Non-Oscillation Theory
at Near Detectors

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Path to Dark Sector Discoveries @ Neutrino Experiments, CSU 2023

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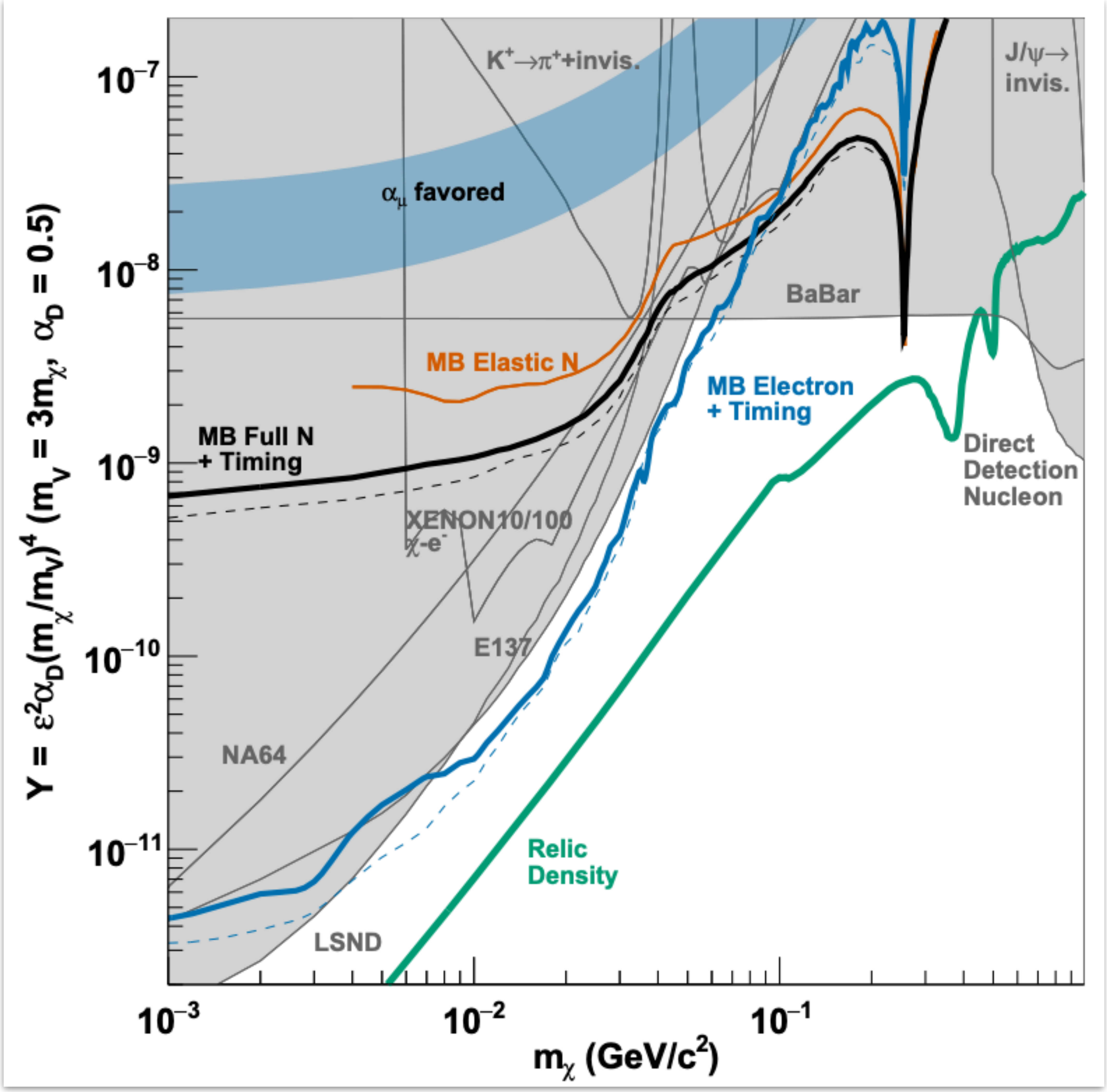
[1912.07622], [2104.05719], [2109.10358] with Berryman, de Gouvêa, Fox, Kayser, & Raaf

Outline

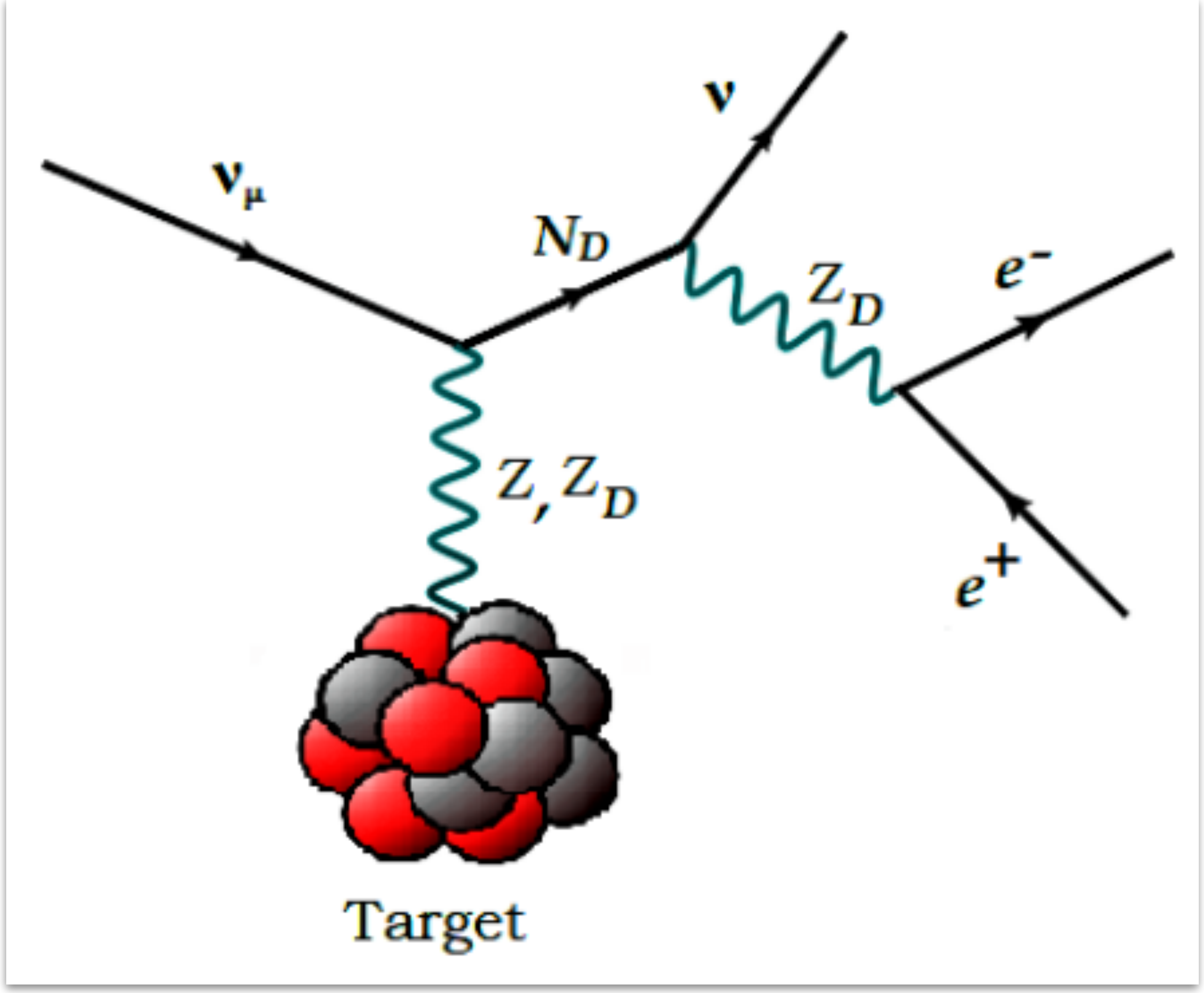
- What will we discover in the next decade(s)?
- How will we be prepared to capitalize on those discoveries?
- What comes next?

The discoveries ahead

What's to come…

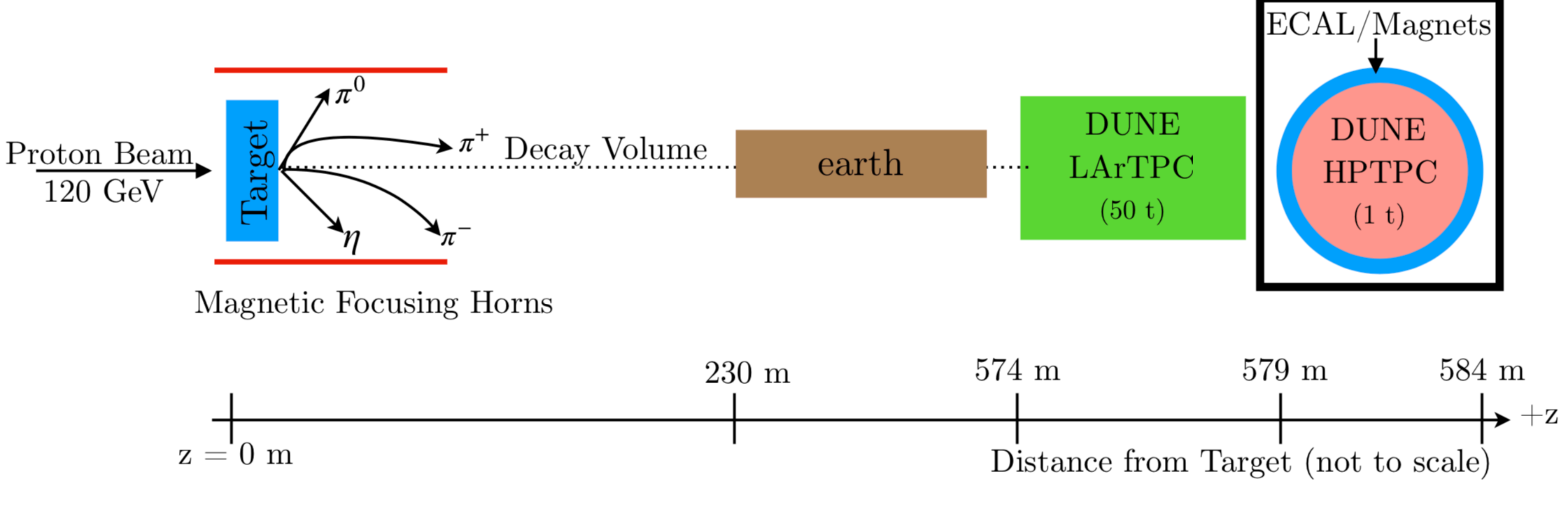


MiniBooNE-DM Collaboration, [1807.06137]

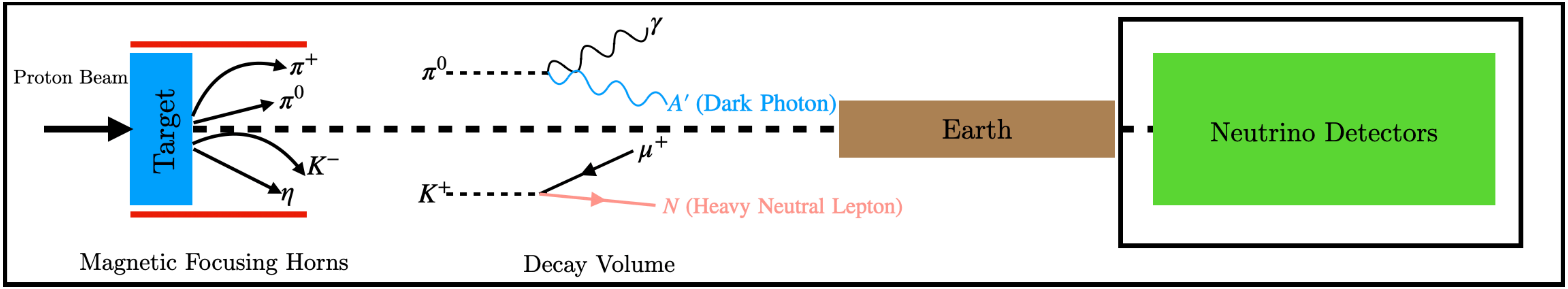


Bertuzzo et al [1807.09877]
Ballett et al [1808.02915]

Berryman, **KJK**, et al [1912.07622]



Near Detectors as LLP Factories



1) Charged and Neutral Mesons are produced in the high-energy/high-intensity proton collisions.

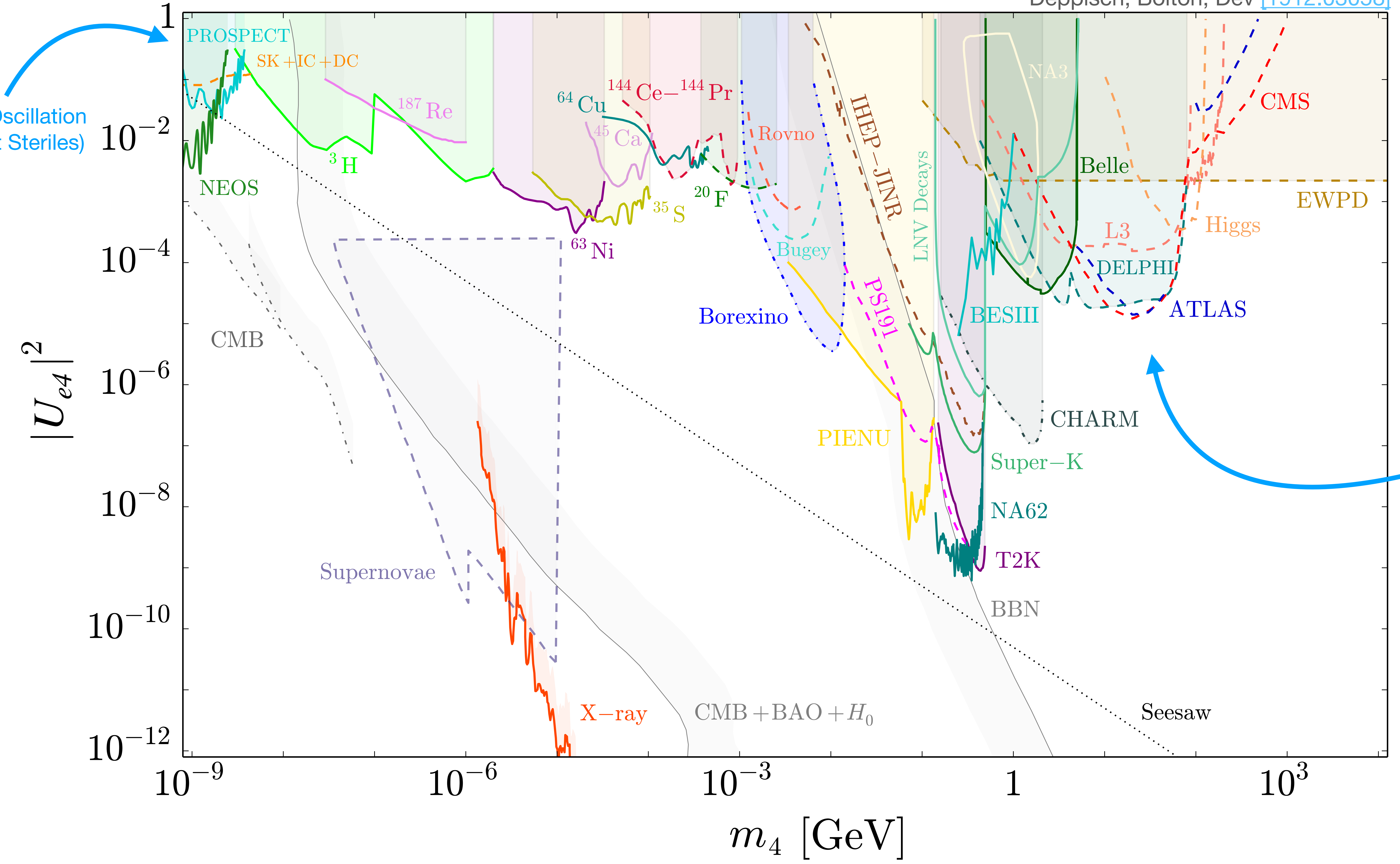
2) Mesons undergo rare decays into dark sector mediators that are long-lived. Some fraction of them travel in the forward direction.

3) Dark Sector particles decay inside the neutrino detector, leaving a striking signature.

HNLs — Current Constraints

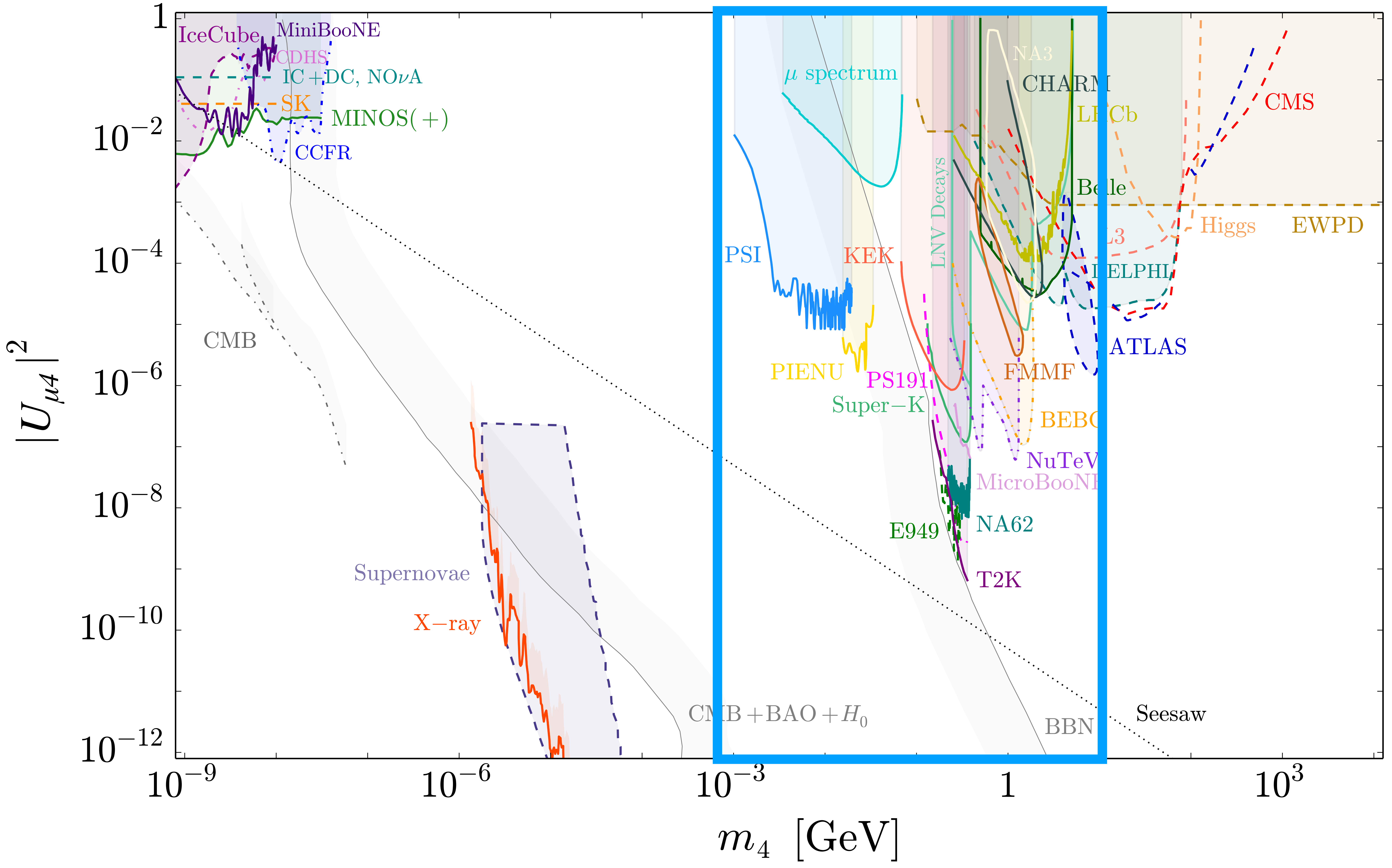
Deppisch, Bolton, Dev [1912.03058]

Constraints from Oscillation Experiments (Light Steriles)



Colliders

Let’s Zoom in a Little…

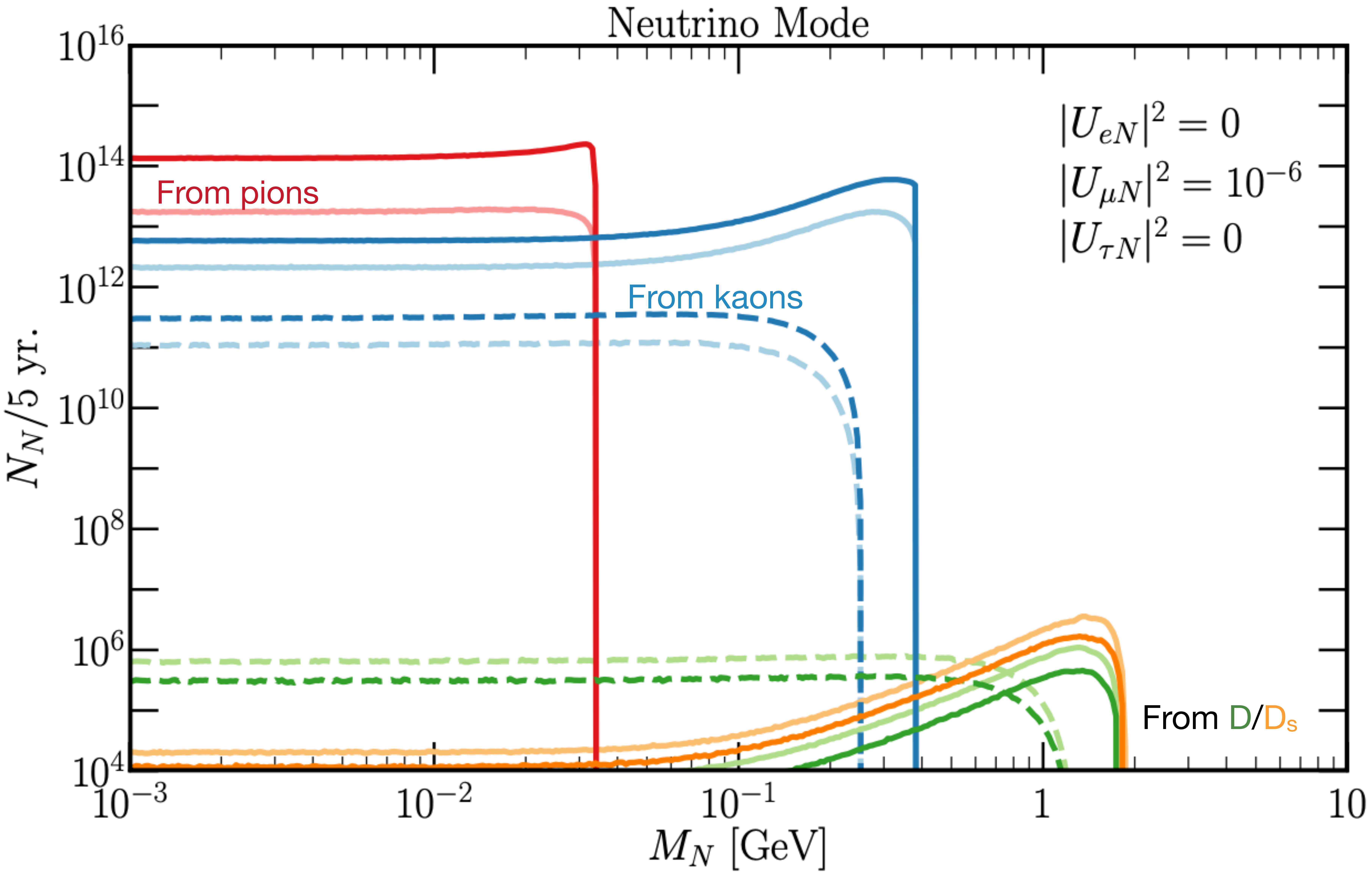


HNLs in the DUNE Beam

Operating with a 120 GeV proton beam, DUNE will produce a bevy of SM mesons.

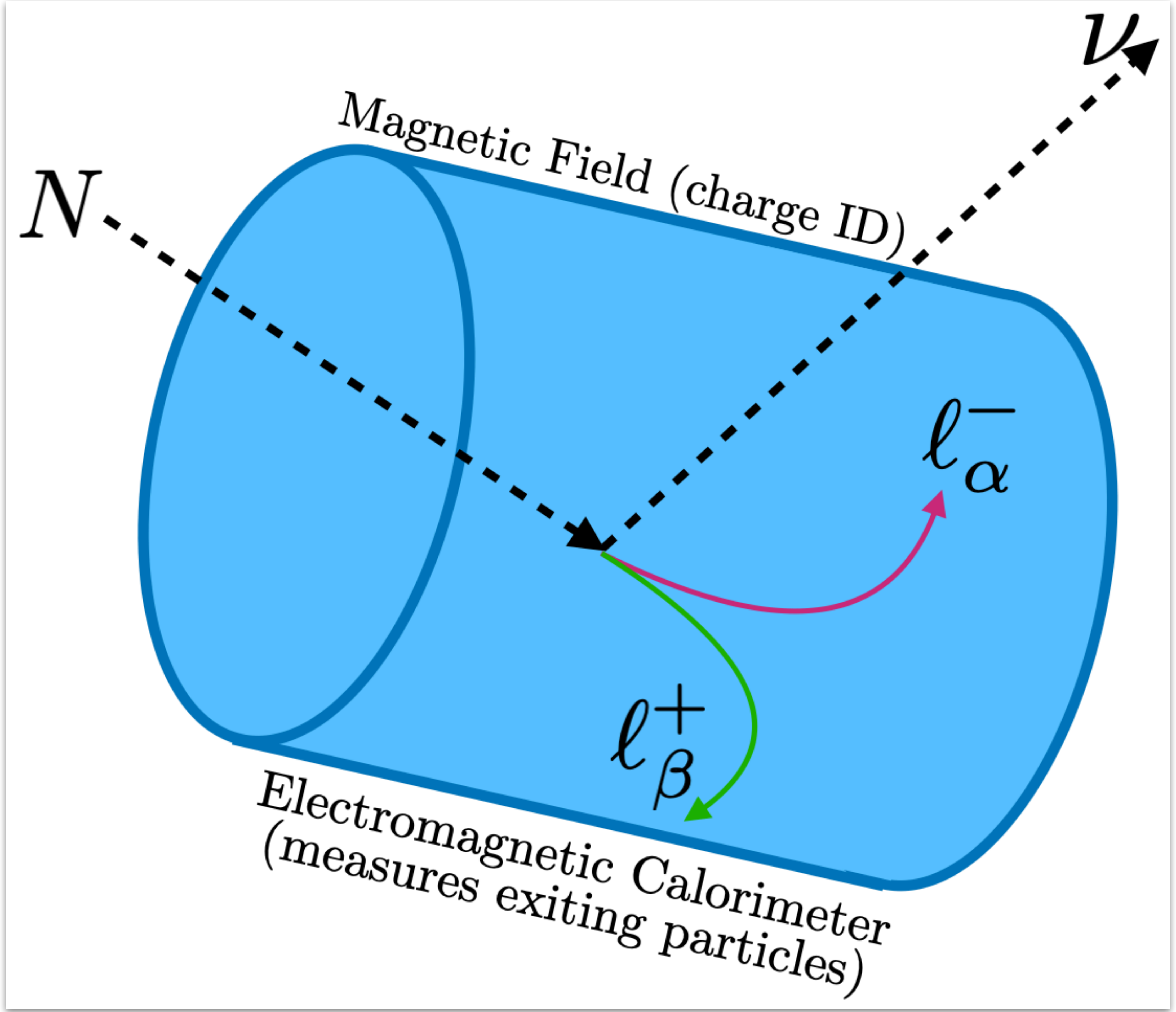
Fluxes simulated assuming 5 years of operation in neutrino mode.

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



Berryman, de Gouvêa, Fox, Kayser, **KJK**, Raaf [1912.07622]

Gaseous Detectors for Decays



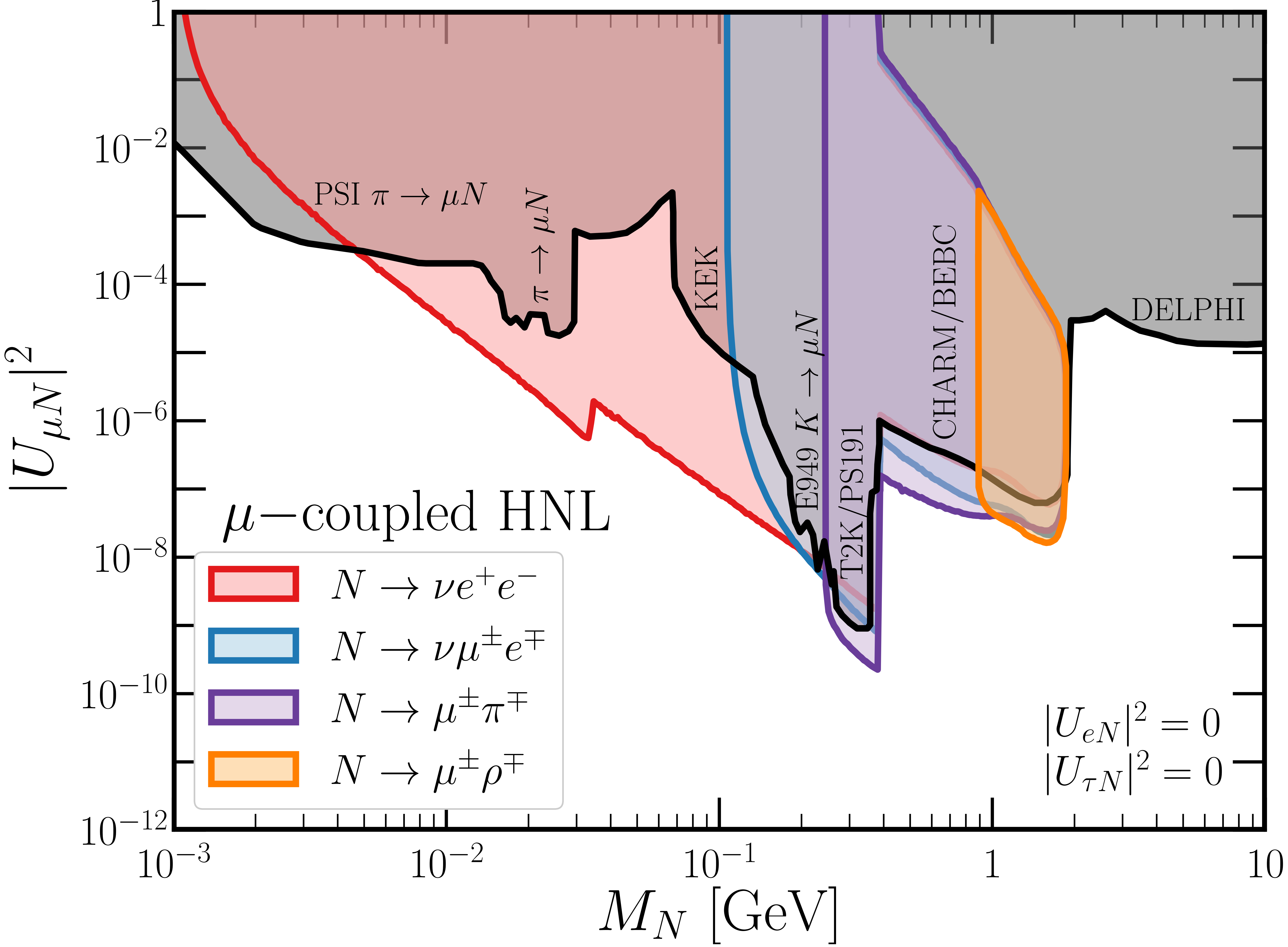
- New-physics particles can decay inside the detector, producing a signal that is difficult for neutrino scattering to mimic.
- This includes decays to charged lepton pairs, a lepton and a pion, etc.
- Low backgrounds in gaseous detectors (like at DUNE) are an ideal site for these searches.

New Physics Signal $\propto$ Volume

Neutrino Scattering Backgrounds $\propto$ Mass

Next-Generation Sensitivity at DUNE

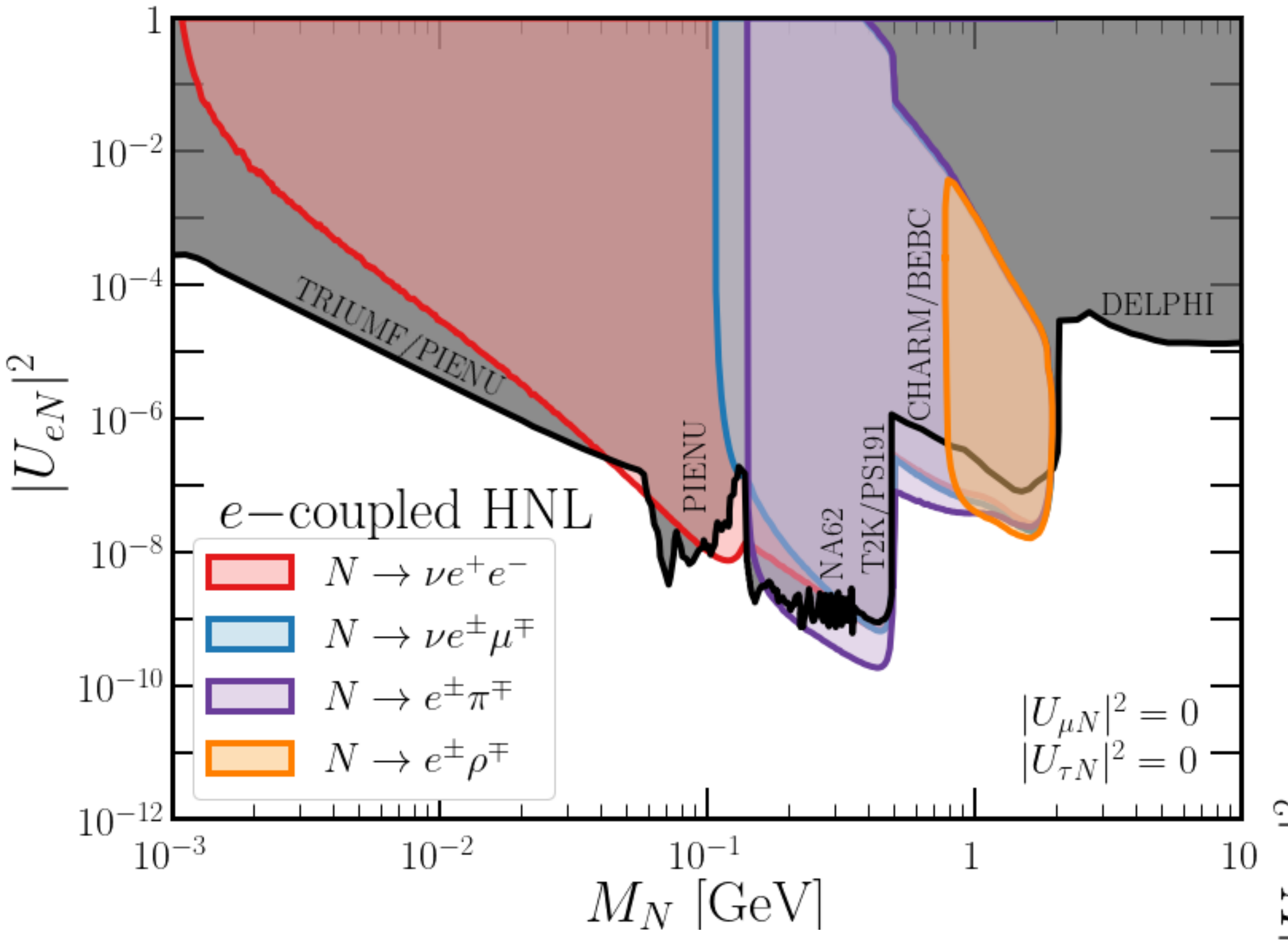
Berryman, **KJK**, et al, [1912.07622], JHEP02 (2020) 174

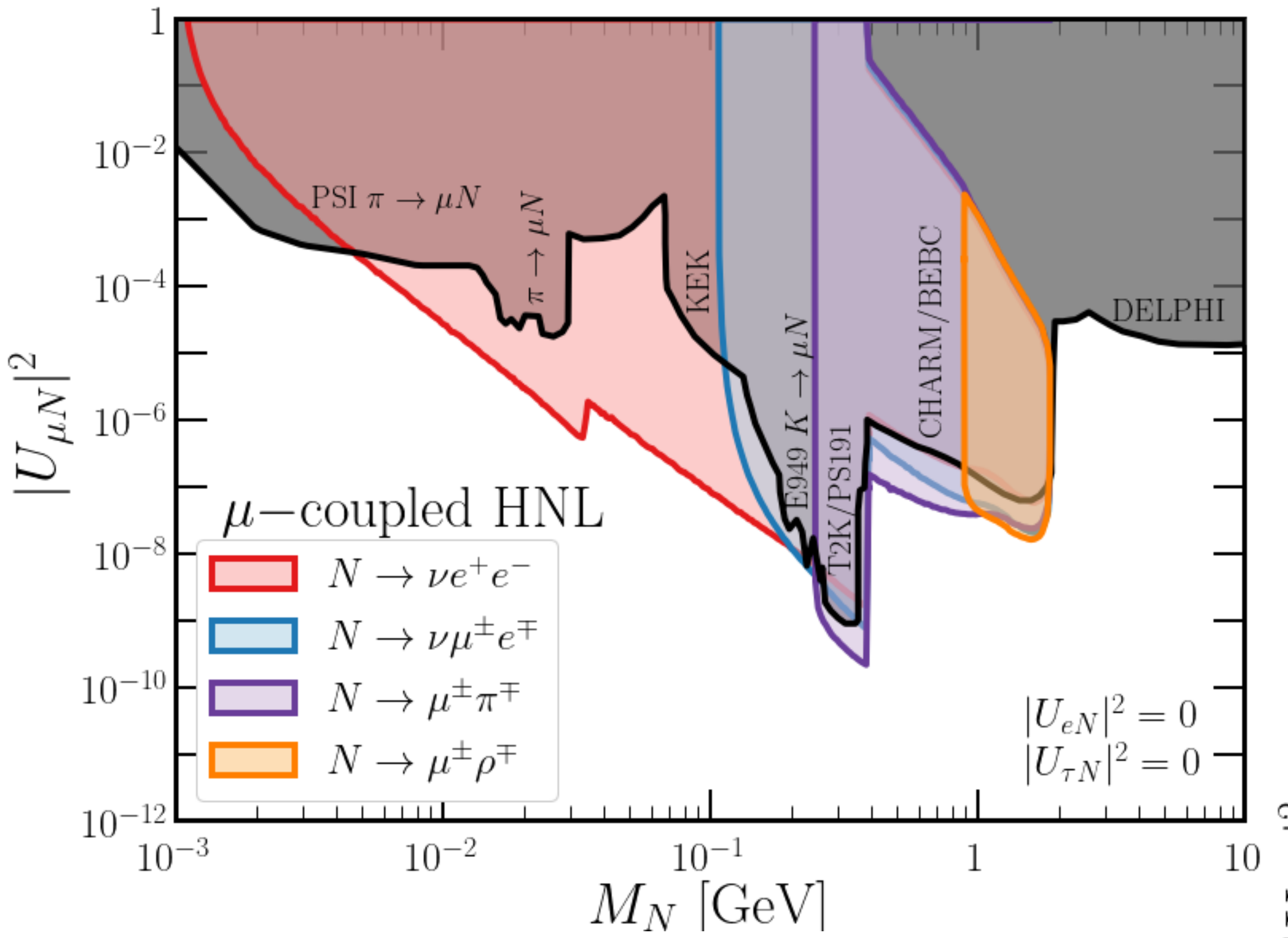


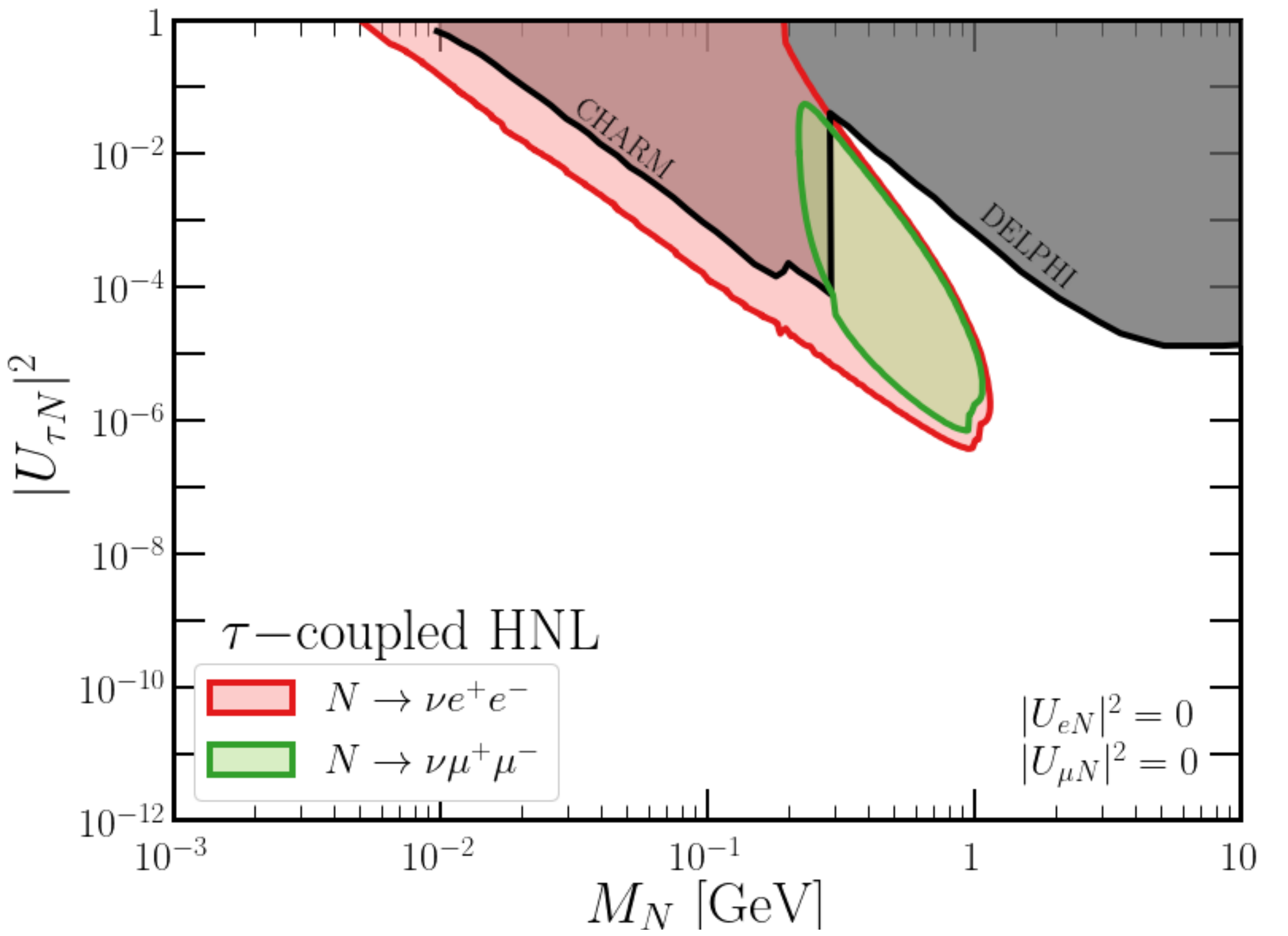
- Tons of parameter space for a potential discovery!
- Searches for different final states (or incorporating other mixing patterns) can extend reach.

More on HNLs at DUNE? Ballett et al [1905.00284], Coloma et al [2007.03701], Breitbach et al [2102.03383]

All single-mixing sensitivity







Berryman, de Gouvêa, Fox, Kayser, **KJK**, Raaf [1912.07622]

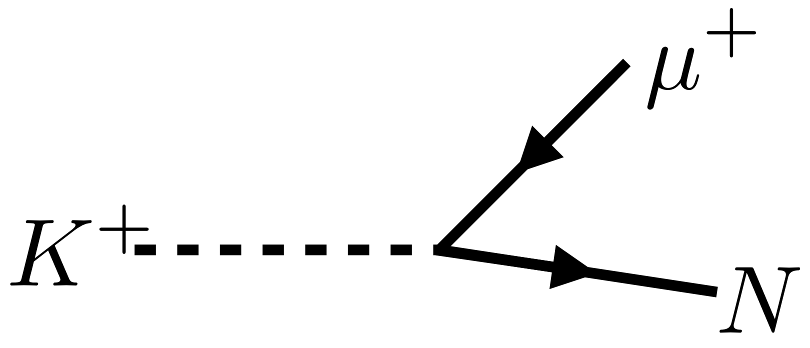
Preparing for post-discovery

LNV in a (Heavy) Neutrino Beam

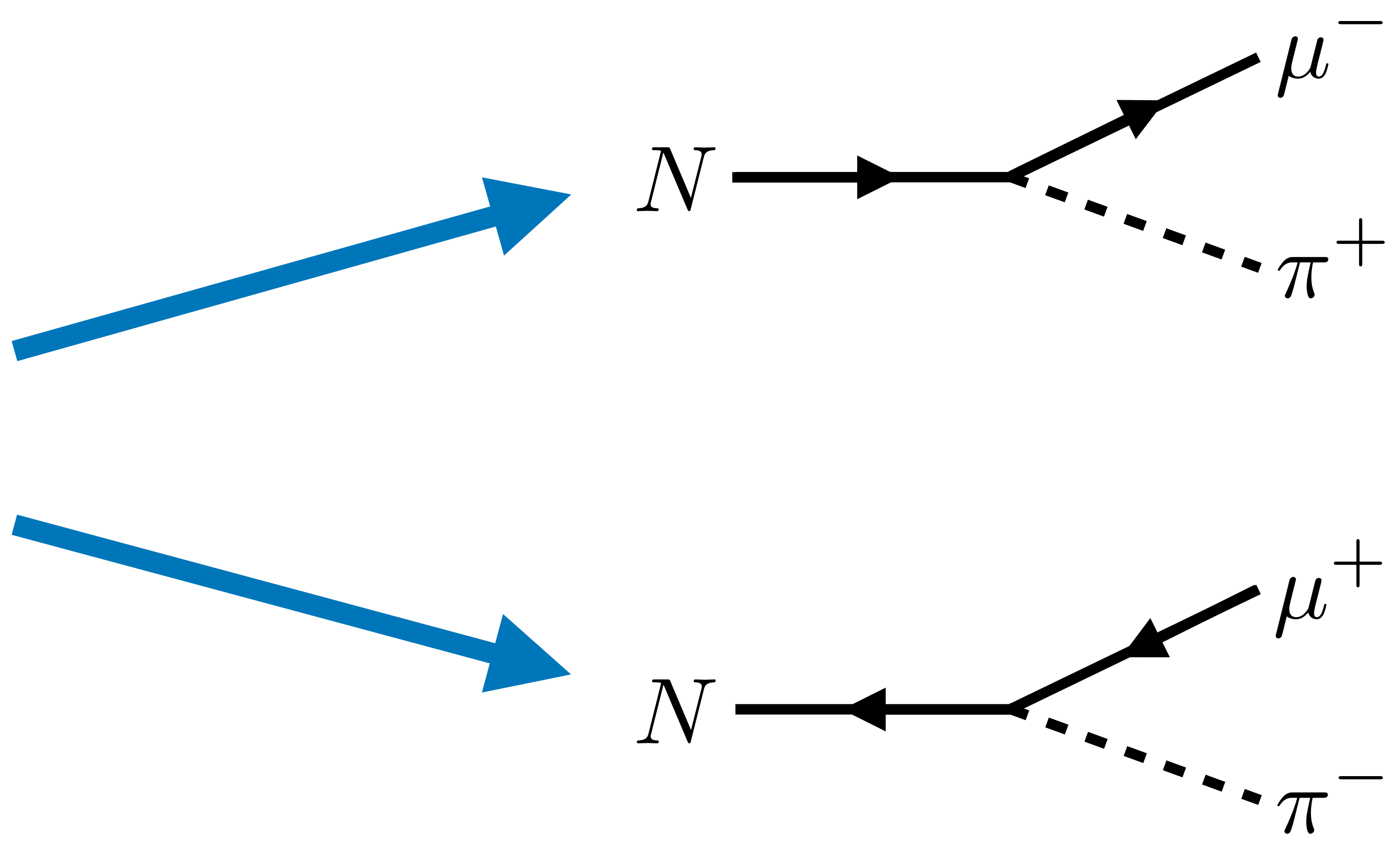
Is the new particle a Dirac or Majorana Fermion?

↔

Do the new particle's interactions preserve or violate Lepton Number conservation?



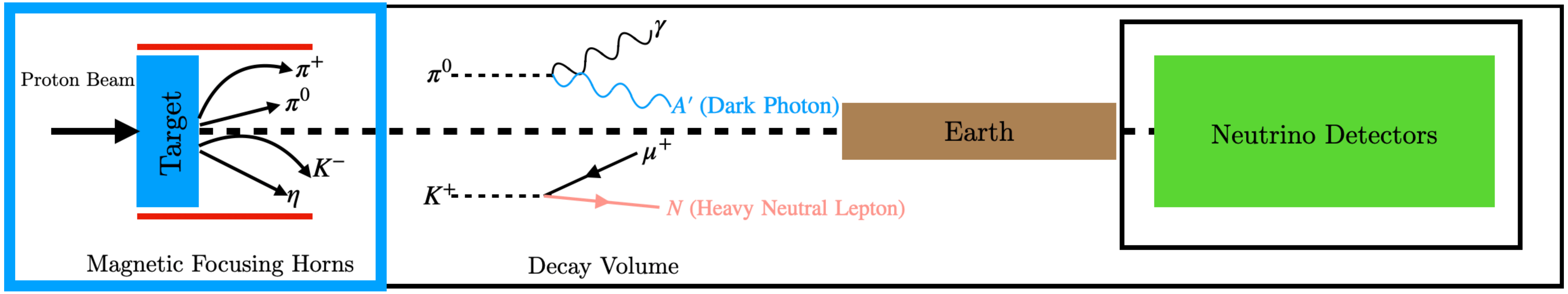
Heavy Neutrino Source



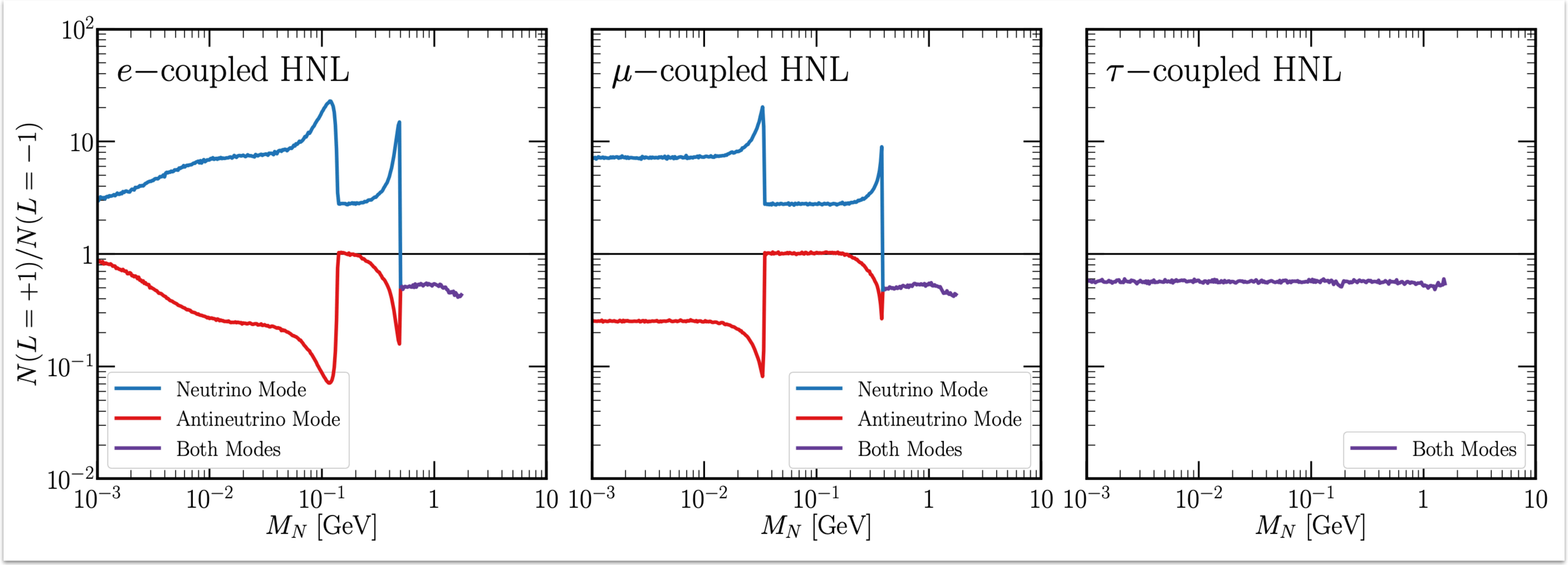
Heavy Neutrino Decay

- Do these two chains occur with equal probability?

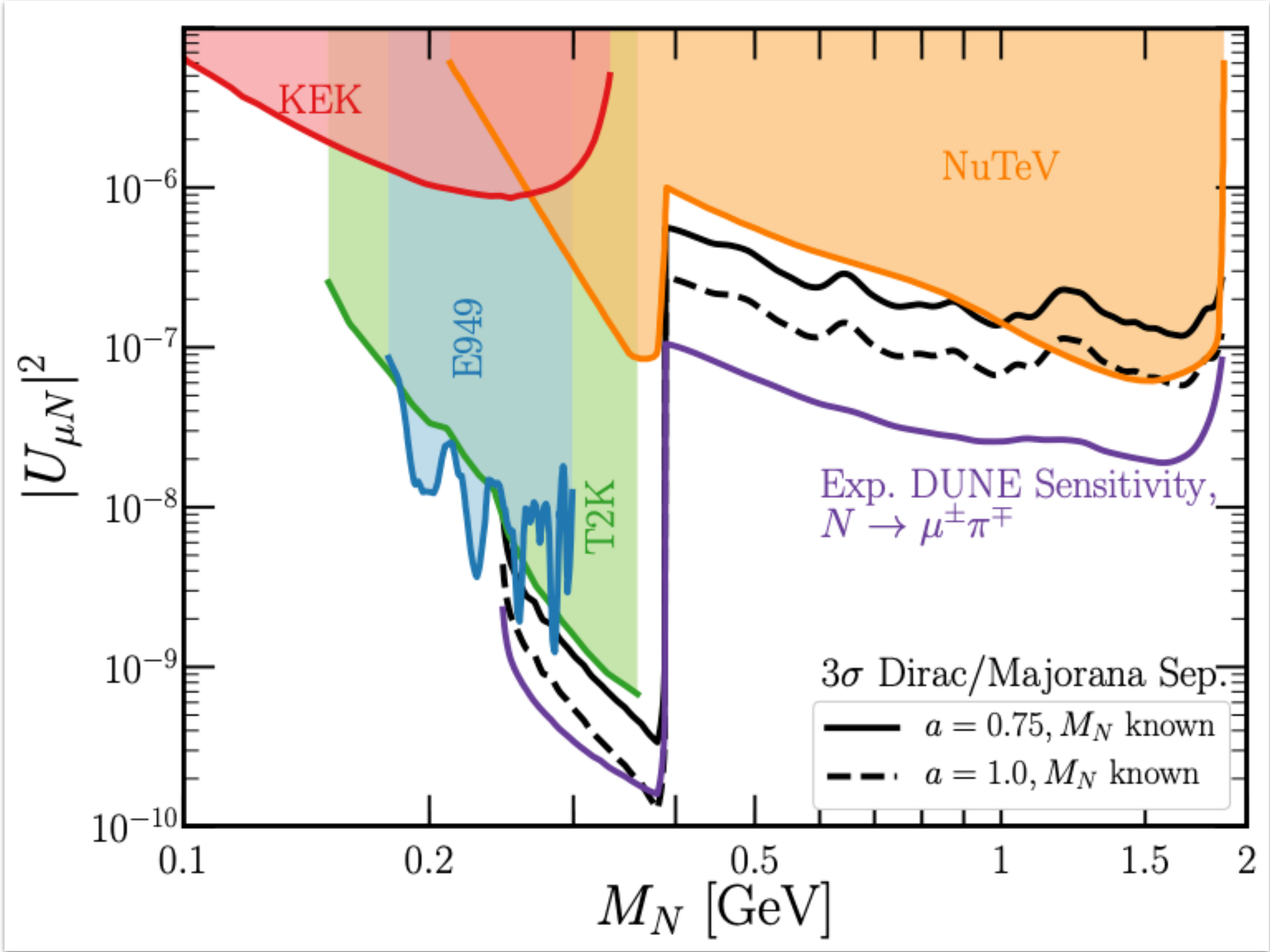
Neutrino vs. Antineutrino Mode



Expected Beam Purity



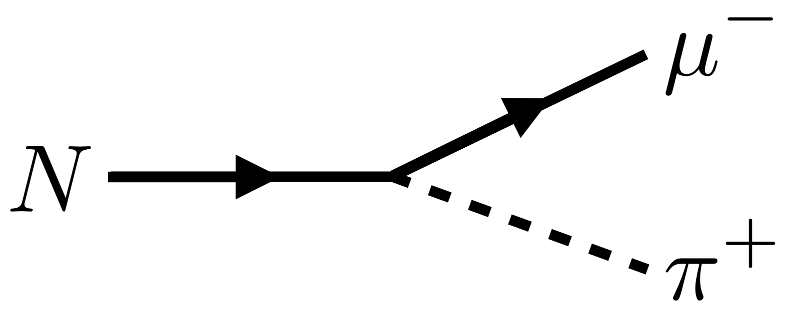
Next-Generation Prospects

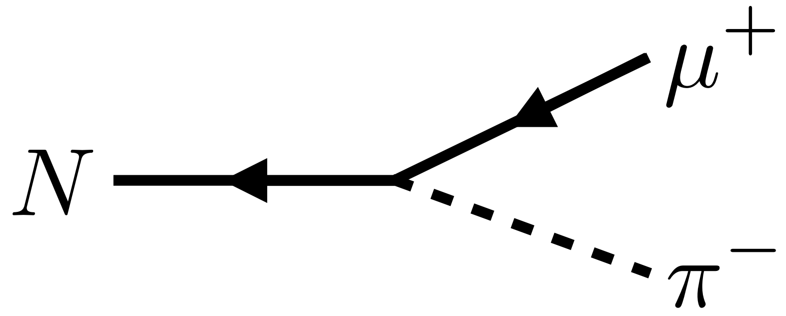


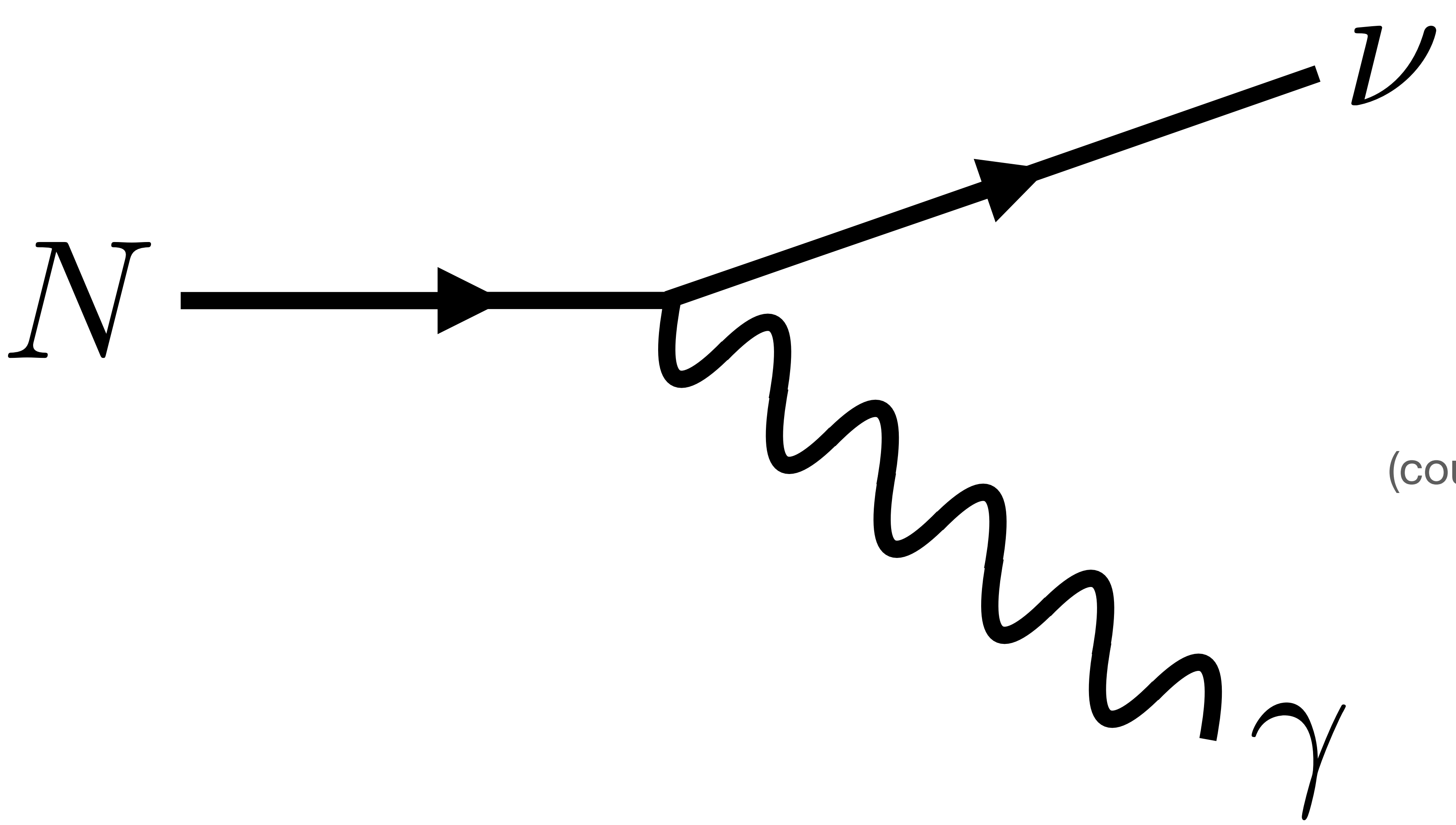
Berryman, de Gouvêa, Fox, Kayser, **KJK**, Raaf [1912.07622]

What if we’re not lucky?

- What if the HNL is lighter than the pion? Then there are no fully-visible final states to decay into, and Lepton Number can’t be identified on an event-by-event basis.





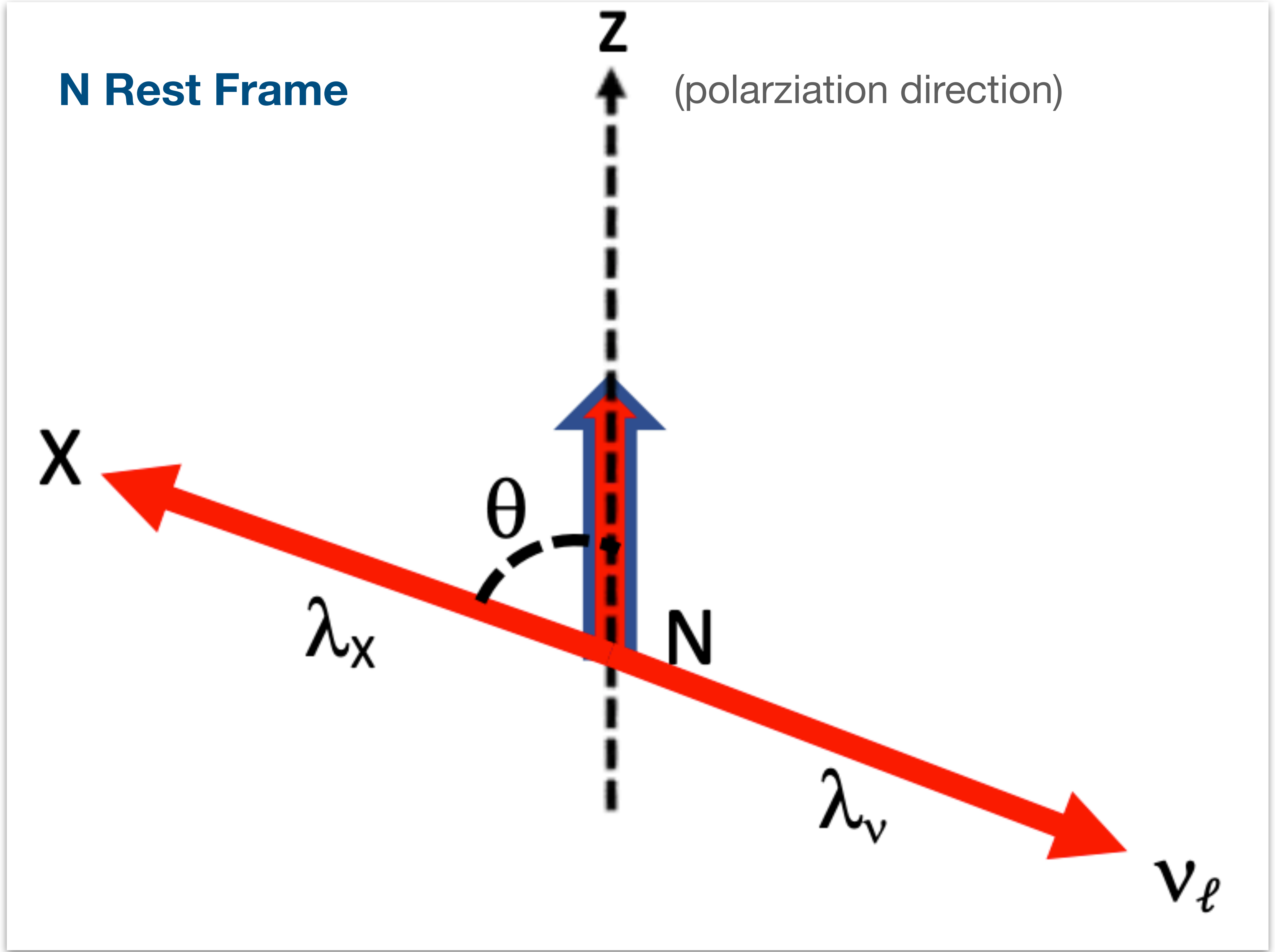


(could also be a charged-lepton pair instead of a photon, etc.)

Still, there are differences between Dirac/Majorana fermions: Measure the *distribution* of outgoing (visible) particles

Two-Body Decays

Balantekin, de Gouvêa, Kayser [1808.10518]



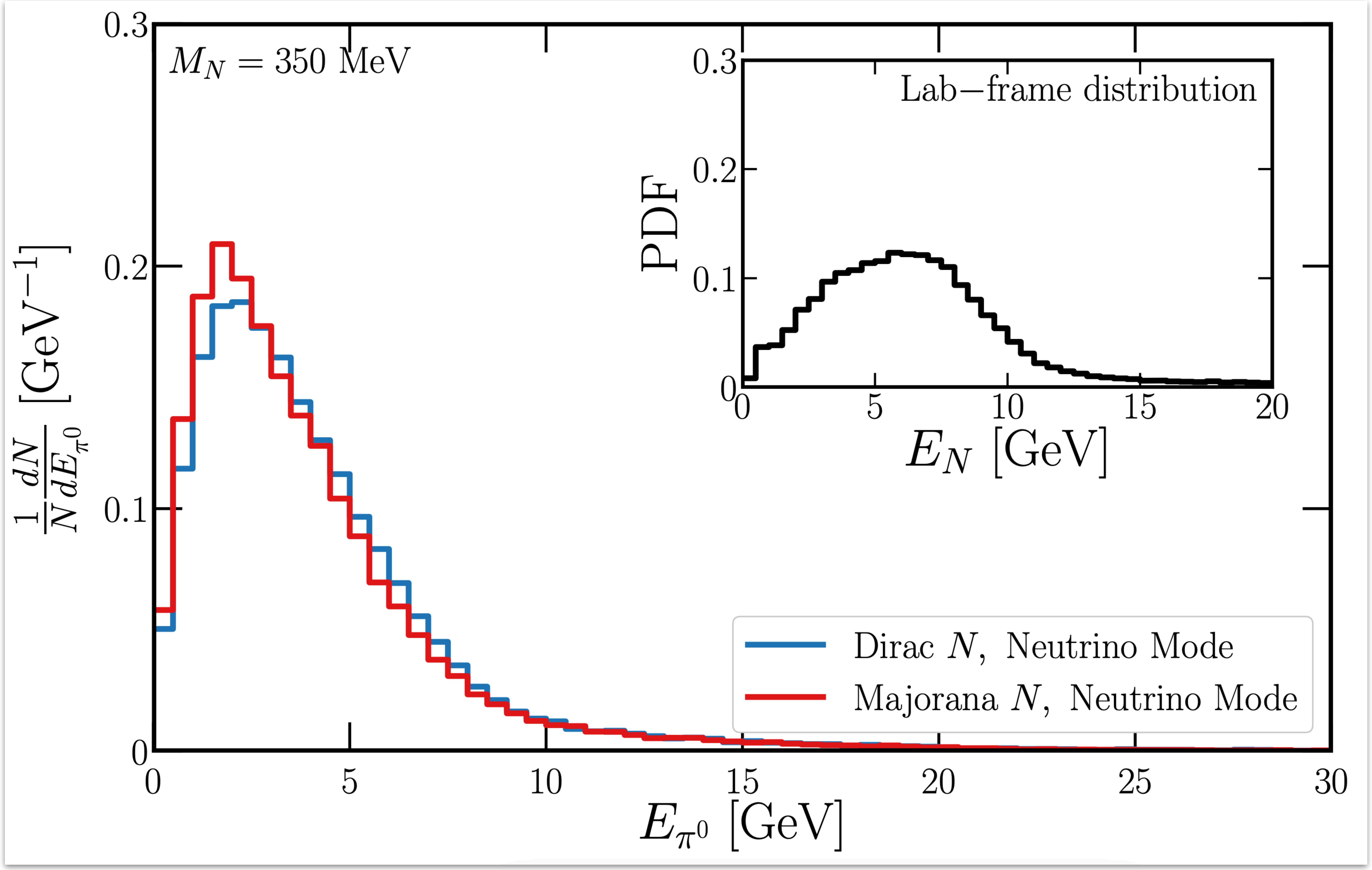
- Using CPT arguments, one can determine that, if N is a Majorana fermion, its decay is isotropic with respect to polarization direction. If it is a Dirac fermion, not necessarily.

$$\frac{d\Gamma}{d\cos\theta} = \frac{\Gamma}{2}(1+\alpha\cos\theta)$$

Boson	γ	π^0	ρ^0	Z^0	H^0
α	$\frac{2\Im(\mu d^*)}{\lvert\mu\rvert^2+\lvert d\rvert^2}$	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

Feasibility in a Neutrino-Beam Environment?

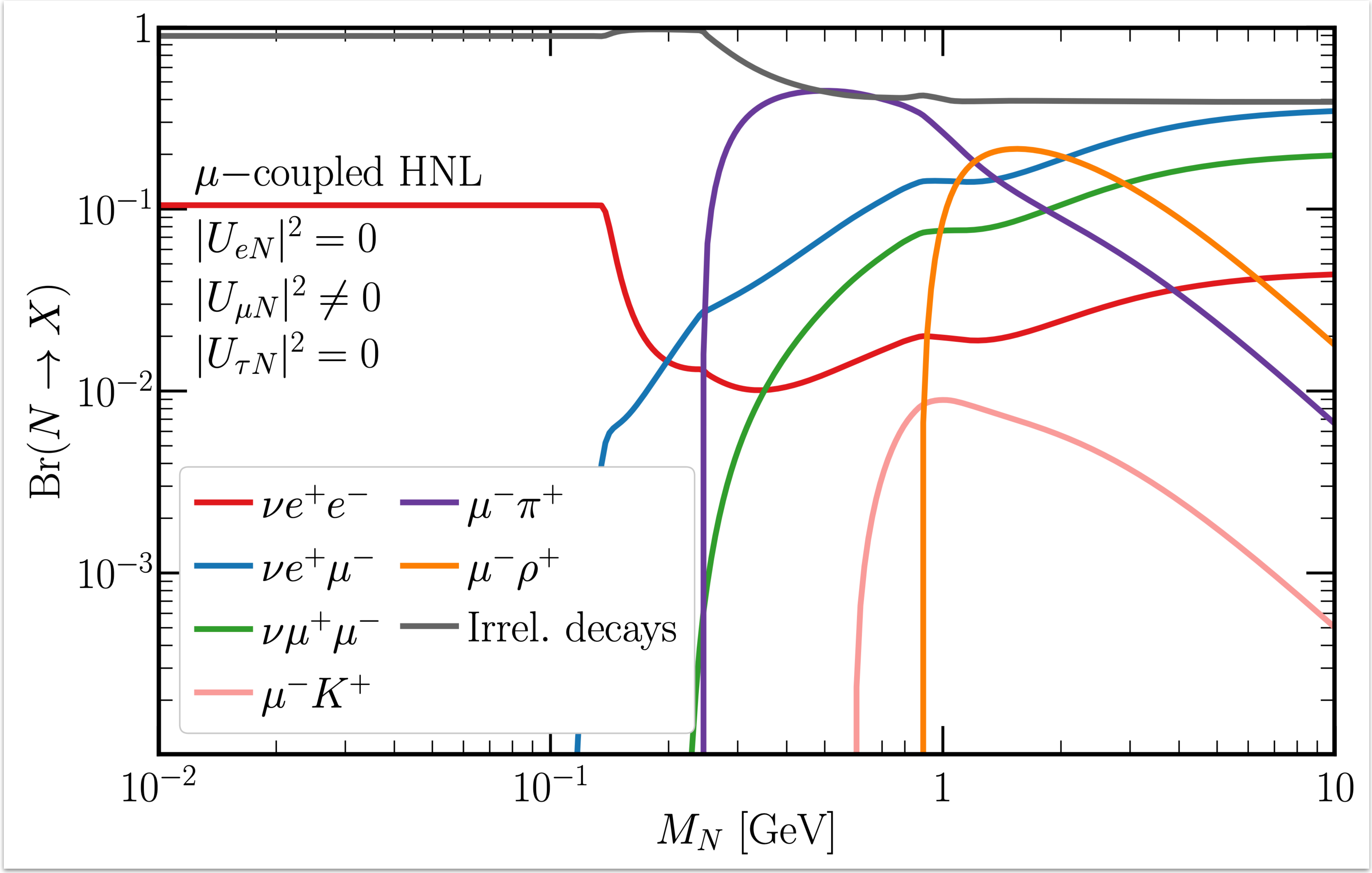
Because most HNLs in a beam environment will be boosted, so will their decay products. Rest-frame anisotropy means differences in lab-frame energies. How distinct are these predictions?



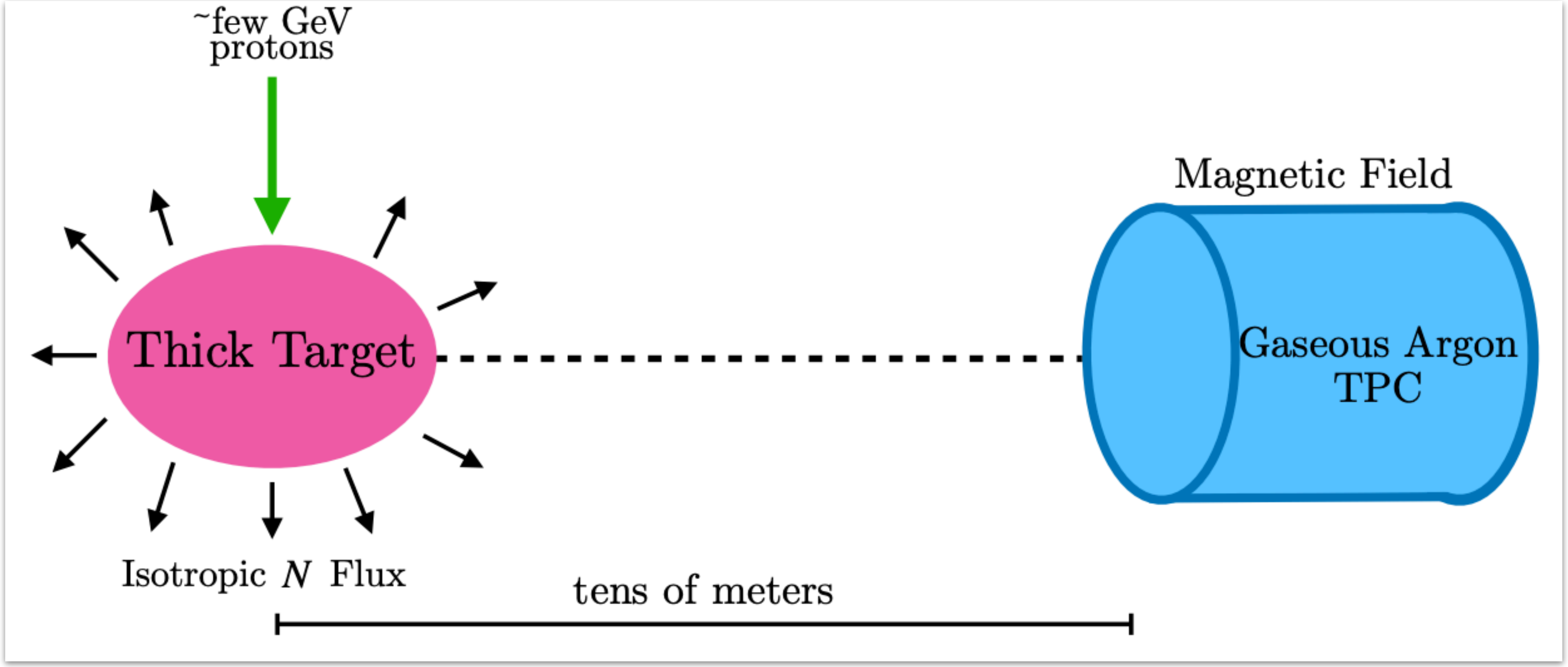
Berryman, **KJK**, et al, [1912.07622], JHEP02 (2020) 174

Going beyond

“Explicit” LNV vs. “Implicit”



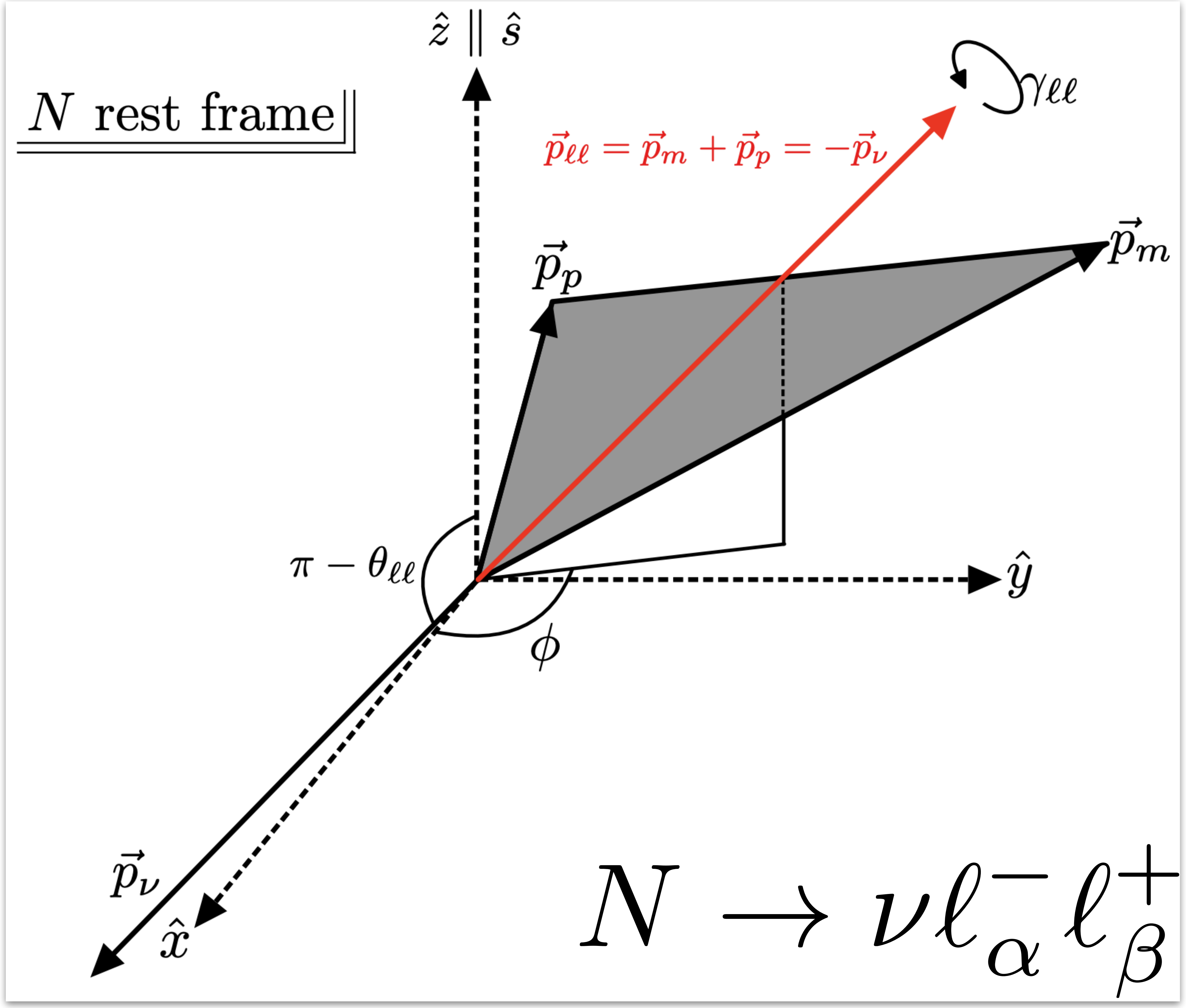
Let's envision a next-next-generation experiment



- Depending on the discovered HNL's mass, we can design a beam to optimize its production (focus on pion production, kaon production, etc.).
- With a detector off-axis, and a thick target, we can expect low-energy HNLs compared to a beam environment. If it's two-body-decays producing HNLs, they'll all have the same energy.
- Furthermore, an off-axis detector can greatly reduce backgrounds from SM neutrinos.

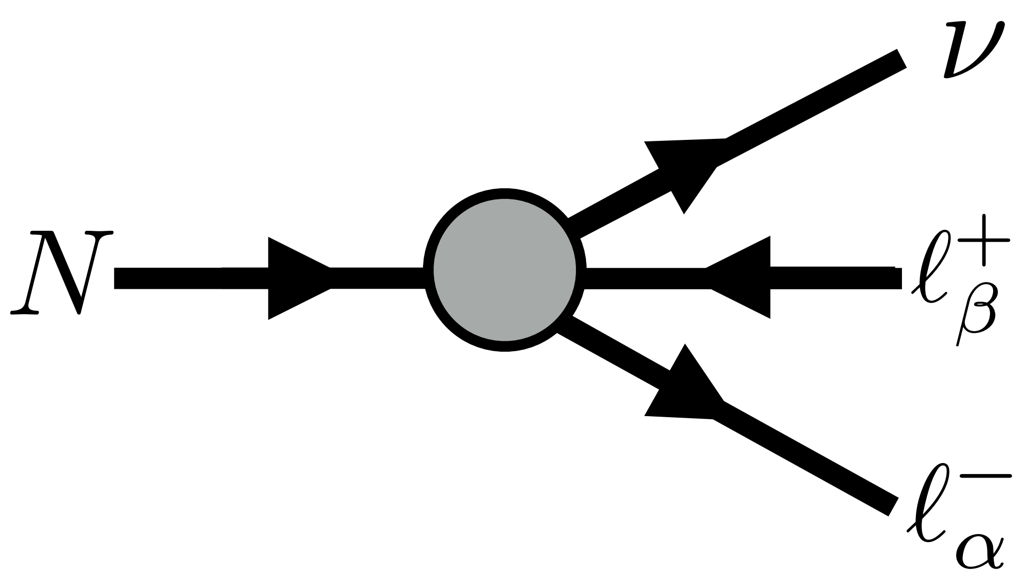
Extending Detection Channels in Such a Facility

Similar CPT as for the two-body case allowed us to extend our analysis to three-body decays. We were able to reach the following conclusions — if N is a Majorana fermion, its decays are forward/backward symmetric if either



- The final-state charged leptons are identical (e.g. electron/positron pair).
- Whatever detection mechanism being used is charge-blind (can't distinguish electron from positron or muon from antimuon)

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



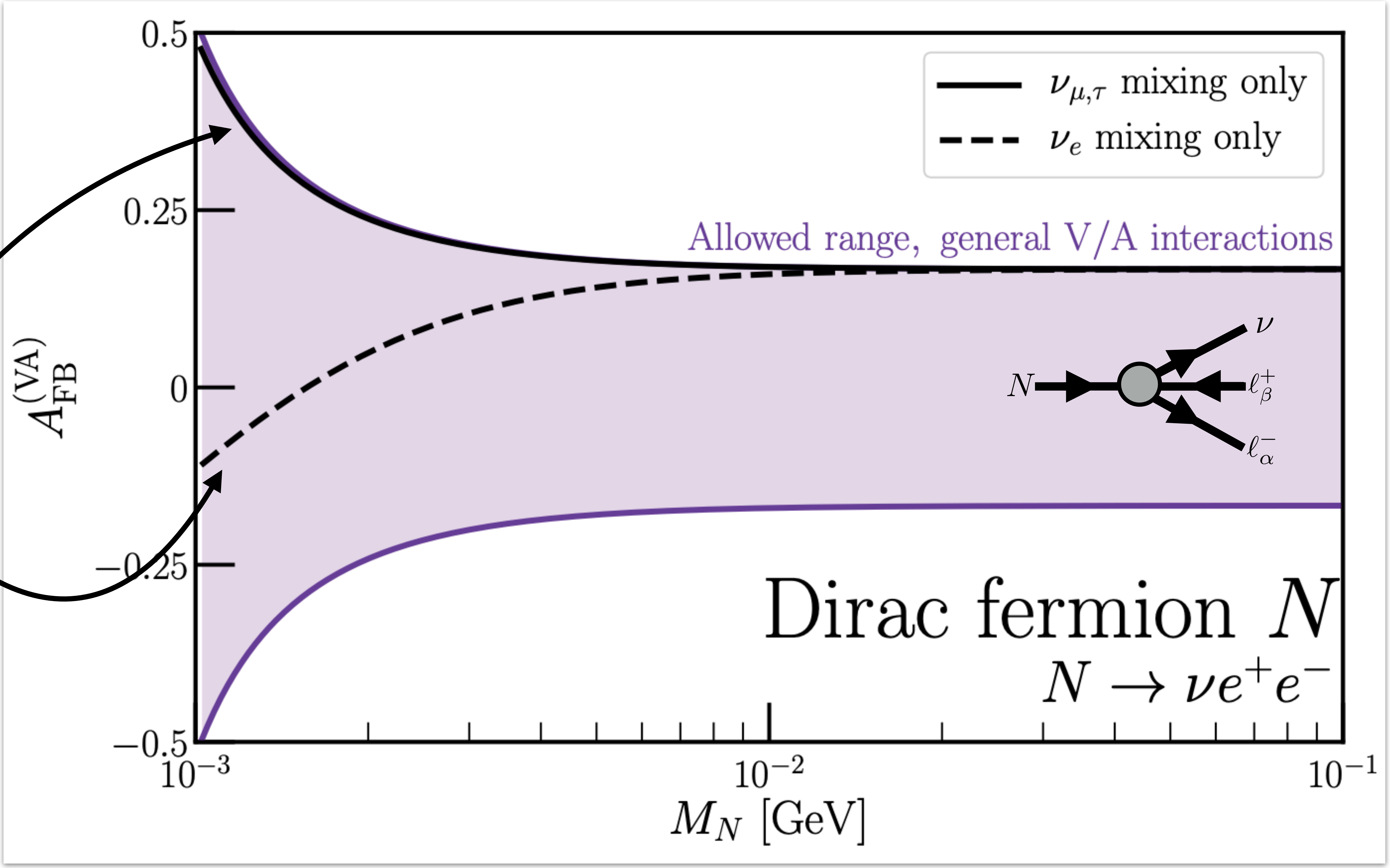
$$\Gamma_N,\ \Gamma_L \in \left\{\mathbb{1},\ \gamma^5,\ \gamma^\mu,\ \gamma^\mu\gamma^5,\ \sigma^{\mu\nu} = \frac{i}{2}\left[\gamma^\mu, \gamma^\nu\right]\right\}$$

de Gouvêa, Fox, Kayser, **KJK** [2104.05719]

How large can Forward/Backward Asymmetry Be?

If a non-zero asymmetry can be measured, one can prove that N is a Dirac fermion!

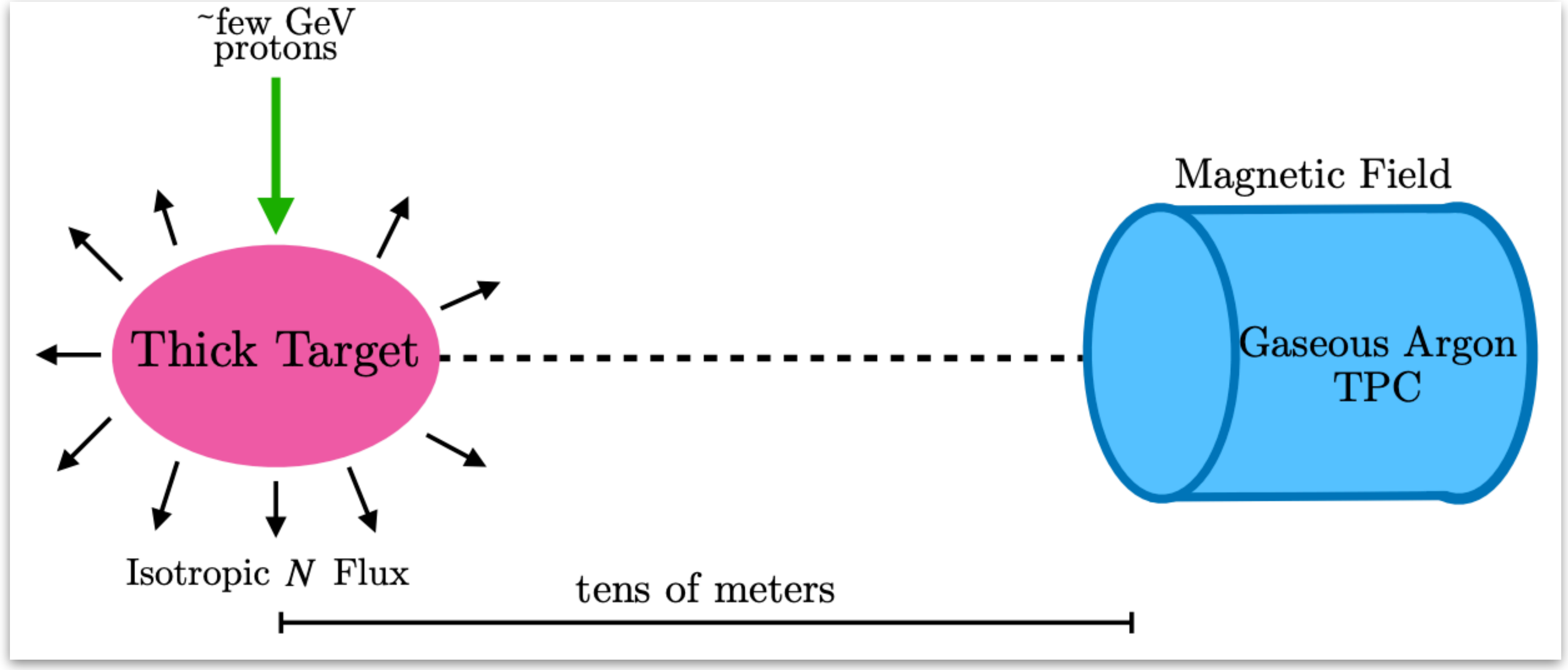
Decays mediated solely via off-shell W- and/or Z-bosons



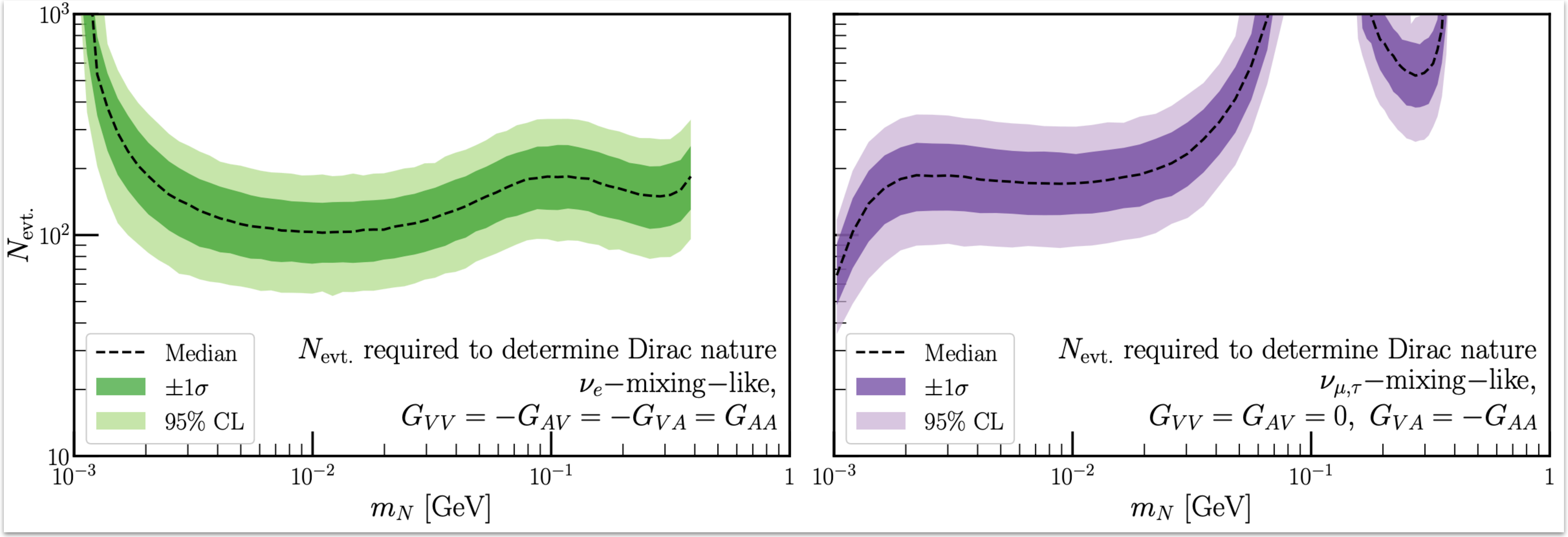
de Gouvêa, Fox, Kayser, **KJK** [2104.05719]

Is this measurement feasible?

de Gouvêa, Fox, Kayser, **KJK** [2104.05719]

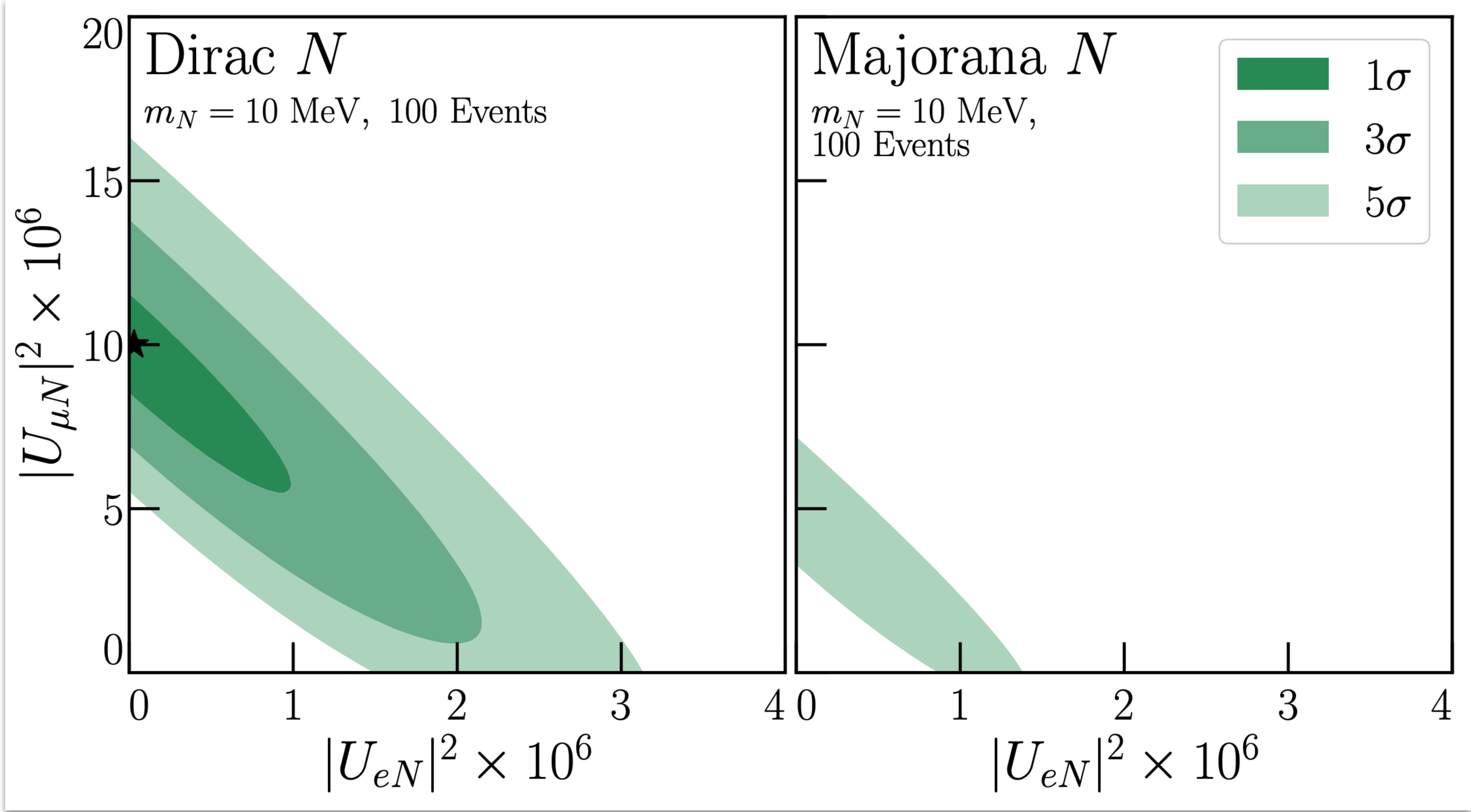


In this alternate environment, we can reconstruct the N rest-frame much more easily. If N is truly a Dirac fermion, how well can we reject the Majorana-fermion hypothesis?



Distinguishing Mixing Patterns

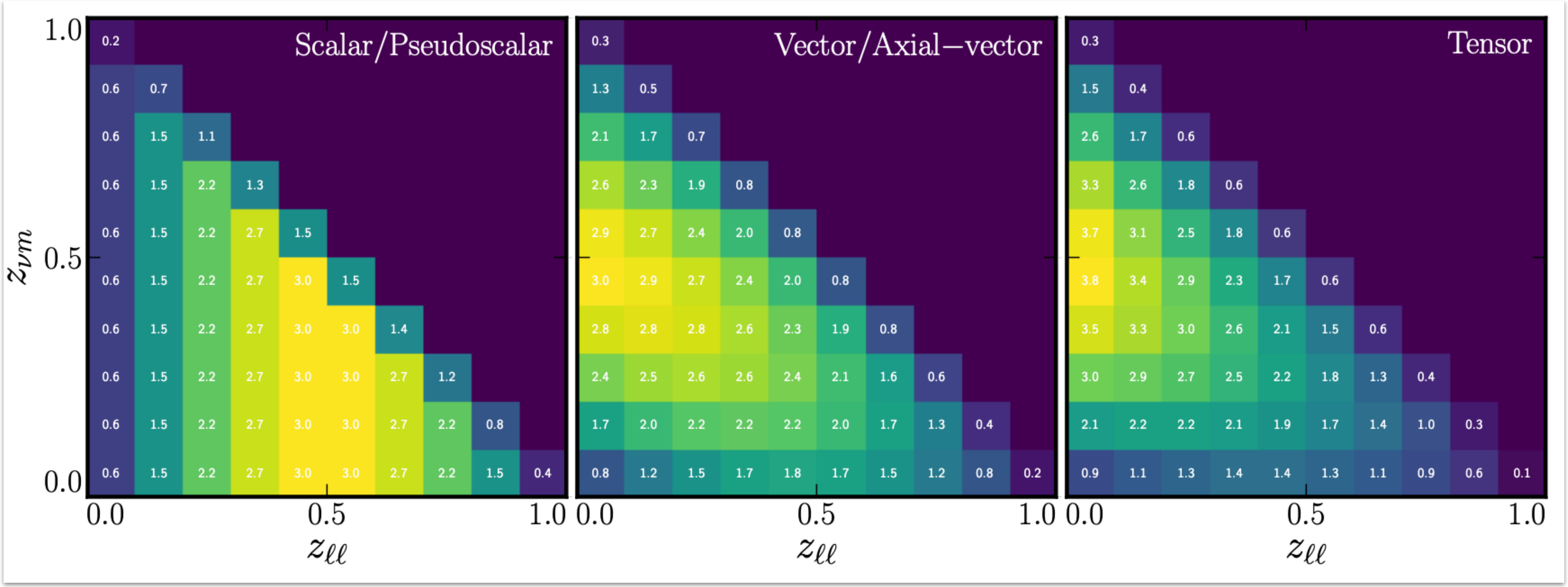
de Gouvêa, Fox, Kayser, Kelly [2109.10358]



Even with a massive mediator, O(100) events is enough to distinguish between neutral-current decays and mixed neutral/charged-current ones.

Measuring the Interaction Structure

de Gouvêa, Fox, Kayser, Kelly [2109.10358]



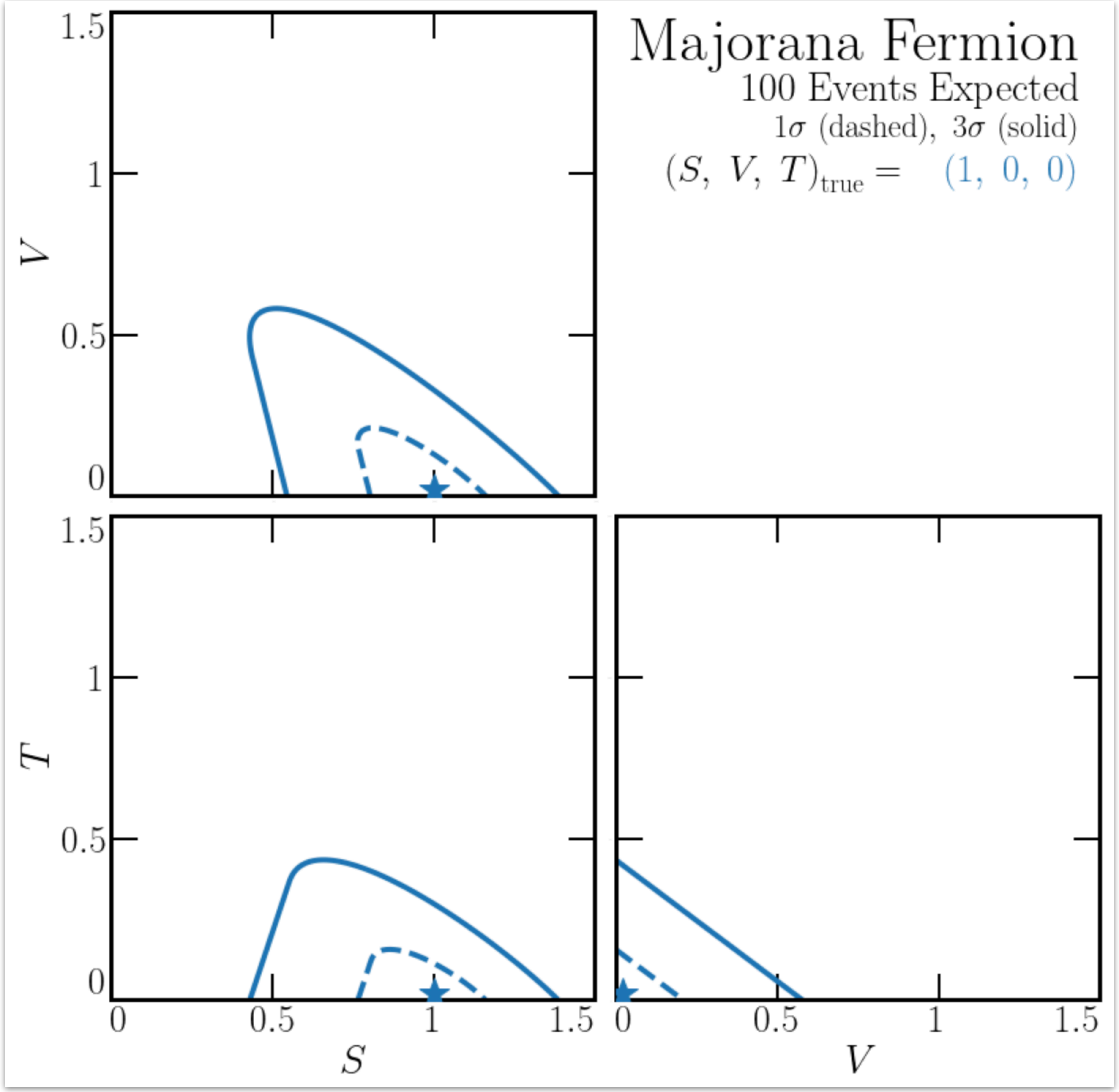
$$z_{\ell\ell} \equiv \left(p_{e^+} + p_{e^-}\right)^2 / m_N^2, \quad z_{\nu m} \equiv \left(p_\nu + p_{e^-}\right)^2 / m_N^2$$

Even if the N is unpolarized, we can still use its decay distributions to infer the type(s) of mediators contributing to its decay.

Distinguishing Mediator Classes

Majorana Fermion decaying via scalar contributions only — how well can we exclude vector/axial-vector/tensor contributions to its decay width?

With 100 events observed, these contributions can be constrained to be fairly small!



Takeaways

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- (Hopefully) with the next generation of new experiments, discoveries await, including physics separate from neutrino oscillations.
- With careful thought, we can be prepared to leverage all data in the wake of new discoveries.
- Some discoveries may require additional facilities to diagnose their origin - should we start planning now?

Thank you!