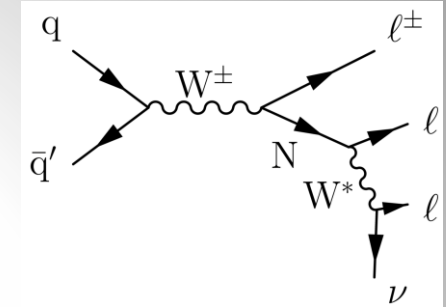


A Snowmass White Paper

Three Generations of Matter (Fermions) spin 1/2

	I	II	III	
main charge	$\frac{2}{3}$ u	$\frac{2}{3}$ c	$\frac{2}{3}$ t	6 g
charm	$\frac{2}{3}$ u	$\frac{2}{3}$ c	$\frac{2}{3}$ t	6 g
main charge	$-\frac{1}{3}$ d	$-\frac{1}{3}$ s	$-\frac{1}{3}$ b	6 γ
charm	$-\frac{1}{3}$ d	$-\frac{1}{3}$ s	$-\frac{1}{3}$ b	6 γ
Quarks	$\frac{2}{3}$ u	$\frac{2}{3}$ c	$\frac{2}{3}$ t	6 g
charm	$\frac{2}{3}$ u	$\frac{2}{3}$ c	$\frac{2}{3}$ t	6 g
main charge	$-\frac{1}{3}$ d	$-\frac{1}{3}$ s	$-\frac{1}{3}$ b	6 γ
charm	$-\frac{1}{3}$ d	$-\frac{1}{3}$ s	$-\frac{1}{3}$ b	6 γ
Leptons	0 e	0 μ	0 τ	3 W
electron	0 e	0 μ	0 τ	3 W
muon	0 e	0 μ	0 τ	3 W
tau	0 e	0 μ	0 τ	3 W
spin 0				125 GeV H
				125 GeV H



The Present and Future Status of Heavy Neutral Leptons

Asli M. Abdullahi^{a,b}, Pablo Barham Alzás^{d,e}, Brian Batell^f, Alexey Boyarsky^g, Saneli Carbajal^h, Animesh Chatterjee^f, José I. Crespo-Anadón^e, Frank F. Deppischⁱ, Albert De Roeck^d, Marco Drewes^j, Alberto Martin Gago^h, Rebeca Gonzalez Suarez^k, Evgueni Goudzovski^l, Athanasios Hatzikoutelis^m, Josu Hernandez-Garcia^c, Matheus Hostert^{n,o,p}, Marco Hufnagel^q, Philip Ilten^r, Alexander Izmaylov^s, Kevin J. Kelly^d, Juraj Klarić^j, Joachim Kopp^{d,t}, Suchita Kulkarni^u, Mathieu Lamoureux^v, Gaia Lanfranchi^w, Jacobo López-Pavón^x, Oleksii Mikulenko^g, Michael Mooney^y, Miha Nemevšek^z, Maksym Ovchinnikov^g, Silvia Pascoli^{aa,b}, Ryan Plestid^{ab,a}, Mohamed Rashad Darwish^{ac}, Federico Leo Redi^d, Oleg Ruchayskiy^{ad}, Richard Ruiz^{ae}, Mikhail Shaposhnikov^{af}, Lesya Shchutska^{ag}, Ian M. Shoemaker^{ah}, Robert Shrock^{ai}, Alex Sousa^r, Nick Van Remortel^{ac}, Vsevolod Syvolap^g, Volodymyr Takhistov^{aj}, Jean-Loup Tastet^{ak}, Inar Timiryasov^{ad}, Aaron C. Vincent^{al}, Jaehoon Yu^{d,am}

Albert De Roeck/CERN
3rd June 2022

Snowmass: White Paper on HNLs

Commissioned by the **Neutrino Physics Frontier** group

– In concert with the EF and RF groups

-> A community white paper on the opportunities for future

HNL Searches: **Overall Editors I. Shoemaker and A. De Roeck**

1. Theory Overview [**Silvia Pascoli, Mikhail Shapohsnikov**]
2. Collider Searches [**Richard Ruiz, Albert de Roeck, Federico Leo Redi**]
3. Beta-decay kink searches [**Mike Mooney**]
4. Fixed Target [**Kevin Kelly, Gaia Lanfranchi**]
5. Atmospheric and Solar Data [**Ryan Plestid, Ian Shoemaker**]
6. Cosmological bounds [**Alexey Boyarsky, Marco Drewes**]

arXiv:2203.08039

Contents

arXiv:2203.08039

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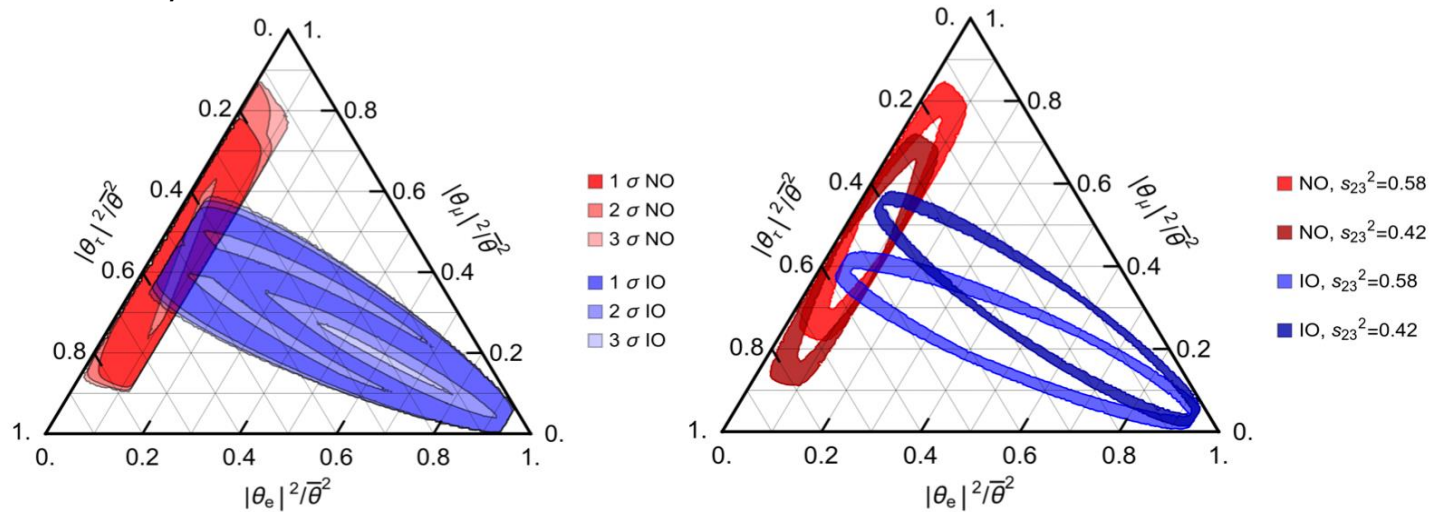
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Content of the paper: Snapshot of the status @ start of 2022

Neutrino Oscillations & HNLs

Theory: Motivation for HNLs and connection with SM neutrino physics

M. Drewes, J.Klaric



Ternary diagrams for the normalized flavour mixings $|\theta_{\alpha h}|^2/\bar{\theta}^2$ (in the large mixing regime) with $\bar{\theta}^2 \equiv \sum_{\alpha} |\theta_{\alpha h}|^2$.

Seesaw-I model (and for the simplest case of 2 HNL states): the regions in normalised mixing angles allowed by the present and future neutrino oscillation data...

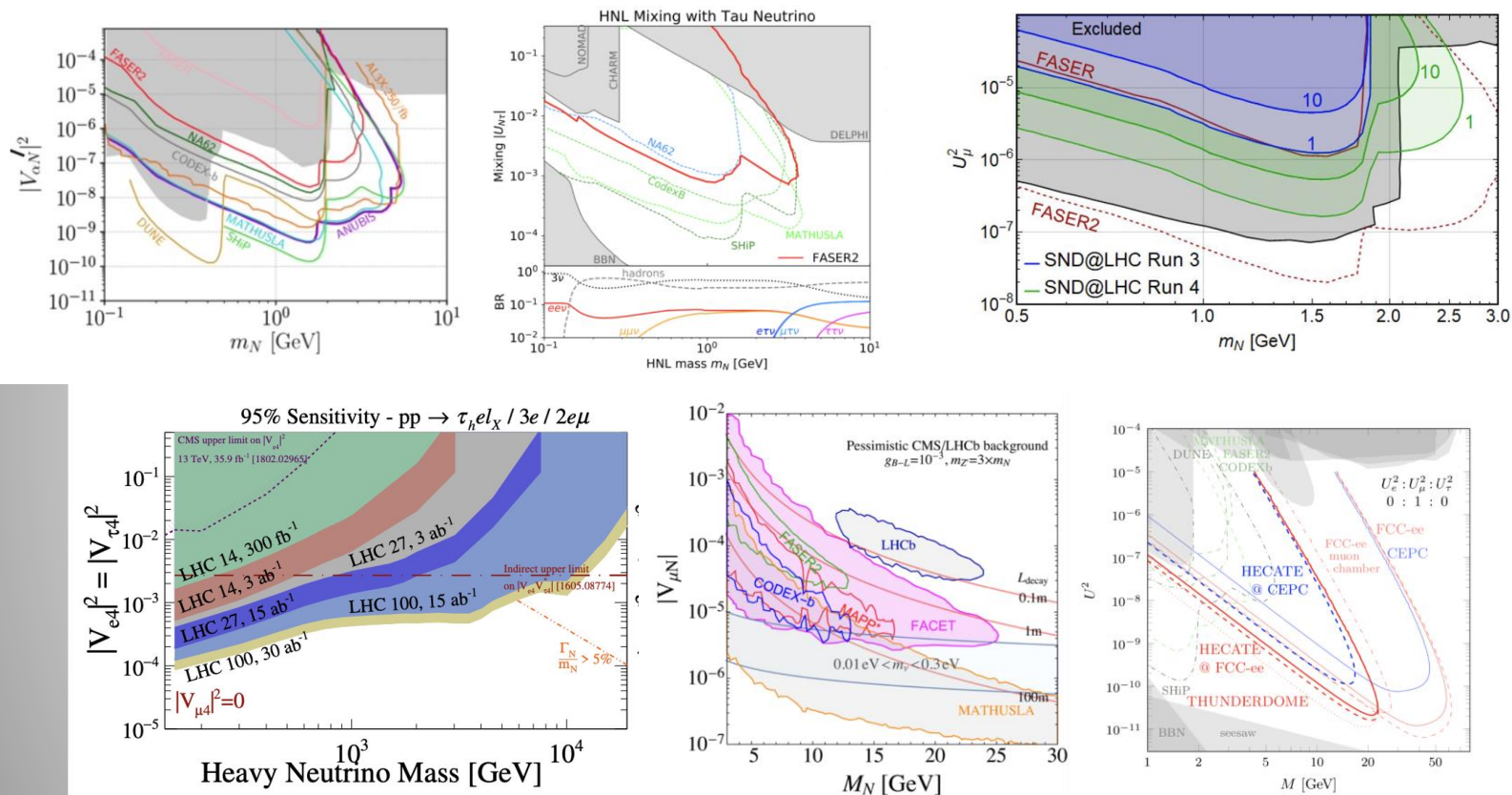
Theory: stress to exploit also non-minimal models in future

First with more than one active flavour, and (next) beyond minimal models

No discussion benchmarks points in this paper -> PBC/FIPS discussion forum

Collider Searches & Prospects

Examples of studies: ...



- Studies are well covered in these LLP meetings, so no details here
- HL-LHC: Prospects for ATLAS/CMS/LHCb? After run-2 analysis completed?
- Ongoing developments on generators from HNL discussion group reported (Phil Ilten, Richard Ruiz)

Searches at Extracted Beams

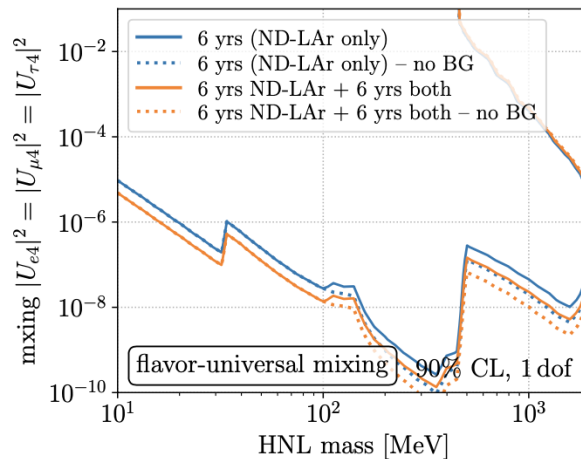
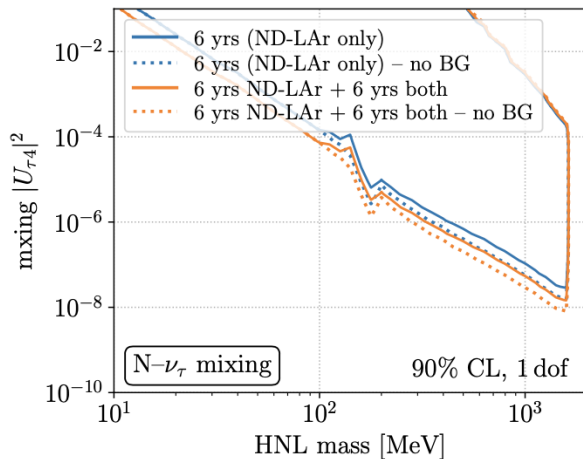
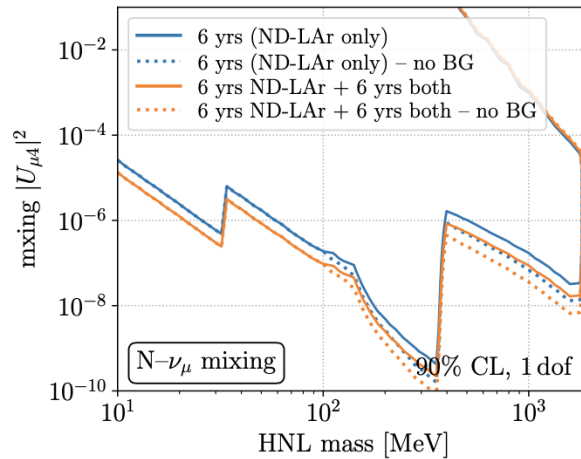
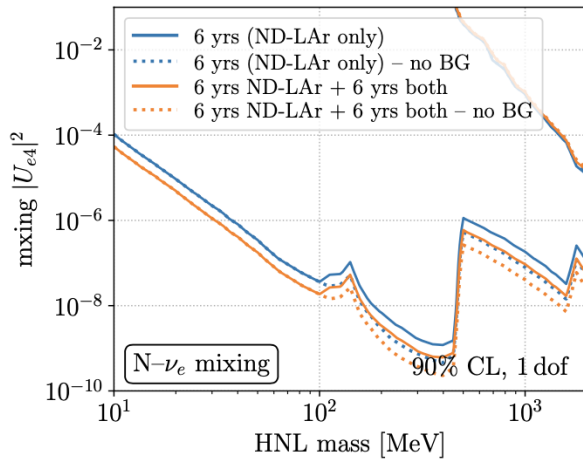
Prospects discussed for following projects

- NA62 CERN
- SHADOWS (a new proposal) CERN
- SHIP CERN
- T2K and T2HK J-PARC
- ArgoNeuT FNAL
- NOvA FNAL
- SBND/ICARUS FNAL
- DUNE FNAL
- DarkQuest FNAL
- PIONEER PSI

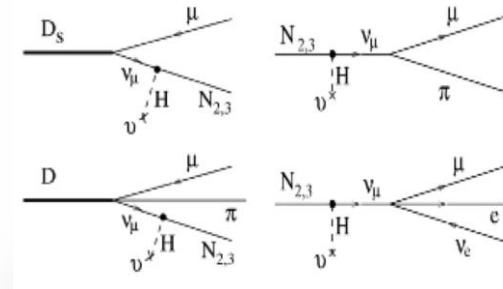
Searches at Extracted Beams

Example: Detailed new study for DUNE with most recent Near Detector configuration & POT profile

NEW



Examples of production and decay



... for up to 12 years of data taking...

Summary of Fixed Target Probes

NEW

Overview and timelines

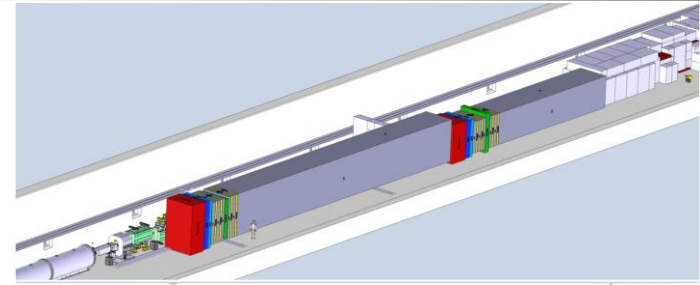
Table 1: Summary of the fixed-target searches for Heavy Neutral Leptons considered throughout Section 5.

experiment/ proposal	lab	beam type	detector technology	detector transverse dimensions	detector decay volume length	distance from dump	N_{pot}	timescale
NA62-K	CERN	p , 400 GeV	spectrometer	$A = \pi r^2$, $r = 1$ m	~ 80 m	~ 100 m	$5 \cdot 10^{19}$	by (2032–2038)
NA62-dump	CERN	p , 400 GeV	spectrometer	$A = \pi r^2$, $r = 1$ m	~ 80 m	~ 100 m	$5 \cdot 10^{19}$	by (2032–2038)
SHADOWS	CERN	p , 400 GeV	spectrometer	2.5×2.5 m ²	~ 20 m	~ 10 m	$5 \cdot 10^{19}$	by (2032–2038)
SHiP	CERN	p , 400 GeV	spectrometer	5×10 m ²	~ 50 m	~ 45 m	$2 \cdot 10^{20}$	
T2K	J-PARC	p , 30 GeV	composite w/ GArTPC	~ 3.3 m ²	~ 1.7 m	280 m	$3.8 \cdot 10^{21}$	2010–2021
T2K-II	J-PARC	p , 30 GeV	composite w/ GArTPC	~ 3.3 m ²	~ 3.6 m	280 m	$+10 \cdot 10^{21}$	2022–2026
Hyper-K	J-PARC	p , 30 GeV	composite w/ GArTPC	~ 3.3 m ²	~ 3.6 m	280 m	$2.70 \cdot 10^{22}$	by 2038
SBND	FNAL	p , 8 GeV	LArTPC	16 m ²	5 m	110 m	$10 \cdot 10^{20}$	2023–2027
MicroBooNE	FNAL	p , 8/120 GeV	LArTPC	6 m ²	10.4 m	463 m/100 m	$1.5 \cdot 10^{21}/2.2 \cdot 10^{21}$	2015–2021
ArgoNeuT	FNAL	p , 120 GeV	LArTPC	0.2 m ²	0.9 m	318 m	$1.25 \cdot 10^{20}$	2009–2010
DUNE ND	FNAL	p , 120 GeV	LAr/GAr TPC	~ 12 m ²	~ 5 m	574 m	$\geq 1.47 \cdot 10^{22}$	~ 2030 –2040
DarkQuest	FNAL	p , 120 GeV	spectrometer	2×4 m ²	20 m	5 m	$1 \cdot 10^{18}$	2024–2025

Future Projects @ CERN

Future probes

See Gaia Lanfranchi's talk at LLP10



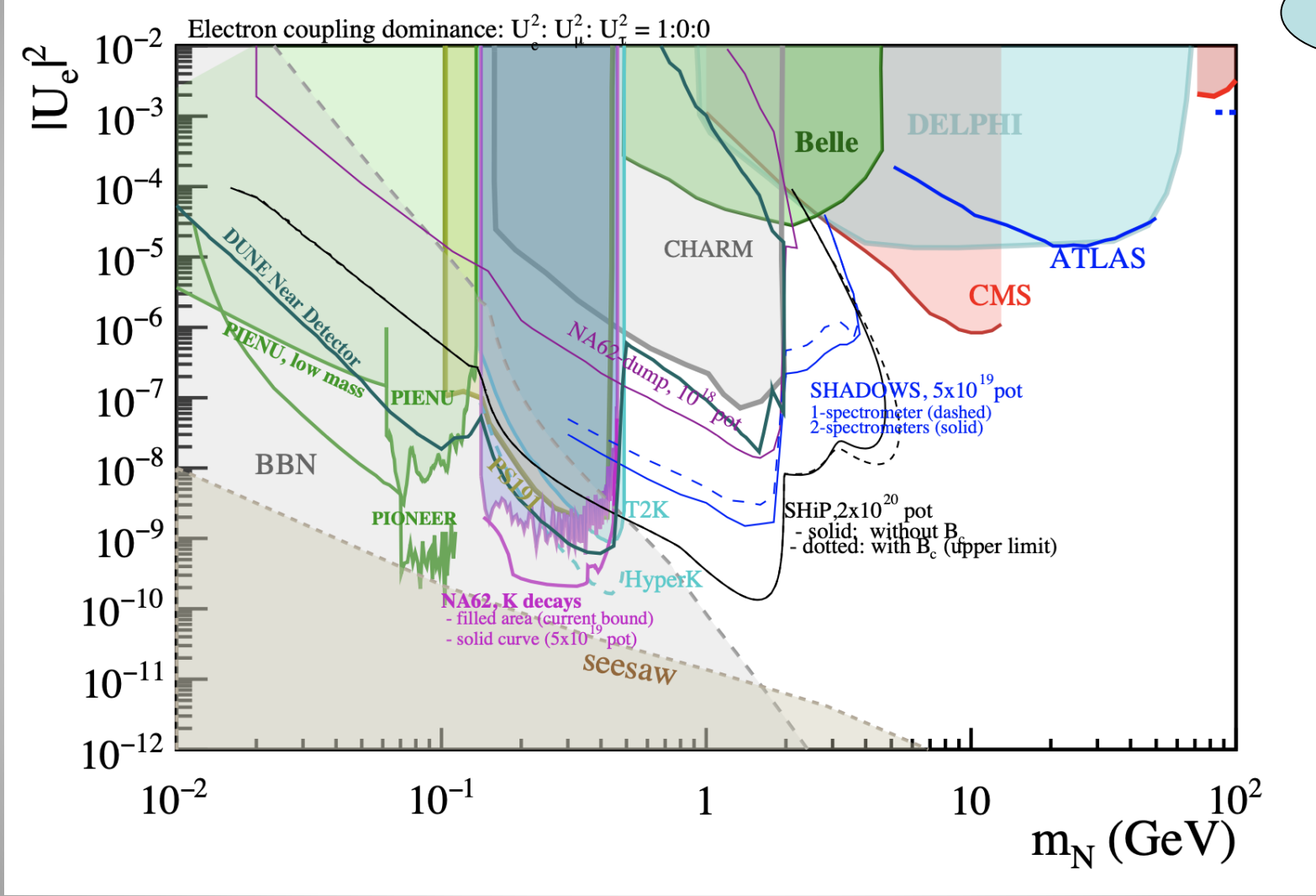
- SHADOWS [Search for Hidden And Dark Objects With the SPS]
 - Same 400 GeV primary proton beam serving NA62.
 - SHADOWS is a new off-axis experiment in the ECN3/TCC8 experimental cavern currently hosting the NA62 experiment to search for feebly-interacting particles (FIPs) emerging from charm and beauty decays.
 - SHADOWS can take data when the beam line is operated in beam-dump mode.
- SHiP [Search for Hidden Particles]
 - The Search for Hidden Particles (SHiP) experiment is a new general purpose fixed target facility proposed at the CERN Super Proton Synchrotron (SPS) accelerator to search for long-lived exotic particles with masses between few hundred MeV and few GeV.

EoI submitted to SPSC
Now with referees..

Exploring more cost-efficient options @ CERN for the Beam Dump Facility. Under (re-)discussion...

Summary Plots: Electron Flavor

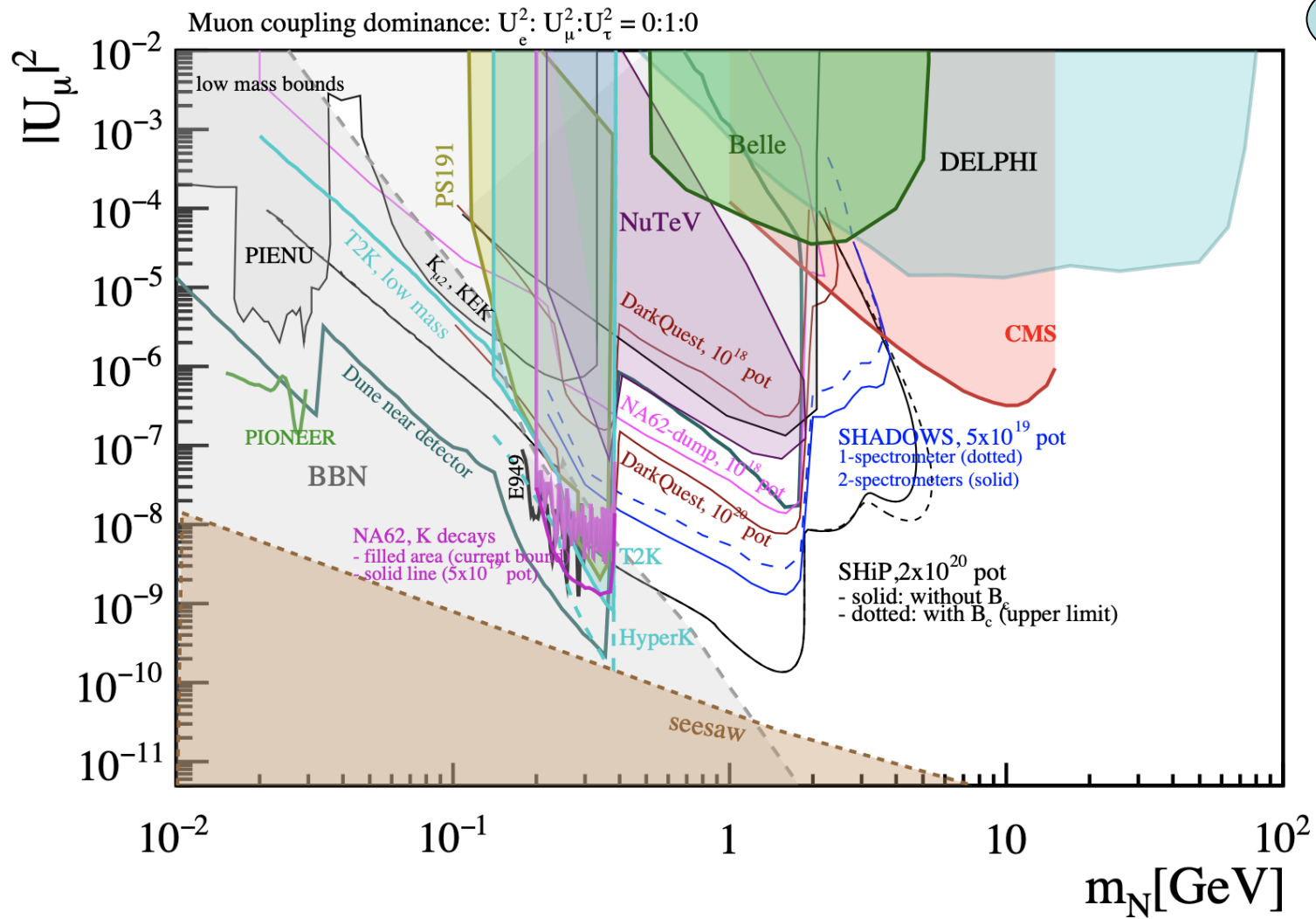
NEW



Complementary regions probed by DUNE, NA62, SHiP and SHADOWS...

Summary Plots: Muon Flavor

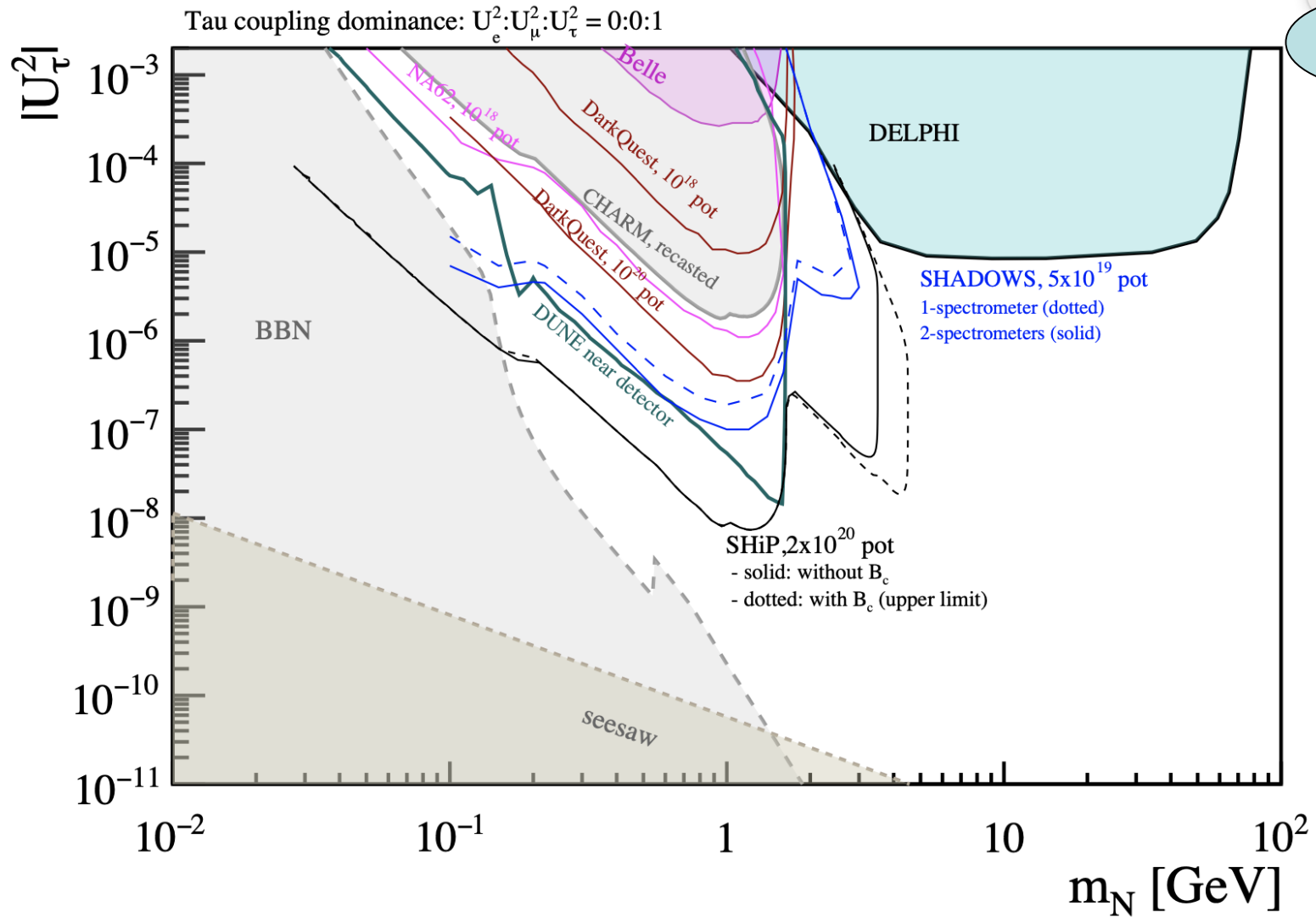
NEW



Complementary regions probed by DUNE, NA62, SHIP and SHADOWS...

Summary Plots: Tau Flavor

NEW

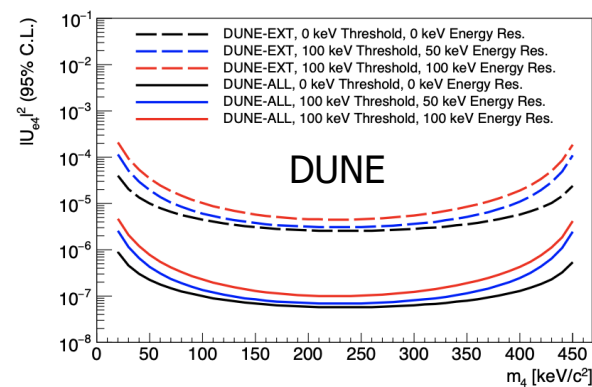
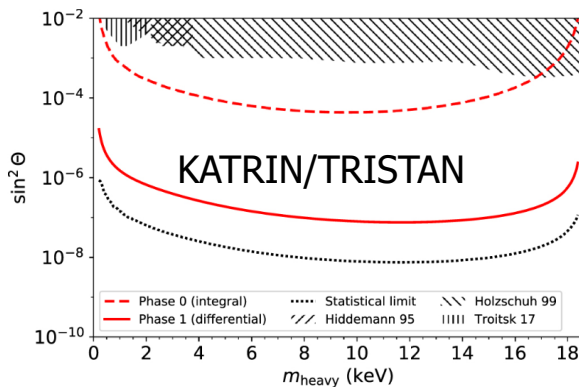
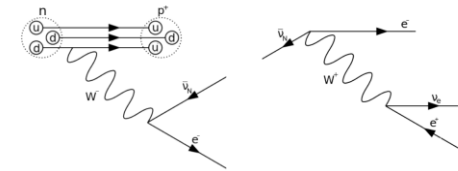
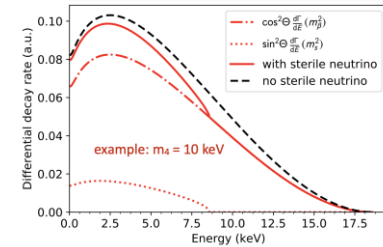


Complementary regions probed by DUNE, NA62, SHIP and SHADOWS...

Nuclear Decay Searches

Searches for low mass HNLs (keV-MeV)

- Beta-decay searches (<450 KeV)
 - KATRIN/TRISTAN, DUNE
- Electron Capture searches (~20-850 KeV)
 - Proposals: HINTER, BeEST..
- Reactor based searches (1-12 MeV)
 - Many experiments exist: SoLid, PROSPECT, STEREO,..
- Neutrinoless Double Beta Decay (10 MeV-1 GeV)

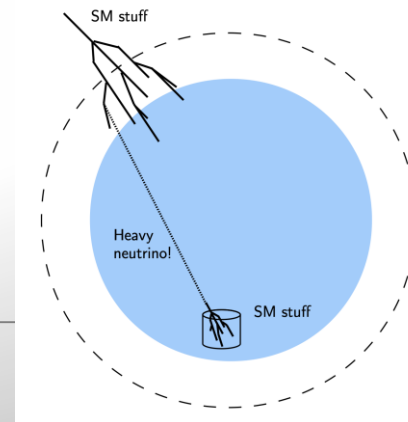
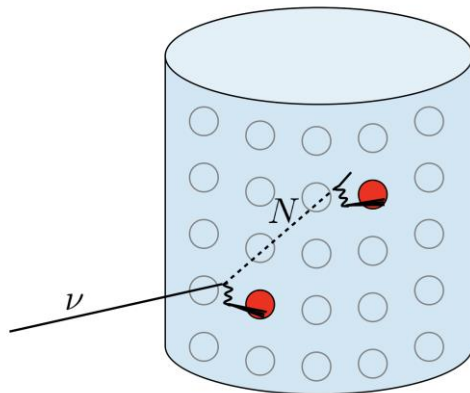


NEW

Atmospheric and Solar Searches

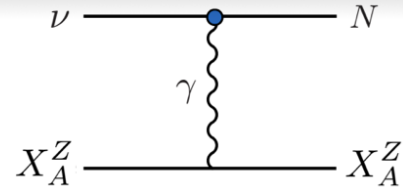
Natural Neutrino Fluxes

- Solar and atmospheric fluxes offer free source of all neutrino flavors.
 - Produce HNLs directly from CR collisions in atmosphere, then they decay in terrestrial detectors (Argüelles, Coloma, Hernández, Muñoz [1910.12839]).
 - Produce HNLs within the Earth via neutrino “up-scattering,” then decay in terrestrial detectors (Plestid [2010.04193, 2010.09523]).
 - Produce them inside detector, and either leave modified recoil spectrum or low-background “double-bang” events (Coloma, Machado, Martinez-Soler, Shoemaker[1707.08573], Atkinson, Coloma, Martinez-Soler, Rocco, Shoemaker[2105.09357]).
- **Many of these are excellent probes of non-minimal HNLs.**

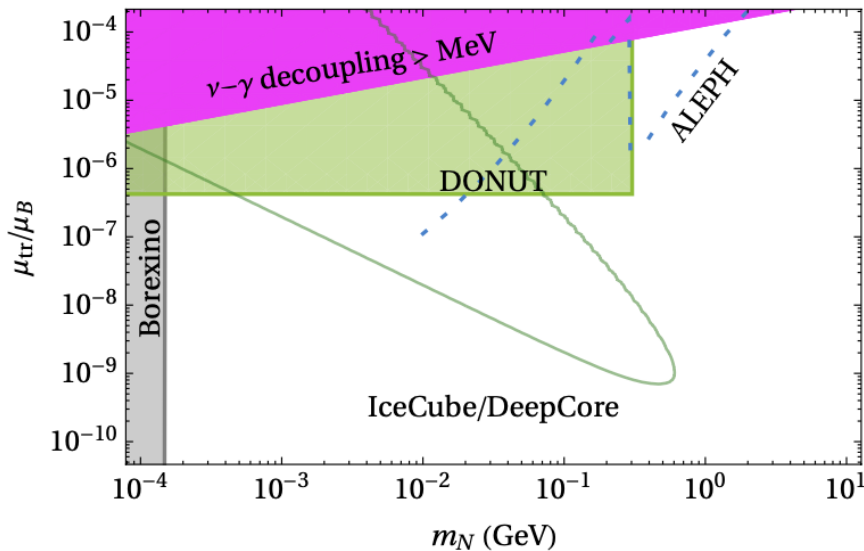


Atmospheric and Solar Searches

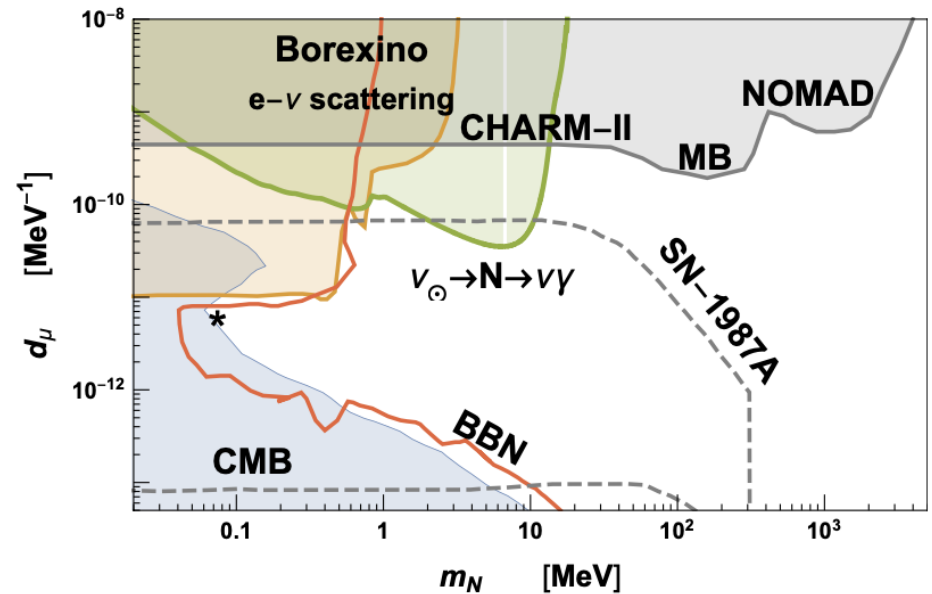
Dipole Portal Constraints from Natural Neutrino Fluxes



Atmospheric Double-bangs



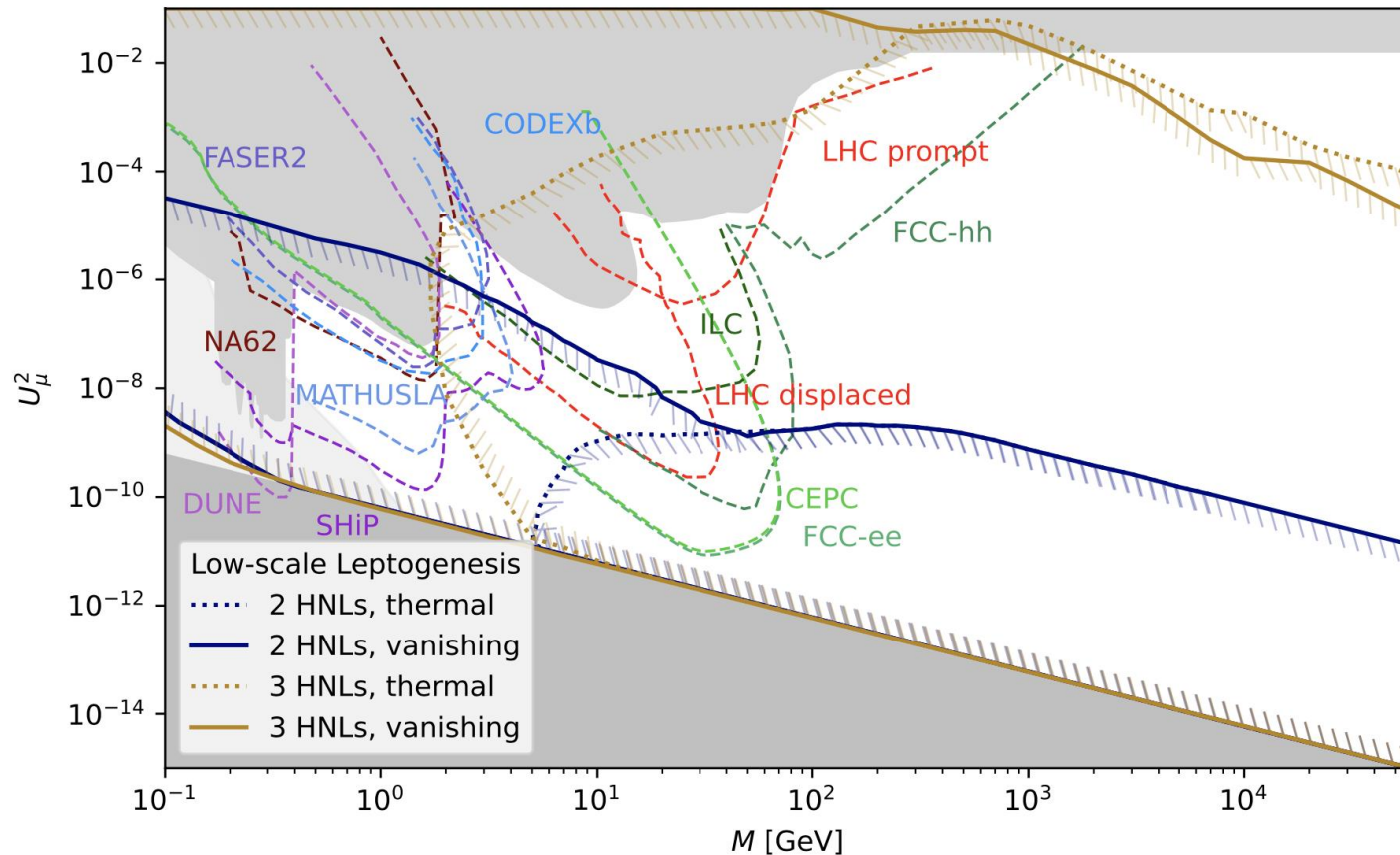
Terrestrial up-scattering of solar neutrinos
→ photons @ Borexino



Cosmological/Astrophysical Searches

NEW

M. Drewes, J.Klaric



- Updated cosmological/astrophysical limits
- Hashed regions is where leptogenesis works (for different models)
-> Many experiments can probe this parameter space!

Final Points/Recommendations

This is a Snowmass White Paper → Recommendations for NF3

- R1: Encourage the present experimental developing program to pursue new ideas and make proposals for HNL sensitive experiments. Should become a key part of these experiment's baseline physics program.
- R2: Future collider facilities should from the start consider the requirements for HNLs searches and long lived particles in general.
- R3: Experimental analyses examine sensitivities to the electron-, muon-, and tau-HNL mixing angles one at a time. Encourage future analyses to examine scenarios beyond single flavor dominance. Benchmarks being discussed/studied in PBC/FIPS meetings.
- R4: The keV mass scale: capitalize on the existing and planned (upgraded) experiments to cover the low mass range. (<10 MeV)
- R5: In case HNL discovery, develop further strategies for property measurements: mixing angles and HNL mass, Majorana, minimal HNL couplings...

Finally: A next workshop:



Registration open on : <https://indico.cern.ch/event/1119695/>

This year the Workshop will be organized along three main directions:

1. MeV-GeV Dark Matter and its searches at accelerator, direct and indirect detection experiments;
2. Heavy neutral leptons and their connection to active neutrino physics;
3. Ultra-light (< 1 eV) FIPs in particle physics, astroparticle, and cosmology.

The Organizing Committee:

James Beacham, Albert De Roeck, Marco Drewes, Bertrand Echenard, Torben Ferber, Maurizio Giannotti, Gian Francesco Giudice, Stefania Gori, Pilar Hernandez, Igor Irastorza, Joerg Jaeckel, Felix Kahlhoefer, Gaia Lanfranchi, Jacobo Lopez Pavon, Jocelyn Monroe, Silvia Pascoli, Maxim Pospelov, Philip Schuster, Mikhail Shaposhnikov, Jessie Shelton, Yevgeni Stadnik, Stefan Ulmer