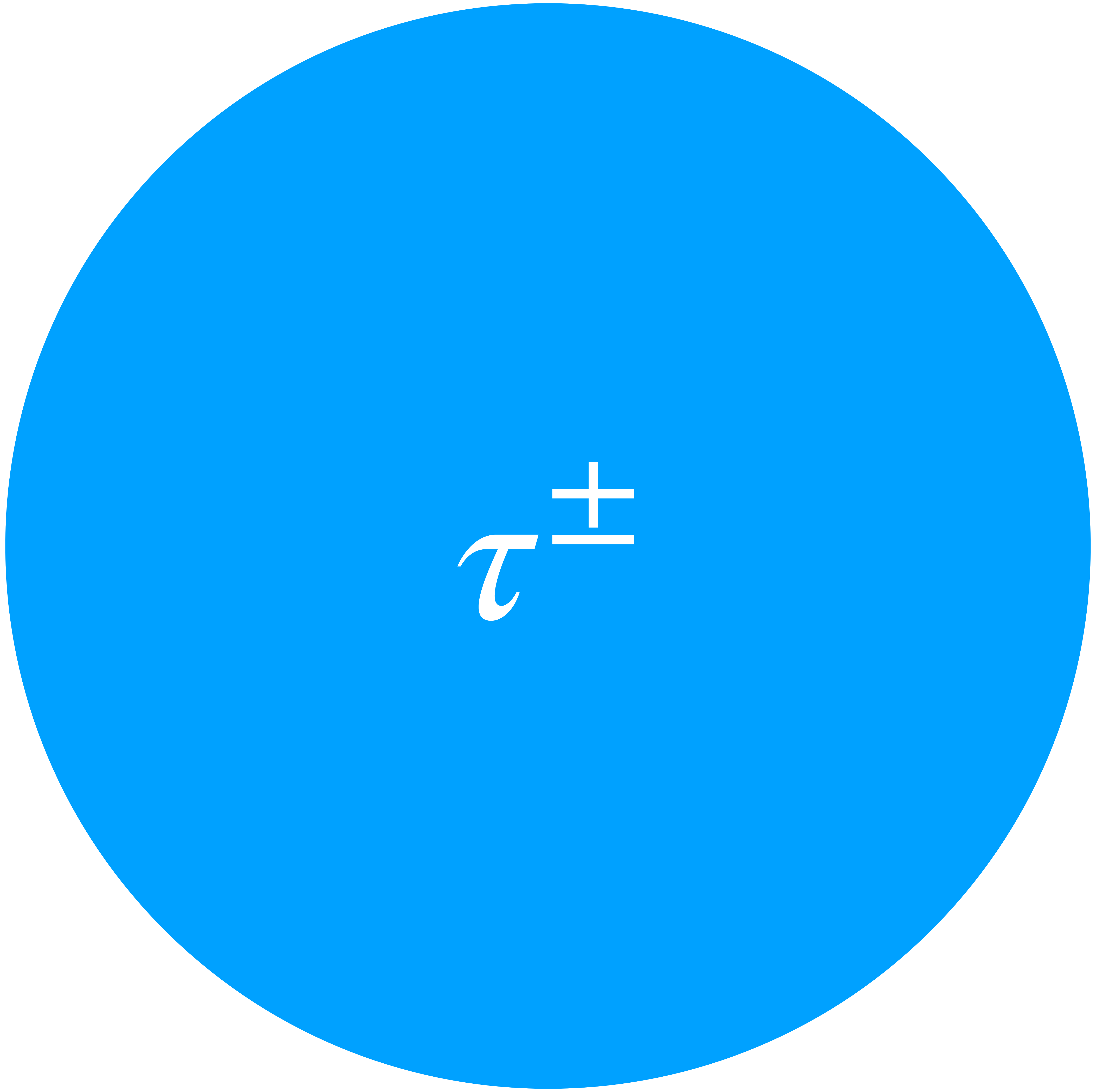
Neutrino & Dark Matter Connections

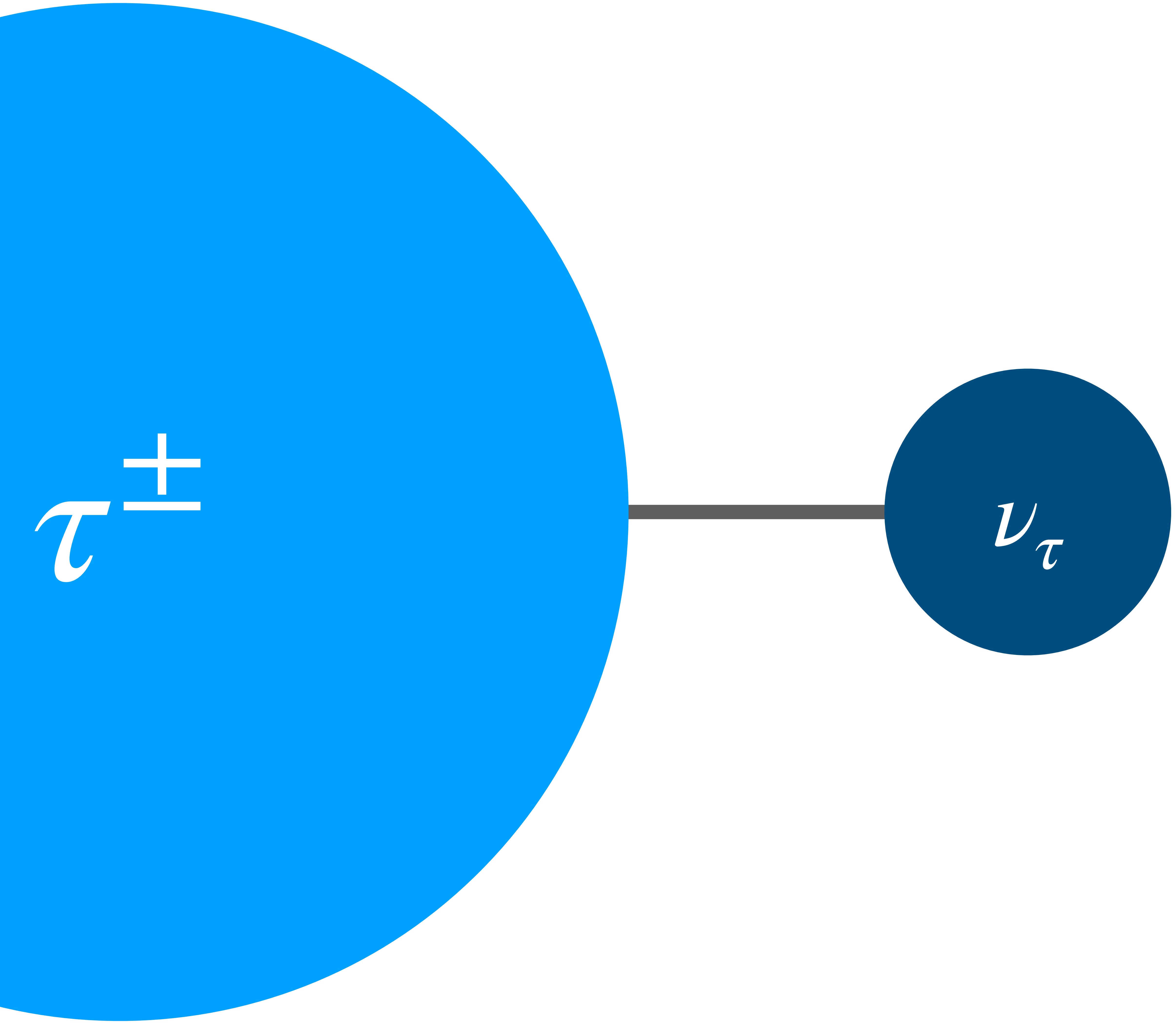
Kevin J. Kelly, Texas A&M University

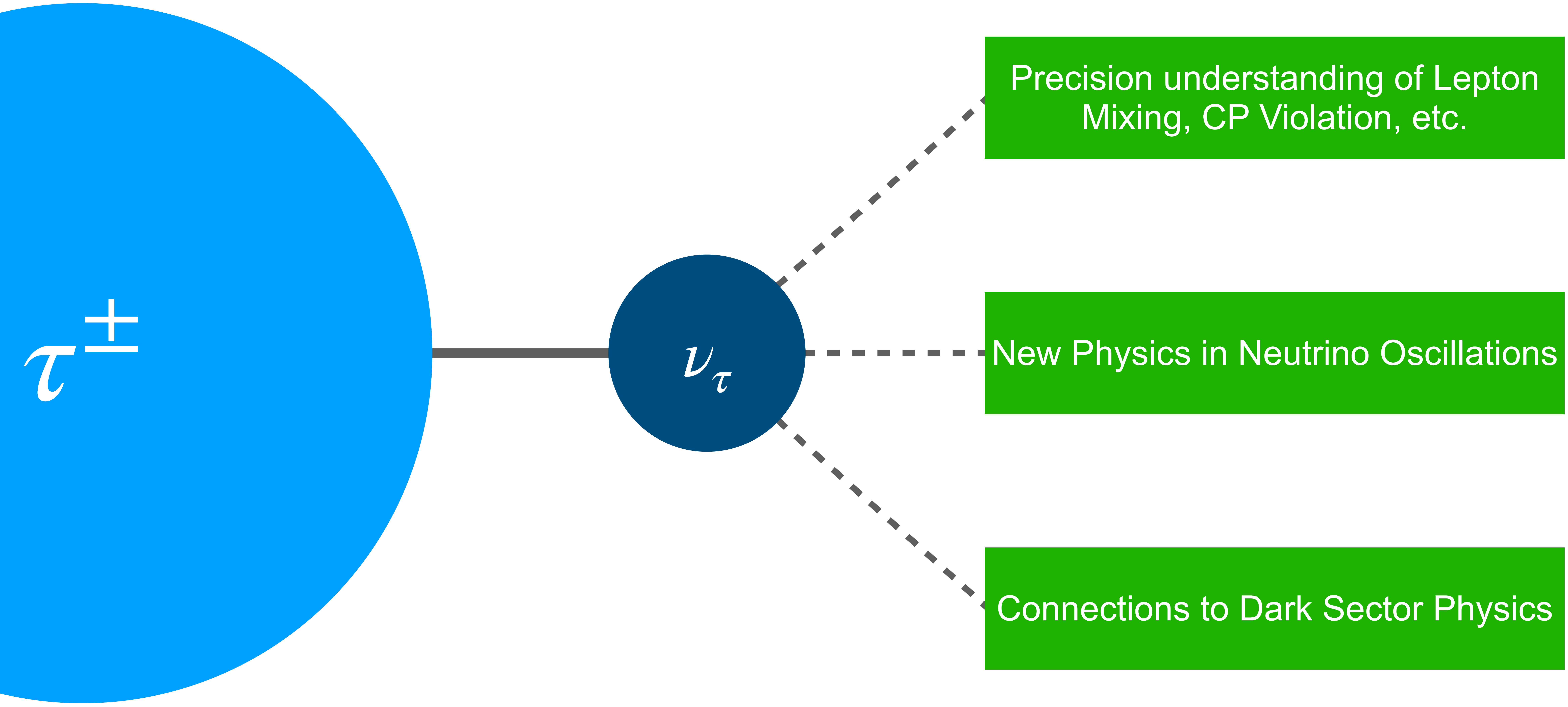
TAU2023 — 4-8 December, 2023

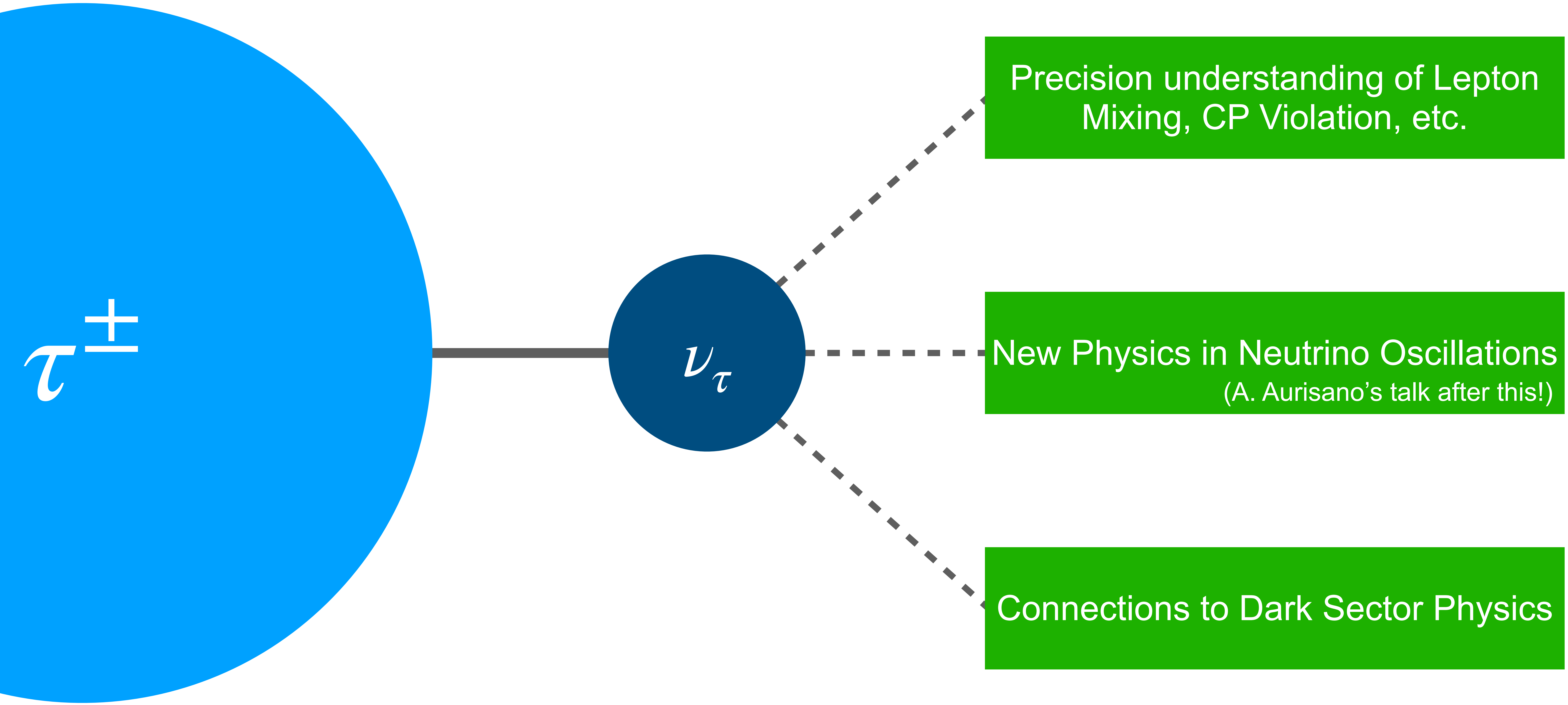
kjkelly@tamu.edu


$\tau^{\pm}$

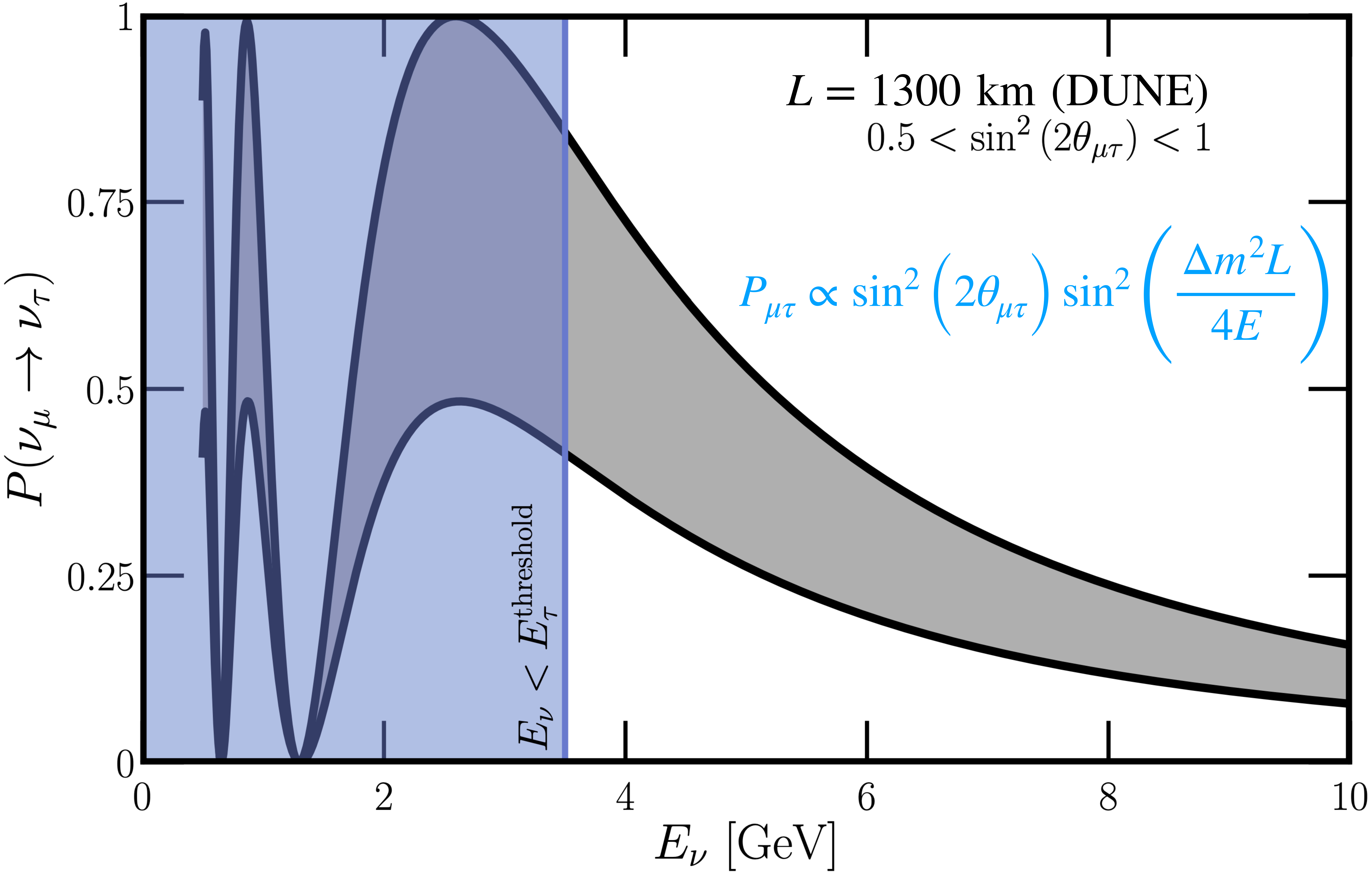
$\tau^{\pm}$


$\tau^{\pm}$
ν_τ

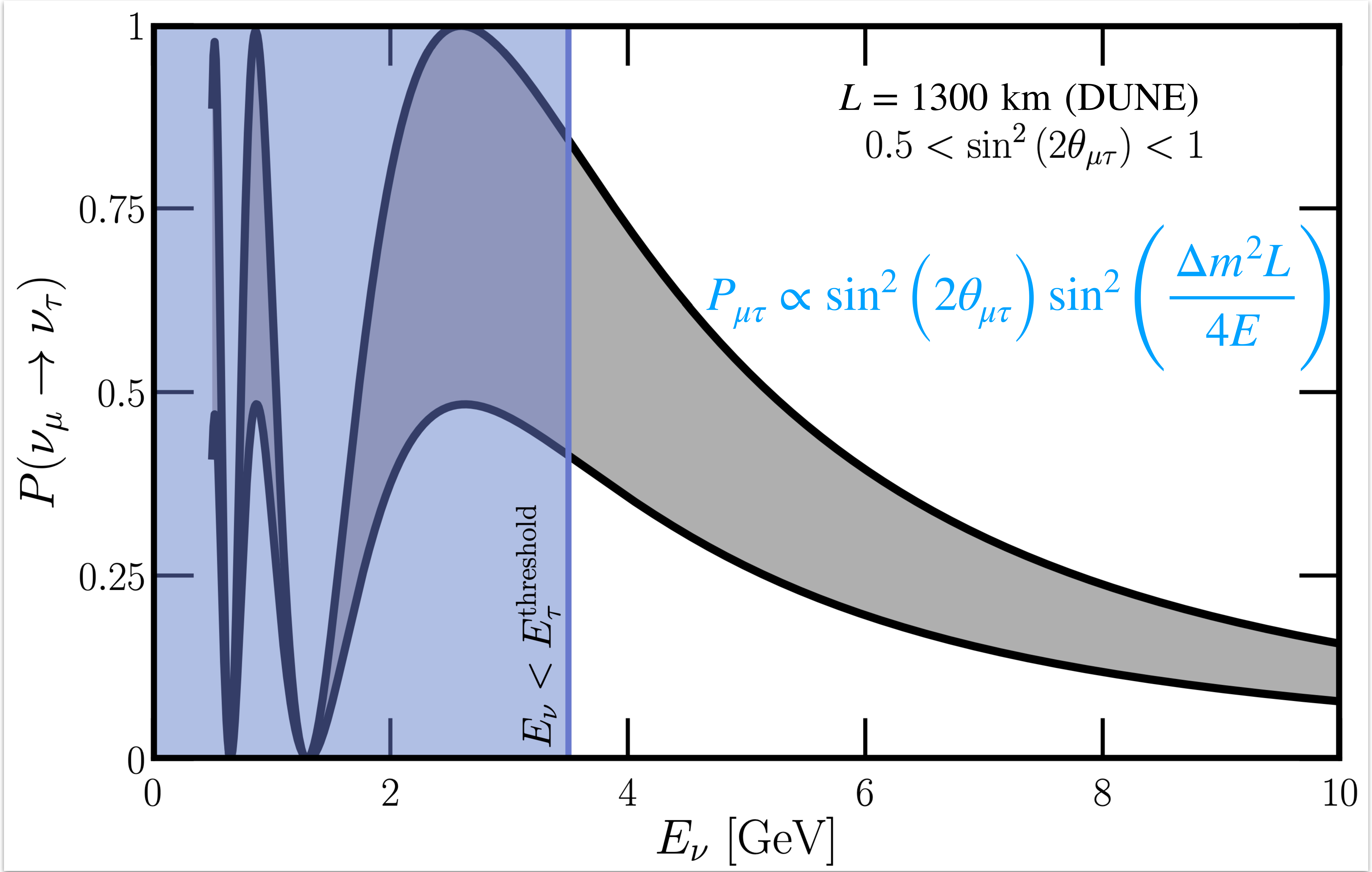

$\tau^\pm$
ν_τ
Precision understanding of Lepton Mixing, CP Violation, etc.
New Physics in Neutrino Oscillations
Connections to Dark Sector Physics


$\tau^{\pm}$
ν_τ
Precision understanding of Lepton Mixing, CP Violation, etc.
New Physics in Neutrino Oscillations
(A. Aurisano's talk after this!)
Connections to Dark Sector Physics

Tau Neutrinos for Three-Flavor Oscillation Physics

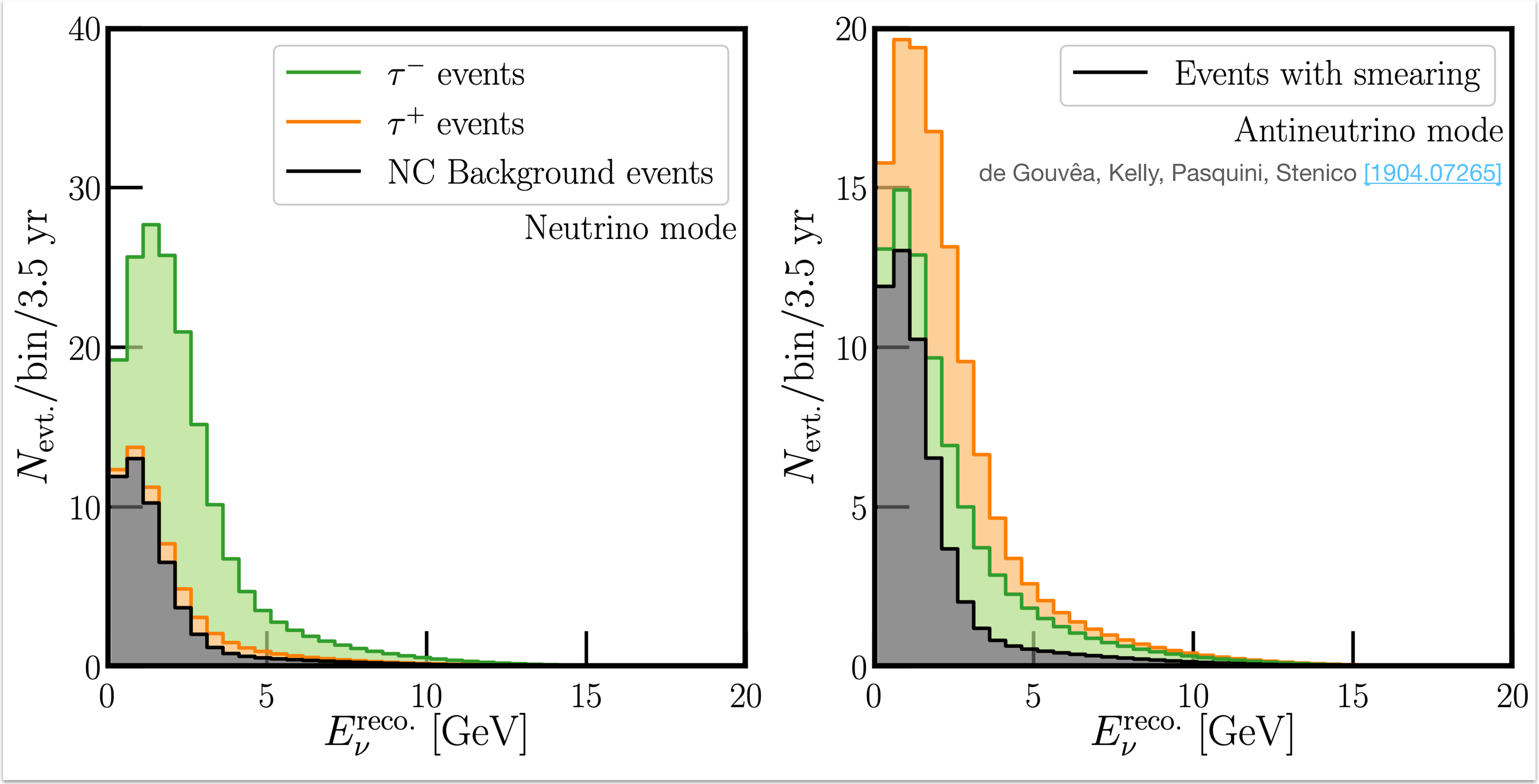


$L = 1300$ km (DUNE)
$0.5 < \sin^2(2\theta_{\mu\tau}) < 1$
$P_{\mu\tau} \propto \sin^2(2\theta_{\mu\tau}) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$
$E_\nu < E_\tau^{\text{threshold}}$
$P(\nu_\mu \to \nu_\tau)$
E_ν [GeV]
0
0.25
0.5
0.75
1
0
2
4
6
8
10



Three-flavor: $\sin^2(2\theta_{\mu\tau}) = 4|U_{\mu 3}|^2 |U_{\tau 3}|^2 = 4|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2 - |U_{e3}|^2\right)$

DUNE & Tau-Neutrino Appearance



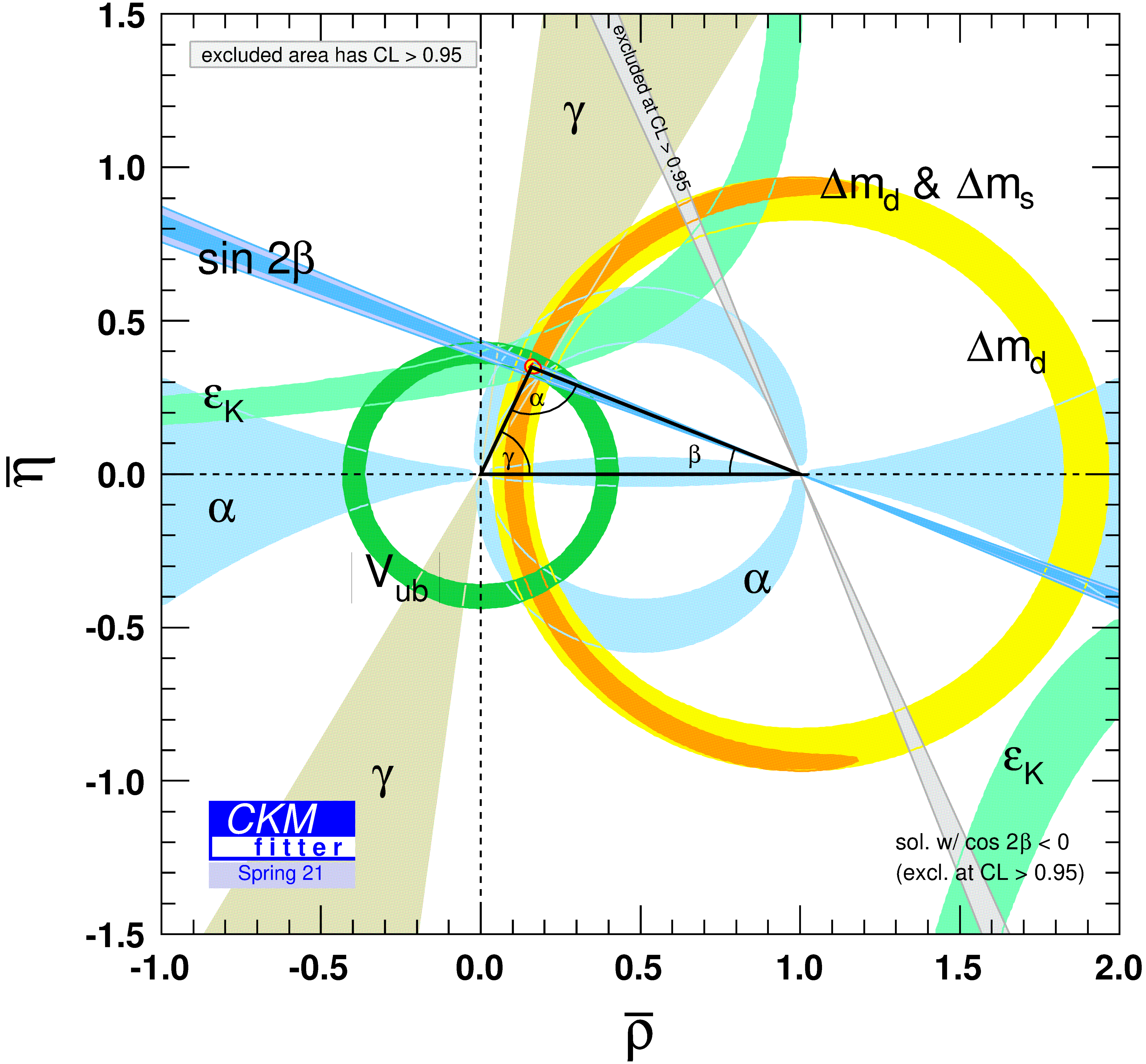
de Gouvêa, Kelly, Pasquini, Stenico [1904.07265]

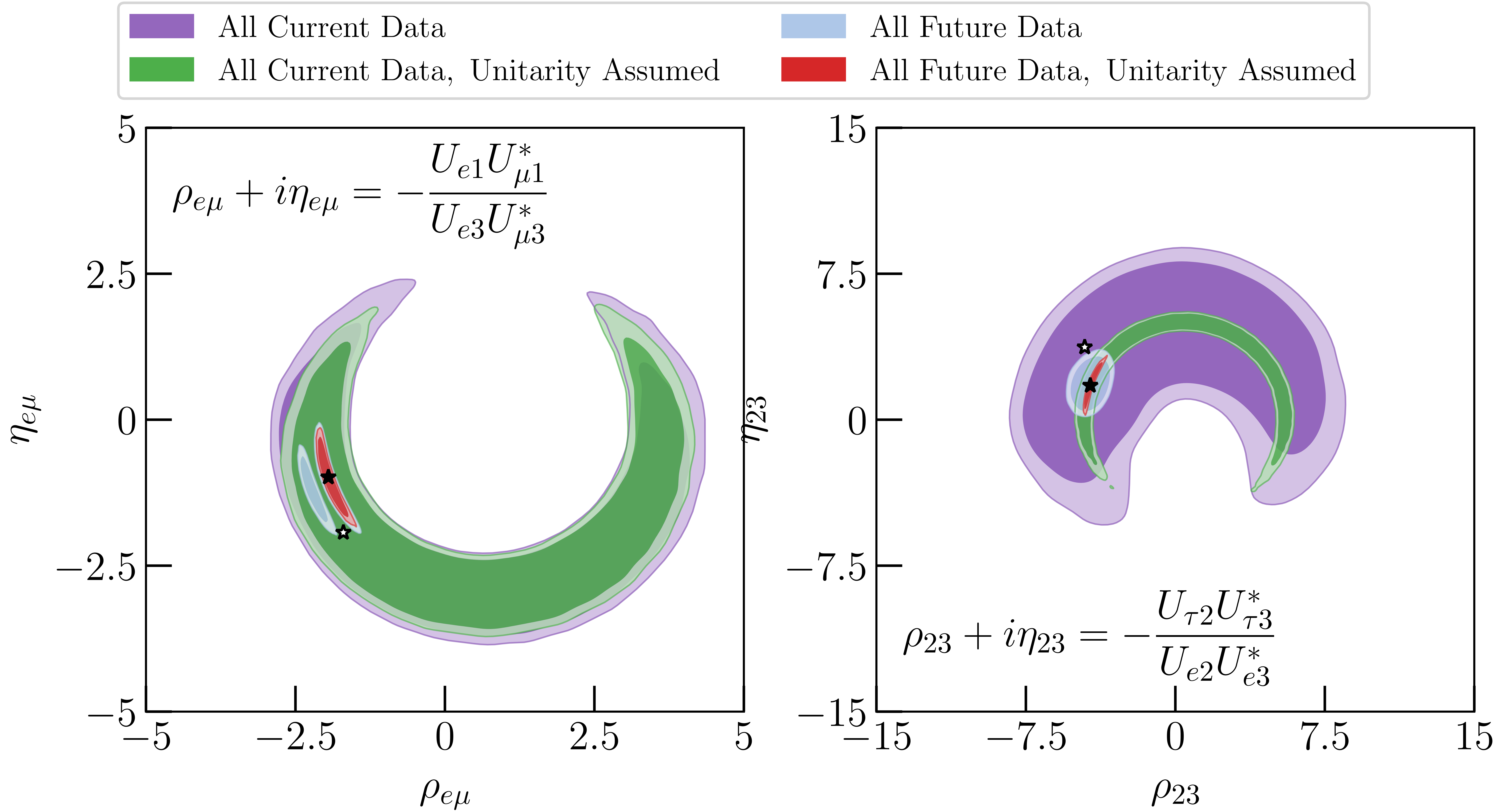
de Gouvêa, Kelly, Pasquini, Stenico [1904.07265]

Why Stress-test?

Tour de force results on quark mixing from the CKMfitter group

Closure tests allow for honest evaluation of our models — is the “three massive neutrinos” paradigm good or not?



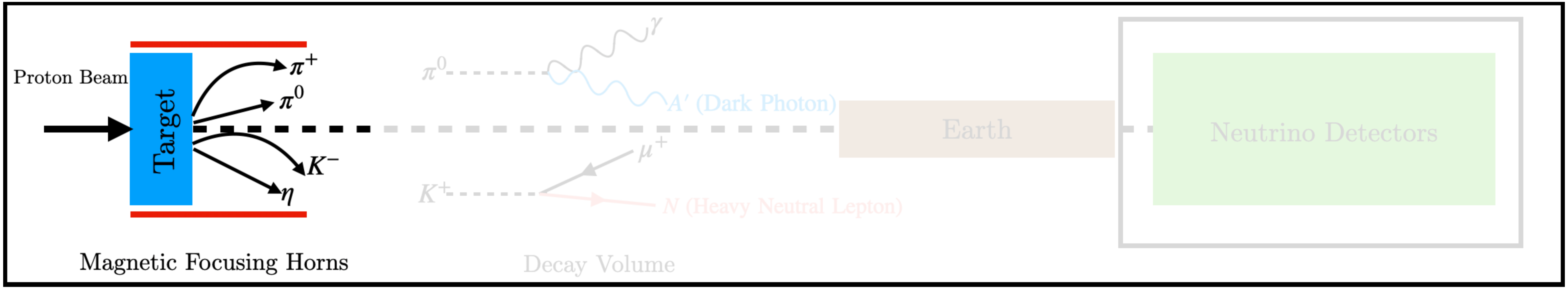


Analogue to the Lepton Sector

Ellis, Kelly, Li [2004.13719]

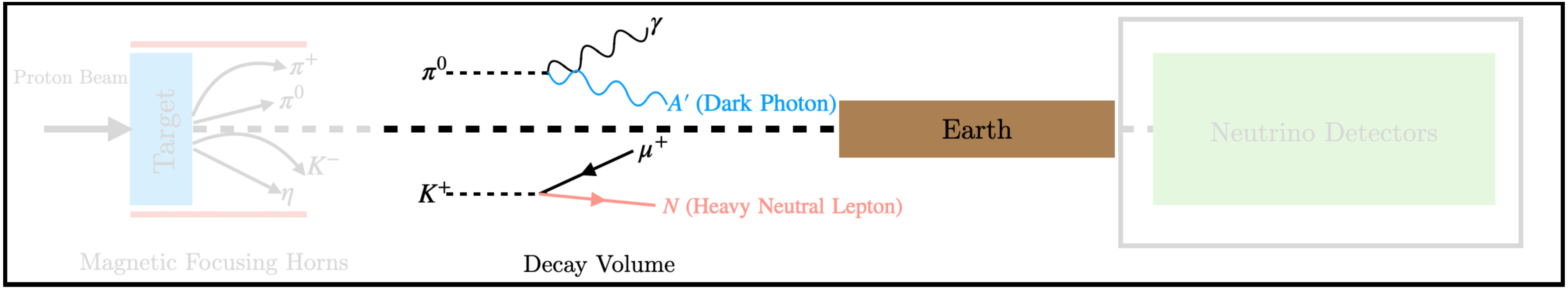
Tau Neutrinos and Dark Sectors

Neutrino Facilities as Dark Sector Machines



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

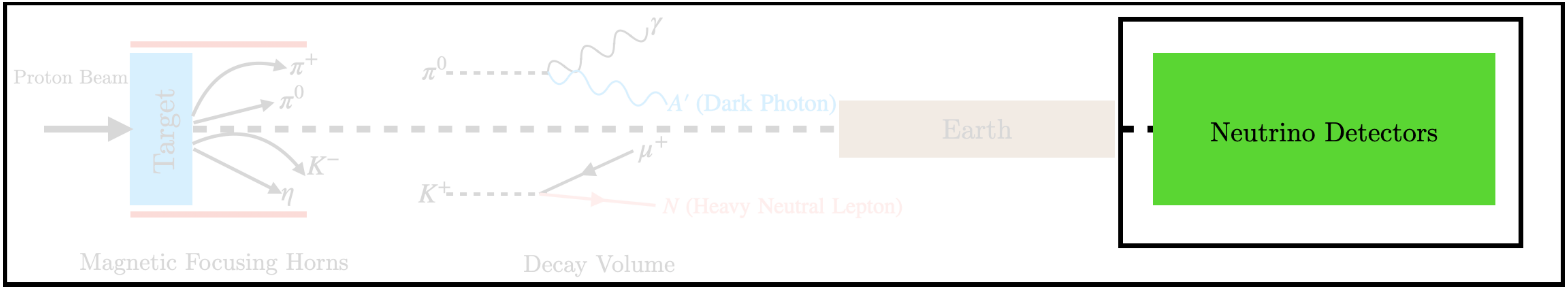
Neutrino Facilities as Dark Sector Machines



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.

Neutrino Facilities as Dark Sector Machines

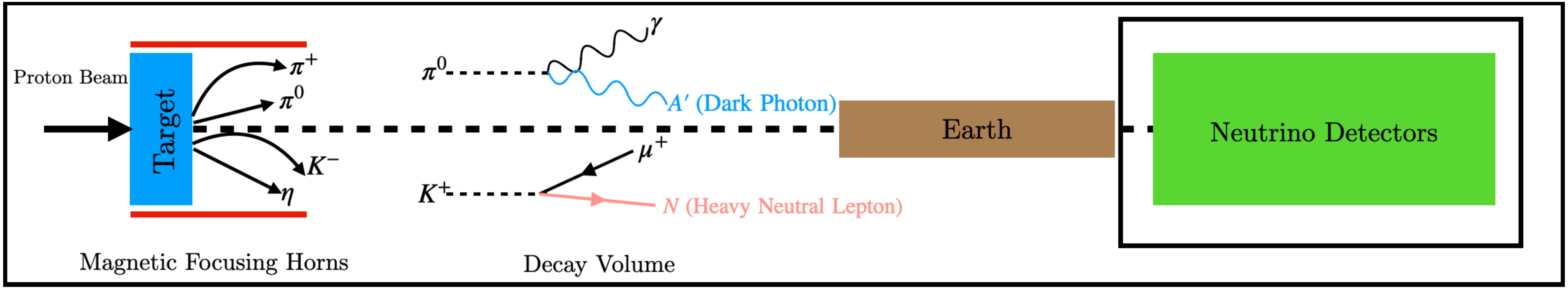


1) Charged and Neutral Mesons are produced in the high-energy/high-intensity proton collisions.

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/interact inside the neutrino detector, leaving a striking signature.

Neutrino Facilities as Dark Sector Machines



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

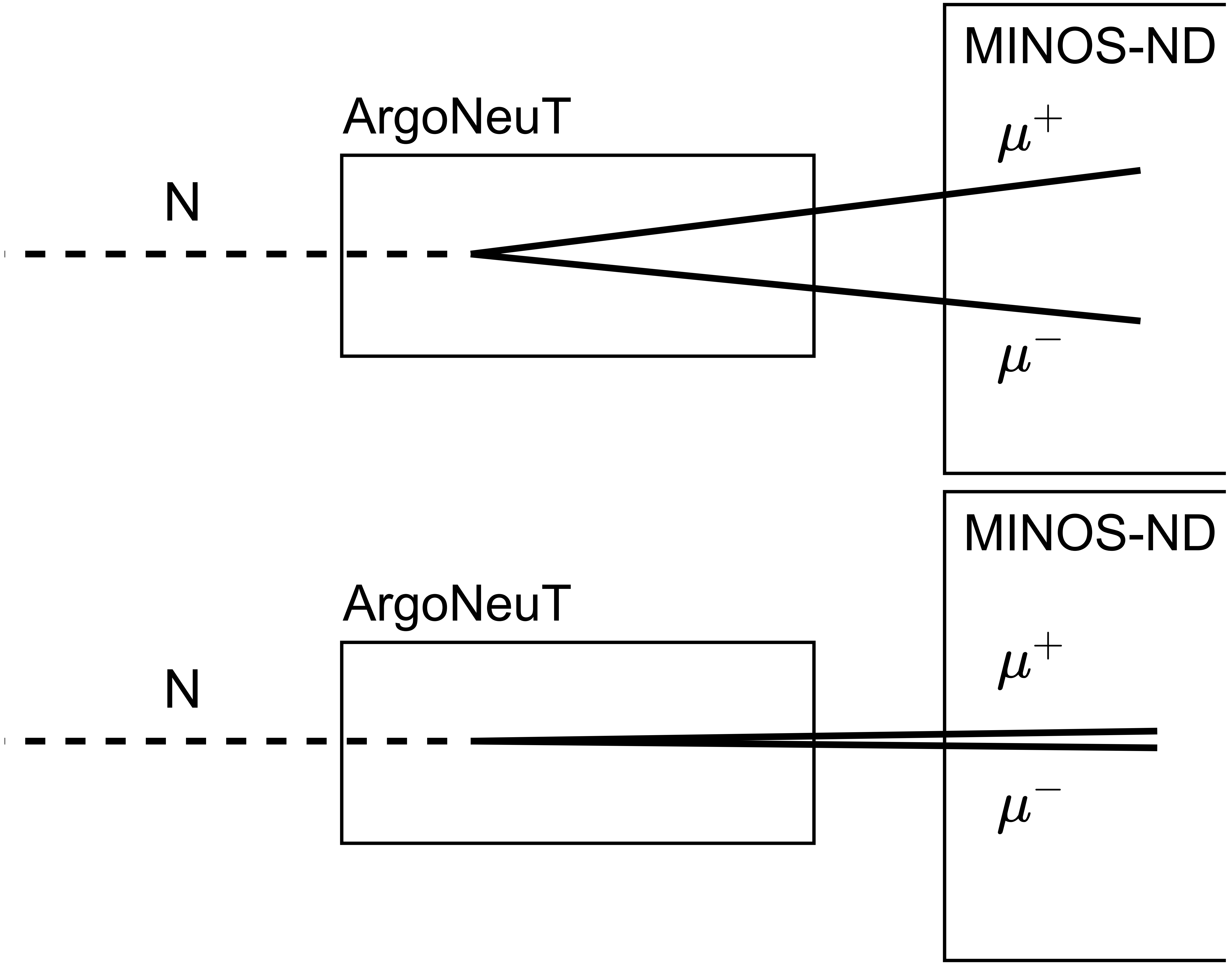
2) Mesons undergo rare decays into dark sector mediators that are long-lived. Some fraction of them travel in the forward direction.

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

ArgoNeuT

Tabletop ton-scale liquid-argon detector at Fermilab that took data in the NuMI beamline (120 GeV protons)

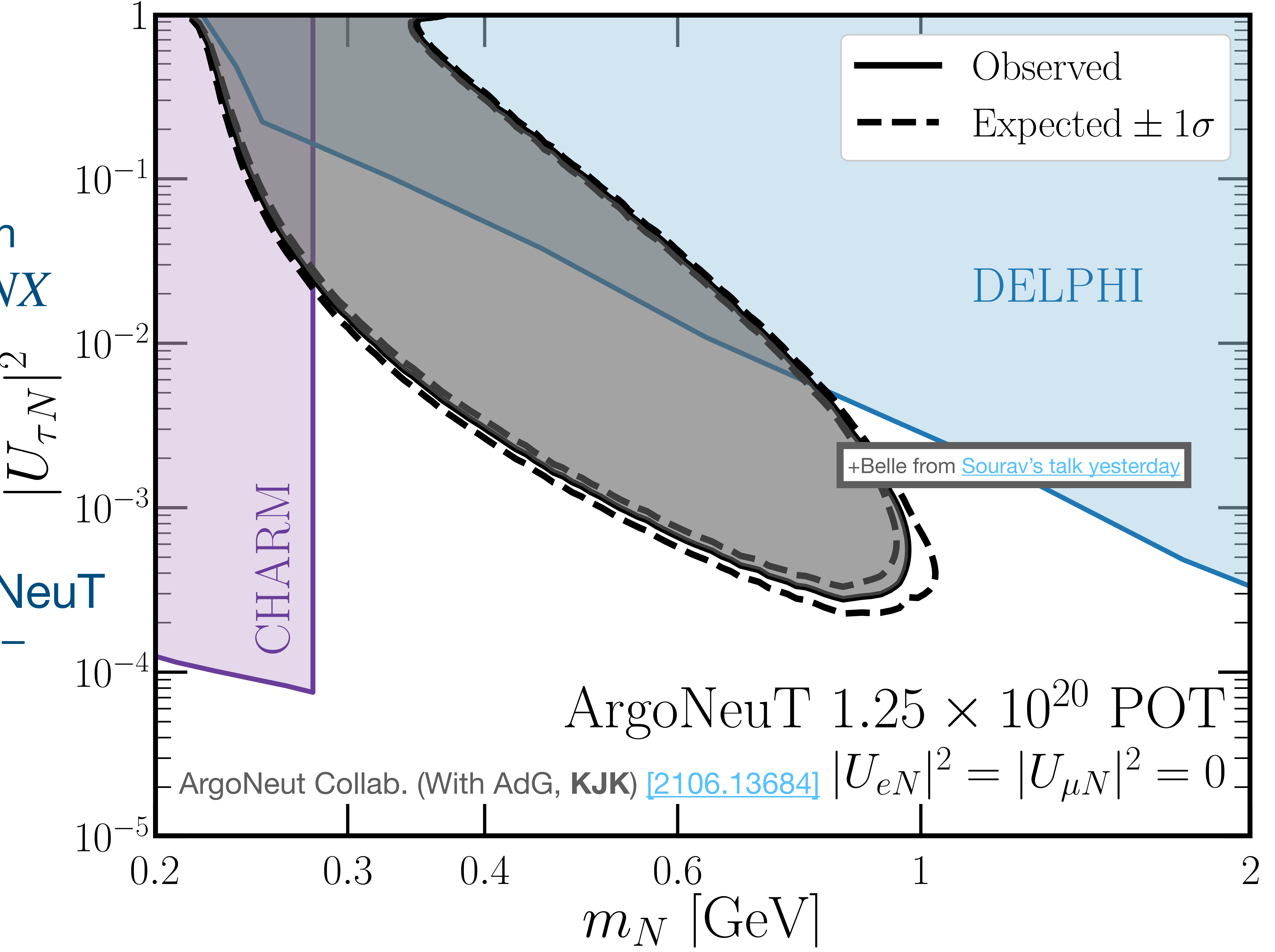
HNL production possible through D-meson production: $D^{\pm} \to \tau^{\pm}$, $\tau^{\pm} \to N$



ArgoNeuT

HNLs produced in
$D^\pm \to \tau^\pm,\ \tau^\pm \to NX$

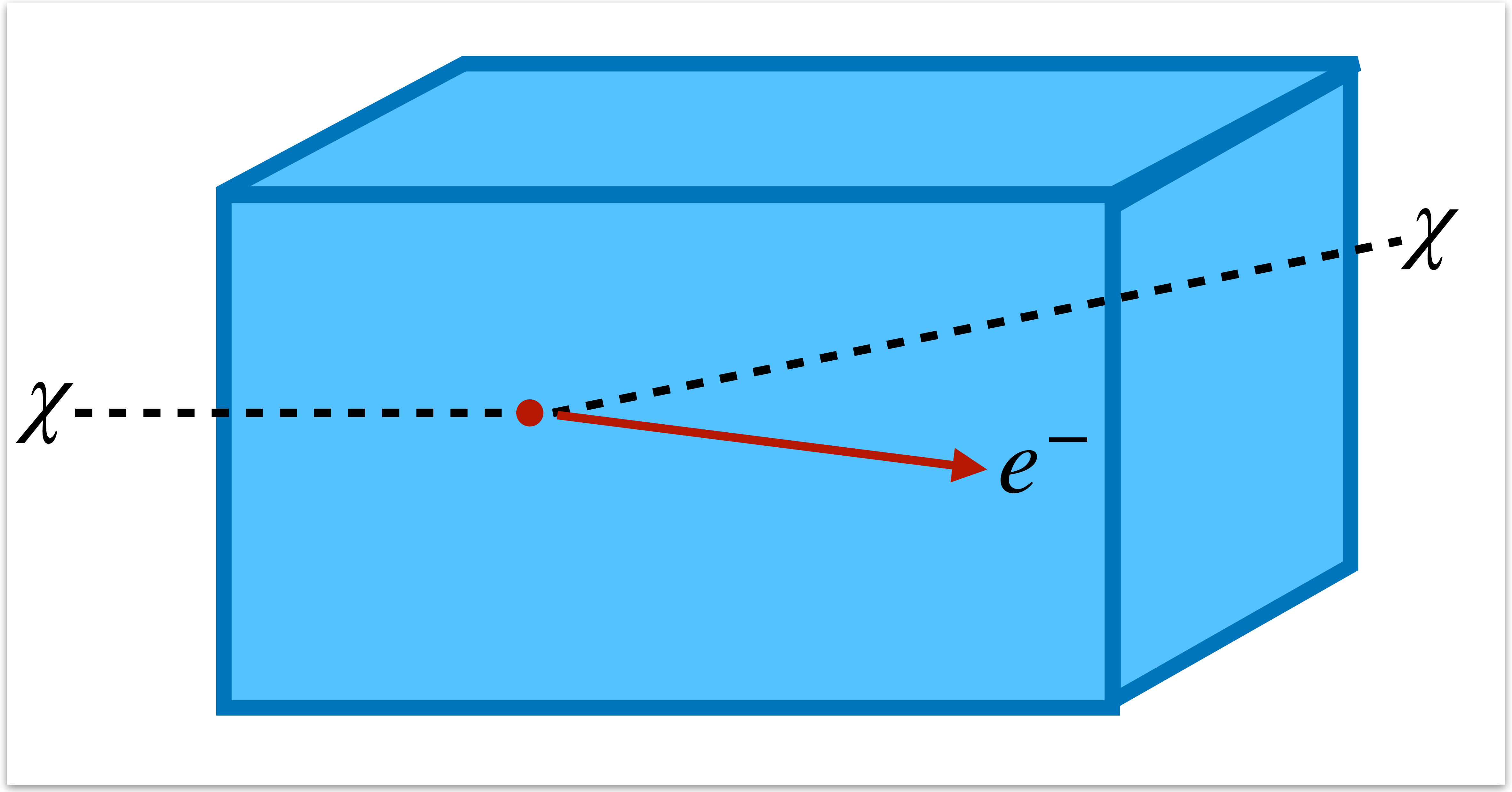
Decay in/near ArgoNeuT
via $N \to \nu_\tau \mu^+ \mu^-$



Full Disclosure…

Complementarity of Neutrino Detectors

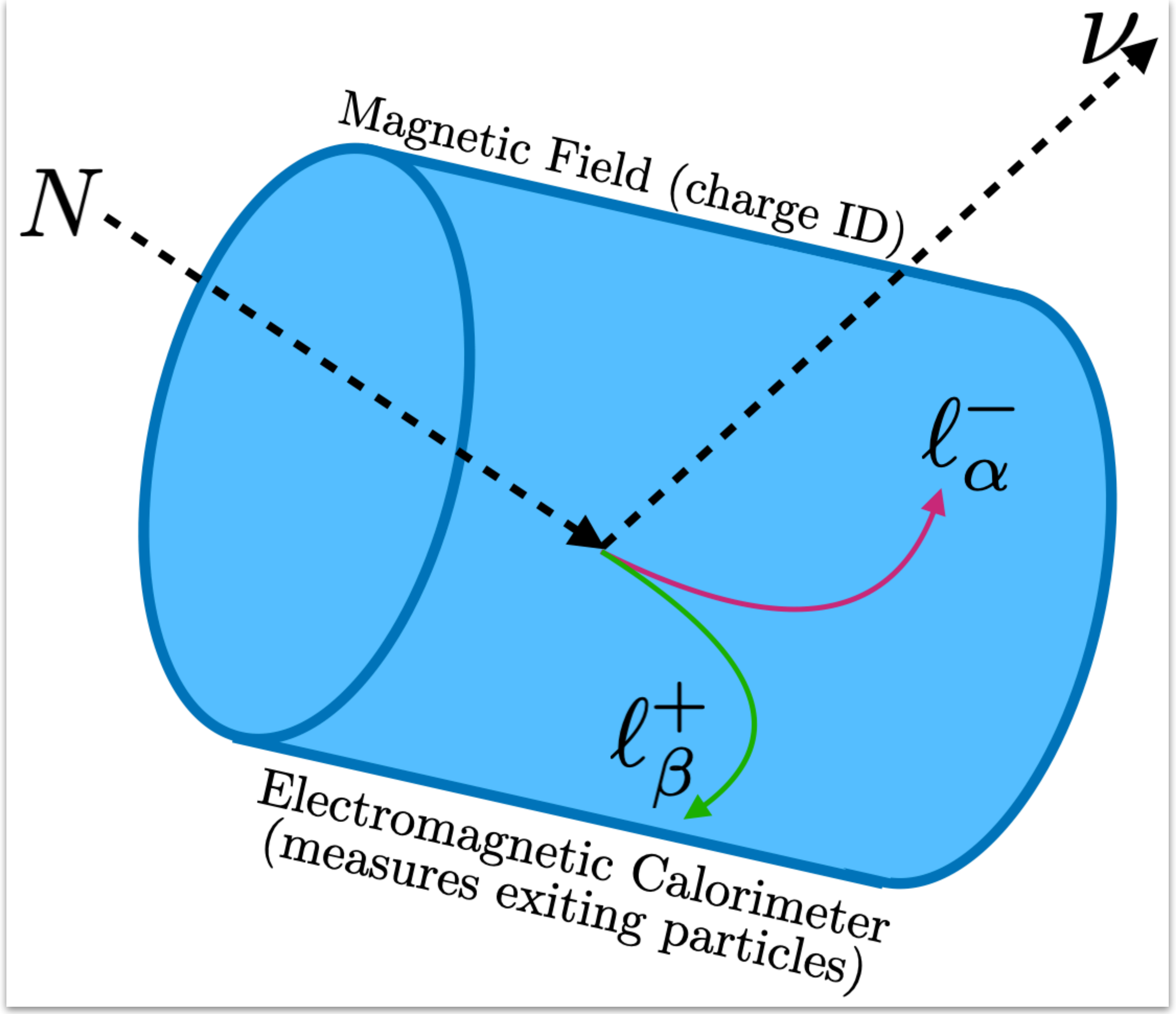
Liquid Detectors (SBND, ICARUS, etc.)



Large mass for rare-particle scattering

Excellent particle ID, energy resolution, etc.

Gaseous Detectors (DUNE NDGAr)

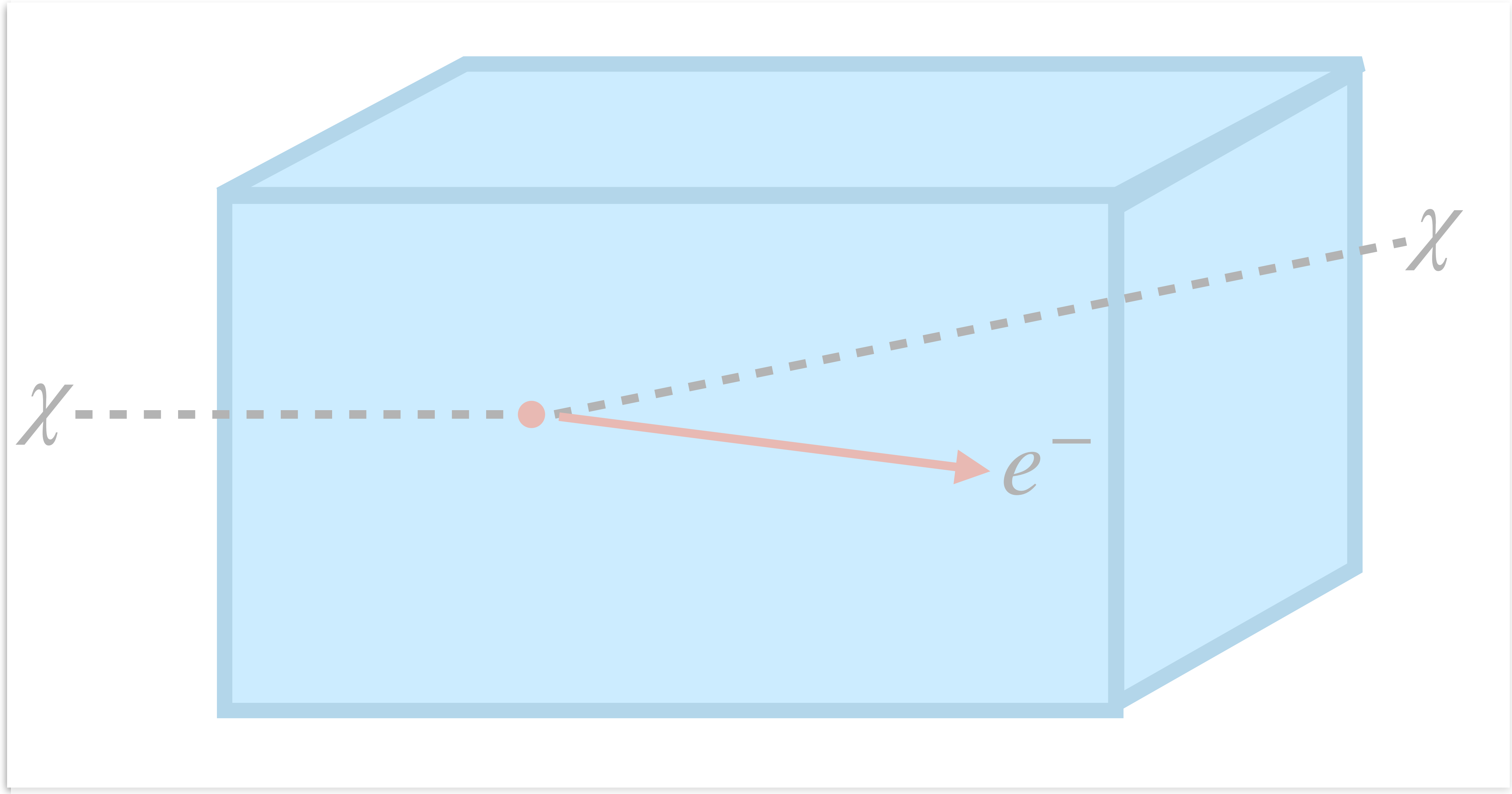


Decay Signal $\propto$ Volume

Neutrino Scattering Backgrounds $\propto$ Mass

Complementarity of Neutrino Detectors

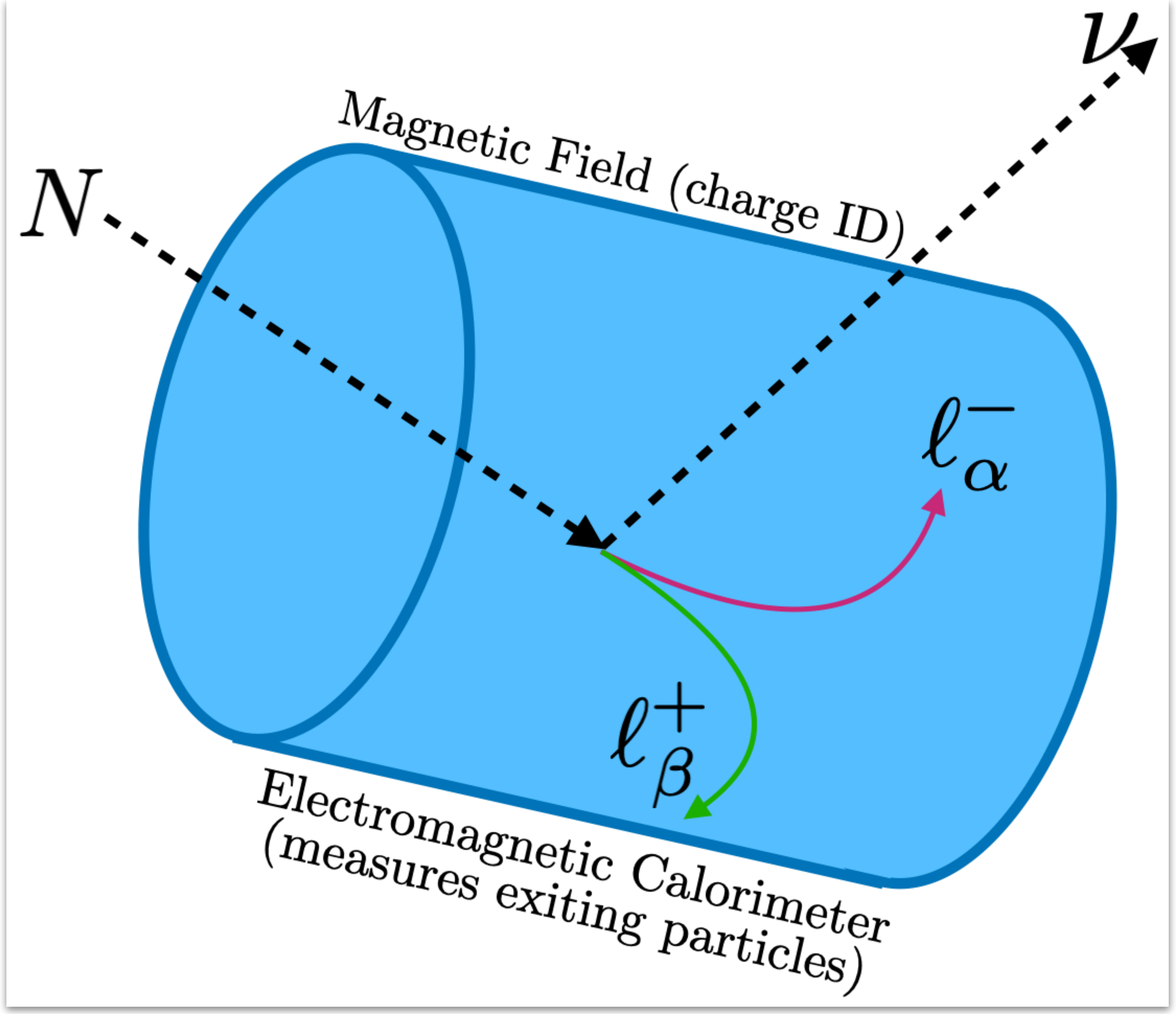
Liquid Detectors (SBND, ICARUS, etc.)



Large mass for rare-particle scattering

Excellent particle ID, energy resolution, etc.

Gaseous Detectors (DUNE NDGAr)

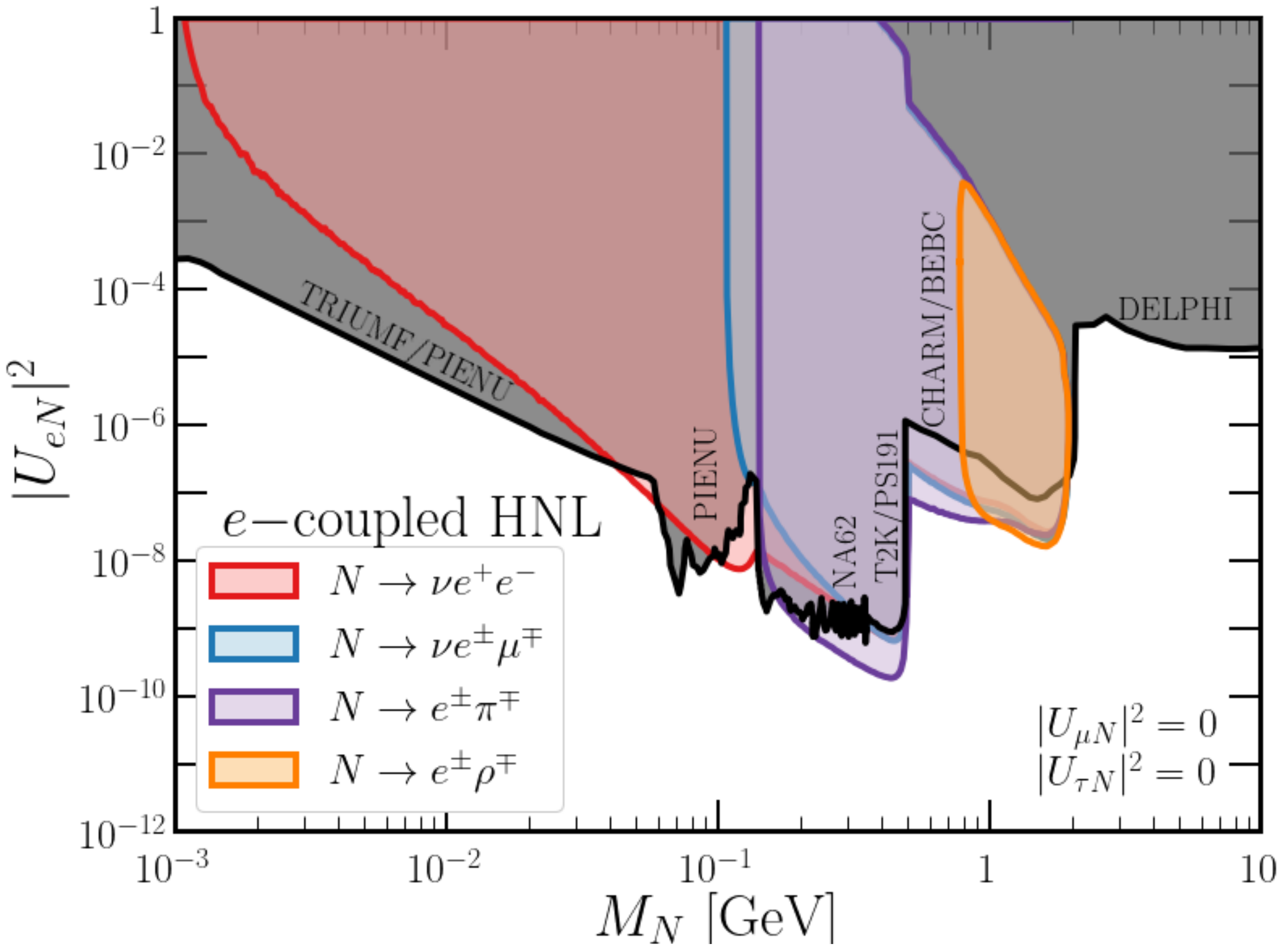


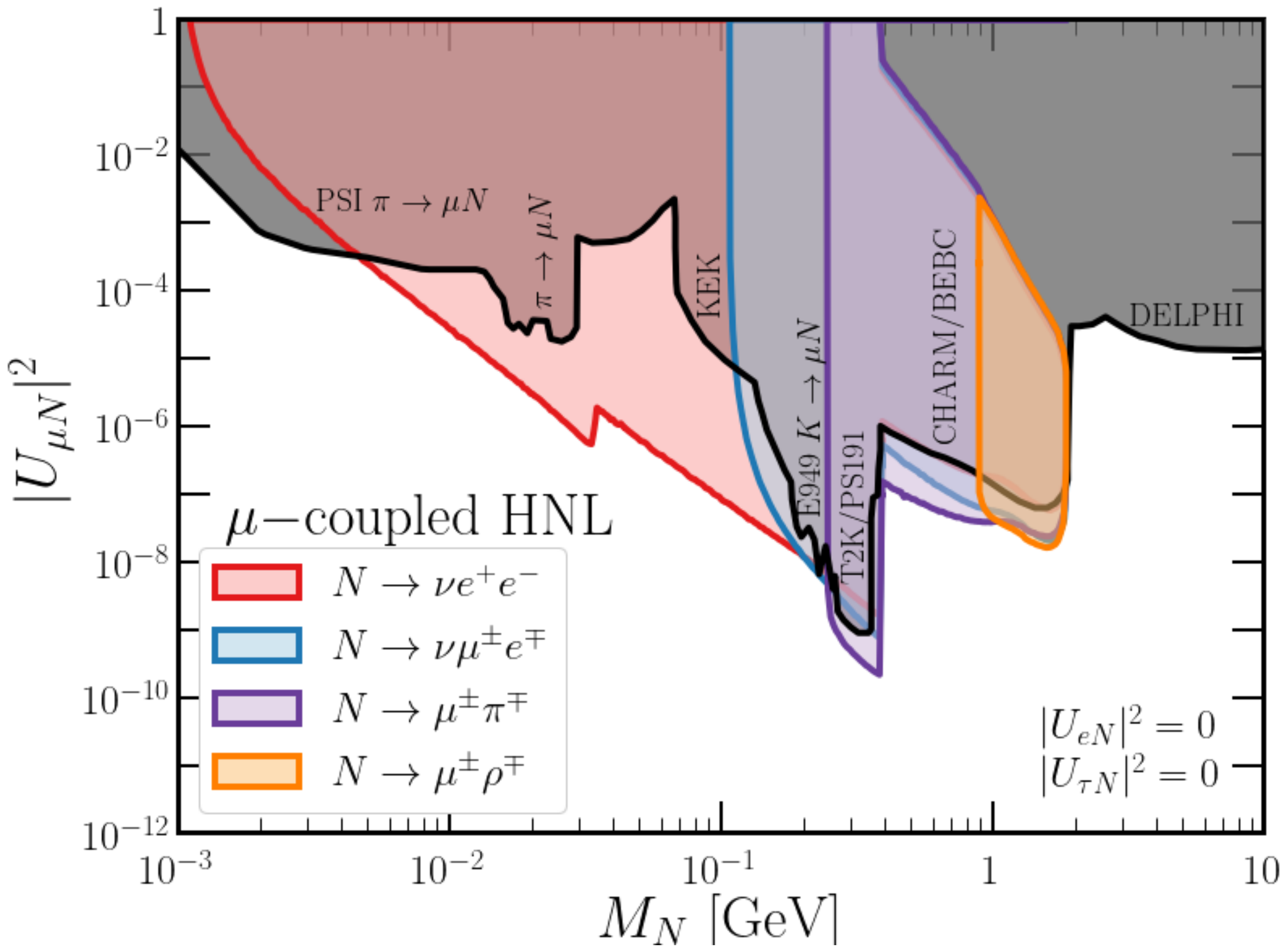
Decay Signal ∝ Volume

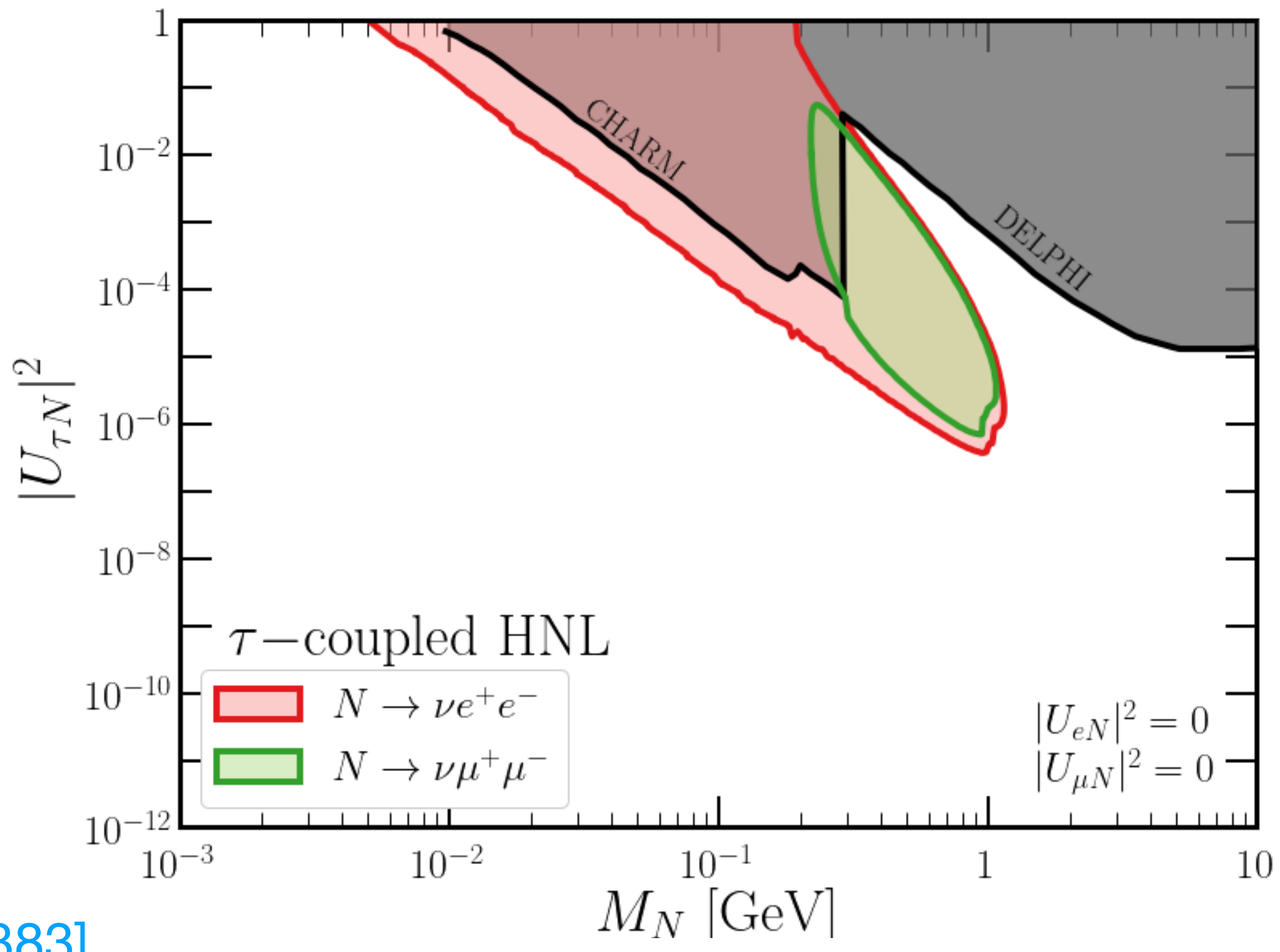
Neutrino Scattering Backgrounds ∝ Mass

DUNE NDGAr's HNL Capability

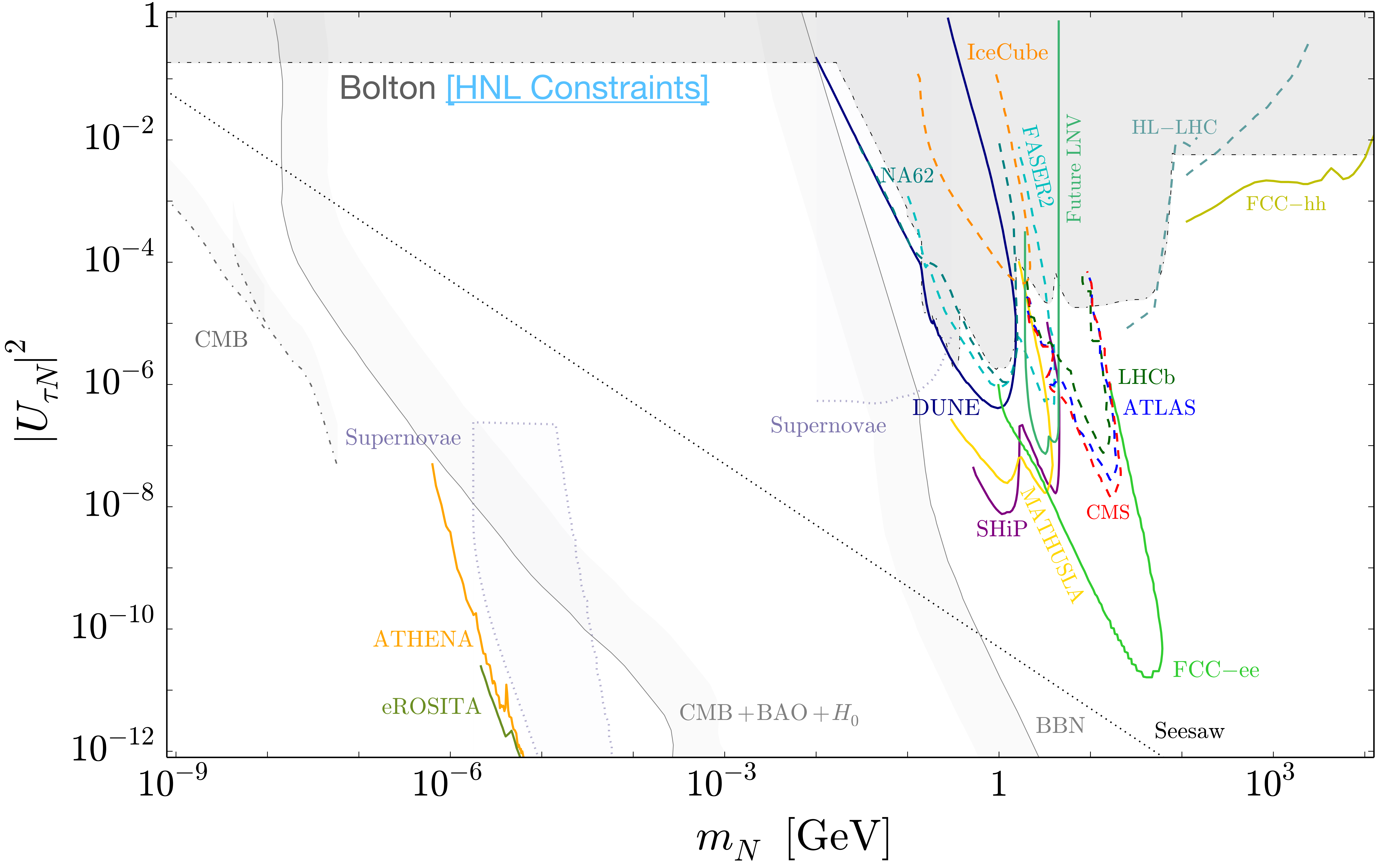
Berryman, de Gouvêa, Fox, Kayser, **KJK**, Raaf [1912.07622]







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



Looking Ahead…

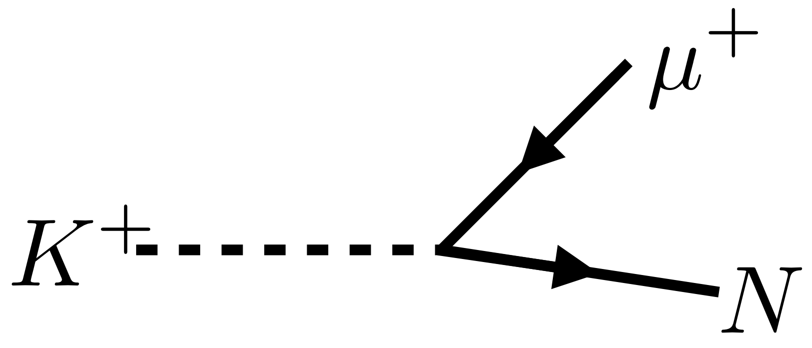
What do we do with a discovery?

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

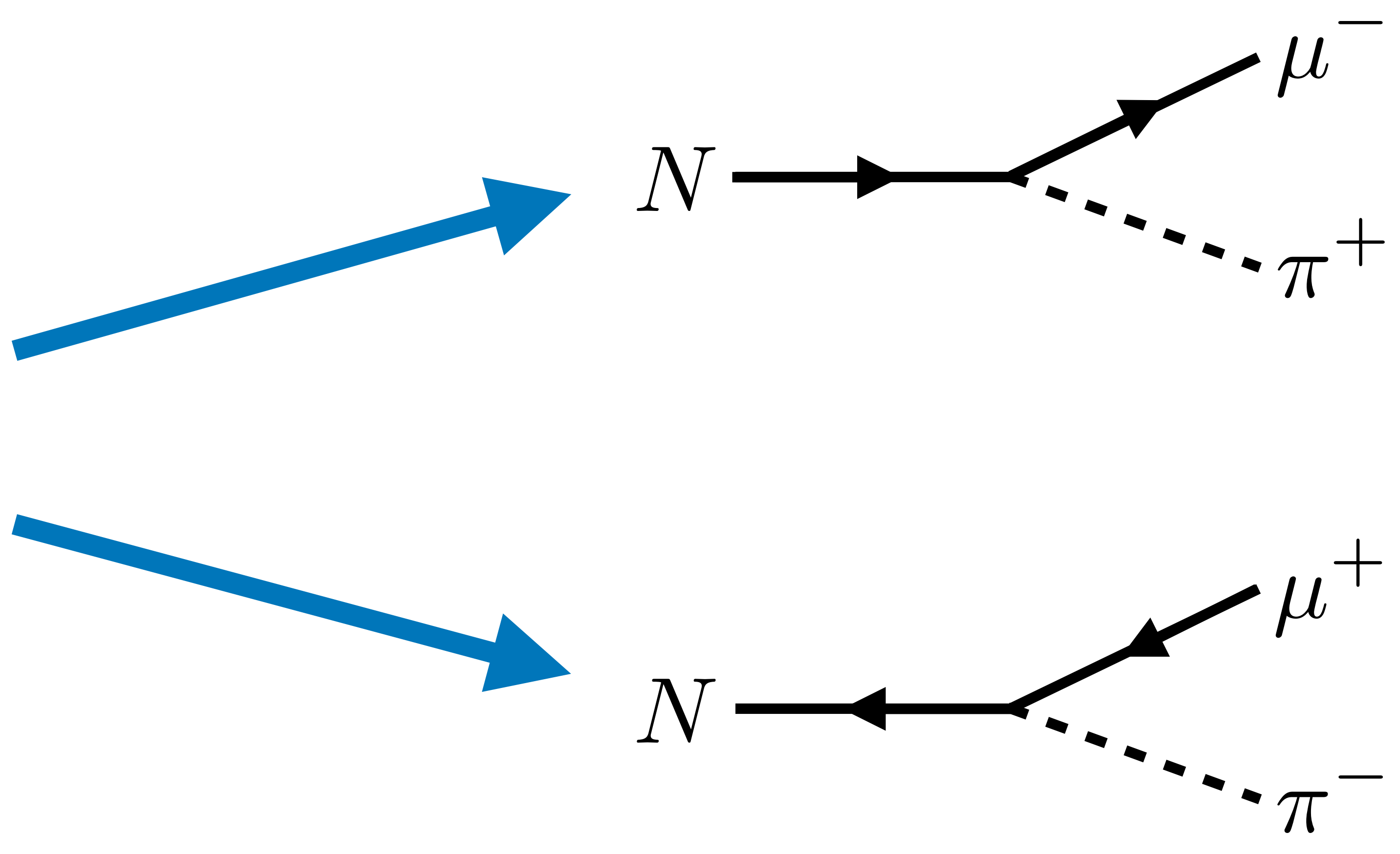
Is the new particle a Dirac or Majorana Fermion?

↔

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



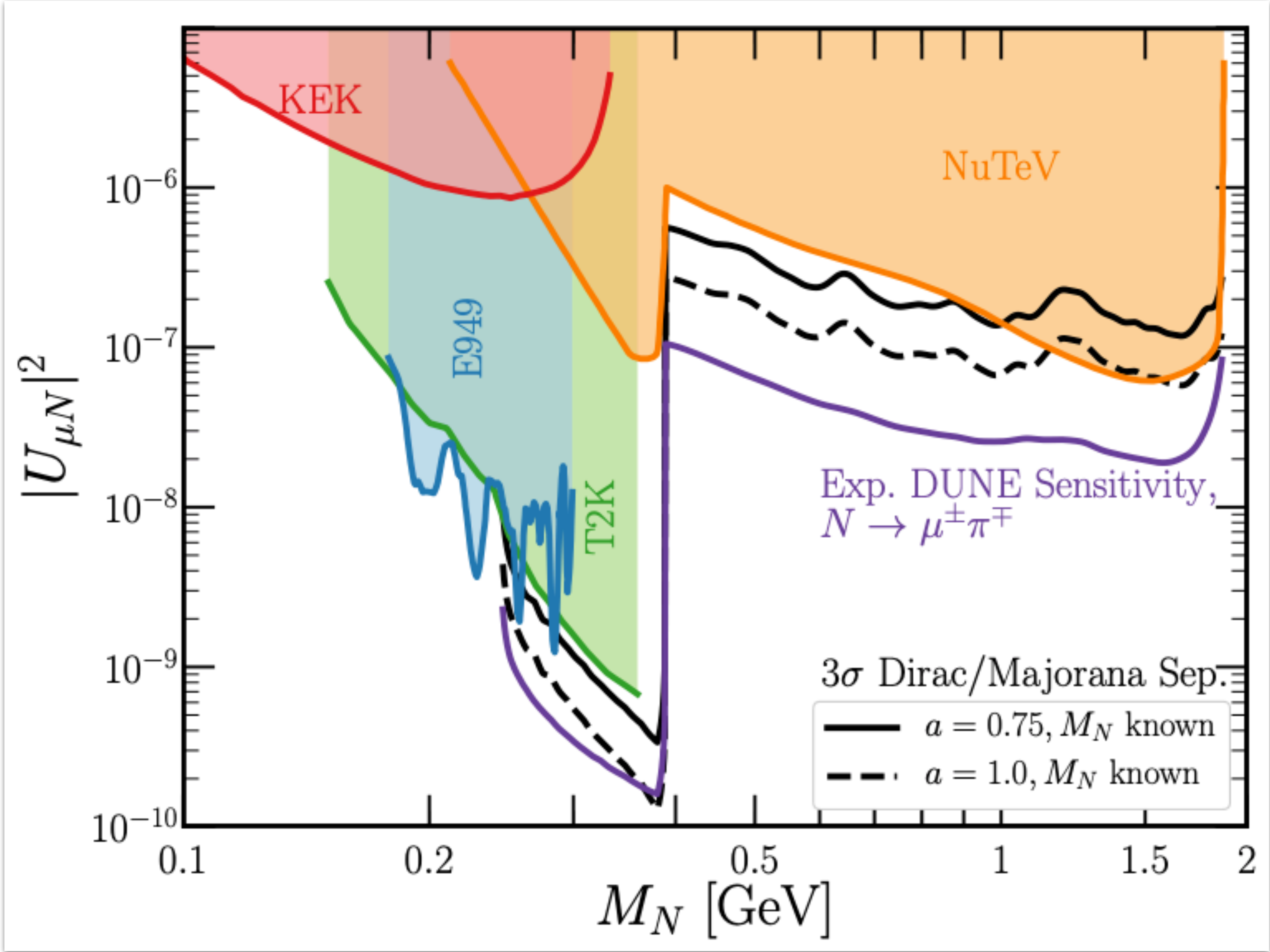
Heavy Neutrino Source



Heavy Neutrino Decay

- Do these two chains occur with equal probability?

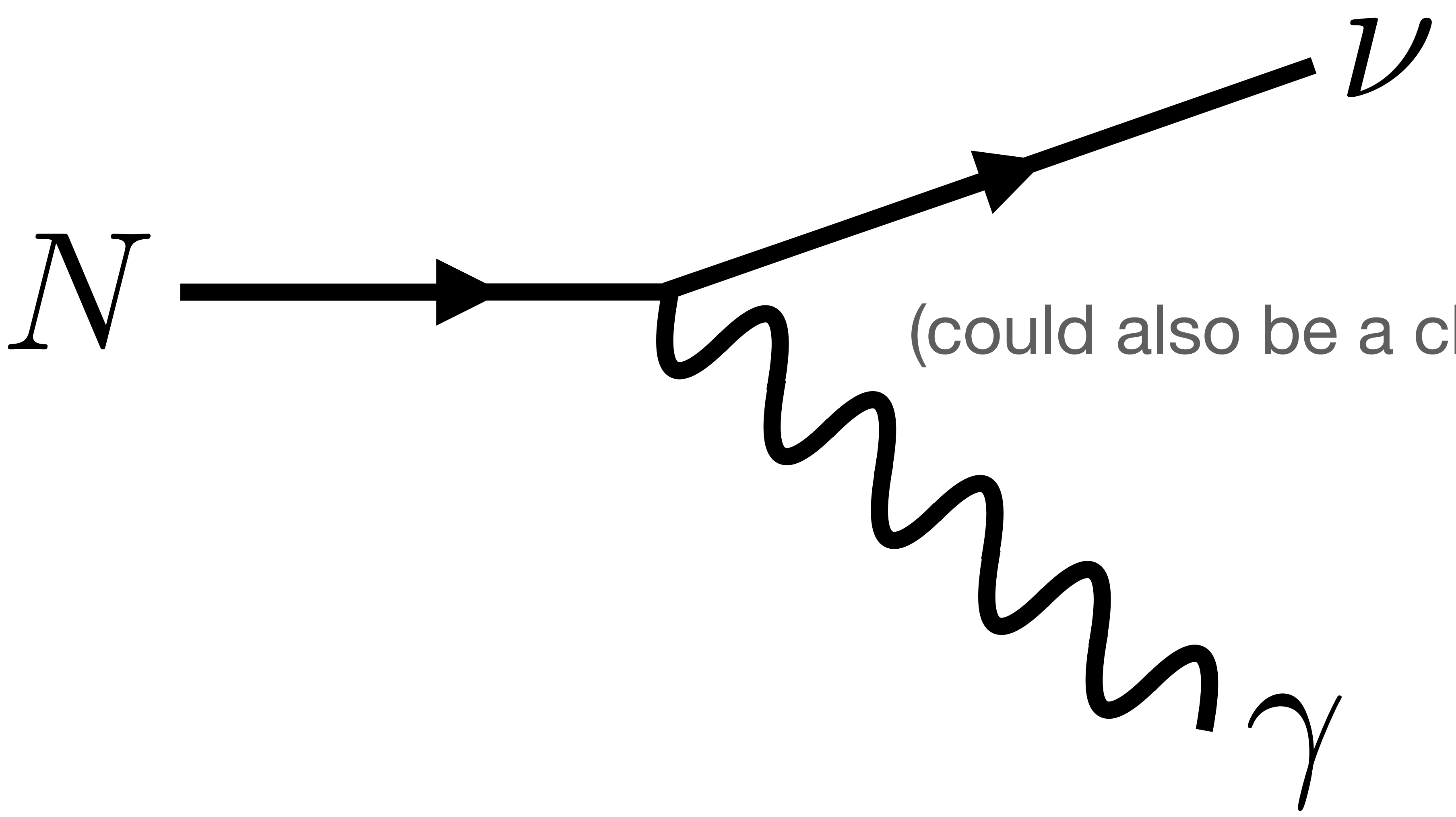
Next-Generation Prospects



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

What if we're not lucky?

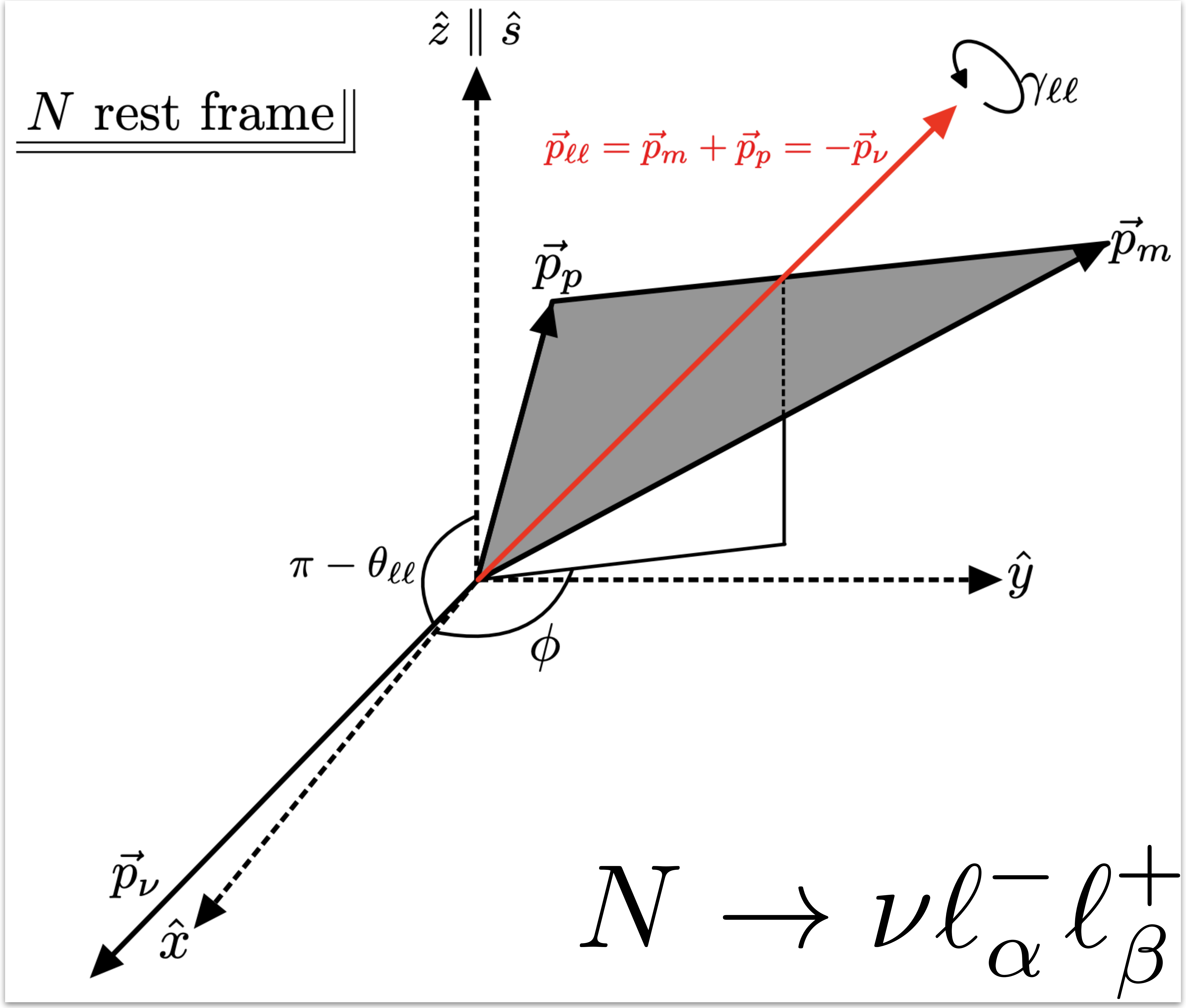
- What if the HNL is lighter than the pion? Then there are no fully-visible final states to decay into, and Lepton Number can't be identified on an event-by-event basis.



(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

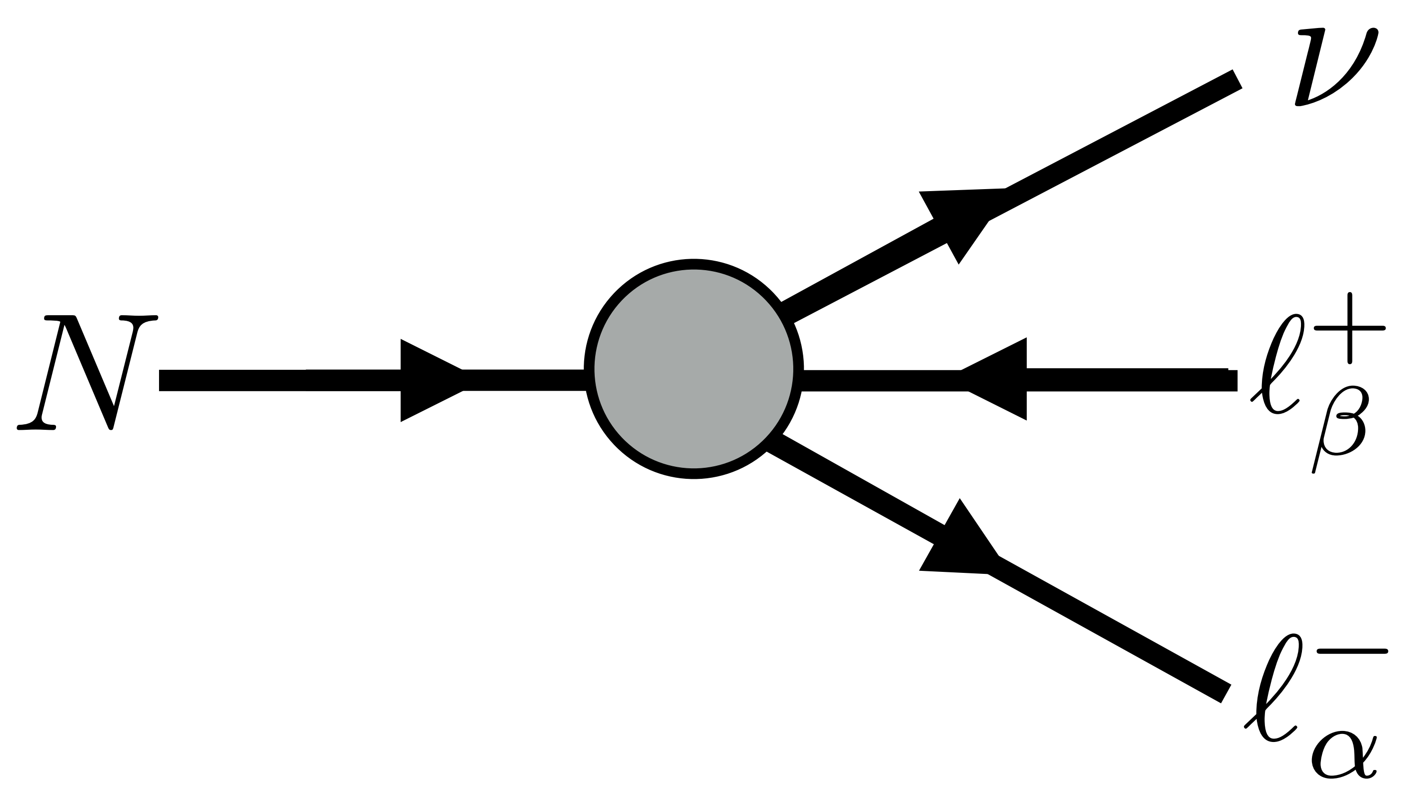
Dirac vs. Majorana in Three-Body Decays



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)

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



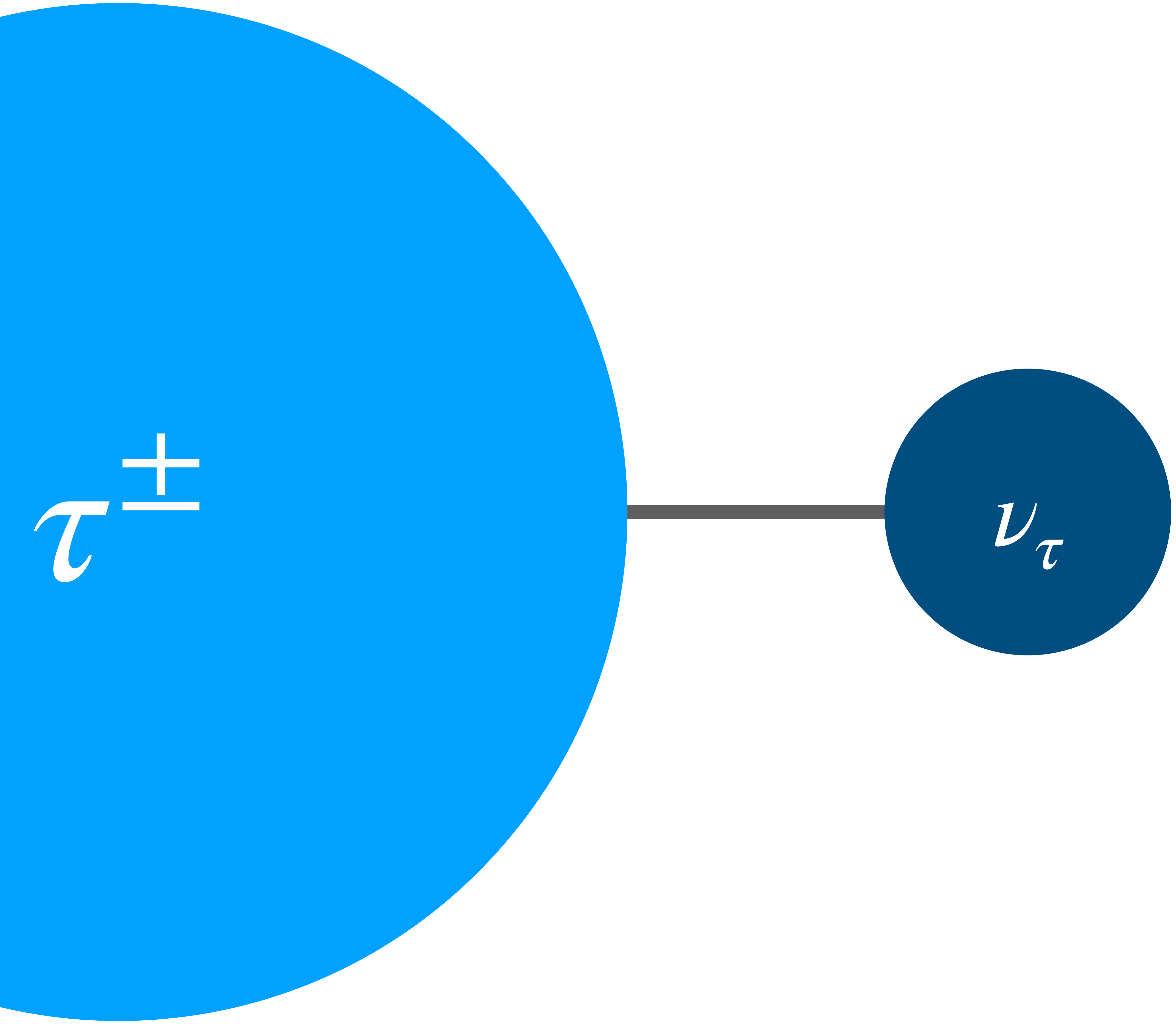
$$\Gamma_N,\ \Gamma_L \in \left\{\mathbb{1},\ \gamma^5,\ \gamma^\mu,\ \gamma^\mu\gamma^5,\ \sigma^{\mu\nu} = \frac{i}{2}\left[\gamma^\mu, \gamma^\nu\right]\right\}$$

de Gouvêa, Fox, Kayser, **KJK** [2104.05719]
(Building off Balantekin, de Gouvêa, Kayser [1808.10518])

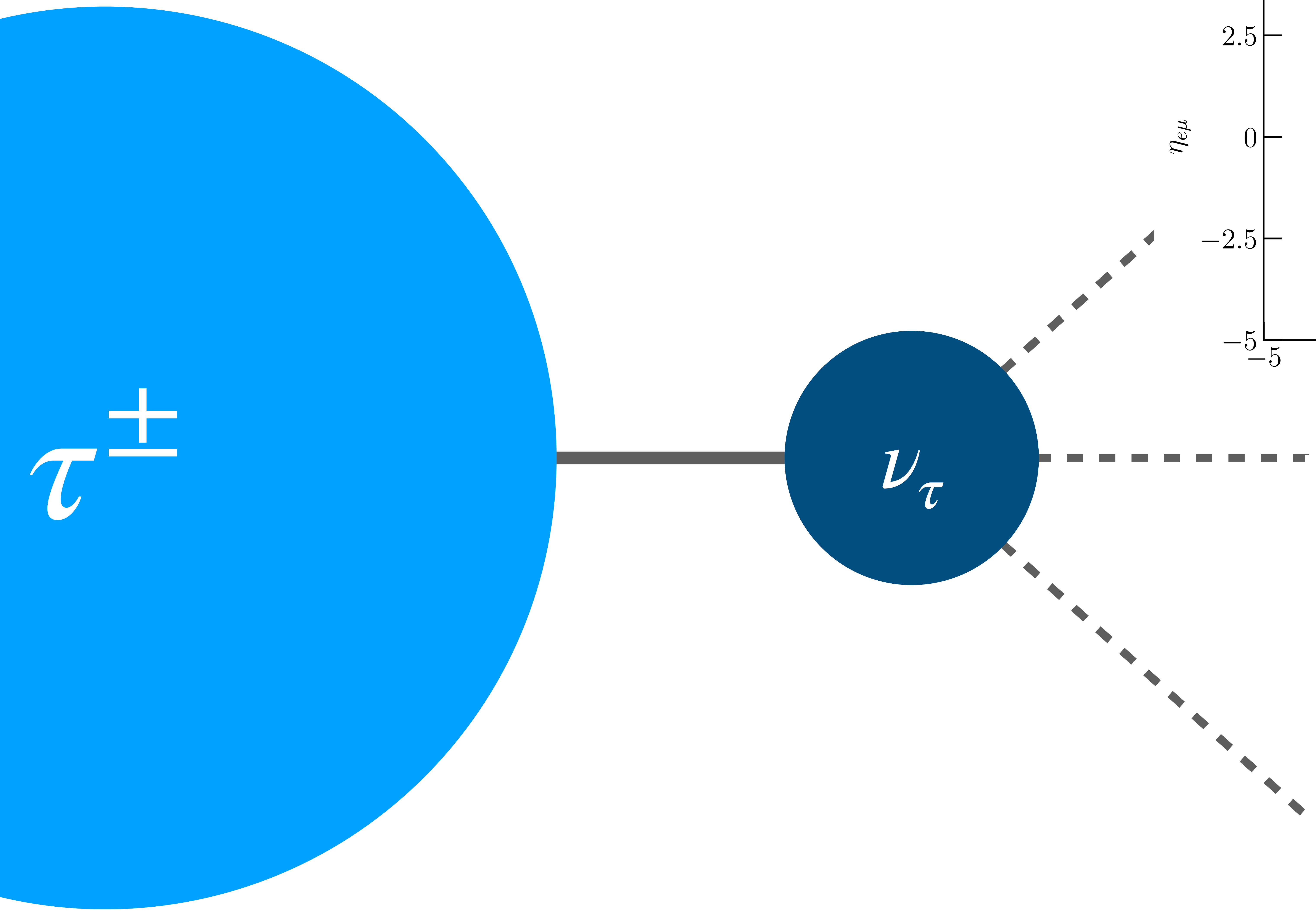
Takeaways

$\tau^{\pm}$

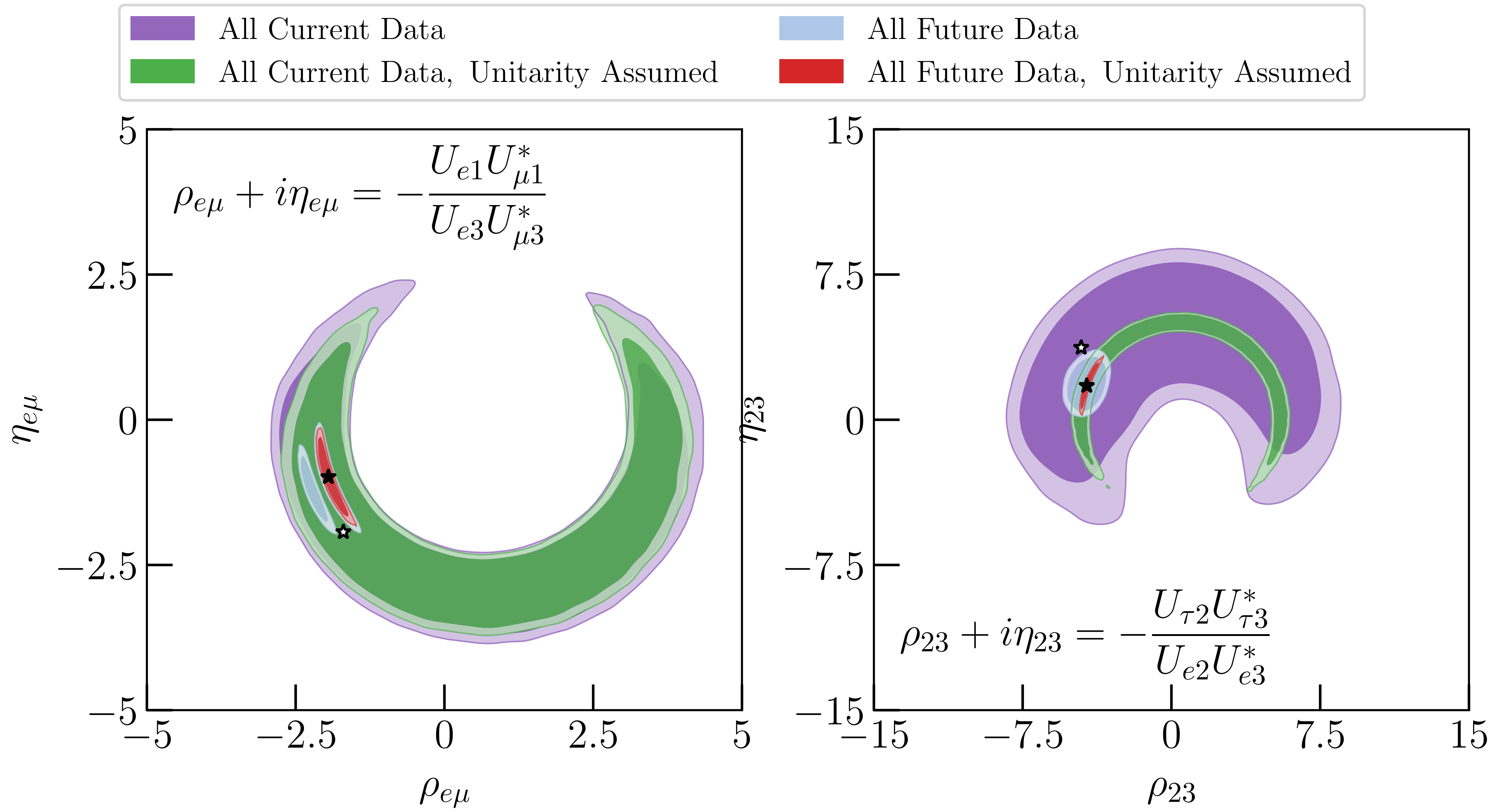
Takeaways



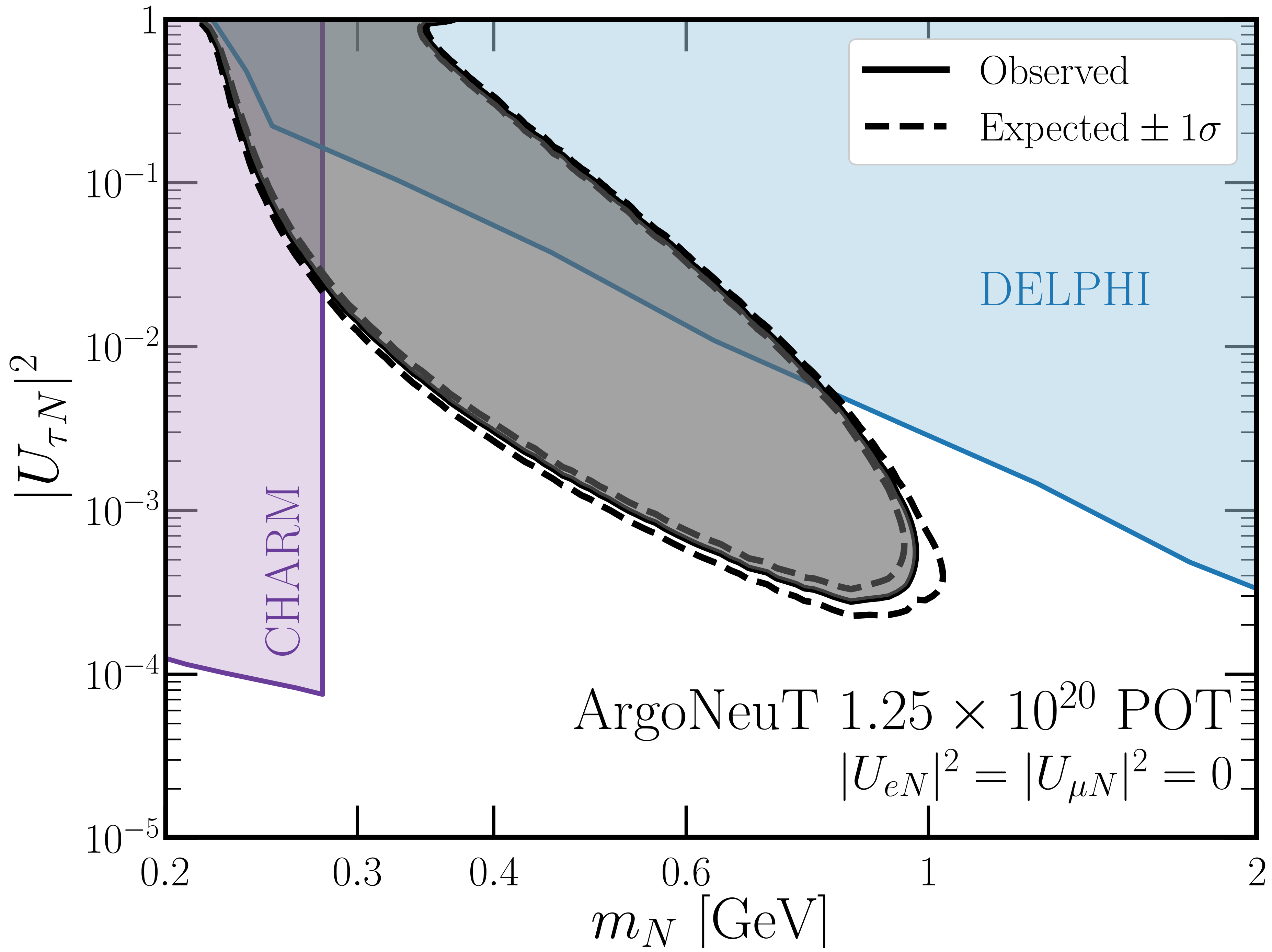
Takeaways



$\tau^\pm$
ν_τ

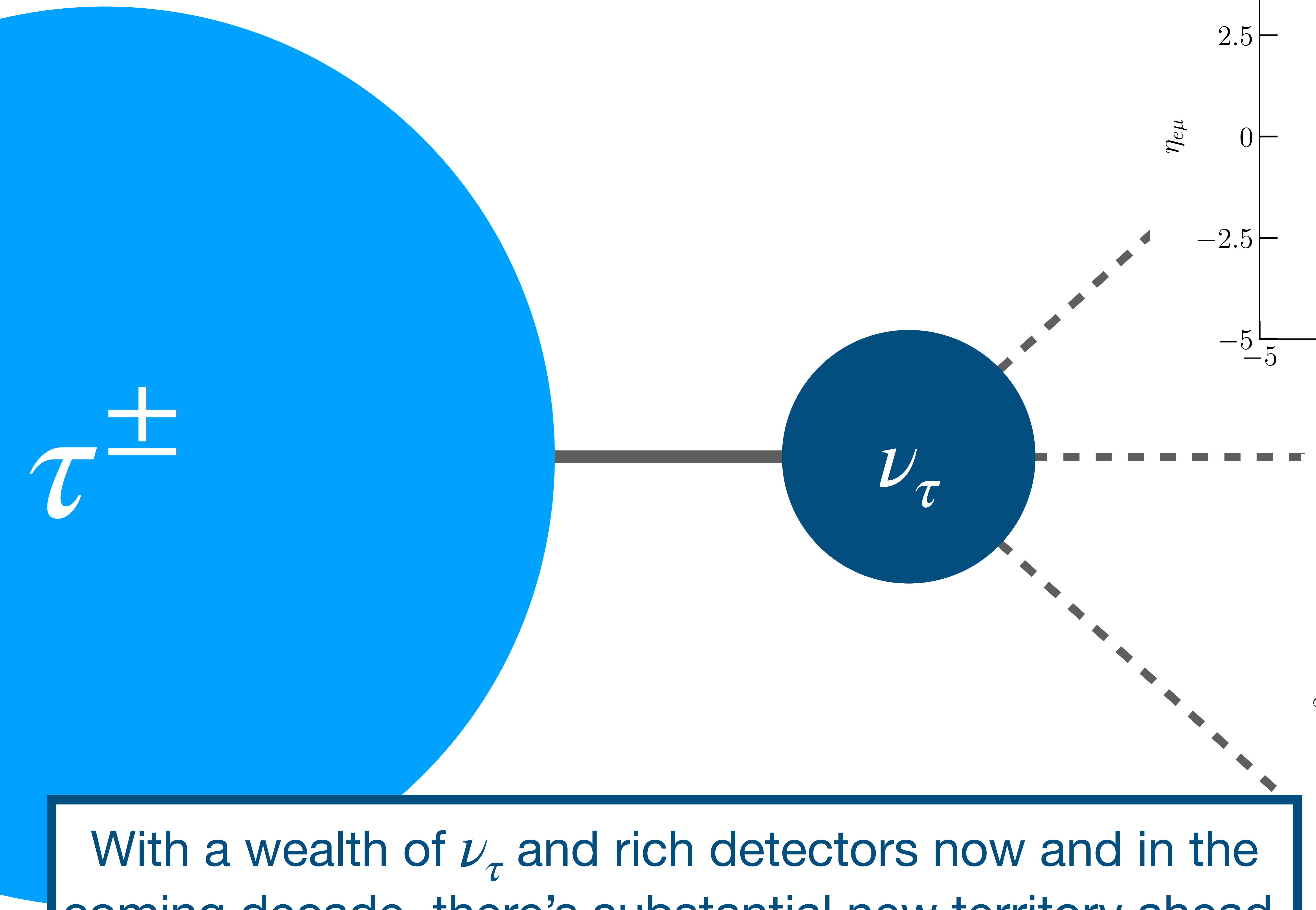


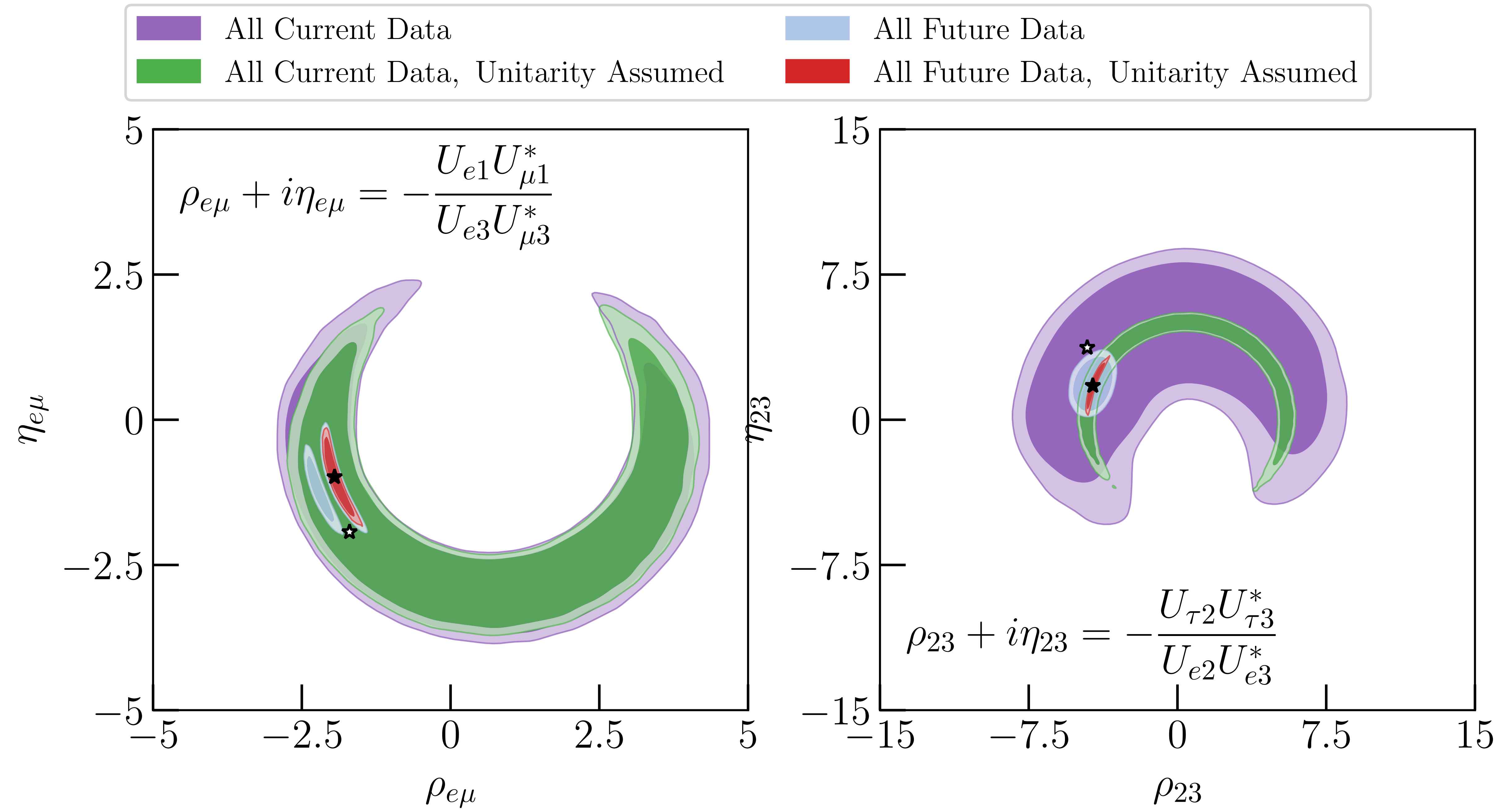
All Current Data
All Current Data, Unitarity Assumed
All Future Data
All Future Data, Unitarity Assumed
$\rho_{e\mu} + i\eta_{e\mu} = -\frac{U_{e1}U^*_{\mu 1}}{U_{e3}U^*_{\mu 3}}$
$\eta_{e\mu}$
$\rho_{e\mu}$
$\rho_{23} + i\eta_{23} = -\frac{U_{\tau 2}U^*_{\tau 3}}{U_{e2}U^*_{e3}}$
η_{23}
ρ_{23}

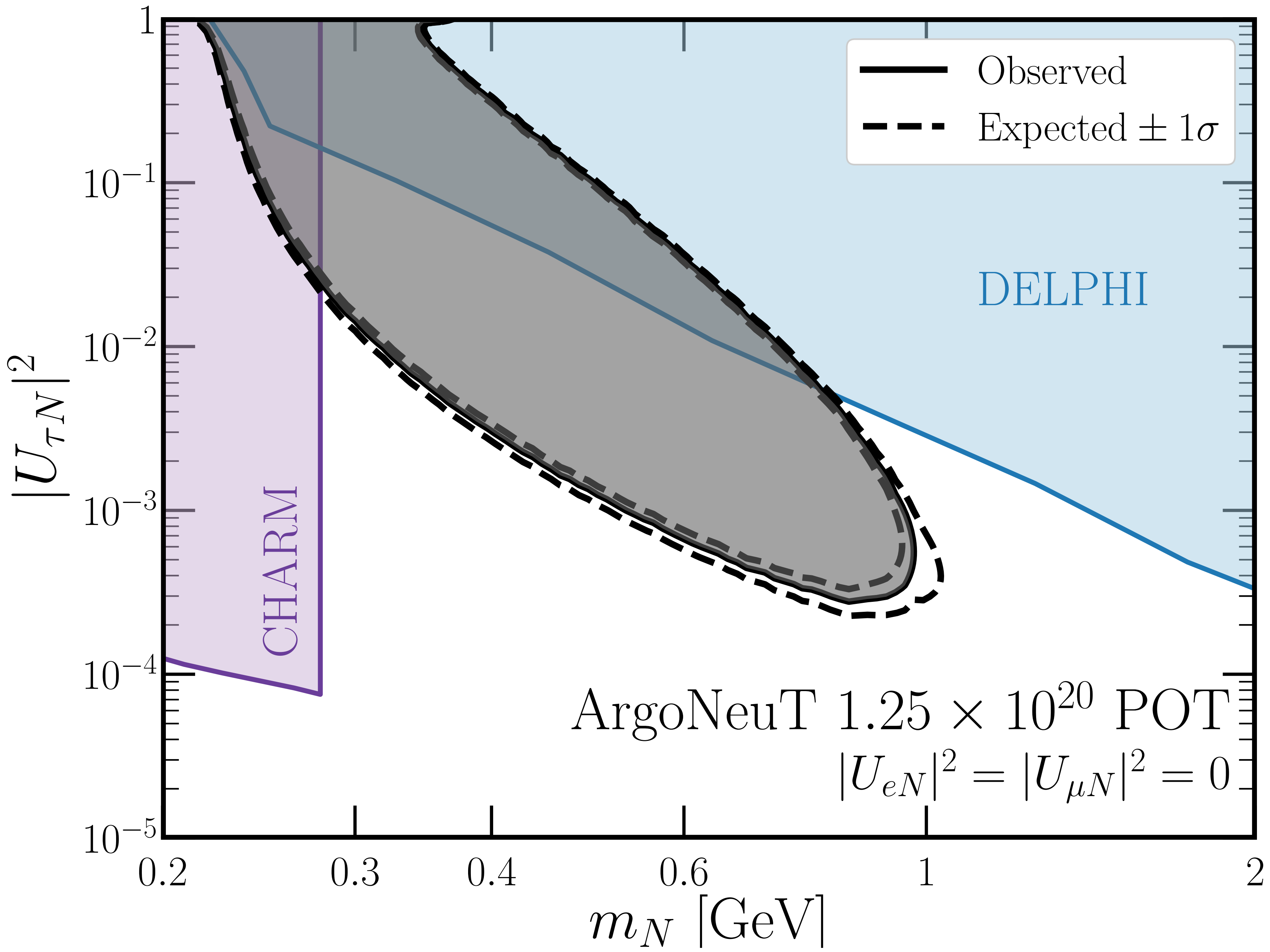


Observed
Expected $\pm 1\sigma$
DELPHI
CHARM
ArgoNeuT 1.25×10^{20} POT
$|U_{eN}|^2 = |U_{\mu N}|^2 = 0$
$|U_{\tau N}|^2$
m_N [GeV]

Takeaways







With a wealth of ν_τ and rich detectors now and in the coming decade, there's substantial new territory ahead. Stay tuned for results, and hopefully discoveries!