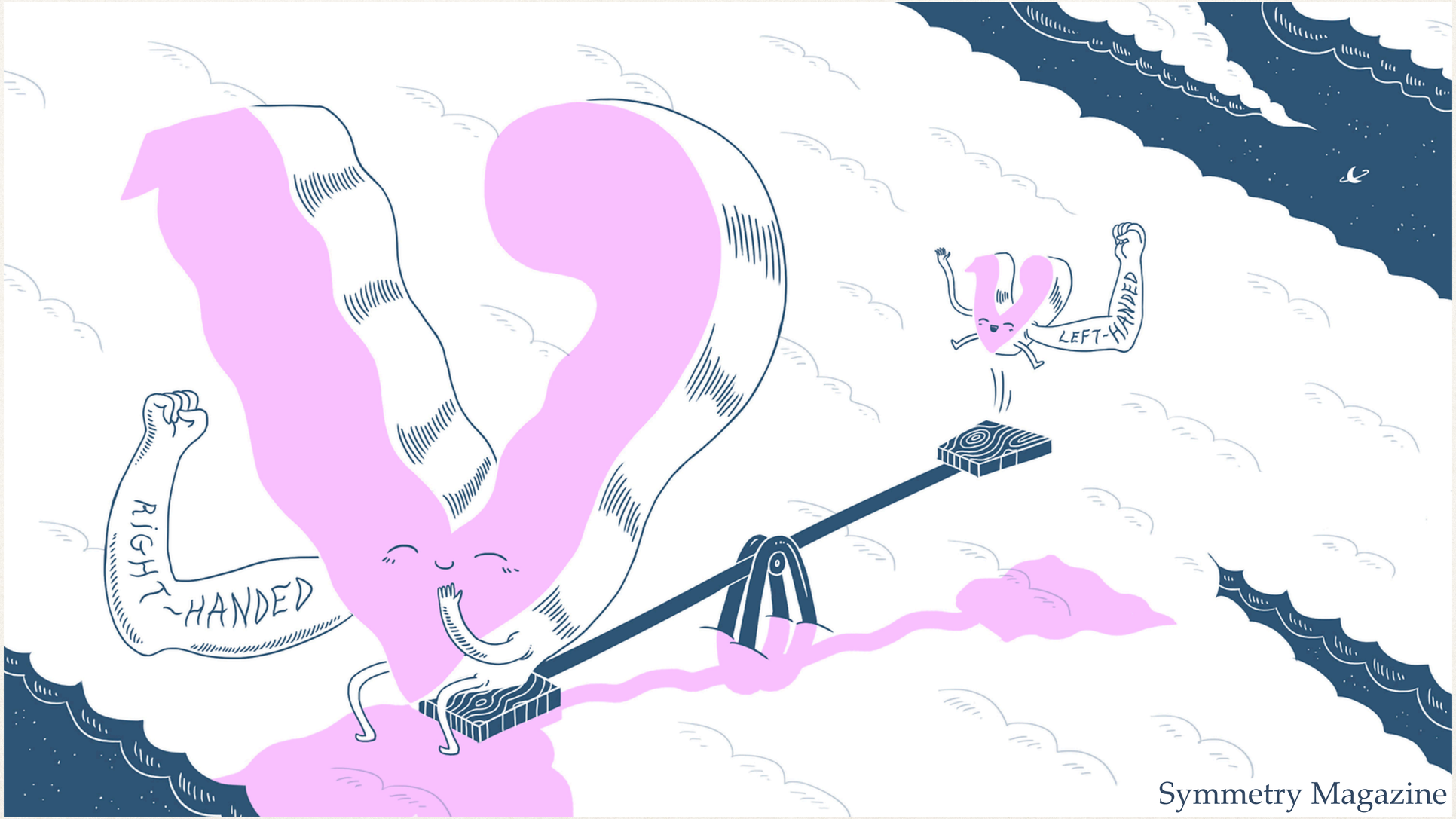
# Heavy Dirac/Majorana Fermion Decays

[2104.05719] (+Ongoing work) with André de Gouvêa, Patrick Fox, and Boris Kayser

Kevin Kelly, Fermilab *PHENO2021*

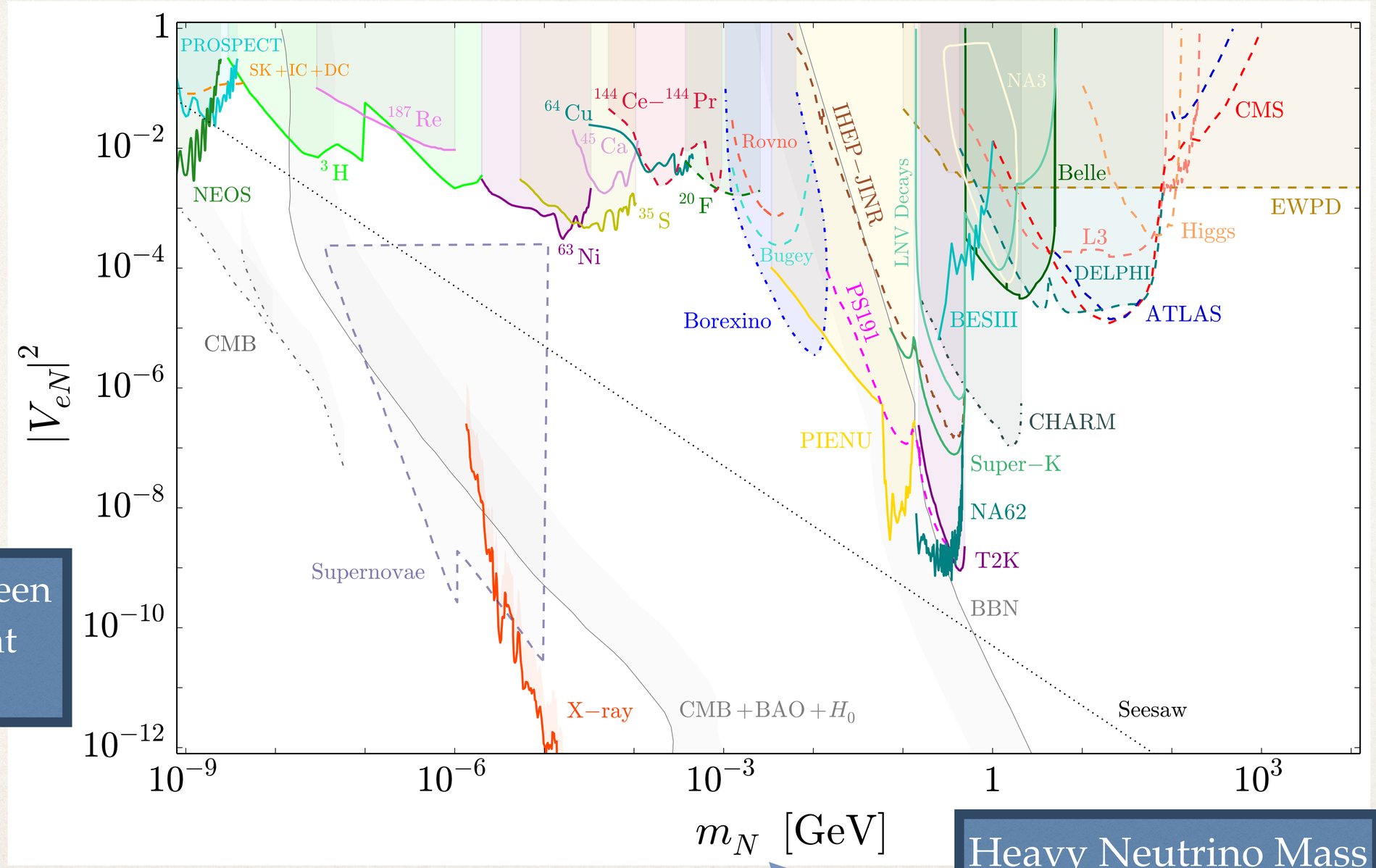
# Heavy Fermions, why?




Symmetry Magazine

Heavy, gauge-singlet fermions (right-handed, or sterile neutrinos) can explain the lightness of SM neutrinos

# Current State of HNL Searches



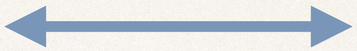

Bolton et al, [1912.03058]

Mixing between heavy / light neutrinos

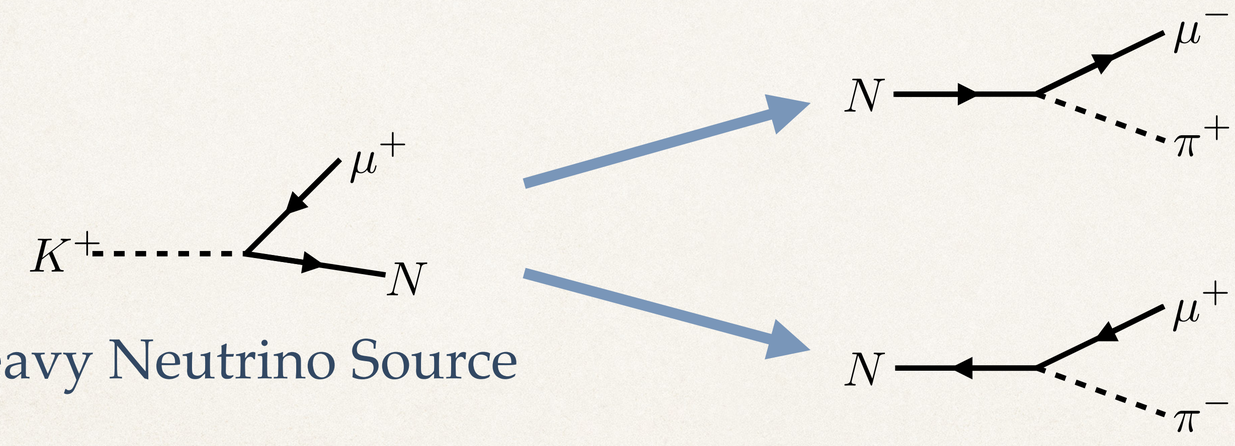
Heavy Neutrino Mass

# If we discover a Heavy Neutrino…

Is the new particle a Dirac or Majorana Fermion?



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

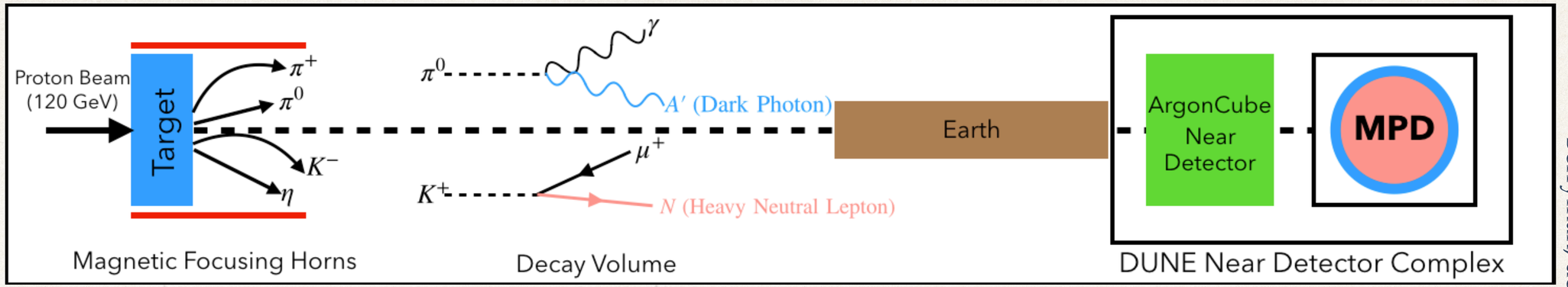



Heavy Neutrino Source

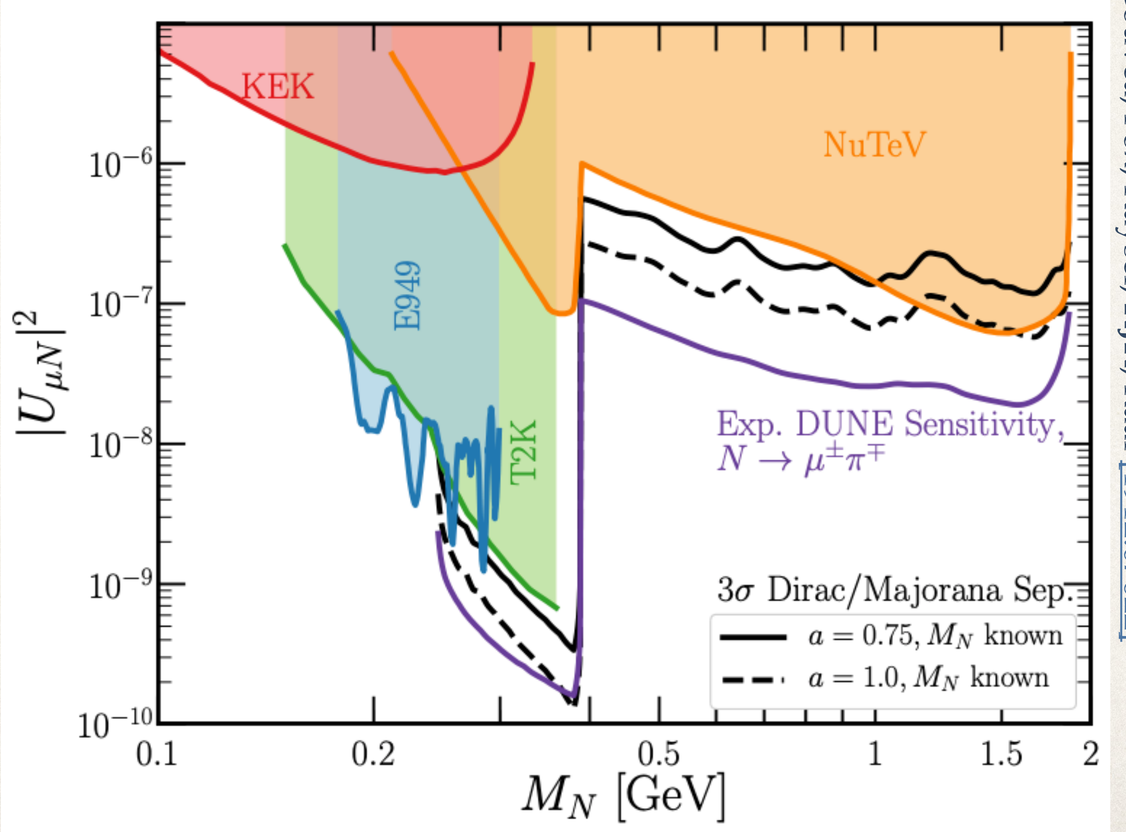
Heavy Neutrino Decay

- Do these two chains happen with equal probability?

# Next-Generation: DUNE



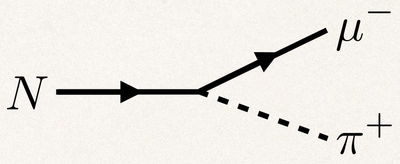

- For sufficient combinations of Heavy Neutrino mass & mixing, not only can the DUNE Near Detector discover the particle, it can determine whether it's a Dirac or Majorana fermion via its fully-charged decays.

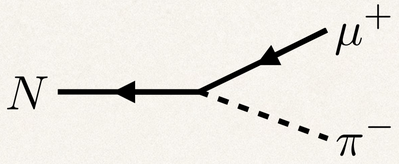


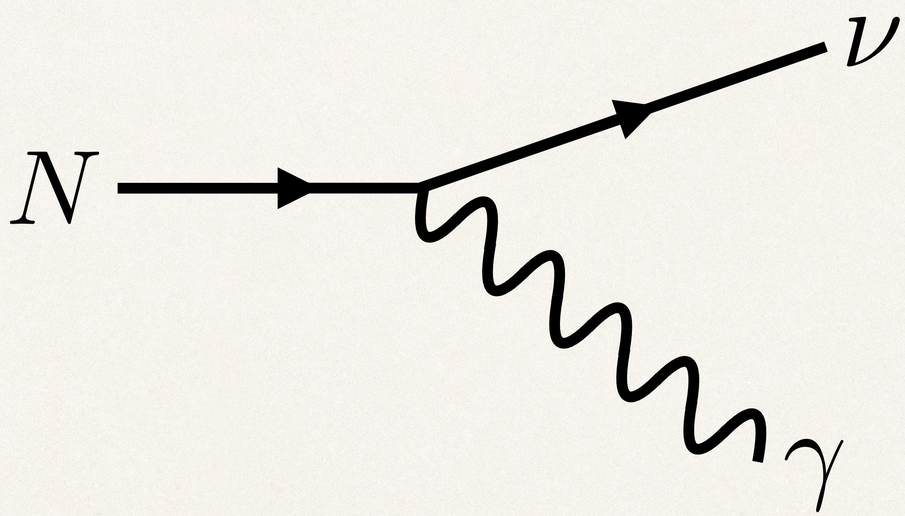

Berryman, de Gouvêa, Fox, Kayser, **KJK**, Raaf [1912.07622]

# What if we're not lucky?

- If a heavy fermion is lighter than the pion, there are no fully-visible (aka no neutrinos) final states where the lepton number is identifiable.



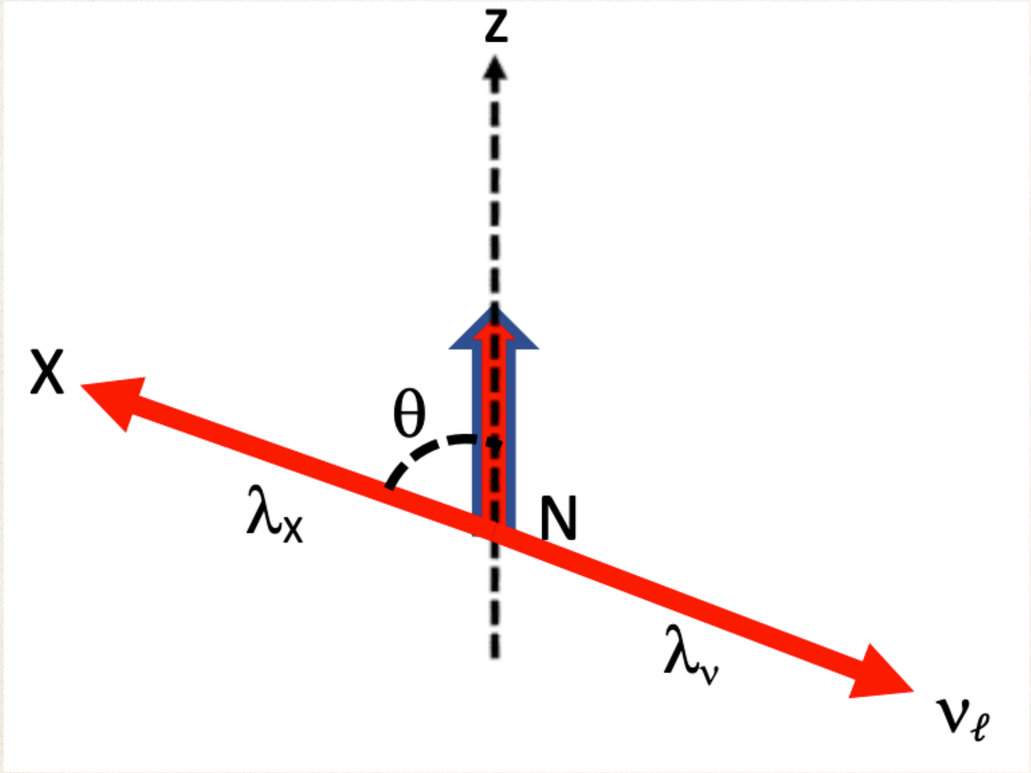




(final state could include a pion instead of a photon, or a charged lepton pair)

There's still hope in Dirac vs. Majorana separation! Measure the *distribution* of outgoing photons.

# Two-Body Decays

Balantekin, de Gouvêa, Kayser [1808.10518]




From CPT arguments, if the heavy neutrino is a Majorana fermion, then the decay is isotropic. If it is a Dirac fermion, not necessarily.

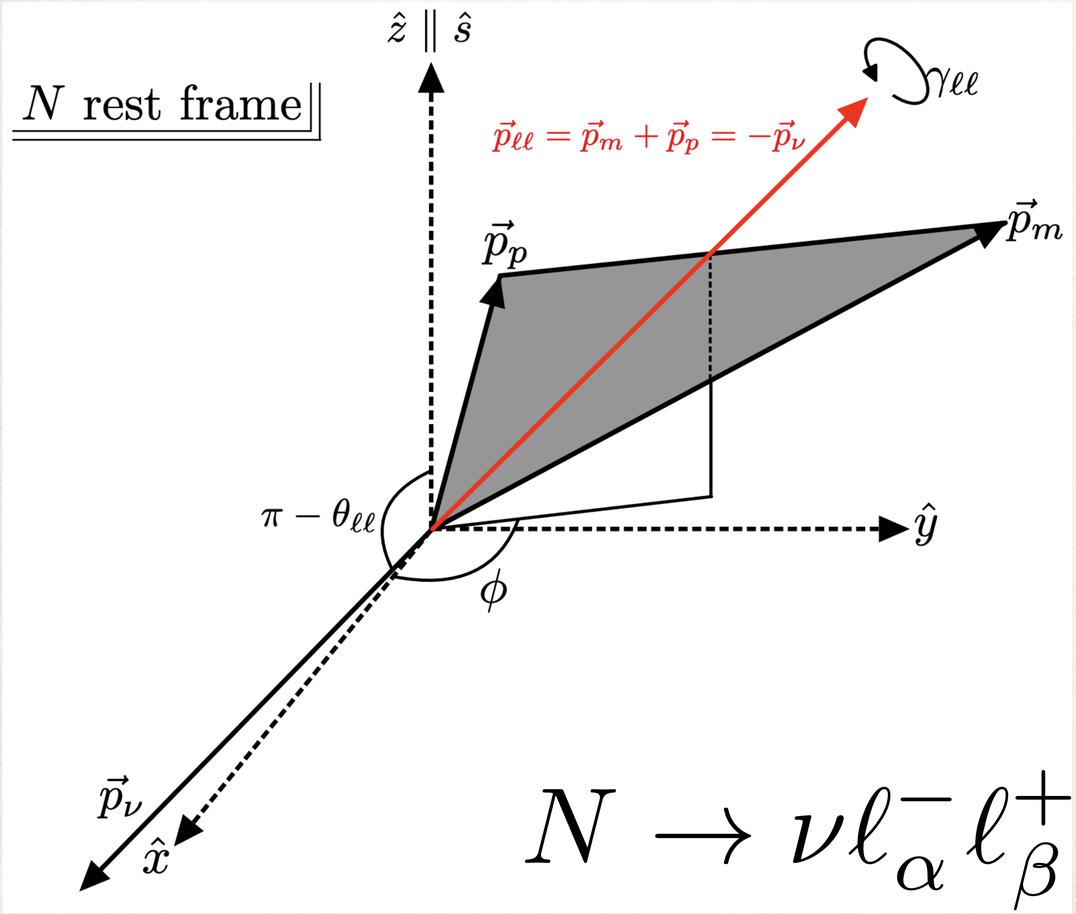
$$\frac{d\Gamma}{d\cos\theta} = \frac{\Gamma}{2}\left(1 + \alpha\cos\theta\right)$$

| 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 |

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

# Extending to Three-Body Decays

Using similar CPT arguments, we demonstrated that, if N is a Majorana fermion, its decays are forward/backward symmetric if either of the following are true:




- The final-state charged leptons are identical (e.g. electron/positron pair).
- The detection mechanism is charge-blind (and final states like electron/antimuon and muon/positron must be summed over).

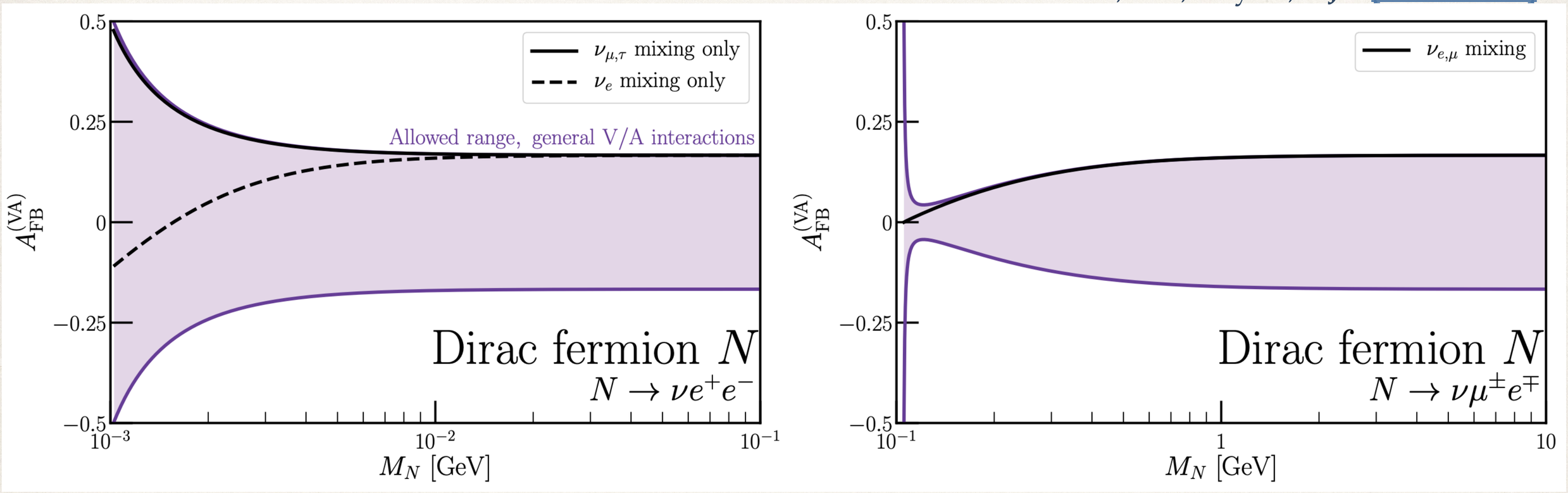
Considered the most generic four-fermion operators for the decay (including interference):

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

# How large can forward/backward asymmetry be?

To be a useful handle for Dirac/Majorana fermion separation, we want Dirac fermions to exhibit large, measurable asymmetries.

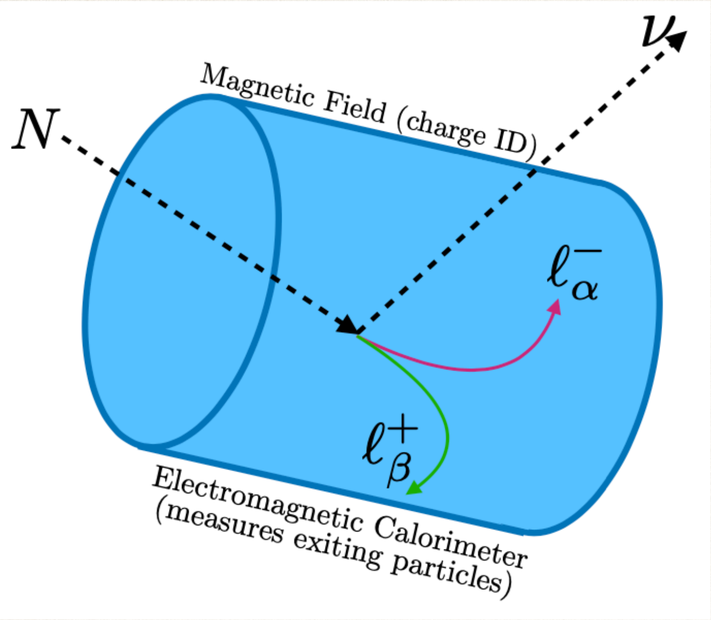
de Gouvêa, Fox, Kayser, **KJK** [2104.05719]




- Black lines: prediction if the decay is mediated purely via off-shell W- and/or Z-bosons

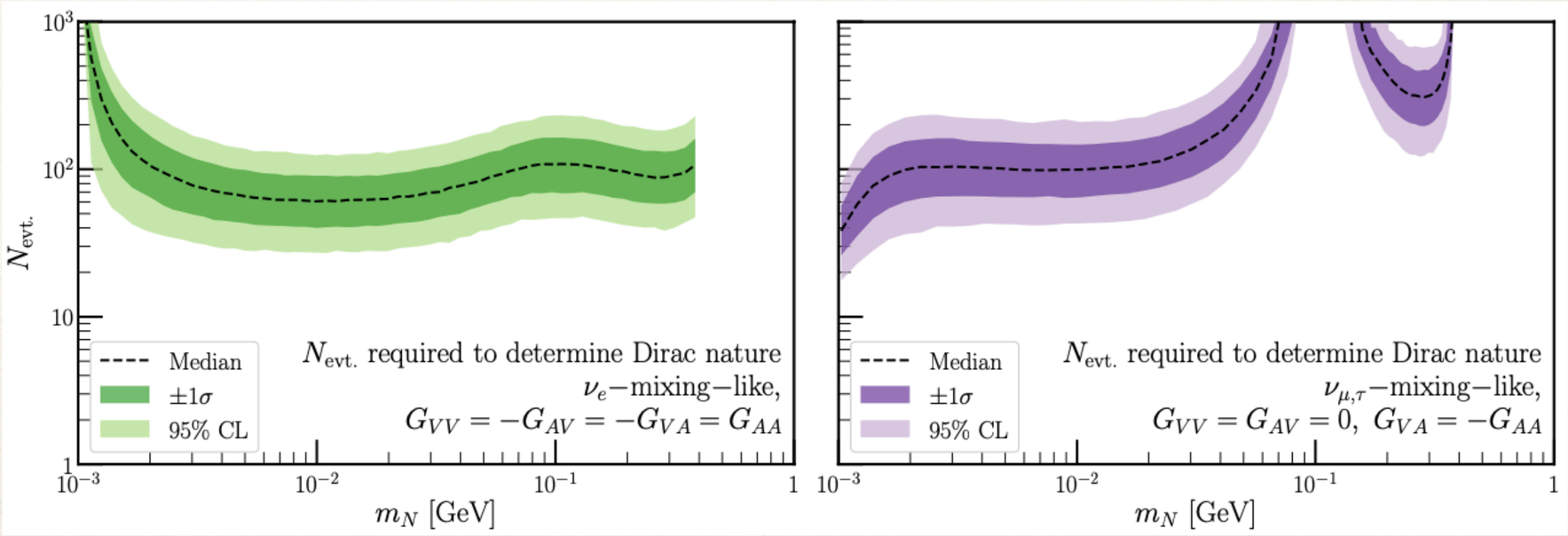
# Is this feasible?

de Gouvêa, Fox, Kayser, **KJK** in prep.




Envision a post-discovery experiment near a meson decay-at-rest source: how many signal events do we need to see to differentiate the null hypothesis (N is a Dirac fermion) from the alternate hypothesis (N is a Majorana fermion)

Depending on particle's mass, polarization, interaction couplings, can be as few as O(80). Even fewer for scalar / pseudoscalar interactions.



# Conclusions

- Heavy, gauge-singlet fermions are a feature of many well-motivated theories of physics beyond the standard model.
  - A bevy of experiments are currently searching for them, and next-generation experiments are well-equipped to expand upon these searches.
- In the wake of a potential discovery, many questions will arise, all connected to the interactions of the new particle and what potential symmetries it respects/violates.
- Upcoming experiments, and more purpose-built post-discovery experiments, can deduce these properties by measuring the distributions of decays of these new fermions.

Thanks!