# Heavy Neutrinos and Where to Find Them

Kevin Kelly, Fermilab

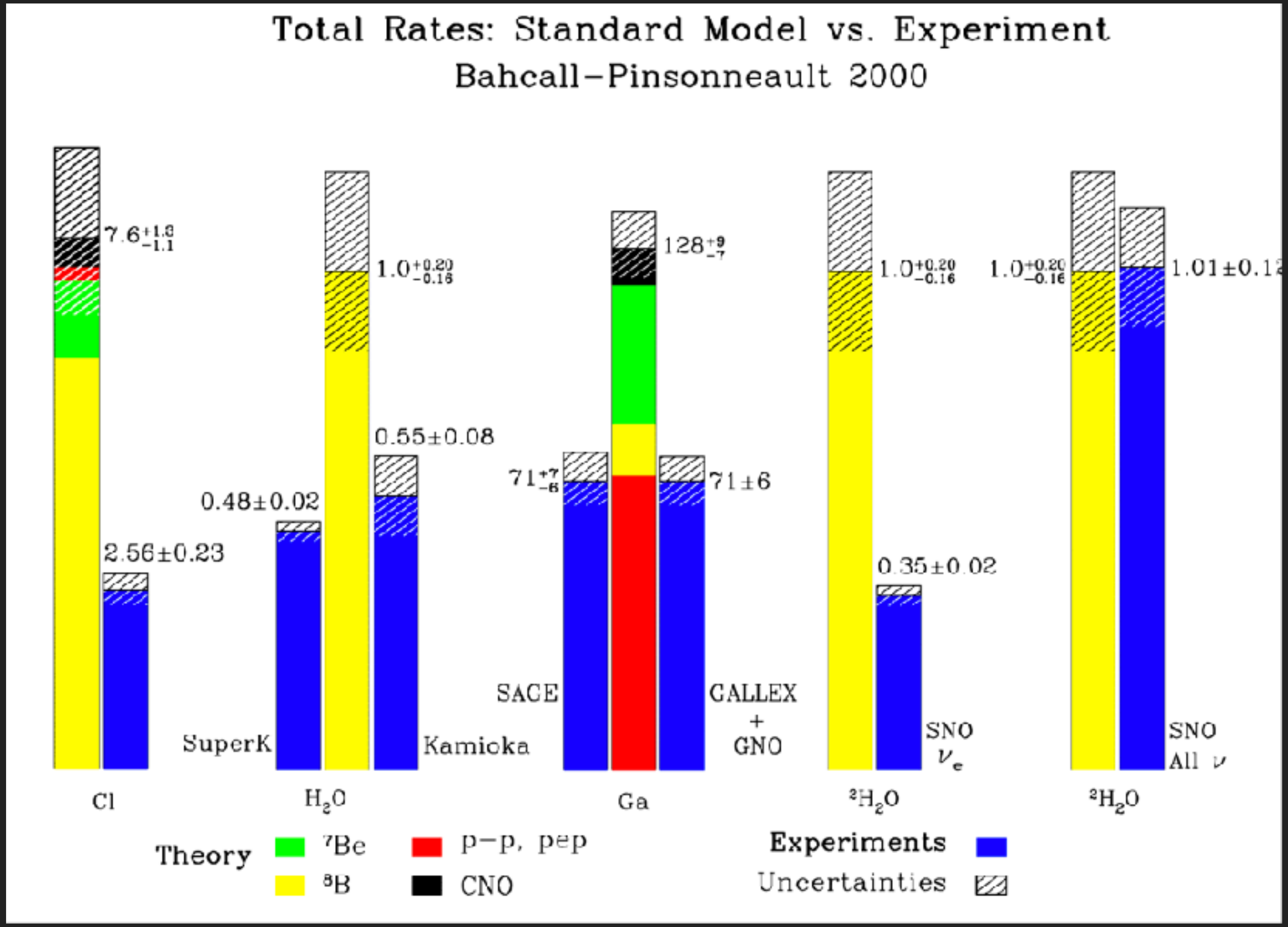
PITT PACC HEP Seminar, 11th Nov., 2020

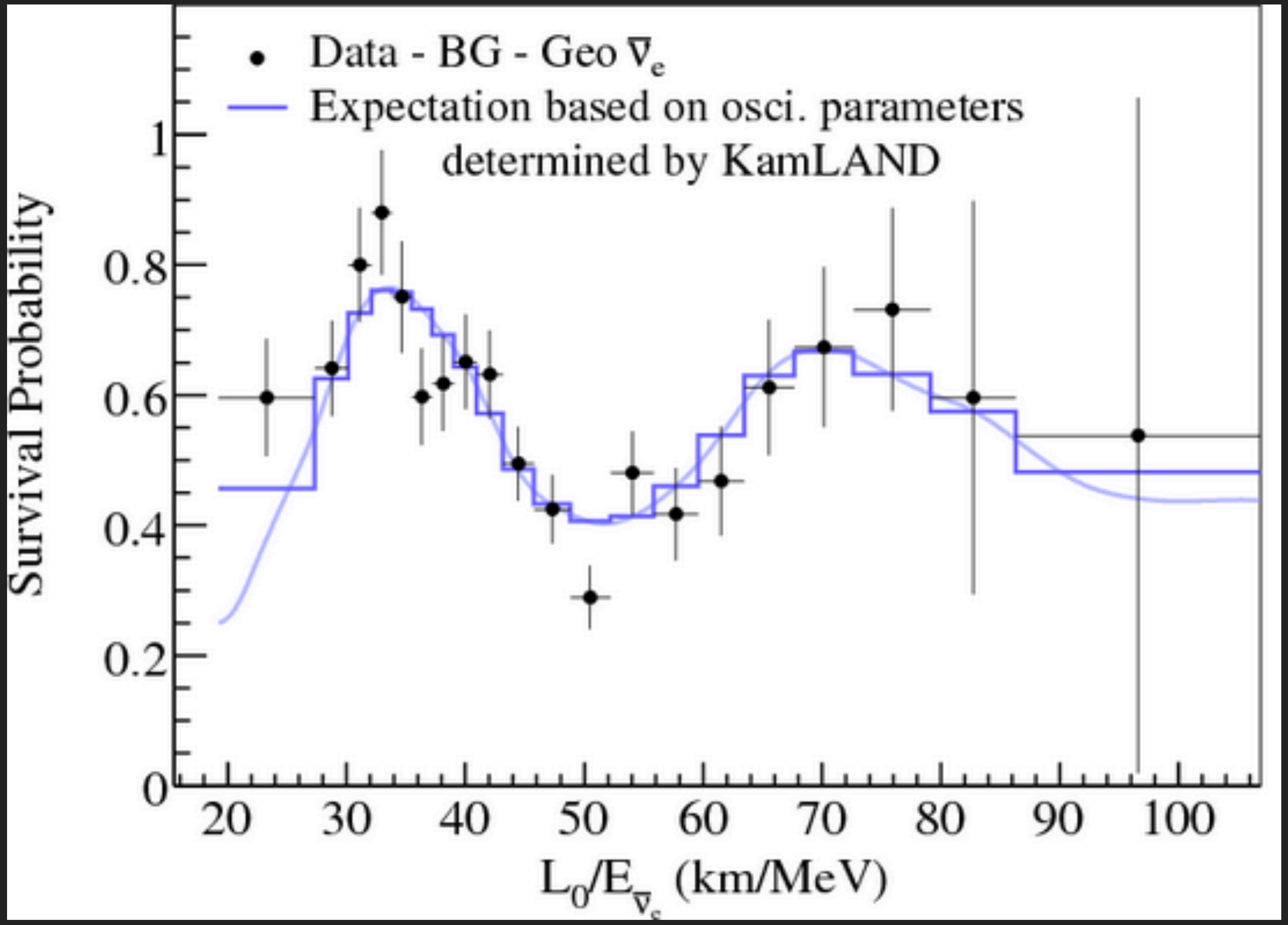
# Outline

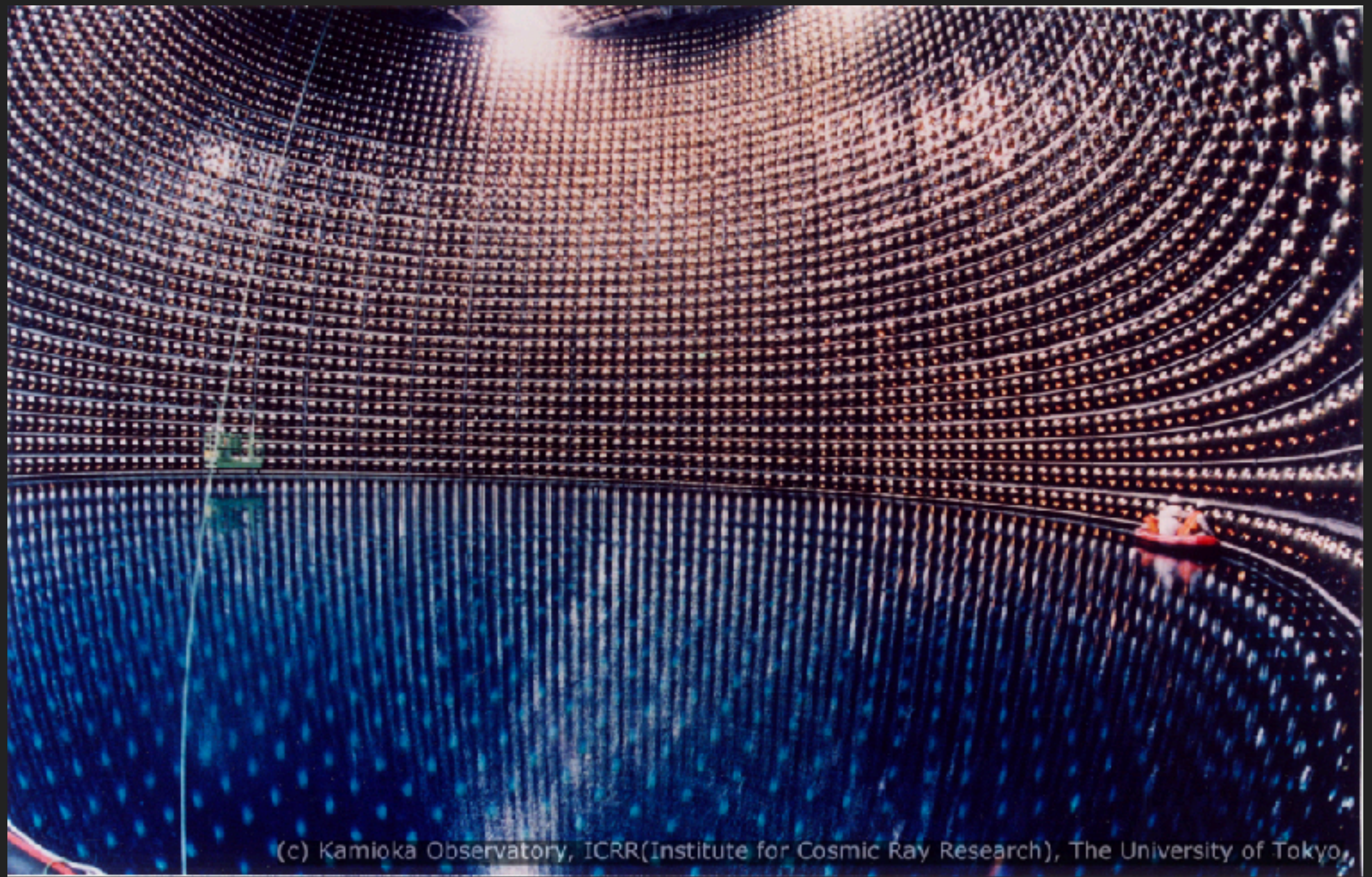
- Motivation for searches for Heavy Neutral Leptons
- Searching for a variety of signatures in an accelerator neutrino experiment.
- IF we discover a Heavy Neutral Lepton,
  - Can we determine if its interactions violate Lepton number?
  - Does it interact with mediators beyond the Standard Model ones?

# Heavy Neutral Leptons & Motivation

# Neutrino Oscillations



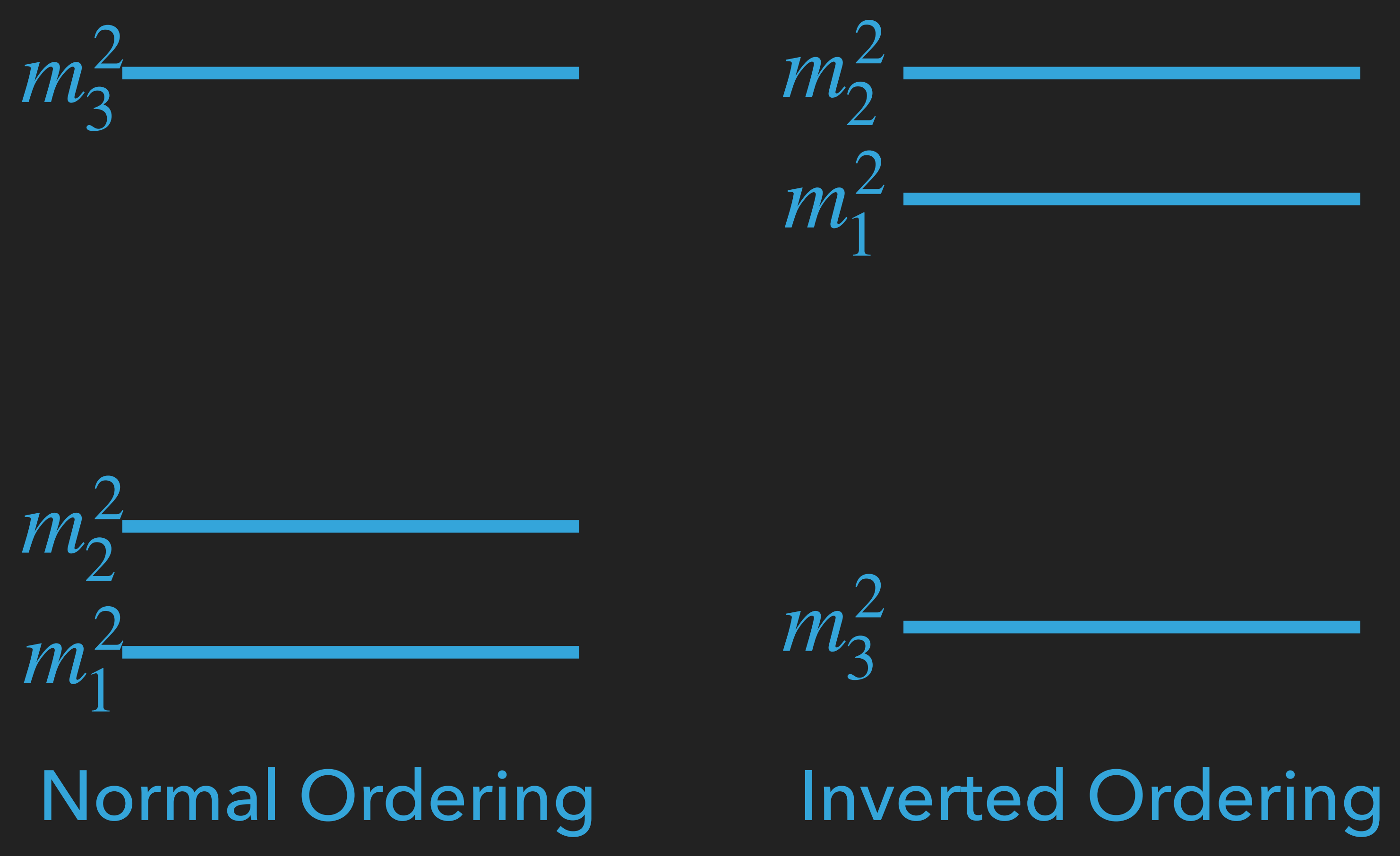




**Anomalous neutrino "disappearance" in solar, reactor, and atmospheric experiments…**

# A Coherent Picture Forms

- Standard assumption for neutrino oscillations: three neutrinos exist, mix via a unitary, 3 x 3 matrix – the PMNS matrix. $\left(c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij}\right)$

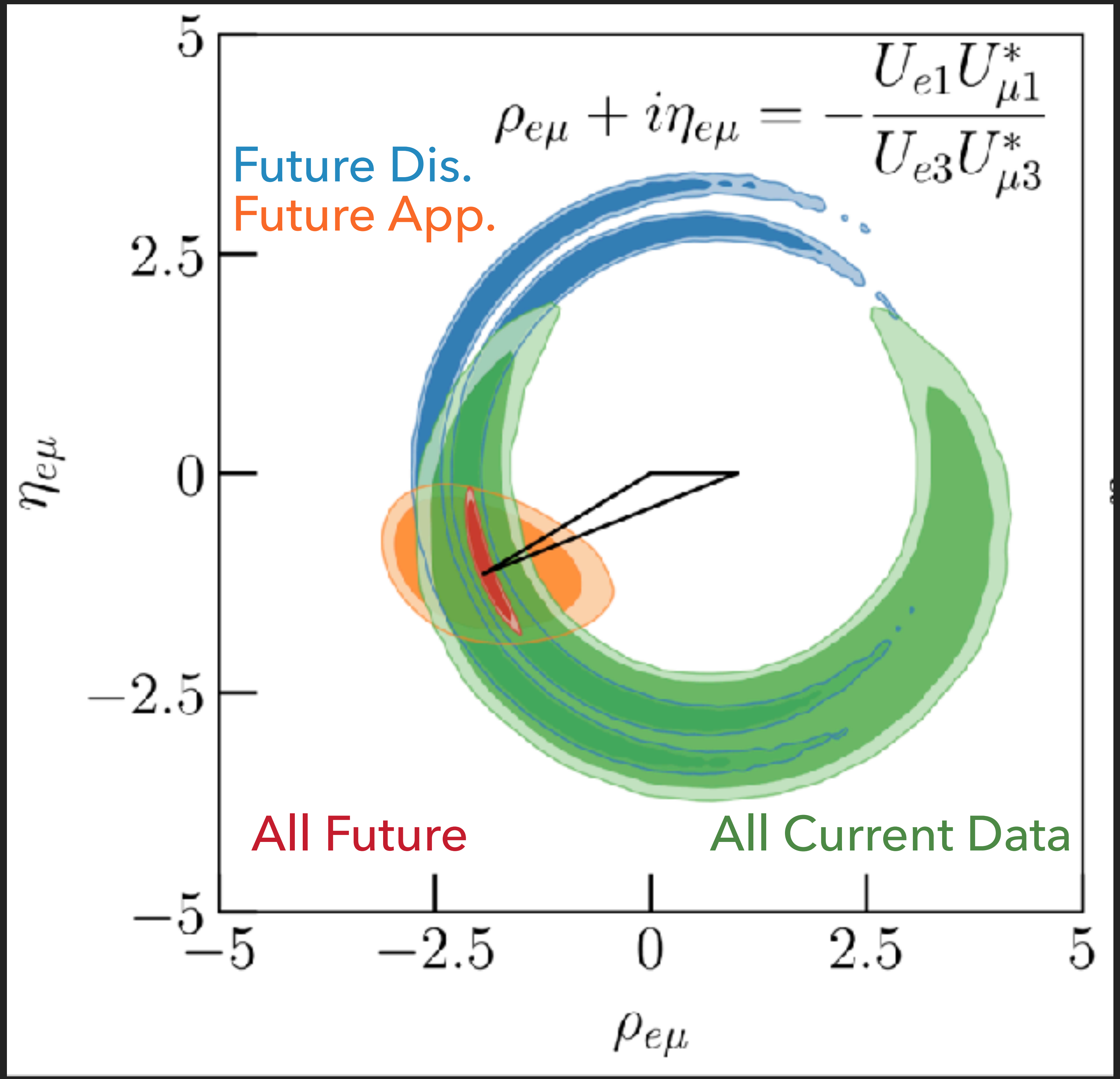
$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}c_{23} \end{pmatrix}$$



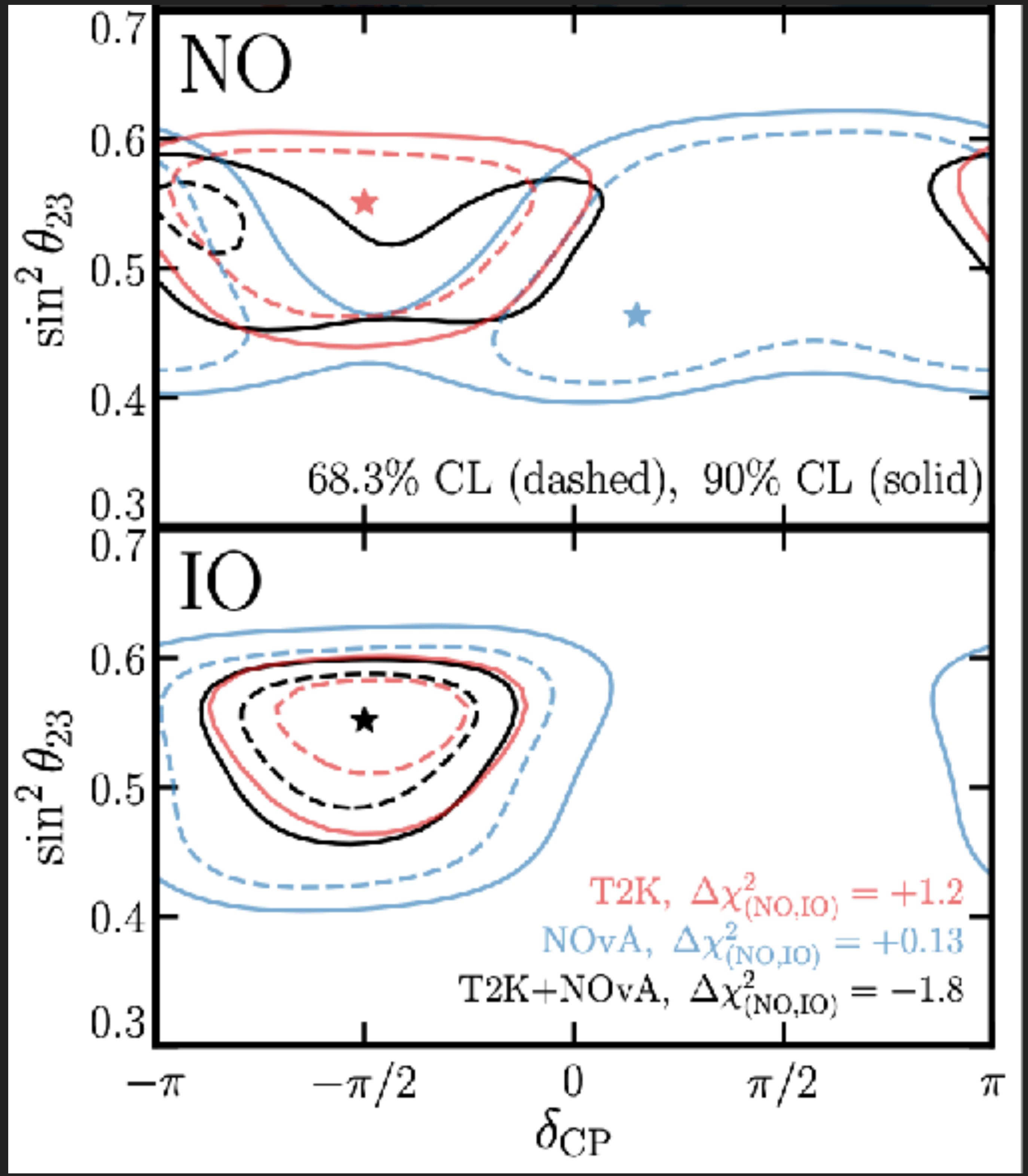

- Two non-zero mass-squared splittings relevant for three-neutrino mixing – different neutrino mass eigenstates have different energy and therefore time-evolve with a different relative phase as they propagate, leading to flavor oscillations.

# Current Status of Three-Neutrino Mixing

- Each of the six relevant parameters measured to varying, O(10%) precision.
- Level of CP Violation in the matrix currently unknown.
- Recent data have cast doubt on our knowledge of the neutrino mass ordering.

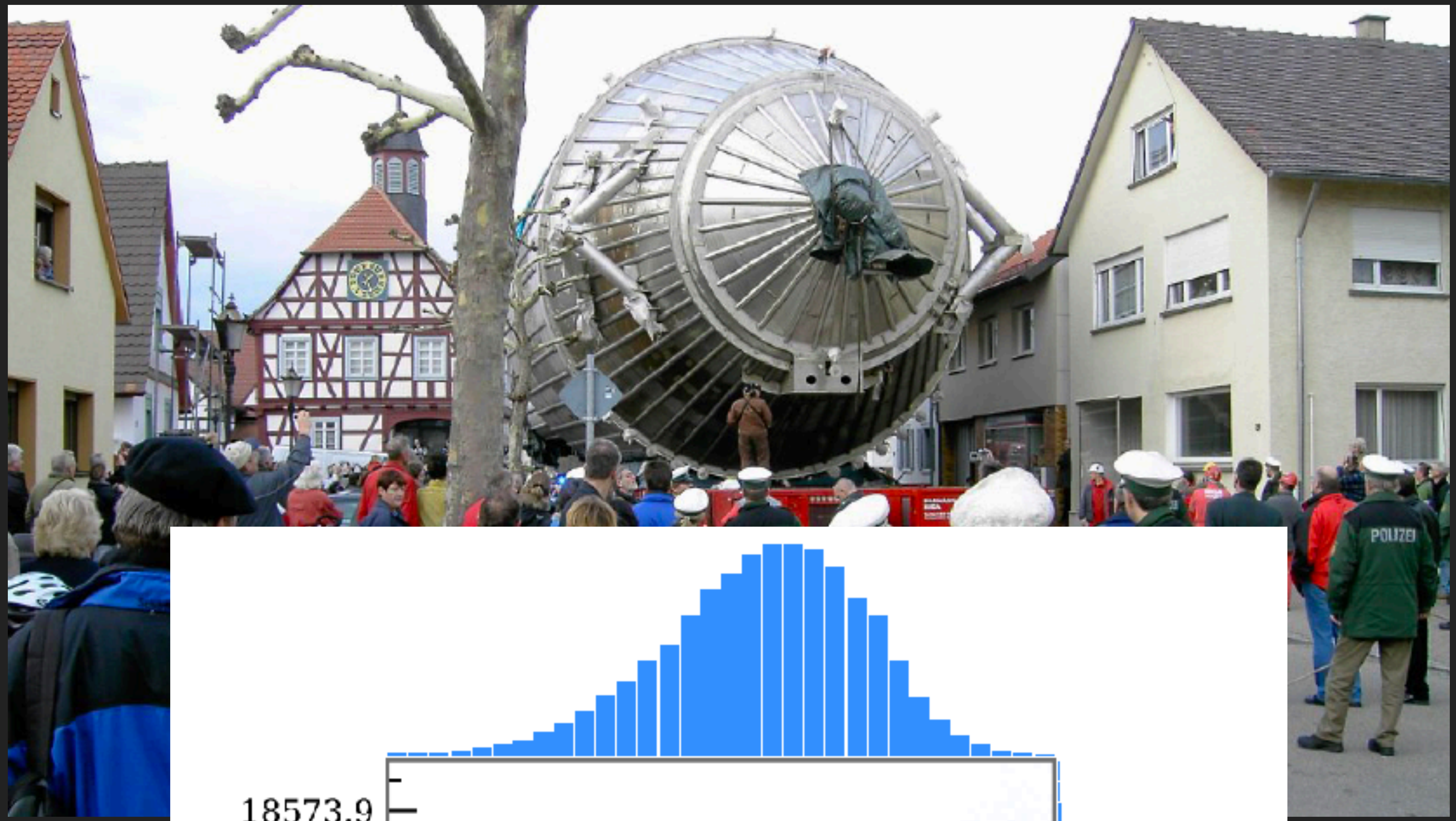


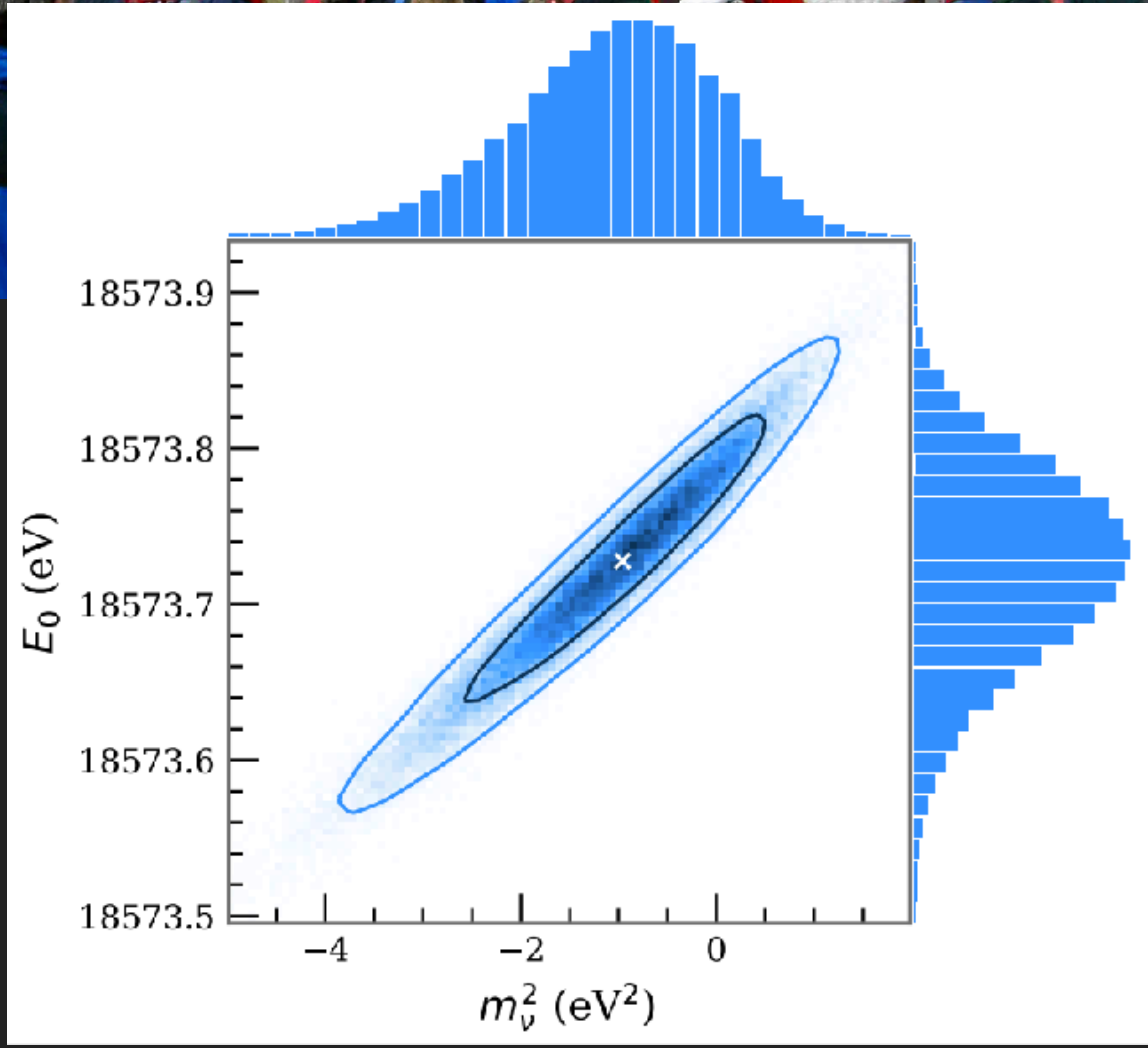

S.A.R. Ellis, KJK, S.W. Li, upcoming v2 of [2004.13719]



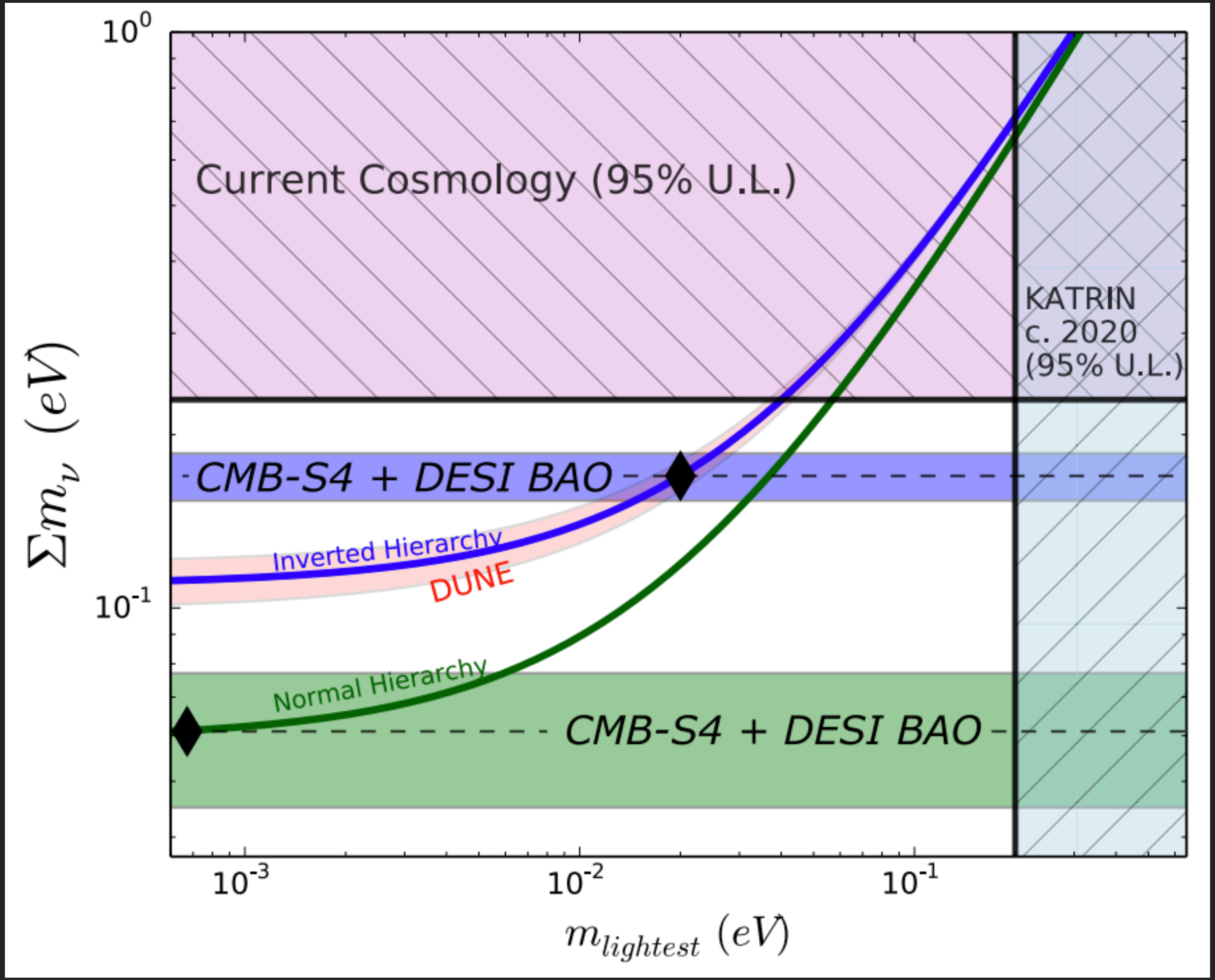

KJK et al, [2007.08526]

# Overall Mass Scale, not Mass Splittings?



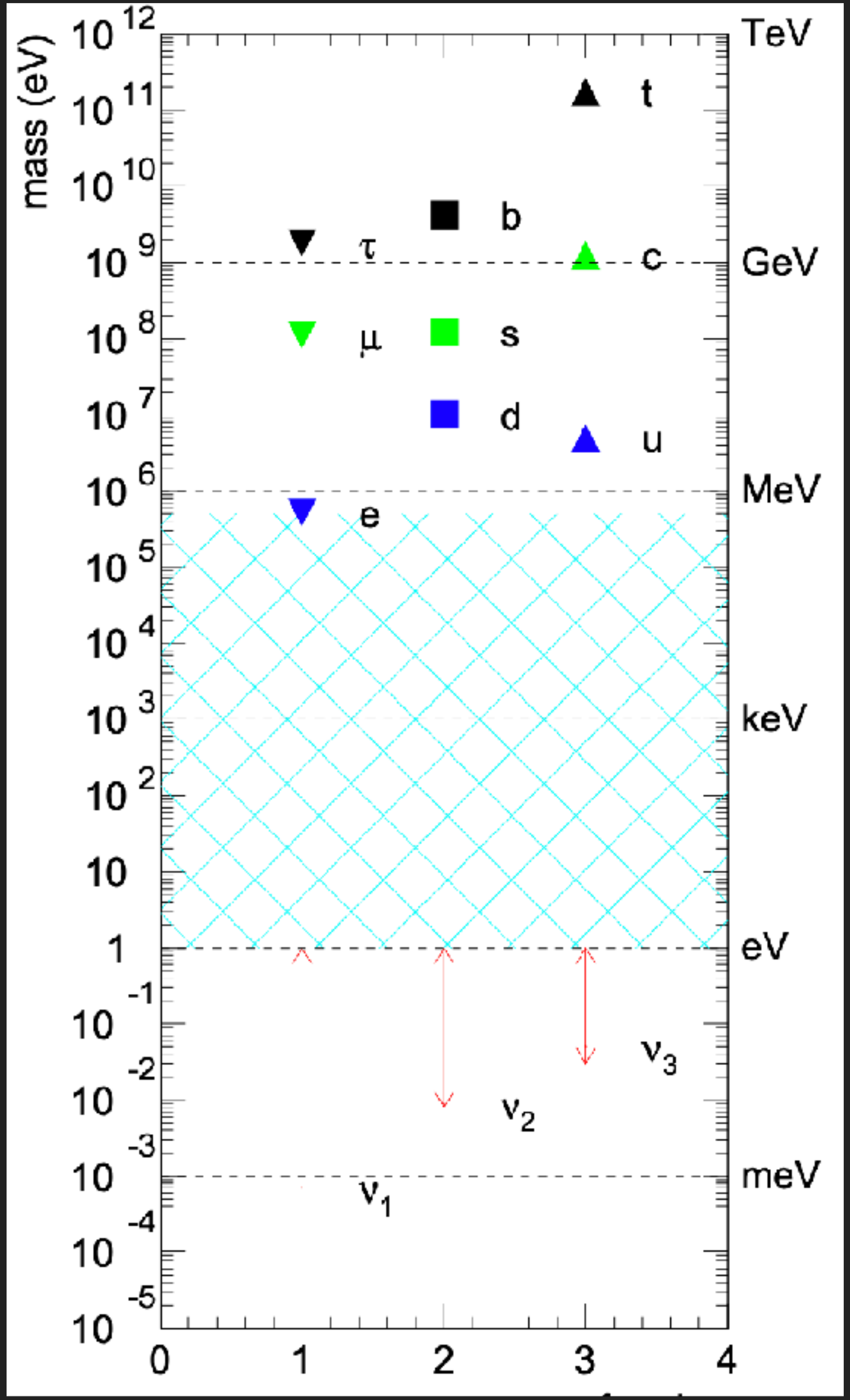



KATRIN Collaboration, [1909.06048]




CMB S4, [1610.02743]

# SM Fermion Masses




- At least two of the three neutrinos have nonzero masses, but all three are at least 6 orders of magnitude lighter than the electron.
- No clear explanation for generating neutrino masses at this scale (very small Yukawa couplings?).
- Could right-handed neutrinos with their own Majorana mass terms be responsible for the lightness of these?

# The Seesaw Mechanism

(consider one light and one heavy neutrino for simplicity)

$$\mathcal{L} \supset -y_\nu \left(LH\right) N + \frac{1}{2} M_N N N$$

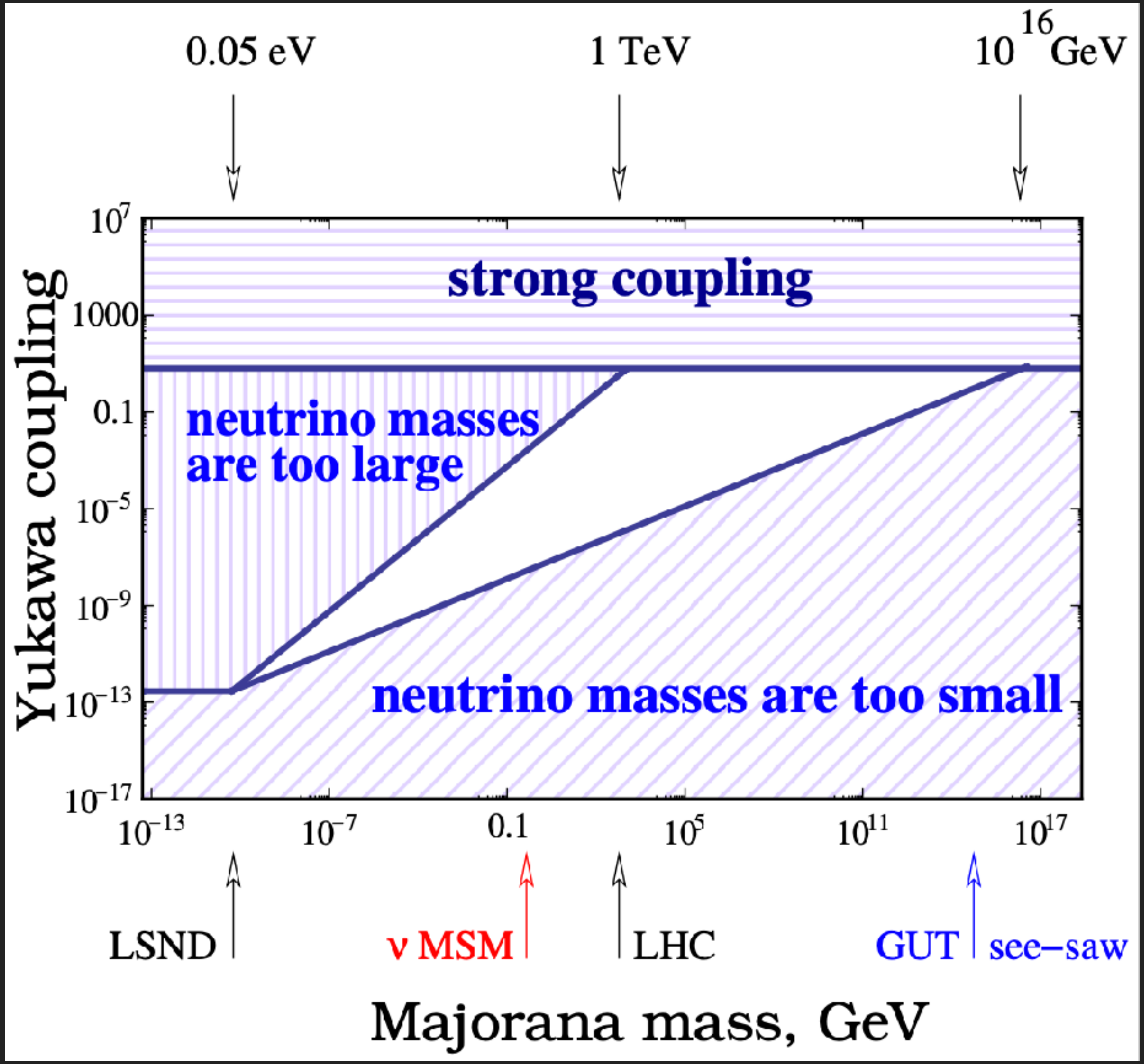
This generates a mass matrix with the structure of

$$\begin{pmatrix} 0 & m \\ m & M_N \end{pmatrix}$$

After diagonalizing, assuming hierarchical mass scales, we obtain two masses for the neutrinos:

$$m_\nu \approx \frac{m^2}{M_N}, \quad M_N$$

# Seesaw Scales




Light Sterile Neutrinos: A White Paper, [1204.5379]

- Different mass scales predict new phenomenology in different regimes.
- Wide range of allowed masses (up to the structure of the Yukawa coupling matrix) to generate the light neutrino masses.
- Further motivation – heavy neutrinos decaying out-of-equilibrium could be responsible for the Baryon Asymmetry of the universe via Leptogenesis.

# Minimal vs Non-Minimal HNL Scenarios

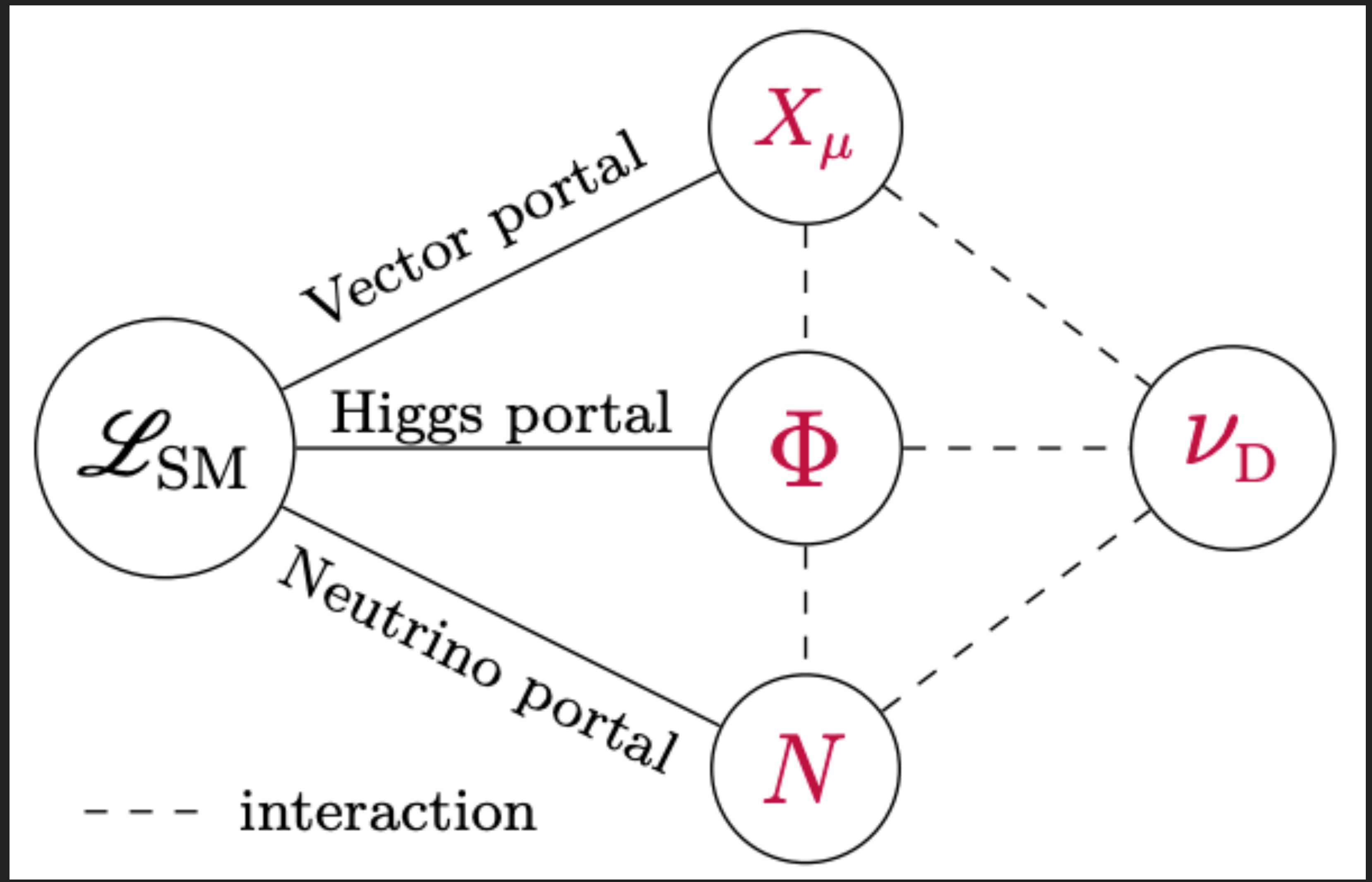
- In the minimal phenomenological scenario, we can introduce one HNL and allow it to mix independently with the neutrino flavor states using new mixing angles,

$$|U_{eN}|^2, \ |U_{\mu N}|^2, \ |U_{\tau N}|^2$$

- This allows for suppressed interactions of N with the SM W/Z bosons and can also mediate decays via the same

$$\Gamma\left(N \to 3\nu\right) \propto G_F^2 M_N^5 \left|U_{\alpha N}\right|^2$$

- Adding in other new-physics symmetries/particles can make for more interesting phenomenology

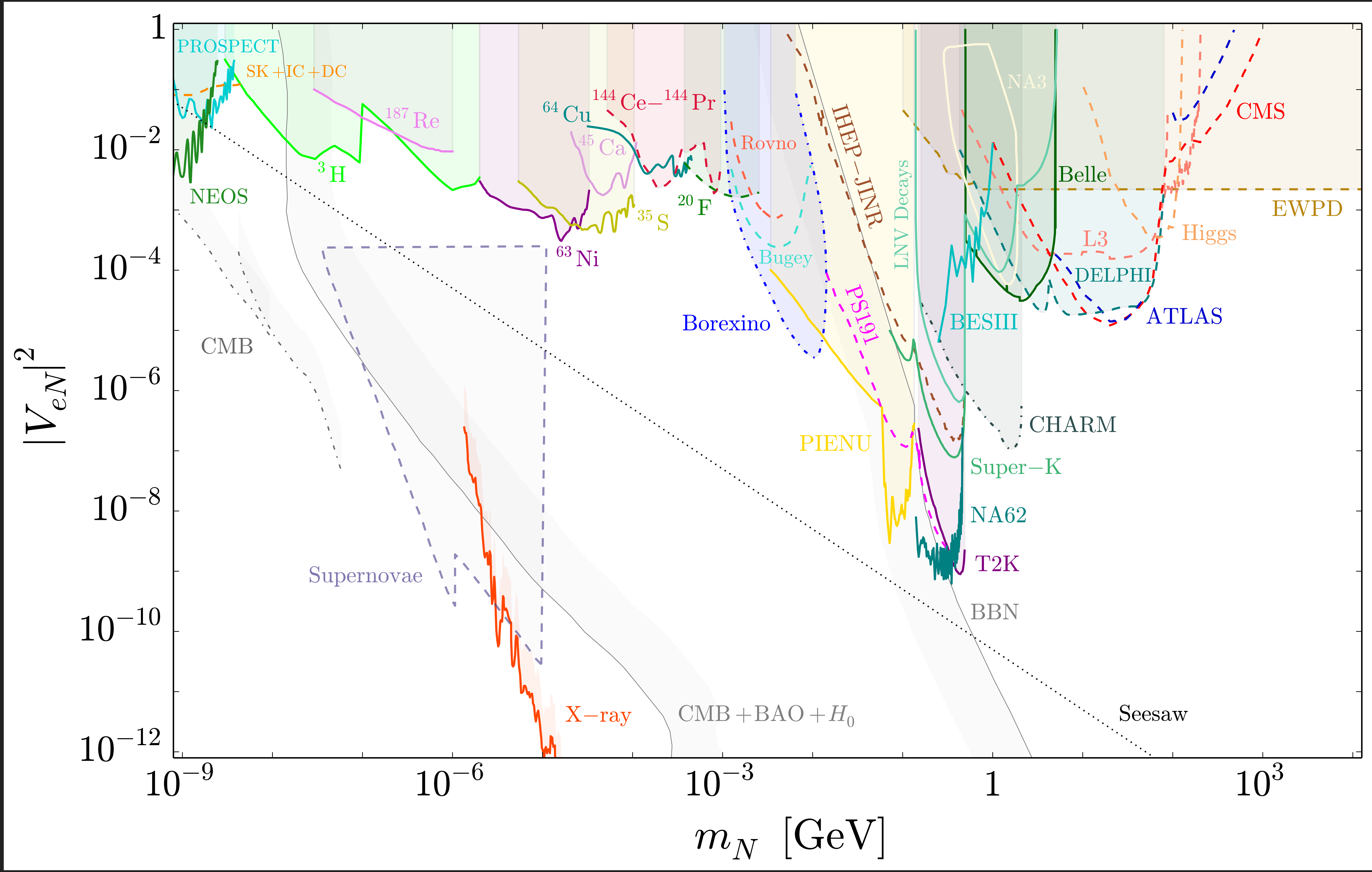



Ballett, Hostert, Pascoli [1903.07589]

# Current & Upcoming Constraints: Minimal HNL

# Electron-Mixing

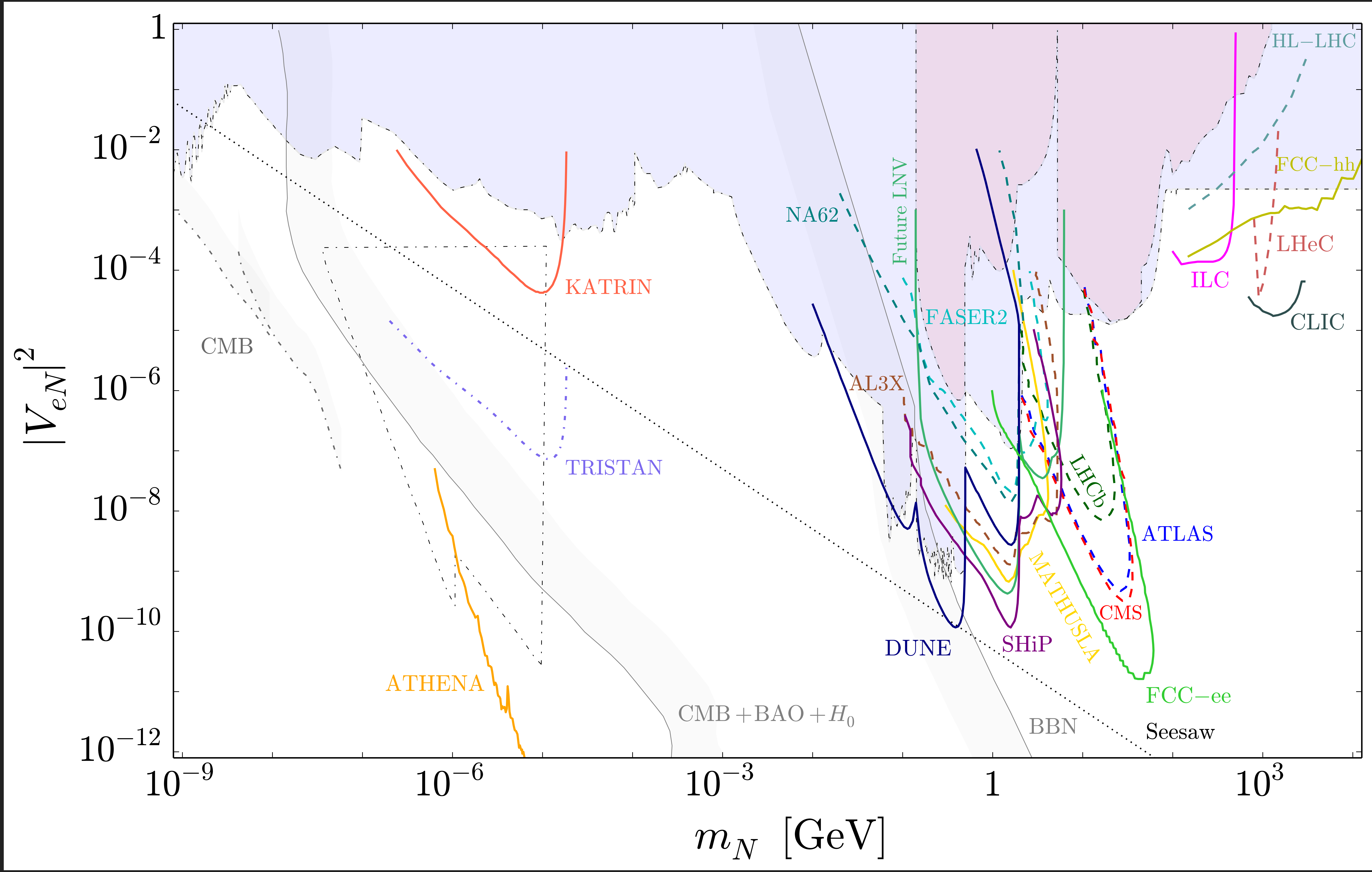





Bolton et al, [1912.03058]

# Electron-Mixing

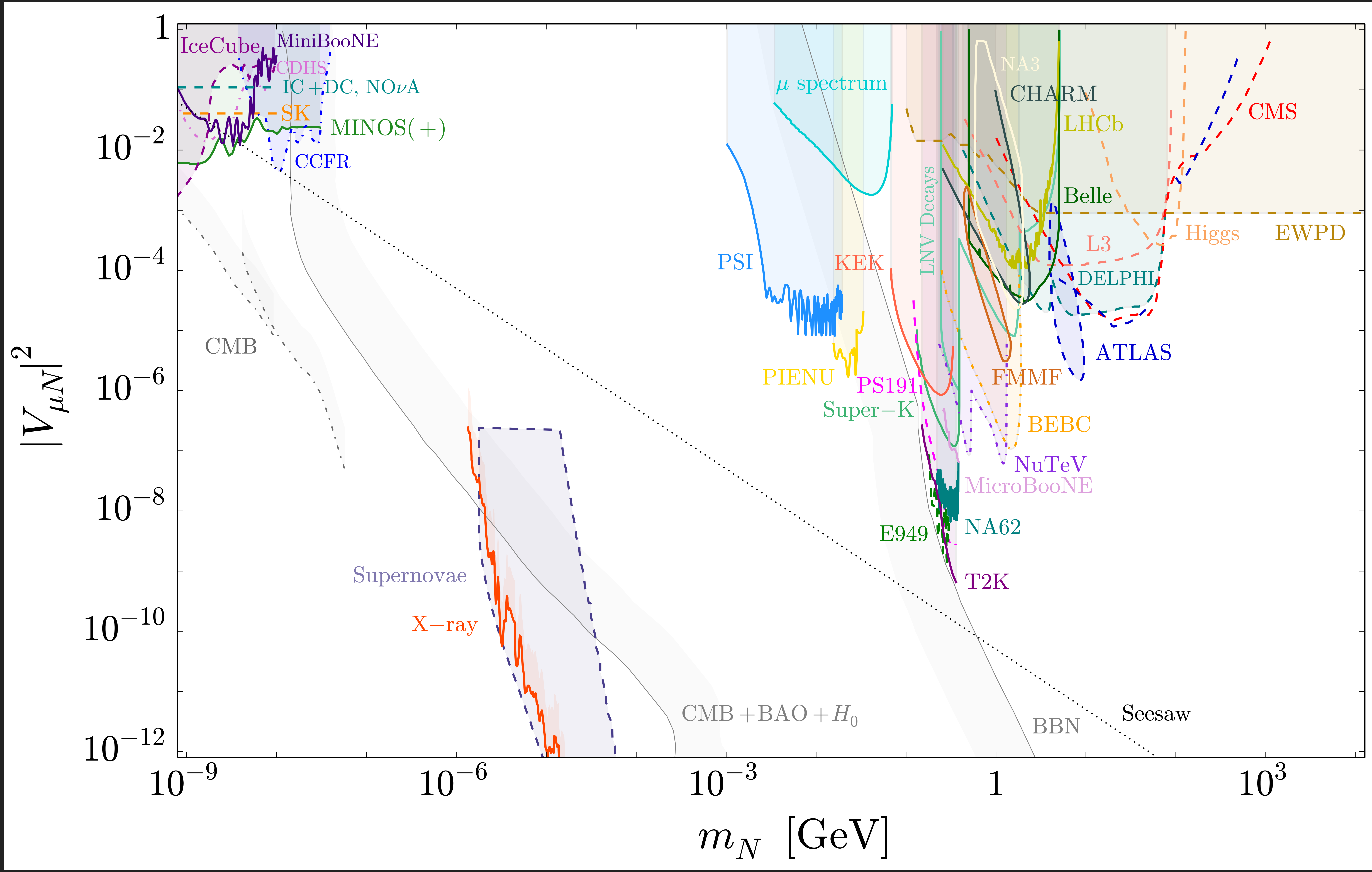





Bolton et al, [1912.03058]

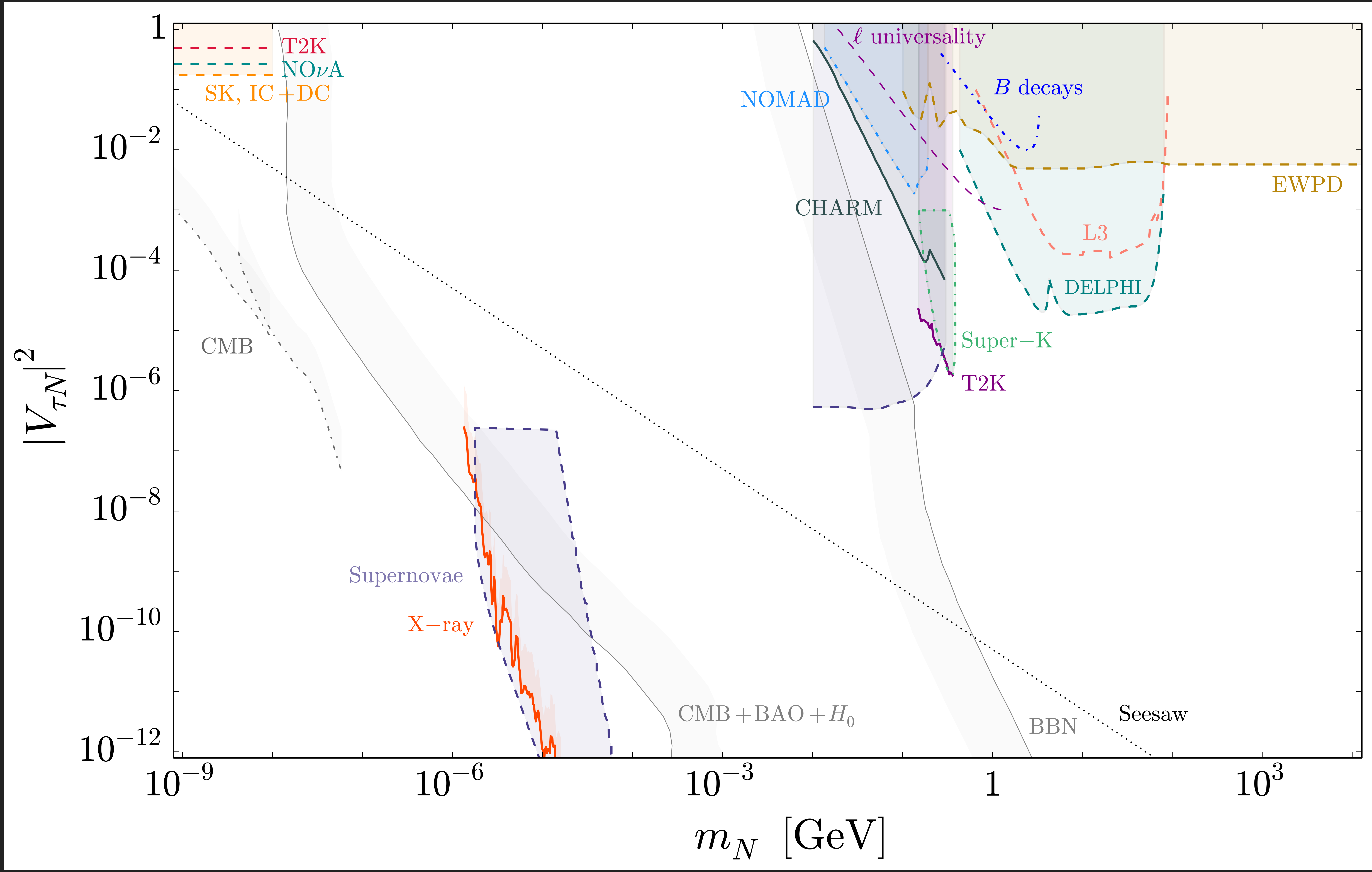
# Muon-Mixing






Bolton et al, [1912.03058]

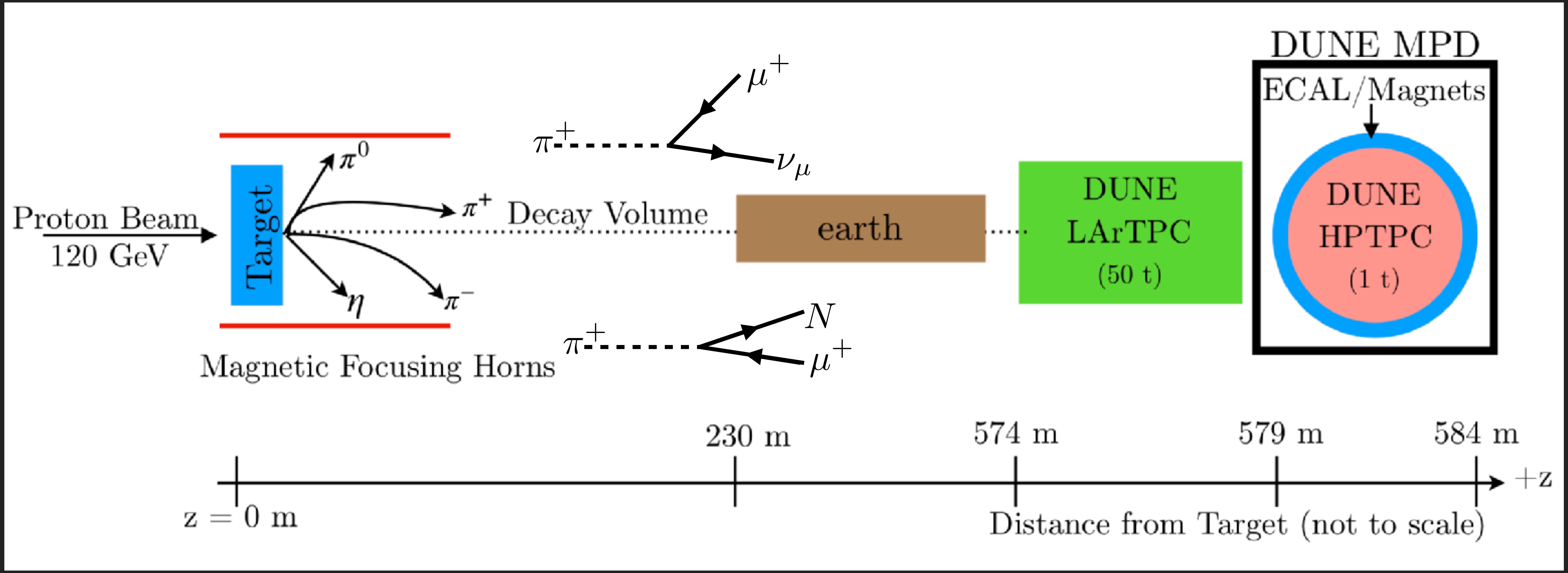
# Tau-Mixing




Bolton et al, [1912.03058]

# Accelerator Neutrino Experiments & HNL

# Accelerator Neutrino Beam Production




A theorist's view of the DUNE target & Near Detector Hall

- Neutrino beams are designed to select neutrinos or antineutrinos using magnetic focusing horns.
- Any source of neutrinos, up to kinematical accessibility, could serve as a source for HNL that are metastable.

Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf [1912.07622]

# Production Modes Considered



- Assuming just mixing with the muon as an example. We include seven different production channels:

$$\pi^+ \to \mu^+ N$$
$$K^+ \to \mu^+ N$$
$$K^+ \to \pi^0 \mu^+ N$$

$$D^+ \to \mu^+ N$$
$$D^+ \to \pi^0 \mu^+ N$$
$$D^+ \to \overline{K^0} \mu^+ N$$
$$D_s^+ \to \mu^+ N$$

Two-body decays into charged leptons and SM neutrinos are helicity suppressed – having N be as massive as (or more massive than) the charged lepton can lead to enhanced branching ratios into HNL.

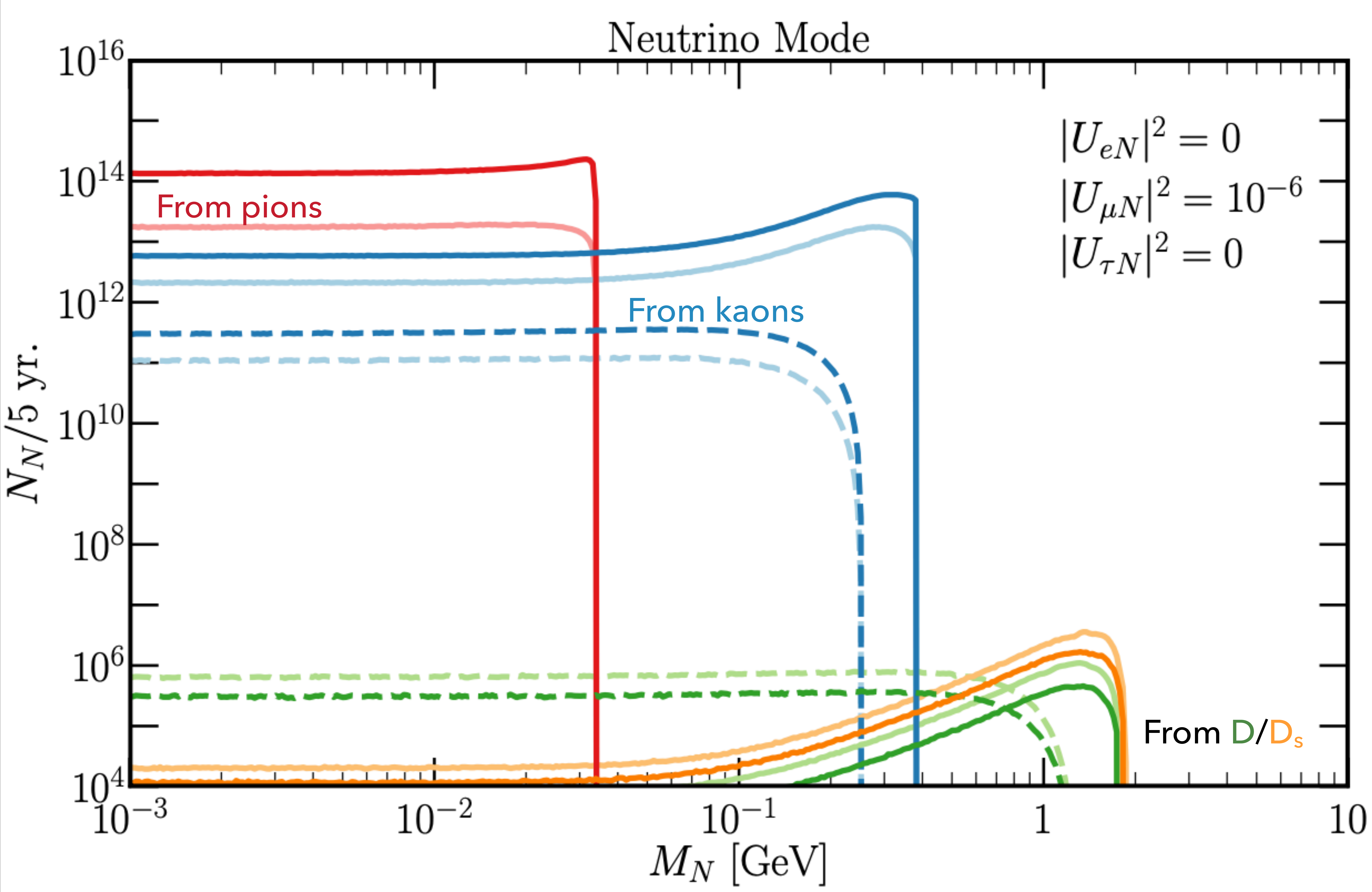
# Heavy Neutrino Flux at DUNE ND



5 years of operation in neutrino mode, mixing only with muon neutrinos.

Includes acceptance efficiency – detector is 5 m in diameter at a distance of 579 m.

Separated by production source (which charged meson)




Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf [1912.07622]

# Neutrino vs. Antineutrino modes

Helicity *enhancement* when N is heavier than the muon


No such enhancement in three-body decays

Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf [1912.07622]

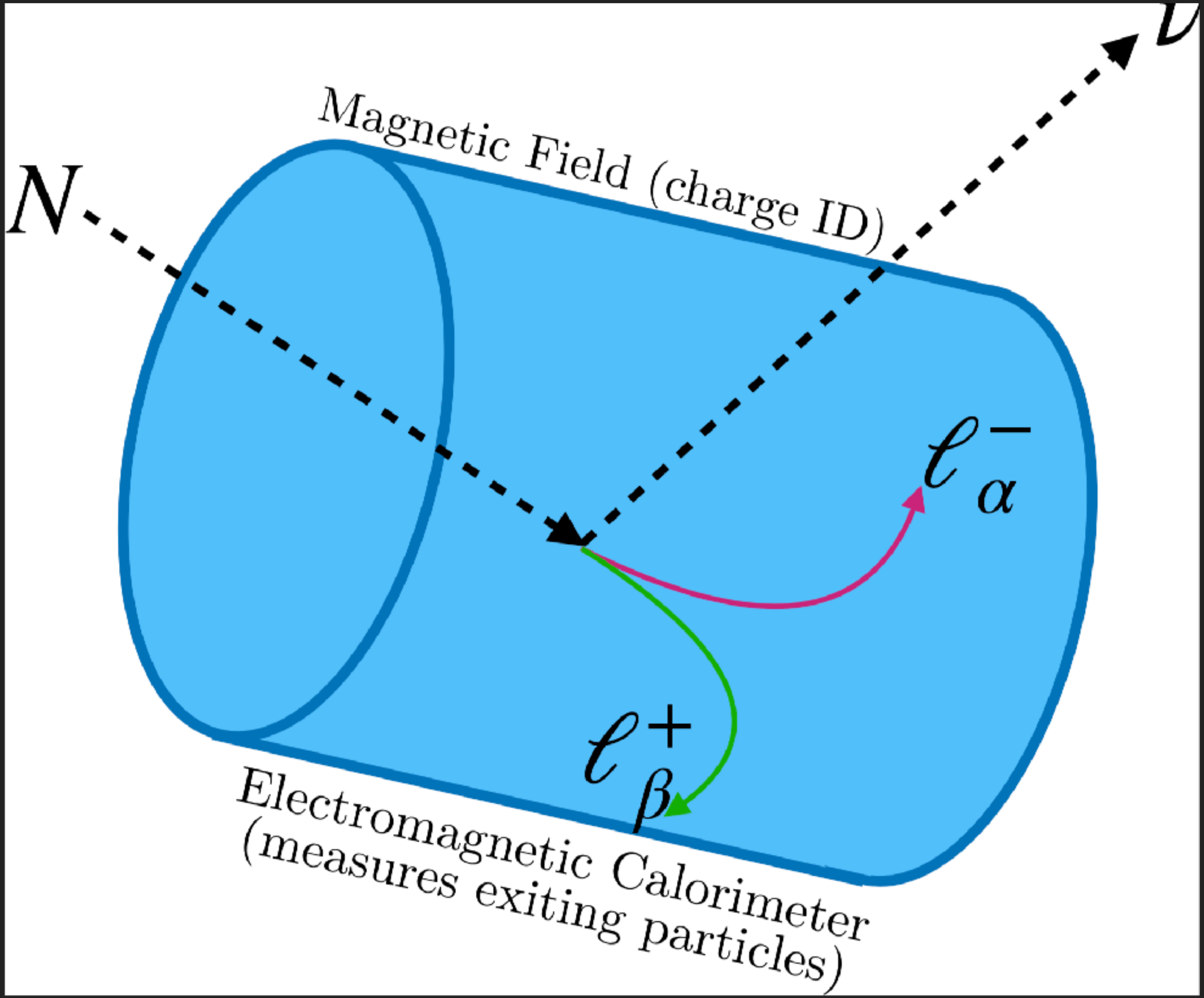
# Flux for Electron Coupling


Helicity enhancement, relative to decays like $\pi^\pm \to e^\pm \nu$ , is readily apparent.

Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf [1912.07622]

# Experimental Signature






- The HNL travels to the gaseous argon near detector and has some probability of decaying within into a final state that is difficult for neutrino interactions to mimic.

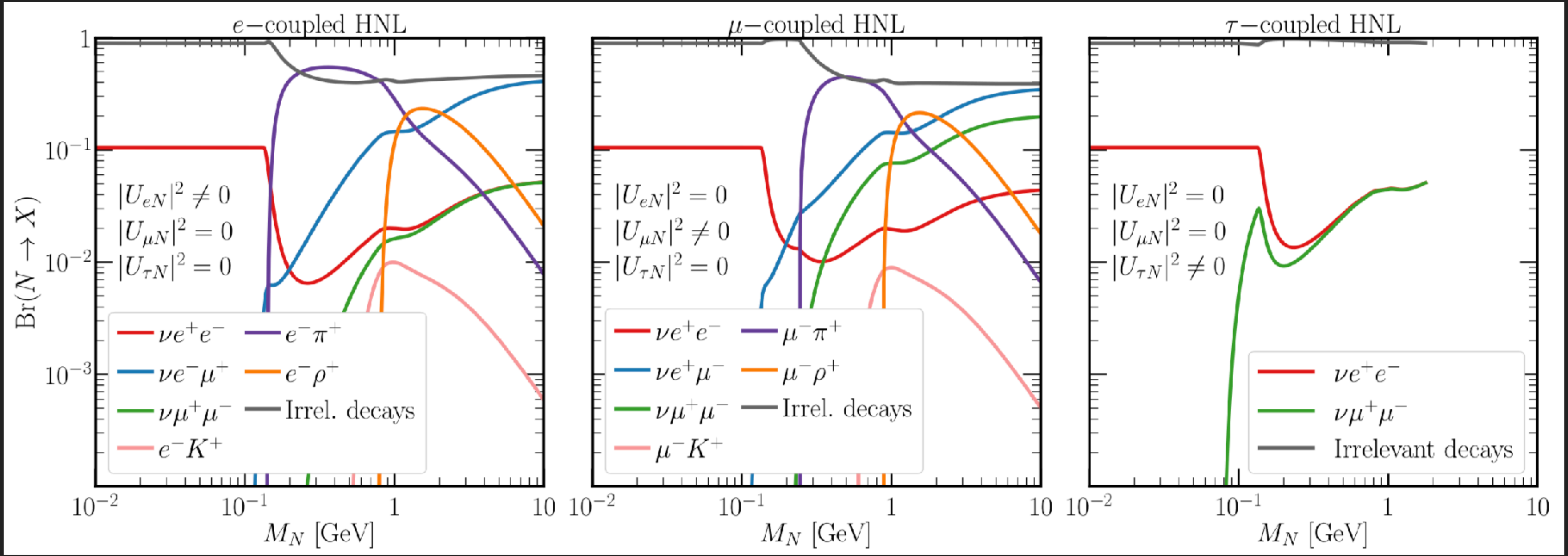
| | |
|---|---|
| $N \to \nu \ell_\beta^+ \ell_\alpha^-$ | $N \to \ell_\alpha^\pm \pi^\mp$ |
| $N \to \ell_\alpha^\pm K^\mp$ | $N \to \ell_\alpha^\pm \rho^\mp$ |
| $N \to \nu \pi^0$ | $N \to \nu\nu\bar{\nu}$ |

- All partial widths calculable in the minimal mixing scenario.

# HNL Branching Fractions



Irrelevant decays: those with just neutrinos or those with a neutrino and one other neutral particle.

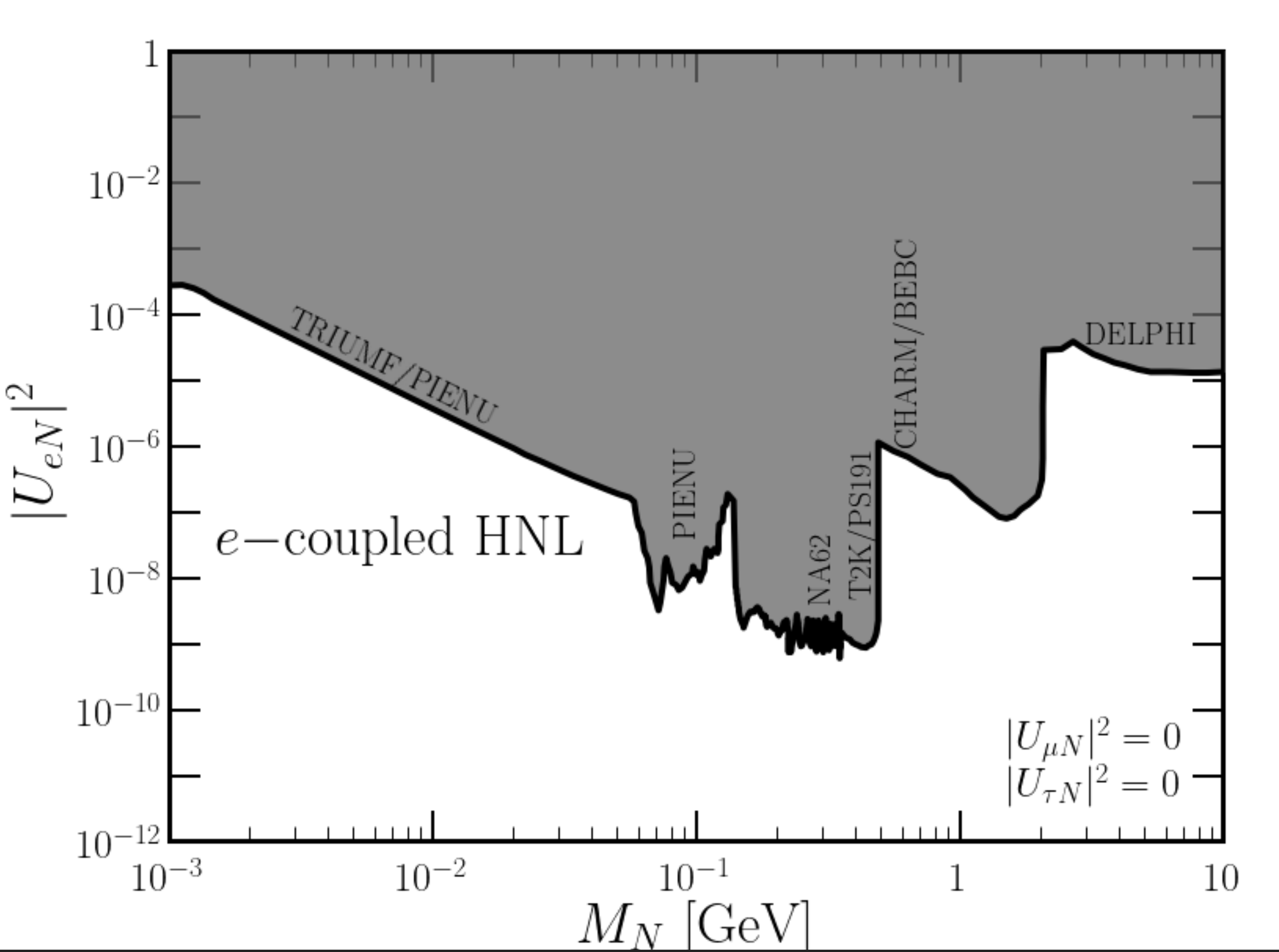



- Non-minimal HNL scenarios (for instance, if N couples to a light Z′) can modify these branching fractions and the lifetime of N significantly.

Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf [1912.07622]

# Sensitivity to HNL at DUNE

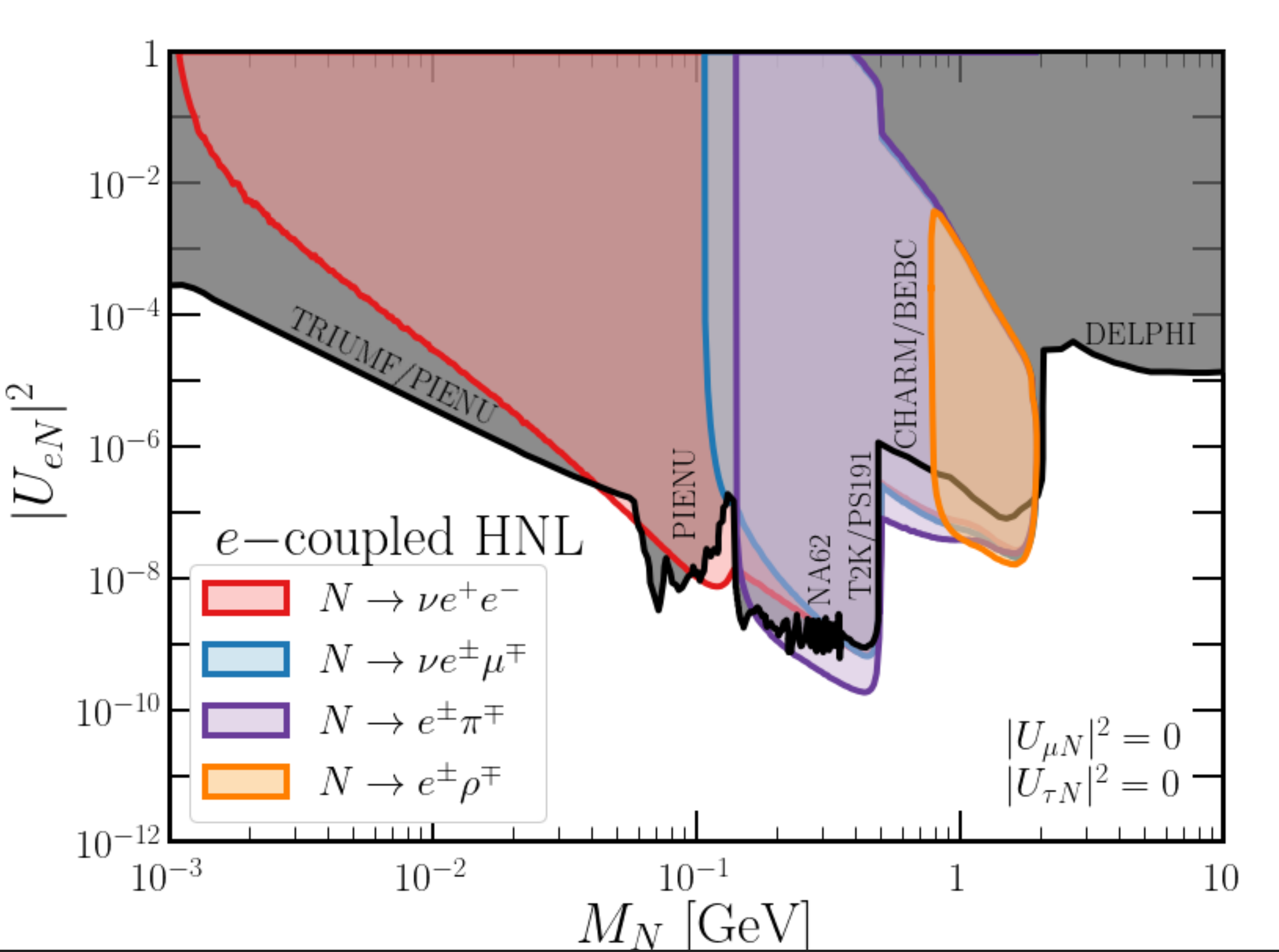
# Electron-Coupled HNL



# Electron-Coupled HNL

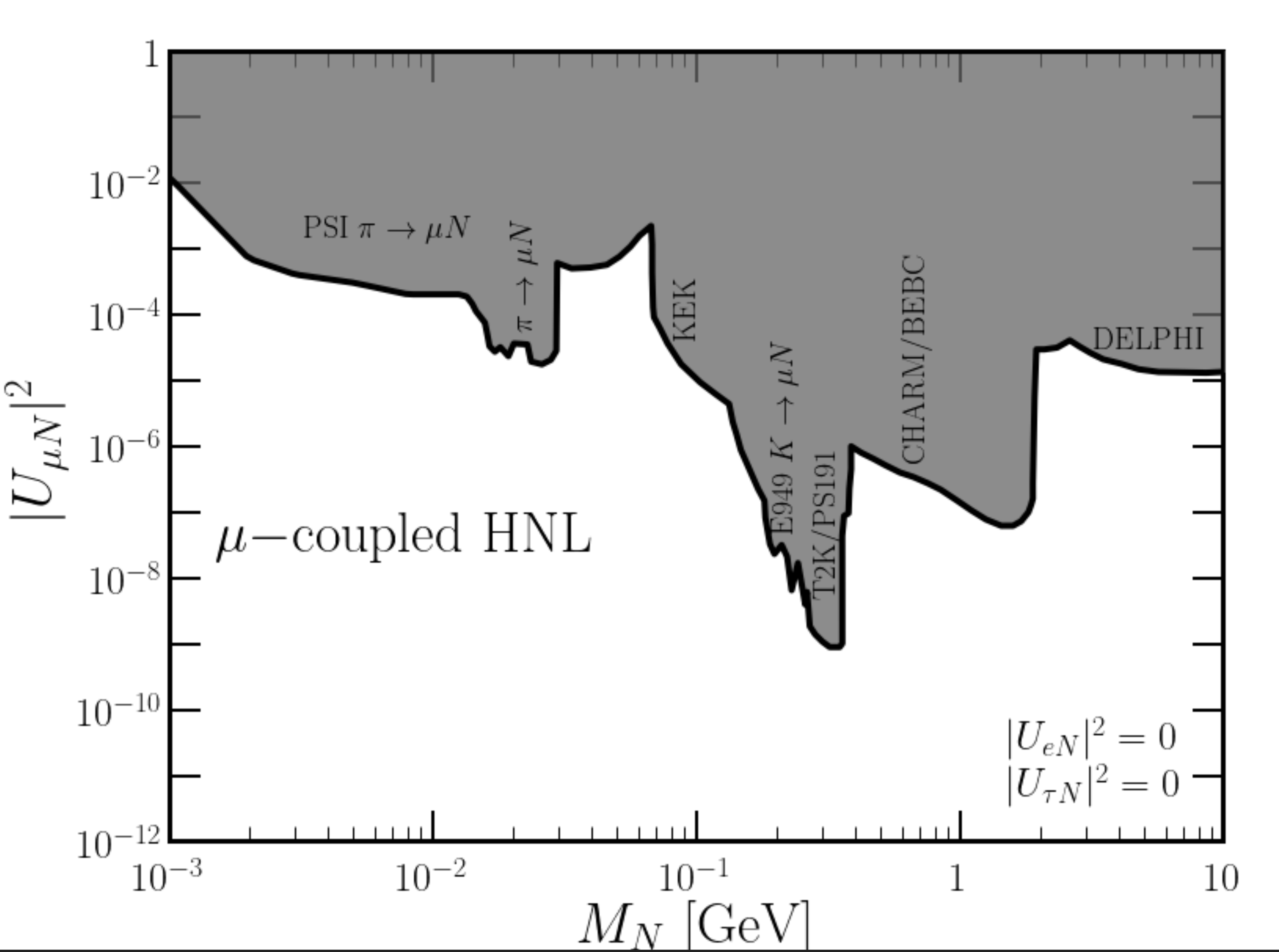


Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf [1912.07622]



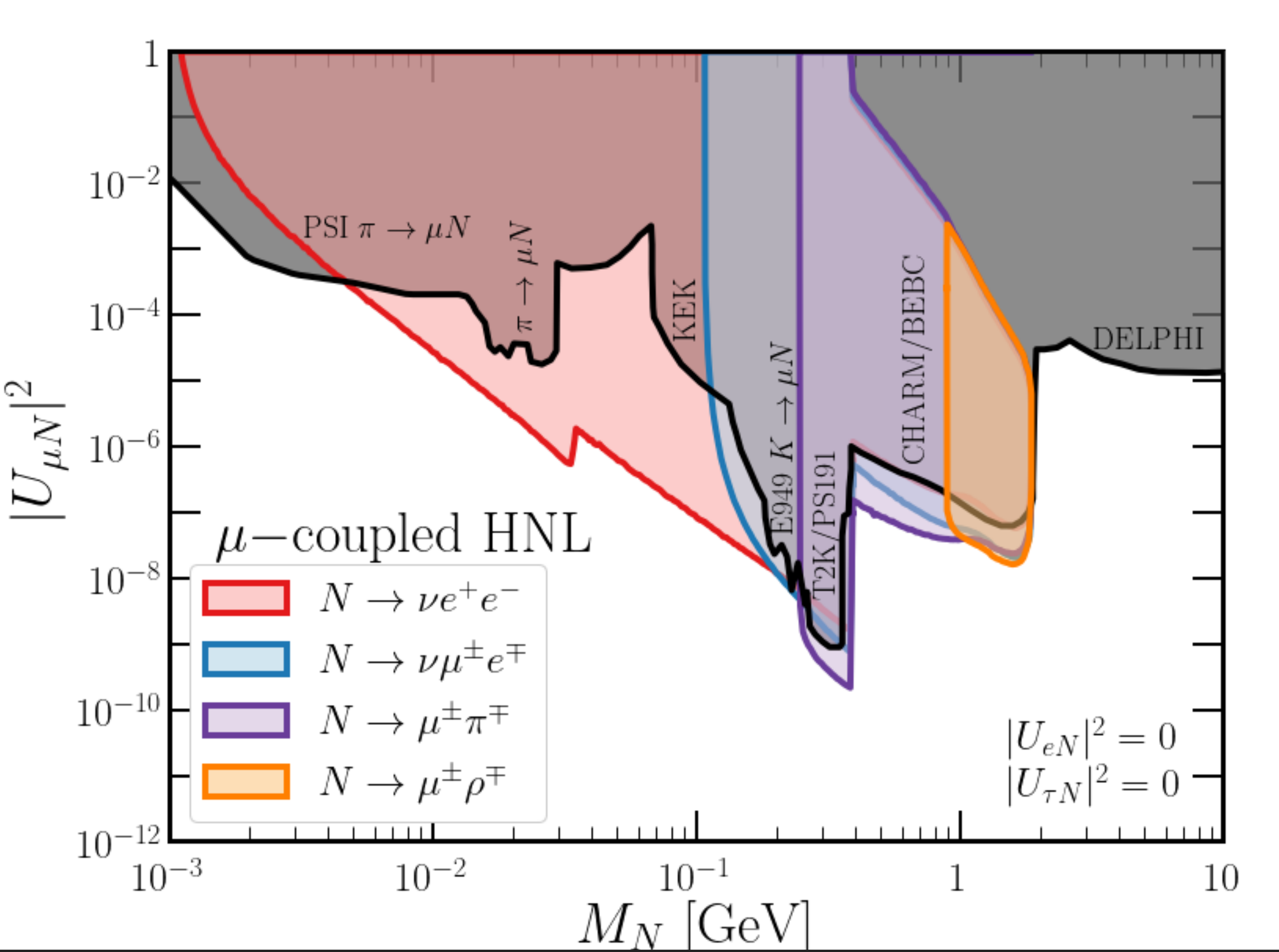
# Muon-Coupled HNL





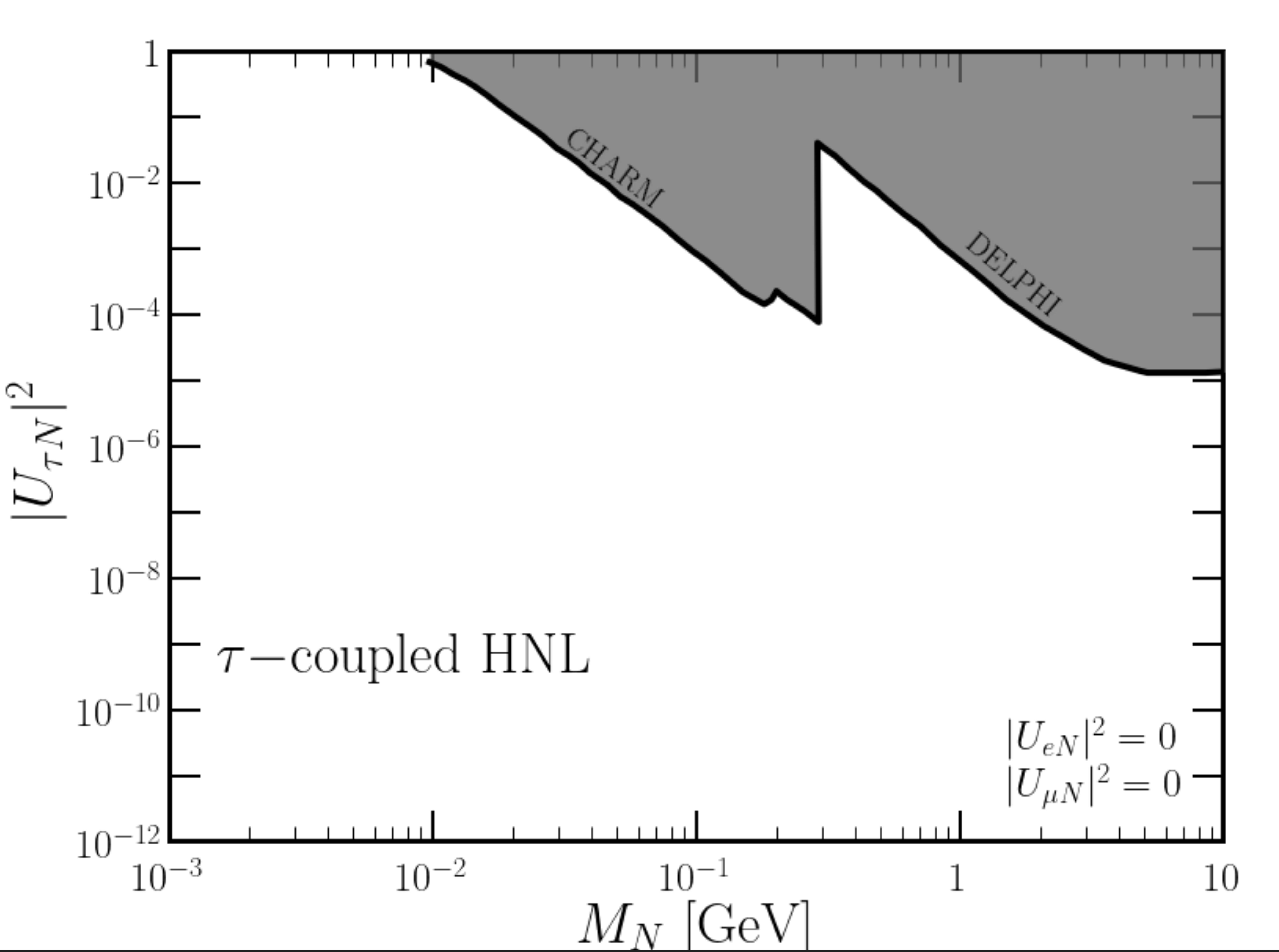
# Muon-Coupled HNL

Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf [1912.07622]



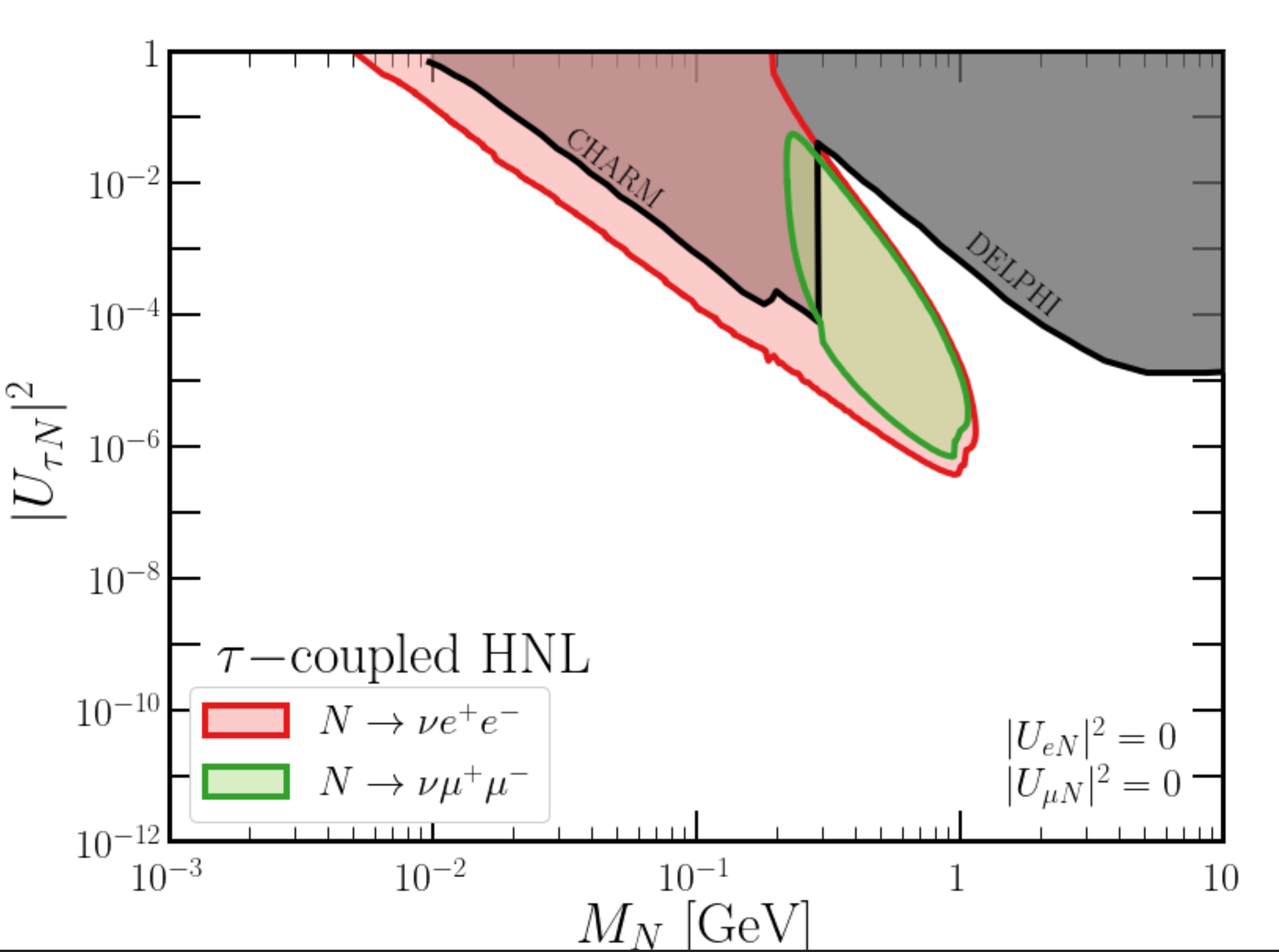
# Tau-Coupled HNL





# Tau-Coupled HNL

Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf [1912.07622]

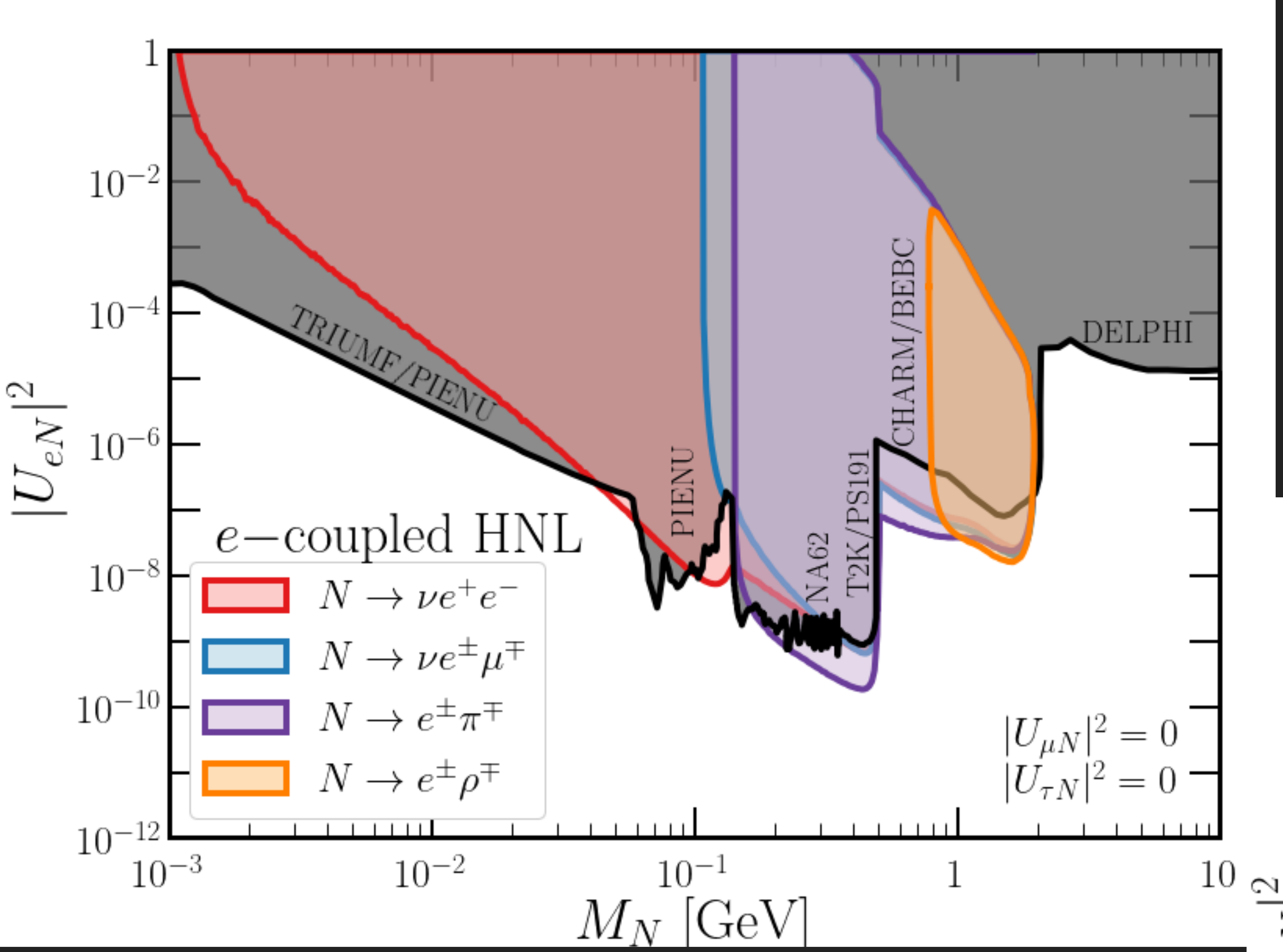



Other upcoming proposals: FASER, SHiP, DarkQuest, etc.

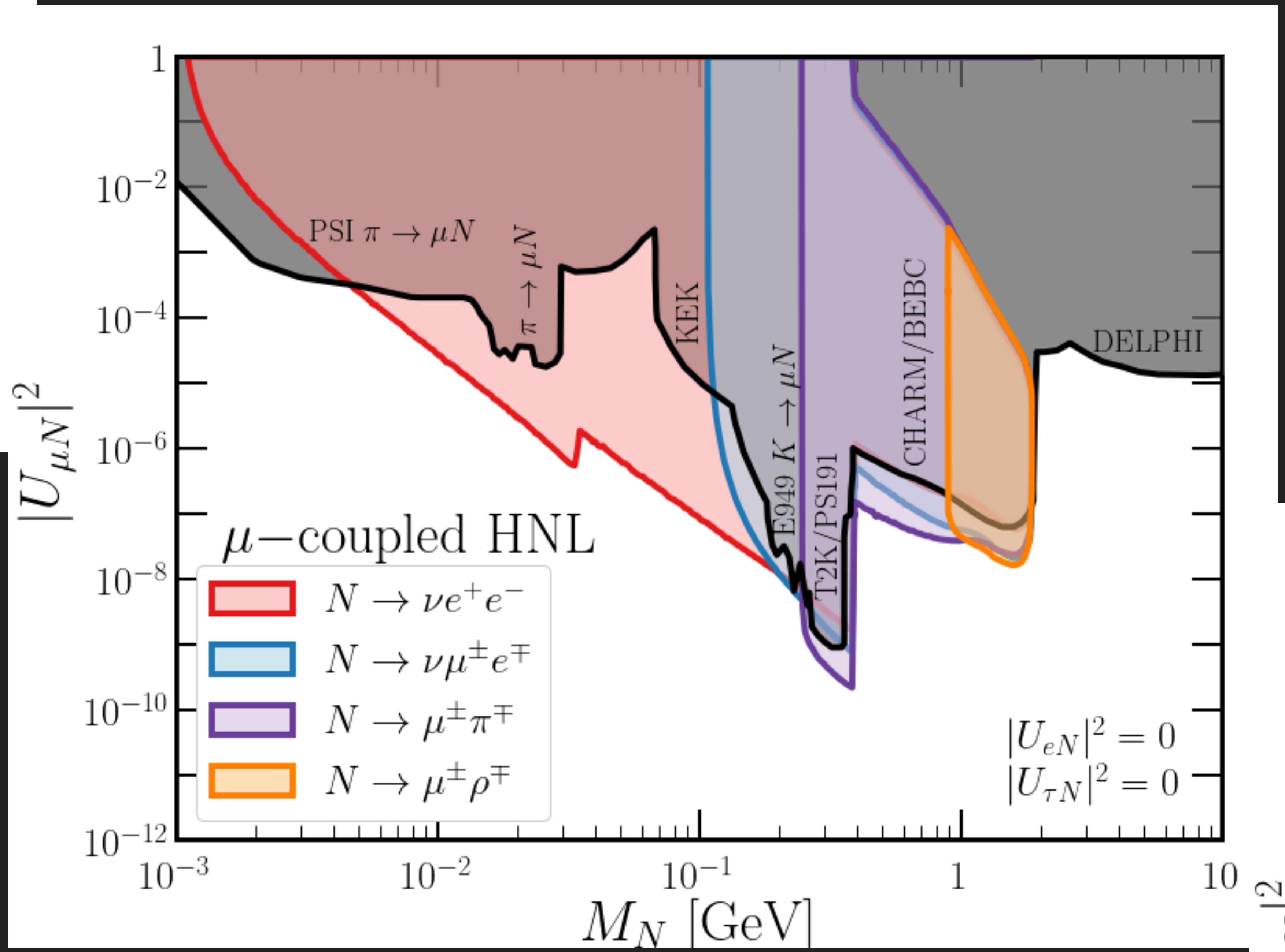
See Batell et al, [2008.08108]

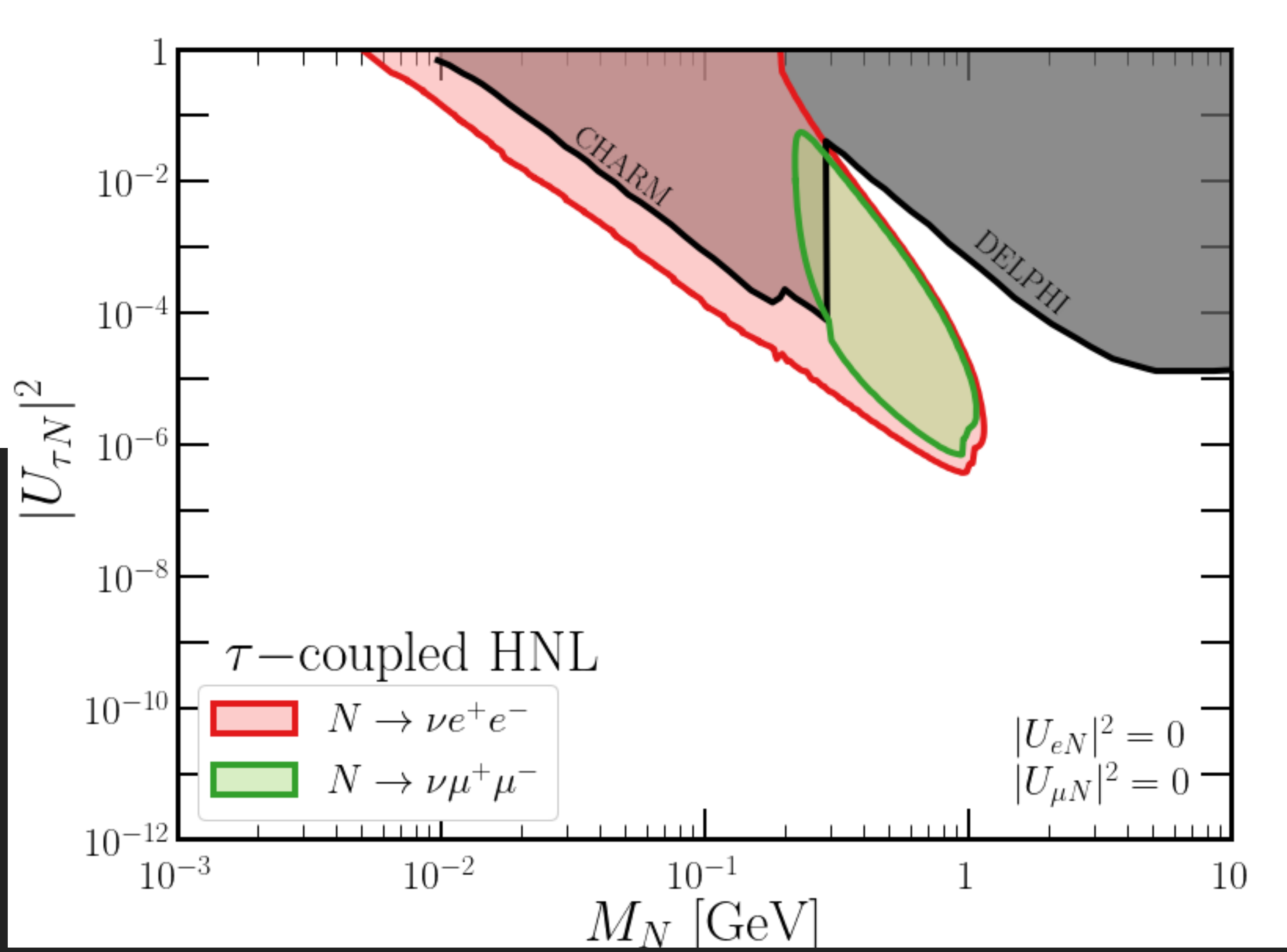
# Sensitivity Summary






- Significant amount of parameter space in each coupling scenario that can be probed by DUNE. Moreover, there exists parameter space where many, many (100s-1000s) events could be detected.

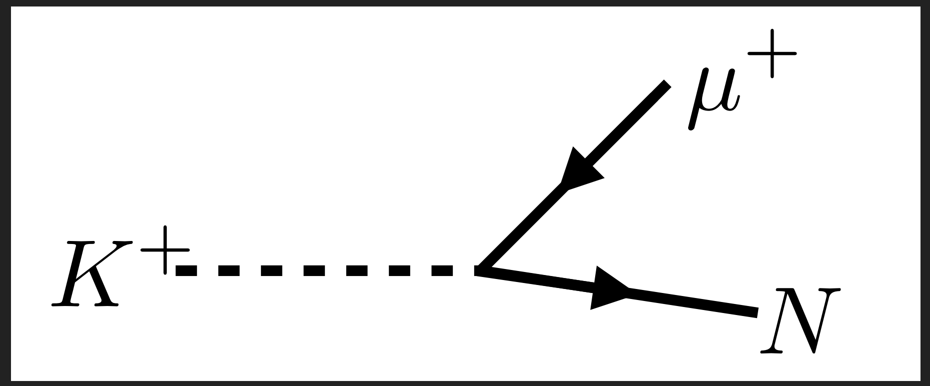



- Can these events be exploited for any other purpose?

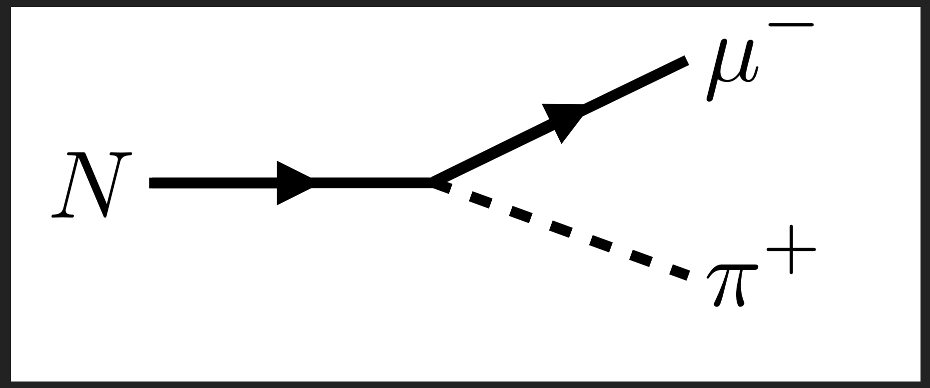
# Dirac vs. Majorana HNL

# Suppose we have a characterized source of HNLs

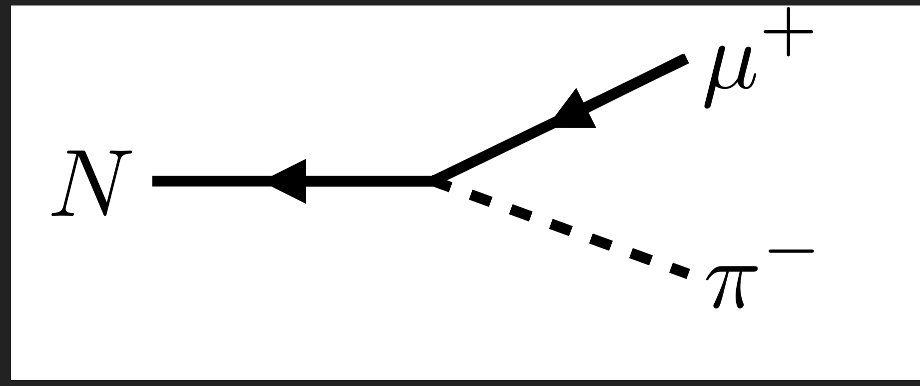



Only positively-charged kaons decaying – negatively-charged ones are not produced, deflected, or absorbed, etc.

If the HNL is a Dirac fermion, it carries lepton number and its decays must conserve LN




If the HNL is a Majorana fermion, then it can decay into the opposite-charge final state with equal probability



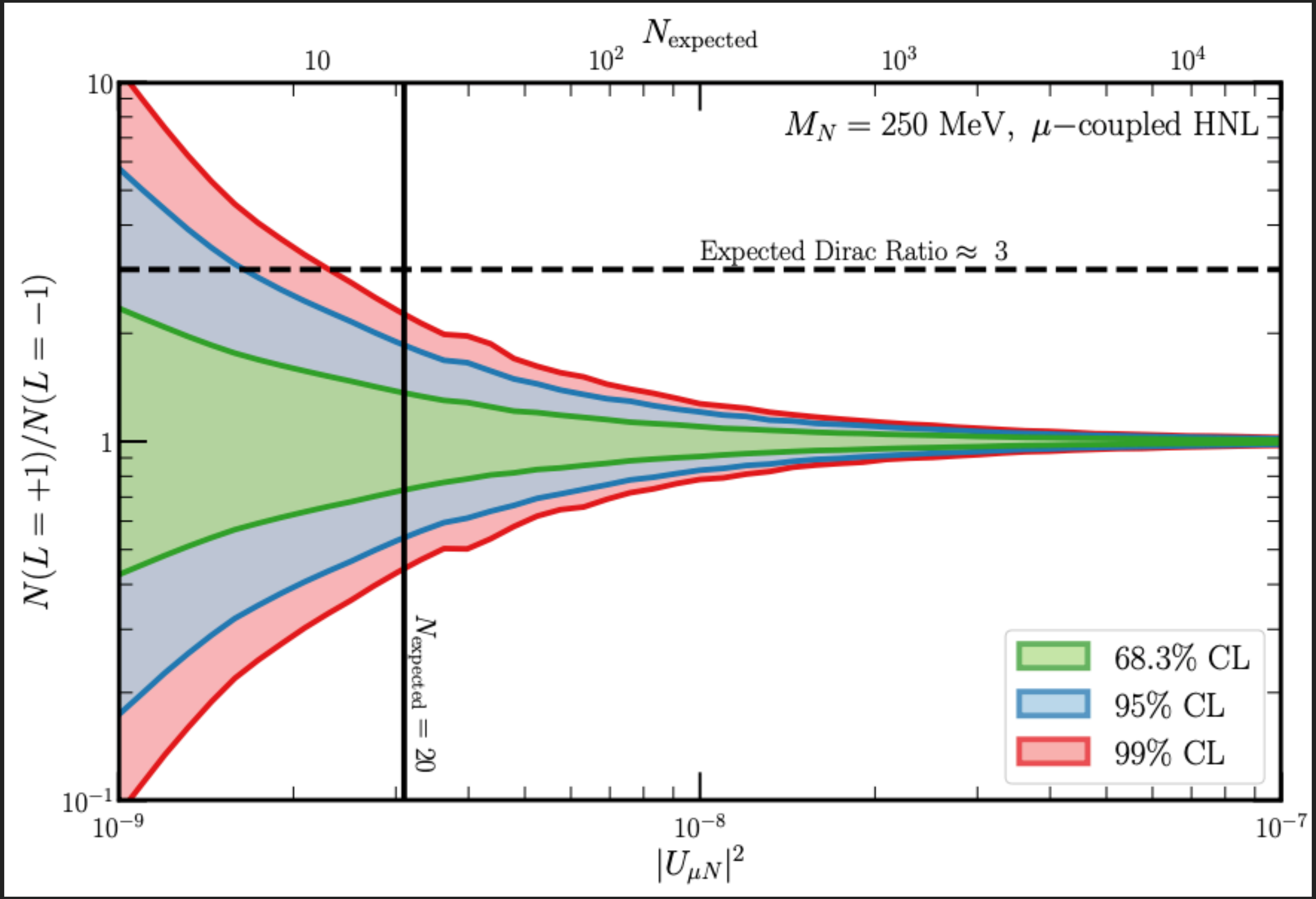

**Measure the ratio of these final states in your detector (assuming you can identify the charges/particles on an event-by-event basis)**

# No production source is perfect…



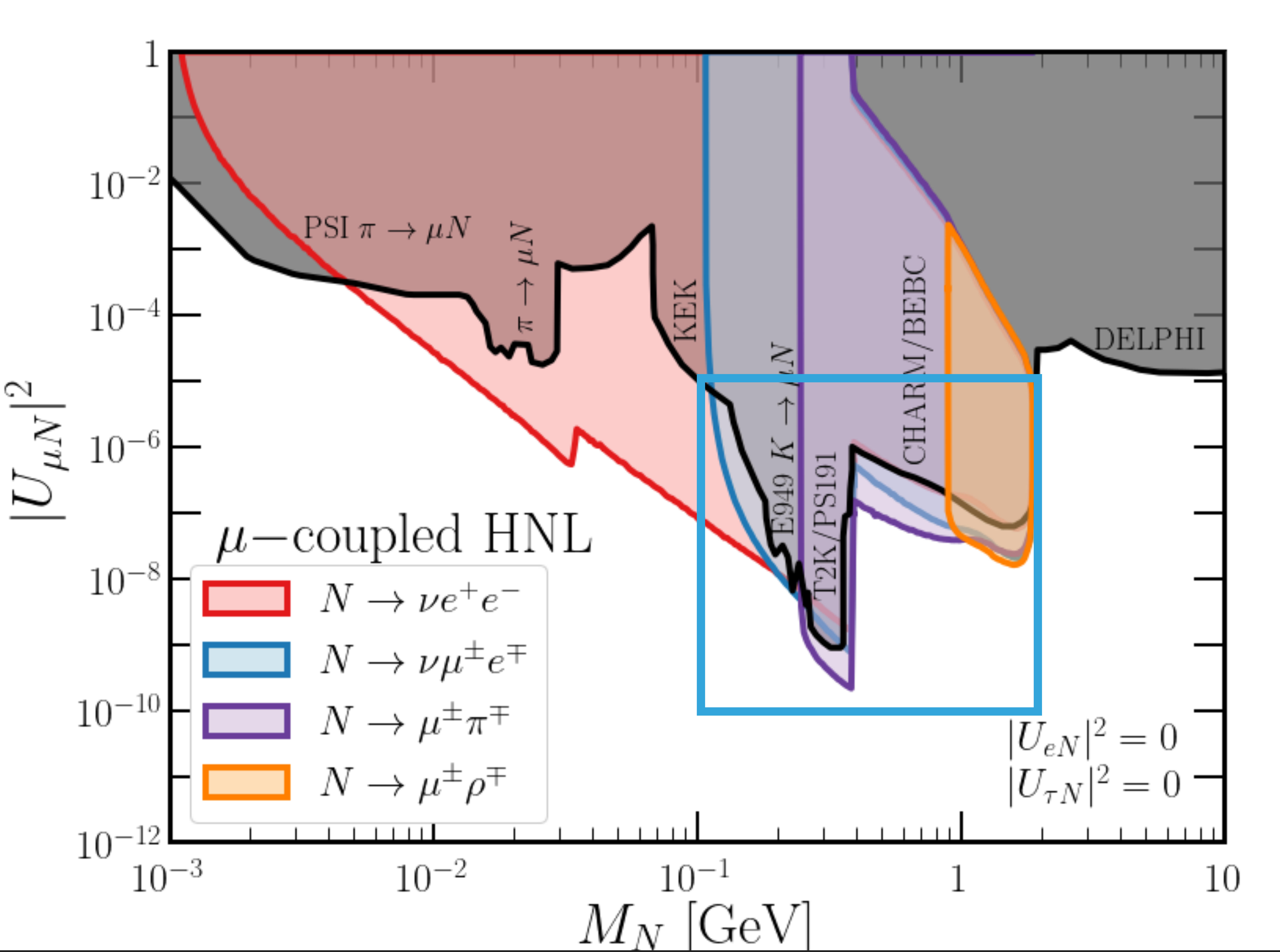
# Toy Example — Identify every decay perfectly






Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf [1912.07622]

# Going Further: Muon-Coupled Channel




Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf [1912.07622]

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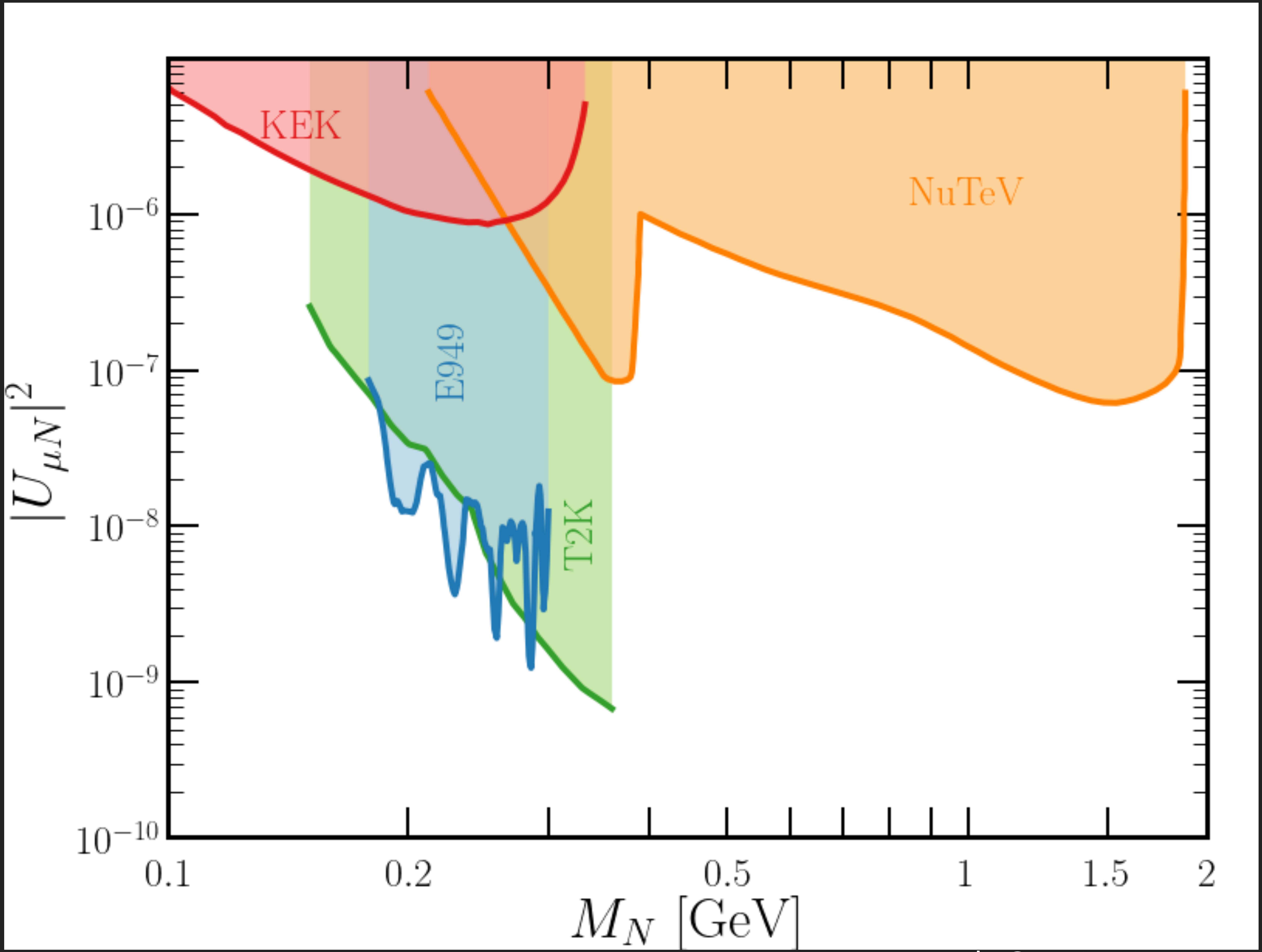


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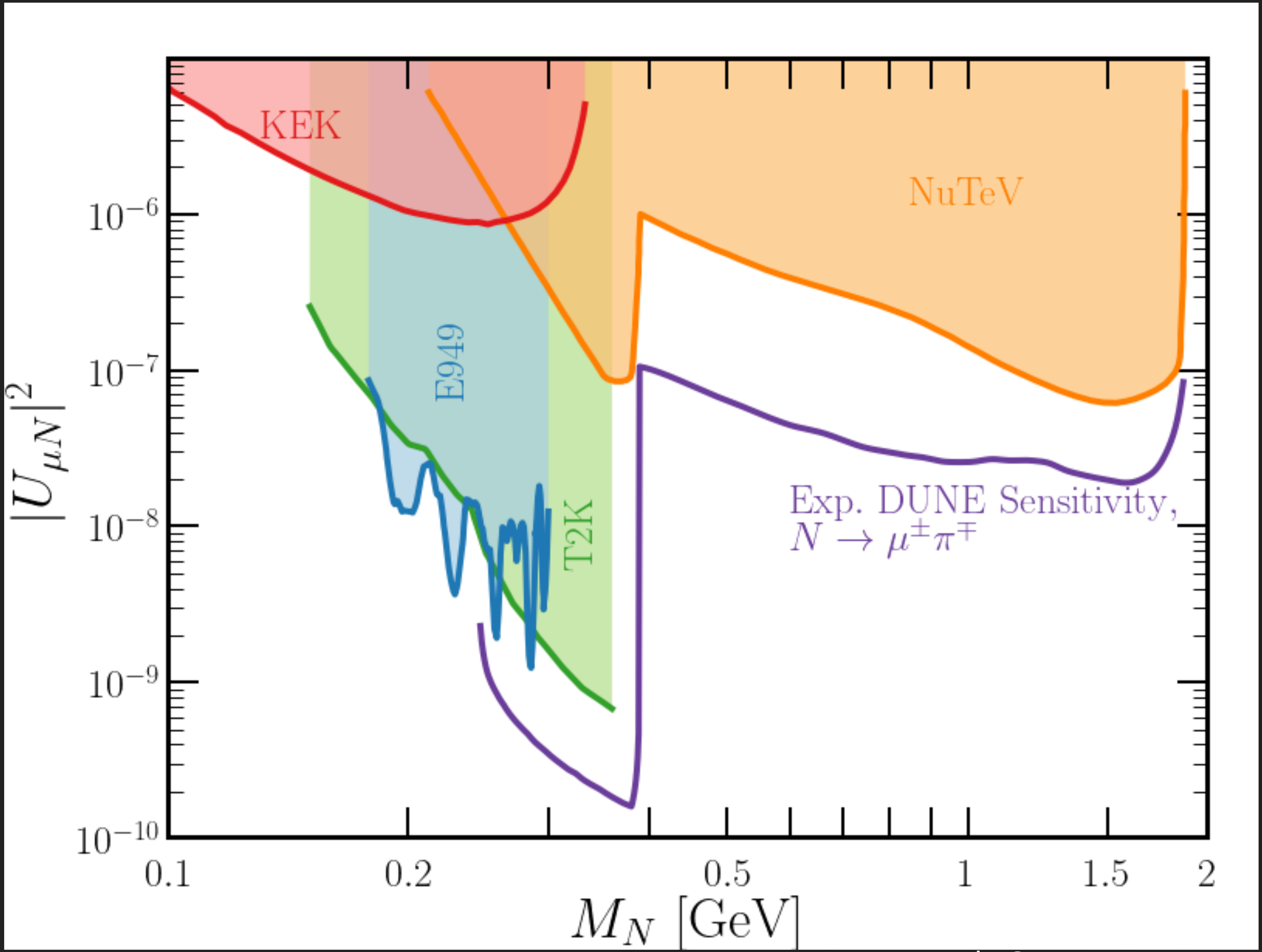


Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf [1912.07622]

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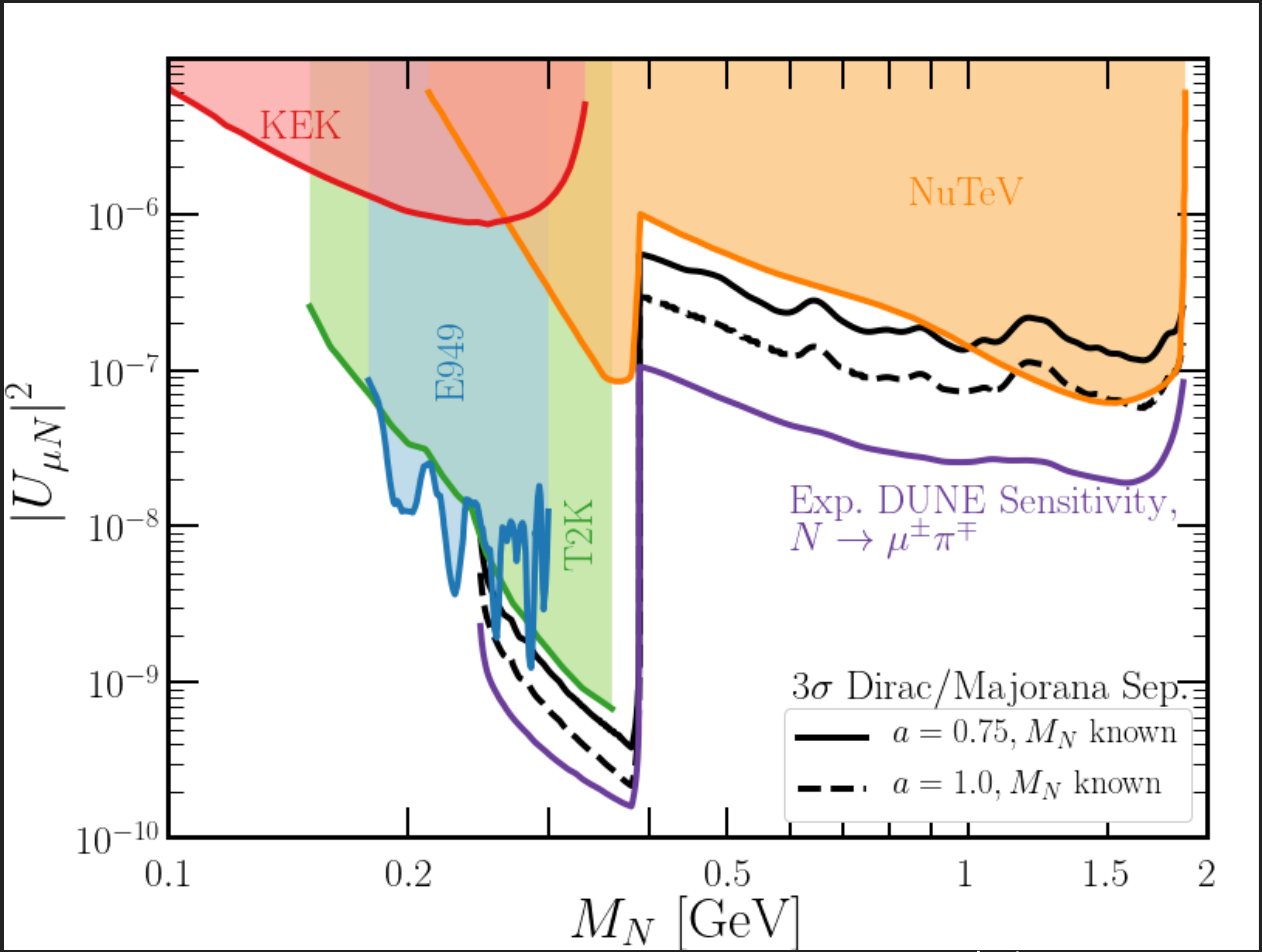
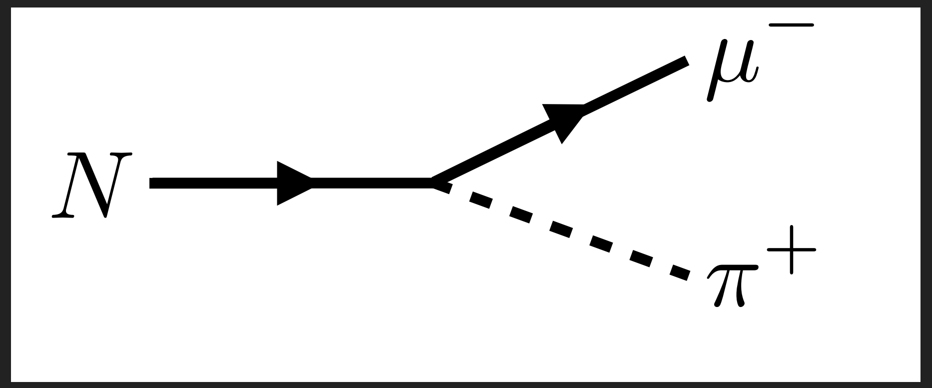
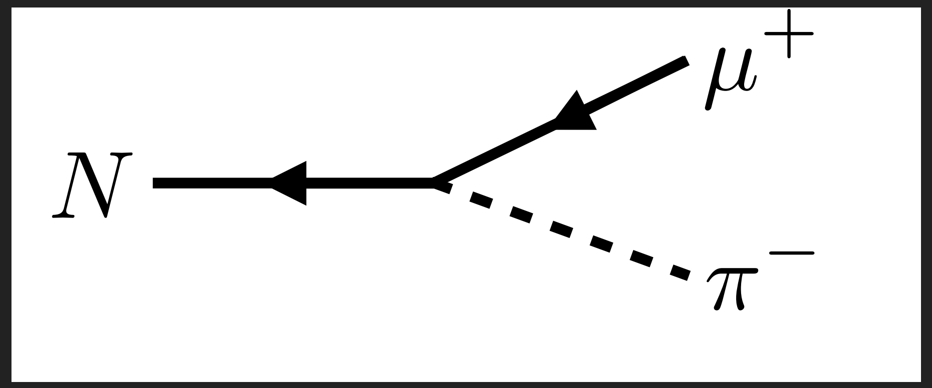
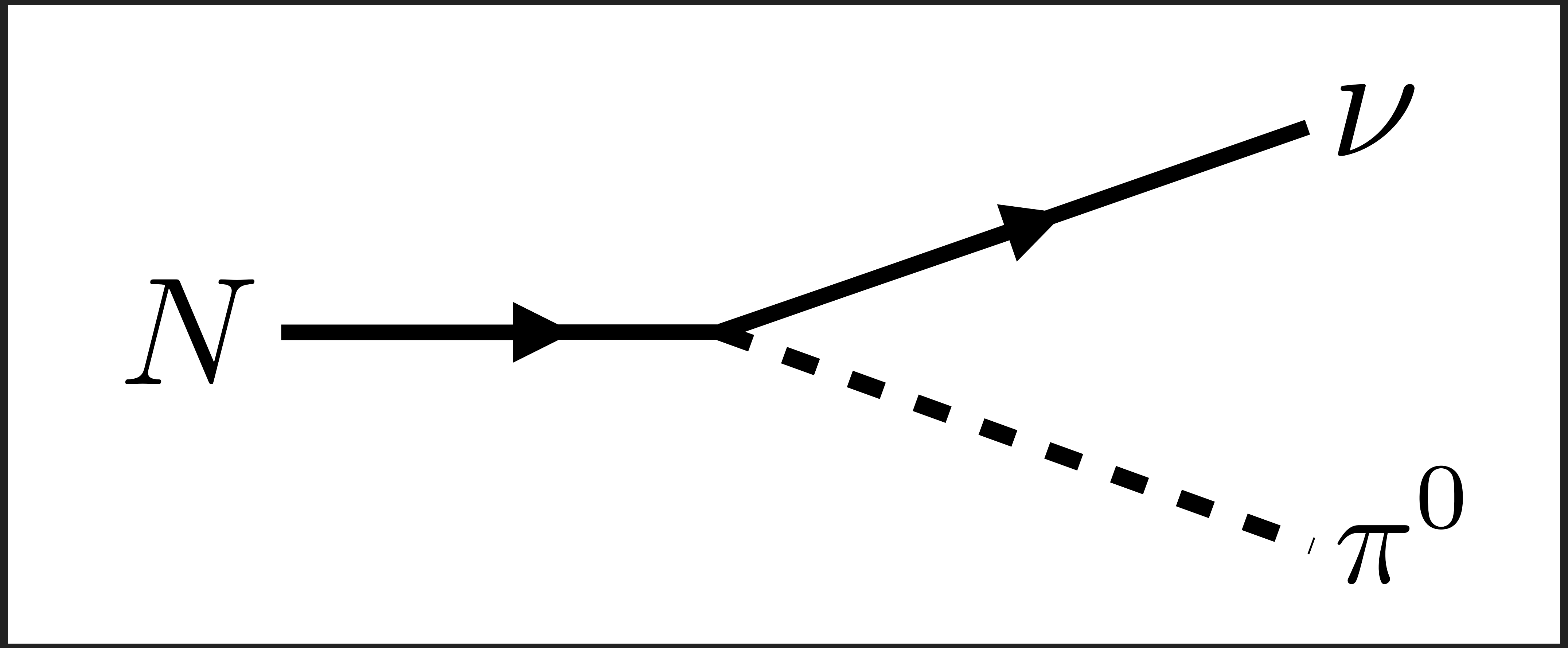



Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf [1912.07622]

# What about decays where we can't identify the lepton number of the final state of the HNL Decay?



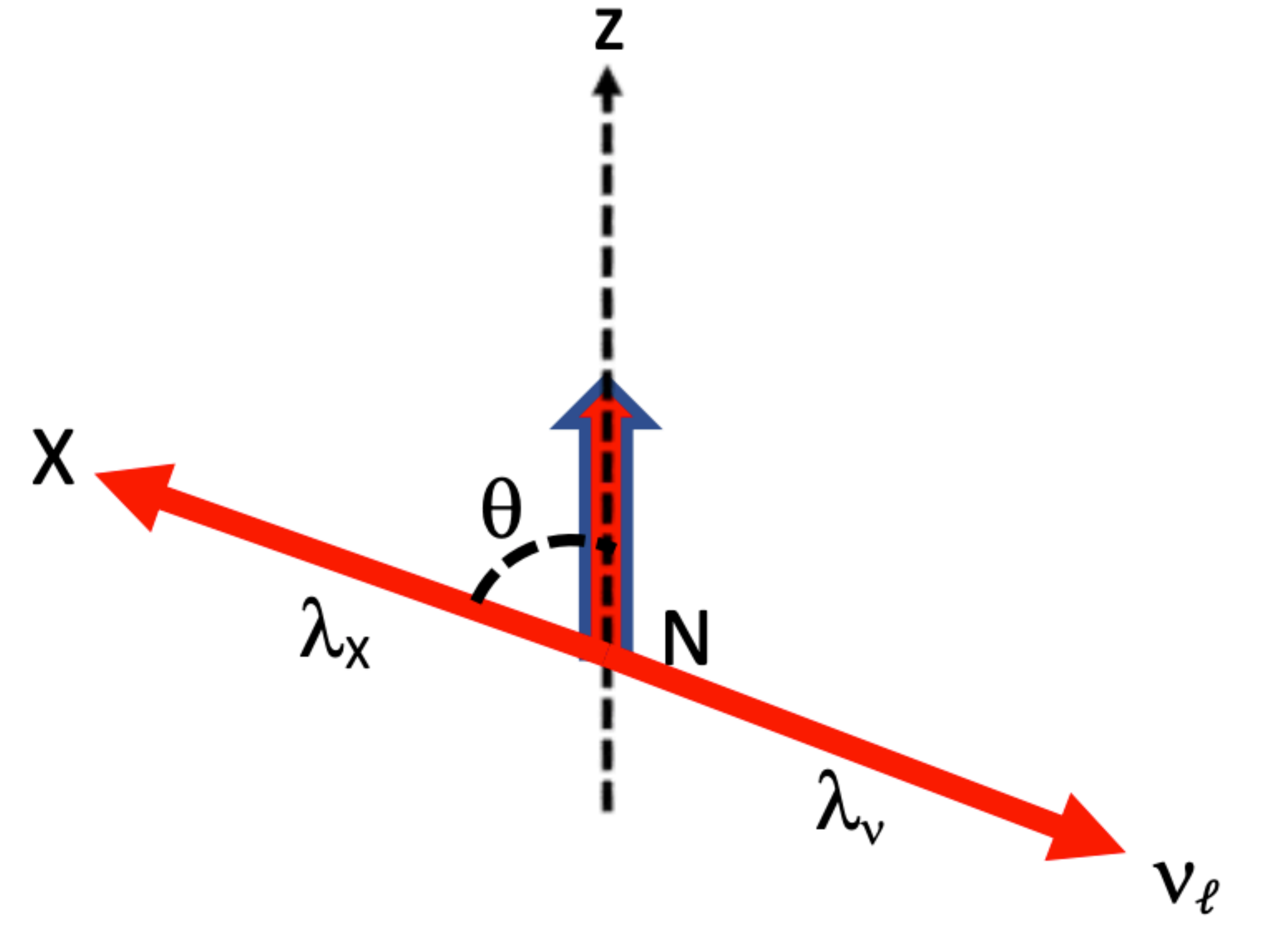




**There's still hope! Measure the *distribution* of outgoing pions.**

# Two-Body Decays

Balantekin, de Gouvêa, Kayser, [1808.10518]

N is perfectly polarized in the z-direction.




$$\frac{d\Gamma}{d\cos\theta_X} = \frac{\Gamma}{2}\left(1+\alpha\cos\theta_X\right)$$

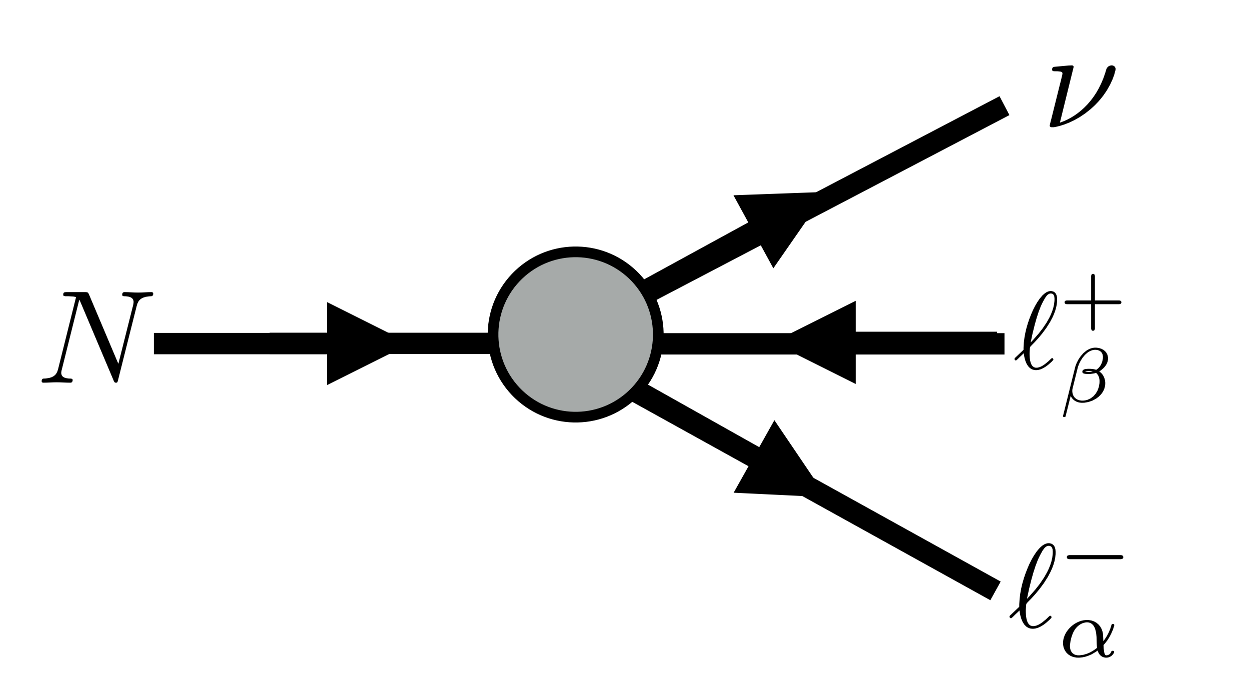
**If N is a Majorana fermion, this decay is isotropic. If N is Dirac, not necessarily.**

| Boson | $\gamma$ | $\pi^0$ | $\rho^0$ | $Z^0$ | $H^0$ |
|---|---|---|---|---|---|
| $\alpha$ | $\frac{2\Im(\mu d^*)}{\lvert\mu\rvert^2+\lvert d\rvert^2}$ | 1 | $\frac{m_4^2-2m_\rho^2}{m_4^2+2m_\rho^2}$ | $\frac{m_4^2-2m_Z^2}{m_4^2+2m_Z^2}$ | 1 |

# Extending to Three-Body Decays

de Gouvêa, Fox, Kayser, Kelly, In Prep.

- Our goal is to be as generic as possible. We're going to consider decays where the only assumption is that any mediator(s) can be integrated out:




- Allowing for any UV completion (scalar/vector mediator, charged or neutral), the matrix elements that contributes to N decay are

$$\mathcal{M}_1 = G_{NL}\left[\overline{u}_\nu \Gamma_N P_S u_N\right]\left[\overline{u}_\alpha \Gamma_L v_\beta\right]$$

$$\mathcal{M}_2 = \overline{G}_{NL}\left[\overline{v}_N P_S \Gamma_N v_\nu\right]\left[\overline{u}_\alpha \Gamma_L v_\beta\right]$$

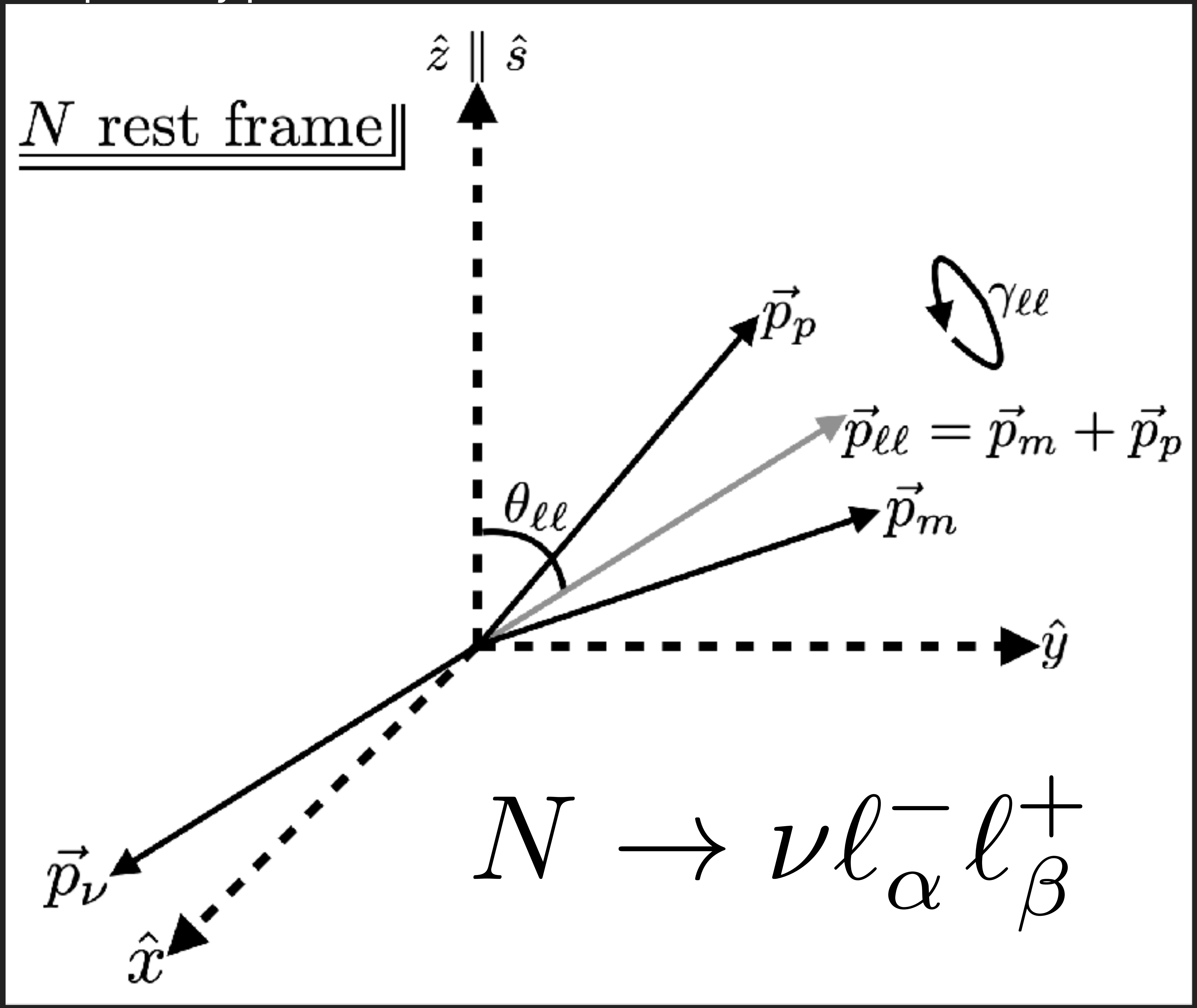
- The matrices entering the matrix elements can be

$$\Gamma_N,\ \Gamma_L \in \left\{\mathbb{1},\ \gamma^5,\ \gamma^\mu,\ \gamma^\mu\gamma^5,\ \sigma^{\mu\nu} = \frac{i}{2}\left[\gamma^\mu, \gamma^\nu\right]\right\}$$

# Three-body Phase Space

de Gouvêa, Fox, Kayser, Kelly, In Prep.

N is perfectly polarized in the z-direction.




$$\frac{d\Gamma(N \to \nu \ell_\alpha^- \ell_\beta^+)}{dm_{\ell\ell}^2 \, d\cos\theta_{\ell\ell} \, dm_{\nu m}^2 \, d\gamma_{\ell\ell} \, d\phi} = \frac{1}{(2\pi)^5} \frac{1}{64 m_N^3} |\mathcal{M}|^2$$

- If we integrate over everything but the charged-lepton pair direction (analogous to the two-body decay),

$$\frac{d\Gamma}{d\cos\theta_{\ell\ell}} = \frac{\Gamma}{2}\left(1 + 2A_{\mathrm{FB}} \cos\theta_{\ell\ell}\right)$$

Forward/backward asymmetry of this decay.

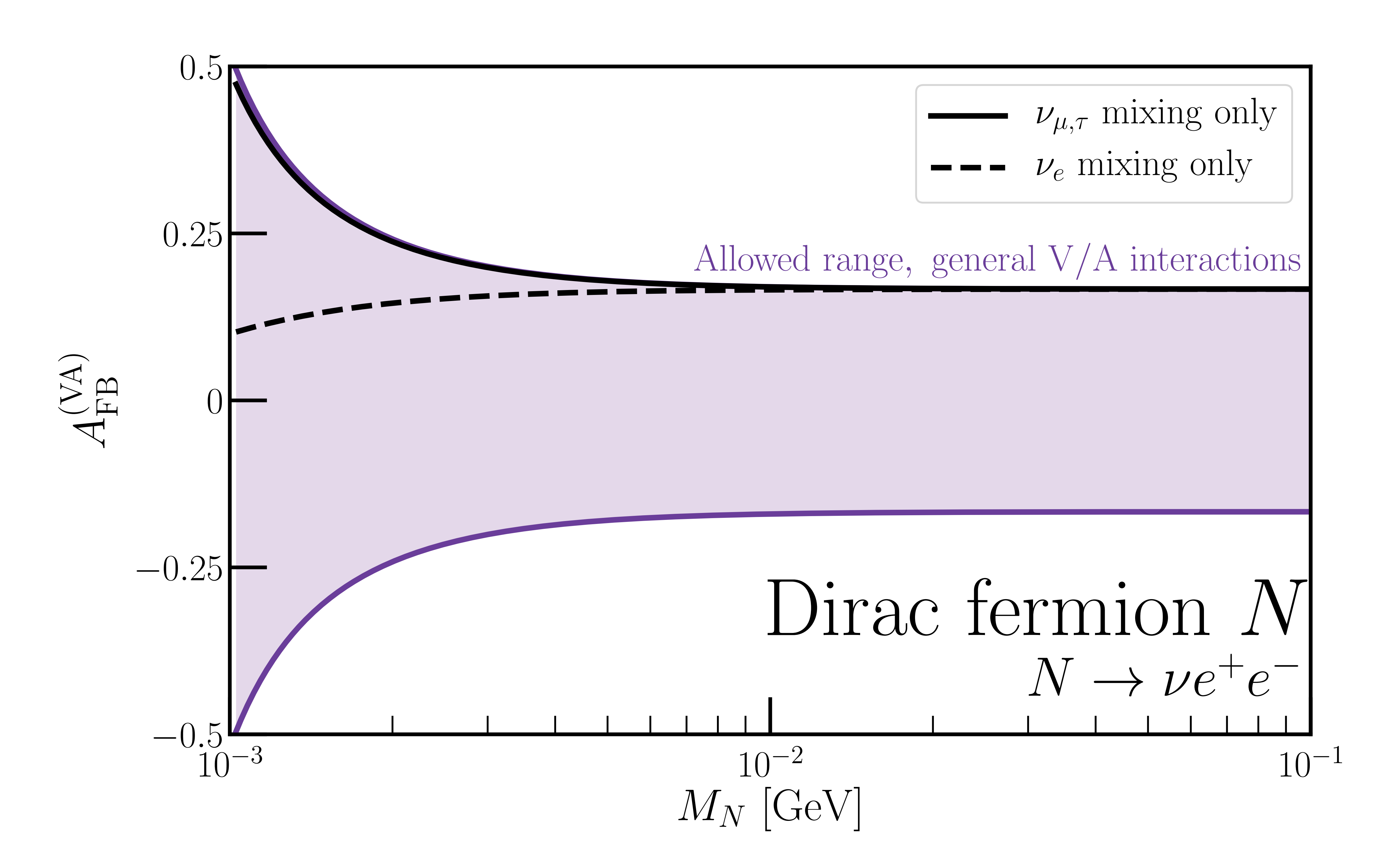
# Forward/Backward Asymmetry

de Gouvêa, Fox, Kayser, Kelly, In Prep.

$$\mathcal{M}_1 = G_{NL}\left[\overline{u}_\nu \Gamma_N P_S u_N\right]\left[\overline{u}_\alpha \Gamma_L v_\beta\right]$$

- Taking different interaction structures separately: if we have only scalar/pseudoscalar interactions, we can attain maximal asymmetry.

- If we allow for only vector/axial-vector interactions, that is not the case. Let's look at different final states separately:




- Black lines correspond to the minimal HNL scenario where N mixes with the light neutrinos and decays via (off-shell) W/Z bosons.
- Decay into electron pairs:
  - Muon/Tau mixing: decay only via the Z boson.
  - Electron mixing: W and Z processes interfere.
- Decay into an electron and a muon:
  - Electron/Muon mixing: decay only via the W boson.

# What about Majorana Fermions?

de Gouvêa, Fox, Kayser, Kelly, In Prep.

$$\mathcal{M}_1 = G_{NL}\left[\overline{u}_\nu \Gamma_N P_S u_N\right]\left[\overline{u}_\alpha \Gamma_L v_\beta\right]$$

$$\mathcal{M}_2 = \overline{G}_{NL}\left[\overline{v}_N P_S \Gamma_N v_\nu\right]\left[\overline{u}_\alpha \Gamma_L v_\beta\right]$$

- Interference of multiple matrix elements makes things more complicated. Moreover, if the final-state charged leptons are identical, then the Hermitian conjugate terms of these matrix elements contribute too.

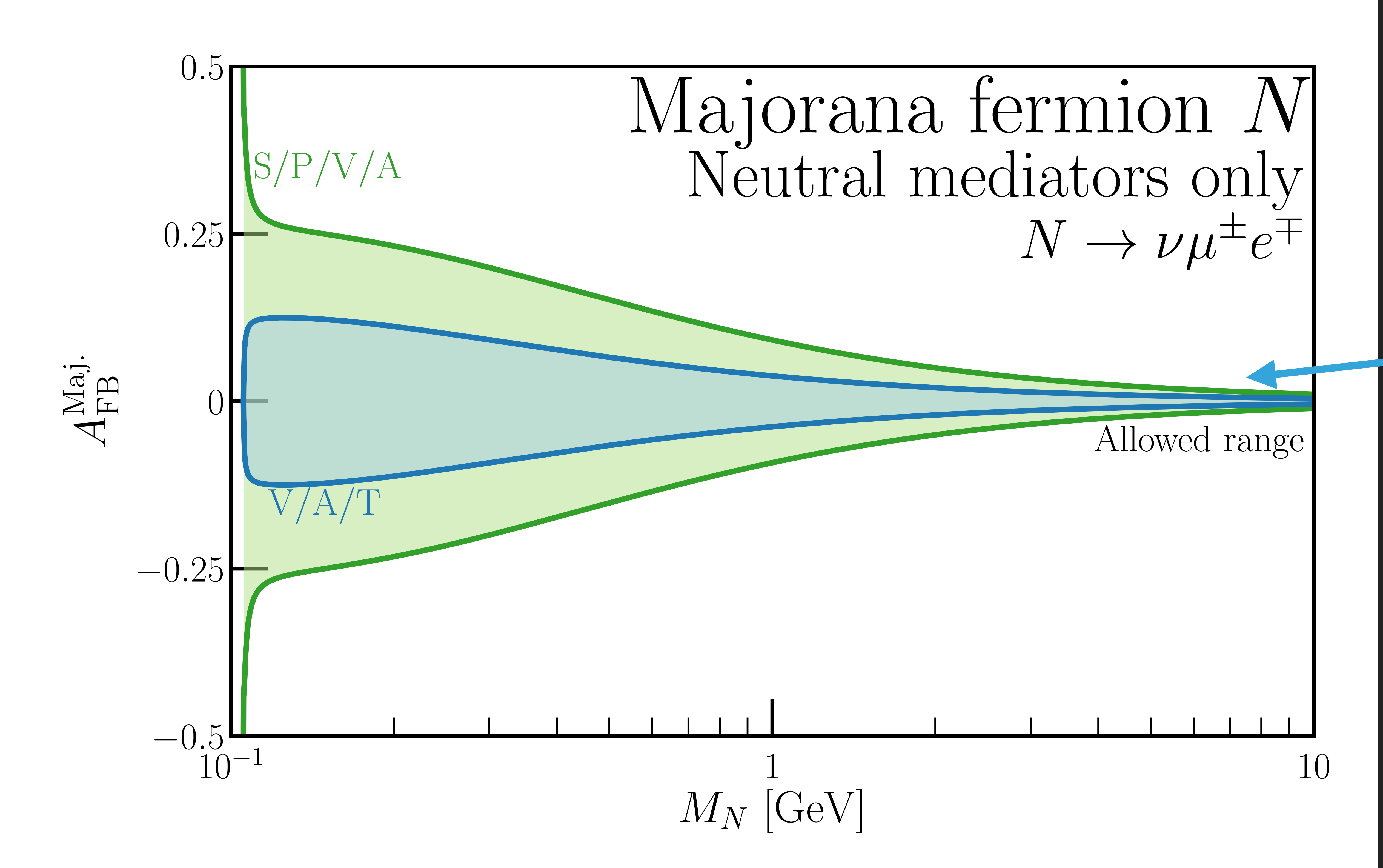
- We find that
  - If the final-state charged leptons are identical, regardless of the interaction structure, the forward/backward asymmetry is zero.
  - If the final-state charged leptons are distinct, that is not necessarily the case.
    - However, if our detector is charge-blind (i.e. cannot distinguish between $\nu\mu^- e^+$ and $\nu\mu^+ e^-$), we must sum over those two final states. This causes *all* spin-dependence to vanish.
    - If we make assumptions about the new mediators (for example, all are neutral), we can constrain the asymmetry for Majorana fermions N.

# Forward/Backward Asymmetry (Majorana)

de Gouvêa, Fox, Kayser, Kelly, In Prep.

$$\Gamma_N,\ \Gamma_L \in \left\{\mathbb{1},\ \gamma^5,\ \gamma^\mu,\ \gamma^\mu\gamma^5,\ \sigma^{\mu\nu} = \frac{i}{2}\left[\gamma^\mu, \gamma^\nu\right]\right\}$$

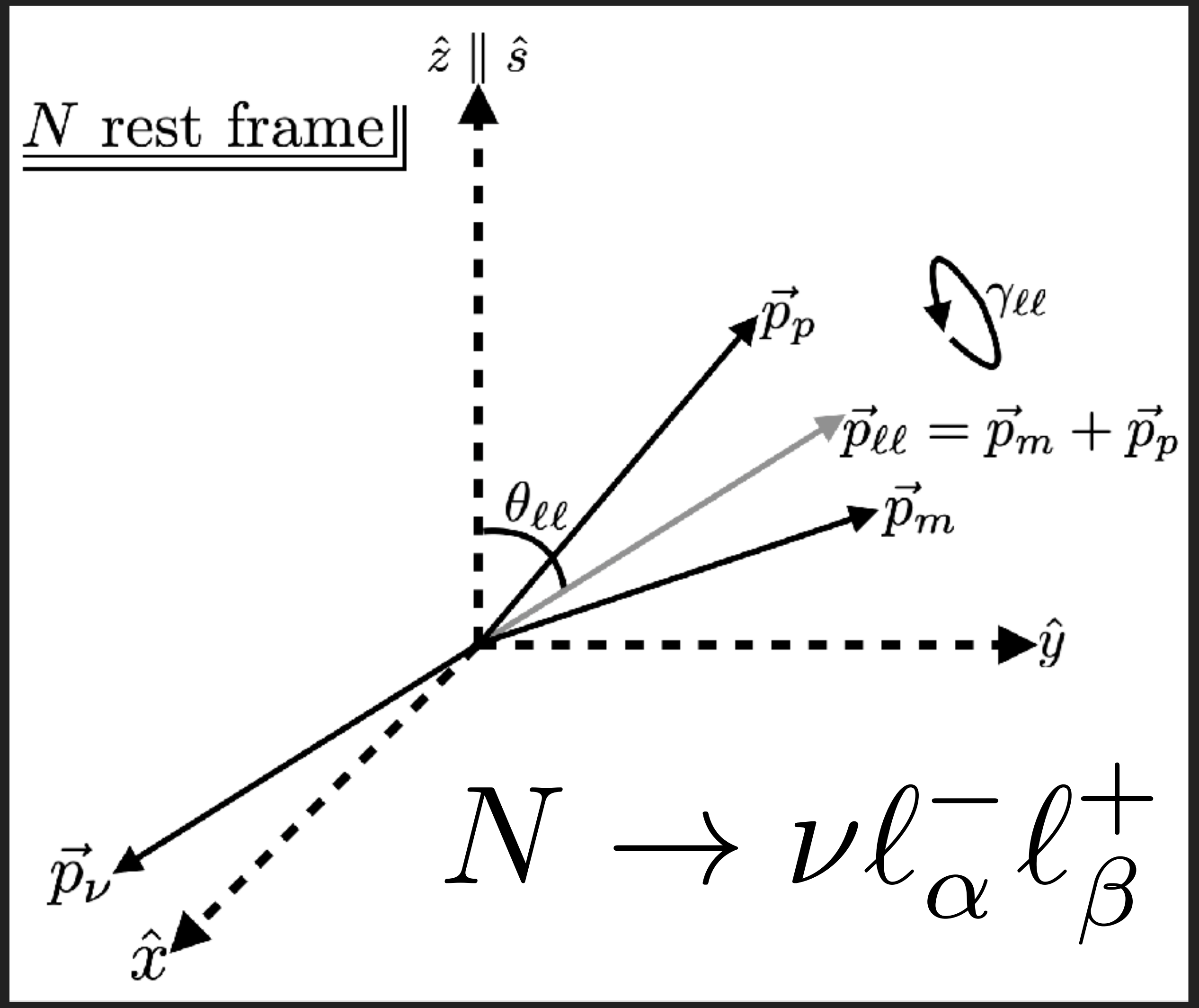
- If we only have neutral mediators, and N is a Majorana fermion, we find that for any forward/backward asymmetry to be generated, we need interference between V/A interactions and either S/P or T ones.



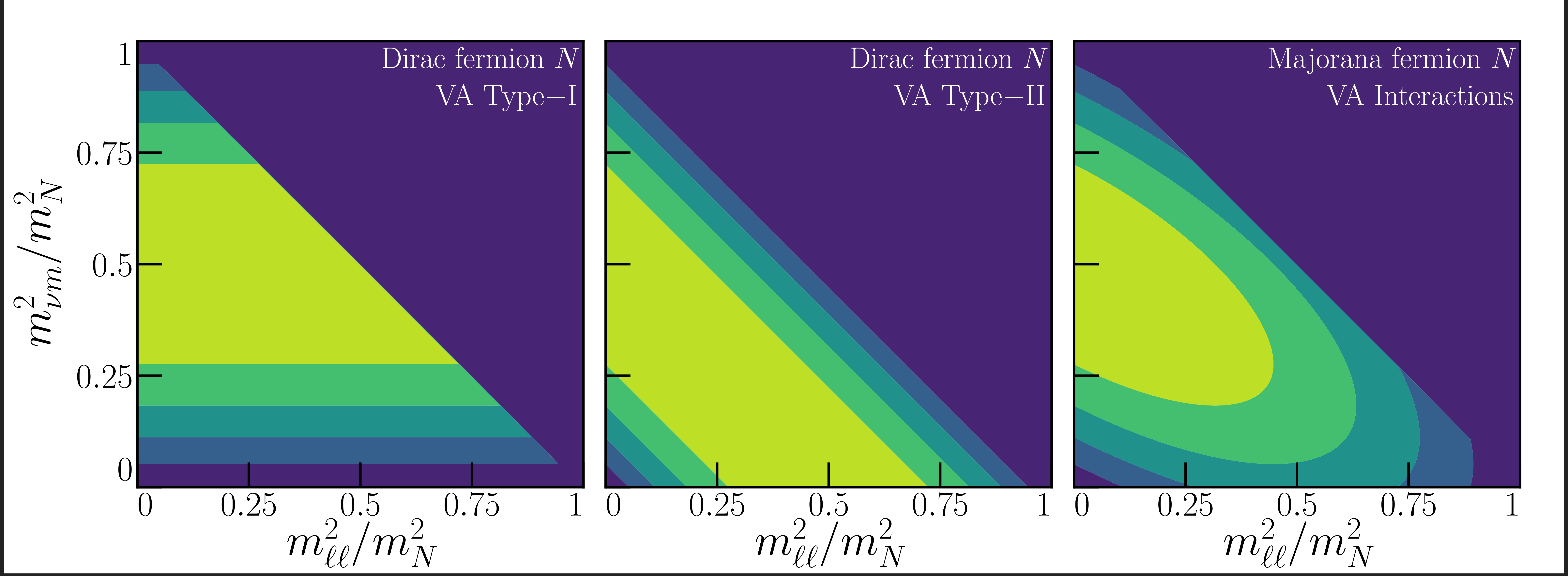

Asymmetry also vanishes when the HNL is much more massive than the daughter charged leptons.

# Even if N is Unpolarized,

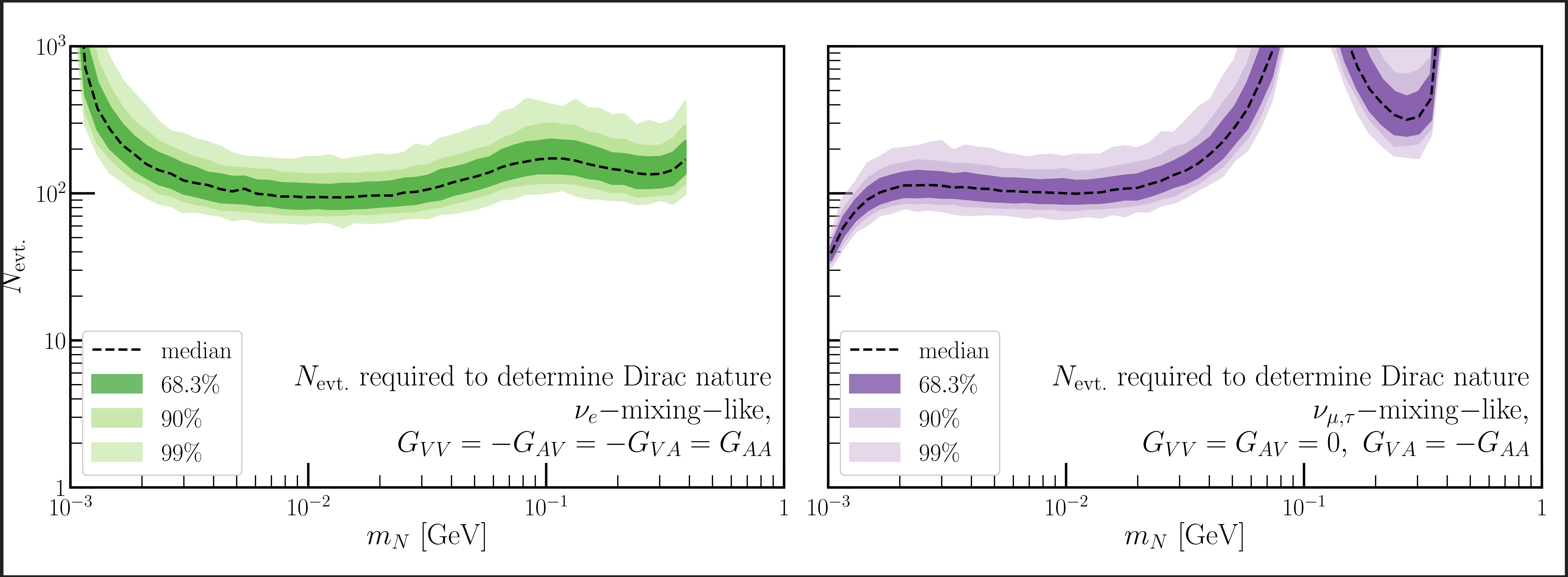
de Gouvêa, Fox, Kayser, Kelly, In Prep.




- If N is unpolarized, its spin direction and any associated angles are unphysical. Nevertheless, we find that for certain interaction structures, there are ways of distinguishing between Dirac and Majorana HNLs.



# How many Events Needed to Make Distinction?




de Gouvêa, Fox, Kayser, Kelly, In Prep.

# Determining the Interaction Structure

# Generic Decay Structure

de Gouvêa, Fox, Kayser, Kelly, In Prep.



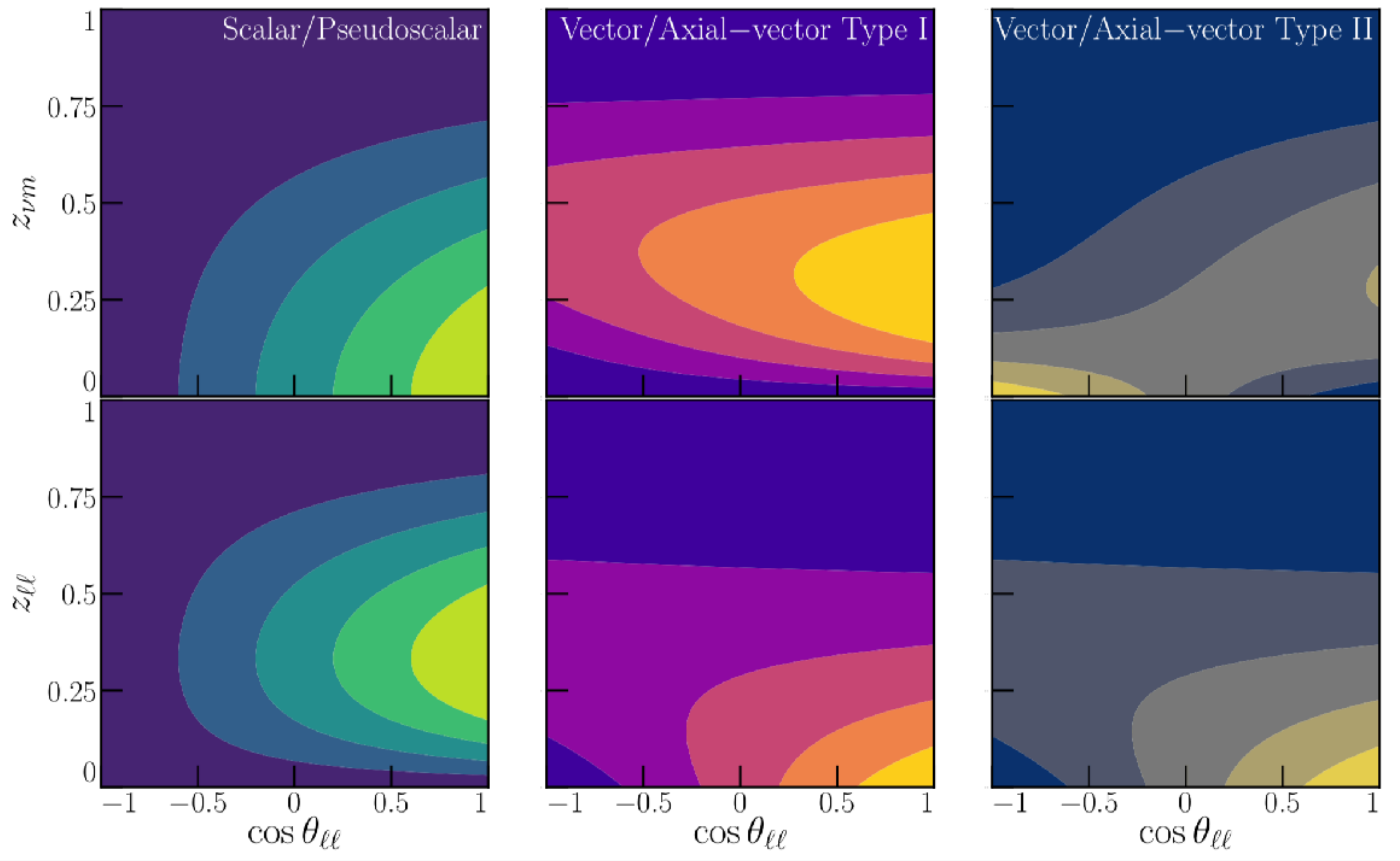
$$\mathcal{M}_1 = G_{NL}\left[\overline{u}_\nu \Gamma_N P_S u_N\right]\left[\overline{u}_\alpha \Gamma_L v_\beta\right]$$

$$\Gamma_N,\ \Gamma_L \in \left\{\mathbb{1},\ \gamma^5,\ \gamma^\mu,\ \gamma^\mu\gamma^5,\ \sigma^{\mu\nu} = \frac{i}{2}\left[\gamma^\mu, \gamma^\nu\right]\right\}$$

**Bright spots:** larger decay rate

$$z_{\nu m} = \frac{(p_\nu + p_\alpha)^2}{m_N^2}$$

$$z_{\ell\ell} = \frac{(p_\alpha + p_\beta)^2}{m_N^2}$$

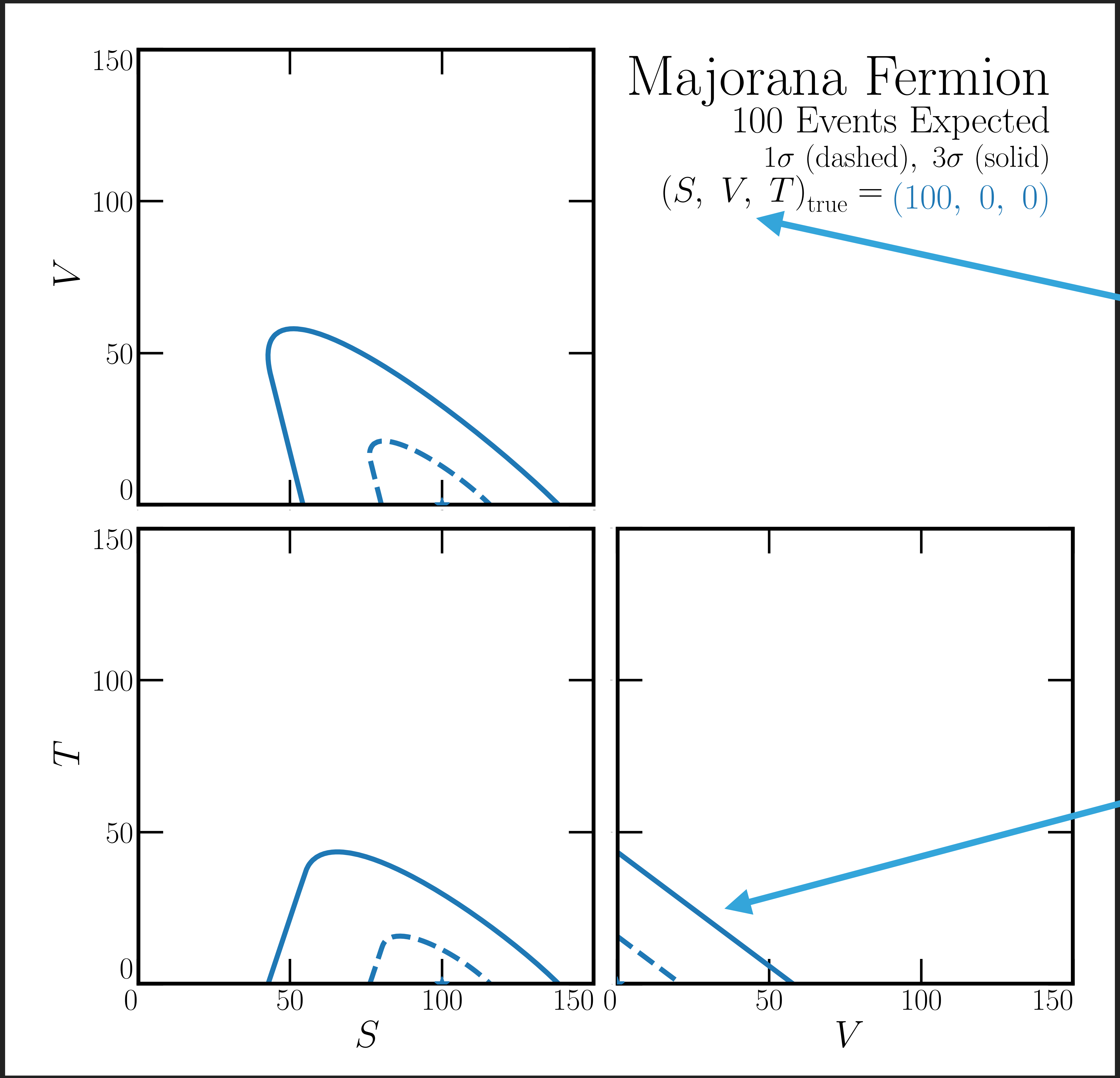



**Precision measurement of different kinematical quantities – identify the structure of the four-fermion interaction**

# Assume N is known to be a Majorana Fermion



- Moreover, let's assume that its decays are mediated by only scalar/pseudoscalar interactions, and that we expect to see O(100) signal events. Can we constrain the vector/axial-vector/tensor contributions to be small?




(S, V, T) can be seen as the contribution to the number of signal events from each type of interaction.

In this hypothesis, we can constrain V < 100 and T < 100 at very high significance.

# Conclusions

- Heavy Neutral Leptons are phenomenologically interesting and upcoming experiments, such as DUNE, may detect them!
- Determining their nature via Lepton-Number-Identifiable decays is possible with many upcoming/planned experiments.
- Other decays pose harder problems – we're working on understanding the two- and three-body decays better to identify prospects for understanding the HNLs.

**Thank you!**