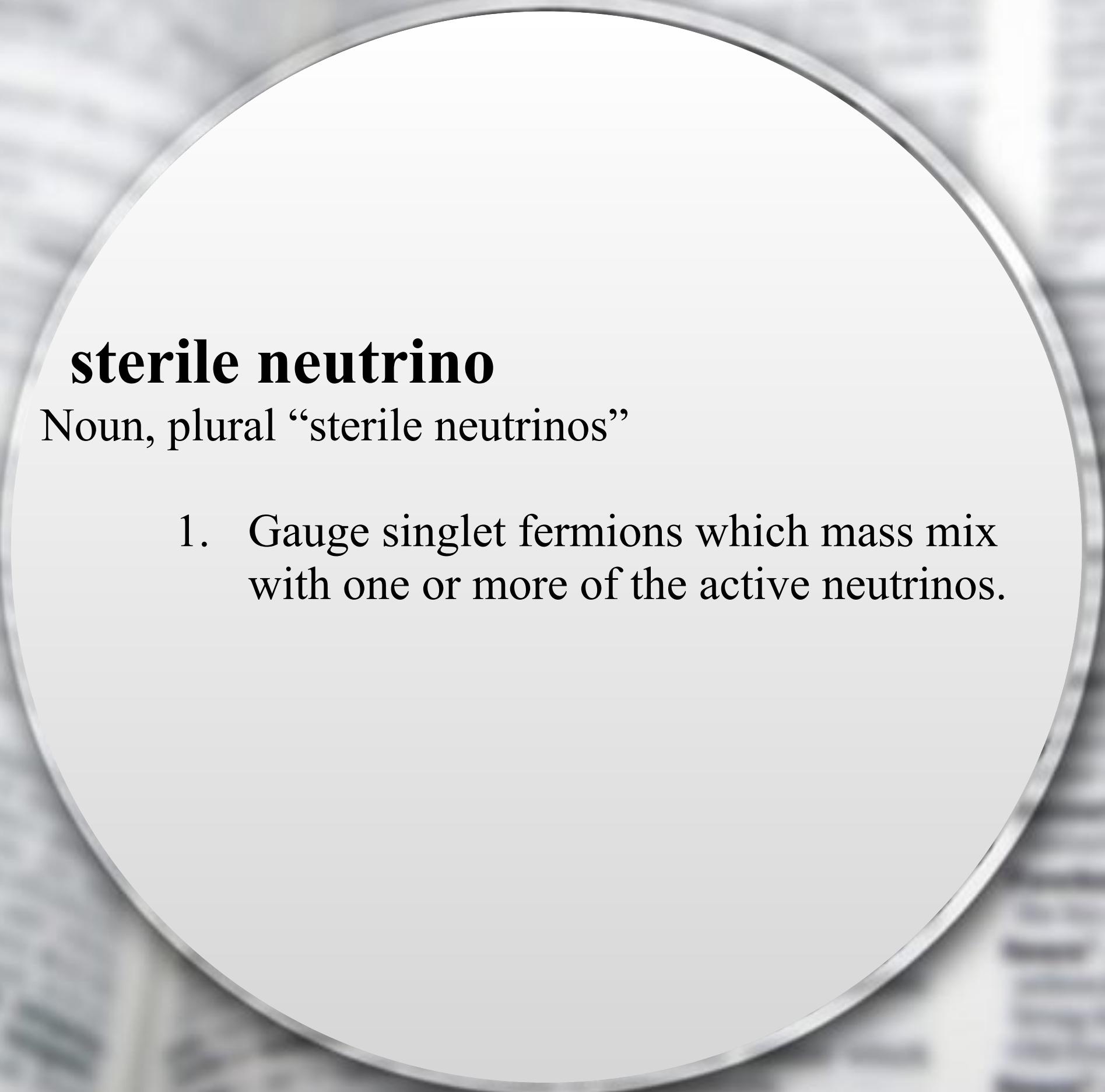


Heavy Neutral Leptons (a.k.a Heavy Sterile Neutrinos)

Ian M. Shoemaker



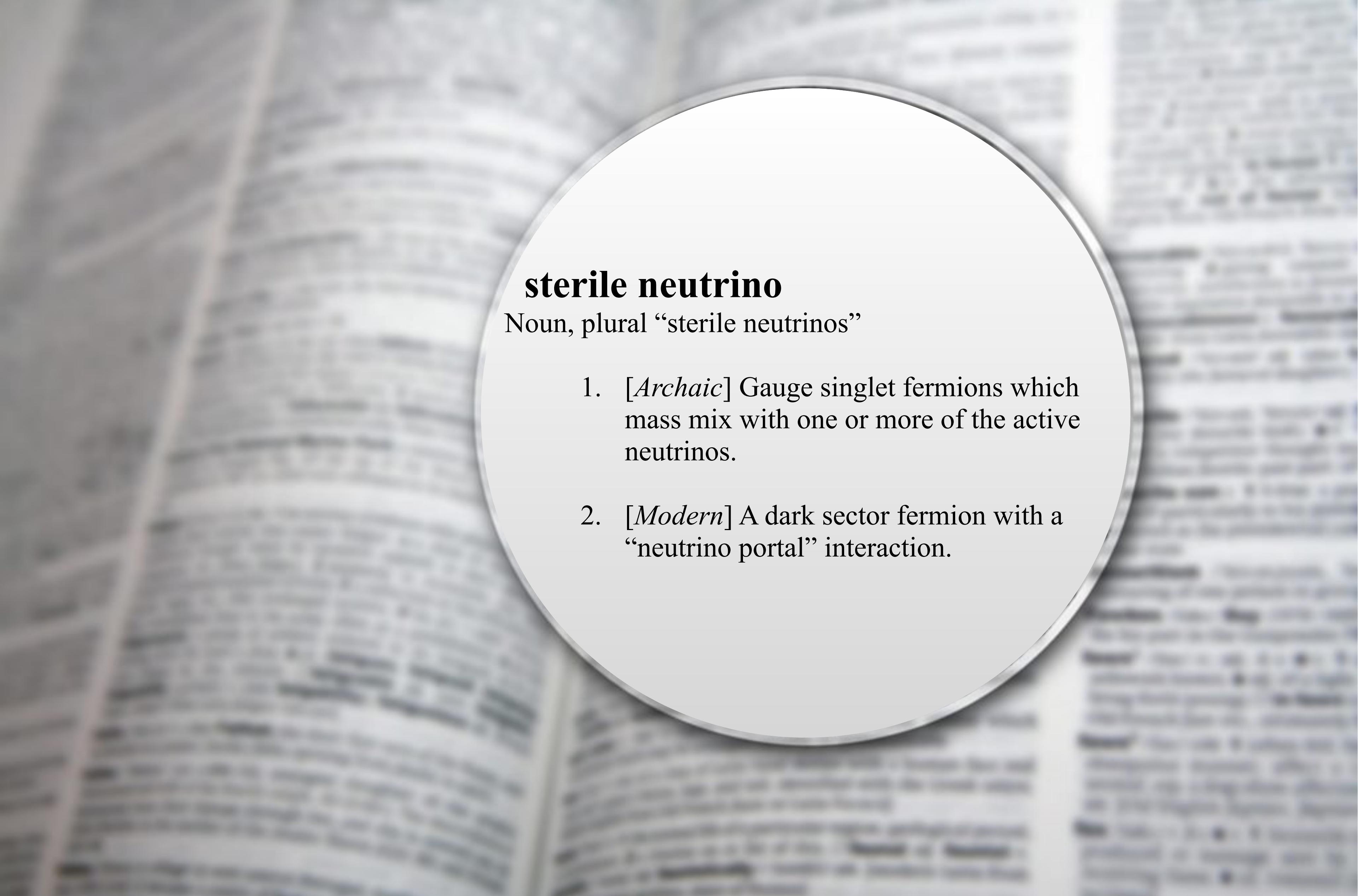
*Snowmass Snowmass BSM@nu Workshop
February 10th, 2022*



sterile neutrino

Noun, plural “sterile neutrinos”

1. Gauge singlet fermions which mass mix with one or more of the active neutrinos.



sterile neutrino

Noun, plural “sterile neutrinos”

1. [Archaic] Gauge singlet fermions which mass mix with one or more of the active neutrinos.
2. [Modern] A dark sector fermion with a “neutrino portal” interaction.

Sterile Neutrinos

$$\{\nu_e, \nu_\mu, \nu_\tau, \nu_{s,1}, \nu_{s,2}, \dots, \nu_{s,N}\}$$

SM gauge singlets

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \bar{\nu}_{s,a} (i\partial_\mu \gamma^\mu) \nu_{s,a} - y_{\alpha a} H \bar{L}_\alpha \nu_{s,a} - \frac{M_{ab}}{2} \bar{\nu}_{s,a}^c \nu_{s,b} + h.c. ,$$

Mass Matrix: $M = \begin{pmatrix} 0 & D_{3 \times N} \\ D_{N \times 3}^T & M_{N \times N} \end{pmatrix}$

- Unlike SM fermions, their # is not constrained by anomaly cancellation.
- Don't know the number of steriles!
- Need at least two of them for atm/sol mass splittings $N=2$.
- If $N=3$, can accommodate oscillations and DM if one is at the keV scale.

How can we find them?

→ Produce them via inherited EW interaction

→ Decay them via inherited EW interaction

White Paper on Heavy Neutral Leptons

Alexey Boyarsky^a, José I. Crespo-Anadón^b, Albert De Roeck^c, Marco Drewes^d, Rebeca Gonzalez Suarez^e, Evgeni Goudzovski^f, Kevin J. Kelly^c, Mathieu Lamoureux^g, Gaia Lanfranchi^h, Jacobo López-Pavónⁱ, Michael Mooney^j, Miha Nemevšek^k, Silvia Pascoli^{l,m}, Ryan Plestid^{n,1}, Federico Leo Redi^p, Richard Ruiz^o, Mikhail Shaposhnikov^p, Ian M. Shoemaker^q, Robert Shrock^r, Aaron C. Vincent^s

^a*Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, 2333 CA Leiden, Netherlands*

^b*Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid E-28040, Spain*

^c*European Organization for Nuclear Research (CERN), 1211 Geneva 23, Switzerland*

^d*Centre for Cosmology, Particle Physics and Phenomenology - CP3 Université catholique de Louvain 2, Chemin du Cyclotron - Box L7.01.05
B-1348 Louvain-la-Neuve Belgium*

^e*Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden*

^f*School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom*

^g*INFN Sezione di Padova, 35131 Padova, Italy*

^h*INFN - Laboratori Nazionali di Frascati, via E. Fermi 40, 00044 Frascati (Rome), Italy*

ⁱ*Instituto de Física Corpuscular, Universidad de Valencia & CSIC, Edificio Institutos de Investigación, Calle Catedrático José Beltrán 2, 46980 Paterna, Spain*

^j*Colorado State University, Fort Collins, CO, 80523, USA*

^k*Jožef Stefan Institute, Jamova 39, 1000, Ljubljana, Slovenia*

^l*Dipartimento di Fisica e Astronomia, Università di Bologna e INFN, Sezione di Bologna, via Irnerio 46, I-40126 Bologna, Italy*

^m*Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham, DH1 3LF, United Kingdom*

ⁿ*Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA*

^o*Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego, Cracow 31-342, Poland*

Major Sections

2	Theory of Heavy Neutral Leptons [Pascoli and Shaposhnikov]	4
2.1	Neutrino Masses	4
2.2	General neutrino mass models and HNLs	4
2.3	Type-I seesaw	4
2.4	ν MSM	6
2.5	Beyond minimal HNL models	7
3	Collider Searches [Nemevšek, Ruiz, de Roeck, Redi]	7
3.1	ATLAS, CMS, and LHCb	7
3.1.1	Current ATLAS and CMS Results	8
3.1.2	Expected future ATLAS and CMS Results	12
3.1.3	Current LHCb Results	13
3.1.4	Expected future LHCb Results	13
3.2	Future LHC Experiments: New experiments for Run 3 and proposals for the HL-LHC era	14
3.2.1	FASER	15
3.2.2	SND@LHC	15
3.2.3	MATHUSLA	16
3.2.4	CODEX-b	16
3.3	AL3X	16
3.3.1	ANUBIS	17
3.3.2	MAPP	18
3.3.3	The Future Physics Facility	18
3.3.4	FACET	19
3.4	FCC	19
3.4.1	FCC _{ee}	19
3.4.2	FCC _{hh}	20
3.4.3	FCC _{eh}	21
3.5	Monte Carlo developments studies at the LHC	21
3.6	varia	22

Major Sections

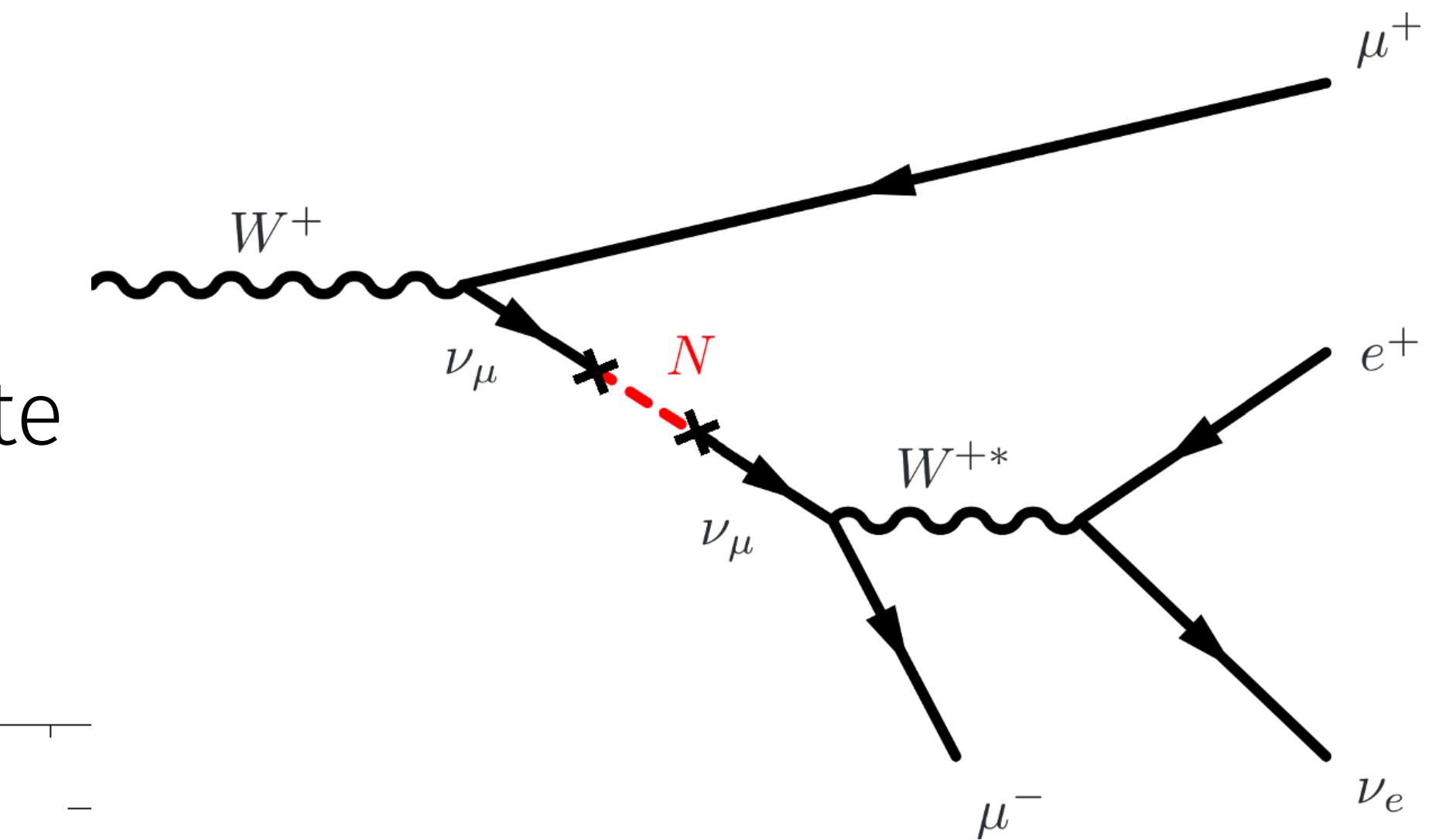
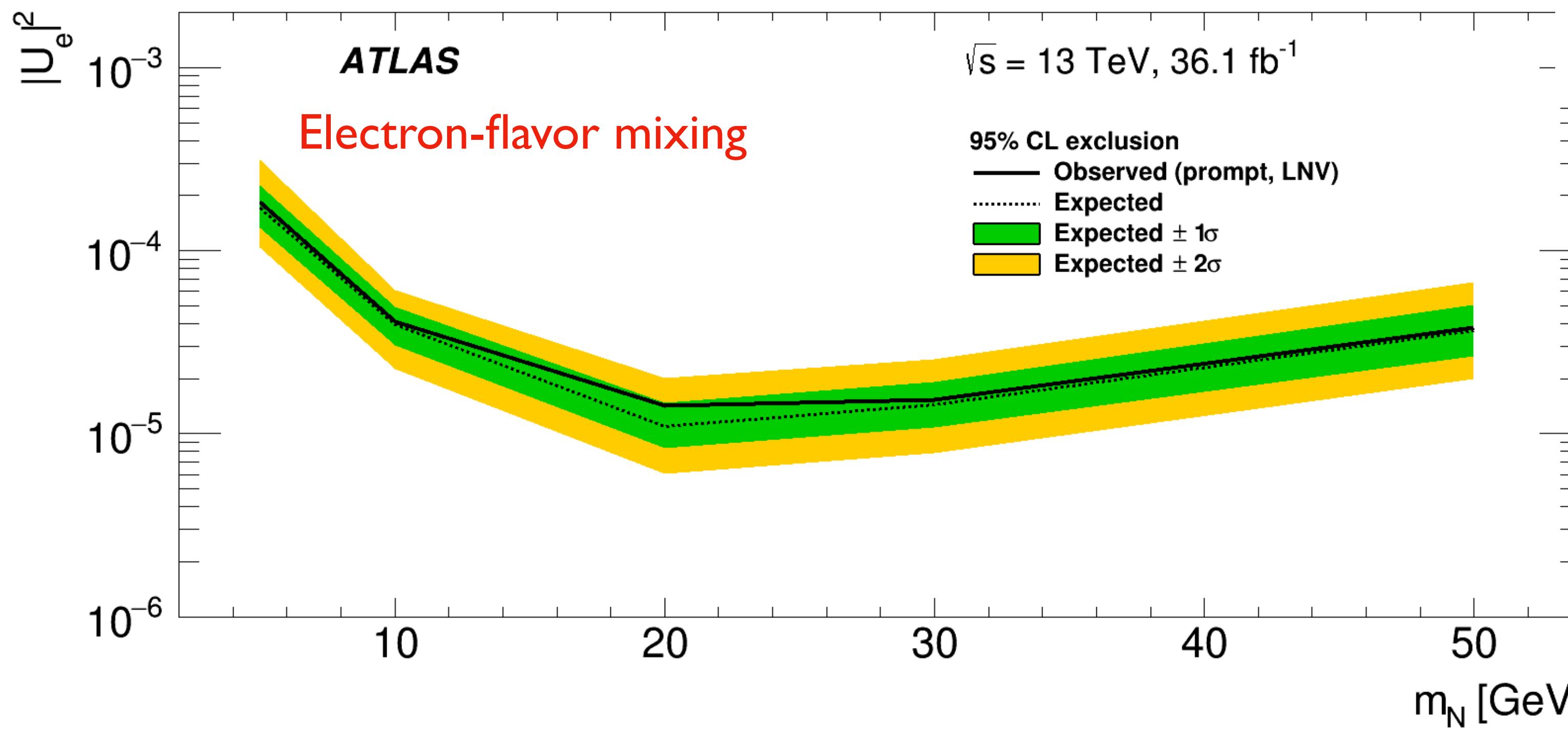
4	Searches at Extracted Beamlines [Kelly, Lanfranchi]	23
4.1	Introduction	23
4.2	Opportunities at CERN: NA62, SHADOWS, and SHiP	23
4.2.1	NA62 at CERN	24
4.2.2	SHADOWS at CERN	25
4.2.3	SHiP at CERN	26
4.3	Opportunities at FNAL and J-PARC: Neutrino-Beam Experiments	26
4.3.1	T2K at J-PARC	27
4.3.2	ArgoNeuT at FNAL	28
4.3.3	NOvA at FNAL	28
4.3.4	T2K-II and Hyper-Kamiokande	28
4.3.5	The Short-Baseline Neutrino experiments: SBND, Icarus, and MicroBooNE at FNAL	29
4.3.6	DUNE near detectors at FNAL	29
4.4	Opportunities at FNAL: DarkQuest	31
4.5	Opportunities at PSI: PIONEER	31
4.6	Post-Discovery Potential	31
4.7	Conclusions	33
5	Atmospheric and Solar Searches [Plestid and Shoemaker]	
5.1	Modified Recoil spectrum:	
5.2	HNLs decaying enroute from the Sun:	
5.3	Upscatter in earth:	
5.4	Production in atmospheric showers:	
5.5	Double bang:	
6	Cosmological and Astrophysical Searches [Boyarsky, Drewes]	
6.1	Constraints from observations	
6.1.1	Big Bang Nucleosynthesis and HNLs	
6.1.2	Cosmic Microwave Background	
6.1.3	HNLs in Astrophysical Settings	
6.2	Solving open problems in cosmology	
6.2.1	Leptogenesis and the origin of ordinary (baryonic) matter	
6.2.2	Dark Matter	

*Some
Examples*

Collider Searches

Tests of neutrino mass models at ATLAS and CMS

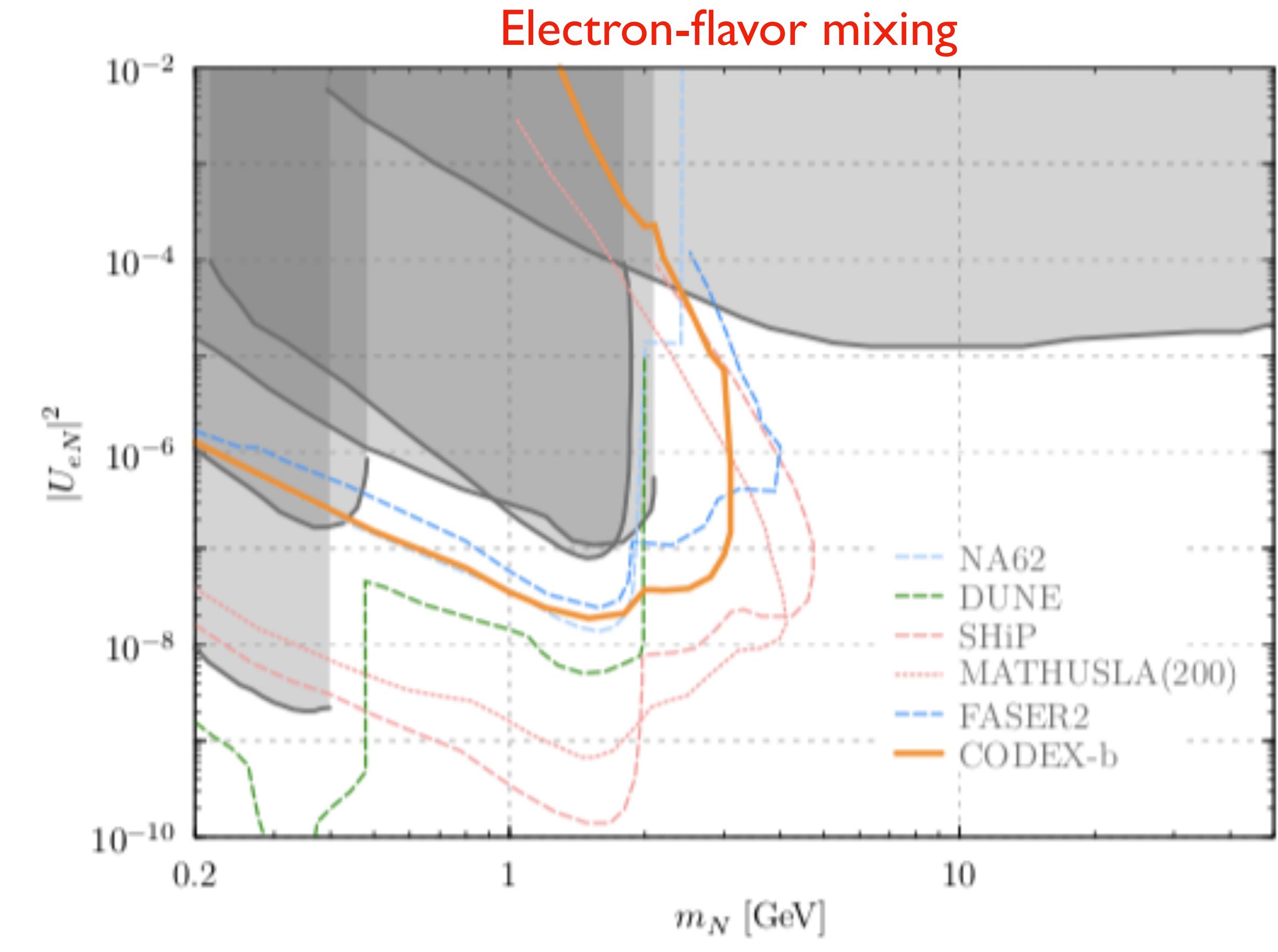
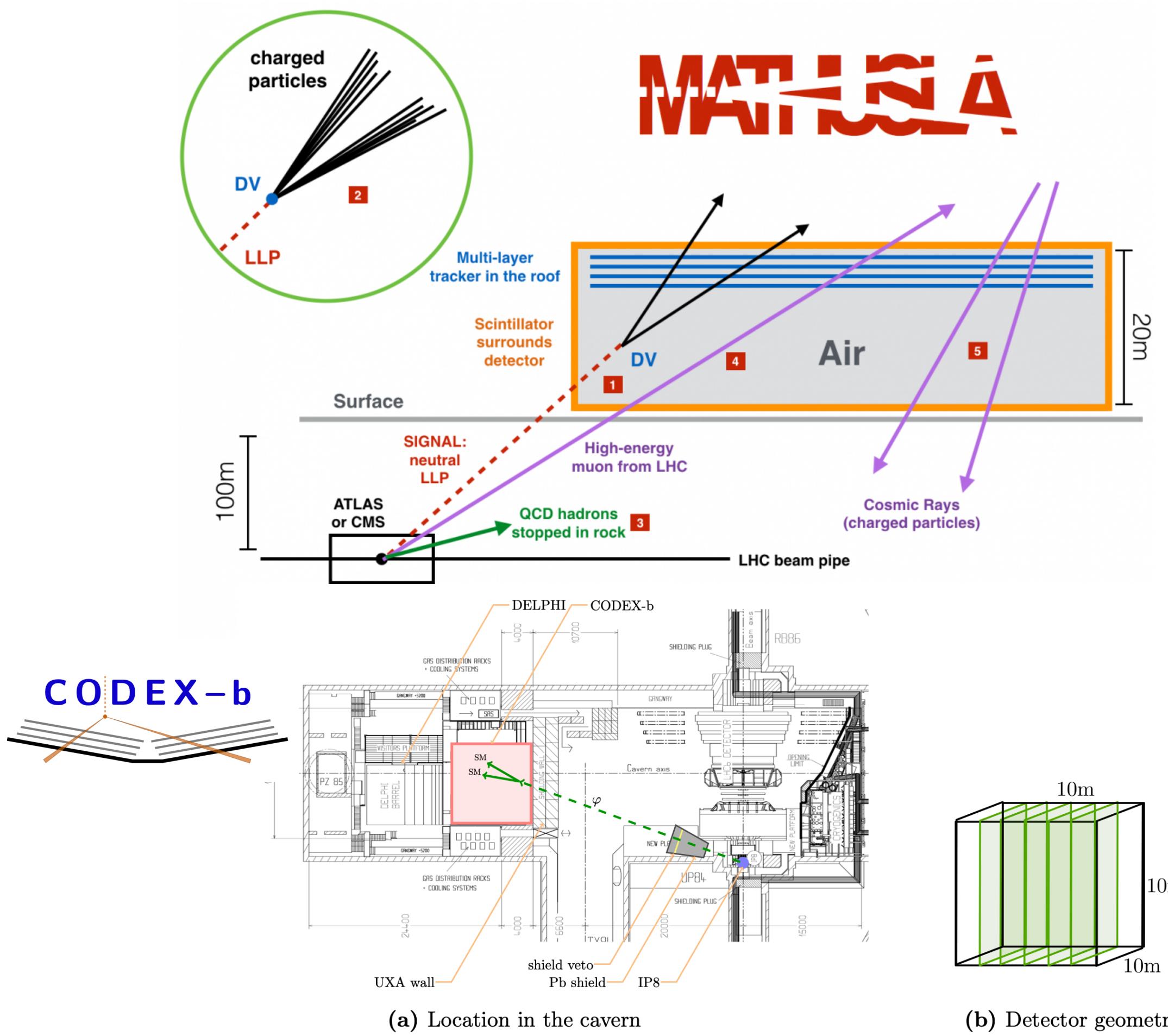
- Signatures
 - prompt: $W^\pm \rightarrow e^\pm e^\pm \mu^\mp \nu_\mu$ & $W^\pm \rightarrow \mu^\pm \mu^\pm e^\mp \nu_e$
 - displaced: prompt μ , displaced vertex with opposite charge $e\mu$ or $\mu\mu$



TAKE HOME:
ATLAS and CMS continues to place leading HNL constraints.
Many run-2 analyses yet to come, and run-3 around the corner.

Future collider probes

- New proposals to search for LLPs: **central/transverse experiments** (e.g. MATHUSLA, CODEX-b), and **forward experiments** (e.g. FASER, SND@LHC).
- Note: SND@LHC and FASER fully funded & installed, ready for data in Run 3.

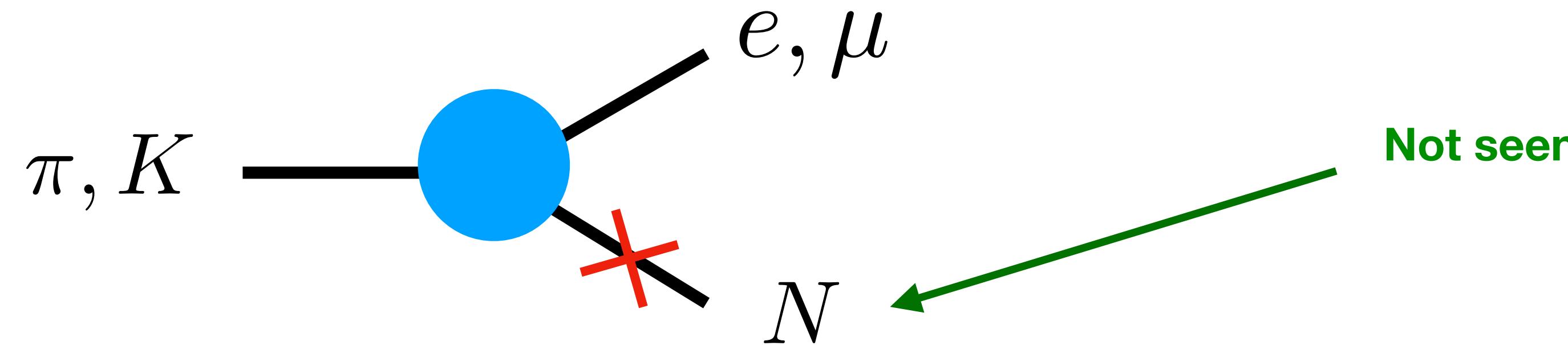


*Some
Examples*

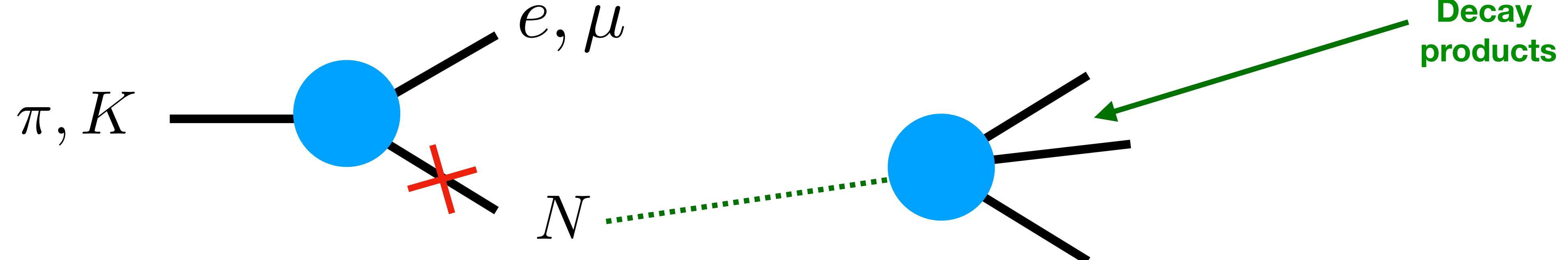
Searches at Extracted Beamlines

Extracted Beamlines

- Missing energy in meson decay.



- Decay in flight @ beam dump & neutrino experiments.

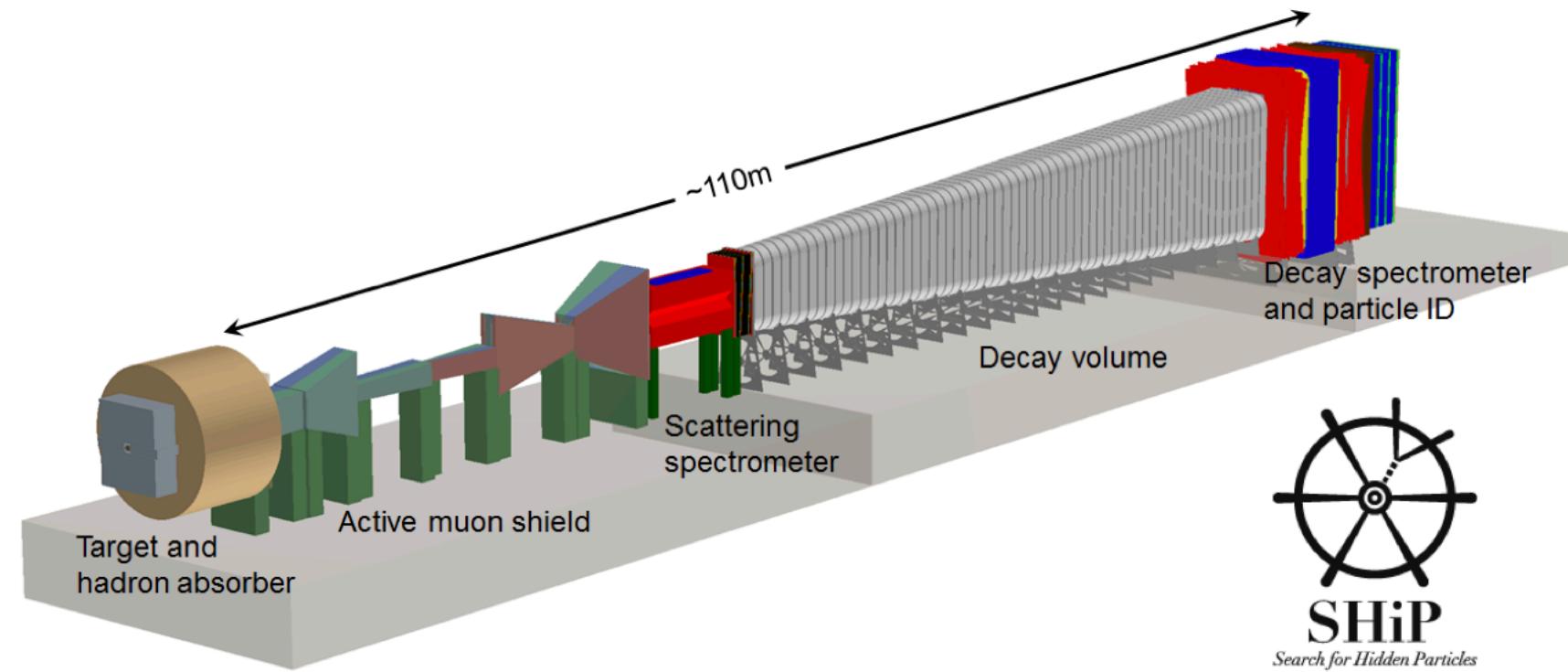


Summary of fixed target probes

Table 1: Summary of the fixed-target searches for Heavy Neutral Leptons considered throughout Section 4.

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 (2032–2040)
NA62-dump	CERN	p , 400 GeV	spectrometer	$A = \pi r^2$, $r = 1$ m	~ 80 m	~ 100 m	$5 \cdot 10^{19}$	by (2032–2040)
SHADOWS	CERN	p , 400 GeV	spectrometer	2.5×2.5 m 2	~ 20 m	~ 10 m	$5 \cdot 10^{19}$	by (2032–2040)
SHiP	CERN	p , 400 GeV	spectrometer	5×10 m 2				
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					
ICARUS	FNAL	p , 8/120 GeV	LArTPC					
MicroBooNE	FNAL	p , 8/120 GeV	LArTPC					
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	$\gtrsim 1.47 \cdot 10^{22}$	~ 2030–2040
DarkQuest	FNAL	p , 120 GeV	spectrometer					

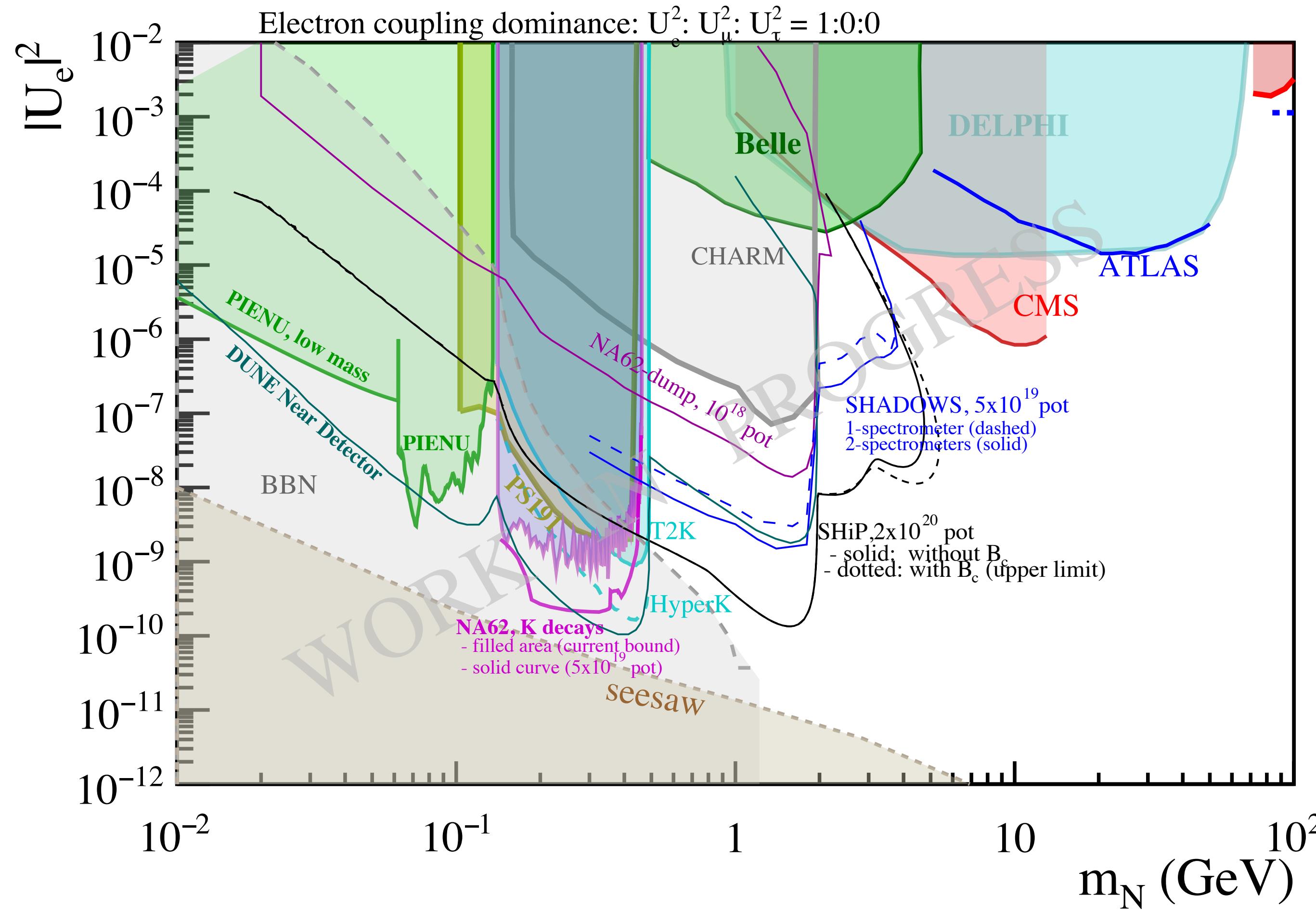
Future probes



- 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.

Future probes

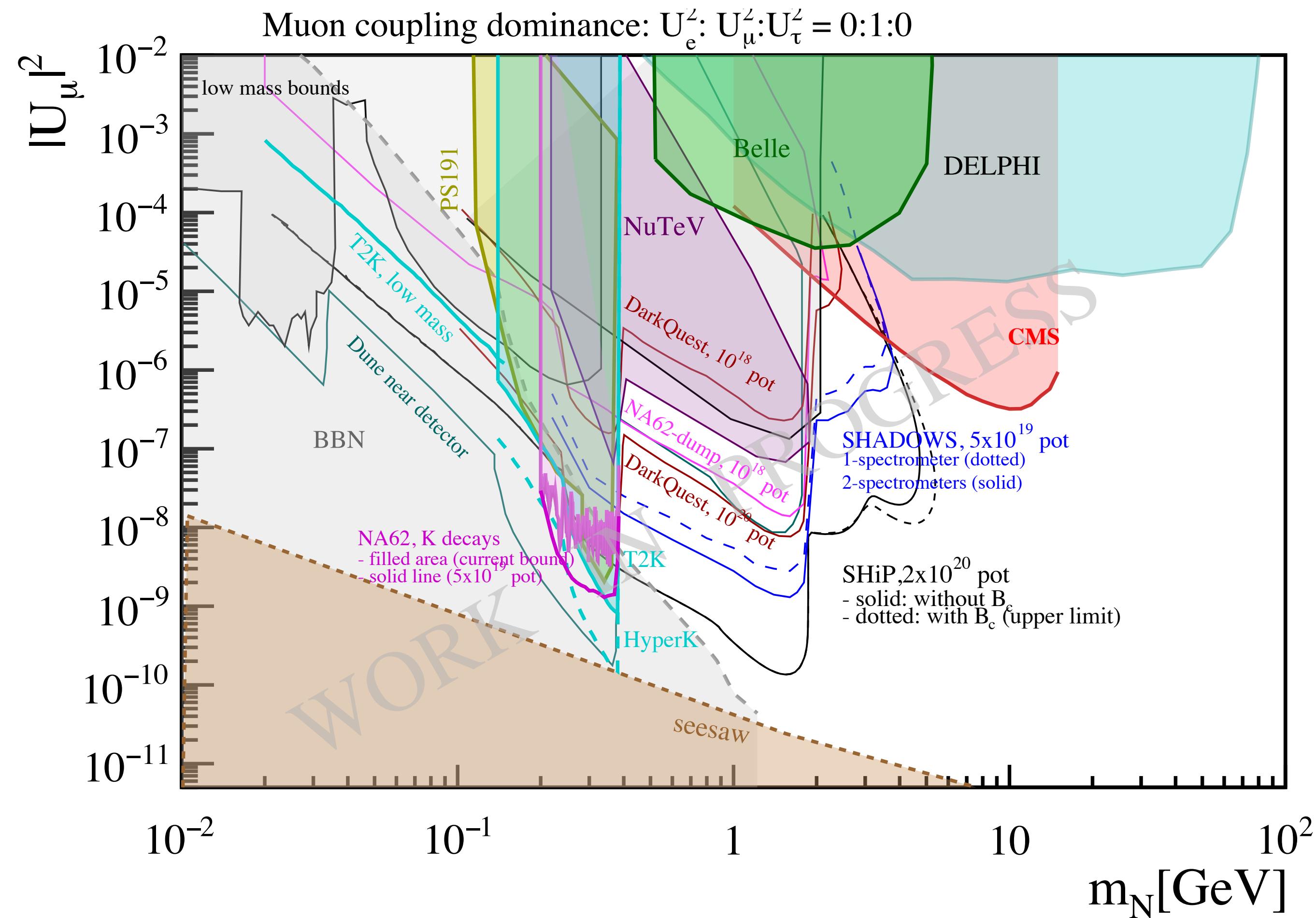
Electron-flavor mixing



TAKE HOME:
Complementary
regions probed by
DUNE, NA62, SHiP
and SHADOWS

Future probes

Muon-flavor mixing

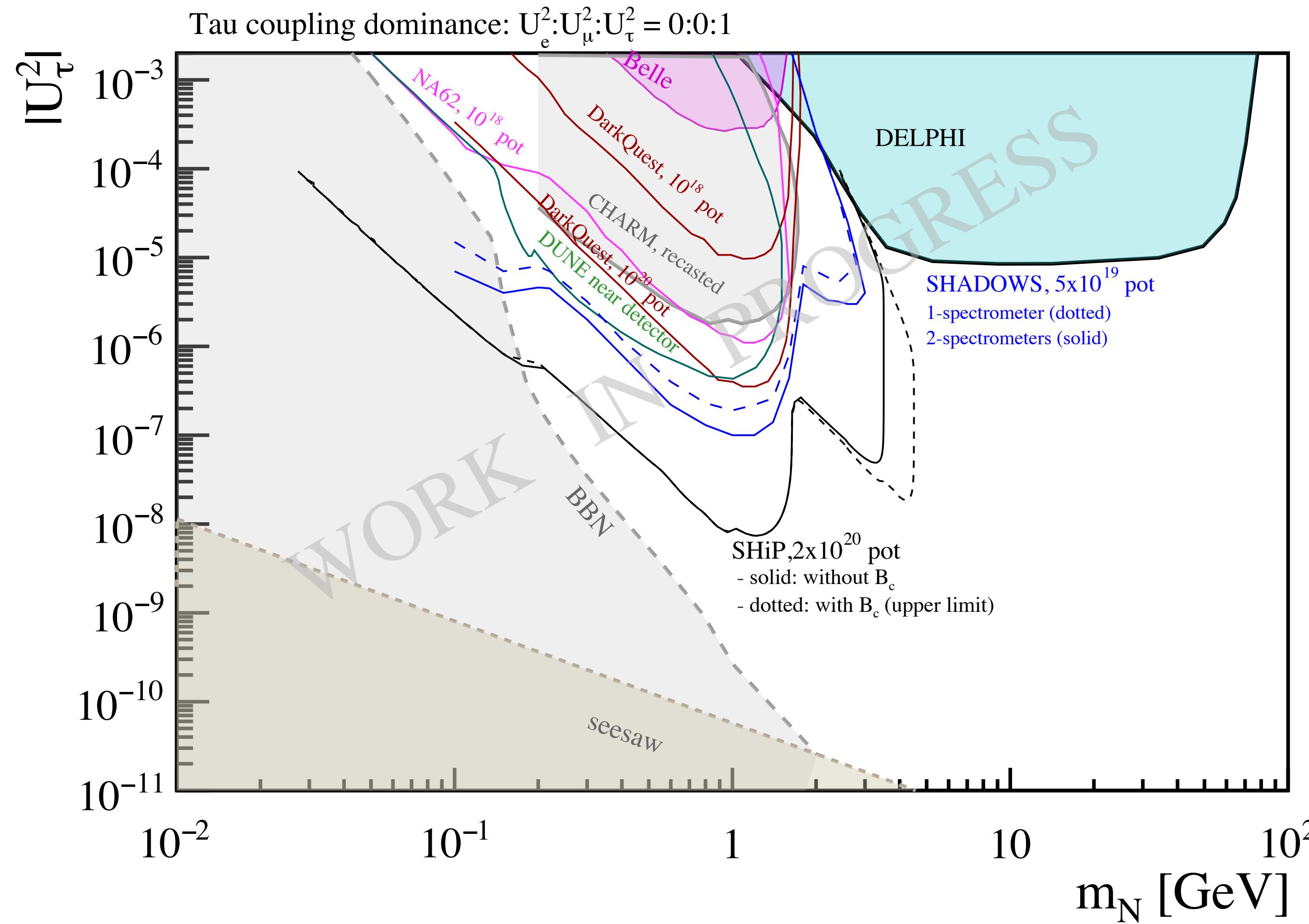


TAKE HOME:

Complementary regions probed by DUNE, NA62, SHiP and SHADOWS

Future probes

Tau-flavor mixing



TAKE HOME:
Complementary
regions probed by
DUNE, NA62, SHiP
and SHADOWS

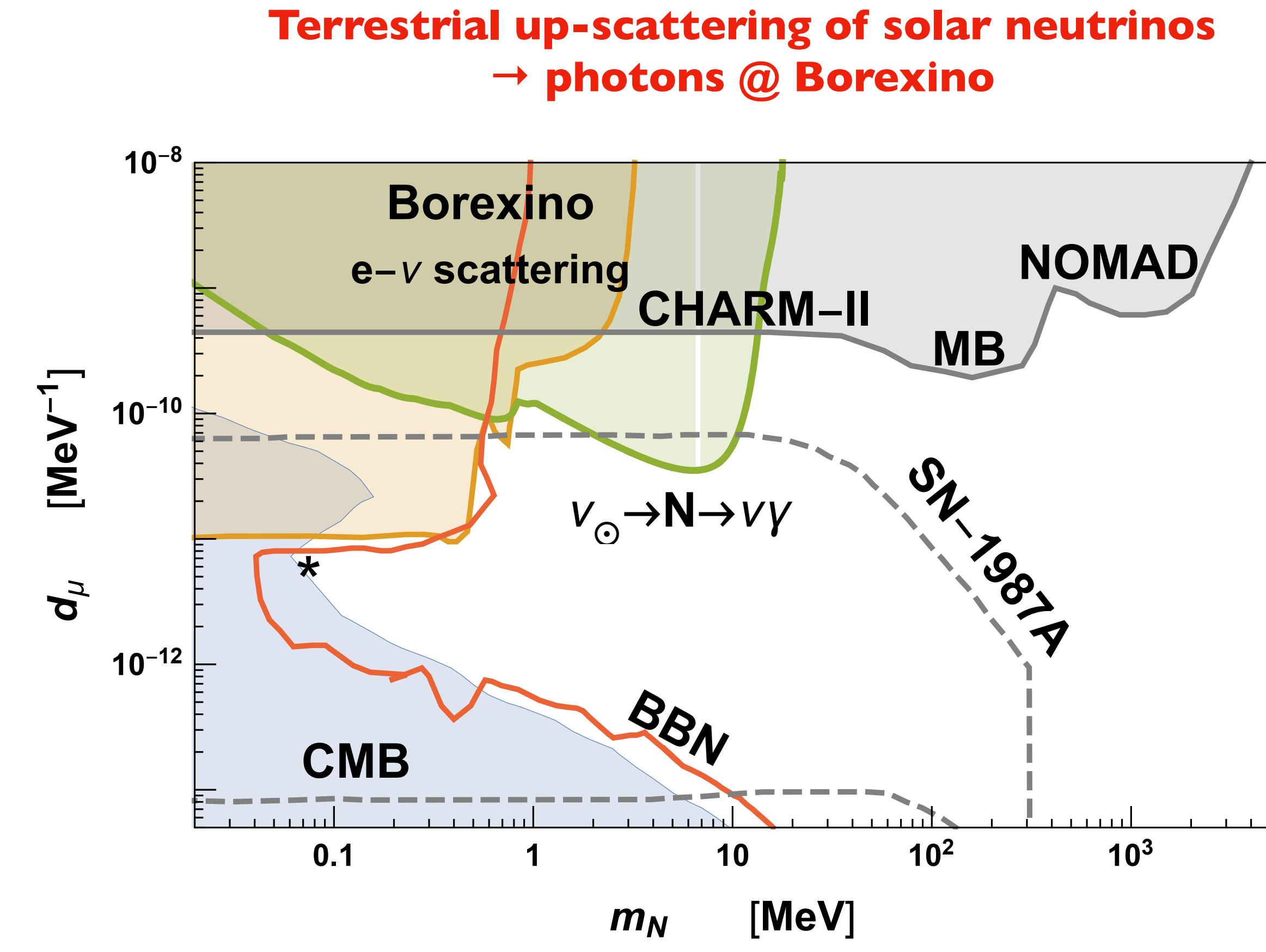
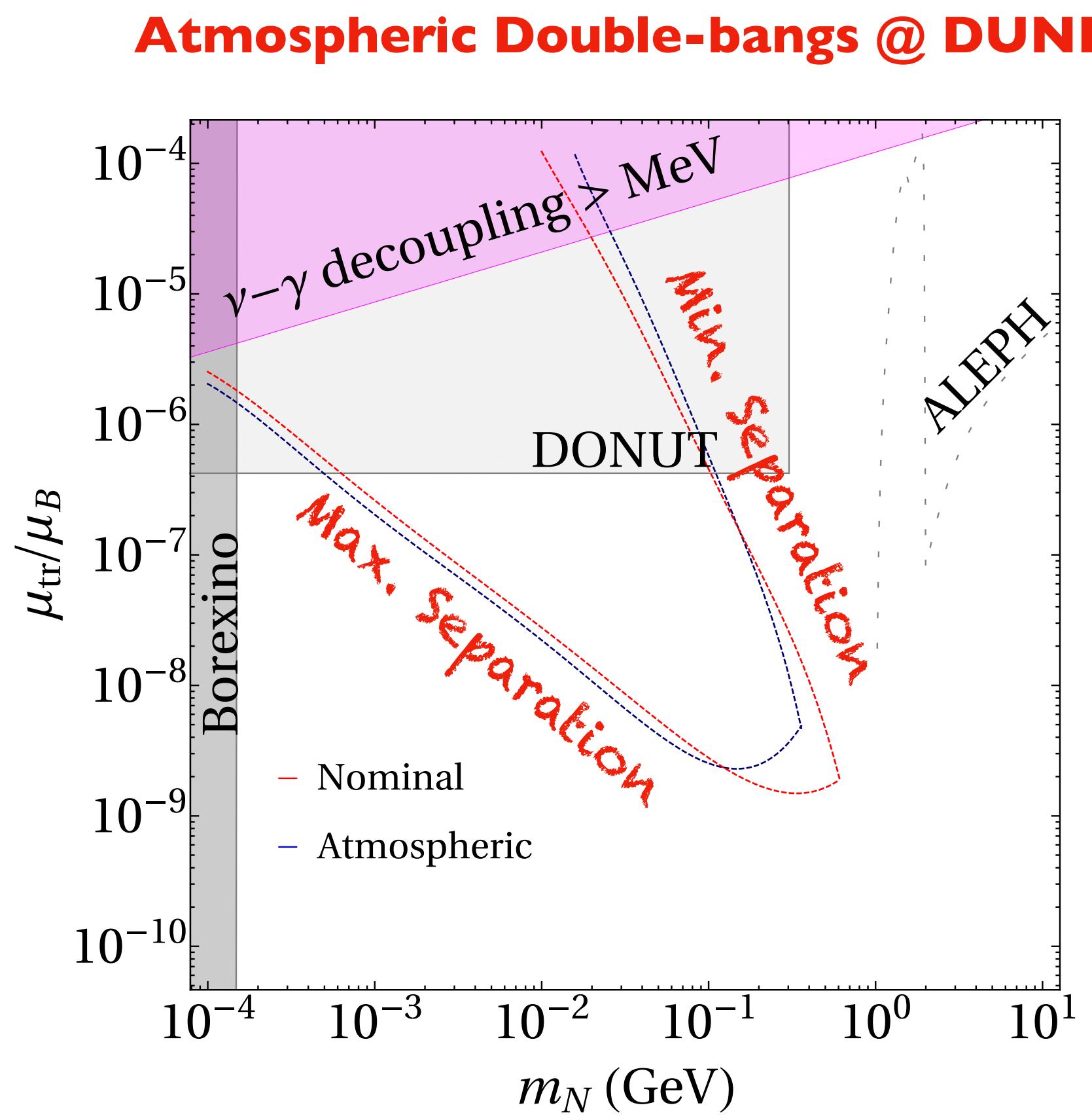
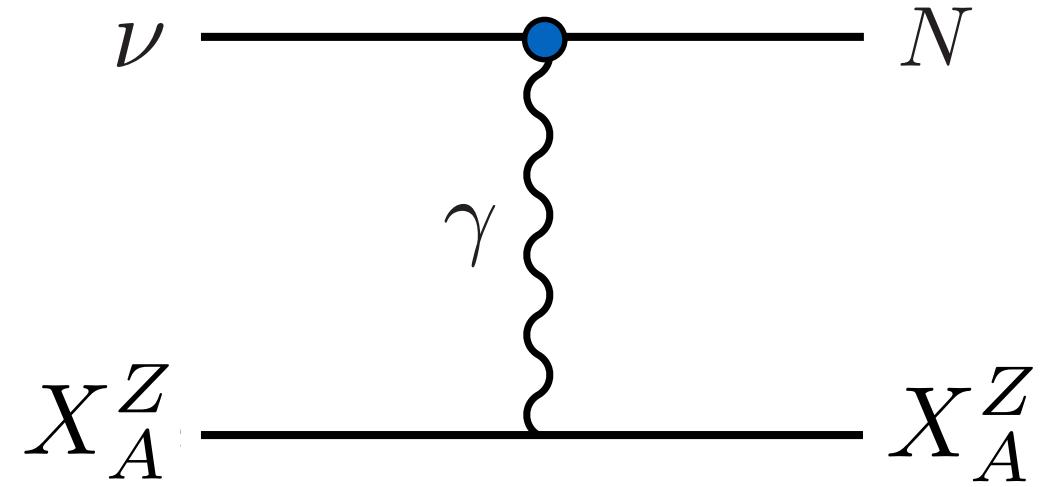
*Some
Examples*

Atmosphere & Solar Probes

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.**

Dipole Portal Constraints from Natural Neutrino Fluxes

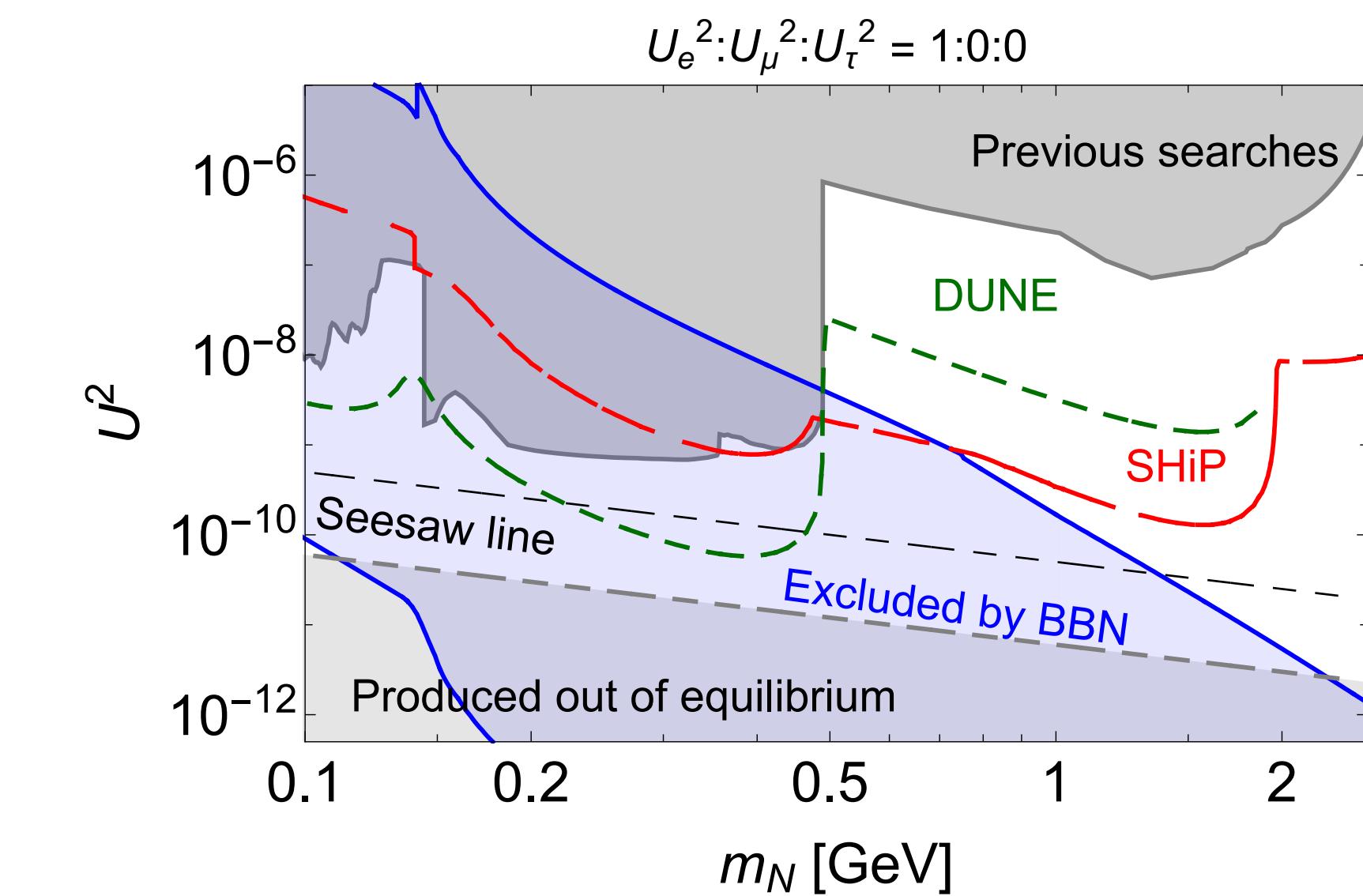


*Some
Examples*

Astrophysics and Cosmology

Astrophysics & Cosmology

- BBN bounds are a complementary probe of HNLs, eating into low-mass low mixing angle terrain.
 - Must lie in a range of mixing angles to be probed: efficient production in early universe (mixing can't be too small) & decay after BBN (mixing can't be too large).



Timeline

- Looking good: ~44 pages, 406 references, 25 figures.
- Section drafts already due Feb. 4
- “Final draft” circulated **Feb. 21**.
- Post to arXiv **March 4th**.
- Submit to journal (J. Phys. G)? ~March 15th.

Summary & Recommendations

- **Summary:** An array of up-coming experimental probes (e.g. FASER, MATHUSLA, SHiP, DUNE ND, NA62, SHADOWS, ...) offer critical complementarity in the hunt for HNLs across a wide range of mass scales, mixing angles, and flavor structures.
- **Recommendation 1:** In order to facilitate apples-to-apples comparisons, and for simplicity, we encourage experimental analyses to examine sensitivity to the electron-, muon-, and tau-HNL mixing angles separately **one at a time**.
 - Of course many other flavor assumptions are possible, and possibly even more realistic. We encourage analyses to examine such scenarios if time allows.
 - Are there well-motivated benchmarks that deviate from the one-at-a-time assumption?
- **Recommendation 2:** Whenever possible, we urge analyses to keep an open mind regarding the possible nature of HNLs, and **take non-minimal HNL scenarios seriously**.
 - Explicitly this consideration may take the form of examining how a given analysis may be modified if HNLs undergo non-minimal production and/or decay.

Summary & Recommendations

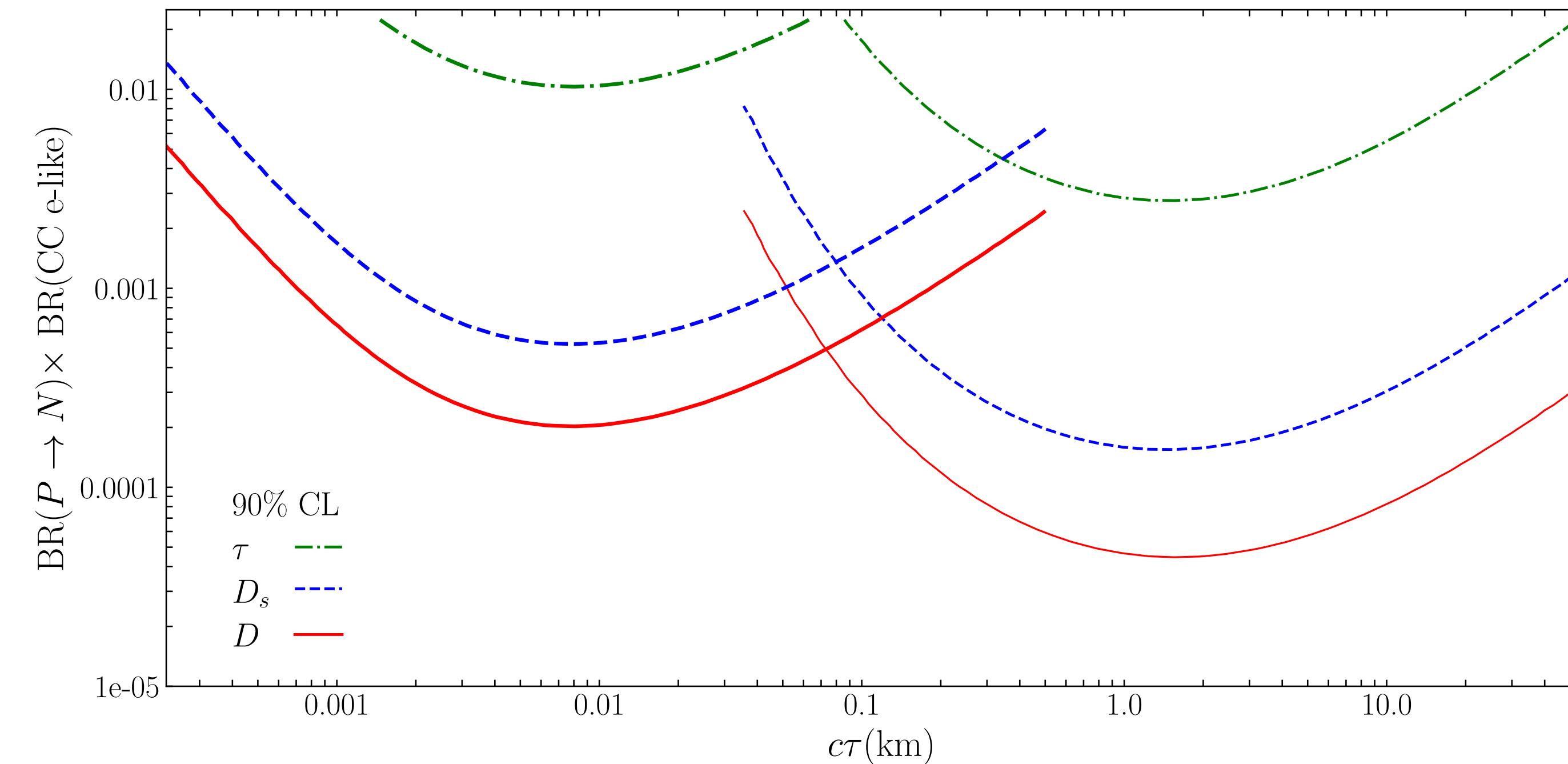
(Comments welcome!)

- **Recommendation 3:** Consider experimental determination of HNL properties in **post-discovery** environment.
 - For example, how well can one simultaneously constrain e-, mu-, and tau-mixing angles if there is a positive HNL signal? How about the HNL mass?

Back-ups

Example of Rec. 2

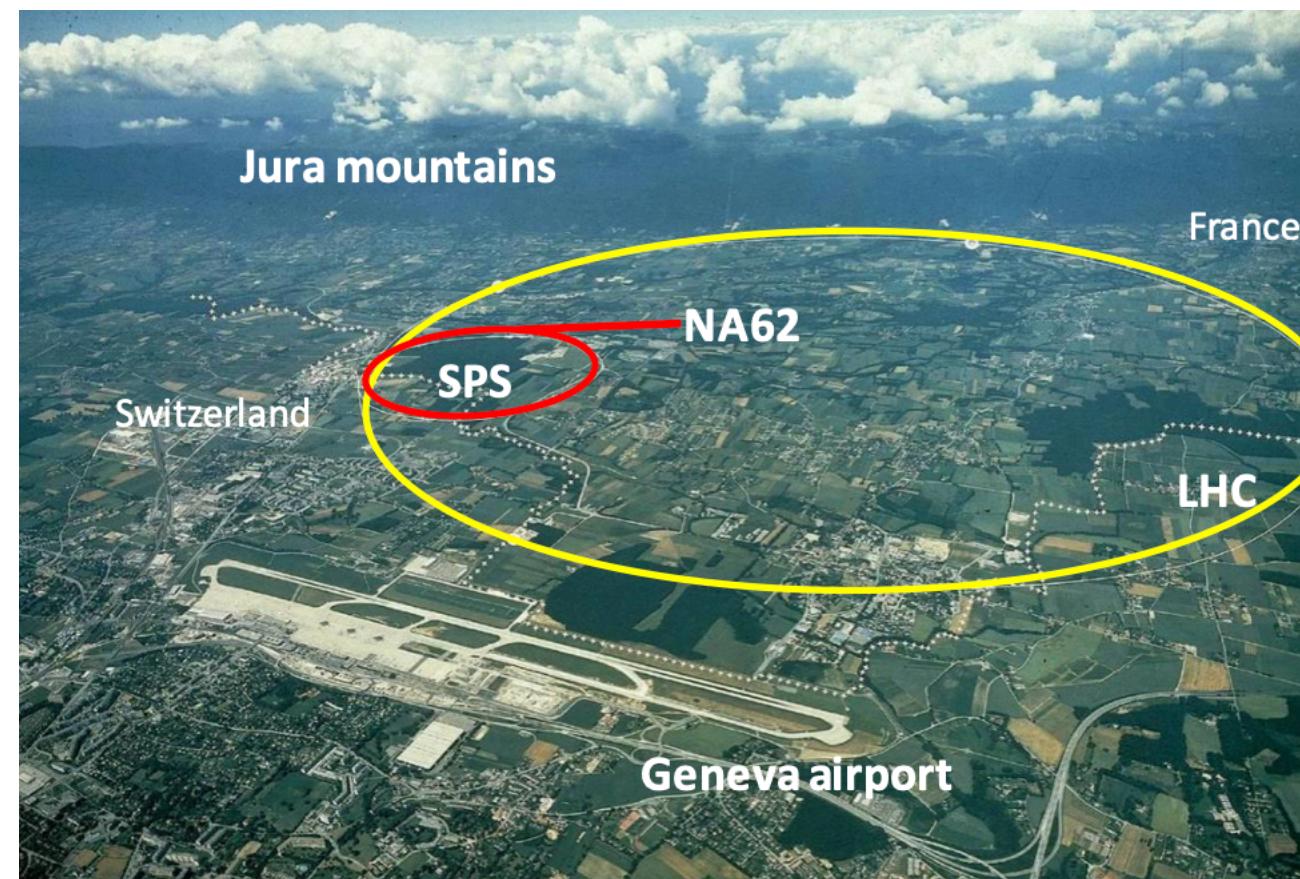
Carlos Argüelles, Pilar Coloma, Pilar Hernández, Víctor Muñoz [1910.12839]



**Pheno motivated
exclusion plot**

Figure 15. Limits on HNL of $m_V = 1\text{GeV}$ from IceCube (thick lines) and SuperKamiokande (thin lines) on the $\text{BR}(P \rightarrow N) \times \text{BR}(N \rightarrow \text{CC-e like})$ vs $c\tau$ plane including production from the parent particles $P = D$ (solid), D_s (dashed) and τ (dash-dotted).

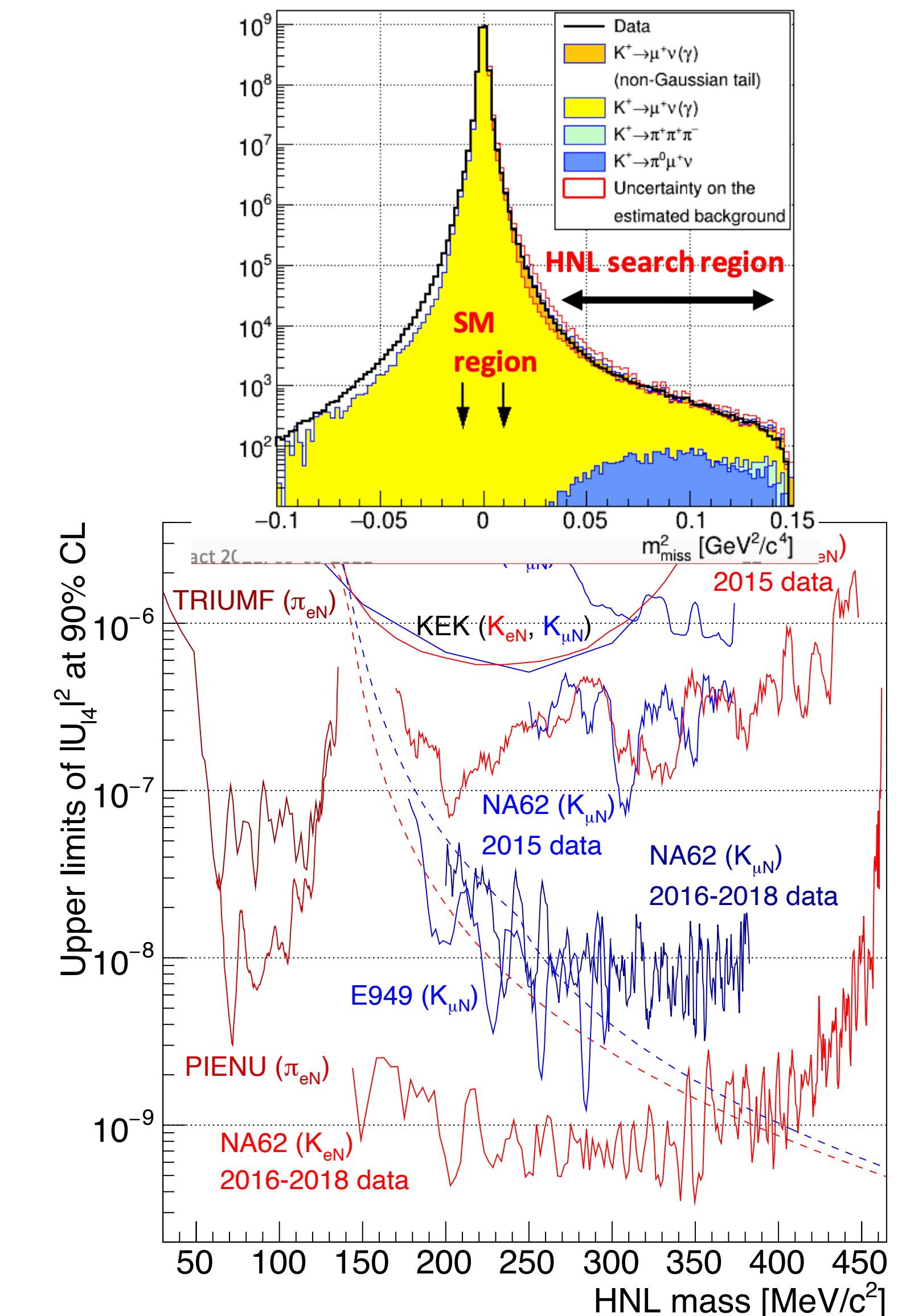
Search for K⁺ decays to a lepton and invisible particles



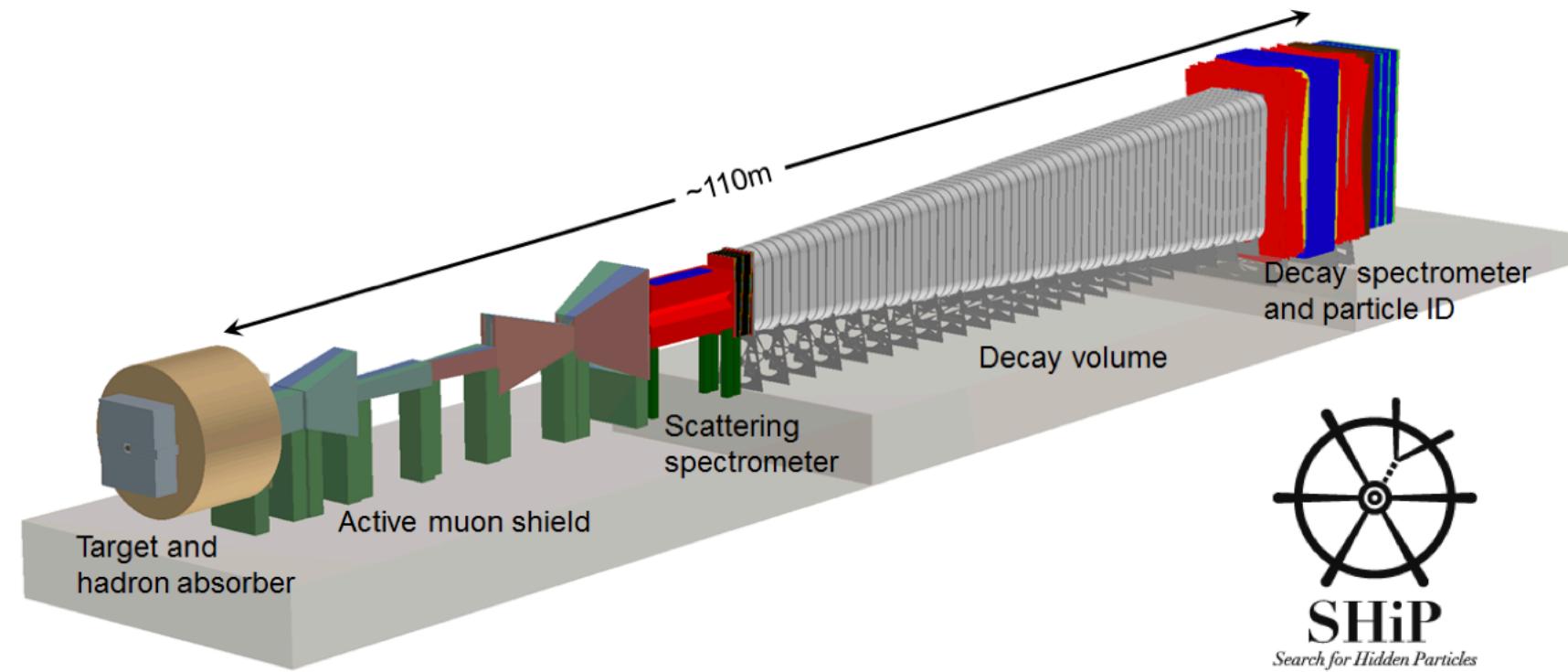
- $m_{\text{miss}}^2 = (P_K - P_l)^2$, P_K and P_l are the Kaon and lepton 4-momenta
- HNL signal: sharp peak in the m_{miss}^2 spectrum

Fixed target Kaon experiment at CERN SPS

TAKE HOME: Upper limits improved by 2(1) order of magnitude on electron(muon) HNL mixing parameter $|U_{l4}|^2$ with full NA62 Run I data with respect to previous best world limits.



Future probes



- 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.

Future collider probes

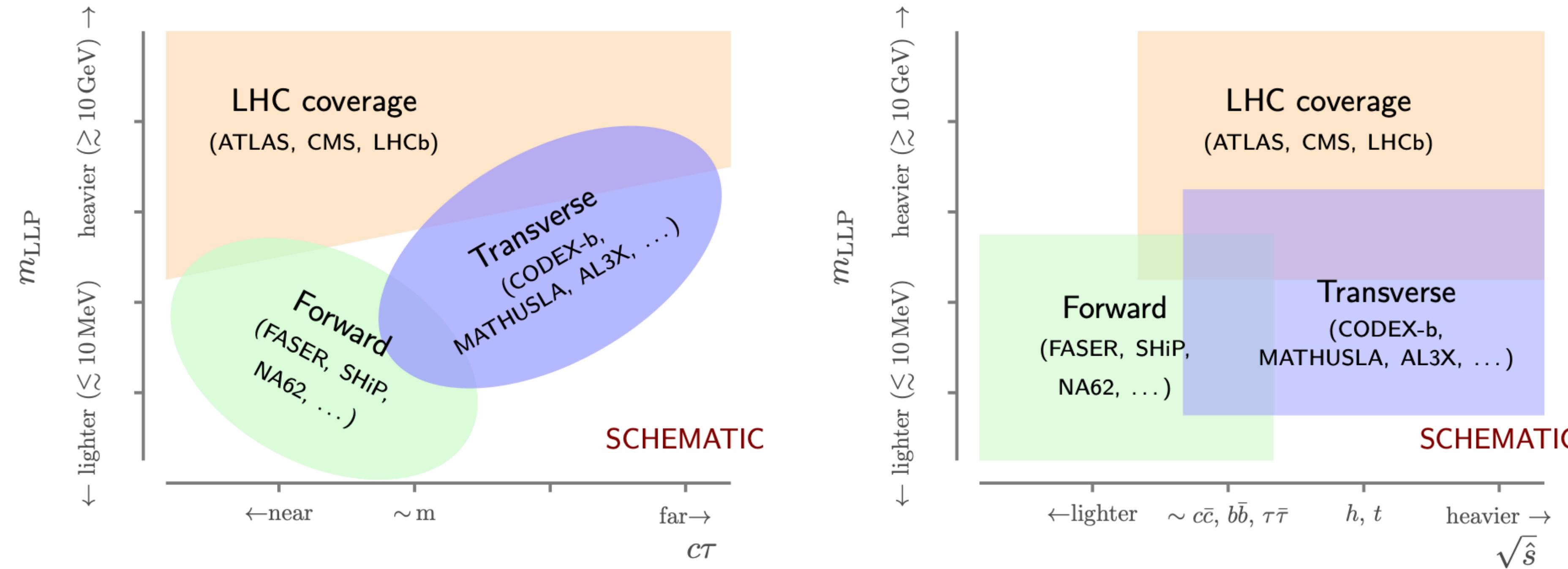
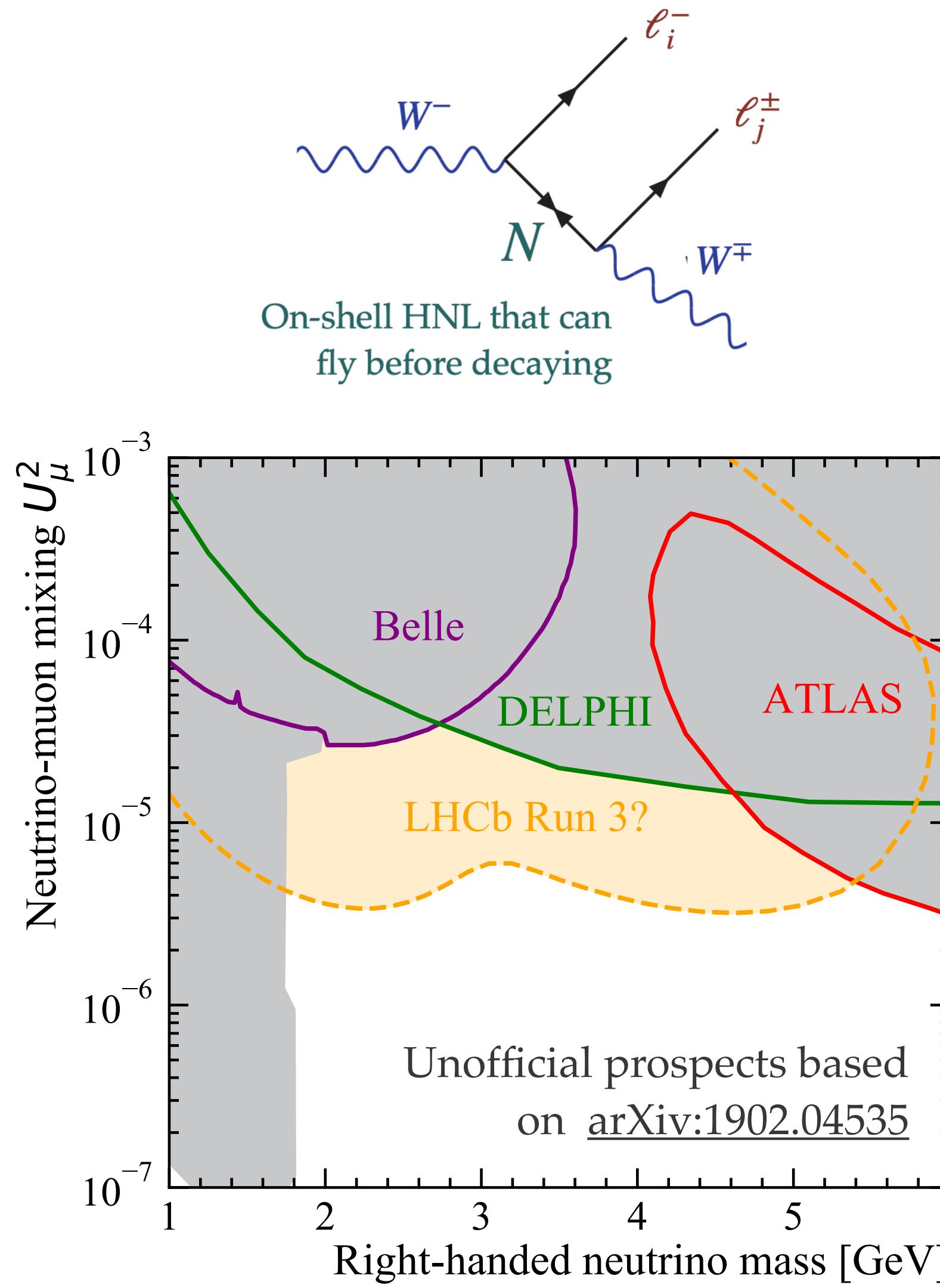


FIG. 1: Schematic summary of reach and coverage of current, planned or proposed experiments in terms of the LLP mass, lifetime and the required parton center-of-mass energy, $\sqrt{\hat{s}}$.

Expression of Interest for the CODEX-b Detector

<https://arxiv.org/pdf/1911.00481.pdf>

Tests of neutrino mass models at LHCb



- LHCb is designed to select heavy-flavour hadrons in LHC collisions

- Can search for particles in similar range:
 $m = 0.1 - 10 \text{ GeV}$, $\tau = 1 - 100 \text{ ps}$
- Complementary to ATLAS and CMS!

- Neutrino mass models can provide heavy neutral leptons (HNL) with such properties

TAKE HOME:
The LHCb experiment can contribute to testing neutrino mass models using the world-largest sample of beauty and charm hadron decays. It provides stringent tests of models with neutral leptons in the GeV mass range.

Upcoming upgrade (2022) to run at 5x luminosity