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NEUTRINO OSCILLATIONS *

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MASTER

I. Introduction

The interest in neutrino oscillations is such that there are several experiments approved or planned for the near future. There are experiments already complete which have searched for oscillations particularly between $\nu_\mu \to \nu_e$. We shall concentrate here on accelerator experiments and try to show the principal limitations on the experimental sensitivity to changes in neutrino flavor. We shall leave a review of the theory to Peter Rosen[1] in these same proceedings, and an excellent review by Herbert Chen[2] also relieves us of the obligation to summarize the present experimental data. Instead we shall give a critical review of the methodology that has been used or proposed for accelerator experiments.

Presently, there is evidence for three flavors of lepton families as we show below

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \qquad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \qquad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

ν_e, ν_μ, ν_τ are the weak eigenstates. In the case that only two flavors mix, it is assumed that there are distinct mass eigenstates ν_1, ν_2 so that for example

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$

$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta \quad .$$

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Of course this is only the most simple possibility and mixing of three or more flavors can be considered. If the masses $m_1 \neq m_2$ then the probability of observing a second flavor in a beam that starts off pure is

$$P = 1 - \sin^2 2\theta \quad \sin^2 (1.27\ \delta m^2 \frac{\ell}{E_\nu})$$

$\sin^2 2\theta$ is a measure of the mixing between the two flavors and the second term gives the oscillation wavelength, which for example, can be derived from uncertainty principle arguments. The wavelength that appears physically is $\lambda = \frac{1.27}{2\pi} \sin^2 (\delta m^2\ \ell/E_\nu)$ and when $\delta m^2 = 25\ eV^2$, $E_\nu = 1500$ MeV then

$$\lambda = 150m.$$

The experiments have different characteristics according to the relation of λ and the dimensions of the apparatus.

At a reactor $E_\nu \sim 10$ MeV and for $\lambda \sim 20m$ $\quad \delta m^2 \sim 1\ eV^2$

At Fermilab $E_\nu \sim 150$ GeV, $\quad \lambda \sim 1.5$ km $\quad \delta m^2 \sim 250\ eV^2$.

To measure δm^2 then λ would have to be comparable to the dimensions of the apparatus so that different ν energies imply a different range of sensitivity of mass difference squared.

Experiments seeking to detect oscillations divide into two types; those that look for appearance of a new flavor in an initially pure beam of another flavor, and those which detect the disappearance of neutrinos from the beam.

II. Appearance Experiments

It is common at accelerators to make a $\overset{(-)}{\nu}_\mu$ beam from pion decay in flight. The experiments then look for electrons from a reaction such as

$$\nu_e + n \rightarrow e^- + p$$

Then the probability of finding the ν_e induced reactions is

$$P = \sin^2 2\theta \sin^2 (1.27\ \delta m^2\ \ell/E_\nu)$$

The limitation on this measurment comes from the ν_e that are in the beam from K decays (K_{e3}) and from muon decays. At the AGS these ν_e are a few times 10^{-3} of the ν_μ in a horn focussed beam, leading to a natural limit of $P \sim 10^{-3}$.

We consider two limits:

a) $(1.27\ \delta m^2 \frac{\ell}{E_\nu}) \gg \pi$

then $\langle \sin^2 (1.27\ \delta m^2 \frac{\ell}{E_\nu}) \rangle = 1/2$

and $\sin^2 2\theta = 2\ P$.

The oscillation wavelength is short compared to distances in the detector and the experiment consists of the observation of the average of the appearance probability giving a direct measurement of $\sin^2 2\theta$ regardless of the δm^2 or E_ν. The limit on the mixing angle is given by the precision on P; in crude terms this limit is the background of ν_e in the beam from decay sources. An improvement can be achieved by running in a narrow band beam where the pions are selected to be monoenergetic and approximately the neutrinos also. The ν_e are from three body decays so that they have a much wider energy distribution. The fraction of the ν_e

under the ν_μ energy peak is thus reduced and the limit on P is improved. It is useful to note that the fractional precision on P depends as $\frac{1}{\sqrt{N}}$, N the number of electron events, so that it is desirable to place the detector close to the neutrino source and increase the number of events as far as possible, providing that the systematics can be understood.

b) The second limit occurs when $\left(1.27\ \delta m^2 \frac{\ell}{E_\nu}\right) \ll \pi$.

When the wavelength is long compared to the apparatus distance and

$$P \sim \sin^2 2\theta \left(\frac{1.27}{E_\nu}\ \ell\ \delta m^2\right)^2 \quad .$$

The optimum strategy is now to move the detector far away because as ℓ increases $P \sim \ell^2$. At the same time the solid angle decreases as $1/\ell^2$ and sensitivity to P is independent of distance. The background however decreases as the solid angle improving the signal to background ratio with distance. In order to optimize the sensitivity the detector should be placed so that one background count is expected.

Specifically for 3×10^{20} protons on target and a 100 ton detector at 100 m with 1 GeV E_ν then we expect 10^7 quasi elastic events.

The electron rate is 10^4 and is reduced to 1 event at 1 km.

With 90% confidence $P \sim 1.5 \times 10^{-3}$

and

$$\sin^2 2\theta = 3 \times 10^{-3}.$$

At $\sin^2 2\theta = 1$ the δm^2 limit is 2×10^{-3} eV^2.

Between these limits the sensitivity to $\sin^2 2\theta$ and δm^2 is given by

$$P \sim \sin^2 2\theta \cdot \sin^2 \left(1.27\ \delta m^2\ \frac{\ell}{E_\nu}\right)$$

and since P is measured this establishes a boundary in $\sin^2 2\theta$ as in Fig. 1 where this boundary is plotted for P = .001 on a log-log plot. This boundary assumes a single value of ℓ and E_ν which is not achieved in practice. Normally the zeros in $\sin^2 (1.27\ \delta m^2\ \ell/E_\nu)$ are not emphasized because of the measurement spread in E_ν and other resolution effects. Notice the straight line between the limit in δm^2 and the limit in $\sin^2 2\theta$.

III. Disappearance Experiments

These experiments do not depend upon a particular oscillation transition but rather observe the beam content at different distances to measure an attenuation. The experiments achieve a much more limited sensitivity than the appearance experiment because of the need to measure the difference between two rates rather than the appearance of a small but characteristic signal. When the wavelength is small compared to the detector, disappearance experiments are not possible but when the wavelength is comparable to the apparatus size and in the long wavelength limit disappearance experiments are useful. We consider the long wavelength case first.

The primary cause of the difference in counting rate in two detectors is due to the solid angle effect. An oscillation signal is the

departure from the $1/\ell^2$ dependence of counting rate. A simple model of an experiment is shown in Fig. 2. There are two detectors at distances ℓ_1 and ℓ_2, and to allow for the solid angle effect, we can choose a

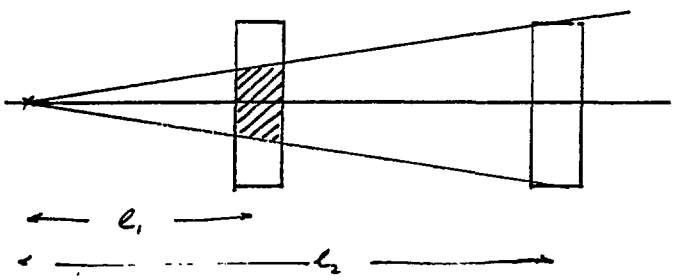

Fig. 2

fiducial volume in the first detector that is defined by the solid angle from the source to the second detector as shown. The problems with this approach mainly stem from the finite characteristics of the source. The source is extended through the decay region, moreover that region is not exactly uniformly illuminated. The transverse momentum of the neutrinos is finite so that the neutrino flux varies over the detector at least at the near position. Moreover the mean neutrino energy also varies across the detector. In our considerations of an oscillation program at Brookhaven,[3] we have considered some of these effects using a rather complete Monte Carlo program and we discuss them below.

a) The Illumination of the Decay Region

At the AGS presently, the decay region is approximately 50 m long. The pions that give rise to the peak of the wide band spectrum have a decay length of about 300 m so that the loss of pions from decay along

the length is not a large effect. However the decay pipe diameter limits the transverse momentum of the pions downstream in the pipe so that the rate of decay is dependent on z position as in Fig. 3. It is also energy dependent as is also evident in Fig. 3

b) The ν flux also varies over the detector face due mainly to the transverse momentum distribution of the parent pions; the use of the fiducial volume as in Fig. 2 reduces this effect although the effect is substantial as we show in Fig. 4a and b. The mean neutrino energy also varies across the face of the detector as we show in Fig. 5. Each of these effects is not so large that they may not be corrected, but the effects we note here is only a partial list of the beam characteristics that must be understood in a disappearance experiment with two well separated detectors.

Another way of appreciating the difficulties of demonstrating a spurious oscillation signal is to compile momentum spectra for neutrinos that pass through the fiducial volumes of the two detectors. If the source is a point then the way that we define fiducial volumes ensures that any neutrino that passes through detector 1 does so also in detector 2. When we do the calculation for a 50 m decay space, and the neutrino momentum spectra from the Monte Carlo we get the distributions shown in Fig. 6.

The Derivative Method

Many of the systematic effects that are of concern in disappearance experiments are ameliorated by putting the two detectors very close together and measuring the difference in the counts in the two halves of the single detector. We can understand the basis of the method with a simple model shown in Fig. 7a. The detector is assumed to be near the half wavelength point from the point source. Then we assume that the ν

energy is well known so that a mass difference squared maps into a well defined wavelenth. Then for a finite length detector 2a, the forward-backward asymmetry

$$\frac{(F-B)}{(F+B)} = - \frac{2 \sin^2(\pi a/2\lambda) \sin(2\pi x/\lambda)}{\pi a/\lambda + \sin(\pi a/\lambda) \cos(2\pi x/\lambda)}$$

This function is plotted in 7b. It is clear that when the first minimum of the oscillating amplitude is at the detector then this asymmetry is zero but rapidly on each side a large asymmetry develops. The amplitude of this function depends on the energy of the neutrino so that a given wavelength can be related to a specific δm^2. In practice the asymmetry would be plotted against 1/E giving the value of δm^2 from the point where the asymmetry curve crosses the axis.

If a finite decay distance d is used, the amplitude of the asymmetry functions is attenuated by the factor

$$\sin\left(\frac{\pi d}{\lambda}\right)/\left(\frac{\pi d}{\lambda}\right) \quad .$$

This assumes a uniform illumination of the decay distance which is the worst case as far as the maximum value of the asymmetry function is concerned.

In Fig. 8 we plot an asymmetry function with a finite decay distance, a finite energy resolution and a realistic running time using quasi elastic events in the Brookhaven detector. The χ^2 for the null hypothesis is shown in Fig. 9 as a function of δm^2. As expected for the AGS neutrino spectrum, and the 75m from center of decay region to center of the detector, the sensitivity peaks at $\delta m = 25$ ev . Although a detailed study of systematic effects has not been made, it is expected that the proximity of the two measuring regions will minimize these systematic problems.

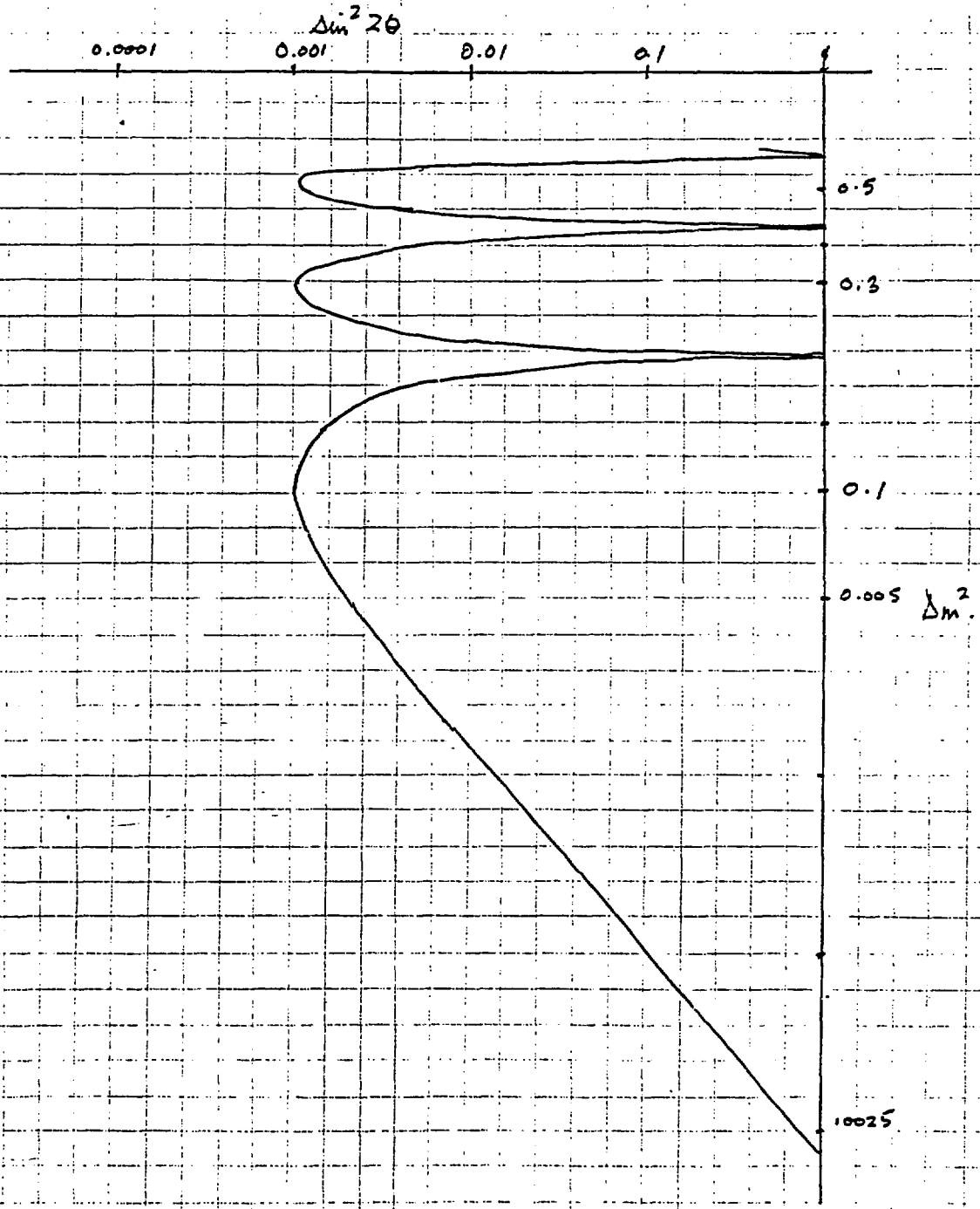

Figure 1

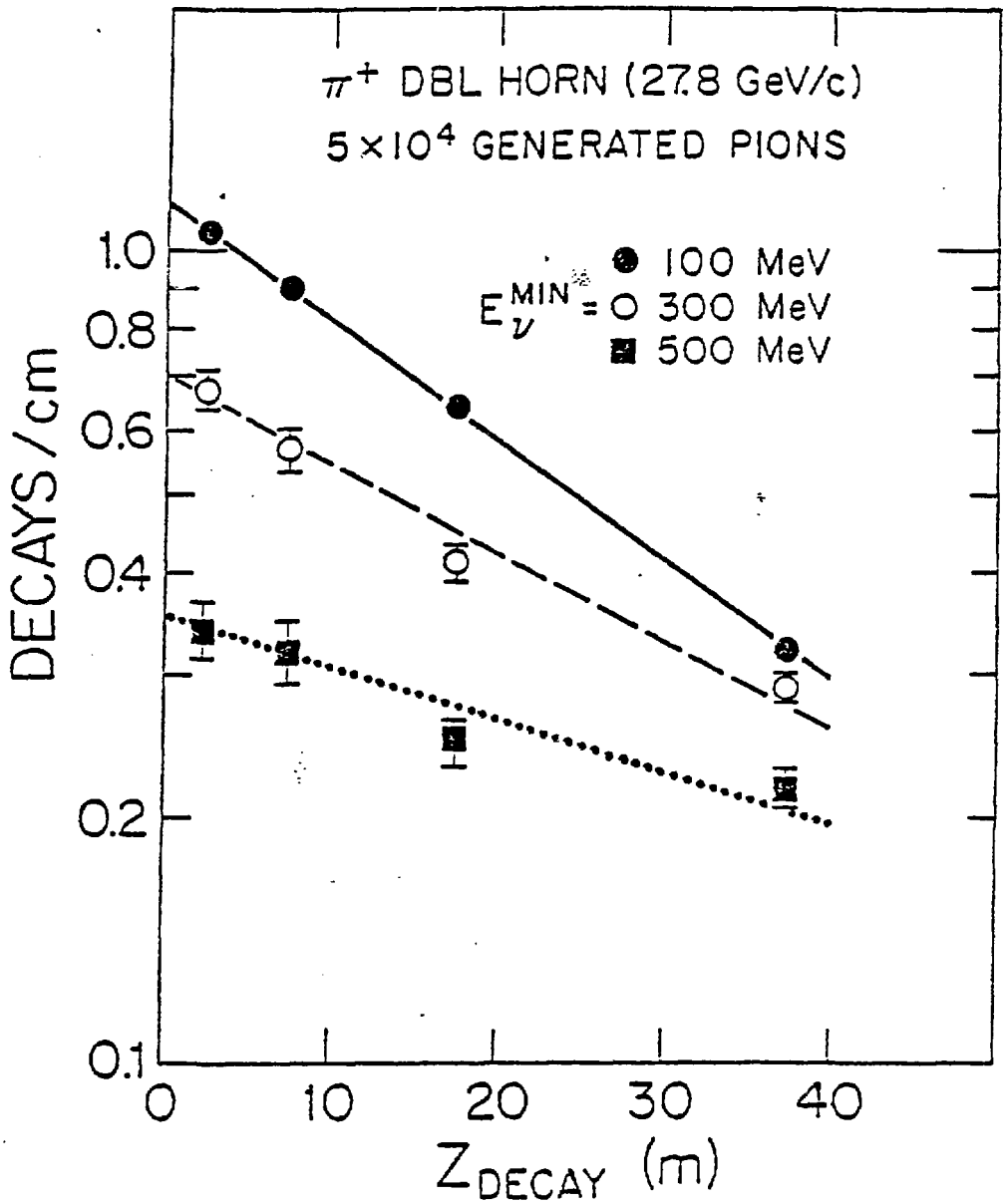

Fig. 3. Decays per cm as a function of z (distance along beam-line) in the region from the target (z = 0.0) to the end of the decay tunnel (z = 50m). Only decay points which produce neutrinos which intercept the E-734 detector (located 110m downstream of the target) with $E_\nu > E^{MIN}$ are plotted. Note as E_ν^{MIN} increases contributions from lower momentum pions are excluded increasing the mean decay lengths of the pions and decreasing the slopes of the points in the figure.

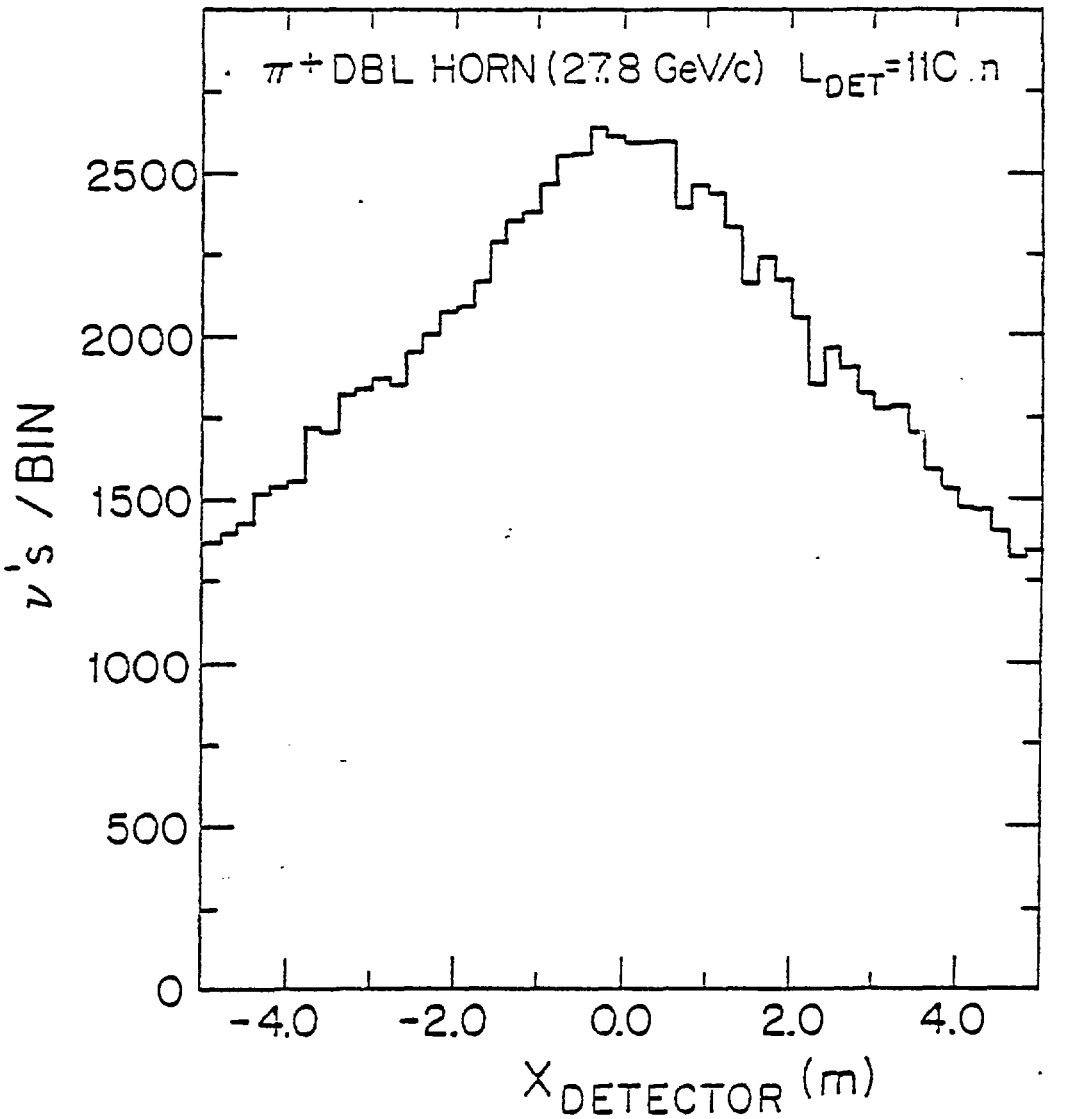

Fig. 4a- -c. Distributions of neutrinos incident on a 10m x 10m area located 110m, 500m, and 1 Km downstream of the target (x projection, y is similar). The normalization at each distance represents identical exposures (5×10^9 pions produced in the target) and reflect the relative fluxes calculated for each detector distance.

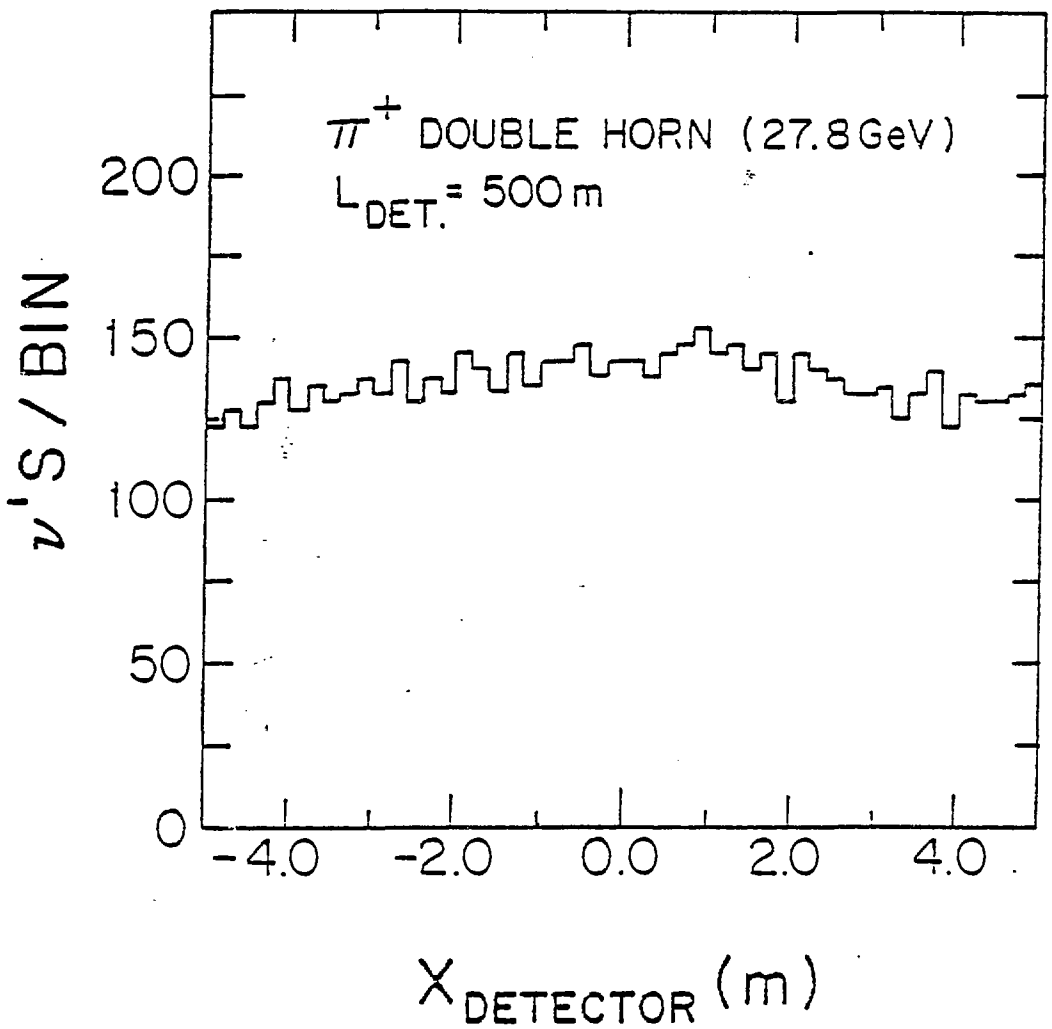
π^+ DOUBLE HORN (27.8 GeV)
$L_{DET.}$ = 500 m
200
150
100
50
0
ν'S / BIN
-4.0
-2.0
0.0
2.0
4.0
$X_{DETECTOR}$ (m)

Fig. 4b

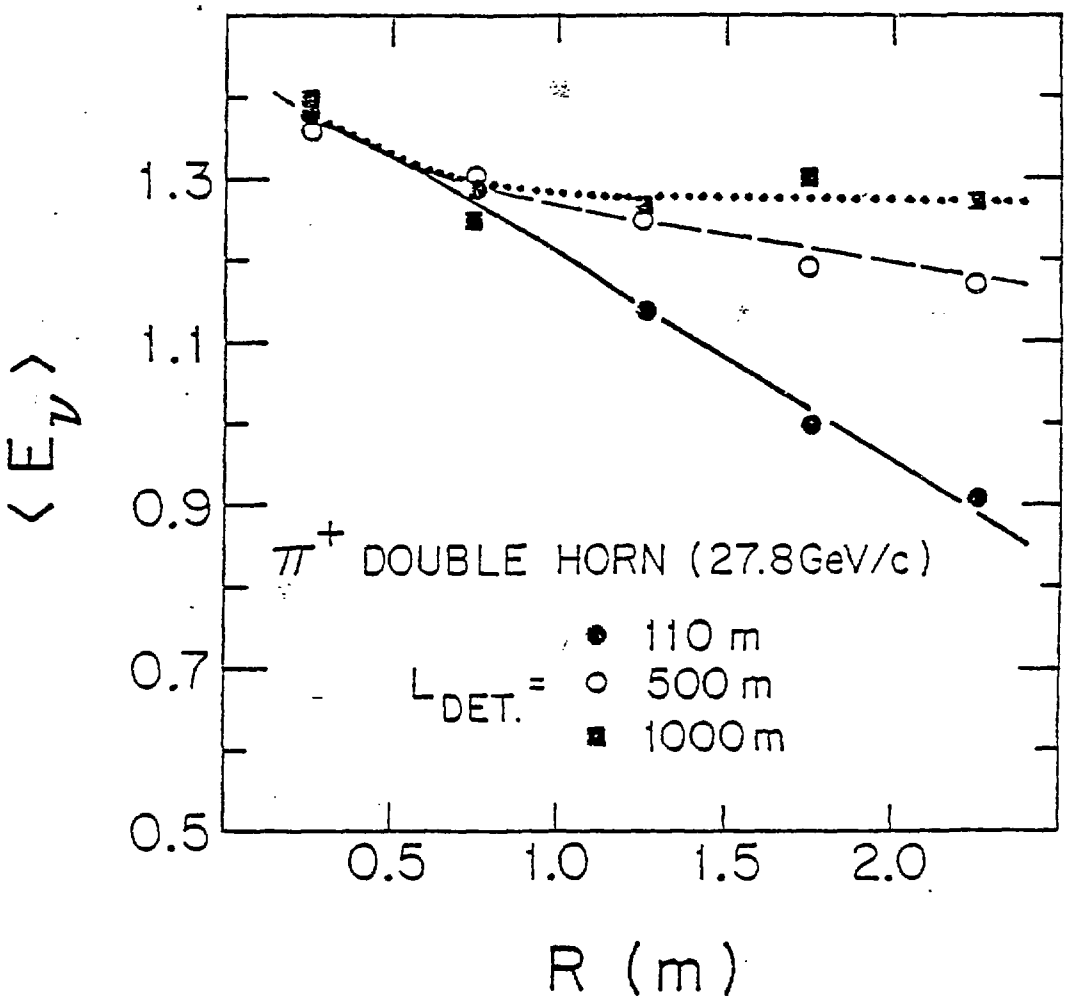

Fig. 5. Variation with radius in the detector of the mean neutrino energy in the beam for detector positions 110m, 500m, and 1 Km downstream from the target.

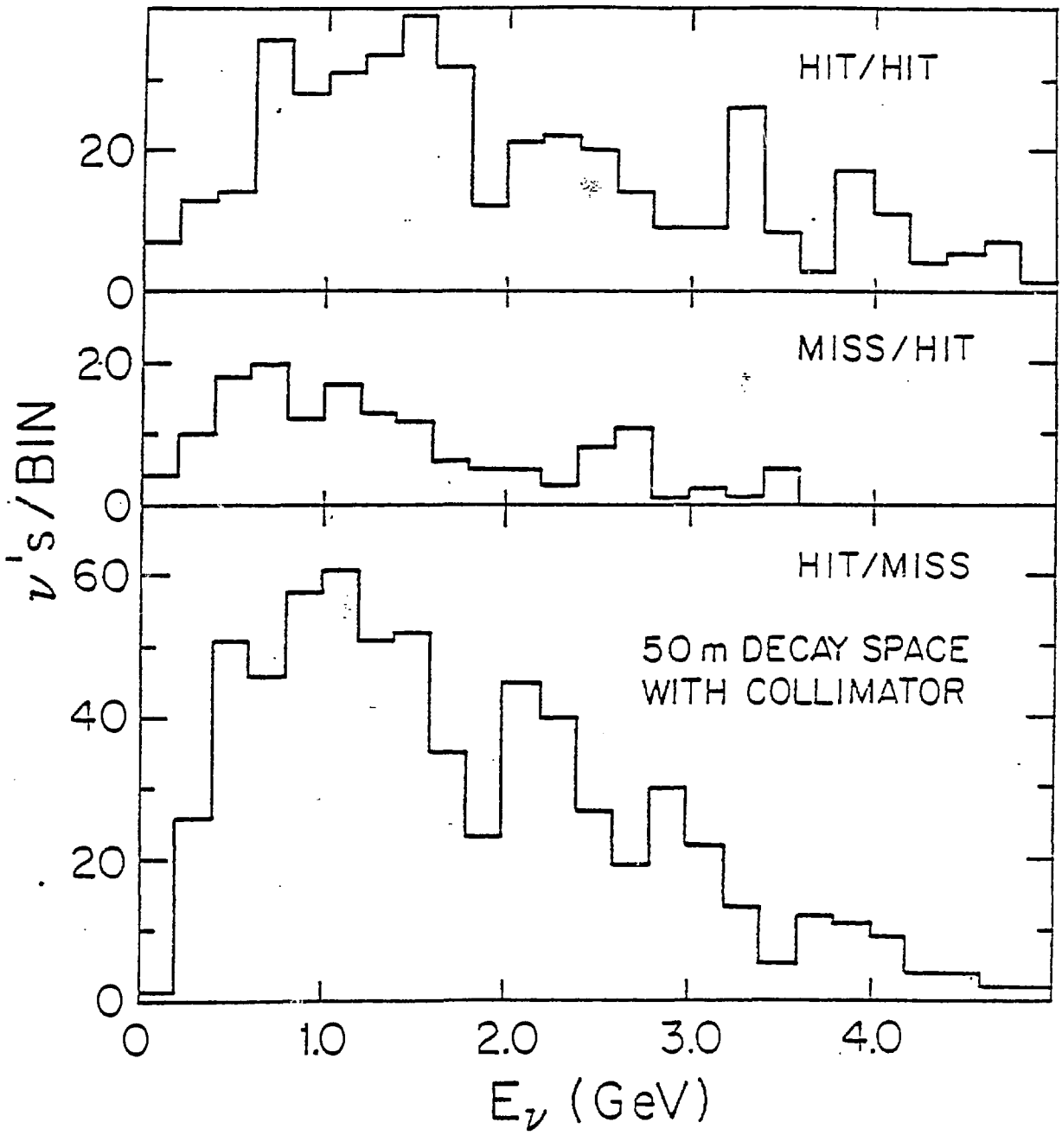
HIT/HIT
MISS/HIT
HIT/MISS
50 m DECAY SPACE
WITH COLLIMATOR
ν's/BIN
0
20
40
60
0
1.0
2.0
3.0
4.0
Eν (GeV)

Figure 6

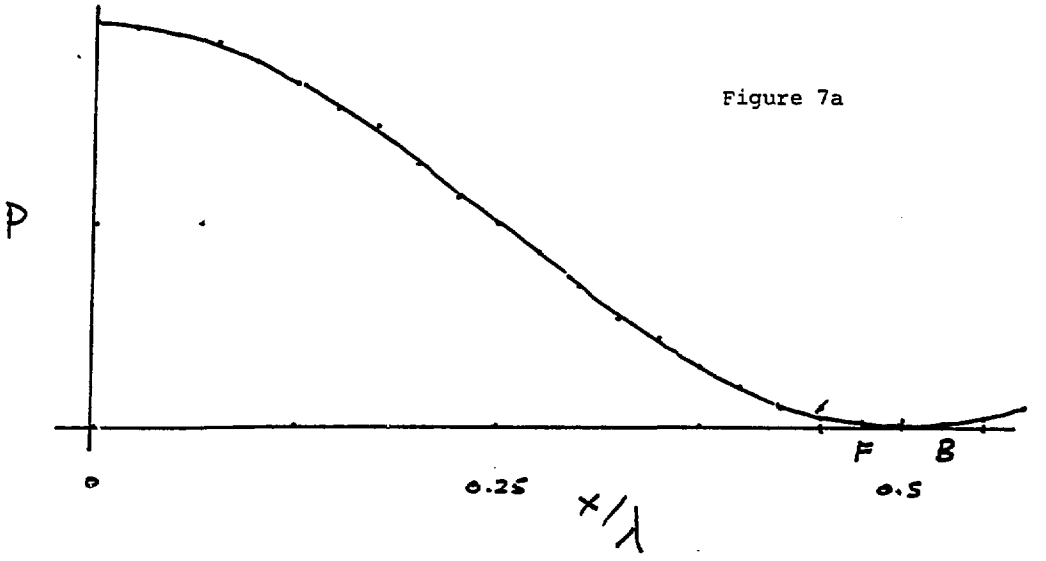

Figure 7a

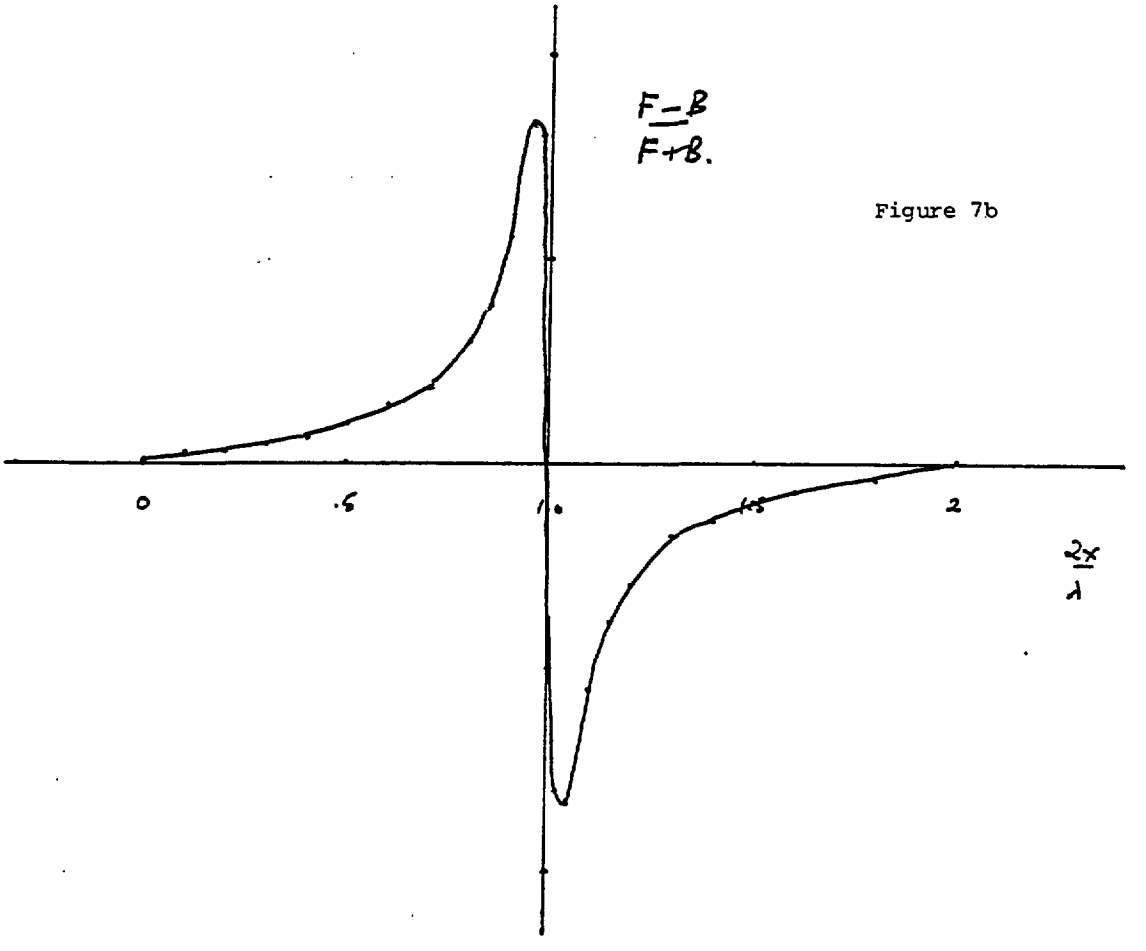

Figure 7b

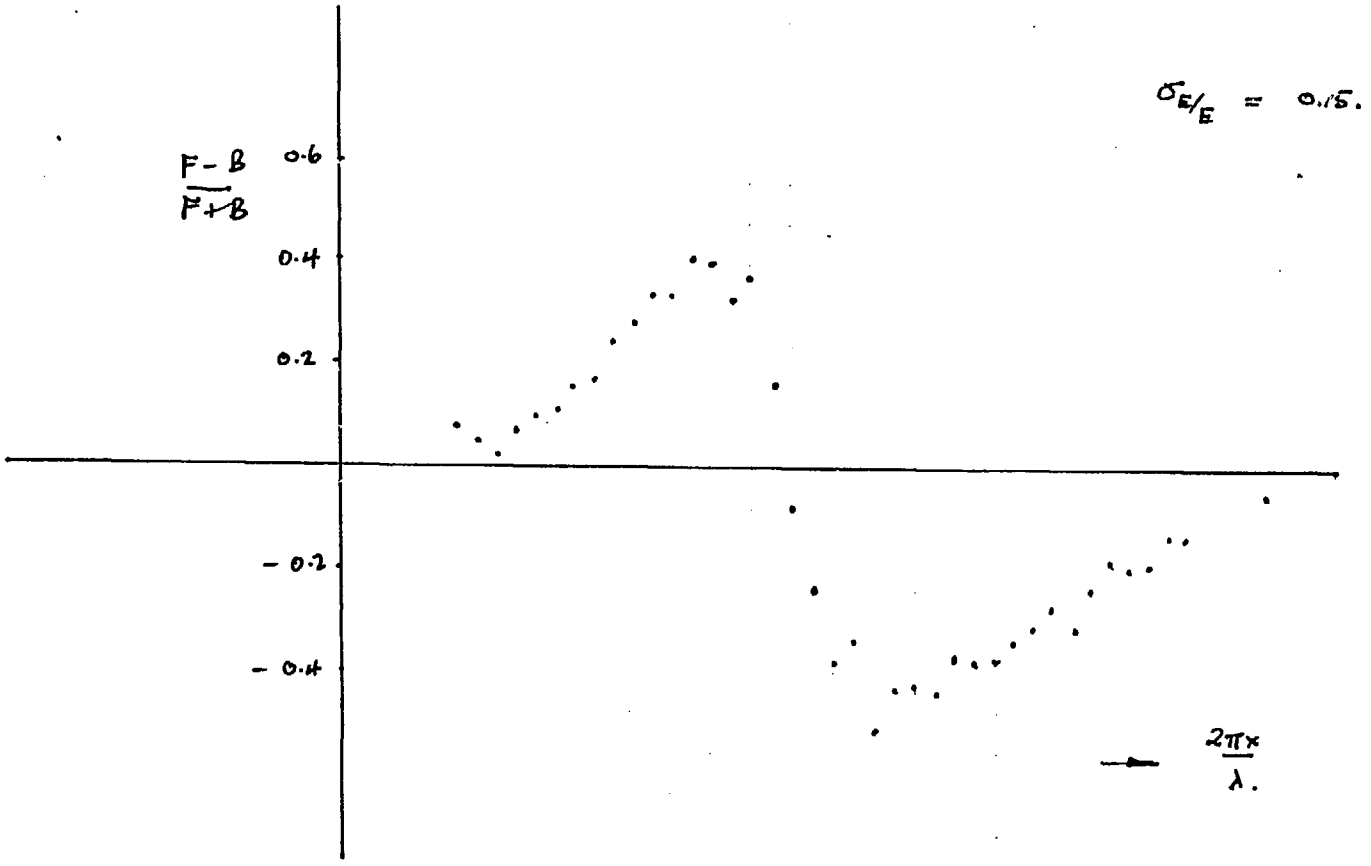

Figure 8

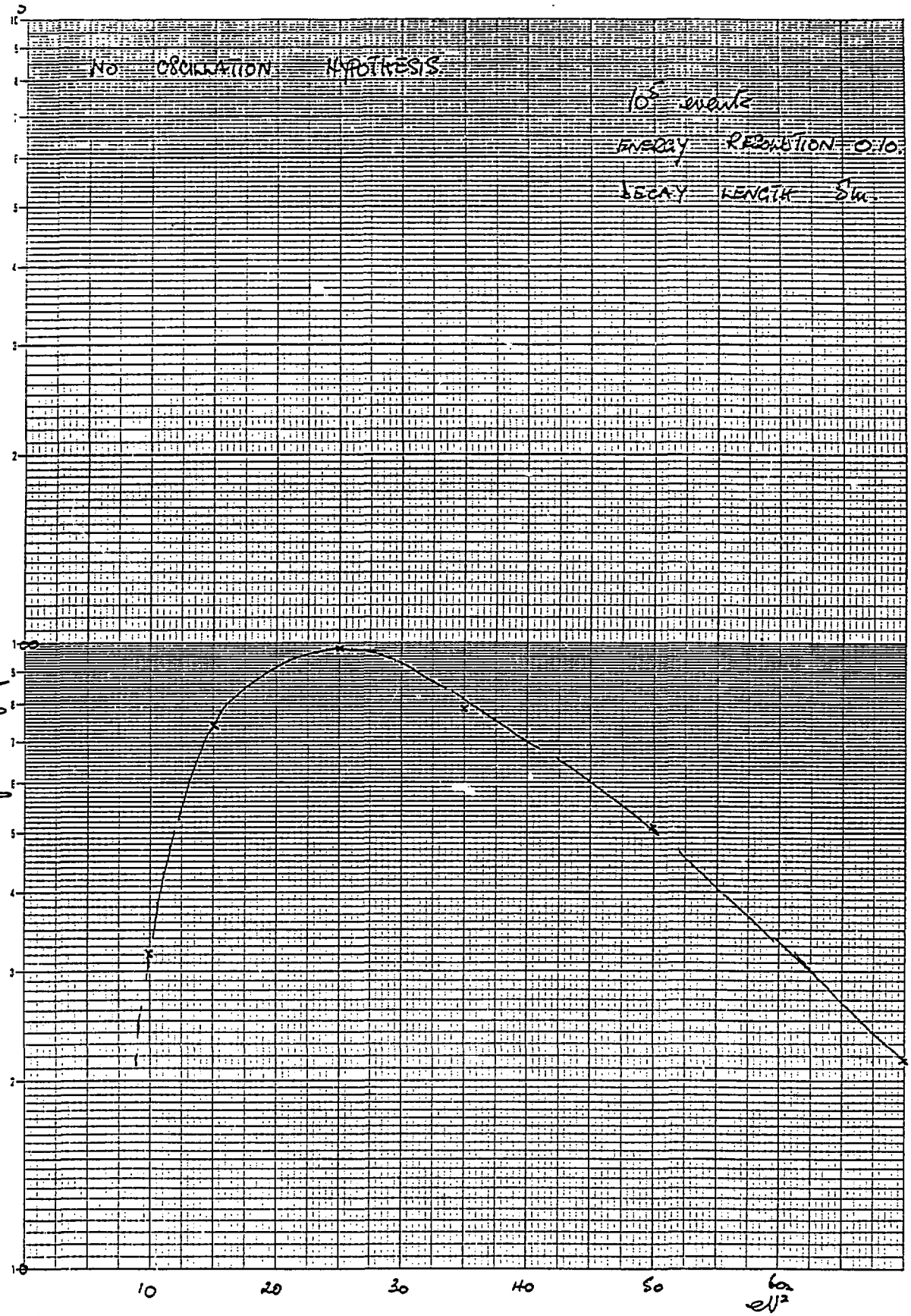
NO OSCILLATION HYPOTHESIS
10^5 events
ENERGY RESOLUTION 0.10
DECAY LENGTH 5m.
χ^2 / degree of freedom
10
20
30
40
50
60
eV^2

Figure 9