

# Heavy Neutral Leptons, Searches for

**OMITTED FROM SUMMARY TABLE**

We define searches for Heavy Neutral Leptons (HNLs) as searches for Dirac or Majorana fermions with sterile neutrino quantum numbers, that are heavy enough to not disrupt the simplest Big Bang Nucleosynthesis bounds and/or unstable on cosmological timescales: Typically HNLs have mass  $\sim$  MeV or higher.

Searches for these particles generically set bounds on the mixing between the HNL and the active neutrinos, as parametrized by the extended  $3 \times 4$  PMNS matrix elements  $U_{\ell x}$  (see the "Neutrino mass, mixing and oscillations" review) where  $\ell = e, \mu$  or  $\tau$ , and we denote the HNL as  $\nu_x$ . While many measurements may be interpreted to place bounds on various combinations of these matrix elements, we quote below limits only for those cases in which one matrix element is assumed to be much larger than the other two, i.e.  $|U_{\ell x}| \gg |U_{\ell' x}|$  for  $\ell' \neq \ell$ .

Experimental searches make use of various different strategies, including e.g. resonance searches in missing mass decay distributions or specific final states, searches for lepton number violating decays, and trilepton signatures. The resulting bounds on  $U_{\ell x}$  are typically dependent on the HNL mass. The quoted limits below are either the best limit near an experimental kinematic threshold, or a characteristic value in the mass range of the experimental sensitivity.

## Limits on heavy neutral lepton mixing parameters

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

Quoted limits are either the best limit near the kinematic threshold of the experiment, or a characteristic value in the mass range of the experimental sensitivity

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3 \times 10^{-7}$	95	1 AAD	25AF ATLS	$m_{\nu_x} \sim 10$ GeV
$<1 \times 10^{-6}$	90	2 DREWES	25 RVUE	$m_{\nu_x} \sim 10$ MeV
$<5 \times 10^{-7}$	95	3 HAYRAPETY...250	CMS	$m_{\nu_x} \sim 10$ GeV
$<0.1$	95	4 AAD	24AW ATLS	$m_{\nu_x} \sim 1$ TeV
$<3 \times 10^{-4}$	95	5 AAD	24BU ATLS	$m_{\nu_x} \sim 20\text{--}50$ GeV
$<4 \times 10^{-6}$	95	6 HAYRAPETY...24AB	CMS	$m_{\nu_x} \sim 20\text{--}60$ GeV
$<1 \times 10^{-3}$	95	6 HAYRAPETY...24AB	CMS	$m_{\nu_x} \gtrsim m_W$
$<1 \times 10^{-5}$	95	7 HAYRAPETY...24S	CMS	$m_{\nu_x} \sim 2.5$ GeV
$<3 \times 10^{-4}$	90	8 AGNES	23A DS50	$m_{\nu_x} \sim 7\text{--}35$ keV
$<3 \times 10^{-8}$	90	9 BAROUKI	22 RVUE	Near $m_{D_s} - m_e$ kin. thres.
$<1 \times 10^{-6}$	95	10 TUMASYAN	22AD CMS	$m_{\nu_x} \sim 8\text{--}14$ GeV, $pp$ at 13 TeV
$<2 \times 10^{-4}$	95	11 FRIEDRICH	21	Near $m_{7\text{Be}} - m_{7\text{Li}}$ kin. thres.
$<1 \times 10^{-9}$	90	12 CORTINA-GIL	20 NA62	$m_{\nu_x} \sim 150\text{--}400$ MeV

$<2 \times 10^{-5}$	95	13 AAD	19F ATLS	$m_{\nu_x} \sim 15\text{--}40$ GeV
$<1 \times 10^{-9}$	90	14 ABE	19B T2K	Near $m_K - m_e$ kin. thres.
$<1 \times 10^{-4}$	90	15 ABLIKIM	19AL BES3	$m_{\nu_x} \sim 0.3\text{--}0.7$ GeV
$<2 \times 10^{-7}$	90	16 BRYMAN	19 RVUE	$m_{\nu_x} \sim 55$ MeV
$<1 \times 10^{-8}$	90	17 AGUILAR-AR...18A	PIEN	$m_{\nu_x} \sim 60\text{--}120$ MeV
$<3 \times 10^{-7}$	90	18 CORTINA-GIL	18 NA62	$m_{\nu_x} \sim 200\text{--}400$ MeV
$<1 \times 10^{-6}$	90	19 PARK	16 BELL	$m_{\nu_x} \sim 1.4$ GeV
$<3 \times 10^{-5}$	90	20 LIVENTSEV	13 BELL	Near $m_{\nu_x} \sim 2\text{--}2.5$ GeV
$<3 \times 10^{-5}$	95	21 ABREU	97I DLPH	$m_{\nu_x} \sim 6\text{--}50$ GeV
$<2 \times 10^{-5}$	95	22 ABREU	97I DLPH	Near $m_{\nu_x} \sim 3.5$ GeV
$<1 \times 10^{-5}$	90	23 BARANOV	93	Near $m_\pi - m_e$ kin. thres.
$<2 \times 10^{-7}$	90	23 BARANOV	93	Near $m_K - m_e$ kin. thres.
$<1 \times 10^{-7}$		24,25 BERNARDI	88 CNTR	Near $m_\pi - m_e$ kin. thres.
$<2 \times 10^{-9}$		25,26 BERNARDI	88 CNTR	Near $m_K - m_e$ kin. thres.
$<1 \times 10^{-7}$	90	27 DORENBOS...	86 CHRM	Near $m_D - m_e$ kin. thres.
$<1 \times 10^{-7}$	90	28 COOPER-...	85 BEBC	Near $m_D - m_e$ kin. thres.
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
not seen		29 ABLIKIM	25BC BES3	$m_{\nu_x} \sim 0.2\text{--}0.8$ GeV
$<1 \times 10^{-6}$	95	30 HAYRAPETY...24v	CMS	Superseded by HAYRAPETYAN 24O. $m_{\nu_x} \sim 10$ GeV
$<5 \times 10^{-7}$	95	31 AAD	23AO ATLS	Superseded by AAD 25AF. $m_{\nu_x} \sim 3\text{--}15$ GeV, $pp$ at 13 TeV
$<2 \times 10^{-5}$	95	32 SIRUNYAN	18K CMS	$m_{\nu_x} \sim 20\text{--}60$ GeV
$<1 \times 10^{-2}$	95	32 SIRUNYAN	18K CMS	$m_{\nu_x} \gtrsim m_W$

<sup>1</sup> AAD 25AF searches for  $W \rightarrow e\nu_x$  with displaced decay  $\nu_x \rightarrow ee\nu$ ,  $\nu_x \rightarrow e\mu\nu$  or  $\nu_x \rightarrow e\pi$  over the range  $m_{\nu_x} \sim 0.5\text{--}16$  GeV. Limits are set for both Dirac and Majorana HNLs, as well as for for case in which the mixing coefficients to all three lepton generations are non-zero.

<sup>2</sup> DREWES 25 searches for displaced decays  $\nu_x \rightarrow e^+e^-\nu_e$  from solar-produced HNLs, mainly via  ${}^8\text{B} \rightarrow {}^8\text{Be}e\nu_x$ , over the range  $m_{\nu_x} \sim 1\text{--}16$  MeV. Limits are derived using data from the space-based detectors Ulysses and the Solar and Heliospheric Observatory. Limits are set for both Dirac and Majorana HNLs, being slightly stronger for the latter.

<sup>3</sup> HAYRAPETYAN 250 searches for  $W \rightarrow e\nu_x$  with displaced decay  $\nu_x \rightarrow ej$ , i.e. with one jet, over the range  $m_{\nu_x} \sim 1\text{--}16.5$  GeV. Limits are set for both Dirac and Majorana HNLs, as well as for the  $e\mu j$  final states in terms of the product of electron and muon-HNL couplings.

<sup>4</sup> AAD 24AW search for scattering of same-sign boson pairs into same-sign electron pairs, mediated by a virtual Majorana HNL, in the HNL mass range 50 GeV to 20 TeV. Limits are also set for  $|V_{eX} V_{\mu X}^*|$ .

<sup>5</sup> AAD 24BU search for same-sign electron pairs in semileptonic decays of top quarks via a Majorana HNL, in the HNL mass range 15–75 GeV.

<sup>6</sup> HAYRAPETYAN 24AB search for  $W \rightarrow e\nu_x \rightarrow eel\nu_\ell$  prompt decays assuming coupling to a single SM generation, between 10–1500 GeV. Above  $m_{\nu_x} \gtrsim m_W$ , sensitivity is greatly reduced by the required virtuality of the HNL. Results are quoted for a mass range below  $m_W$  and just above  $m_W$ , for Majorana HNLs. Similar (weaker) limits also for Dirac HNLs are presented.

- <sup>7</sup> HAYRAPETYAN 24S search for  $W \rightarrow e\nu_x$  followed by  $\nu_x$  displaced decay in flight to electromagnetic and hadronic showers in the CMS muon chamber, in the mass range  $m_{\nu_x} \sim 1\text{--}3$  GeV. Limits are set for both Majorana and Dirac HNLs. This long-lived particle style search results in an exclusion region in the coupling-mass plane whose upper contour is determined by an insufficiently long HNL lifetime to reach the muon chambers, and lower contour by insufficient HNL production. The intersection of these, and thus the extent of the experimental sensitivity, occurs at  $m_{\nu_x} \sim 3$  GeV.
- <sup>8</sup> Search for ionization signals in an LArTPC. Assumes the candidate particle is 100% of dark matter.
- <sup>9</sup> Reanalysis of BEBC results (cf. COOPER-SARKAR 85) to update searches for  $D_s^\pm \rightarrow \nu_x e^\pm$  using a corrected formula for the HNL decay probabilities, additional production channels, and an improved fit for the charm meson distributions. Assumes a Majorana HNL.
- <sup>10</sup> TUMASYAN 22AD search for  $W \rightarrow e\nu_x, \nu_x \rightarrow e\mu\nu_\mu$  and set limits for Dirac and Majorana Heavy Neutral Leptons. The data correspond to an integrated luminosity of  $138 \text{ fb}^{-1}$ .
- <sup>11</sup> Search in electron capture decay  ${}^7\text{Be} \rightarrow {}^7\text{Li}\nu_x$ . Kinematic threshold is  $\sim 850$  keV.
- <sup>12</sup> Search for  $K^+ \rightarrow e^+\nu_x$ . Assumes lifetime of  $\nu_x > 50$  ns.
- <sup>13</sup> Limit from prompt lepton number violating trilepton search.
- <sup>14</sup>  $K^+ \rightarrow e^+\nu_x$ , with  $\nu_x$  decay through  $U_{ex}$ . ABE 19B also considers bounds on  $|U_{\ell x} U_{\ell' x}|$  for combinations of lepton flavors in the  $\nu_x$  decay final state.
- <sup>15</sup> Searches for a Majorana Heavy Neutral Lepton producing a  $\pi^- e^+$  resonance in the same sign dilepton decay  $D \rightarrow K \pi^- e^+ e^+$ .
- <sup>16</sup> BRYMAN 19 sets best limits  $|U_{ex}|^2 < 1 \times 10^{-4}\text{--}2 \times 10^{-7}$  in the mass range  $m_{\nu_x} \sim 2\text{--}55$  MeV, respectively, using the precision branching ratio measurement in AGUILAR-AREVALO 15. See also BRYMAN 19A.
- <sup>17</sup> Search for  $\pi^+ \rightarrow e^+\nu_x$ .
- <sup>18</sup> Search for  $K^+ \rightarrow e^+\nu_x$ .
- <sup>19</sup> PARK 16 quotes an approximate limit  $B(B^+ \rightarrow e^+\nu_x) < 3 \times 10^{-6}$  in the mass range  $m_{\nu_x} \sim 0.2\text{--}1.4$  GeV.
- <sup>20</sup> Search for  $B^+ \rightarrow e^+\nu_x$ .
- <sup>21</sup> Search for prompt  $\nu_x$  decay signatures.
- <sup>22</sup> Search for displaced  $\nu_x$  decay signatures.
- <sup>23</sup> Searches for  $K$  or  $\pi \rightarrow e^+\nu_x, \nu_x \rightarrow e^+e^-\nu_e$  using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron. BARANOV 93 also considers limits for  $|U_{ex} U_{\mu x}|$  from  $K$  or  $\pi \rightarrow \mu^+\nu_x, \nu_x \rightarrow e^+e^-\nu_e$ .
- <sup>24</sup>  $\pi^+ \rightarrow e^+\nu_x$ , with  $\nu_x$  decay through  $U_{ex}$ .
- <sup>25</sup> BERNARDI 88 also considers bounds on  $|U_{ex} U_{\mu x}|$ .
- <sup>26</sup>  $K^+ \rightarrow e^+\nu_x$ , with  $\nu_x$  decay through  $U_{ex}$ .
- <sup>27</sup>  $D^+ \rightarrow e^+\nu_x$ , with  $\nu_x \rightarrow e^-\ell^+\nu_\ell$ .
- <sup>28</sup>  $D^+ \rightarrow e^+\nu_x$ , with  $\nu_x \rightarrow e^-\ell^+\nu_\ell$  or  $\nu_x \rightarrow e^-\pi^+$ .
- <sup>29</sup> ABLIKIM 25BC search for  $D_s^+ \rightarrow \phi e^+\nu_x, \nu_x \rightarrow \pi^- e^+$  in the mass range 0.2–0.8 GeV, and set limits on its branching fraction in the range  $10^{-5}\text{--}10^{-2}$  at 90% CL, respectively.
- <sup>30</sup> HAYRAPETYAN 24V searches for  $W \rightarrow e\nu_x$  with displaced decay  $\nu_x \rightarrow ej$ , i.e. with one jet, over the range  $m_{\nu_x} \sim 2\text{--}20$  GeV. Limits are set for both Dirac and Majorana HNLs.
- <sup>31</sup> AAD 23AO search for  $W \rightarrow \nu_x e$ , for both Majorana and Dirac HNL scenarios. Also consider scenarios involving multiflavor mixing, with correspondingly weaker limits.
- <sup>32</sup> Superseded by HAYRAPETYAN 24AB.

### Limits on $|U_{\mu x}|^2$

Quoted limits are either the best limit near the kinematic threshold of the experiment, or a characteristic value in the mass range of the experimental sensitivity

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1 \times 10^{-7}$	95	1 AAD	25AF ATLS	$m_{\nu_x} \sim 12 \text{ GeV}$
$<2 \times 10^{-7}$	95	2 HAYRAPETY...25O	CMS	$m_{\nu_x} \sim 10 \text{ GeV}$
$<1 \times 10^{-4}$	95	3 AAD	24BU ATLS	$m_{\nu_x} \sim 20\text{--}50 \text{ GeV}$
$<3 \times 10^{-8}$	90	4 ABRATENKO 24	MBNE	Near $m_K - m_\pi - m_\mu$ kin. thres.
$<1 \times 10^{-6}$	90	4 ABRATENKO 24	MBNE	$m_{\nu_x} \sim 150 \text{ MeV}$
$<3 \times 10^{-6}$	95	5 HAYRAPETY...24AB	CMS	$m_{\nu_x} \sim 20\text{--}60 \text{ GeV}$
$<1 \times 10^{-3}$	95	5 HAYRAPETY...24AB	CMS	$m_{\nu_x} \gtrsim m_W$
$<3 \times 10^{-5}$	95	6 HAYRAPETY...24AC	CMS	$m_{\nu_x} \sim 1\text{--}3 \text{ GeV}$
$<5 \times 10^{-6}$	95	7 HAYRAPETY...24S	CMS	$m_{\nu_x} \sim 3 \text{ GeV}$
$<0.1$	95	8 AAD	23CE ATLS	Near $m_{\nu_x} \sim 0.1\text{--}2 \text{ TeV}$
$<0.1$	95	9 TUMASYAN	23AC CMS	Near $m_{\nu_x} \sim 0.1\text{--}3 \text{ TeV}$
$<5 \times 10^{-9}$	90	10 ABRATENKO 22A	MBNE	Near $m_K - m_\mu$ kin. thres.
$<3 \times 10^{-7}$	95	11 TUMASYAN	22AD CMS	$m_{\nu_x} \sim 8\text{--}14 \text{ GeV}$ , $pp$ at 13 TeV
$<1 \times 10^{-3}$	95	12 AAIJ	21AA LHCb	$m_{\nu_x} \sim 5\text{--}50 \text{ GeV}$ , $pp$ at 7, 8 TeV
$<2 \times 10^{-4}$	95	13 AAIJ	21AA LHCb	$m_{\nu_x} \sim 5\text{--}50 \text{ GeV}$ , $pp$ at 7, 8 TeV
$<5 \times 10^{-9}$	90	14,15 CORTINA-GIL 21	NA62	Near $m_K - m_\mu$ kin. thres.
$<2 \times 10^{-2}$	90	16 PRIM	20 BELL	$m_{\nu_x} \sim 1 \text{ GeV}$
$<2 \times 10^{-5}$	95	17 AAD	19F ATLS	$m_{\nu_x} \sim 10\text{--}50 \text{ GeV}$
$<2 \times 10^{-6}$	95	18 AAD	19F ATLS	$m_{\nu_x} \sim 10 \text{ GeV}$
$<1 \times 10^{-9}$	90	19 ABE	19B T2K	Near $m_K - m_\mu$ kin. thres.
$<5 \times 10^{-6}$	90	20,21 AGUILAR-AR...19B	PIEN	$m_{\nu_x} \sim 16\text{--}30 \text{ MeV}$
$<1 \times 10^{-5}$	90	21 AGUILAR-AR...19B	PIEN	Near $m_\pi - m_\mu$ kin. thres.
$<3 \times 10^{-7}$	90	14 CORTINA-GIL 18	NA62	$m_{\nu_x} \sim 250\text{--}350 \text{ MeV}$
$<3 \times 10^{-6}$	90	14 LAZZERONI 17A	NA62	Near $m_K - m_\mu$ kin. thres.
$<5 \times 10^{-2}$	90	22 PARK	16 BELL	$m_{\nu_x} \sim 1.4 \text{ GeV}$
$<1 \times 10^{-8}$	90	14 ARTAMONOV 15A	B949	$m_{\nu_x} \sim 200\text{--}300 \text{ MeV}$
$<3 \times 10^{-5}$	90	23 LIVENTSEV 13	BELL	Near $m_{\nu_x} \sim 2\text{--}2.5 \text{ GeV}$
$<2.0 \times 10^{-8}$	95	24 DAUM	00 KARM	$m_{\nu_x} = 33.905 \text{ MeV}$
$<8 \times 10^{-8}$	90	25 VAITAITIS 99	CCFR	Near $m_K - m_\mu$ kin. thres.
$<6 \times 10^{-8}$	90	26 VAITAITIS 99	CCFR	Near $m_{D_s} - m_\mu$ kin. thres.
$<3 \times 10^{-5}$	95	27 ABREU 97I	DLPH	$m_{\nu_x} \sim 6\text{--}50 \text{ GeV}$
$<2 \times 10^{-5}$	95	28 ABREU 97I	DLPH	Near $m_{\nu_x} \sim 3.5 \text{ GeV}$
$<3 \times 10^{-5}$	90	29 VILAIN 95C	CHM2	Near $m_K - m_\mu$ kin. thres.
$<3 \times 10^{-8}$		30,31 BERNARDI 88	CNTR	Near $m_\mu + m_\pi$ kin. thres.
$<2 \times 10^{-9}$		31,32 BERNARDI 88	CNTR	Near $m_K - m_\mu$ kin. thres.
$<1 \times 10^{-7}$	90	33 DORENBOS... 86	CHRM	Near $m_D - m_\mu$ kin. thres.

<1	$\times 10^{-7}$	90	34 COOPER-...	85	BEBC	Near $m_D - m_\mu$ kin. thres.
<1	$\times 10^{-6}$	90	35 HAYANO	82	CNTR	$m_{\nu_X} \sim 200\text{--}300$ MeV
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●						
<5	$\times 10^{-7}$	95	36 HAYRAPETY...24v		CMS	Superseded by HAYRAPETYAN 240. $m_{\nu_X} \sim 10$ GeV
<5	$\times 10^{-7}$	95	37 AAD	23A0	ATLS	Superseded by AAD 25AF. $m_{\nu_X} \sim 3\text{--}15$ GeV, $pp$ at 13 TeV
<1	$\times 10^{-7}$	90	38 ABRATENKO	20	MBNE	Superseded by ABRATENKO 22A
<2	$\times 10^{-5}$	95	39 SIRUNYAN	18K	CMS	$m_{\nu_X} \sim 20\text{--}60$ GeV
<5	$\times 10^{-3}$	95	39 SIRUNYAN	18K	CMS	$m_{\nu_X} \gtrsim m_W$

- <sup>1</sup> AAD 25AF searches for  $W \rightarrow \mu\nu_X$  with displaced decay  $\nu_X \rightarrow \mu\mu\nu$ ,  $\nu_X \rightarrow e\mu\nu$  or  $\nu_X \rightarrow \mu\pi$  over the range  $m_{\nu_X} \sim 0.5\text{--}16$  GeV. Limits are set for both Dirac and Majorana HNLs, as well as for case in which the mixing coefficients to all three lepton generations are non-zero.
- <sup>2</sup> HAYRAPETYAN 250 searches for  $W \rightarrow \mu\nu_X$  with displaced decay  $\nu_X \rightarrow \mu j$ , i.e. with one jet, over the range  $m_{\nu_X} \sim 1\text{--}16.5$  GeV. Limits are set for both Dirac and Majorana HNLs, as well as for the  $e\mu j$  final states in terms of the product of electron and muon-HNL couplings.
- <sup>3</sup> AAD 24BU search for same-sign muon pairs in semileptonic decays of top quarks via a Majorana HNL, in the HNL mass range 15–75 GeV.
- <sup>4</sup> ABRATENKO 24 search for  $K^+ \rightarrow \mu^+\nu_X$ , with  $\nu_X \rightarrow \nu_\mu e^+ e^-$  and  $\nu_X \rightarrow \nu_\mu \pi^0 \rightarrow \nu_\mu \gamma\gamma$  in the mass ranges  $m_{\nu_X} \sim 10\text{--}150$  MeV and  $m_{\nu_X} \sim 150\text{--}245$  MeV, respectively, for the case of a Majorana HNL. The  $\pi^0$  mode dominates above  $m_{\nu_X} \sim 150$  MeV.
- <sup>5</sup> HAYRAPETYAN 24AB search for  $W \rightarrow \mu\nu_X \rightarrow \mu\mu\ell\nu_\ell$  prompt decays assuming coupling to a single SM generation, between 10–1500 GeV. Above  $m_{\nu_X} \gtrsim m_W$ , sensitivity is greatly reduced by the required virtuality of the HNL. Results are quoted for a mass range below  $m_W$  and just above  $m_W$ , for Majorana HNLs. Similar (weaker) limits also for Dirac HNLs are presented.
- <sup>6</sup> HAYRAPETYAN 24AC search for  $B \rightarrow X\mu\nu_X$  and  $B \rightarrow \mu\nu_X$  followed by displaced  $\nu_X \rightarrow \mu\pi^\pm$  decay, where  $X$  is an unreconstructed hadronic system, for Majorana HNLs. Also considers mixed flavor scenarios with  $e\mu$  final state lepton pairs, and presents similar (weaker) limits for Dirac HNLs.
- <sup>7</sup> HAYRAPETYAN 24S search for  $W \rightarrow \mu\nu_X$  followed by  $\nu_X$  displaced decay in flight to electromagnetic and hadronic showers in the CMS muon chamber, in the mass range  $m_{\nu_X} \sim 1\text{--}3$  GeV. Limits are set for both Majorana and Dirac HNLs. This long-lived particle style search results in an exclusion region in the coupling-mass plane whose upper contour is determined by an insufficiently long HNL lifetime to reach the muon chambers, and lower contour by insufficient HNL production. The intersection of these, and thus the extent of the experimental sensitivity, occurs at  $m_{\nu_X} \sim 3.5$  GeV.
- <sup>8</sup> AAD 23CE search for Majorana HNLs via vector boson fusion  $W^\pm W^\pm \rightarrow \mu^\pm \mu^\pm$ . Limits set in a  $m_{\nu_X}$  mass range from 50 GeV up to 20 TeV, using the Phenomenological Type-I Seesaw model as a benchmark scenario.
- <sup>9</sup> TUMASYAN 23AC search for Majorana HNLs via vector boson fusion  $W^\pm W^\pm \rightarrow \mu^\pm \mu^\pm$ . Limits set in a  $m_{\nu_X}$  mass range from 50 GeV up to 25 TeV.
- <sup>10</sup> ABRATENKO 22A search for  $K^+ \rightarrow \mu^+\nu_X$ , with  $\nu_X \rightarrow \mu^\mp \pi^\pm$ , in the mass range  $m_{\nu_X} \sim 246\text{--}385$  MeV. Also considers limits from  $\nu_X \rightarrow \mu^- \pi^+$  only, for the case of a Dirac HNL.

- 11 TUMASYAN 22AD search for  $W \rightarrow \mu\nu_X, \nu_X \rightarrow \mu e \nu_e$  and set limits for Dirac and Majorana Heavy Neutral Leptons. The data correspond to an integrated luminosity of  $138 \text{ fb}^{-1}$ .
- 12 Limit from prompt lepton number conserving  $W \rightarrow \mu\mu j$  search.
- 13 Limit from prompt lepton number violating  $W \rightarrow \mu\mu j$  search.
- 14 Search for  $K^+ \rightarrow \mu^+ \nu_X$ .
- 15 Assumes a lifetime exceeding 50 ns, and searches over  $m_{\nu_X}$  range 200–384 MeV.
- 16 Search for  $B^+ \rightarrow \mu^+ \nu_X$  in the mass range  $m_{\nu_X} \sim 0\text{--}1.5 \text{ GeV}$ .
- 17 Limit from prompt lepton number violating trilepton search.
- 18 Limit from displaced lepton violating or conserving trilepton searches.
- 19  $K^+ \rightarrow \mu^+ \nu_X$ , with  $\nu_X$  decay through  $U_{\mu X}$ . ABE 19B also considers bounds on  $|U_{\ell X} U_{\ell' X}|$  for combinations of lepton flavors in the  $\nu_X$  decay final state.
- 20 Limit requires muon kinetic energy  $> 1.2 \text{ MeV}$ .
- 21 Search for  $\pi^+ \rightarrow \mu^+ \nu_X$ .
- 22 PARK 16 quotes an approximate limit  $B(B^+ \rightarrow \mu^+ \nu_X) < 3 \times 10^{-6}$  in the mass range  $m_{\nu_X} \sim 0.2\text{--}1.4 \text{ GeV}$ .
- 23 Search for  $B^+ \rightarrow \mu^+ \nu_X$ .
- 24 DAUM 00 quotes a branching ratio bound  $B(\pi^+ \rightarrow \mu^+ \nu_X) < 6.0 \times 10^{-10}$  at 95% CL.
- 25  $K^+ \rightarrow \mu^+ \nu_X$ , with  $\nu_X \rightarrow \mu X$ .
- 26  $D_s \rightarrow \mu^+ \nu_X$ , with  $\nu_X \rightarrow \mu X$ .
- 27 Search for prompt  $\nu_X$  decay signatures.
- 28 Search for displaced  $\nu_X$  decay signatures.
- 29 Search for Heavy Neutral Leptons produced by neutral current muon neutrino interactions, with  $\nu_X \rightarrow \mu^+ \mu^- \nu_\mu$ .
- 30  $K^+ \rightarrow \mu^+ \nu_X$ , with  $\nu_X$  decay through  $U_{\mu X}$  and  $m_{\nu_X} < m_\mu + m_\pi$ .
- 31 BERNARDI 88 also considers bounds on  $|U_{eX} U_{\mu X}|$ .
- 32  $K^+ \rightarrow \mu^+ \nu_X$ , with  $\nu_X \rightarrow \mu^- \pi^+$ .
- 33  $D^+ \rightarrow \mu^+ \nu_X$ , with  $\nu_X \rightarrow \mu^- \ell^+ \nu_\ell$ .
- 34  $D^+ \rightarrow \mu^+ \nu_X$ , with  $\nu_X \rightarrow \mu^- \ell^+ \nu_\ell$  or  $\nu_X \rightarrow \mu^- \pi^+$ .
- 35 Search for  $K^+ \rightarrow \mu^+ \nu_X (\gamma)$ .
- 36 HAYRAPETYAN 24V searches for  $W \rightarrow \mu\nu_X$  with displaced decay  $\nu_X \rightarrow \mu j$ , i.e. with one jet, over the range  $m_{\nu_X} \sim 2\text{--}20 \text{ GeV}$ . Limits are set for both Dirac and Majorana HNLs.
- 37 AAD 23AO search for  $W \rightarrow \nu_X \mu$ , for both Majorana and Dirac HNL scenarios. Also consider scenarios involving multiflavor mixing, with correspondingly weaker limits.
- 38  $K^+ \rightarrow \mu^+ \nu_X$ , with  $\nu_X \rightarrow \mu^- \pi^+$ , in the mass range  $m_{\nu_X} \sim 260\text{--}385 \text{ MeV}$ . ABRATENKO 20 also considers  $\nu_X \rightarrow \mu^+ \pi^-$  for the case of a Majorana HNL.
- 39 Superseded by HAYRAPETYAN 24AB.

### Limits on $|U_{\tau X}|^2$

Quoted limits are either the best limit near the kinematic threshold of the experiment, or a characteristic value in the mass range of the experimental sensitivity

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<0.1$	95	1 AAD	24BU ATLS	$m_{\nu_X} \sim 20\text{--}50 \text{ GeV}$
$<6 \times 10^{-4}$	95	2 HAYRAPETY...24AB	CMS	$m_{\nu_X} \sim 20\text{--}60 \text{ GeV}$
$<1 \times 10^{-1}$	95	2 HAYRAPETY...24AB	CMS	$m_{\nu_X} \gtrsim m_W$
$<3 \times 10^{-4}$	95	3 HAYRAPETY...24S	CMS	$m_{\nu_X} \sim 2 \text{ GeV}$

$<1 \times 10^{-2}$	95	4 HAYRAPETY...24V	CMS	$m_{\nu_X} \sim 3\text{--}20 \text{ GeV}$
$<1 \times 10^{-3}$	90	5 NAYAK	24 BELL	Near $m_\tau - m_\pi$ kin. thres.
$<1 \times 10^{-5}$	95	6 LEES	23A BABR	Near $m_\tau - 3m_\pi$ kin. thres.
$<2 \times 10^{-6}$	90	7 BAROUKI	22 RVUE	Near $m_\tau - m_\nu$ kin. thres.
$<3 \times 10^{-4}$	90	8 ACCIARRI	21 ARNT	Near $m_{\nu_X} \lesssim 970 \text{ MeV}$
$<3 \times 10^{-6}$	90	9 BOIARSKA	21 RVUE	Near $m_{\nu_X} \sim 0.8\text{--}1.6 \text{ GeV}$
$<2 \times 10^{-4}$	90	10 ORLOFF	02 CHRМ	Near $m_D - m_\tau$ kin. thres.
$<1 \times 10^{-4}$	90	11 ORLOFF	02 CHRМ	$m_{\nu_X} \sim 200\text{--}250 \text{ MeV}$
$<3 \times 10^{-5}$	95	12 ABREU	97I DLPH	$m_{\nu_X} \sim 6\text{--}50 \text{ GeV}$
$<2 \times 10^{-5}$	95	13 ABREU	97I DLPH	Near $m_{\nu_X} \sim 3.5 \text{ GeV}$

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

14 LIVENTSEV	23 BELL	Near $m_{\nu_X} \sim 0.8\text{--}1.2 \text{ GeV}$
15 TUMASYAN	22H CMS	$pp$ at 13 TeV

- <sup>1</sup> AAD 24BU search for same-sign tau pairs in semileptonic decays of top quarks via a Majorana HNL, in the HNL mass range 15–75 GeV.
- <sup>2</sup> HAYRAPETYAN 24AB search for  $W \rightarrow \tau \nu_X \rightarrow \tau \tau \ell \nu_\ell$  prompt decays assuming coupling to a single SM generation, between 10–1500 GeV. Above  $m_{\nu_X} \gtrsim m_W$ , sensitivity is greatly reduced by the required virtuality of the HNL. Results are quoted for a mass range below  $m_W$  and just above  $m_W$ , for Majorana HNLs. Similar (weaker) limits also for Dirac HNLs are presented.
- <sup>3</sup> HAYRAPETYAN 24S search for  $W \rightarrow \tau \nu_X$  followed by  $\nu_X$  displaced decay in flight to electromagnetic and hadronic showers in the CMS muon chamber, in the mass range  $m_{\nu_X} \sim 1\text{--}2 \text{ GeV}$ . Limits are set for both Majorana and Dirac HNLs. This long-lived particle style search results in an exclusion region in the coupling-mass plane whose upper contour is determined by an insufficiently long HNL lifetime to reach the muon chambers, and lower contour by insufficient HNL production. The intersection of these, and thus the extent of the experimental sensitivity, occurs at  $m_{\nu_X} \sim 2 \text{ GeV}$ .
- <sup>4</sup> HAYRAPETYAN 24V searches for  $W \rightarrow \tau \nu_X$  with displaced decay  $\nu_X \rightarrow \tau j$ , i.e. with one jet, over the range  $m_{\nu_X} \sim 3\text{--}20 \text{ GeV}$ . Limits are set for both Dirac and Majorana HNLs.
- <sup>5</sup> NAYAK 24 searches for  $\tau \rightarrow \pi \nu_X$  with displaced decay  $\nu_X \rightarrow \nu_\tau \mu^+ \mu^-$  in the Belle central drift chamber (CDC). This long-lived particle style search results in an exclusion region in the coupling-mass plane whose upper contour is determined by an insufficiently long HNL lifetime to reach the CDC, and lower contour by insufficient HNL production. Limits are set for both Dirac and Majorana HNLs.
- <sup>6</sup> Search for  $\tau^\pm \rightarrow \pi^\pm \pi^+ \pi^- \nu_X$ .
- <sup>7</sup> Reanalysis of BEBC results (cf. COOPER-SARKAR 85) to include searches for  $D_s^\pm \rightarrow \nu_\tau \tau^\pm, \tau^\pm \rightarrow \nu_X \pi^\pm, \nu_X \rho^\pm$ , or  $\nu_X \nu_\tau \ell^\pm$  via  $U_{\tau X}$ . Assumes a Majorana HNL.
- <sup>8</sup> Search for  $\nu_X \rightarrow \mu^+ \mu^- \nu$ .
- <sup>9</sup> Reanalysis of CHARM results (cf. ORLOFF 02) to include searches for  $\nu_X \rightarrow \nu \ell^+ \ell^-$  decays, and including the production of HNLs from  $\tau$  decays.
- <sup>10</sup>  $D_s \rightarrow \tau^+ \nu_X$ , with  $\nu_X$  decay via  $U_{\tau X}$ .
- <sup>11</sup>  $D_s \rightarrow \nu_\tau \tau^+, \tau^+ \rightarrow \nu_X X$ , with  $\nu_X$  decay via  $U_{\tau X}$ .
- <sup>12</sup> Search for prompt  $\nu_X$  decay signatures.
- <sup>13</sup> Search for displaced  $\nu_X$  decay signatures. Kinematical suppression of  $\nu_X \rightarrow \tau X$  at lower masses leads to rapid loosening of the  $|U_{\tau X}|$  bound compared to that for  $|U_{eX}|$  and  $|U_{\mu X}|$ .
- <sup>14</sup> Search for  $\tau \rightarrow \pi \nu_X, \nu_X \rightarrow \pi e$  or  $\pi \mu$  in the range 0.2–1.6 GeV. LIVENTSEV 23 reports results for the sum  $\sum_{\ell=e,\mu,\tau} |U_{\ell X}|^2$  in a model-dependent context, but which

may be roughly reinterpreted as a limit  $|U_{eX} U_{\tau X}|^2 + |U_{\mu X} U_{\tau X}|^2 \lesssim 5 \times 10^{-9}$  in either Majorana or Dirac HNL scenarios.

- <sup>15</sup> TUMASYAN 22H sets limits on an approximately mass-degenerate vector-like lepton SU(2) doublet coupling to the  $\tau$ . Some of the reported signal region distributions might be used to set limits for heavy neutral leptons coupled to the  $\tau$ . The data correspond to an integrated luminosity of  $138 \text{ fb}^{-1}$ .

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