Heavy Neutral Leptons, Searches for

NODE=S077

OMITTED FROM SUMMARY TABLE

NODE=S077

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

NODE=S077255

Limits on $\left|U_{ex}\right|^2$

NODE=S077A00

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

NODE=S077A00

NODE=S077A00

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	$m_{\nu_x} \sim$ 20–50 GeV	
$<4 \times 10^{-6}$	95	[3] HAYRAPETY...	24AB	CMS	$m_{\nu_x} \sim$ 20–60 GeV	
$<1 \times 10^{-3}$	95	[3] HAYRAPETY...	24AB	CMS	$m_{\nu_x} \gtrsim m_W$	OCCUR=2
$<1 \times 10^{-5}$	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	$m_{\nu_x} \sim$ 3–15 GeV, pp at 13 TeV	
$<3 \times 10^{-4}$	90	[7] AGNES	23A	DS50	$m_{\nu_x} \sim$ 7–35 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	$m_{\nu_x} \sim$ 8–14 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	$m_{\nu_x} \sim$ 150–400 MeV	
$<2 \times 10^{-5}$	95	[12] AAD	19F	ATLS	$m_{\nu_x} \sim$ 15–40 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	$m_{\nu_x} \sim$ 0.3–0.7 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	$m_{\nu_x} \sim$ 60–120 MeV	
$<3 \times 10^{-7}$	90	[17] CORTINA-GIL	18	NA62	$m_{\nu_x} \sim$ 200–400 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 $m_{\nu_x} \sim$ 2–2.5 GeV	
$<3 \times 10^{-5}$	95	[20] ABREU	97I	DLPH	$m_{\nu_x} \sim$ 6–50 GeV	
$<2 \times 10^{-5}$	95	[21] ABREU	97I	DLPH	Near $m_{\nu_x} \sim$ 3.5 GeV	OCCUR=2
$<1 \times 10^{-5}$	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.	OCCUR=2
$<1 \times 10^{-7}$		[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.	OCCUR=2
$<1 \times 10^{-7}$	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	$m_{\nu_x} \sim$ 20–60 GeV	
$<1 \times 10^{-2}$	95	[28] SIRUNYAN	18K	CMS	$m_{\nu_x} \gtrsim m_W$	OCCUR=2

[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 $|V_{ex} V^*_{\mu x}|$. NODE=S077A00;LINKAGE=BA

[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. NODE=S077A00;LINKAGE=CA

[3] HAYRAPETYAN 24AB search for $W \rightarrow e\nu_x \rightarrow ee\ell\nu_\ell$ prompt decays assuming coupling to a single SM generation, between 10–1500 GeV. Above m_{ν_x} ¿ 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. NODE=S077A00;LINKAGE=X

[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 $m_{\nu_x} \sim$ 1–3 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. NODE=S077A00;LINKAGE=Z

[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 $m_{\nu_x} \sim$ 2–20 GeV. Limits are set for both Dirac and Majorana HNLs. NODE=S077A00;LINKAGE=AA

[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. NODE=S077A00;LINKAGE=V

[7] Search for ionization signals in an LArTPC. Assumes the candidate particle is 100% of dark matter. NODE=S077A00;LINKAGE=U

[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. NODE=S077A00;LINKAGE=W

[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}. NODE=S077A00;LINKAGE=S

[10] Search in electron capture decay ^{7}Be $\rightarrow$ ^{7}Liν_x. Kinematic threshold is $\sim$ 850 keV. NODE=S077A00;LINKAGE=R

[11] Search for $K^+ \rightarrow e^+\nu_x$. Assumes lifetime of $\nu_x > 50$ ns. NODE=S077A00;LINKAGE=P

[12] Limit from prompt lepton number violating trilepton search. NODE=S077A00;LINKAGE=A

[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. NODE=S077A00;LINKAGE=B

[14] Searches for a Majorana Heavy Neutral Lepton producing a $\pi^- e^+$ resonance in the same sign dilepton decay $D \rightarrow K\pi^- e^+ e^+$. NODE=S077A00;LINKAGE=I

[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. NODE=S077A00;LINKAGE=T

[16] Search for $\pi^+ \rightarrow e^+\nu_x$. NODE=S077A00;LINKAGE=J

[17] Search for $K^+ \rightarrow e^+\nu_x$. NODE=S077A00;LINKAGE=M

[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. NODE=S077A00;LINKAGE=N

[19] Search for $B^+ \rightarrow e^+\nu_x$. NODE=S077A00;LINKAGE=Q

[20] Search for prompt ν_x decay signatures. NODE=S077A00;LINKAGE=C

[21] Search for displaced ν_x decay signatures. NODE=S077A00;LINKAGE=O

[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 $\pi \rightarrow \mu^+\nu_x$, $\nu_x \rightarrow e^+e^-\nu_e$. NODE=S077A00;LINKAGE=D

[23] $\pi^+ \rightarrow e^+\nu_x$, with ν_x decay through U_{ex}. NODE=S077A00;LINKAGE=F

[24] BERNARDI 88 also considers bounds on $|U_{ex} U_{\mu x}|$. NODE=S077A00;LINKAGE=H

[25] $K^+ \rightarrow e^+\nu_x$, with ν_x decay through U_{ex}. NODE=S077A00;LINKAGE=G

[26] $D^+ \rightarrow e^+\nu_x$, with $\nu_x \rightarrow e^-\ell^+\nu_\ell$. NODE=S077A00;LINKAGE=K

[27] $D^+ \rightarrow e^+\nu_x$, with $\nu_x \rightarrow e^-\ell^+\nu_\ell$ or $\nu_x \rightarrow e^-\pi^+$. NODE=S077A00;LINKAGE=L

[28] Superseded by HAYRAPETYAN 24AB. NODE=S077A00;LINKAGE=Y

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

NODE=S077A01

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

NODE=S077A01

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	$m_{\nu_x} \sim$ 5–50 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 GeV
$<2 \times 10^{-5}$	95	[17] AAD	19F	ATLS	$m_{\nu_x} \sim$ 10–50 GeV
$<2 \times 10^{-6}$	95	[18] AAD	19F	ATLS	$m_{\nu_x} \sim$ 10 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	$m_{\nu_x} \sim$ 16–30 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	$m_{\nu_x} \sim$ 250–350 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 GeV
$<1 \times 10^{-8}$	90	[14] ARTAMONOV	15A	B949	$m_{\nu_x} \sim$ 200–300 MeV
$<3 \times 10^{-5}$	90	[23] LIVENTSEV	13	BELL	Near $m_{\nu_x} \sim$ 2–2.5 GeV
$<2.0 \times 10^{-8}$	95	[24] DAUM	00	KARM	$m_{\nu_x} =$ 33.905 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	$m_{\nu_x} \sim$ 6–50 GeV
$<2 \times 10^{-5}$	95	[28] ABREU	97I	DLPH	Near $m_{\nu_x} \sim$ 3.5 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	$m_{\nu_x} \sim$ 200–300 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	$m_{\nu_x} \sim$ 20–60 GeV
$<5 \times 10^{-3}$	95	[37] SIRUNYAN	18K	CMS	$m_{\nu_x} \gtrsim m_W$

NODE=S077A01

OCCUR=2 (ABRATENKO 24, $m_{\nu_x} \sim$ 150 MeV); OCCUR=2 (HAYRAPETY... 24AB, $\gtrsim m_W$); OCCUR=2 (AAIJ 21AA, $<2 \times 10^{-4}$); OCCUR=2 (AAD 19F, 10 GeV); OCCUR=2 (AGUILAR-AR... 19B, near $m_\pi - m_\mu$); OCCUR=2 (VAITAITIS 99, D_s); OCCUR=2 (ABREU 97I, 3.5 GeV); OCCUR=2 (BERNARDI 88, $m_K - m_\mu$); OCCUR=2 (SIRUNYAN 18K, $\gtrsim m_W$)

[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.

NODE=S077A01;LINKAGE=JA

[2] ABRATENKO 24 search for $K^+ \to \mu^+ \nu_x$, with $\nu_x \to \nu_\mu e^+ e^-$ and $\nu_x \to \nu_\mu \pi^0 \to \nu_\mu \gamma\gamma$ in the mass ranges $m_{\nu_x} \sim$ 10–150 MeV and $m_{\nu_x} \sim$ 150–245 MeV, respectively, for the case of a Majorana HNL. The π^0 mode dominates above $m_{\nu_x} \sim$ 150 MeV.

NODE=S077A01;LINKAGE=DA

[3] HAYRAPETYAN 24AB search for $W \to \mu\nu_x \to \mu\mu\ell\nu_\ell$ prompt decays assuming coupling to a single SM generation, between 10–1500 GeV. Above m_{ν_x} ¿ 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.

NODE=S077A01;LINKAGE=EA

[4] HAYRAPETYAN 24AC search for $B \to X\mu\nu_X$ and $B \to \mu\nu_X$ followed by displaced $\nu_X \to \mu\pi^{\pm}$ 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. NODE=S077A01;LINKAGE=FA

[5] HAYRAPETYAN 24S search for $W \to \mu\nu_X$ followed by ν_X displaced decay in flight to electromagnetic and hadronic showers in the CMS muon chamber, in the mass range $m_{\nu_X} \sim$ 1–3 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. NODE=S077A01;LINKAGE=HA

[6] HAYRAPETYAN 24V searches for $W \to \mu\nu_X$ with displaced decay $\nu_X \to \mu j$, i.e. with one jet, over the range $m_{\nu_X} \sim$ 2–20 GeV. Limits are set for both Dirac and Majorana HNLs. NODE=S077A01;LINKAGE=IA

[7] AAD 23AO search for $W \to \nu_X\mu$, for both Majorana and Dirac HNL scenarios. Also consider scenarios involving multiflavor mixing, with correspondingly weaker limits. NODE=S077A01;LINKAGE=AA

[8] AAD 23CE search for Majorana HNLs via vector boson fusion $W^{\pm}W^{\pm} \to \mu^{\pm}\mu^{\pm}$. 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. NODE=S077A01;LINKAGE=CA

[9] TUMASYAN 23AC search for Majorana HNLs via vector boson fusion $W^{\pm}W^{\pm} \to \mu^{\pm}\mu^{\pm}$. Limits set in a m_{ν_X} mass range from 50 GeV up to 25 TeV. NODE=S077A01;LINKAGE=BA

[10] ABRATENKO 22A search for $K^+ \to \mu^+\nu_X$, with $\nu_X \to \mu^{\mp}\pi^{\pm}$, in the mass range $m_{\nu_X} \sim$ 246–385 MeV. Also considers limits from $\nu_X \to \mu^-\pi^+$ only, for the case of a Dirac HNL. NODE=S077A01;LINKAGE=Z

[11] TUMASYAN 22AD search for $W \to \mu\nu_X$, $\nu_X \to \mu e\nu_e$ and set limits for Dirac and Majorana Heavy Neutral Leptons. The data correspond to an integrated luminosity of 138 fb^{-1}. NODE=S077A01;LINKAGE=Y

[12] Limit from prompt lepton number conserving $W \to \mu\mu j$ search. NODE=S077A01;LINKAGE=V

[13] Limit from prompt lepton number violating $W \to \mu\mu j$ search. NODE=S077A01;LINKAGE=W

[14] Search for $K^+ \to \mu^+\nu_X$. NODE=S077A01;LINKAGE=P

[15] Assumes a lifetime exceeding 50 ns, and searches over m_{ν_X} range 200–384 MeV. NODE=S077A01;LINKAGE=X

[16] Search for $B^+ \to \mu^+\nu_X$ in the mass range $m_{\nu_X} \sim$ 0–1.5 GeV. NODE=S077A01;LINKAGE=T

[17] Limit from prompt lepton number violating trilepton search. NODE=S077A01;LINKAGE=C

[18] Limit from displaced lepton violating or conserving trilepton searches. NODE=S077A01;LINKAGE=D

[19] $K^+ \to \mu^+\nu_X$, 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. NODE=S077A01;LINKAGE=E

[20] Limit requires muon kinetic energy $>$ 1.2 MeV. NODE=S077A01;LINKAGE=A

[21] Search for $\pi^+ \to \mu^+\nu_X$. NODE=S077A01;LINKAGE=G

[22] PARK 16 quotes an approximate limit B$(B^+ \to \mu^+\nu_X) < 3\times10^{-6}$ in the mass range $m_{\nu_X} \sim$ 0.2–1.4 GeV. NODE=S077A01;LINKAGE=Q

[23] Search for $B^+ \to \mu^+\nu_X$. NODE=S077A01;LINKAGE=U

[24] DAUM 00 quotes a branching ratio bound B$(\pi^+ \to \mu^+\nu_X) < 6.0\times10^{-10}$ at 95% CL. NODE=S077A01;LINKAGE=B

[25] $K^+ \to \mu^+\nu_X$, with $\nu_X \to \mu X$. NODE=S077A01;LINKAGE=L

[26] $D_s \to \mu^+\nu_X$, with $\nu_X \to \mu X$. NODE=S077A01;LINKAGE=M

[27] Search for prompt ν_X decay signatures. NODE=S077A01;LINKAGE=F

[28] Search for displaced ν_X decay signatures. NODE=S077A01;LINKAGE=R

[29] Search for Heavy Neutral Leptons produced by neutral current muon neutrino interactions, with $\nu_X \to \mu^+\mu^-\nu_\mu$. NODE=S077A01;LINKAGE=K

[30] $K^+ \to \mu^+\nu_X$, with ν_X decay through $U_{\mu x}$ and $m_{\nu_X} < m_\mu + m_\pi$. NODE=S077A01;LINKAGE=H

[31] BERNARDI 88 also considers bounds on $|U_{ex}\, U_{\mu x}|$. NODE=S077A01;LINKAGE=I

[32] $K^+ \to \mu^+\nu_X$, with $\nu_X \to \mu^-\pi^+$. NODE=S077A01;LINKAGE=J

[33] $D^+ \to \mu^+\nu_X$, with $\nu_X \to \mu^-\ell^+\nu_\ell$. NODE=S077A01;LINKAGE=N

[34] $D^+ \to \mu^+\nu_X$, with $\nu_X \to \mu^-\ell^+\nu_\ell$ or $\nu_X \to \mu^-\pi^+$. NODE=S077A01;LINKAGE=O

[35] Search for $K^+ \to \mu^+\nu_X(\gamma)$. NODE=S077A01;LINKAGE=KA

[36] $K^+ \to \mu^+\nu_X$, with $\nu_X \to \mu^-\pi^+$, in the mass range $m_{\nu_X} \sim$ 260–385 MeV. ABRATENKO 20 also considers $\nu_X \to \mu^+\pi^-$ for the case of a Majorana HNL. NODE=S077A01;LINKAGE=S

[37] Superseded by HAYRAPETYAN 24AB. NODE=S077A01;LINKAGE=GA

Limits on $|U_{\tau x}|^2$

NODE=S077A02

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

NODE=S077A02

NODE=S077A02

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.1	95	[1] AAD	24BU	ATLS	$m_{\nu_x} \sim$ 20–50 GeV
$<6 \times 10^{-4}$	95	[2] HAYRAPETY...	24AB	CMS	$m_{\nu_x} \sim$ 20–60 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 GeV
$<1 \times 10^{-2}$	95	[4] HAYRAPETY...	24V	CMS	$m_{\nu_x} \sim$ 3–20 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 $m_{\nu_x} \sim$ 0.8–1.6 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	$m_{\nu_x} \sim$ 200–250 MeV
$<3 \times 10^{-5}$	95	[12] ABREU	97I	DLPH	$m_{\nu_x} \sim$ 6–50 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 $m_{\nu_x} \sim$ 0.8–1.2 GeV
		[15] TUMASYAN	22H	CMS	pp at 13 TeV

OCCUR=2

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[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. NODE=S077A02;LINKAGE=P

[2] HAYRAPETYAN 24AB search for $W \to \tau\nu_x \to \tau\tau\ell\nu_\ell$ prompt decays assuming coupling to a single SM generation, between 10–1500 GeV. Above m_{ν_x} ¿ 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. NODE=S077A02;LINKAGE=L

[3] HAYRAPETYAN 24S search for $W \to \tau\nu_x$ followed by ν_x displaced decay in flight to electromagnetic and hadronic showers in the CMS muon chamber, in the mass range $m_{\nu_x} \sim$ 1–2 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. NODE=S077A02;LINKAGE=M

[4] HAYRAPETYAN 24V searches for $W \to \tau\nu_x$ with displaced decay $\nu_x \to \tau j$, i.e. with one jet, over the range $m_{\nu_x} \sim$ 3–20 GeV. Limits are set for both Dirac and Majorana HNLs. NODE=S077A02;LINKAGE=N

[5] NAYAK 24 searches for $\tau \to \pi\nu_x$ with displaced decay $\nu_x \to \nu_\tau\mu^+\mu^-$ 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. NODE=S077A02;LINKAGE=O

[6] Search for $\tau^\pm \to \pi^\pm\pi^+\pi^-\nu_x$. NODE=S077A02;LINKAGE=J

[7] Reanalysis of BEBC results (cf. COOPER-SARKAR 85) to include searches for $D_s^\pm \to \nu_\tau\tau^\pm$, $\tau^\pm \to \nu_x\pi^\pm$, $\nu_x\rho^\pm$, or $\nu_x\nu_\tau\ell^\pm$ via $U_{\tau x}$. Assumes a Majorana HNL. NODE=S077A02;LINKAGE=I

[8] Search for $\nu_x \to \mu^+\mu^-\nu$. NODE=S077A02;LINKAGE=E

[9] Reanalysis of CHARM results (cf. ORLOFF 02) to include searches for $\nu_x \to \nu\ell^+\ell^-$ decays, and including the production of HNLs from τ decays. NODE=S077A02;LINKAGE=F

[10] $D_s \to \tau^+\nu_x$, with ν_x decay via $U_{\tau x}$. NODE=S077A02;LINKAGE=B

[11] $D_s \to \nu_\tau\tau^+$, $\tau^+ \to \nu_x X$, with ν_x decay via $U_{\tau x}$. NODE=S077A02;LINKAGE=C

[12] Search for prompt ν_x decay signatures. NODE=S077A02;LINKAGE=A

[13] 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 $|U_{\mu x}|$. NODE=S077A02;LINKAGE=D

[14] Search for $\tau \to \pi\nu_x$, $\nu_x \to \pi e$ or $\pi\mu$ in the range 0.2–1.6 GeV. LIVENTSEV 23 reports results for the sum $\Sigma_{\ell=e,\mu,\tau}|U_{\ell x}|^2$ 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. NODE=S077A02;LINKAGE=K

[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}. NODE=S077A02;LINKAGE=G

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