Searches for Dark Sectors in Neutrino Experiments

Kevin Kelly, FNAL

APCTP: Dark Matter as a Portal to New Physics

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[1912.07622] with Jeffrey M. Berryman, André de Gouvêa, Patrick J. Fox, Boris J. Kayser, and Jennifer L. Raaf;

@kjkelly_physics

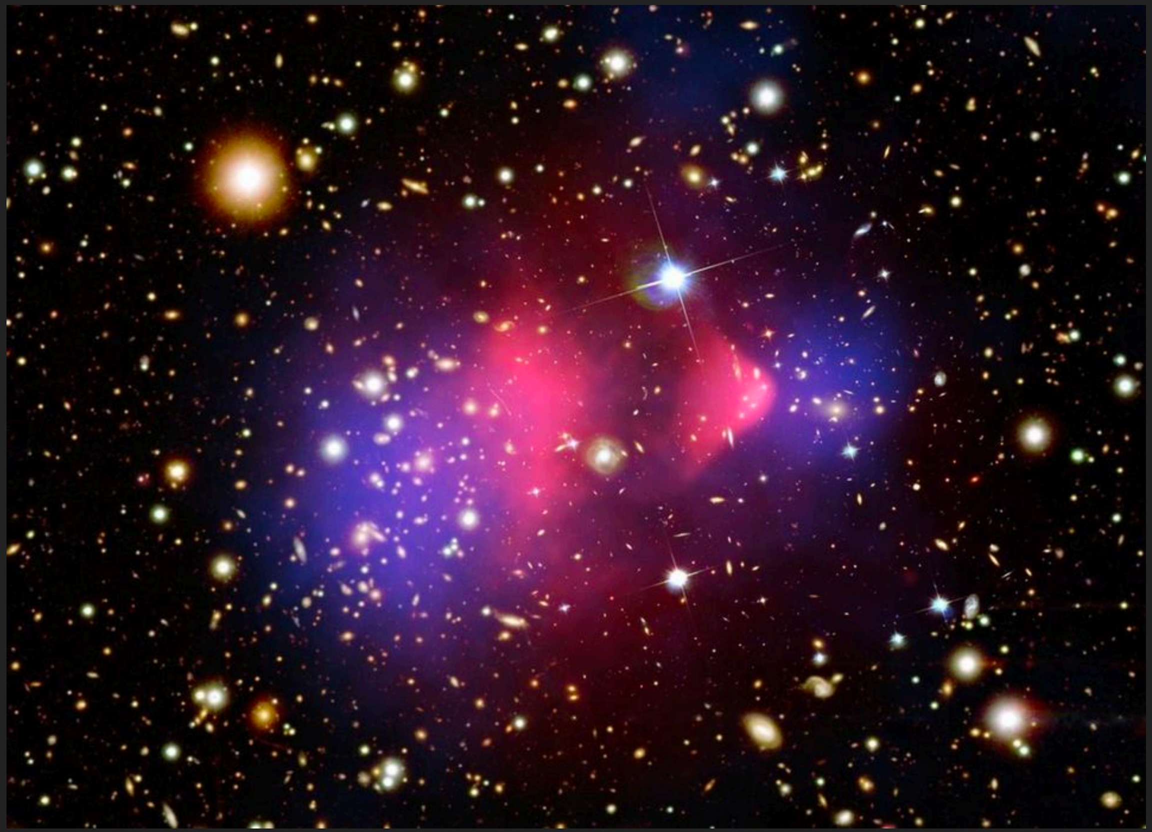
Fermilab

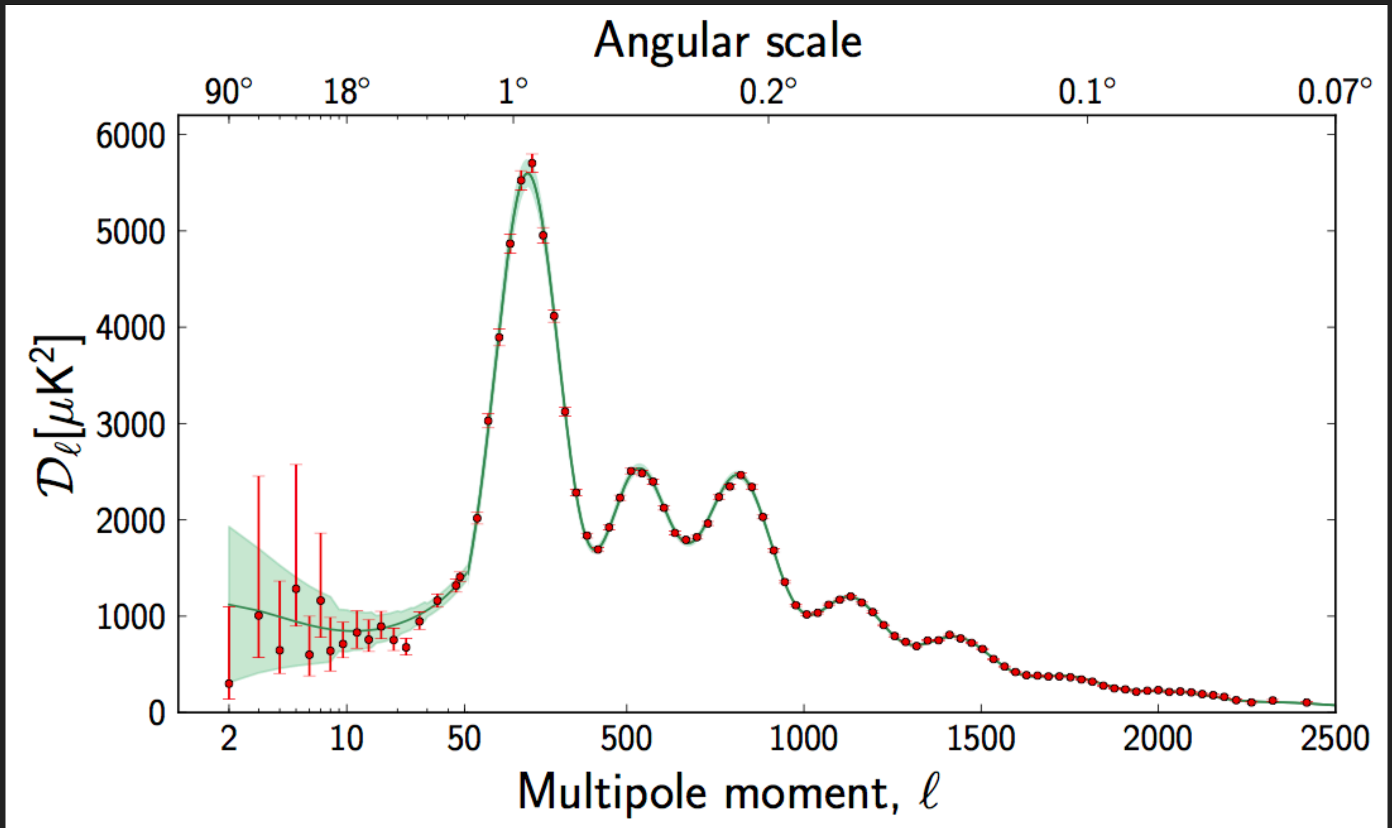
Outline

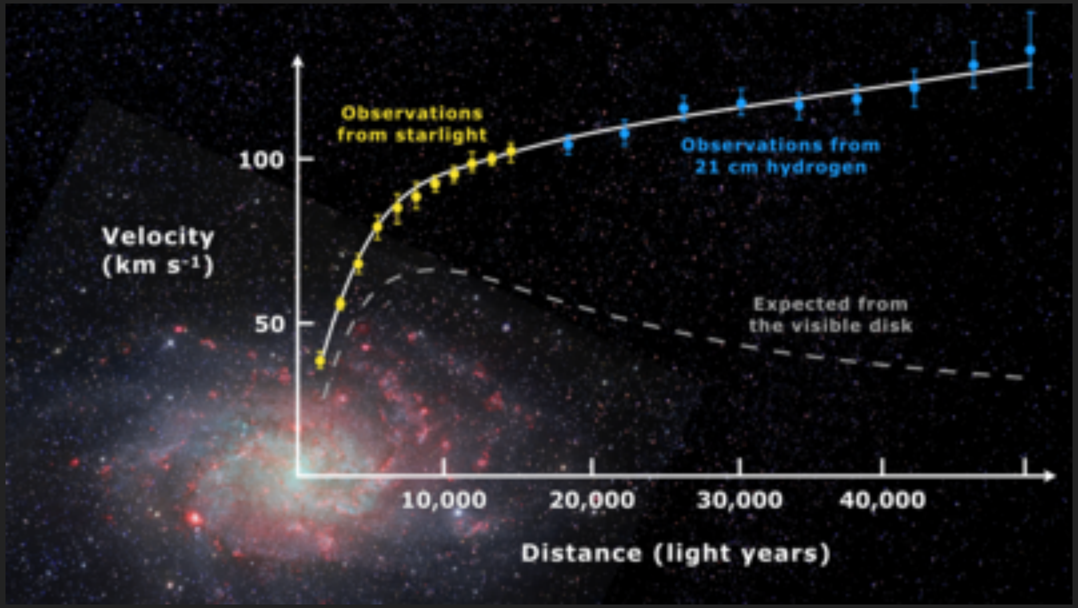
- Theoretical Motivation
- The DUNE Near Detector Complex
- DUNE as a Meson Facility
- Sensitivity to New Particle Decays

Theoretical Motivation

Dark Matter Exists!



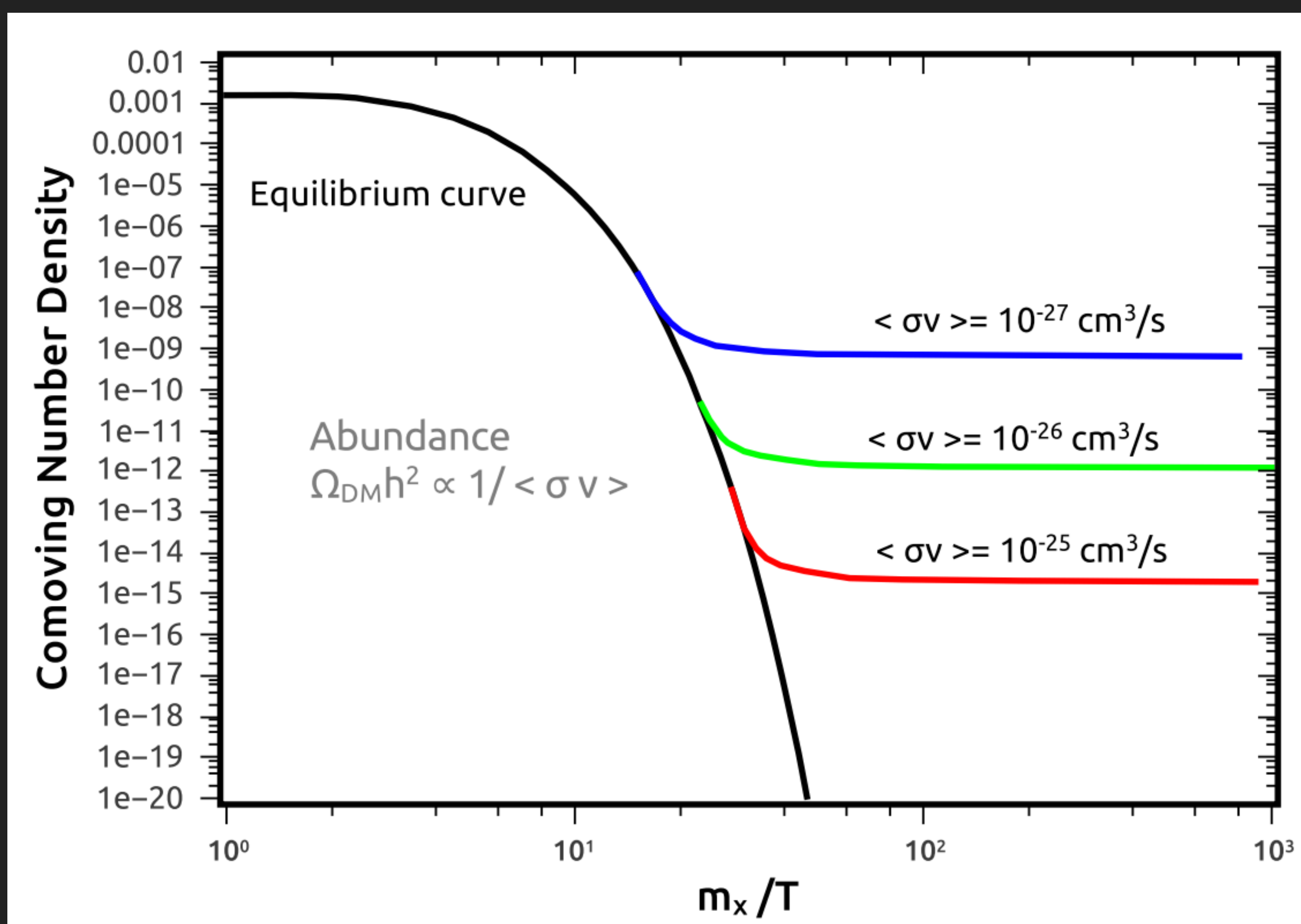


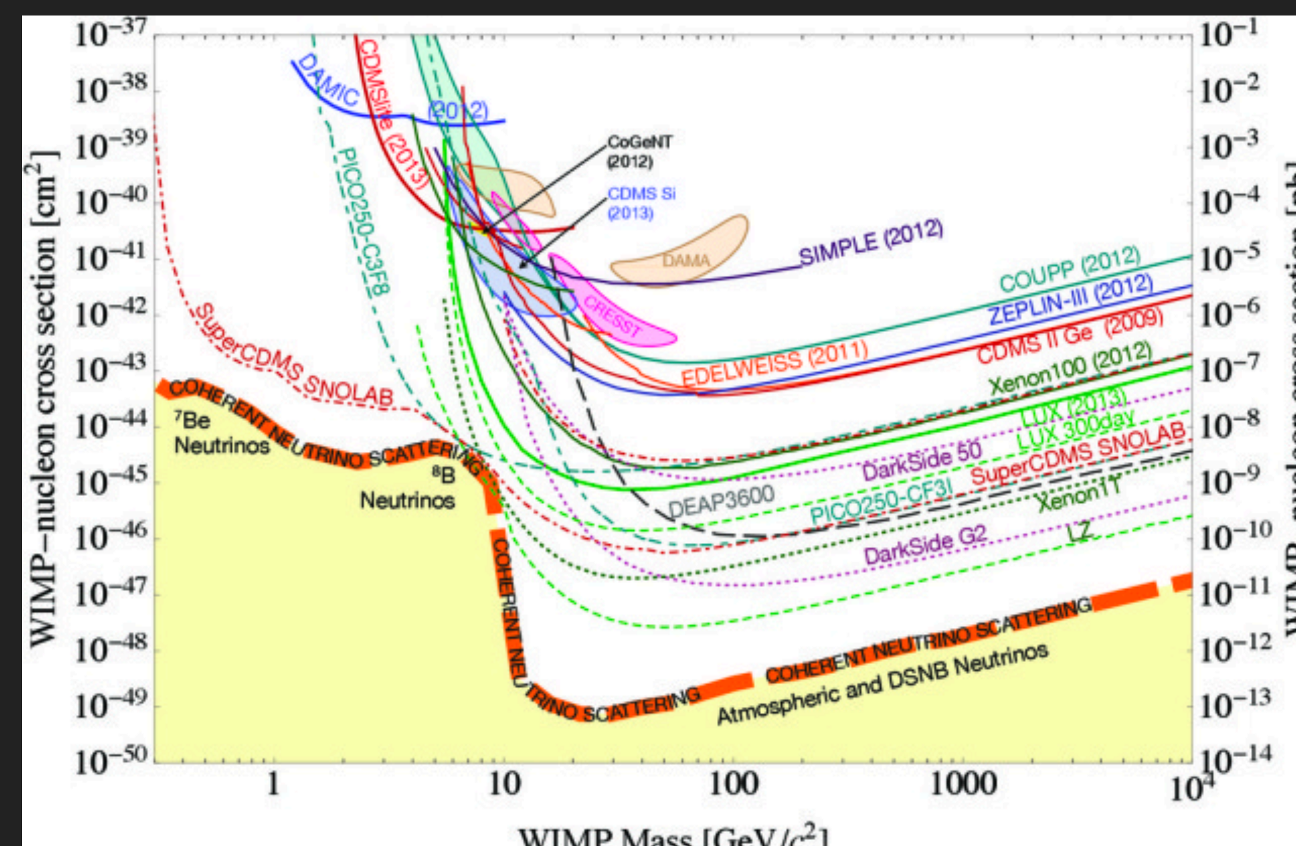


- Abundance of evidence for dark matter, but no clear answer from a particle physics perspective.

Previous Standard-Bearer: WIMP Paradigm

- Highly predictive paradigm: dark matter initially in thermal equilibrium with standard model. DM undergoes freeze-out, locking in its relic abundance. Weak-scale mass interacting via the SM W/Z bosons gives correct abundance.





Lack of Signal: Where do we look now?

- Lighter DM is a possibility, but in order for freeze-out to give the correct relic abundance, new mediators are required.
- How should these mediators talk to SM particles?
- Using renormalizability as a guiding principle

$$F^{\mu\nu}F'_{\mu\nu}$$

$$|H|^2 S^2$$

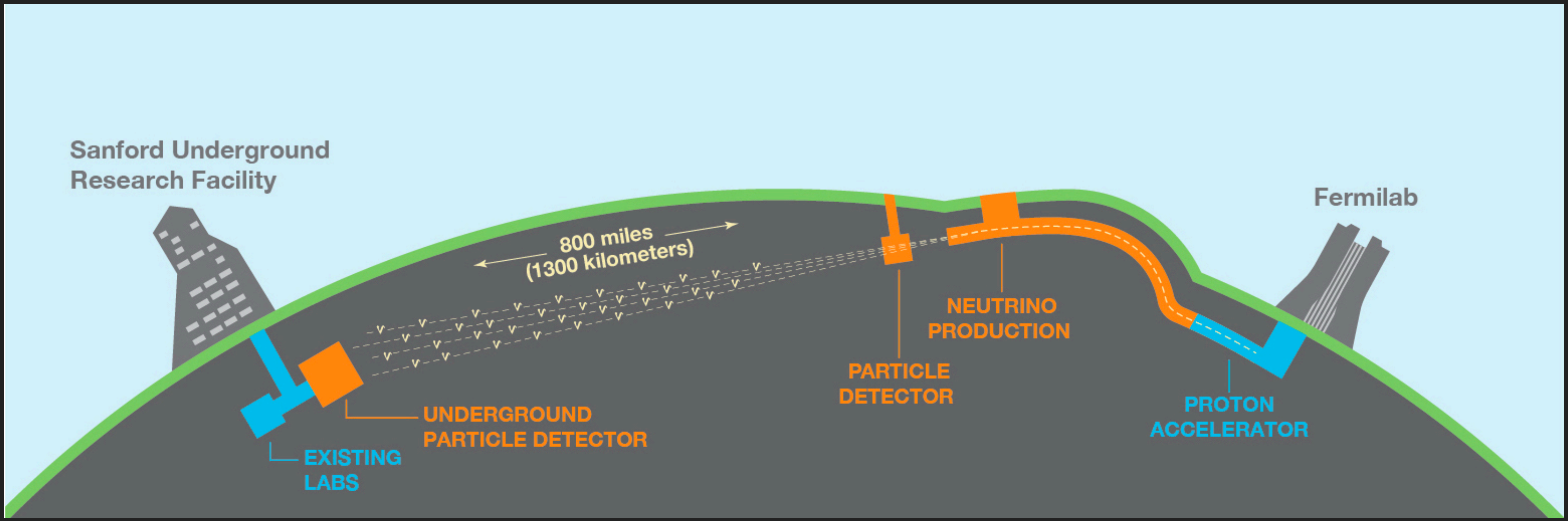
$$V^{\mu}J_{\mu}^{\mathrm{SM}}$$

$$(LH)\,N$$

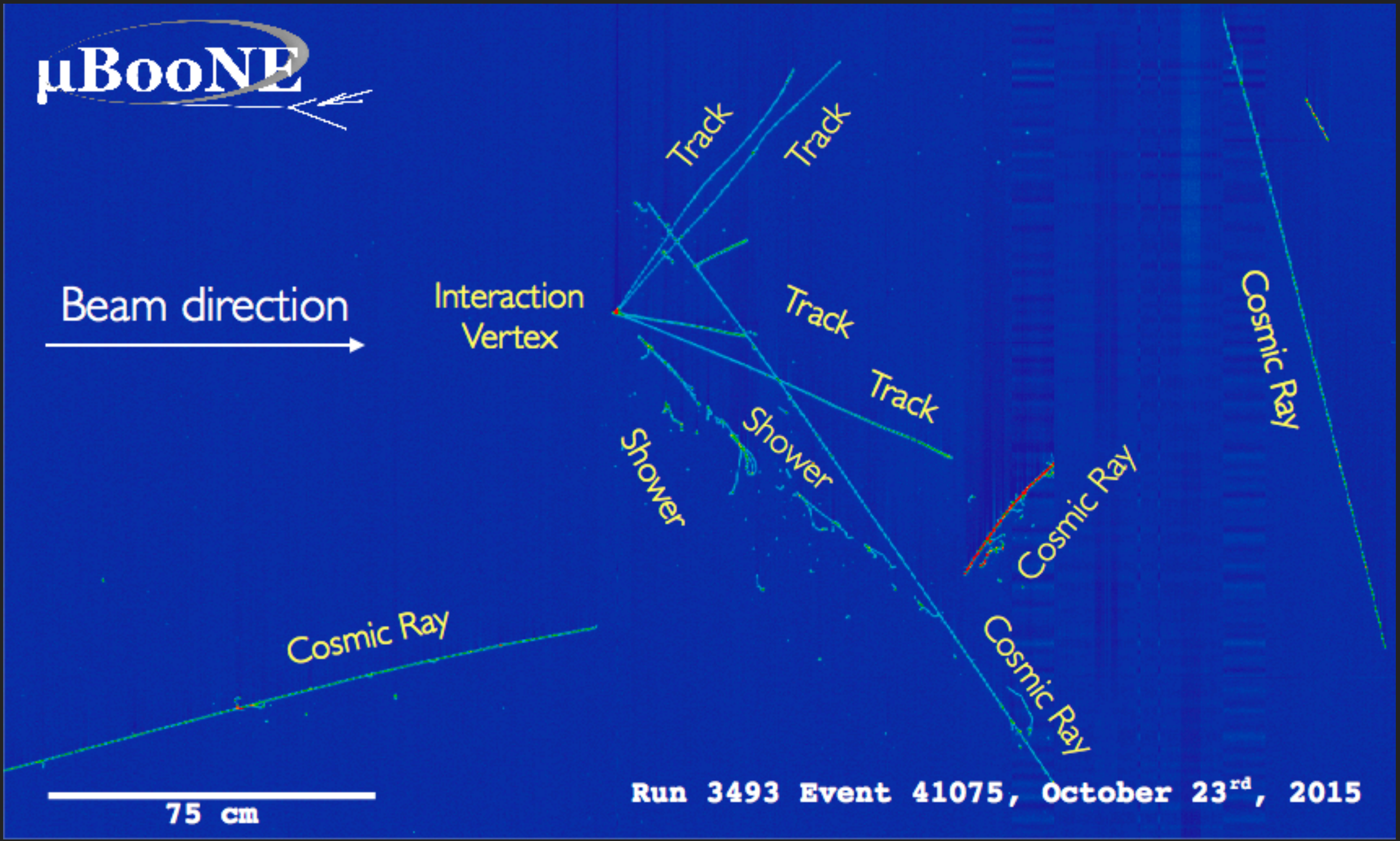
The DUNE Experiment

The Next Generation of Neutrino Experiments

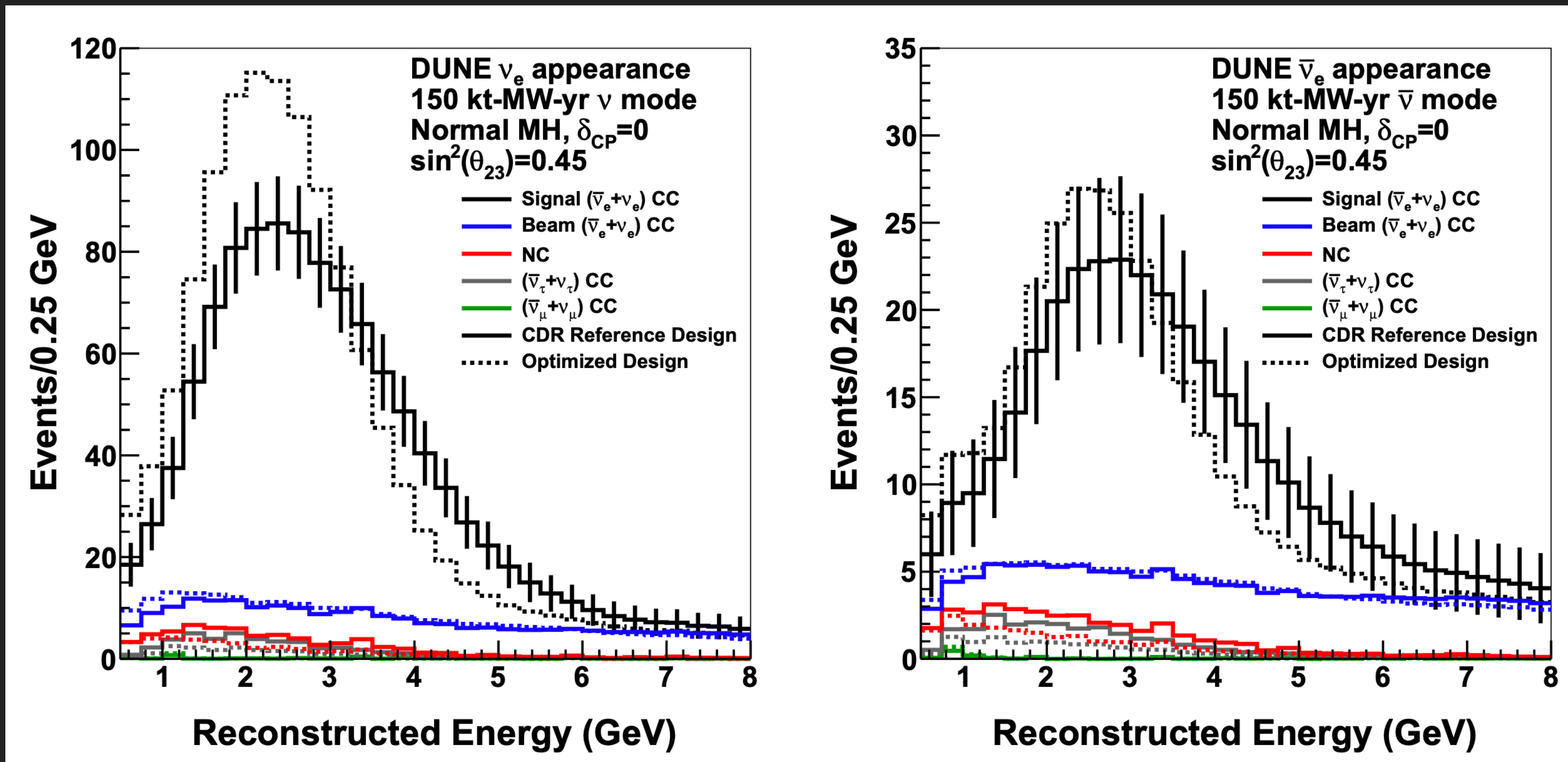
- Long-baseline neutrino experiment, beam originating at Fermilab, with four liquid argon detectors in South Dakota (each 10 kilotons).
- Broad-energy beam, several GeV in energy
- Liquid argon TPC provides excellent particle identification and energy measurements.



Liquid Argon TPC



DUNE Goals

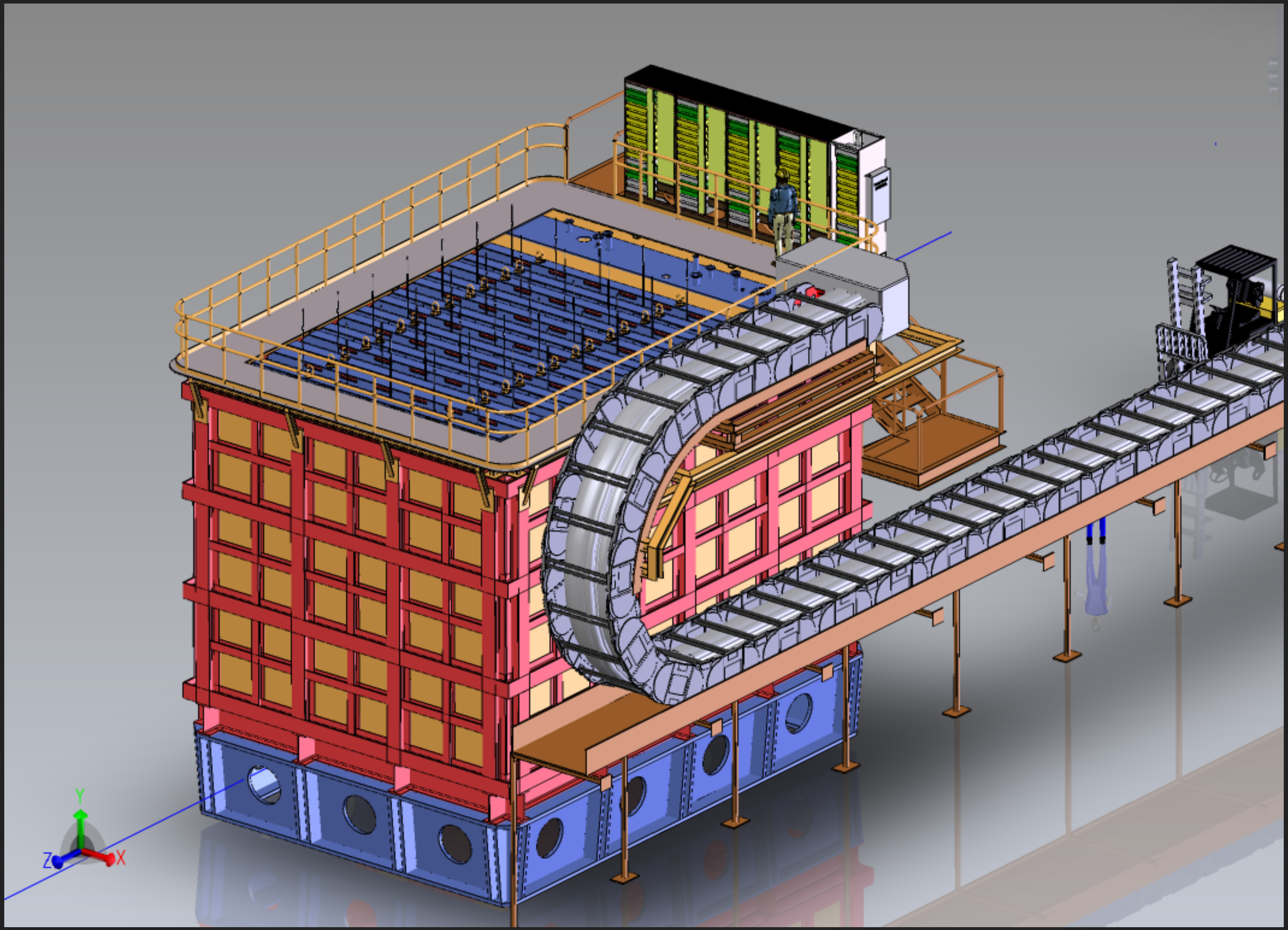


- Measure electron neutrino appearance spectrum to obtain knowledge of the muon-to-electron neutrino oscillation probability.
- Determine whether CP is violated in the lepton sector, etc.

The DUNE Near Detector Complex

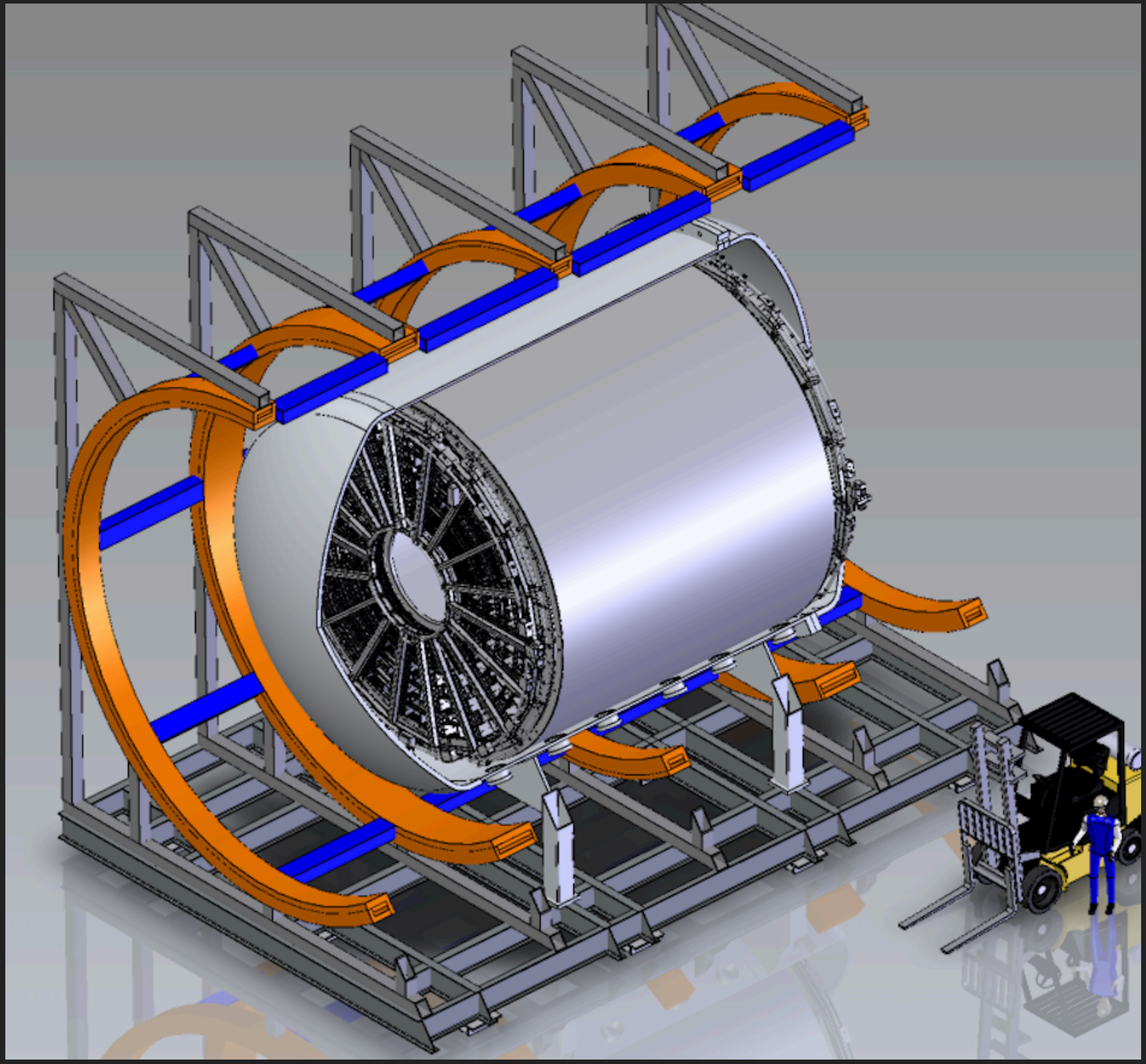
Mission of the Near Detector

- In order to study far detector oscillation physics precisely, DUNE plans to have a liquid argon near detector (same material as far detector) that will constrain the flux to the percent level.



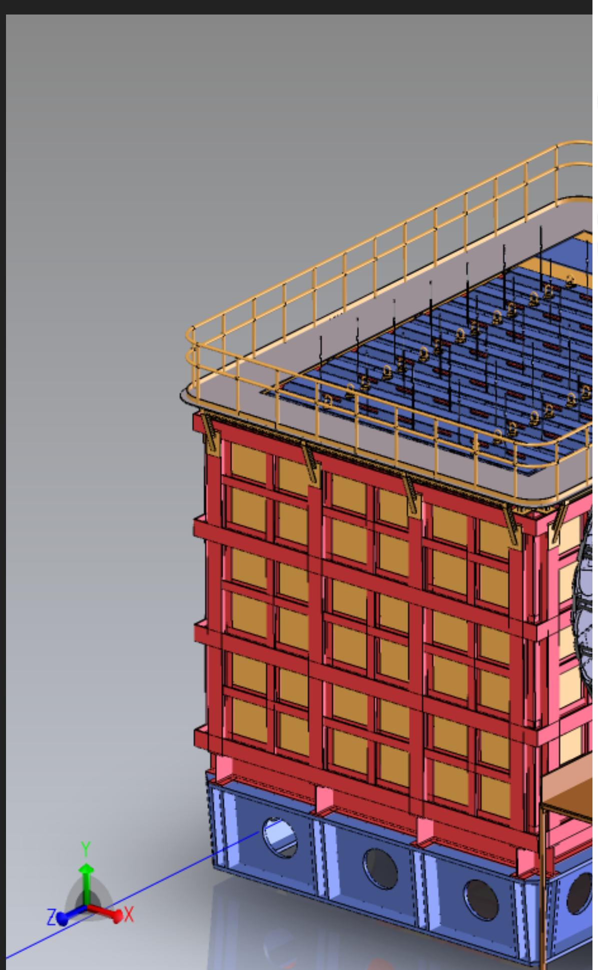
Caveats

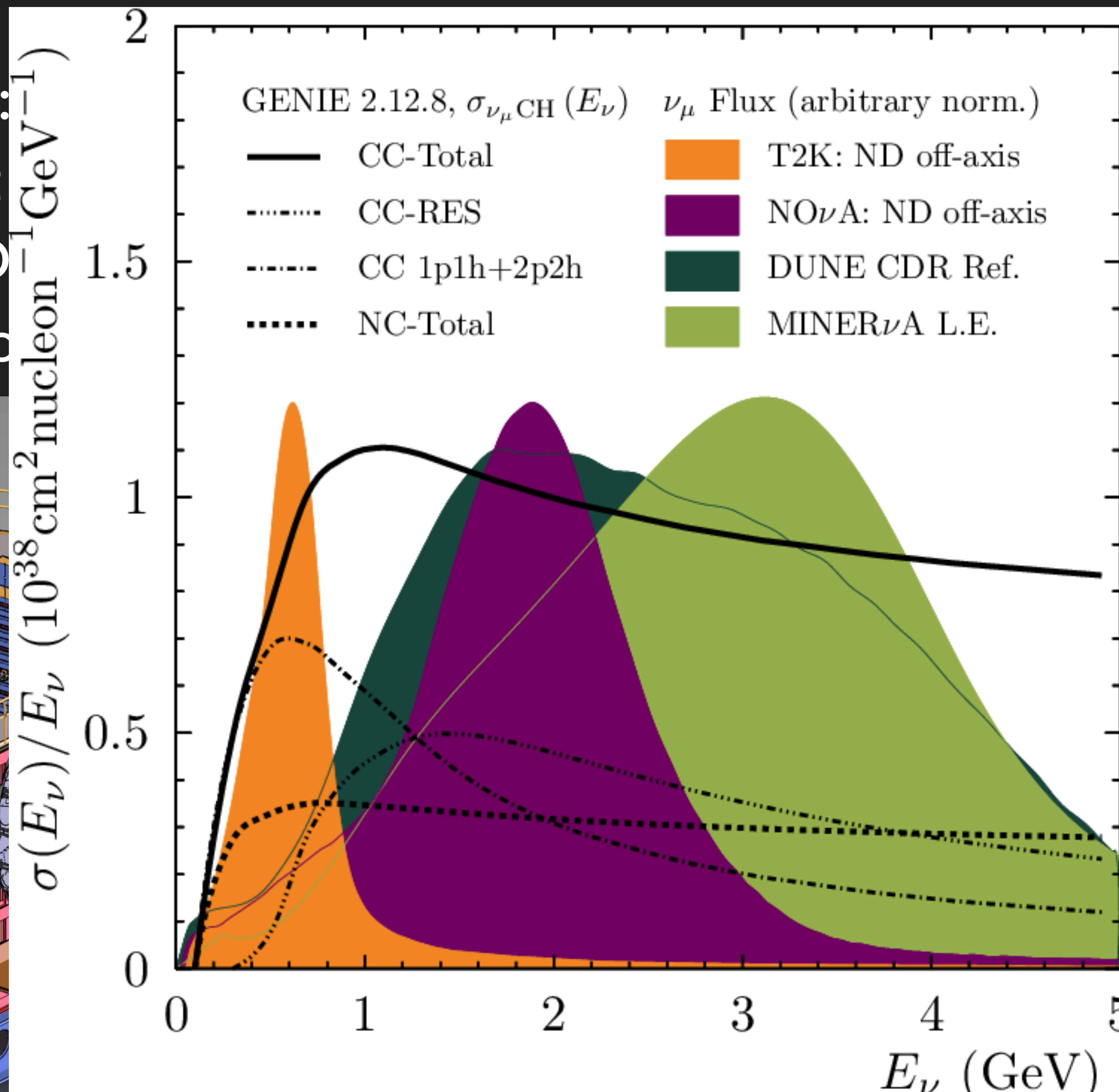
- Because the ND is small compared to the FD, containment is an issue – many charged tracks will exit the liquid argon, and their energy cannot be measured precisely.
  - Solution: Place a gaseous argon TPC downstream of the liquid argon one – precision measurements of any tracks that exit the LAr.

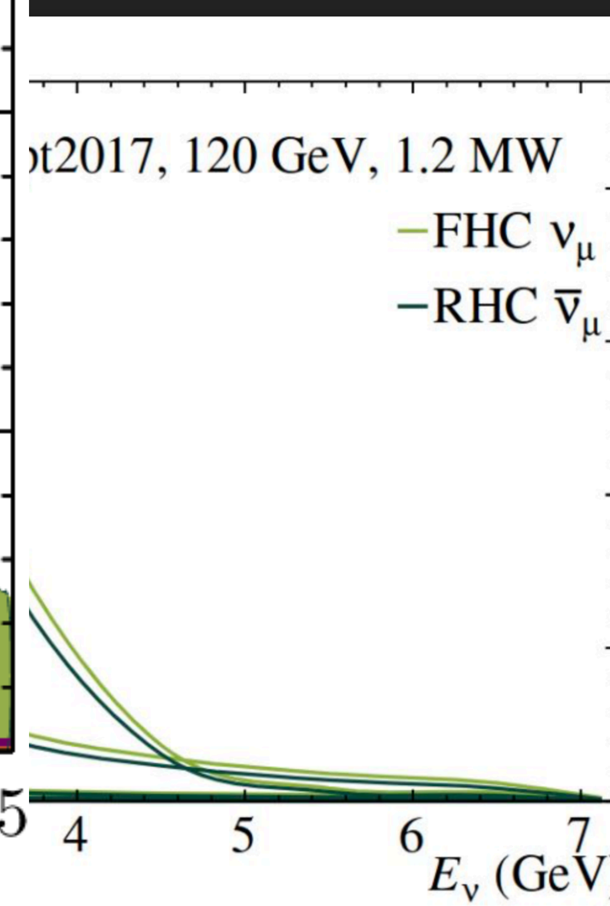


Caveats

- Many uncertainties exist with the neutrino cross section on argon, especially in the energy range DUNE intends on operating
  - Solution: ... x changes to different ... -axis angle. Allows D... nstrain the cross sec...







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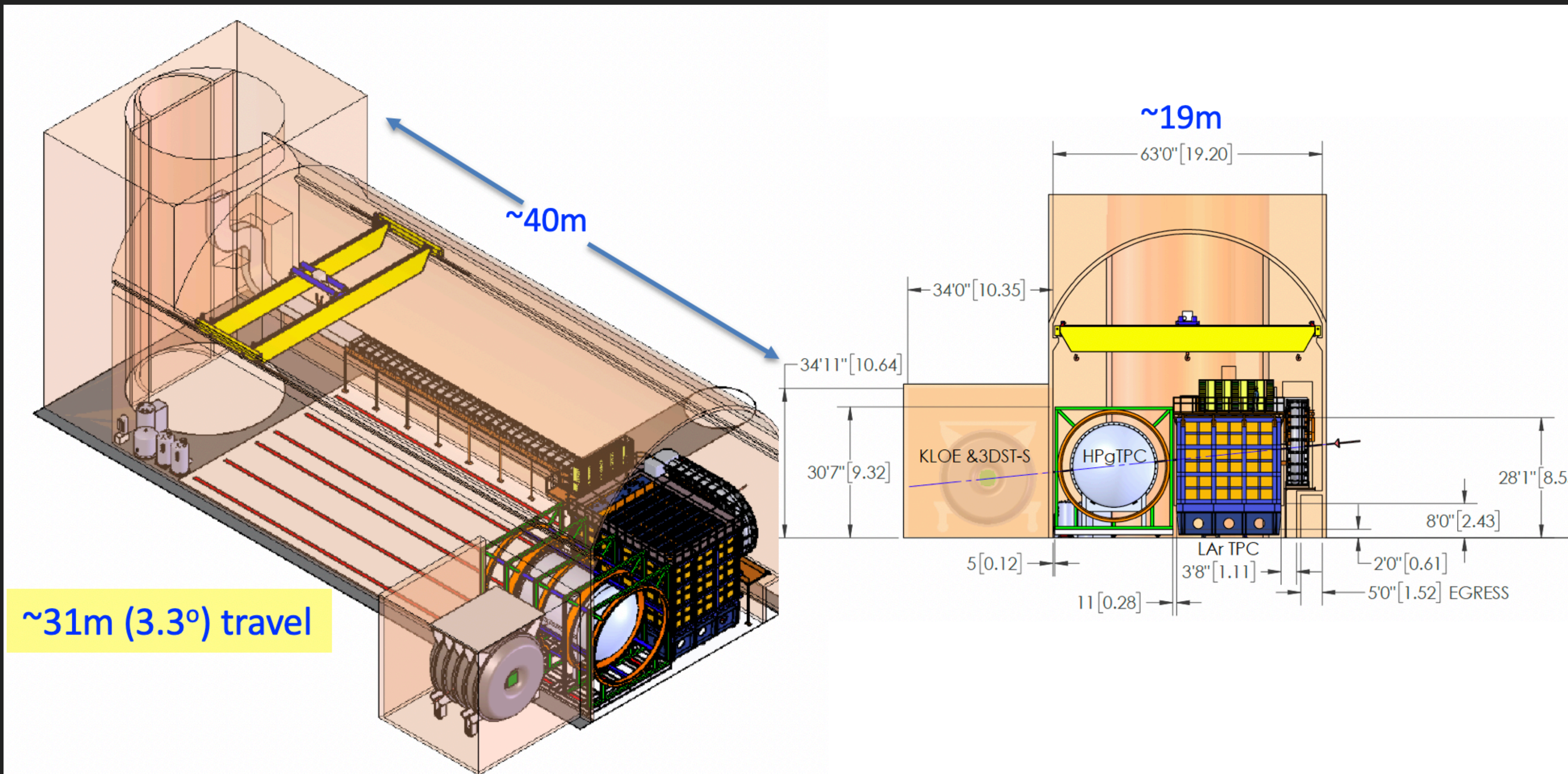
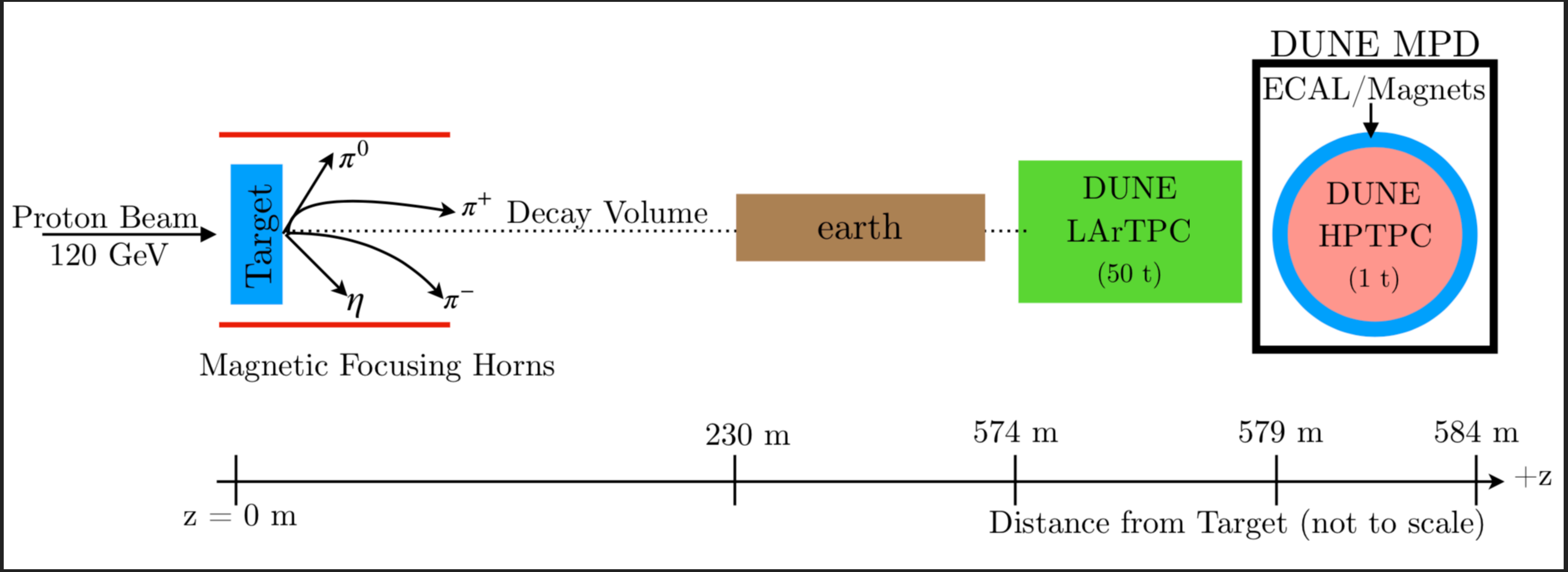
Near Detector Hall



Our Focus

- The DUNE Multi-Purpose Detector, consisting of the Gas TPC, ECAL surrounding it, and potentially a muon tagger (to separate muons and pions that exit the Gas TPC).



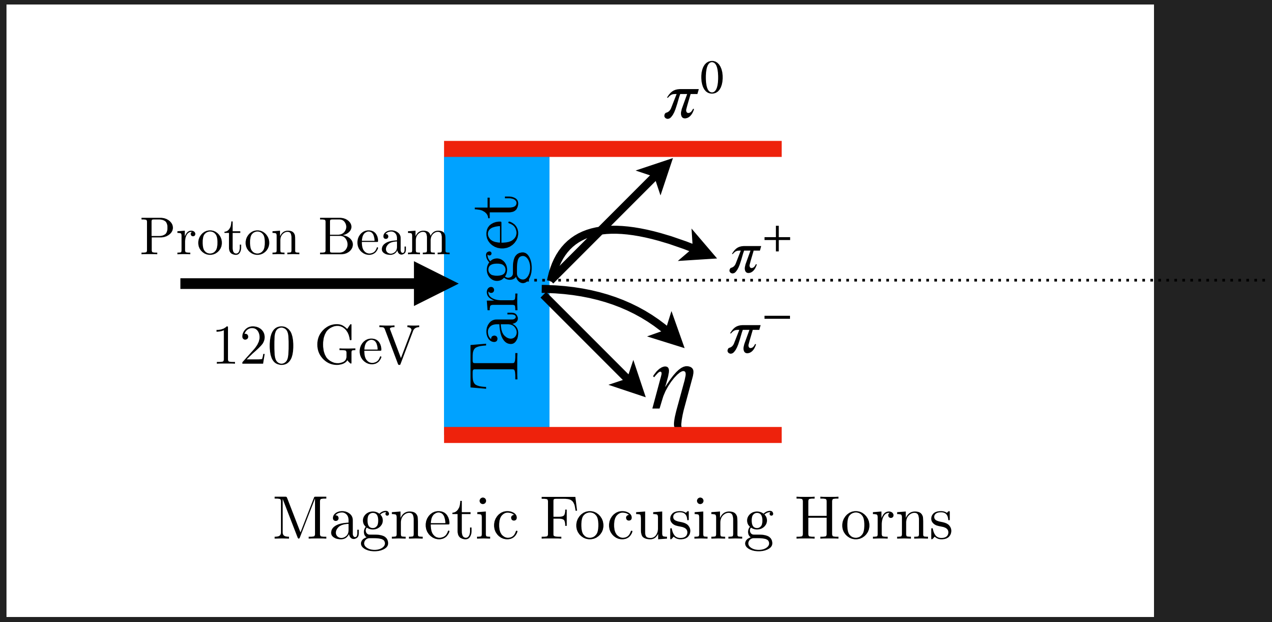
A theorist's view of the DUNE target & Near Detector Hall

DUNE: The Next Generation ~~Neutrino~~ Facility

Meson

Common Element of all four Renormalizable Portals

- All of the mediator scenarios we focus on predict that the new physics particle can be produced in a variety of meson decays.
- DUNE's intense proton beam (120 GeV) produces a huge number of charged and neutral mesons.



A theorist's view of the DUNE Target/Focusing Horn System

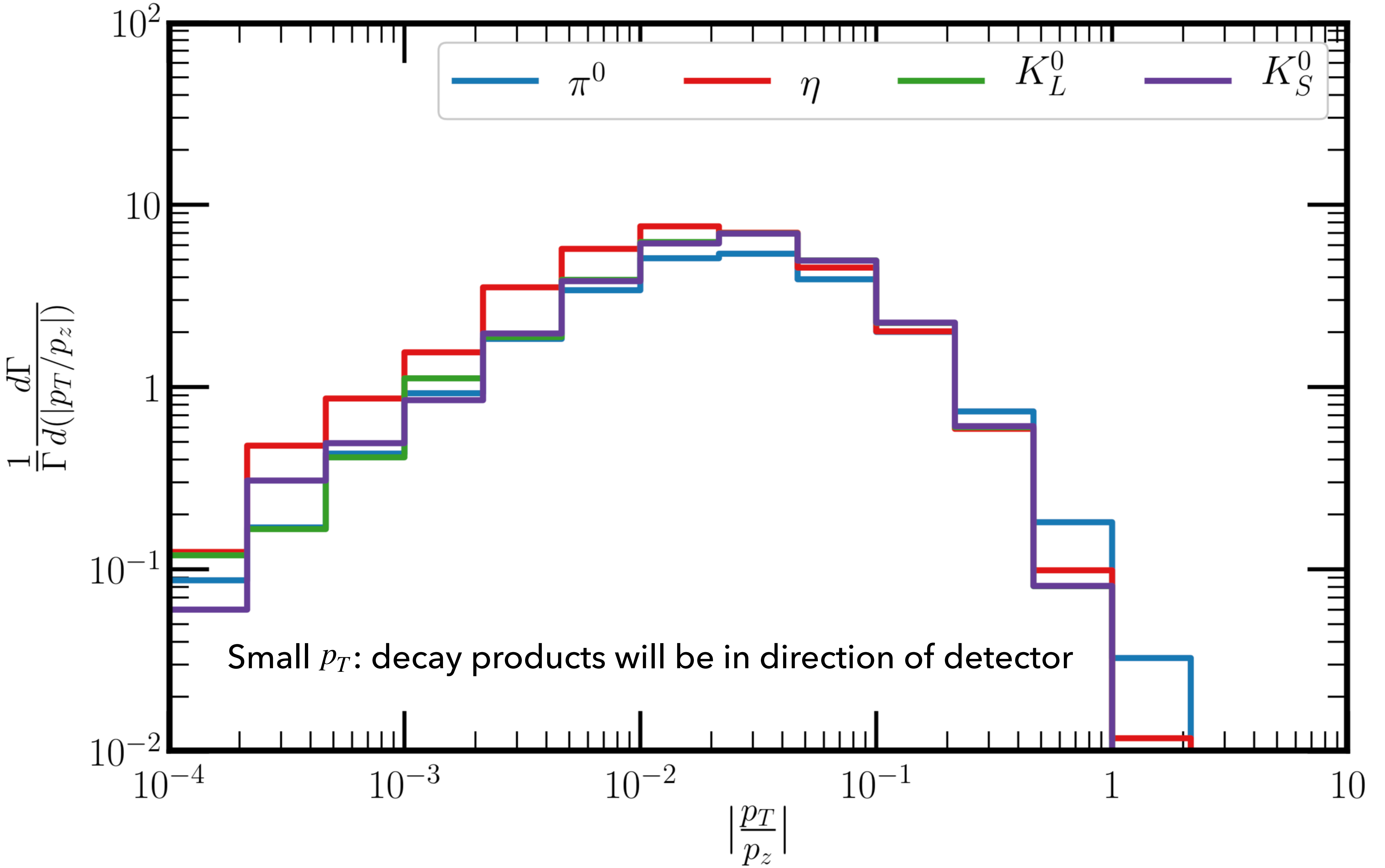
Meson Production Part 1: Neutral Mesons

- Of interest for our simulations are pions, etas, and kaons. Number produced on average per proton on target (120 GeV):

Species	π^0	η	K_L^0	K_S^0
Mesons/POT	2.9	0.33	0.19	0.19

- We want these mesons to decay into new physics particles that themselves are directed toward the DUNE Near Detector – far away and in the beam direction.
- Pythia8 gives us four vectors of neutral mesons after 120 GeV protons hitting protons/neutrons in the lab frame.

Neutral Mesons — Kinematic Boost Focusing



Meson Production Part 2: Charged Mesons

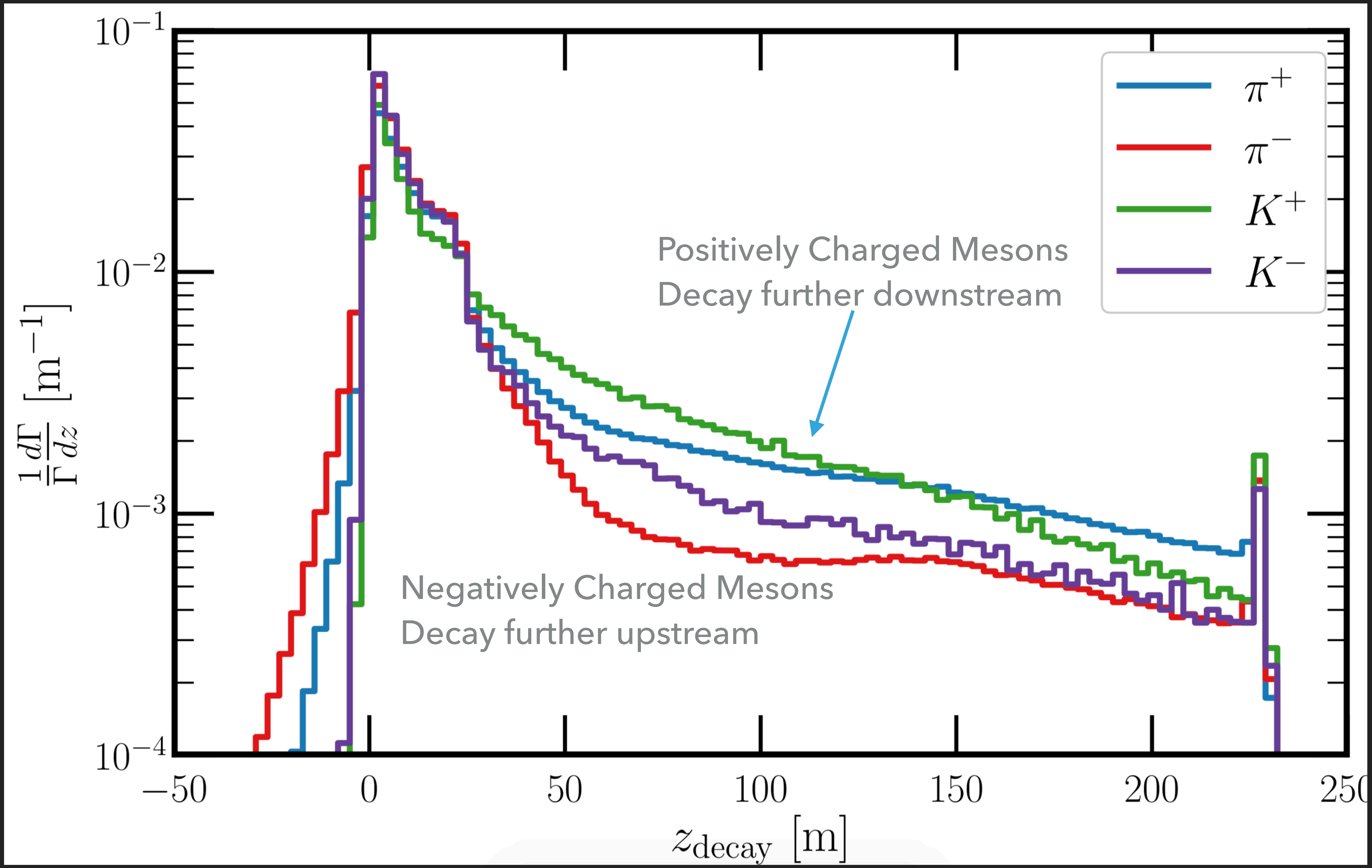
- DUNE is more than just a meson factory – its goal is to produce an intense, pure neutrino beam. To do so, the magnetic focusing horns select mesons of a particular sign, which decay to either neutrinos or antineutrinos.
- Because charged pions generate the bulk of the neutrino flux, the goal is to focus one sign of pion over the other as best as possible.

Species	π^+	π^-	K^+	K^-
Mesons/POT	2.7	2.4	0.24	0.16

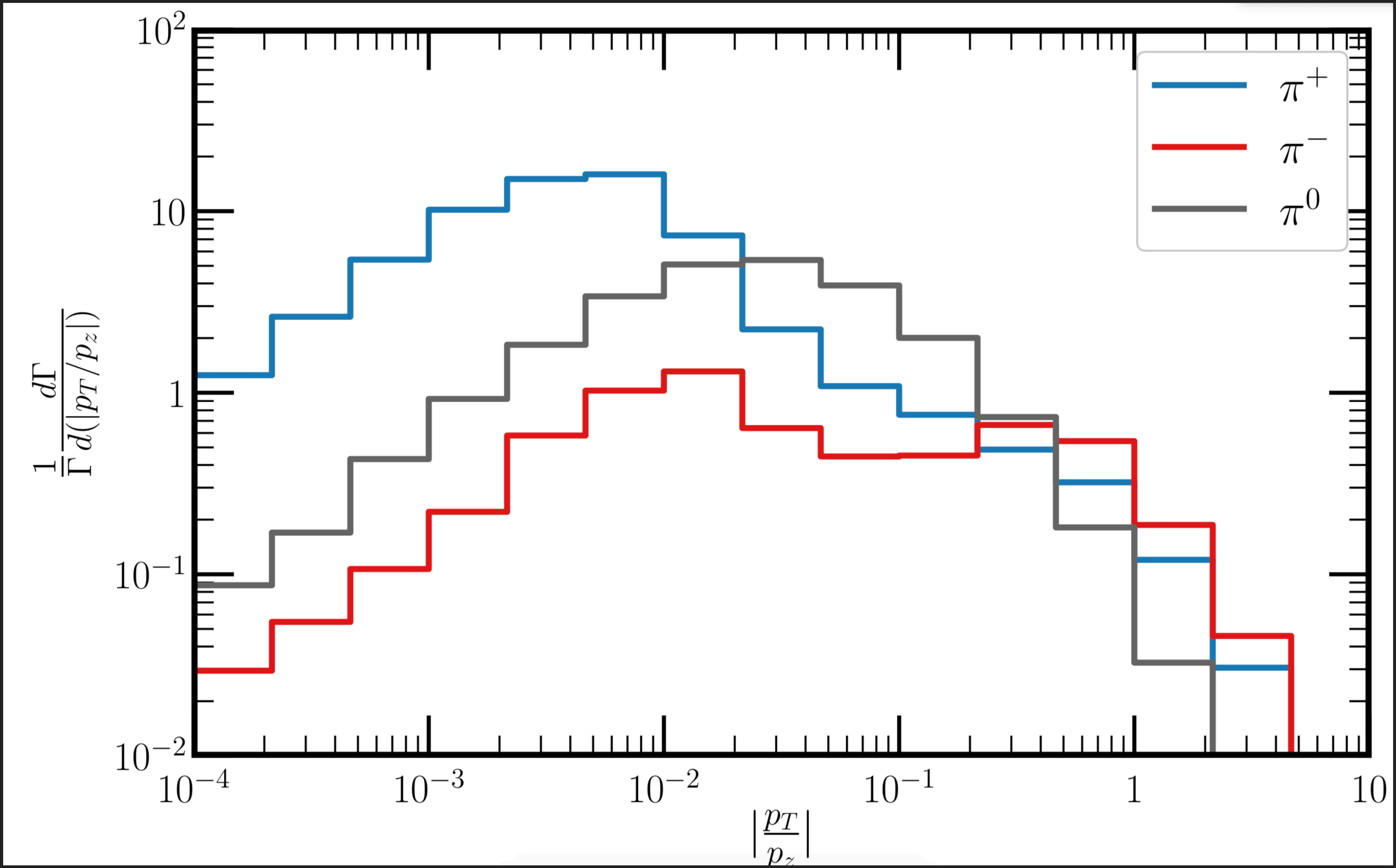
D^+	D^-	D_s^+	D_s^-
3.7×10^{-6}	6.0×10^{-6}	1.2×10^{-6}	1.6×10^{-6}

Effects of Focusing Horns

- The DUNE Beam Interface Working Group has the output from GEANT/FLUKA simulations, taking into account focusing horns.



How (de)focused are the (negatively) positively charged mesons?



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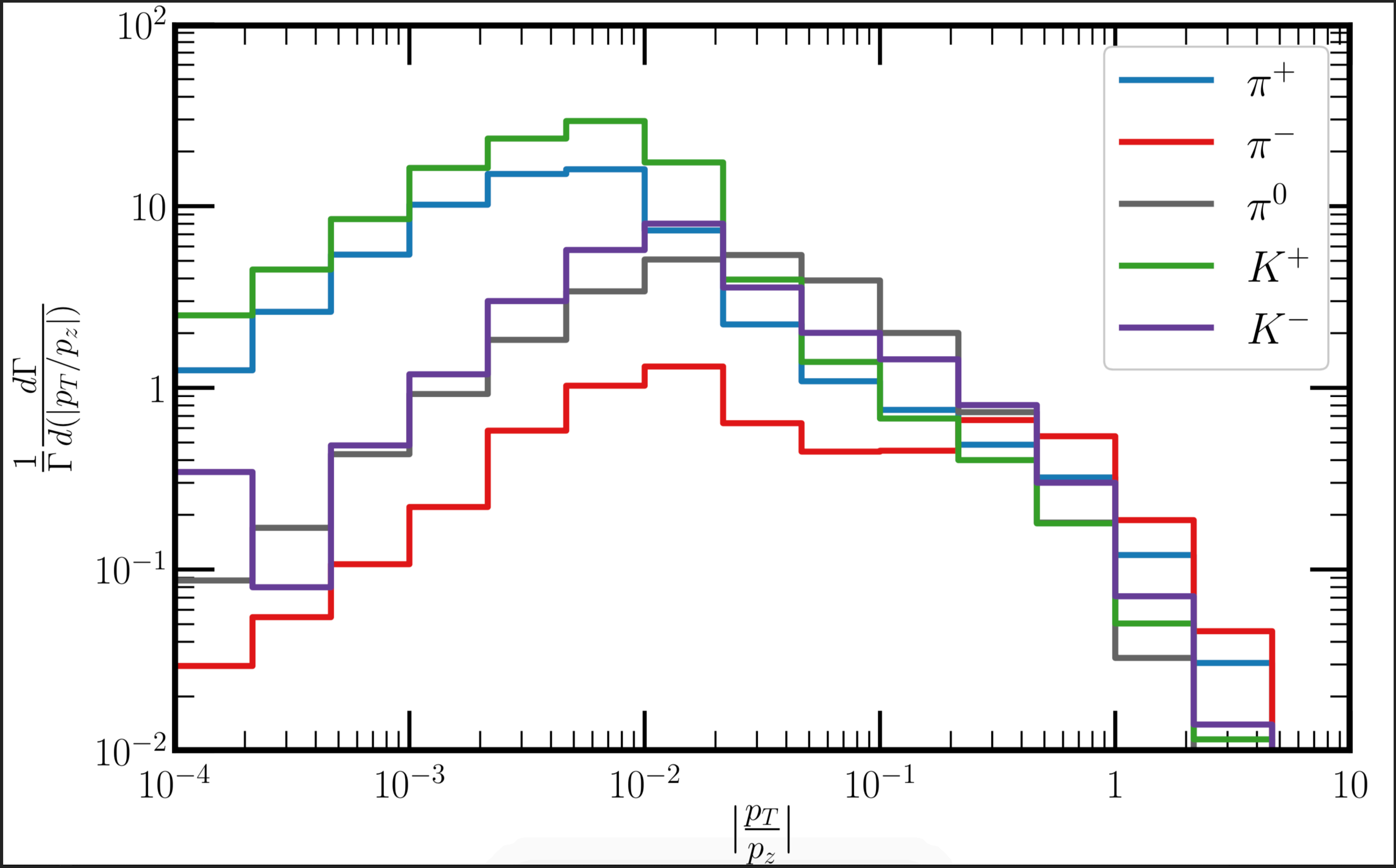

Decays of New Physics Particles

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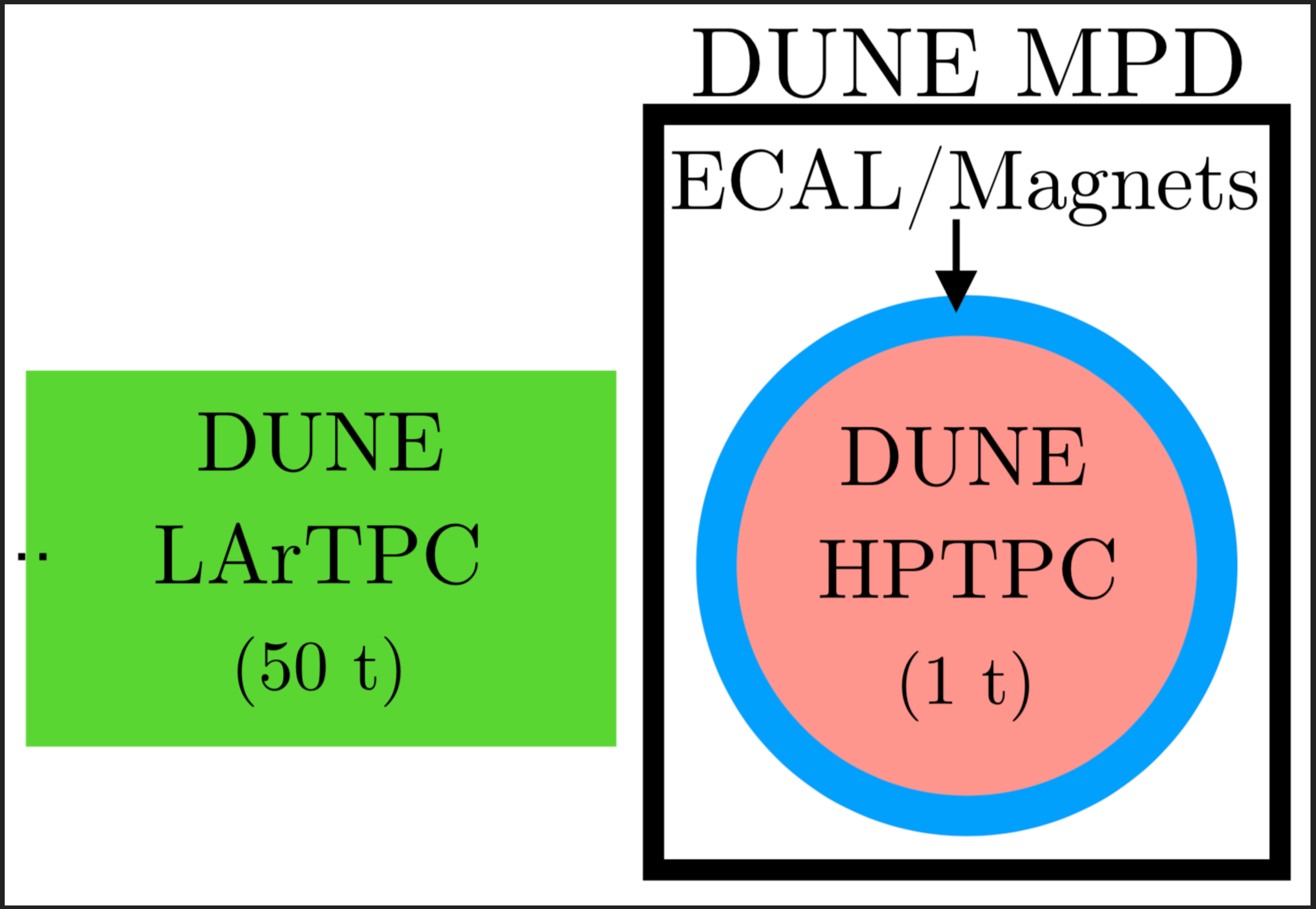
Why Decays?

- If searching for new physics via a scattering process, signal and background (from neutrino-related events) both scale like detector mass.
- On the other hand, if searching for a decay, signal will scale like detector volume, whereas neutrino-related scattering background still scales like mass.



Overarching Approach

- Assume a new physics particle X that can be produced in the decays of some SM particle P.

$$P \to SX$$

- Fixing the mass of X, we simulate the decays of P into S and X, and keep track of the fraction of X that are pointing to the DUNE MPD (as well as their energies).

- Given this energy spectrum, and the various decay channels of X, we can determine how many “interesting” decays will occur within the DUNE MPD in a certain operation time.

Dark Photons

Kinetically-Mixed with the Standard Model

Assumptions about the Model

- Assume a new U(1) exists that can mix with the SM hypercharge group,

$$\mathscr{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\varepsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{M^2_{A'}}{2}A'_\mu A'^\mu$$

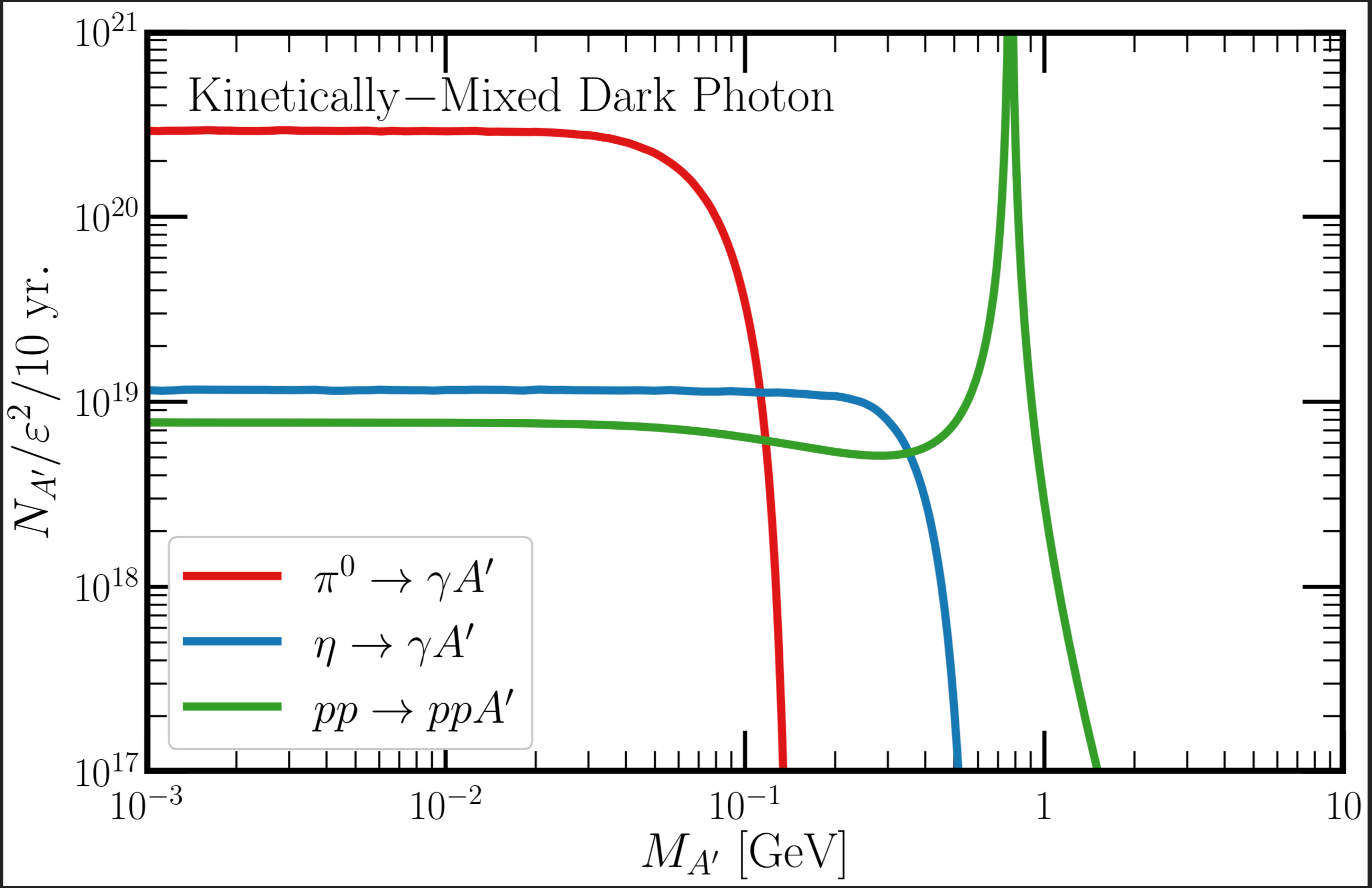
- Such mixing allows for production via neutral meson decays and proton bremsstrahlung,

$$\pi^0 \rightarrow \gamma A'$$
$$\eta \rightarrow \gamma A'$$
$$pp \rightarrow ppA'$$

- Branching ratios: $\mathrm{Br}(\mathfrak{m} \to \gamma A') = \mathrm{Br}(\mathfrak{m} \to \gamma\gamma) \times 2\varepsilon^2 \left(1 - \frac{M^2_{A'}}{m^2_{\mathfrak{m}}}\right)^3$

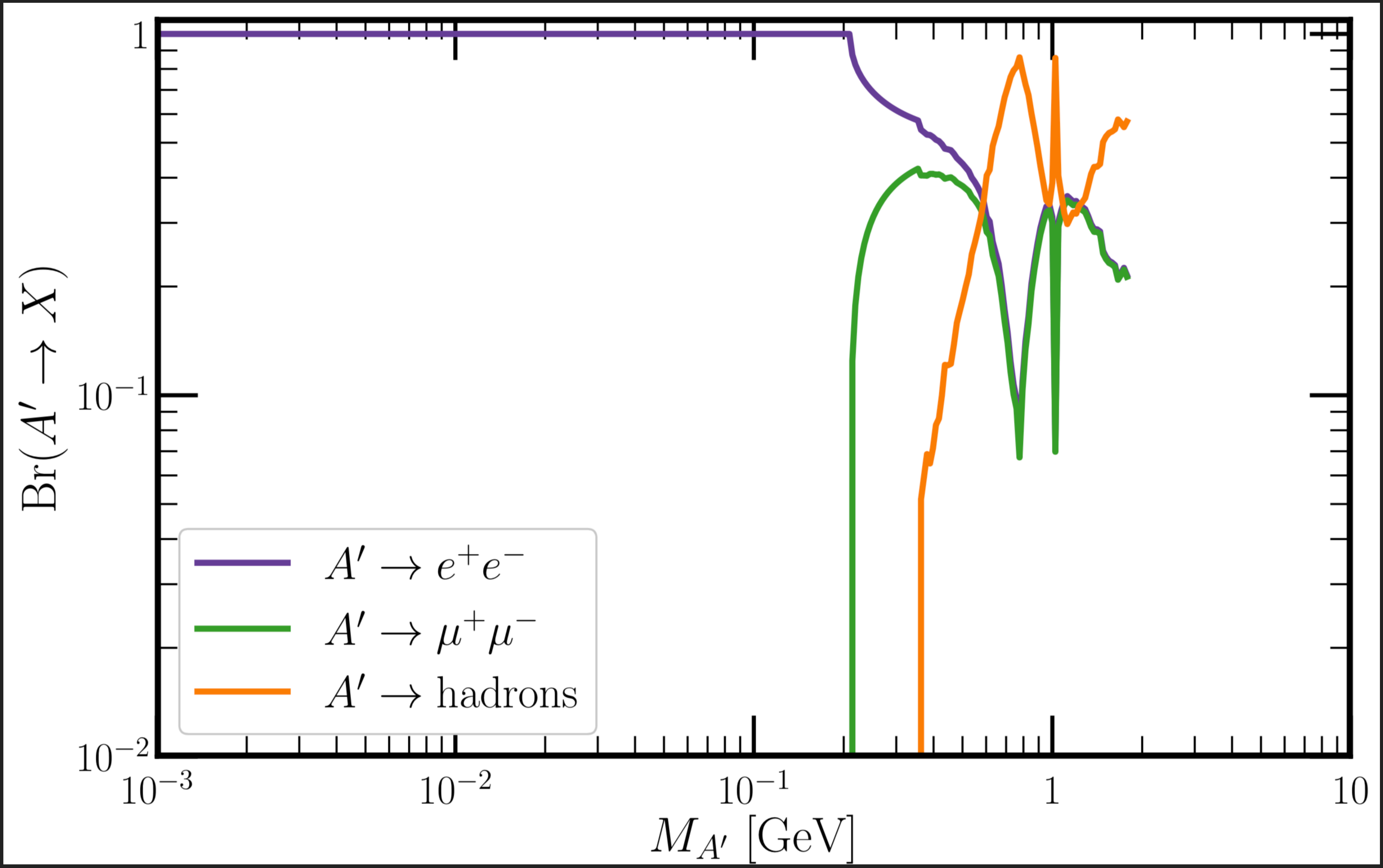
Flux of Dark Photons at the Near Detector

- Taking into account geometrical acceptance,



Decay Modes of A'

- Depending on its mass, A' can decay into pairs of charged leptons or hadrons,



Backgrounds for A′ Decay Search

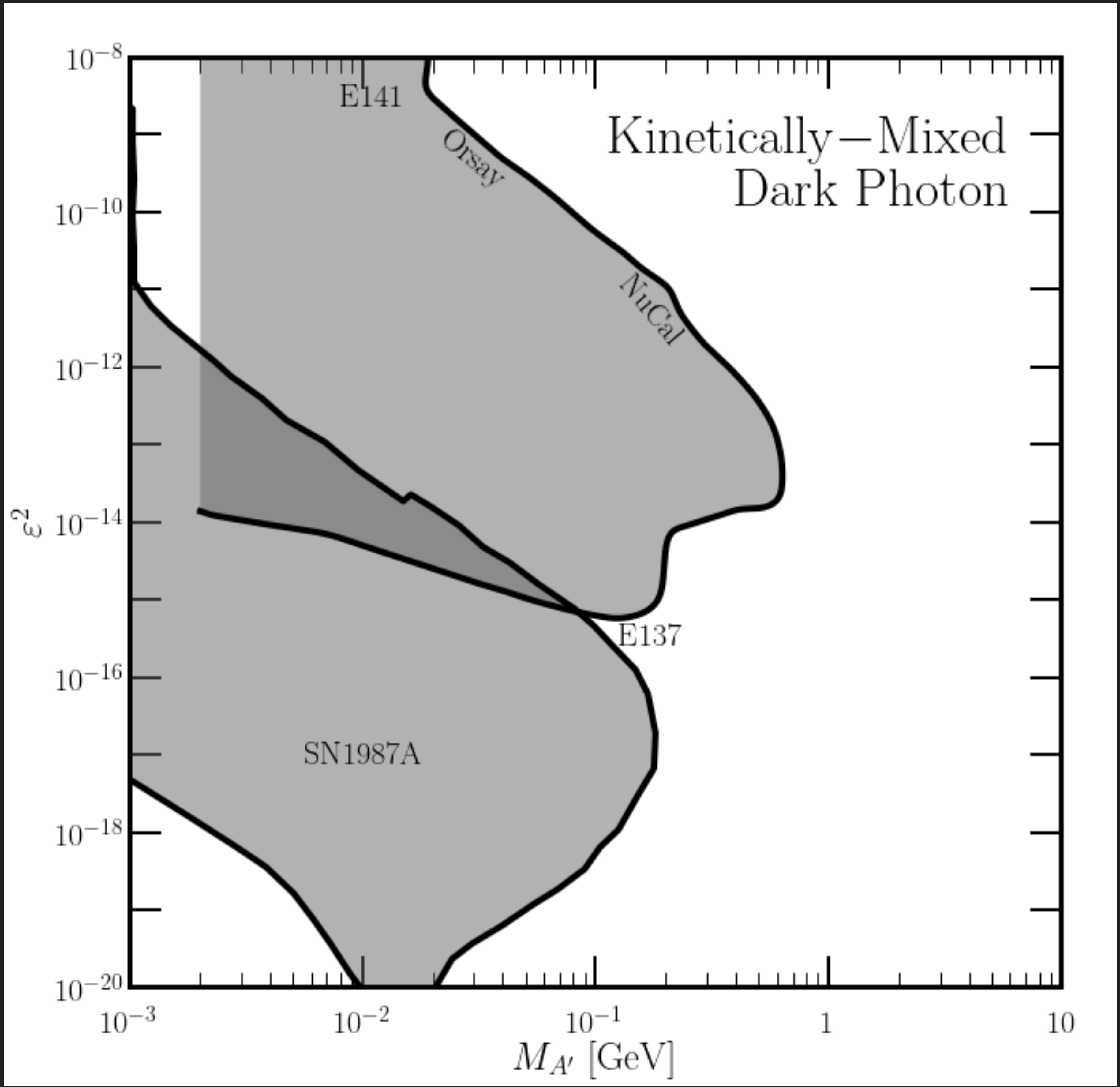
- Decays to electron/positron pairs
  - Unlike in liquid argon, photons in the gaseous argon tend not to convert (conversion length of a couple of meters). Those that do can fake electron/positron pairs. The biggest backgrounds of this sort will come from neutral current single pion events

$$\nu + \mathrm{Ar} \to \nu + \mathrm{Ar} + \pi^0,$$
$$\pi^0 \to \gamma\gamma$$

- Decays to muon/pion pairs
  - These can be faked by muon charged-current events with a single charged pion, where the particles are misidentified – kinematical cuts and a muon tagger should mitigate this background.

$$\nu + X \to X' + \mu^- + \pi^+$$

Existing Limits for Dark Photon Searches



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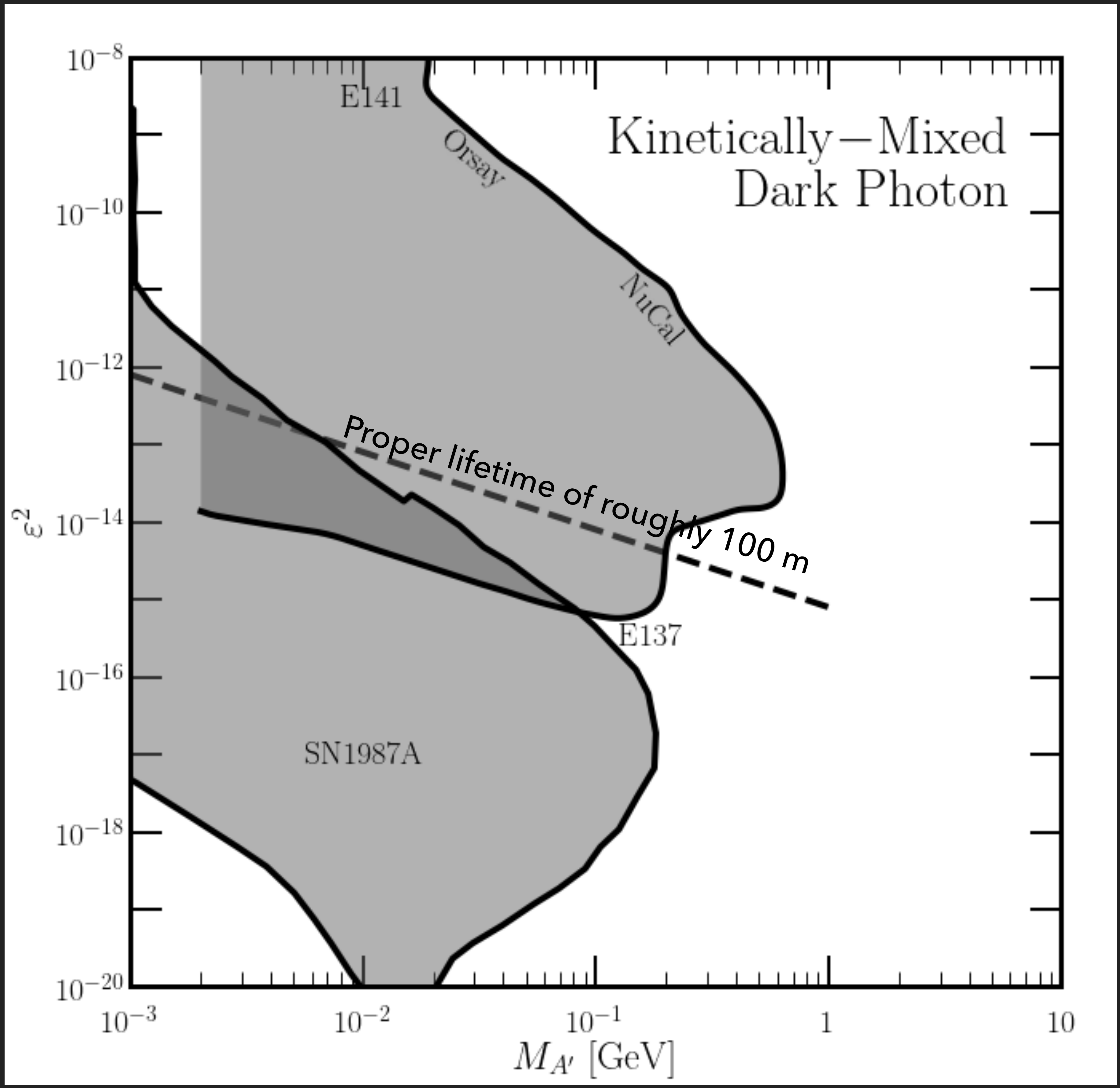
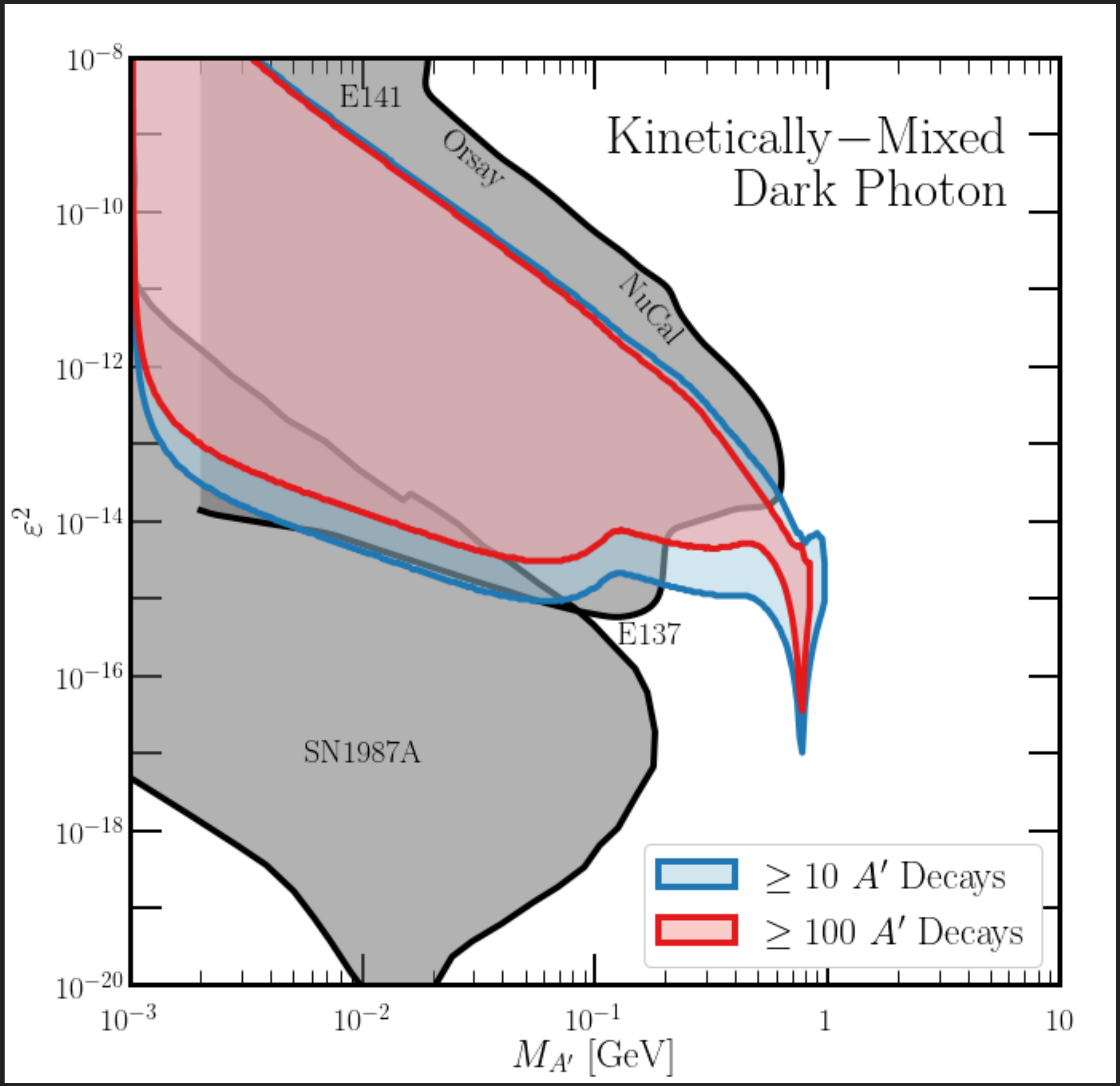
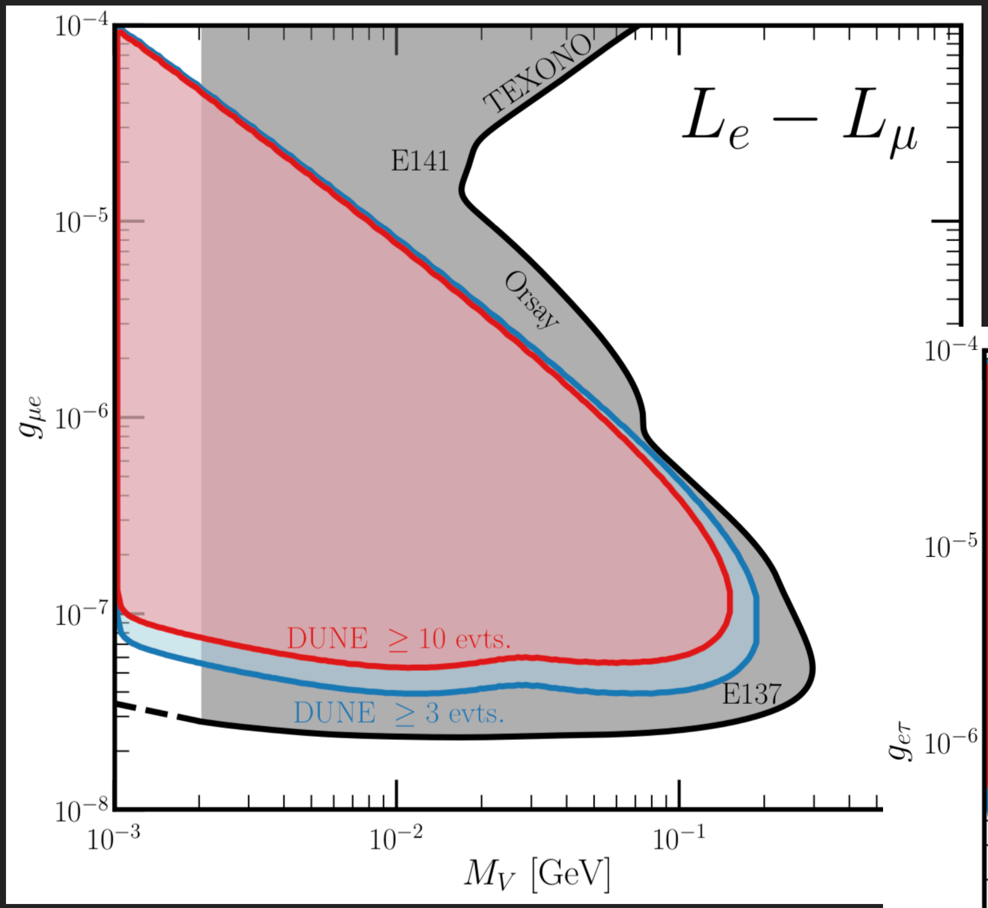
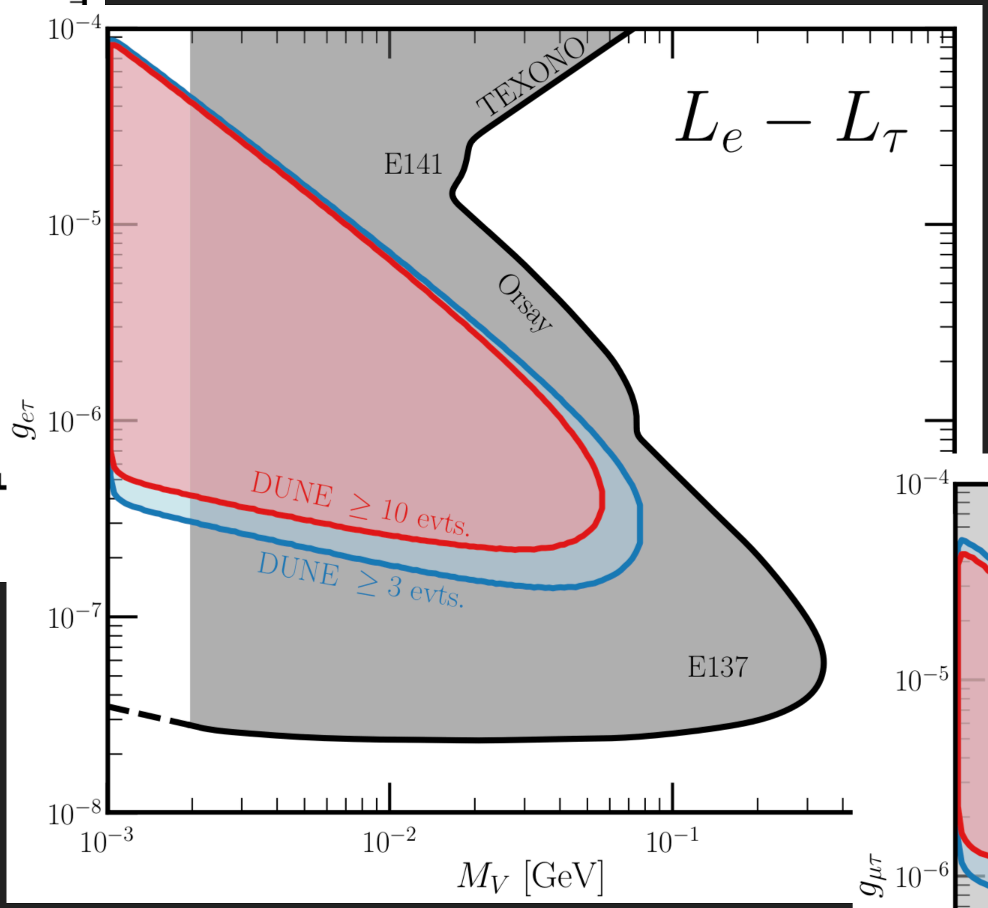


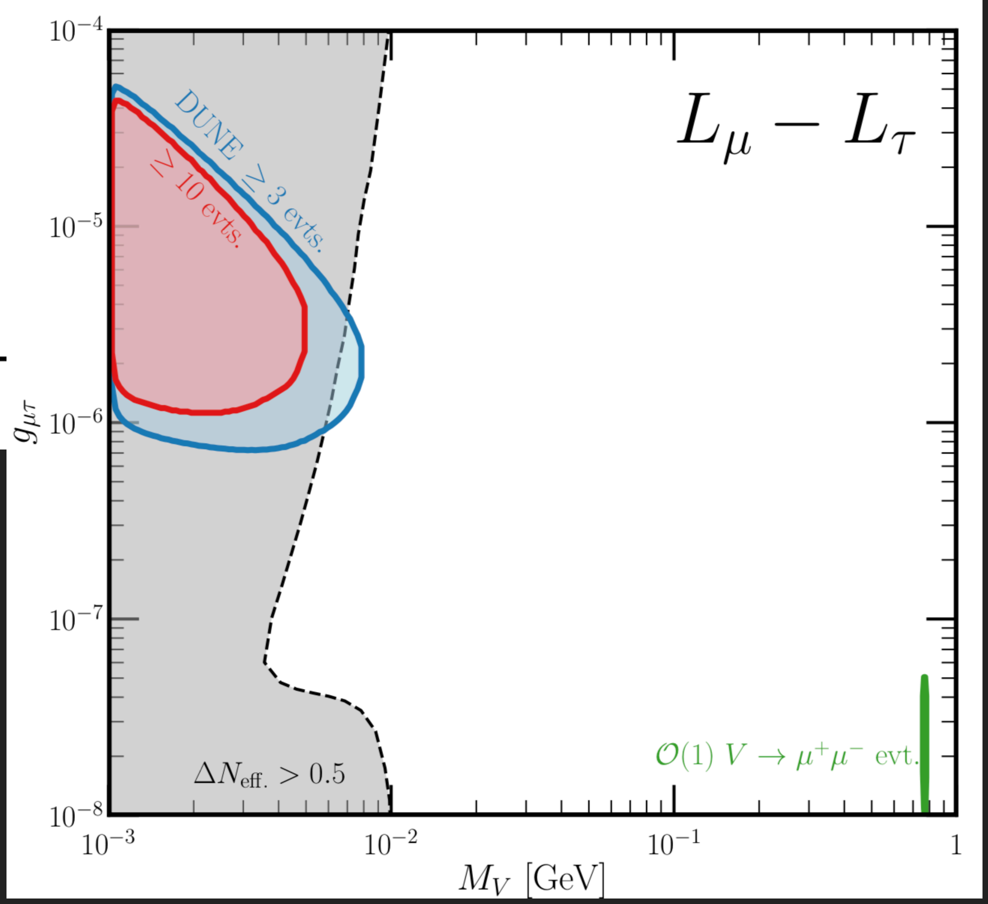
DUNE MPD Sensitivity



Similar Model to Search for: Leptophilic Gauge Bosons







Heavy Neutral Leptons

Model Assumptions

- HNL N with mass M_N that couples to the standard model only via mixing with the lepton doublet, via $\mathscr{L} \supset -y_N LHN$
- For simplicity, we assume that N mixes with only one flavor of SM lepton at a time, i.e. only one of $|U_{eN}|^2, |U_{\mu N}|^2, |U_{\tau N}|^2$ is nonzero.
  - This allows for predictable production and decay channels for N. A nontrivial combination of mixing angles could be analyzed, in principle.

HNL Production

- Let's take mixing with the muon as an example. We include seven different production channels:

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

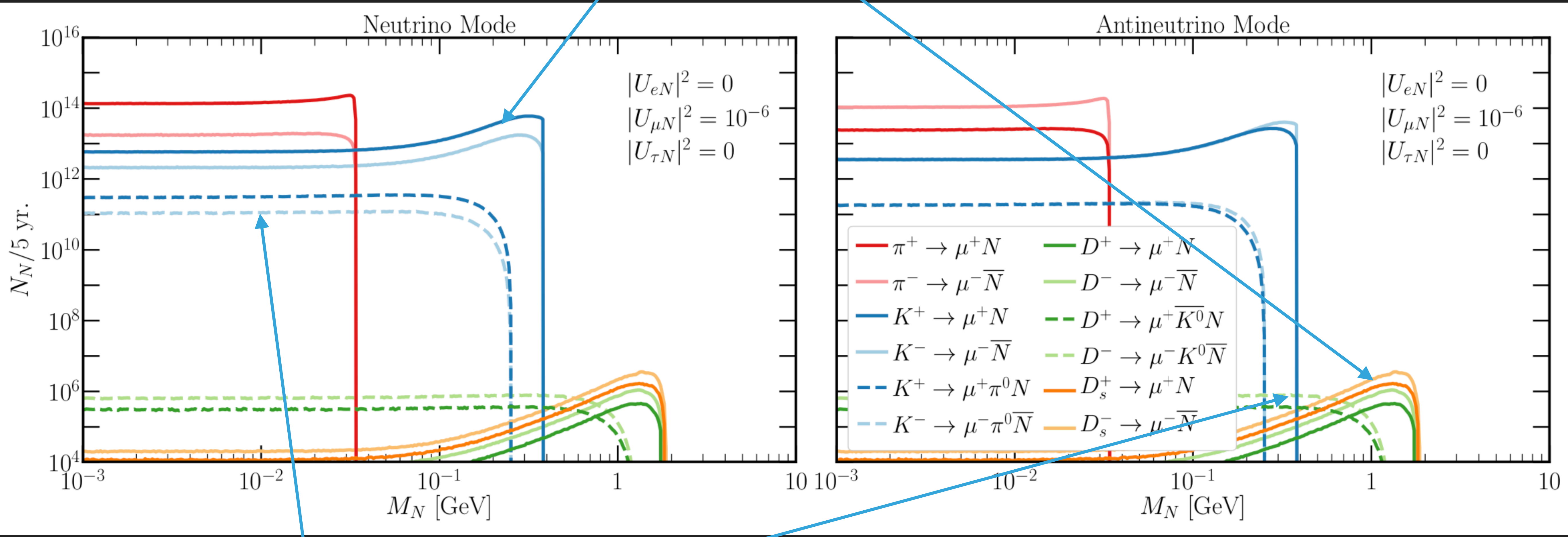
$$D^+ \to \mu^+ N$$
$$D^+ \to \pi^0 \mu^+ N$$
$$D^+ \to \overline{K^0} \mu^+ N$$
$$D_s^+ \to \mu^+ N$$

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.

N Flux at Near Detector

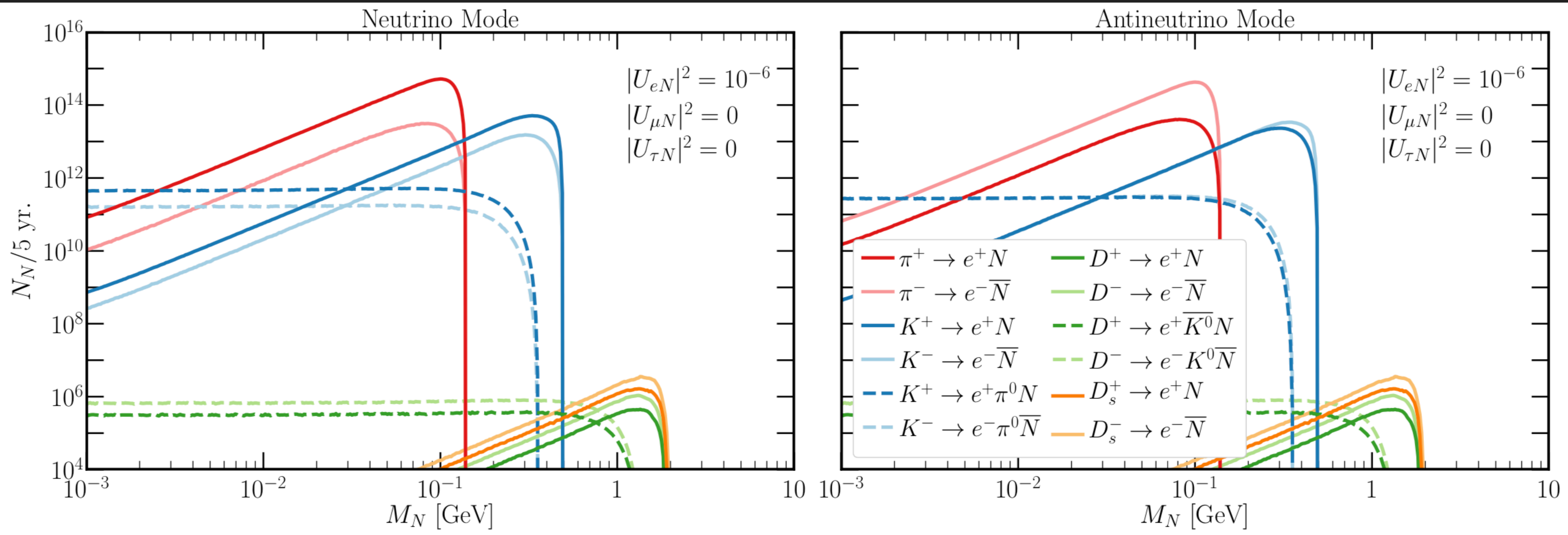
- Assuming $|U_{\mu N}|^2 = 10^{-6}$, 5 years each in neutrino/antineutrino modes

Helicity *enhancement* when N is heavier than the muon



No such enhancement in three-body decays

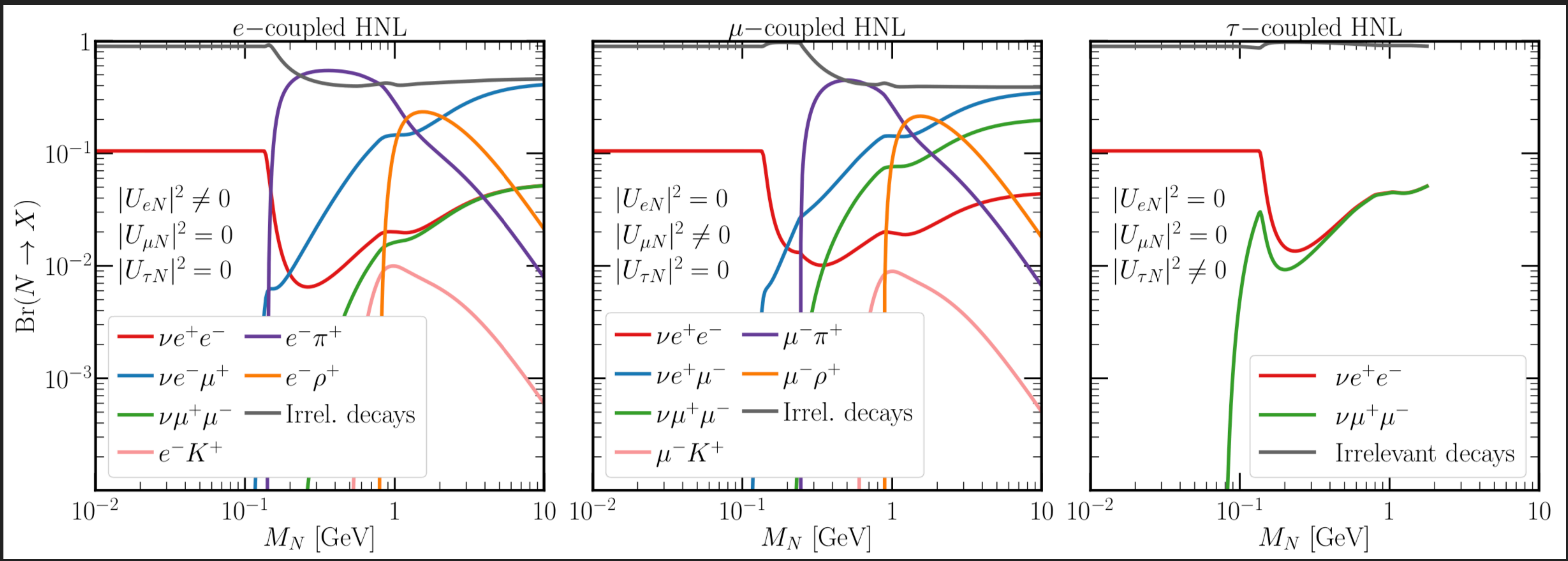
N flux, Electron Coupling



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

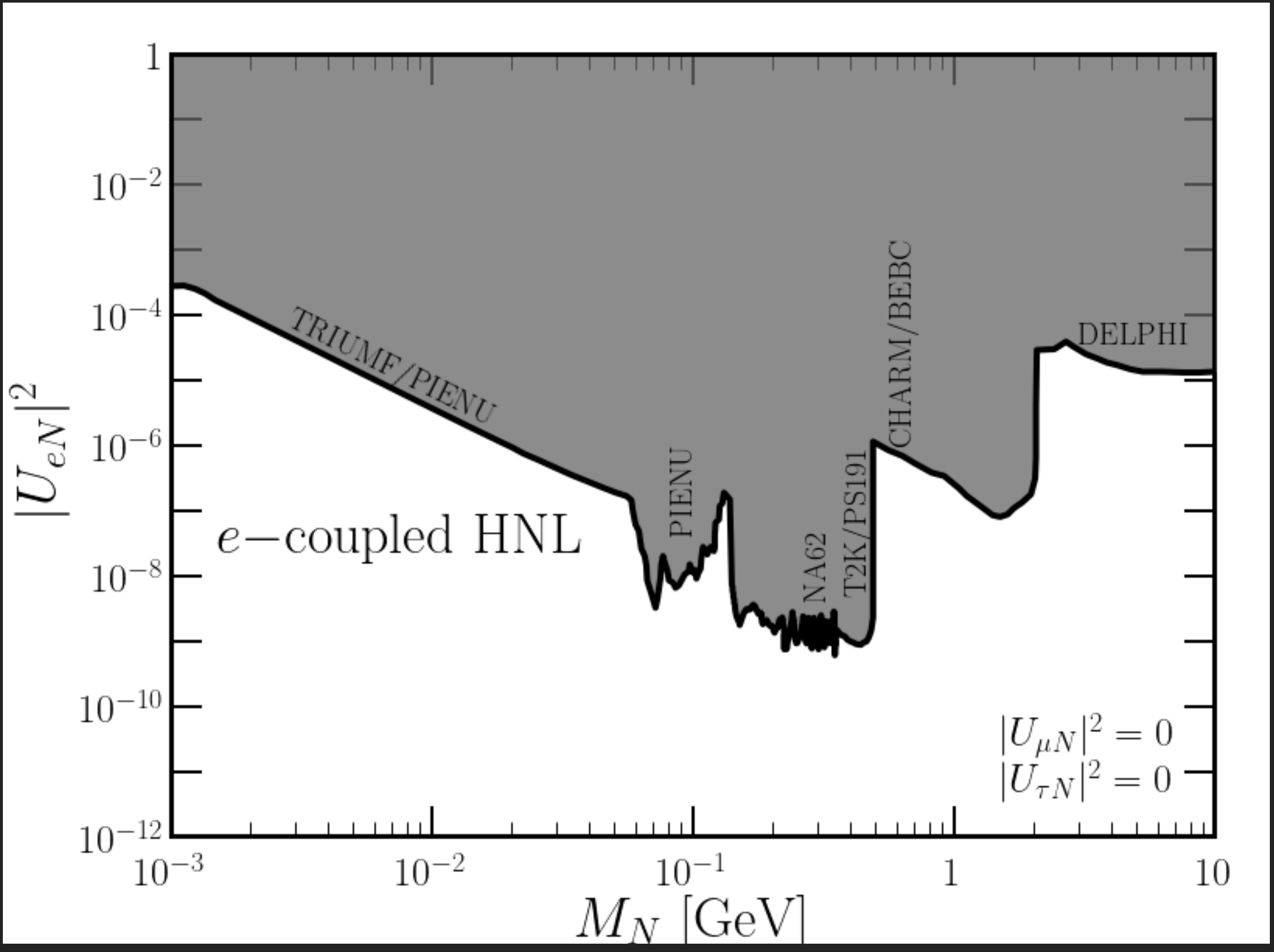
How does N Decay?

- Again, assuming only one mixing, the decay widths of N are well-prescribed. Additional new physics (such as a light Z′) could modify this significantly.

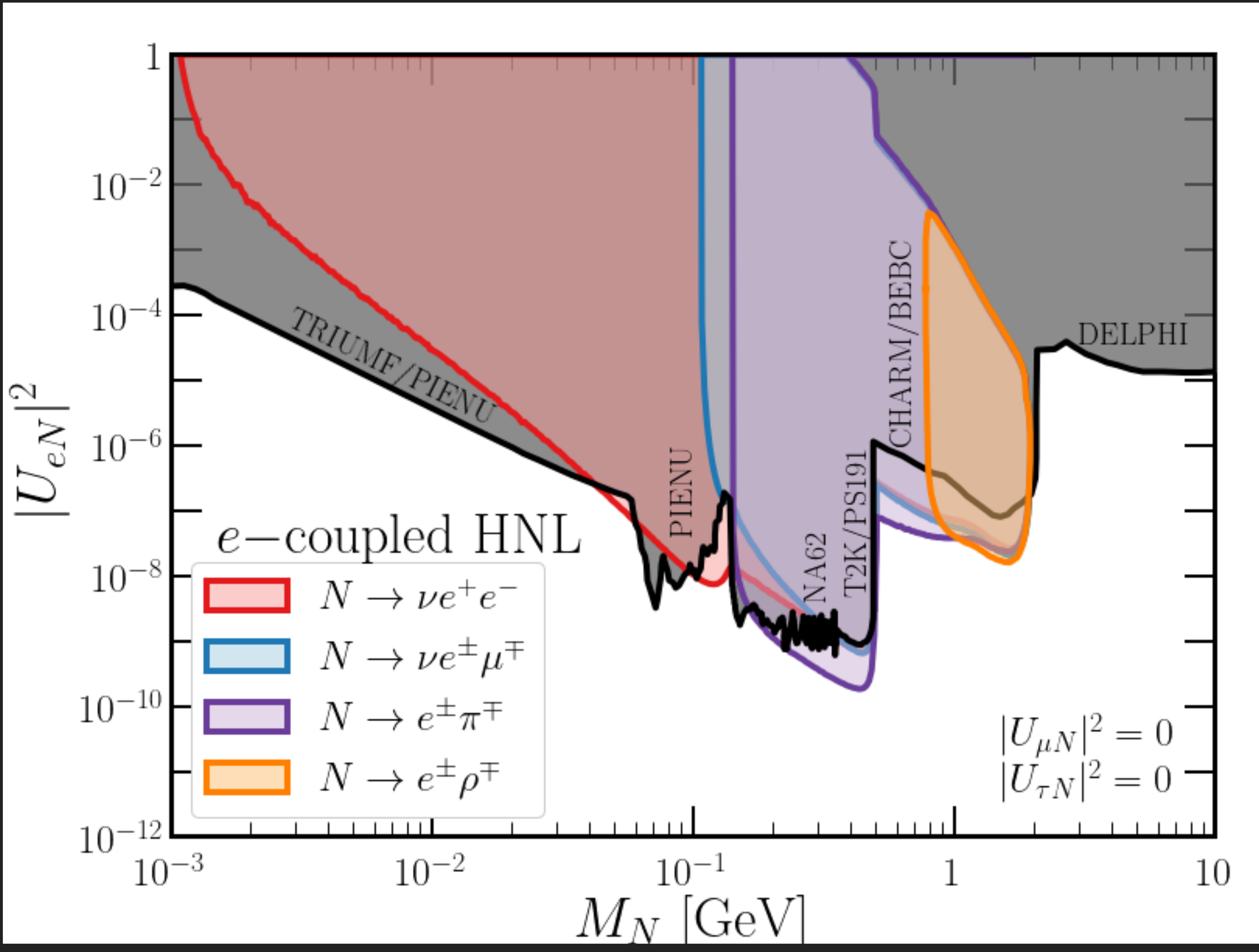


Irrelevant decays: those with just neutrinos ($N \to \nu\nu\bar{\nu}$) or those with a neutrino and one other neutral particle.

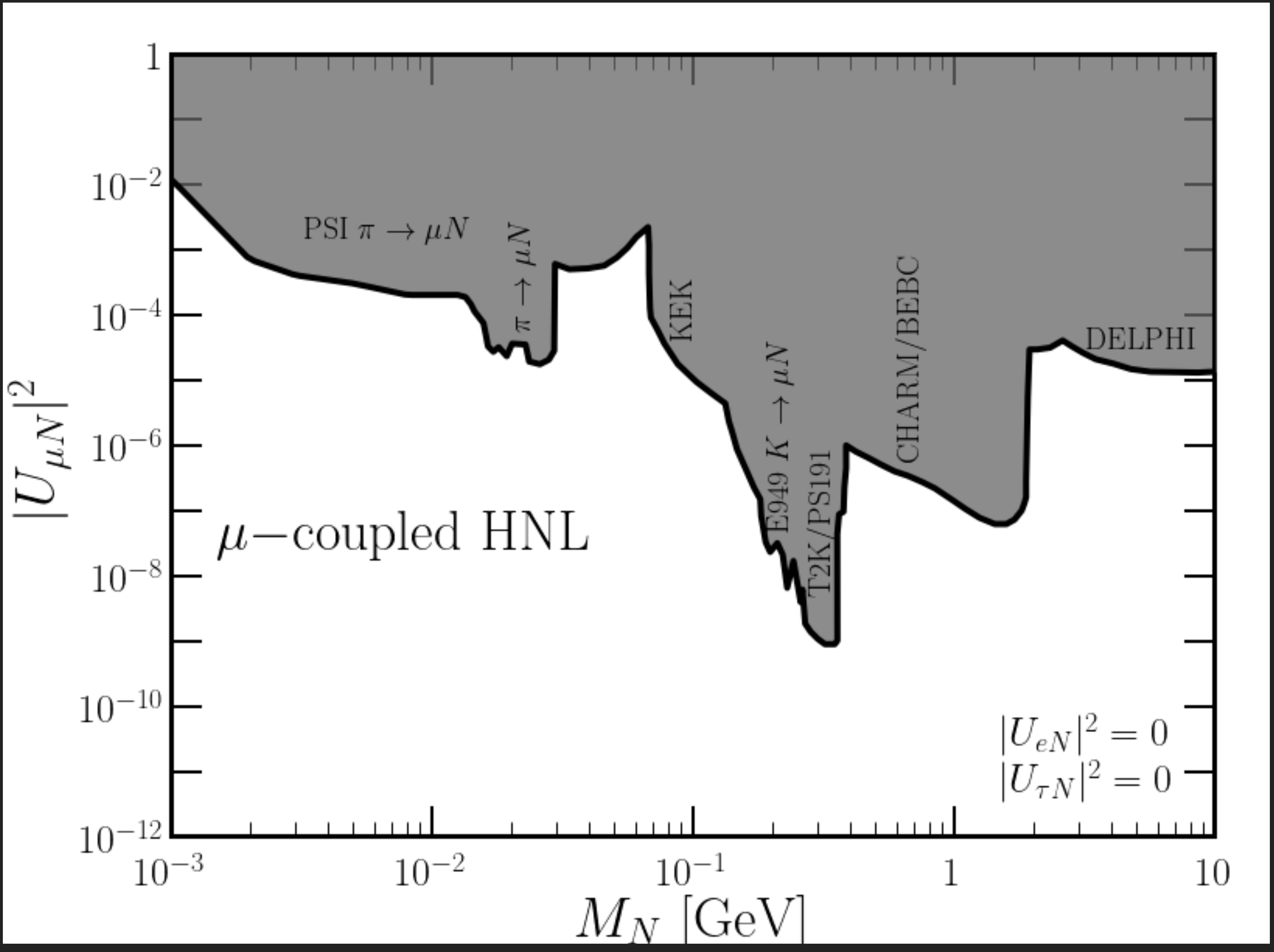
HNL Sensitivity, Electron-Coupled



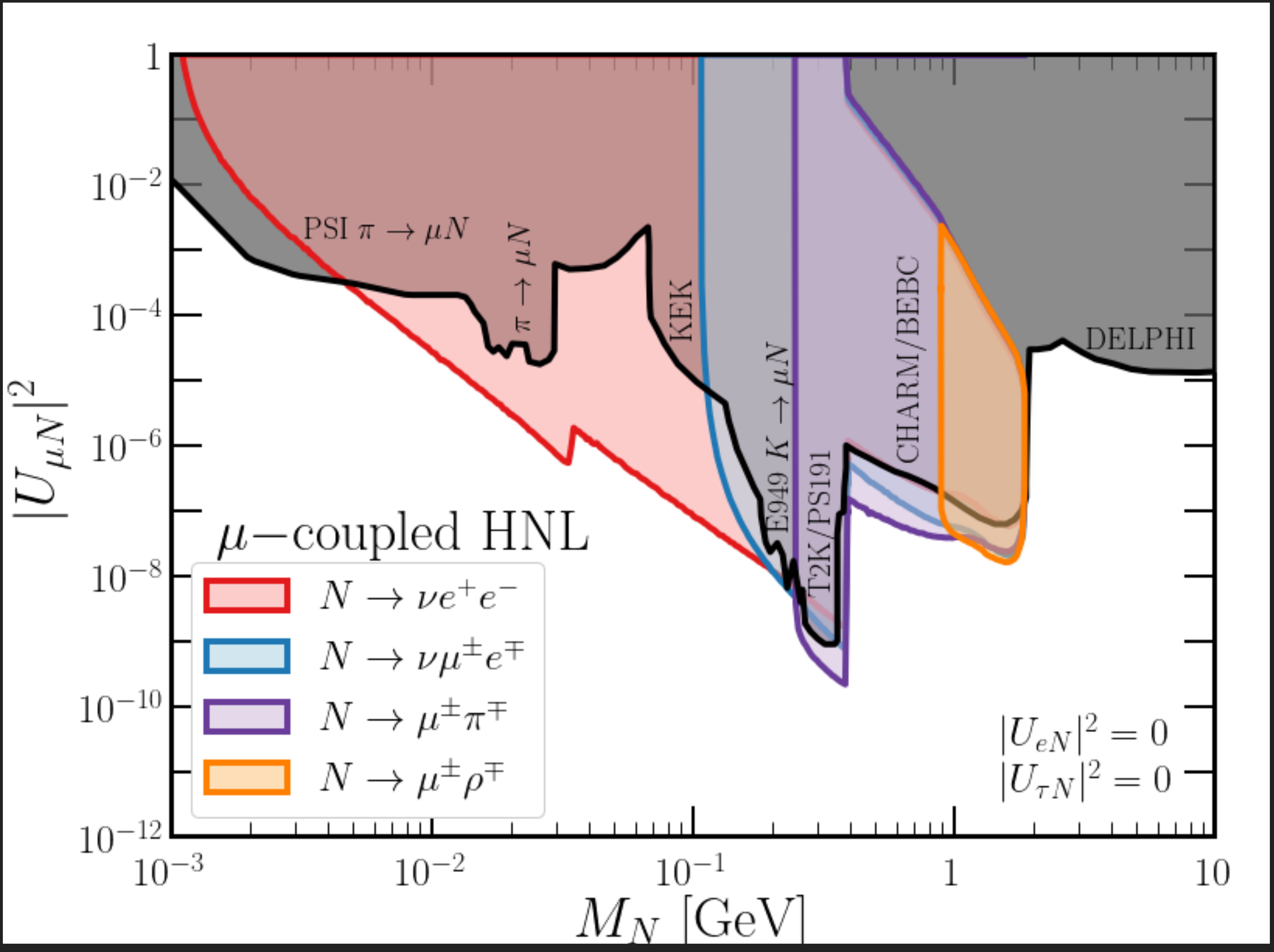
HNL Sensitivity, Electron-Coupled



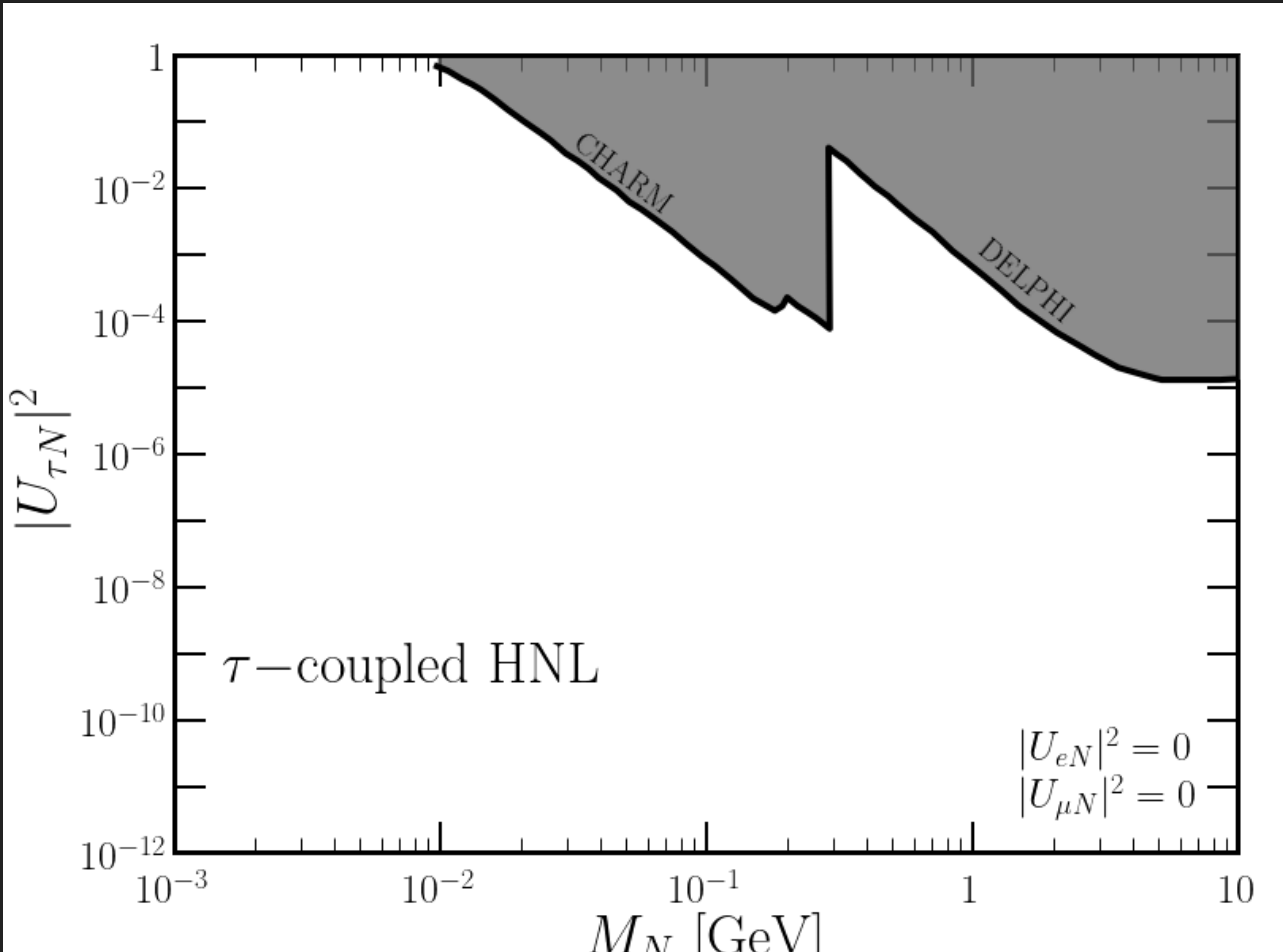
HNL Sensitivity, Muon-Coupled



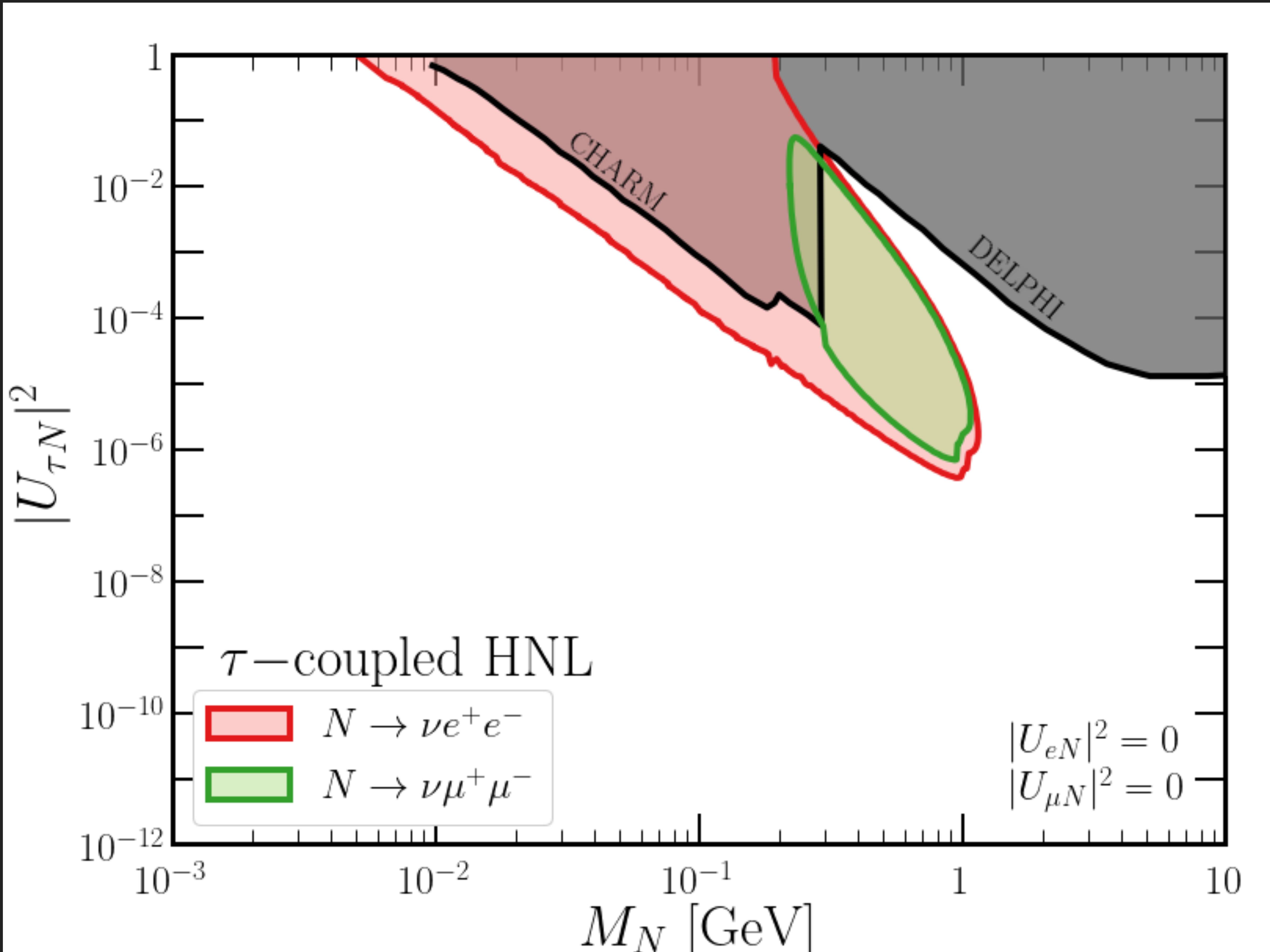
HNL Sensitivity, Muon-Coupled



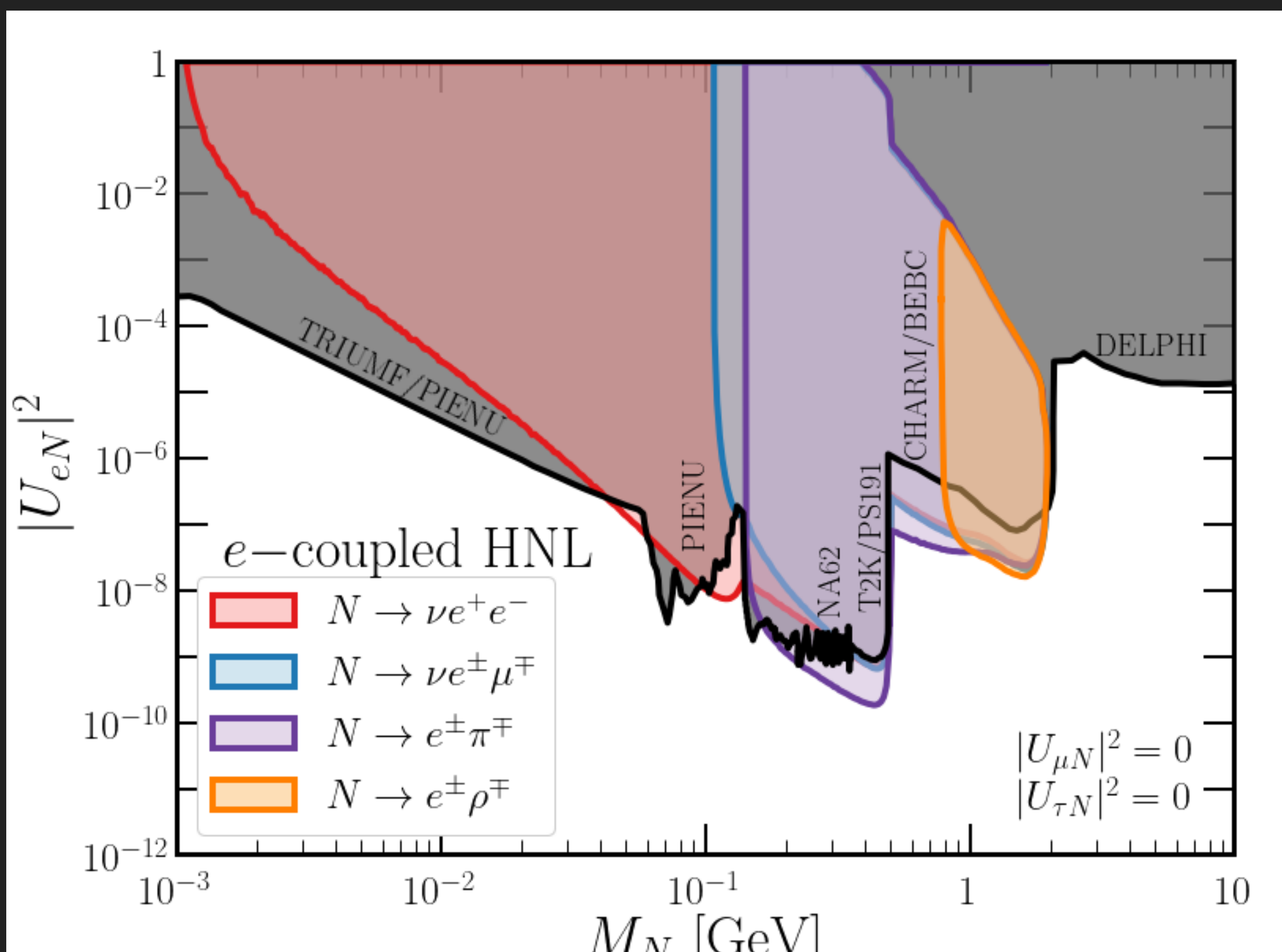
HNL Sensitivity, Tau-Coupled

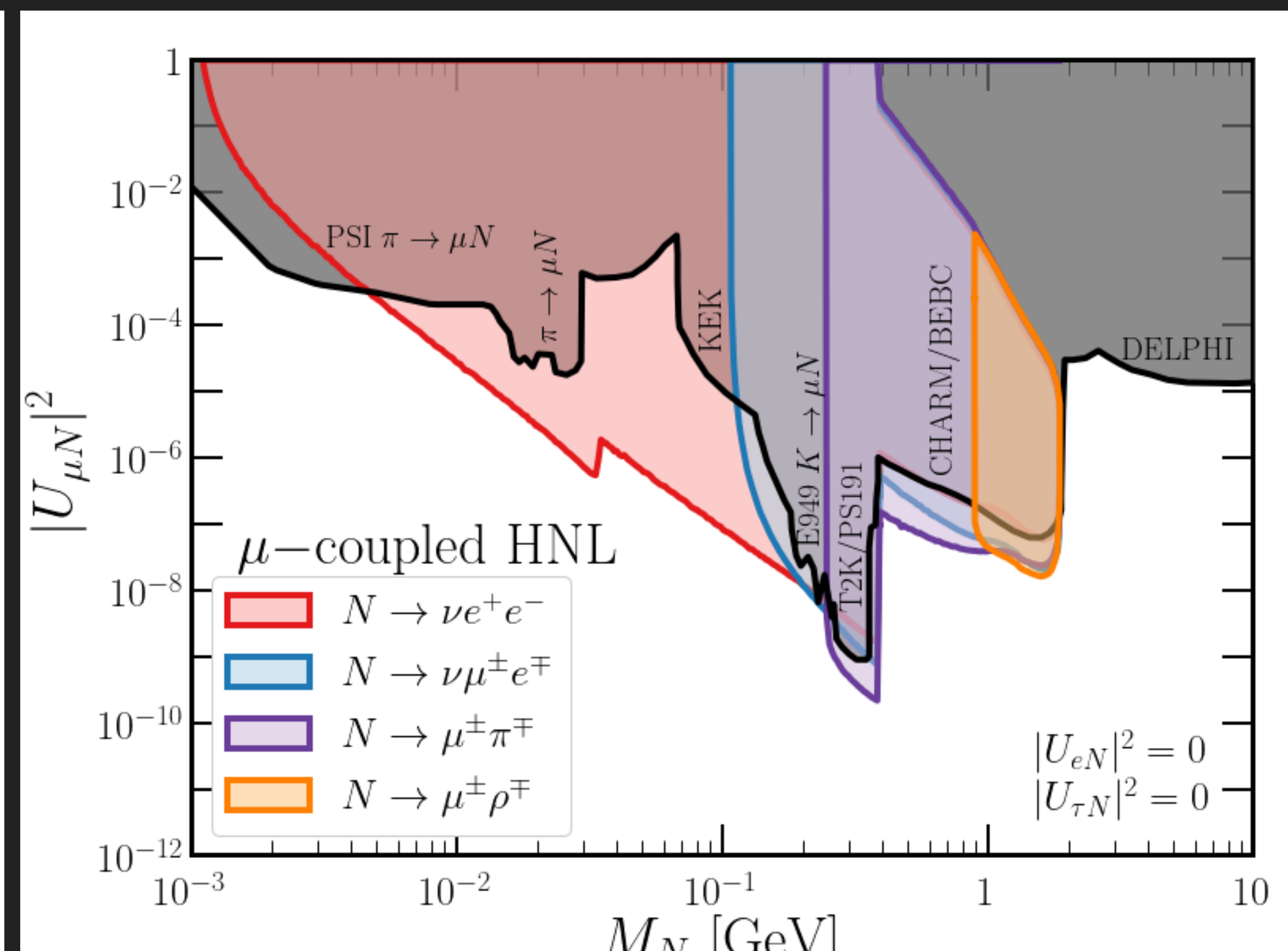


HNL Sensitivity, Tau-Coupled



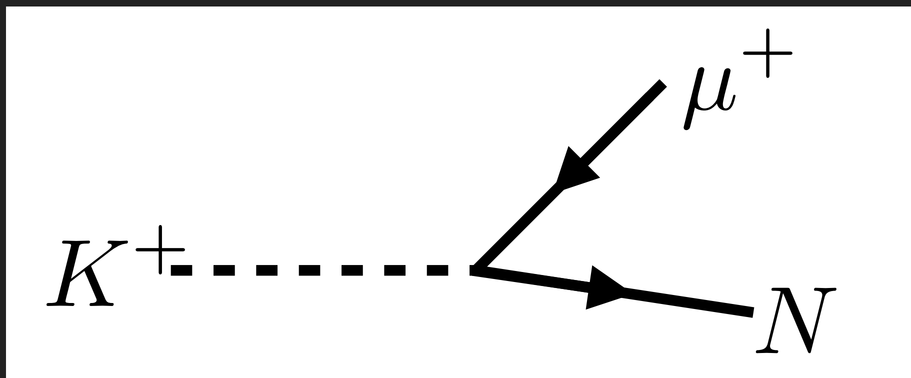
Further Discovery Potential?





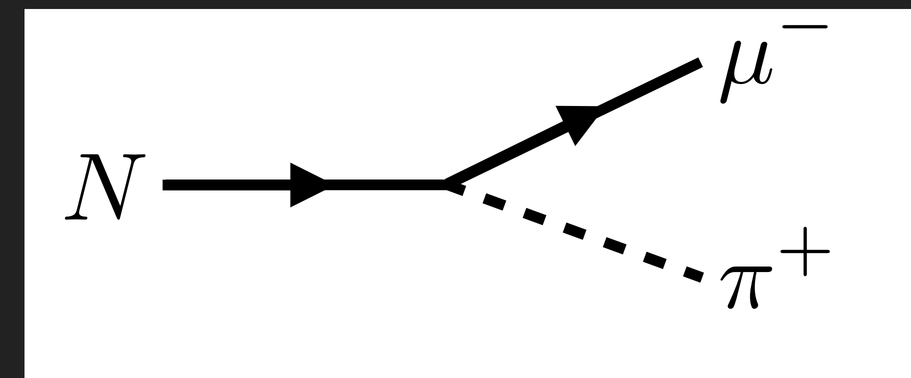
Regions of currently unexplored parameter space where DUNE will cover – potential for way more than ~10 signal events. Can we do something with this?

Can we deduce the nature of these HNL?

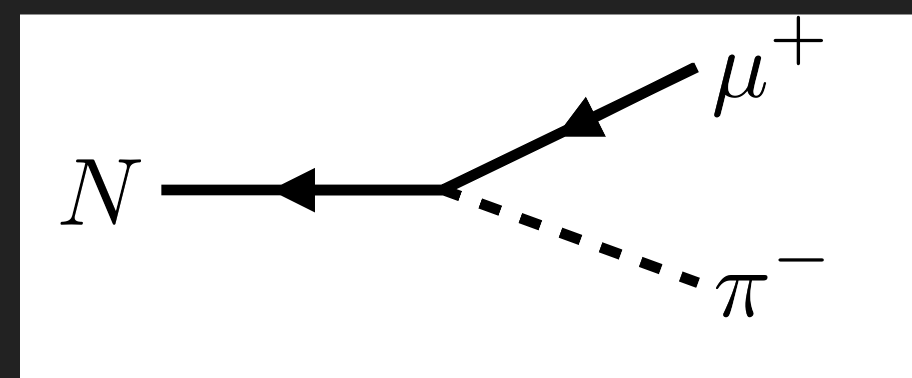


Only positively-charged kaons decaying – negatively-charged ones are not produced, deflected, or absorbed, etc.

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

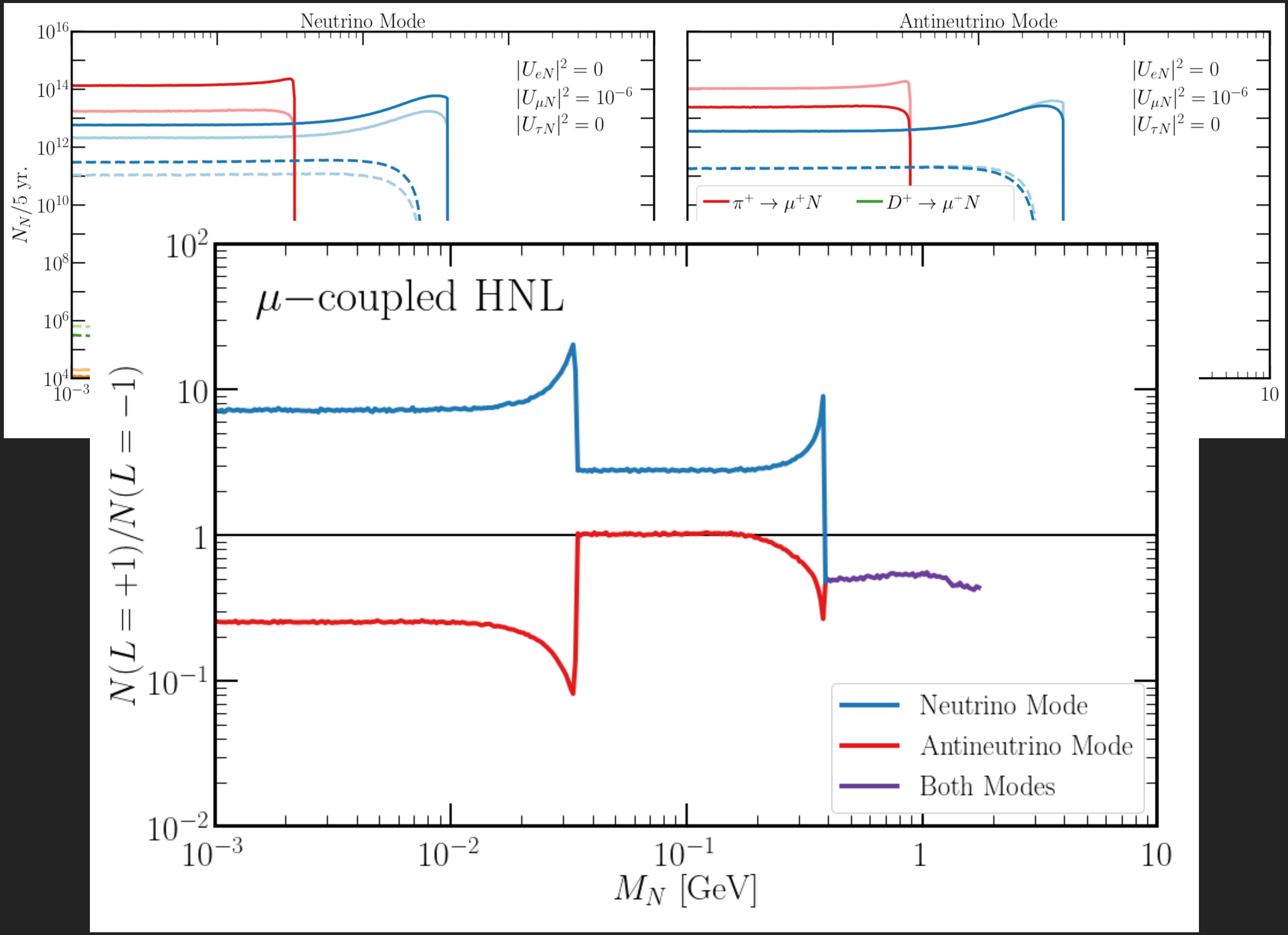


If the HNL is a Majorana fermion, then it can decay into the opposite-charge final state with equal probability

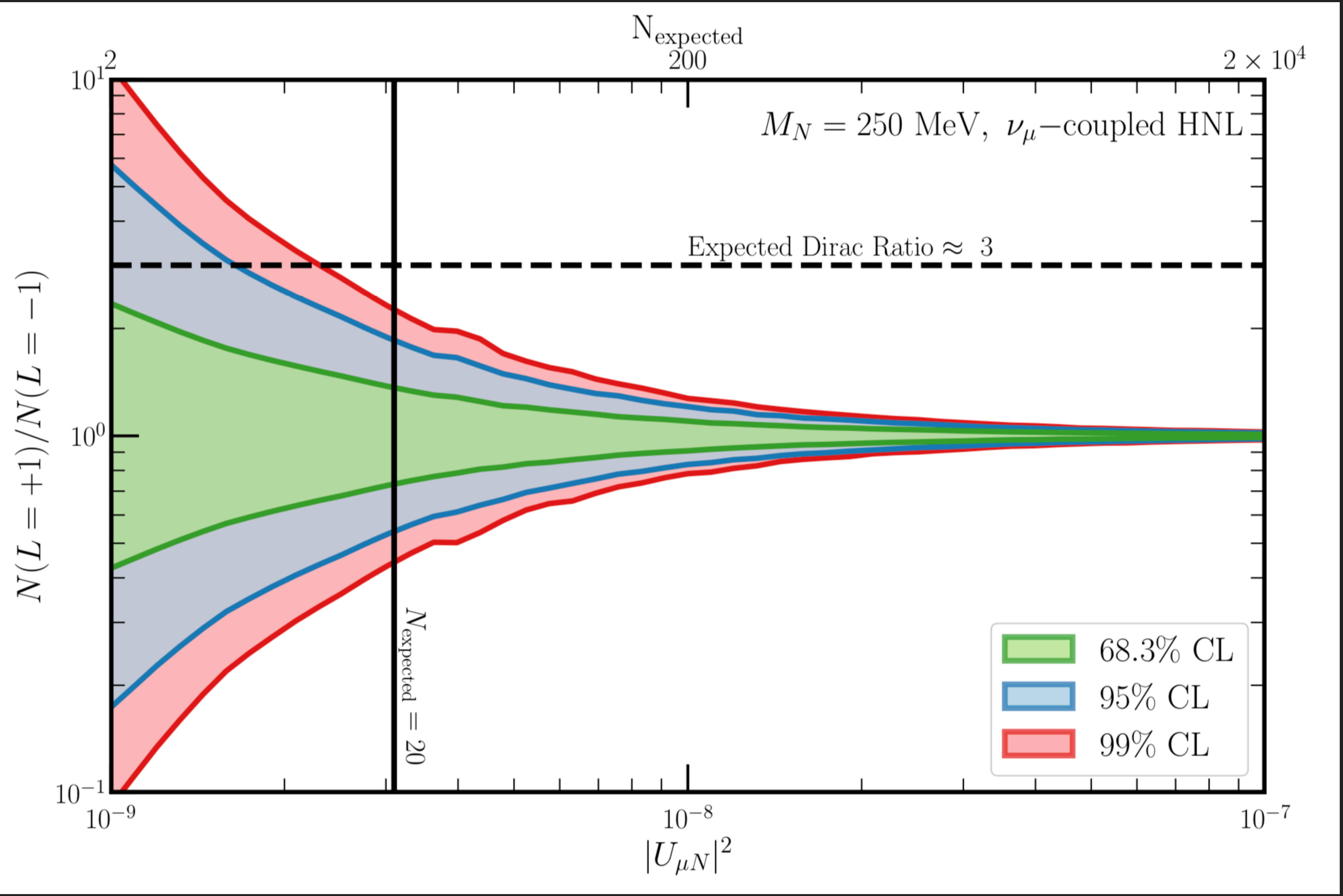


Measure the ratio of these final states in your detector (assuming you can identify the charges/particles on an event-by-event basis)

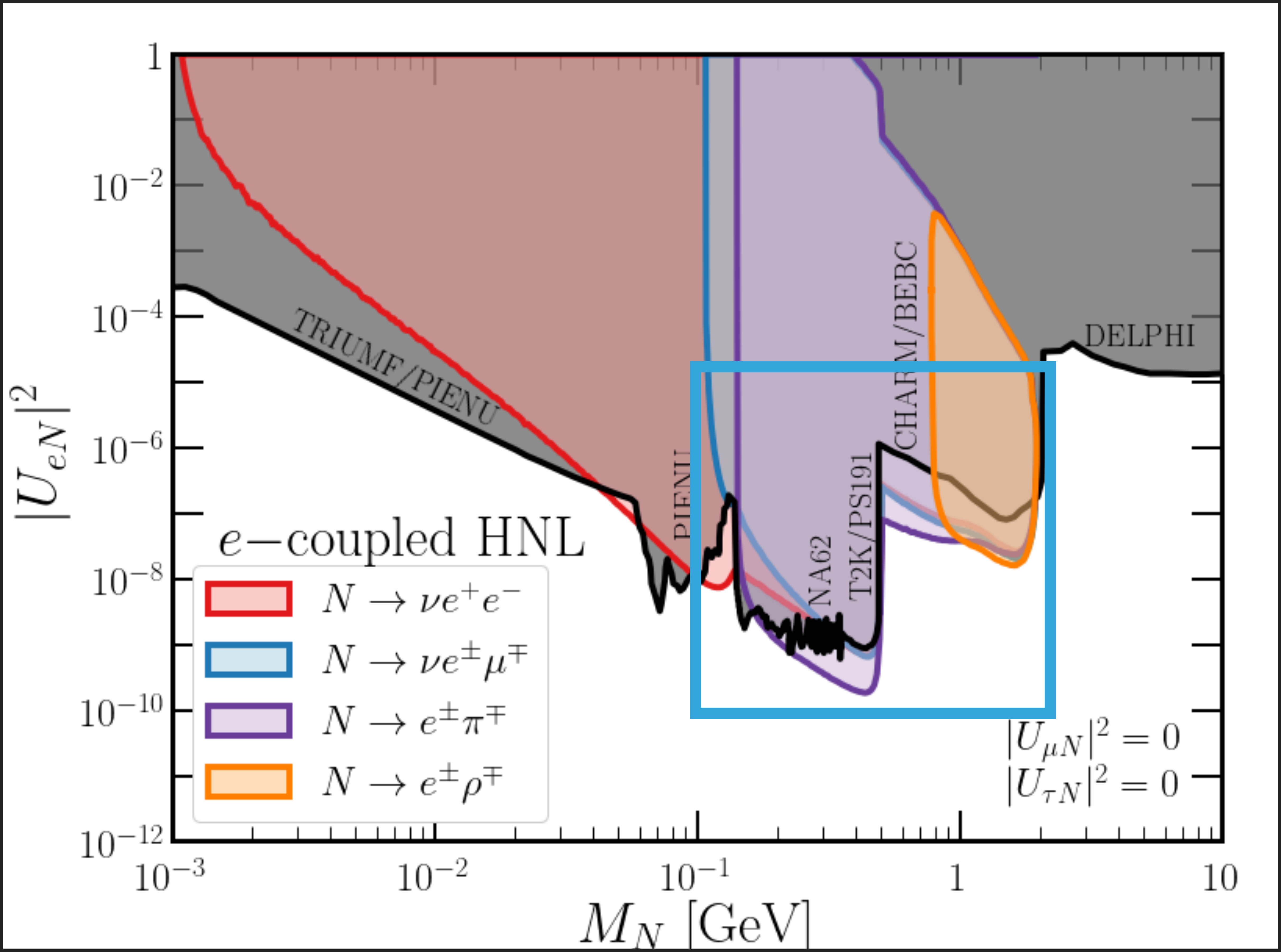
How Pure is the Beam?



Toy Exercise: Assume we identify every decay perfectly



Going Further: Electron-Coupled Channel



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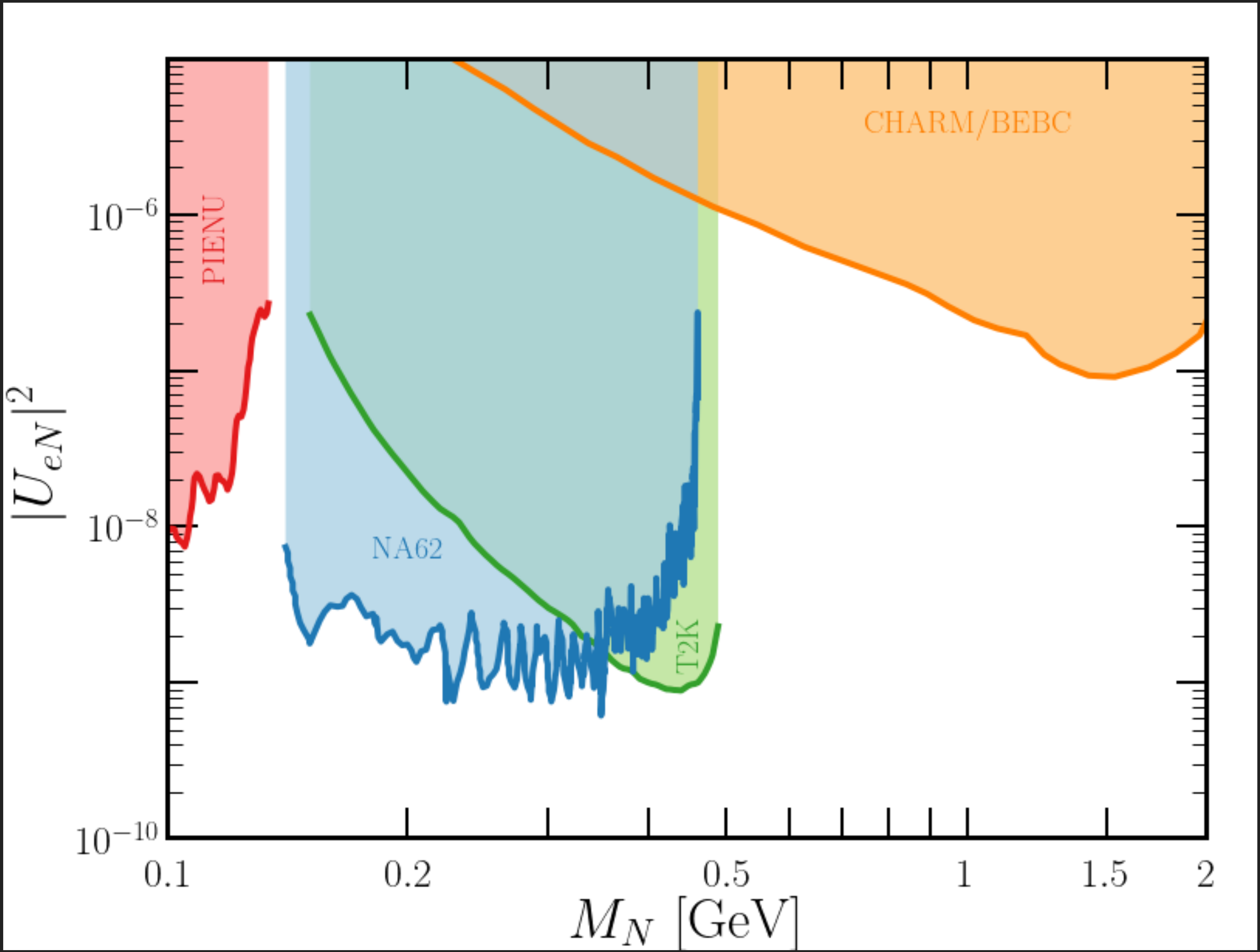

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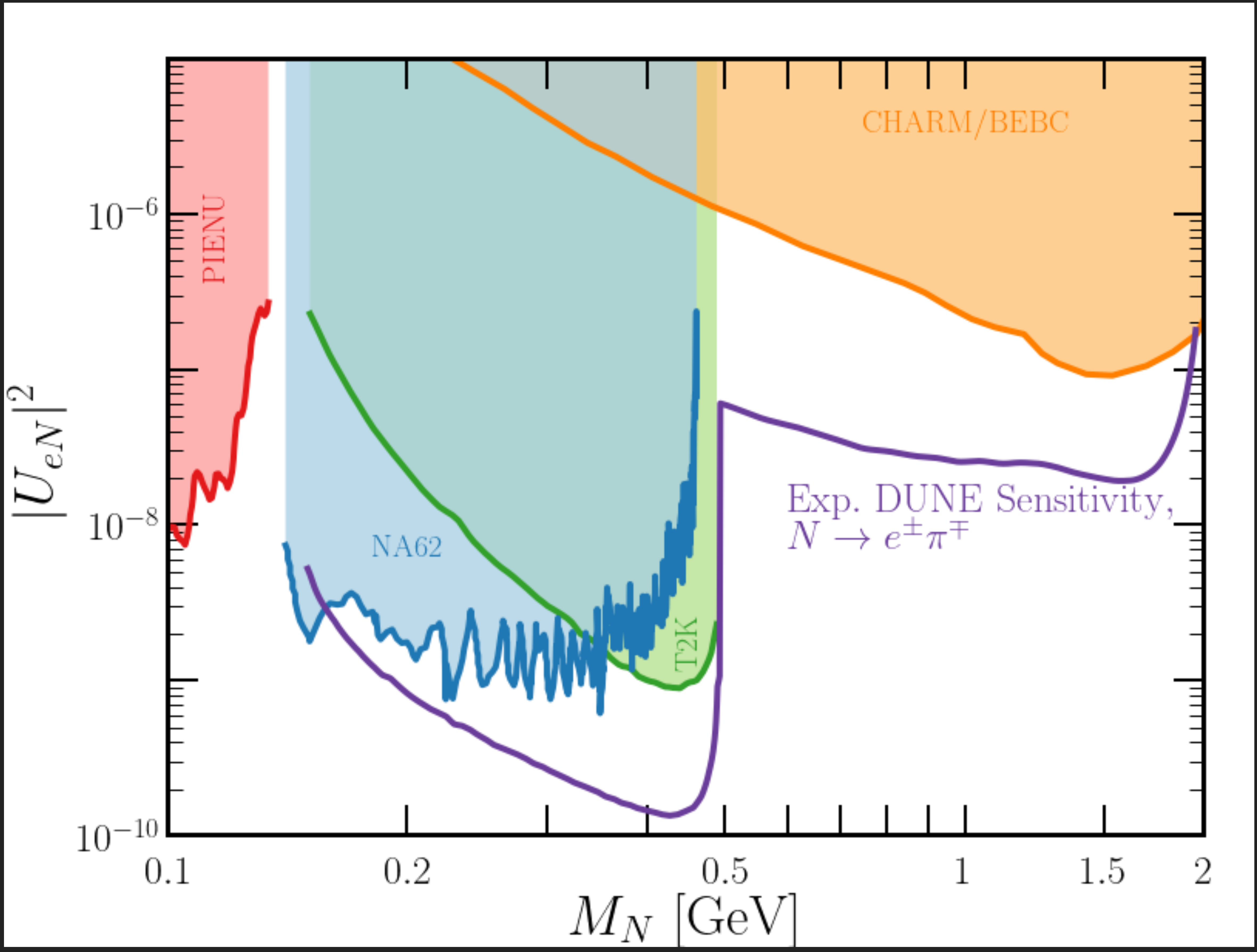

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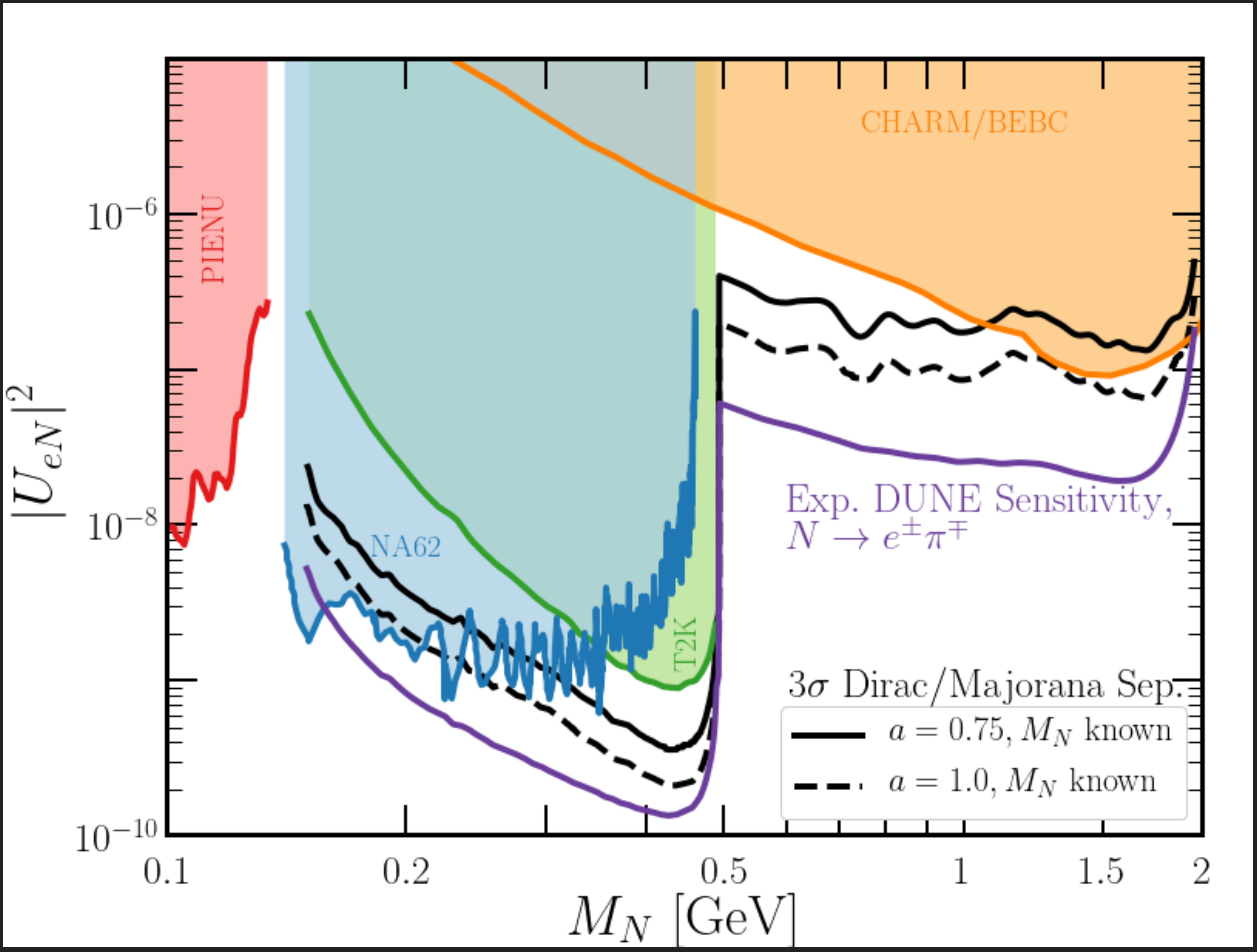
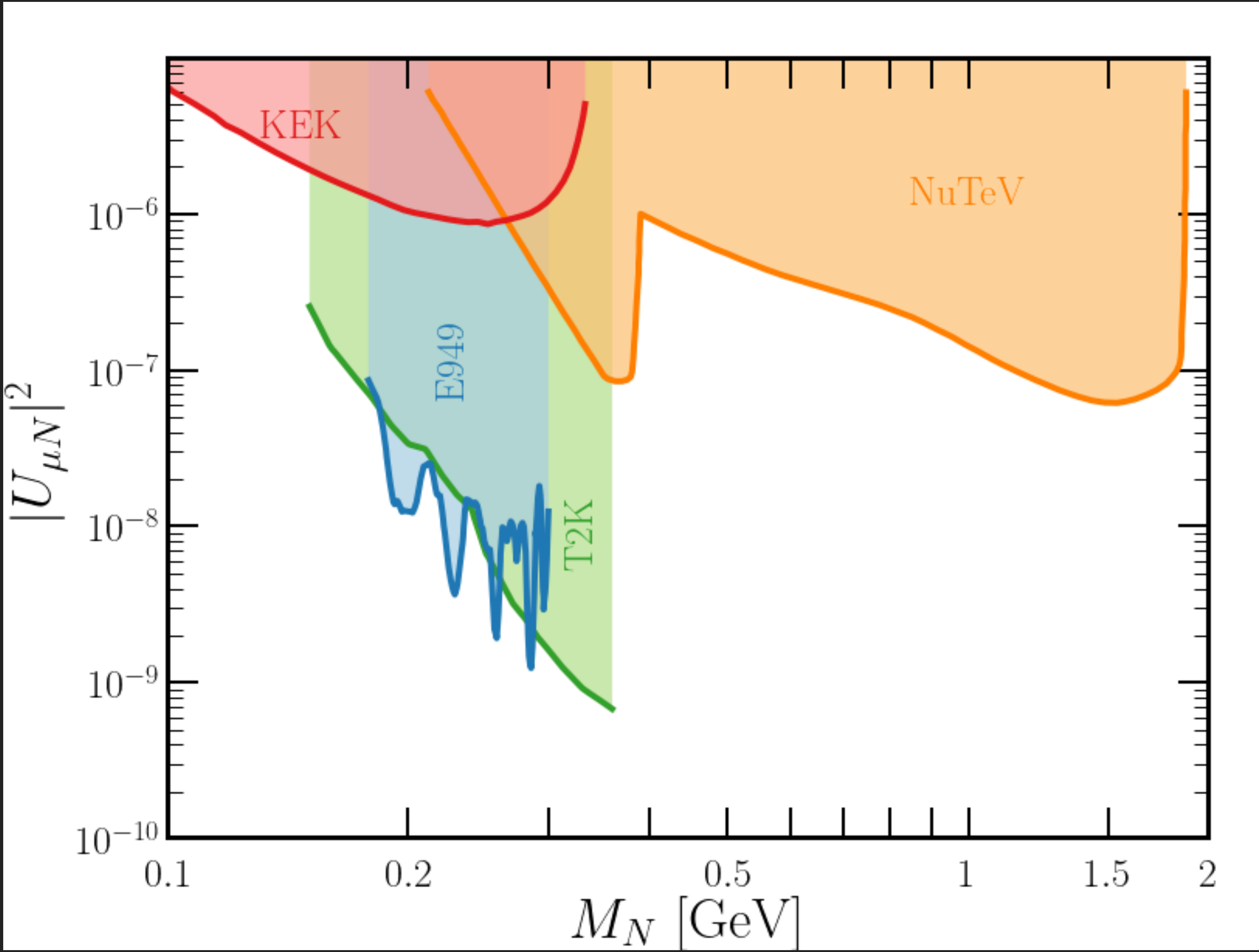
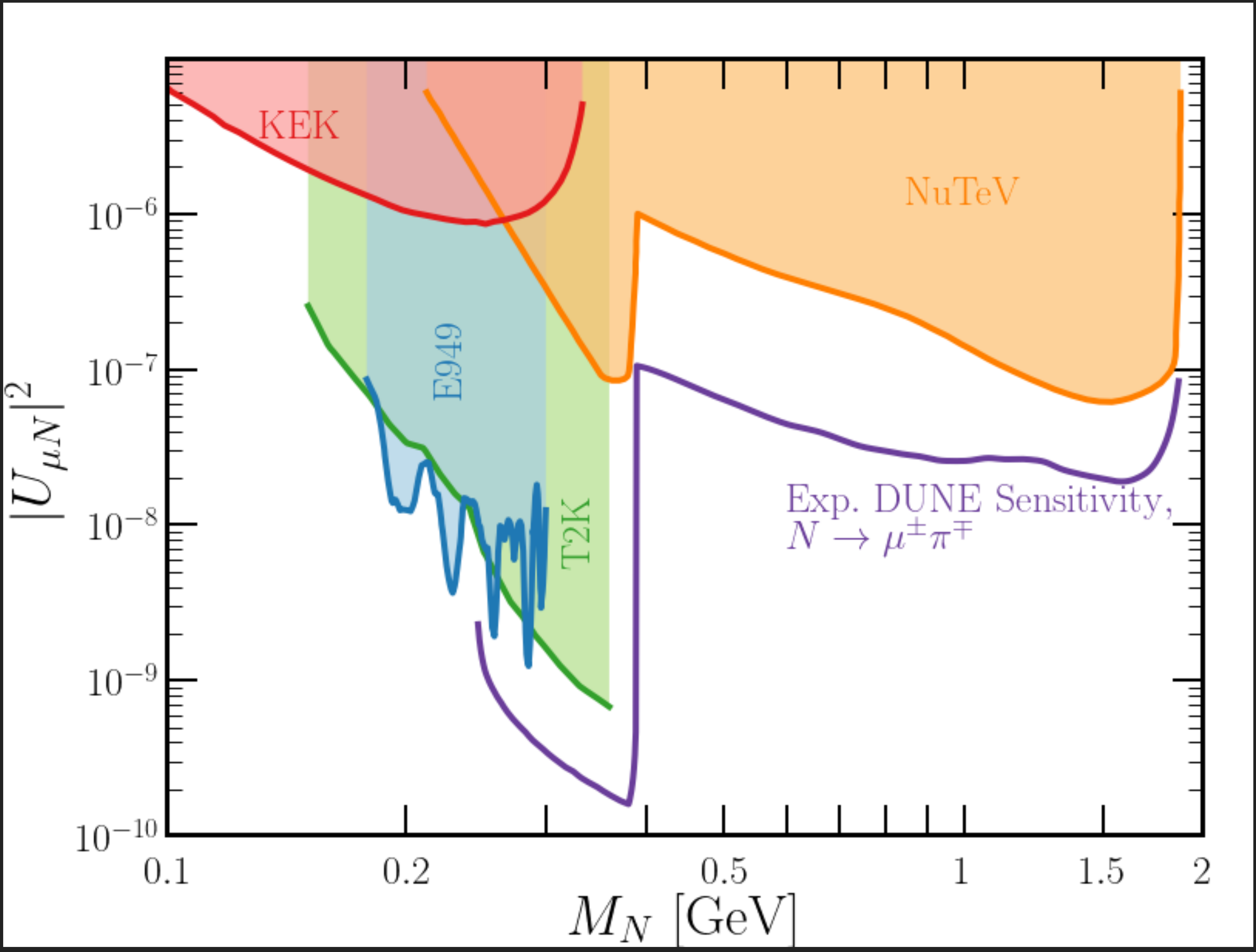


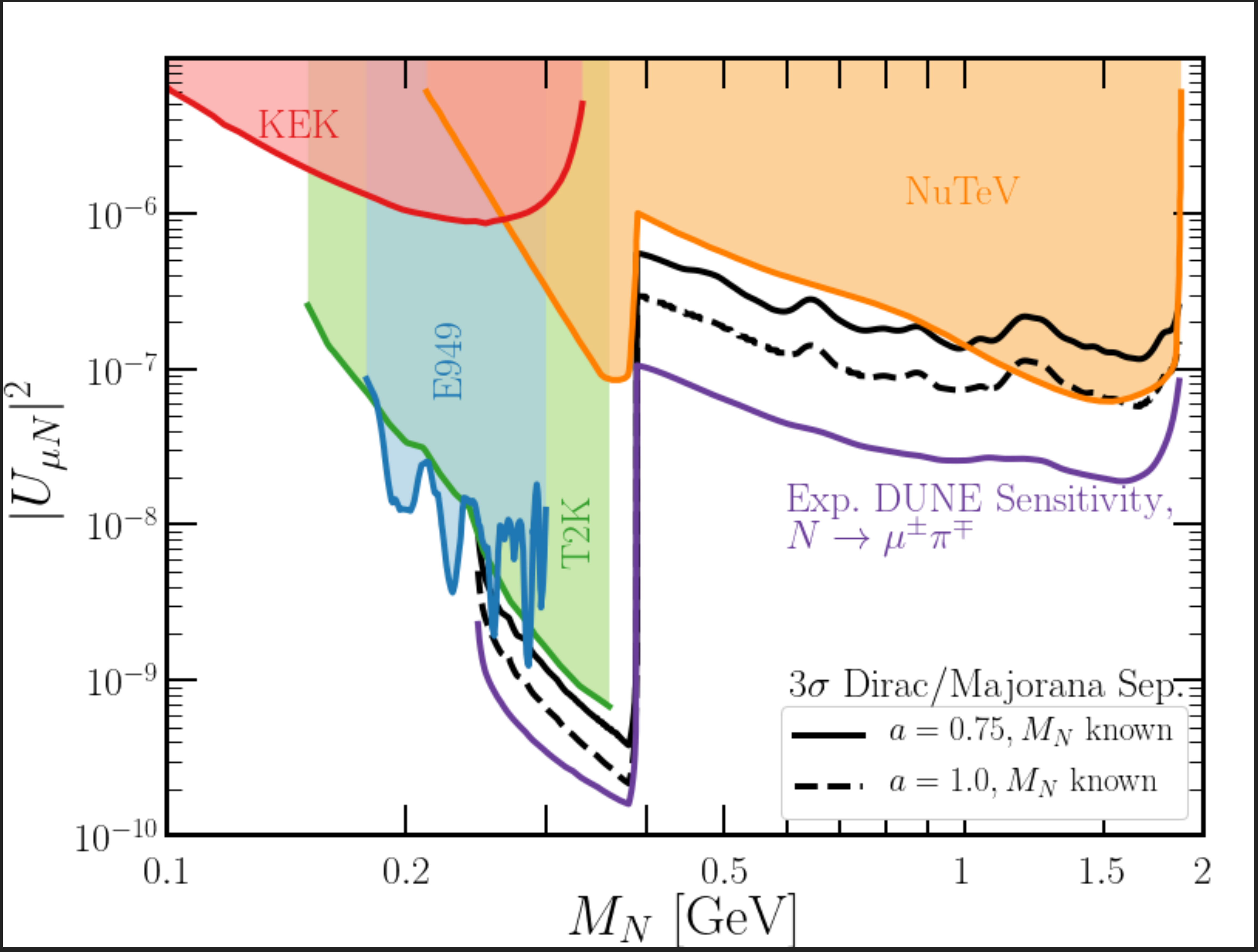
Going Further: Muon-Coupled Channel



Going Further: Muon-Coupled Channel



Going Further: Muon-Coupled Channel



Conclusions

- The upcoming DUNE experiment has a ton to offer, even beyond "standard" neutrino oscillation physics.
- Its near detector complex has a suite of instruments that can be leveraged in new ways.
- We have shown that the gaseous argon Multi-Purpose Detector is well-suited to search for decays of long-lived particles that could be mediators to a dark sector.
- Also, the movable DUNE-PRISM concept can reduce systematic uncertainties and enable us to search for dark matter scattering in the detector.

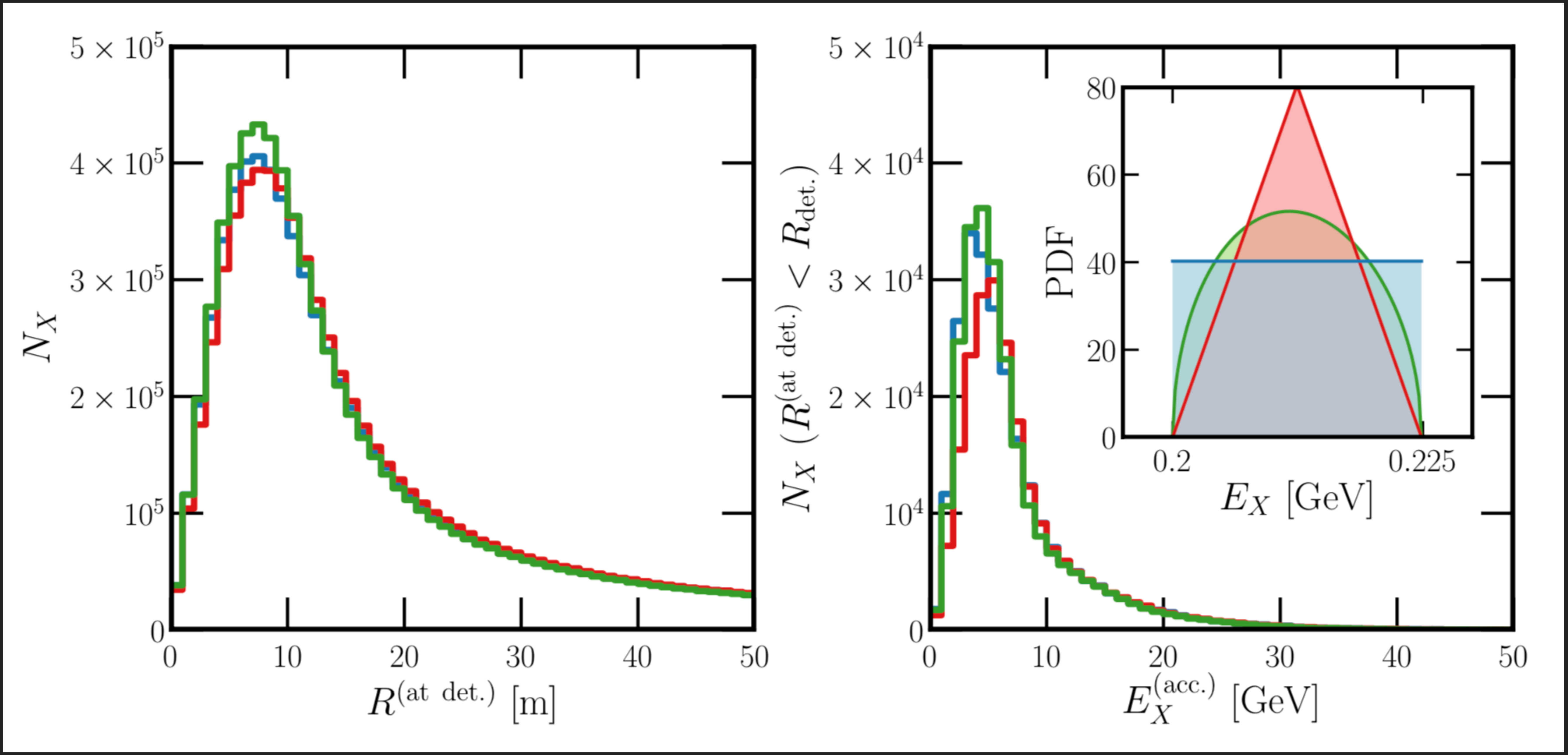
Thank you!

Backup

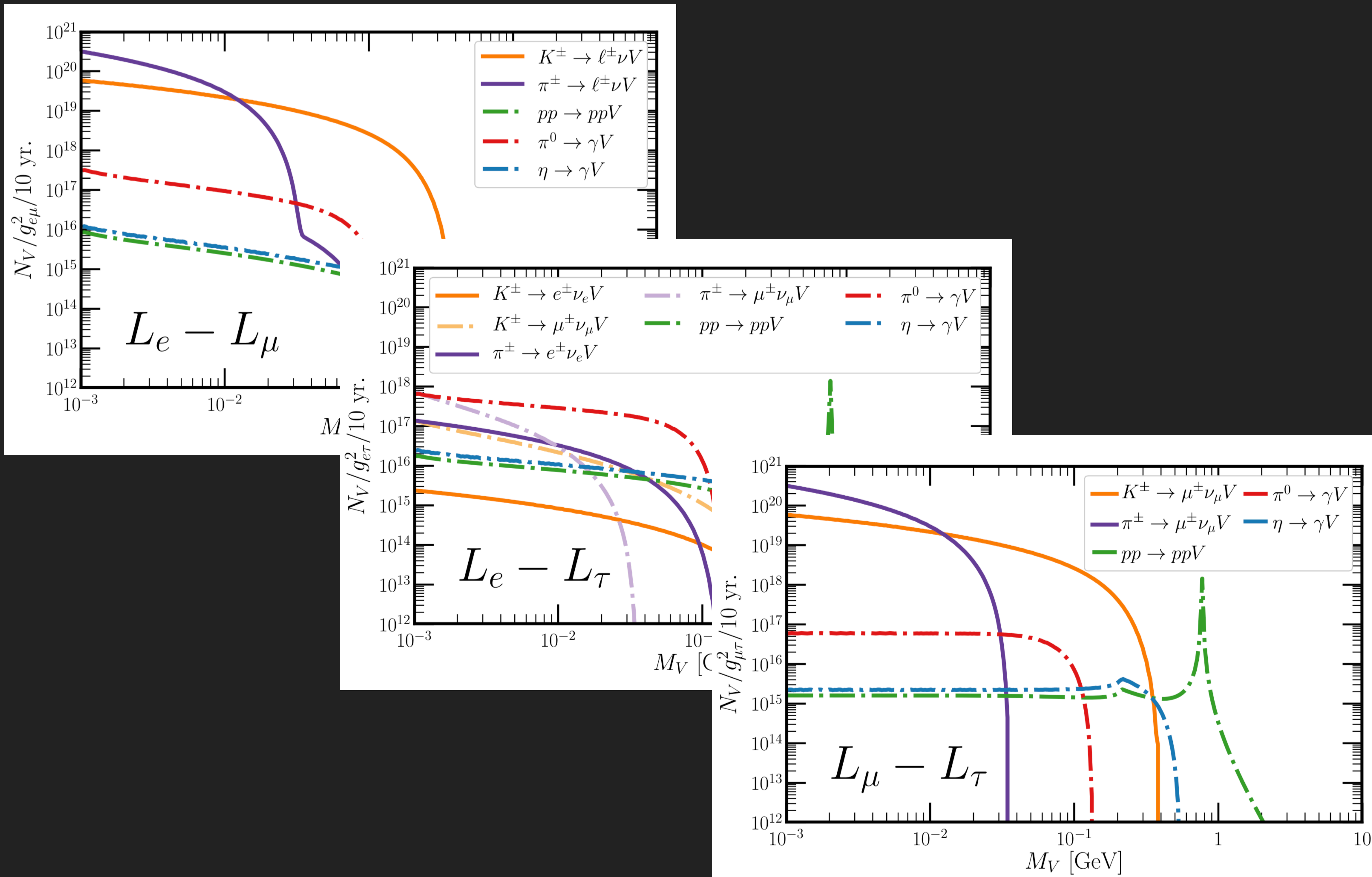
Meson Production – 80 GeV vs. 120 GeV

Meson Type	Particle ID	80 GeV pp	80 GeV pn	120 GeV pp	120 GeV pn
π^+	211	2.5	2.2	2.8	2.5
π^-	-211	1.9	2.2	2.2	2.6
K^+	321	0.21	0.19	0.24	0.23
K^-	-321	0.12	0.12	0.15	0.16
D^+	411	1.1×10^{-6}	1.4×10^{-6}	3.6×10^{-6}	3.7×10^{-6}
D^-	-411	2.3×10^{-6}	2.8×10^{-6}	5.7×10^{-6}	6.2×10^{-6}
D_s^+	431	2.8×10^{-7}	4.4×10^{-7}	1.1×10^{-6}	1.2×10^{-6}
D_s^-	-431	4.3×10^{-7}	6.7×10^{-7}	1.5×10^{-6}	1.7×10^{-6}
π^0	111	2.49	2.52	2.86	2.89
η	221	0.28	0.28	0.32	0.33
K_L^0	130	0.15	0.16	0.18	0.19
K_S^0	310	0.15	0.16	0.18	0.19

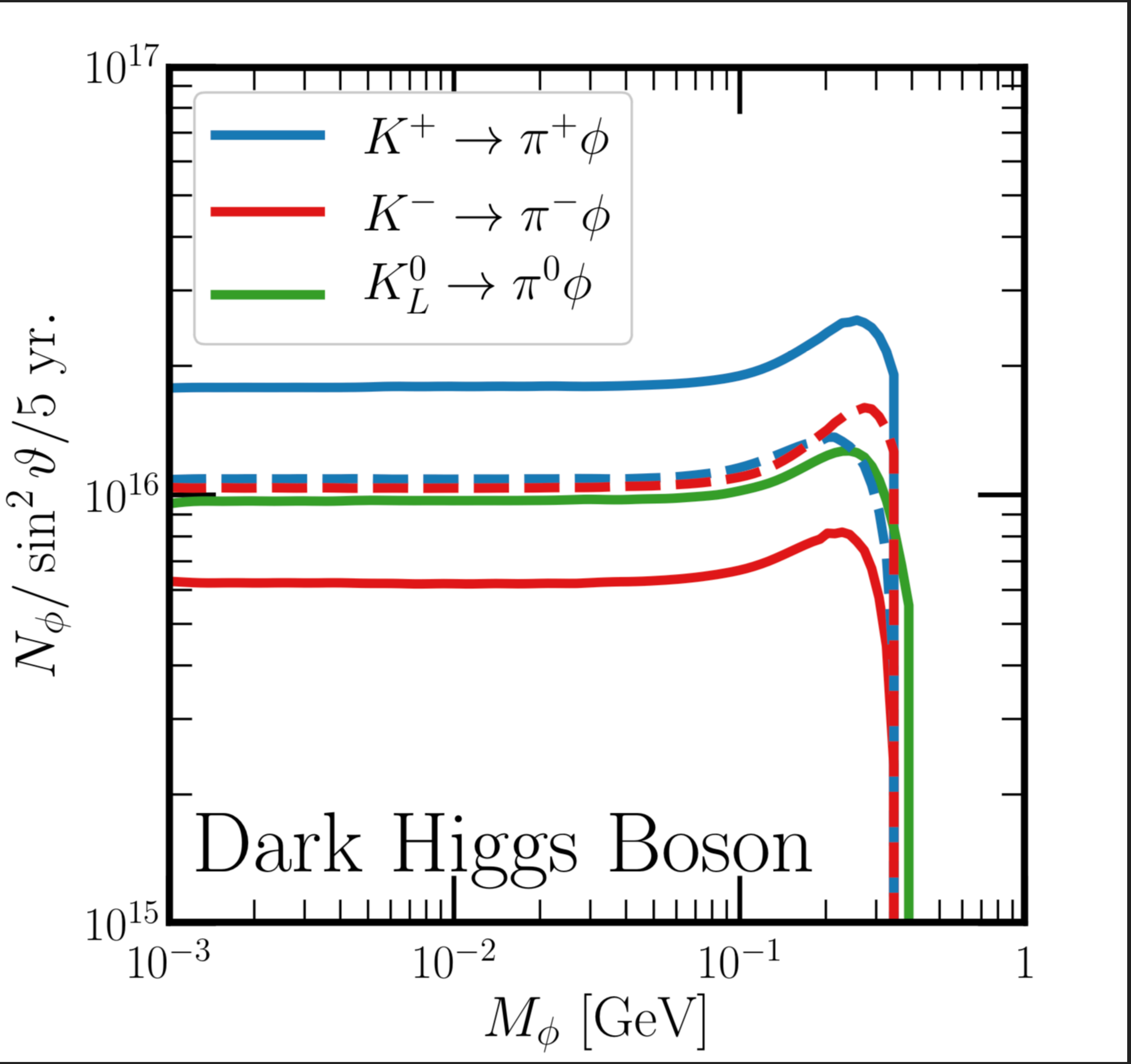
Three-Body Decay Simulations



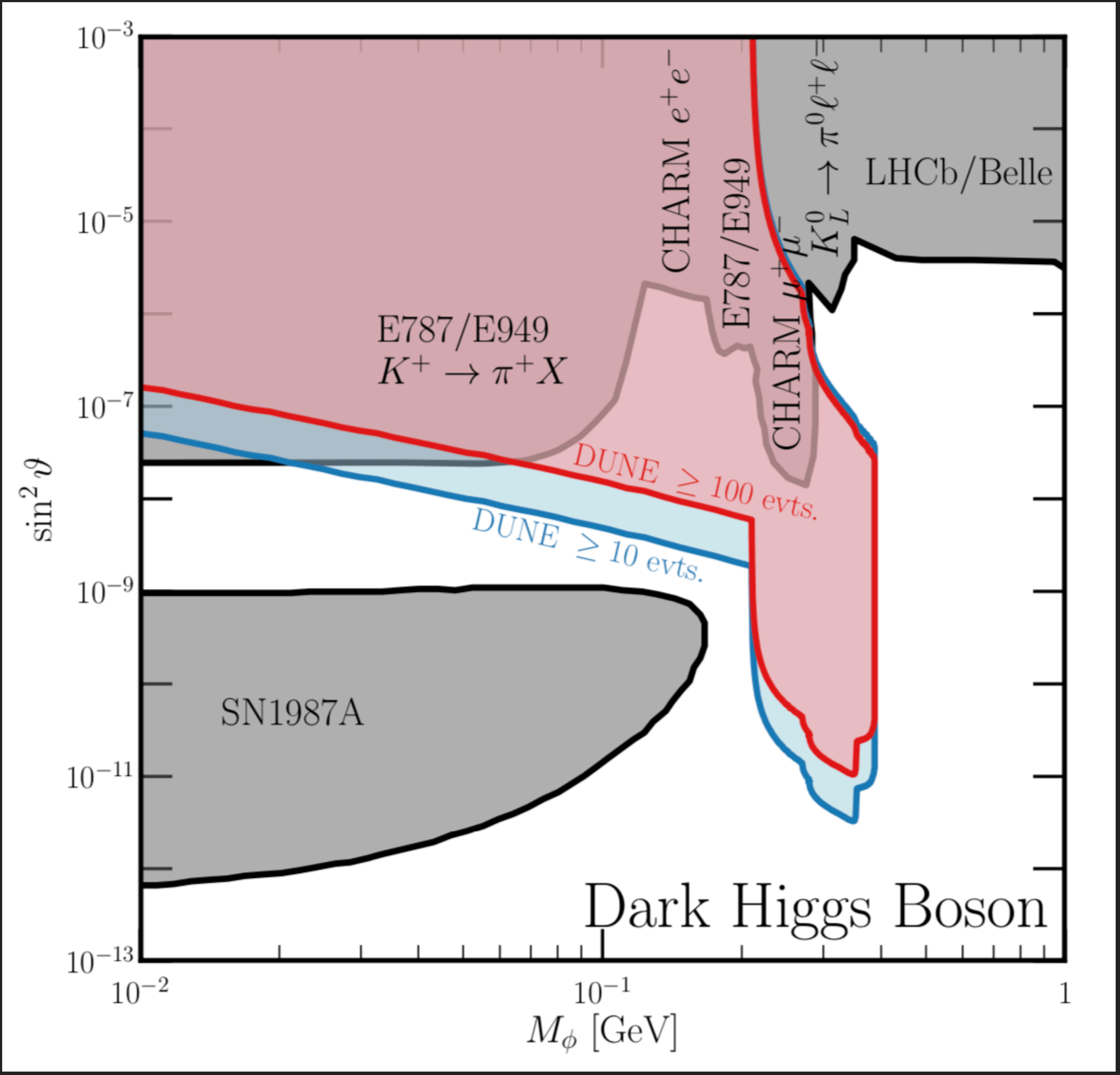
Leptophilic Gauge Boson Production



Dark Higgs Boson Production



Dark Higgs Boson Sensitivity



Kinematics for Dirac/Majorana Distinction