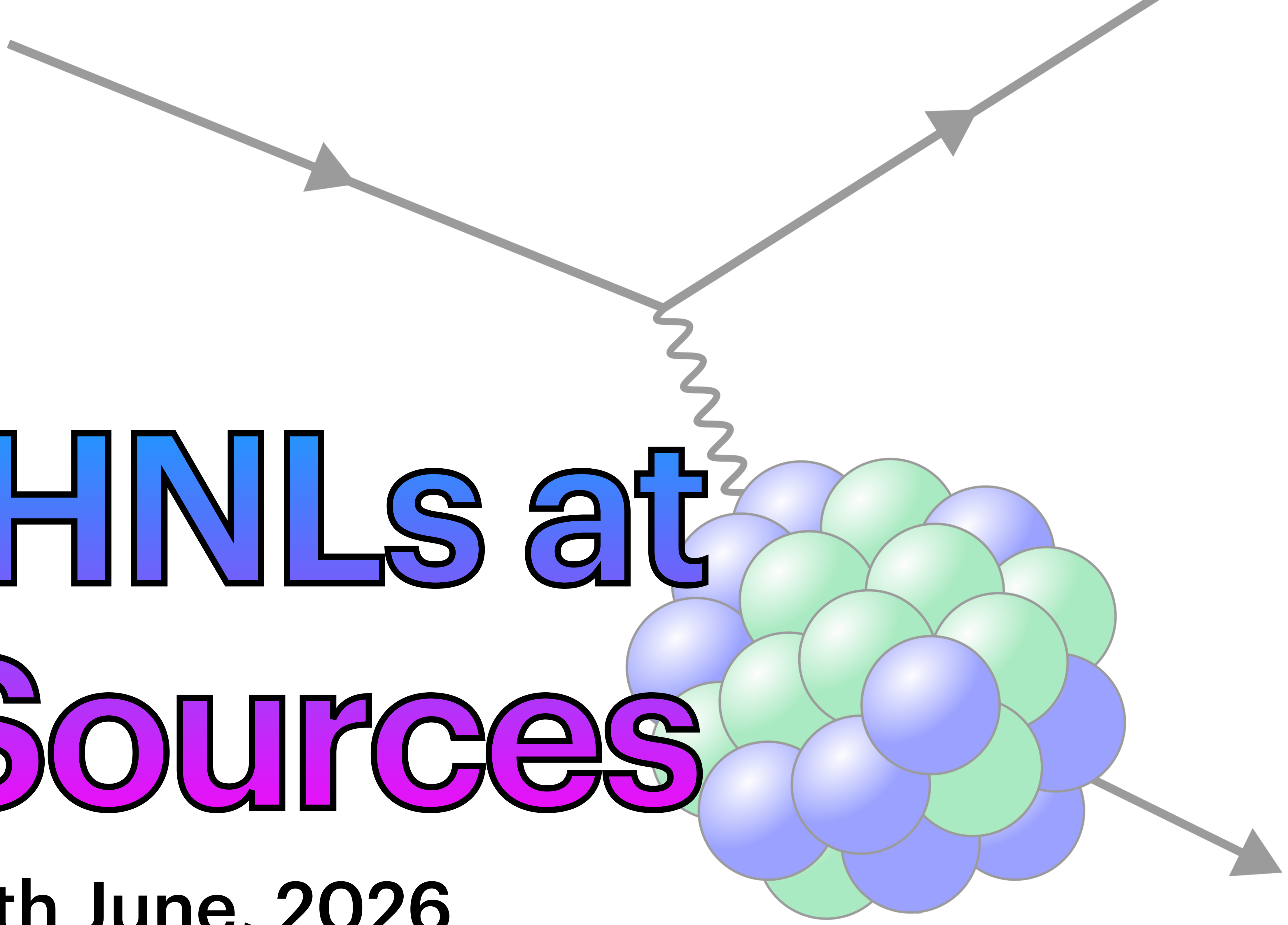
Long-lived HNLs at Spallation Sources



IRN Neutrino meeting, 2th June, 2026

IJCLab Orsay, France

Based on arXiv:2606.XXXXX in collaboration with Valentina De Romeri, Alfredo Galindo-Uribarri, Víctor Martín Lozano and Gonzalo Sánchez García

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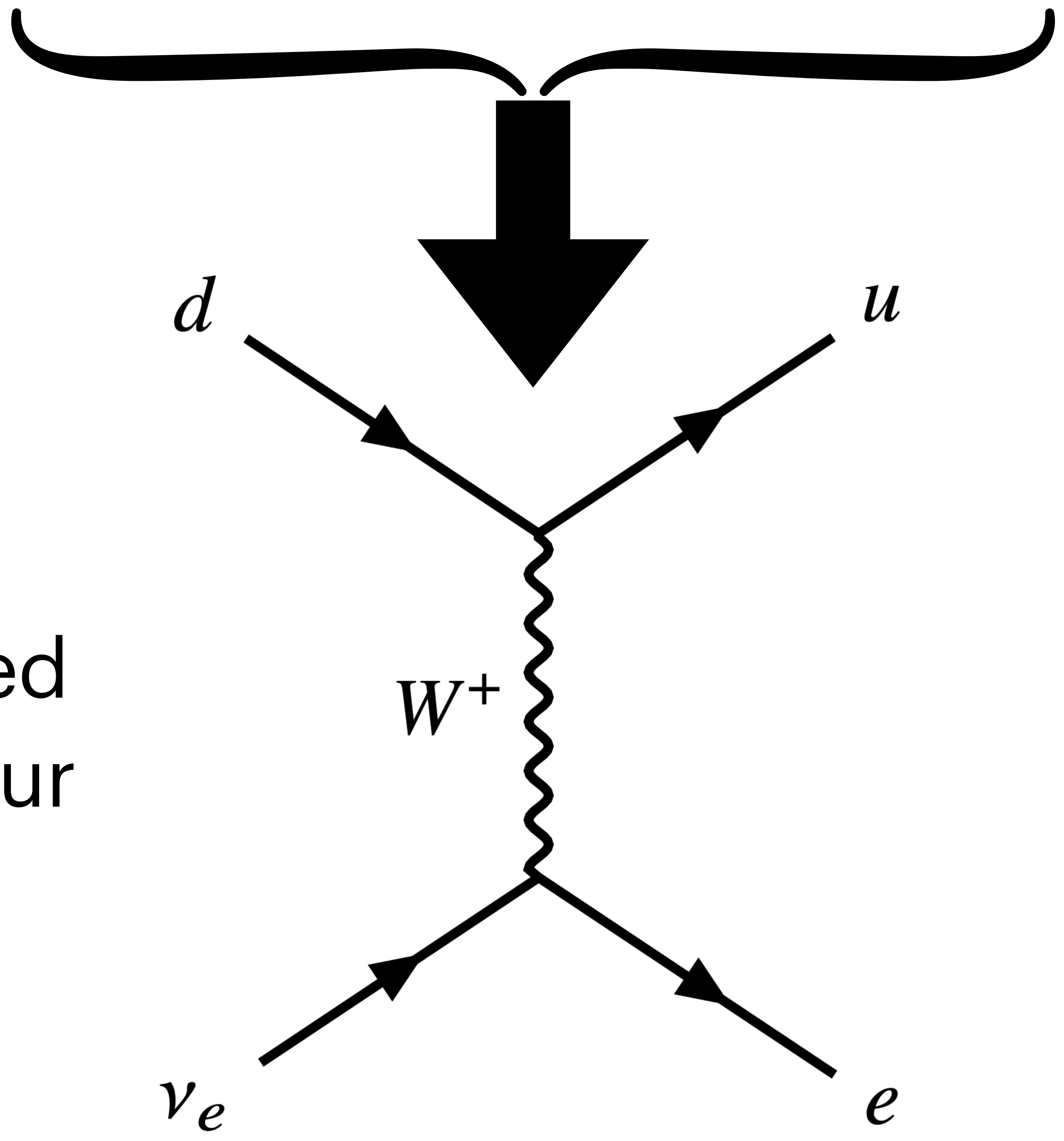
Neutrinos in the Standard Model

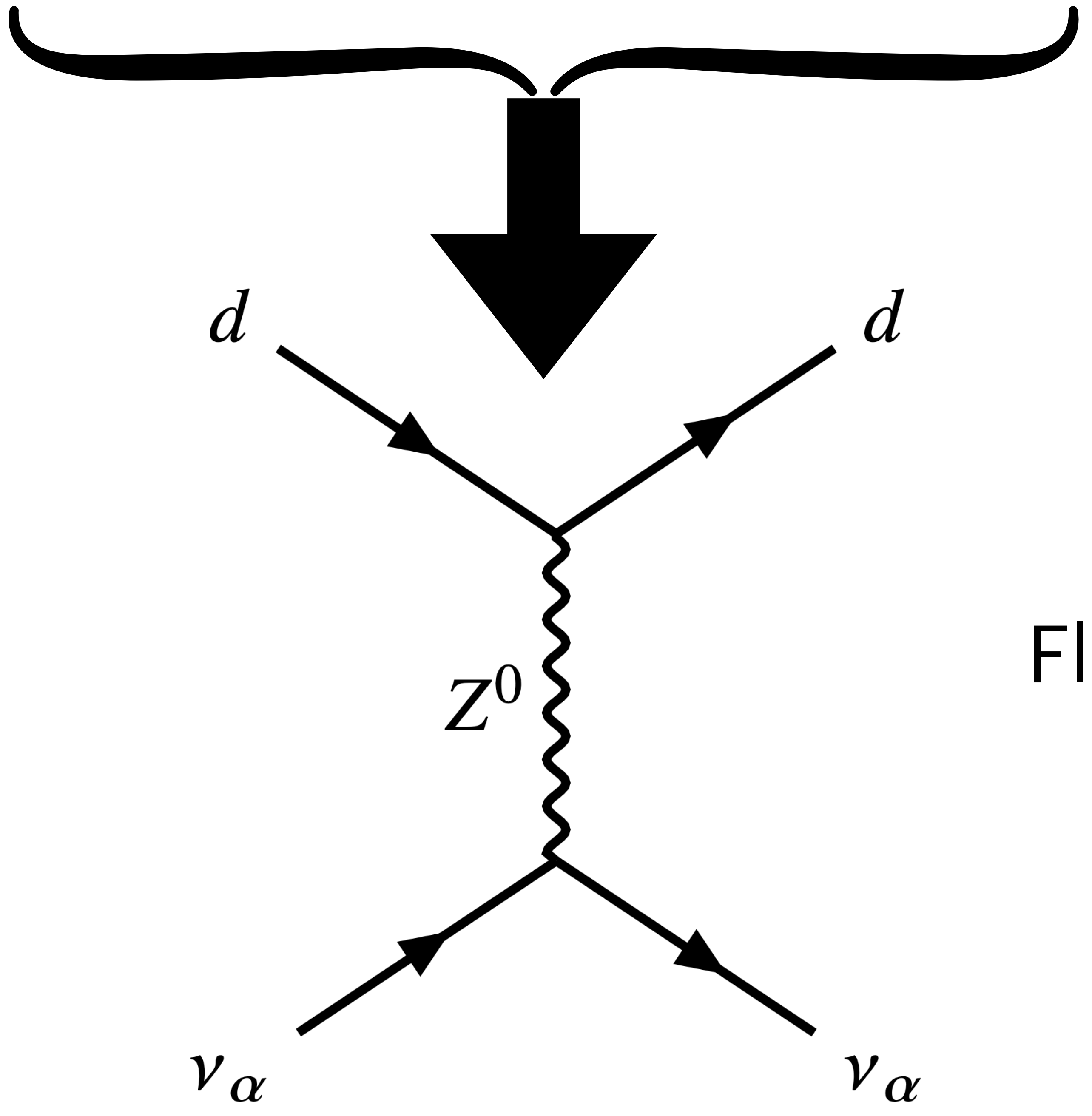
Neutrinos in **SM** are **massless** and **weakly interacting**:

$$\mathscr{L}_{SM} \subset -\frac{g}{\sqrt{2}}\sum_{\alpha}\bar{\nu}_{\alpha L}\gamma^{\mu}\ell_{\alpha L}W_{\mu} - \frac{g}{2\cos\theta_W}\sum_{\alpha}\bar{\nu}_{\alpha L}\gamma^{\mu}\ell_{\alpha L}Z_{\mu} + h.c.$$

Lepton and neutrino produced of the same flavour



Charged current (CC)



Neutral current (NC)

Flavour blind

Nonetheless, we know at least two of three light neutrino are **massive** ⟶ Physics beyond SM!

Heavy neutral leptons

One of the simplest extensions of SM is to **add** (at least) **two fermionic singlets** or **HNLs** that mix with the SM neutrinos:

$$\nu_\ell = U_{\ell N} N + \sum_{i=3}^{3} U_{\ell i} \nu_i$$

In the **minimal HNL Lagrangian** the charged and neutral current interactions with the SM leptons are defined as

$$\mathscr{L} \supseteq -\frac{g}{\sqrt{2}} U^*_{\ell N} \overline{\ell} W^-_\mu \gamma^\mu P_L N - \frac{g}{2\cos\theta_W} U^*_{\ell N} \overline{\nu}_\ell Z_\mu \gamma^\mu P_L N + \mathrm{h.c.}$$

$U_{\ell N} \ll 1$ ⟶ Long-Lived Particle

Our case: **only one of the HNLs is** kinematically accesible, which **mixes** with the light states. We assume them to be **pseudo-Dirac** with Majorana mass term negligible, $m_N \lesssim 1$ GeV.

E. Fernández-Martínez, M. González-López, J. Hernández-García, M. Hostert, J. López-Pavón [2304.06772]

Current limits on HNLs

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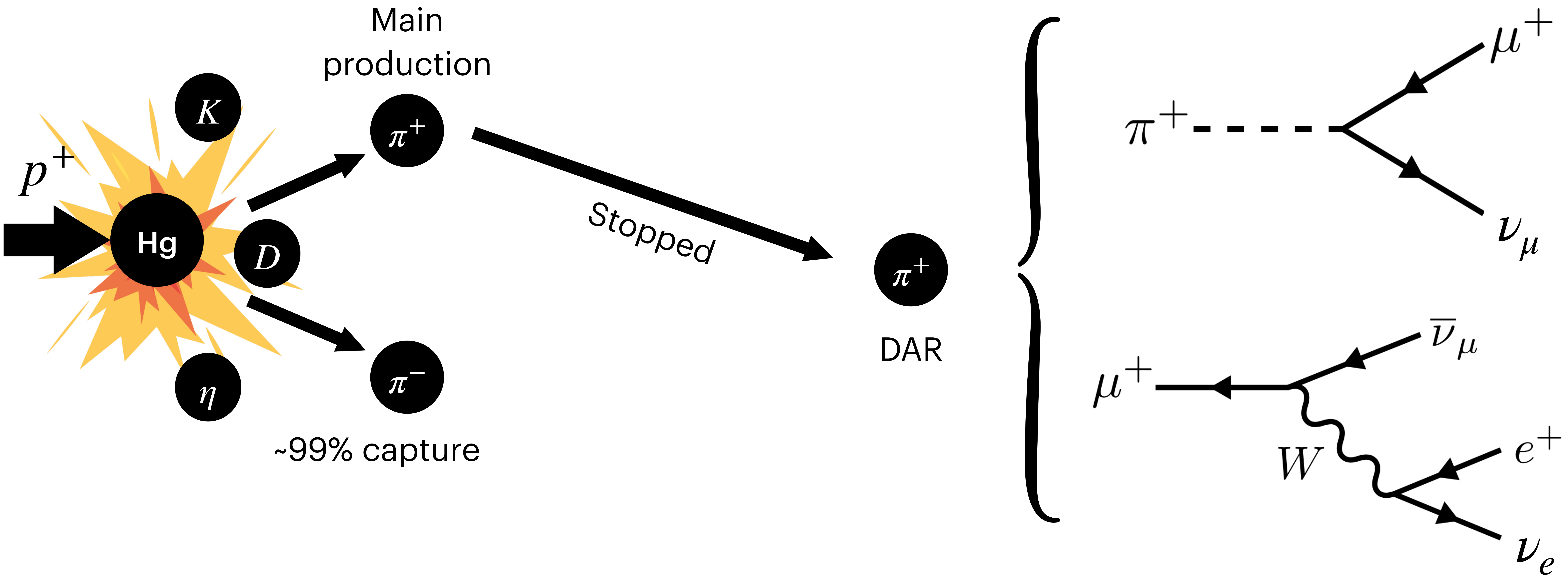
Parameter space **potentially accesible** via **spallation sources**!

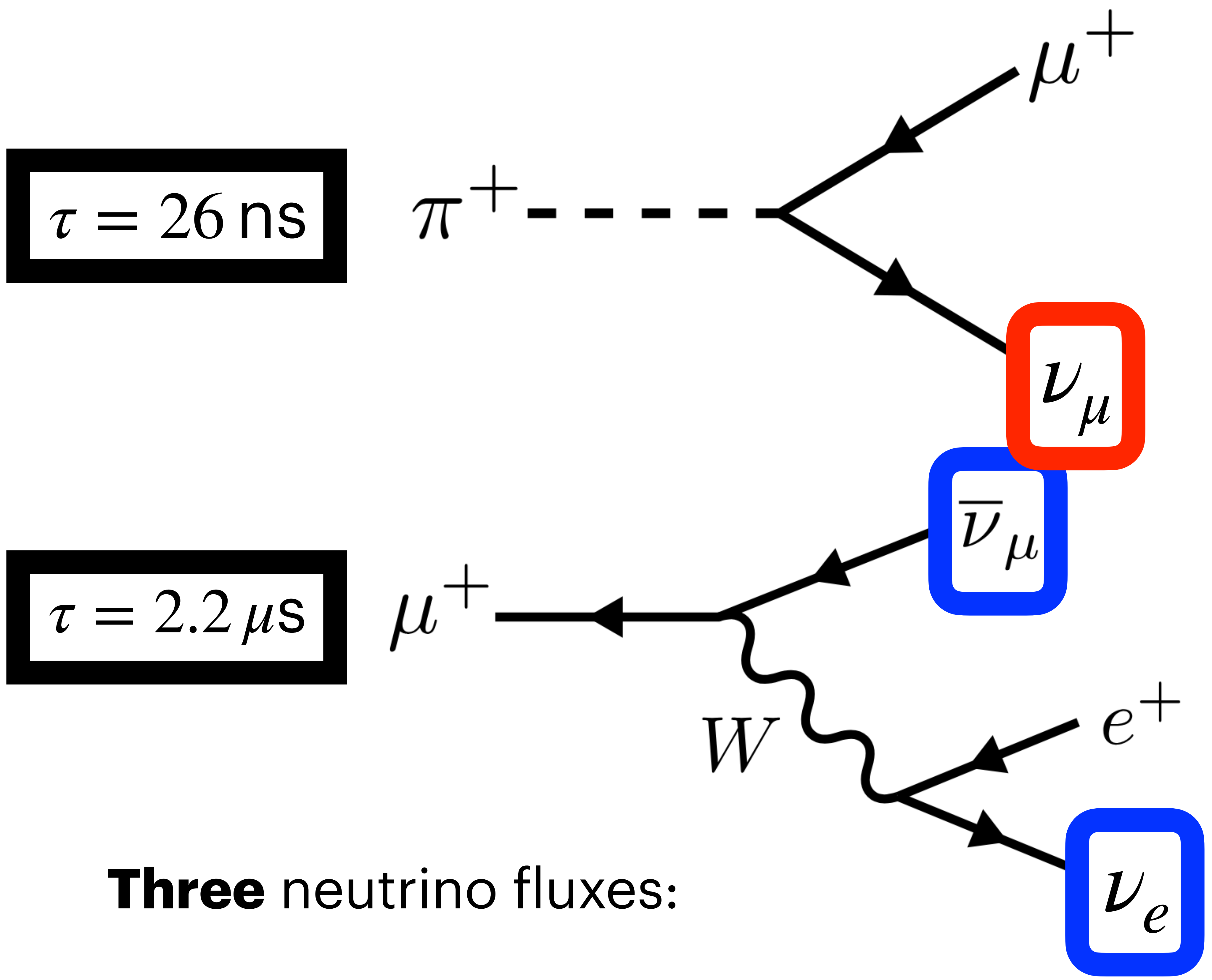
SM neutrinos from stopped π at spallation sources

Pions as byproduct in spallation sources. **Three SM neutrino fluxes** produced from these pions.



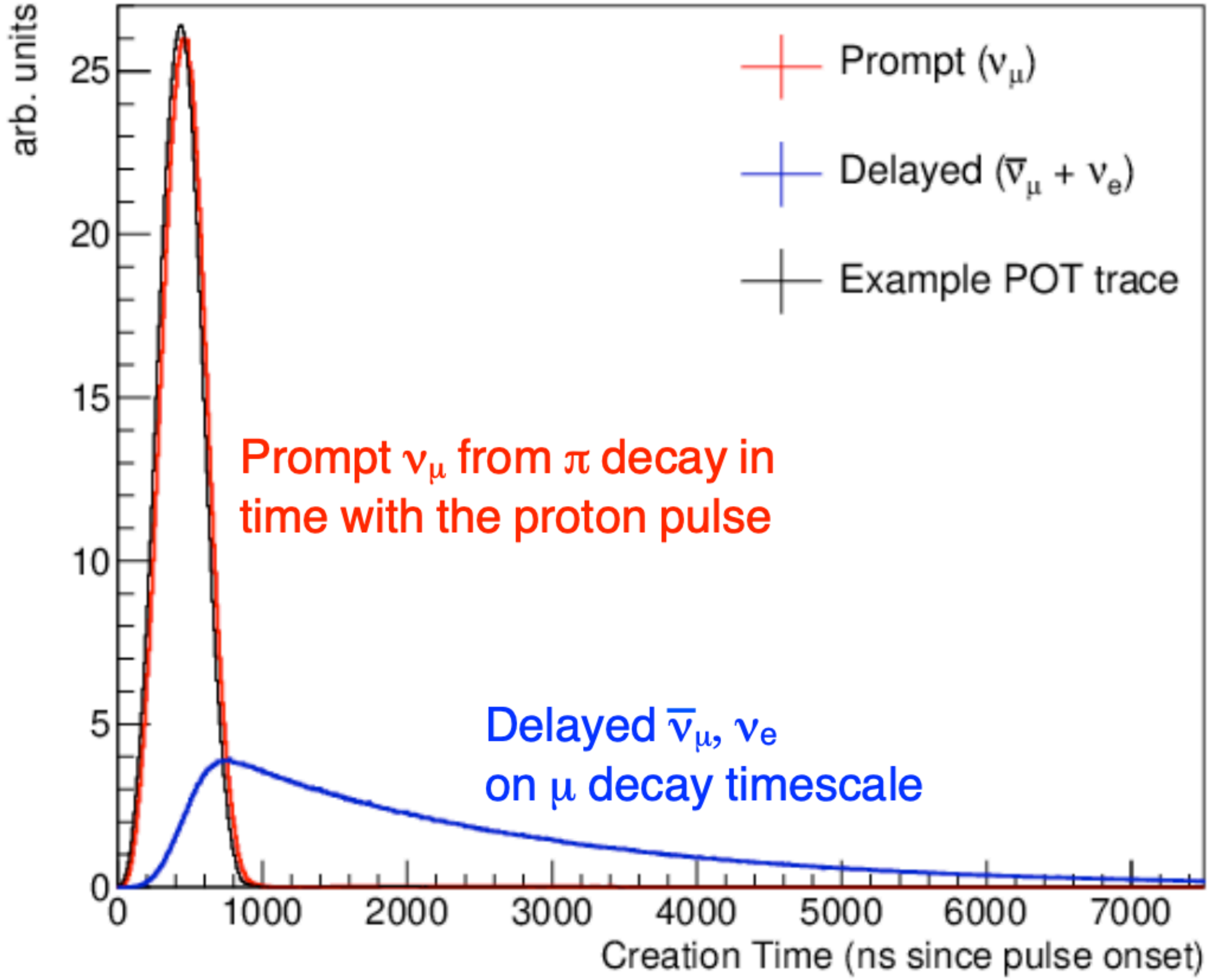
Timing of the SM neutrino signal

Pulsed beam and **arriving time of the neutrinos** help us to **distinguish** between **contributions** and **backgrounds**.



Three neutrino fluxes:

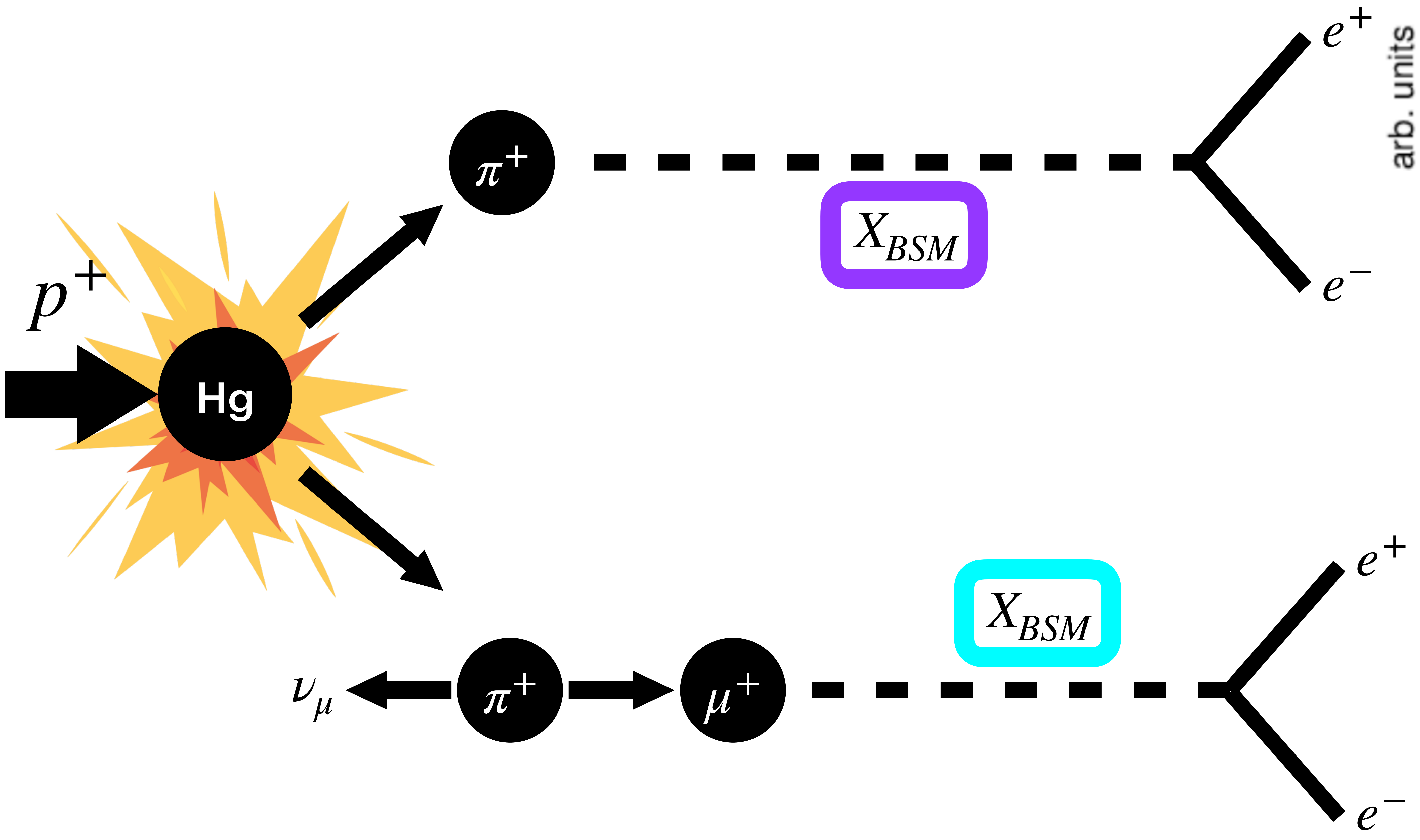
- **1 prompt**
- **2 delayed**

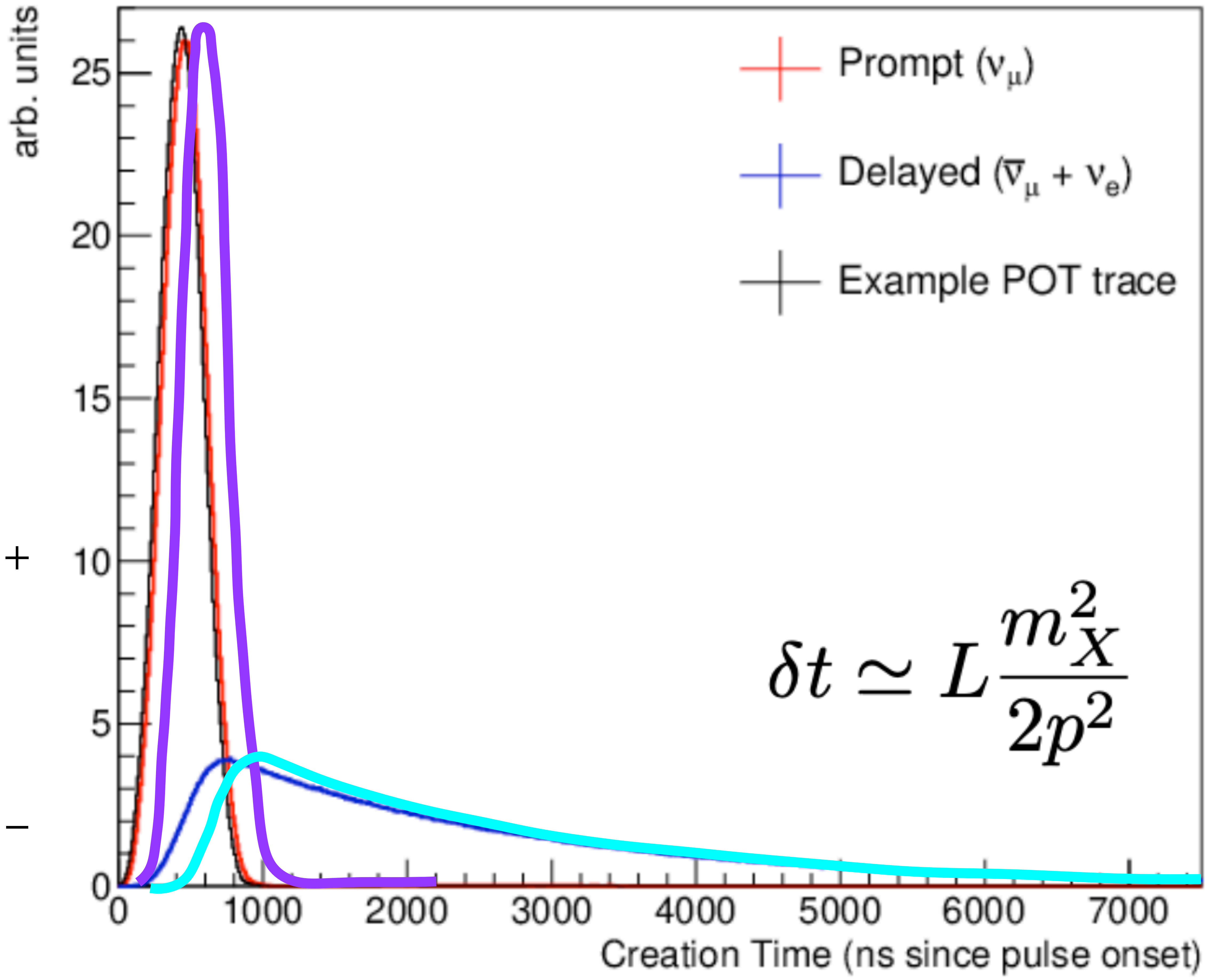


M. Hostert, S. Urrea [2509.14085]

Spallation sources and physics BSM

Heavy new physics would give us a **delayed signal** with respect to the SM neutrino flux.





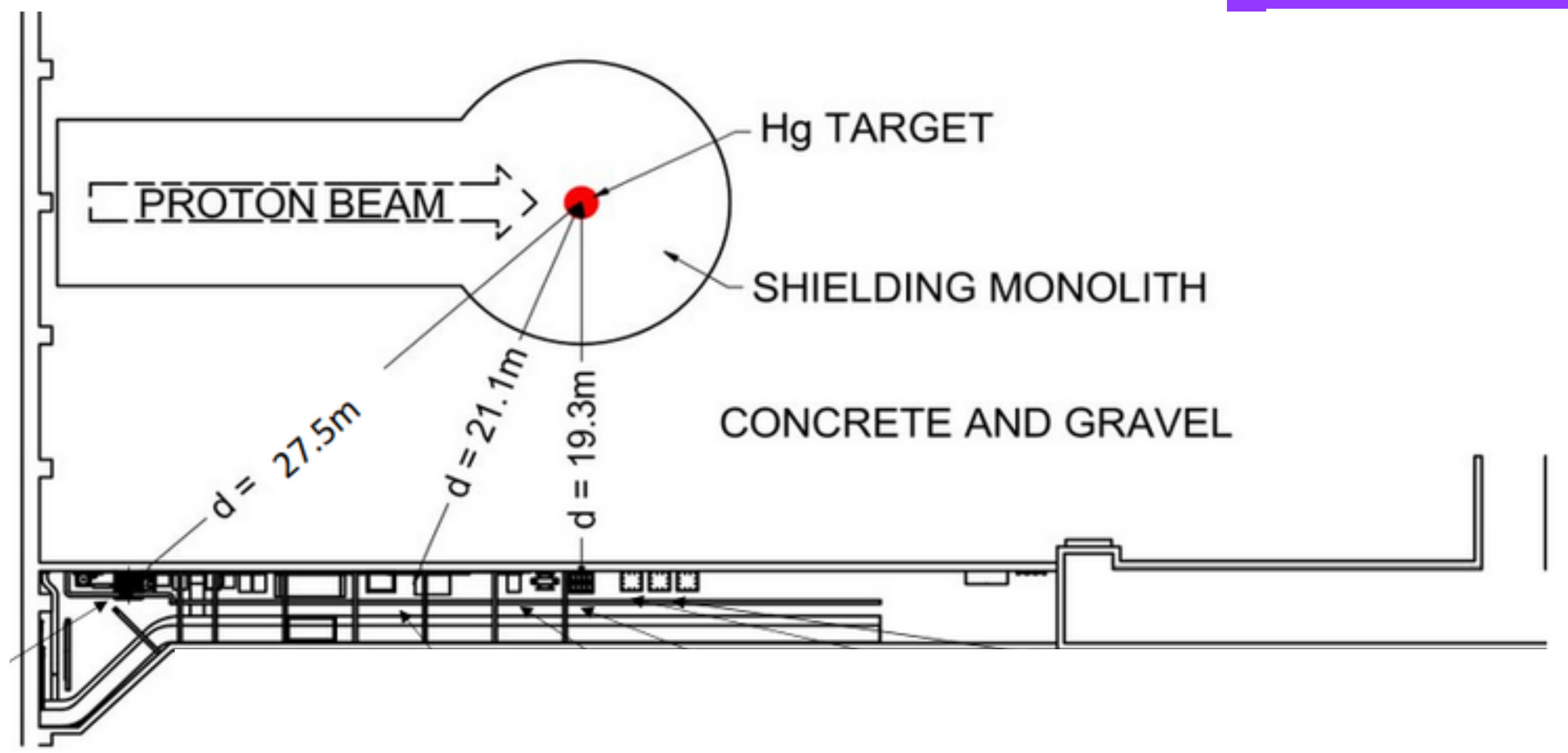
Spallation sources we consider

Spallation sources we consider

SPALLATION NEUTRON SOURCE

Beam characteristics:

- Mercury target
- $(1.0 \to 1.7 \to 2.0)$ MW
- $(1 \to 1.3)$ GeV p^+
- $(9\,\% \to 11\%)$ πDAR/POT



In this talk I will focus on SNS!

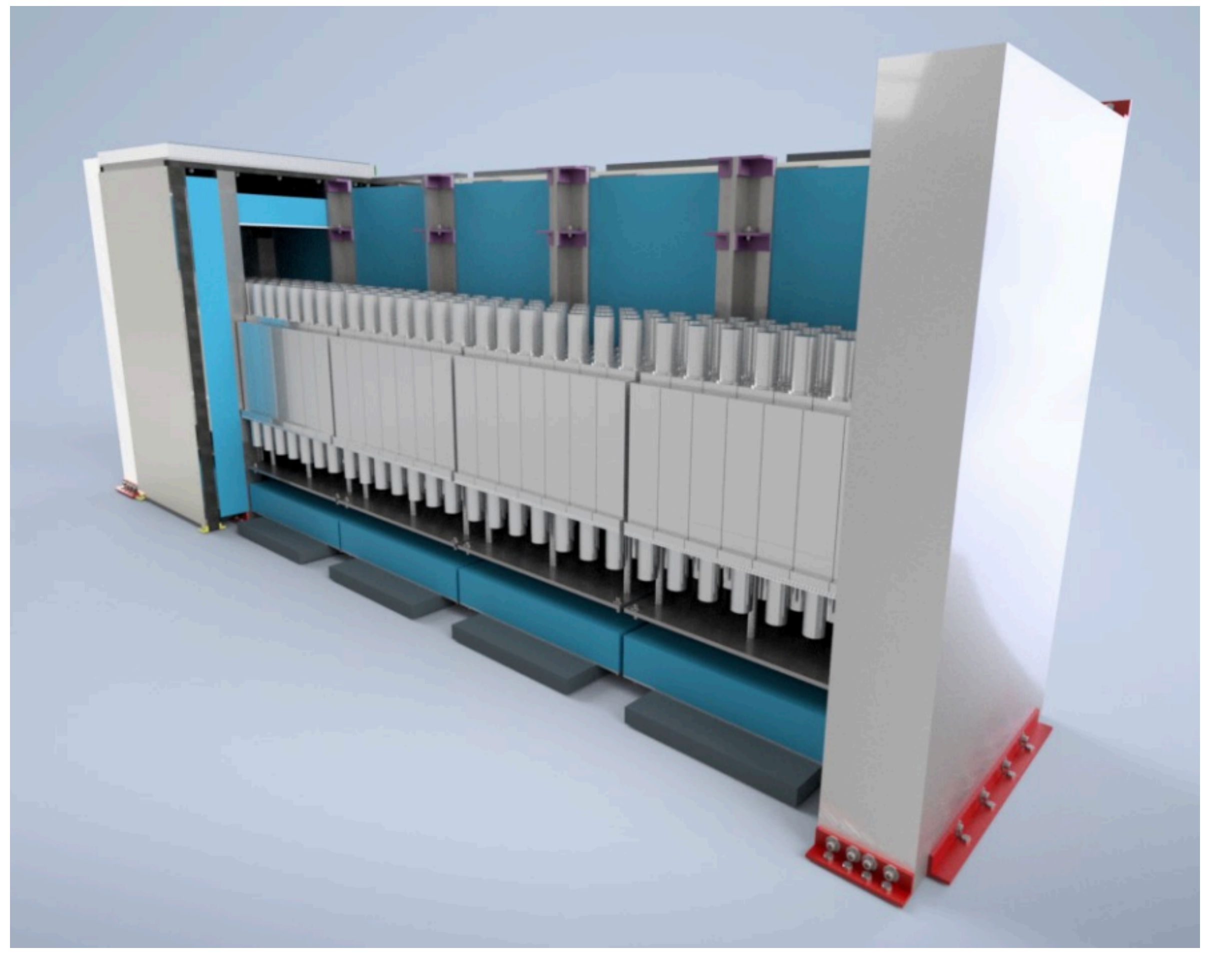
COHERENT Collaboration [2602.15652]
[2204.04575v1]
[2406.13806]

COHERENT experiment

COHERENT was built with CEνNS detection in mind.
Nevertheless, BSM searches **could** be performed.

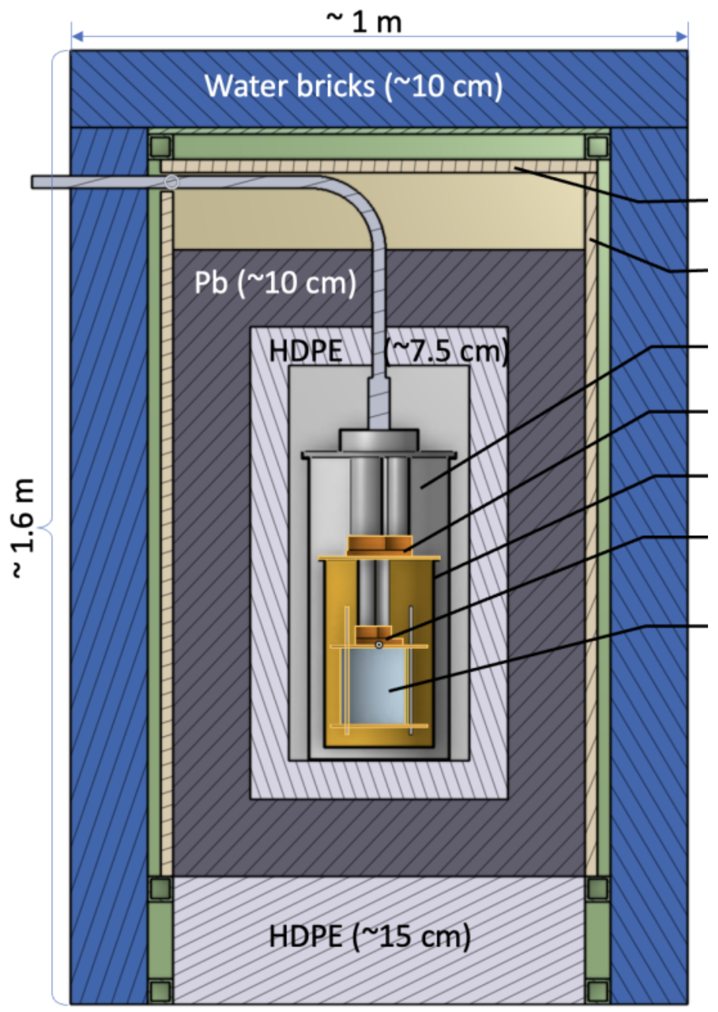
A priori good features for LLP detection:

- Volume
- Flux
- Distance
- Backgrounds

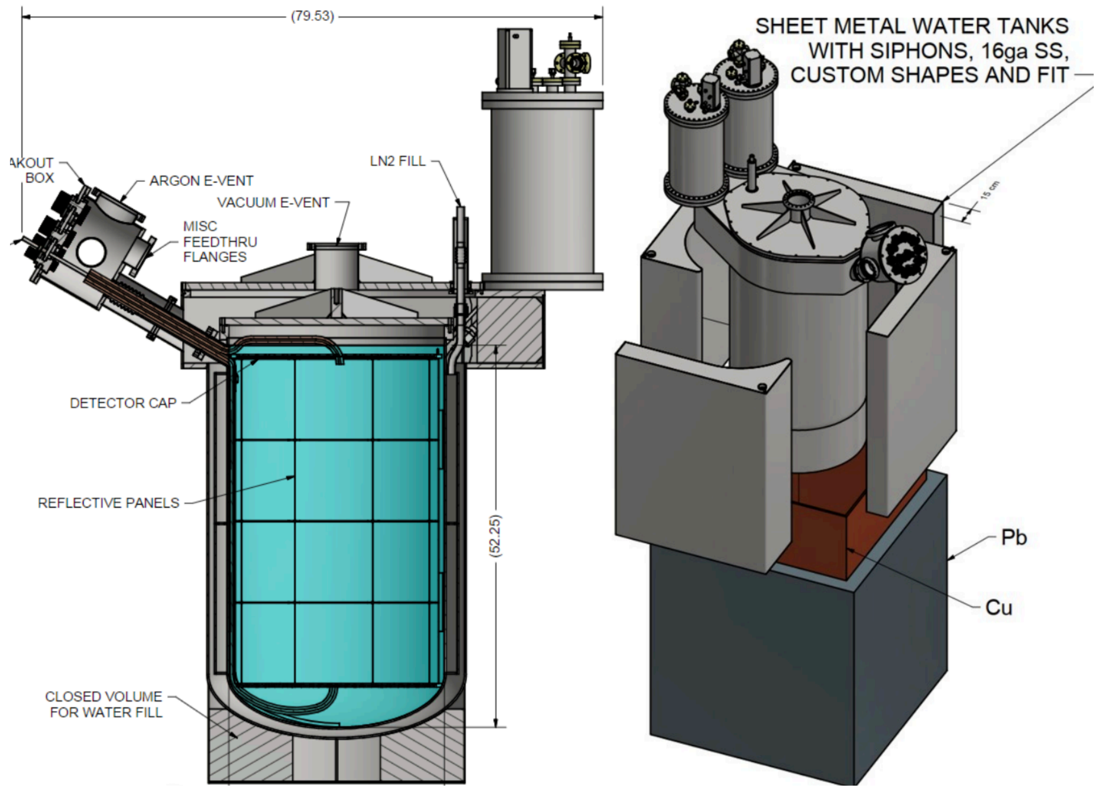


NaIvETE

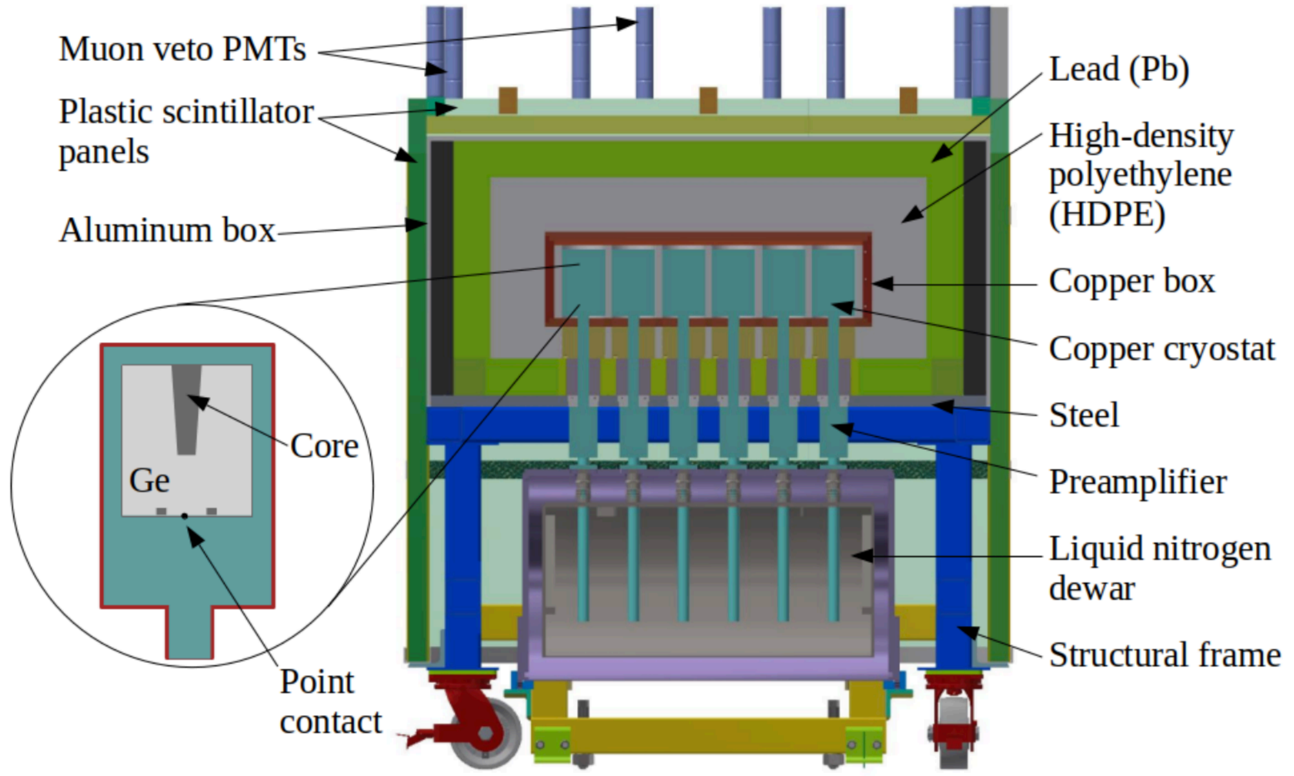
D_2O+H_2O



Cryo-CsI



LAr



Ge-mini

Setup considered

COHERENT Collaboration [2602.15652]
COHERENT Collaboration [2603.17951]

From running data

Detector	Total N^{POT}	c_{π^+}	Mass [Kg]
Ge	4.68×10^{22}	0.09	8.53
NaI v1	1.728×10^{23}	0.11	2400
NaI v2			3500
LAr			476
D2O+H2O			1000
cryo-CsI-1			10
cryo-CsI-2			100
LAr-750			750
LAr-10t			1000

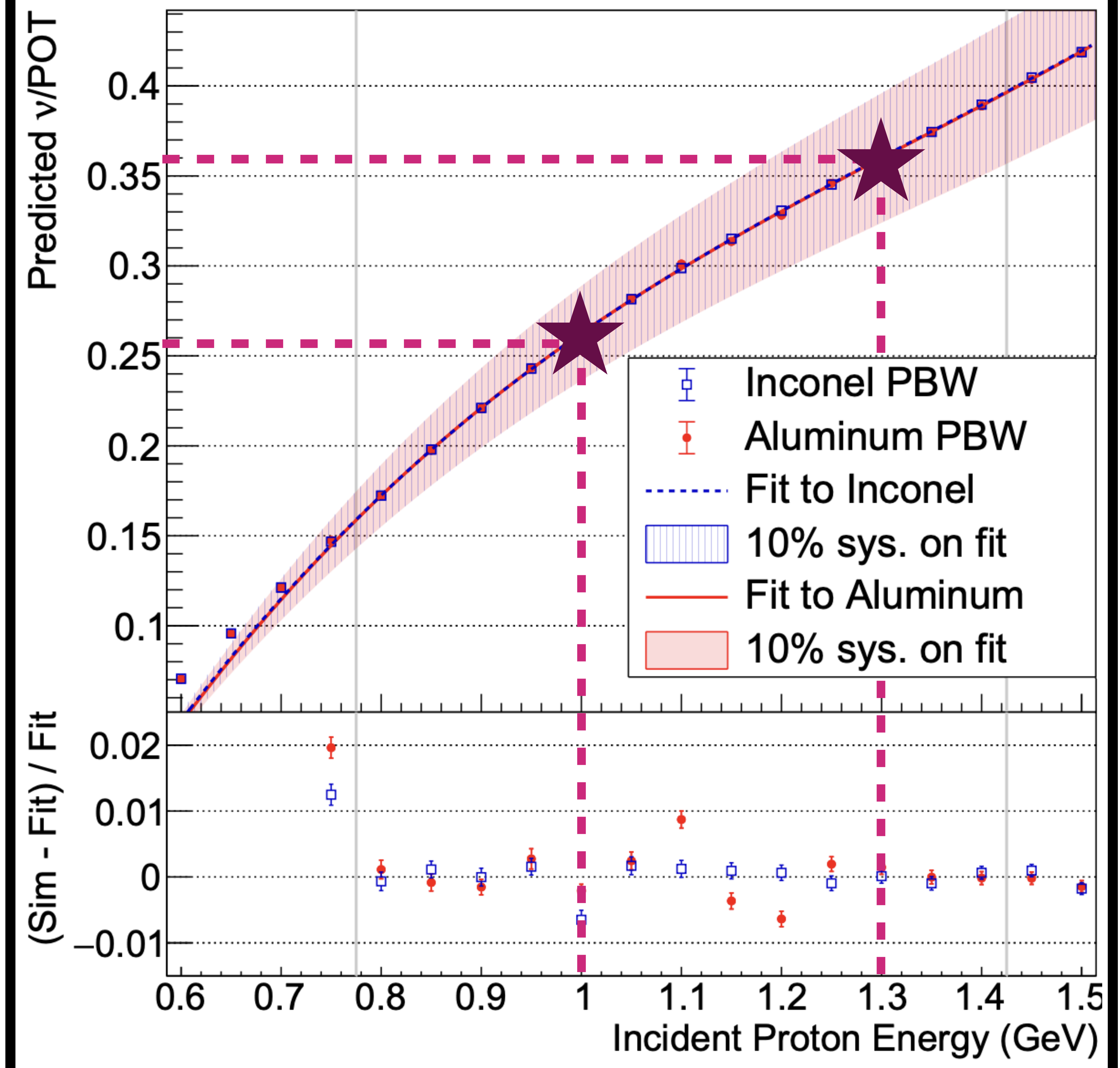
Running or near future (Ge, NaI v1, NaI v2, LAr)

Proposals for future experiments (D2O+H2O, cryo-CsI-1, cryo-CsI-2, LAr-750, LAr-10t)

Preliminary setup

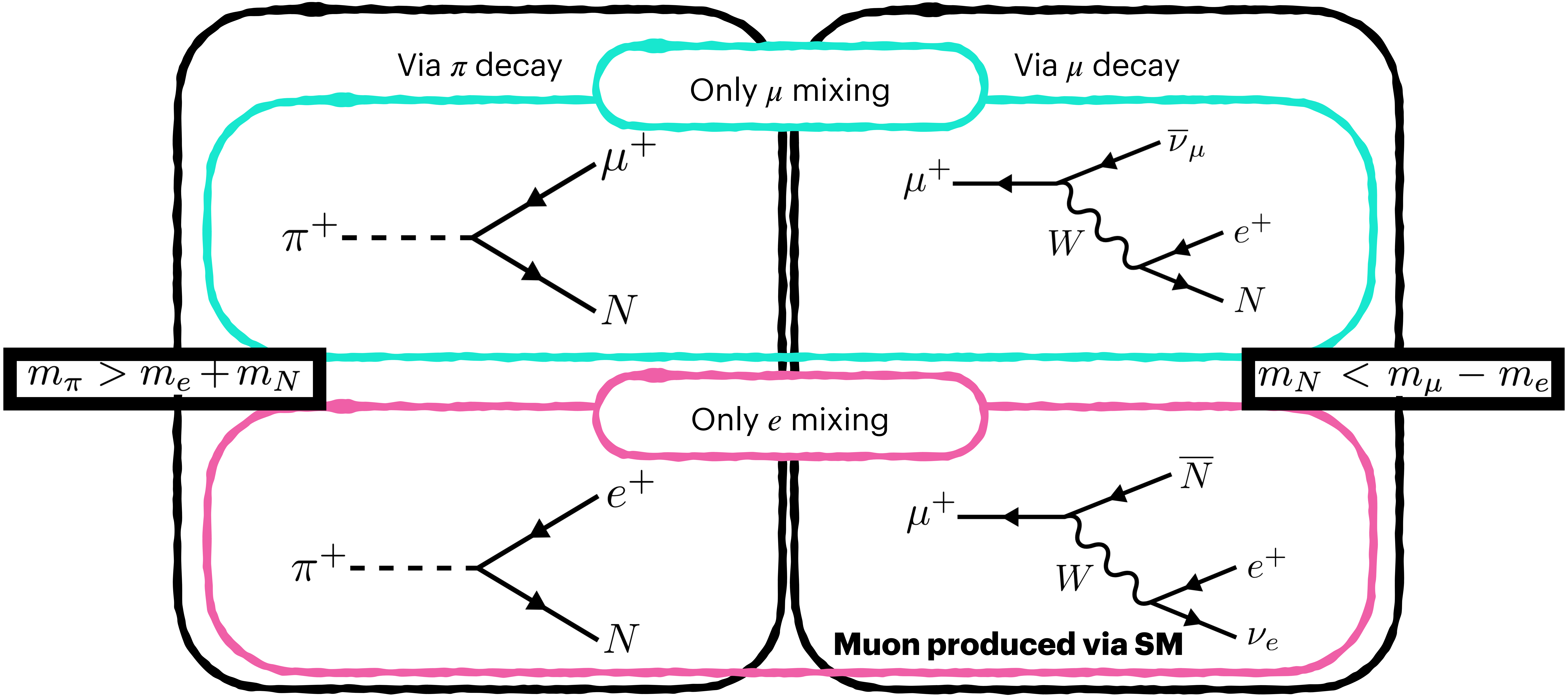
$$N^{POT} \propto \frac{P[\text{MW}]}{E[\text{GeV}]} t[\text{s}]$$

Fraction of **total number of neutrinos** produced per proton on target



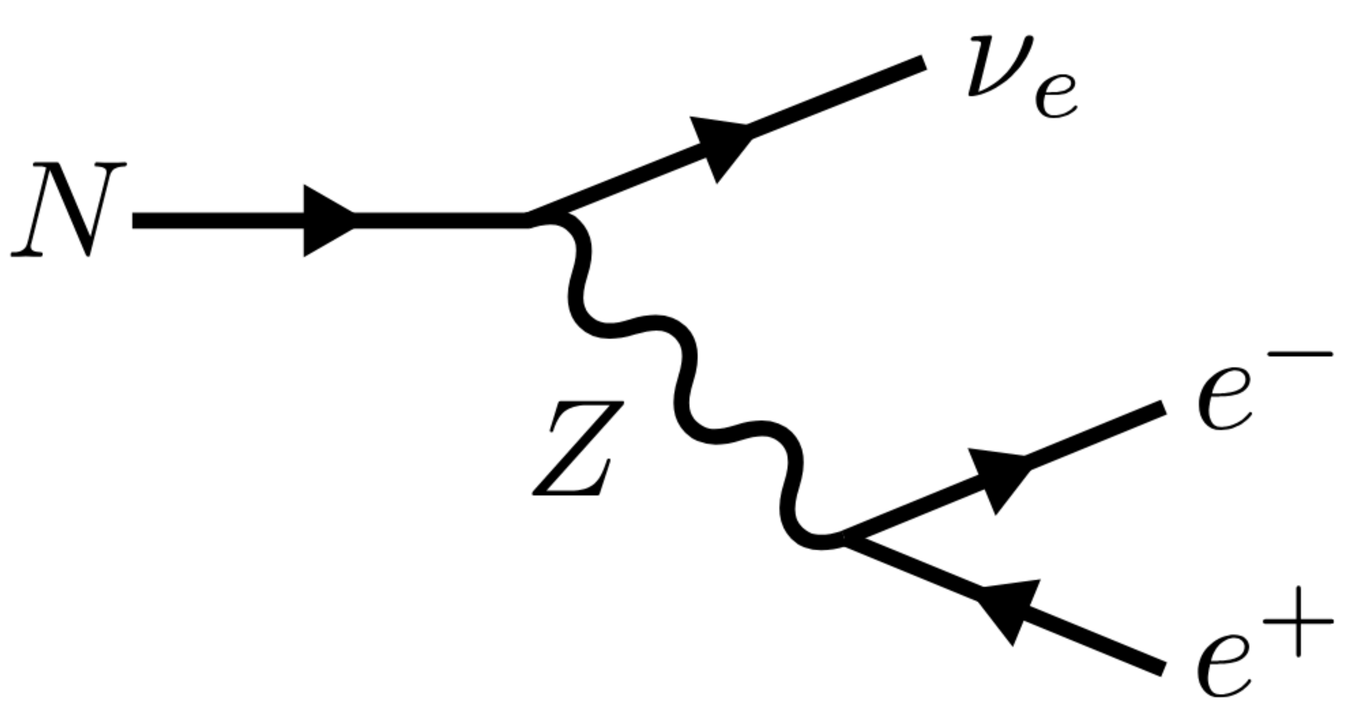
Production of HNLs at SNS

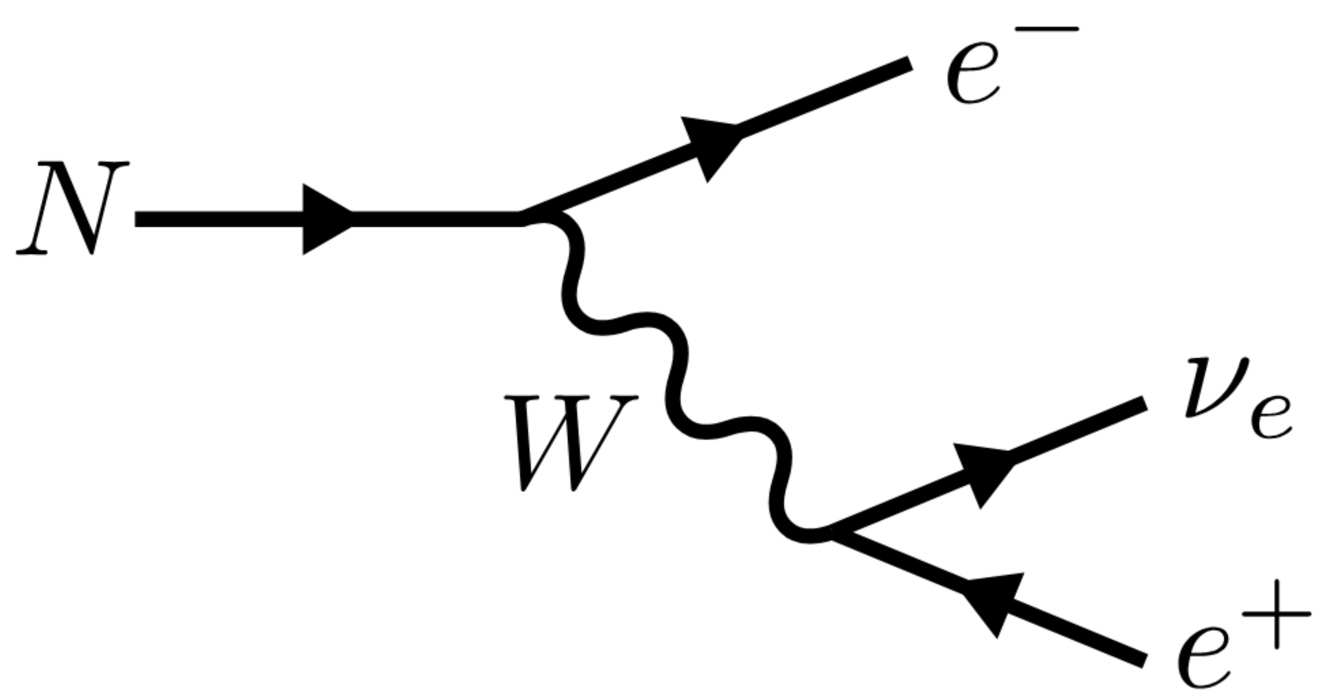
One mixing activated at the time. τ kinematically forbidden.



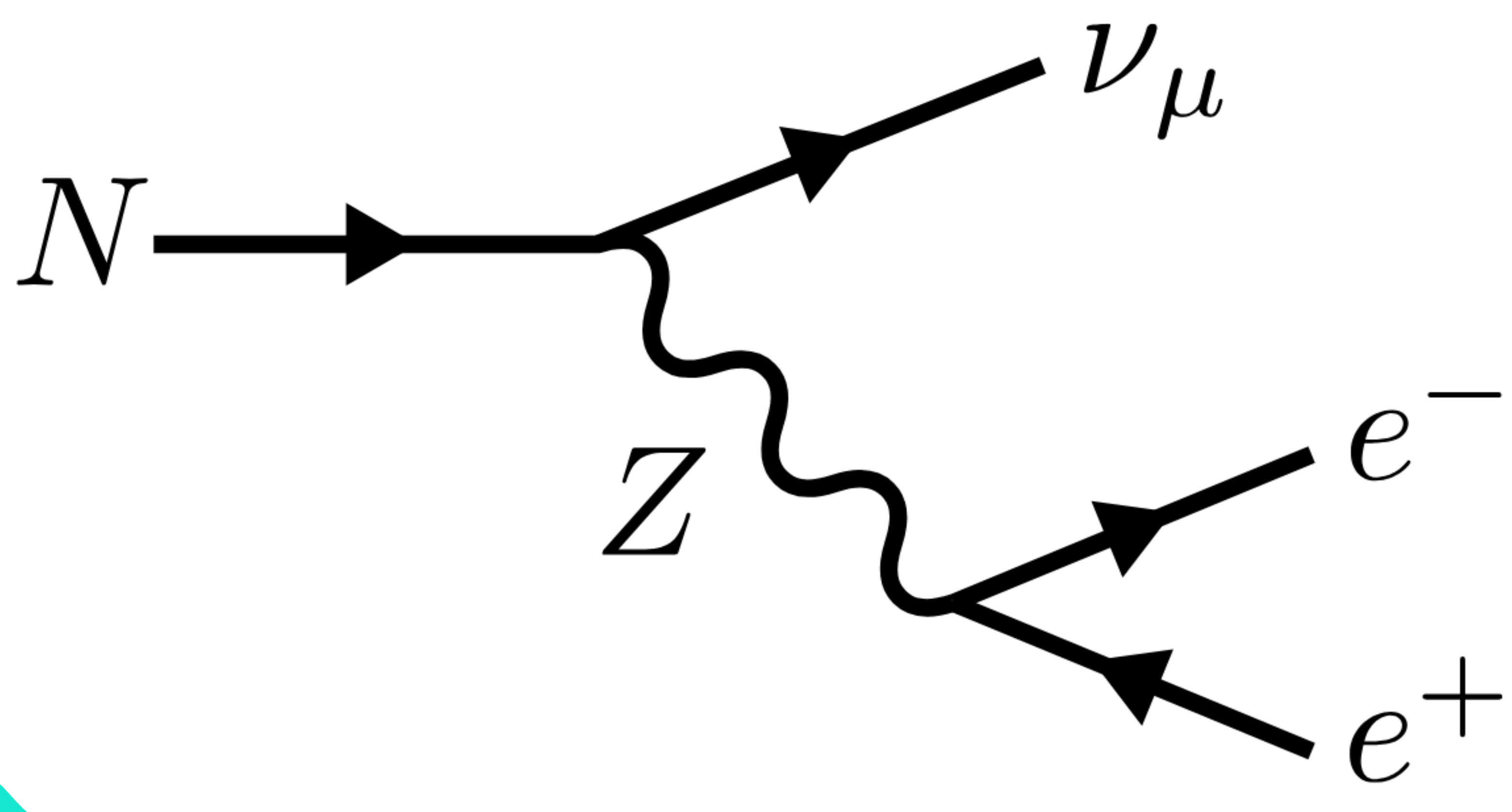
Decay of HNLs

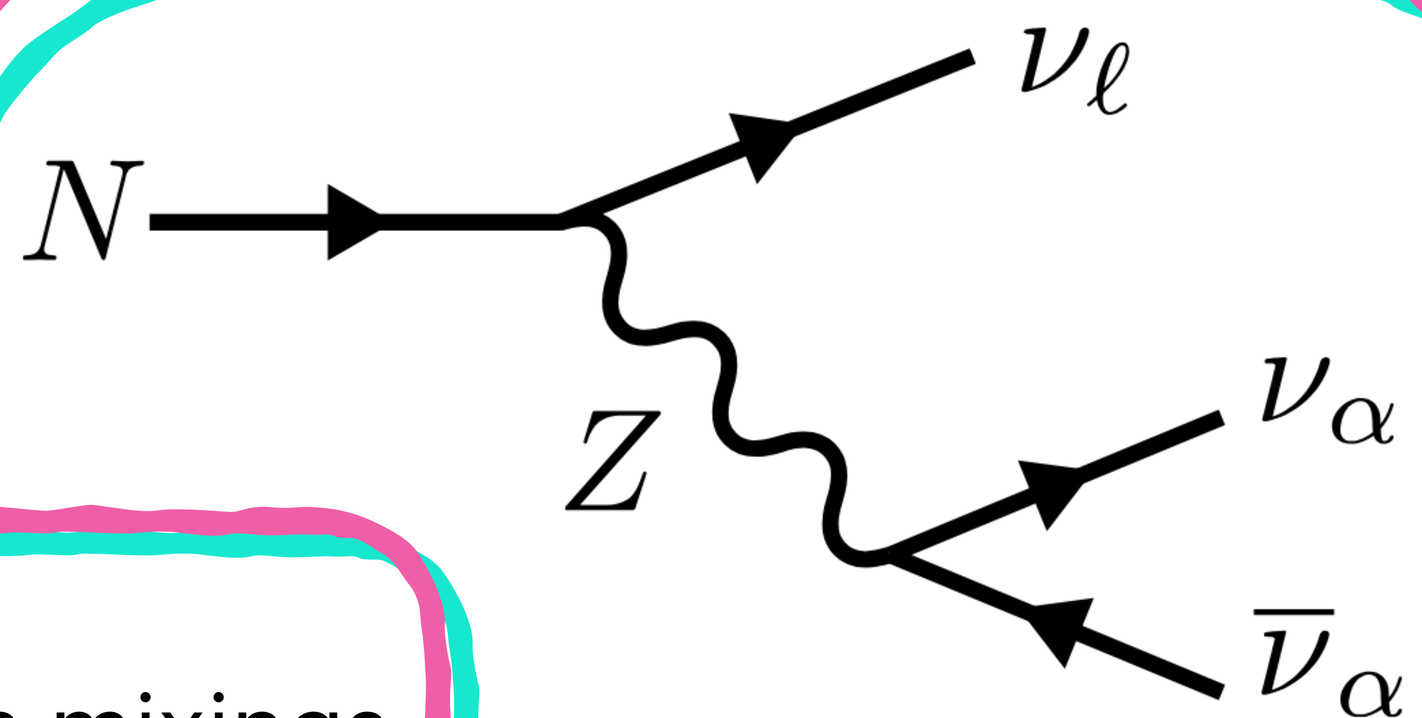
Only e mixing





Only μ mixing





Both mixings

Detection pipeline

We seek a signal of a e^+e^- **pair**.

- Probability peaks for large L, given the long decay lengths for this parameter space.
- Isotropic flux decreases rapidly with distance L.
- Backgrounds considered through flat efficiency.

$$\mathscr{P}_{\text{decay}}(E) = e^{-L/\lambda}\left(1 - e^{-s/\lambda}\right)$$

Master formula

$$N_{\text{decay}} = \int \mathrm{d}E \left.\frac{\mathrm{d}N^{HNL}}{\mathrm{d}E}\right|^{\text{det}} \mathscr{P}_{\text{decay}}(E)\, \mathscr{B}(N \to e^+e^-\nu)\, \varepsilon(E)$$

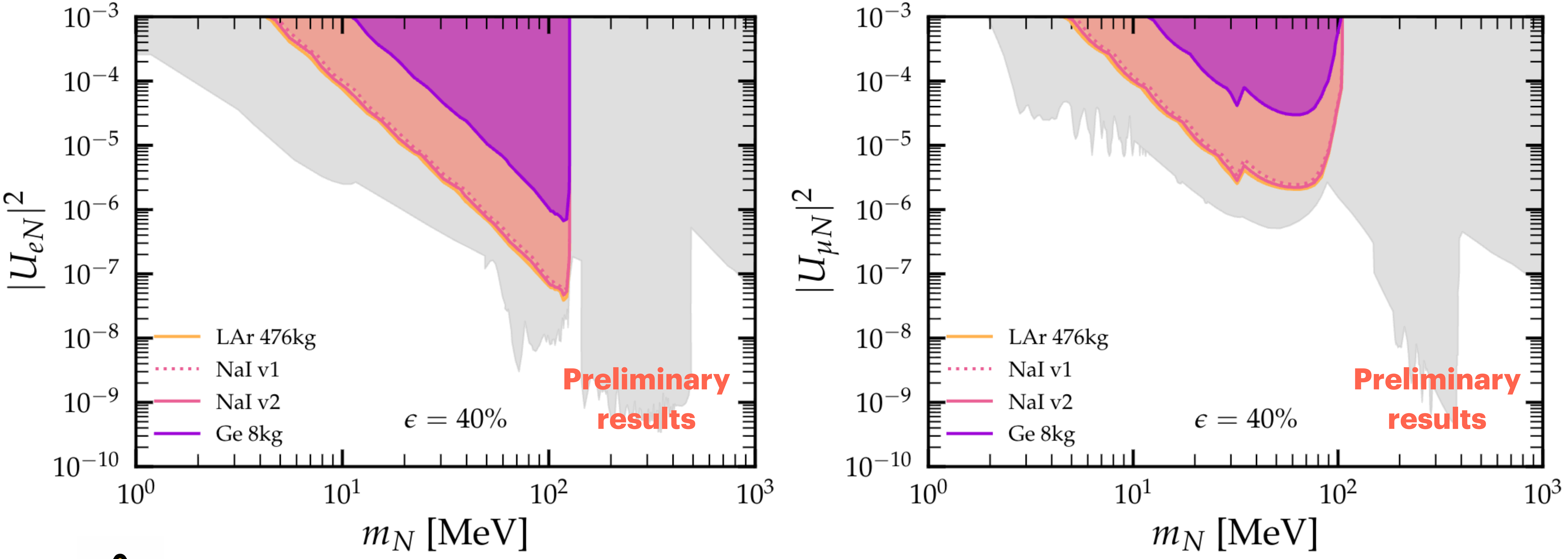
$$\left.\frac{\mathrm{d}N^{HNL}}{\mathrm{d}E}\right|^{\text{det}} = \left.\frac{\mathrm{d}N^{HNL}}{\mathrm{d}E}\right|^{\text{prod}} \times \frac{A_{\text{det}}}{4\pi L^2}$$

40%

Even if decay lengths are large, **a shorter baseline** would increase the number of detected events.

Current sensitivities at COHERENT

2.3 event-contour (90% C.L.)

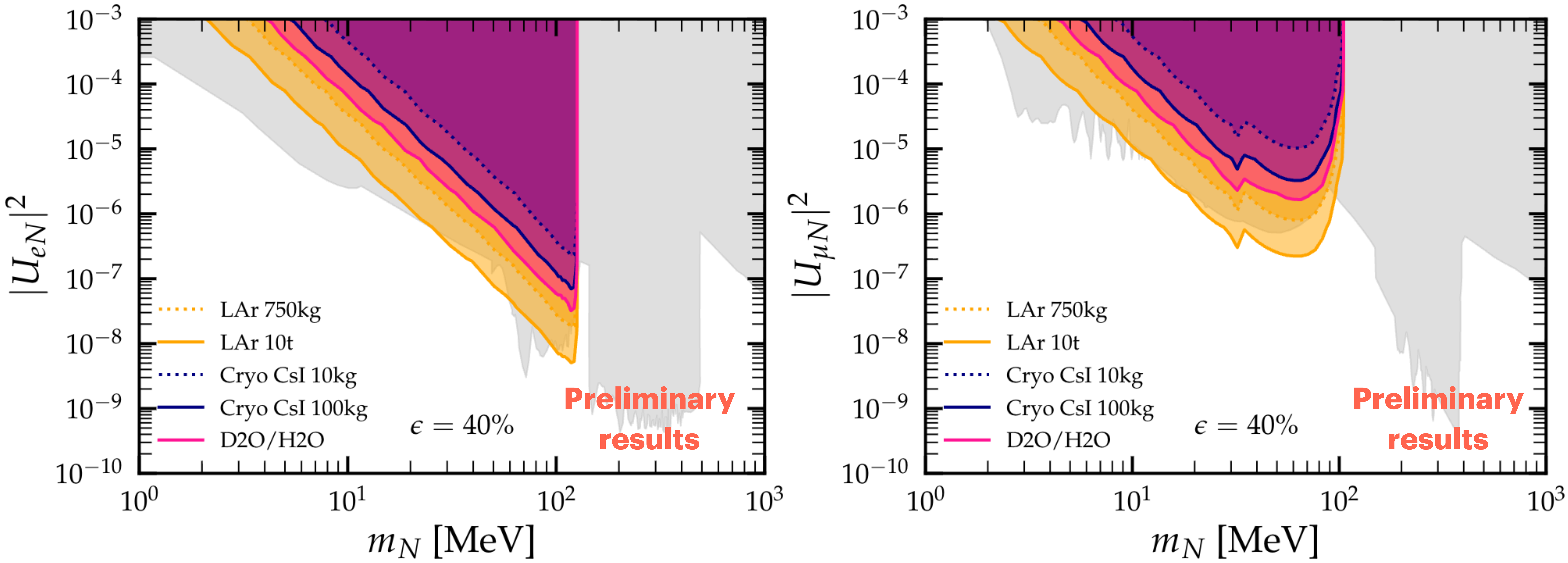


Reminder: this experimental setup was not originally built for this kind of process!

The **current** experimental setup **does not allow for improvement** of the current limits.
They are still **competitive** with current limits at certain mass range and with conservative efficiency.

Future sensitivities at COHERENT

2.3 event-contour (90% C.L.)



The **proposed** experimental setup will **allow for improvements** to the current limits **by almost an order of magnitude** at certain masses of the parameter space.

Conclusions

- HNLs are good candidates for **neutrino masses** explanation.
- HNLs could be **potentially produced** at Spallation Sources.
- Focus on SNS and COHERENT experiment:
    - Current experiments with **limited** capability for improving limits, but **competitive.**
    - Future proposals **potentially improve** the current limits by one order of magnitude at certain mass scales.
- **Similar analysis** will be done in other facilities like J-PARC, CSNS and the future ESS.
- Flat efficiency considered. **Further analysis of backgrounds needed.**

Given COHERENT **experimental baselines and volumes, dedicated searches** of HNLs would be **feasible.**

Backup

E. Fernández-Martínez, M. González-López, J. Hernández-García, M. Hostert, J. López-Pavón [2304.06772]

HNL limits: electron mixing case

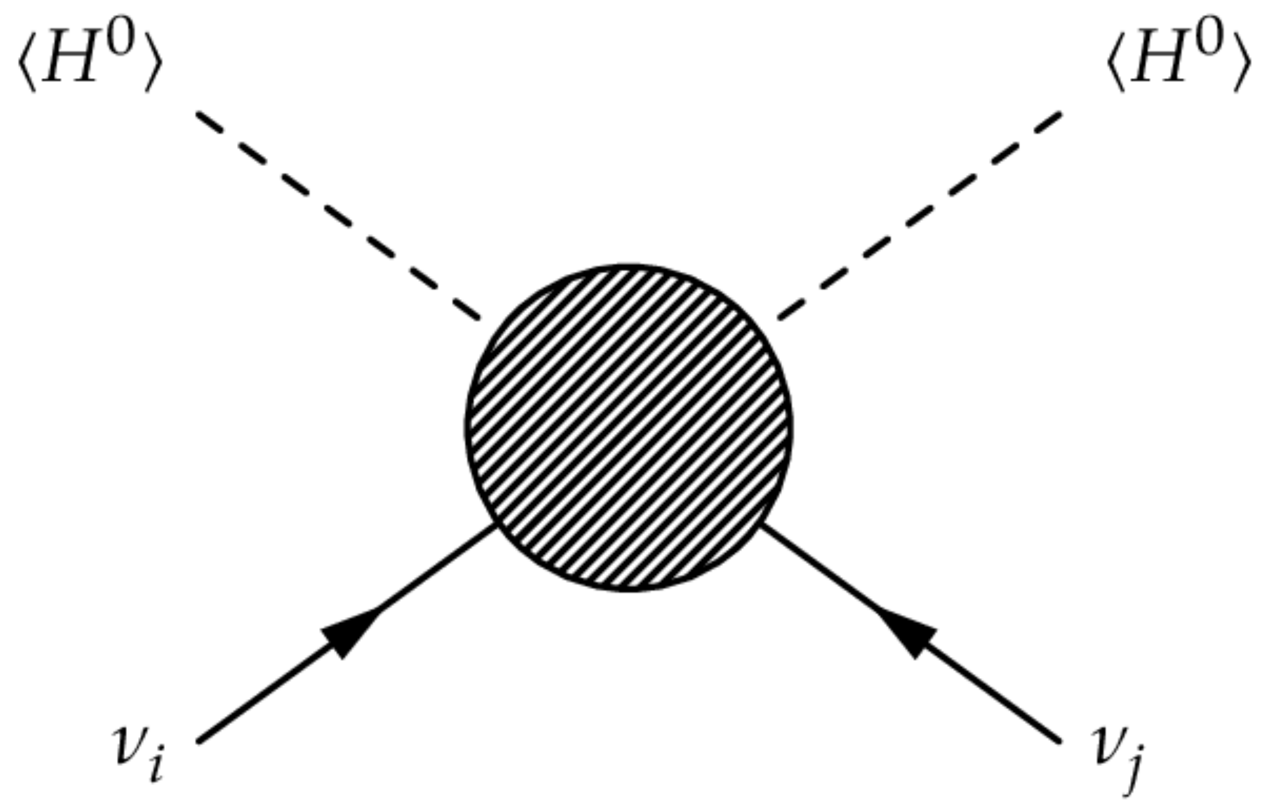
E. Fernández-Martínez, M. González-López, J. Hernández-García, M. Hostert, J. López-Pavón [2304.06772]

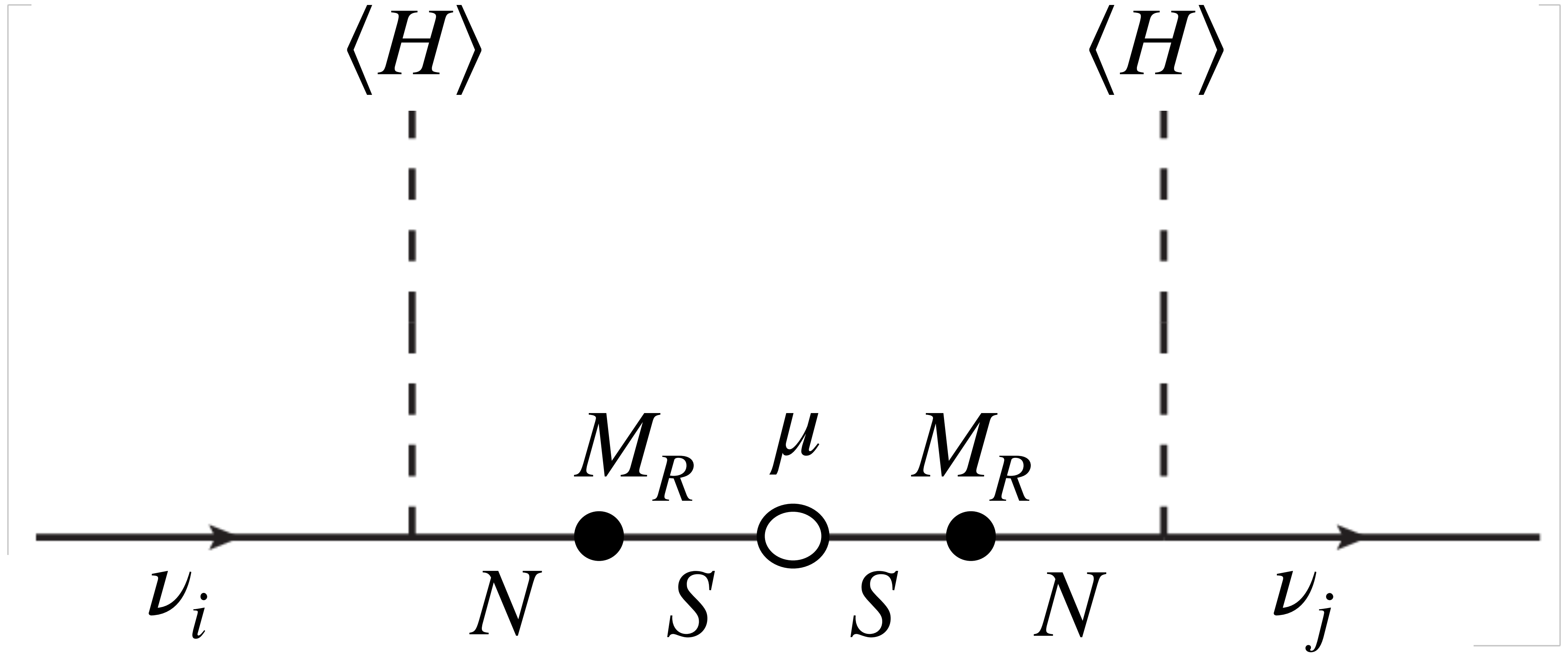
HNL limits: muon mixing case

E. Fernández-Martínez, M. González-López, J. Hernández-García, M. Hostert, J. López-Pavón [2304.06772]

HNL limits: tau mixing case

Inverted Seesaw



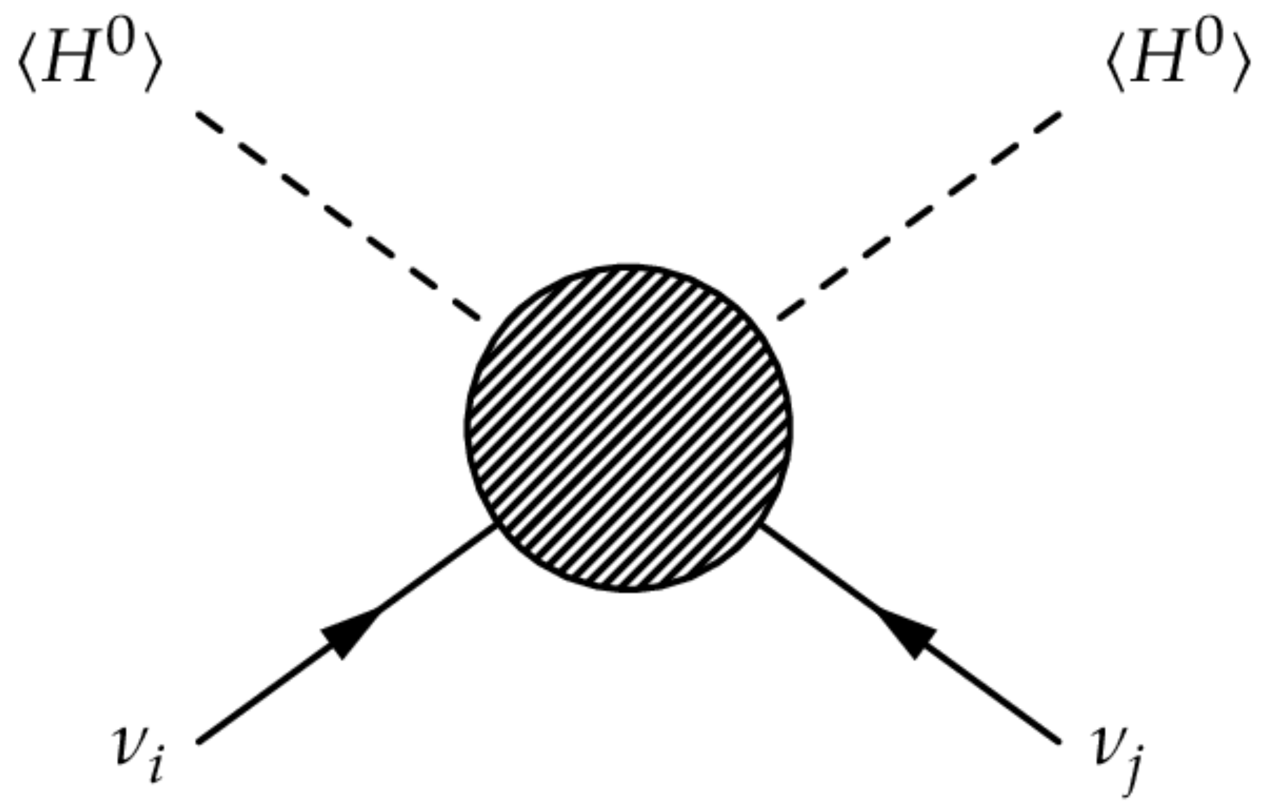


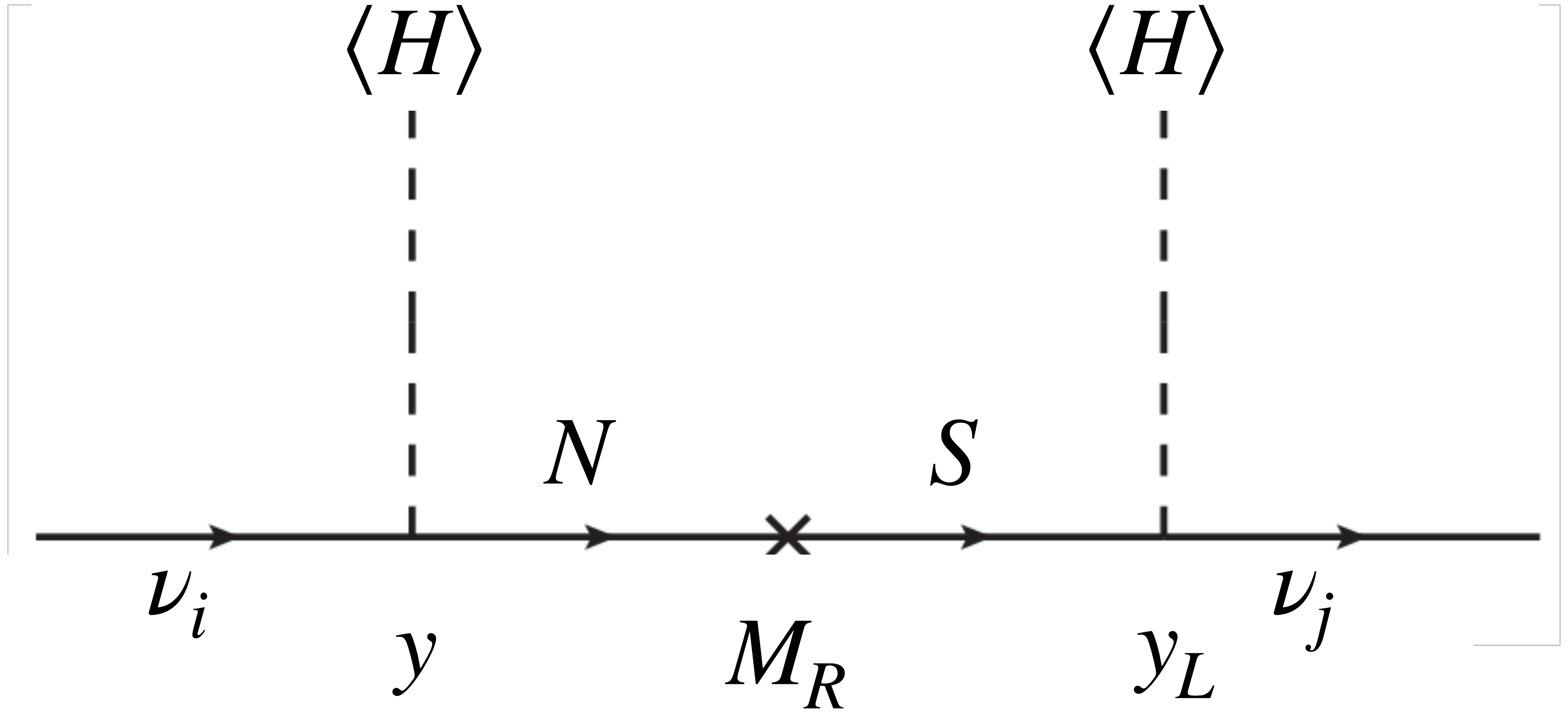
$$\begin{matrix} \nu_L & N & S \end{matrix}$$

$$\mathcal{M}_{ISS} = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu \end{pmatrix} \quad \begin{cases} m_\nu \approx \dfrac{m_D}{M_R}\mu\dfrac{m_D}{M_R} \\ V_{\nu N} \approx \dfrac{m_D}{M_R} \end{cases}$$

- Small neutrino mass by small μ.
- Large mixing automatically allowed.

Linear Seesaw





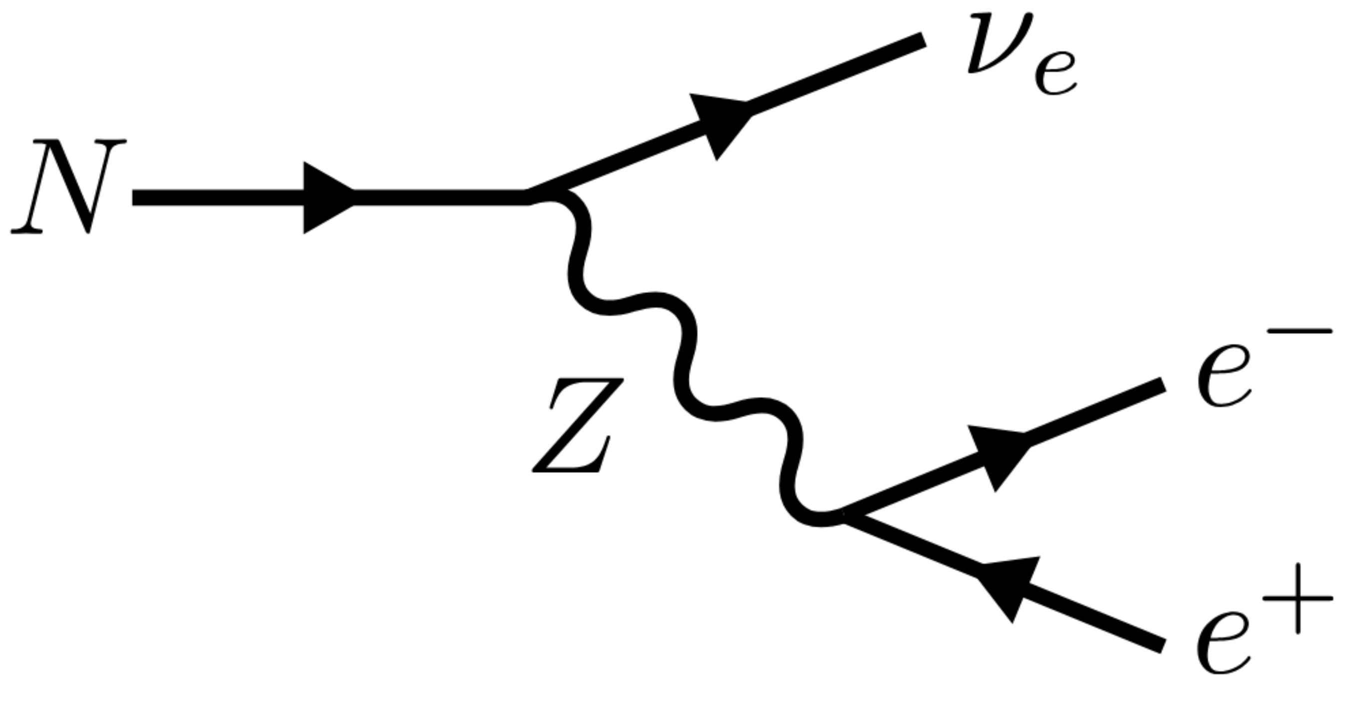
$$\begin{matrix} \nu_L & N & S \end{matrix}$$

$$\mathscr{M}_{LSS} = \begin{pmatrix} 0 & m_D^T & M_L^T \\ m_D^T & 0 & M_R \\ M_L^T & M_R^T & 0 \end{pmatrix} \begin{cases} m_\nu \approx (M_L M_R^{-1} m_D) + (\ldots)^T \\ V_{\nu N} \approx \dfrac{m_D}{M_R} \end{cases}$$

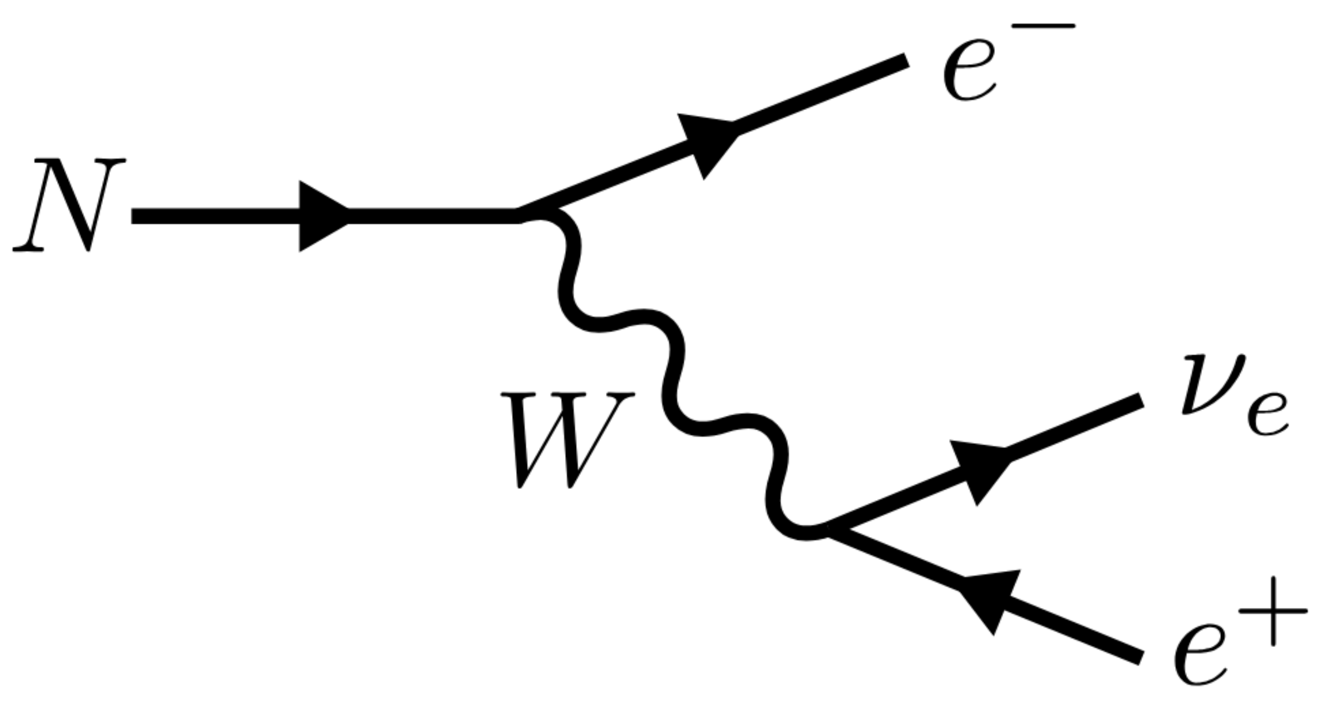
- Small neutrino mass by small M_L.
- Large mixing automatically allowed.

Decay width of HNLs

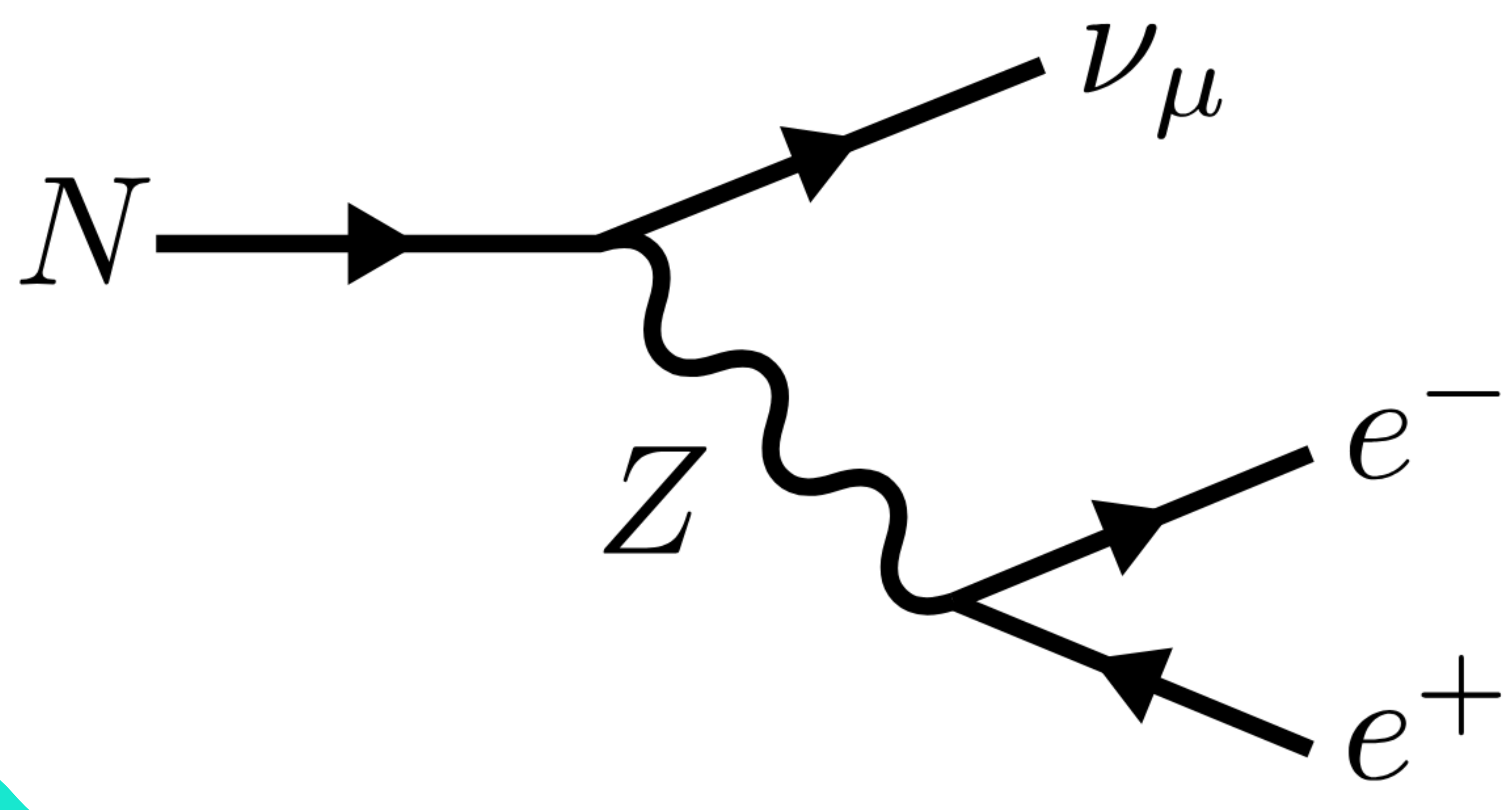
Only e mixing



$$\Gamma(N \to \nu_e e^- e^+) = \frac{G_F^2 |U_{eN}|^2}{768\pi^3} m_N^5 \times \left(1 + 4\sin^2\theta_W + 8\sin^4\theta_W\right)$$

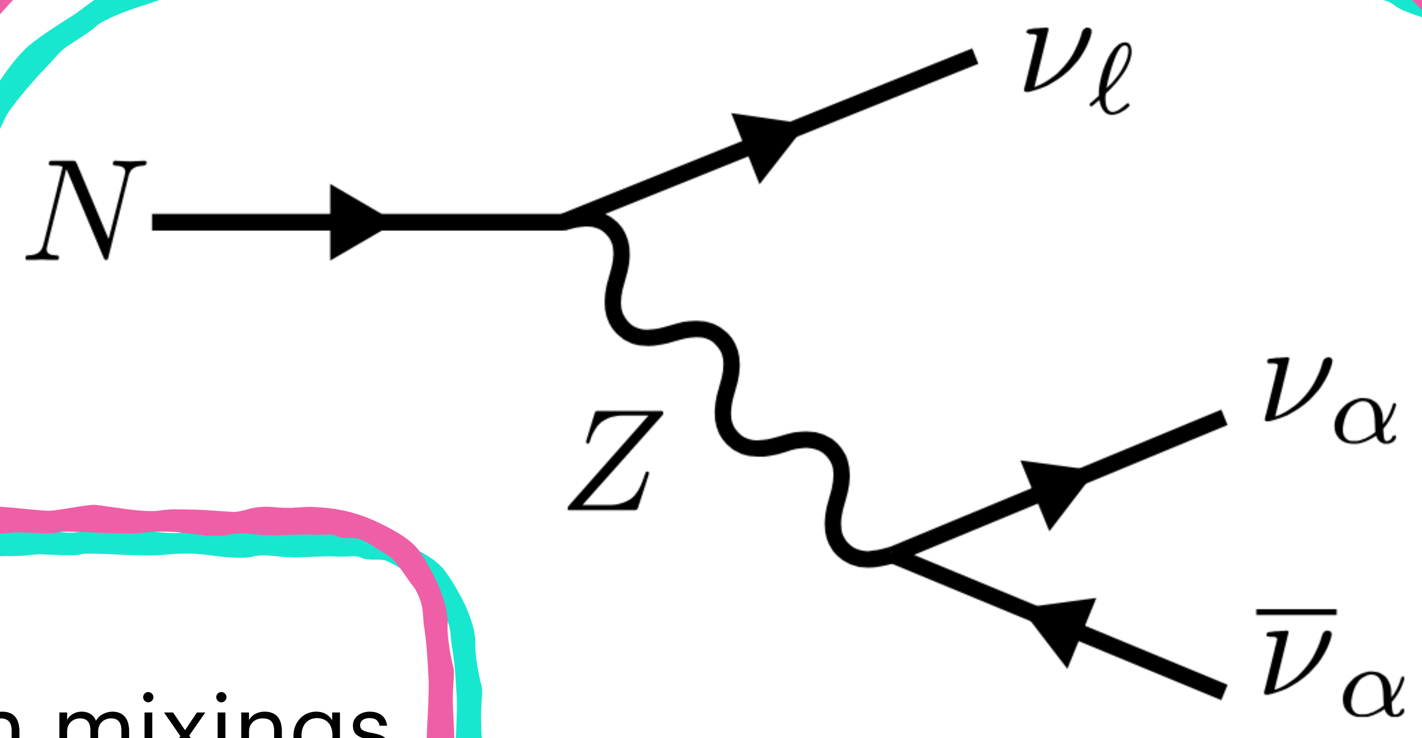


Only μ mixing



$$\Gamma(N \to \nu_\mu e^- e^+) = \frac{G_F^2 |U_{\mu N}|^2}{768\pi^3} m_N^5 \times \left(1 - 4\sin^2\theta_W + 8\sin^4\theta_W\right)$$

Both mixings



$$\Gamma(N \to \nu_\ell \nu_\alpha \overline{\nu}_\alpha) = \frac{G_F^2 |U_{\ell N}|^2}{768\pi^3} m_N^5$$

CEνNS cross section