

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 3×4 PMNS matrix elements $U_{\ell x}$ (see the "Neutrino mass, mixing and oscillations" review) where $\ell = e, \mu$ or τ , and we denote the HNL as ν_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
<0.1	95	1 AAD	24AW ATLS	$m_{\nu_x} \sim 1$ TeV
$<3 \times 10^{-4}$	95	2 AAD	24BU ATLS	$m_{\nu_x} \sim 20\text{--}50$ GeV
$<4 \times 10^{-6}$	95	3 HAYRAPETY...24AB	CMS	$m_{\nu_x} \sim 20\text{--}60$ GeV
$<1 \times 10^{-3}$	95	3 HAYRAPETY...24AB	CMS	$m_{\nu_x} \gtrsim m_W$
$<1 \times 10^{-5}$	95	4 HAYRAPETY...24S	CMS	$m_{\nu_x} \sim 2.5$ GeV
$<1 \times 10^{-6}$	95	5 HAYRAPETY...24V	CMS	$m_{\nu_x} \sim 10$ GeV
$<5 \times 10^{-7}$	95	6 AAD	23AO ATLS	$m_{\nu_x} \sim 3\text{--}15$ GeV, pp at 13 TeV
$<3 \times 10^{-4}$	90	7 AGNES	23A DS50	$m_{\nu_x} \sim 7\text{--}35$ keV
$<3 \times 10^{-8}$	90	8 BAROUKI	22 RVUE	Near $m_{D_s} - m_e$ kin. thres.
$<1 \times 10^{-6}$	95	9 TUMASYAN	22AD CMS	$m_{\nu_x} \sim 8\text{--}14$ GeV, pp at 13 TeV
$<2 \times 10^{-4}$	95	10 FRIEDRICH	21	Near $m_{^7\text{Be}} - m_{^7\text{Li}}$ kin. thres.
$<1 \times 10^{-9}$	90	11 CORTINA-GIL	20 NA62	$m_{\nu_x} \sim 150\text{--}400$ MeV
$<2 \times 10^{-5}$	95	12 AAD	19F ATLS	$m_{\nu_x} \sim 15\text{--}40$ GeV

$<1 \times 10^{-9}$	90	13 ABE	19B T2K	Near $m_K - m_e$ kin. thres.
$<1 \times 10^{-4}$	90	14 ABLIKIM	19AL BES3	$m_{\nu_x} \sim 0.3\text{--}0.7$ GeV
$<2 \times 10^{-7}$	90	15 BRYMAN	19 RVUE	$m_{\nu_x} \sim 55$ MeV
$<1 \times 10^{-8}$	90	16 AGUILAR-AR...	18A PIEN	$m_{\nu_x} \sim 60\text{--}120$ MeV
$<3 \times 10^{-7}$	90	17 CORTINA-GIL	18 NA62	$m_{\nu_x} \sim 200\text{--}400$ MeV
$<1 \times 10^{-6}$	90	18 PARK	16 BELL	$m_{\nu_x} \sim 1.4$ GeV
$<3 \times 10^{-5}$	90	19 LIVENTSEV	13 BELL	Near $m_{\nu_x} \sim 2\text{--}2.5$ GeV
$<3 \times 10^{-5}$	95	20 ABREU	97I DLPH	$m_{\nu_x} \sim 6\text{--}50$ GeV
$<2 \times 10^{-5}$	95	21 ABREU	97I DLPH	Near $m_{\nu_x} \sim 3.5$ GeV
$<1 \times 10^{-5}$	90	22 BARANOV	93	Near $m_\pi - m_e$ kin. thres.
$<2 \times 10^{-7}$	90	22 BARANOV	93	Near $m_K - m_e$ kin. thres.
$<1 \times 10^{-7}$		23,24 BERNARDI	88 CNTR	Near $m_\pi - m_e$ kin. thres.
$<2 \times 10^{-9}$		24,25 BERNARDI	88 CNTR	Near $m_K - m_e$ kin. thres.
$<1 \times 10^{-7}$	90	26 DORENBOS...	86 CHRM	Near $m_D - m_e$ kin. thres.
$<1 \times 10^{-7}$	90	27 COOPER-...	85 BEBC	Near $m_D - m_e$ kin. thres.

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

$<2 \times 10^{-5}$	95	28 SIRUNYAN	18K CMS	$m_{\nu_x} \sim 20\text{--}60$ GeV
$<1 \times 10^{-2}$	95	28 SIRUNYAN	18K CMS	$m_{\nu_x} \gtrsim m_W$

¹ 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 $|V_{ex} V_{\mu x}^*|$.

² 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.

³ HAYRAPETYAN 24AB search for $W \rightarrow e\nu_x \rightarrow e e \ell \nu_\ell$ 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.

⁴ HAYRAPETYAN 24S search for $W \rightarrow e\nu_x$ followed by ν_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.

⁵ 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.

⁶ 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.

⁷ Search for ionization signals in an LArTPC. Assumes the candidate particle is 100% of dark matter.

⁸ 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.

⁹ 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 fb^{-1} .

- ¹⁰ Search in electron capture decay ${}^7\text{Be} \rightarrow {}^7\text{Li}\nu_X$. Kinematic threshold is ~ 850 keV.
- ¹¹ Search for $K^+ \rightarrow e^+\nu_X$. Assumes lifetime of $\nu_X > 50$ ns.
- ¹² Limit from prompt lepton number violating trilepton search.
- ¹³ $K^+ \rightarrow e^+\nu_X$, with ν_X decay through U_{eX} . ABE 19B also considers bounds on $|U_{\ell X} U_{\ell' X}|$ for combinations of lepton flavors in the ν_X decay final state.
- ¹⁴ Searches for a Majorana Heavy Neutral Lepton producing a $\pi^- e^+$ resonance in the same sign dilepton decay $D \rightarrow K \pi^- e^+ e^+$.
- ¹⁵ BRYMAN 19 sets best limits $|U_{eX}|^2 < 1 \times 10^{-4} - 2 \times 10^{-7}$ in the mass range $m_{\nu_X} \sim 2-55$ MeV, respectively, using the precision branching ratio measurement in AGUILAR-AREVALO 15. See also BRYMAN 19A.
- ¹⁶ Search for $\pi^+ \rightarrow e^+\nu_X$.
- ¹⁷ Search for $K^+ \rightarrow e^+\nu_X$.
- ¹⁸ 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.
- ¹⁹ Search for $B^+ \rightarrow e^+\nu_X$.
- ²⁰ Search for prompt ν_X decay signatures.
- ²¹ Search for displaced ν_X decay signatures.
- ²² 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 $\pi \rightarrow \mu^+\nu_X$, $\nu_X \rightarrow e^+ e^- \nu_e$.
- ²³ $\pi^+ \rightarrow e^+\nu_X$, with ν_X decay through U_{eX} .
- ²⁴ BERNARDI 88 also considers bounds on $|U_{eX} U_{\mu X}|$.
- ²⁵ $K^+ \rightarrow e^+\nu_X$, with ν_X decay through U_{eX} .
- ²⁶ $D^+ \rightarrow e^+\nu_X$, with $\nu_X \rightarrow e^- \ell^+ \nu_\ell$.
- ²⁷ $D^+ \rightarrow e^+\nu_X$, with $\nu_X \rightarrow e^- \ell^+ \nu_\ell$ or $\nu_X \rightarrow e^- \pi^+$.
- ²⁸ 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
$<1 \times 10^{-4}$	95	1 AAD	24BU ATLS	$m_{\nu_X} \sim 20-50$ GeV
$<3 \times 10^{-8}$	90	2 ABRATENKO 24	MBNE	Near $m_K - m_\pi - m_\mu$ kin. thres.
$<1 \times 10^{-6}$	90	2 ABRATENKO 24	MBNE	$m_{\nu_X} \sim 150$ MeV
$<3 \times 10^{-6}$	95	3 HAYRAPETY...24AB	CMS	$m_{\nu_X} \sim 20-60$ GeV
$<1 \times 10^{-3}$	95	3 HAYRAPETY...24AB	CMS	$m_{\nu_X} \gtrsim m_W$
$<3 \times 10^{-5}$	95	4 HAYRAPETY...24AC	CMS	$m_{\nu_X} \sim 1-3$ GeV
$<5 \times 10^{-6}$	95	5 HAYRAPETY...24S	CMS	$m_{\nu_X} \sim 3$ GeV
$<5 \times 10^{-7}$	95	6 HAYRAPETY...24V	CMS	$m_{\nu_X} \sim 10$ GeV
$<5 \times 10^{-7}$	95	7 AAD	23AO ATLS	$m_{\nu_X} \sim 3-15$ GeV, pp at 13 TeV
<0.1	95	8 AAD	23CE ATLS	Near $m_{\nu_X} \sim 0.1-2$ TeV
<0.1	95	9 TUMASYAN	23AC CMS	Near $m_{\nu_X} \sim 0.1-3$ 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	$m_{\nu_X} \sim 8-14$ GeV, pp at 13 TeV
$<1 \times 10^{-3}$	95	12 AAIJ	21AA LHCB	$m_{\nu_X} \sim 5-50$ 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	$m_{\nu_x} \sim 200\text{--}300 \text{ MeV}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1 \times 10^{-7}$	90	³⁶ ABRATENKO	20 MBNE	Superseded by ABRATENKO 22A
$<2 \times 10^{-5}$	95	³⁷ SIRUNYAN	18K CMS	$m_{\nu_x} \sim 20\text{--}60 \text{ GeV}$
$<5 \times 10^{-3}$	95	³⁷ SIRUNYAN	18K CMS	$m_{\nu_x} \gtrsim m_W$

¹ 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.

² 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 $m_{\nu_x} \sim 10\text{--}150 \text{ MeV}$ and $m_{\nu_x} \sim 150\text{--}245 \text{ MeV}$, respectively, for the case of a Majorana HNL. The π^0 mode dominates above $m_{\nu_x} \sim 150 \text{ MeV}$.

³ 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.

⁴ 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.

- ⁵ HAYRAPETYAN 24S search for $W \rightarrow \mu\nu_X$ followed by ν_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.
- ⁶ 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 $m_{\nu_X} \sim 2\text{--}20$ GeV. Limits are set for both Dirac and Majorana HNLs.
- ⁷ 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.
- ⁸ AAD 23CE search for Majorana HNLs via vector boson fusion $W^\pm W^\pm \rightarrow \mu^\pm \mu^\pm$. Limits set in a m_{ν_X} mass range from 50 GeV up to 20 TeV, using the Phenomenological Type-I Seesaw model as a benchmark scenario.
- ⁹ TUMASYAN 23AC search for Majorana HNLs via vector boson fusion $W^\pm W^\pm \rightarrow \mu^\pm \mu^\pm$. Limits set in a m_{ν_X} mass range from 50 GeV up to 25 TeV.
- ¹⁰ 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 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_{ν_X} range 200–384 MeV.
- ¹⁶ Search for $B^+ \rightarrow \mu^+ \nu_X$ in the mass range $m_{\nu_X} \sim 0\text{--}1.5$ 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 ν_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 ν_X decay final state.
- ²⁰ Limit requires muon kinetic energy > 1.2 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 $m_{\nu_X} \sim 0.2\text{--}1.4$ 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 ν_X decay signatures.
- ²⁸ Search for displaced ν_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 ν_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 $K^+ \rightarrow \mu^+ \nu_X$, 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.

³⁷ 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		$m_{\nu_X} \sim 20\text{--}50$ GeV
$<6 \times 10^{-4}$	95	² HAYRAPETYAN...24AB CMS		$m_{\nu_X} \sim 20\text{--}60$ GeV
$<1 \times 10^{-1}$	95	² HAYRAPETYAN...24AB CMS		$m_{\nu_X} \gtrsim m_W$
$<3 \times 10^{-4}$	95	³ HAYRAPETYAN...24S CMS		$m_{\nu_X} \sim 2$ GeV
$<1 \times 10^{-2}$	95	⁴ HAYRAPETYAN...24V CMS		$m_{\nu_X} \sim 3\text{--}20$ 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 $m_{\nu_X} \lesssim 970$ MeV
$<3 \times 10^{-6}$	90	⁹ BOIARSKA 21 RVUE		Near $m_{\nu_X} \sim 0.8\text{--}1.6$ GeV
$<2 \times 10^{-4}$	90	¹⁰ ORLOFF 02 CHRM		Near $m_D - m_\tau$ kin. thres.
$<1 \times 10^{-4}$	90	¹¹ ORLOFF 02 CHRM		$m_{\nu_X} \sim 200\text{--}250$ MeV
$<3 \times 10^{-5}$	95	¹² ABREU 97I DLPH		$m_{\nu_X} \sim 6\text{--}50$ GeV
$<2 \times 10^{-5}$	95	¹³ ABREU 97I DLPH		Near $m_{\nu_X} \sim 3.5$ GeV

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

¹⁴ LIVENTSEV 23 BELL Near $m_{\nu_X} \sim 0.8\text{--}1.2$ GeV

¹⁵ TUMASYAN 22H CMS pp at 13 TeV

¹ 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.

² 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.

³ HAYRAPETYAN 24S search for $W \rightarrow \tau \nu_X$ followed by ν_X displaced decay in flight to electromagnetic and hadronic showers in the CMS muon chamber, in the mass range $m_{\nu_X} \sim 1\text{--}2$ 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 $m_{\nu_X} \sim 2$ GeV.

⁴ 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 $m_{\nu_X} \sim 3\text{--}20$ GeV. Limits are set for both Dirac and Majorana HNLs.

⁵ 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.

- ⁶ Search for $\tau^\pm \rightarrow \pi^\pm \pi^+ \pi^- \nu_X$.
- ⁷ 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.
- ⁸ Search for $\nu_X \rightarrow \mu^+ \mu^- \nu$.
- ⁹ 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 τ decays.
- ¹⁰ $D_s \rightarrow \tau^+ \nu_X$, with ν_X decay via $U_{\tau X}$.
- ¹¹ $D_s \rightarrow \nu_\tau \tau^+, \tau^+ \rightarrow \nu_X X$, with ν_X decay via $U_{\tau X}$.
- ¹² Search for prompt ν_X decay signatures.
- ¹³ Search for displaced ν_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 $|U_{\mu X}|$.
- ¹⁴ 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.
- ¹⁵ TUMASYAN 22H sets limits on an approximately mass-degenerate vector-like lepton SU(2) doublet coupling to the τ . Some of the reported signal region distributions might be used to set limits for heavy neutral leptons coupled to the τ . The data correspond to an integrated luminosity of 138 fb^{-1} .

REFERENCES FOR Heavy Neutral Leptons, Searches for

AAD	24AW	PL B856 138865	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	24BU	PR D110 112004	G. Aad <i>et al.</i>	(ATLAS Collab.)
ABRATENKO	24	PRL 132 041801	P. Abratenko <i>et al.</i>	(MicroBooNE Collab.)
HAYRAPETY...	24AB	JHEP 2406 123	A. Hayrapetyan <i>et al.</i>	(CMS Collab.)
HAYRAPETY...	24AC	JHEP 2406 183	A. Hayrapetyan <i>et al.</i>	(CMS Collab.)
HAYRAPETY...	24S	PR D110 012004	A. Hayrapetyan <i>et al.</i>	(CMS Collab.)
HAYRAPETY...	24V	JHEP 2403 105	A. Hayrapetyan <i>et al.</i>	(CMS Collab.)
NAYAK	24	PR D109 L111102	M. Nayak <i>et al.</i>	(BELLE Collab.)
AAD	23AO	PRL 131 061803	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	23CE	EPJ C83 824	G. Aad <i>et al.</i>	(ATLAS Collab.)
AGNES	23A	PRL 130 101002	P. Agnes <i>et al.</i>	(DarkSide-50 Collab.)
LEES	23A	PR D107 052009	J.P. Lees <i>et al.</i>	(BABAR Collab.)
LIVENTSEV	23	PRL 131 211802	D. Liventsev <i>et al.</i>	(BELLE Collab.)
TUMASYAN	23AC	PRL 131 011803	A. Tumasyan <i>et al.</i>	(CMS Collab.)
ABRATENKO	22A	PR D106 092006	P. Abratenko <i>et al.</i>	(MicroBooNE Collab.)
BAROUKI	22	SCP 13 118	R. Barouki, G. Marocco, S. Sarkar	(OXF)
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.)
ACCIIARRI	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.A. 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.)
SIRUNYAN	18K	PRL 120 221801	A.M. Sirunyan <i>et al.</i>	(CMS 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. Artamanov <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+)
HAYANO	82	PRL 49 1305	R.S. Hayano <i>et al.</i>	(TOKY, KEK, TSUK)
