu}$ (TRIUMF)
$K_{\mu\nu}$ (KEK)
$\pi \rightarrow e\nu_H$
$K \rightarrow \mu\nu_H$
$K \rightarrow e\nu_H$
$\nu_H \rightarrow \nu_e e^+ e^-$
$\nu_H \rightarrow \nu_e \gamma\gamma$
0
100
200
300
400
500
Mass , m_{ν_H} (MeV)
$|U_{He}| \times |U_{H\ell}|$

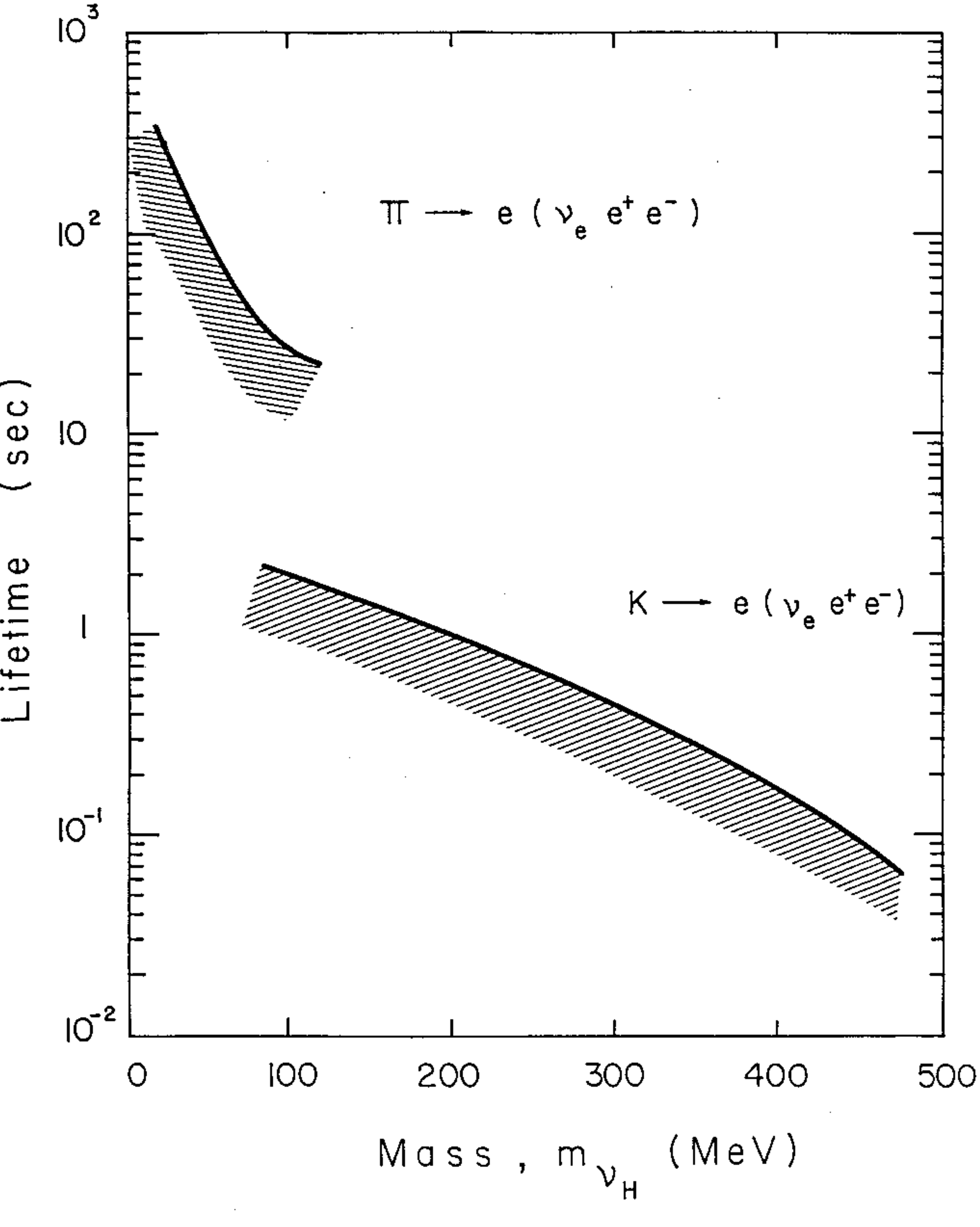

10^3
10^2
10
1
10^{-1}
10^{-2}
Lifetime (sec)
0
100
200
300
400
500
Mass, m_{ν_H} (MeV)
$\pi \longrightarrow e\,(\nu_e\, e^+ e^-)$
$K \longrightarrow e\,(\nu_e\, e^+ e^-)$

Fig. 7