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 $\ell = e$, μ 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. $\left|U_{\ell x}\right| \gg \left|U_{\ell' x}\right|$ 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 $\left|U_{ex}\right|^2$

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
$<2\times10^{-5}$	95	[1] AAD	19F	ATLS	$m_{\nu_x} \sim$ 15–40 GeV
$<1\times10^{-9}$	90	[2] ABE	19B	T2K	Near $m_K - m_e$ kin. thres.
$<1\times10^{-4}$	90	[3] ABLIKIM	19AL	BES3	$m_{\nu_x} \sim$ 0.3–0.7 GeV
$<1\times10^{-8}$	90	[4] AGUILAR-AR...	18A	PIEN	$m_{\nu_x} \sim$ 60–120 MeV ¡br¿
$<3\times10^{-7}$	90	[5] CORTINA-GIL	18	NA62	$m_{\nu_x} \sim$ 200–400 MeV
$<3\times10^{-5}$	95	[6] ABREU	97I	DLPH	$m_{\nu_x} \sim$ 6–50 GeV
$<2\times10^{-5}$	95	[7] ABREU	97I	DLPH	Near $m_{\nu_x} \sim$ 3.5 GeV
$<1\times10^{-5}$	90	[8] BARANOV	93		Near $m_\pi - m_e$ kin. thres.
$<2\times10^{-7}$	90	[8] BARANOV	93		Near $m_K - m_e$ kin. thres.
$<1\times10^{-7}$		[9,10] BERNARDI	88	CNTR	Near $m_\pi - m_e$ kin. thres.
$<2\times10^{-9}$		[10,11] BERNARDI	88	CNTR	Near $m_K - m_e$ kin. thres.
$<1\times10^{-7}$	90	[12] DORENBOS...	86	CHRM	Near $m_D - m_e$ kin. thres.
$<1\times10^{-7}$	90	[13] COOPER-...	85	BEBC	Near $m_D - m_e$ kin. thres.

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

[14] PARK	16	BELL	$m_{\nu_x} \sim$ 0.2–1.4 GeV	

[1] Limit from prompt lepton number violating trilepton search.
[2] $K^+ \to e^+ \nu_x$, 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.
[3] Searches for a Majorana Heavy Neutral Lepton producing a $\pi^- e^+$ resonance in the same sign dilepton decay $D \to K \pi^- e^+ e^+$.
[4] Search for $\pi^+ \to e^+ \nu_x$.
[5] Search for $K^+ \to e^+ \nu_x$.
[6] Search for prompt ν_x decay signatures.
[7] Search for displaced ν_x decay signatures.
[8] Searches for K or $\pi \to e^+ \nu_x$, $\nu_x \to e^+ e^- \nu_e$ 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 $\pi \to \mu^+ \nu_x$, $\nu_x \to e^+ e^- \nu_e$.
[9] $\pi^+ \to e^+ \nu_x$, with ν_x decay through U_{ex}.
[10] BERNARDI 88 also considers bounds on $|U_{ex}\ U_{\mu x}|$.
[11] $K^+ \to e^+ \nu_x$, with ν_x decay through U_{ex}.
[12] $D^+ \to e^+ \nu_x$, with $\nu_x \to e^- \ell^+ \nu_\ell$.
[13] $D^+ \to e^+ \nu_x$, with $\nu_x \to e^- \ell^+ \nu_\ell$ or $\nu_x \to e^- \pi^+$.
[14] PARK 16 quotes an approximate limit $B(B^+ \to e^+ \nu_x) < 3 \times 10^{-6}$ in the mass range $m_{\nu_x} \sim$ 0.2–1.4 GeV.

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
$<2 \times 10^{-5}$	95	[1] AAD	19F	ATLS	$m_{\nu_x} \sim$ 10–50 GeV
$<2 \times 10^{-6}$	95	[2] AAD	19F	ATLS	$m_{\nu_x} \sim$ 10 GeV
$<1 \times 10^{-9}$	90	[3] ABE	19B	T2K	Near $m_K - m_\mu$ kin. thres.
$<5 \times 10^{-6}$	90	[4,5] AGUILAR-AR...	19B	PIEN	$m_{\nu_x} \sim$ 16–30 MeV
$<1 \times 10^{-5}$	90	[5] AGUILAR-AR...	19B	PIEN	Near $m_\pi - m_\mu$ kin. thres.
$<3 \times 10^{-7}$	90	[6] CORTINA-GIL	18	NA62	$m_{\nu_x} \sim$ 250–350 MeV
$<3 \times 10^{-6}$	90	[6] LAZZERONI	17A	NA62	Near $m_K - m_\mu$ kin. thres.
$<1 \times 10^{-8}$	90	[6] ARTAMONOV	15A	B949	$m_{\nu_x} \sim$ 200–300 MeV
$<2.0 \times 10^{-8}$	95	[7] DAUM	00	KARM	$m_{\nu_x} =$ 33.905 MeV
$<8 \times 10^{-8}$	90	[8] VAITAITIS	99	CCFR	Near $m_K - m_\mu$ kin. thres.
$<6 \times 10^{-8}$	90	[9] VAITAITIS	99	CCFR	Near $m_{D_s} - m_\mu$ kin. thres.
$<3 \times 10^{-5}$	95	[10] ABREU	97I	DLPH	$m_{\nu_x} \sim$ 6–50 GeV
$<2 \times 10^{-5}$	95	[11] ABREU	97I	DLPH	Near $m_{\nu_x} \sim$ 3.5 GeV
$<3 \times 10^{-5}$	90	[12] VILAIN	95C	CHM2	Near $m_K - m_\mu$ kin. thres.
$<3 \times 10^{-8}$		[13,14] BERNARDI	88	CNTR	Near $m_\mu + m_\pi$ kin. thres.
$<2 \times 10^{-9}$		[14,15] BERNARDI	88	CNTR	Near $m_K - m_\mu$ kin. thres.
$<1 \times 10^{-7}$	90	[16] DORENBOS...	86	CHRM	Near $m_D - m_\mu$ kin. thres.
$<1 \times 10^{-7}$	90	[17] COOPER-...	85	BEBC	Near $m_D - m_\mu$ kin. thres.

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

[18] PARK 16 BELL $m_{\nu_x} \sim$ 0.2–1.4 GeV

[1] Limit from prompt lepton number violating trilepton search.
[2] Limit from displaced lepton violating or conserving trilepton searches.
[3] $K^+ \to \mu^+ \nu_x$, 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.
[4] Limit requires muon kinetic energy > 1.2 MeV.
[5] Search for $\pi^+ \to \mu^+ \nu_x$.
[6] Search for $K^+ \to \mu^+ \nu_x$.
[7] DAUM 00 quotes a branching ratio bound $B(\pi^+ \to \mu^+ \nu_x) < 6.0 \times 10^{-10}$ at 95% CL.
[8] $K^+ \to \mu^+ \nu_x$, with $\nu_x \to \mu X$.
[9] $D_s \to \mu^+ \nu_x$, with $\nu_x \to \mu X$.
[10] Search for prompt ν_x decay signatures.
[11] Search for displaced ν_x decay signatures.
[12] Search for Heavy Neutral Leptons produced by neutral current muon neutrino interactions, with $\nu_x \to \mu^+ \mu^- \nu_\mu$.
[13] $K^+ \to \mu^+ \nu_x$, with ν_x decay through $U_{\mu x}$ and $m_{\nu_x} < m_\mu + m_\pi$.
[14] BERNARDI 88 also considers bounds on $|U_{ex}\ U_{\mu x}|$.
[15] $K^+ \to \mu^+ \nu_x$, with $\nu_x \to \mu^- \pi^+$.
[16] $D^+ \to \mu^+ \nu_x$, with $\nu_x \to \mu^- \ell^+ \nu_\ell$.
[17] $D^+ \to \mu^+ \nu_x$, with $\nu_x \to \mu^- \ell^+ \nu_\ell$ or $\nu_x \to \mu^- \pi^+$.
[18] PARK 16 quotes an approximate limit $B(B^+ \to \mu^+ \nu_x) < 3 \times 10^{-6}$ in the mass range $m_{\nu_x} \sim$ 0.2–1.4 GeV.

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
$<2 \times 10^{-4}$	90	[1] ORLOFF	02	CHRM	Near $m_D - m_\tau$ kin. thres.
$<1 \times 10^{-4}$	90	[2] ORLOFF	02	CHRM	$m_{\nu_x} \sim$ 200–250 MeV
$<3 \times 10^{-5}$	95	[3] ABREU	97I	DLPH	$m_{\nu_x} \sim$ 6–50 GeV
$<2 \times 10^{-5}$	95	[4] ABREU	97I	DLPH	Near $m_{\nu_x} \sim$ 3.5 GeV

[1] $D_s \to \tau^+ \nu_x$, with ν_x decay via $U_{\tau x}$.
[2] $D_s \to \nu_\tau \tau^+$, $\tau^+ \to \nu_x X$, with ν_x decay via $U_{\tau x}$.
[3] Search for prompt ν_x decay signatures.
[4] Search for displaced ν_x decay signatures. Kinematical suppression of $\nu_x \to \tau X$ at lower masses leads to rapid loosening of the $|U_{\tau x}|$ bound compared to that for $|U_{ex}|$ and $|U_{\mu x}|$.

REFERENCES FOR Heavy Neutral Leptons, Searches for

AAD	19F	JHEP 1910 265	G. Aad *et al.*	(ATLAS Collab.)
ABE	19B	PR D100 052006	K. Abe *et al.*	(T2K Collab.)
ABLIKIM	19AL	PR D99 112002	M. Ablikim *et al.*	(BESIII Collab.)
AGUILAR-AR...	19B	PL B798 134980	A. Aguilar-Arevalo *et al.*	(PIENU Collab.)
AGUILAR-AR...	18A	PR D97 072012	A. Aguilar-Arevalo *et al.*	(PIENU Collab.)
CORTINA-GIL	18	PL B778 137	E. Cortina Gil *et al.*	(NA62 Collab.)
LAZZERONI	17A	PL B772 712	C. Lazzeroni *et al.*	(NA62 Collab.)
PARK	16	PR D94 012003	C.-S. Park *et al.*	(BELLE Collab.)
ARTAMONOV	15A	PR D91 052001	A.V. Artamanov *et al.*	(E949 Collab.)
ORLOFF	02	PL B550 8	J. Orloff *et al.*	(CHARM Collab.)
DAUM	00	PRL 85 1815	M. Daum *et al.*	(KARMEN Collab.)
VAITAITIS	99	PRL 83 4943	A. Vaitaitis *et al.*	(CCFR Collab.)
ABREU	97I	ZPHY C74 57	P. Abreu *et al.*	(DELPHI Collab.)
Also		ZPHY C75 580 (errat.)	P. Abreu *et al.*	(DELPHI Collab.)
VILAIN	95C	PL B351 387	P. Vilain *et al.*	(CHARM II Collab.)
Also		PL B343 453	P. Vilain *et al.*	(CHARM II Collab.)
BARANOV	93	PL B302 336	S.A. Baranov *et al.*	(JINR, SERP, BUDA)
BERNARDI	88	PL B203 332	G. Bernardi *et al.*	(PARIN, CERN, INFN+)
DORENBOS...	86	PL 166B 473	J. Dorenbosch *et al.*	(CHARM Collab.)
COOPER-...	85	PL 160B 207	A.M. Cooper-Sarkar *et al.*	(CERN, LOIC+)