

# Heavy Neutral Leptons, Searches for

## (A) Heavy Neutral Leptons

### ———— Stable Neutral Heavy Lepton MASS LIMITS ————

Note that LEP results in combination with REUSSER 91 exclude a fourth stable neutrino with  $m < 2400$  GeV.

| <u>VALUE (GeV)</u> | <u>CL%</u> | <u>DOCUMENT ID</u> | <u>TECN</u> | <u>COMMENT</u>     |
|--------------------|------------|--------------------|-------------|--------------------|
| <b>&gt;45.0</b>    | 95         | ABREU              | 92B         | DLPH Dirac         |
| <b>&gt;39.5</b>    | 95         | ABREU              | 92B         | DLPH Majorana      |
| >44.1              | 95         | ALEXANDER          | 91F         | OPAL Dirac         |
| >37.2              | 95         | ALEXANDER          | 91F         | OPAL Majorana      |
| none 3–100         | 90         | SATO               | 91          | KAM2 Kamiokande II |
| >42.8              | 95         | <sup>1</sup> ADEVA | 90S         | L3 Dirac           |
| >34.8              | 95         | <sup>1</sup> ADEVA | 90S         | L3 Majorana        |
| >42.7              | 95         | DECAMP             | 90F         | ALEP Dirac         |

<sup>1</sup>ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies  $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 > 6.2 \times 10^{-8}$  at  $m_{L0} = 20$  GeV and  $> 5.1 \times 10^{-10}$  for  $m_{L0} = 40$  GeV.

### ———— Heavy Neutral Lepton MASS LIMITS ————

Limits apply only to heavy lepton type given in comment at right of data Listings.

See the “Quark and Lepton Compositeness, Searches for” Listings for limits on radiatively decaying excited neutral leptons, *i.e.*  $\nu^* \rightarrow \nu\gamma$ .

| <u>VALUE (GeV)</u> | <u>CL%</u> | <u>DOCUMENT ID</u> | <u>TECN</u> | <u>COMMENT</u>                 |
|--------------------|------------|--------------------|-------------|--------------------------------|
| <b>&gt;101.3</b>   | 95         | ACHARD             | 01B         | L3 Dirac coupling to $e$       |
| <b>&gt;101.5</b>   | 95         | ACHARD             | 01B         | L3 Dirac coupling to $\mu$     |
| <b>&gt; 90.3</b>   | 95         | ACHARD             | 01B         | L3 Dirac coupling to $\tau$    |
| <b>&gt; 89.5</b>   | 95         | ACHARD             | 01B         | L3 Majorana coupling to $e$    |
| <b>&gt; 90.7</b>   | 95         | ACHARD             | 01B         | L3 Majorana coupling to $\mu$  |
| <b>&gt; 80.5</b>   | 95         | ACHARD             | 01B         | L3 Majorana coupling to $\tau$ |

● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●

|        |    |                         |     |                                   |
|--------|----|-------------------------|-----|-----------------------------------|
| > 76.0 | 95 | ABBIENDI                | 00i | OPAL Majorana, coupling to $e$    |
| > 88.0 | 95 | ABBIENDI                | 00i | OPAL Dirac, coupling to $e$       |
| > 76.0 | 95 | ABBIENDI                | 00i | OPAL Majorana, coupling to $\mu$  |
| > 88.1 | 95 | ABBIENDI                | 00i | OPAL Dirac, coupling to $\mu$     |
| > 53.8 | 95 | ABBIENDI                | 00i | OPAL Majorana, coupling to $\tau$ |
| > 71.1 | 95 | ABBIENDI                | 00i | OPAL Dirac, coupling to $\tau$    |
| > 76.5 | 95 | ABREU                   | 990 | DLPH Dirac coupling to $e$        |
| > 79.5 | 95 | ABREU                   | 990 | DLPH Dirac coupling to $\mu$      |
| > 60.5 | 95 | ABREU                   | 990 | DLPH Dirac coupling to $\tau$     |
| > 63   | 95 | <sup>2,3</sup> BUSKULIC | 96S | ALEP Dirac                        |
| > 54.3 | 95 | <sup>2,4</sup> BUSKULIC | 96S | ALEP Majorana                     |

<sup>2</sup> BUSKULIC 96S requires the decay length of the heavy lepton to be  $< 1$  cm, limiting the square of the mixing angle  $|U_{\ell j}|^2$  to  $10^{-10}$ .

<sup>3</sup> BUSKULIC 96S limit for mixing with  $\tau$ . Mass is  $> 63.6$  GeV for mixing with  $e$  or  $\mu$ .

<sup>4</sup> BUSKULIC 96S limit for mixing with  $\tau$ . Mass is  $> 55.2$  GeV for mixing with  $e$  or  $\mu$ .

**————— Astrophysical Limits on Neutrino MASS for  $m_\nu > 1$  GeV —————**

| <u>VALUE (GeV)</u>  | <u>CL%</u> | <u>DOCUMENT ID</u>    | <u>TECN</u> | <u>COMMENT</u>         |
|---|------------|-----------------------|-------------|------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |            |                       |             |                        |
| none 60–115   |            | <sup>5</sup> FARGION  | 95          | ASTR Dirac             |
| none 9.2–2000   |            | <sup>6</sup> GARCIA   | 95          | COSM Nucleosynthesis   |
| none 26–4700  |            | <sup>6</sup> BECK     | 94          | COSM Dirac             |
| none 6 – hundreds   |            | <sup>7,8</sup> MORI   | 92B         | KAM2 Dirac neutrino    |
| none 24 – hundreds  |            | <sup>7,8</sup> MORI   | 92B         | KAM2 Majorana neutrino |
| none 10–2400  | 90         | <sup>9</sup> REUSSER  | 91          | CNTR HPGe search       |
| none 3–100  | 90         | SATO                  | 91          | KAM2 Kamiokande II     |
|   |            | <sup>10</sup> ENQVIST | 89          | COSM                   |
| none 12–1400  |            | <sup>6</sup> CALDWELL | 88          | COSM Dirac $\nu$       |
| none 4–16   | 90         | <sup>6,7</sup> OLIVE  | 88          | COSM Dirac $\nu$       |
| none 4–35   | 90         | OLIVE                 | 88          | COSM Majorana $\nu$    |
| $>4.2$ to $4.7$   |            | SREDNICKI             | 88          | COSM Dirac $\nu$       |
| $>5.3$ to $7.4$   |            | SREDNICKI             | 88          | COSM Majorana $\nu$    |
| none 20–1000  | 95         | <sup>6</sup> AHLEN    | 87          | COSM Dirac $\nu$       |
| $>4.1$  |            | GRIEST                | 87          | COSM Dirac $\nu$       |

<sup>5</sup> FARGION 95 bound is sensitive to assumed  $\nu$  concentration in the Galaxy. See also KONOPLICH 94.

<sup>6</sup> These results assume that neutrinos make up dark matter in the galactic halo.

<sup>7</sup> Limits based on annihilations in the sun and are due to an absence of high energy neutrinos detected in underground experiments.

<sup>8</sup> MORI 92B results assume that neutrinos make up dark matter in the galactic halo. Limits based on annihilations in earth are also given.

<sup>9</sup> REUSSER 91 uses existing  $\beta\beta$  detector (see FISHER 89) to search for CDM Dirac neutrinos.

<sup>10</sup> ENQVIST 89 argue that there is no cosmological upper bound on heavy neutrinos.

**(B) Other Bounds from Nuclear and Particle Decays**

**————— Limits on  $|U_{ex}|^2$  as Function of  $m_{\nu_x}$  —————**

**Peak and kink search tests**

Limits on  $|U_{ex}|^2$  as function of  $m_{\nu_j}$

| <u>VALUE</u>        | <u>CL%</u> | <u>DOCUMENT ID</u>    | <u>TECN</u> | <u>COMMENT</u>                                      |
|---------------------|------------|-----------------------|-------------|---|
| $<1 \times 10^{-7}$ | 90         | <sup>11</sup> BRITTON | 92B         | CNTR $50 \text{ MeV} < m_{\nu_x} < 130 \text{ MeV}$ |

• • • We do not use the following data for averages, fits, limits, etc. • • •

|                         |    |                      |     |      |                       |
|-------------------------|----|----------------------|-----|------|-----------------------|
| <5 × 10 <sup>-6</sup>   | 90 | DELEENER-...         | 91  |      | $m_{\nu_x} = 20$ MeV  |
| <5 × 10 <sup>-7</sup>   | 90 | DELEENER-...         | 91  |      | $m_{\nu_x} = 40$ MeV  |
| <3 × 10 <sup>-7</sup>   | 90 | DELEENER-...         | 91  |      | $m_{\nu_x} = 60$ MeV  |
| <1 × 10 <sup>-6</sup>   | 90 | DELEENER-...         | 91  |      | $m_{\nu_x} = 80$ MeV  |
| <1 × 10 <sup>-6</sup>   | 90 | DELEENER-...         | 91  |      | $m_{\nu_x} = 100$ MeV |
| <5 × 10 <sup>-7</sup>   | 90 | AZUELOS              | 86  | CNTR | $m_{\nu_x} = 60$ MeV  |
| <2 × 10 <sup>-7</sup>   | 90 | AZUELOS              | 86  | CNTR | $m_{\nu_x} = 80$ MeV  |
| <3 × 10 <sup>-7</sup>   | 90 | AZUELOS              | 86  | CNTR | $m_{\nu_x} = 100$ MeV |
| <1 × 10 <sup>-6</sup>   | 90 | AZUELOS              | 86  | CNTR | $m_{\nu_x} = 120$ MeV |
| <2 × 10 <sup>-7</sup>   | 90 | AZUELOS              | 86  | CNTR | $m_{\nu_x} = 130$ MeV |
| <1 × 10 <sup>-4</sup>   | 90 | <sup>12</sup> BRYMAN | 83B | CNTR | $m_{\nu_x} = 5$ MeV   |
| <1.5 × 10 <sup>-6</sup> | 90 | BRYMAN               | 83B | CNTR | $m_{\nu_x} = 53$ MeV  |
| <1 × 10 <sup>-5</sup>   | 90 | BRYMAN               | 83B | CNTR | $m_{\nu_x} = 70$ MeV  |
| <1 × 10 <sup>-4</sup>   | 90 | BRYMAN               | 83B | CNTR | $m_{\nu_x} = 130$ MeV |
| <1 × 10 <sup>-4</sup>   | 68 | <sup>13</sup> SHROCK | 81  | THEO | $m_{\nu_x} = 10$ MeV  |
| <5 × 10 <sup>-6</sup>   | 68 | <sup>13</sup> SHROCK | 81  | THEO | $m_{\nu_x} = 60$ MeV  |
| <1 × 10 <sup>-5</sup>   | 68 | <sup>14</sup> SHROCK | 80  | THEO | $m_{\nu_x} = 80$ MeV  |
| <3 × 10 <sup>-6</sup>   | 68 | <sup>14</sup> SHROCK | 80  | THEO | $m_{\nu_x} = 160$ MeV |

<sup>11</sup> BRITTON 92B is from a search for additional peaks in the  $e^+$  spectrum from  $\pi^+ \rightarrow e^+ \nu_e$  decay at TRIUMF. See also BRITTON 92.

<sup>12</sup> BRYMAN 83B obtain upper limits from both direct peak search and analysis of  $B(\pi \rightarrow e\nu)/B(\pi \rightarrow \mu\nu)$ . Latter limits are not listed, except for this entry (i.e. — we list the most stringent limits for given mass).

<sup>13</sup> Analysis of  $(\pi^+ \rightarrow e^+ \nu_e)/(\pi^+ \rightarrow \mu^+ \nu_\mu)$  and  $(K^+ \rightarrow e^+ \nu_e)/(K^+ \rightarrow \mu^+ \nu_\mu)$  decay ratios.

<sup>14</sup> Analysis of  $(K^+ \rightarrow e^+ \nu_e)$  spectrum.

### Kink search in nuclear $\beta$ decay

High-sensitivity follow-up experiments show that indications for a neutrino with mass 17 keV (Simpson, Hime, and others) were not valid. Accordingly, we no longer list the experiments by these authors and some others which made positive claims of 17 keV neutrino emission. Complete listings are given in the 1994 edition (Physical Review **D50** 1173 (1994)) and in the 1998 edition (The European Physical Journal **C3** 1 (1998)). We list below only the best limits on  $|U_{ex}|^2$  for each  $m_{\nu_x}$ . See WIETFELDT 96 for a comprehensive review.

| VALUE<br>(units 10 <sup>-3</sup> ) | CL% | $m_{\nu_j}$ (keV) | ISOTOPE           | METHOD             | DOCUMENT ID                |
|------------------------------------|-----|-------------------|-------------------|--------------------|----------------------------|
| < 4–20                             | 90  | 700–3500          | <sup>38</sup> mK  | Trap               | <sup>15</sup> TRINCZEK 03  |
| < 9–116                            | 95  | 1–0.1             | <sup>187</sup> Re | cryog.             | <sup>16</sup> GALEAZZI 01  |
| < 1                                | 95  | 10–90             | <sup>35</sup> S   | Mag spect          | <sup>17</sup> HOLZSCHUH 00 |
| < 4                                | 95  | 14–17             | <sup>241</sup> Pu | Electrostatic spec | <sup>18</sup> DRAGON 99    |
| < 1                                | 95  | 4–30              | <sup>63</sup> Ni  | Mag spect          | <sup>19</sup> HOLZSCHUH 99 |
| < 10–40                            | 90  | 370–640           | <sup>37</sup> Ar  | EC ion recoil      | <sup>20</sup> HINDI 98     |
| < 10                               | 95  | 1                 | <sup>3</sup> H    | SPEC               | <sup>21</sup> HIDDEMANN 95 |

|           |    |           |                  |               |                     |    |
|-----------|----|-----------|------------------|---------------|---------------------|----|
| < 6       | 95 | 2         | $^3\text{H}$     | SPEC          | $^{21}$ HIDDEMANN   | 95 |
| < 2       | 95 | 3         | $^3\text{H}$     | SPEC          | $^{21}$ HIDDEMANN   | 95 |
| < 0.7     | 99 | 16.3–16.6 | $^3\text{H}$     | Prop chamber  | $^{22}$ KALBFLEISCH | 93 |
| < 2       | 95 | 13–40     | $^{35}\text{S}$  | Si(Li)        | $^{23}$ MORTARA     | 93 |
| < 0.73    | 95 | 17        | $^{63}\text{Ni}$ | Mag spect     | OHSHIMA             | 93 |
| < 1.0     | 95 | 10–24     | $^{63}\text{Ni}$ | Mag spect     | KAWAKAMI            | 92 |
| < 0.9–2.5 | 90 | 1200–6800 | $^{20}\text{F}$  | beta spectrum | $^{24}$ DEUTSCH     | 90 |
| < 8       | 90 | 80        | $^{35}\text{S}$  | Mag spect     | $^{25}$ APALIKOV    | 85 |
| < 1.5     | 90 | 60        | $^{35}\text{S}$  | Mag spect     | APALIKOV            | 85 |
| < 3.0     | 90 | 5–50      |                  | Mag spect     | MARKEY              | 85 |
| < 0.62    | 90 | 48        | $^{35}\text{S}$  | Si(Li)        | OHI                 | 85 |
| < 0.90    | 90 | 30        | $^{35}\text{S}$  | Si(Li)        | OHI                 | 85 |
| < 4       | 90 | 140       | $^{64}\text{Cu}$ | Mag spect     | $^{26}$ SCHRECK...  | 83 |
| < 8       | 90 | 440       | $^{64}\text{Cu}$ | Mag spect     | $^{26}$ SCHRECK...  | 83 |
| <100      | 90 | 0.1–3000  |                  | THEO          | $^{27}$ SHROCK      | 80 |
| < 0.1     | 68 | 80        |                  | THEO          | $^{28}$ SHROCK      | 80 |

<sup>15</sup> TRINCZEK 03 is a search for admixture of heavy neutrino to  $\nu_e$ , in contrast to  $\bar{\nu}_e$  used in many other searches. Full kinematic reconstruction of the neutrino momentum by use of a magneto optical trap.

<sup>16</sup> GALEAZZI 01 use an cryogenic microcalorimeter to search for mass 50–1000 eV neutrino admixtures using the  $^{187}\text{Re}$  beta spectrum with 2.4 keV endpoint. They derive limits for the admixture of heavy neutrinos, ranging from  $9 \times 10^{-3}$  for mass 1 keV to 0.116 for mass 100 eV. This is a significant improvement with respect to HIDDEMANN 95, especially for masses below  $\sim 500$  MeV, where the limit is about a factor of  $\sim 2$  higher.

<sup>17</sup> HOLZSCHUH 00 use an iron-free  $\beta$  spectrometer to measure the  $^{35}\text{S}$   $\beta$  decay spectrum. An analysis of the spectrum in the energy range 56–173 keV is used to derive limits for the admixture of heavy neutrinos. This extends the range of neutrino masses explored in HOLZSCHUH 99.

<sup>18</sup> DRAGON 99 analyze the  $\beta$  decay spectrum of  $^{241}\text{Pu}$  in the energy range 0.2–9.2 keV to derive limits for the admixture of heavy neutrinos. It is not competitive with HOLZSCHUH 99.

<sup>19</sup> HOLZSCHUH 99 use an iron-free  $\beta$  spectrometer to measure the  $^{63}\text{Ni}$   $\beta$  decay spectrum. An analysis of the spectrum in the energy range 33–67.8 keV is used to derive limits for the admixture of heavy neutrinos.

<sup>20</sup> HINDI 98 obtain a limit on heavy neutrino admixture from EC decay of  $^{37}\text{Ar}$  by measuring the time-of-flight distribution of the recoiling ions in coincidence with x-rays or Auger electrons. The authors report upper limit for  $|U_{ex}|^2$  of  $\approx 3\%$  for  $m_{\nu_x}=500$  keV, 1% for  $m_{\nu_x}=550$  keV, 2% for  $m_{\nu_x}=600$  keV, and 4% for  $m_x=650$  keV. Their reported limits for  $m_{\nu_x} \leq 450$  keV are inferior to the limits of SCHRECKENBACH 83.

<sup>21</sup> In the beta spectrum from tritium  $\beta$  decay nonvanishing or mixed  $m_{\bar{\nu}_1}$  state in the mass region 0.01–4 keV. For  $m_{\nu_x} < 1$  keV, their upper limit on  $|U_{ex}|^2$  becomes less

<sup>22</sup> KALBFLEISCH 93 extends the 17 keV neutrino search of BAHRAN 92, using an improved proportional chamber to which a small amount of  $^3\text{H}$  is added. Systematics are significantly reduced, allowing for an improved upper limit. The authors give a 99% confidence limit on  $|U_{ex}|^2$  as a function of  $m_{\nu_x}$  in the range from 13.5 keV to 17.5 keV. See also the related papers BAHRAN 93, BAHRAN 93B, and BAHRAN 95 on theoretical aspects of beta spectra and fitting methods for heavy neutrinos.

<sup>23</sup> MORTARA 93 limit is from study using a high-resolution solid-state detector with a superconducting solenoid. The authors note that “The sensitivity to neutrino mass is verified by measurement with a mixed source of  $^{35}\text{S}$  and  $^{14}\text{C}$ , which artificially produces a distortion in the beta spectrum similar to that expected from the massive neutrino.”

- <sup>24</sup> DEUTSCH 90 search for emission of heavy  $\bar{\nu}_e$  in super-allowed beta decay of  $^{20}\text{F}$  by spectral analysis of the electrons.  
<sup>25</sup> This limit was taken from the figure 3 of APALIKOV 85; the text gives a more restrictive limit of  $1.7 \times 10^{-3}$  at CL = 90%.  
<sup>26</sup> SCHRECKENBACH 83 is a combined measurement of the  $\beta^+$  and  $\beta^-$  spectrum.  
<sup>27</sup> SHROCK 80 was a retroactive analysis of data on several superallowed  $\beta$  decays to search for kinks in the Kurie plot.  
<sup>28</sup> Application of test to search for kinks in  $\beta$  decay Kurie plots.

### Searches for Decays of Massive $\nu$

Limits on  $|U_{eX}|^2$  as function of  $m_{\nu_X}$

| VALUE   | CL% | DOCUMENT ID           | TECN     | COMMENT                     |
|---|-----|-----------------------|----------|-----------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                       |          |                             |
| $<1.6 \times 10^{-4}$   | 90  | <sup>29</sup> BACK    | 03A CNTR | $m_{\nu_X} = 4$ MeV         |
| $<4.5 \times 10^{-5}$   | 90  | <sup>29</sup> BACK    | 03A CNTR | $m_{\nu_X} = 7$ MeV         |
| $<3.8 \times 10^{-5}$   | 90  | <sup>29</sup> BACK    | 03A CNTR | $m_{\nu_X} = 10$ MeV        |
| $<1.5 \times 10^{-3}$   | 95  | ACHARD                | 01 L3    | $m_{\nu_X} = 80$ GeV        |
| $<2 \times 10^{-2}$   | 95  | ACHARD                | 01 L3    | $m_{\nu_X} = 175$ GeV       |
| $<0.3$  | 95  | ACHARD                | 01 L3    | $m_{\nu_X} = 200$ GeV       |
| $<4 \times 10^{-3}$   | 95  | ACCIARRI              | 99K L3   | $m_{\nu_X} = 80$ GeV        |
| $<5 \times 10^{-2}$   | 95  | ACCIARRI              | 99K L3   | $m_{\nu_X} = 175$ GeV       |
| $<2 \times 10^{-5}$   | 95  | <sup>30</sup> ABREU   | 97I DLPH | $m_{\nu_X} = 6$ GeV         |
| $<3 \times 10^{-5}$   | 95  | <sup>30</sup> ABREU   | 97I DLPH | $m_{\nu_X} = 50$ GeV        |
| $<1.8 \times 10^{-3}$   | 90  | <sup>31</sup> HAGNER  | 95 MWPC  | $m_{\nu_h} = 1.5$ MeV       |
| $<2.5 \times 10^{-4}$   | 90  | <sup>31</sup> HAGNER  | 95 MWPC  | $m_{\nu_h} = 4$ MeV         |
| $<4.2 \times 10^{-3}$   | 90  | <sup>31</sup> HAGNER  | 95 MWPC  | $m_{\nu_h} = 9$ MeV         |
| $<1 \times 10^{-5}$   | 90  | <sup>32</sup> BARANOV | 93       | $m_{\nu_X} = 100$ MeV       |
| $<1 \times 10^{-6}$   | 90  | <sup>32</sup> BARANOV | 93       | $m_{\nu_X} = 200$ MeV       |
| $<3 \times 10^{-7}$   | 90  | <sup>32</sup> BARANOV | 93       | $m_{\nu_X} = 300$ MeV       |
| $<2 \times 10^{-7}$   | 90  | <sup>32</sup> BARANOV | 93       | $m_{\nu_X} = 400$ MeV       |
| $<6.2 \times 10^{-8}$   | 95  | ADEVA                 | 90S L3   | $m_{\nu_X} = 20$ GeV        |
| $<5.1 \times 10^{-10}$  | 95  | ADEVA                 | 90S L3   | $m_{\nu_X} = 40$ GeV        |
| all values ruled out  | 95  | <sup>33</sup> BURCHAT | 90 MRK2  | $m_{\nu_X} < 19.6$ GeV      |
| $<1 \times 10^{-10}$  | 95  | <sup>33</sup> BURCHAT | 90 MRK2  | $m_{\nu_X} = 22$ GeV        |
| $<1 \times 10^{-11}$  | 95  | <sup>33</sup> BURCHAT | 90 MRK2  | $m_{\nu_X} = 41$ GeV        |
| all values ruled out  | 95  | DECAMP                | 90F ALEP | $m_{\nu_X} = 25.0-42.7$ GeV |
| $<1 \times 10^{-13}$  | 95  | DECAMP                | 90F ALEP | $m_{\nu_X} = 42.7-45.7$ GeV |
| $<5 \times 10^{-3}$   | 90  | AKERLOF               | 88 HRS   | $m_{\nu_X} = 1.8$ GeV       |
| $<2 \times 10^{-5}$   | 90  | AKERLOF               | 88 HRS   | $m_{\nu_X} = 4$ GeV         |
| $<3 \times 10^{-6}$   | 90  | AKERLOF               | 88 HRS   | $m_{\nu_X} = 6$ GeV         |
| $<1.2 \times 10^{-7}$   | 90  | BERNARDI              | 88 CNTR  | $m_{\nu_X} = 100$ MeV       |
| $<1 \times 10^{-8}$   | 90  | BERNARDI              | 88 CNTR  | $m_{\nu_X} = 200$ MeV       |
| $<2.4 \times 10^{-9}$   | 90  | BERNARDI              | 88 CNTR  | $m_{\nu_X} = 300$ MeV       |

|                       |    |                          |     |      |                       |
|-----------------------|----|--------------------------|-----|------|-----------------------|
| $<2.1 \times 10^{-9}$ | 90 | BERNARDI                 | 88  | CNTR | $m_{\nu_x} = 400$ MeV |
| $<2 \times 10^{-2}$   | 68 | <sup>34</sup> OBERAUER   | 87  |      | $m_{\nu_x} = 1.5$ MeV |
| $<8 \times 10^{-4}$   | 68 | <sup>34</sup> OBERAUER   | 87  |      | $m_{\nu_x} = 4.0$ MeV |
| $<8 \times 10^{-3}$   | 90 | BADIER                   | 86  | CNTR | $m_{\nu_x} = 400$ MeV |
| $<8 \times 10^{-5}$   | 90 | BADIER                   | 86  | CNTR | $m_{\nu_x} = 1.7$ GeV |
| $<8 \times 10^{-8}$   | 90 | BERNARDI                 | 86  | CNTR | $m_{\nu_x} = 100$ MeV |
| $<4 \times 10^{-8}$   | 90 | BERNARDI                 | 86  | CNTR | $m_{\nu_x} = 200$ MeV |
| $<6 \times 10^{-9}$   | 90 | BERNARDI                 | 86  | CNTR | $m_{\nu_x} = 400$ MeV |
| $<3 \times 10^{-5}$   | 90 | DORENBOS...              | 86  | CNTR | $m_{\nu_x} = 150$ MeV |
| $<1 \times 10^{-6}$   | 90 | DORENBOS...              | 86  | CNTR | $m_{\nu_x} = 500$ MeV |
| $<1 \times 10^{-7}$   | 90 | DORENBOS...              | 86  | CNTR | $m_{\nu_x} = 1.6$ GeV |
| $<7 \times 10^{-7}$   | 90 | <sup>35</sup> COOPER-... | 85  | HLBC | $m_{\nu_x} = 0.4$ GeV |
| $<8 \times 10^{-8}$   | 90 | <sup>35</sup> COOPER-... | 85  | HLBC | $m_{\nu_x} = 1.5$ GeV |
| $<1 \times 10^{-2}$   | 90 | <sup>36</sup> BERGSMA    | 83B | CNTR | $m_{\nu_x} = 10$ MeV  |
| $<1 \times 10^{-5}$   | 90 | <sup>36</sup> BERGSMA    | 83B | CNTR | $m_{\nu_x} = 110$ MeV |
| $<6 \times 10^{-7}$   | 90 | <sup>36</sup> BERGSMA    | 83B | CNTR | $m_{\nu_x} = 410$ MeV |
| $<1 \times 10^{-5}$   | 90 | GRONAU                   | 83  |      | $m_{\nu_x} = 160$ MeV |
| $<1 \times 10^{-6}$   | 90 | GRONAU                   | 83  |      | $m_{\nu_x} = 480$ MeV |

<sup>29</sup> BACK 03A searched for heavy neutrinos emitted from  $^8\text{B}$  decay in the Sun using the decay  $\nu_h \rightarrow \nu_e e^+ e^-$  in the Counting Test Facility (the prototype of the Borexino detector) and obtained limits on heavy neutrino admixture for the  $\nu_h$  mass range 1.1–12 MeV.

<sup>30</sup> ABREU 97i long-lived  $\nu_x$  analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity except at 3.5 GeV, where the limit is the same as at 6 GeV.

<sup>31</sup> HAGNER 95 obtain limits on heavy neutrino admixture from the decay  $\nu_h \rightarrow \nu_e e^+ e^-$  at a nuclear reactor for the  $\nu_h$  mass range 2–9 MeV.

<sup>32</sup> BARANOV 93 is a search for neutrino decays into  $e^+ e^- \nu_e$  using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron. The limits are not as good as those achieved earlier by BERGSMA 83 and BERNARDI 86, BERNARDI 88.

<sup>33</sup> BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89c, and WENDT 87.

<sup>34</sup> OBERAUER 87 bounds from search for  $\nu \rightarrow \nu' e e$  decay mode using reactor (anti)neutrinos.

<sup>35</sup> COOPER-SARKAR 85 also give limits based on model-dependent assumptions for  $\nu_\tau$  flux. We do not list these. Note that for this bound to be nontrivial,  $x$  is not equal to 3, i.e.  $\nu_x$  cannot be the dominant mass eigenstate in  $\nu_\tau$  since  $m_{\nu_3} < 70$  MeV (ALBRECHT 85i). Also, of course,  $x$  is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

<sup>36</sup> BERGSMA 83B also quote limits on  $|U_{e3}|^2$  where the index 3 refers to the mass eigenstate dominantly coupled to the  $\tau$ . Those limits were based on assumptions about the  $D_S$  mass and  $D_S \rightarrow \tau \nu_\tau$  branching ratio which are no longer valid. See COOPER-SARKAR 85.

————— Limits on Coupling of  $\mu$  to  $\nu_x$  as Function of  $m_{\nu_x}$  —————

**Peak search test**

Limits on  $B(\pi \text{ (or } K) \rightarrow \mu\nu_x)$ .

| <u>VALUE</u>  | <u>CL%</u> | <u>DOCUMENT ID</u> | <u>TECN</u> | <u>COMMENT</u>                                 |
|---|------------|--------------------|-------------|--|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |            |                    |             |  |
|   |            | 37 ASTIER          | 02 NOMD     | $\pi \rightarrow \mu X$ for $m_X=33.9$ MeV     |
| $<6.0 \times 10^{-10}$  | 95         | 38 DAUM            | 00 CNTR     | $\pi \rightarrow \mu X$ for $m_X=33.9$ MeV     |
|   |            | 39 FORMAGGIO       | 00 CNTR     | $\pi \rightarrow \mu X$ for $m_X=33.9$ MeV     |
| $<0.22$   | 90         | 40 ASSAMAGAN       | 98 SILI     | $m_{\nu_x} = 0.53$ MeV                         |
| $<0.029$  | 90         | 40 ASSAMAGAN       | 98 SILI     | $m_{\nu_x} = 0.75$ MeV                         |
| $<0.016$  | 90         | 40 ASSAMAGAN       | 98 SILI     | $m_{\nu_x} = 1.0$ MeV                          |
| $<4-6 \times 10^{-5}$   |            | 41 BRYMAN          | 96 CNTR     | $m_{\nu_x} = 30-33.91$ MeV                     |
| $\sim 1 \times 10^{-16}$  |            | 42 ARMBRUSTER      | 95 KARM     | $m_{\nu_x} = 33.9$ MeV                         |
| $<4 \times 10^{-7}$   | 95         | 43 BILGER          | 95 LEPS     | $m_{\overline{\nu}_x} = 33.9$ MeV              |
| $<7 \times 10^{-8}$   | 95         | 43 BILGER          | 95 LEPS     | $m_{\nu_x} = 33.9$ MeV                         |
| $<2.6 \times 10^{-8}$   | 95         | 43 DAUM            | 95B TOF     | $m_{\nu_x} = 33.9$ MeV                         |
| $<2 \times 10^{-2}$   | 90         | DAUM               | 87          | $m_{\nu_x} = 1$ MeV                            |
| $<1 \times 10^{-3}$   | 90         | DAUM               | 87          | $m_{\nu_x} = 2$ MeV                            |
| $<6 \times 10^{-5}$   | 90         | DAUM               | 87          | $3 \text{ MeV} < m_{\nu_x} < 19.5 \text{ MeV}$ |
| $<3 \times 10^{-2}$   | 90         | 44 MINEHART        | 84          | $m_{\nu_x} = 2$ MeV                            |
| $<1 \times 10^{-3}$   | 90         | 44 MINEHART        | 84          | $m_{\nu_x} = 4$ MeV                            |
| $<3 \times 10^{-4}$   | 90         | 44 MINEHART        | 84          | $m_{\nu_x} = 10$ GeV                           |
| $<5 \times 10^{-6}$   | 90         | 45 HAYANO          | 82          | $m_{\nu_x} = 330$ MeV                          |
| $<1 \times 10^{-4}$   | 90         | 45 HAYANO          | 82          | $m_{\nu_x} = 70$ MeV                           |
| $<9 \times 10^{-7}$   | 90         | 45 HAYANO          | 82          | $m_{\nu_x} = 250$ MeV                          |
| $<1 \times 10^{-1}$   | 90         | 44 ABELA           | 81          | $m_{\nu_x} = 4$ MeV                            |
| $<7 \times 10^{-5}$   | 90         | 44 ABELA           | 81          | $m_{\nu_x} = 10.5$ MeV                         |
| $<2 \times 10^{-4}$   | 90         | 44 ABELA           | 81          | $m_{\nu_x} = 11.5$ MeV                         |
| $<2 \times 10^{-5}$   | 90         | 44 ABELA           | 81          | $m_{\nu_x} = 16-30$ MeV                        |

37 ASTIER 02 search for anomalous pion decay into a 33.9 MeV neutral particle. No evidence was found and the sensitivity to the branching ratio  $B(\pi \rightarrow \mu X) \cdot B(X \rightarrow \nu e^+ e^-)$  is as low as  $3.7 \times 10^{-15}$ , depending on the X lifetime.

38 DAUM 00 search for anomalous pion decay into a 33.9 MeV neutral particle that might be responsible for the time-distribution anomaly observed by the KARMEN Collaboration.

39 FORMAGGIO 00 search for anomalous pion decay into a 33.9 MeV neutral particle  $Q^0$  that might be responsible for the time-distribution anomaly observed by the KARMEN Collaboration. In the E815 (NuTeV) experiment at Fermilab no evidence was found, with sensitivity for the pion branching ratio  $B(\pi \rightarrow \mu Q^0) \cdot B(Q^0 \rightarrow \text{visible})$  as low as  $10^{-13}$ .

40 ASSAMAGAN 98 obtain a limit on heavy neutrino admixture from  $\pi^+$  decay essentially at rest, by measuring with good resolution the momentum distribution of the muons. However, the search uses an ad hoc shape correction. The authors report upper limit for

$|U_{\mu x}|^2$  of 0.22 for  $m_{\nu} = 0.53$  MeV, 0.029 for  $m_{\nu} = 0.75$  MeV, and 0.016 for  $m_{\nu} = 1.0$  MeV at 90%CL.

- 41 BRYMAN 96 search for massive unconventional neutrinos of mass  $m_{\nu_x}$  in  $\pi^+$  decay.
- 42 ARMBRUSTER 95 study the reactions  $^{12}\text{C}(\nu_e, e^-) ^{12}\text{N}$  and  $^{12}\text{C}(\nu, \nu') ^{12}\text{C}^*$  induced by neutrinos from  $\pi^+$  and  $\mu^+$  decay at the ISIS neutron spallation source at the Rutherford-Appleton laboratory. An anomaly in the time distribution can be interpreted as the decay  $\pi^+ \rightarrow \mu^+ \nu_x$ , where  $\nu_x$  is a neutral weakly interacting particle with mass  $\approx 33.9$  MeV and spin 1/2. The lower limit to the branching ratio is a function of the lifetime of the new massive neutral particle, and reaches a minimum of a few  $\times 10^{-16}$  for  $\tau_x \sim 5$  s.
- 43 From experiments of  $\pi^+$  and  $\pi^-$  decay in flight at PSI, to check the claim of the KARMEN Collaboration quoted above (ARMBRUSTER 95).
- 44  $\pi^+ \rightarrow \mu^+ \nu_\mu$  peak search experiment.
- 45  $K^+ \rightarrow \mu^+ \nu_\mu$  peak search experiment.

### Peak search test

Limits on  $|U_{\mu x}|^2$  as function of  $m_{\nu_x}$

| VALUE   | CL% | DOCUMENT ID     | TECN | COMMENT                    |
|---|-----|-----------------|------|----------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                 |      |                            |
| $< 1-10 \times 10^{-4}$   |     | 46 BRYMAN 96    | CNTR | $m_{\nu_x} = 30-33.91$ MeV |
| $< 2 \times 10^{-5}$  | 95  | 47 ASANO 81     |      | $m_{\nu_x} = 70$ MeV       |
| $< 3 \times 10^{-6}$  | 95  | 47 ASANO 81     |      | $m_{\nu_x} = 210$ MeV      |
| $< 3 \times 10^{-6}$  | 95  | 47 ASANO 81     |      | $m_{\nu_x} = 230$ MeV      |
| $< 6 \times 10^{-6}$  | 95  | 48 ASANO 81     |      | $m_{\nu_x} = 240$ MeV      |
| $< 5 \times 10^{-7}$  | 95  | 48 ASANO 81     |      | $m_{\nu_x} = 280$ MeV      |
| $< 6 \times 10^{-6}$  | 95  | 48 ASANO 81     |      | $m_{\nu_x} = 300$ MeV      |
| $< 1 \times 10^{-2}$  | 95  | CALAPRICE 81    |      | $m_{\nu_x} = 7$ MeV        |
| $< 3 \times 10^{-3}$  | 95  | 49 CALAPRICE 81 |      | $m_{\nu_x} = 33$ MeV       |
| $< 1 \times 10^{-4}$  | 68  | 50 SHROCK 81    | THEO | $m_{\nu_x} = 13$ MeV       |
| $< 3 \times 10^{-5}$  | 68  | 50 SHROCK 81    | THEO | $m_{\nu_x} = 33$ MeV       |
| $< 6 \times 10^{-3}$  | 68  | 51 SHROCK 81    | THEO | $m_{\nu_x} = 80$ MeV       |
| $< 5 \times 10^{-3}$  | 68  | 51 SHROCK 81    | THEO | $m_{\nu_x} = 120$ MeV      |

- 46 BRYMAN 96 search for massive unconventional neutrinos of mass  $m_{\nu_x}$  in  $\pi^+$  decay. They interpret the result as an upper limit for the admixture of a heavy sterile or otherwise
- 47  $K^+ \rightarrow \mu^+ \nu_\mu$  peak search experiment.
- 48 Analysis of experiment on  $K^+ \rightarrow \mu^+ \nu_\mu \nu_x \bar{\nu}_x$  decay.
- 49  $\pi^+ \rightarrow \mu^+ \nu_\mu$  peak search experiment.
- 50 Analysis of magnetic spectrometer experiment, bubble chamber experiment, and emulsion experiment on  $\pi^+ \rightarrow \mu^+ \nu_\mu$  decay.
- 51 Analysis of magnetic spectrometer experiment on  $K \rightarrow \mu, \nu_\mu$  decay.



## Peak Search in Muon Capture

Limits on  $|U_{\mu x}|^2$  as function of  $m_{\nu_x}$

| VALUE   | DOCUMENT ID | COMMENT              |
|---|-------------|----------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |             |                      |
| $<1 \times 10^{-1}$   | DEUTSCH 83  | $m_{\nu_x} = 45$ MeV |
| $<7 \times 10^{-3}$   | DEUTSCH 83  | $m_{\nu_x} = 70$ MeV |
| $<1 \times 10^{-1}$   | DEUTSCH 83  | $m_{\nu_x} = 85$ MeV |

## Searches for Decays of Massive $\nu$

Limits on  $|U_{\mu x}|^2$  as function of  $m_{\nu_x}$

| VALUE   | CL% | DOCUMENT ID  | TECN     | COMMENT                     |
|---|-----|--------------|----------|-----------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |              |          |                             |
| $<5 \times 10^{-7}$   | 90  | 52 VAITAITIS | 99 CCFR  | $m_{\nu_x} = 0.28$ GeV      |
| $<8 \times 10^{-8}$   | 90  | 52 VAITAITIS | 99 CCFR  | $m_{\nu_x} = 0.37$ GeV      |
| $<5 \times 10^{-7}$   | 90  | 52 VAITAITIS | 99 CCFR  | $m_{\nu_x} = 0.50$ GeV      |
| $<6 \times 10^{-8}$   | 90  | 52 VAITAITIS | 99 CCFR  | $m_{\nu_x} = 1.50$ GeV      |
| $<2 \times 10^{-5}$   | 95  | 53 ABREU     | 97I DLPH | $m_{\nu_x} = 6$ GeV         |
| $<3 \times 10^{-5}$   | 95  | 53 ABREU     | 97I DLPH | $m_{\nu_x} = 50$ GeV        |
| $<3 \times 10^{-6}$   | 90  | GALLAS       | 95 CNTR  | $m_{\nu_x} = 1$ GeV         |
| $<3 \times 10^{-5}$   | 90  | 54 VILAIN    | 95C CHM2 | $m_{\nu_x} = 2$ GeV         |
| $<6.2 \times 10^{-8}$   | 95  | ADEVA        | 90S L3   | $m_{\nu_x} = 20$ GeV        |
| $<5.1 \times 10^{-10}$  | 95  | ADEVA        | 90S L3   | $m_{\nu_x} = 40$ GeV        |
| all values ruled out  | 95  | 55 BURCHAT   | 90 MRK2  | $m_{\nu_x} < 19.6$ GeV      |
| $<1 \times 10^{-10}$  | 95  | 55 BURCHAT   | 90 MRK2  | $m_{\nu_x} = 22$ GeV        |
| $<1 \times 10^{-11}$  | 95  | 55 BURCHAT   | 90 MRK2  | $m_{\nu_x} = 41$ GeV        |
| all values ruled out  | 95  | DECAMP       | 90F ALEP | $m_{\nu_x} = 25.0-42.7$ GeV |
| $<1 \times 10^{-13}$  | 95  | DECAMP       | 90F ALEP | $m_{\nu_x} = 42.7-45.7$ GeV |
| $<5 \times 10^{-3}$   | 90  | AKERLOF      | 88 HRS   | $m_{\nu_x} = 1.8$ GeV       |
| $<2 \times 10^{-5}$   | 90  | AKERLOF      | 88 HRS   | $m_{\nu_x} = 4$ GeV         |
| $<3 \times 10^{-6}$   | 90  | AKERLOF      | 88 HRS   | $m_{\nu_x} = 6$ GeV         |
| $<1 \times 10^{-7}$   | 90  | BERNARDI     | 88 CNTR  | $m_{\nu_x} = 200$ MeV       |
| $<3 \times 10^{-9}$   | 90  | BERNARDI     | 88 CNTR  | $m_{\nu_x} = 300$ MeV       |
| $<4 \times 10^{-4}$   | 90  | 56 MISHRA    | 87 CNTR  | $m_{\nu_x} = 1.5$ GeV       |
| $<4 \times 10^{-3}$   | 90  | 56 MISHRA    | 87 CNTR  | $m_{\nu_x} = 2.5$ GeV       |
| $<0.9 \times 10^{-2}$   | 90  | 56 MISHRA    | 87 CNTR  | $m_{\nu_x} = 5$ GeV         |
| $<0.1$  | 90  | 56 MISHRA    | 87 CNTR  | $m_{\nu_x} = 10$ GeV        |
| $<8 \times 10^{-4}$   | 90  | BADIER       | 86 CNTR  | $m_{\nu_x} = 600$ MeV       |
| $<1.2 \times 10^{-5}$   | 90  | BADIER       | 86 CNTR  | $m_{\nu_x} = 1.7$ GeV       |
| $<3 \times 10^{-8}$   | 90  | BERNARDI     | 86 CNTR  | $m_{\nu_x} = 200$ MeV       |
| $<6 \times 10^{-9}$   | 90  | BERNARDI     | 86 CNTR  | $m_{\nu_x} = 350$ MeV       |
| $<1 \times 10^{-6}$   | 90  | DORENBOS...  | 86 CNTR  | $m_{\nu_x} = 500$ MeV       |

- $<1 \times 10^{-7}$  90 DORENBOS... 86 CNTR  $m_{\nu_x} = 1600$  MeV
- $<0.8 \times 10^{-5}$  90 57 COOPER-... 85 HLBC  $m_{\nu_x} = 0.4$  GeV
- $<1.0 \times 10^{-7}$  90 57 COOPER-... 85 HLBC  $m_{\nu_x} = 1.5$  GeV
- 52 VAITAITIS 99 search for  $L_{\mu}^0 \rightarrow \mu X$ . See paper for rather complicated limit as function of  $m_{\nu_x}$ .
- 53 ABREU 97I long-lived  $\nu_x$  analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity except at 3.5 GeV, where the limit is the same as at 6 GeV.
- 54 VILAIN 95C is a search for the decays of heavy isosinglet neutrinos produced by neutral current neutrino interactions. Limits were quoted for masses in the range from 0.3 to 24 GeV. The best limit is listed above.
- 55 BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.
- 56 See also limits on  $|U_{3x}|$  from WENDT 87.
- 57 COOPER-SARKAR 85 also give limits based on model-dependent assumptions for  $\nu_{\tau}$  flux. We do not list these. Note that for this bound to be nontrivial,  $x$  is not equal to 3, i.e.  $\nu_x$  cannot be the dominant mass eigenstate in  $\nu_{\tau}$  since  $m_{\nu_3} < 70$  MeV (ALBRECHT 85). Also, of course,  $x$  is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

### Limits on $|U_{\tau x}|^2$ as a Function of $m_{\nu_x}$

| VALUE   | CL% | DOCUMENT ID | TECN     | COMMENT                     |
|---|-----|-------------|----------|-----------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |             |          |                             |
| $<1 \times 10^{-2}$   | 90  | 58 ORLOFF   | 02 CHRM  | $m_{\nu_x} = 45$ MeV        |
| $<1.4 \times 10^{-4}$   | 90  | 58 ORLOFF   | 02 CHRM  | $m_{\nu_x} = 180$ MeV       |
| $<0.025$  | 90  | ASTIER      | 01       | $m_{\nu_x} = 45$ MeV        |
| $<0.002$  | 90  | ASTIER      | 01       | $m_{\nu_x} = 140$ MeV       |
| $<2 \times 10^{-5}$   | 95  | 59 ABREU    | 97I DLPH | $m_{\nu_x} = 6$ GeV         |
| $<3 \times 10^{-5}$   | 95  | 59 ABREU    | 97I DLPH | $m_{\nu_x} = 50$ GeV        |
| $<6.2 \times 10^{-8}$   | 95  | ADEVA       | 90S L3   | $m_{\nu_x} = 20$ GeV        |
| $<5.1 \times 10^{-10}$  | 95  | ADEVA       | 90S L3   | $m_{\nu_x} = 40$ GeV        |
| all values ruled out  | 95  | 60 BURCHAT  | 90 MRK2  | $m_{\nu_x} < 19.6$ GeV      |
| $<1 \times 10^{-10}$  | 95  | 60 BURCHAT  | 90 MRK2  | $m_{\nu_x} = 22$ GeV        |
| $<1 \times 10^{-11}$  | 95  | 60 BURCHAT  | 90 MRK2  | $m_{\nu_x} = 41$ GeV        |
| all values ruled out  | 95  | DECAMP      | 90F ALEP | $m_{\nu_x} = 25.0-42.7$ GeV |
| $<1 \times 10^{-13}$  | 95  | DECAMP      | 90F ALEP | $m_{\nu_x} = 42.7-45.7$ GeV |
| $<5 \times 10^{-2}$   | 80  | AKERLOF     | 88 HRS   | $m_{\nu_x} = 2.5$ GeV       |
| $<9 \times 10^{-5}$   | 80  | AKERLOF     | 88 HRS   | $m_{\nu_x} = 4.5$ GeV       |

- 58 ORLOFF 02 use the negative result of a search for neutral particles decaying into two electrons performed by CHARM to get these limits for a mostly isosinglet heavy neutrino.
- 59 ABREU 97I long-lived  $\nu_x$  analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity.
- 60 BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

### Limits on $|U_{ax}|^2$

Where  $a = e, \mu$  from  $\rho$  parameter in  $\mu$  decay.

| VALUE   | CL% | DOCUMENT ID | TECN | COMMENT                   |
|---|-----|-------------|------|---------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |             |      |                           |
| $<1 \times 10^{-2}$   | 68  | SHROCK      | 81B  | THEO $m_{\nu_x} = 10$ GeV |
| $<2 \times 10^{-3}$   | 68  | SHROCK      | 81B  | THEO $m_{\nu_x} = 40$ MeV |
| $<4 \times 10^{-2}$   | 68  | SHROCK      | 81B  | THEO $m_{\nu_x} = 70$ MeV |

### Limits on $|U_{1j} \times U_{2j}|$ as Function of $m_{\nu_j}$

| VALUE   | CL% | DOCUMENT ID           | TECN | COMMENT                    |
|---|-----|-----------------------|------|----------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                       |      |                            |
| $<3 \times 10^{-5}$   | 90  | <sup>61</sup> BARANOV | 93   | $m_{\nu_j} = 80$ MeV       |
| $<3 \times 10^{-6}$   | 90  | <sup>61</sup> BARANOV | 93   | $m_{\nu_j} = 160$ MeV      |
| $<6 \times 10^{-7}$   | 90  | <sup>61</sup> BARANOV | 93   | $m_{\nu_j} = 240$ MeV      |
| $<2 \times 10^{-7}$   | 90  | <sup>61</sup> BARANOV | 93   | $m_{\nu_j} = 320$ MeV      |
| $<9 \times 10^{-5}$   | 90  | BERNARDI              | 86   | CNTR $m_{\nu_j} = 25$ MeV  |
| $<3.6 \times 10^{-7}$   | 90  | BERNARDI              | 86   | CNTR $m_{\nu_j} = 100$ MeV |
| $<3 \times 10^{-8}$   | 90  | BERNARDI              | 86   | CNTR $m_{\nu_j} = 200$ MeV |
| $<6 \times 10^{-9}$   | 90  | BERNARDI              | 86   | CNTR $m_{\nu_j} = 350$ MeV |
| $<1 \times 10^{-2}$   | 90  | BERGSMA               | 83B  | CNTR $m_{\nu_j} = 10$ MeV  |
| $<1 \times 10^{-5}$   | 90  | BERGSMA               | 83B  | CNTR $m_{\nu_j} = 140$ MeV |
| $<7 \times 10^{-7}$   | 90  | BERGSMA               | 83B  | CNTR $m_{\nu_j} = 370$ MeV |

<sup>61</sup>BARANOV 93 is a search for neutrino decays into  $e^+ e^- \nu_e$  using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron.

### REFERENCES FOR Heavy Neutral Leptons, Searches for

|           |      |                               |                              |                    |
|-----------|------|-------------------------------|------------------------------|--------------------|
| BACK      | 03A  | JETPL 78 261                  | H.O. Back <i>et al.</i>      | (Borexino Collab.) |
|           |      | Translated from ZETFP 78 707. |                              |                    |
| TRINCZEK  | 03   | PRL 90 012501                 | M. Trinczek <i>et al.</i>    |                    |
| ASTIER    | 02   | PL B527 23                    | P. Astier <i>et al.</i>      | (NOMAD Collab.)    |
| ORLOFF    | 02   | PL B550 8                     | J. Orloff <i>et al.</i>      |                    |
| ACHARD    | 01   | PL B517 67                    | P. Achard <i>et al.</i>      | (L3 Collab.)       |
| ACHARD    | 01B  | PL B517 75                    | P. Achard <i>et al.</i>      | (L3 Collab.)       |
| ASTIER    | 01   | PL B506 27                    | P. Astier <i>et al.</i>      | (NOMAD Collab.)    |
| GALEAZZI  | 01   | PRL 86 1978                   | M. Galeazzi <i>et al.</i>    |                    |
| ABBIENDI  | 00I  | EPJ C14 73                    | G. Abbiendi <i>et al.</i>    | (OPAL Collab.)     |
| DAUM      | 00   | PRL 85 1815                   | M. Daum <i>et al.</i>        |                    |
| FORMAGGIO | 00   | PRL 84 4043                   | J.A. Formaggio <i>et al.</i> |                    |
| HOLZSCHUH | 00   | PL B482 1                     | E. Holzschuh <i>et al.</i>   |                    |
| ABREU     | 99O  | EPJ C8 41                     | P. Abreu <i>et al.</i>       | (DELPHI Collab.)   |
| ACCIARRI  | 99K  | PL B461 397                   | M. Acciarri <i>et al.</i>    | (L3 Collab.)       |
| DRAGOUN   | 99   | JPG 25 1839                   | O. Dragoun <i>et al.</i>     |                    |
| HOLZSCHUH | 99   | PL B451 247                   | E. Holzschuh <i>et al.</i>   |                    |
| VAITAITIS | 99   | PRL 83 4943                   | A. Vaitaitis <i>et al.</i>   | (CCFR Collab.)     |
| ASSAMAGAN | 98   | PL B434 158                   | K. Assamagan <i>et al.</i>   |                    |
| HINDI     | 98   | PR C58 2512                   | M.M. Hindi <i>et al.</i>     |                    |
| PDG       | 98   | EPJ C3 1                      | C. Caso <i>et al.</i>        |                    |
| ABREU     | 97I  | ZPHY C74 57                   | P. Abreu <i>et al.</i>       | (DELPHI Collab.)   |
|           | Also | ZPHY C75 580 (erratum)        | P. Abreu <i>et al.</i>       | (DELPHI Collab.)   |
| BRYMAN    | 96   | PR D53 558                    | D.A. Bryman, T. Numao        | (TRIUMF)           |
| BUSKULIC  | 96S  | PL B384 439                   | D. Buskalic <i>et al.</i>    | (ALEPH Collab.)    |
| WIETFELDT | 96   | PRPL 273 149                  | F.E. Wietfeldt, E.B. Norman  | (LBL)              |

|             |     |                               |  |                         |
|-------------|-----|-------------------------------|--|-------------------------|
| ARMBRUSTER  | 95  | PL B348 19                    | B. Armbruster <i>et al.</i>                      | (KARMEN Collab.)        |
| BAHRAN      | 95  | PL B354 481                   | M.Y. Bahran, G.R. Kalbfleisch                    | (OKLA)                  |
| BILGER      | 95  | PL B363 41                    | R. Bilger <i>et al.</i>                          | (TUBIN, KARLE, PSI)     |
| DAUM        | 95B | PL B361 179                   | M. Daum <i>et al.</i>                            | (PSI, UVA)              |
| FARGION     | 95  | PR D52 1828                   | D. Fargion <i>et al.</i>                         | (ROMA, KIAM, MPEI)      |
| GALLAS      | 95  | PR D52 6                      | E. Gallas <i>et al.</i>                          | (MSU, FNAL, MIT, FLOR)  |
| GARCIA      | 95  | PR D51 1458                   | E. Garcia <i>et al.</i>                          | (ZARA, SCUC, PNL)       |
| HAGNER      | 95  | PR D52 1343                   | C. Hagner <i>et al.</i>                          | (MUNT, LAPP, CPPM)      |
| HIDDEMANN   | 95  | JPG 21 639                    | K.H. Hiddemann, H. Daniel, O. Schwentker         | (MUNT)                  |
| VILAIN      | 95C | PL B351 387                   | P. Vilain <i>et al.</i>                          | (CHARM II Collab.)      |
| Also        |     | PL B343 453                   | P. Vilain <i>et al.</i>                          | (CHARM II Collab.)      |
| BECK        | 94  | PL B336 141                   | M. Beck <i>et al.</i>                            | (MPIH, KIAE, SASSO)     |
| KONOPLICH   | 94  | PAN 57 425                    | R.V. Konoplich, M.Y. Khlopov                     | (MPEI)                  |
| PDG         | 94  | PR D50 1173                   | L. Montanet <i>et al.</i>                        | (CERN, LBL, BOST+)      |
| BAHRAN      | 93  | PR D47 R754                   | M. Bahran, G.R. Kalbfleisch                      | (OKLA)                  |
| BAHRAN      | 93B | PR D47 R759                   | M. Bahran, G.R. Kalbfleisch                      | (OKLA)                  |
| BARANOV     | 93  | PL B302 336                   | S.A. Baranov <i>et al.</i>                       | (JINR, SERP, BUDA)      |
| KALBFLEISCH | 93  | PL B303 355                   | G.R. Kalbfleisch, M.Y. Bahran                    | (OKLA)                  |
| MORTARA     | 93  | PRL 70 394                    | J.L. Mortara <i>et al.</i>                       | (ANL, LBL, UCB)         |
| OHSHIMA     | 93  | PR D47 4840                   | T. Ohshima <i>et al.</i>                         | (KEK, TUAT, RIKEN+)     |
| ABREU       | 92B | PL B274 230                   | P. Abreu <i>et al.</i>                           | (DELPHI Collab.)        |
| BAHRAN      | 92  | PL B291 336                   | M.Y. Bahran, G.R. Kalbfleisch                    | (OKLA)                  |
| BRITTON     | 92  | PRL 68 3000                   | D.I. Britton <i>et al.</i>                       | (TRIU, CARL)            |
| Also        |     | PR D49 28                     | D.I. Britton <i>et al.</i>                       | (TRIU, CARL)            |
| BRITTON     | 92B | PR D46 R885                   | D.I. Britton <i>et al.</i>                       | (TRIU, CARL)            |
| KAWAKAMI    | 92  | PL B287 45                    | H. Kawakami <i>et al.</i>                        | (INUS, KEK, SCUC+)      |
| MORI        | 92B | PL B289 463                   | M. Mori <i>et al.</i>                            | (KAM2 Collab.)          |
| ALEXANDER   | 91F | ZPHY C52 175                  | G. Alexander <i>et al.</i>                       | (OPAL Collab.)          |
| DELEENER... | 91  | PR D43 3611                   | N. de Leener-Rosier <i>et al.</i>                | (LOUV, ZURI+)           |
| REUSSER     | 91  | PL B255 143                   | D. Reusser <i>et al.</i>                         | (NEUC, CIT, PSI)        |
| SATO        | 91  | PR D44 2220                   | N. Sato <i>et al.</i>                            | (Kamiokande Collab.)    |
| ADEVA       | 90S | PL B251 321                   | B. Adeva <i>et al.</i>                           | (L3 Collab.)            |
| BURCHAT     | 90  | PR D41 3542                   | P.R. Burchat <i>et al.</i>                       | (Mark II Collab.)       |
| DECAMP      | 90F | PL B236 511                   | D. Decamp <i>et al.</i>                          | (ALEPH Collab.)         |
| DEUTSCH     | 90  | NP A518 149                   | J. Deutsch, M. Lebrun, R. Prieels                |                         |
| JUNG        | 90  | PRL 64 1091                   | C. Jung <i>et al.</i>                            | (Mark II Collab.)       |
| ABRAMS      | 89C | PRL 63 2447                   | G.S. Abrams <i>et al.</i>                        | (Mark II Collab.)       |
| ENQVIST     | 89  | NP B317 647                   | K. Enqvist, K. Kainulainen, J. Maalampi          | (HELS)                  |
| FISHER      | 89  | PL B218 257                   | P.H. Fisher <i>et al.</i>                        | (CIT, NEUC, PSI)        |
| AKERLOF     | 88  | PR D37 577                    | C.W. Akerlof <i>et al.</i>                       | (HRS Collab.)           |
| BERNARDI    | 88  | PL B203 332                   | G. Bernardi <i>et al.</i>                        | (PARIN, CERN, INFN+)    |
| CALDWELL    | 88  | PRL 61 510                    | D.O. Caldwell <i>et al.</i>                      | (UCSB, UCB, LBL)        |
| OLIVE       | 88  | PL B205 553                   | K.A. Olive, M. Srednicki                         | (MINN, UCSB)            |
| SREDNICKI   | 88  | NP B310 693                   | M. Srednicki, R. Watkins, K.A. Olive             | (MINN, UCSB)            |
| AHLEN       | 87  | PL B195 603                   | S.P. Ahlen <i>et al.</i>                         | (BOST, SCUC, HARV+)     |
| DAUM        | 87  | PR D36 2624                   | M. Daum <i>et al.</i>                            | (SIN, UVA)              |
| GRIEST      | 87  | NP B283 681                   | K. Griest, D. Seckel                             | (UCSC, CERN)            |
| Also        |     | NP B296 1034 (erratum)        | K. Griest, D. Seckel                             | (UCSC, CERN)            |
| MISHRA      | 87  | PRL 59 1397                   | S.R. Mishra <i>et al.</i>                        | (COLU, CIT, FNAL+)      |
| OBERAUER    | 87  | PL B198 113                   | L.F. Oberauer, F. von Feilitzsch, R.L. Mossbauer |                         |
| WENDT       | 87  | PRL 58 1810                   | C. Wendt <i>et al.</i>                           | (Mark II Collab.)       |
| AZUELOS     | 86  | PRL 56 2241                   | G. Azuelos <i>et al.</i>                         | (TRIU, CNRC)            |
| BADIER      | 86  | ZPHY C31 21                   | J. Badier <i>et al.</i>                          | (NA3 Collab.)           |
| BERNARDI    | 86  | PL 166B 479                   | G. Bernardi <i>et al.</i>                        | (CURIN, INFN, CDEF+)    |
| DORENBOS... | 86  | PL 166B 473                   | J. Dorenbosch <i>et al.</i>                      | (CHARM Collab.)         |
| ALBRECHT    | 85I | PL 163B 404                   | H. Albrecht <i>et al.</i>                        | (ARGUS Collab.)         |
| APALIKOV    | 85  | JETPL 42 289                  | A.M. Apalikov <i>et al.</i>                      | (ITEP)                  |
|             |     | Translated from ZETFP 42 233. |  |                         |
| COOPER...   | 85  | PL 160B 207                   | A.M. Cooper-Sarkar <i>et al.</i>                 | (CERN, LOIC+)           |
| MARKEY      | 85  | PR C32 2215                   | J. Markey, F. Boehm                              | (CIT)                   |
| OHI         | 85  | PL 160B 322                   | T. Ohi <i>et al.</i>                             | (TOKY, INUS, KEK)       |
| MINEHART    | 84  | PRL 52 804                    | R.C. Minehart <i>et al.</i>                      | (UVA, SIN)              |
| BERGSMA     | 83  | PL 122B 465                   | F. Bergsma <i>et al.</i>                         | (CHARM Collab.)         |
| BERGSMA     | 83B | PL 128B 361                   | F. Bergsma <i>et al.</i>                         | (CHARM Collab.)         |
| BRYMAN      | 83B | PRL 50 1546                   | D.A. Bryman <i>et al.</i>                        | (TRIU, CNRC)            |
| DEUTSCH     | 83  | PR D27 1644                   | J.P. Deutsch, M. Lebrun, R. Prieels              | (LOUV)                  |
| GRONAU      | 83  | PR D28 2762                   | M. Gronau  | (HAIF)                  |
| SCHRECK...  | 83  | PL 129B 265                   | K. Schreckenbach <i>et al.</i>                   | (ISNG, ILLG)            |
| HAYANO      | 82  | PRL 49 1305                   | R.S. Hayano <i>et al.</i>                        | (TOKY, KEK, TSUK)       |
| ABELA       | 81  | PL 105B 263                   | R. Abela <i>et al.</i>                           | (SIN)                   |
| ASANO       | 81  | PL 104B 84                    | Y. Asano <i>et al.</i>                           | (KEK, TOKY, INUS, OSAK) |

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| CALAPRICE | 81  | PL 106B 175 | F.P. Calaprice <i>et al.</i> | (PRIN, IND) |
| SHROCK    | 81  | PR D24 1232 | R.E. Shrock                  | (STON)      |
| SHROCK    | 81B | PR D24 1275 | R.E. Shrock                  | (STON)      |
| SHROCK    | 80  | PL 96B 159  | R.E. Shrock                  | (STON)      |

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