Heavy Neutral Lepton Searches at ICARUS-NuMI

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BASED ON ARXIV: 2408.03383. IN COLLABORATION WITH A. DE ROECK AND A. CHATTERJEE

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CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
VNIVERSITAT DE VALÈNCIA
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LLPs: Portals to BSM Physics

Long-Lived Particles (LLPs) could be the portal to hidden sectors addressing different Standard Model open problems

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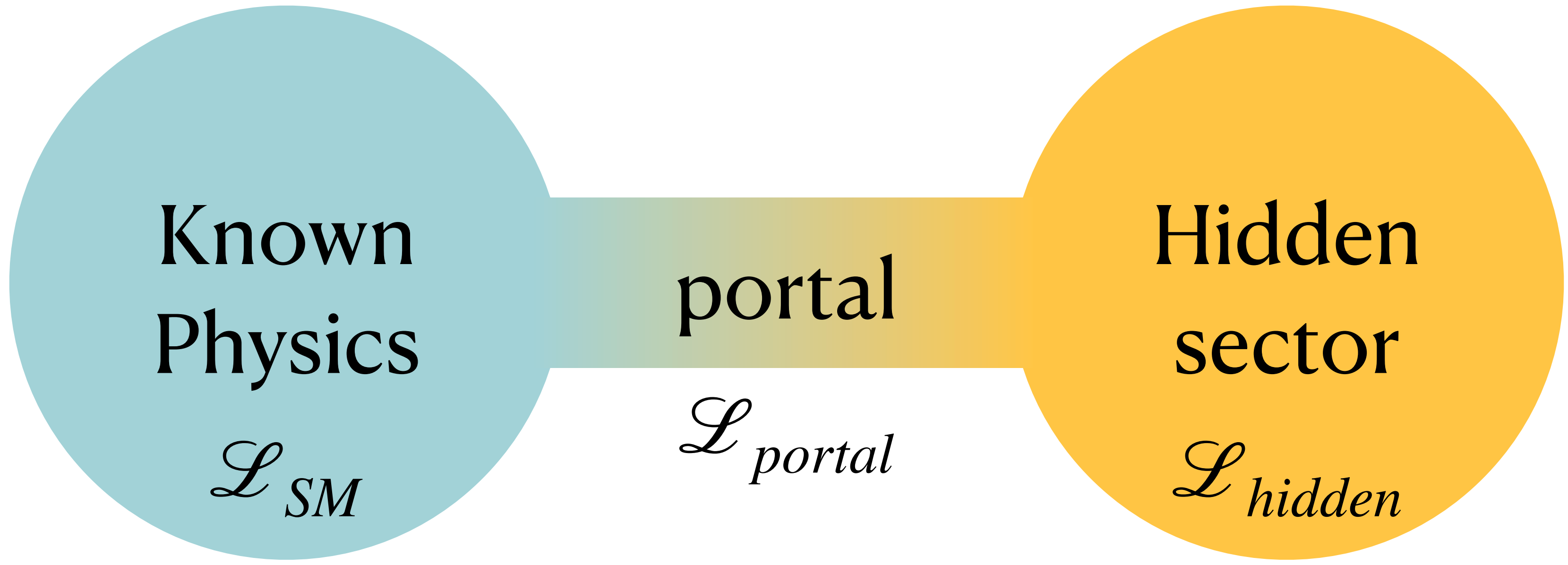

BSM portal	New particle	New parameters	SM open problem
Fermion portal	HNLs – N	$M_N, U_{\alpha N}$	Neutrino masses
Axion portal	ALPs – a	m_a, f_a	Strong CP
Scalar portal	Dark scalar – S	m_S, θ	Vacuum stability
Vector portal	Dark photon – Z'	$m_{Z'}, \epsilon$	DM candidate

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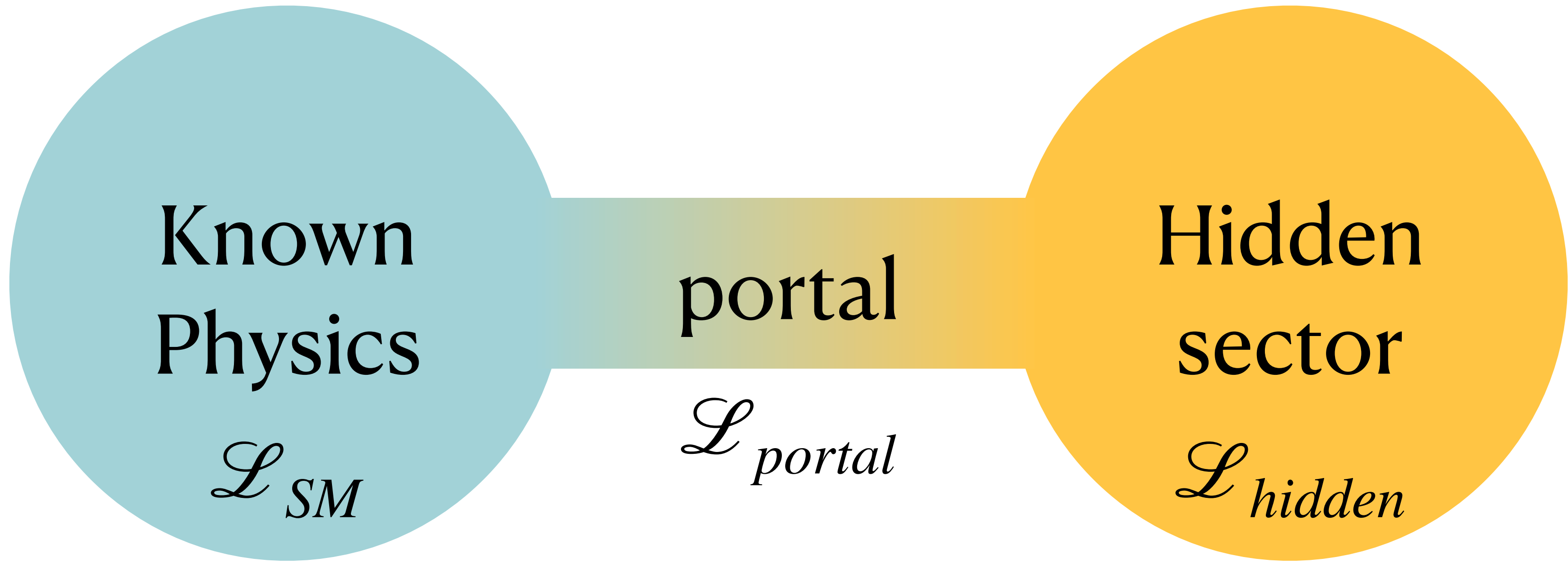

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LLPs signals at neutrino experiments

Neutrinos are feebly-interacting particles

- intense sources needed
- large detectors needed

Interactions $\rightarrow$ scale with detector mass

LLPs decays $\rightarrow$ scale with detector volume

Generally lower backgrounds if

- Detector has low density/mass
- decays can be fully reconstructed $\Rightarrow$
  instrumented detector (ECAL, magnetic field, ...)

Phenomenology of Heavy Neutral Leptons

Origin of neutrino masses and mixings

Minimal model: 2 HNLs needed. Phenomenology given by 4 free parameters:

- HNL mass, M_N
- mixing with three ν_α, $U_{\alpha N}$

HNL mixes with active neutrinos

$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha N} N$$

Heavy Neutral Leptons (HNLs)

HNL CC and NC interactions:

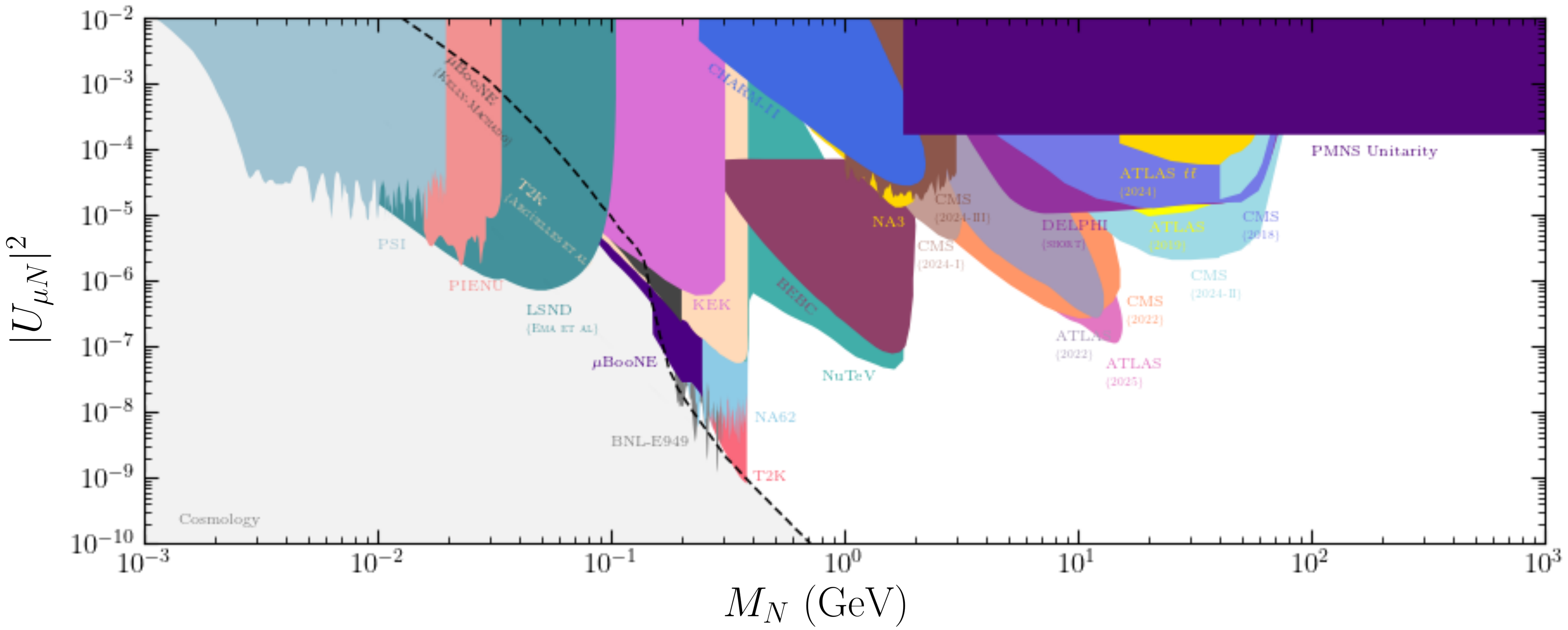
$$\mathscr{L}_{N,int} \supset -\frac{m_W}{v}\overline{N}U^*_{\alpha N}\gamma^\mu \ell_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\overline{N}U^*_{\alpha N}\gamma^\mu \nu_{L\alpha}Z_\mu$$

$U_{\alpha N} \ll 1 \Rightarrow$ weaker than weak interaction

Experimental results shown single flavor dominance $\Rightarrow$ HNL coupled to one flavor at a time:

e dominance	μ dominance	τ dominance
$\lvert U_{eN}\rvert^2 : \lvert U_{\mu N}\rvert^2 : \lvert U_{\tau N}\rvert^2 = 1:0:0$	$\lvert U_{eN}\rvert^2 : \lvert U_{\mu N}\rvert^2 : \lvert U_{\tau N}\rvert^2 = 0:1:0$	$\lvert U_{eN}\rvert^2 : \lvert U_{\mu N}\rvert^2 : \lvert U_{\tau N}\rvert^2 = 0:0:1$

Heavy Neutral Leptons: present bounds



Present bounds on the HNL mixing from ν oscillations, kinks in beta-decay, peaks in meson decays, beam-dumps, colliders, and non-unitarity of the PMNS.

https://github.com/mhostert/Heavy-Neutrino-Limits
E. Fernandez-Martinez, M. Gonzalez-Lopez, JHG, M. Hostert, J. Lopez-Pavon. JHEP **09** 2023 001

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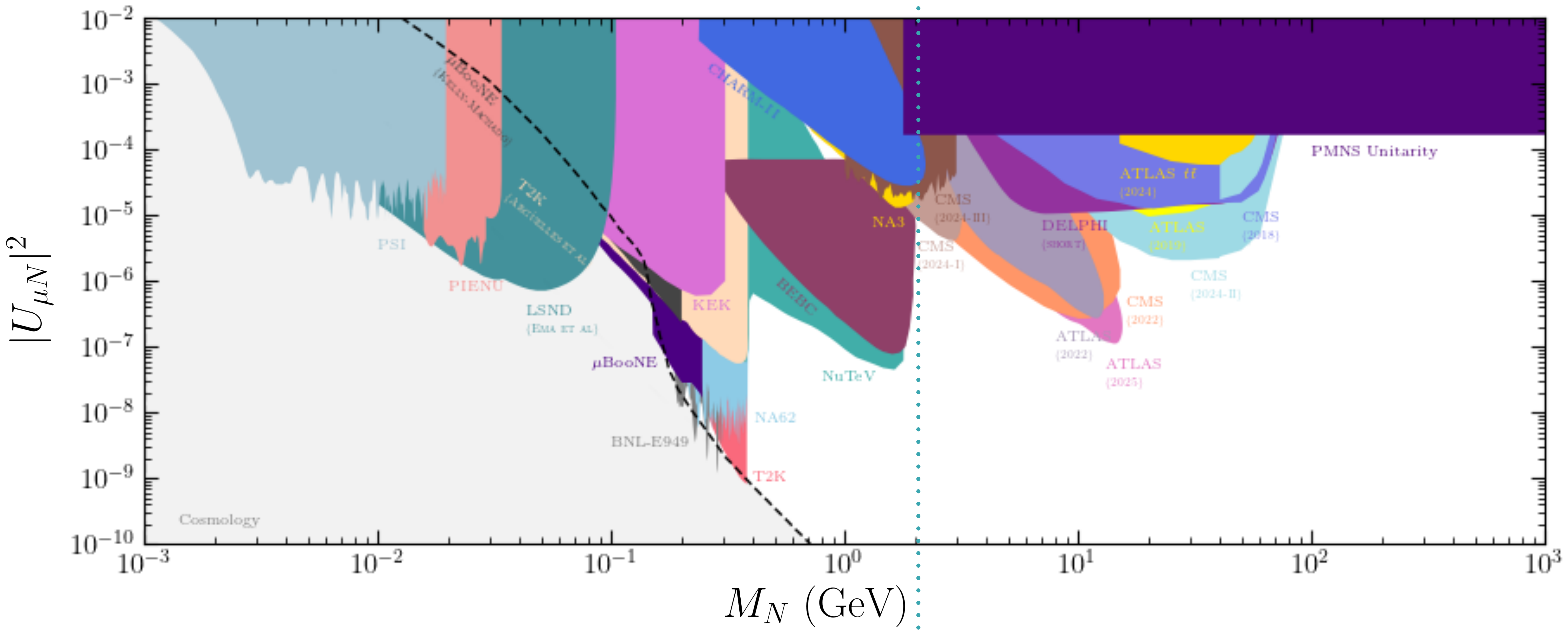

Present bounds in the HNL mass window up to ~ 2 GeV led by peak searches and beam-dump experiments

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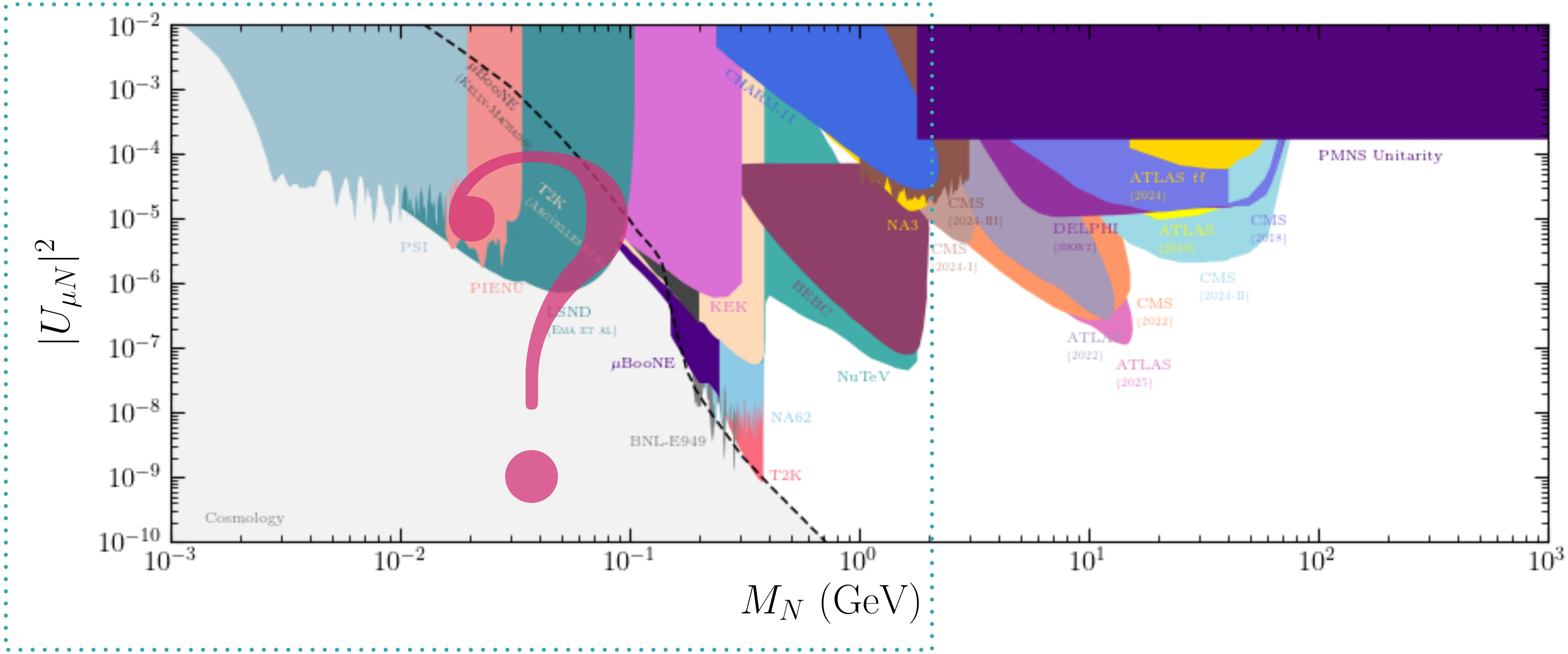

Bounds from on-going and near future experiments.

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The ICARUS experiment at SBN

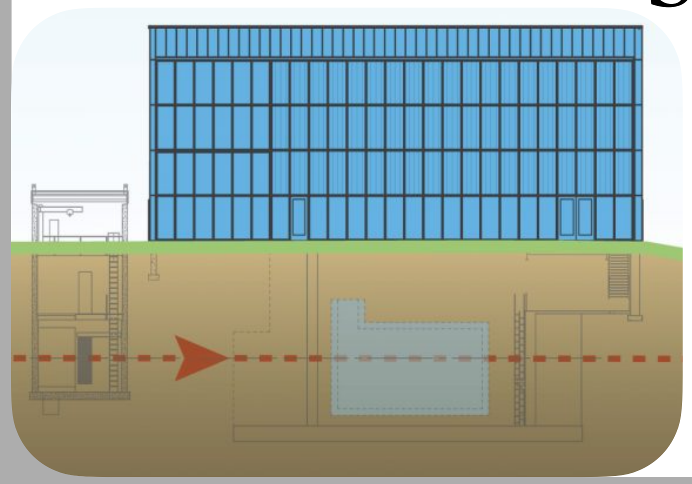
Proposed to:

- Clarify LSND and MiniBooNE anomalies
- Explore sterile neutrino in the eV mass scale

Three liquid Ar TPCs

Taking data since 2015

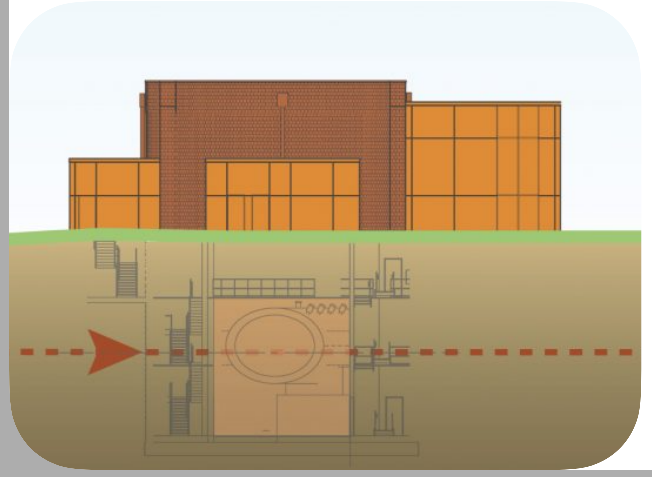
SBND



270 tons
Baseline: 110 m

2024

μBooNE



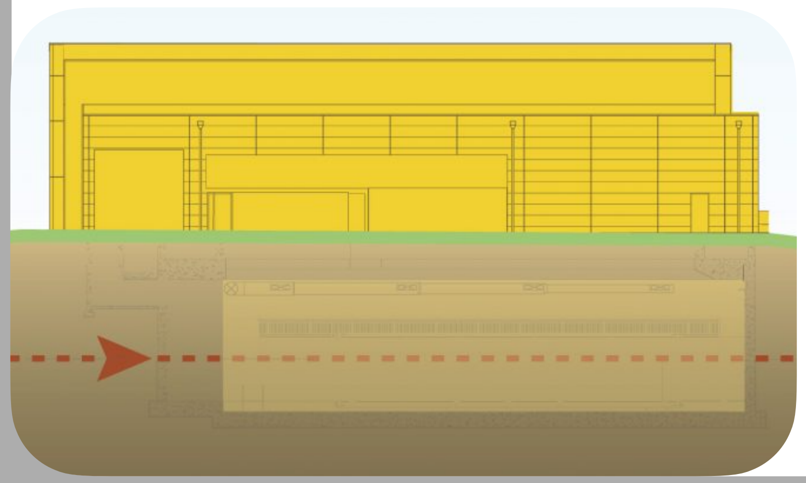
170 tons
Baseline: 470 m

2015 – 2021

Short-Baseline Neutrino (SBN)

ICARUS

760 tons
Baseline: 600 m



2021

Exposed to the Booster Neutrino Beam (BNB) produced from 8 GeV protons from the booster

Experimental setup: SBN

ICARUS	μBooNE	SBND
760 tons of Ar	170 tons of Ar	270 tons of Ar

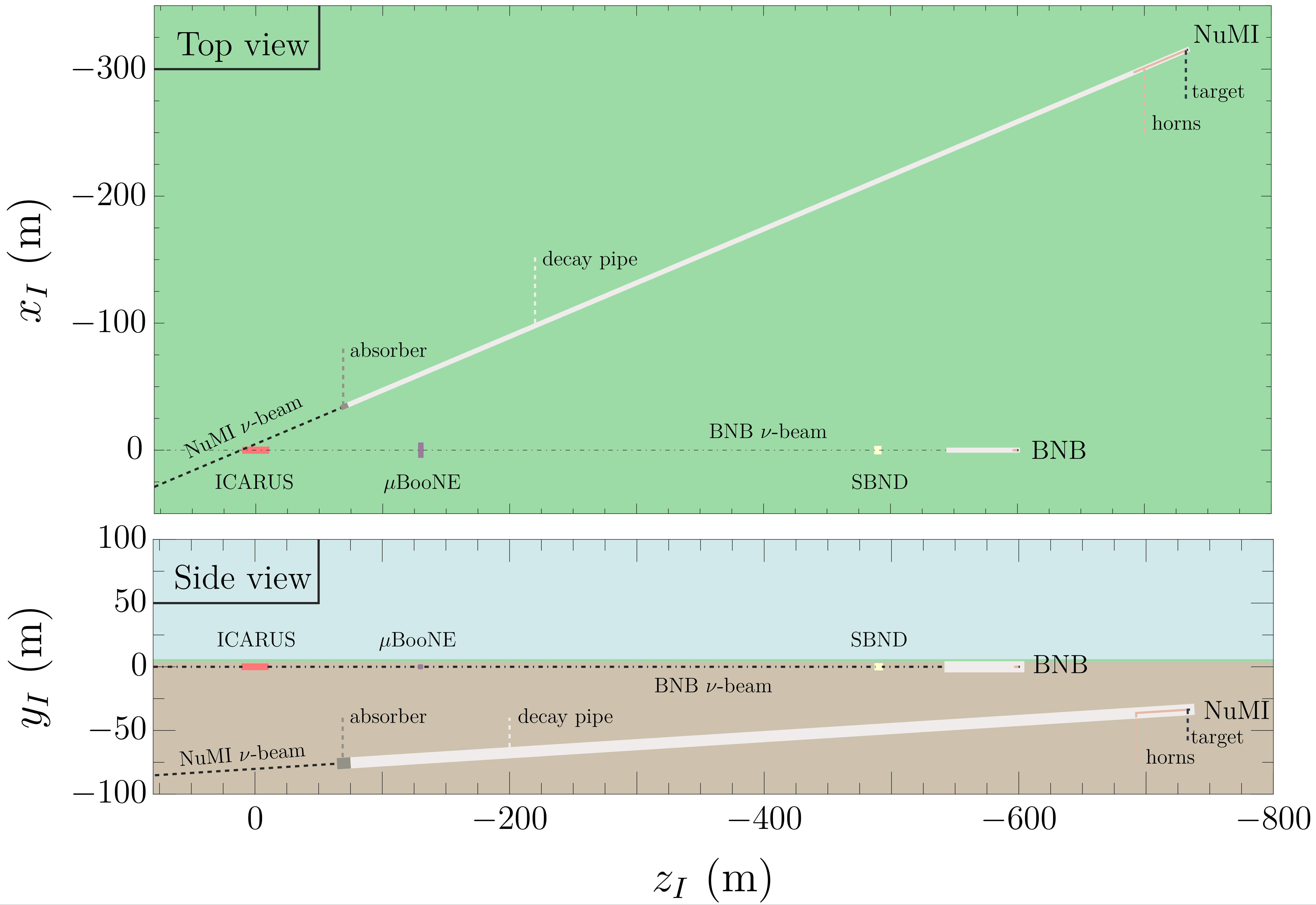
Experimental setup: BNB and NuMI

ICARUS is also exposed to the NuMI ν-beam.

NuMI: 120 GeV protons from main injector against graphite target, accumulating $6.6 \cdot 10^{20}$ PoT/year.

C. Rubbia (ICARUS-WA104, LAr1-ND, MicroBooNE), (2015)

Experimental setup: BNB and NuMI

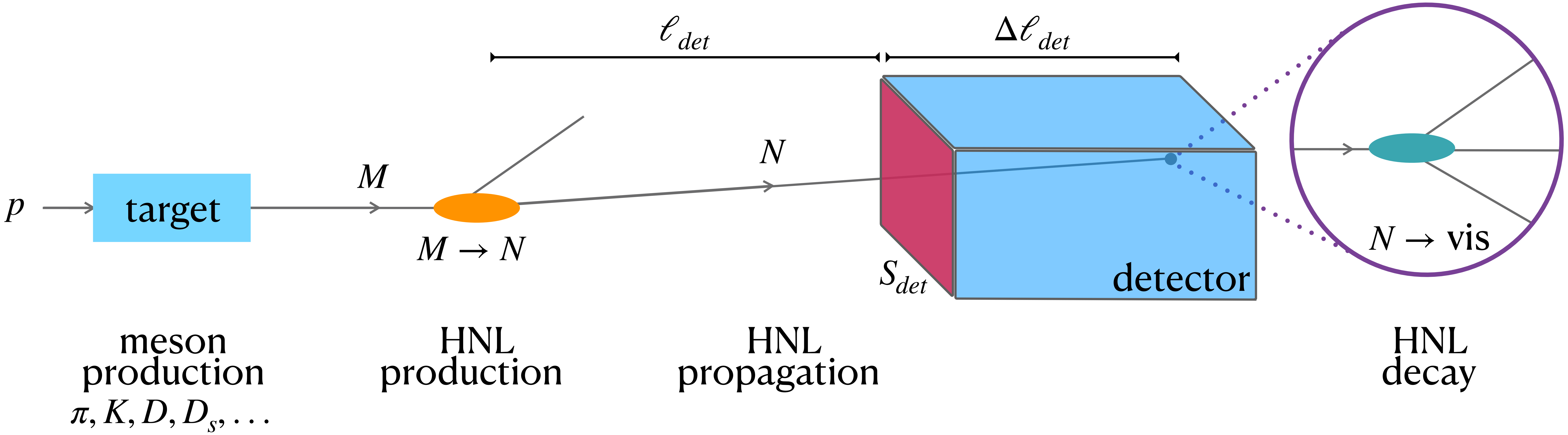


Off-axis NuMI flux crossing ICARUS
400 mrad

NuMI downward inclination
57 mrad

HNLs at beam-dump experiments

HNLs could be produced via meson decay at the beam-dump experiment beam



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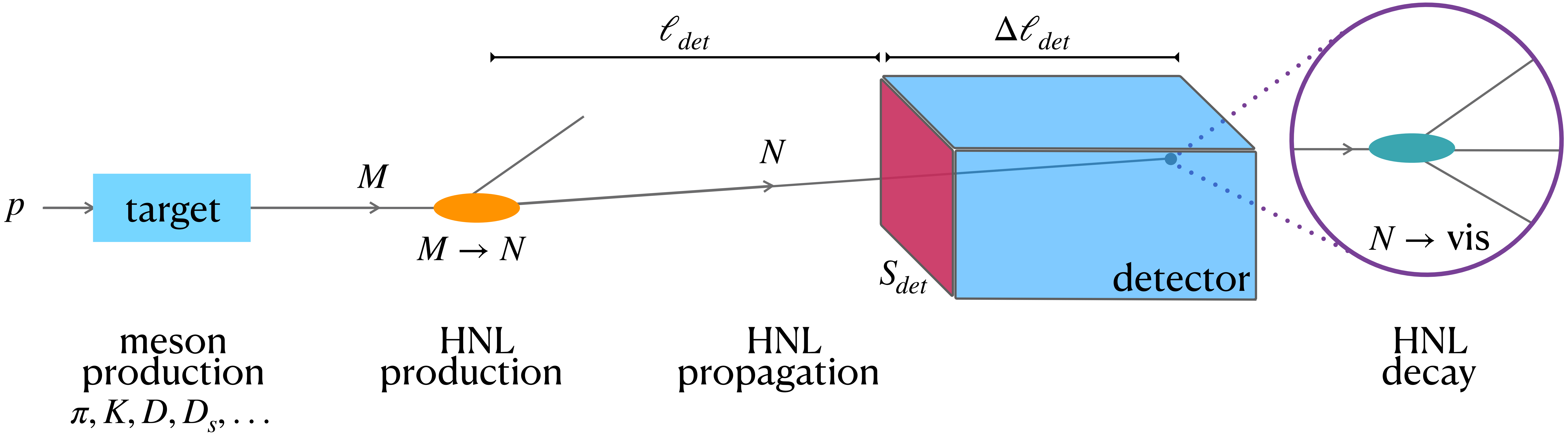

The number of decay events

$$N_{ev} = N_M \mathrm{BR}(M \to N)\mathrm{BR}(N \to \mathrm{vis})\epsilon_{det} \int dS \int dE_\Psi P(c\tau_N/M_N, E_N, \Omega_N) \frac{dn^{M \to N}}{dS dE_N}$$

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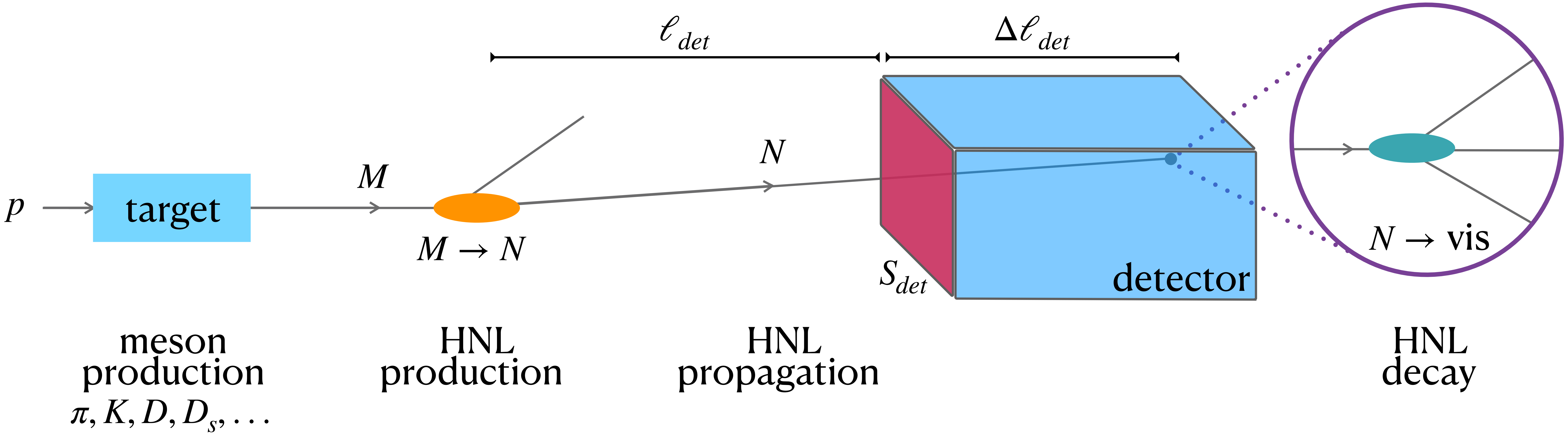

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experiment-dependent quantities

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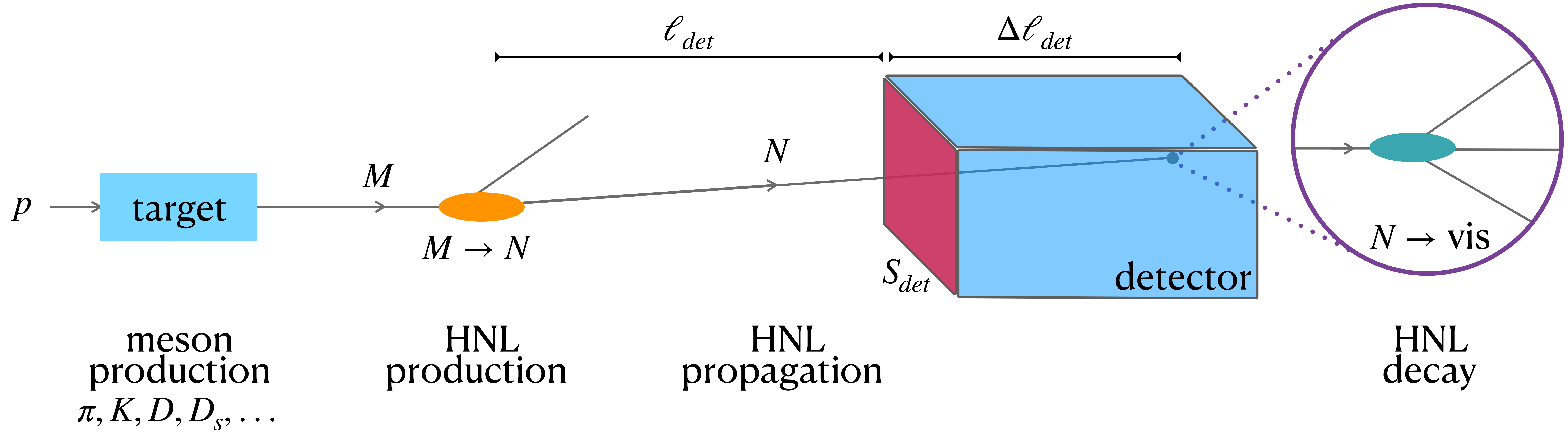

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HNL production

HNL decay

model-dependent quantities

The simulations

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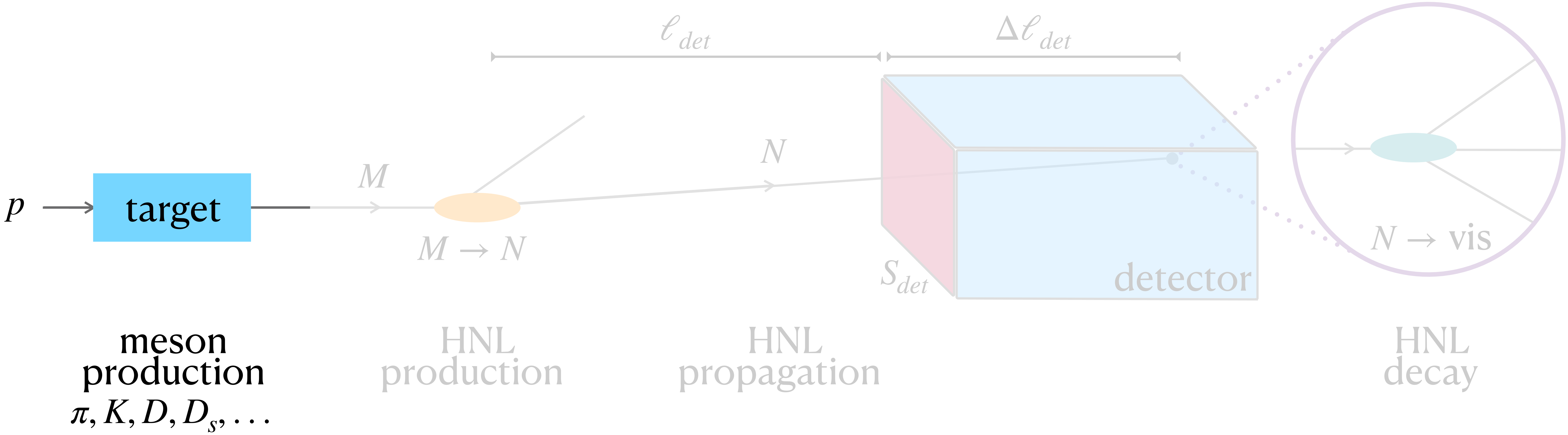

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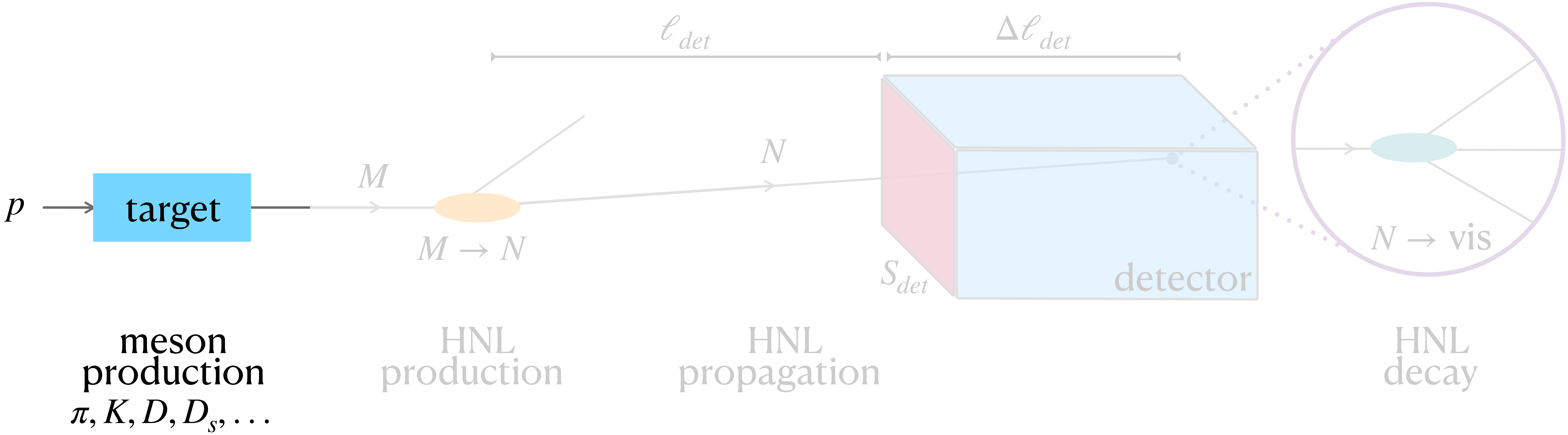

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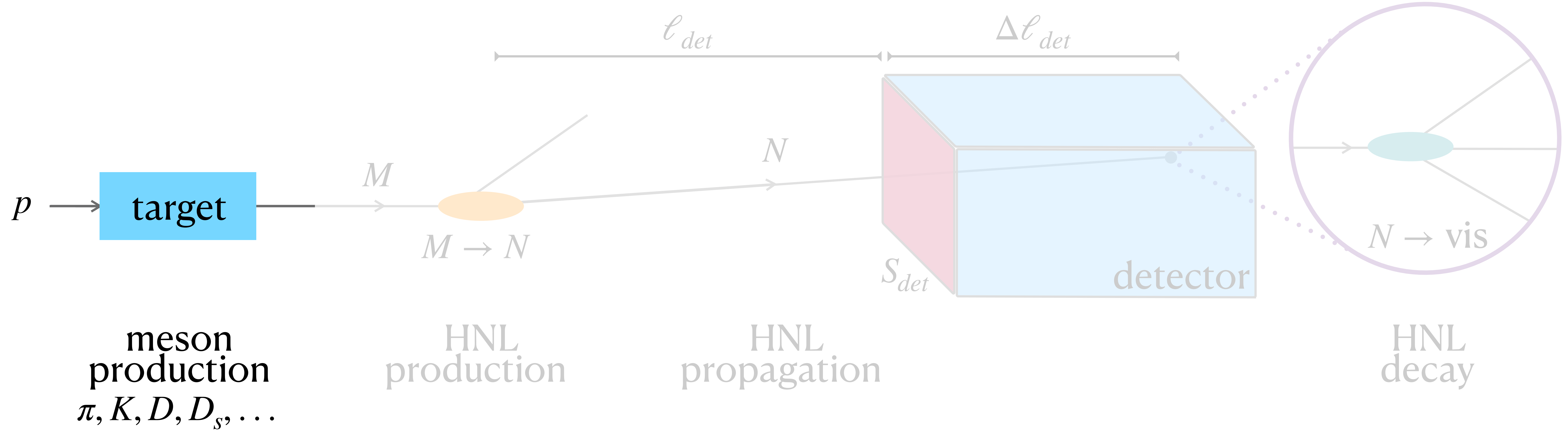

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- Meson production at the target station: we consider the mesons with relevant branching fraction to neutrinos
  - $\pi^\pm$ & $K^\pm$: GEANT4 simulations including the interaction of 120 GeV protons on the graphite target, the production of mesons, and the re-interaction and focusing in the magnetic horns (G4NuMI)

L. Aliaga Soplin, Neutrino Flux Prediction for the NuMI Beamline, Ph.D. thesis, William-Mary Coll. (2016)

The simulations

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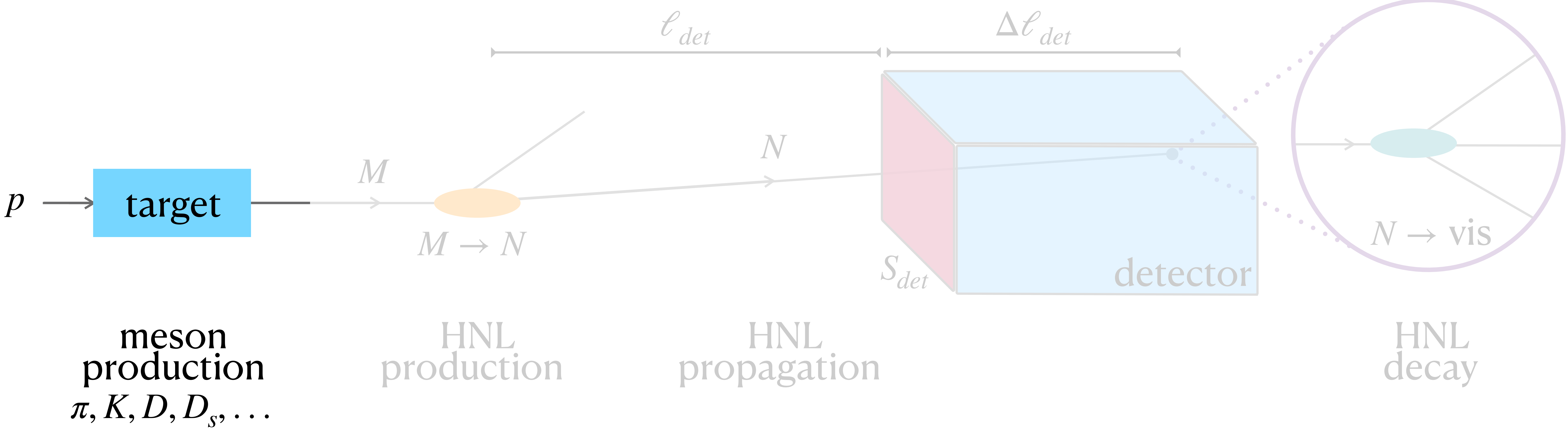

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  - $D^\pm, D_s^\pm$ & $\tau^\pm$: simulated with GEANT4 + Pythia8

P. Coloma, E. Fernandez-Martınez, M. Gonzalez-Lopez, J. Hernandez-Garcıa, Z. Pavlovic, Eur.Phys.J.C **81** (2021) 1, 78

The simulations

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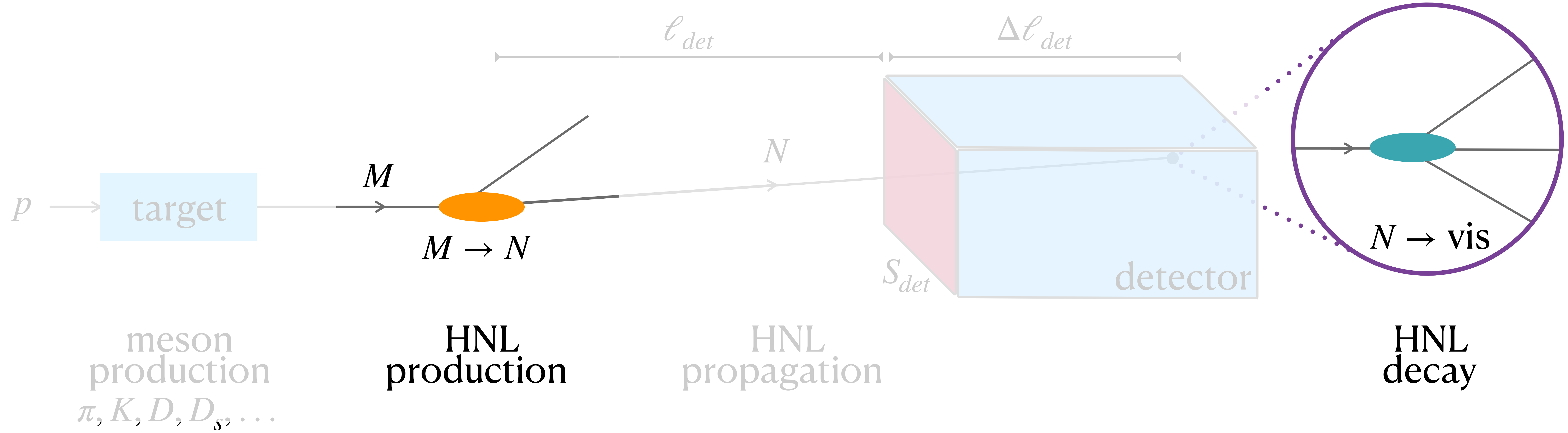


Three sets of simulations are needed in order to estimate the number of events:

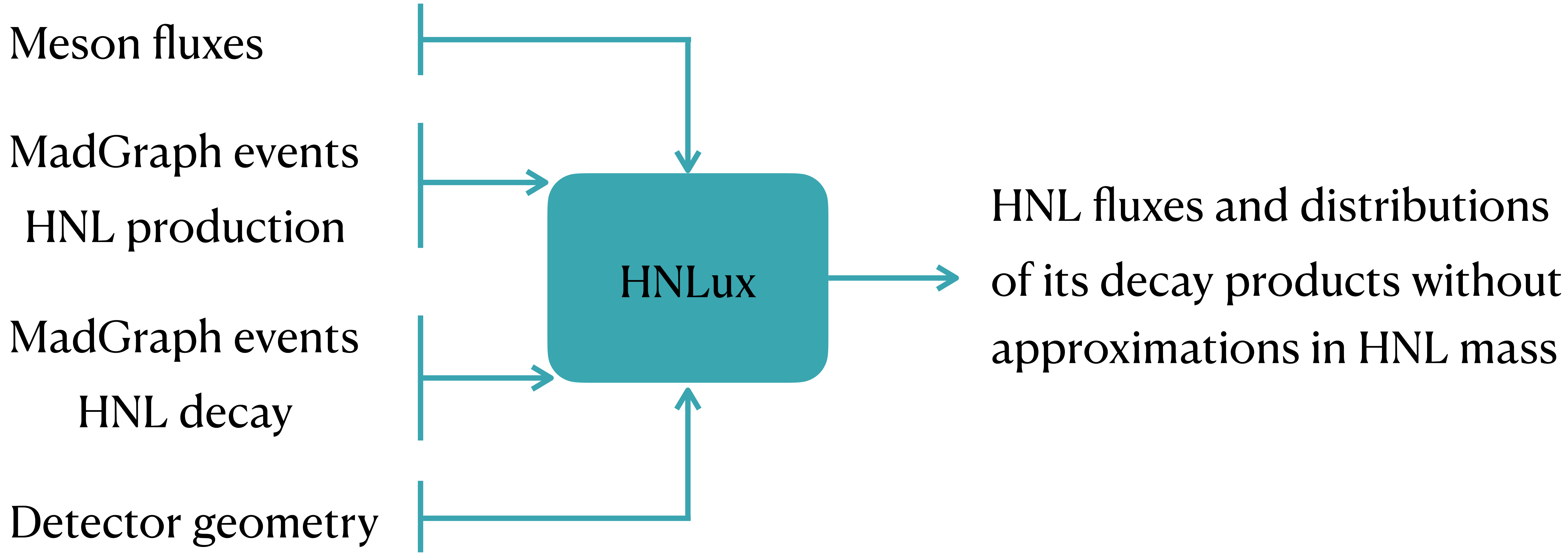
- Meson production at the target station: we consider the mesons with relevant branching fraction to neutrinos
- MonteCarlo simulations of HNL production and HNL decay:

We use a FeynRules model file that contains effective op. describing interactions between light mesons and HNL. Interfacing the model file with an event generator allows for the simulation of fully differential event distributions.

https://feynrules.irmp.ucl.ac.be/wiki/HNLs

The simulations

The simulations of HNL fluxes were performed with HNLux:



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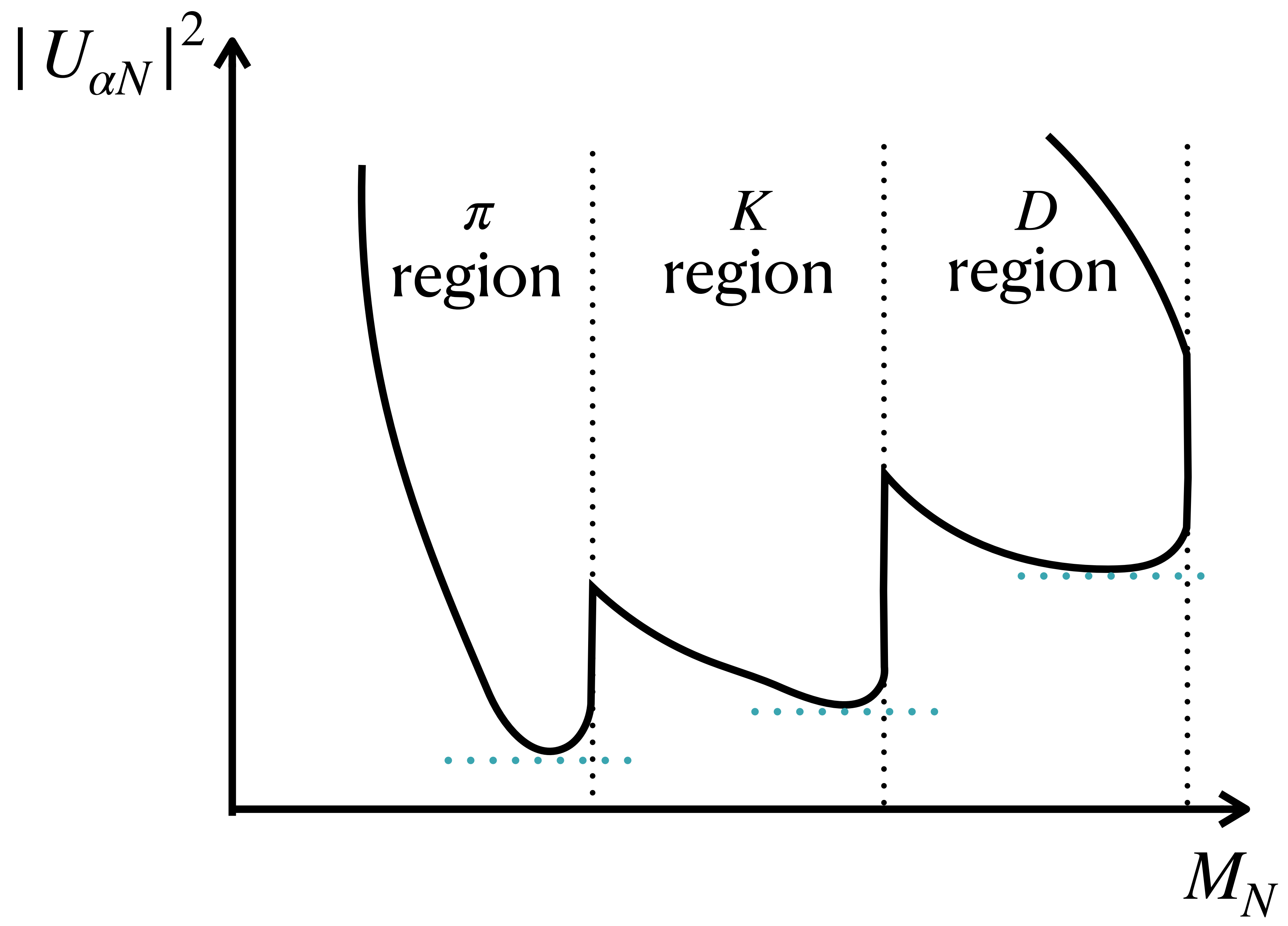
The shape of the sensitivity line

The HNL sensitivity line shows a characteristic shape coming from:



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  - proton E
  - luminosity (PoT)
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$N_\pi > N_K > N_D \Rightarrow$
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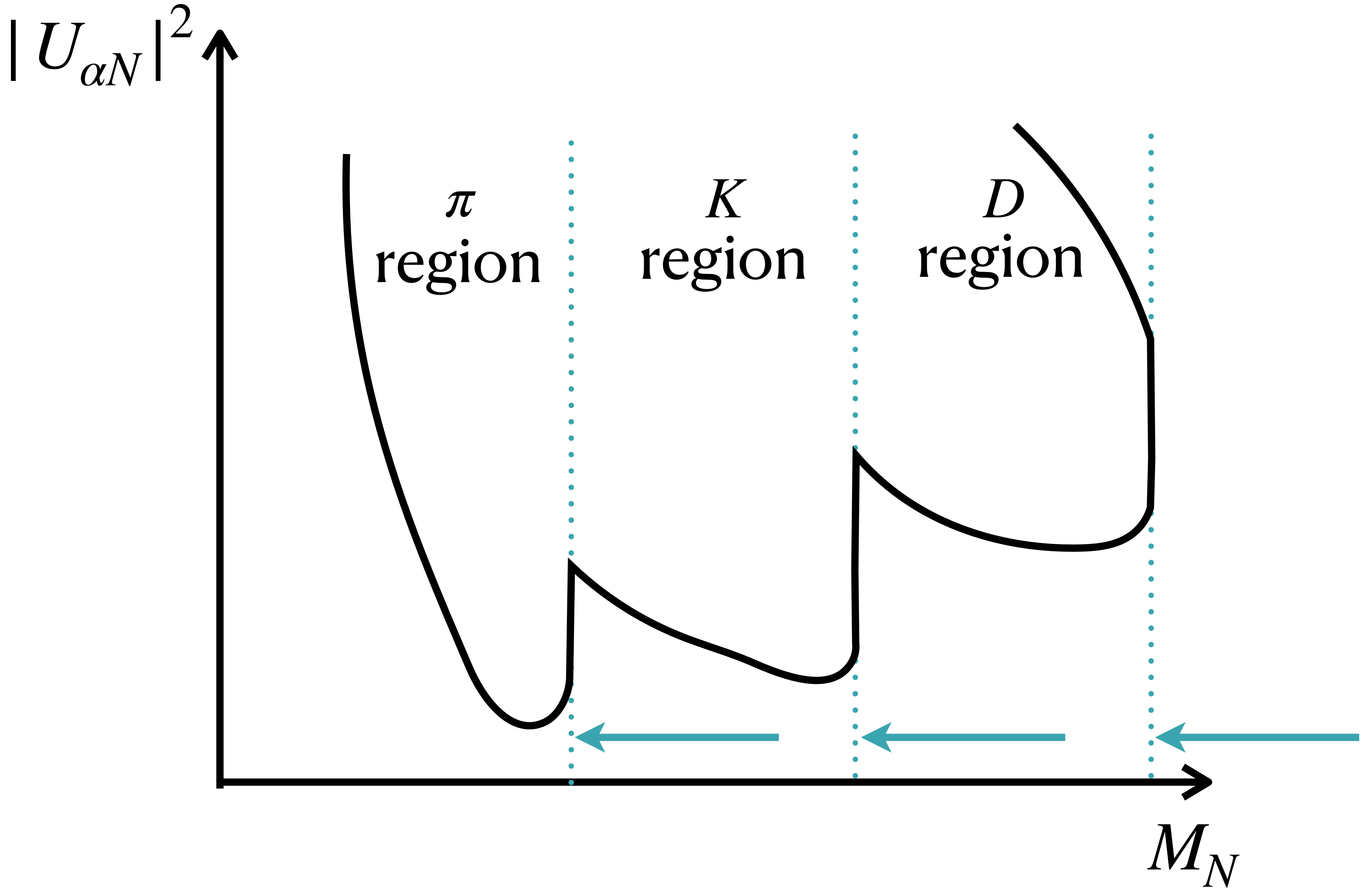

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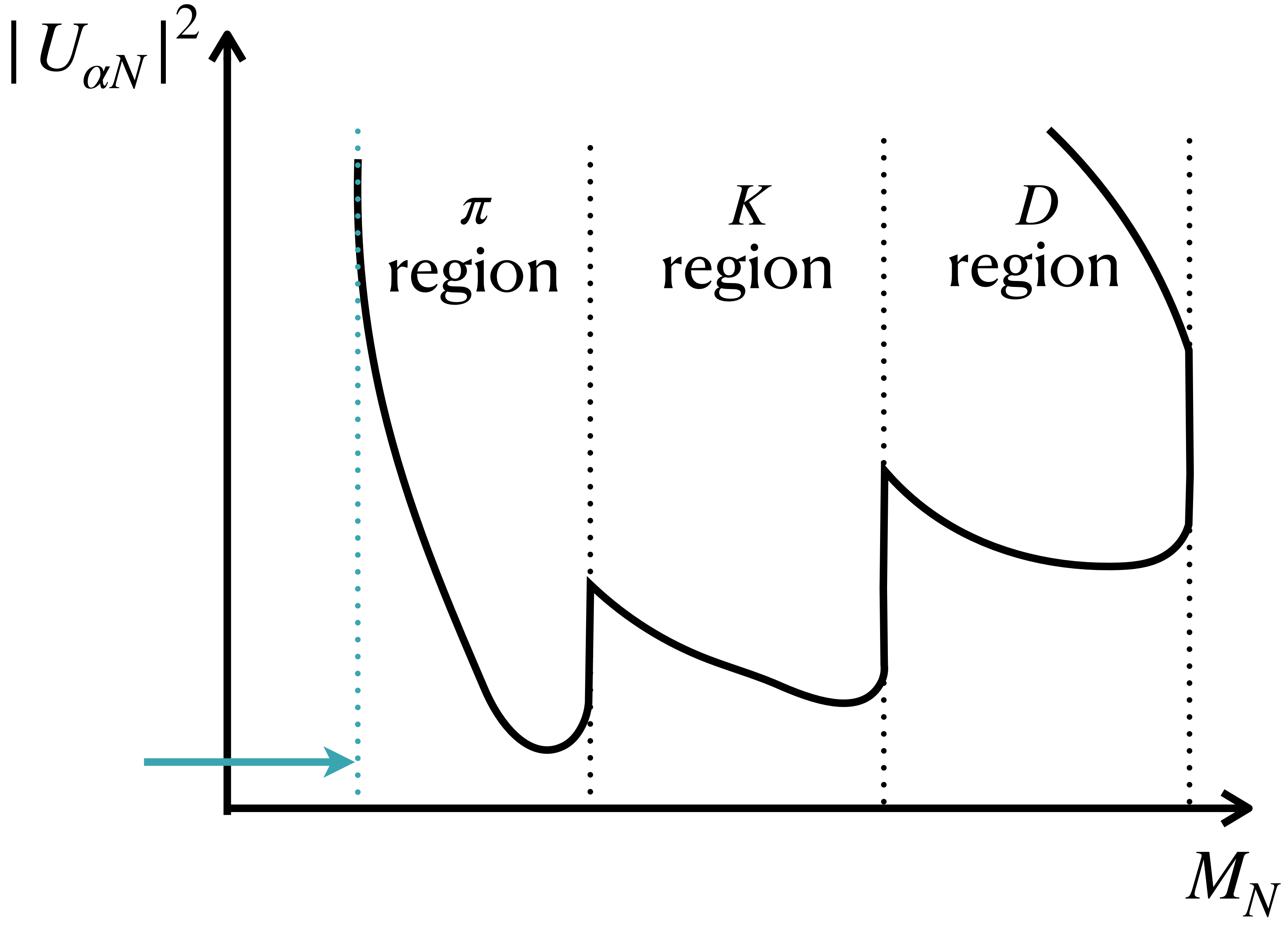

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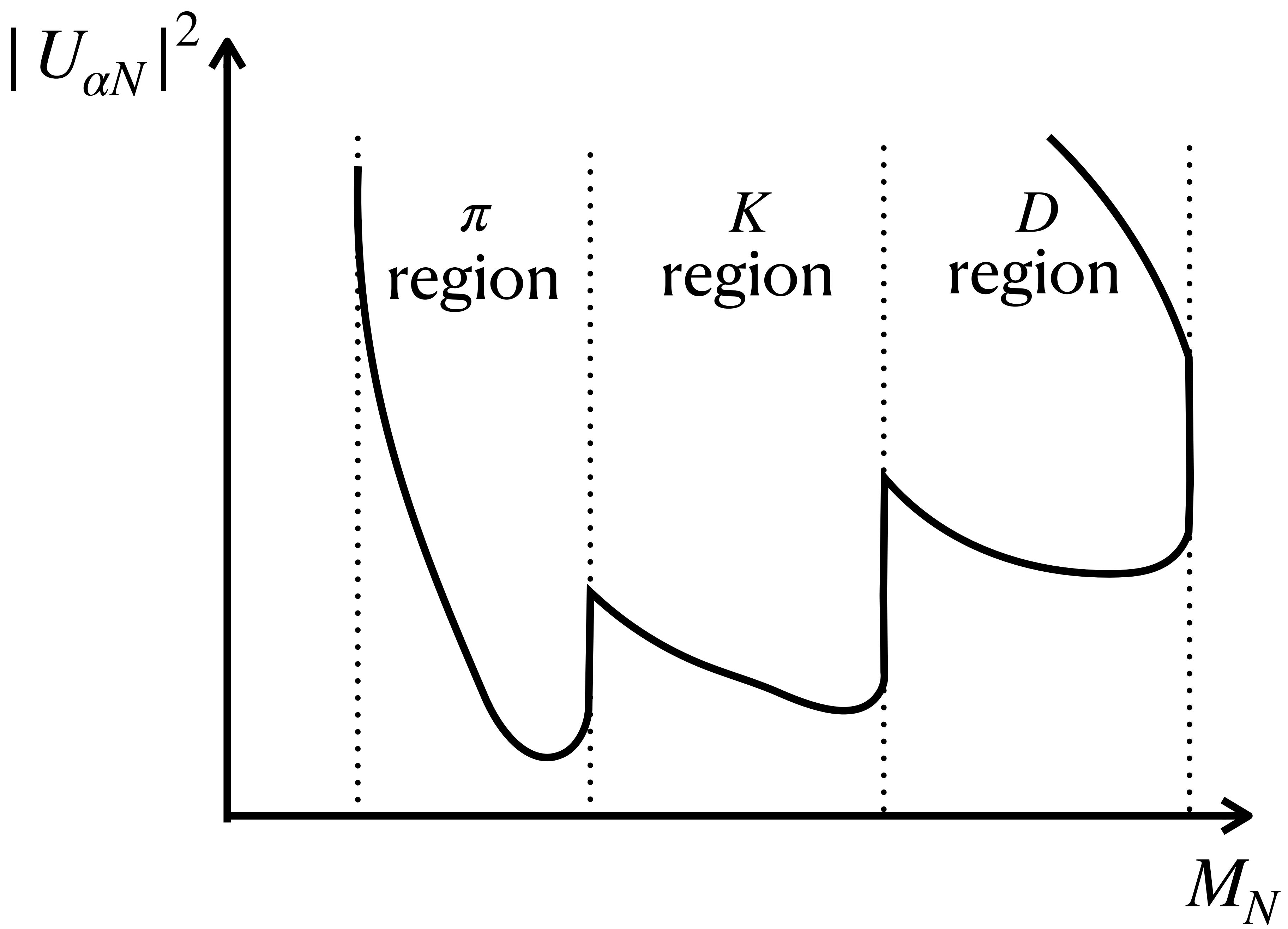

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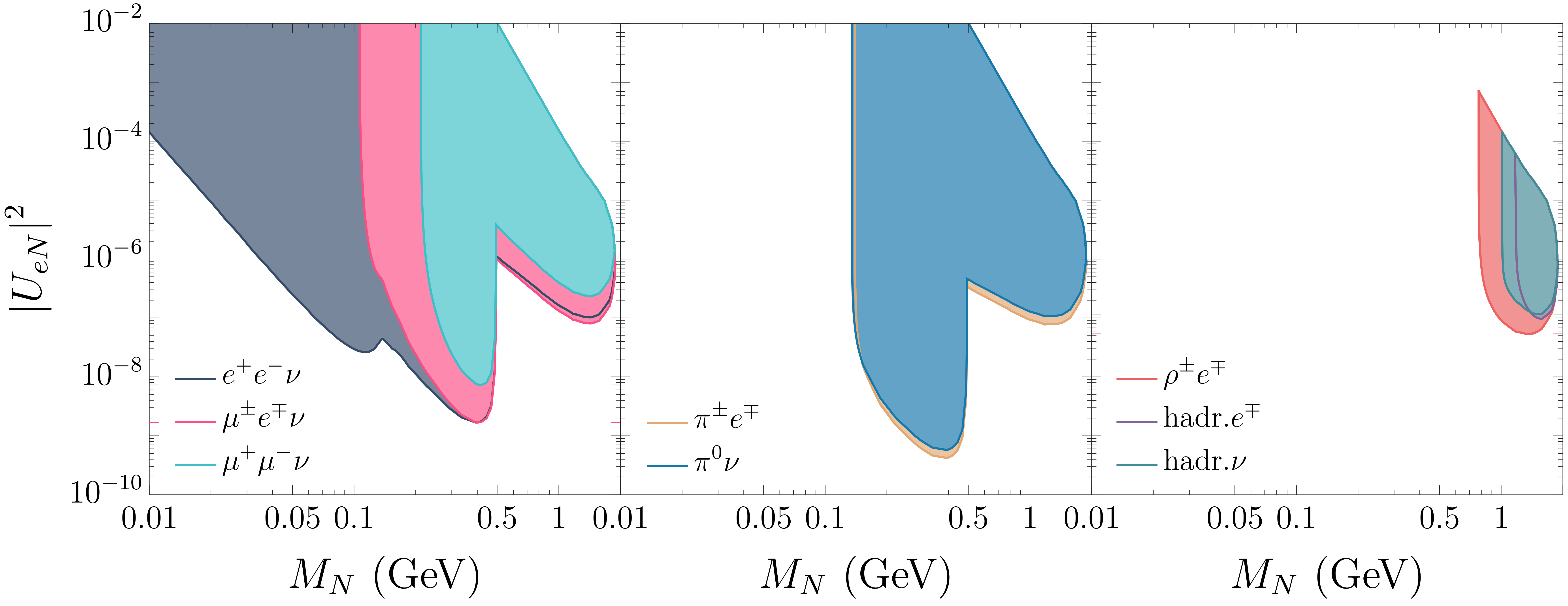
$|U_{\tau N}|^2$ only via $D/D_s \to \tau$, and τ decays $\Rightarrow$ less sensitivity due to suppressed production yield

HNL sensitivity: signal only

Following the Feldman and Cousins prescription for a Poisson distribution with no background:

$$N_{ev}^{ex} < 2.3 \Rightarrow 90\,\%\ \text{CL}$$



- $1.32 \cdot 10^{21}$ PoT from NuMI beam $\Rightarrow \sim$ by end of 2026
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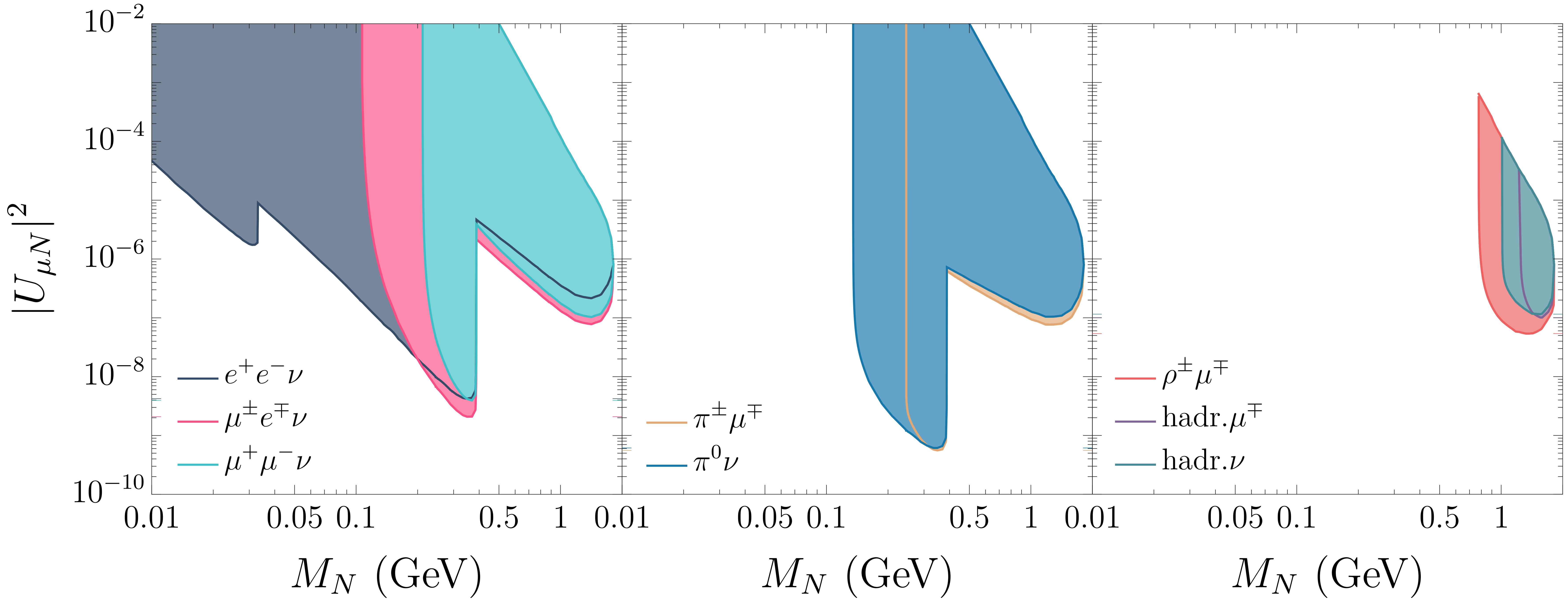

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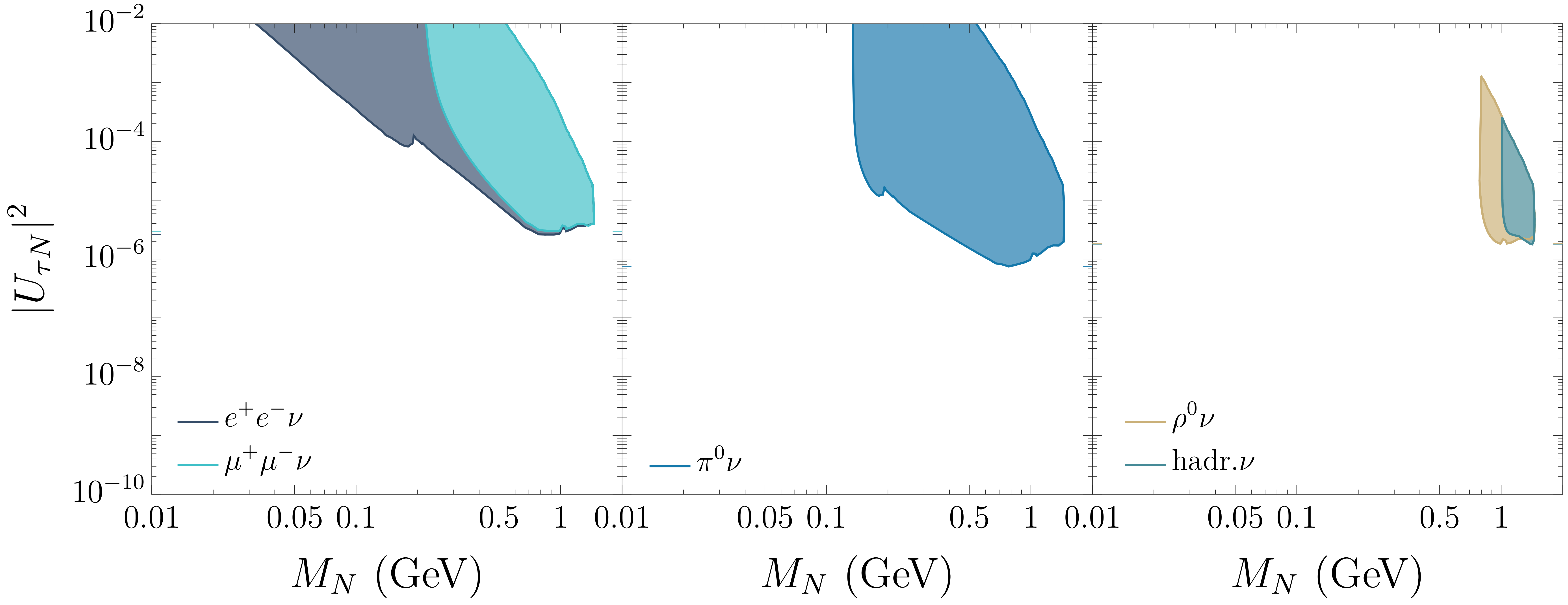

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The impact of the background

The dominant background comes from the CC and NC SM neutrino interactions with the ^{40}Ar.

If we focus on HNL decay channels with higher BR, we can distinguish among the following three topologies:

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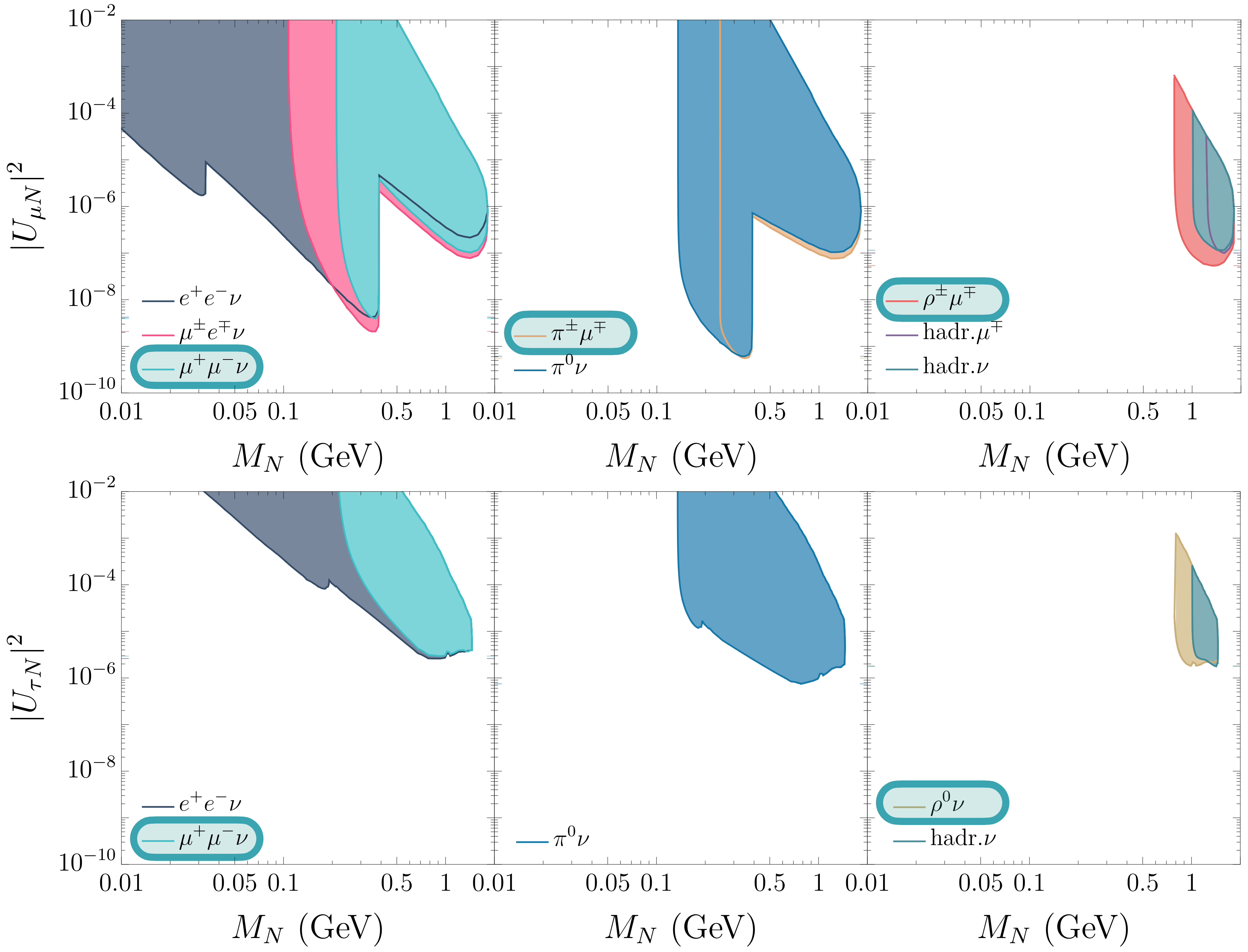

Decay channel	Main source of background
$N \to \pi^+\mu^-$ $N \to \rho^+\mu^-, \pi^+\pi^0\mu^-$ $N \to \rho^0\nu, \pi^+\pi^-\nu$	Single pion production from ν_μ resonant or coherent nucleus scattering
$N \to \mu^+\mu^-\nu$	Charm production in CC deep inelastic ν_μ nucleus scattering (suppressed)

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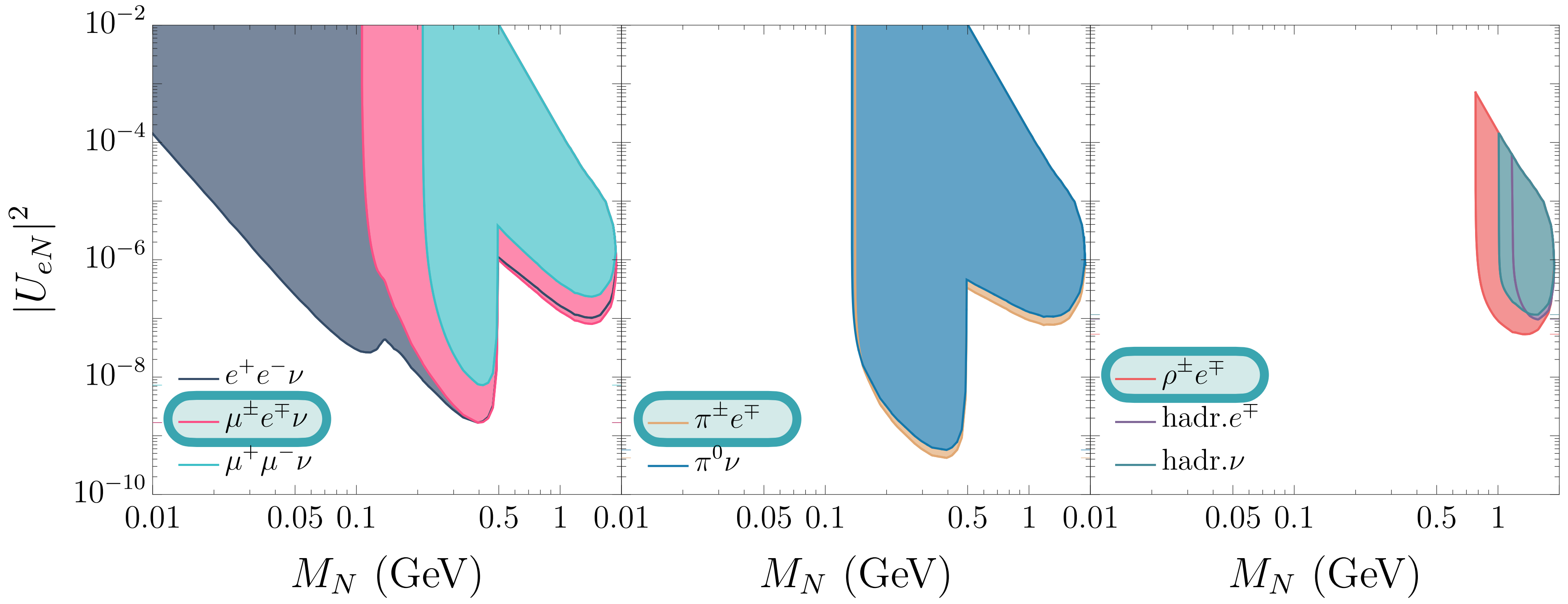
- Channels with one e-like track/shower and one μ-like track



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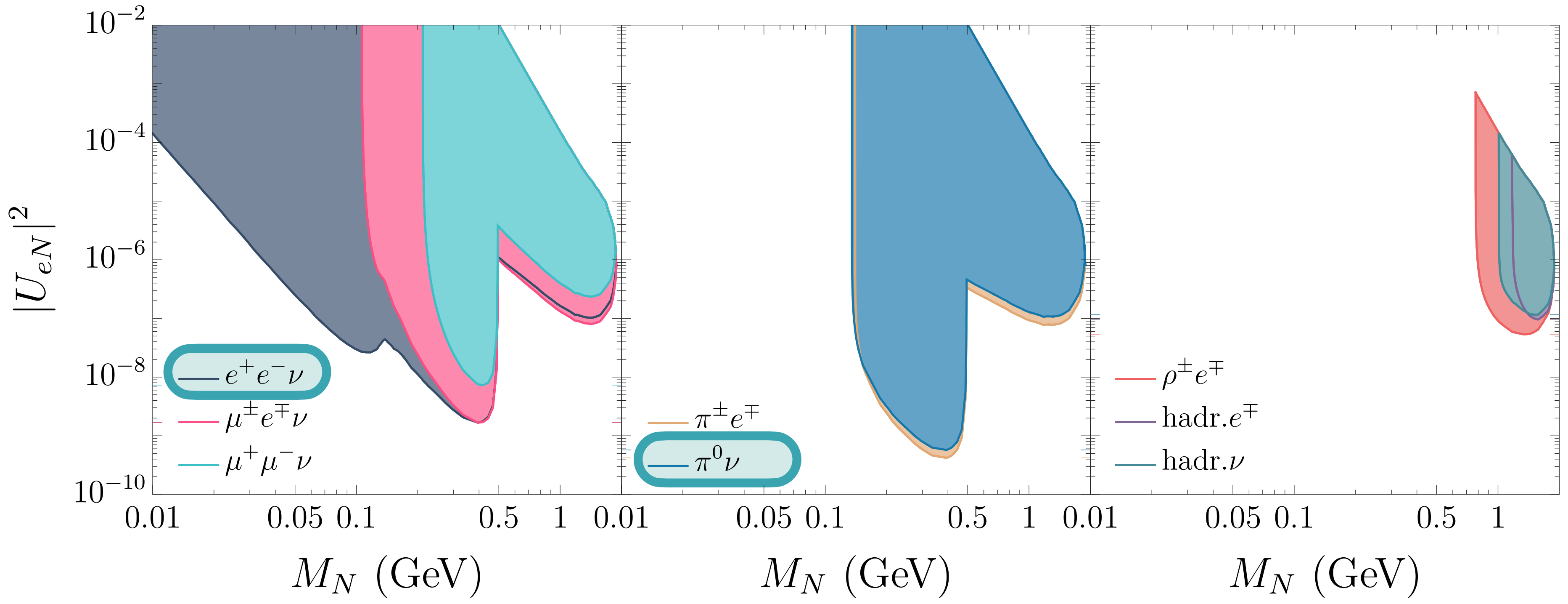

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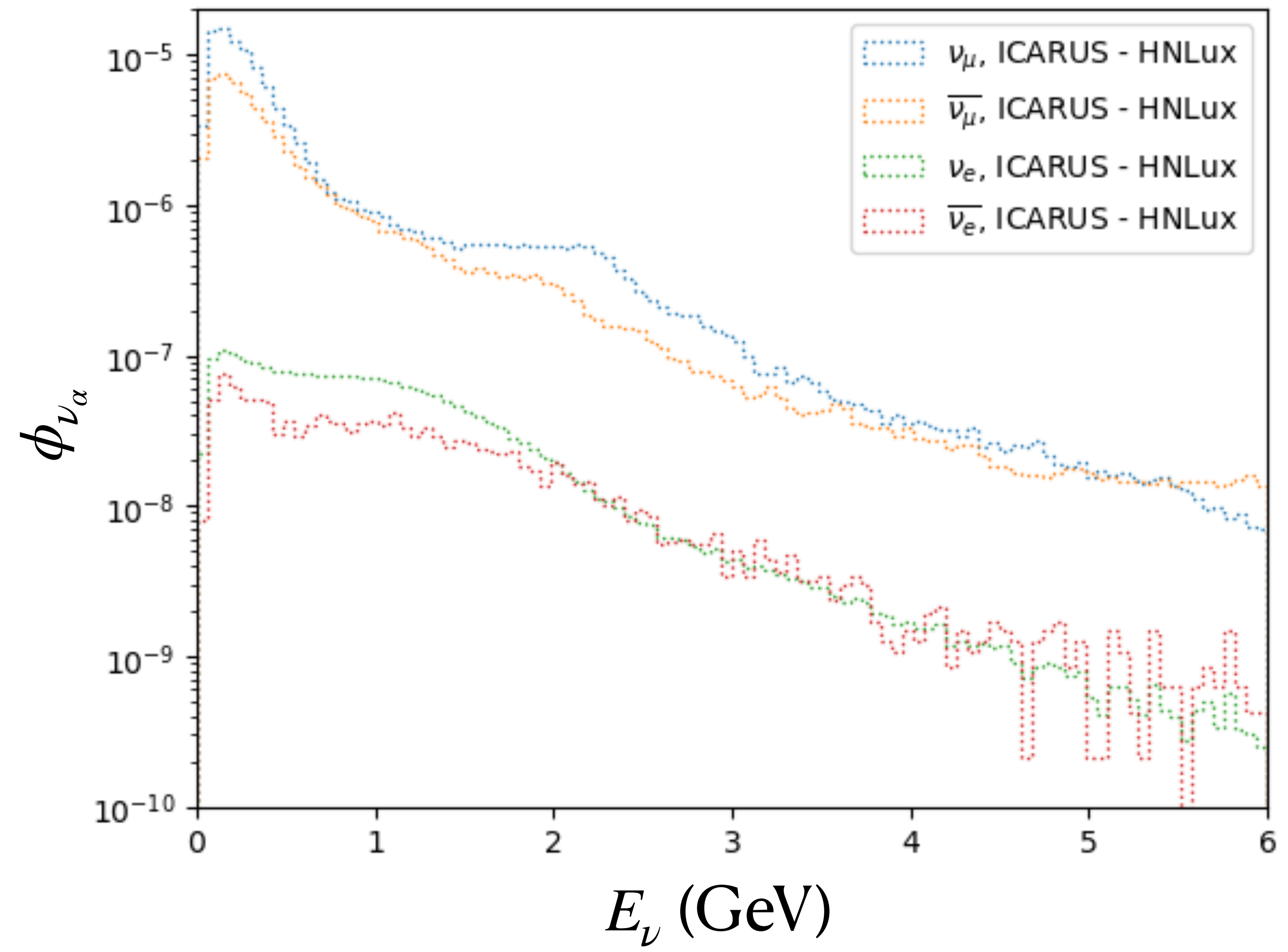
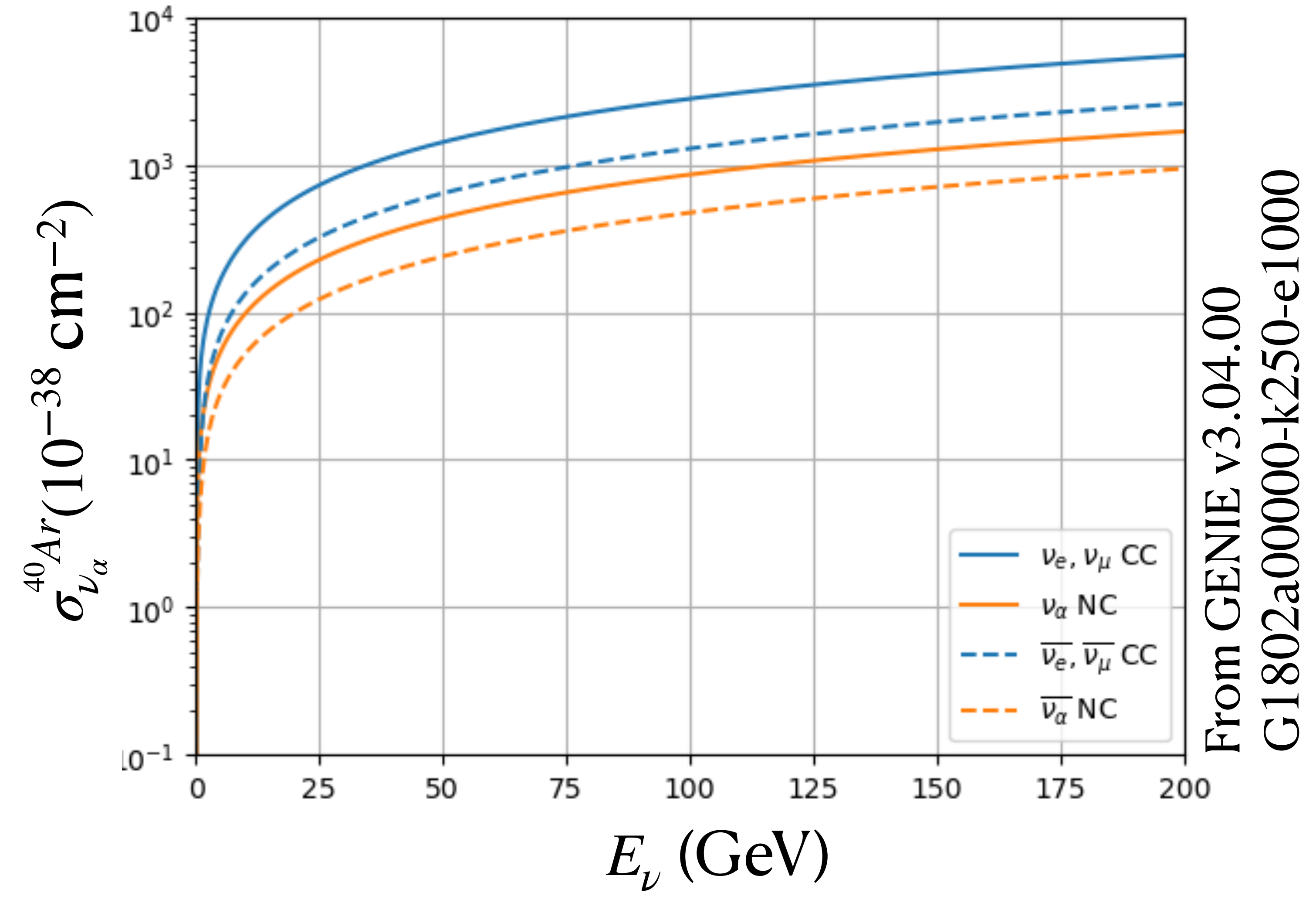
ν_α-^{40}Ar number of interactions





Number of ν_α-^{40}Ar interactions in the detector given by

$$n_{ev} = n_t \int \phi_{\nu_\alpha} \sigma^{40Ar}_{\nu_\alpha}$$

number of targets ICARUS

In one year:

	CC ν_α-^{40}Ar	NC ν_α-^{40}Ar
$\alpha = e$	19142	2109
$\alpha = \mu$	341257	42610

Kinematical cuts

Momentum distributions of signal and background very different.

HNLs come from meson decays produced at the target ⇒ HNLs highly boosted:

- Low reconstructed transverse momentum p_T
- Small angle θ between μ-like tracks

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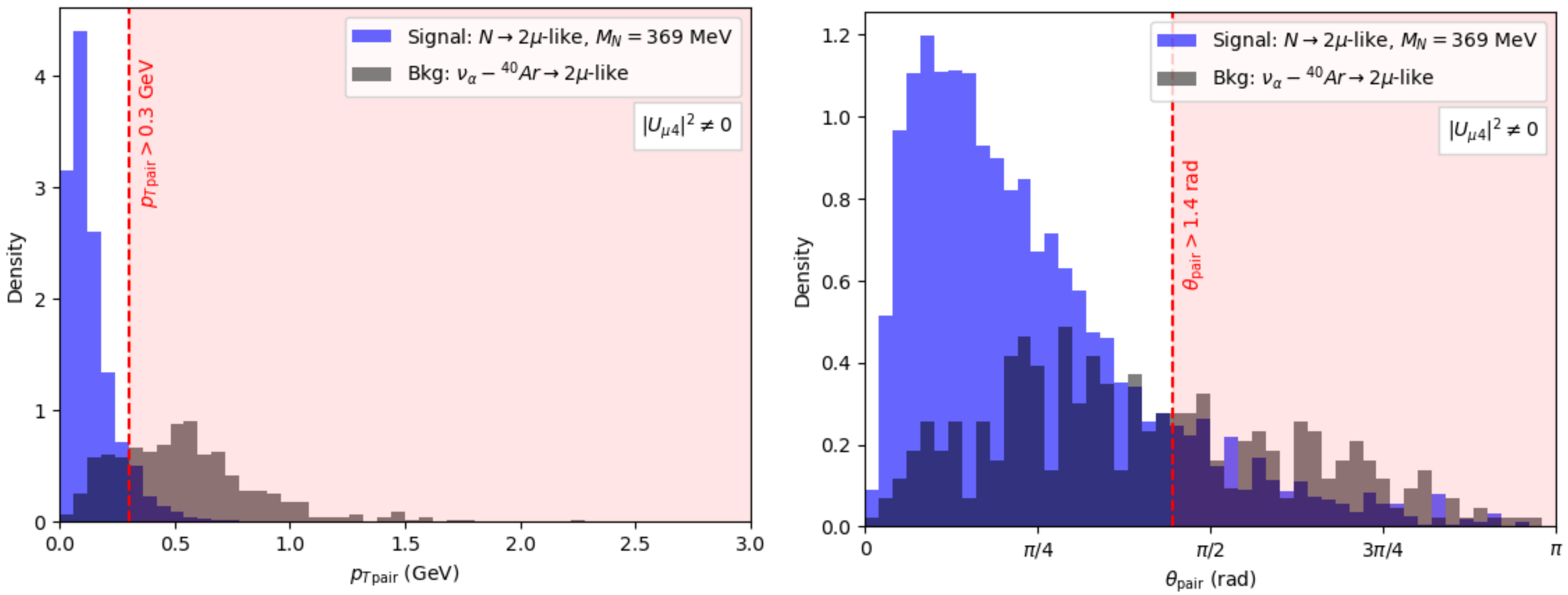
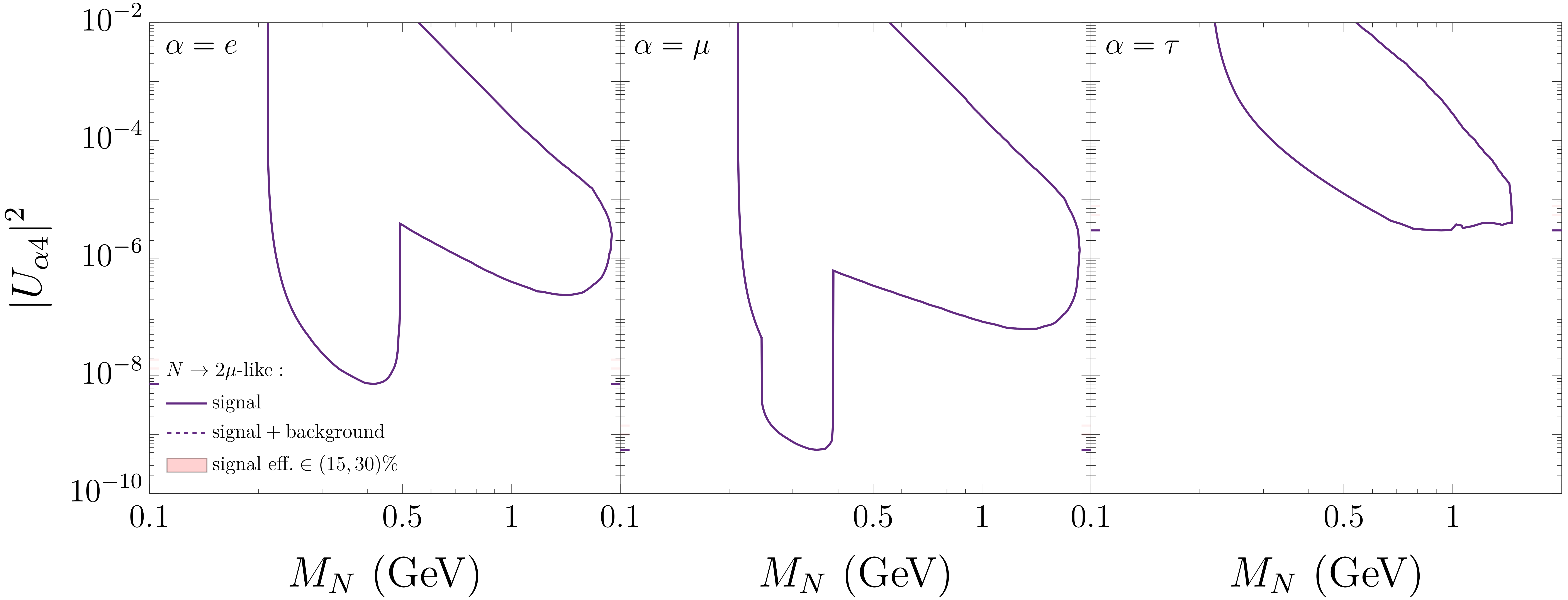


By applying kinematical cuts:

- Bkg. rej. eff. up to $\simeq 90\,\%$
- Signal eff. up to $\simeq 92\,\%$

HNL sensitivity: signal + background

Combining the channels with two μ-like tracks



- Solid purple line: F&C analysis assuming no background

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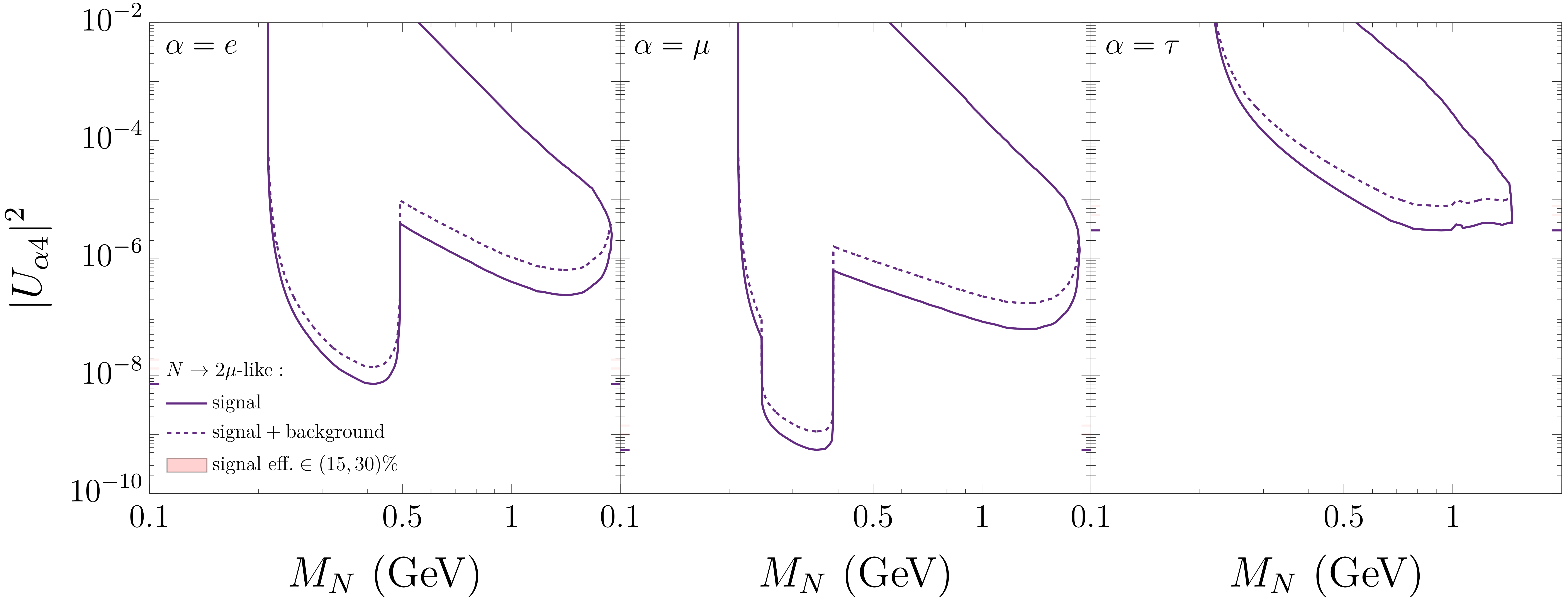

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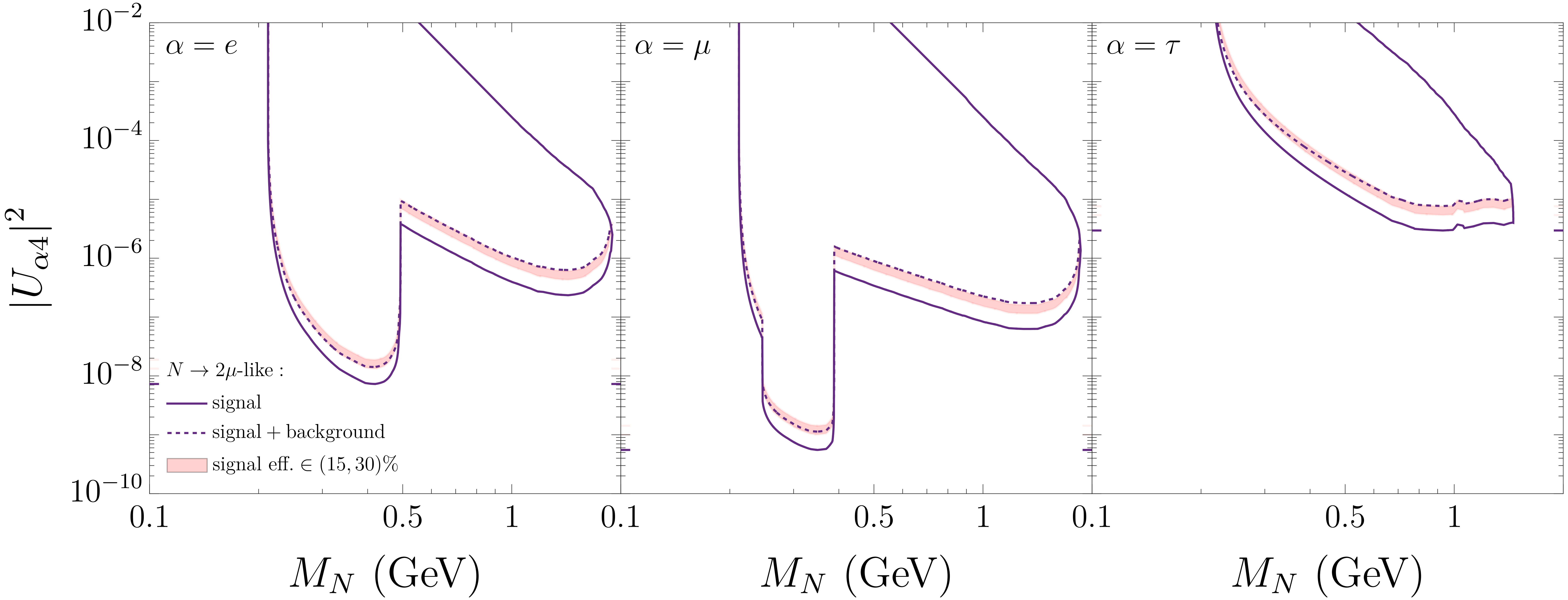

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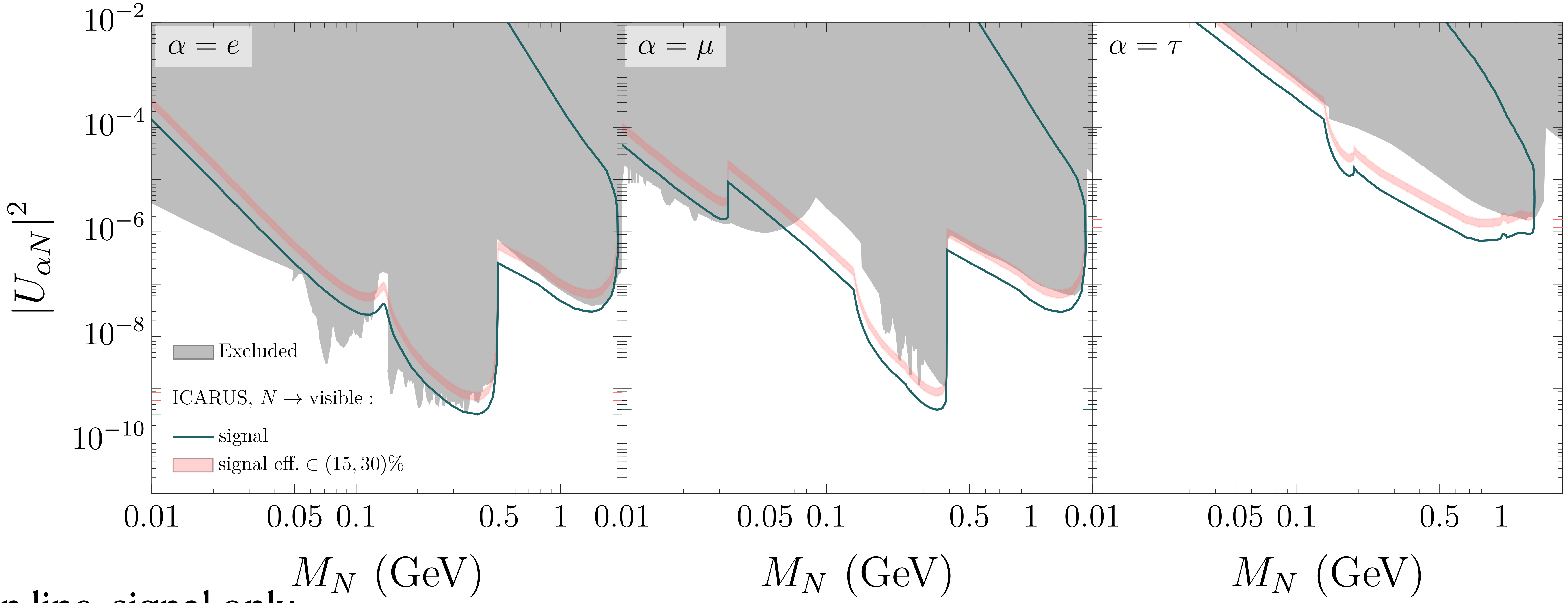
- Dashed purple line: unbinned Gaussian χ^2 analysis including both signal and bkg after event kinematical cuts
- Pink band: (15, 30) % signal efficiency cut to the negligible background case that covers the signal + bkg result

HNL sensitivity: ICARUS over present constraints

Combining leading HNL decay channels and following the Feldman and Cousins prescription ⇒

90 % CL ICARUS-like expected bounds assuming $1.32 \cdot 10^{21}$ PoT



- Green line: signal only
- Pink band: (15, 30) % signal efficiency cut ⇒ conservative limit

HNL sensitivity: ICARUS over present constraints

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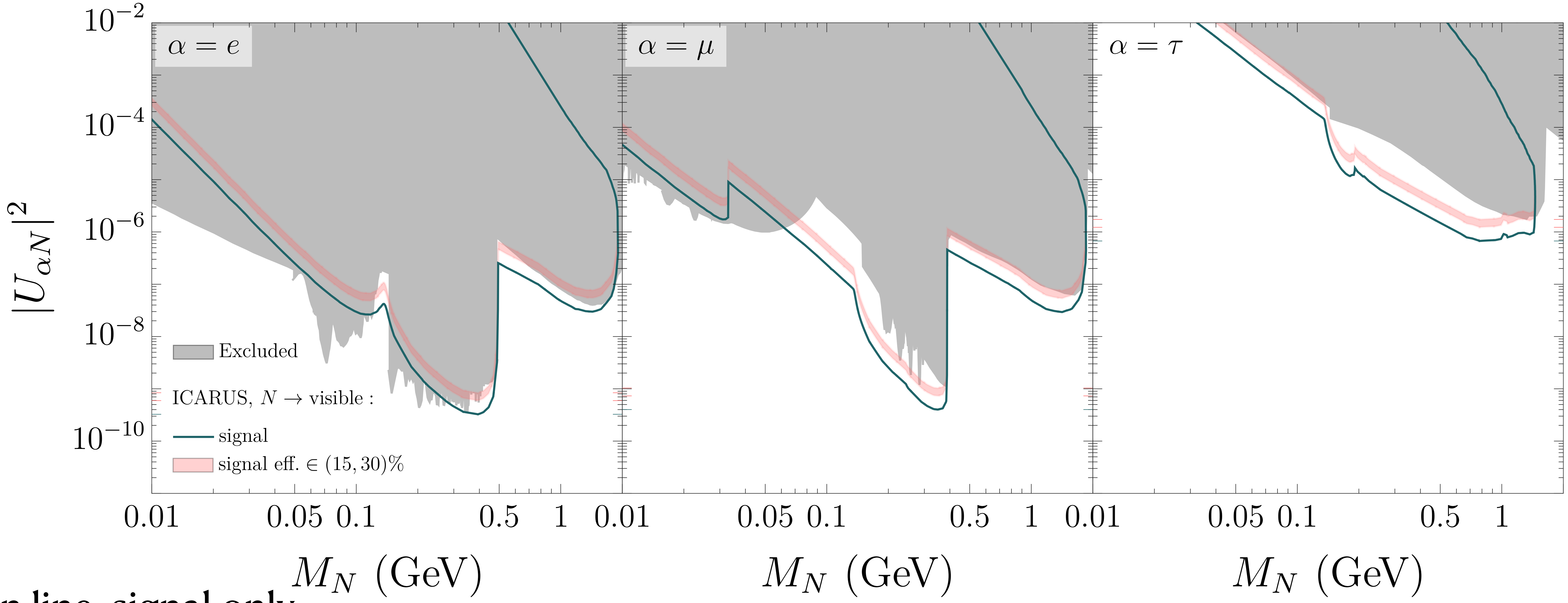

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Sensitivity results compatible with arXiv: 2409.04394

Summary

- We have computed, for the first time, the expected sensitivity of ICARUS to HNLs from NuMI.
- ICARUS shows potential for testing unexplored regions of the HNL parameter space.
- The ICARUS collaboration should analyze the data accumulated by the end of 2026 and perform a full dedicated analysis

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Thanks!

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Back-up

Status of NuMI after 2024 power failure

A major power failure of a transformer on the NuMI beam line at the end of August 2024 stopped its activity.

As a result, NuMI is not running, and its continuation until the end of 2026 is not yet clear.

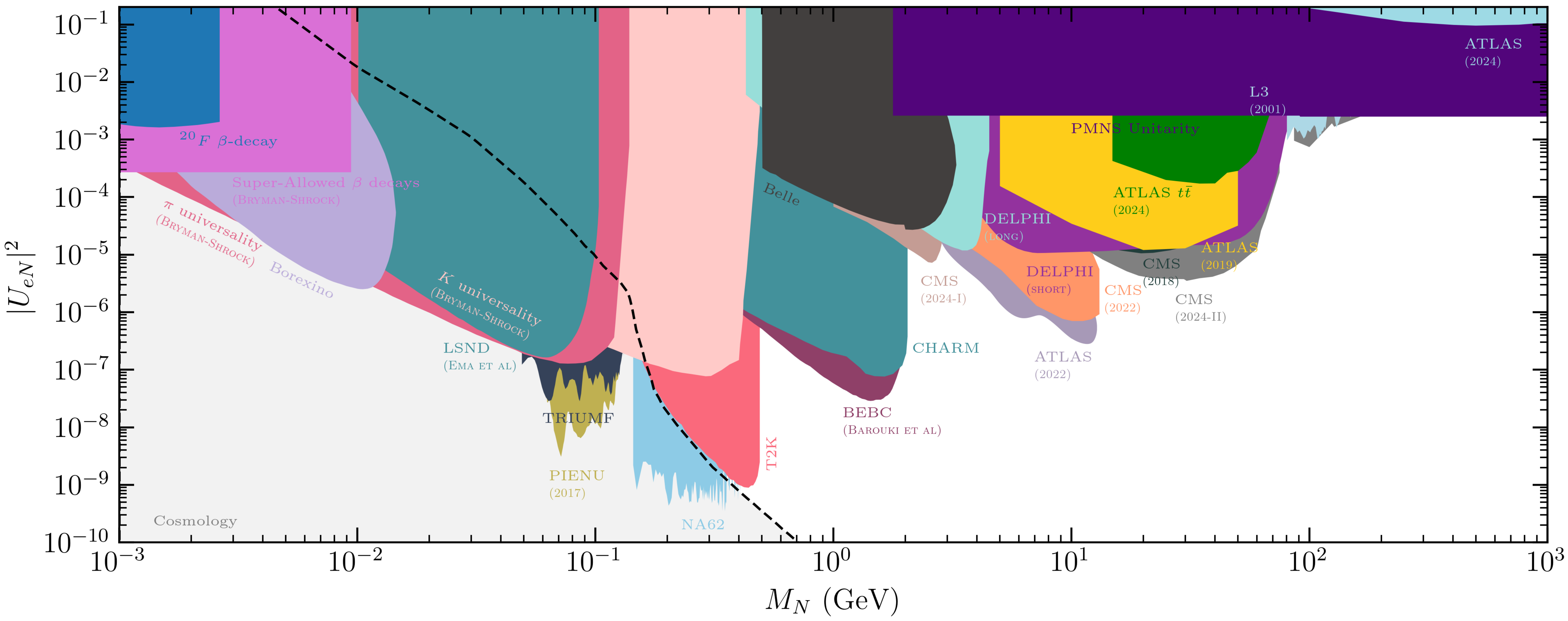
From 2027 on, Fermilab will focus on the LBNF beam line for DUNE.

ICARUS has so far collected $\sim 6 \cdot 10^{20}$ PoT $\Rightarrow$ roughly half of what was assumed for our results ($1.32 \cdot 10^{21}$ PoT).

If NuMI resumes its activity during 2026, ICARUS could still collect $\sim 1.32 \cdot 10^{21}$ PoT.

Otherwise, our sensitivity results should be corrected by a factor of $\sim \sqrt{2}$.

Heavy Neutral Leptons: present bounds



Present bounds in the HNL mixing from ν oscillations, kinks in beta-decay, peaks in meson decays, beam-dumps, colliders, and non-unitarity of the PMNS.

https://github.com/mhostert/Heavy-Neutrino-Limits
E. Fernandez-Martinez, M. Gonzalez-Lopez, JHG, M. Hostert, J. Lopez-Pavon. JHEP **09** 2023 001

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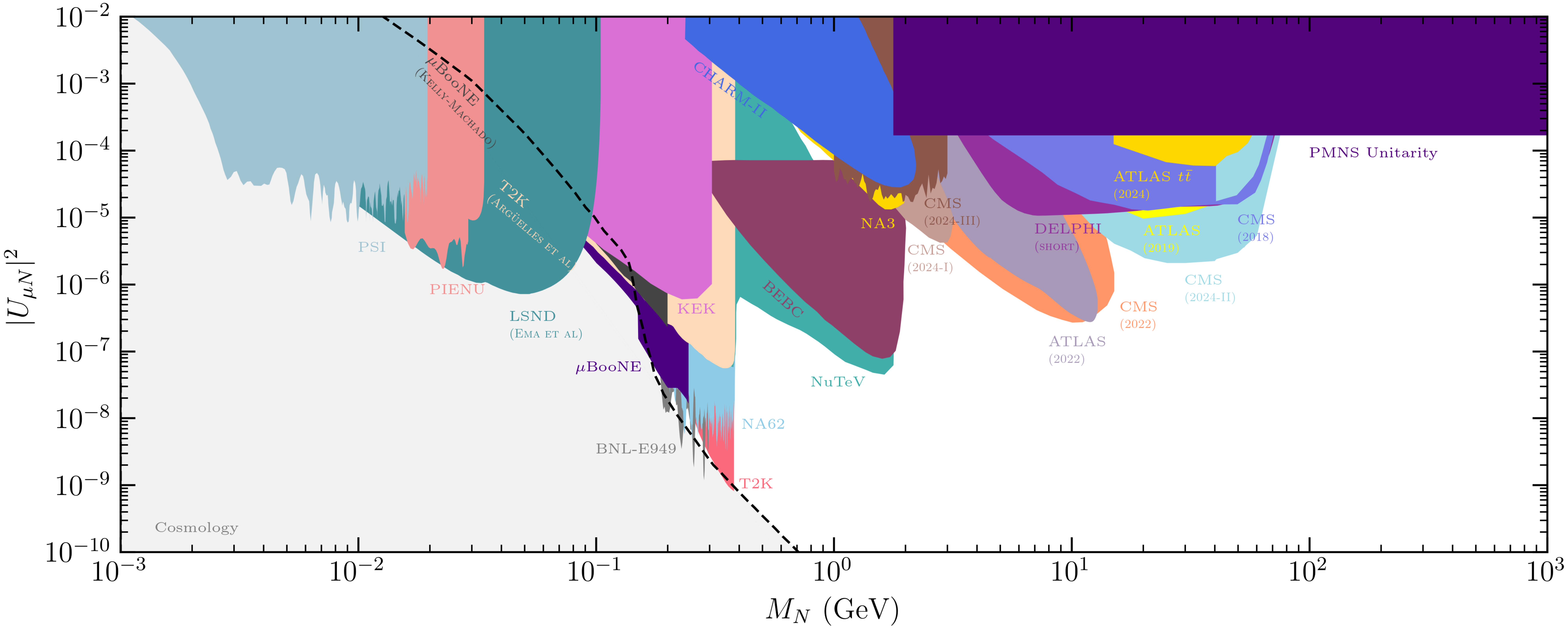

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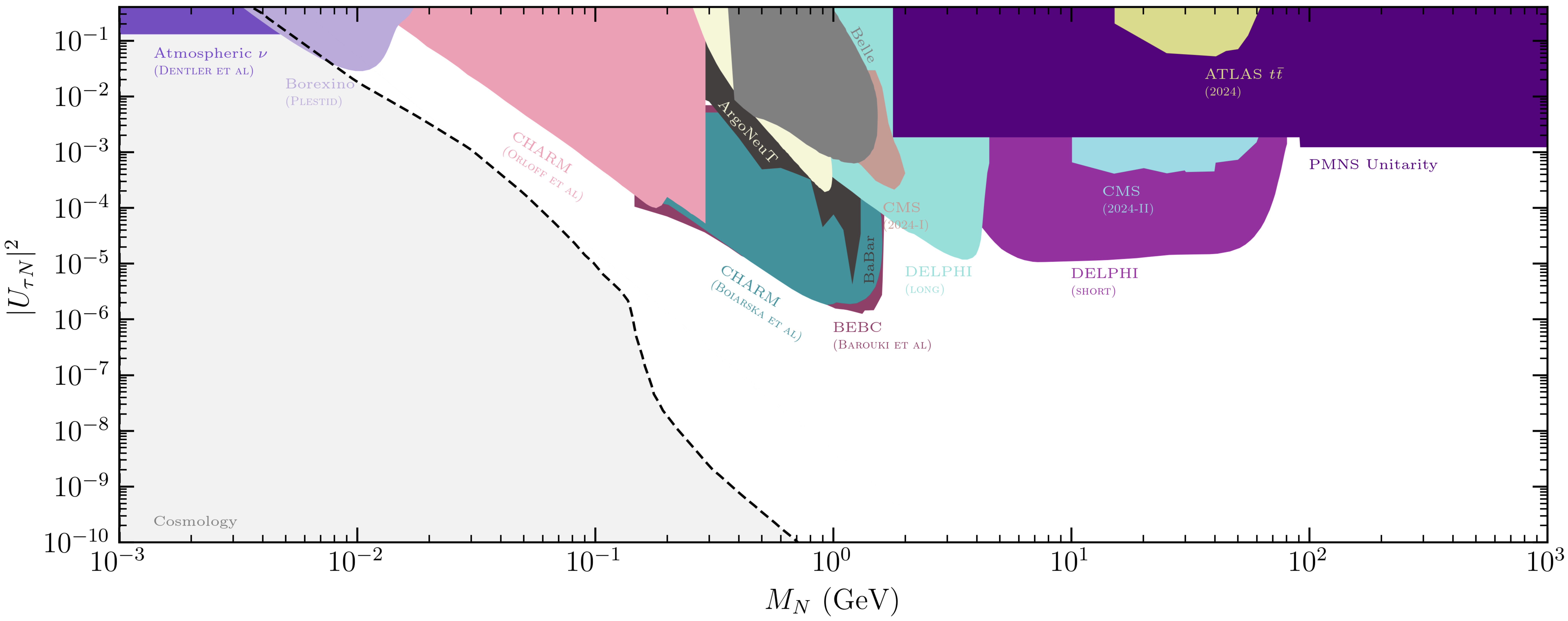

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Heavy Neutral Leptons: production and decay

- HNL production

Leptonic and semileptonic meson decays

	$\pi \to$	$K^0 \to$	$K \to$	$D \to$	$D_s \to$	$\tau \to$
$\lvert U_{eN}\rvert^2$	eN	—	eN	eN	eN	—
	—	$\pi^0 eN$	πeN	$K^0 eN$	—	—
$\lvert U_{\mu N}\rvert^2$	μN	—	μN	μN	μN	—
	—	$\pi^0 \mu N$	$\pi \mu N$	$K^0 \mu N$	—	—
$\lvert U_{\tau N}\rvert^2$	—	—	—	τN	τN	πN
	—	—	—	—	—	$\pi\pi^0 N$
	—	—	—	—	—	$e\nu N$
	—	—	—	—	—	$\mu\nu N$

	π	K	D	D_s	τ
P^+/PoT	6.0	1.1	$1.2 \cdot 10^{-5}$	$3.3 \cdot 10^{-6}$	$2.1 \cdot 10^{-7}$
P^-/PoT	4.1	0.4	$1.9 \cdot 10^{-5}$	$4.6 \cdot 10^{-6}$	$3.0 \cdot 10^{-7}$

Table I. Averaged parent production yield at the NuMI target per PoT during its neutrino mode. A pre-selection of light mesons that would produce neutrinos towards the region where ICARUS is placed has been done.

- HNL decay

Visible HNL decay channels with higher branching ratio

	$N \to$				
$\lvert U_{eN}\rvert^2$	$ee\nu$	$\mu\mu\nu$	$e\mu\nu$	e hadr.	ν hadr.
	$\nu\pi^0$	$e\pi$	$e\rho$	—	
$\lvert U_{\mu N}\rvert^2$	$ee\nu$	$\mu\mu\nu$	$e\mu\nu$	μ hadr.	ν hadr.
	$\nu\pi^0$	$\mu\pi$	$\mu\rho$	—	
$\lvert U_{\tau N}\rvert^2$	$ee\nu$	$\mu\mu\nu$	—	—	ν hadr.
	$\nu\pi^0$	—	—	$\nu\rho^0$	

Statistical analisys

- Feldman and Cousins

Prescription for a Poisson distribution with no background and under the hypothesis of no events being observed

$$N^{ex}(\phi) < 2.44\,, \quad \text{for } 90\,\%\,\text{CL}$$

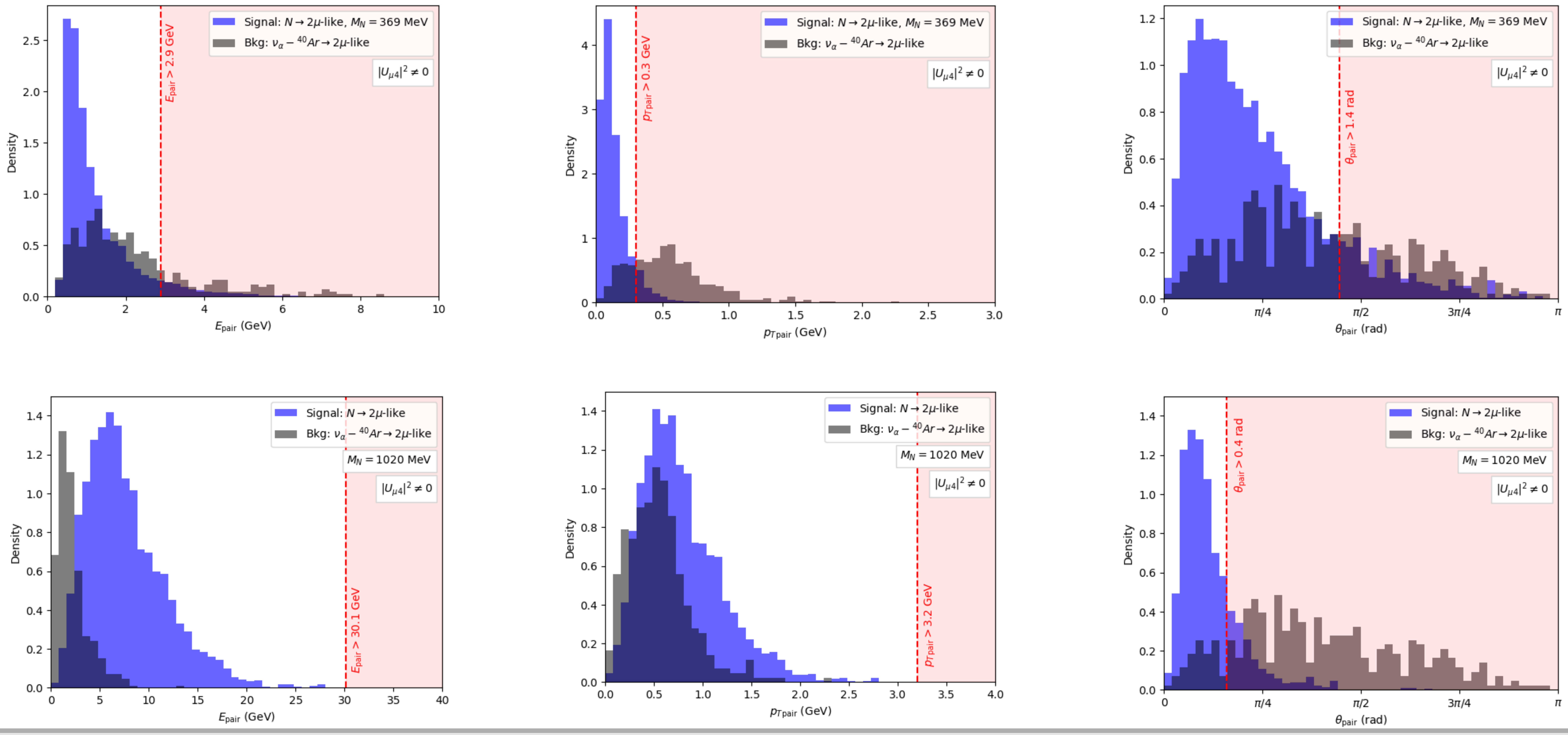
- Unbinned Gaussian χ^2

$$\chi^2 = min_\xi\left\{ \left(\frac{N^{ex}(\phi,\xi) - N^{ob}(\xi)}{\sigma_N(\xi)} \right)^2 + \left(\frac{\xi}{\sigma_f} \right)^2 \right\}$$

where $N^{ex}(\phi,\xi)$ is the total expected event rate including both signal and background events, and $N^{ob}(\xi)$ is the observed events; with the uncertainty on the flux normalization, σ_f, taken as $20\,\%$, and $\sigma_N(\xi) = \sqrt{N^{ob}(\xi)}$ is the statistical error.

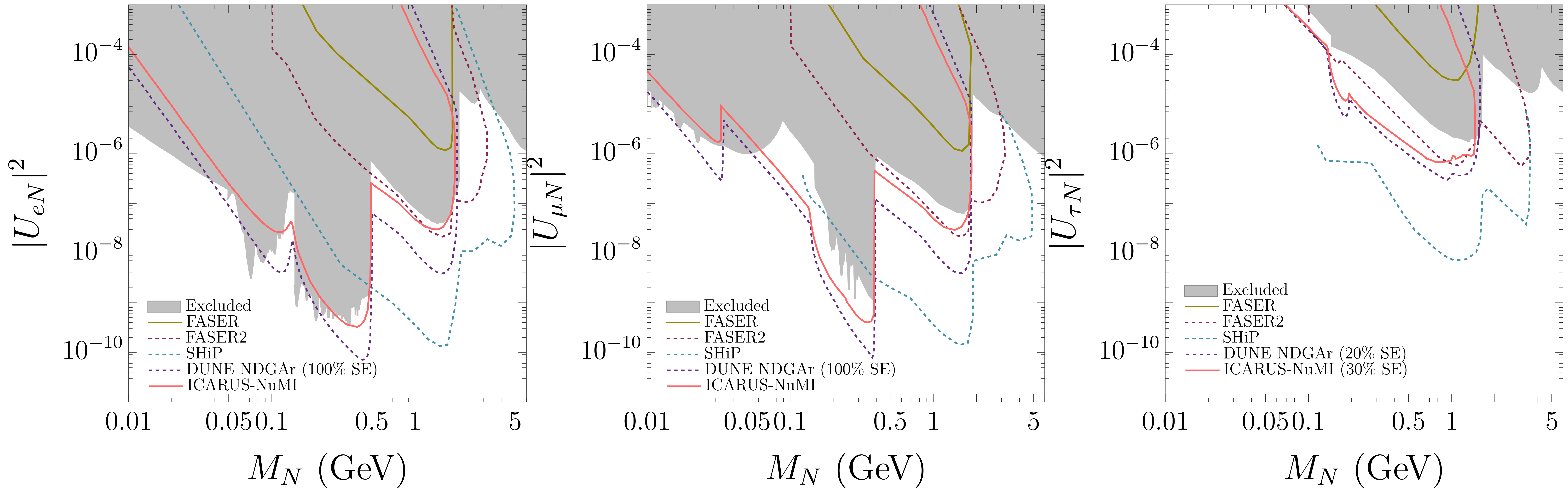
$$\chi^2 < 4.61\,, \quad \text{for } 90\,\%\,\text{CL}$$

Kinematical cuts



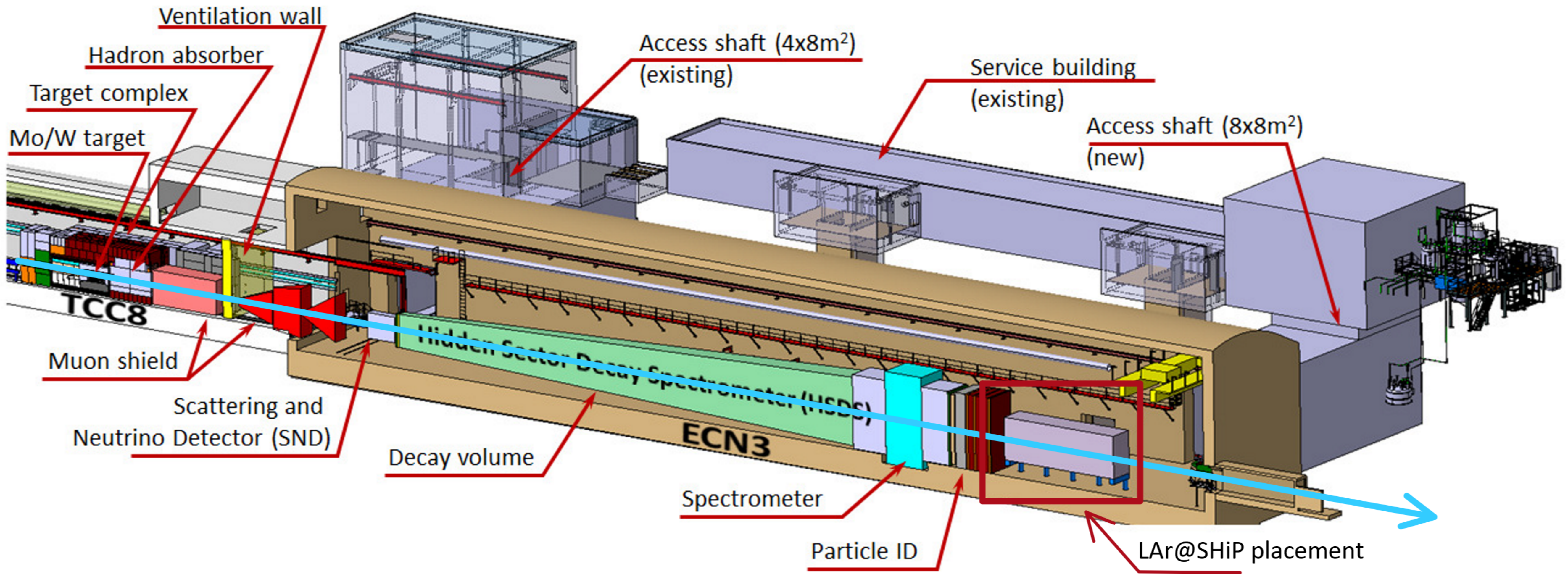
Present and nHNL sensitivity: present and near-future

Expected sensitivities assuming signal only (no background)



2 years of ICARUS NuMI (2026). 4.5 years of DUNE Phase II (2040). 15 years of SHiP (2045).

The SHiP experiment

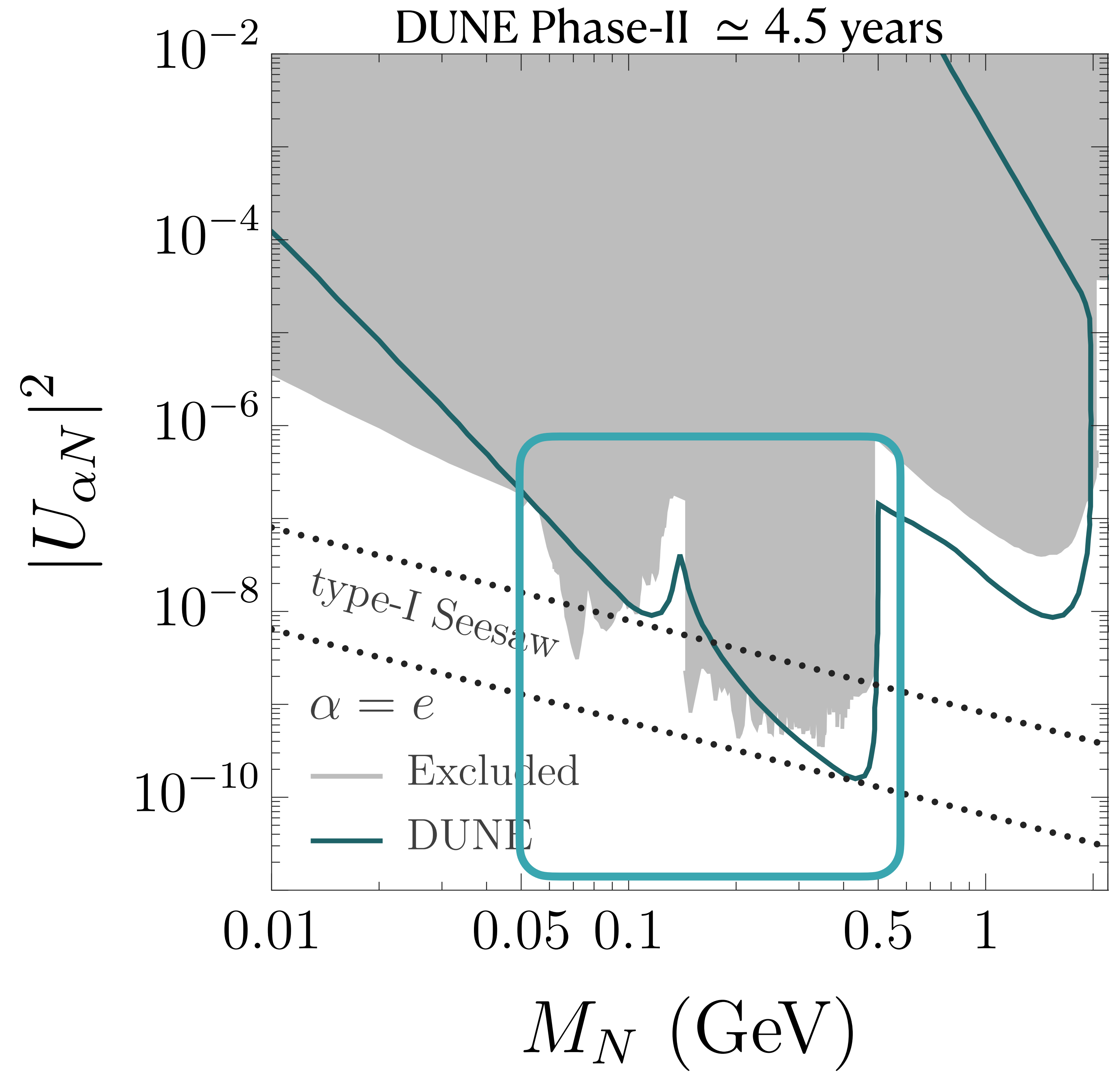


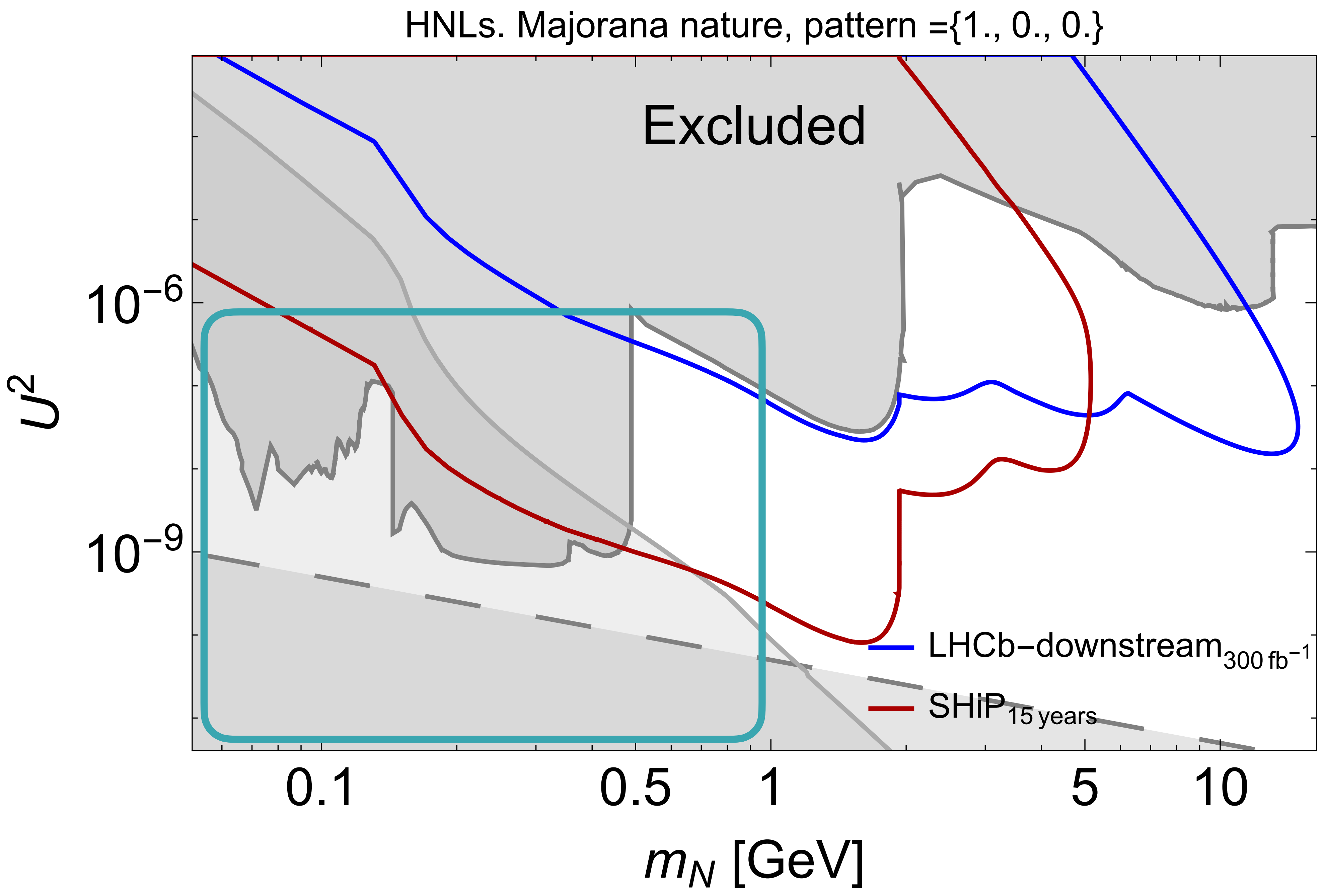
SHiP experiment highlights:

- Proton energy of 400 GeV
- Expected running time $\simeq 2030 - 2045$
- Large beam intensity $4 \cdot 10^{19}$ PoT/year $\Rightarrow$ an expected total of $\simeq 6 \cdot 10^{20}$ PoT
- "Background-free" experiment for many scenarios
- Fully instrumented

designed for LLP searches

HNLs searches: DUNE ND-GAr vs SHiP





Better sensitivity of DUNE ND-GAr in the π and K regions

Maksym Ovchynnikov - Search for new physics at SHiP (IFIC seminar)

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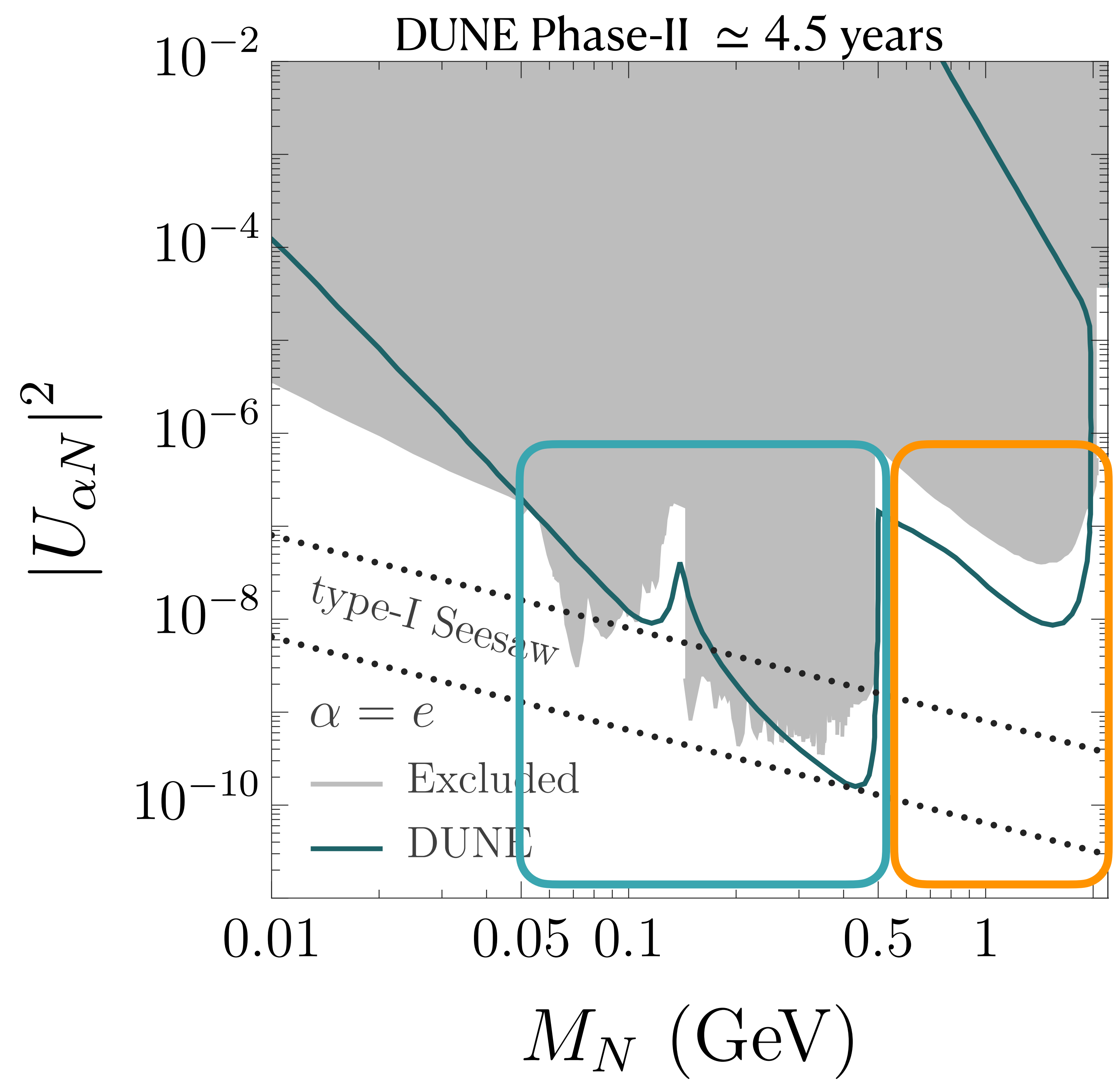

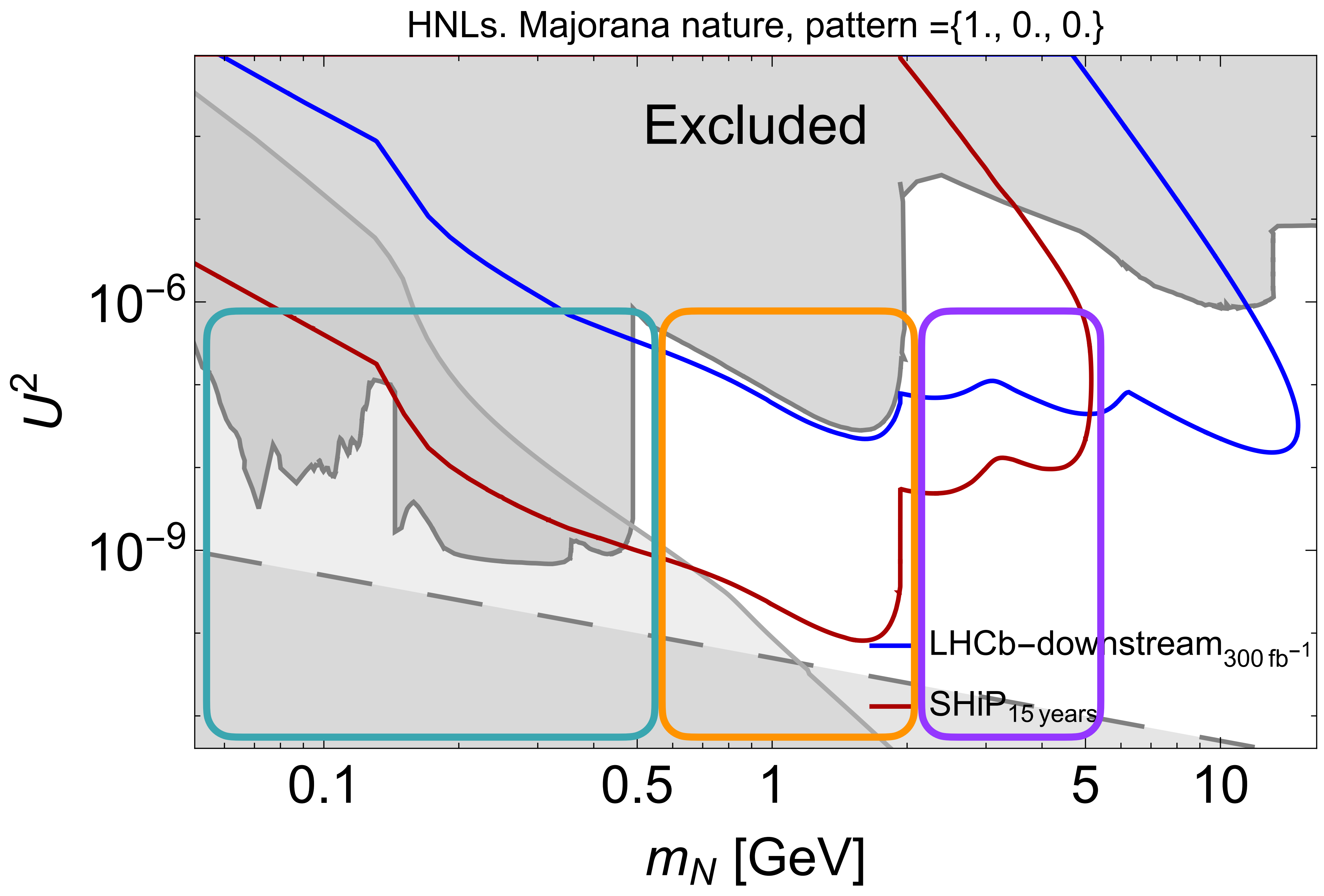

Better sensitivity of DUNE ND-GAr in the π and K regions | Better sensitivity of SHiP in the D and B regions

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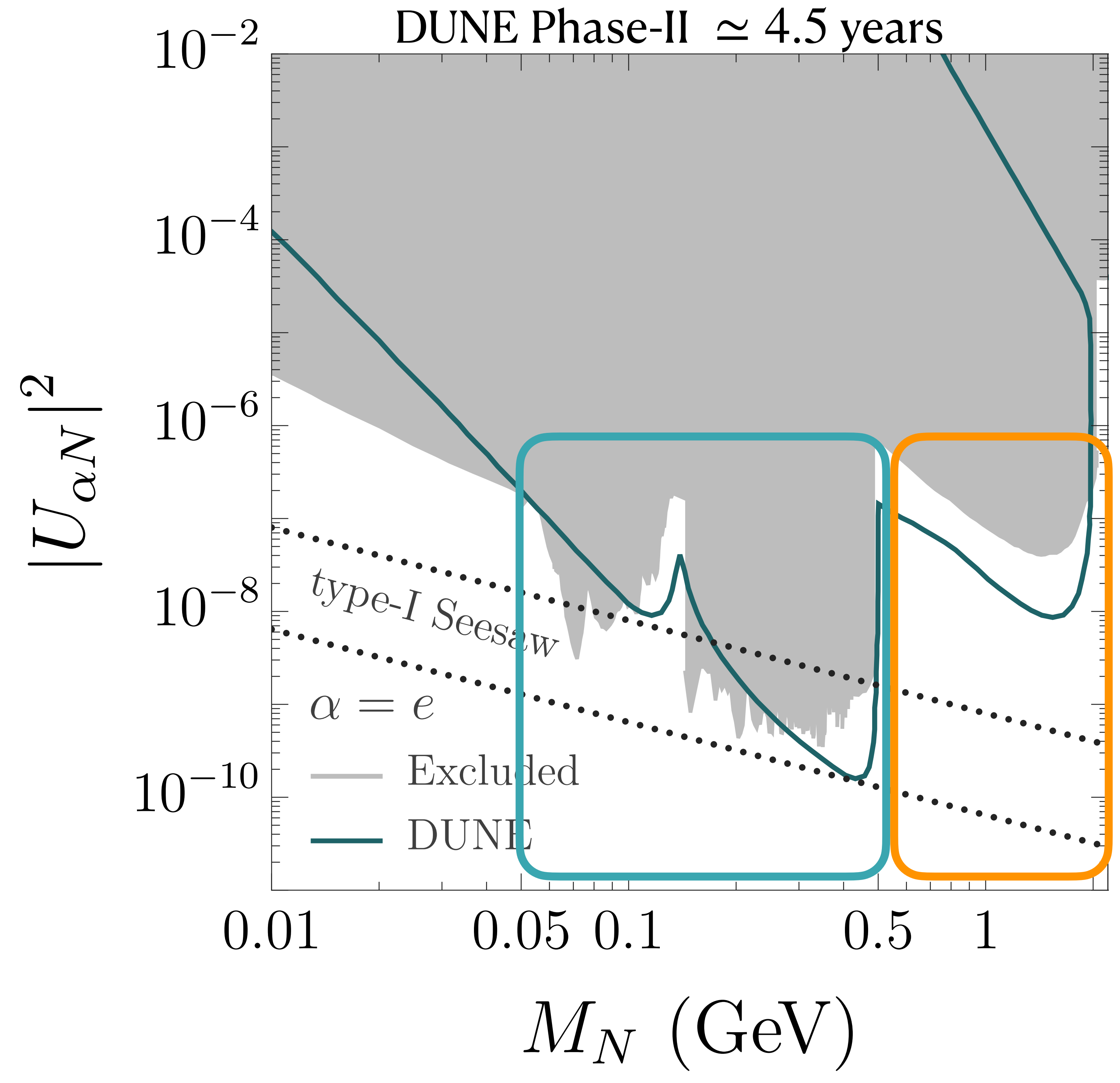

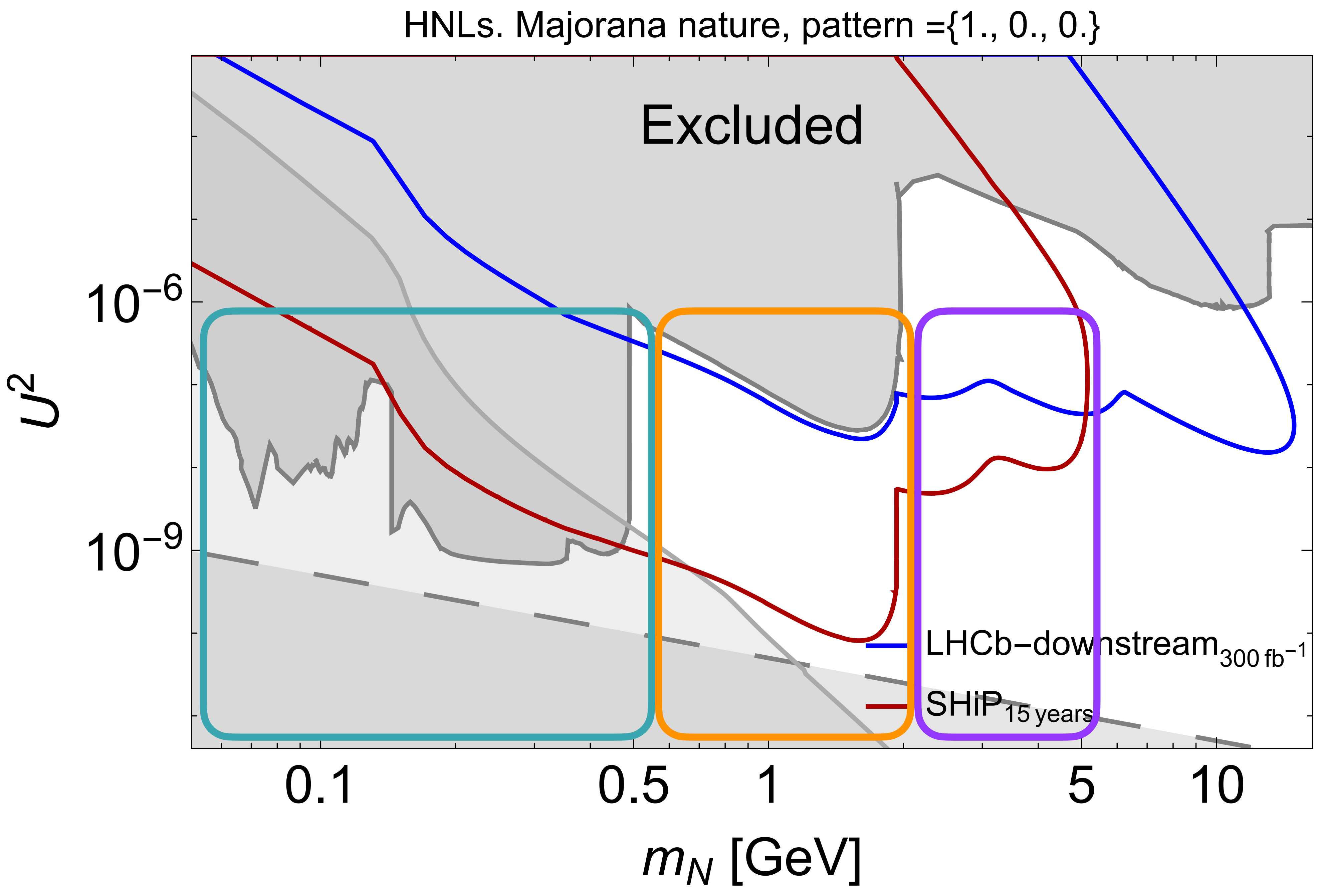

Better sensitivity of DUNE ND-GAr in the π and K regions | Better sensitivity of SHiP in the D and B regions

Similar results for the $|U_{\mu N}|^2$. Better sensitivity of SHiP in the $|U_{\tau N}|^2$ since it comes from D decays.

Maksym Ovchynnikov - Search for new physics at SHiP (IFIC seminar)