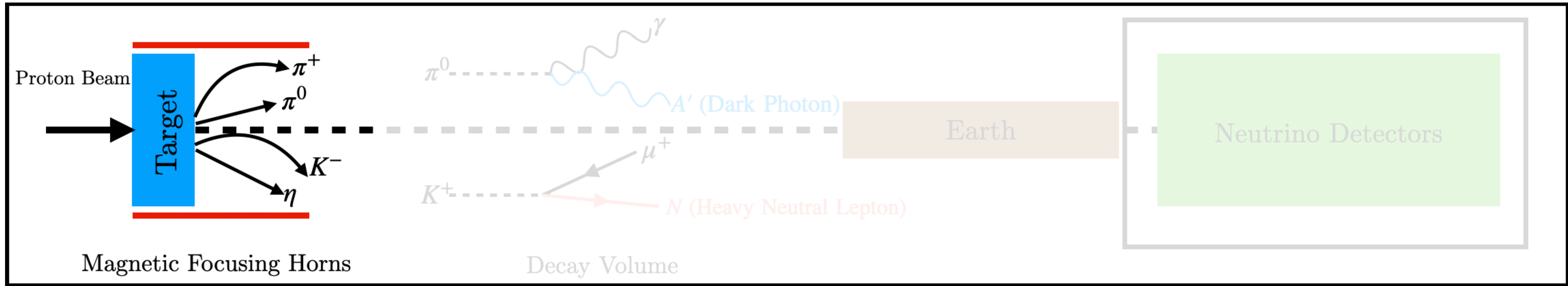


# Dark Matter & Dark Sector Searches @DUNE Phase II

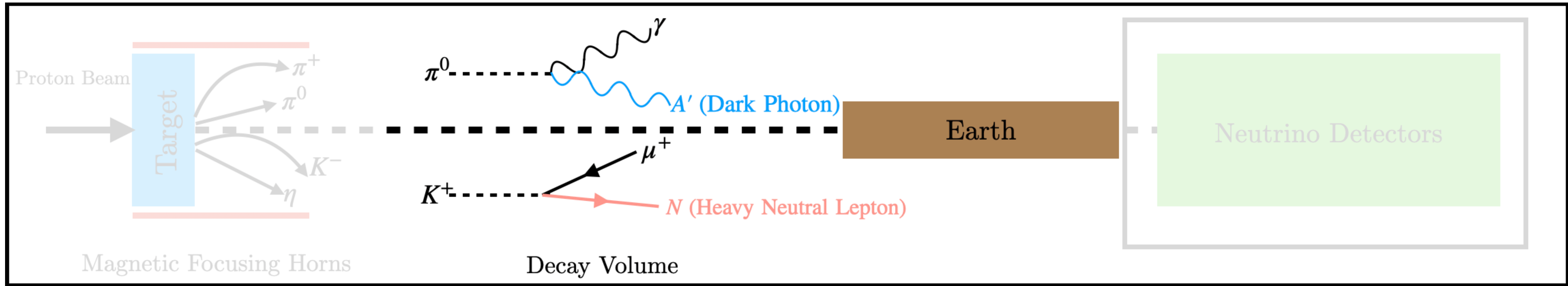
Kevin J. Kelly, Texas A&M University  
Phase-II Workshop, 20-22 June 2023  
[kjkelly@tamu.edu](mailto:kjkelly@tamu.edu)

# Neutrino Facilities as Dark Sector Machines



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

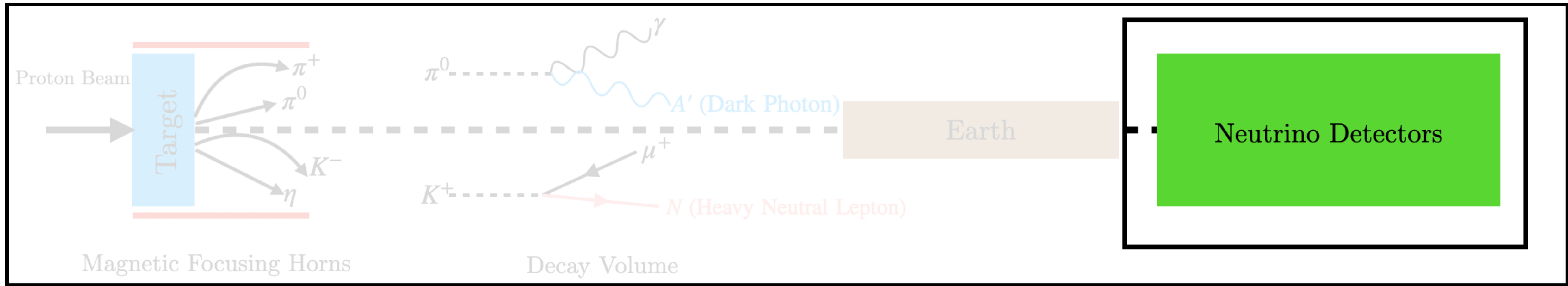
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1) Charged and Neutral Mesons are produced in the high-energy/high-intensity proton collisions.

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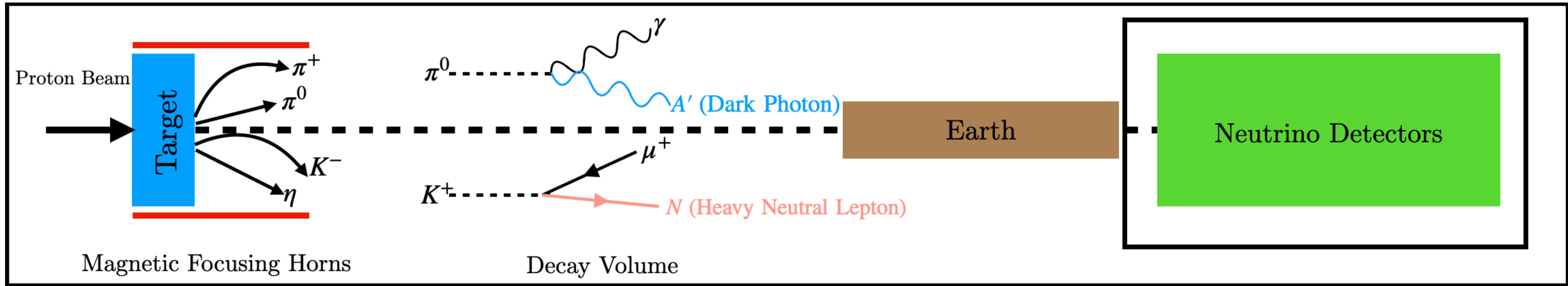


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3) Dark Sector particles decay/interact inside the neutrino detector, leaving a striking signature.

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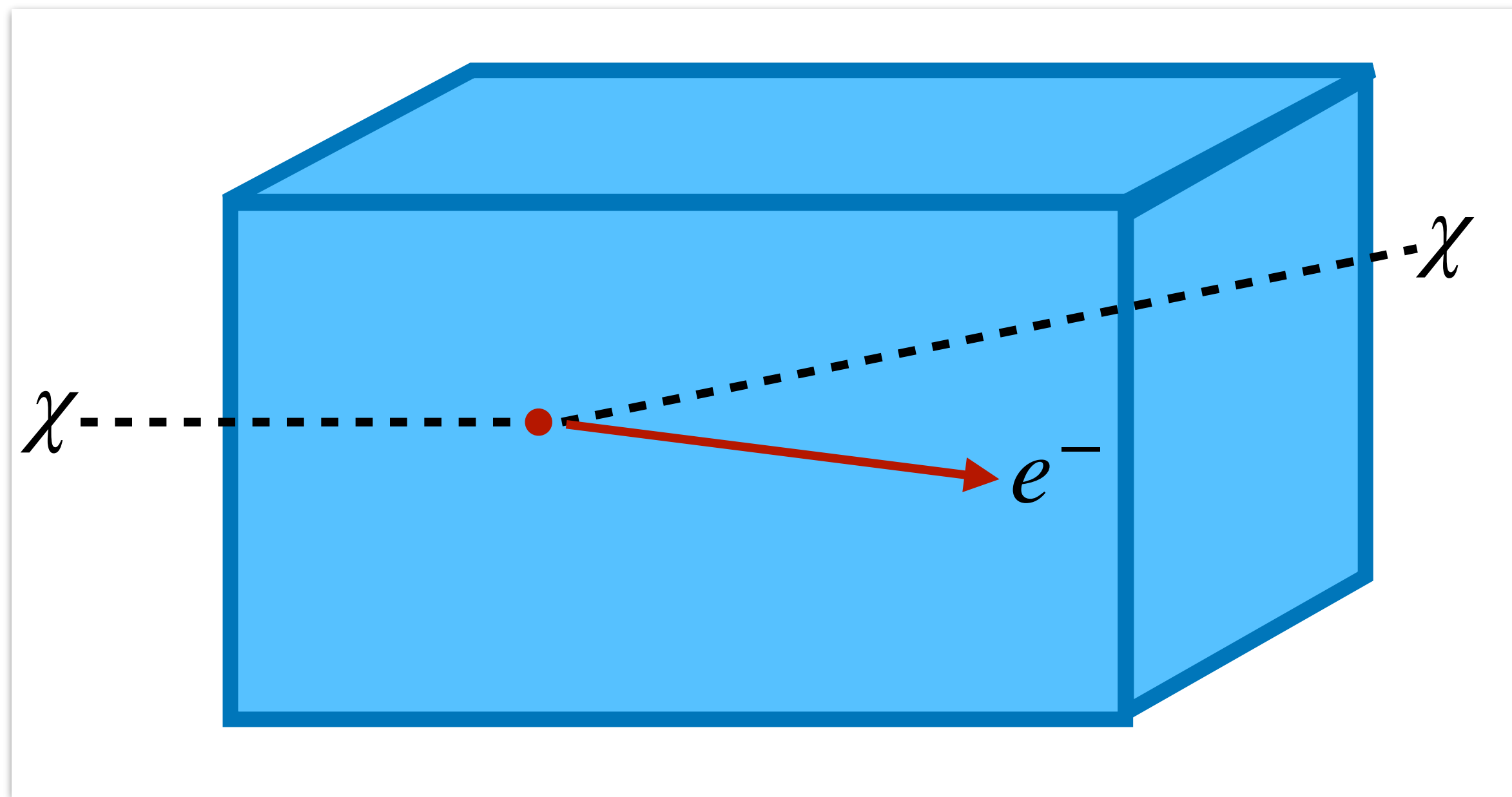
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# Complementarity of Neutrino Detectors

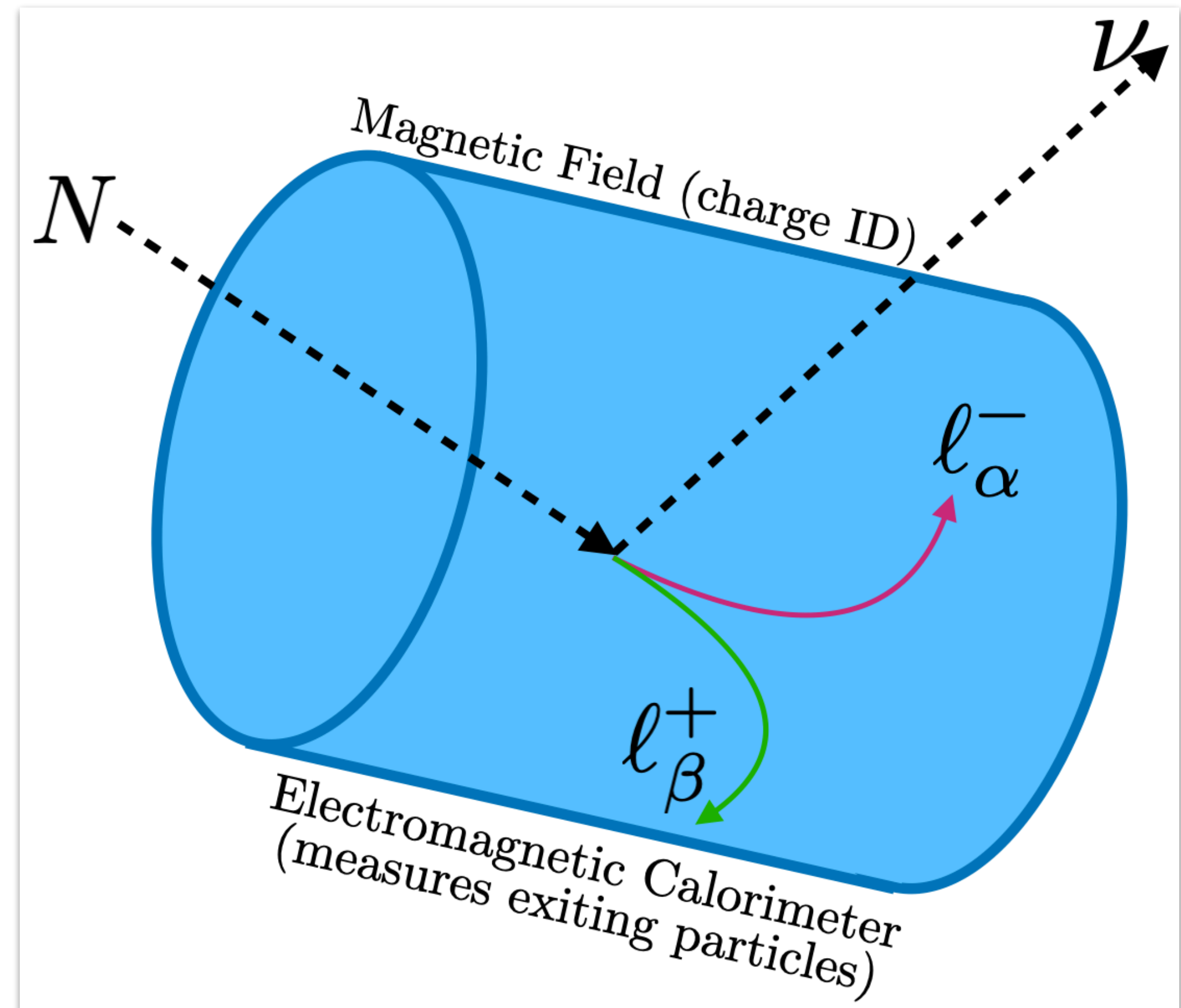
Liquid Detectors (SBND, ICARUS, etc.)



Large mass for rare-particle scattering

Excellent particle ID, energy resolution, etc.

Gaseous Detectors (DUNE NDGAr)

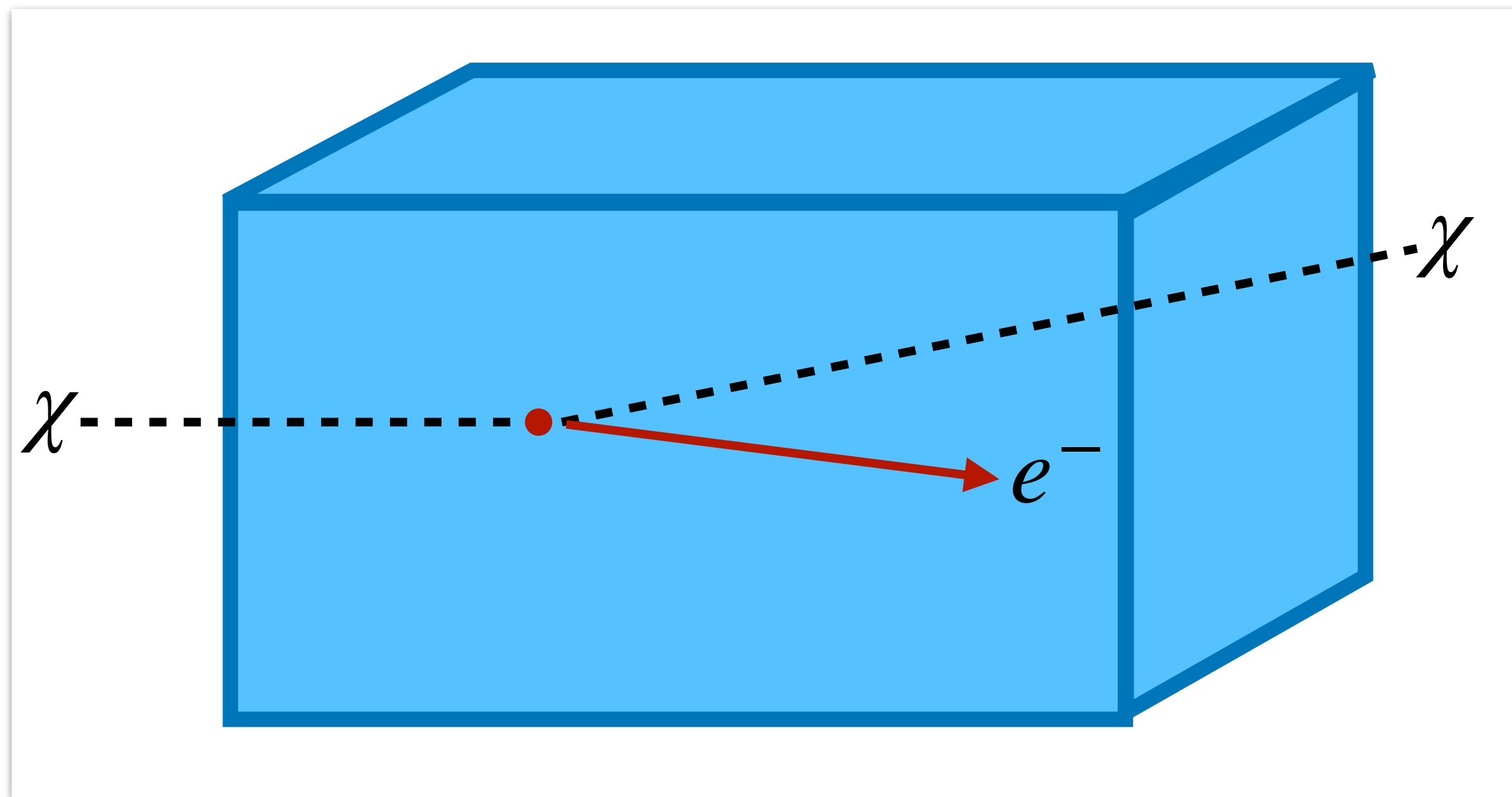


Decay Signal  $\propto$  Volume

Neutrino Scattering Backgrounds  $\propto$  Mass

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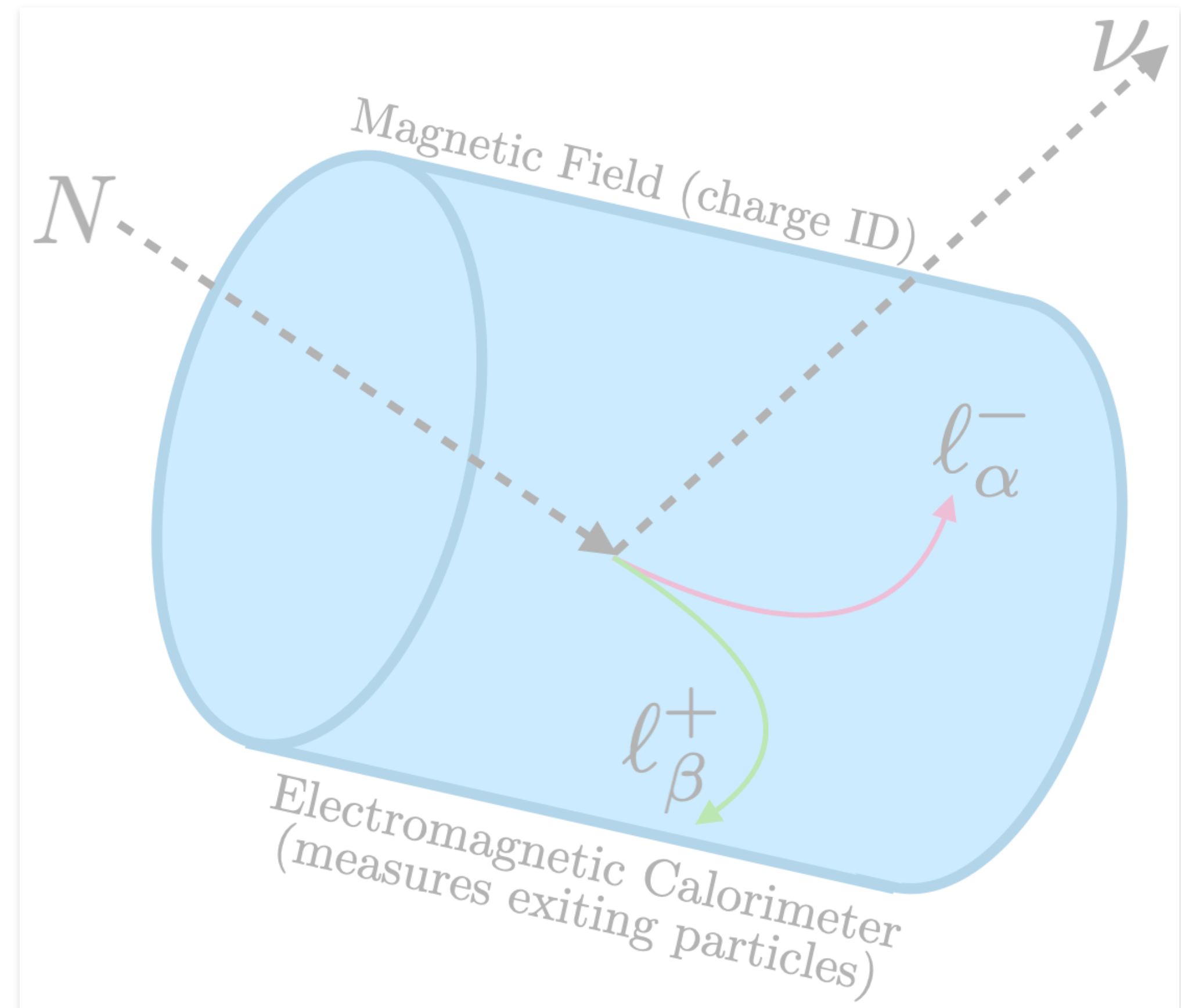
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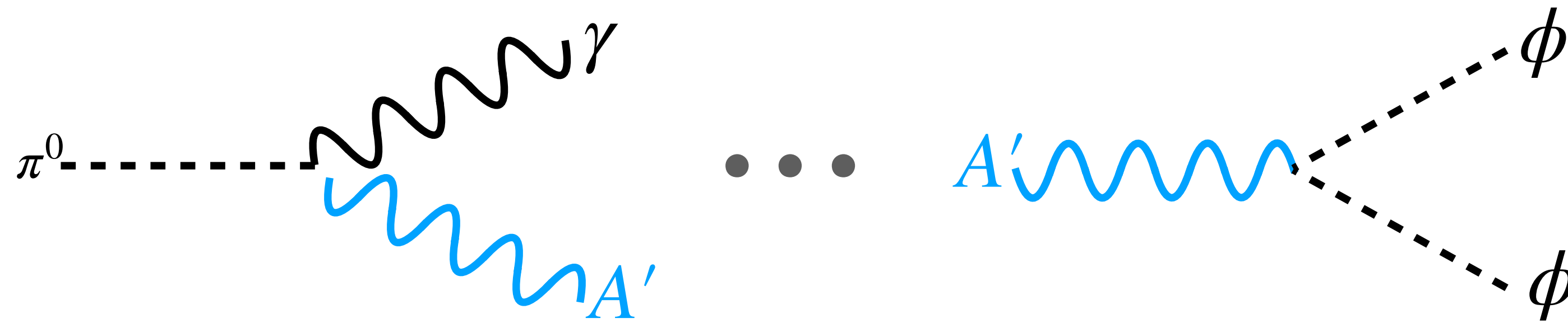


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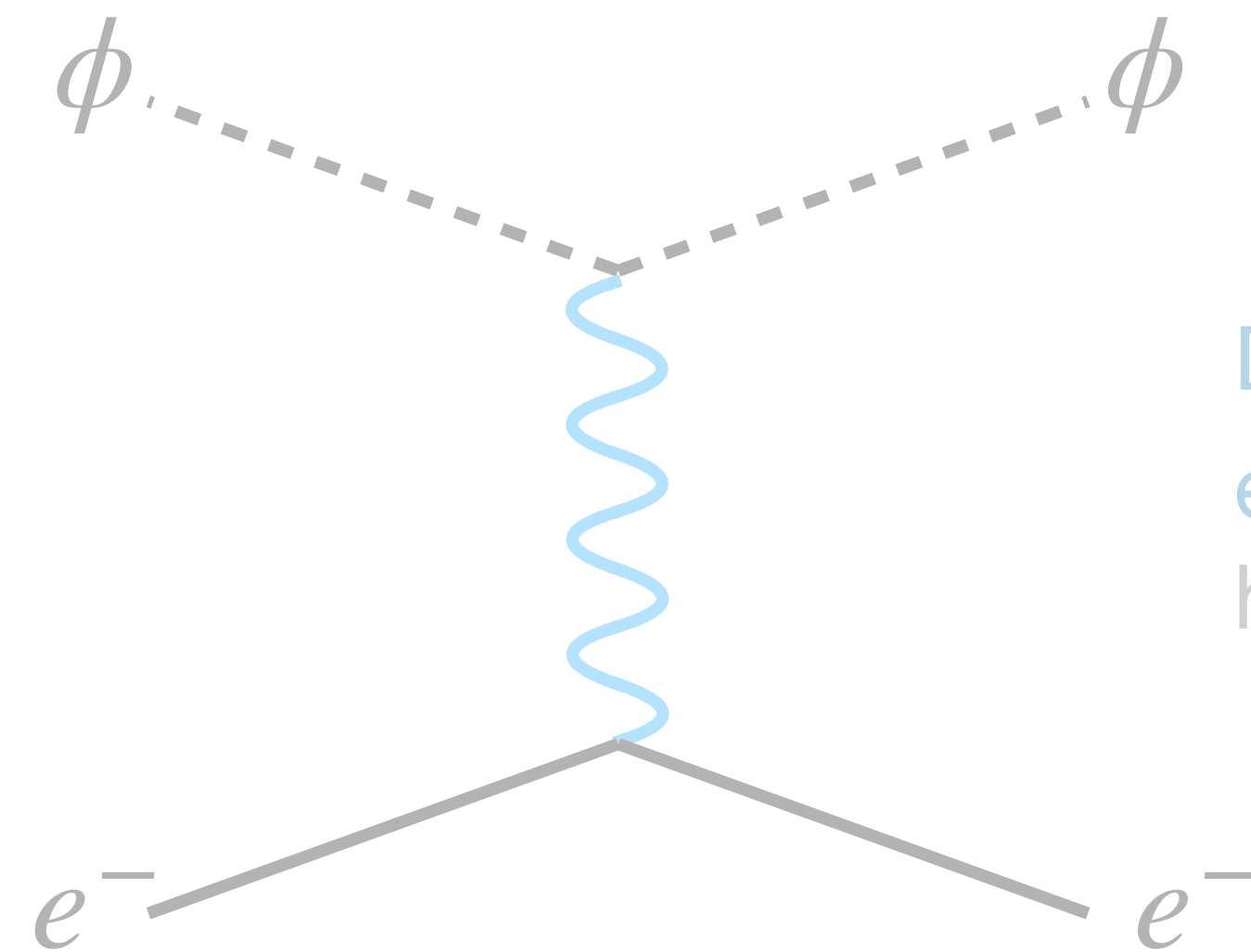
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# Scattering of Dark Sectors

Example scenario: vector-coupled dark matter.



Flux will be unfocused (relative to neutrino beam), but much will be boosted forward

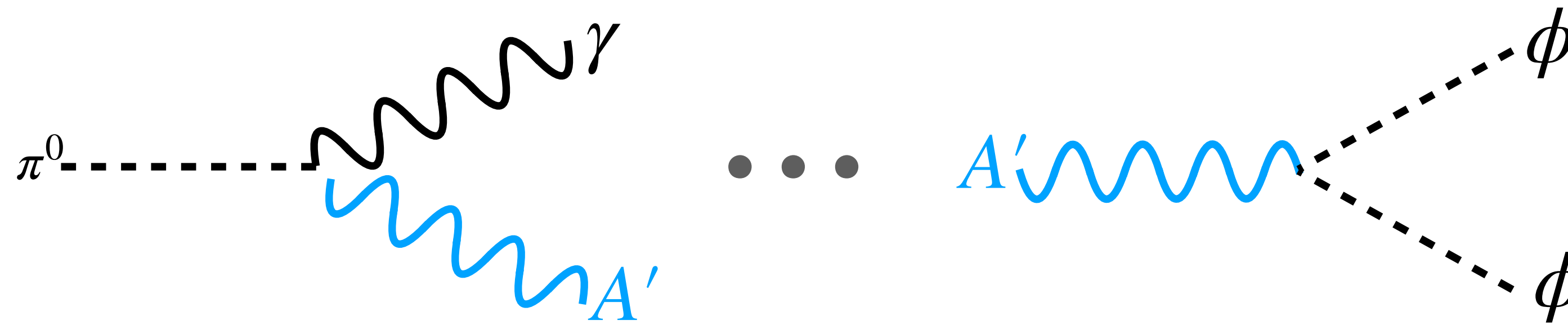


Dark-sector particle  $\phi$  can scatter off electrons via the mediator  $A'$ :  
high-energy, forward electron signature.

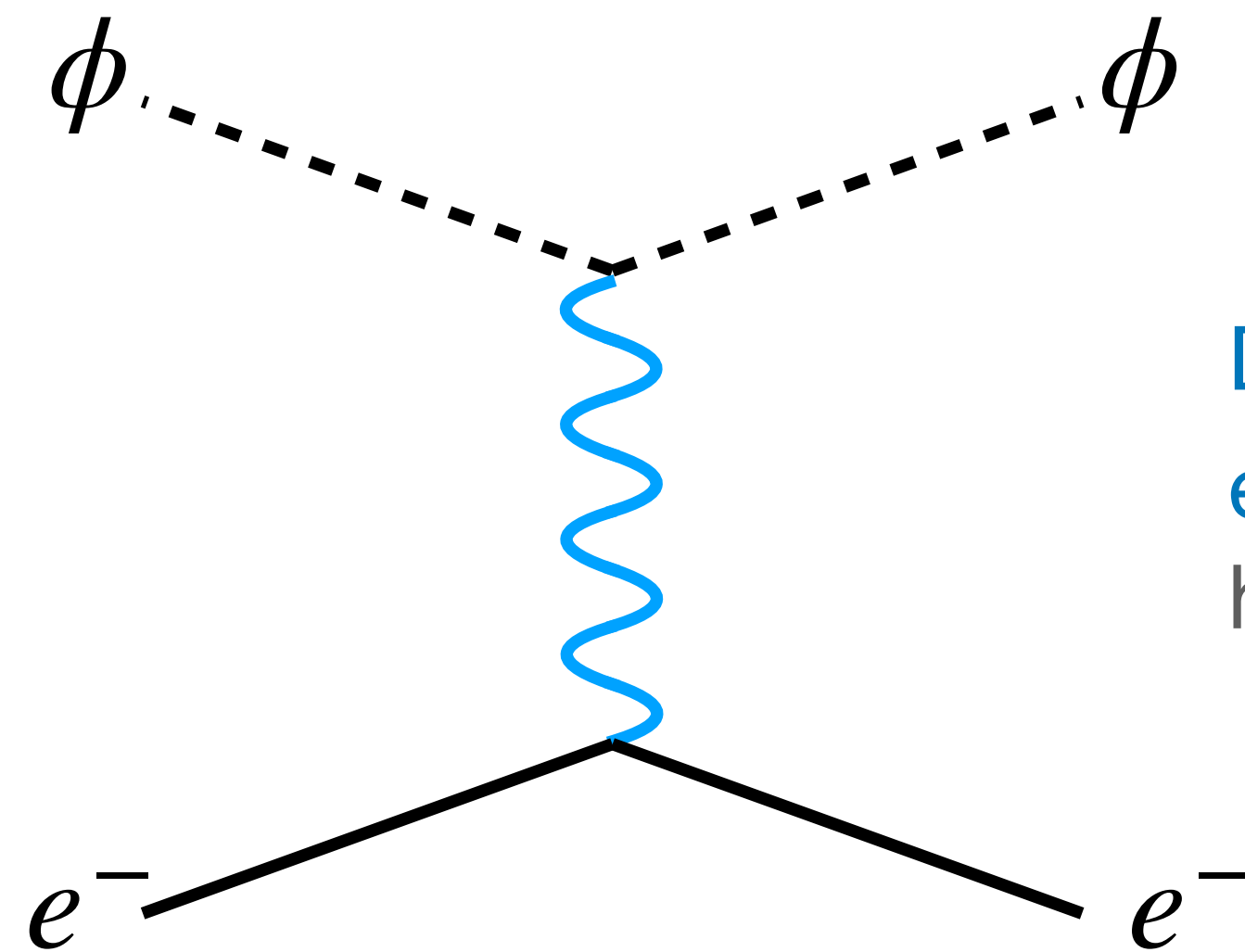


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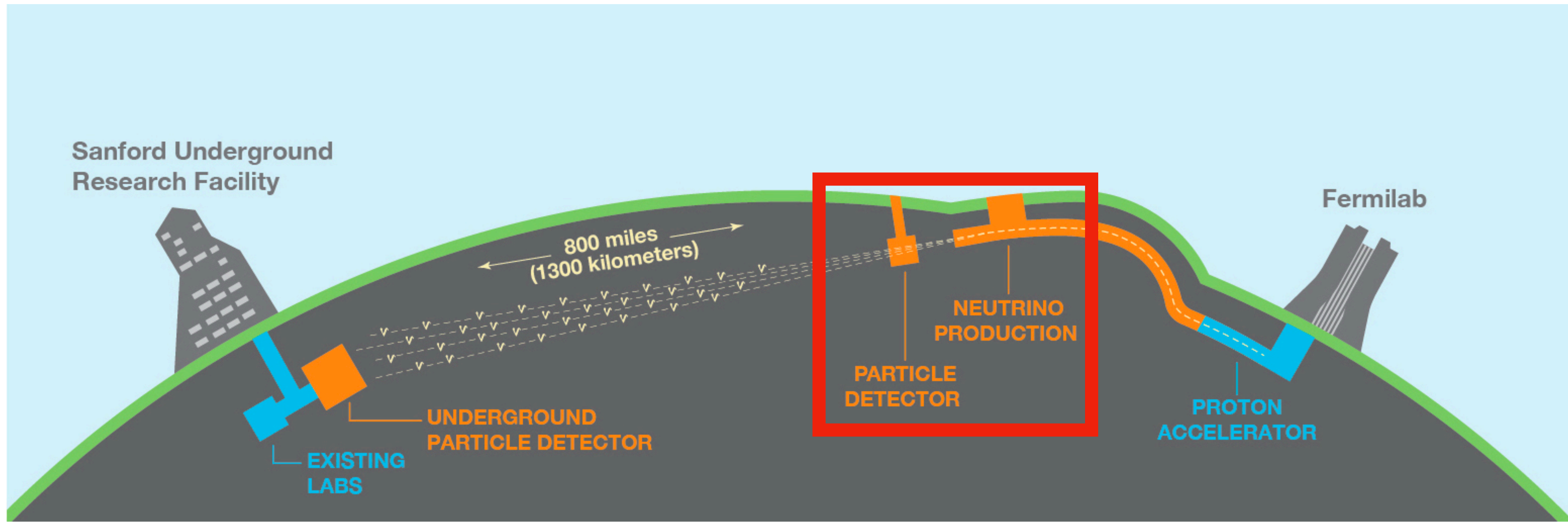


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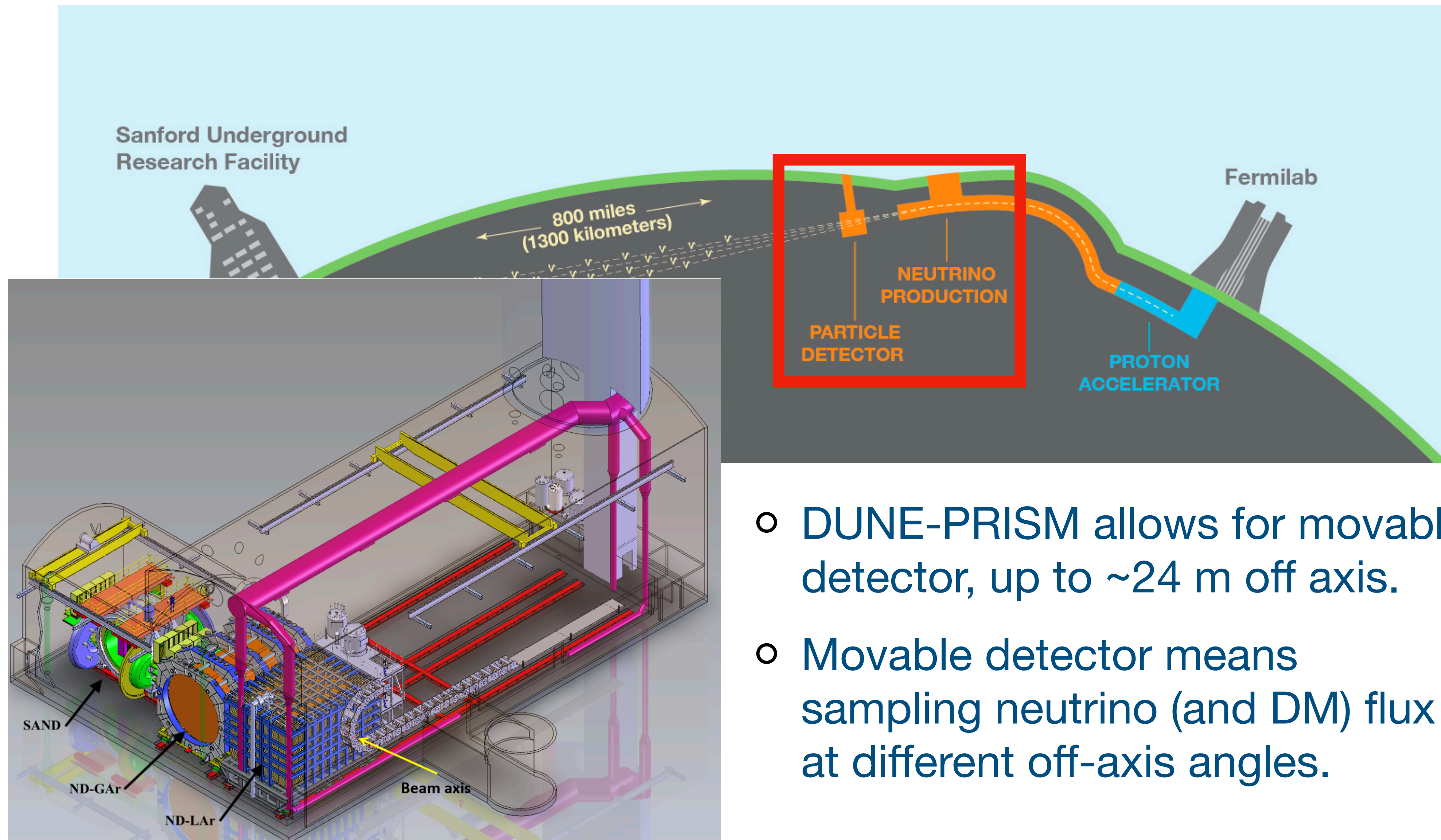


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# Why DUNE-ND?



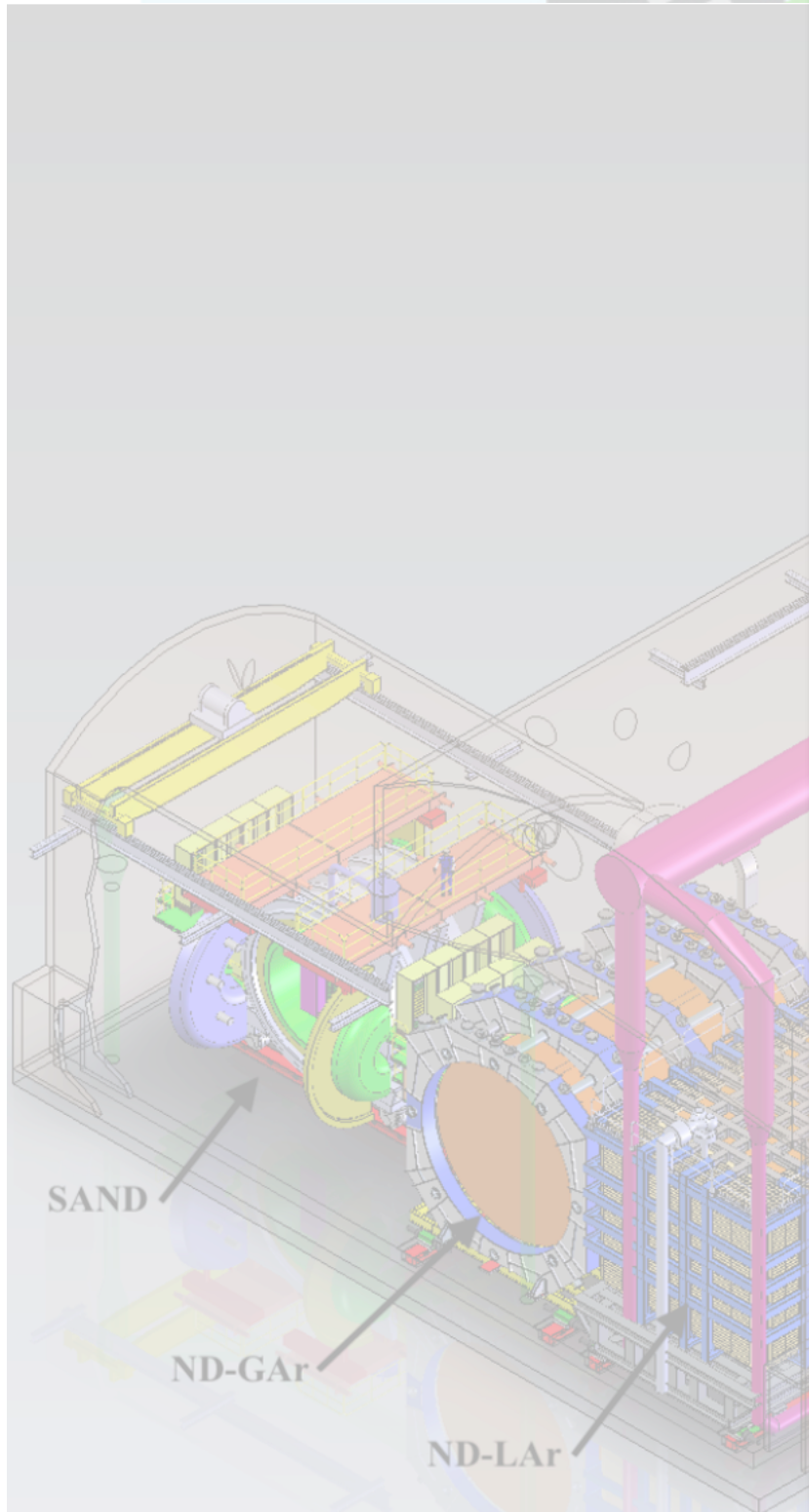
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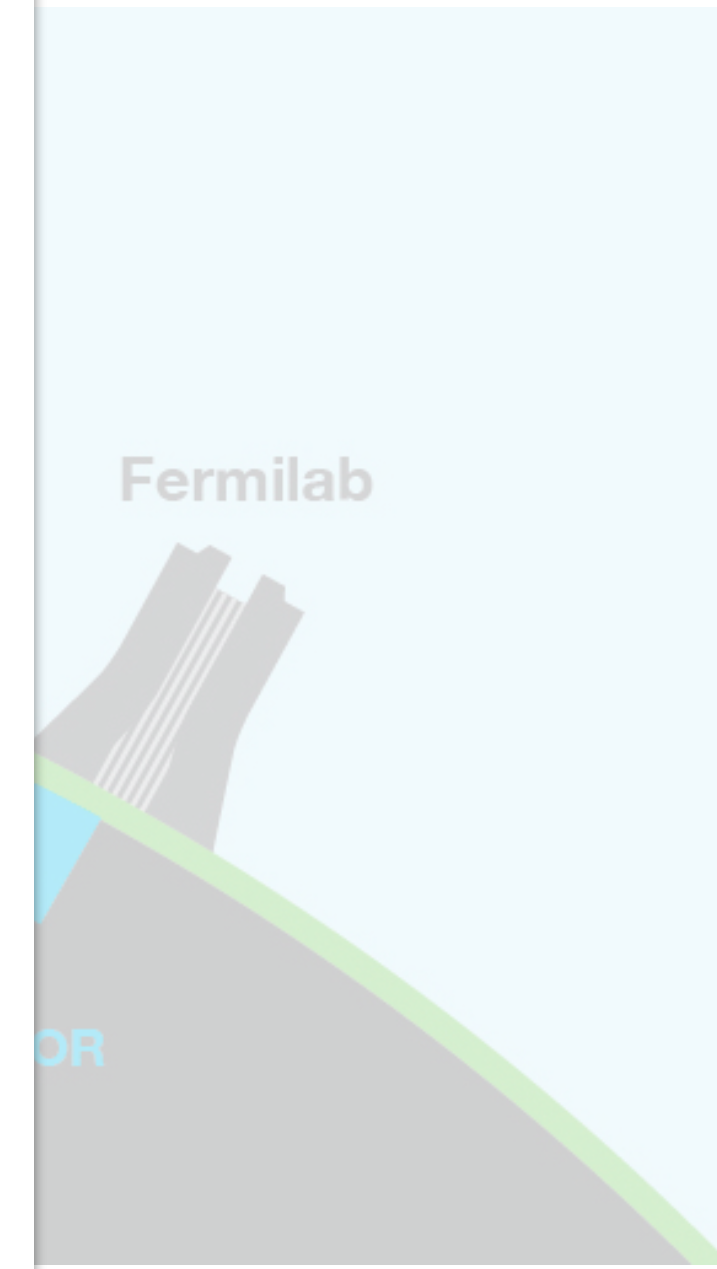
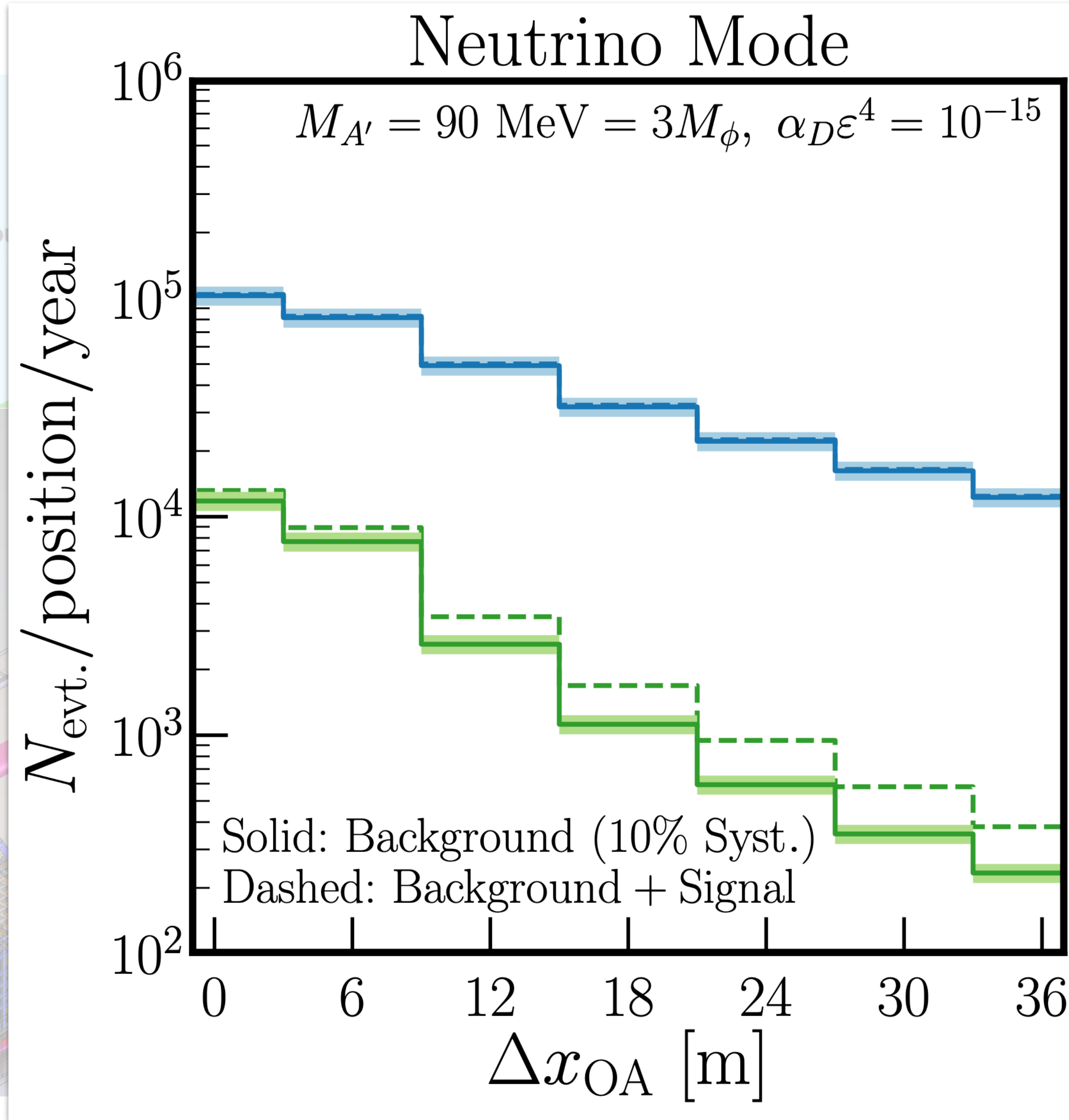
- DUNE-PRISM allows for movable detector, up to ~24 m off axis.
- Movable detector means sampling neutrino (and DM) flux at different off-axis angles.

# Why DUNE-ND?

De Romeri, Kelly, Machado [1903.10505]



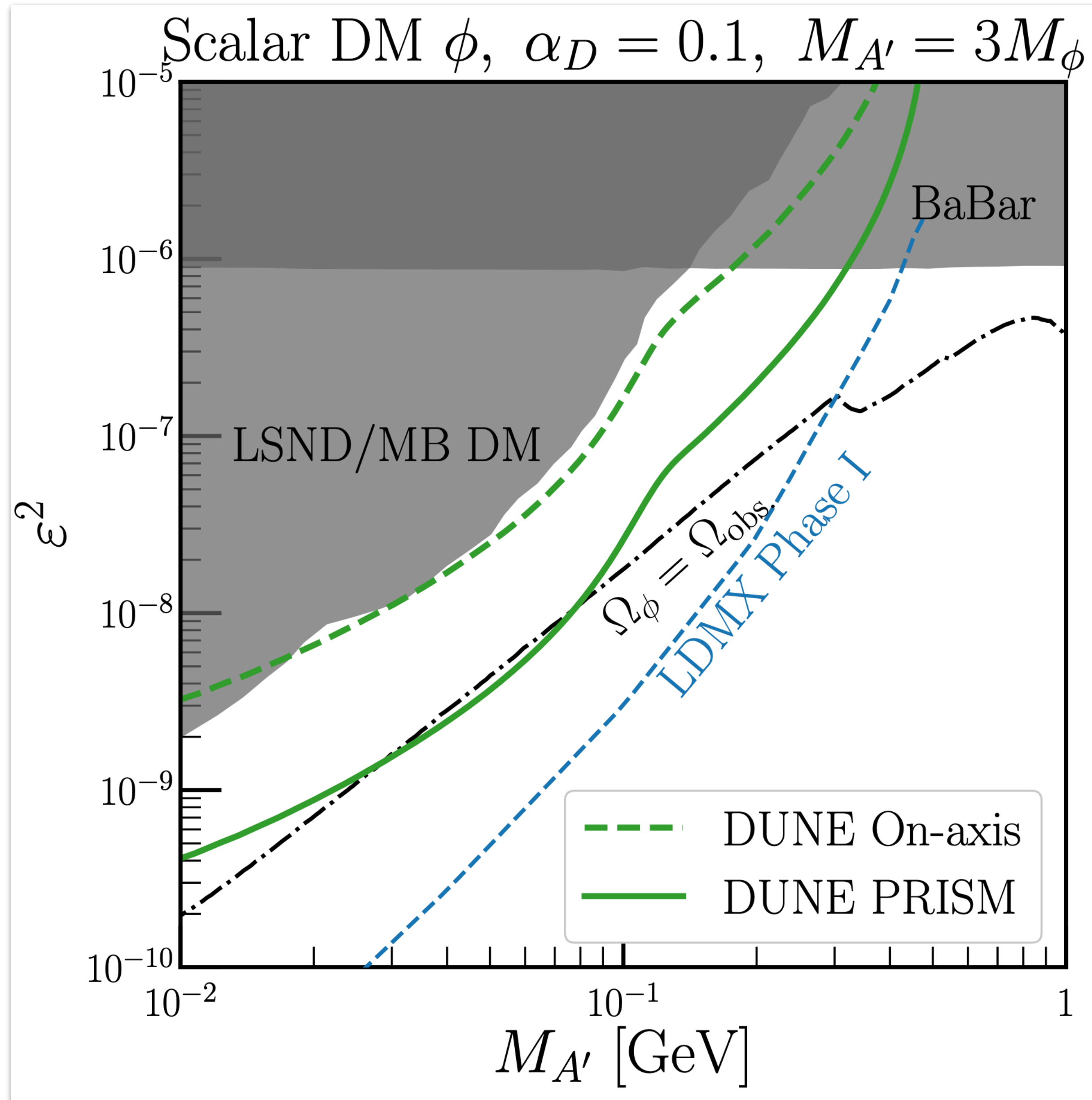
DUNE Collaboration, [2103.13910]



is for movable  
m off axis.

means  
(and DM) flux  
angles.

# Search Sensitivity

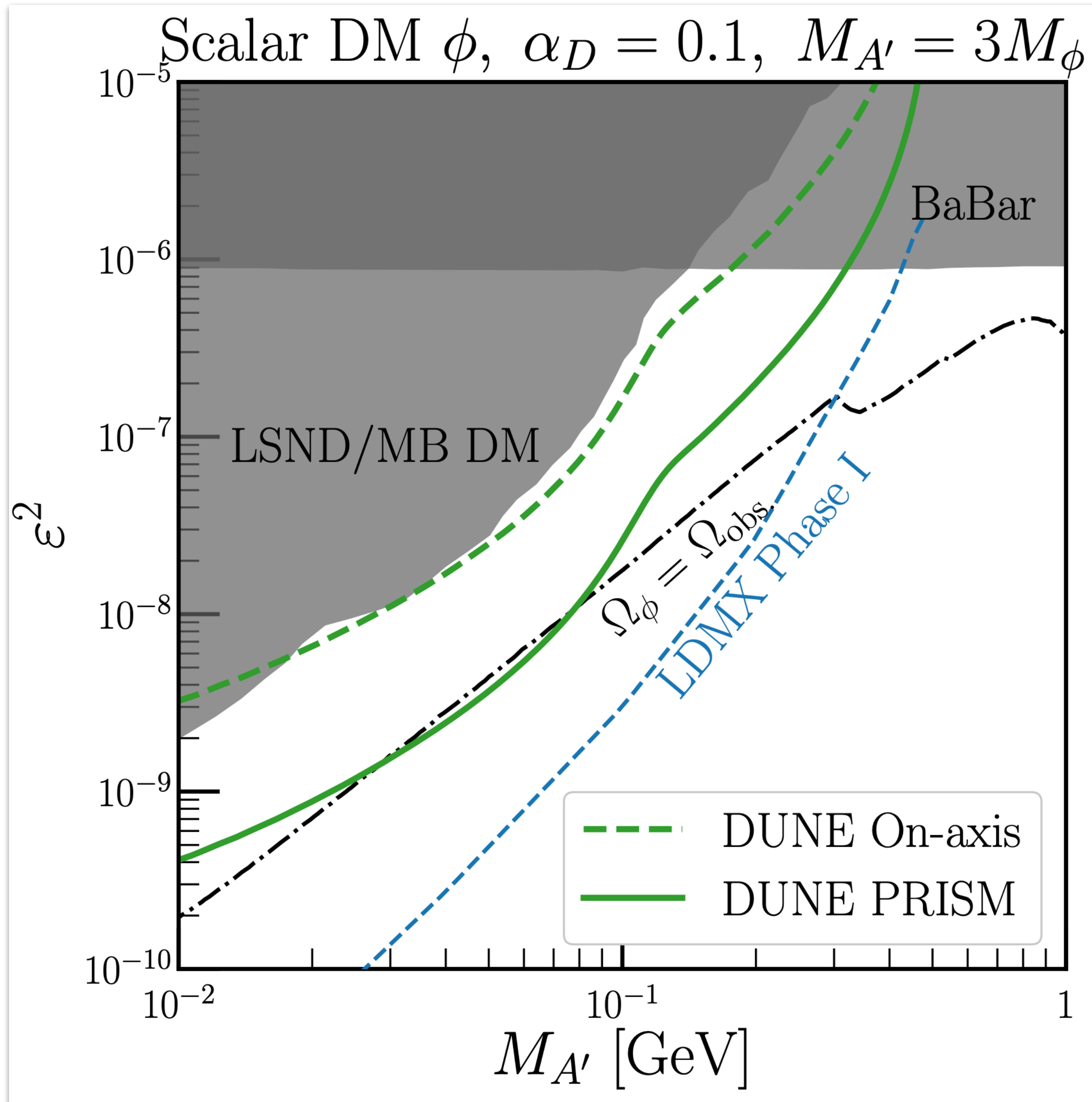


- Combining on- and off-axis searches allows to reduce systematic uncertainties.
- This allows for searches in novel parts of parameter space preferred if  $\phi$  comprises the dark matter.
- Seven years' data at DUNE, reasonably competitive with LDMX Phase I.

Similar study incorporating spectral measurements, etc.:  
Breitbach et al [\[2102.03383\]](#)

Consideration of a DUNE Off-Target mode:  
Brdar et al [\[2206.06380\]](#)

# Search Sensitivity



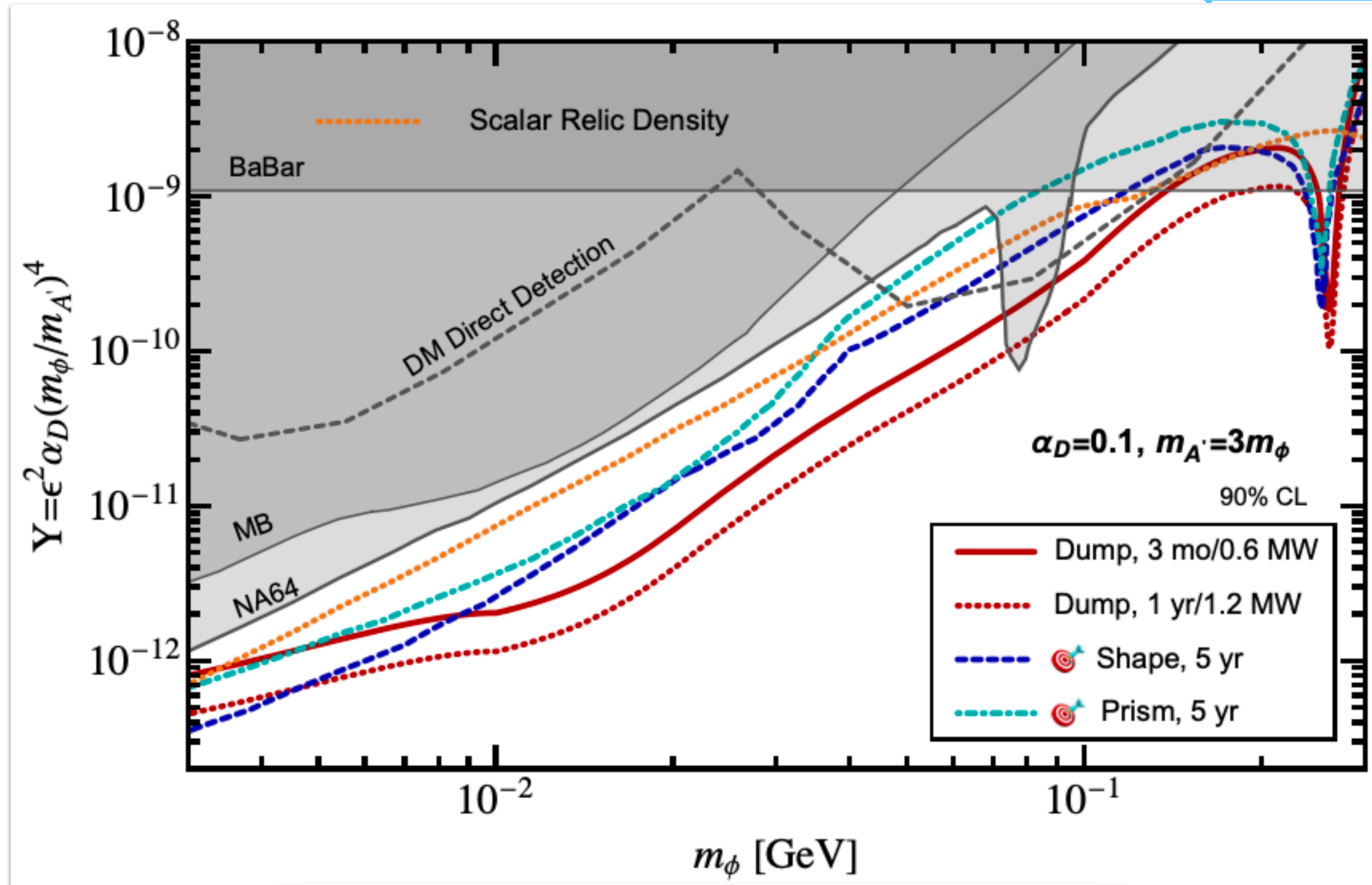
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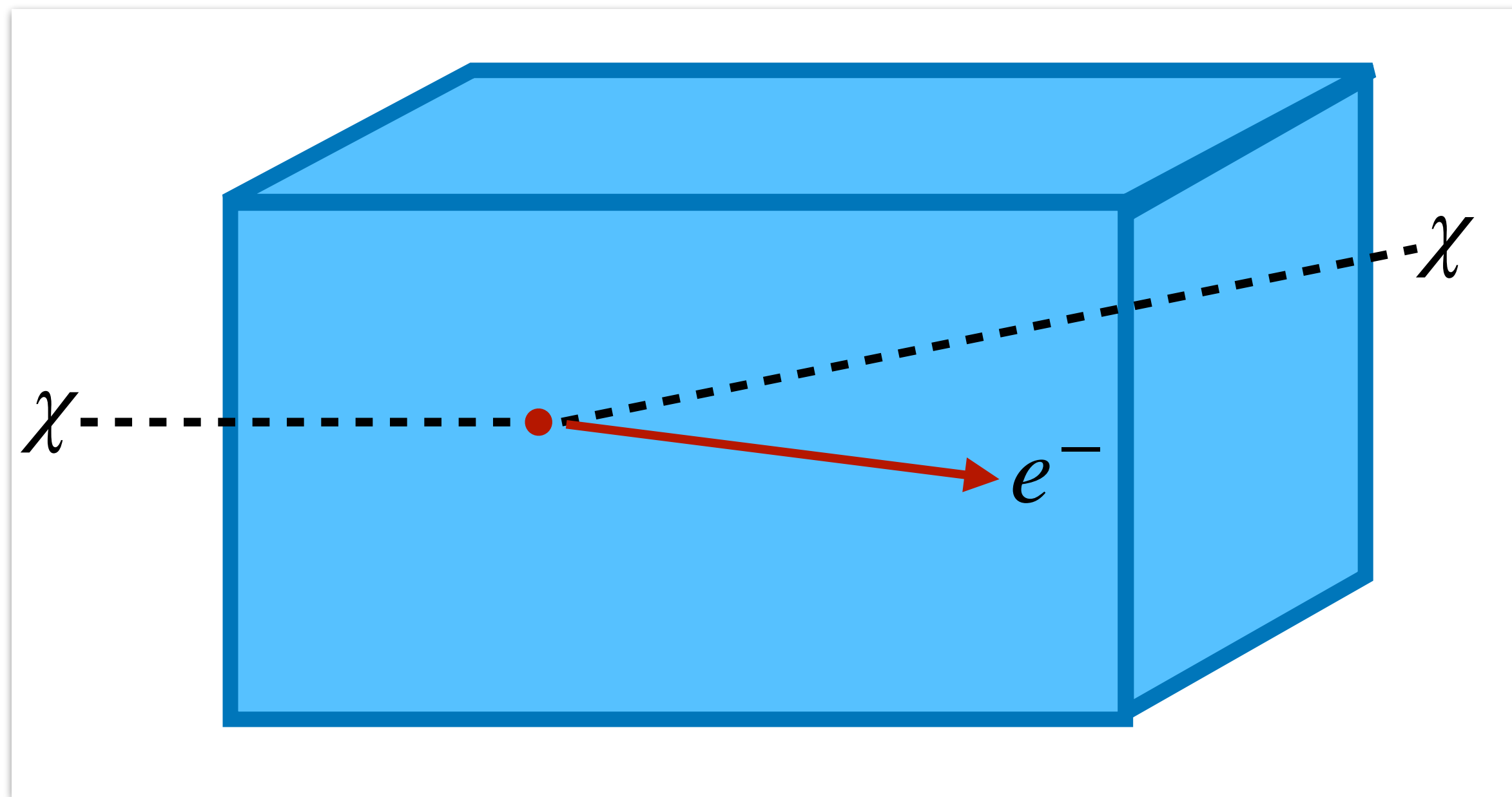
# “Target-less” DUNE in a Phase-II Era?

Brdar et al [\[2206.06380\]](#)



# Complementarity of Neutrino Detectors

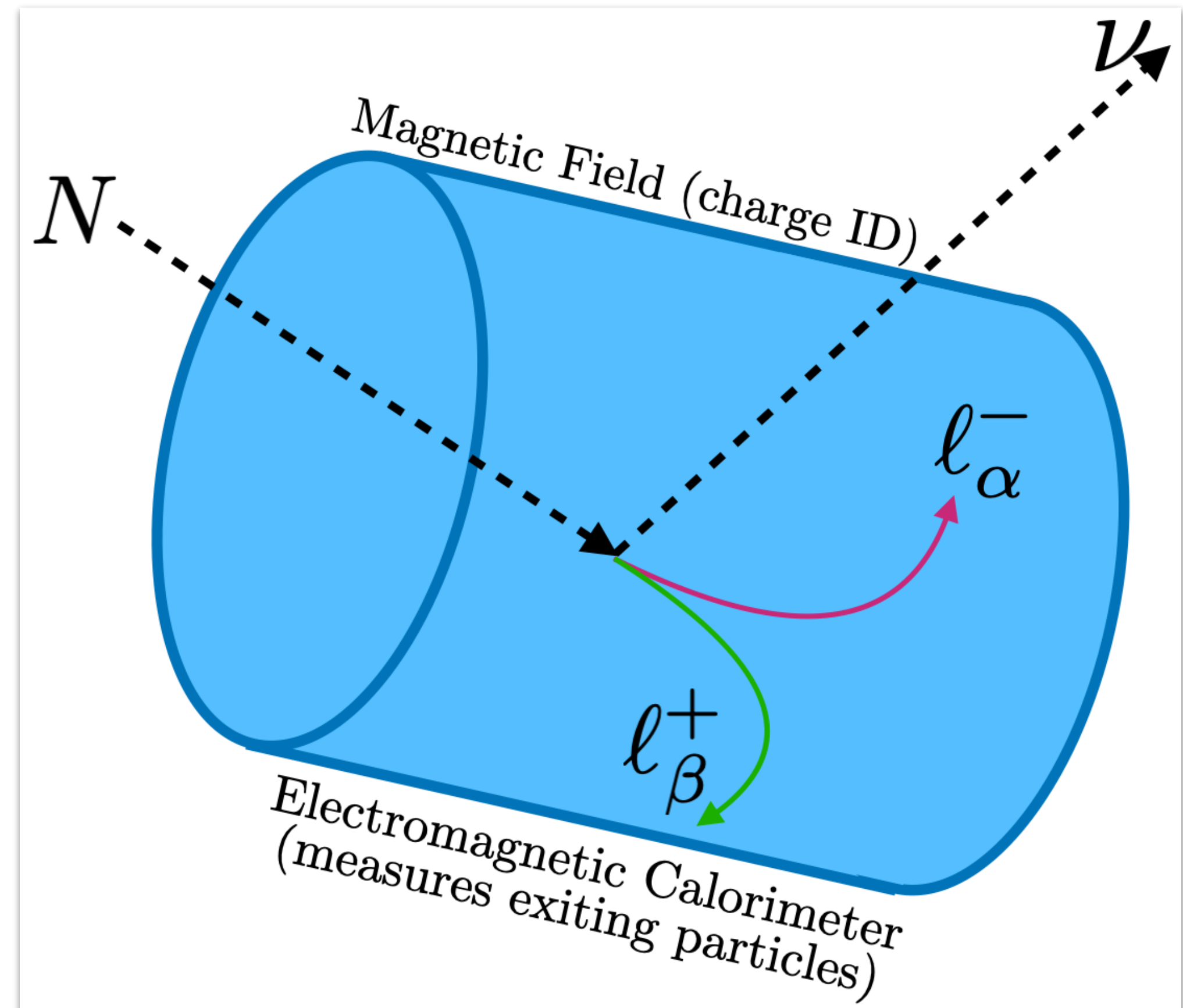
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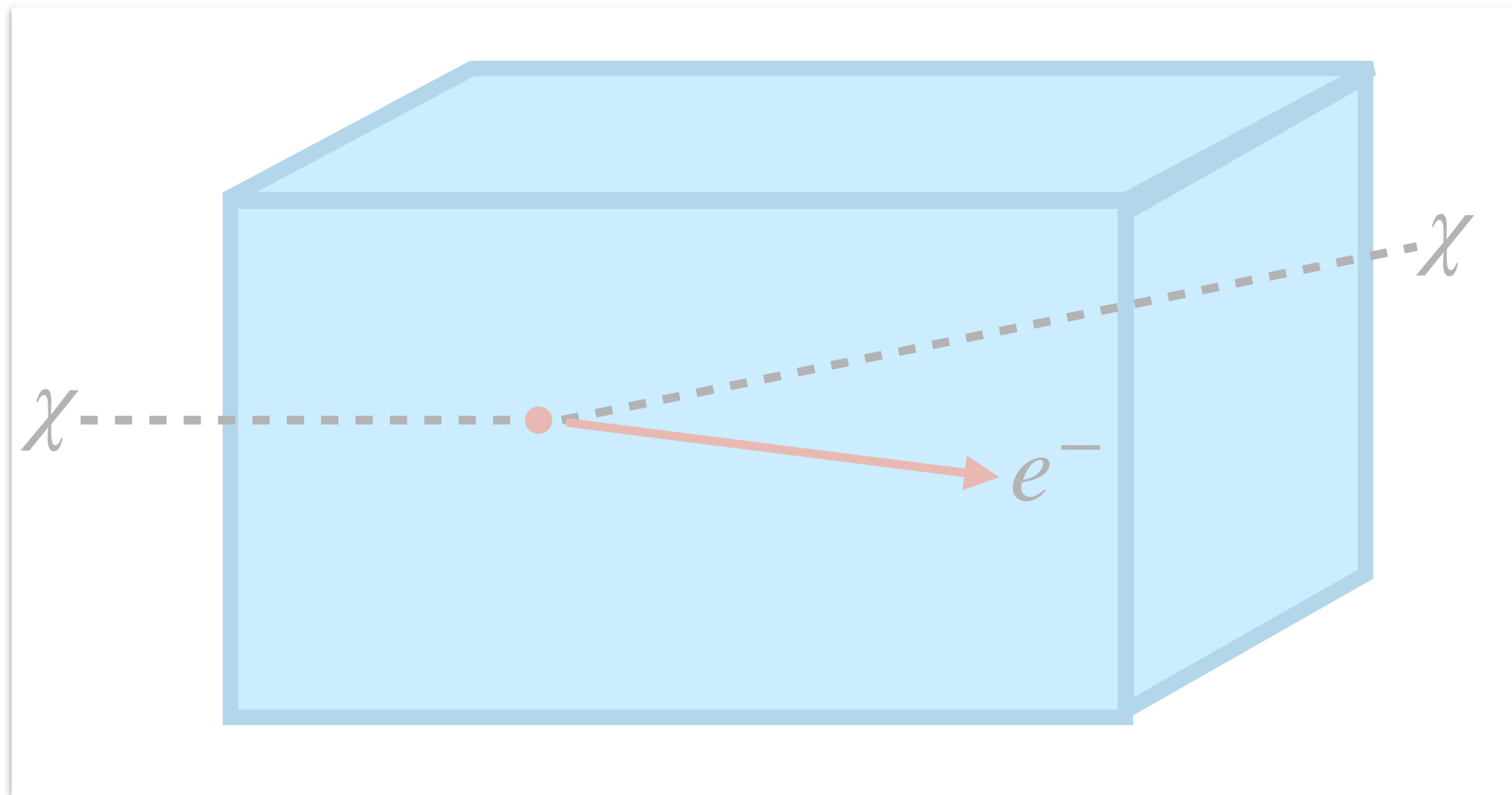
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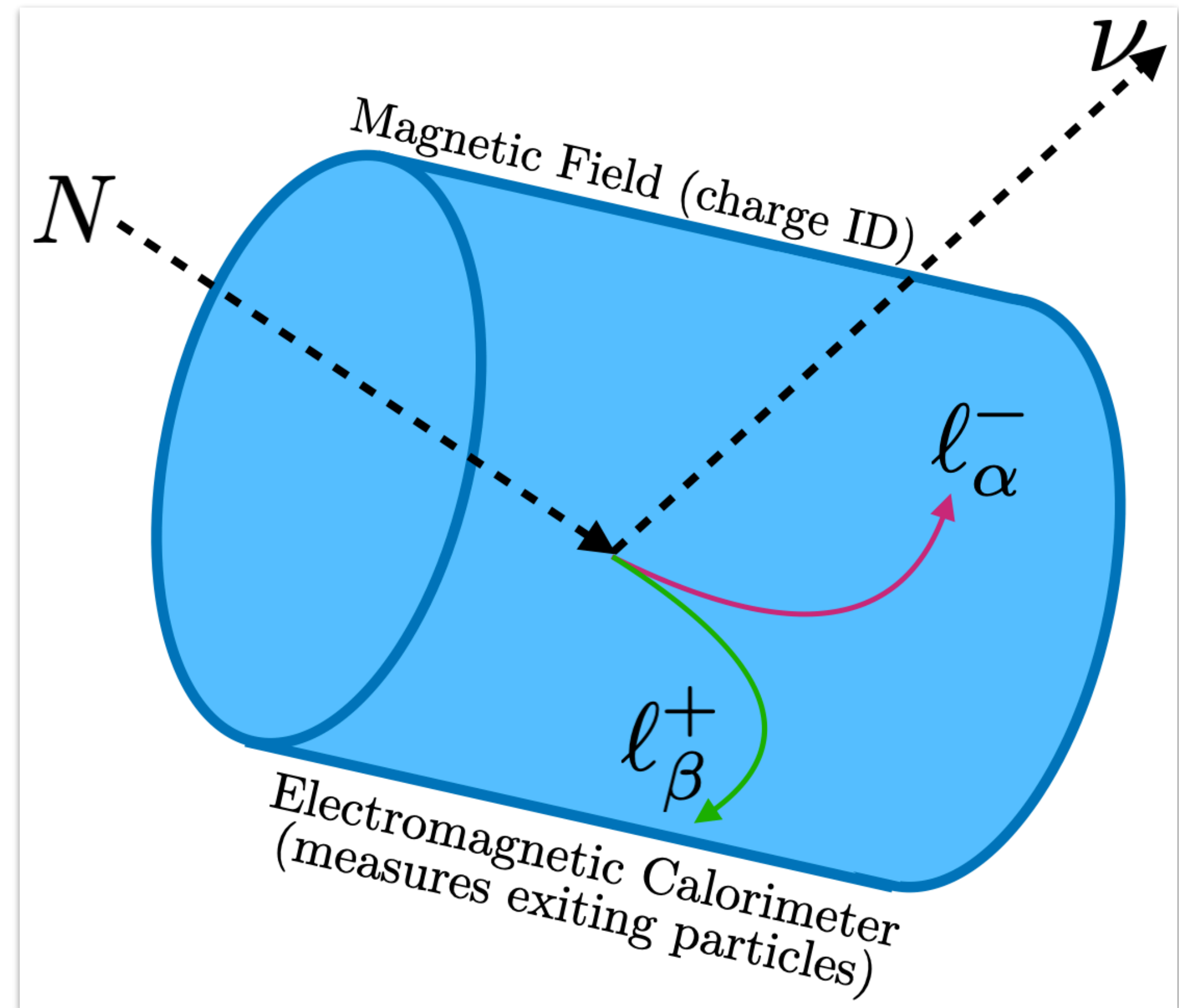
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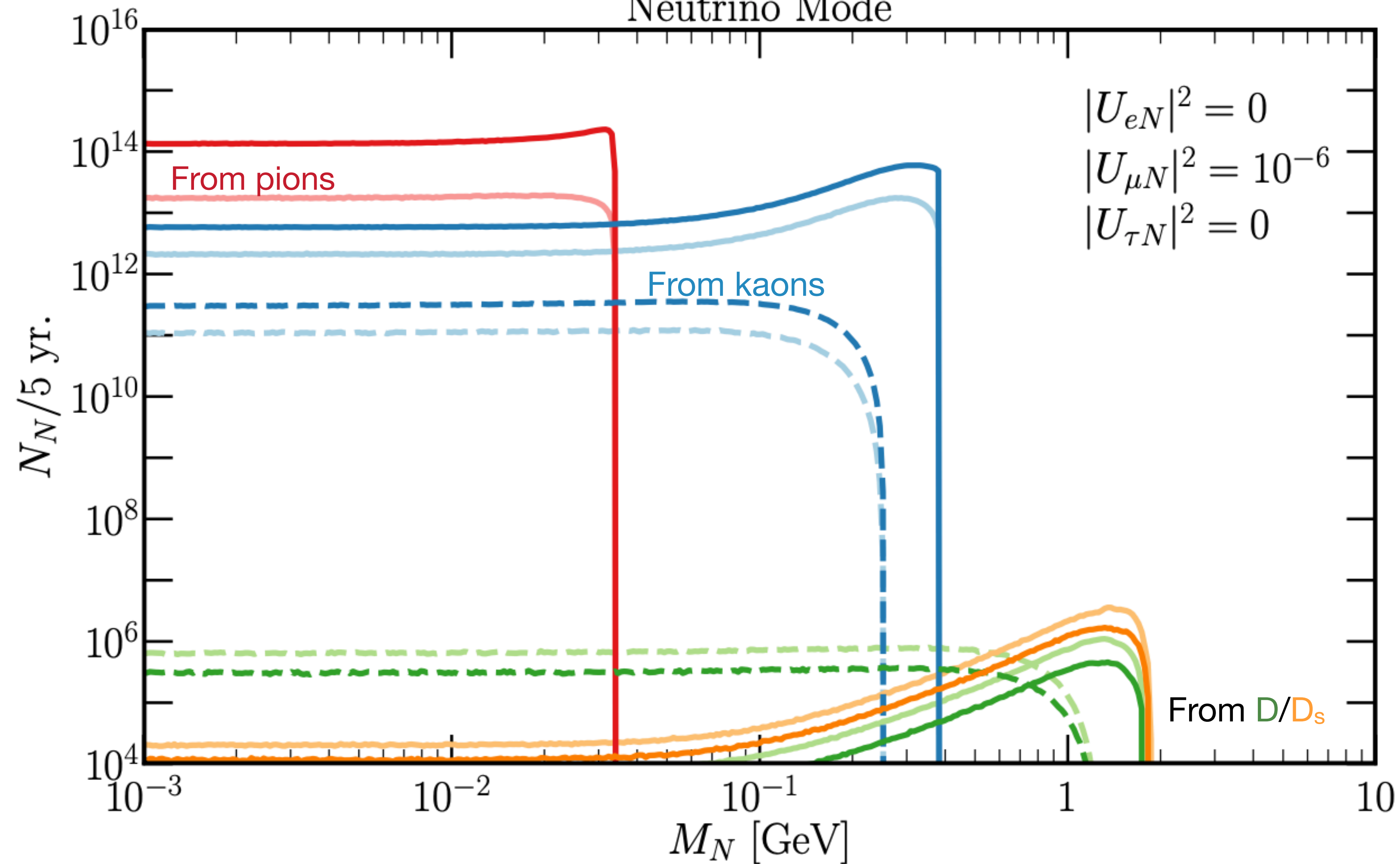
# HNLs in the DUNE Beam

Berryman, de Gouvêa, Fox, Kayser, **KJK**, Raaf [[1912.07622](#)]  
Neutrino Mode

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

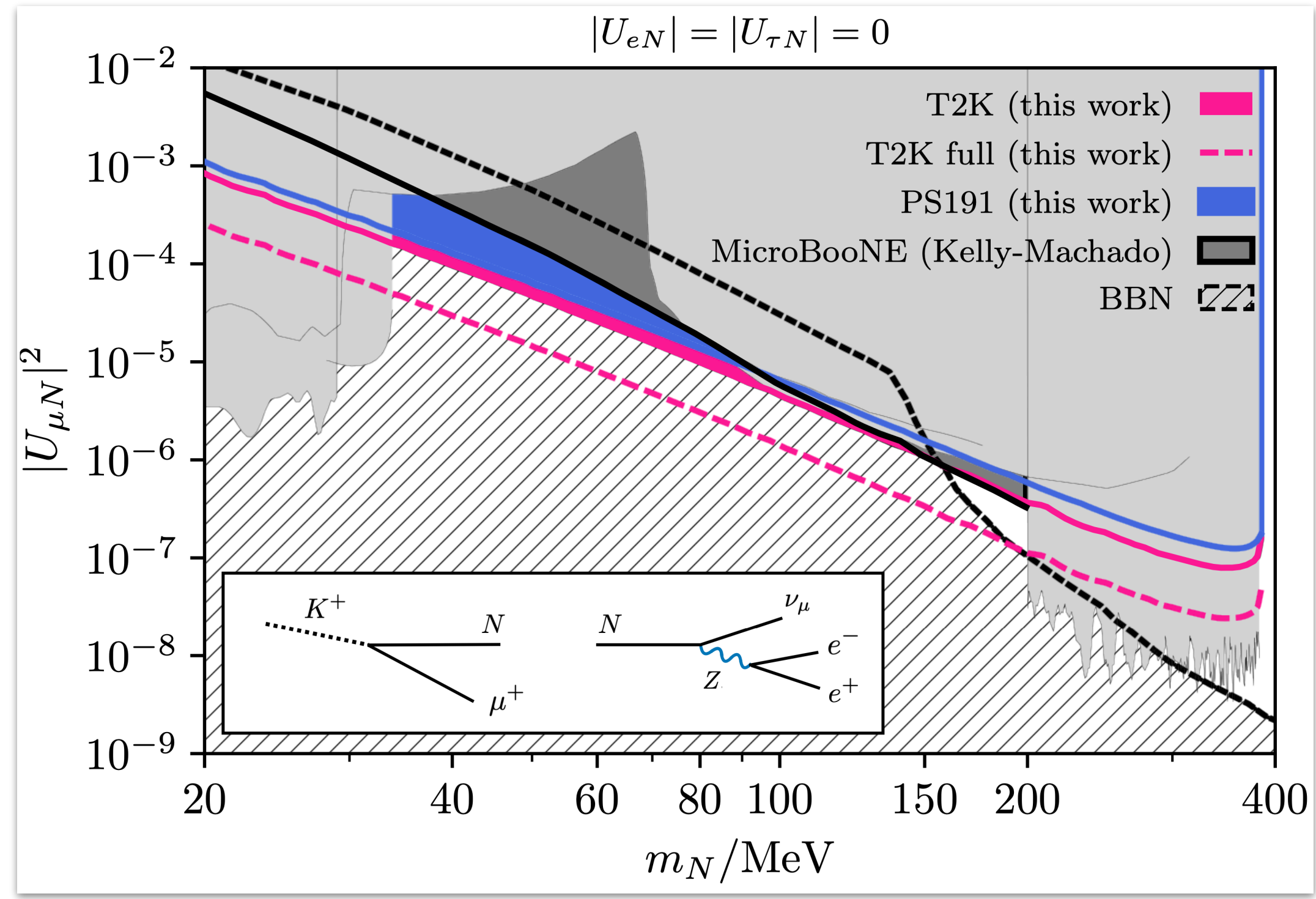
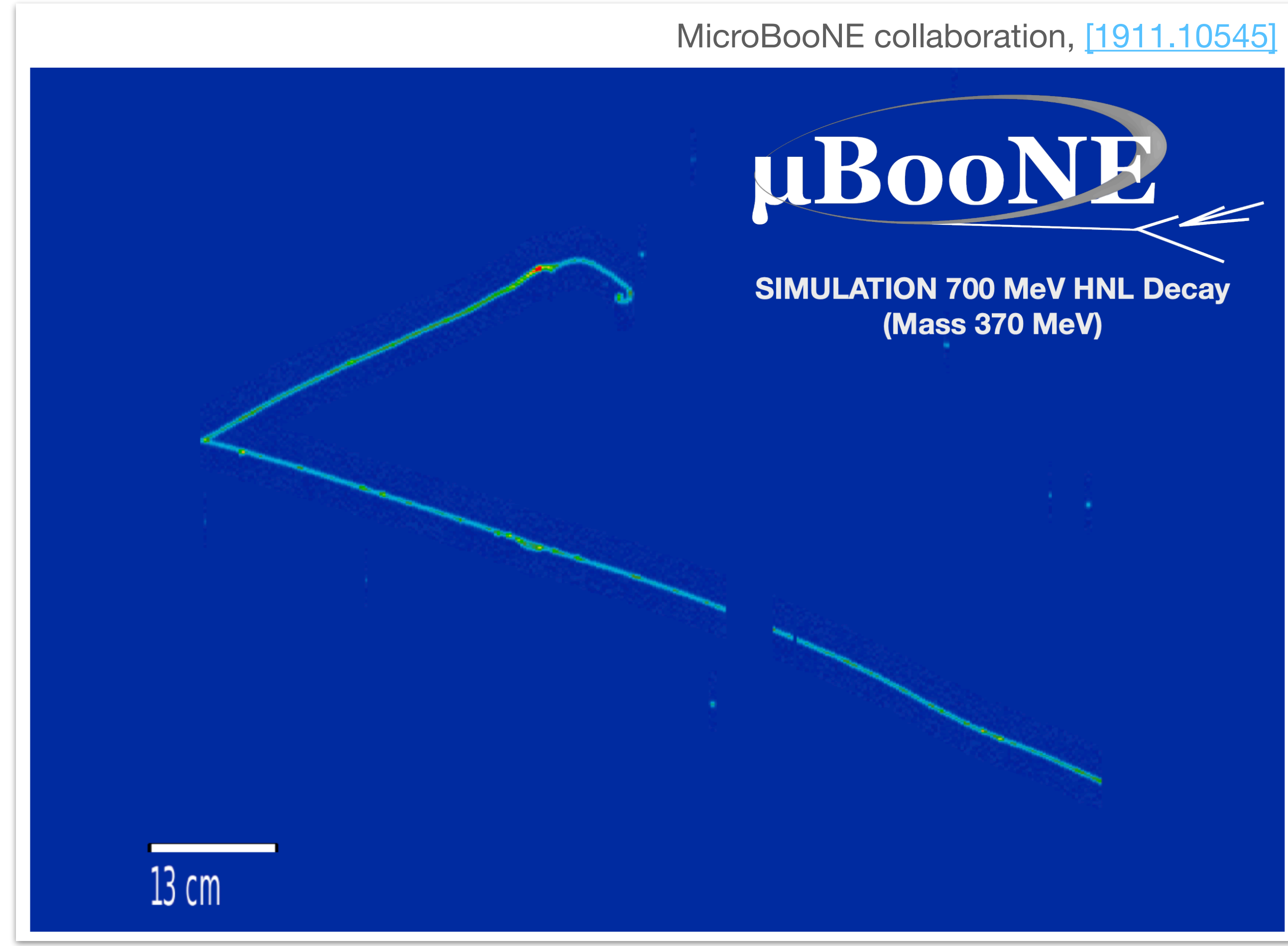
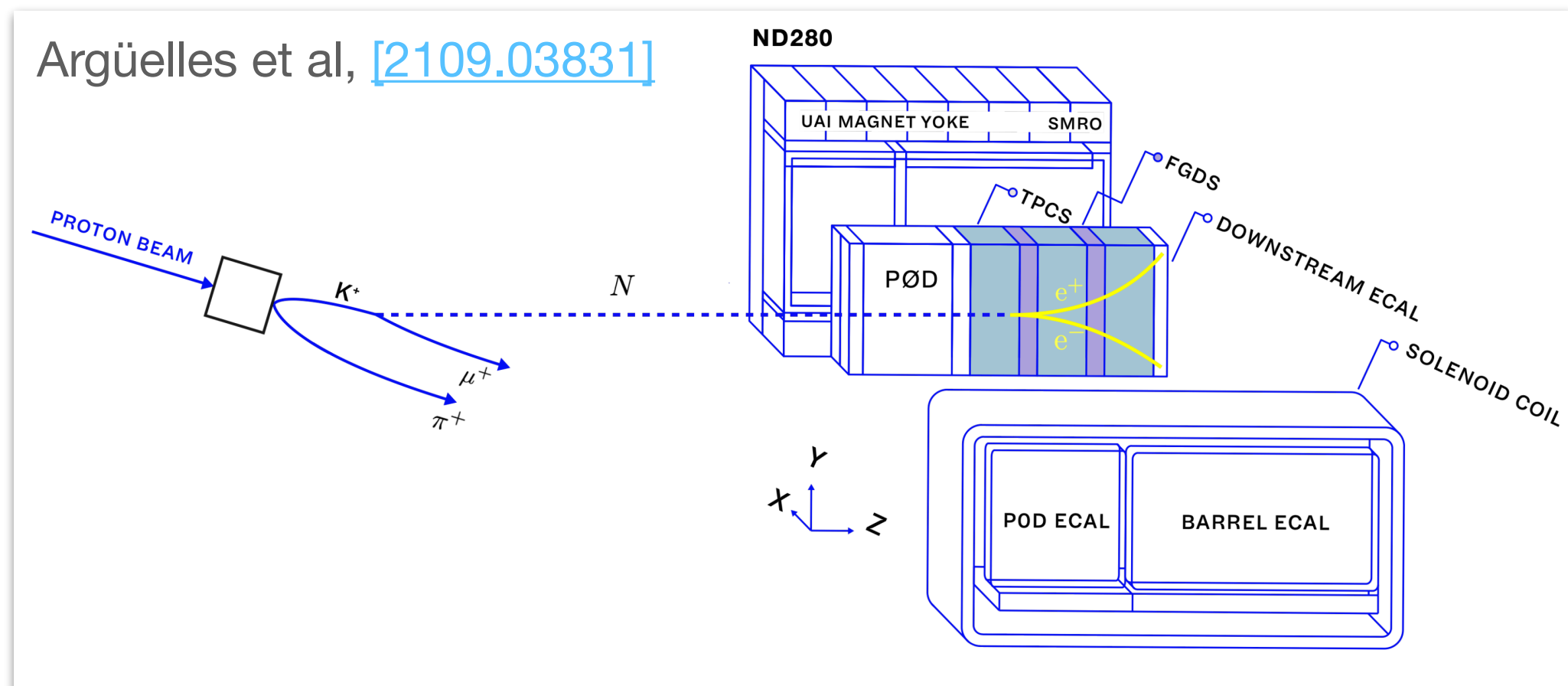
Includes acceptance efficiency — small solid angle for a detector like DUNE-ND.

Similar fluxes are easy\* to simulate for different target/detector configurations.



Mass-reach of HNLs limited by beam energy: what SM mesons can be produced?

# Current Searches — T2K & MicroBooNE



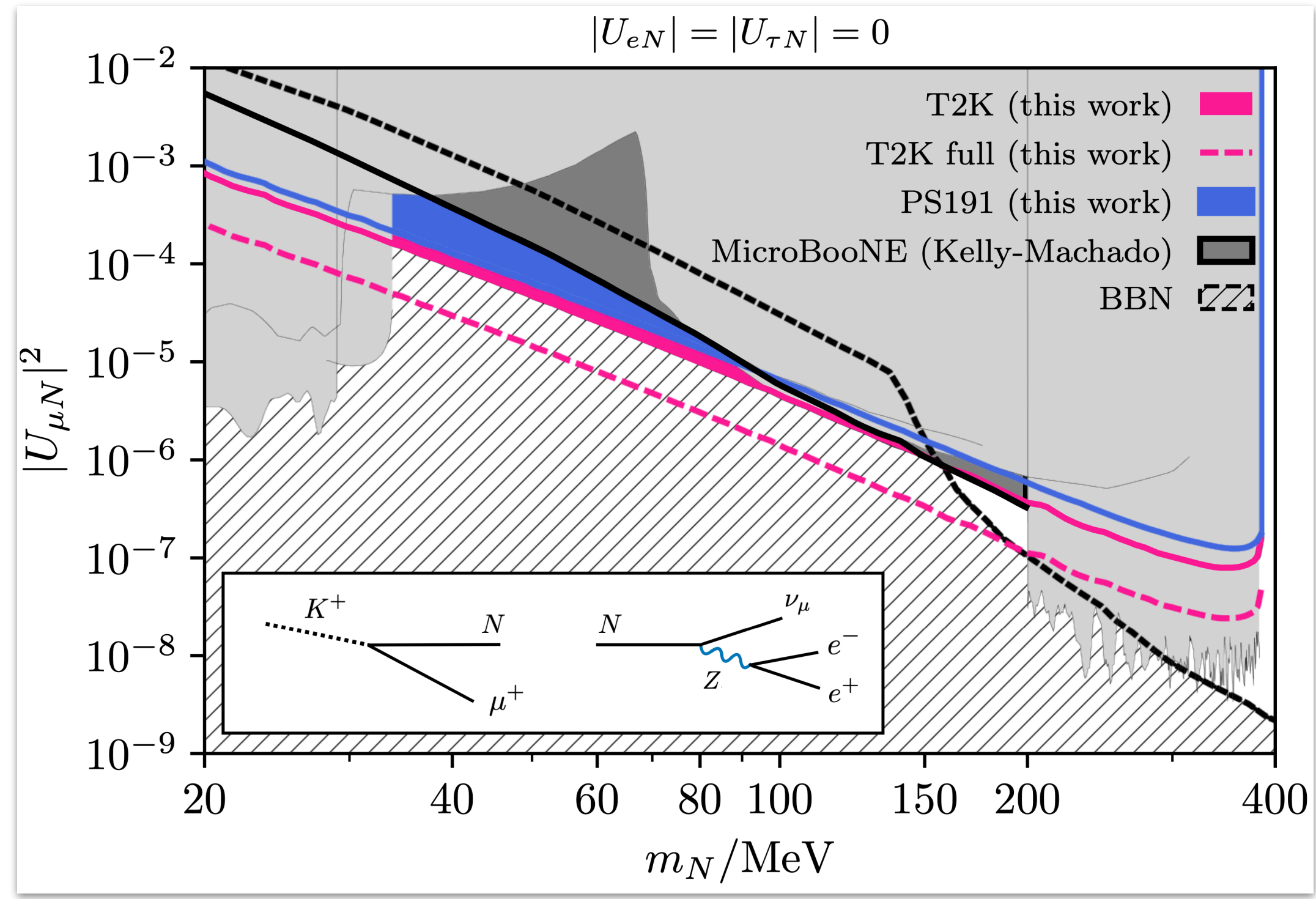
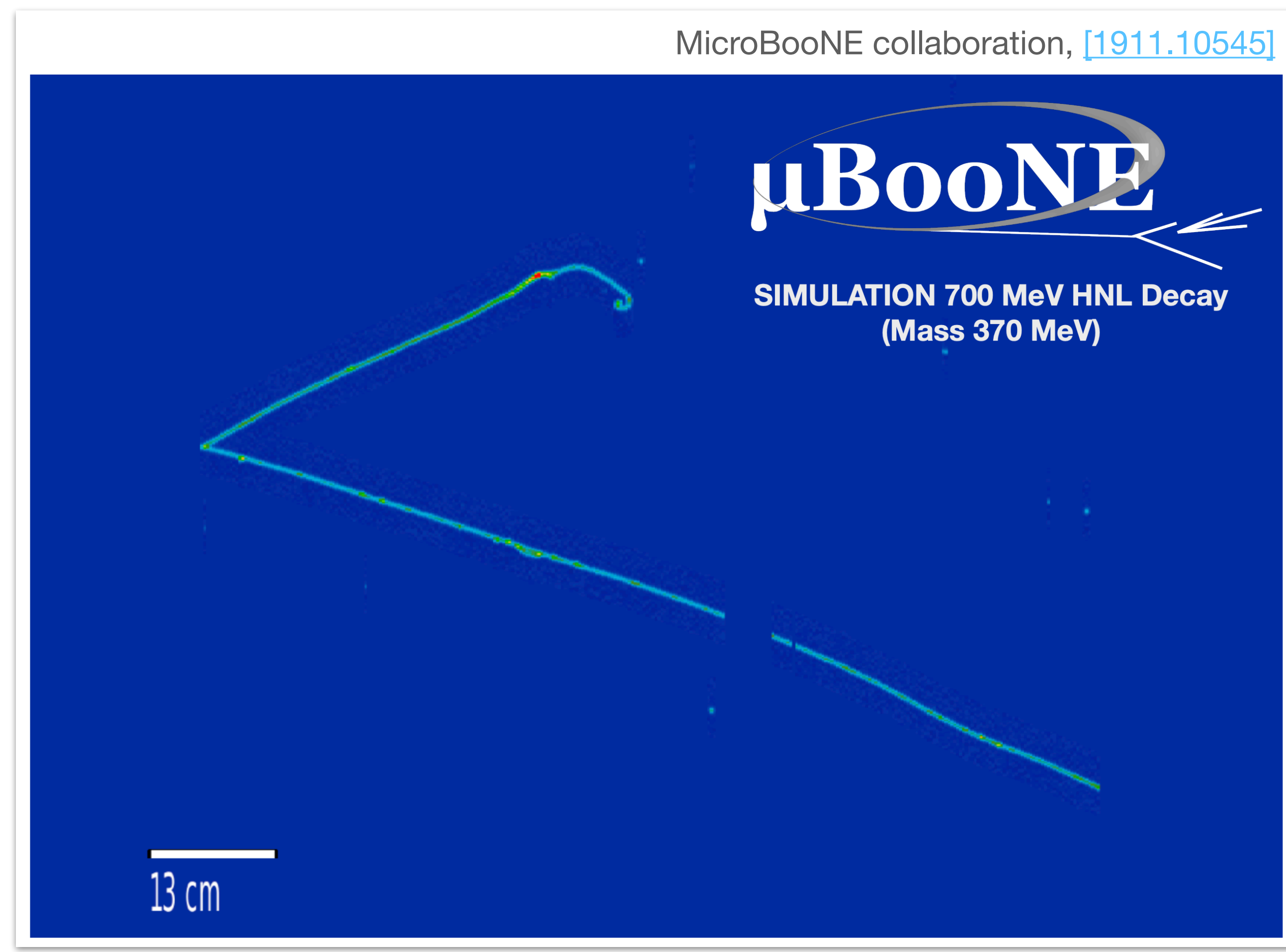
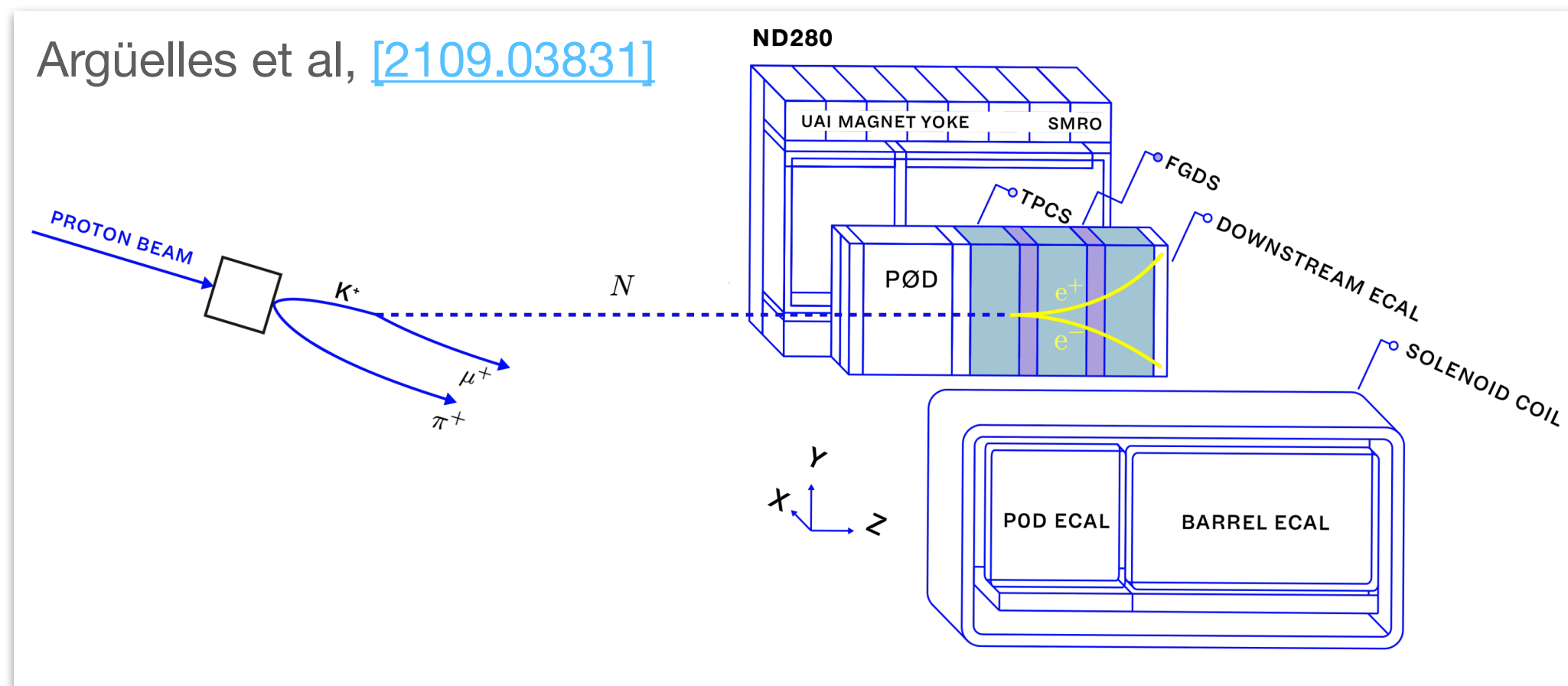
See also: T2K collaboration, [\[1902.07598\]](#)

Limiting factor in many current searches? **Background Rejection**

$$N \rightarrow \nu e^+ e^- \approx \text{NC} \pi^0 \rightarrow \gamma \gamma$$

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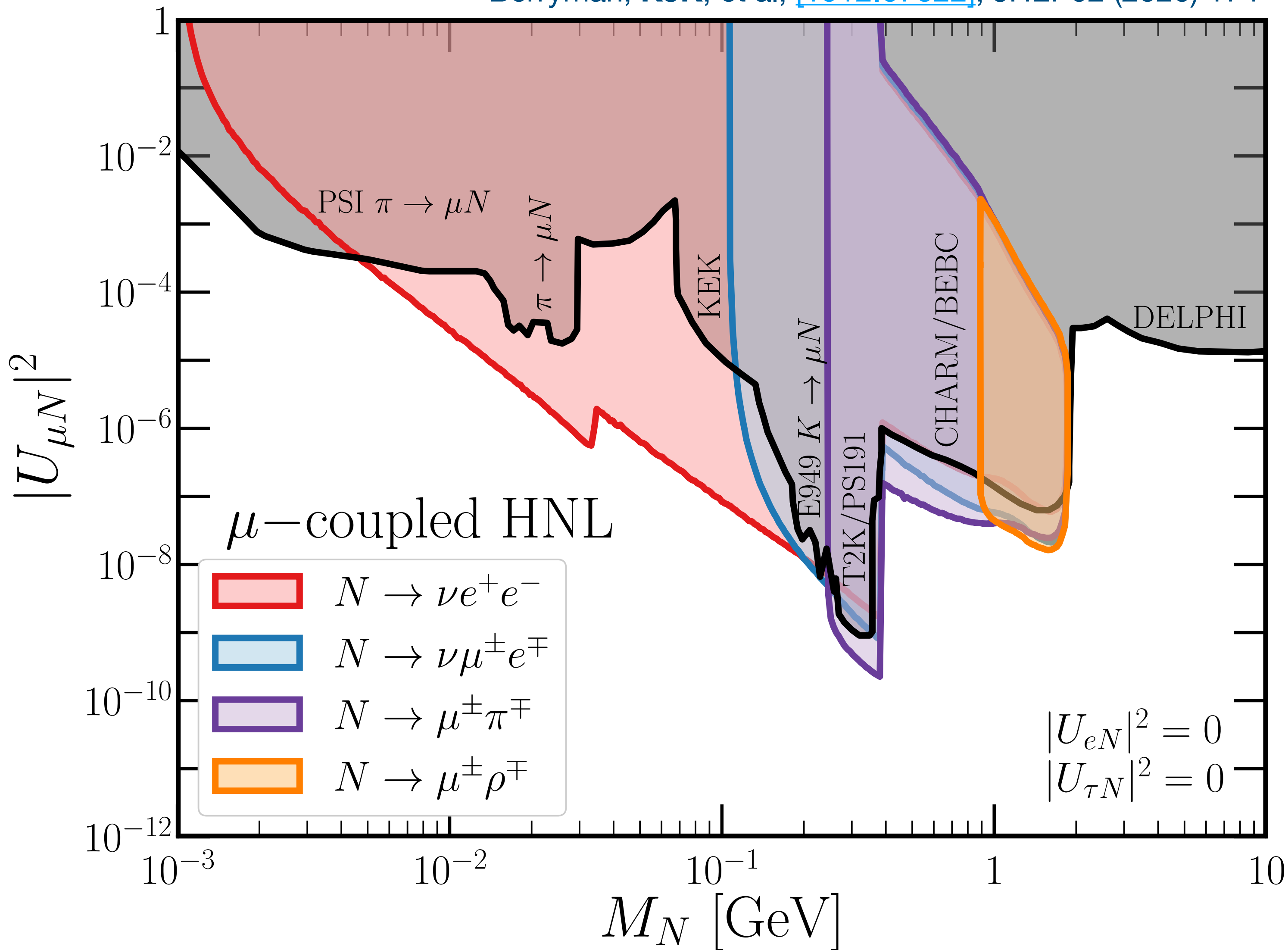
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# Discovery Potential at DUNE-NDGAr

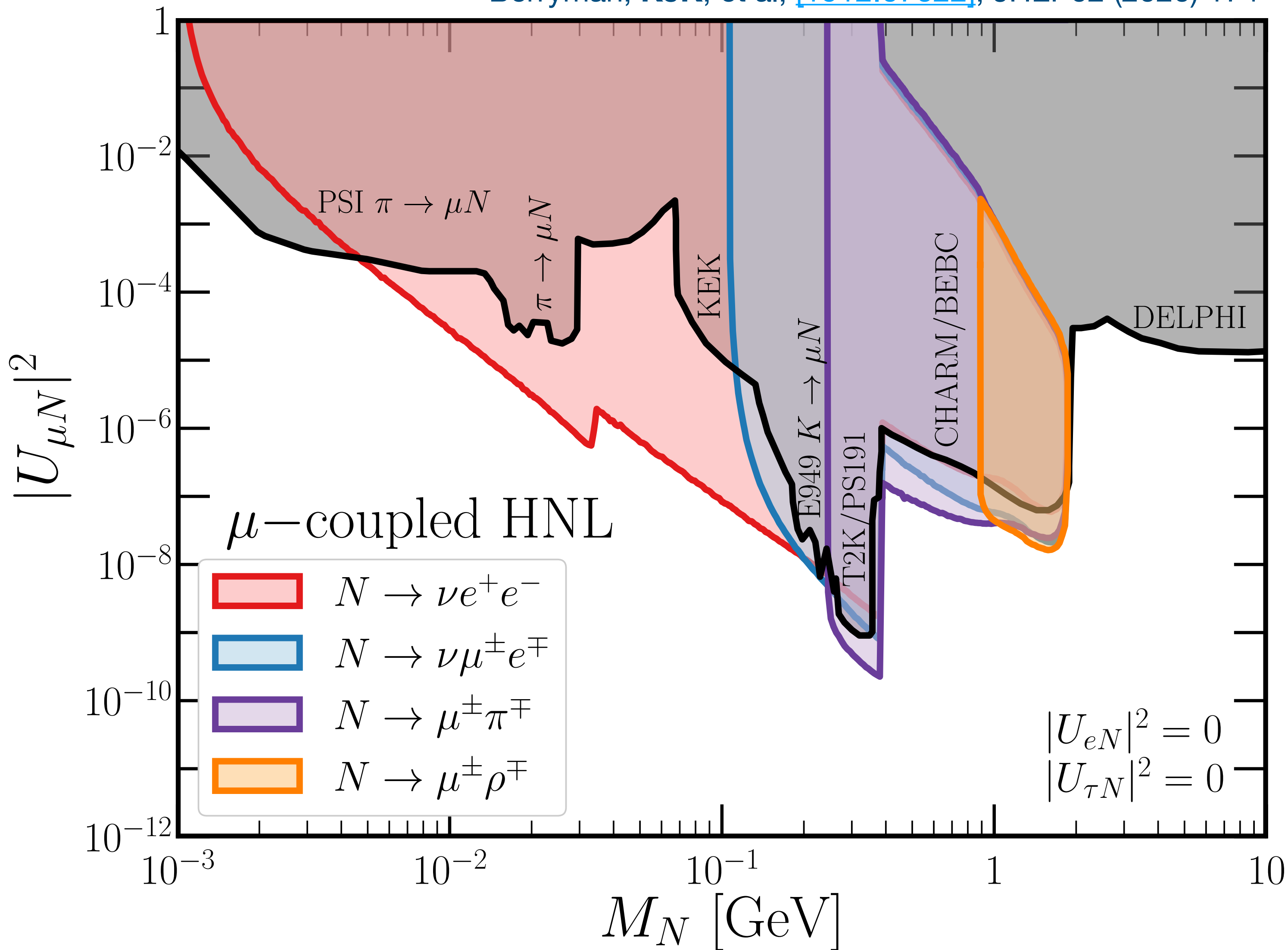
Berryman, **KJK**, et al, [[1912.07622](#)], JHEP02 (2020) 174



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

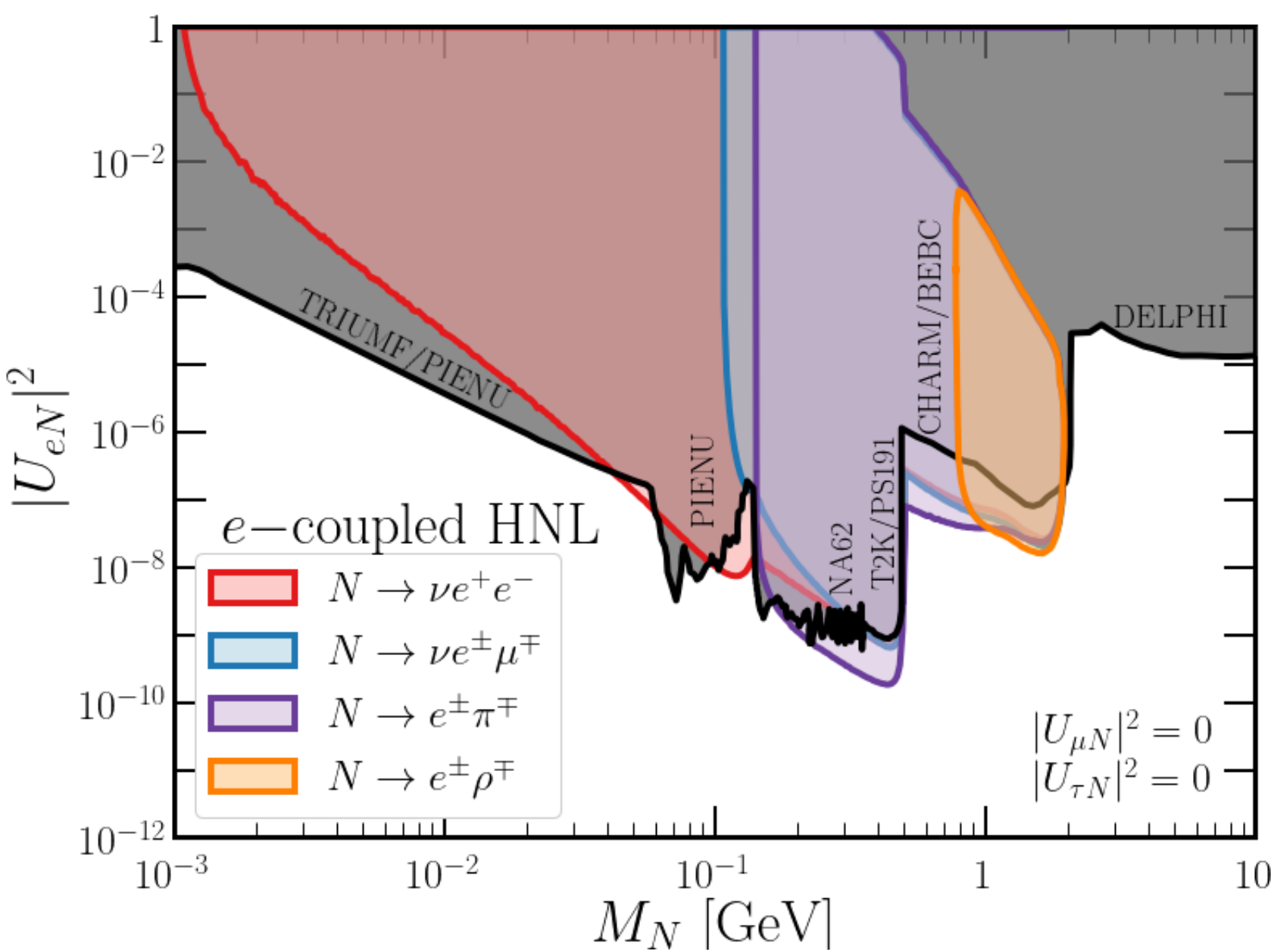
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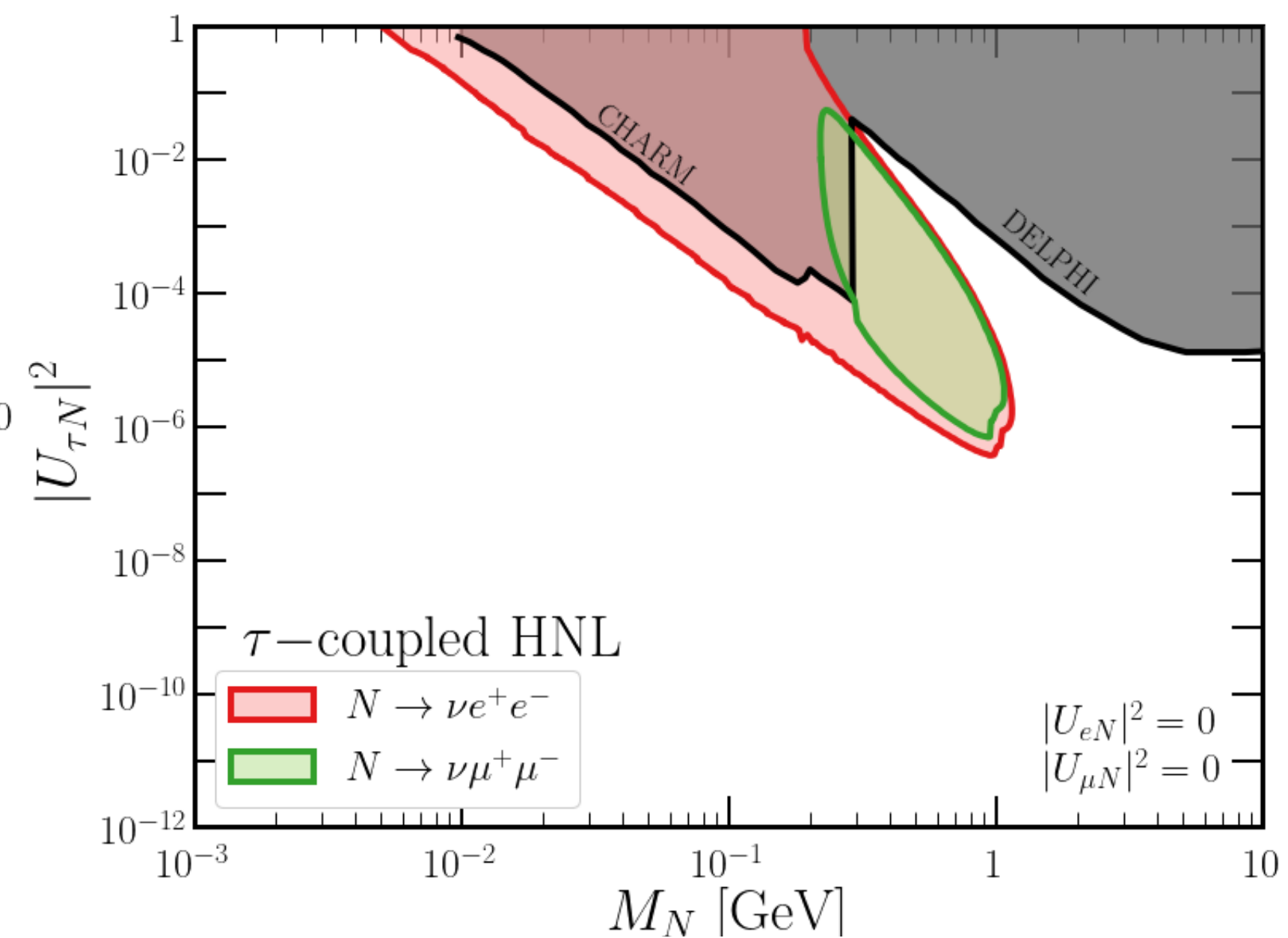
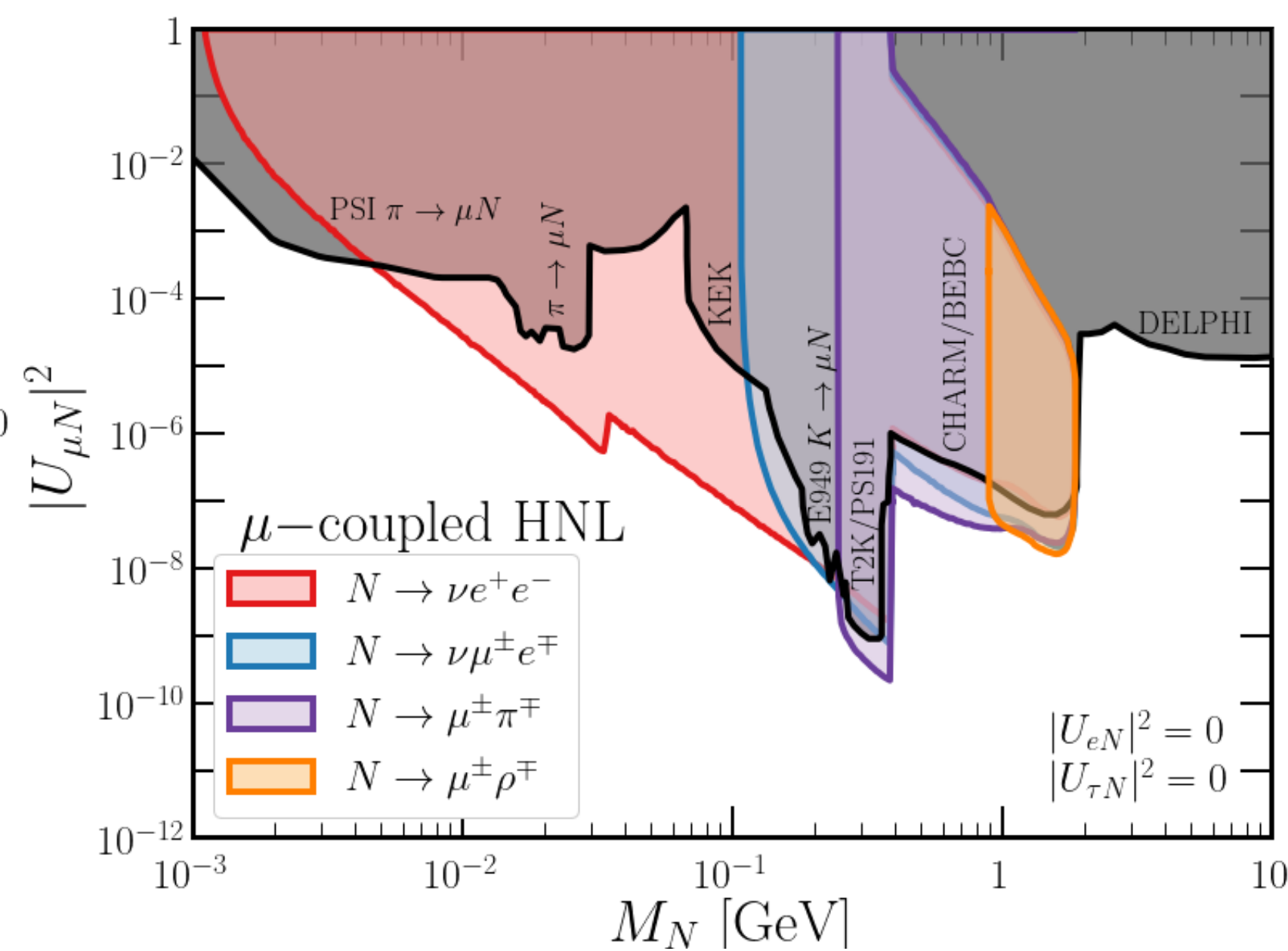


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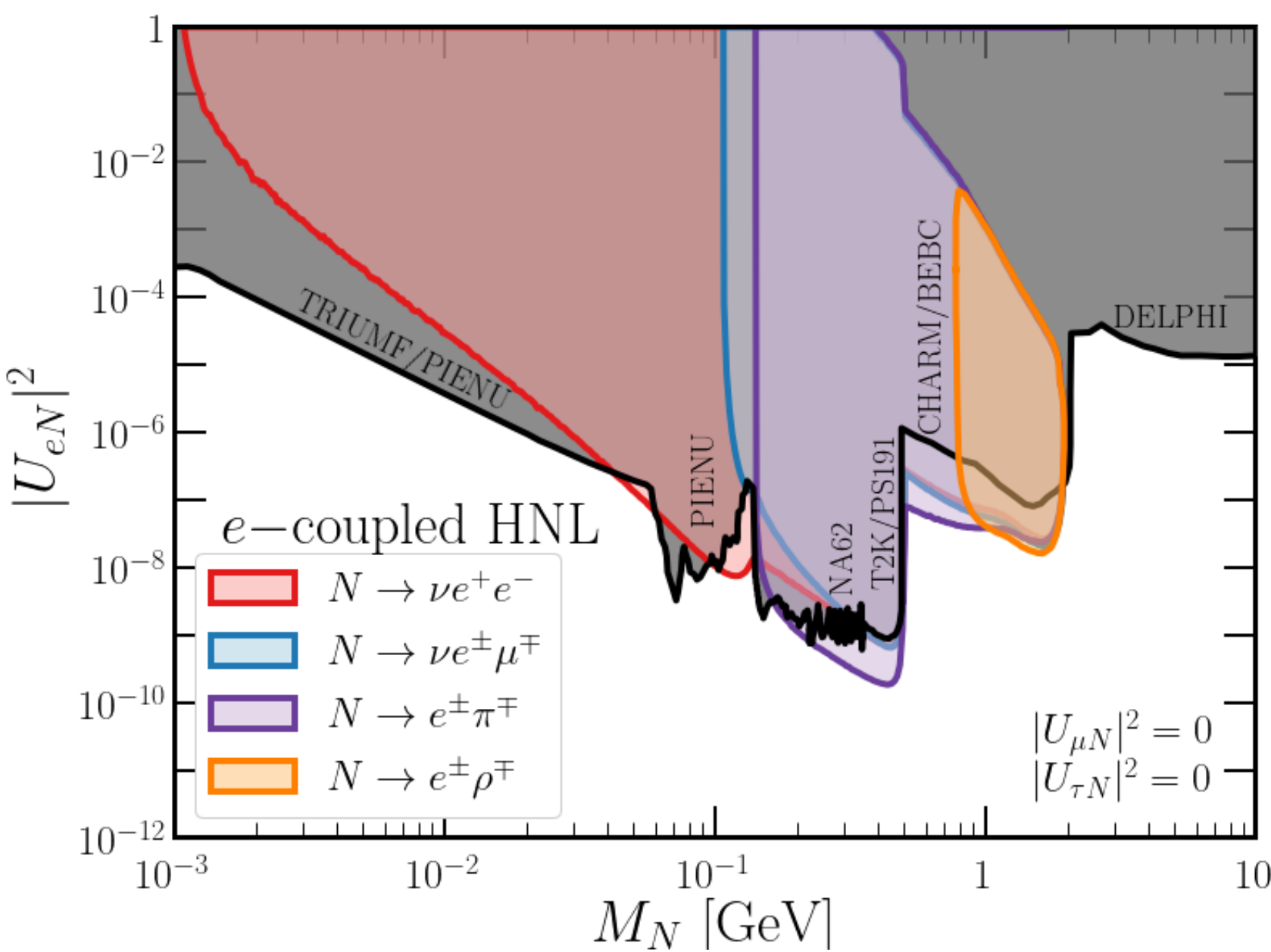


Berryman, de Gouvêa, Fox, Kayser, **KJK**, Raaf [[1912.07622](https://arxiv.org/abs/1912.07622)]

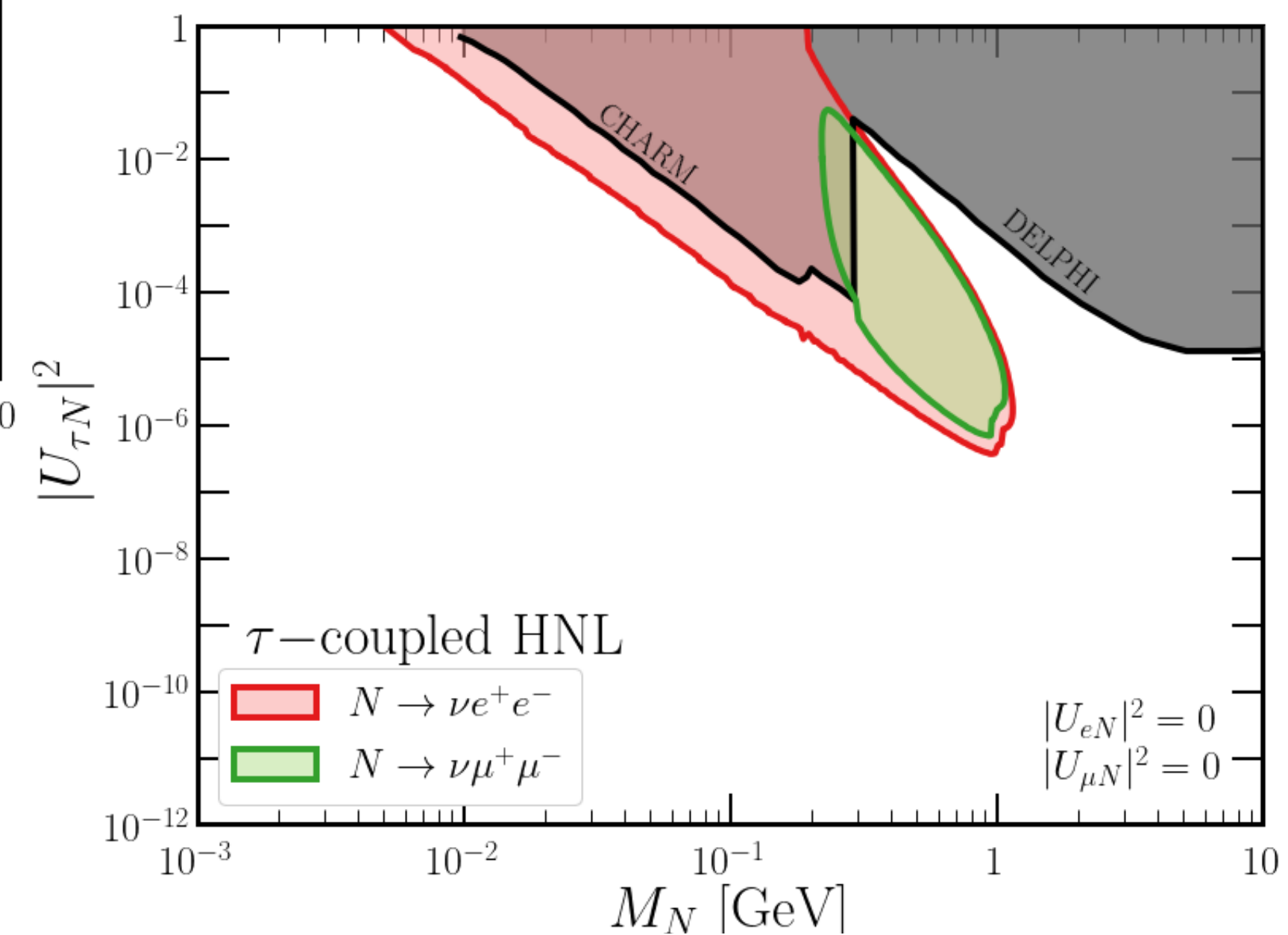
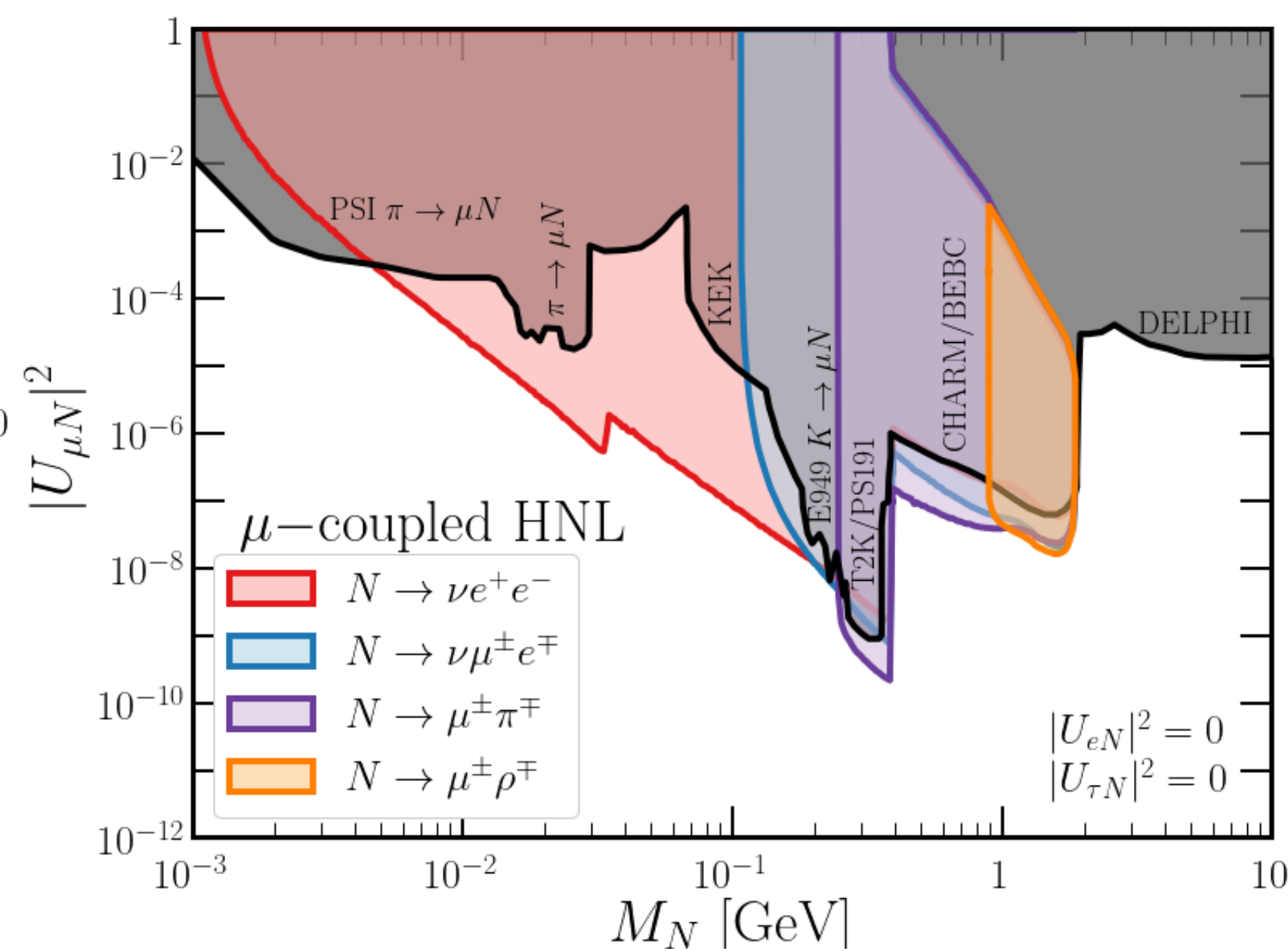


Is there a “smarter” way to think about neutrino detectors and LLP searches, especially with many overlapping final-states?

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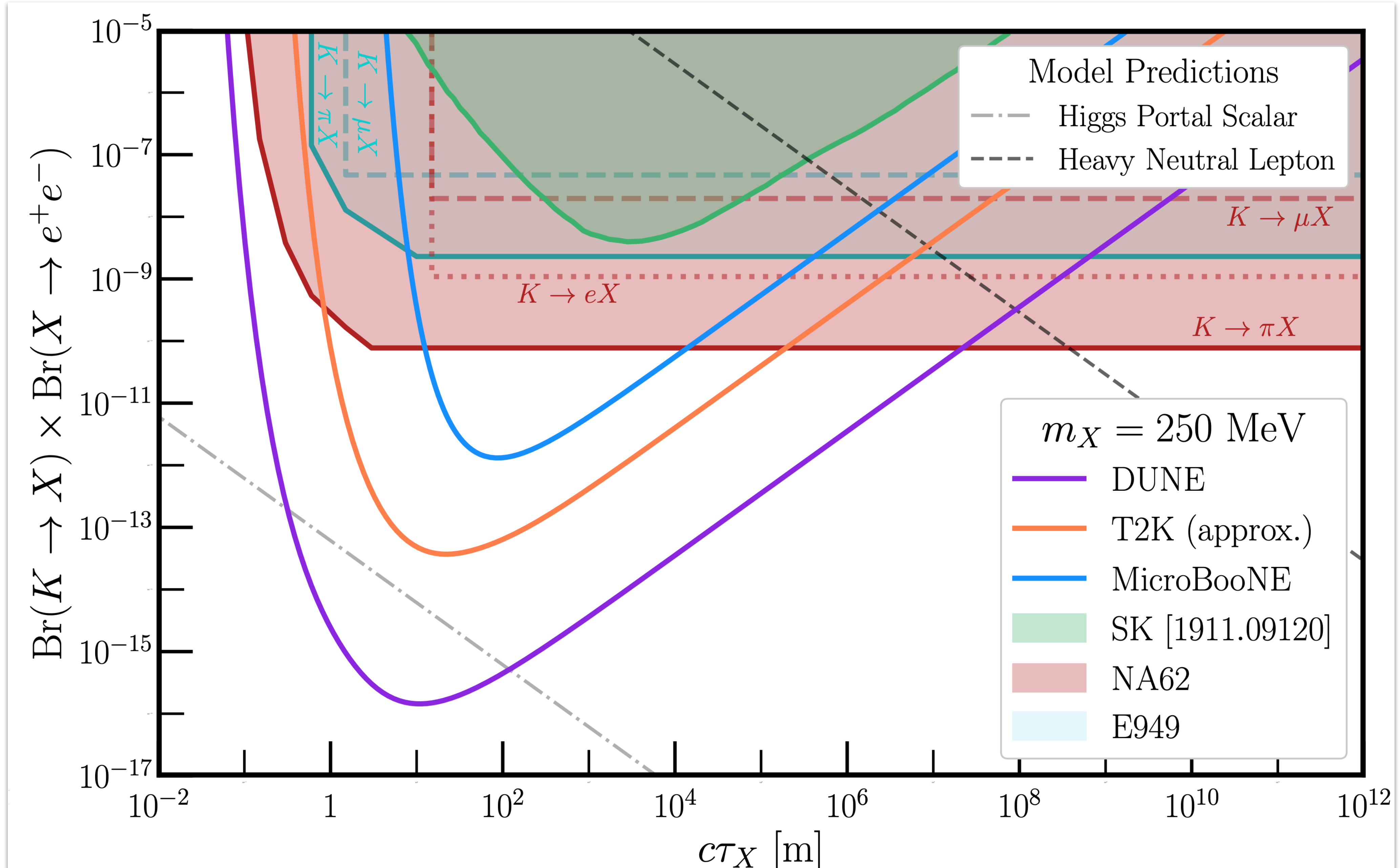


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# Model-Independence in LLP Searches

Batelli, Huang, Kelly, [2304.11189]

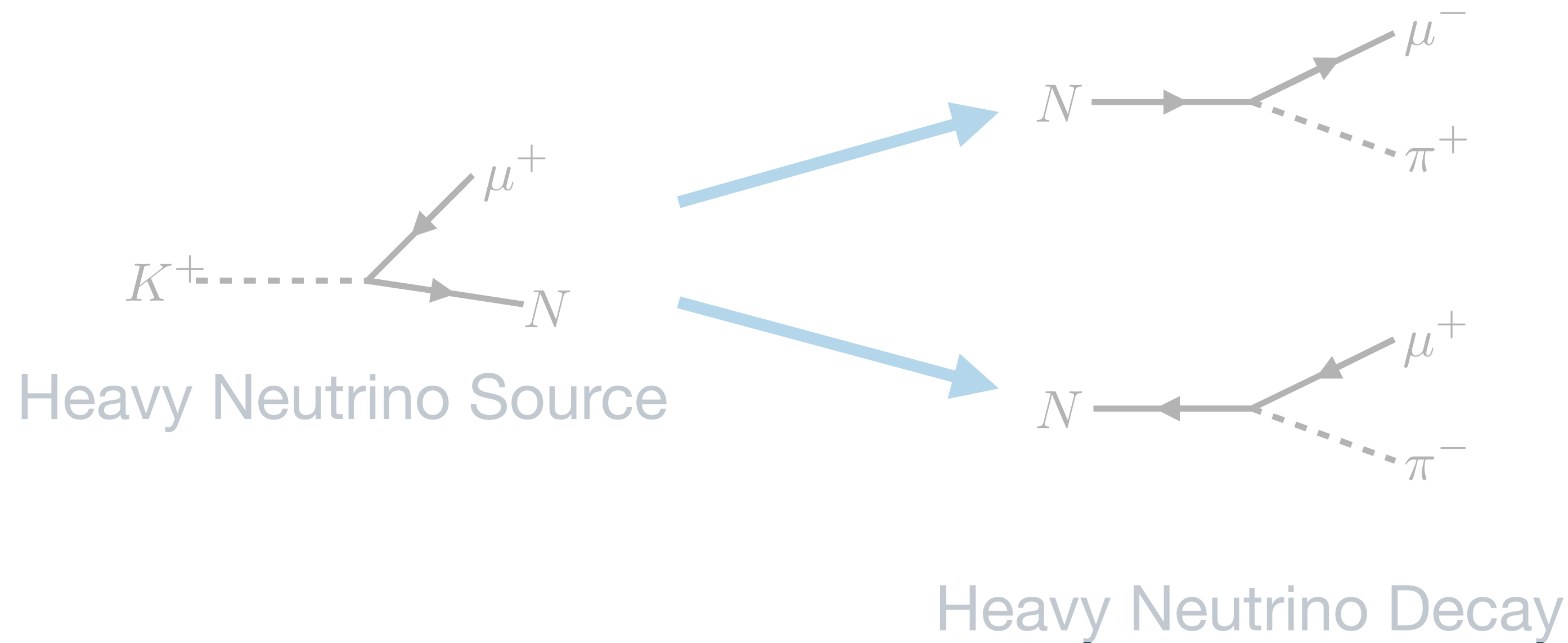


# Lepton-Number-Violation in a (Heavy) Neutrino Beam

Is the new particle a Dirac or Majorana Fermion?



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



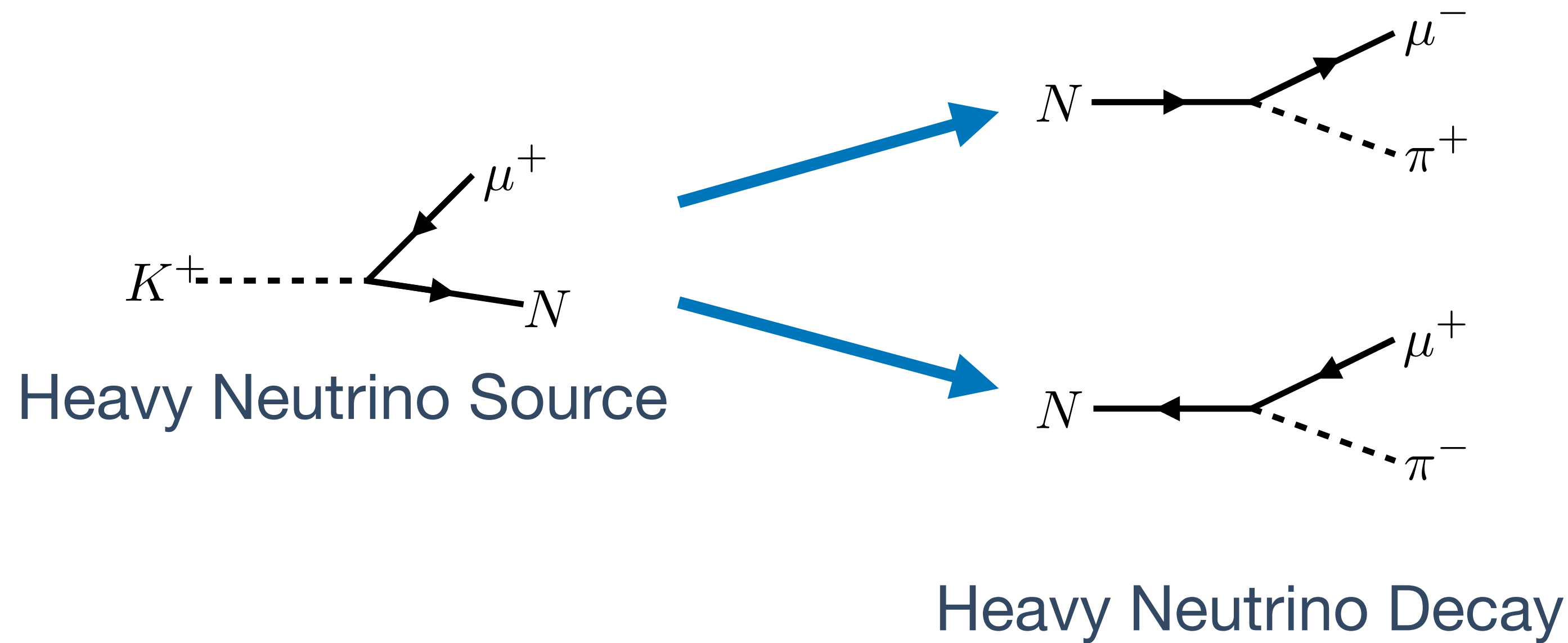
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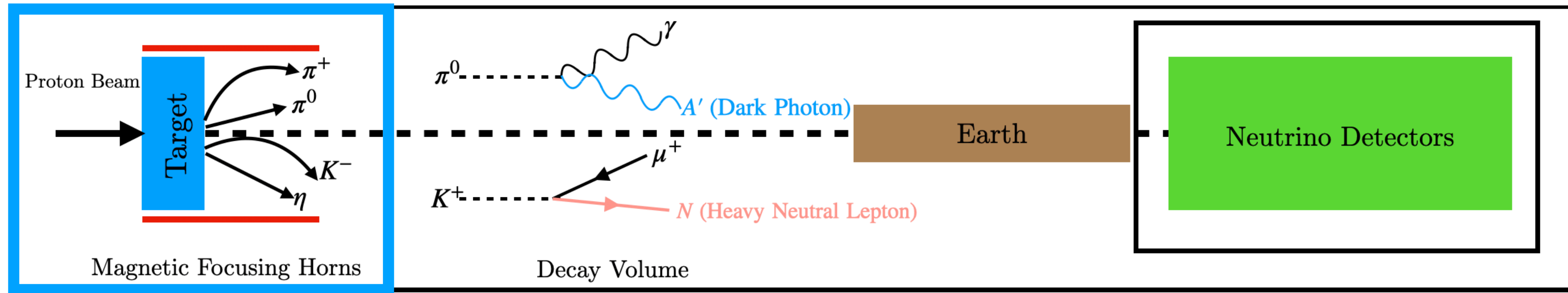


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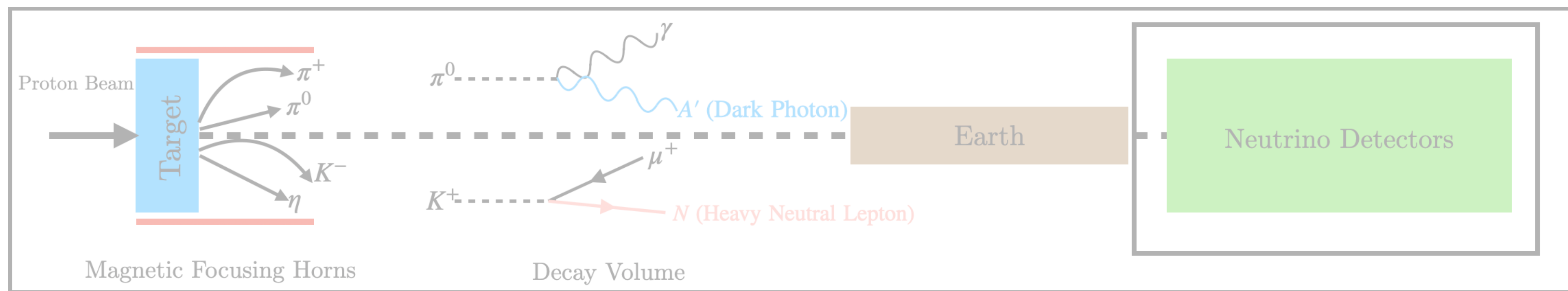


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# Neutrino vs. Antineutrino Mode

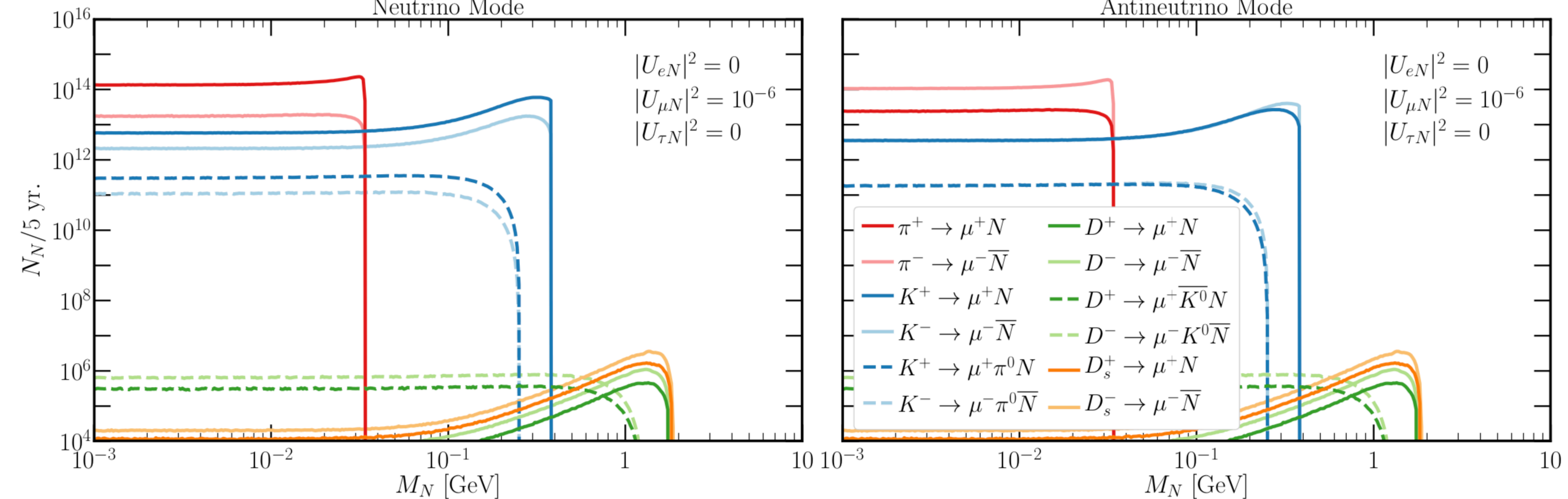


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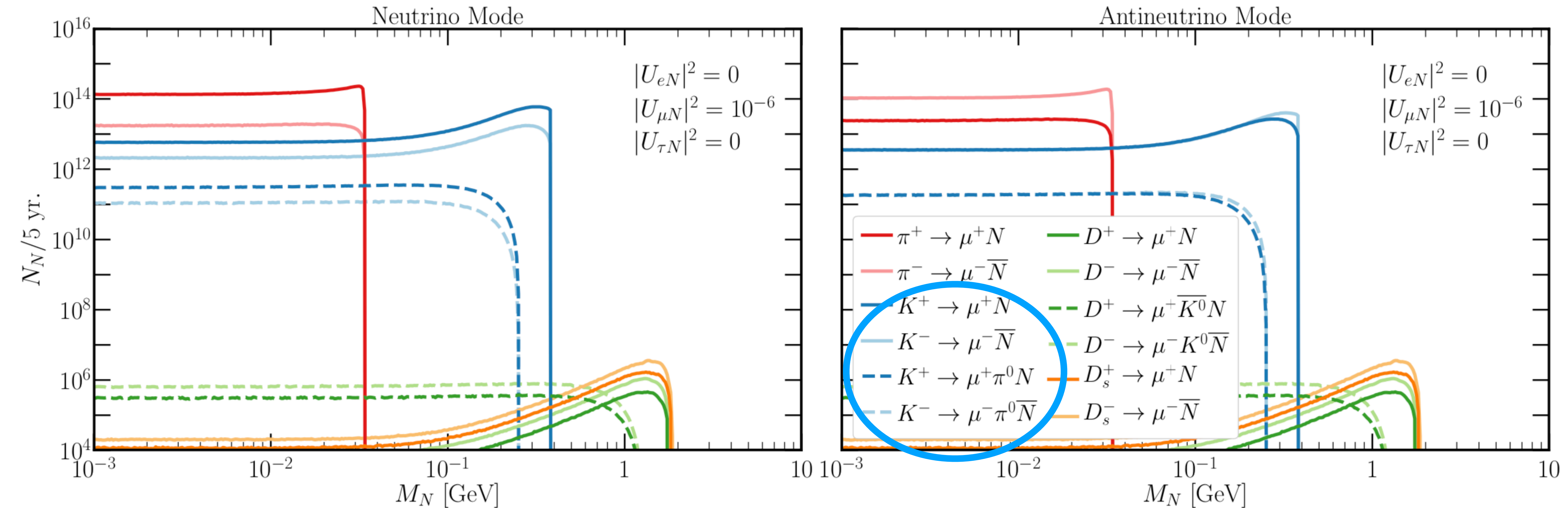
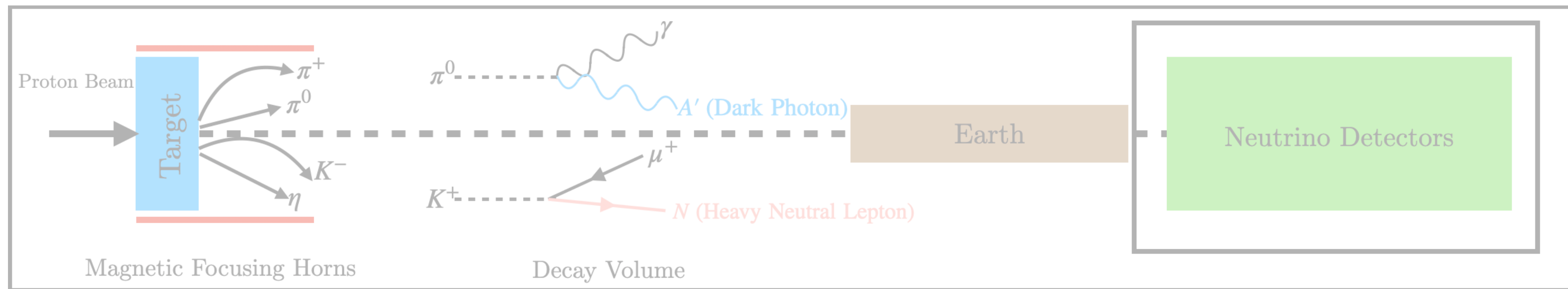


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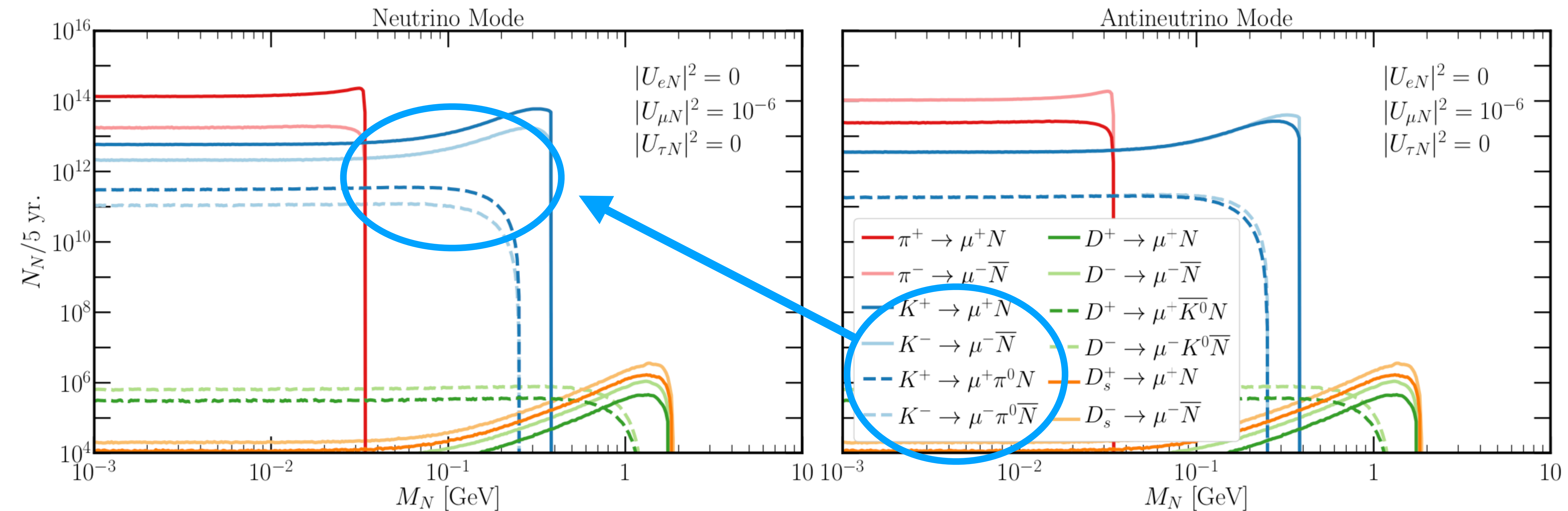
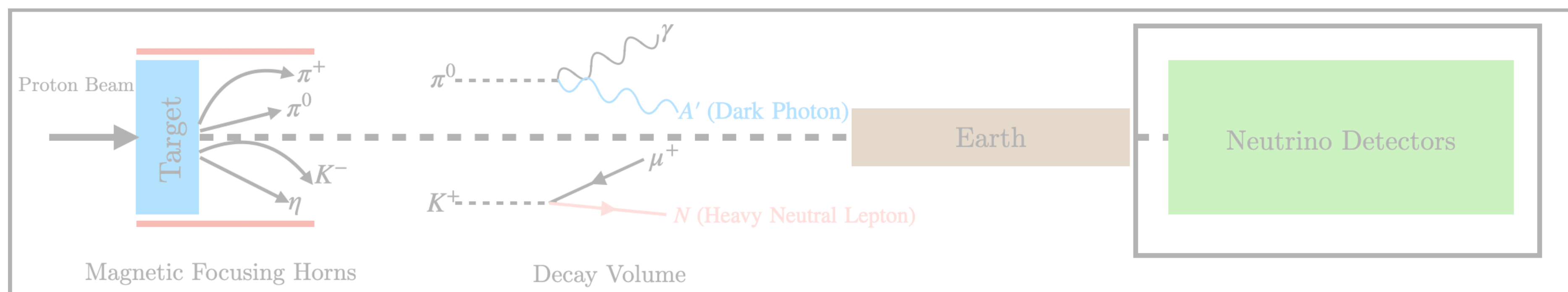
Antineutrino Mode



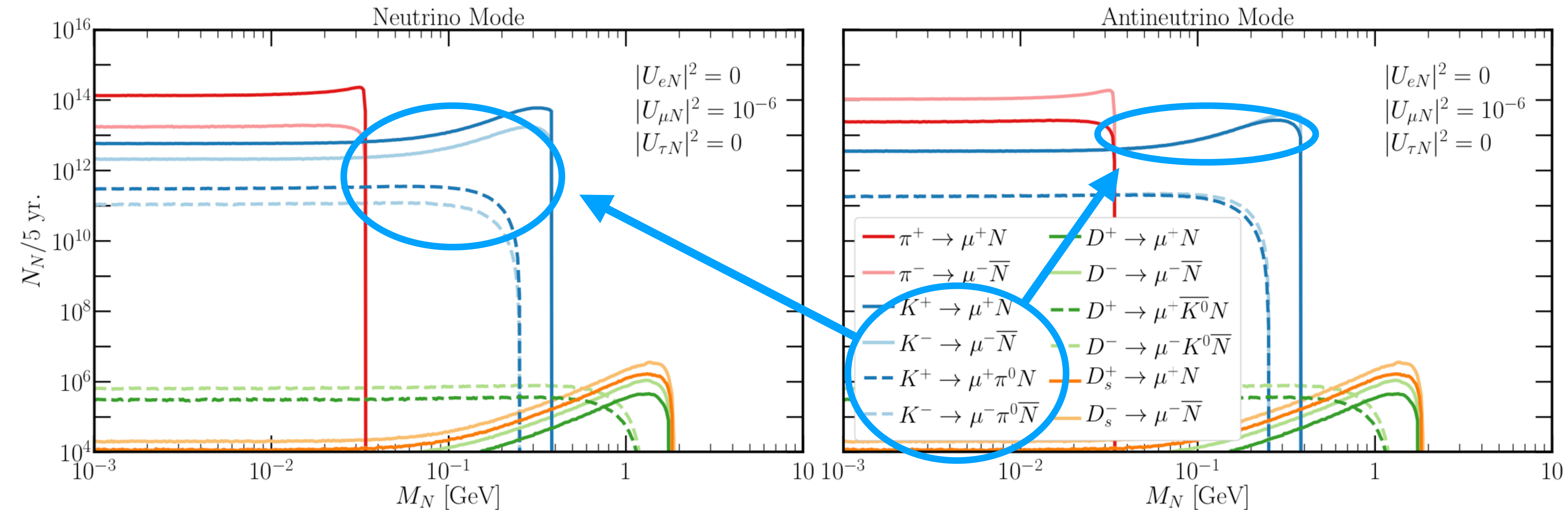
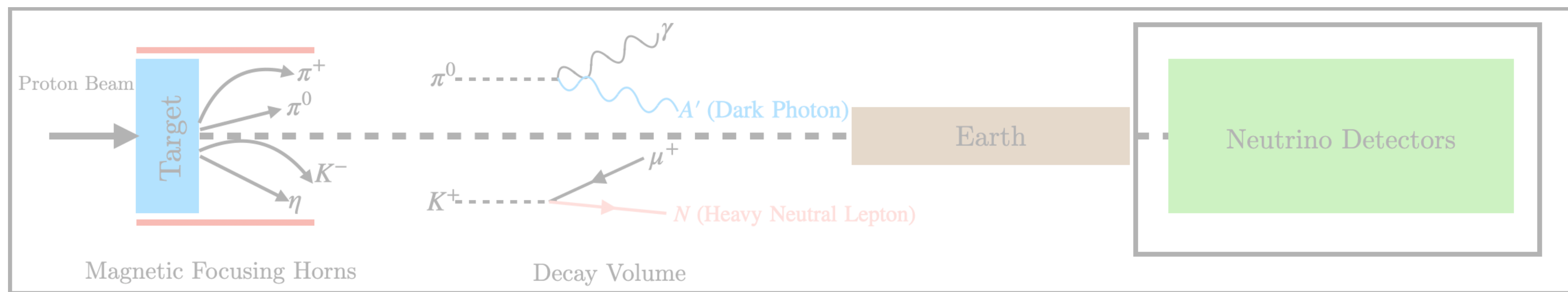
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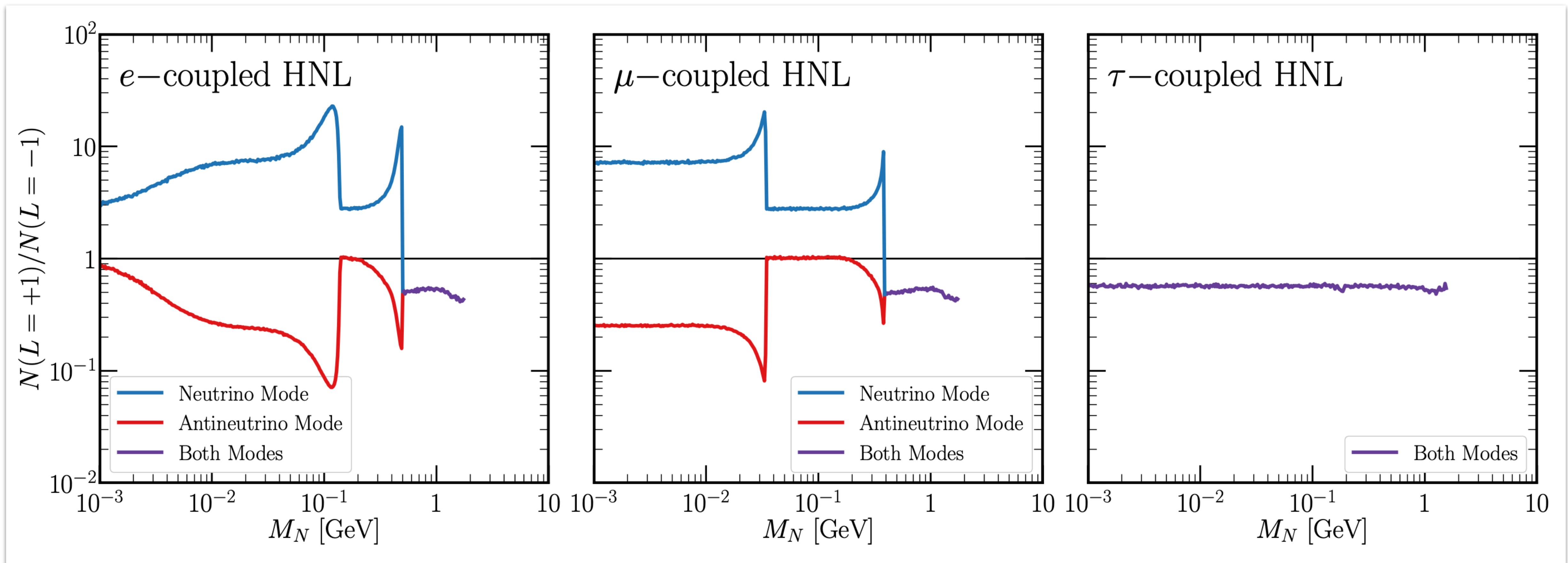


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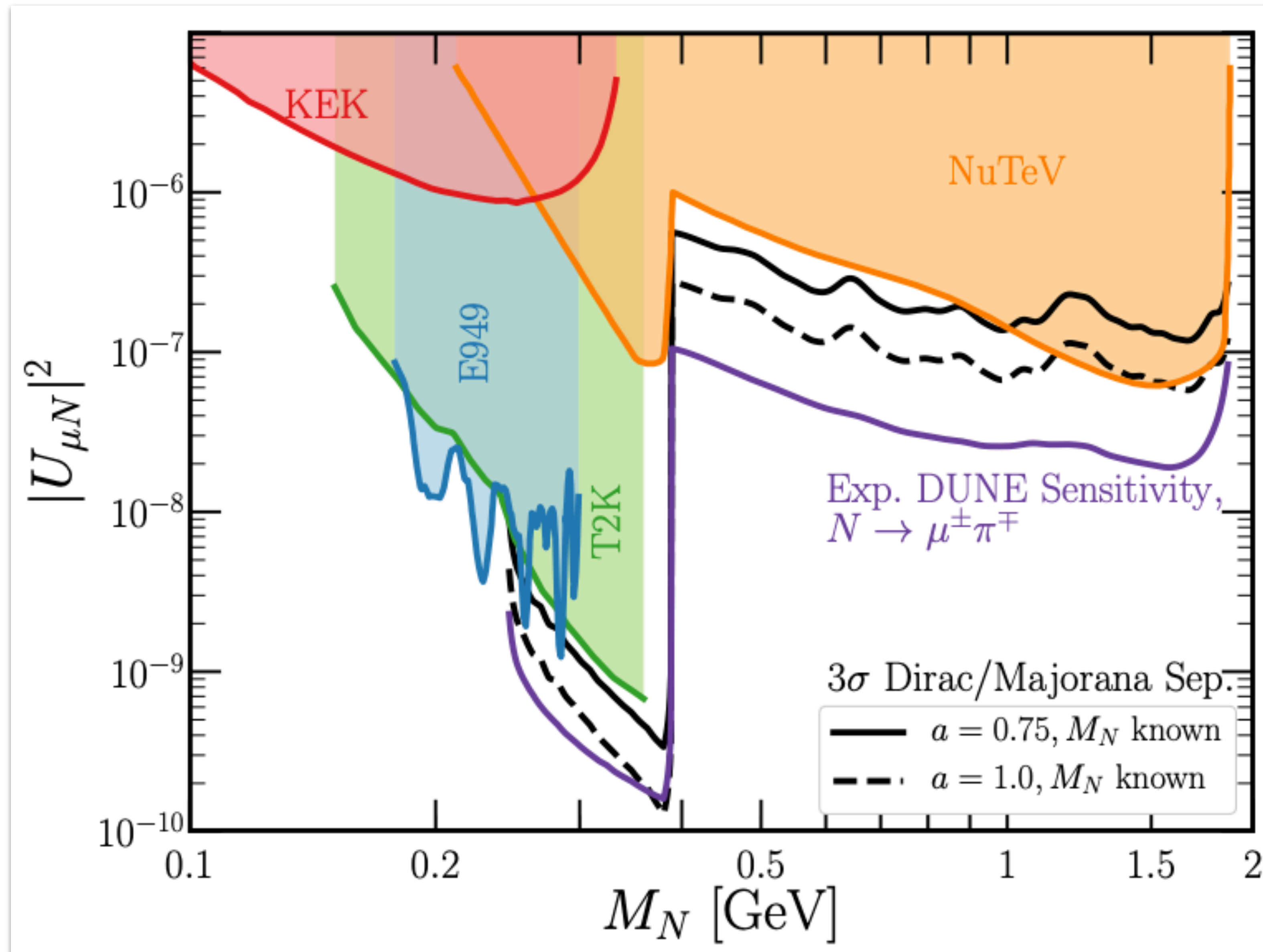




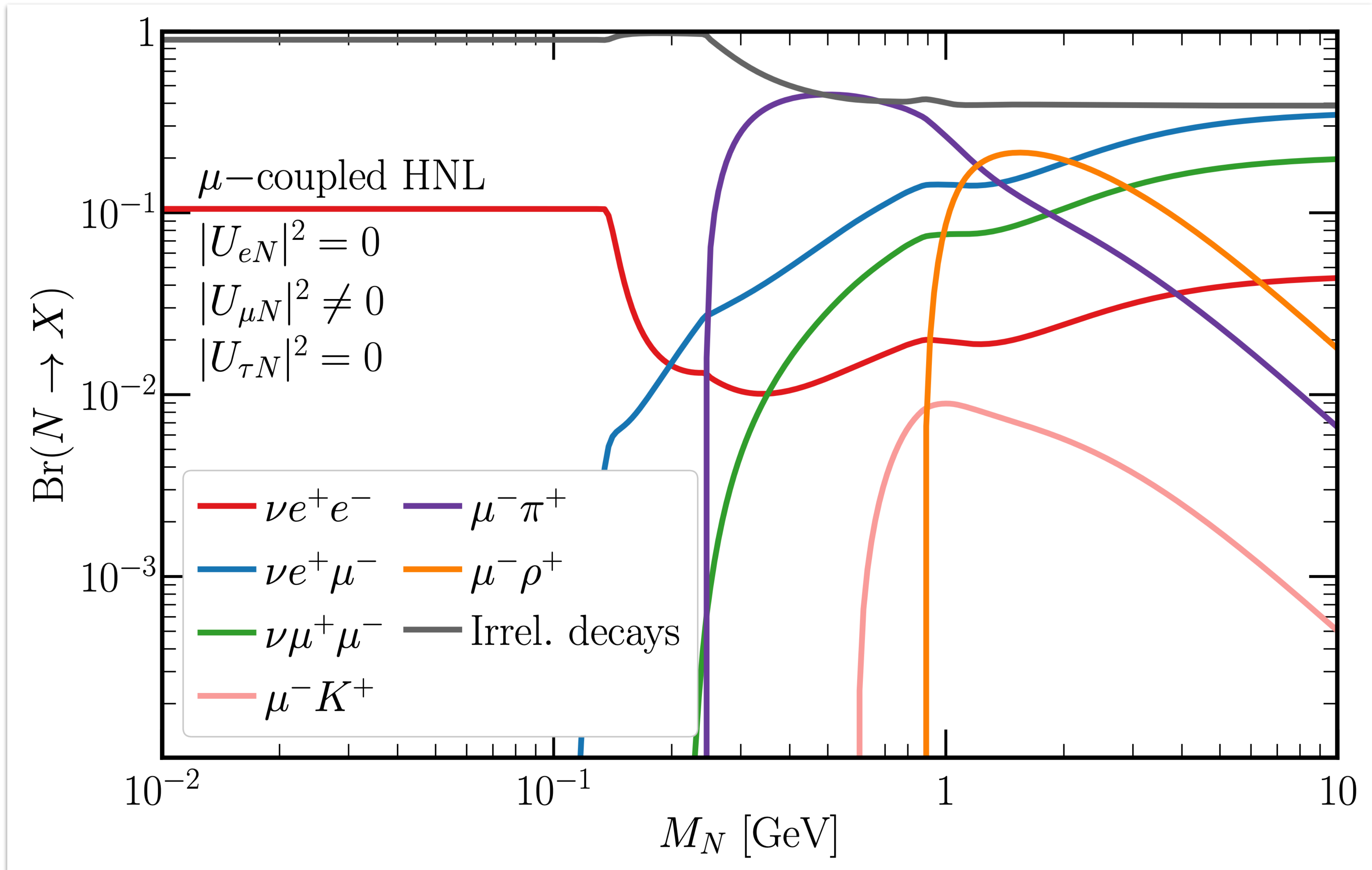
# Expected Beam Purity



# Next-Generation Prospects

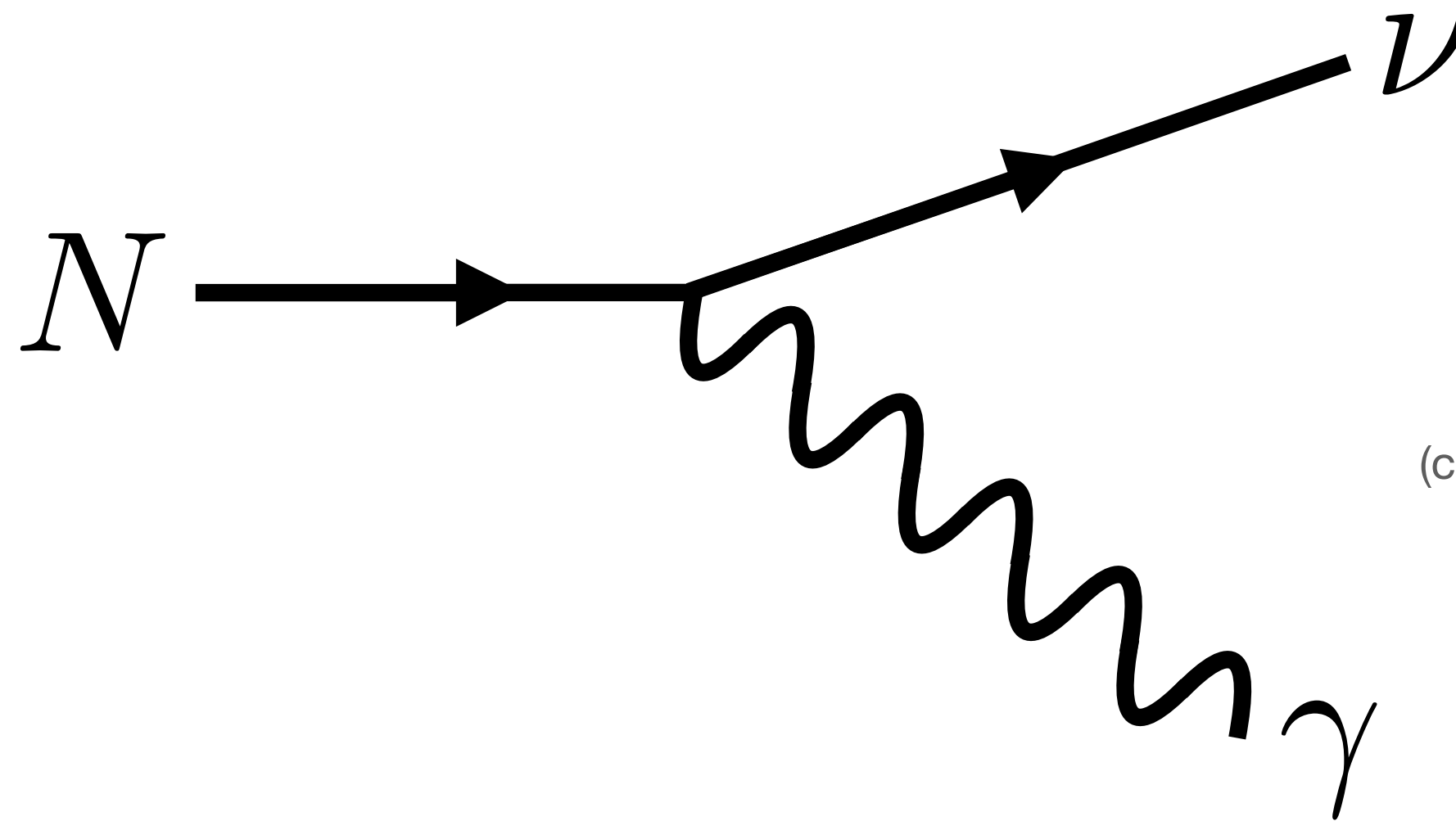
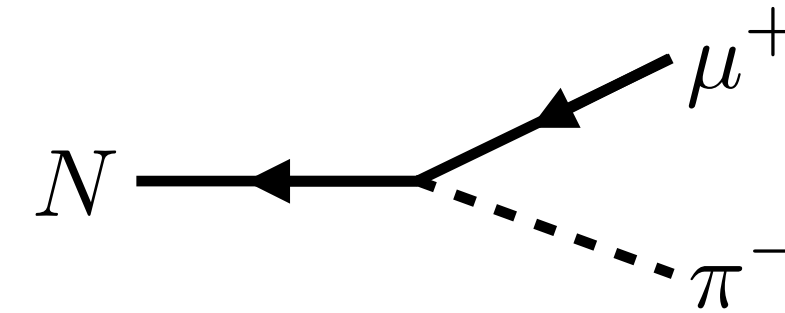
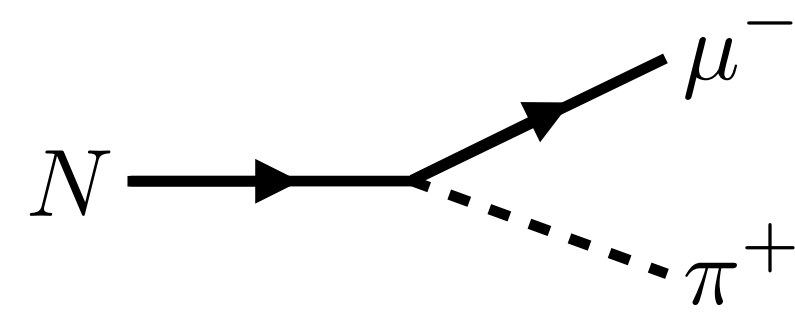


# “Explicit” LNV vs. “Implicit”



# What if we're not lucky?

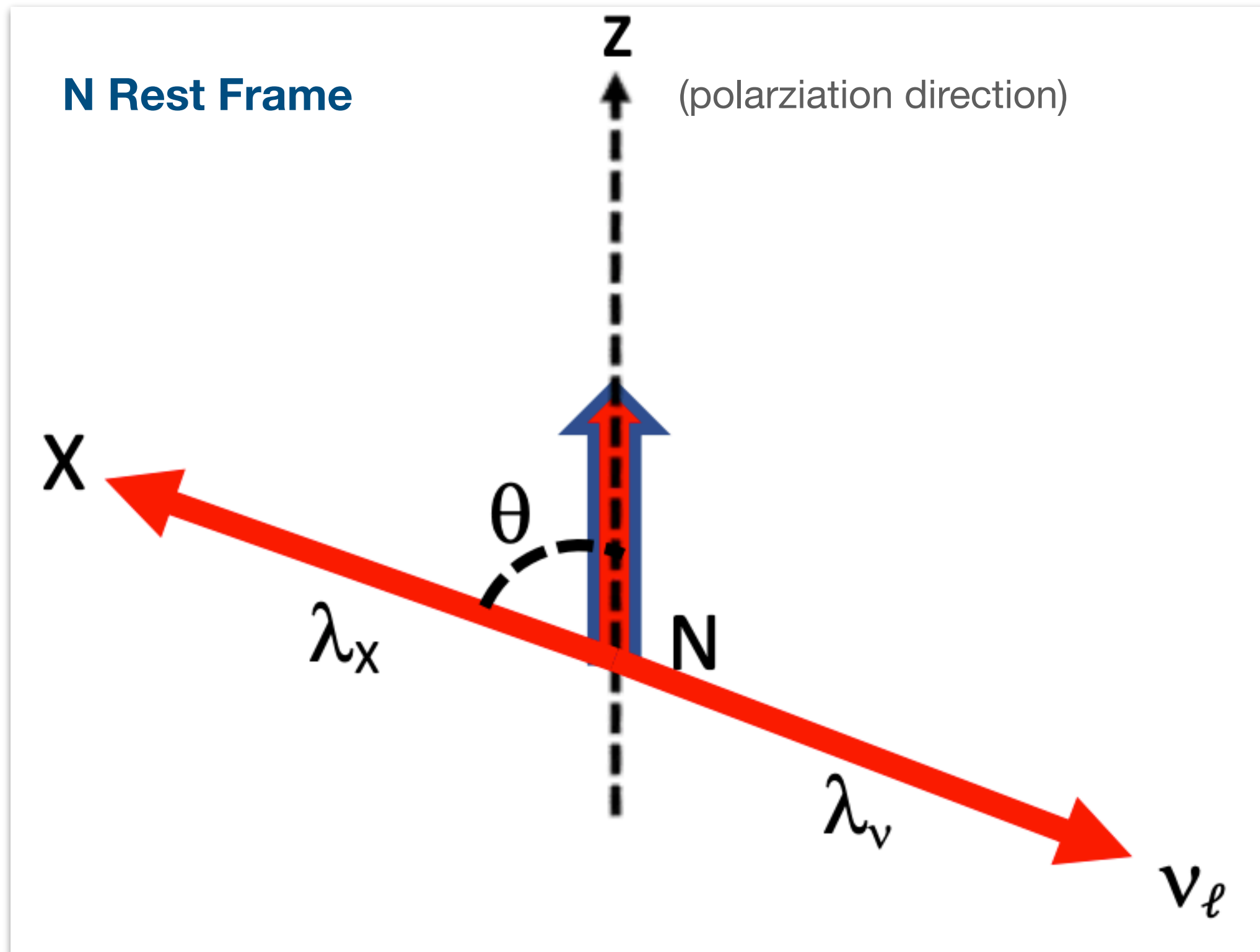
- What if the HNL is lighter than the pion? Then there are no fully-visible final states to decay into, and Lepton Number can't be identified on an event-by-event basis.



(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



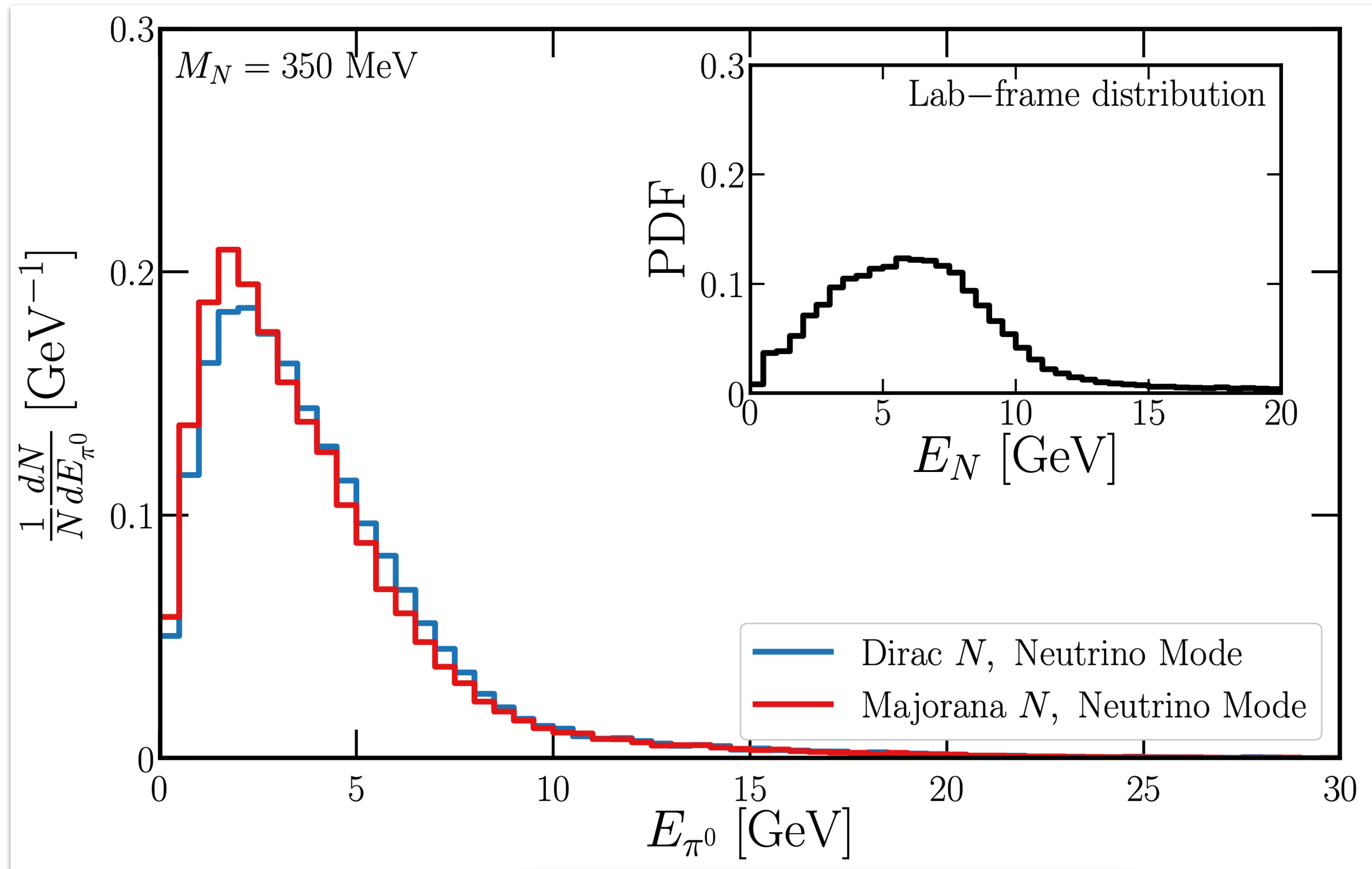
- Using CPT arguments, one can determine that, if  $N$  is a Majorana fermion, its decay is isotropic with respect to polarization direction. If it is a Dirac fermion, not necessarily.

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

| Boson    | $\gamma$                                | $\pi^0$ | $\rho^0$                                      | $Z^0$                                   | $H^0$ |
|----------|---|---------|---|---|-------|
| $\alpha$ | $\frac{2\Im(\mu d^*)}{ \mu ^2 +  d ^2}$ | 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?

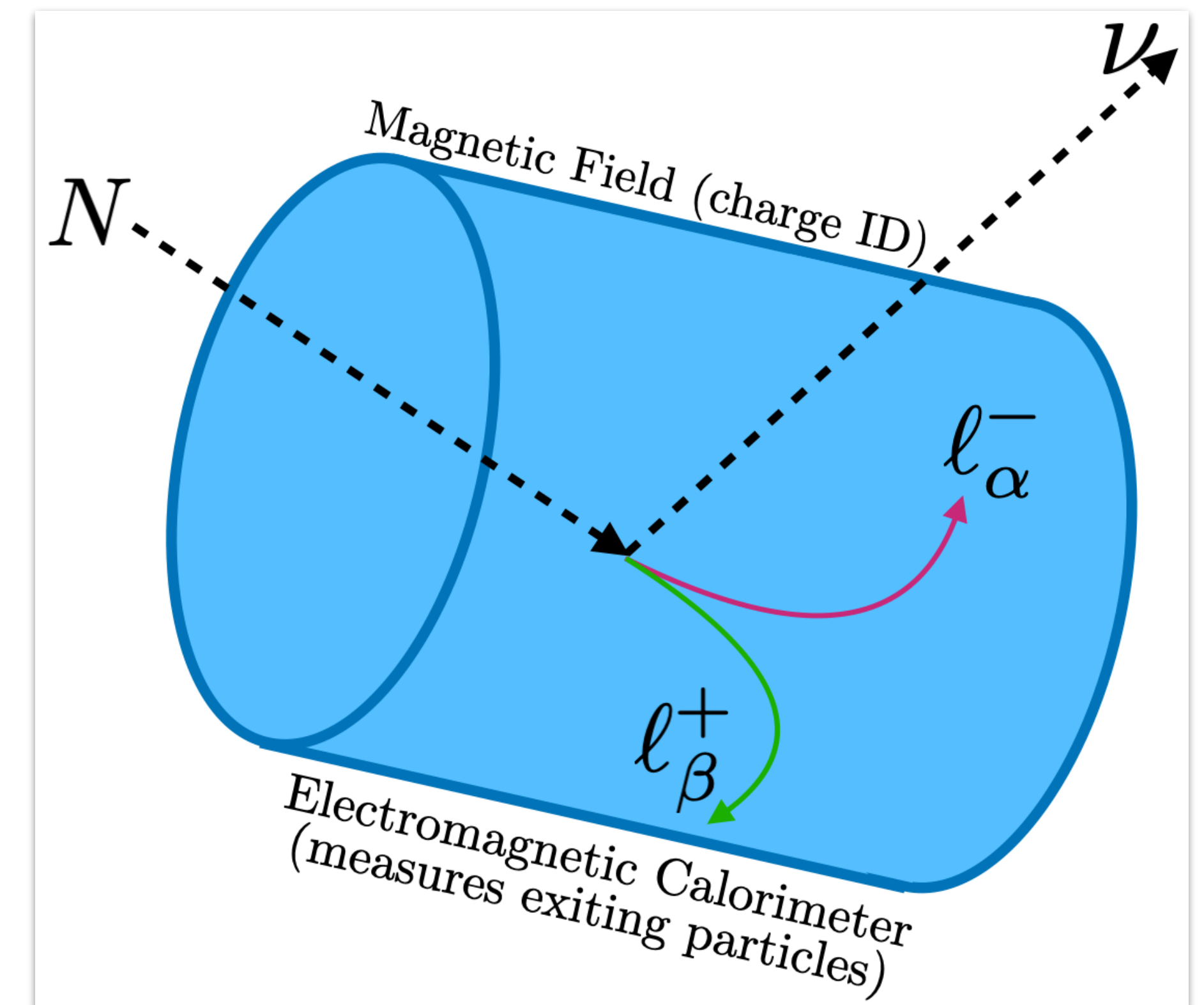
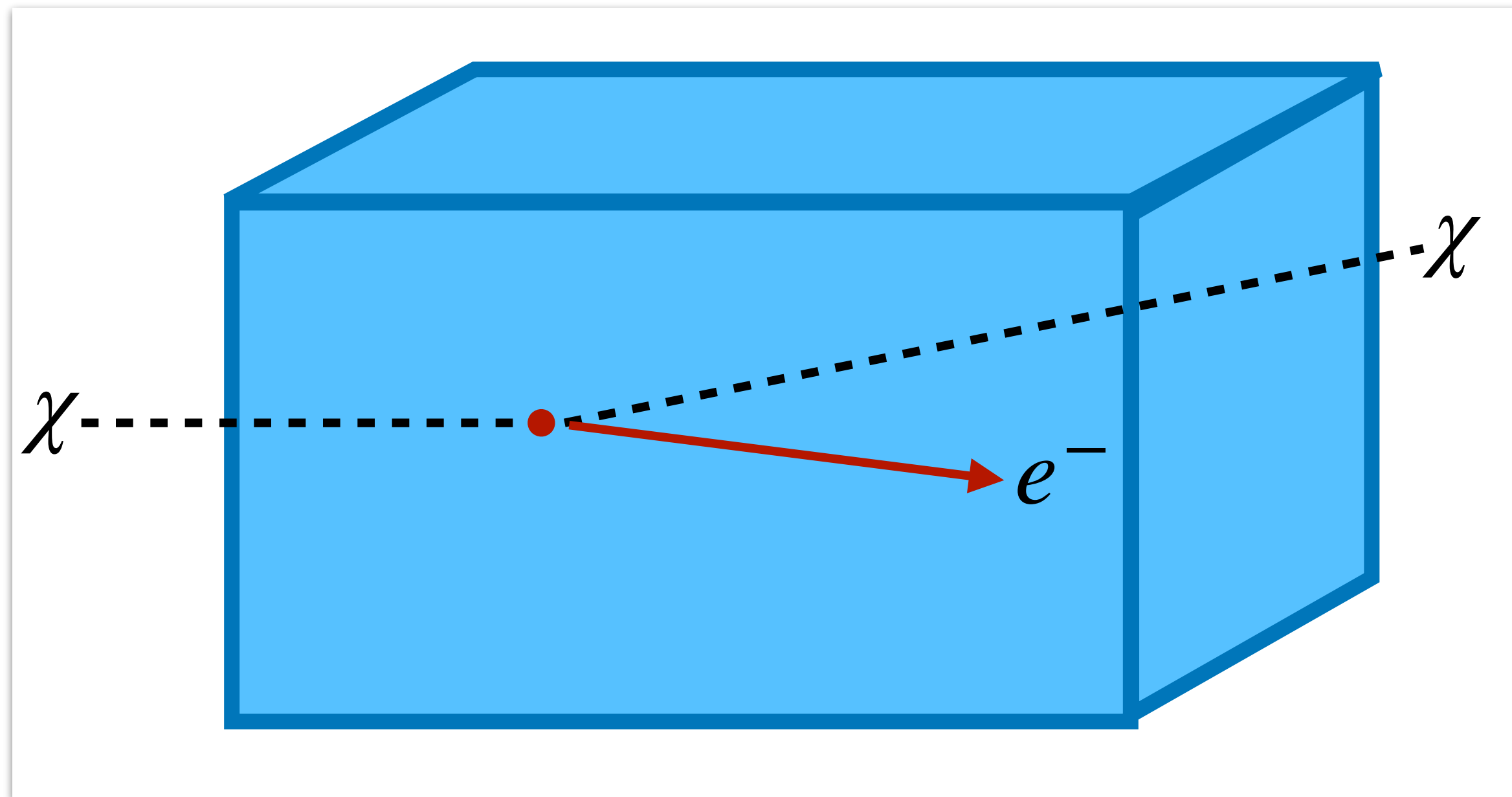
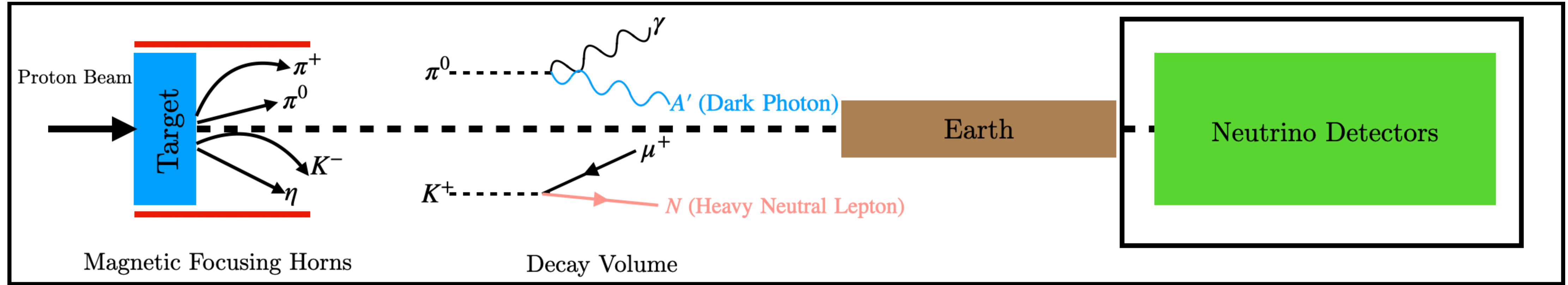


Post-discovery opportunities,  
leveraging Phase-II technology?

de Gouvêa, Fox, Kayser, **KJK** [\[2104.05719\]](#)

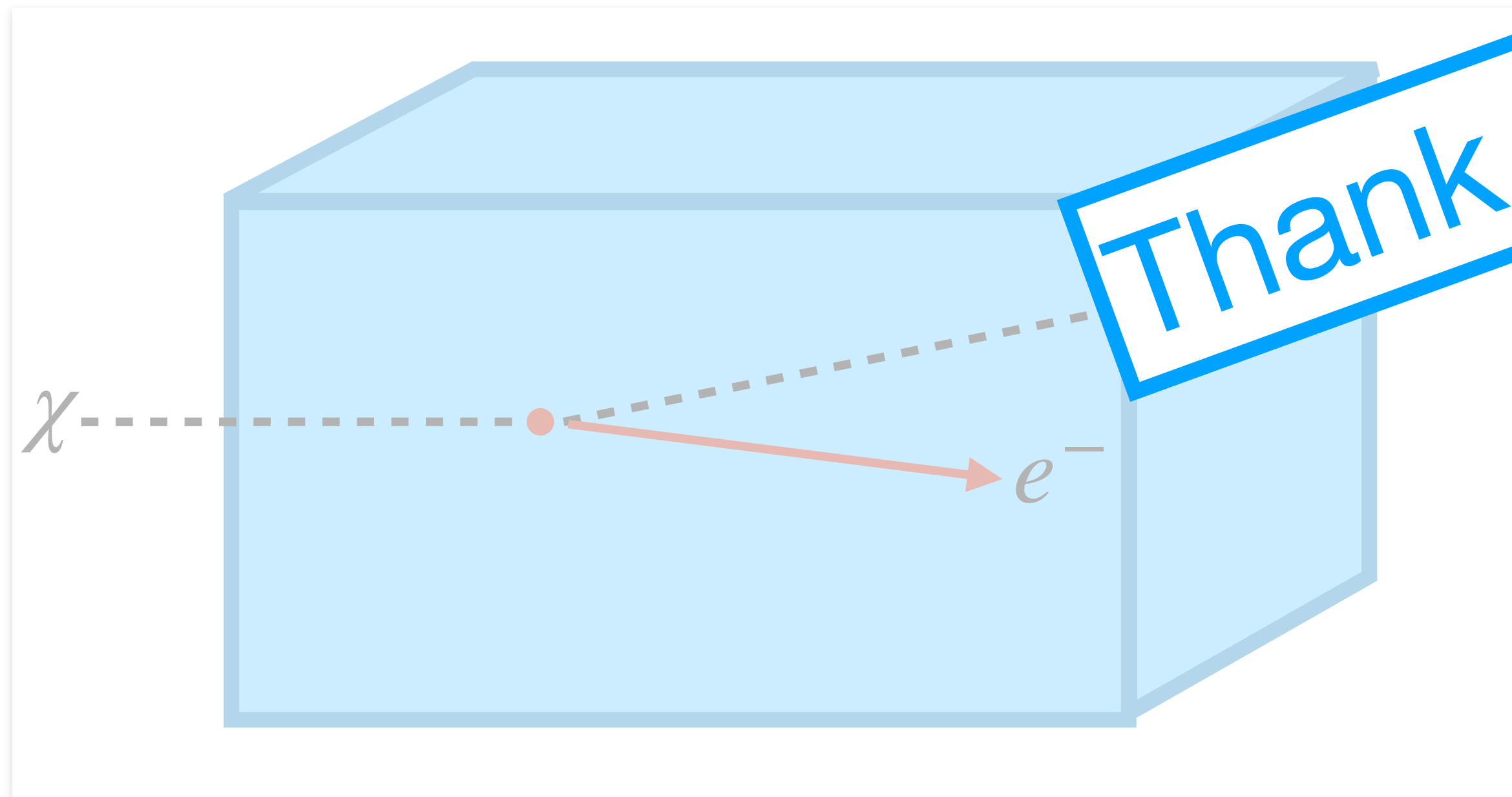
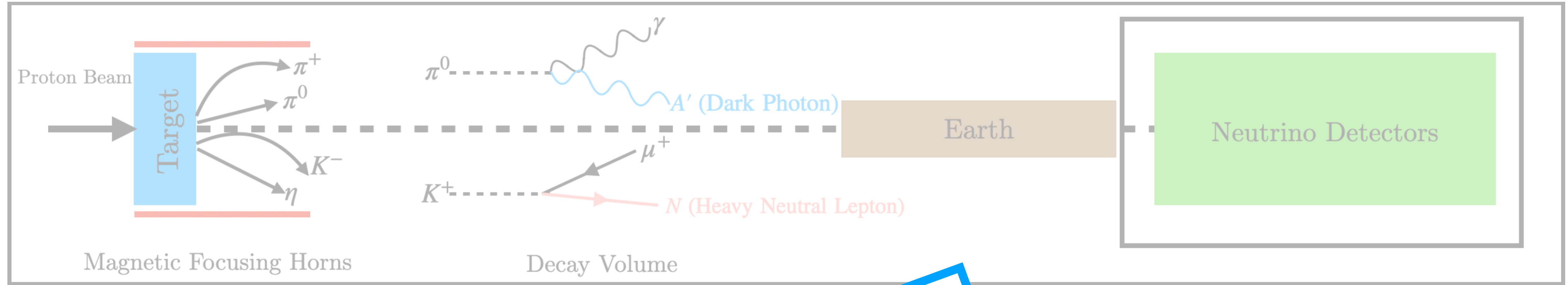
de Gouvêa, Fox, Kayser, **KJK** [\[2109.10358\]](#)

# Takeaways

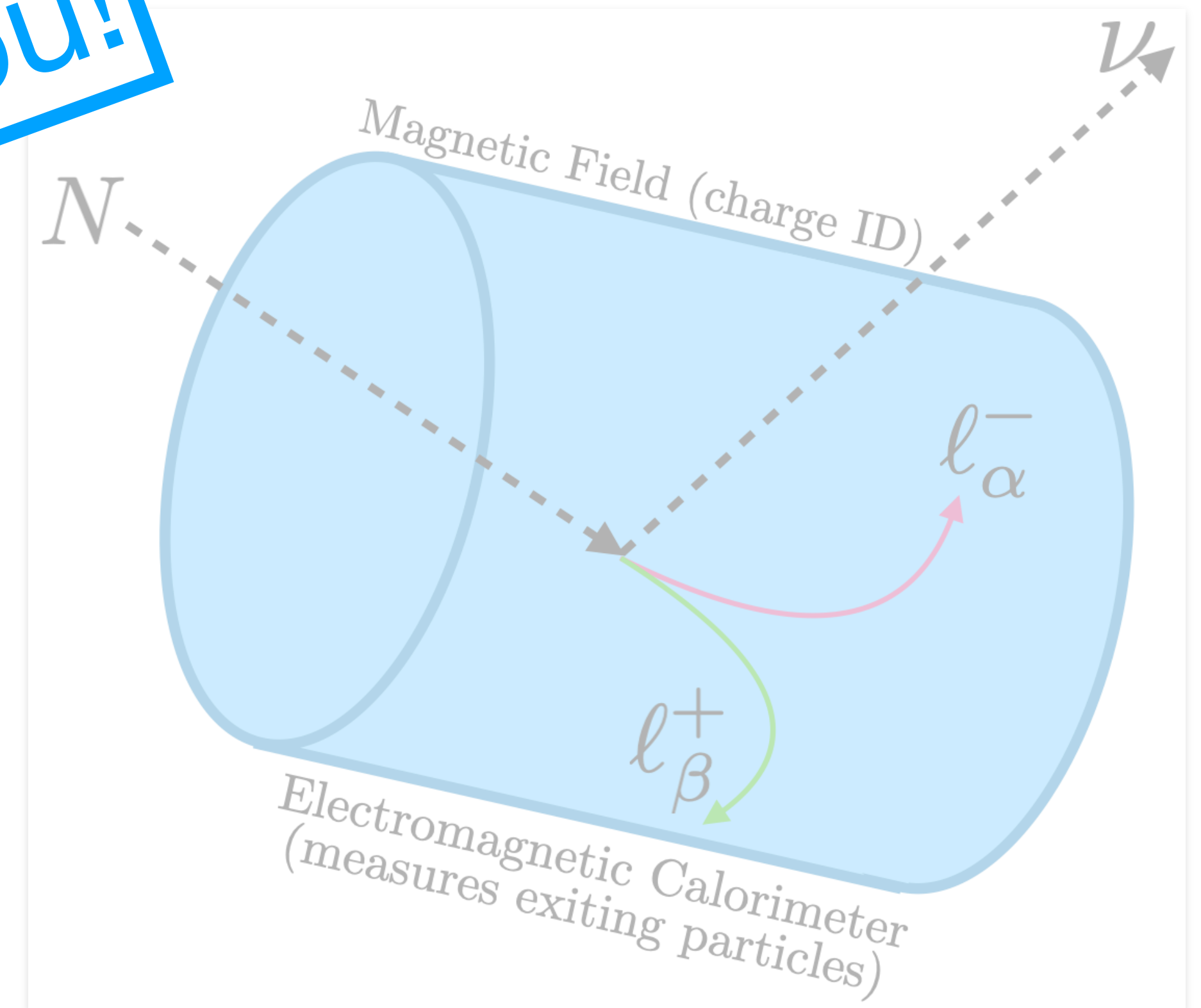


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# Takeaways



Thank you!



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