

# 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
$<1 \times 10^{-6}$	95	1 TUMASYAN	22AD CMS	$m_{\nu_x} \sim 8-14$ GeV, $pp$ at 13 TeV
$<2 \times 10^{-4}$	95	2 FRIEDRICH	21	Near $m_{7\text{Be}} - m_{7\text{Li}}$ kin. thres.
$<1 \times 10^{-9}$	90	3 CORTINA-GIL	20 NA62	$m_{\nu_x} \sim 150-400$ MeV
$<2 \times 10^{-5}$	95	4 AAD	19F ATLS	$m_{\nu_x} \sim 15-40$ GeV
$<1 \times 10^{-9}$	90	5 ABE	19B T2K	Near $m_K - m_e$ kin. thres.
$<1 \times 10^{-4}$	90	6 ABLIKIM	19AL BES3	$m_{\nu_x} \sim 0.3-0.7$ GeV
$<1 \times 10^{-7}$	90	7 BRYMAN	19 RVUE	$m_{\nu_x} \sim 60$ MeV
$<1 \times 10^{-8}$	90	8 AGUILAR-AR...18A	PIEN	$m_{\nu_x} \sim 60-120$ MeV $jbr_i$
$<3 \times 10^{-7}$	90	9 CORTINA-GIL	18 NA62	$m_{\nu_x} \sim 200-400$ MeV
$<1 \times 10^{-6}$	90	10 PARK	16 BELL	$m_{\nu_x} \sim 1.4$ GeV
$<3 \times 10^{-5}$	90	11 LIVENTSEV	13 BELL	Near $m_{\nu_x} \sim 2-2.5$ GeV
$<3 \times 10^{-5}$	95	12 ABREU	97I DLPH	$m_{\nu_x} \sim 6-50$ GeV

$<2 \times 10^{-5}$	95	13 ABREU	971	DLPH	Near $m_{\nu_X} \sim 3.5$ GeV
$<1 \times 10^{-5}$	90	14 BARANOV	93		Near $m_{\pi} - m_e$ kin. thres.
$<2 \times 10^{-7}$	90	14 BARANOV	93		Near $m_K - m_e$ kin. thres.
$<1 \times 10^{-7}$		15,16 BERNARDI	88	CNTR	Near $m_{\pi} - m_e$ kin. thres.
$<2 \times 10^{-9}$		16,17 BERNARDI	88	CNTR	Near $m_K - m_e$ kin. thres.
$<1 \times 10^{-7}$	90	18 DORENBOS...	86	CHRM	Near $m_D - m_e$ kin. thres.
$<1 \times 10^{-7}$	90	19 COOPER-...	85	BEBC	Near $m_D - m_e$ kin. thres.

<sup>1</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>2</sup> Search in electron capture decay  ${}^7\text{Be} \rightarrow {}^7\text{Li}\nu_X$ . Kinematic threshold is  $\sim 850$  keV.

<sup>3</sup> Search for  $K^+ \rightarrow e^+\nu_X$ . Assumes lifetime of  $\nu_X > 50$  ns.

<sup>4</sup> Limit from prompt lepton number violating trilepton search.

<sup>5</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>6</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>7</sup> BRYMAN 19 sets best limits  $|U_{eX}|^2 < 4 \times 10^{-4} - 1 \times 10^{-7}$  in the mass range  $m_{\nu_X} \sim 2-60$  MeV, respectively, using the precision branching ratio measurement in AGUILAR-AREVALO 15. See also BRYMAN 19A.

<sup>8</sup> Search for  $\pi^+ \rightarrow e^+\nu_X$ .

<sup>9</sup> Search for  $K^+ \rightarrow e^+\nu_X$ .

<sup>10</sup> PARK 16 quotes an approximate limit  $B(B^+ \rightarrow e^+\nu_X) < 3 \times 10^{-6}$  in the mass range  $m_{\nu_X} \sim 0.2-1.4$  GeV.

<sup>11</sup> Search for  $B^+ \rightarrow e^+\nu_X$ .

<sup>12</sup> Search for prompt  $\nu_X$  decay signatures.

<sup>13</sup> Search for displaced  $\nu_X$  decay signatures.

<sup>14</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>15</sup>  $\pi^+ \rightarrow e^+\nu_X$ , with  $\nu_X$  decay through  $U_{eX}$ .

<sup>16</sup> BERNARDI 88 also considers bounds on  $|U_{eX} U_{\mu X}|$ .

<sup>17</sup>  $K^+ \rightarrow e^+\nu_X$ , with  $\nu_X$  decay through  $U_{eX}$ .

<sup>18</sup>  $D^+ \rightarrow e^+\nu_X$ , with  $\nu_X \rightarrow e^- \ell^+ \nu_\ell$ .

<sup>19</sup>  $D^+ \rightarrow e^+\nu_X$ , with  $\nu_X \rightarrow e^- \ell^+ \nu_\ell$  or  $\nu_X \rightarrow e^- \pi^+$ .

### 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
$<5 \times 10^{-9}$	90	1 ABRATENKO 22A	MBNE	Near $m_K - m_\mu$ kin. thres.
$<3 \times 10^{-7}$	95	2 TUMASYAN 22AD	CMS	$m_{\nu_X} \sim 8-14$ GeV, $pp$ at 13 TeV
$<1 \times 10^{-3}$	95	3 AAIJ 21AA	LHCB	$m_{\nu_X} \sim 5-50$ GeV, $pp$ at 7, 8 TeV
$<2 \times 10^{-4}$	95	4 AAIJ 21AA	LHCB	$m_{\nu_X} \sim 5-50$ GeV, $pp$ at 7, 8 TeV
$<5 \times 10^{-9}$	90	5,6 CORTINA-GIL 21	NA62	Near $m_K - m_\mu$ kin. thres.
$<2 \times 10^{-2}$	90	7 PRIM 20	BELL	$m_{\nu_X} \sim 1$ GeV

$<2 \times 10^{-5}$	95	8	AAD	19F	ATLS	$m_{\nu_x} \sim 10\text{--}50$ GeV
$<2 \times 10^{-6}$	95	9	AAD	19F	ATLS	$m_{\nu_x} \sim 10$ GeV
$<1 \times 10^{-9}$	90	10	ABE	19B	T2K	Near $m_K - m_\mu$ kin. thres.
$<5 \times 10^{-6}$	90	11,12	AGUILAR-AR...	19B	PIEN	$m_{\nu_x} \sim 16\text{--}30$ MeV
$<1 \times 10^{-5}$	90	12	AGUILAR-AR...	19B	PIEN	Near $m_\pi - m_\mu$ kin. thres.
$<3 \times 10^{-7}$	90	5	CORTINA-GIL	18	NA62	$m_{\nu_x} \sim 250\text{--}350$ MeV
$<3 \times 10^{-6}$	90	5	LAZZERONI	17A	NA62	Near $m_K - m_\mu$ kin. thres.
$<5 \times 10^{-2}$	90	13	PARK	16	BELL	$m_{\nu_x} \sim 1.4$ GeV
$<1 \times 10^{-8}$	90	5	ARTAMONOV	15A	B949	$m_{\nu_x} \sim 200\text{--}300$ MeV
$<3 \times 10^{-5}$	90	14	LIVENTSEV	13	BELL	Near $m_{\nu_x} \sim 2\text{--}2.5$ GeV
$<2.0 \times 10^{-8}$	95	15	DAUM	00	KARM	$m_{\nu_x} = 33.905$ MeV
$<8 \times 10^{-8}$	90	16	VAITAITIS	99	CCFR	Near $m_K - m_\mu$ kin. thres.
$<6 \times 10^{-8}$	90	17	VAITAITIS	99	CCFR	Near $m_{D_s} - m_\mu$ kin. thres.
$<3 \times 10^{-5}$	95	18	ABREU	97I	DLPH	$m_{\nu_x} \sim 6\text{--}50$ GeV
$<2 \times 10^{-5}$	95	19	ABREU	97I	DLPH	Near $m_{\nu_x} \sim 3.5$ GeV
$<3 \times 10^{-5}$	90	20	VILAIN	95C	CHM2	Near $m_K - m_\mu$ kin. thres.
$<3 \times 10^{-8}$		21,22	BERNARDI	88	CNTR	Near $m_\mu + m_\pi$ kin. thres.
$<2 \times 10^{-9}$		22,23	BERNARDI	88	CNTR	Near $m_K - m_\mu$ kin. thres.
$<1 \times 10^{-7}$	90	24	DORENBOS...	86	CHRM	Near $m_D - m_\mu$ kin. thres.
$<1 \times 10^{-7}$	90	25	COOPER-...	85	BEBC	Near $m_D - m_\mu$ kin. thres.

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

$<1 \times 10^{-7}$	90	26	ABRATENKO	20	MBNE	Superseded by ABRATENKO 22A
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<sup>1</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.

<sup>2</sup> 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  $138 \text{ fb}^{-1}$ .

<sup>3</sup> Limit from prompt lepton number conserving  $W \rightarrow \mu \mu j$  search.

<sup>4</sup> Limit from prompt lepton number violating  $W \rightarrow \mu \mu j$  search.

<sup>5</sup> Search for  $K^+ \rightarrow \mu^+ \nu_x$ .

<sup>6</sup> Assumes a lifetime exceeding 50 ns, and searches over  $m_{\nu_x}$  range 200–384 MeV.

<sup>7</sup> Search for  $B^+ \rightarrow \mu^+ \nu_x$  in the mass range  $m_{\nu_x} \sim 0\text{--}1.5$  GeV.

<sup>8</sup> Limit from prompt lepton number violating trilepton search.

<sup>9</sup> Limit from displaced lepton violating or conserving trilepton searches.

<sup>10</sup>  $K^+ \rightarrow \mu^+ \nu_x$ , 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.

<sup>11</sup> Limit requires muon kinetic energy  $> 1.2$  MeV.

<sup>12</sup> Search for  $\pi^+ \rightarrow \mu^+ \nu_x$ .

<sup>13</sup> PARK 16 quotes an approximate limit  $B(B^+ \rightarrow \mu^+ \nu_x) < 3 \times 10^{-6}$  in the mass range  $m_{\nu_x} \sim 0.2\text{--}1.4$  GeV.

<sup>14</sup> Search for  $B^+ \rightarrow \mu^+ \nu_x$ .

<sup>15</sup> DAUM 00 quotes a branching ratio bound  $B(\pi^+ \rightarrow \mu^+ \nu_x) < 6.0 \times 10^{-10}$  at 95% CL.

- 16  $K^+ \rightarrow \mu^+ \nu_X$ , with  $\nu_X \rightarrow \mu X$ .
- 17  $D_S \rightarrow \mu^+ \nu_X$ , with  $\nu_X \rightarrow \mu X$ .
- 18 Search for prompt  $\nu_X$  decay signatures.
- 19 Search for displaced  $\nu_X$  decay signatures.
- 20 Search for Heavy Neutral Leptons produced by neutral current muon neutrino interactions, with  $\nu_X \rightarrow \mu^+ \mu^- \nu_\mu$ .
- 21  $K^+ \rightarrow \mu^+ \nu_X$ , with  $\nu_X$  decay through  $U_{\mu X}$  and  $m_{\nu_X} < m_\mu + m_\pi$ .
- 22 BERNARDI 88 also considers bounds on  $|U_{eX} U_{\mu X}|$ .
- 23  $K^+ \rightarrow \mu^+ \nu_X$ , with  $\nu_X \rightarrow \mu^- \pi^+$ .
- 24  $D^+ \rightarrow \mu^+ \nu_X$ , with  $\nu_X \rightarrow \mu^- \ell^+ \nu_\ell$ .
- 25  $D^+ \rightarrow \mu^+ \nu_X$ , with  $\nu_X \rightarrow \mu^- \ell^+ \nu_\ell$  or  $\nu_X \rightarrow \mu^- \pi^+$ .
- 26  $K^+ \rightarrow \mu^+ \nu_X$ , with  $\nu_X \rightarrow \mu^- \pi^+$ , in the mass range  $m_{\nu_X} \sim 260\text{--}385$  MeV.  
 ABRATENKO 20 also considers  $\nu_X \rightarrow \mu^+ \pi^-$  for the case of a Majorana HNL.

### 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
$<3 \times 10^{-4}$	90	1 ACCIARRI 21	ARNT	Near $m_{\nu_X} \lesssim 970$ MeV
$<3 \times 10^{-6}$	90	2 BOIARSKA 21	RVUE	Near $m_{\nu_X} \sim 0.8\text{--}1.6$ GeV
$<2 \times 10^{-4}$	90	3 ORLOFF 02	CHRM	Near $m_D - m_\tau$ kin. thres.
$<1 \times 10^{-4}$	90	4 ORLOFF 02	CHRM	$m_{\nu_X} \sim 200\text{--}250$ MeV
$<3 \times 10^{-5}$	95	5 ABREU 97i	DLPH	$m_{\nu_X} \sim 6\text{--}50$ GeV
$<2 \times 10^{-5}$	95	6 ABREU 97i	DLPH	Near $m_{\nu_X} \sim 3.5$ GeV

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

7 TUMASYAN 22H CMS  $pp$  at 13 TeV

- 1 Search for  $\nu_X \rightarrow \mu^+ \mu^- \nu$ .
- 2 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.
- 3  $D_S \rightarrow \tau^+ \nu_X$ , with  $\nu_X$  decay via  $U_{\tau X}$ .
- 4  $D_S \rightarrow \nu_\tau \tau^+$ ,  $\tau^+ \rightarrow \nu_X X$ , with  $\nu_X$  decay via  $U_{\tau X}$ .
- 5 Search for prompt  $\nu_X$  decay signatures.
- 6 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  $|U_{\mu X}|$ .
- 7 TUMASYAN 22H sets limits on an approximately mass-degenerate vector-like lepton SU(2) doublet coupled 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  $138 \text{ fb}^{-1}$ .

## REFERENCES FOR Heavy Neutral Leptons, Searches for

ABRATENKO 22A	PR D106 092006	P. Abratenko <i>et al.</i>	(MicroBooNE Collab.)
TUMASYAN 22AD	JHEP 2207 081	A. Tumasyan <i>et al.</i>	(CMS Collab.)
TUMASYAN 22H	PR D105 112007	A. Tumasyan <i>et al.</i>	(CMS Collab.)
AAIJ 21AA	EPJ C81 248	R. Aaij <i>et al.</i>	(LHCb Collab.)
ACCIARRI 21	PRL 127 121801	R. Acciarri <i>et al.</i>	(ArgoNeuT Collab.)
BOIARSKA 21	PR D104 095019	I. Boiarska <i>et al.</i>	(BOHR, LEID)
CORTINA-GIL 21	PL B816 136259	E. Cortina Gil <i>et al.</i>	(NA62 Collab.)

FRIEDRICH	21	PRL 126 021803	S. Friedrich <i>et al.</i>	(BeEST Collab.)
ABRATENKO	20	PR D101 052001	P. Abratenko <i>et al.</i>	(MiniBooNE Collab.)
CORTINA-GIL	20	PL B807 135599	E. Cortina Gil <i>et al.</i>	(NA62 Collab.)
PRIM	20	PR D101 032007	M.T. Prim <i>et al.</i>	(BELLE Collab.)
AAD	19F	JHEP 1910 265	G. Aad <i>et al.</i>	(ATLAS Collab.)
ABE	19B	PR D100 052006	K. Abe <i>et al.</i>	(T2K Collab.)
ABLIKIM	19AL	PR D99 112002	M. Ablikim <i>et al.</i>	(BESIII Collab.)
AGUILAR-AR...	19B	PL B798 134980	A. Aguilar-Arevalo <i>et al.</i>	(PIENU Collab.)
BRYMAN	19	PR D100 053006	D. Bryman, R. Shrock	(BRCO, TRIU, STON)
BRYMAN	19A	PR D100 073011	D.A. Bryman, R. Shrock	(BRCO, TRIU, STON)
AGUILAR-AR...	18A	PR D97 072012	A. Aguilar-Arevalo <i>et al.</i>	(PIENU Collab.)
CORTINA-GIL	18	PL B778 137	E. Cortina Gil <i>et al.</i>	(NA62 Collab.)
LAZZERONI	17A	PL B772 712	C. Lazzeroni <i>et al.</i>	(NA62 Collab.)
PARK	16	PR D94 012003	C.-S. Park <i>et al.</i>	(BELLE Collab.)
AGUILAR-AR...	15	PRL 115 071801	A. Aguilar-Arevalo <i>et al.</i>	(PIENU Collab.)
ARTAMONOV	15A	PR D91 052001	A.V. Artamonov <i>et al.</i>	(E949 Collab.)
LIVENTSEV	13	PR D87 071102	D. Liventsev <i>et al.</i>	(BELLE Collab.)
Also		PR D95 099903 (errat.)	D. Liventsev <i>et al.</i>	(BELLE Collab.)
ORLOFF	02	PL B550 8	J. Orloff <i>et al.</i>	(CHARM Collab.)
DAUM	00	PRL 85 1815	M. Daum <i>et al.</i>	(KARMEN Collab.)
VAITAITIS	99	PRL 83 4943	A. Vaitaitis <i>et al.</i>	(CCFR Collab.)
ABREU	97I	ZPHY C74 57	P. Abreu <i>et al.</i>	(DELPHI Collab.)
Also		ZPHY C75 580 (errat.)	P. Abreu <i>et al.</i>	(DELPHI Collab.)
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.)
BARANOV	93	PL B302 336	S.A. Baranov <i>et al.</i>	(JINR, SERP, BUDA)
BERNARDI	88	PL B203 332	G. Bernardi <i>et al.</i>	(PARIN, CERN, INFN+)
DORENBOS...	86	PL 166B 473	J. Dorenbosch <i>et al.</i>	(CHARM Collab.)
COOPER-...	85	PL 160B 207	A.M. Cooper-Sarkar <i>et al.</i>	(CERN, LOIC+)