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ABSTRACT

We have searched for an admixture of a heavy neutrino state ν_x in the decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$ by analyzing the momentum spectrum of a surface muon beam in a magnetic spectrometer. No indications for such a neutrino state were found. In the mass range $0.53\,\mathrm{MeV} \leq m_{\nu_x} \leq 1.0\,\mathrm{MeV}$, not covered by previous experiments, we obtain upper limits of the branching fraction $\Gamma(\pi^+ \rightarrow \mu^+\nu_x)/[\Gamma(\pi^+ \rightarrow \mu^+\nu_2)+\Gamma(\pi^+ \rightarrow \mu^+\nu_x)]$ between 22 % and 1.6 % (c.l. = 0.9).

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In a recent experiment at PSI [1, 2], we determined the upper limit of the muon-neutrino mass and the charged-pion mass by momentum analysis of a surface muon beam [3, 4]. In that experiment, π^+-mesons were produced by 590 MeV protons in a pion production target made of graphite. A fraction of the pions come to rest near to or at the surface of this target so that the decay muons can exit from it. The muons can lose energy on their way to the surface of the target, and instead of a line from the two-body decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{1}$$

at 29.79 MeV/c one observes an approximately flat muon momentum spectrum with a sharp cut-off at 29.79 MeV/c [1, 2].

In Ref. [1, 2], the particle ν_μ was assumed to be in a mass eigenstate. However, if one considers the possibility of non-zero neutrino masses, one must also consider leptonic mixing which could occur in analogy to quark mixing. In general, the weak eigenstates ν_l $(l = e, \mu, \tau)$ would then consist of a mixture of mass eigenstates

$$\nu_l = \sum_i U_{li} \nu_i . \tag{2}$$

Here ν_i $(i = 1, 2, 3, \ldots)$ are the mass eigenstates, and U_{li} the corresponding transformation matrix elements [5-8]. The mass eigenstates can be defined so that the mixing matrix U_{li} is almost diagonal, i.e. ν_μ is predominantly ν_2.

Thus, if neutrinos are massive and nondegenerate, the initial momentum spectrum of muons from stopped pions in the decay (1), if kinematically allowed, would consist of monochromatic lines at momenta of

$$p_{\mu,i} = \left[\frac{({m_\pi}^2 + {m_\mu}^2 - {m_{\nu_i}}^2)^2}{4{m_\pi}^2} - {m_\mu}^2 \right]^{\frac{1}{2}} \tag{3}$$

From the momentum of these lines, the squared masses of the neutrino states are found to be

$$m_{\nu_i}{}^2 = m_\pi{}^2 + m_\mu{}^2 - 2m_\pi \left(m_\mu^2 + p_{\mu,i}{}^2\right)^{\frac{1}{2}} \tag{4}$$

In our experiment [1, 2], the admixture of a heavy neutrino in pion decay would lead to an additional edge at a lower momentum in the muon momentum spectrum. This is illustrated in Fig. 1.

Searches for such admixtures of heavy neutrino states have been performed in pion decay at rest and in flight [9-15]. While the decay-in-flight experiments [13, 14] are sensitive to a narrow mass range only, the decay-at-rest experiments cover almost the entire range allowed by the kinematics of the decay (1). Here, a limiting factor at the upper end of the mass scale for heavy neutrino states is the threshold for the detection of the decay muon, whereas at the lower end of the mass scale, searches are limited by the finite energy or momentum resolution of the detectors used.

For heavy neutrino states with masses $m_{\nu_x} < 16\,\mathrm{MeV}$, the best limits previously obtained originate from an experiment [10] where pions were stopped in a high-purity germanium detector; the kinetic energy of the muon was measured with a resolution of 4.3 keV (rms) corresponding to a relative kinetic energy resolution of $1.0 \cdot 10^{-3}$. In our measurement of the muon momentum in pion decay at rest [1, 2], we used a magnetic spectrometer equipped with a silicon microstrip detector. The relative momentum resolution obtained was $1.8 \cdot 10^{-4}$ (rms) corresponding to a kinetic energy resolution of $3.5 \cdot 10^{-4}$. In the present work, we use this good energy resolution to re-analyze the data taken, in order to search for a heavy neutrino state in the mass range $\mathrm{m}_{\nu_x} \leq 1.5\,\mathrm{MeV}$.

The experimental apparatus is described in Ref [1, 2]. Our data consist of 44 muon momentum spectra recorded at six different spectrometer field settings ranging from 275.4 to 276.4 mT. In the present study, all spectra taken at the same magnetic field values were added, which led to the six spectra shown in Fig. 2.

In Fig. 2, one microstrip (width = 0.05 mm) corresponds to a relative momentum bite of $\Delta p/p = 6.9 \cdot 10^{-5}$. The sharp cut-off in these spectra corresponds to decay muons which originated at the surface of the pion production target. The distribution to the right of this edge contains muons from stopped pion decays inside the production target. This distribution is expected to be approximately uniform; however, slight drifts or changes of the beam magnet settings led to distortions, mostly because the dispersion trajectory at the entry of the spectrometer differed from the ideal case (for a detailed discussion we refer to Ref. [2]). The distribution to the left of the cut-off is due to so-called cloud muons, i.e. muons from decay in flight of π^+ mesons in the beam channel.

In the analysis, simulated distributions, generated by a Monte Carlo programme [1, 2] were fitted to the experimental spectra, using the computer package MINUIT [16]. It was assumed that the process $\pi^+ \rightarrow \mu^+ + \nu_\mu$ consists of exactly two components, namely (i) $\pi^+ \rightarrow \mu^+ + \nu_2$, and (ii) $\pi^+ \rightarrow \mu^+ + \nu_x$. The following free parameters were varied to obtain the best fits to the experimental numbers of muons per microstrip:

(1) A normalization factor P_1 by which all Monte Carlo numbers of events were multiplied.

(2) A constant background P_2 attributed to cloud muons, which was added to each bin of the Monte Carlo histogram.

(3) and (4) The coefficients P_3 and P_4 of a second-order polynomial correction function $f(j) = 1 + P_3 \cdot (j - j_0) + P_4 \cdot (j - j_0)^2$, where j is the microstrip number, and j_0 is a fixed number, chosen to be at the peak of the distribution. The factor $f(j)$ was introduced to take into account the distortions of the muon momentum distribution mentioned above (see also Ref. [2]).

(5) A horizontal shift P_5 applied to the Monte Carlo histogram. This corresponds to a change in the initial muon momentum $p_{\mu,2}$ from its assumed value of 29.792 MeV/c.

(6) The standard deviation P_6 of a Gaussian distribution with which the Monte Carlo distributions were folded; it originates from the motion of the pions trapped in the graphite target [1, 2], leading to a Doppler broadening of the decay-muon momentum distribution.

(7) The branching fraction $\eta \equiv P_7$ of the decay involving a heavy neutrino state ν_x with a fixed mass value, and the decay involving the light neutrino ν_2.

$$\eta = \frac{\Gamma(\pi^+ \to \mu^+\nu_x)}{\Gamma(\pi^+ \to \mu^+\nu_2) + \Gamma(\pi^+ \to \mu^+\nu_x)}. \tag{5}$$

The corresponding additional edge was assumed to have the same shape as the main edge, so that the simulated distribution could simply be shifted to the position corresponding to the hypothetically fixed neutrino mass m_{ν_x}.

Each fit was performed for all six spectra simultaneously with a fixed position of the additional edge corresponding to m_{ν_x}, with m_{ν_x} ranging from 0.53 to 1.5 MeV. In the fit, the four parameters P_1, P_2, P_3, and P_4 were different for each magnetic field value used, whereas the three parameters P_5, P_6, and P_7 were the same for all six spectra investigated. Thus, the number of free parameters was $6 \cdot 4 + 3 = 27$.

The parameter χ^2 to be minimized is defined by

$$\chi^2 = \sum_{k=1}^{6} \sum_{j=j_{\min}(k)}^{j_{\max}(k)} \left(\frac{d_k(j) - s_k(j)}{\sigma_k(j)} \right)^2 . \qquad (6)$$

Here k is the index for the six different magnetic fields values B_k; j is the microstrip number; d_k is the data histogram for the spectra taken at the magnetic field value B_k; $\sigma_k(j)$ is the error of $d_k(j)$; and s_k is the simulated histogram for the magnetic field value B_k.

For the relevant strips in our detector, the relative efficiencies were found to be close, but not exactly equal to unity (see also Ref. [2]). This was not due to a systematic trend but to an apparently random fluctuation of the number of events in excess of the uncertainty originating from counting statistics. As a consequence, for the analysis the uncertainty $\sigma_k(j)$ of the number of events $d_k(j)$ in strip j was defined to be

$$\sigma_k(j) = \left(d_k(j) + [0.011 \cdot d_k(j)]^2 \right)^{\frac{1}{2}} . \qquad (7)$$

The results quoted below were obtained by using a fitting region of 66 strips for each of the six spectra. An example of a fit is shown in Fig. 2. Here, the assumed neutrino mass m_{ν_x} is 1.37 MeV corresponding to a shift of 12 strips between the main and the additional edge in each spectrum; the total χ^2 is 342.6 for 366 DOF.

The fitted branching fraction η (cf. Eq. (5)) for the decay of a pion into a muon and a heavy neutrino state ν_x is plotted in Fig. 3 as a function of the assumed neutrino mass m_{ν_x}. The errors shown in Fig. 3 are the MINOS-errors [16], i.e. the deviations $\Delta\eta$ which correspond to the maximal extensions of the closed hypersurfaces $\chi^2 = \chi^2_{min} + 1$. For neutrino masses below 0.53 MeV, i.e. for a shift between main and additional edges of less than 1.8 strips, the fits did not converge.

The χ^2-values of the fits are good and they change only slightly with the assumed neutrino mass. In Fig. 3, one can see that the fitted branching fractions do not scatter statistically but change smoothly with the assumed neutrino mass. This occurs because the same data-set was always used so that the extracted branching fractions are strongly correlated.

Over the mass range investigated ($0.53\,\mathrm{MeV} \leq m_{\nu_x} \leq 1.5\,\mathrm{MeV}$) the fits are compatible with the assumption of no admixture of a heavy neutrino state. In order to compare our results with those of Ref. [10], we used the same method to derive upper limits $\eta(\mathrm{UL})$ of the branching fraction η from the data shown in Fig. 3: If the fitted branching fraction $\eta(\chi^2_{min})$ was greater than zero we used $\eta(\mathrm{UL}) = \eta(\chi^2_{min}) + \Delta\eta(90\,\%)$, where $\Delta\eta(90\,\%)$ is the positive MINOS error defined by the hypersurface $\chi^2 = \chi^2_{min} + 1.64$. For branching fractions $\eta(\chi^2_{min})$ below zero, we used $\eta(\mathrm{UL}) = \Delta\eta(90\,\%)$, in order to obtain a conservative upper limit. The results for the upper limit $\eta(\mathrm{UL})$ are shown in Fig. 4.

Conclusions: In our experimental data [1, 2], primarily intended to determine the upper limit of the muon-neutrino mass and the charged-pion mass, we have searched for heavy neutrino states in the mass range between 0.53 MeV and 1.5 MeV. We found no evidence for an admixture of a heavy neutrino state. Although our momentum resolution is better than that achieved in Ref. [10], we did not improve the upper limits for $\mathrm{m}_{\nu_x} > 1\,\mathrm{MeV}$. This is because we searched not for an isolated peak (as in Ref. [9-12]) but for an additional edge superimposed onto a large 'background' originating from the pion decay $\pi^+ \rightarrow \mu^+ + \nu_2$, involving the light neutrino ν_2. In the mass range 0.53 MeV $\leq m_{\nu_x} \leq$ 1 MeV which was not covered by previous experiments, our upper limit of the branching fraction η (cf. Fig. 4) is 22 % at $m_{\nu_x} = 0.53$ MeV, 2.9 % at $m_{\nu_x} = 0.75$ MeV, and 1.6 % at $m_{\nu_x} = 1.0$ MeV (c.l.=0.9).

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Figure captions

Fig. 1:

Idealized muon momentum spectrum: a) muon momentum spectrum from pion decay at rest in an infinitesimally small target; b) muon momentum spectrum from pion decay at rest after the muons have left a finite-sized pion stop target.

Fig. 2:

Example of a simultaneous fit to all 6 spectra. Experimental data are indicated by crosses. The fitted distributions are indicated by histograms. The momentum increases to the left. The position of the assumed heavy neutrino state, in this example a hypothetical additional edge corresponding to $\mathrm{m}_{\nu_x} = 1.37\,\mathrm{MeV}$, is indicated by vertical arrows.

Fig. 3:

Fitted branching fraction $\eta = \Gamma(\pi^+ \to \mu^+ + \nu_x)/[\Gamma(\pi^+ \to \mu^+ + \nu_2) + \Gamma(\pi^+ \to \mu^+ + \nu_x)]$ of a heavy neutrino admixture as a function of the assumed heavy neutrino mass m_{ν_x}; ν_2 is the light neutrino mass-eigenstate predominantly present in pion decay.

Fig. 4:

Upper limit (c.l. $= 0.9$) of the branching fraction η (cf. Fig. 3). Full dots: this experiment; solid line: data from Ref. [10].

Figure 1:

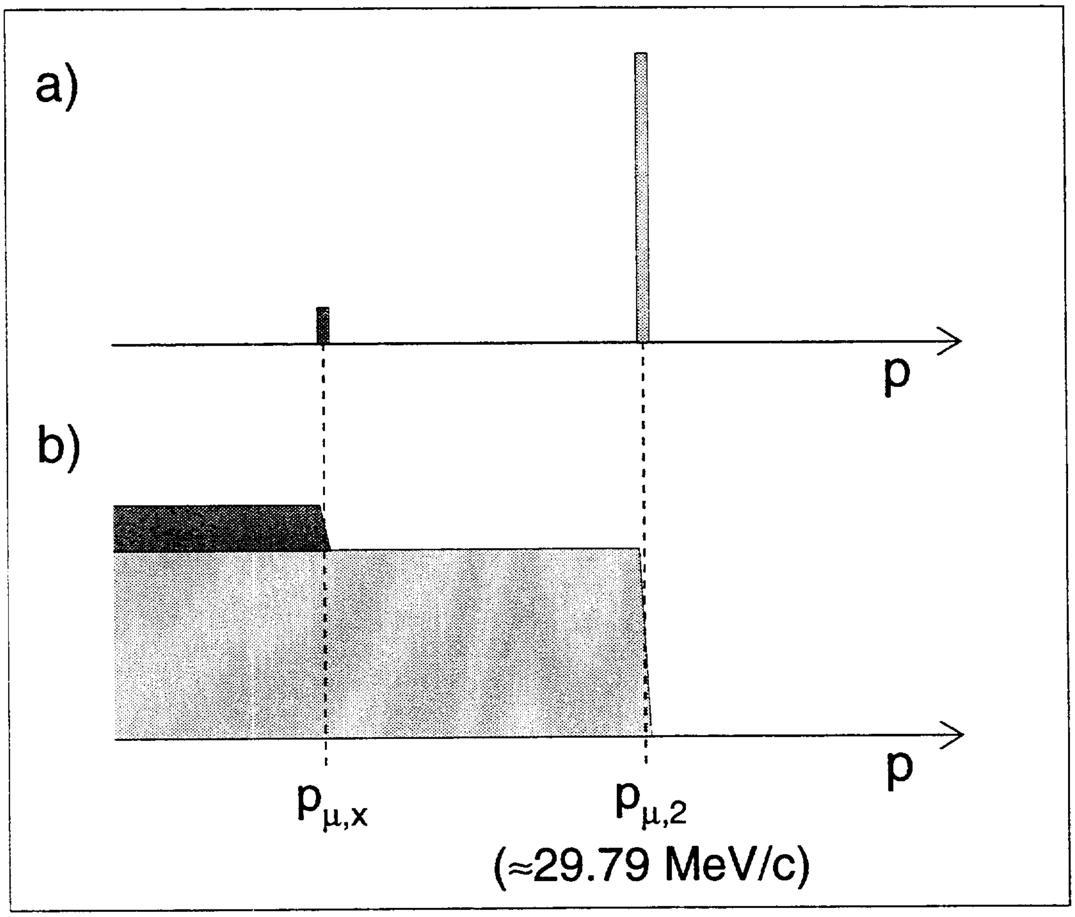


Figure 2:

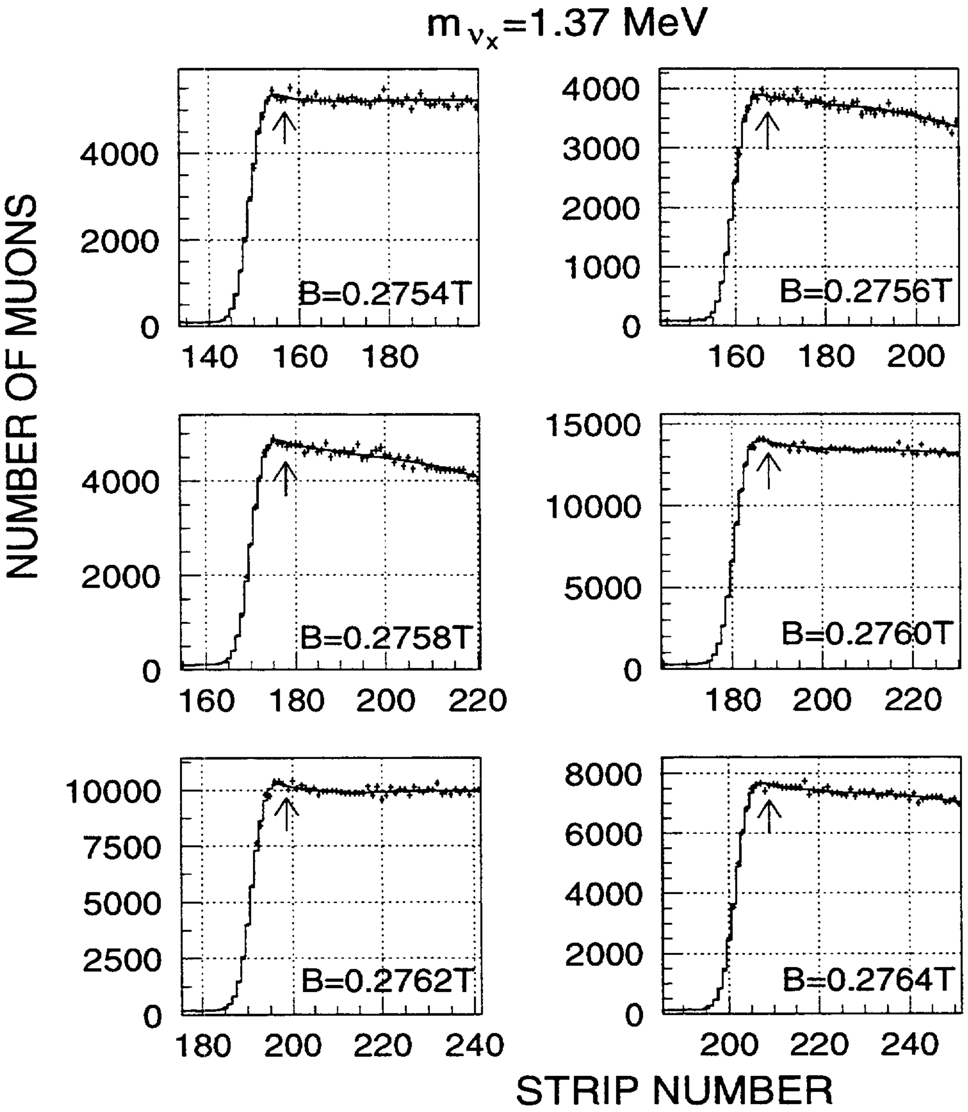

m_{ν_x}=1.37 MeV
NUMBER OF MUONS
STRIP NUMBER
B=0.2754T
B=0.2756T
B=0.2758T
B=0.2760T
B=0.2762T
B=0.2764T
0
2000
4000
1000
3000
5000
10000
15000
2500
7500
6000
8000
140
160
180
200
220
240

Figure 3:

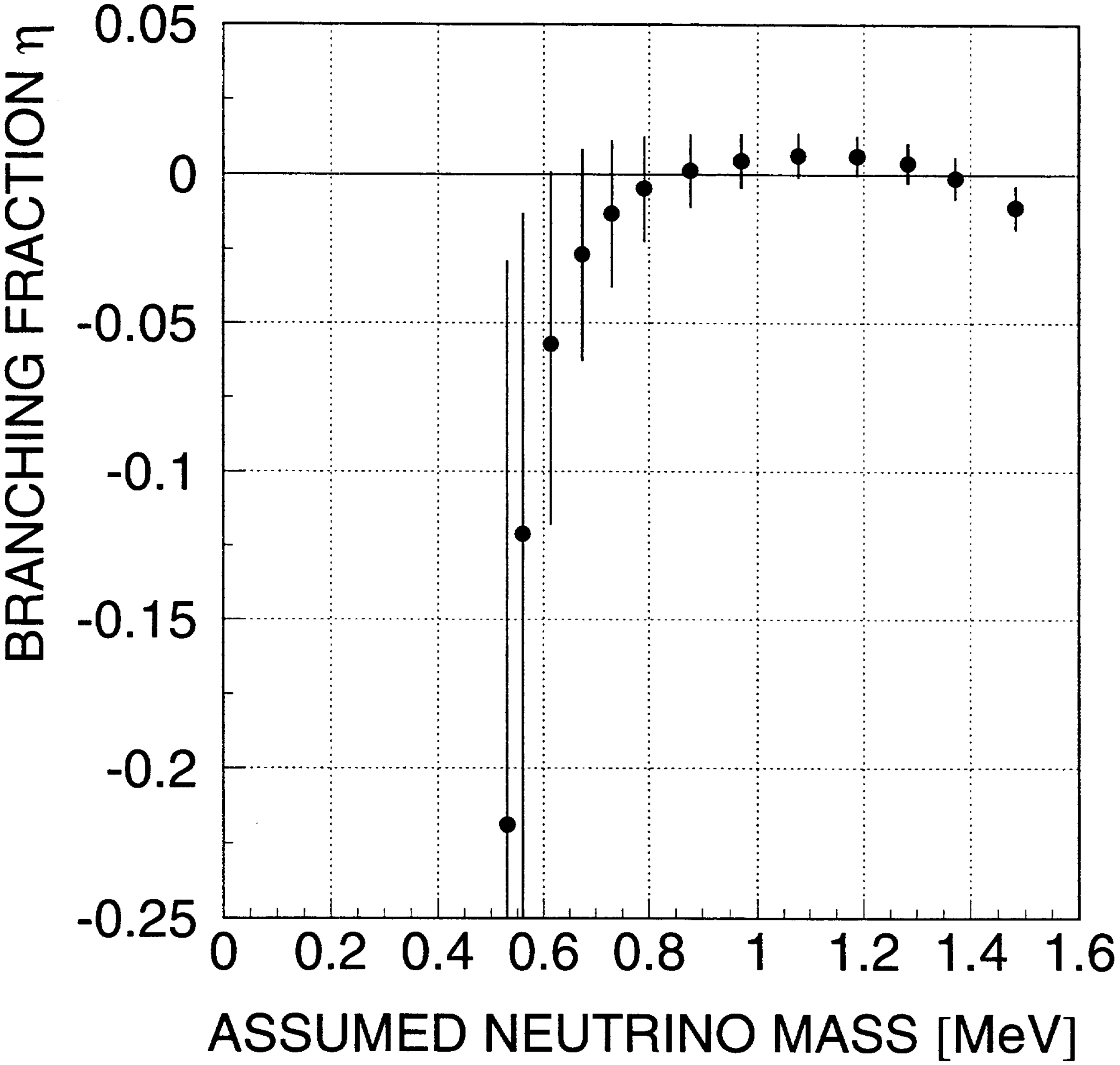
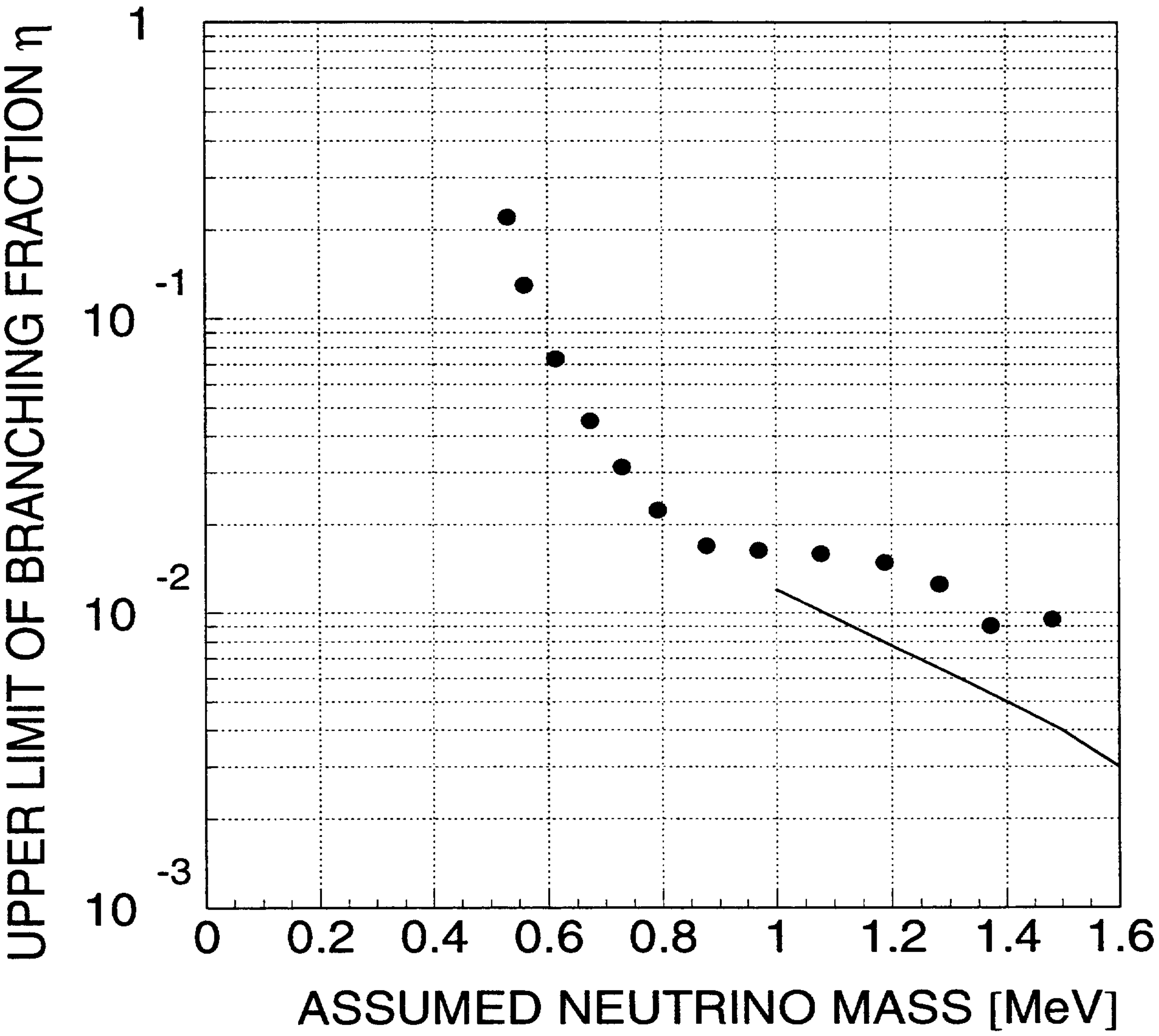

BRANCHING FRACTION η
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
ASSUMED NEUTRINO MASS [MeV]

Figure 4:



UPPER LIMIT OF BRANCHING FRACTION η
1
10 -1
10 -2
10 -3
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
ASSUMED NEUTRINO MASS [MeV]