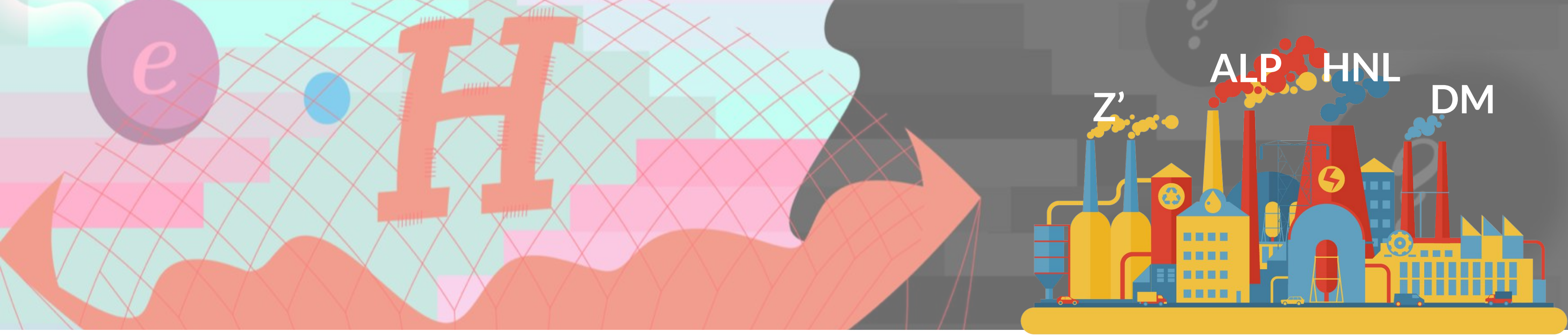


HNLs from Heavy ALP decays at Neutrino Facilities

...based on 2311.07713

PLANCK 2024

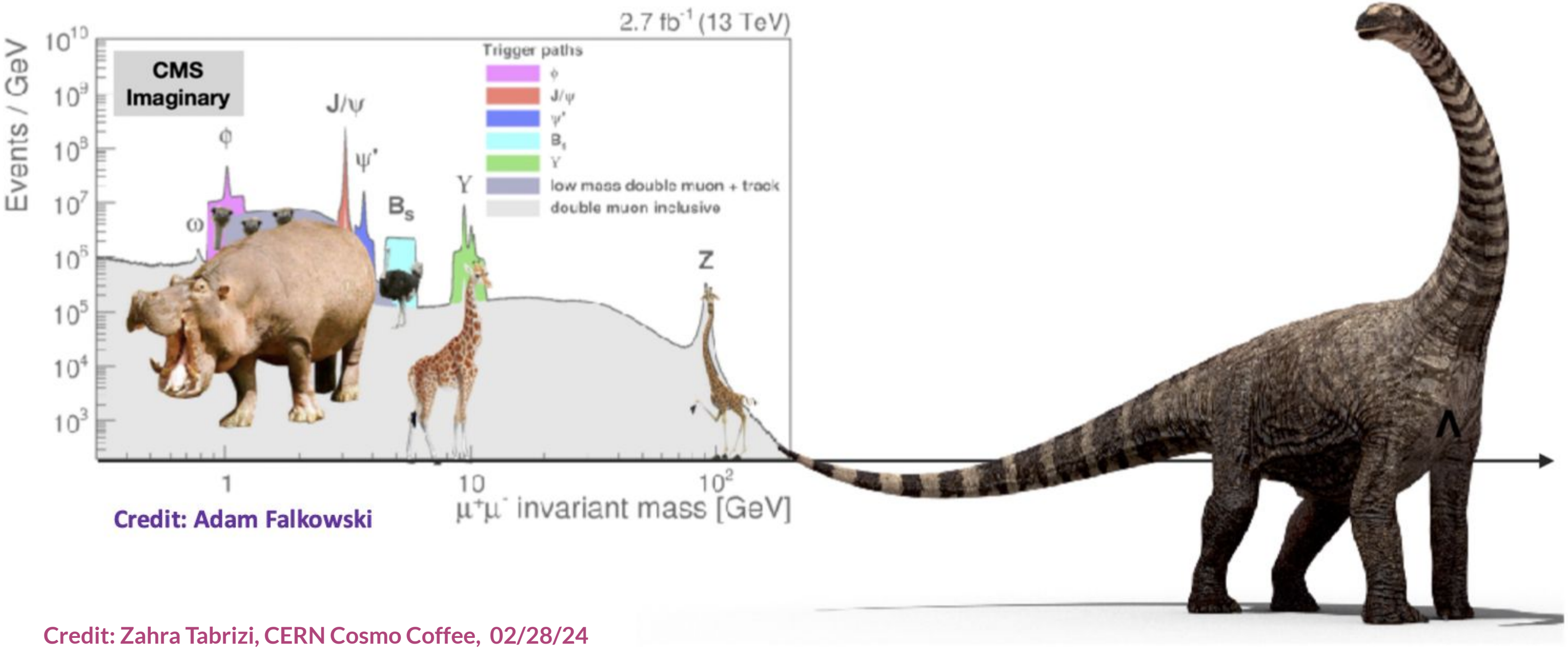
Asli M. Abdullahi

6 June 2024

Instituto de Física Teórica UAM-CSIC

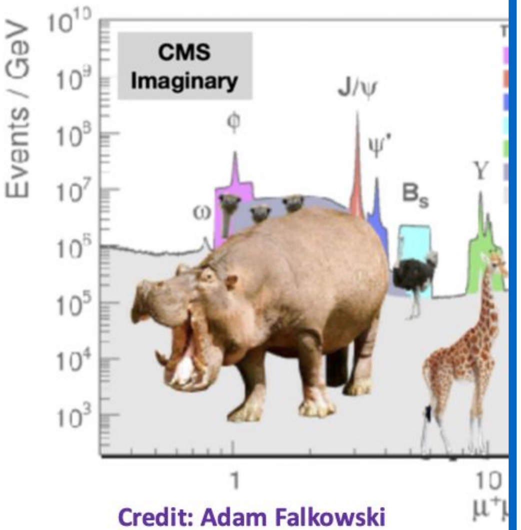
CSIC
Consejo Superior de Investigaciones Científicas

Fantastic Beasts and How to Find Them
With Neutrino Detectors



Credit: Zahra Tabrizi, CERN Cosmo Coffee, 02/28/24

Fantastic B
Wi



Credit: Adam Falkowski

WHY NEUTRINO EXPERIMENTS?

- ➔ High POT (~1e21)
  - → *large flux of charged and neutral mesons*
  - → *Potentially sizeable flux of BSM particles*
- ➔ Large detector masses ~ O(1e2) tonnes
  - → *Potentially larger interaction cross-sections*
- ➔ Good PID (p, μ, e, γ reconstructed) and calorimetry
- ➔ Parasitic → *shared cost with neutrino projects*

**See talk by Richard Van de Water,
U.S. Cosmic Visions 2017**

"Future possibilities at Proton fixed target experiments"

Production and detection

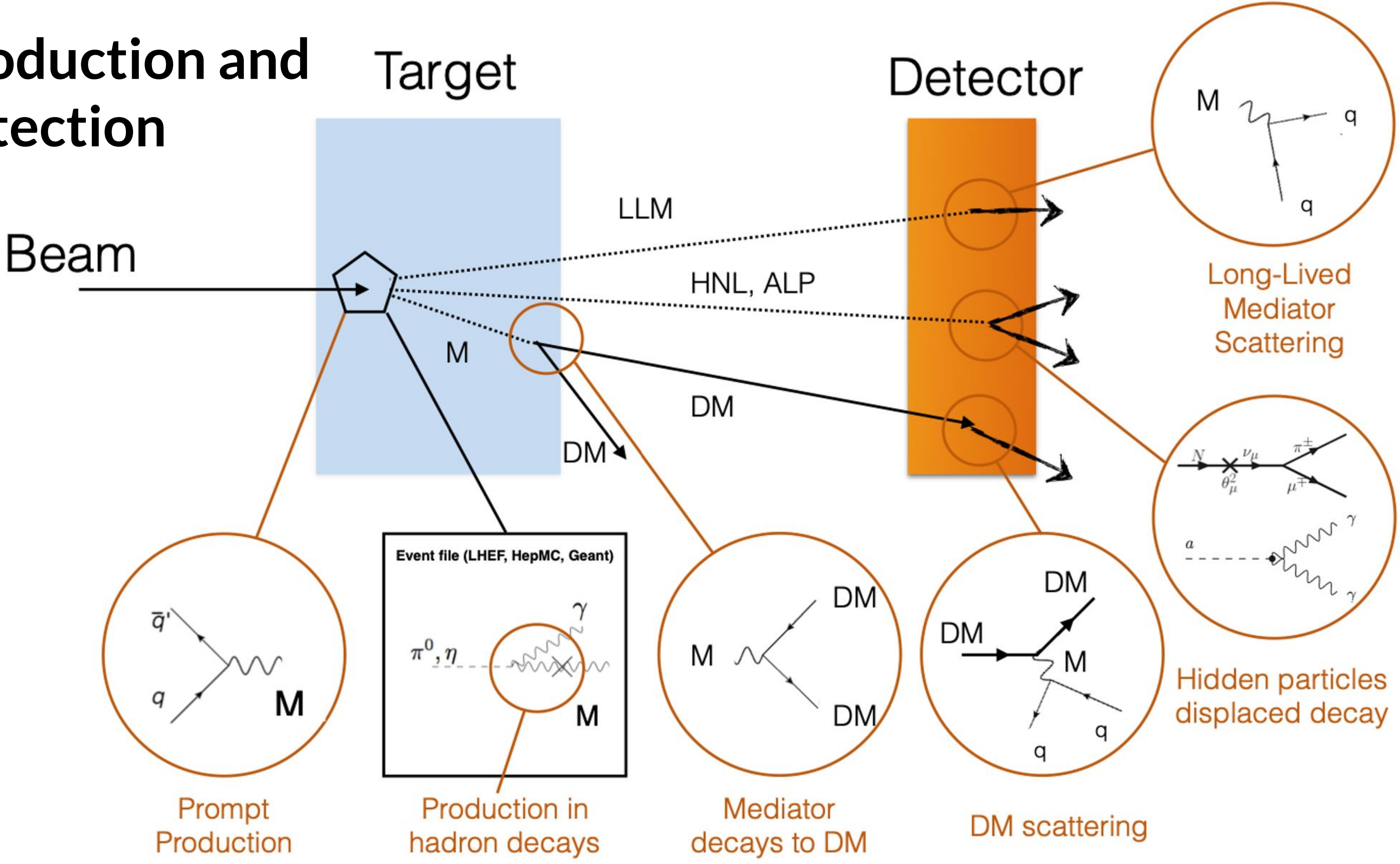


Fig. 1 of 1812.06771 (Buonocore et al.)

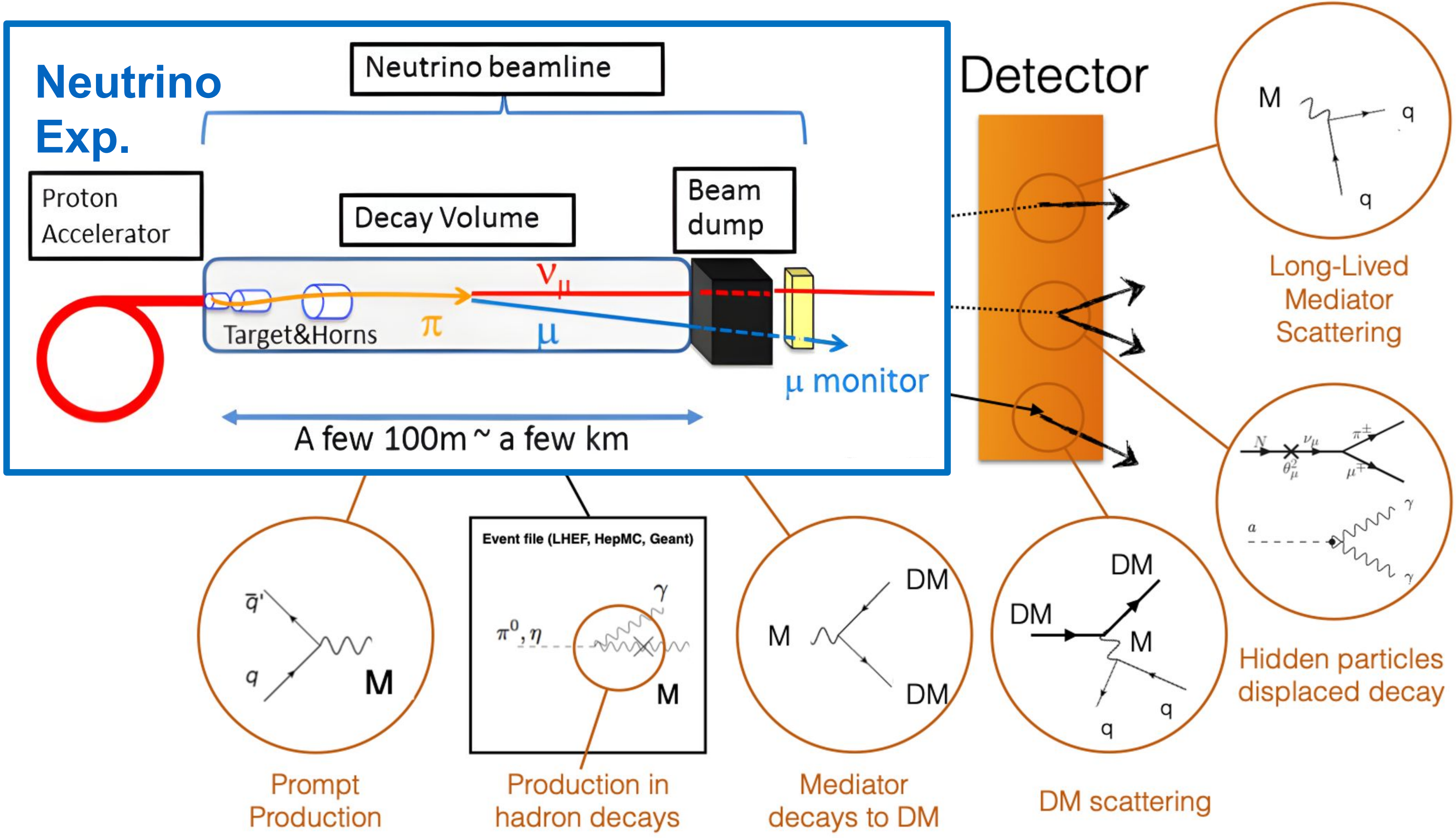


Fig. 1 of 1812.06771 (Buonocore et al.)

Plethora of NP

Among the NP options are:

- Light Z’
- HNLs
- Light Dark Matter
- ALPs
- …..

“Heavy Neutral Leptons via Axion-Like Particles at Neutrino Facilities”
AA, A. de Gouvea, B. Dutta, I. Shoemaker and Z. Tabrizi
ArXiv: 2311.07713 [hep-ph]

“A panorama of new-physics explanations to the MiniBooNE excess”
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ArXiv: 2308.02543 [hep-ph]

“Constraining light thermal inelastic dark matter with NA64’
AA, B. Banto Oberhauser, P. Crivelli, M. Hostert, D. Massaro, L. Molina Bueno, M. Mongillo, S. Pascoli
ArXiv: 2302.05414 [hep-ph]

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Plethora of NP

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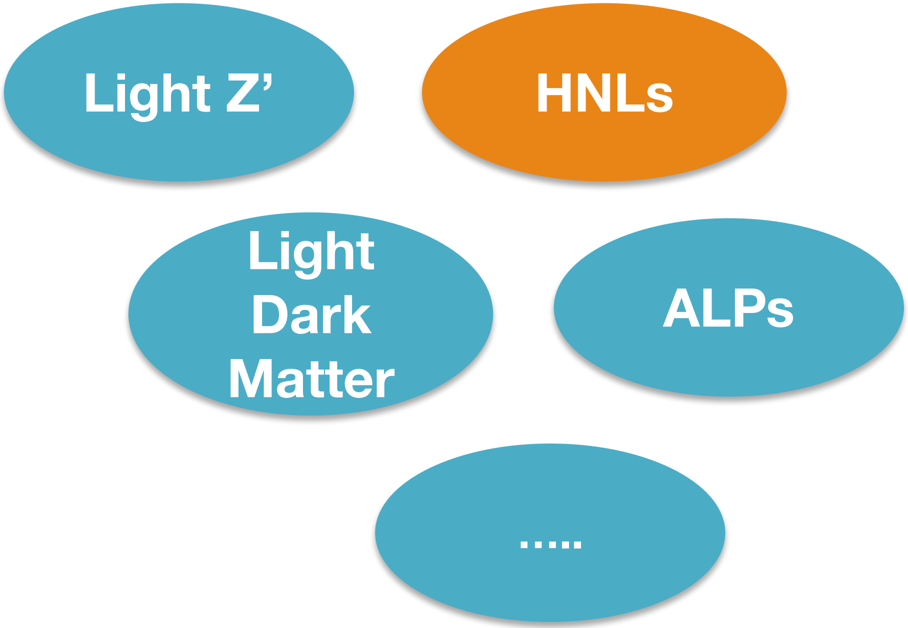

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Heavy Neutral Leptons: Minimal scenario

$$\mathcal{L} \supset -y\bar{L}\left(i\sigma^2 H^*\right)N - \frac{M_N}{2}\overline{N^c}N$$

- Singlet N couples to SM leptons through Higgs
  $\longrightarrow$ The only renormalizable coupling to a singlet fermion

- Mass mixing with SM neutrinos and active–sterile neutrino oscillations

HNLs: Minimal scenario

$$\mathcal{L} \supset -y\bar{L}\left(i\sigma^2 H^*\right)N - \frac{M_N}{2}\overline{N^c}N$$

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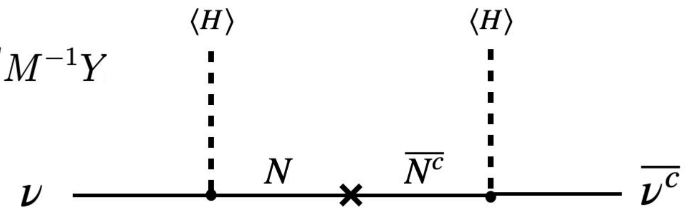
- Could explain neutrino mass $\longrightarrow$ Type 1 seesaw

$$M_\nu \simeq -\frac{v^2}{2} Y^T M^{-1} Y$$



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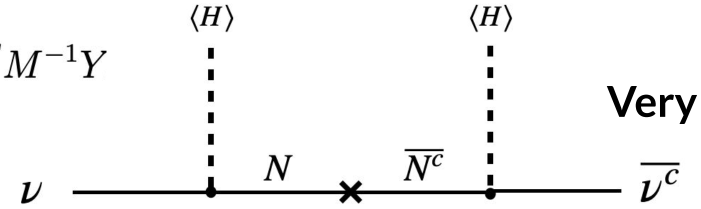
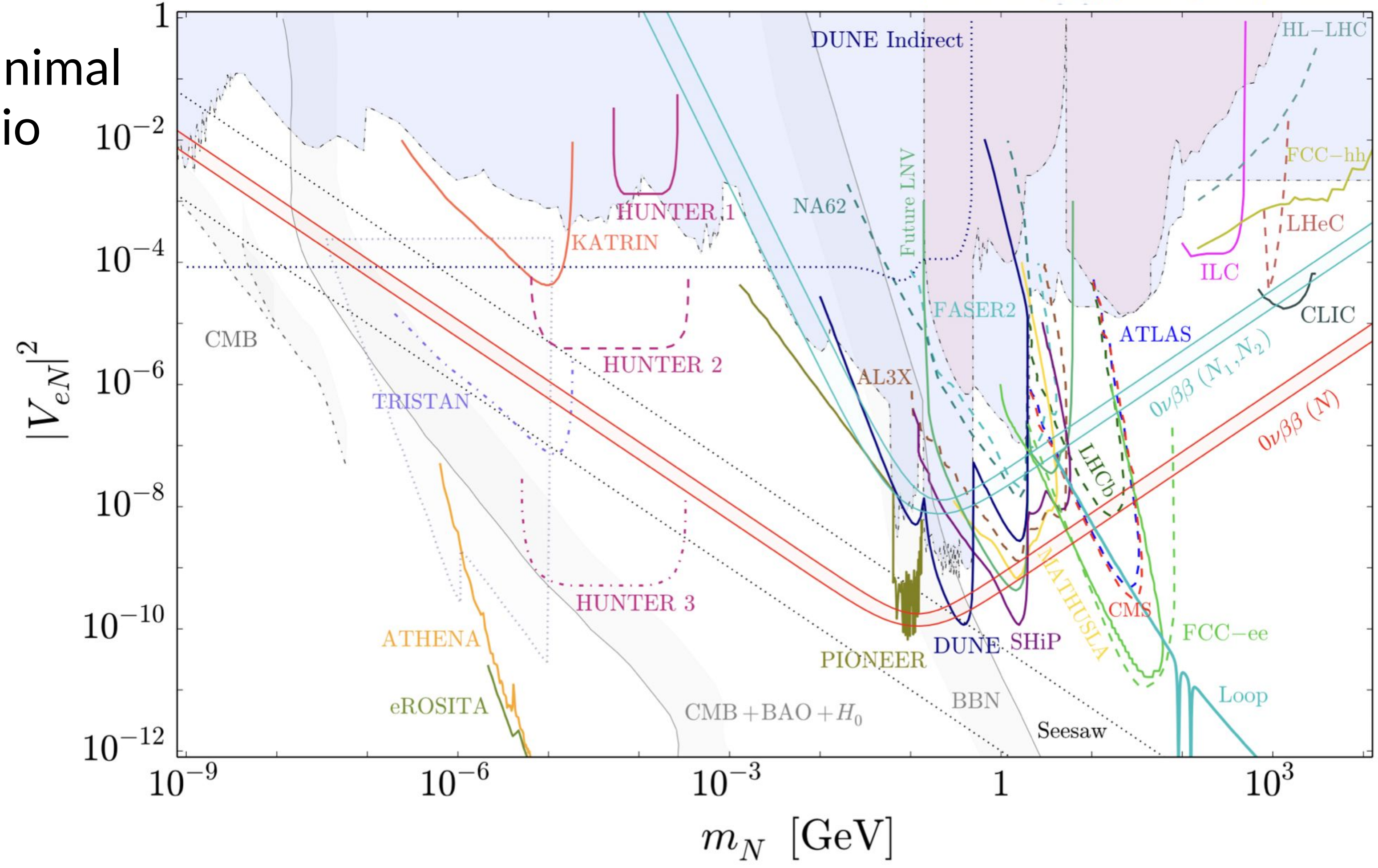


Very heavy N $\longrightarrow$ $m_\nu \simeq -\frac{m_D^2}{M}$

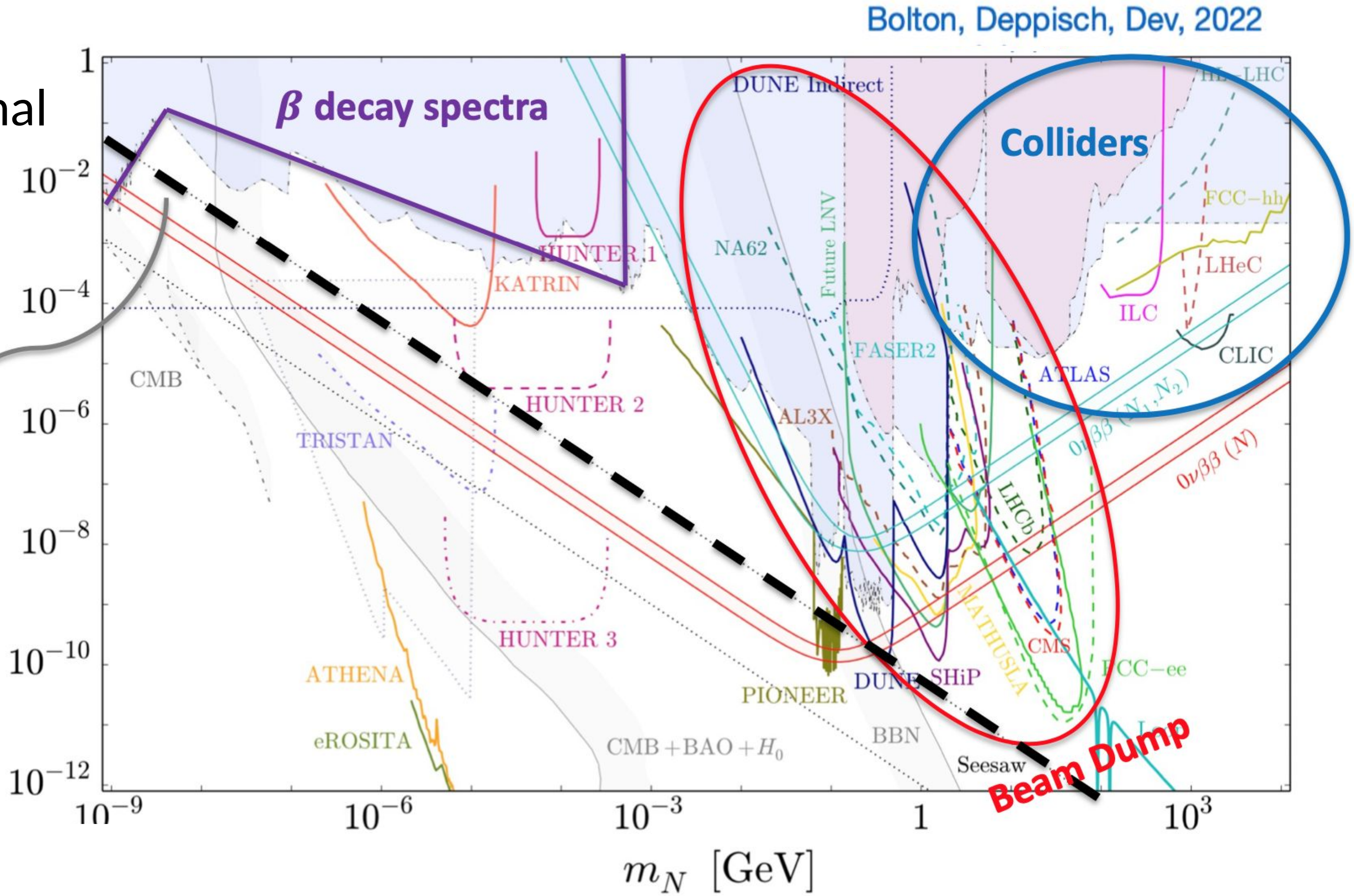
Very small mixing $\longrightarrow$ $|U_{\alpha h}|^2 \simeq 10^{-10}\frac{[\mathrm{GeV}]}{M}$

HNLs:
The minimal scenario

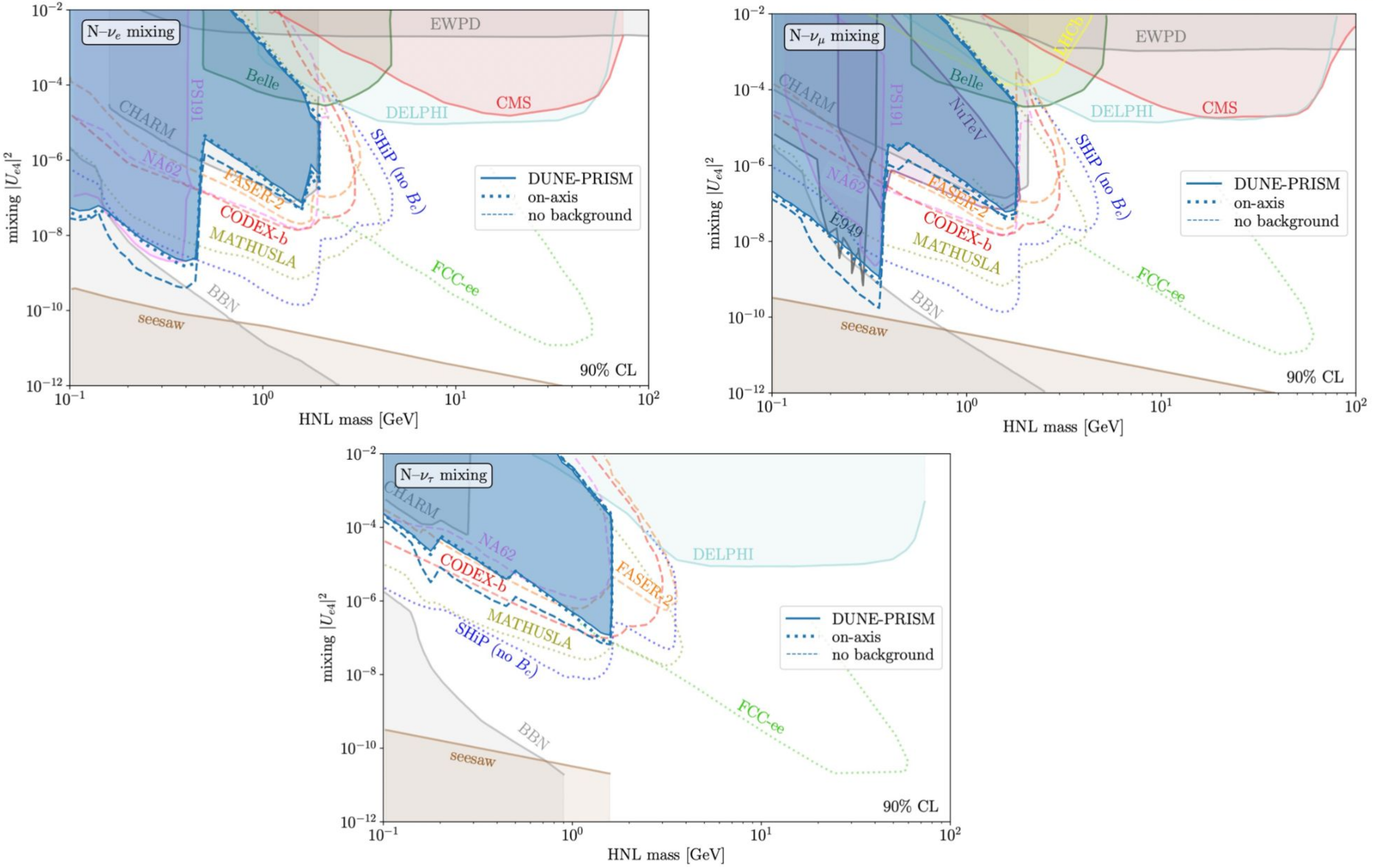
Bolton, Deppisch, Dev, 2022



HNLs:
The minimal scenario

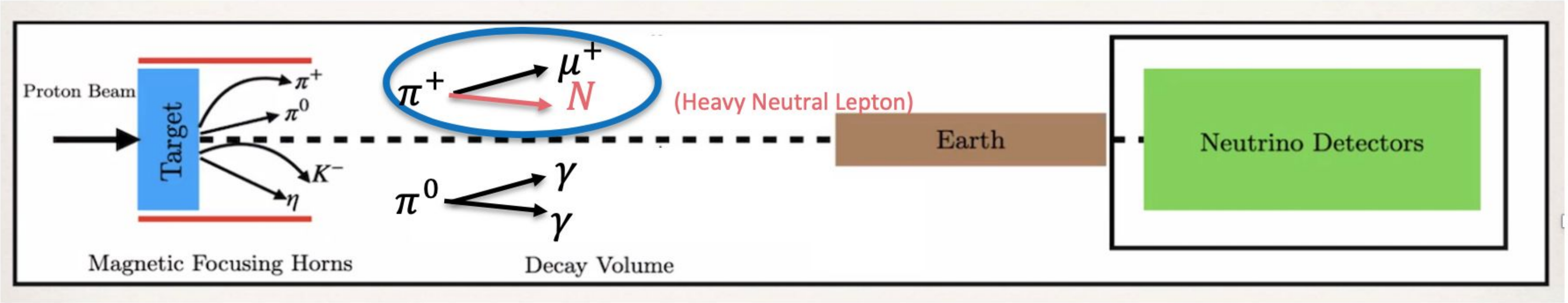


seesaw line
where the simplest seesaw model predicts the correct neutrino masses

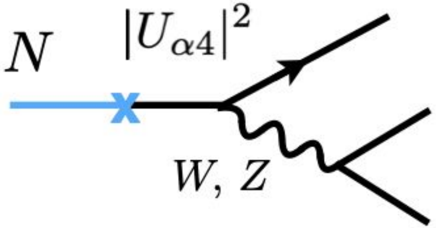

N–ν_e mixing
EWPD
Belle
CMS
DELPHI
PS191
CHARM
NA62
SHiP (no B_c)
FASER-2
CODEX-b
MATHUSLA
FCC-ee
BBN
seesaw
DUNE-PRISM
on-axis
no background
90% CL
mixing $|U_{e4}|^2$
HNL mass [GeV]
N–ν_μ mixing
LHCb
NuTeV
E949
N–ν_τ mixing

HNLs: Minimal scenario

ROADBLOCK: Production and detection through neutrino mixing



Event rate suppressed by $|U_{\alpha N}|^4$

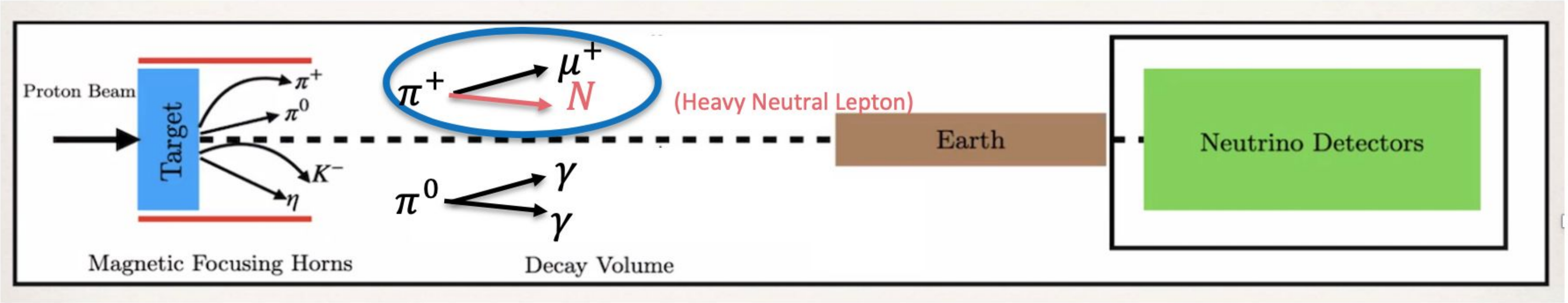


Typically **long-lived** and have **weaker-than-weak** interactions

→ Challenging to probe **seesaw region** and below

HNLs: Minimal scenario

ROADBLOCK: Production and detection through neutrino mixing



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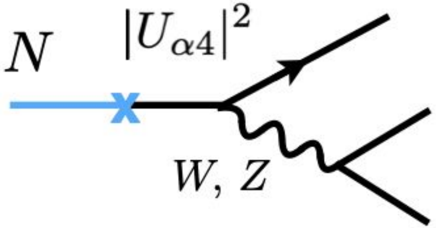
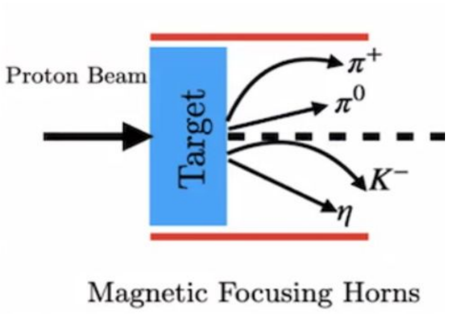
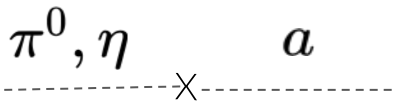


How to bypass the roadblock?

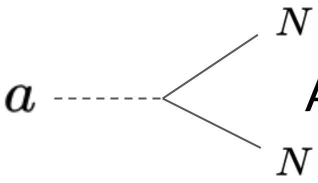
HNL production via ALP

Option: Decoupled production and detection mechanisms





@Target



ALP decay-in-flight

- New pseudoscalar, a, couples to HNLs directly
- Analogous to $\pi^+ \to l^+ + \nu$ in SM

"Heavy Neutral Leptons via Axion-Like Particles at Neutrino Facilities"
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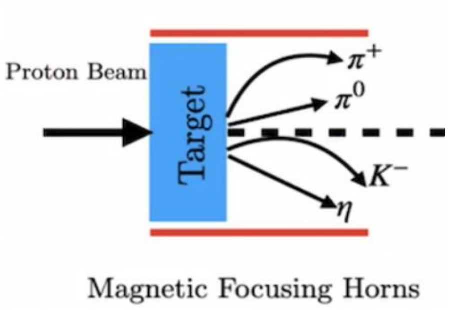
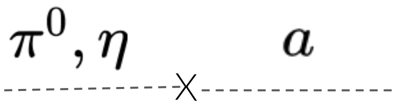
HNL production via ALP

Option: Decoupled production and detection mechanisms





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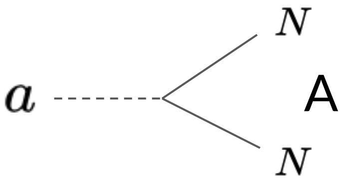

ALP decay-in-flight

The ALP a mixes with SM neutral mesons π^0, η

$$\begin{cases} \pi^0 \to \pi^0 + g_{\pi a} a \\ \eta \to \eta^0 + g_{\eta a} a \end{cases}$$

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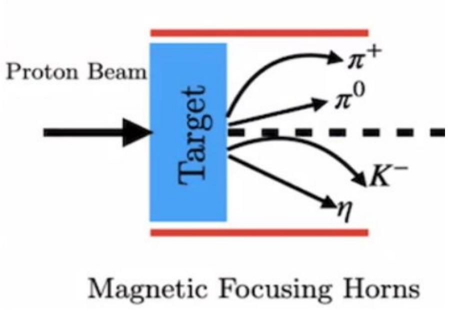
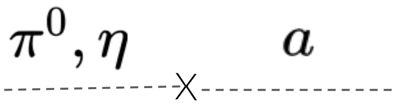
HNL production via ALP

Option: **Decoupled production and detection mechanisms**





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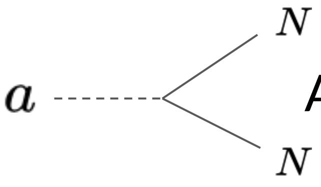

ALP decay-in-flight

No neutrino mixing suppression at production

The ALP a mixes with SM

$+ g_{\pi a} a$

$\eta \to \eta^0 + g_{\eta a} a$

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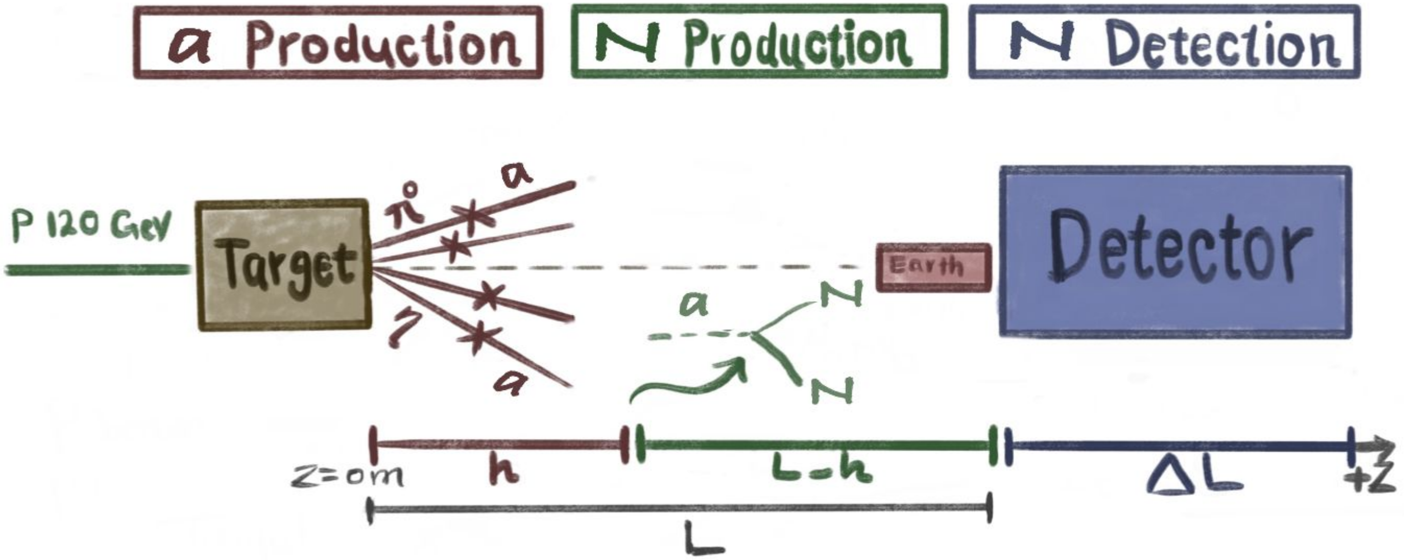
HNL production via ALP

Option: Decoupled production and detection mechanisms

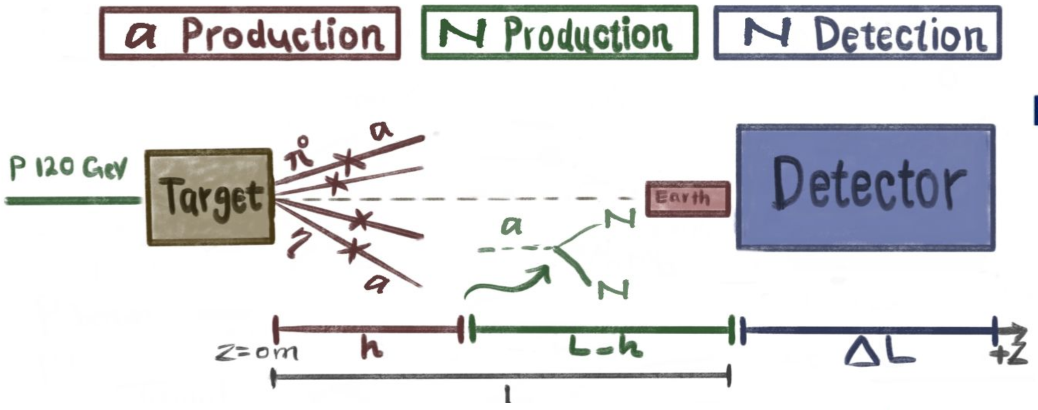


$$\pi^0 = \pi^0_{phys} + \theta_a a$$

→ **Depends on the Dark Sector properties (e.g. mass, etc)**

HNL production via ALP

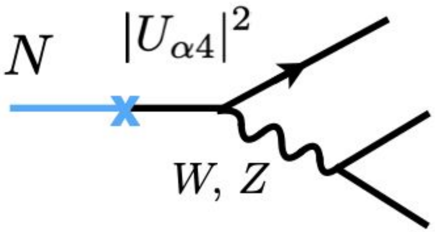
Option: Decoupled production and detection mechanisms



HNL event rate ~ $\theta_a^2 |U_\alpha|^2$

- Enhanced wrt the usual HNL if $\theta_a^2 \gg |U_\alpha|^2$
- Different angular distributions

HNL can decay inside the detector as usual



Our through a new mediator, e.g. Z'

HNL production via ALP

Theoretical realization:

"Dark Matter and Neutrino Mass from the Smallest Non-Abelian Chiral Dark Sector"
J. M. Berryman, A. de Gouvea, K. J. Kelly, Y. Zhang
ArXiv: 1706.02722 [hep-ph]

2 The Model

Following the results discussed in detail in Ref. [5], $SU(3) \times SU(2)$ is the smallest, non-abelian, chiral gauge theory that does not contain a $U(1)$ gauge group. The minimal* fermion content is

$$Q_D(3,2), \quad u_D^c(\bar{3},1), \quad d_D^c(\bar{3},1), \quad L_D(1,2), \tag{2.1}$$

$$\mathcal{L} \supset \frac{g_2}{2\sqrt{2}} \left[\bar{q}_1\gamma_\mu(1-\gamma_5)q_2 X_+^\mu + \bar{q}_2\gamma_\mu(1-\gamma_5)q_1 X_-^\mu\right] + \frac{g_2}{4}\left[\bar{q}_1\gamma_\mu(1-\gamma_5)q_1 - \bar{q}_2\gamma_\mu(1-\gamma_5)q_2\right] X_3^\mu, \tag{2.5}$$

where $X_\pm^\mu = (X_1^\mu \mp iX_2^\mu)/\sqrt{2}$. In section 4.1, we will introduce dark pions, composite states made of a dark quark and a dark antiquark. We will define $\{\pi_D^+, \pi_D^0, \pi_D^-\} = \{q_1\bar{q}_2, (q_1\bar{q}_1 - q_2\bar{q}_2)/\sqrt{2}, q_2\bar{q}_1\}$, *i.e.*, the "charge" assignments correspond to the sign of the quark couplings to X_3 (third-component of dark $SU(2)$).

HNL production via ALP

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Following the results … iral

gauge theory that doe …

… 2.1)

$$\mathcal{L} \supset \frac{g_2}{2\sqrt{2}} \left[\bar{q}_1 \gamma_\mu (\ldots _2\right] X_3^\mu, \qquad (2.5)$$

Disclaimer:

This is a pheno talk. Discussion is general and not tied to any specific model

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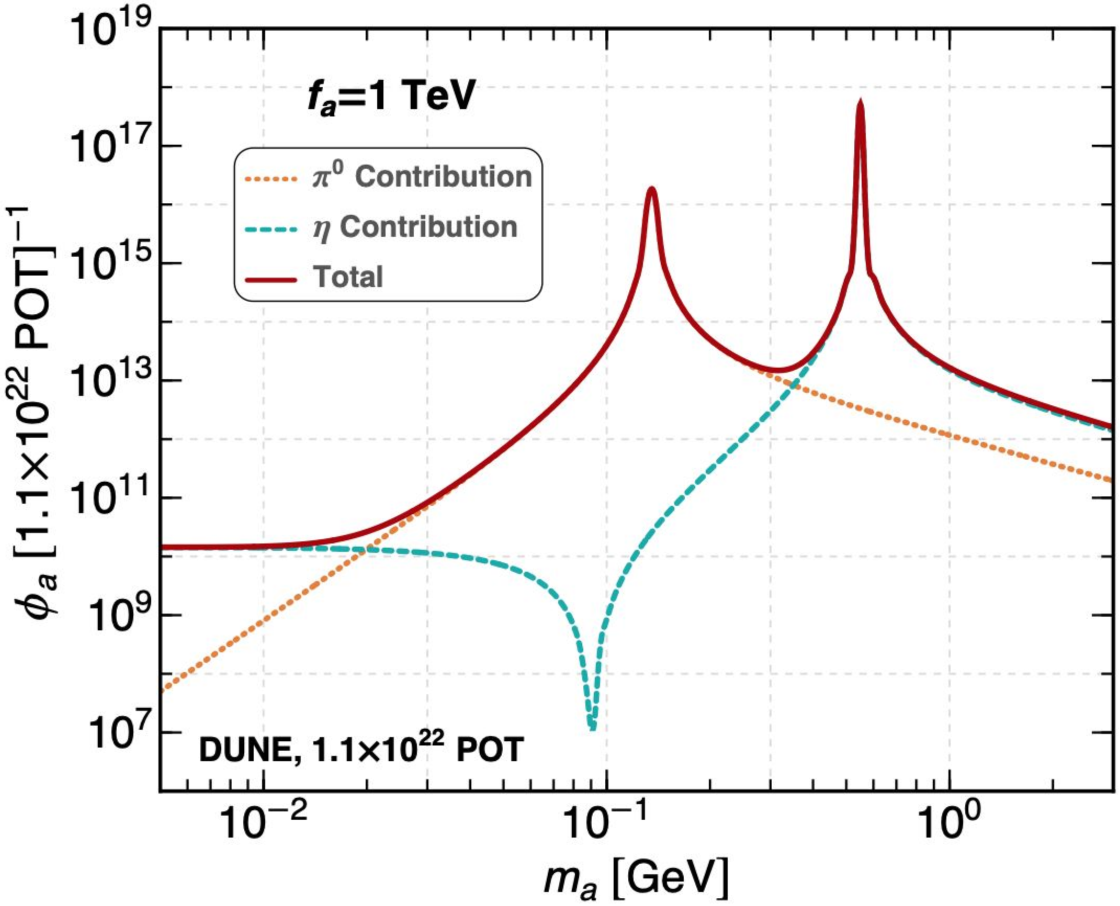
ALP flux

Contributions from:

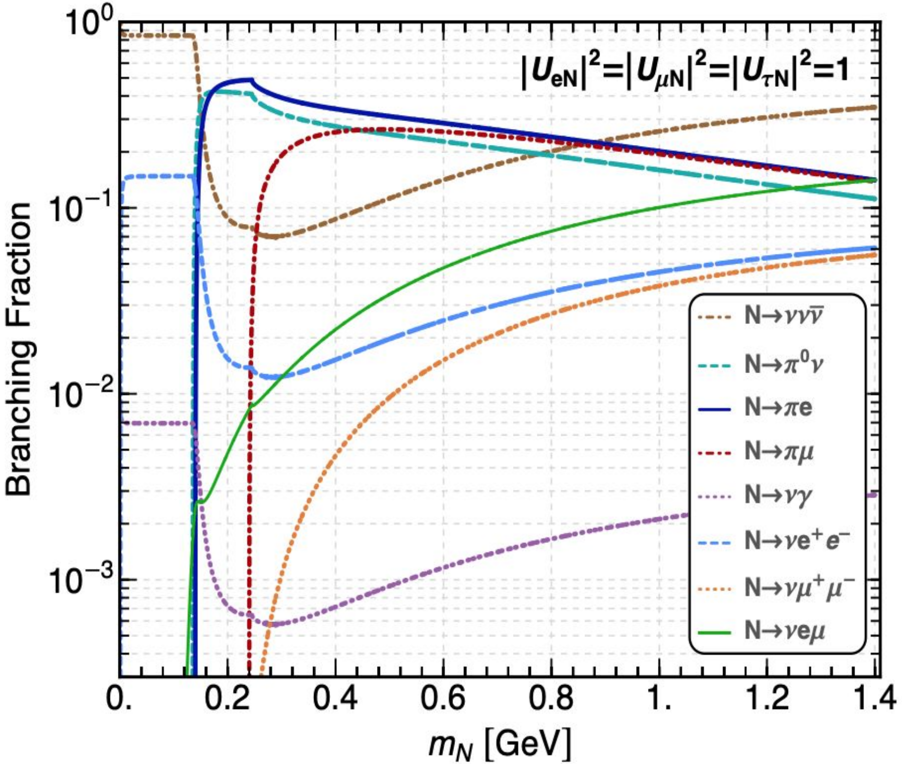
$$\pi^0 \to \pi^0 + g_{\pi a} a\,,$$
$$\eta \to \eta^0 + g_{\eta a} a\,,$$

To obtain ALP flux

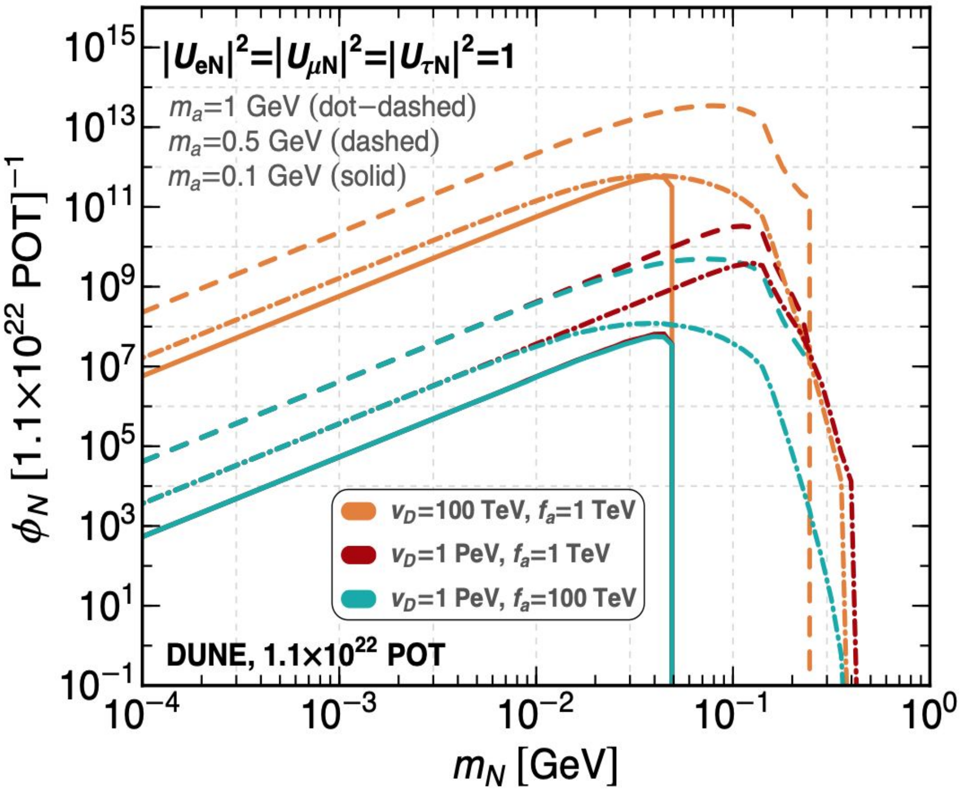
$$\frac{d^2\phi_a}{dE_a d\theta_a} = g^2_{\mathbf{m}a} \frac{E_a}{E_\mathbf{m}} \frac{d^2\phi_\mathbf{m}}{dE_\mathbf{m} d\theta_\mathbf{m}}$$



HNL flux

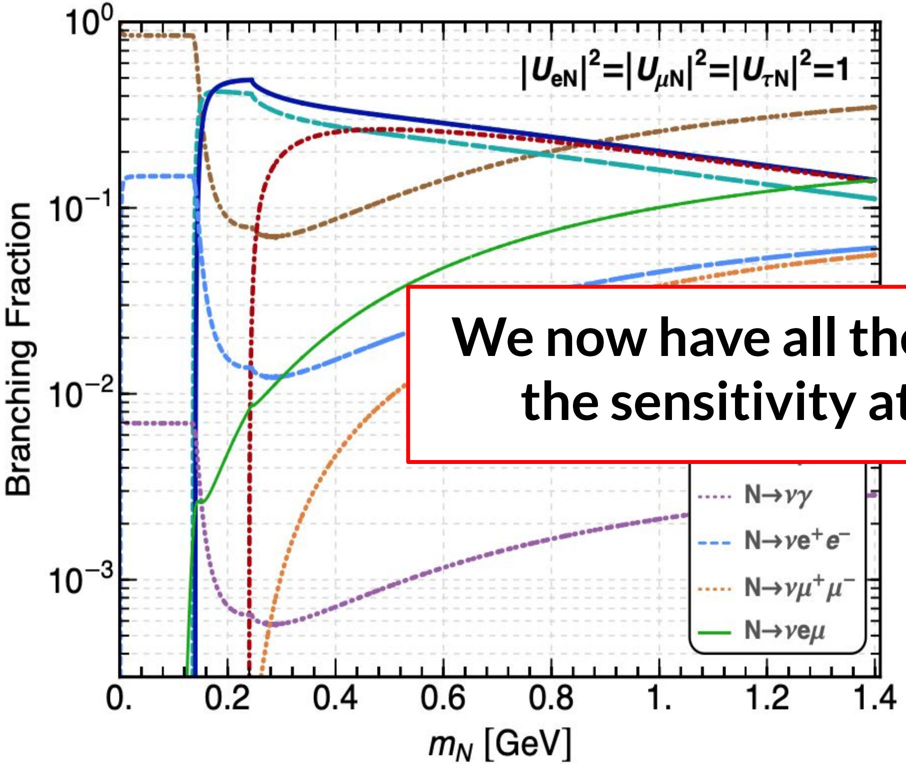


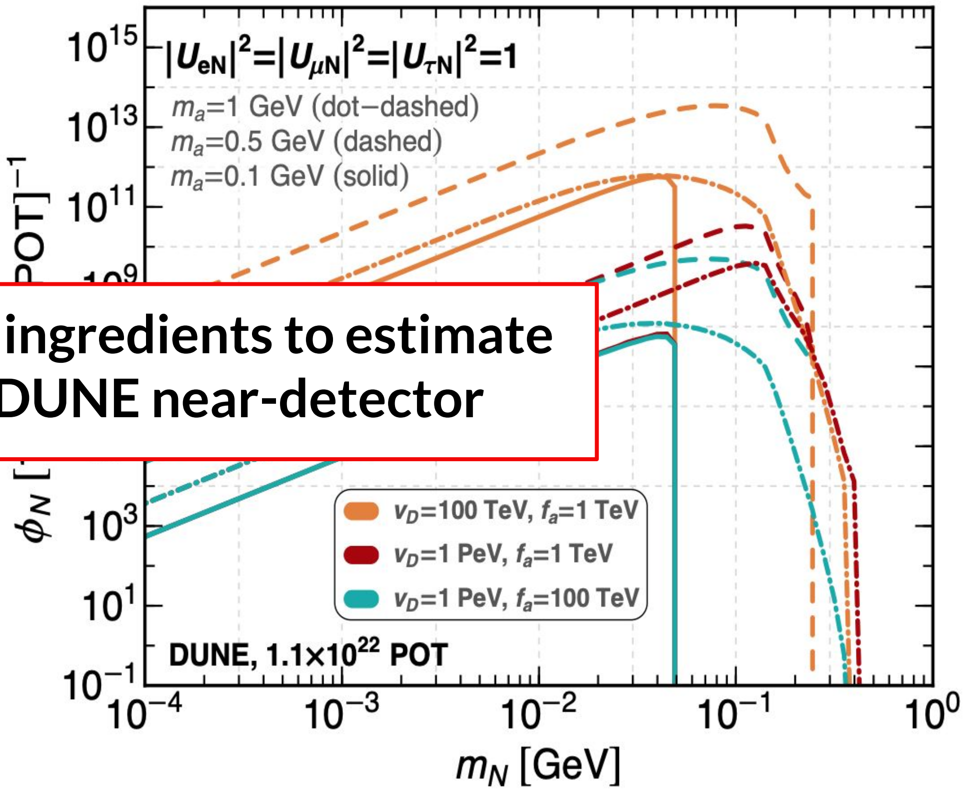
$|U_{eN}|^2=|U_{\mu N}|^2=|U_{\tau N}|^2=1$
Branching Fraction
m_N [GeV]
N→$\nu\nu\bar{\nu}$
N→$\pi^0\nu$
N→πe
N→$\pi\mu$
N→$\nu\gamma$
N→νe^+e^-
N→$\nu\mu^+\mu^-$
N→$\nu e\mu$



$|U_{eN}|^2=|U_{\mu N}|^2=|U_{\tau N}|^2=1$
m_a=1 GeV (dot−dashed)
m_a=0.5 GeV (dashed)
m_a=0.1 GeV (solid)
ϕ_N [1.1×10^{22} POT]$^{-1}$
v_D=100 TeV, f_a=1 TeV
v_D=1 PeV, f_a=1 TeV
v_D=1 PeV, f_a=100 TeV
DUNE, 1.1×10^{22} POT
m_N [GeV]

HNL flux

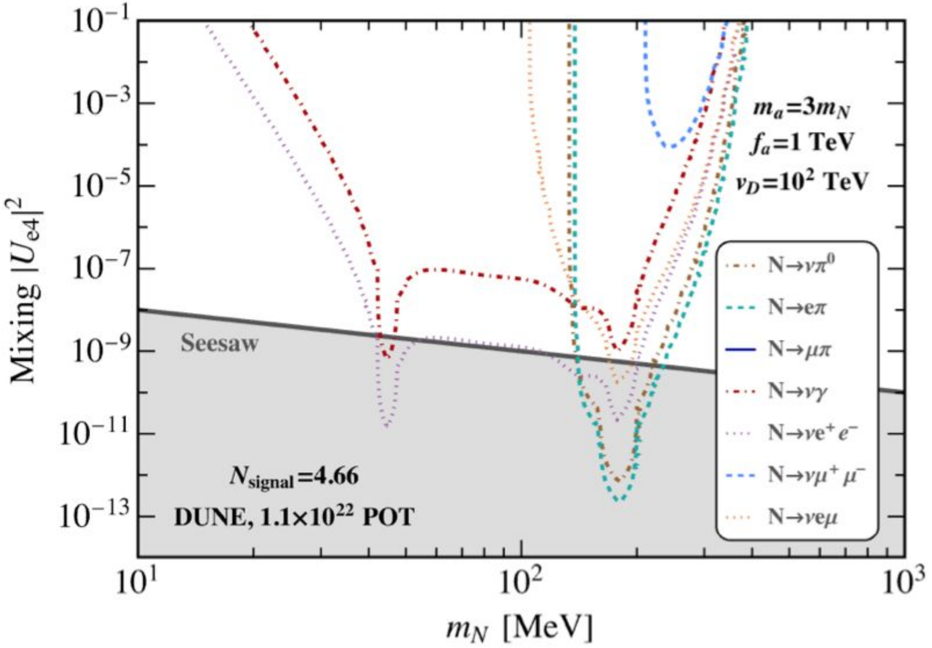


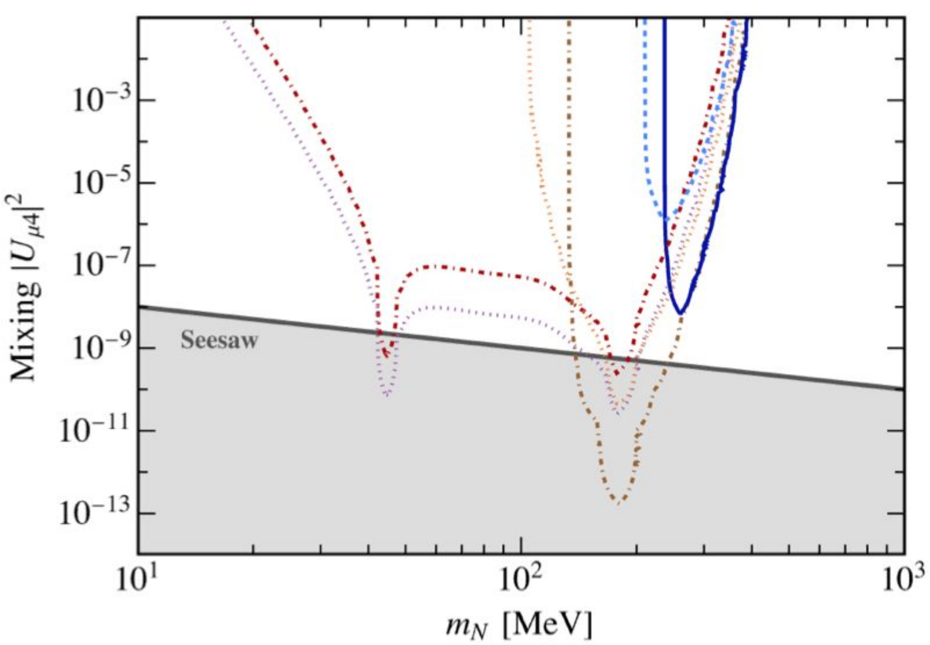


We now have all the ingredients to estimate the sensitivity at DUNE near-detector

Sensitivity at DUNE

Potential sensitivity to the seesaw region!



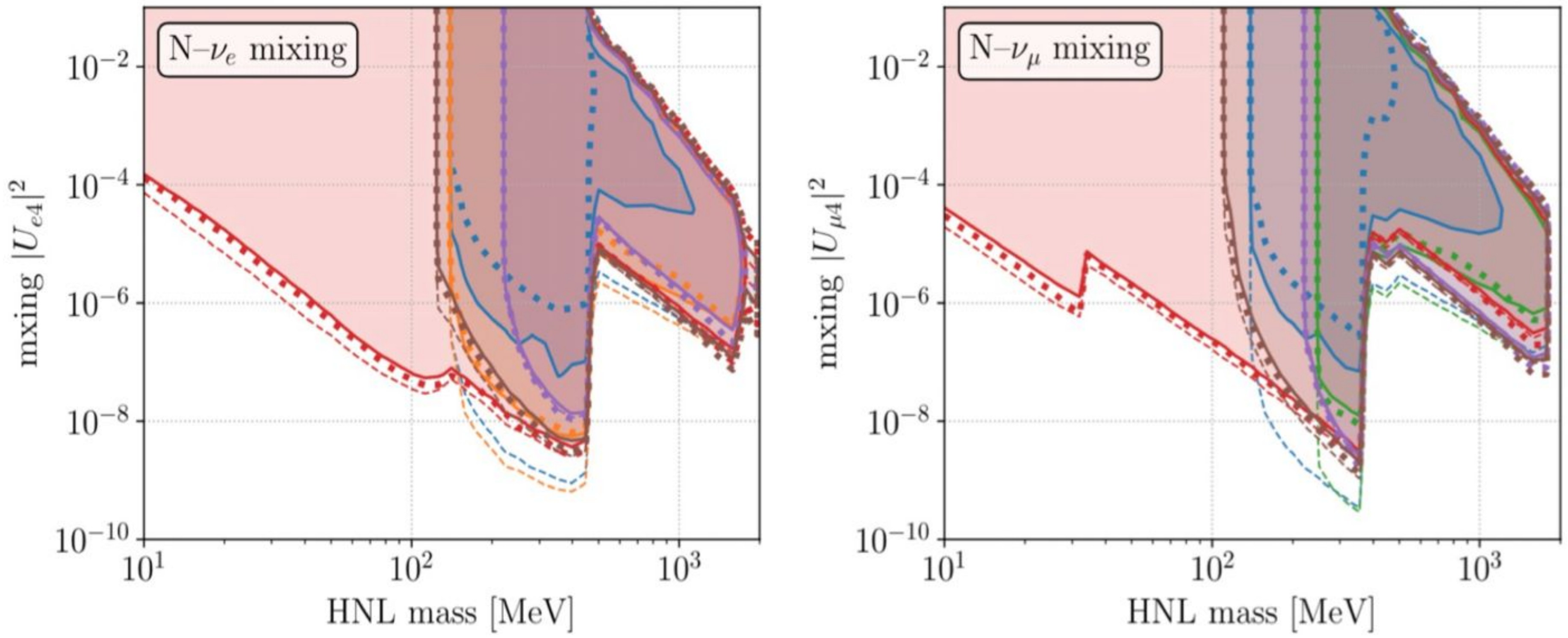


Sensitivity doesn't vary significantly between flavours

Sensitivity at DUNE

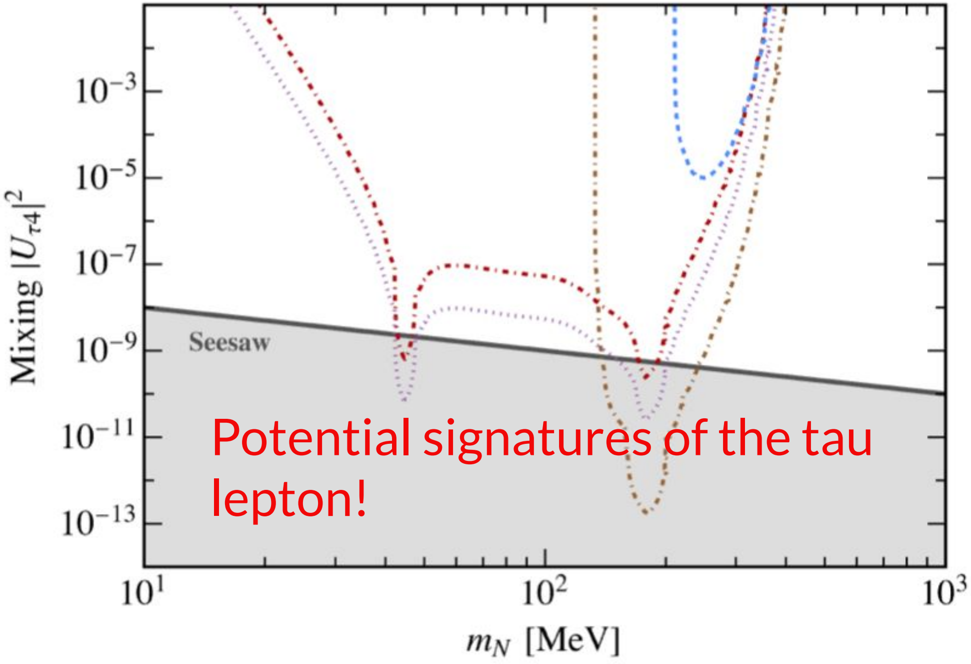
Breitbach, Buonocore, Frugiuele, Kopp, Mittnacht, JHEP (2022)

$$|\mathbf{U}_{e4}|^2 \sim 7|\mathbf{U}_{\mu4}|^2$$



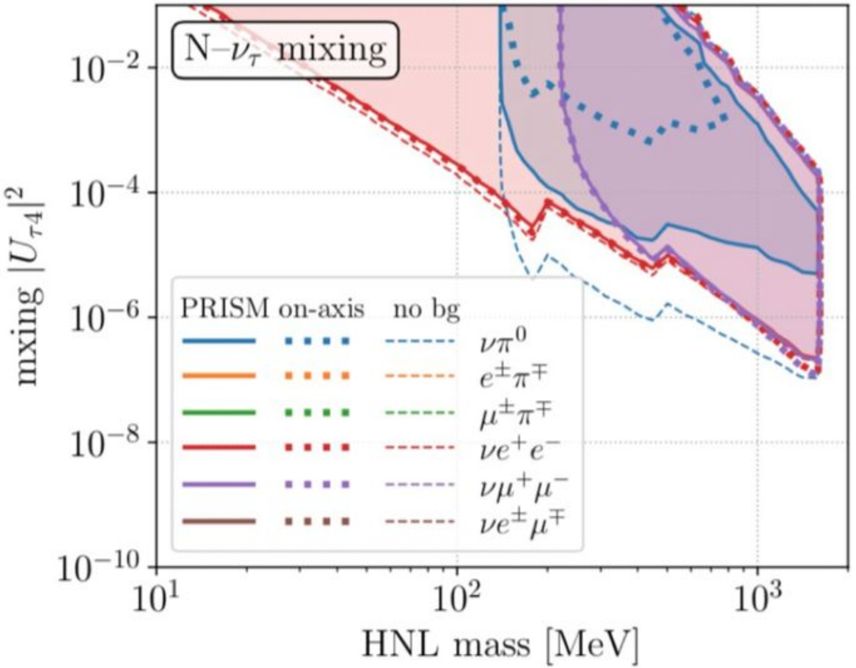
Sensitivity at DUNE

Weak dependence on flavour **significant** for tau mixing



Potential signatures of the tau lepton!

$$|\mathbf{U}_{\tau 4}|^2 \sim 10^3 |\mathbf{U}_{\mu 4}|^2$$



Main Takeaways

- Neutrino experiments are excellent place to search for new physics
  → *large flux of charged and neutral mesons*

- Minimal HNL models face strong mixing suppression

- Decoupling the production and detection can enhance HNL production rate

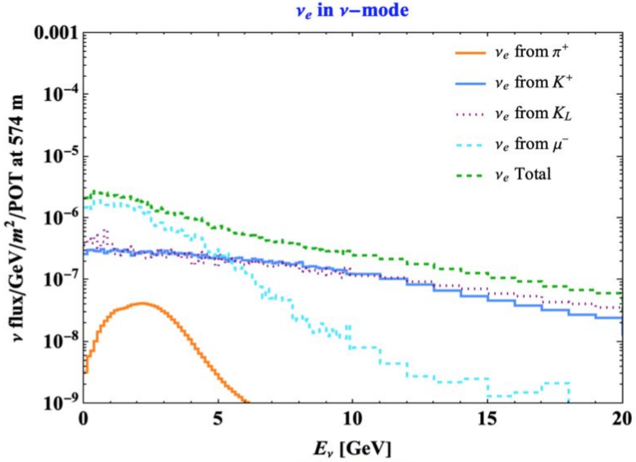
- Production flavour insensitive

- Potentially strong sensitivities as DUNE ND-like experiments

Thank you for your attention!

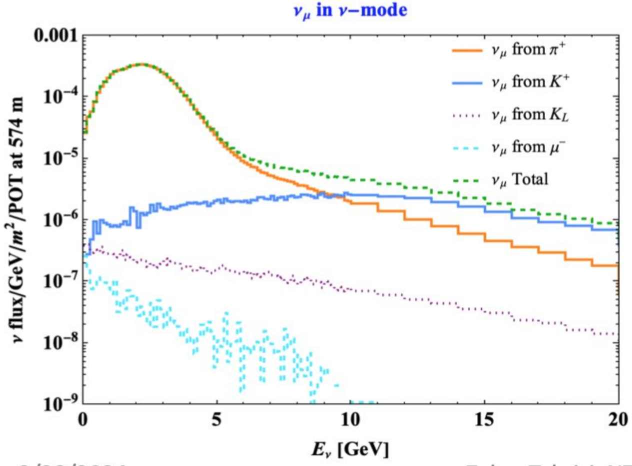
Back-up

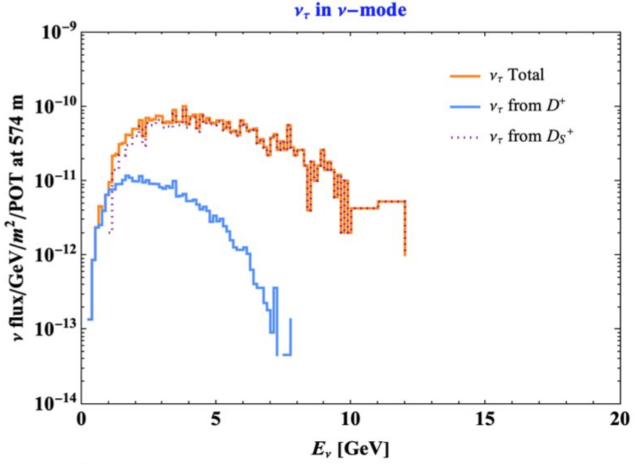
SM neutrino fluxes



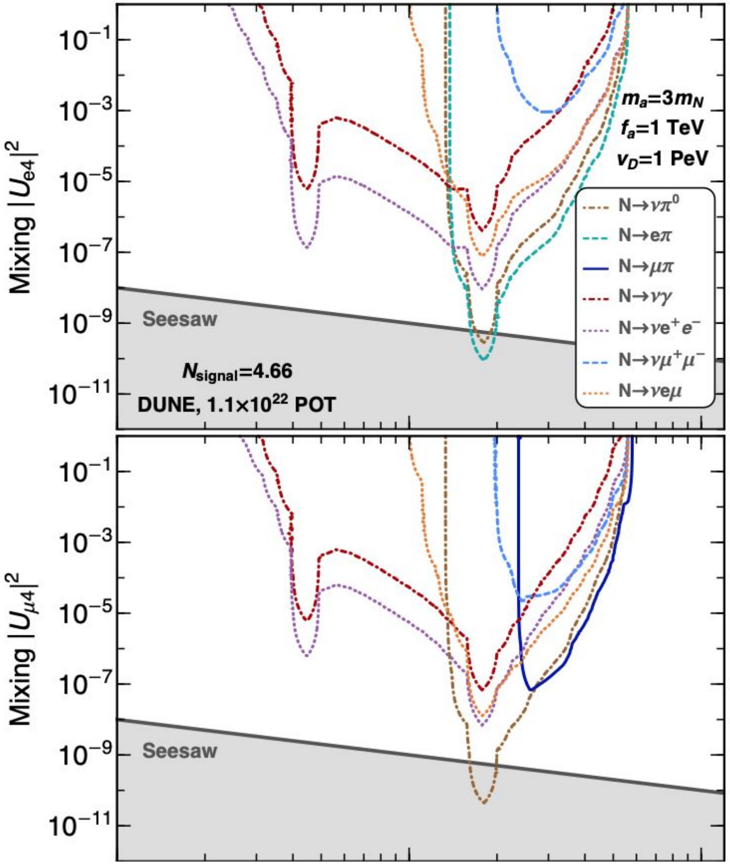
Neutrino fluxes dependent on kaon, pion and charmed meson fluxes which vary significantly

$$\phi_{\nu_e} \sim 2\times10^{-2}\ \phi_{\nu_\mu} \sim 10^4 \phi_{\nu_\tau}$$





Sensitivity at DUNE



$$v_D = 10^3 \text{ TeV}$$