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SEARCHING FOR HEAVY NEUTRAL LEPTONS*

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ABSTRACT

The motivation for searches for heavy neutral leptons is recalled. The status of such searches in high energy physics experiments is reviewed in the context of major improvements in detection sensitivity and the order of magnitude increase in mass range accessible experimentally.

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I. INTRODUCTION

Searching for heavy neutral leptons is motivated from several directions. From a general perspective, the number of quarks and leptons in Nature is a quantity whose value is presently unknown and which is outside of the standard model's predictive capabilities. In particular, one would like to know how many generations or families there are, if any, beyond the presently known three. If the known fundamental fermions are taken as a basis on which to judge, then the lightest member of a new, fourth generation should be its neutrino. This could make it most accessible for discovery by experiments now or in the very near future.

The values of the masses of quarks and leptons also are not explained within the standard model. Understanding the vanishing or very small values of neutrino masses compared to other lepton or quark masses could be part of the key to a more general understanding of masses and of physics beyond the standard model. In particular, there are theories which seek to account for the small (if they are indeed non-vanishing) masses of the three known neutrinos by invoking the existence of heavy neutral leptons. Such leptons generally mix with the corresponding light neutrino via the same mechanism which gives the latter a small mass, thereby allowing for production and decay of the heavy neutral leptons through the charged-current weak interaction.

Yet another impetus for asserting the existence of such particles comes from grand unification, i. e. encompassing the $SU(3) \times SU(2) \times U(1)$ gauge group of the standard model in a larger group. The representations of such a group often have room for one or more neutral leptons beyond the known ones. Theories in which the symmetry between right and left is restored at high energy suggest the existence of such particles as well.

At the same time that theoretical interest has been increasing,[1-3] the scope and sensitivity of experimental techniques has also been undergoing a dramatic change.[4] High flux hadron beams at both low and high energy now permit very low limits being placed on the emission of neutral leptons in leptonic or semileptonic hadron decays. At electron-positron colliders, center-of-mass energies and integrated luminosities have reached the level where weak interaction cross sections are capable of being responsible for production of detectable numbers of new neutral leptons. This, along with the concurrent development of precision vertex detectors at such machines,[5] has made it possible to extend the mass range under investigation by over an order of magnitude. While previously one was limited by the mass of the decaying hadron, in many cases the kinematic limit now is simply the center-of-mass energy of the electron-positron collision. The near future should see this line of analysis take another large jump in sensitivity through the study of Z decays into neutral lepton pairs. This will permit a high sensitivity sweep of the mass range from zero to half the Z mass.

With this coincidence of theoretical interest and rapidly rising sensitivity in experimental techniques, we review here the present status of the search for neutral heavy leptons in high energy physics experiments.[6] We start with a short discussion of some of the theoretical ideas which stimulate these searches and the definition of the relevant parameters. Then we examine the various techniques which have been or will be used to search for neutral heavy leptons, collecting along the way the regions of masses and mixing matrix elements which have already been excluded. We conclude with a discussion of the level of sensitivity to which presently available techniques can be pushed and the additional opportunities for searches which are opened by machines now under construction.

II. TYPES OF NEUTRAL LEPTONS

The most straightforward extension of the presently known neutral leptons, i.e. the electron, muon, and tau neutrinos, is to add a fourth, so-called "sequential" neutrino as a part of a fourth generation consisting of a charge $2e/3$ quark, a charge $-e/3$ quark, a charge $-e$ lepton, and a neutrino. The left-handed quarks and leptons reside in weak isospin doublets, while all right-handed fermions are singlets, as for the first three generations. Moreover, in the canonical version of the standard model there is no right-handed neutrino field at all and simply no way to obtain a massive neutrino: the neutrino is left-handed and massless. More generally, going slightly beyond the standard model, it is entirely possible to supply a right-handed singlet field and make such a neutrino a massive fermion. Then, just as for the quark sector, the weak and mass eigenstates will not coincide. This is conveniently expressed in terms of a unitary matrix U which "rotates" the neutrino mass eigenstates (the column index, labelled by the generation number) to the weak eigenstates (the row index, labelled by the corresponding charged lepton). For example, the neutrino which is in a left-handed doublet with the electron, ν_e, is the superposition of mass eigenstates, ν_j , given by

$$\nu_e = \sum_{j=1}^{4} U_{e\,j} \nu_j \tag{1}$$

in the case of four generations. Here, since all the neutral leptons have the same value of weak isospin, there are no lepton flavor-changing neutral currents.[7] This generalizes to adding an arbitrary number of generations. The unitary property of the matrix U implies that the Z couples to each pair of neutrino mass eigenstates with the same universal strength, but there are no couplings of the Z (at tree level) to different mass eigenstates.

Such a heavy neutrino will in general be unstable. It can decay through the emission of a W boson into a charged lepton, ℓ, with the standard coupling strength multiplied by $U_{\ell 4}$. If the heavy neutrino has a mass $m > M_W + m_\ell$, the decay proceeds into a charged lepton and a "real" W. If on the other hand $m < M_W$, as we shall take to be the case for our present discussion, then the W is "virtual" and materializes through its standard weak couplings to pairs of leptons or quarks, as allowed by phase space. For example, for our prototypical fourth generation sequential neutrino with m $\ll M_W$, the decay $\nu_4 \rightarrow e^- + W^+_{virtual} \rightarrow e^- + e^+\nu_e$ occurs at the rate

$$\Gamma(\nu_4 \rightarrow e^- + e^+\nu_e) = |U_{e4}|^2 \, \frac{G_F^2 m^5}{192\pi^3}, \tag{2}$$

where the masses of the final leptons have been neglected. Similar formulas hold for the decay widths into other channels, with those where the W materializes into hadrons being calculated inclusively in the usual way, i.e. as if there were a pair of free quarks in place of the hadrons in the final state. The rate for the latter process picks up an extra factor of three over the purely leptonic decay rate in Eq. (2) because of color. Since there are no tree level diagrams for decay involving neutral currents, the decay products of such a "sequential" neutrino contain at least two charged leptons or hadrons. If no charged-current decays are allowed, either because mixing matrix elements vanish or because the relevant charged leptons are heavier than ν_4, then higher order diagrams can result in the dominant decays having only neutral particles in the final state, e.g. radiative decays to other neutrinos.

Neutral leptons are also predicted which behave as singlets under the weak isospin of the standard model. Such is the case, for example, in some grand unified models such as $O(10)$, where the 16 dimensional representation includes all the usual quarks and leptons of one generation plus a right-handed singlet, neutral lepton.[8] In left-right symmetric theories as well, there are often heavy neutral leptons.[9] In particular, they arise as the partners of the usual charged leptons under the additional $SU(2)$ gauge group with right-handed couplings, but are singlets under the usual $SU(2)$ gauge group with left-handed couplings of the standard model.

A particularly attractive reason for having further singlet neutral leptons is the so-called "see-saw" mechanism[10] for generating neutrino masses. With each left-handed neutrino one associates a right-handed partner, N, as in the sixteen dimensional representation of $O(10)$, so that the mass matrix involving ν and N looks like

$$M = \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} . \tag{3}$$

Here m_D is a Dirac mass, presumably comparable to a quark or charged lepton mass of that generation, and M is a large Majorana mass. The eigenstates of this matrix will have masses of m_D^2/M and M approximately. Thus we have light neutrinos as well as heavy ones. The mixing matrix elements, $U_{\ell N}$, between the light neutrinos (which are members of the usual left-handed isodoublets with corresponding charged leptons, ℓ) and the heavy neutral singlets are of order m_D/M. We can also arrange matters so that the light neutrino remains massless, but still mixes with a singlet Dirac heavy neutral lepton.[11,12] In either case, as we have light and heavy neutrinos belonging to two different representations of weak isospin, there is no Glashow-Iliopoulos-Maiani mechanism[7] and neutrino flavor-changing neutral-currents occur. Their strength, aside from Clebsch-Gordan coefficients, is in fact the same as that of the charged-current between the corresponding charged lepton and N, i.e. proportional to the value of the matrix element $U_{\ell N}$. The coupling of the Z to a pair of heavy neutrinos is doubly suppressed, i.e. proportional to $|U_{\ell N}|^2$.

Such heavy neutrinos are potentially unstable not only through charged-current decays to a charged lepton ℓ involving emission of a W^+, but through neutral-current decays to ν_ℓ through emission of a Z^0. As noted above, the amplitudes for both these processes are proportional to the same mixing matrix element $U_{\ell N}$. A calculation[2] of the relative branching ratios shows that about two-thirds to the decays proceed through the charged-current and one-third through the neutral current; only about a tenth of all decays result in a final state consisting of only neutrinos.

Another possibility is the existence of mirror neutrinos, i.e. neutral leptons in right-handed doublets under the usual $SU(2)$, together with corresponding mirror charged leptons.[13] Such neutral leptons are left-handed singlets; hence the name mirror fermions as they are just the mirror image of the usual fermions in the standard model. A recent case in point is provided by the $O(18)$ grand unified model[14] which predicts a fourth generation with the usual left-handed weak interaction couplings as well as four(!) generations of quarks and leptons with right-handed couplings. Each of these generations contains a neutral lepton with a mass below about 40 GeV.

In the right-hand sector, with the mirror fermions in doublets one has full strength Z couplings to pairs of mirror leptons, related in the standard way to W couplings. In this regard, the mirror neutrinos are like sequential neutrinos. However, in the left-hand sector the mirror neutrinos are singlets and consequently, as discussed above in the case of singlet neutrinos, one has both charged-current and flavor-changing neutral-current couplings between mirror neutrinos and the usual leptons, suppressed by factors of the relevant mixing matrix elements. If the masses of the other mirror fermions permit it, a mirror neutrino will dominantly decay through its full strength right-handed couplings in the mirror sector. But if mixing matrix elements or lack of phase space prohibit this, then the decay proceeds through mixing with the usual fermions in left-handed doublets, suppressed in rate by squares of mixing matrix elements, and in the pattern of singlet neutrinos discussed previously.

III. SEARCH TECHNIQUES AND RESULTS

A variety of techniques have been used over the years in high energy physics experiments to search for neutral heavy leptons. We shall examine them in more or less historical order of their use. Putting a somewhat arbitrary lower limit of 10 MeV on what we mean by "heavy", as we discuss each of the techniques we will also show the corresponding bounds that have been achieved experimentally. In doing so, we first present the bounds that follow for the case of a fourth generation "sequential" heavy Dirac neutrino, but discuss as well what happens if the neutral lepton is an SU(2) singlet or is a mirror lepton.

Before the searches at electron-positron colliders, most of the previous limits on mixing of a heavy neutrino with the electron or muon neutrino came from hadron leptonic or semileptonic decays. A direct and powerful technique[15] is to study pion or kaon decays at rest, searching for additional monochromatic peaks in the electron or muon momentum spectra in the leptonic decays $\pi \rightarrow e\nu$, $\pi \rightarrow \mu\nu$, $K \rightarrow e\nu$, or $K \rightarrow \mu\nu$, as appropriate. Upper limits on the mixing with a fourth generation neutrino extracted using this technique are shown[16-19] as the limiting curves for $|U_{e4}|^2$ labelled (1), (2), and (3) in Figure 1 and the curves for $|U_{\mu4}|^2$ labelled (3) and (12) in Figure 2. At the present time, limits on the square of these mixing matrix elements are in the region of 10^{-6} from such experimental searches.

A different, but related technique in that it relies on the decay in flight of the same hadrons, namely π and K mesons, arose when it was realized[20] that the heavy neutral leptons so produced would themselves decay downstream. It was therefore possible to use existing neutrino detectors or modifications thereof to conduct searches for the subsequent decay of the heavy neutral leptons produced in high intensity π and K beams. In the potentially observed experimental rate, the square of a mixing matrix element enters twice: first in the production where the neutral lepton is born in π or K decay through mixing with the electron or muon neutrino, and then again when the heavy lepton decays weakly into ordinary leptons or leptons and quarks. Depending on the beam and the particular sensitivities of the detector these two mixing matrix elements could be the same or different. Limits obtained from π and K beams using this technique[21,22] are given by curves (4) and (10) in Figure 1 , where it is seen that for neutral lepton masses below the K mass they now provide the best upper limits on $|U_{e4}|^2$, going down to below 10^{-8}.

Once we are utilizing hadron decays in flight, we need not restrict our attention to π and K decays, as we are limited by their masses. Charmed meson decays extend the range of investigation considerably. To enhance their proportion of the neutrino flux one employs a beam dump to absorb longer lived hadrons before they can decay weakly, leaving short lived mesons (and baryons) which have "prompt" decays, typically a small fraction of an absorption length. With the increased mass range opened up by the charmed meson masses, both purely leptonic and semileptonic decays are potential sources of new neutral leptons in an interesting mass range. Some of the recent limits[23–25] obtained in this manner are given by curves (5), (9), and (11) in Figures 1 and 2 for $|U_{e4}|^2$ and $|U_{\mu 4}|^2$, respectively. It is also possible to get limits on $|U_{e4}U_{\mu 4}|$ using hadron decays in flight (either with beams or in beam dumps) by, for example, producing the heavy neutrino in association with a muon and detecting its charged-current decay involving an electron.[21,22,] Note that the excluded regions generally have an upper as well as lower boundary, the former corresponding to a mixing matrix element which is large enough that the heavy neutral lepton will decay before it arrives in the detector volume and no limit will be set. In this regard an experiment that is closer to the beam dump (as in Ref. 24) generally will do better on excluding "large" values of the mixing matrix elements, but worse on "small" values.

There is no reason to stop at charm with this technique. Hadrons containing bottom and even top quarks can be employed; one is only limited by their production cross sections in hadron-hadron collisions. Indeed it has been pointed out[26] that beam dump experiments utilizing B meson decays could extend the limits to masses of roughly 2.5 GeV/c^2 at the 10^{-6} level. One should also note that all the limits we have discussed up to now involve charged-current weak interactions to produce the heavy neutral lepton in association with ordinary charged leptons. Hence the relevant mixing matrix elements and amplitudes at the production vertex are independent of whether a doublet, a singlet, or a mirror neutral lepton is under scrutiny.

To extend the search to the domain of yet higher masses we turn to electron-positron colliders where we are limited kinematically only by the center-of-mass energy for $e^+e^- \to \overline{\nu}_4\nu_e$ (and half of it for pair production of heavy neutrinos). If the neutrino is in a left-handed doublet, as for a fourth generation neutrino, then its production proceeds in lowest order through W exchange with a cross section[27] for $s \ll M_W^2$

$$\sigma(e^+e^- \to \overline{\nu}_4\nu_e) = |U_{e4}|^2 \, \frac{G_F^2 s}{6\pi} \, (1 - m^2/s)^2(1 + m^2/2s) \qquad (4)$$

where m is the neutrino mass and s the square of the center-of-mass energy.

Such a process will be observed as an electron-positron collision which results in an event with missing energy and momentum (due to the ν_e) on one side and, if m is not too large, a jet of decay products of ν_4 on the other side, i.e. a monojet event. Such events have been searched for recently at PEP and PETRA in another context.[28–31] By combining the PEP data one obtains[32] the upper limit shown as curve (7) in Fig. 1. This is already a considerable improvement over the limit following from universality[33] shown as curve (6), and can be improved still further, as we discuss below.

In contrast with Eq. (4), the cross section for production of a pair of "sequential" Dirac neutrinos through a "virtual" Z:

$$\sigma(e^+e^- \to \overline{\nu}_4\nu_4) =$$

$$\frac{G_F^2 s}{24\pi} \frac{(1-4m^2/s)^{1/2}(1-m^2/s)}{1-s/M_Z^2} \left(1-4\sin^2\theta_W + 8\sin^4\theta_W\right) \tag{5}$$

does not contain a factor of $|U_{e4}|^2$. With the presently accumulated luminosity at PEP, dozens of such heavy neutrino pairs should have be produced in each experimental region as long as their mass is at least slightly below the beam energy. Since the decay width is still proportional to the square of a mixing matrix element, a search for secondary decay vertices sweeps out a region in the $|U|^2$ versus m plane. The results of such a search between 0.2 and 10 cm from the interaction point are shown[34] as the diagonal region going up to masses of almost 14 GeV/c^2, bounded by curve (8) in Figures 1 and 2.

What happens to all these bounds if we had been considering a singlet neutrino rather than a "sequential" neutrino in a doublet? All the bounds that come from hadron leptonic or semileptonic decay remain the same (aside from slight shifts in limits for those experiments which rely on detecting particular decays whose predicted branching ratios change somewhat due to additional neutral-current interactions).[35] The cross section for $e^+e^- \to Z_{virtual} \to \overline{N}N$ picks up a factor of $|U|^4$ over Eq. (5), making it negligibly small given present experimental sensitivities and interesting values of $|U|^2$, and we unfortunately lose the restrictions obtained from the search for secondary vertices in electron-positron annihilation. In the case of $e^+e^- \to N\overline{\nu}_e$, we now have both W exchange and direct-channel Z contributions and the expression for the cross section becomes

$$\sigma(e^+e^- \to N\overline{\nu}_e) =$$

$$|U_{eN}|^2 \frac{G_F^2 s}{24\pi} \left(1 - \frac{m^2}{s}\right)^2 \left(1 + \frac{m^2}{2s}\right) \left(1 + 4\sin^2\theta_W + 8\sin^4\theta_W\right) . \tag{6}$$

If $\sin^2\theta_W = 0.22$, then the cross section in Eq. (6) is 0.57 times that in Eq. (5) and the monojet searches have the reduced sensitivity shown in Figure 3.

In contrast to the reduced sensitivity to mixing of N with the electron neutrino in monojet searches, we gain from the neutrino flavor changing coupling of the Z a direct-channel Z contribution to $e^+e^- \to N\overline{\nu}_\mu$ which is proportional to $|U_{\mu N}|^2$:

$$\sigma(e^+e^- \to N\overline{\nu}_\mu) =$$

$$|U_{\mu N}|^2 \frac{G_F^2 s}{24\pi} \left(1 - \frac{m^2}{s}\right)^2 \left(1 + \frac{m^2}{2s}\right) \left(1 - 4\sin^2\theta_W + 8\sin^2\theta_W\right) . \tag{7}$$

An identical expression with τ in place of μ follows from potential mixing with the tau neutrino. The limit that is obtained for $|U_{\mu N}|^2$ from Eq. (7) from existing experiments is not better than that from universality, so only the latter is shown as curve (6) in Figure 4.

However, the presence of neutrino flavor changing couplings of the Z does lead to a new limit on $|U_{\mu N}|^2$ from the lack of observation of the process ν_μ+nucleus $\to$ $N + \ldots$, followed by decay of the N. The region bounded by curve (13) in Figure 4 has been excluded by the CHARM collaboration[23] in this way.

The experimental situation for mirror neutrinos is somewhat of a cross between those for sequential and right-handed singlet heavy neutral leptons. Since mirror neutrinos lie in right-handed doublets, they have full strength couplings to the Z (like sequential neutrinos) and the limits from electron-positron annihilation experiments pertain to them (curve (8) in Figures 1 and 2). On the other hand, being left-handed singlets, they also have flavor changing couplings to the Z and limits following from production through such couplings (such as curve (13) in Figure 4) also are applicable.

IV. FUTURE POSSIBILITIES

In the near future it should be possible to considerably extend many of the limits by further analysis of existing data. Particularly in electron-positron annihilation the boundary of the excluded region (curve (8) in Figures 1 and 2) can be pushed downward by looking for vertices further from the interaction point than the present 10 cm, and pushed upward by looking for vertices closer than 0.2 cm to the interaction point. In this latter case, one may give up on looking for a secondary vertex altogether, and conduct a search for $e^+e^- \rightarrow \overline{\nu}_4\nu_4$ directly[36] by searching for "low" mass jets plus ordinary charged leptons from the charged-current decay of the heavy neutral leptons. Published searches[37] are not sensitive enough to exclude a further region in Figure 1, but there is sufficient data now to exclude a region above that covered by the existing vertex search, out to masses of 5 to 7 GeV/c^2 before backgrounds overtake a potential signal.[38] There is in fact one published event from the CELLO detector[39] at PETRA involving muons and jets which could have its origin in production and decay of a heavy neutral lepton with a mass of about 20 GeV/c^2, but no other experiment has produced confirming evidence for events with such an interpretation. The limits coming from searches for "monojets" from $e^+e^- \rightarrow \overline{\nu}_4\nu_e$ may be extended as well by an increase in data, analysis of higher energy data from PETRA, and changing experimental cuts to maximize acceptance for larger values of the heavy neutral lepton's mass. Combining all the experiments it should be possible, for example, to exclude values of $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ above 10^{-6} up to masses of about 20 GeV/c^2. Upper limits on $|U_{e4}|^2$ of 10^{-2} to 10^{-3} should be obtainable from PETRA data for masses up to 30 GeV/c^2 from monojet searches.

A larger range of masses is now accessible in principle from W and Z production at $\bar{p}p$ colliders[40] followed by their decay into new leptons, e.g. $W \to \ell N$. A particularly striking, monojet signature occurs when the heavy neutral lepton decays into neutrinos and one obtains an event with missing energy and momentum plus a balancing charged lepton or, if from the decay of a Z, the decay products of another neutral lepton. Present searches conducted in this manner are not very sensitive, in large part because of serious backgrounds from both hadronic and electroweak processes, and in part because the accumulated Z and W samples are not enormous. As the accumulated luminosity and energy go up the limits will become more stringent. Moreover, there is the possibility of producing new gauge bosons which may couple more strongly than the Z to additional heavy neutral leptons or be at a high enough mass to decay into them directly.[41]

A still higher mass region for certain heavy neutral leptons can be explored at ep colliders. Earlier experiments have searched for heavy leptons in $\mu + nucleus \to N + \ldots$ and were sensitive to a heavy lepton below 9 GeV/c^2 with full strength right handed couplings.[42] At HERA the process $ep \to N + \ldots$ will permit the exploration of the region of masses over 100 GeV/c^2, especially for neutrinos coupled to right-handed currents.[43]

A dramatic increase in sensitivity will occur when the SLC and LEP come into full operation. With six percent of Z decays going into neutrino-antineutrino for each light neutrino in a weak doublet, additional sequential or mirror neutrinos will be very amenable to detection. The presence of such particles with low masses can be ascertained by "neutrino counting", i.e. tagging Z decays into unseen neutrals and seeing if the resulting decay width is accounted for by the known neutrinos. Those with higher masses will generally decay through mixing, but here the technique of using vertex detectors will enable us to exclude masses up to about 40 GeV/c^2 and mixing matrix elements squared down to around 10^{-10}. Monojet searches looking for $Z \rightarrow N\overline{\nu}$ could be sensitive to weak singlet heavy neutral leptons with masses up to a large fraction of the Z mass and mixing matrix elements to the known neutrinos down to about 10^{-5}

The last few years have seen a large extension in both the accessible mass range and in the sensitivity to small mixing matrix elements with the known neutrinos in searches for heavy neutral leptons. The next few years should see these techniques applied to Z decays at lepton colliders and to gauge boson decays at $\overline{p}p$ and ep colliders with resulting stringent limits on, or the discovery of, neutral leptons with masses up to those of the W and Z.

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35. Care must also be taken on whether Dirac or Majorana neutrinos are under consideration since, for example, limits on mixing matrix elements derived from those experiments which detect heavy lepton decays in a given fiducial volume depend on their decay rates, which generally differ in the two cases. See R. E. Shrock, Phys. Rev. D24, 1275 (1981) and Phys. Lett. 112B, 382 (1982).

36. R. Thun, Phys. Lett. 134B, 459 (1984).

37. D. Errede *et al.*, Phys. Lett. 149B, 519 (1984); M. L. Perl *et al.*, Phys. Rev. D32, 2859 (1985).

38. G. J. Feldman (private communication).

39. H. J. Behrend *et al.*, Phys. Lett. B141, 145 (1984).

40. See, for example, V. Barger *et al.*, Ref. 2.

41. See, for example, J. L. Rosner, Comments Nucl. Part. Phys. 14, 229 (1985).

42. A. R. Clark *et al.*, Phys. Rev. Lett. 46, 299 (1981).

43. See, for example, R. J. Cashmore *et al.*, Phys. Rep. 122, 275 (1985).

FIGURE CAPTIONS

1. Limits on $|U_{e4}|^2$ as a function of the mass M_4 of a sequential, fourth generation neutrino as obtained from (1) TRIUMF $\pi \to e\nu$, Ref. 16; (2) SIN $\pi \to e\nu$, Ref. 17; (3) KEK $K \to e\nu$, Ref. 18; (4) CHARM experiment at CERN with a wide band beam, Ref. 21; (5) CHARM experiment at CERN using a beam dump, Ref. 23; (6) Universality, Ref. 33; (7) Monojet searches at PEP, Ref. 32; (8) Mark II secondary vertex search at PEP, Ref. 34; (9) Beam dump experiment at Fermilab, Ref. 24; (10) Wide band beam experiment at the PS at CERN, Ref. 22; (11) BEBC experiment at CERN using a beam dump, Ref. 25.

2. Limits on $|U_{\mu4}|^2$ as a function of the mass M_4 of a sequential, fourth generation neutrino as obtained from (3) KEK $K \to \mu\nu$, Ref. 18; (5) CHARM experiment at CERN using a beam dump, Ref. 23; (6) Universality, Ref. 33; (8) Mark II secondary vertex search at PEP, Ref. 34; (9) Beam dump experiment at Fermilab, Ref. 24; (11) BEBC experiment a CERN using a beam dump, Ref. 25; (12) SIN $\pi \to \mu\nu$, Ref. 19.

3. Limits on $|U_{eN}|^2$ as a function the mass M_N of a singlet heavy neutral lepton as obtained from various experiments, with curves labelled as in Figure 1.

4. Limits on $|U_{\mu N}|^2$ as a function of the mass M_N of a singlet heavy neutral lepton as obtained from various experiments, with curves labelled as in Figure 2, plus (13) CHARM experiment at CERN using a muon neutrino beam, Ref. 23.

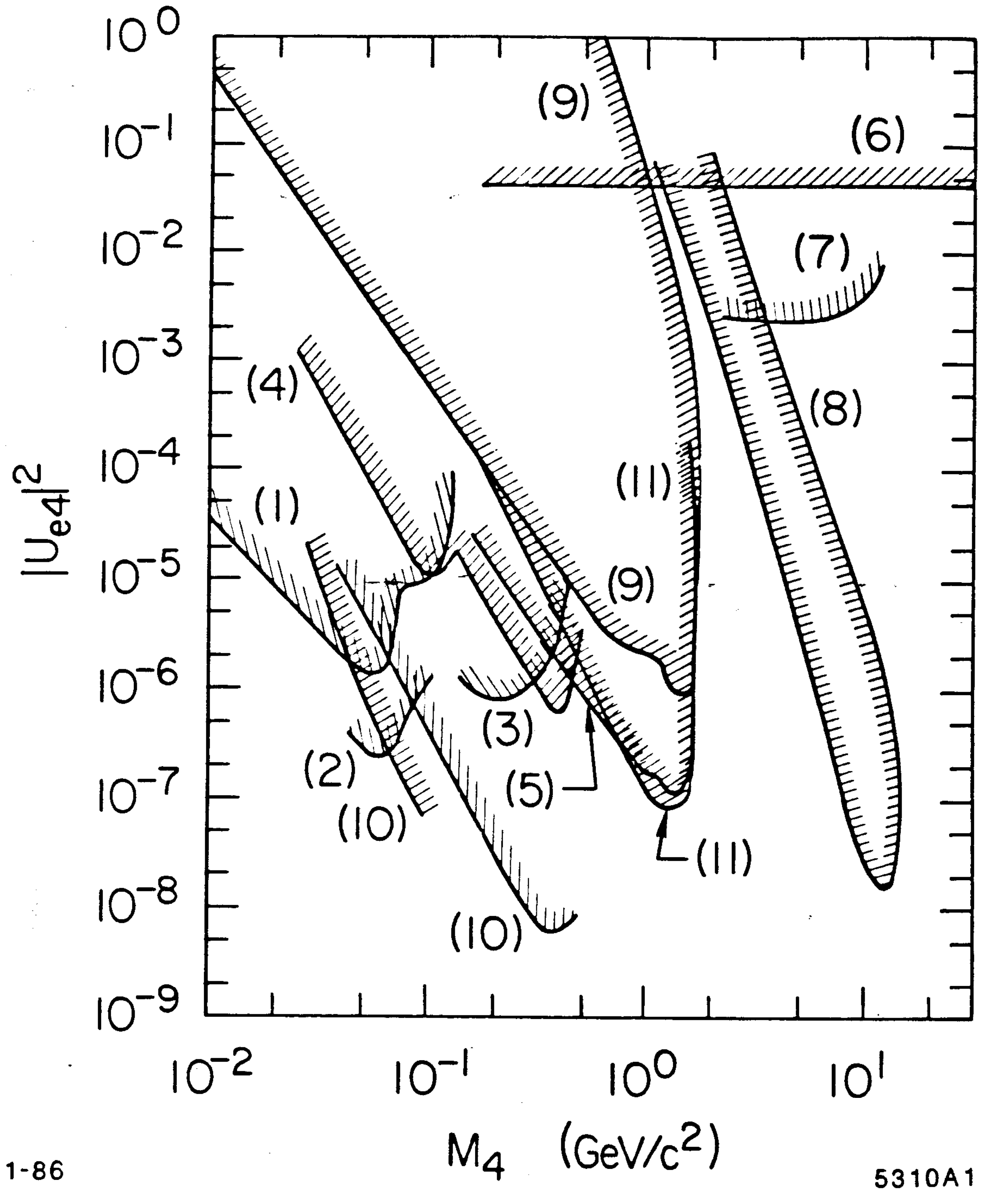
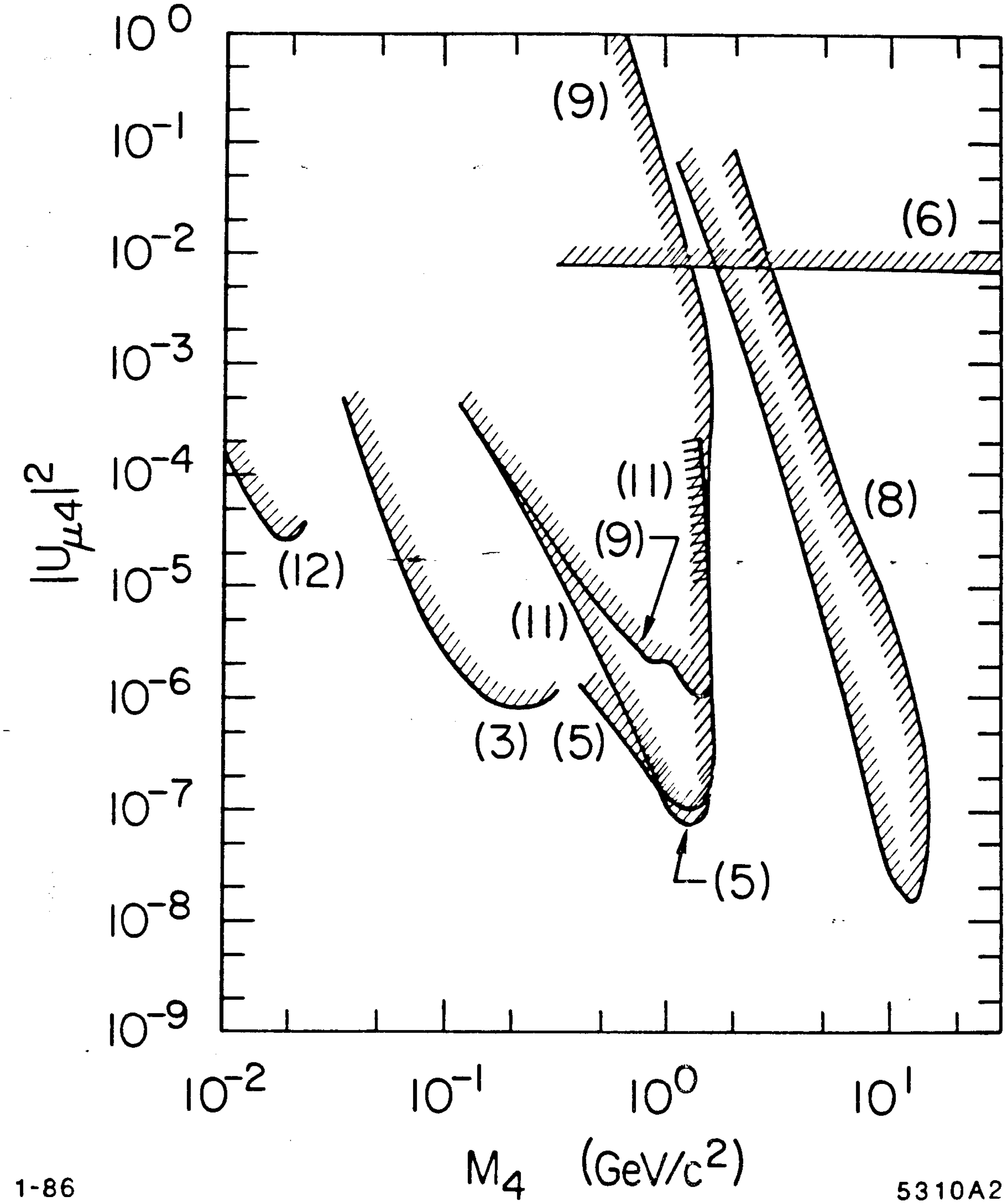
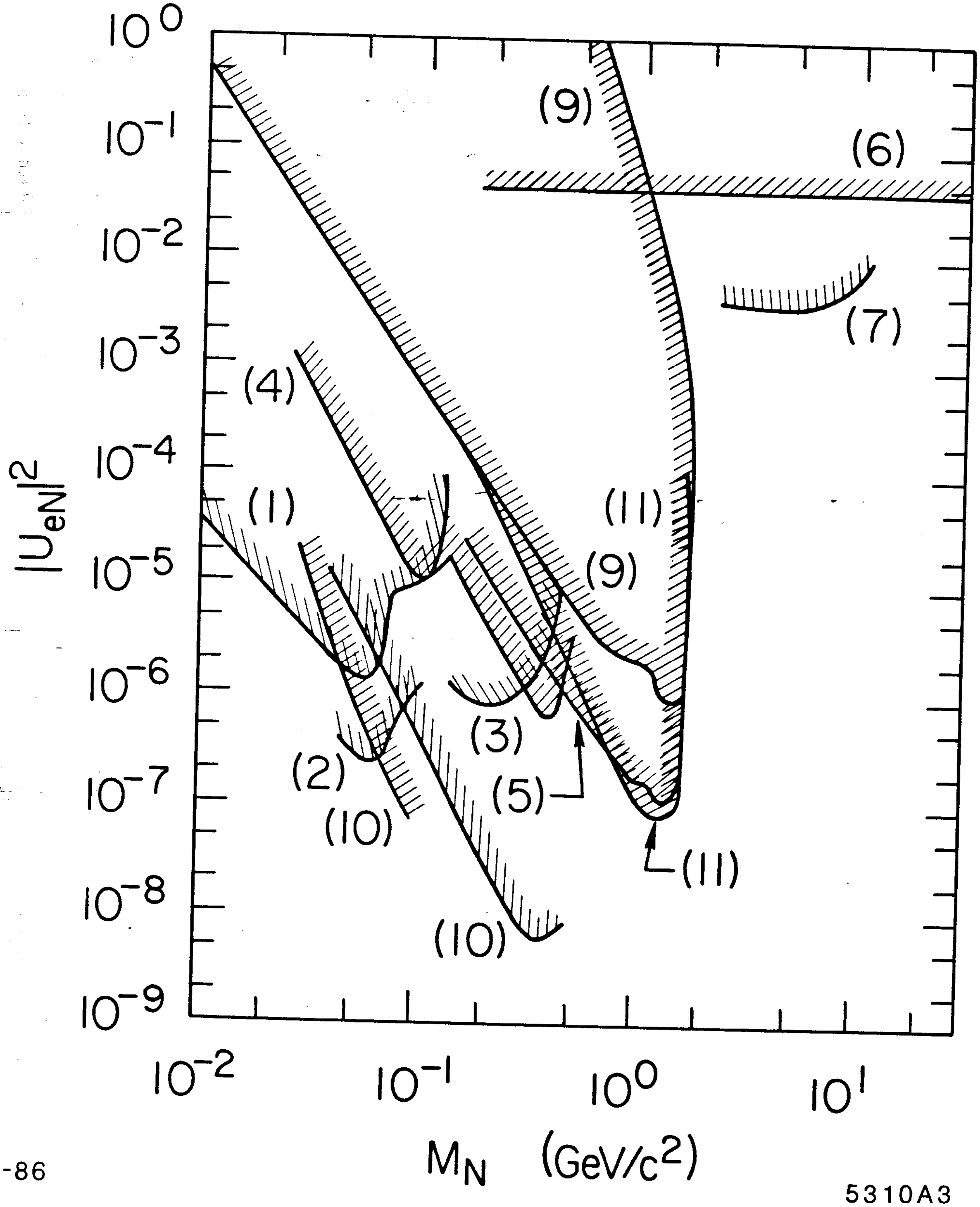

10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
|Ue4|^2
10^-2
10^-1
10^0
10^1
M4 (GeV/c^2)
(1)
(2)
(3)
(4)
(5)
(6)
(7)
(8)
(9)
(9)
(10)
(10)
(11)
(11)
1-86
5310A1

FIG. 1



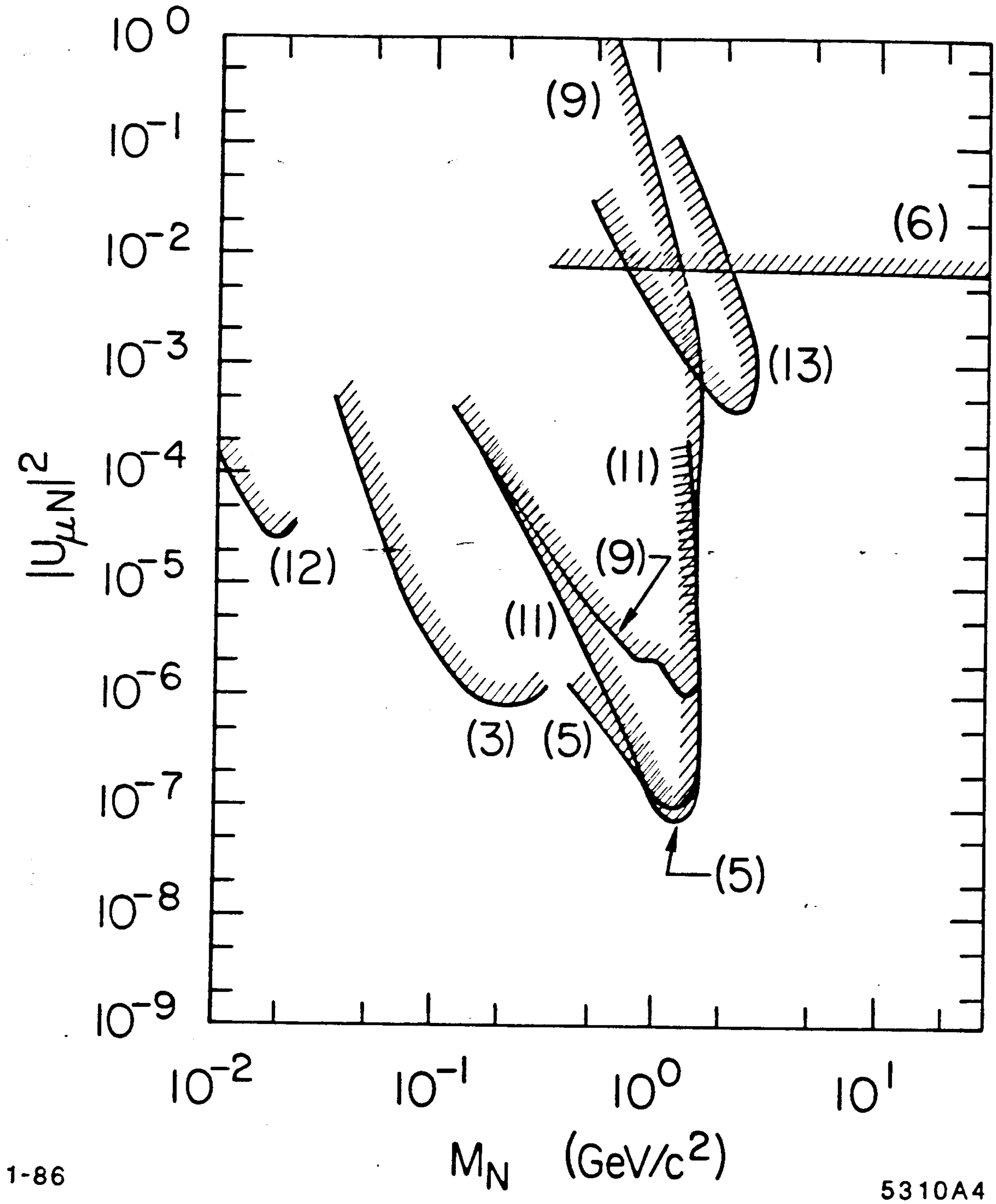
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$|U_{\mu 4}|^2$
(9)
(6)
(8)
(11)
(9)
(12)
(11)
(3)
(5)
(5)
10^{-2}
10^{-1}
10^0
10^1
M_4 (GeV/c^2)
1-86
5310A2

FIG. 2



10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
|U_eN|^2
(1)
(2)
(3)
(4)
(5)
(6)
(7)
(9)
(9)
(10)
(10)
(11)
(11)
10^-2
10^-1
10^0
10^1
M_N (GeV/c^2)
1-86
5310A3

FIG. 3



(9)
(6)
(13)
(11)
(12)
(9)
(11)
(3)
(5)
(5)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$|U_{\mu N}|^2$
10^{-2}
10^{-1}
10^0
10^1
M_N (GeV/c^2)
1-86
5310A4

FIG. 4