Recent developments
in neutrino theory

Kevin J. Kelly, Texas A&M University
DPF-PHENO 2024
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Outline

- ν Physics

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  - New ν Physics

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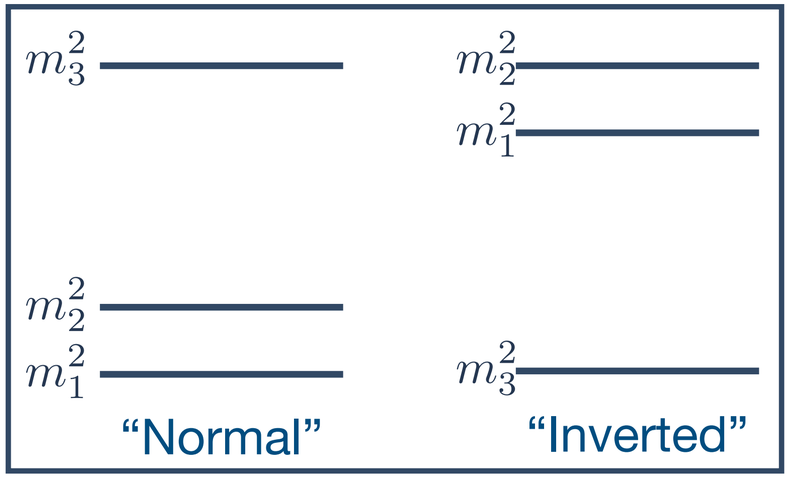
ν Physics

Neutrino Masses

Decades of experimental results have uncovered two unexpected facts:

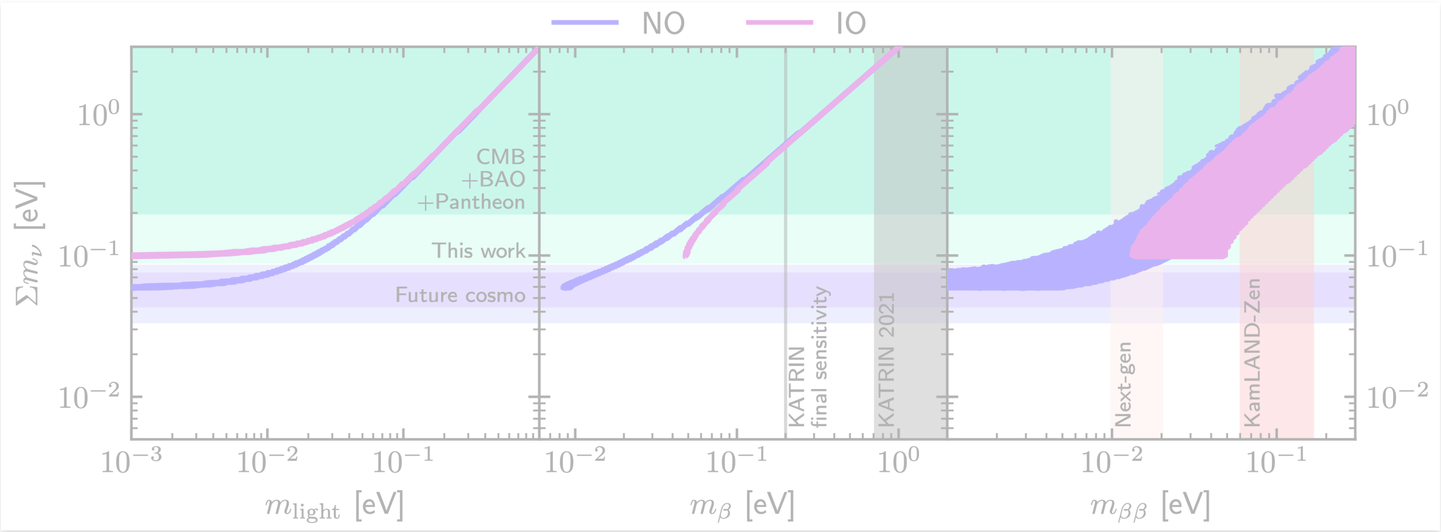


see, e.g., [2205.02195]

Neutrino Oscillations: nonzero mass-squared splittings between mass eigenstates — at least two of these states must have mass. The SM, as formulated, does not include massive neutrinos.

$$\Delta m^2_{\text{Solar}} \approx 7.5 \times 10^{-5}\ \text{eV}^2$$

$$\Delta m^2_{\text{Atm.}} \approx 2.5 \times 10^{-3}\ \text{eV}^2$$



Di Valentino et al, [2106.15267]

At the same time, the scale of these masses is *extremely* small — no direct evidence of masses above the eV scale in laboratory or cosmological probes.

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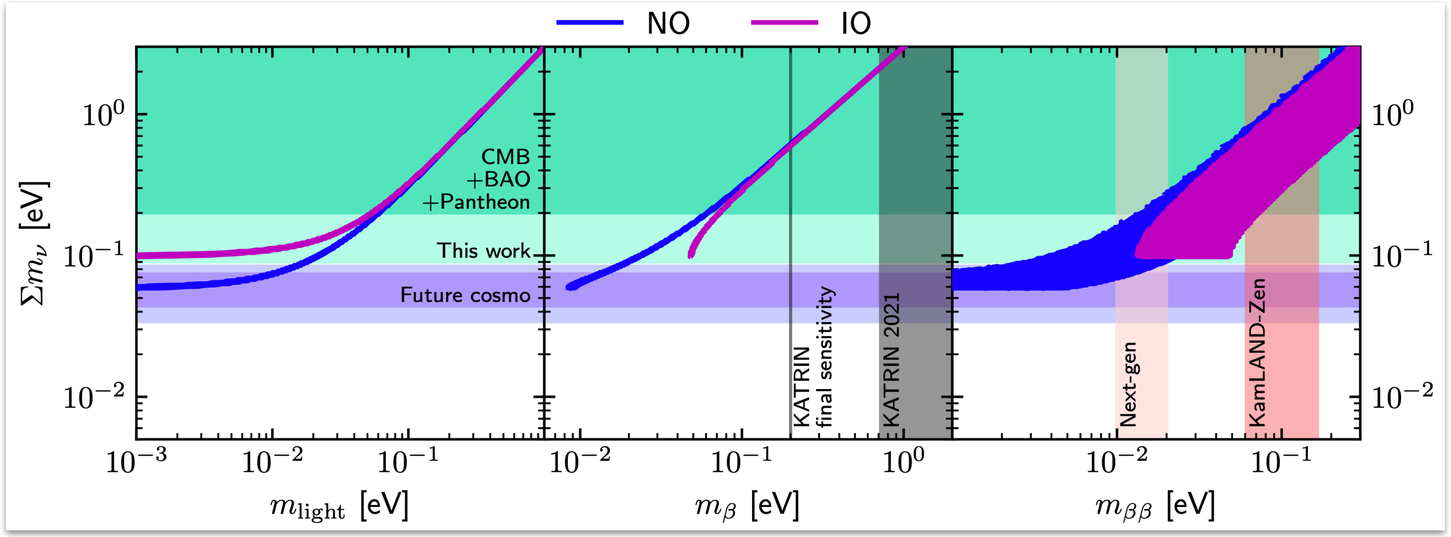

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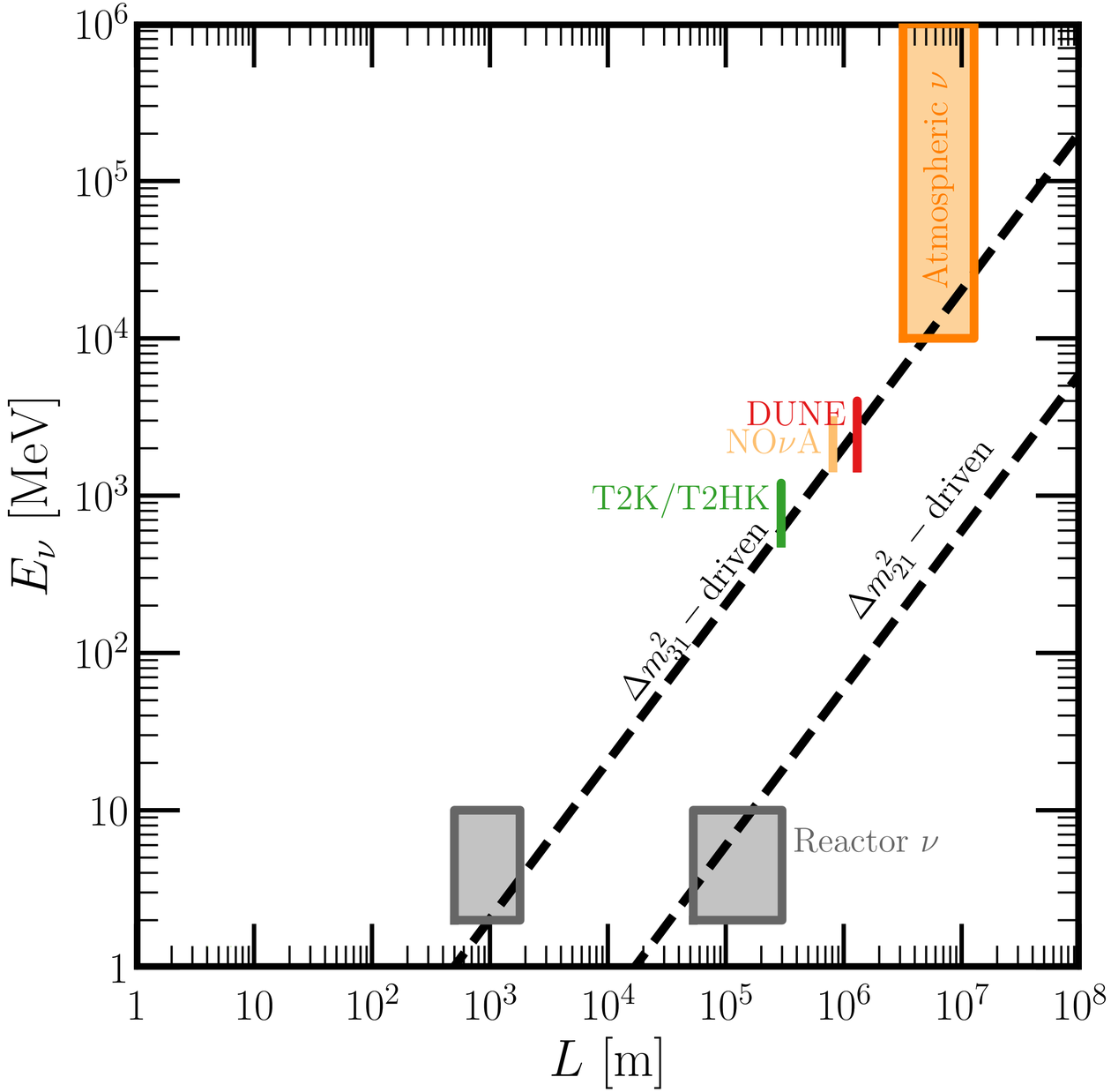
What can we learn by measuring oscillations?



Survival/Disappearance Probability

$$P_{\alpha\alpha} \approx 1 - \sin^2\left(2\theta_{\alpha\alpha}\right) \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

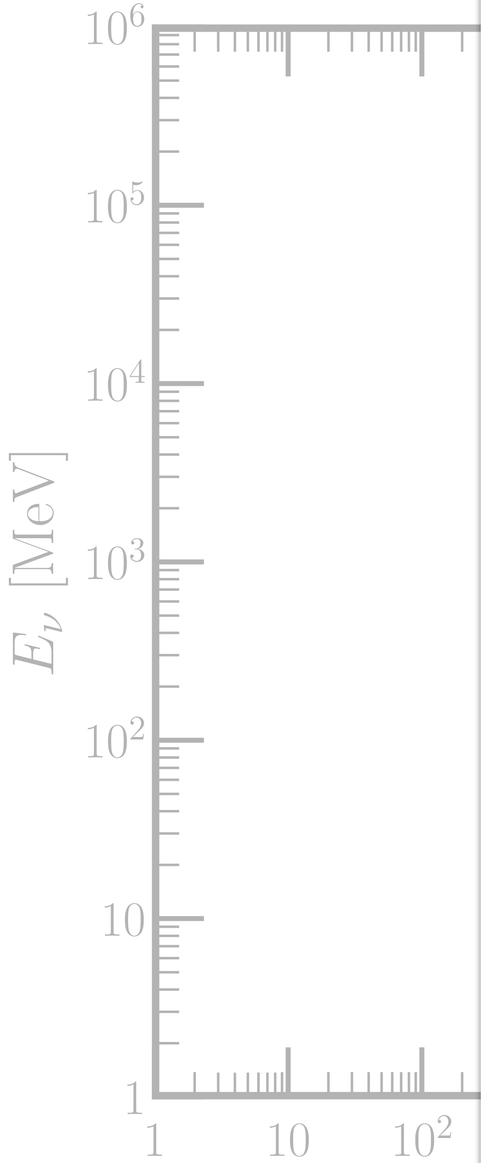
Appearance Probability

$$P_{\alpha\beta} \approx \sin^2\left(2\theta_{\alpha\beta}\right) \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

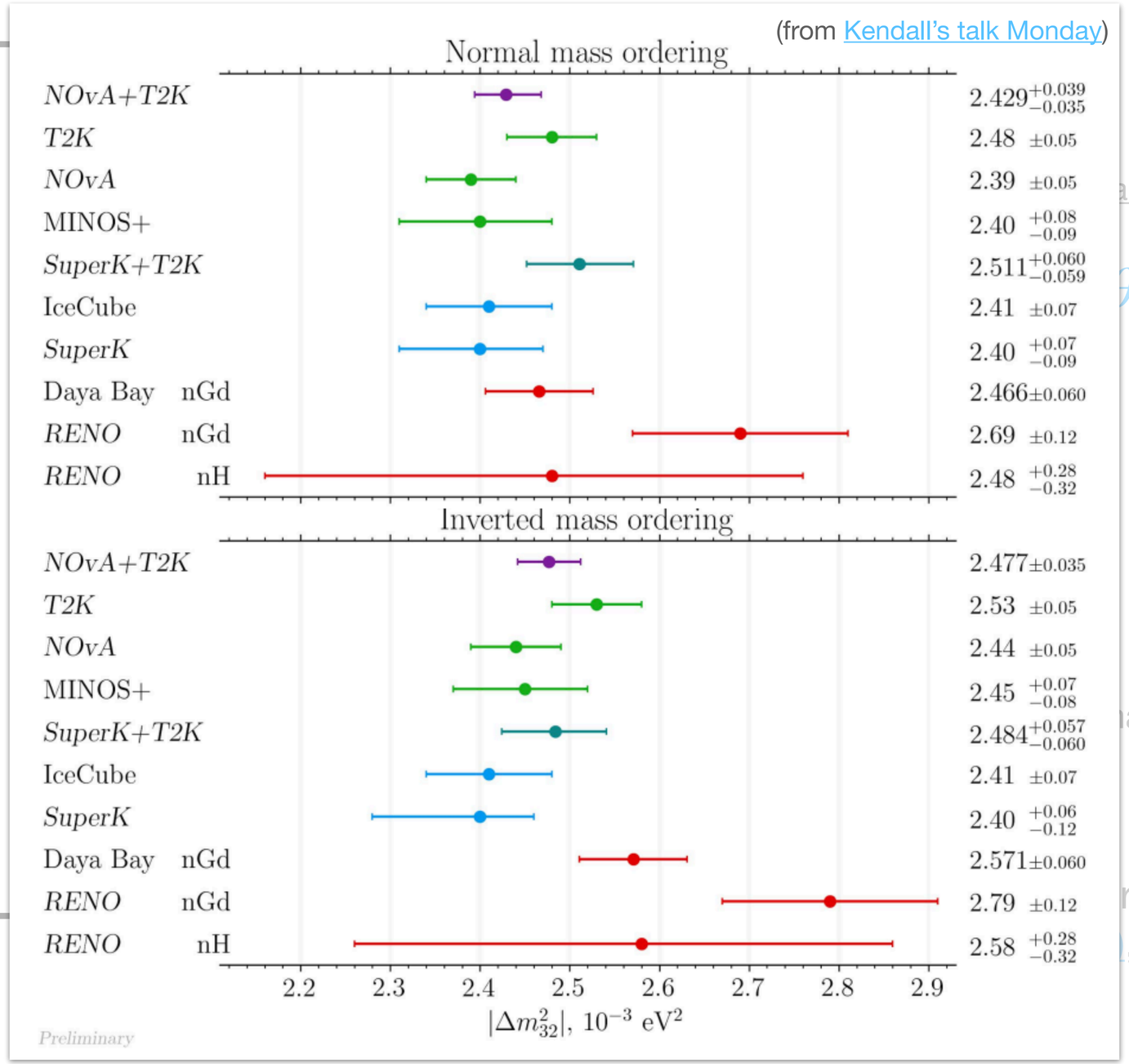
($\theta_{\alpha\beta}$: function of mixing matrix elements $U_{\alpha i}$)

More on three-flavor oscillation physics?
Kendall (Monday), Patrick (Monday)

What can we learn by measuring oscillations?



(from Kendall's talk Monday)



ability

$$\theta_{\alpha\alpha}) \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

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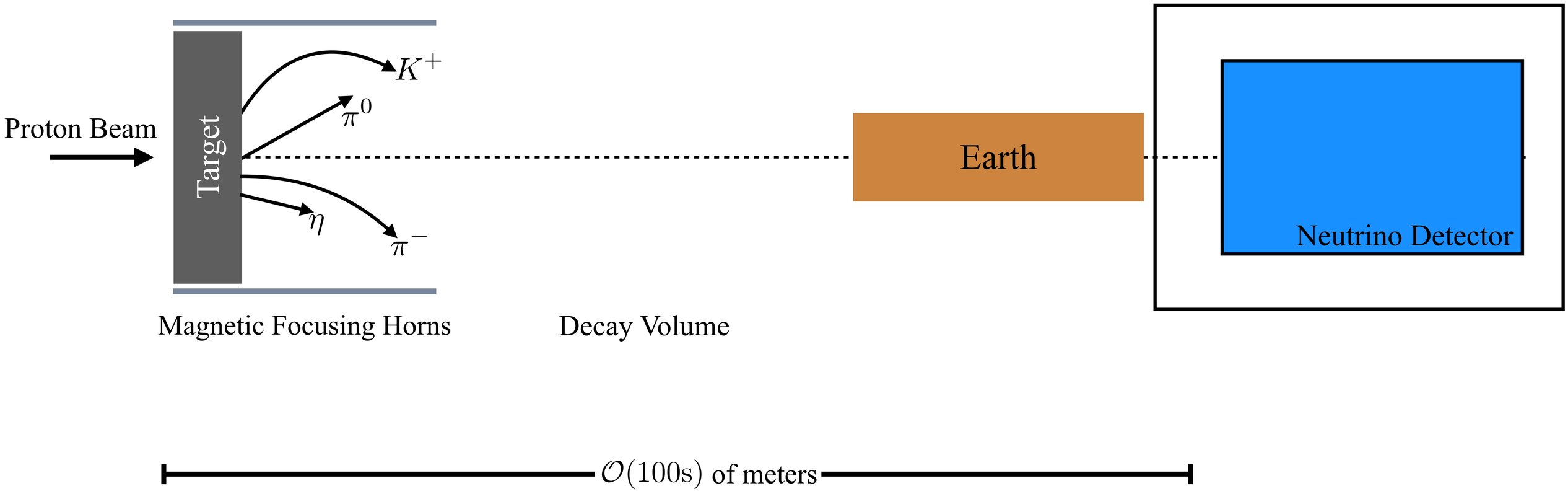
Accelerator Neutrinos 101

(with apologies to the experimental & accelerator physicists in the audience)



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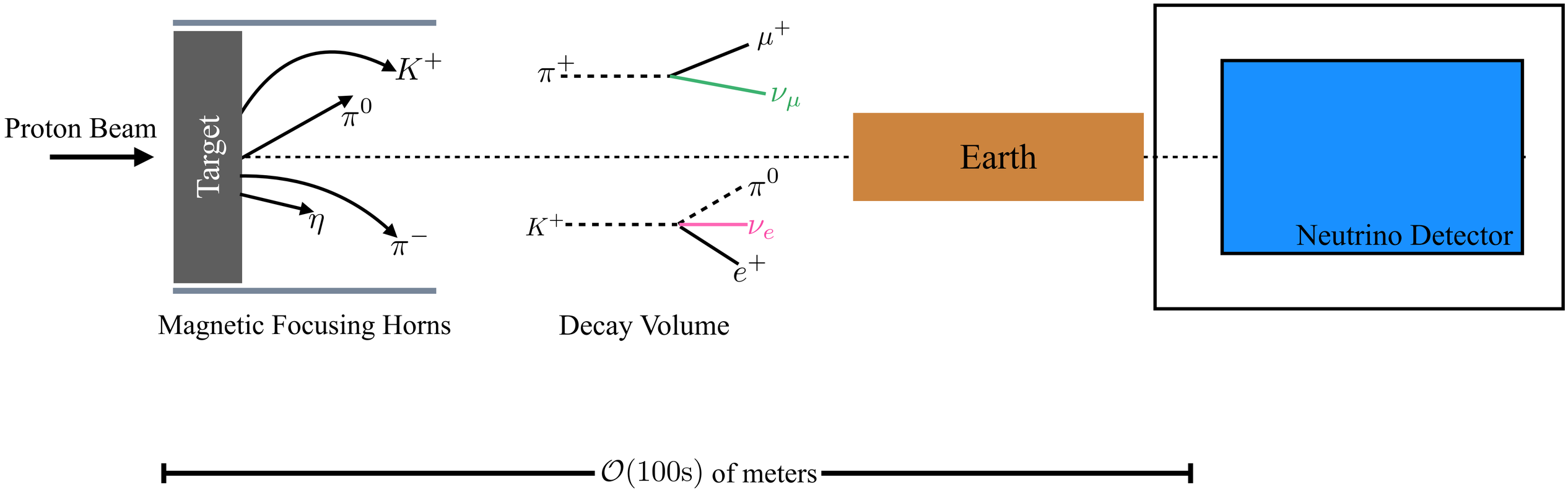

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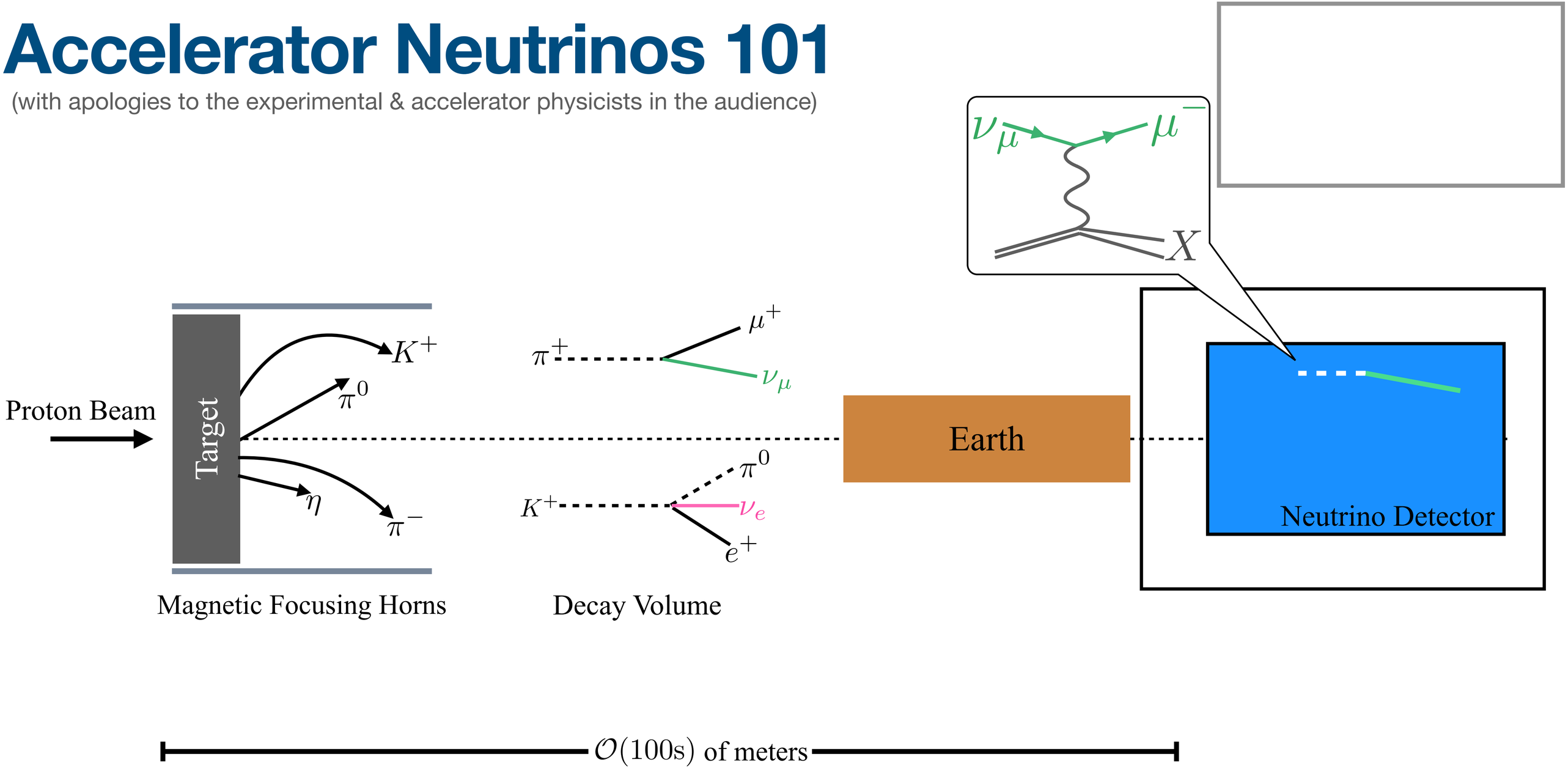

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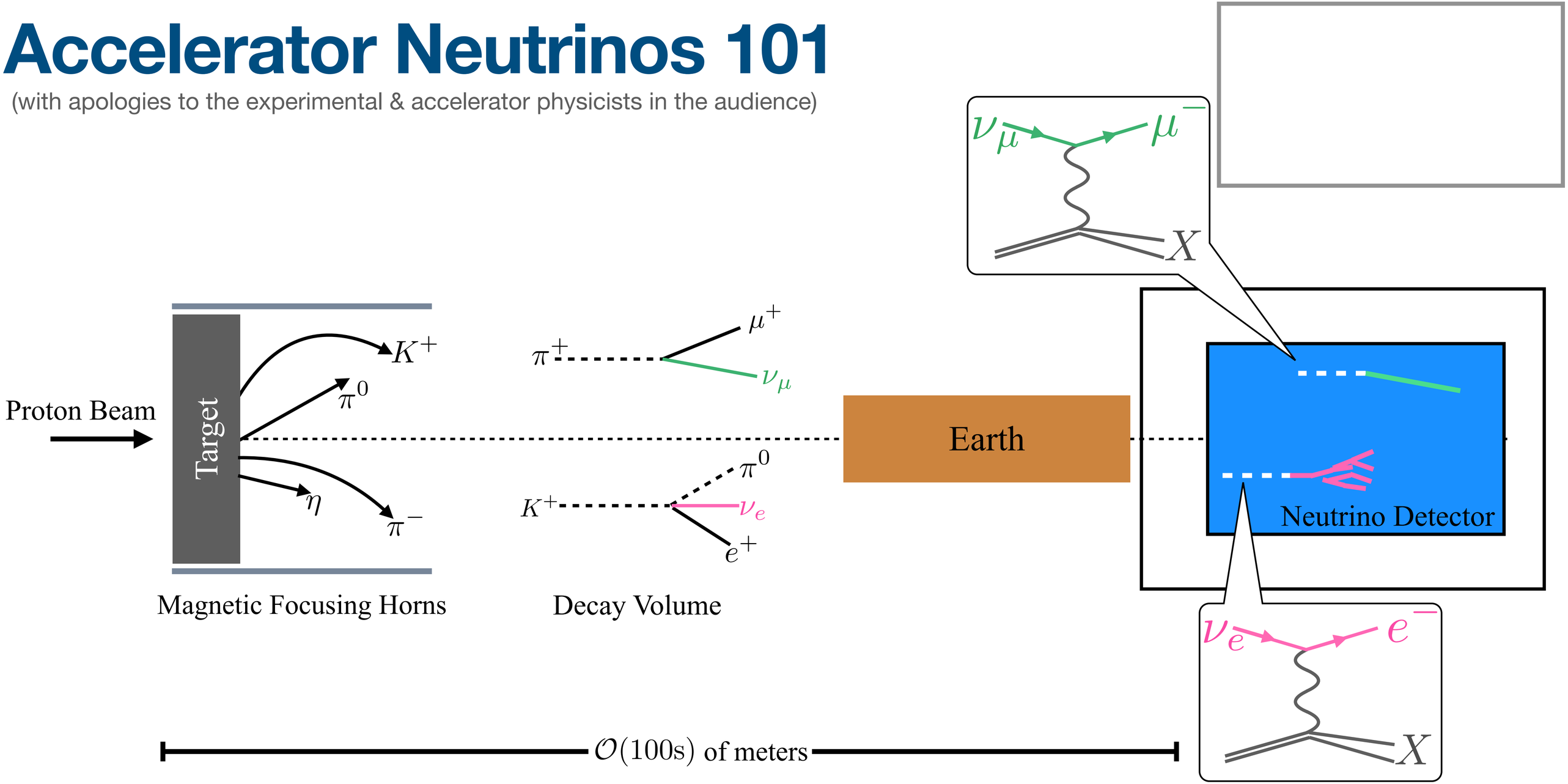
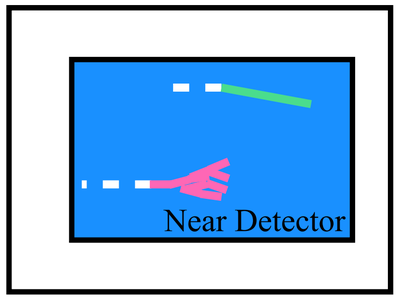


Oscillations from Accelerator Neutrinos

Measure “zero-distance” rates at near detector….



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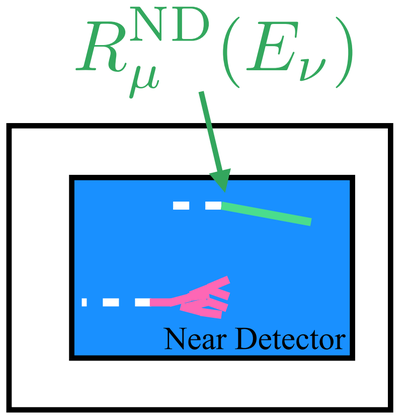

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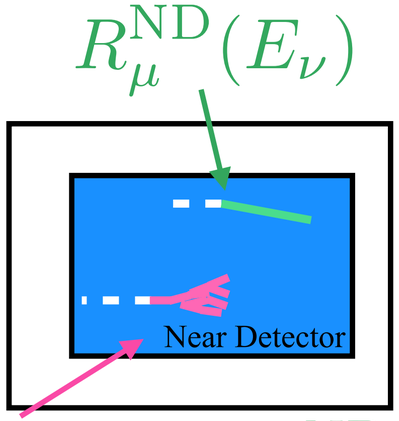

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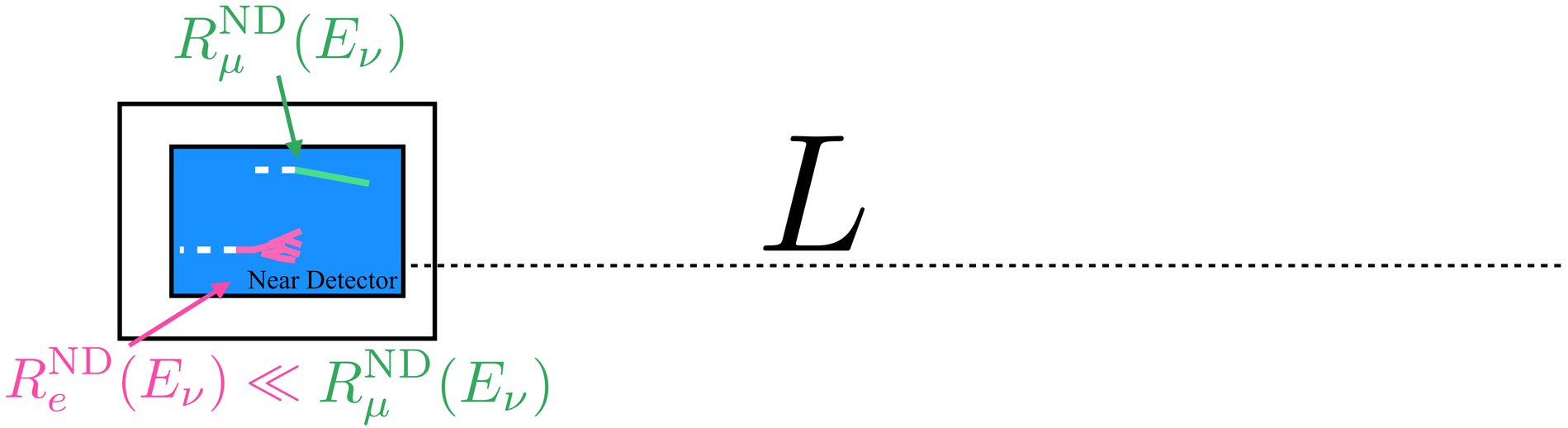

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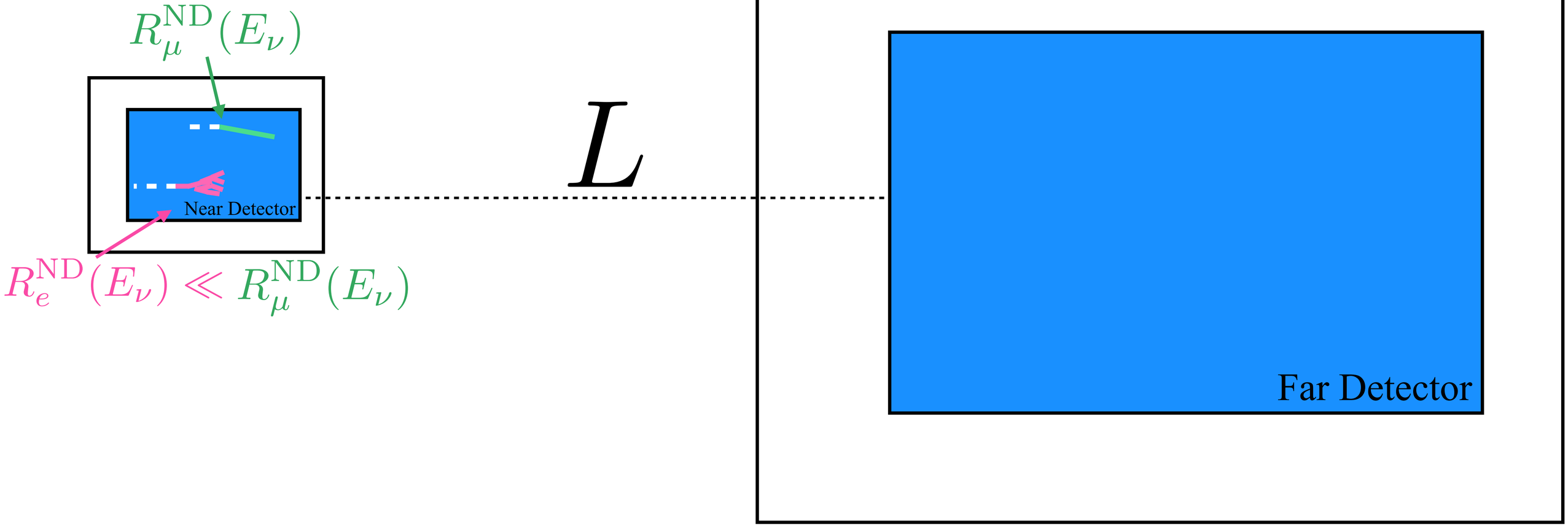

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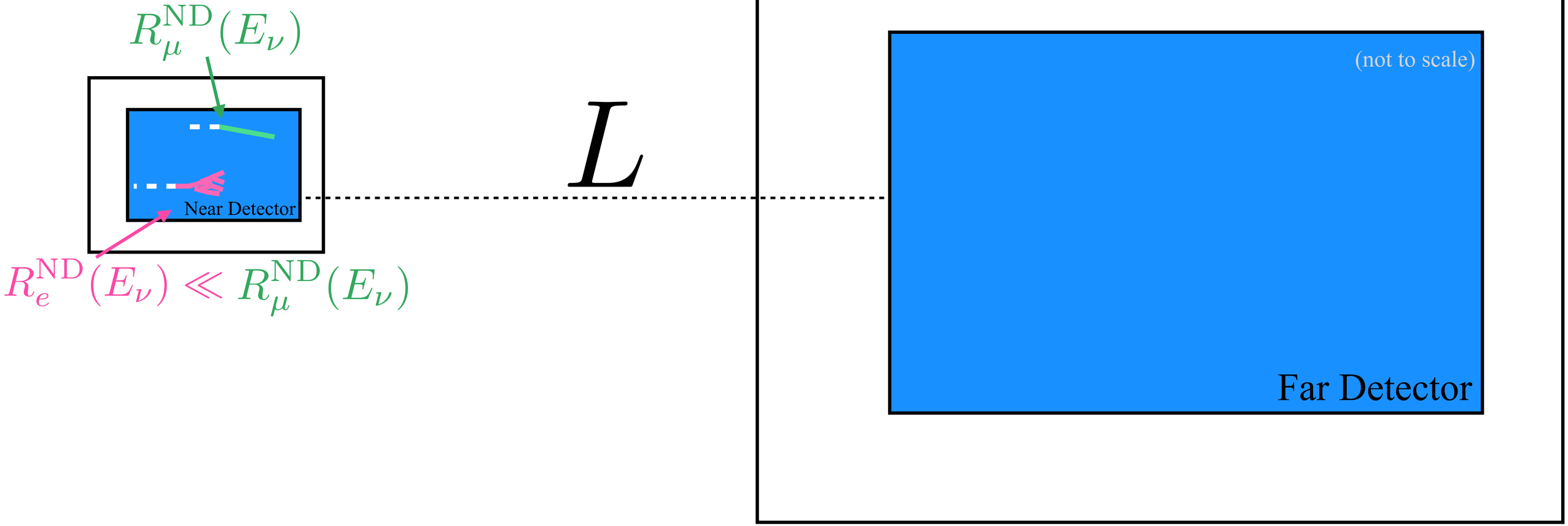

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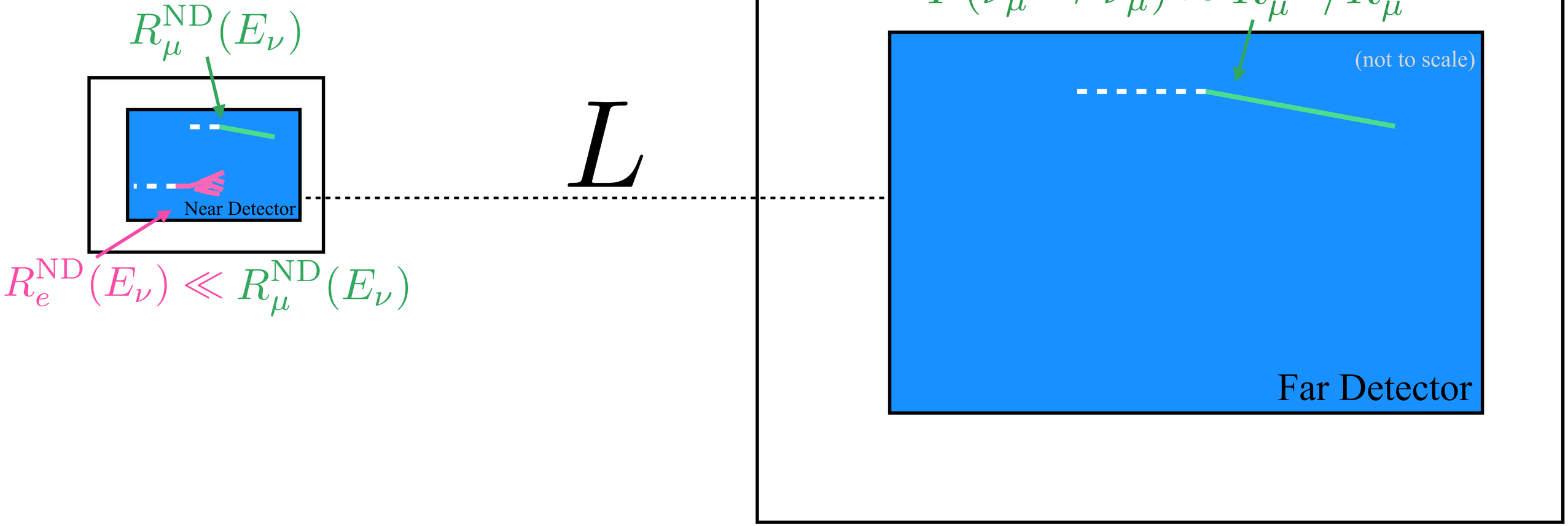

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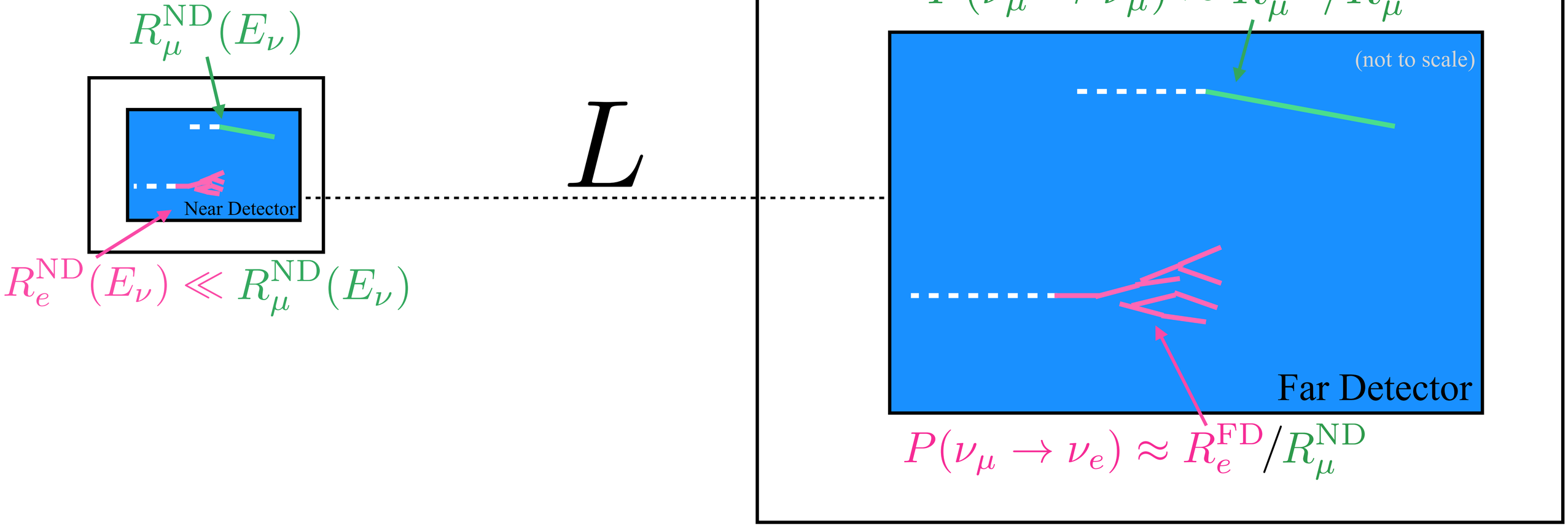

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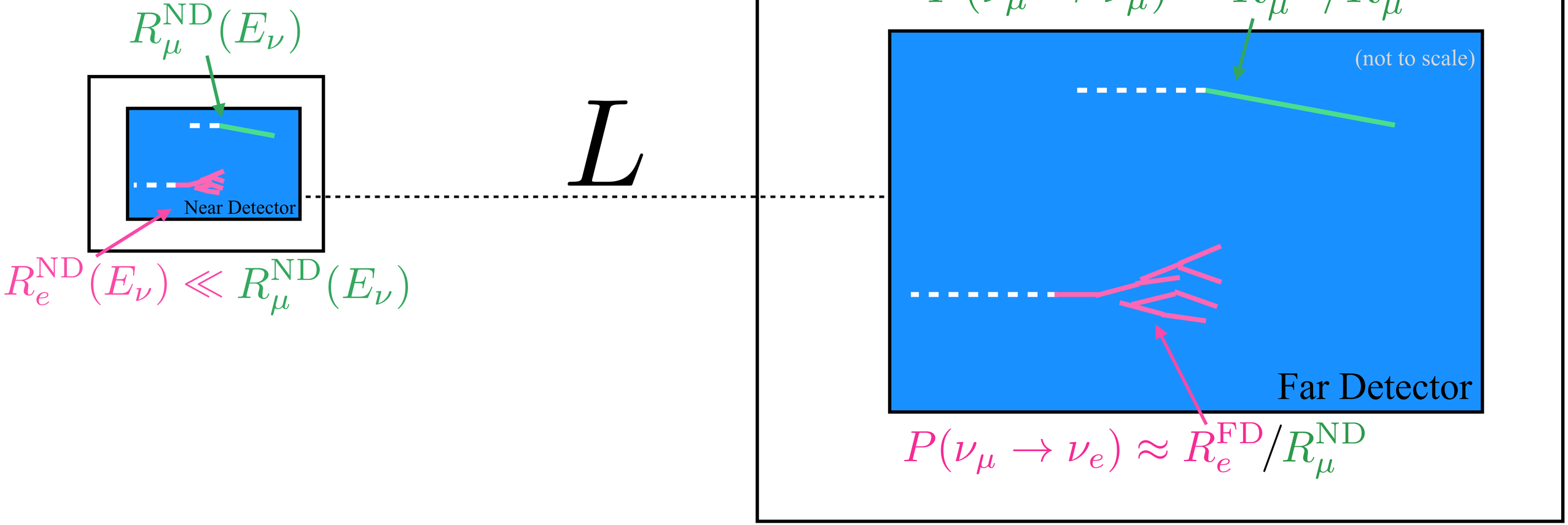
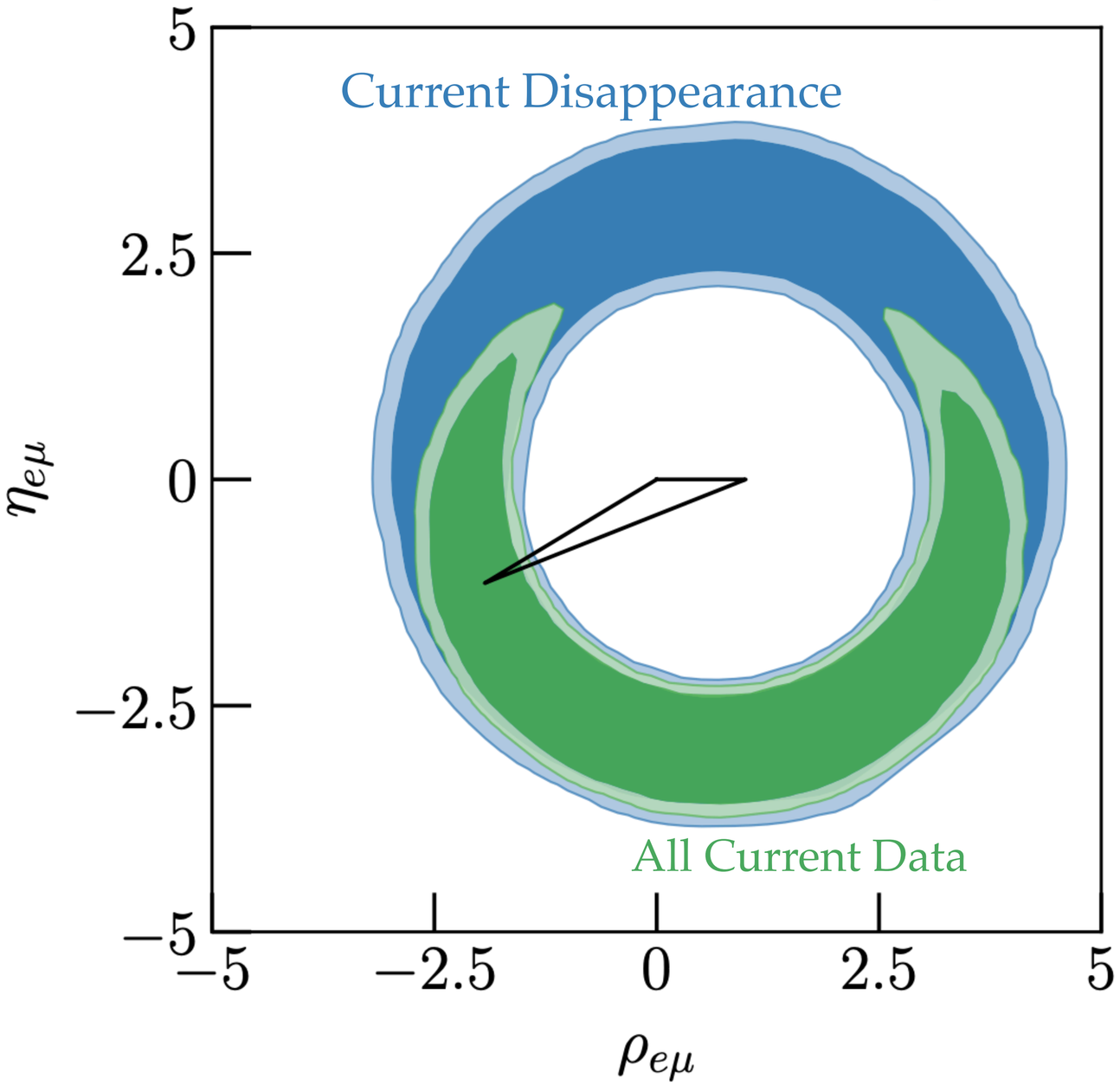


…compare against far-detector rates to determine oscillation probabilities

Measurements with Long-Baseline Neutrinos



$$\rho_{e\mu} + i\eta_{e\mu} = -\frac{U_{e1}U^*_{\mu 1}}{U_{e3}U^*_{\mu 3}}$$

What do we know now? What do we hope to learn in the next ~decade?

Example: how much CP violation is there in the lepton sector? Similar to area of CKM triangle(s) in the quark sector

Ellis, KJK, Li [2004.13719]

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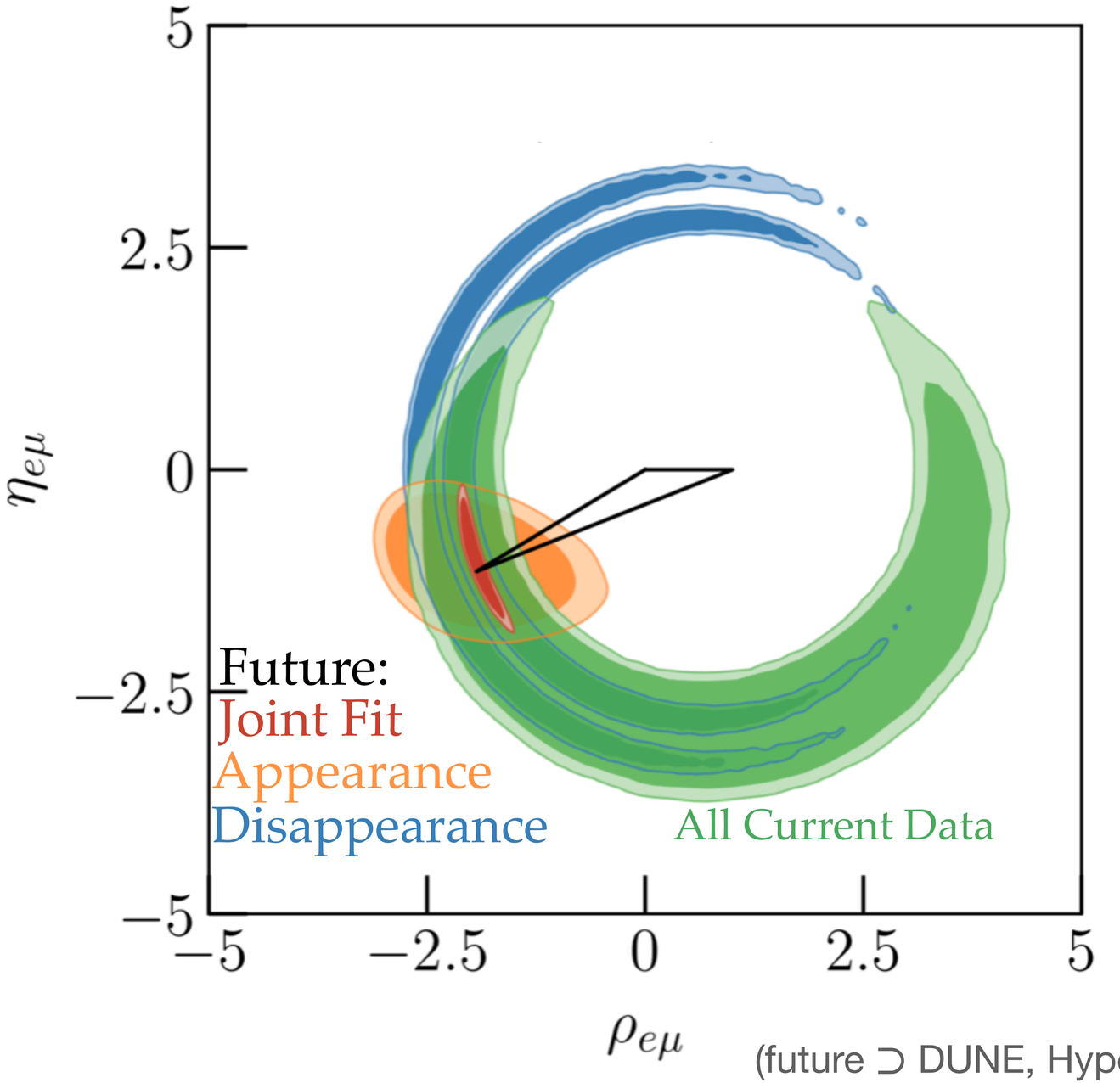

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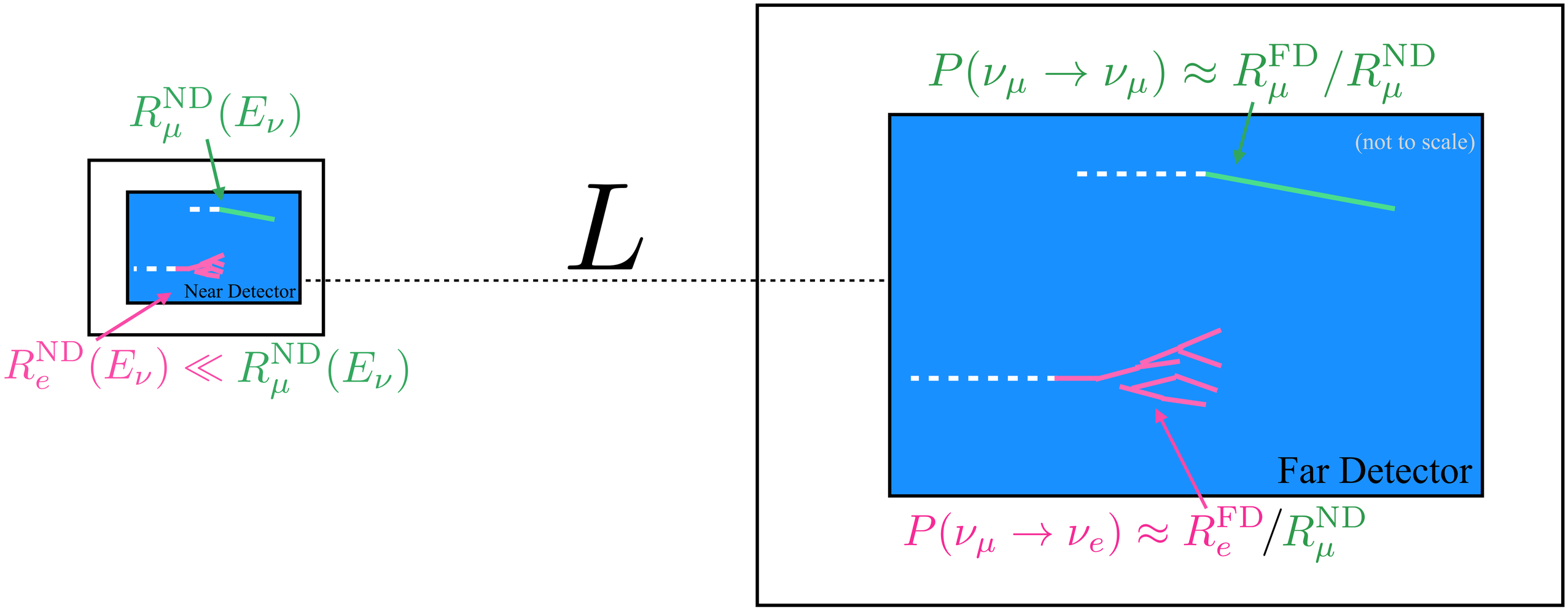
(future ⊃ DUNE, Hyper-Kamiokande, JUNO, IceCube Gen-2)

Ellis, KJK, Li [2004.13719]

New ν Physics

Deviations from Three-neutrino Expectation?



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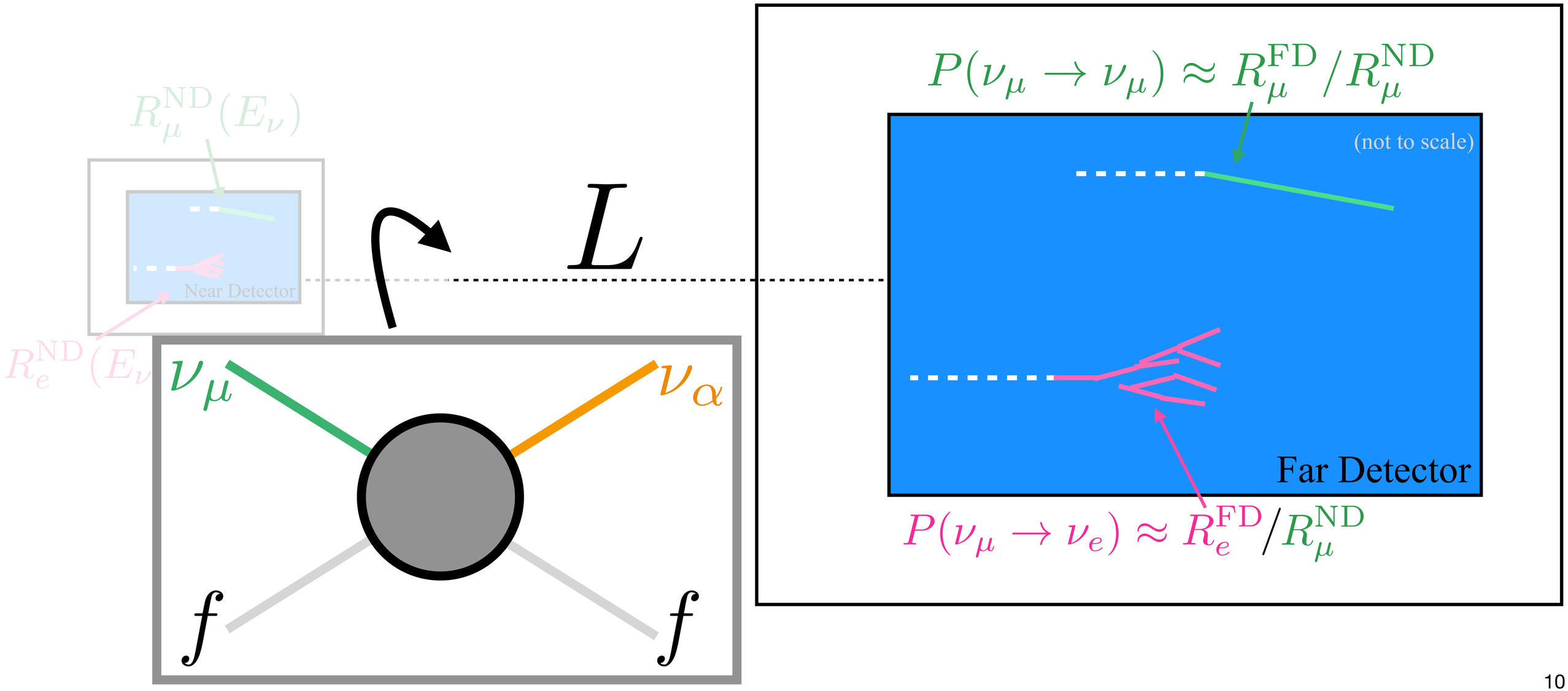

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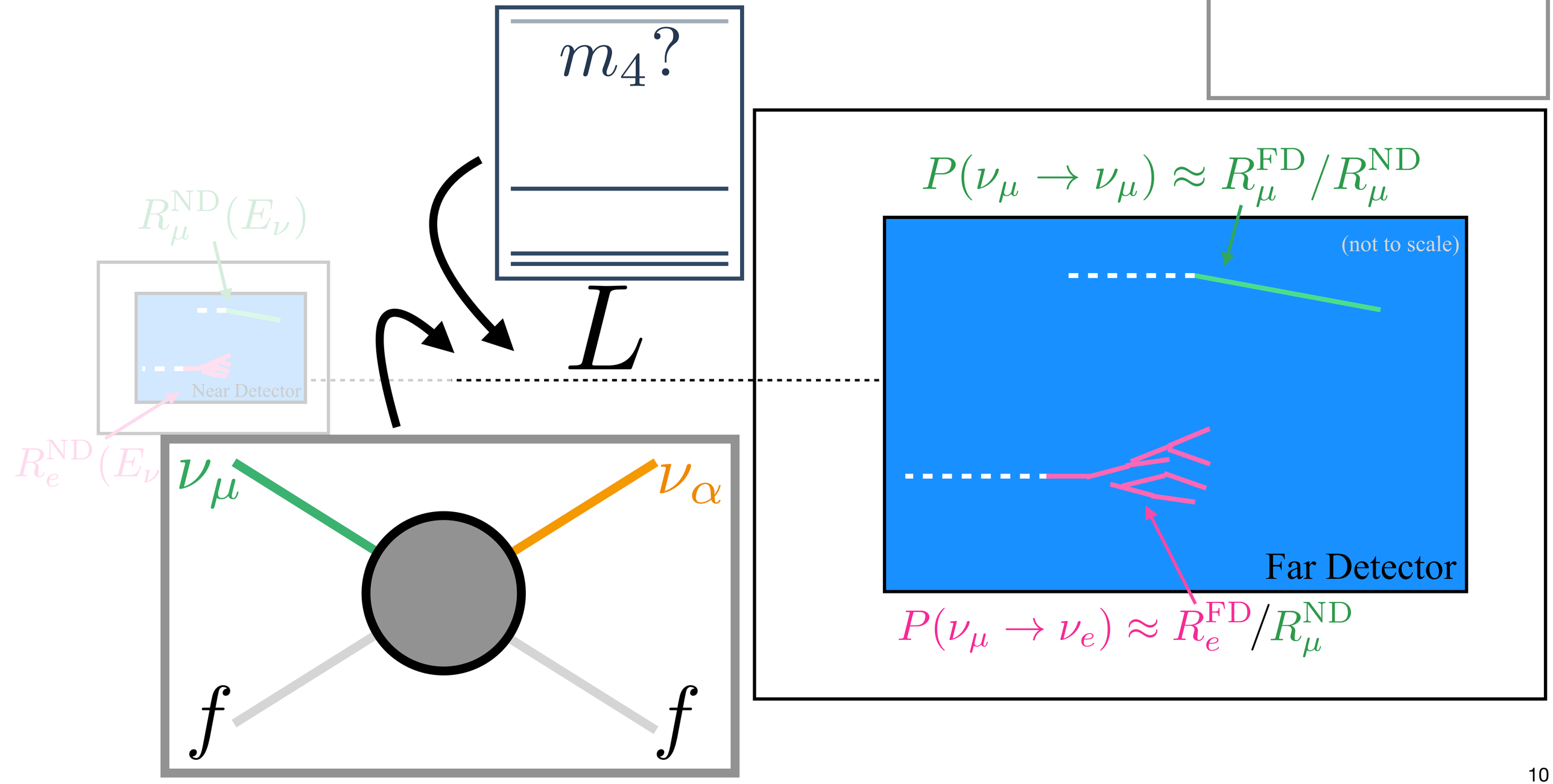
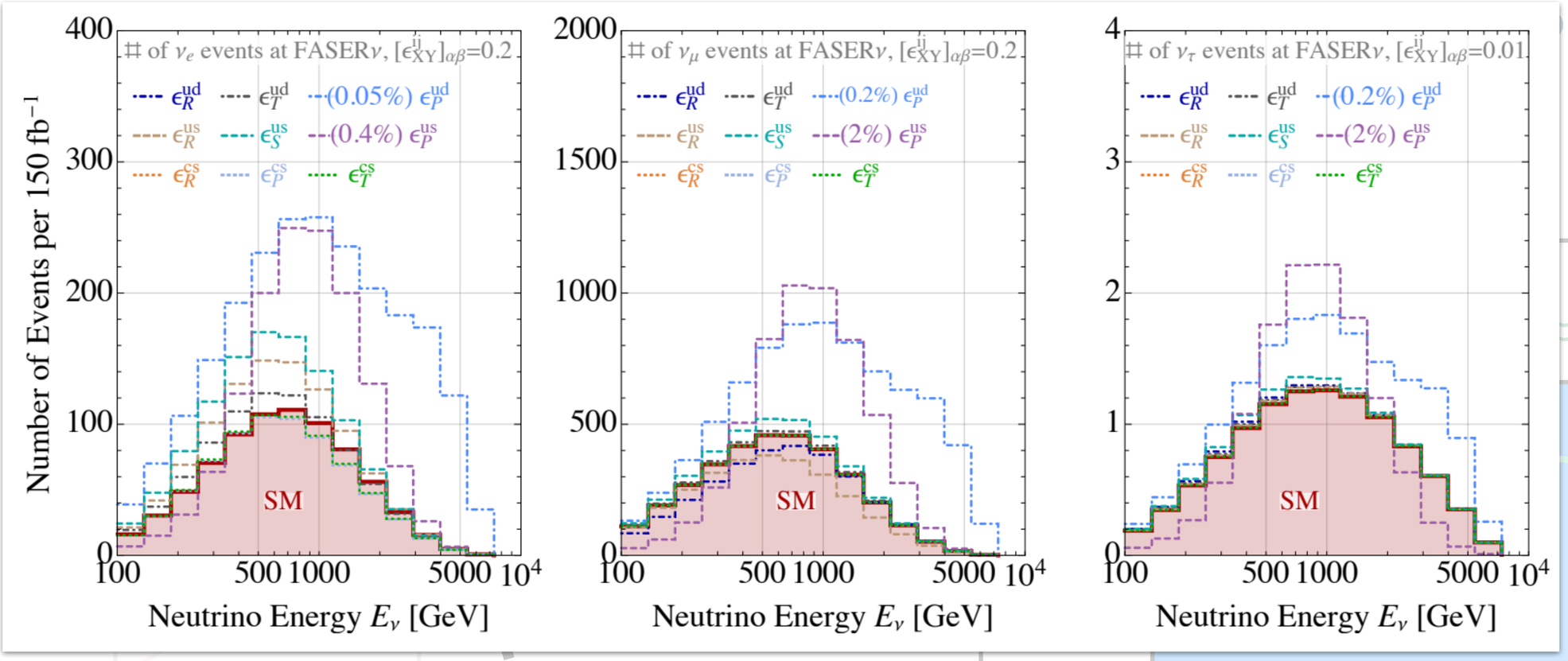
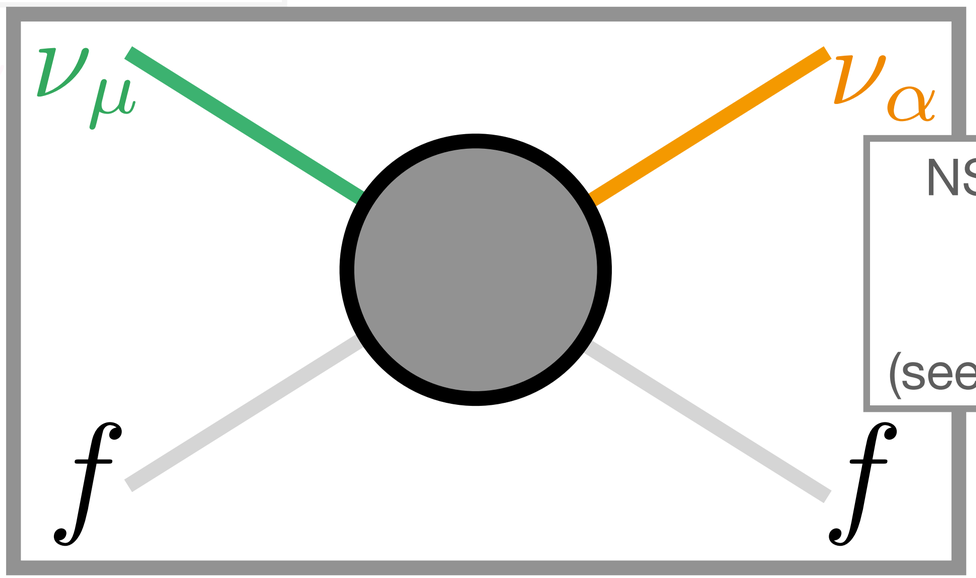


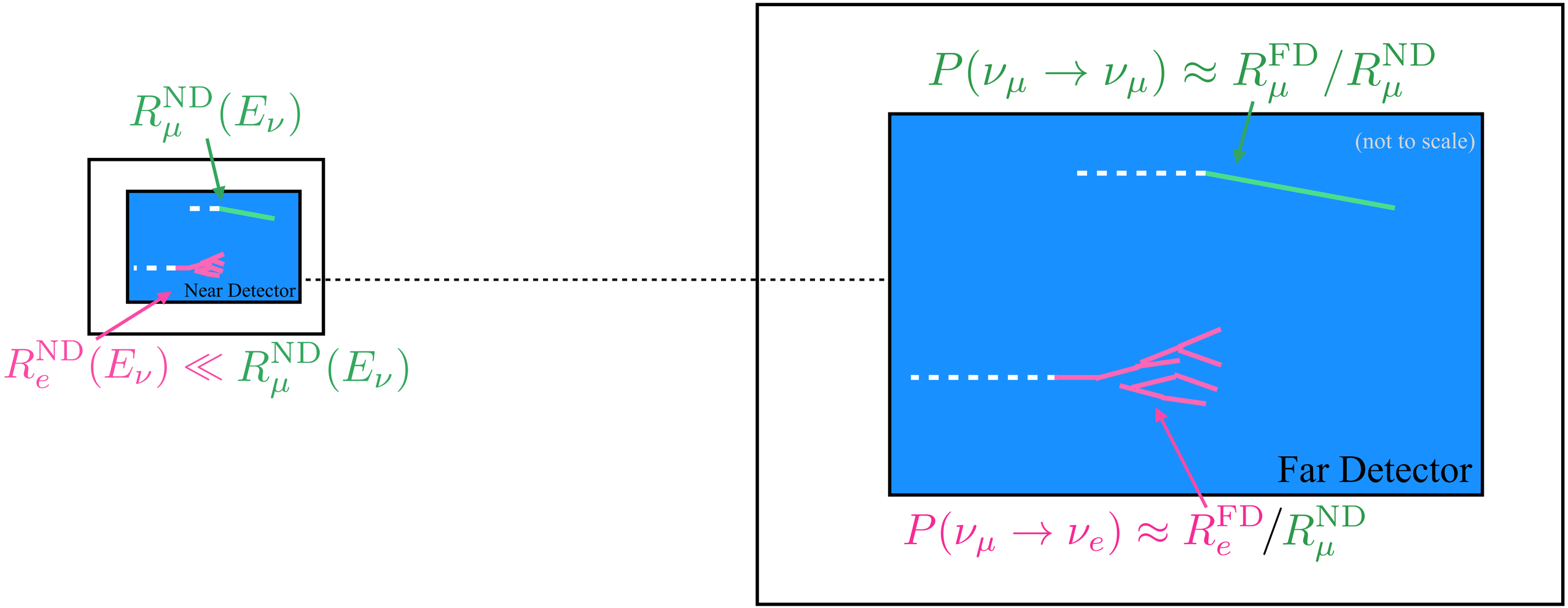




NSI effects can be searched for in scattering as well, for instance in FASERν with LHC-produced neutrinos!

(see Zahra's talk Tuesday and Falkowski et al [2105.12136])

Deviations at Near Detector?



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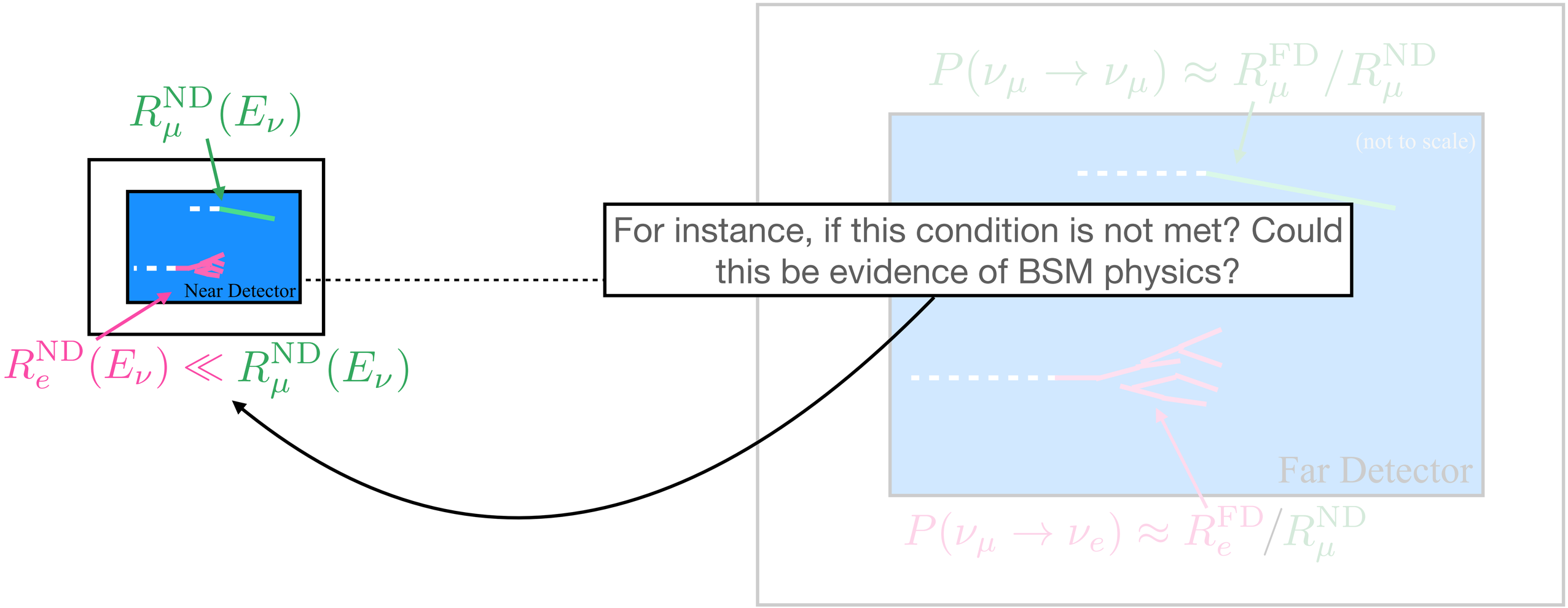
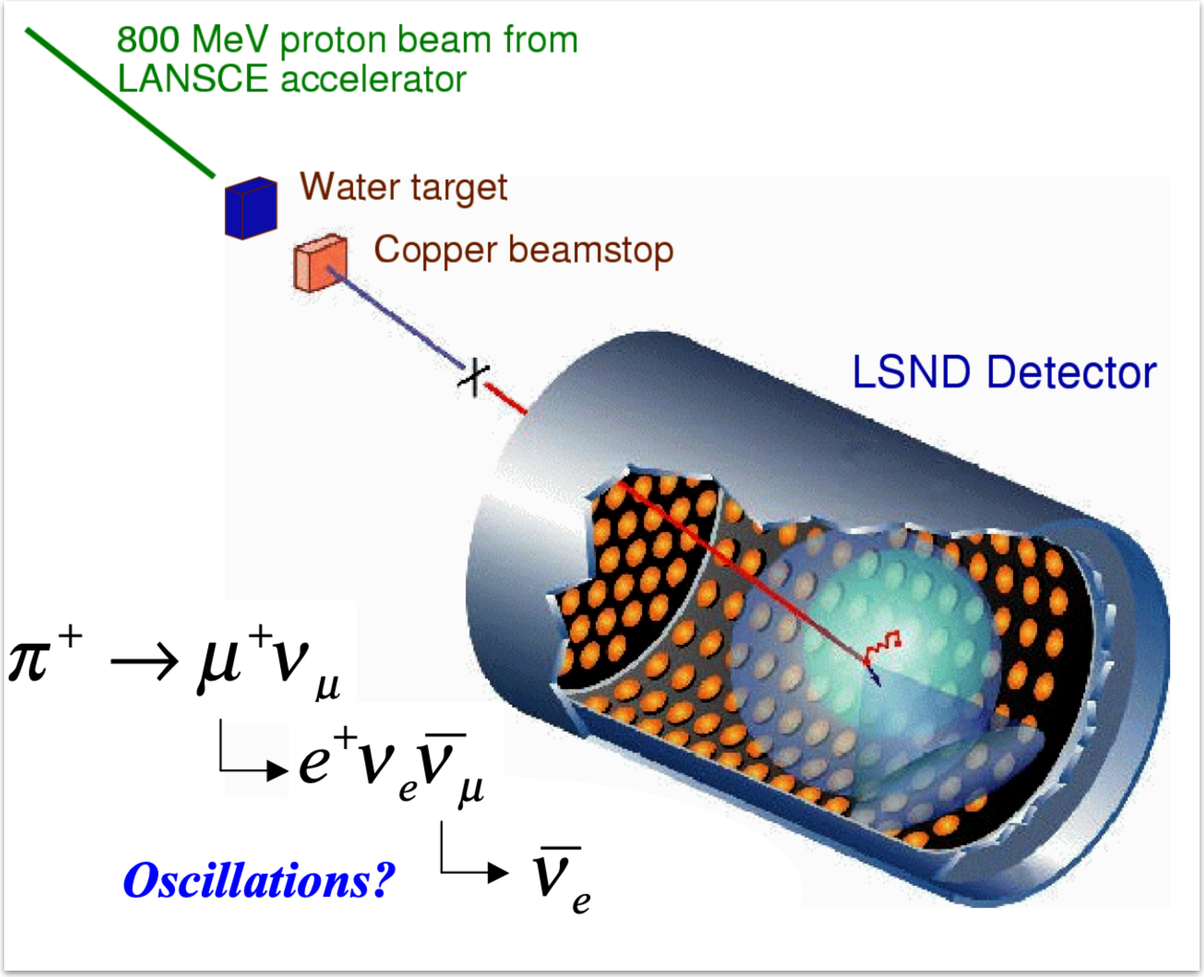


Liquid Scintillator Neutrino Detector (LSND)



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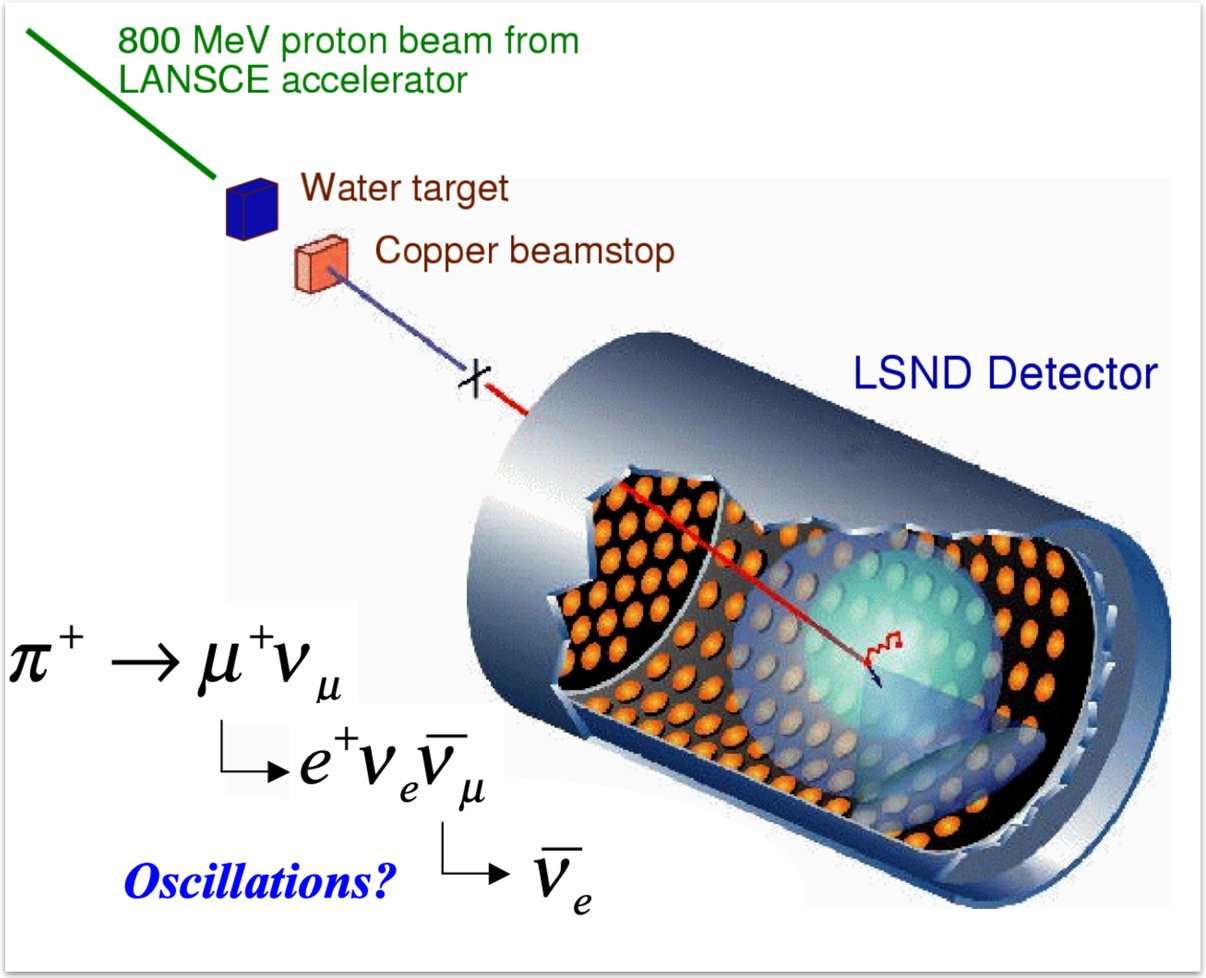
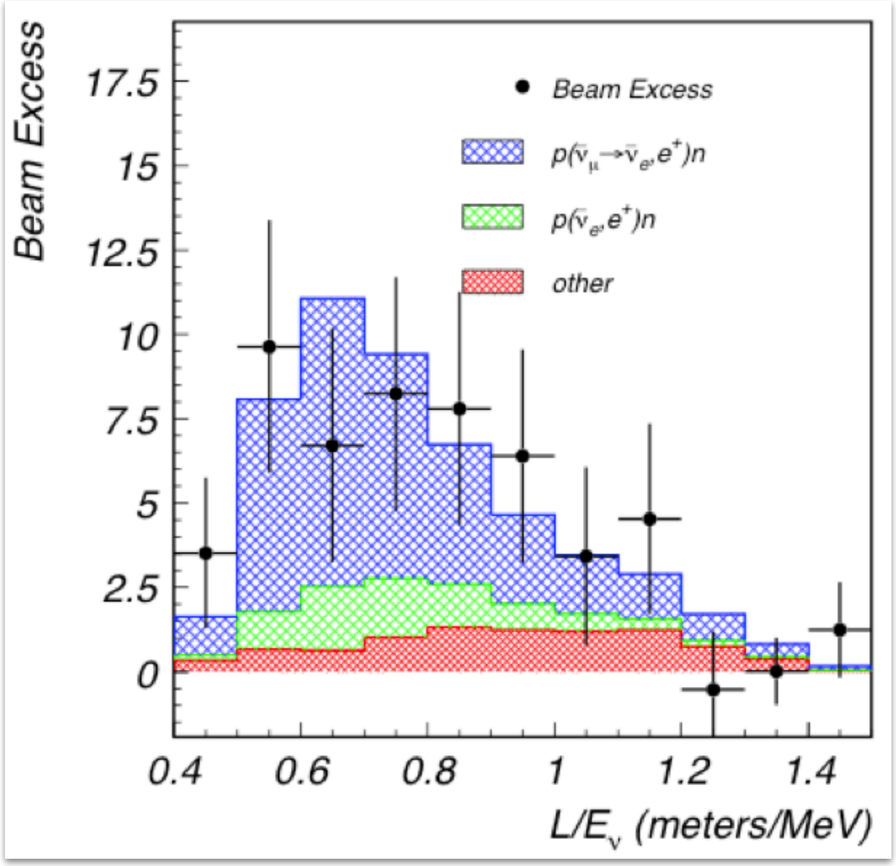


$\bar{\nu}_\mu \rightarrow \bar{\nu}_e ?$



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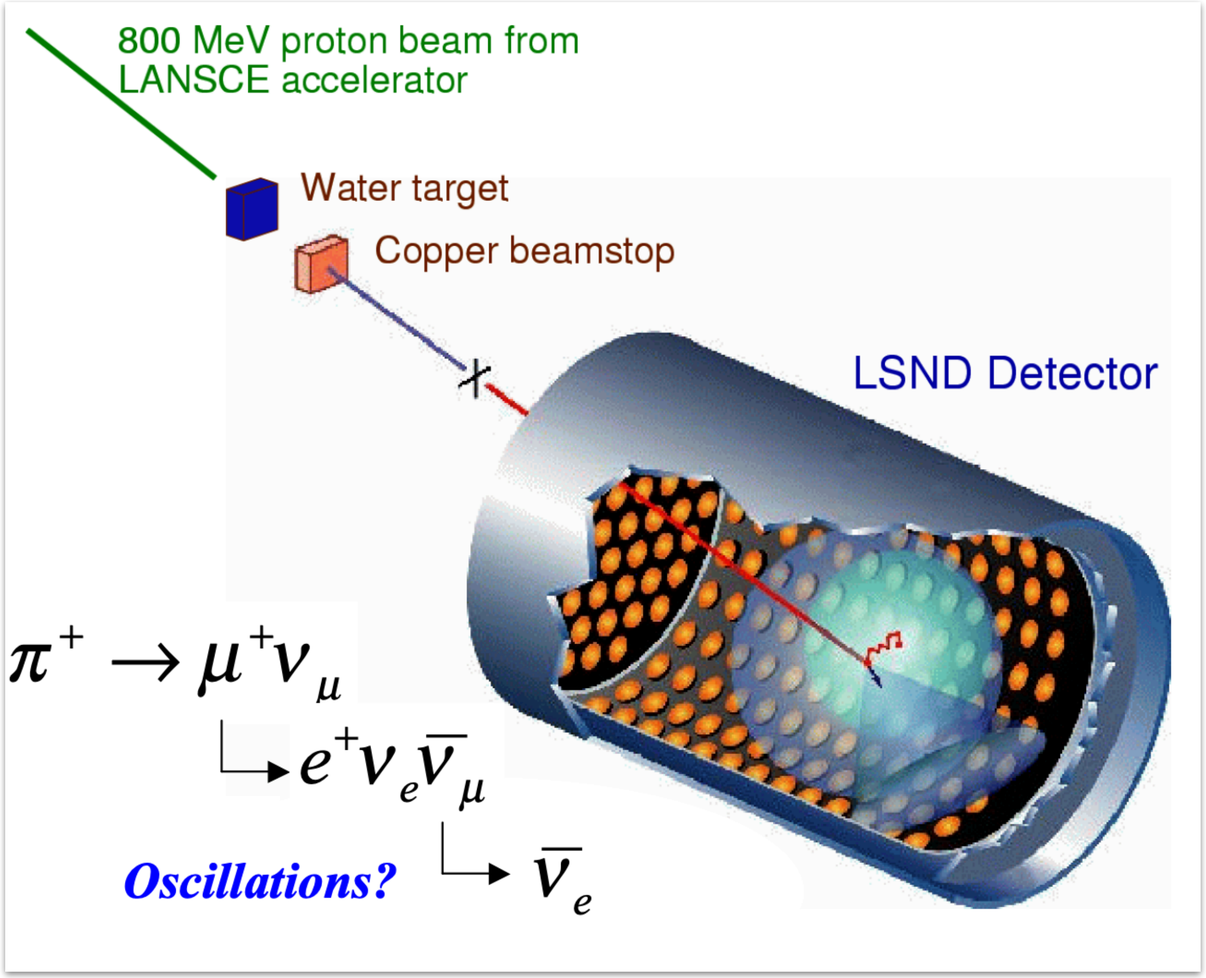

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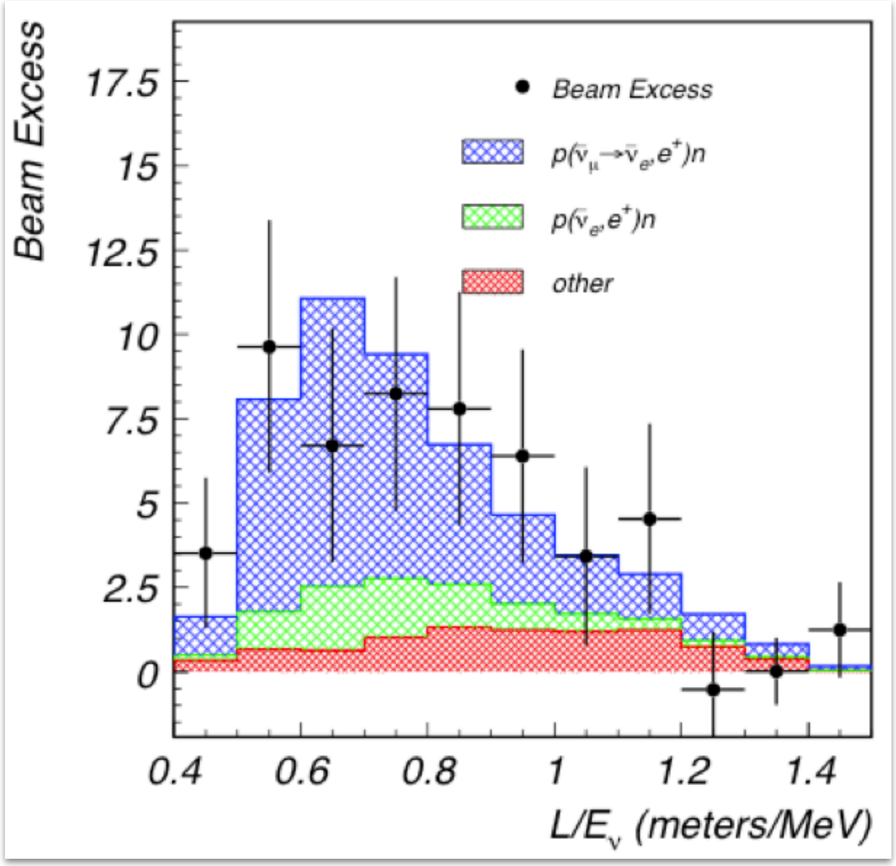
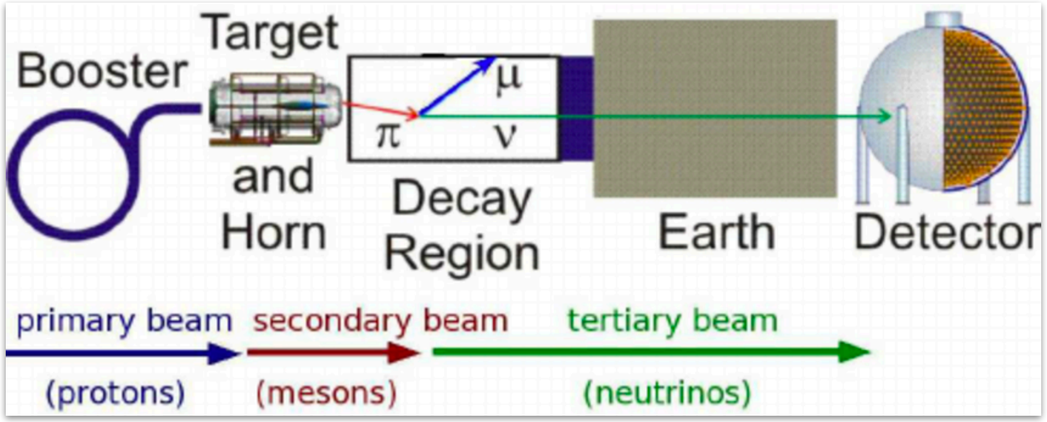


Neutrinos (mostly) from pion/muon decay-at-rest — O(30) MeV, roughly 50 meter baseline length.

Observed excess — $87.9 \pm 22.4 \pm 6.0 \longrightarrow P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right) \approx 2.6 \times 10^{-3}$

MiniBooNE

Designed to test the LSND anomaly — very different L, E, but similar L/E



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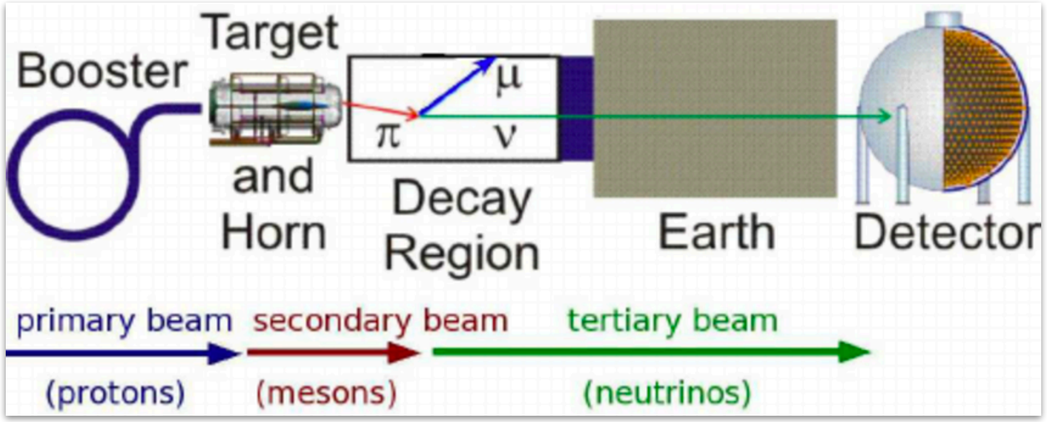

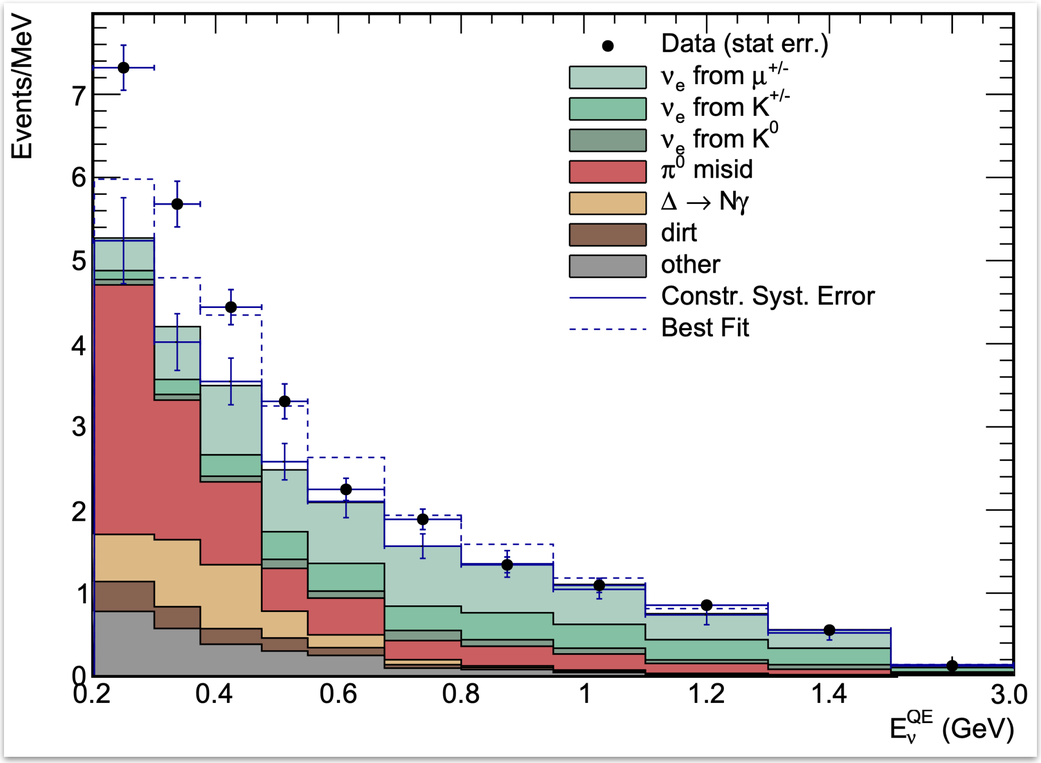

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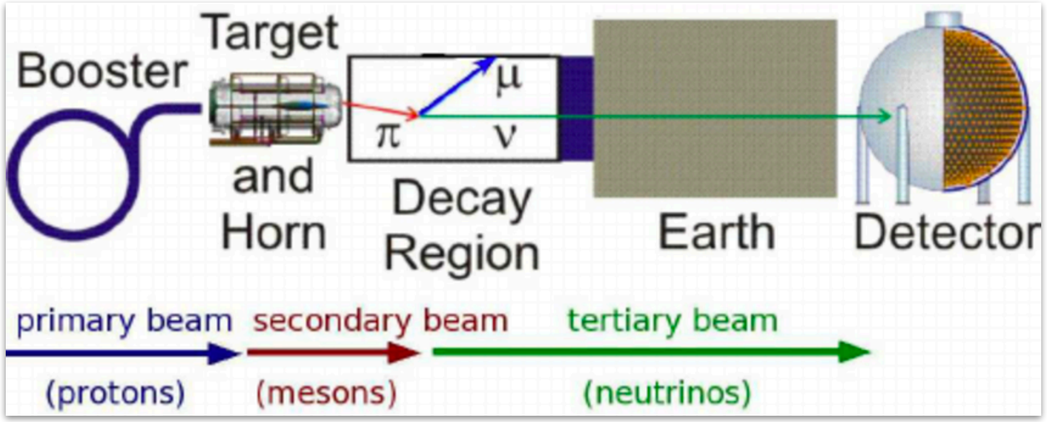
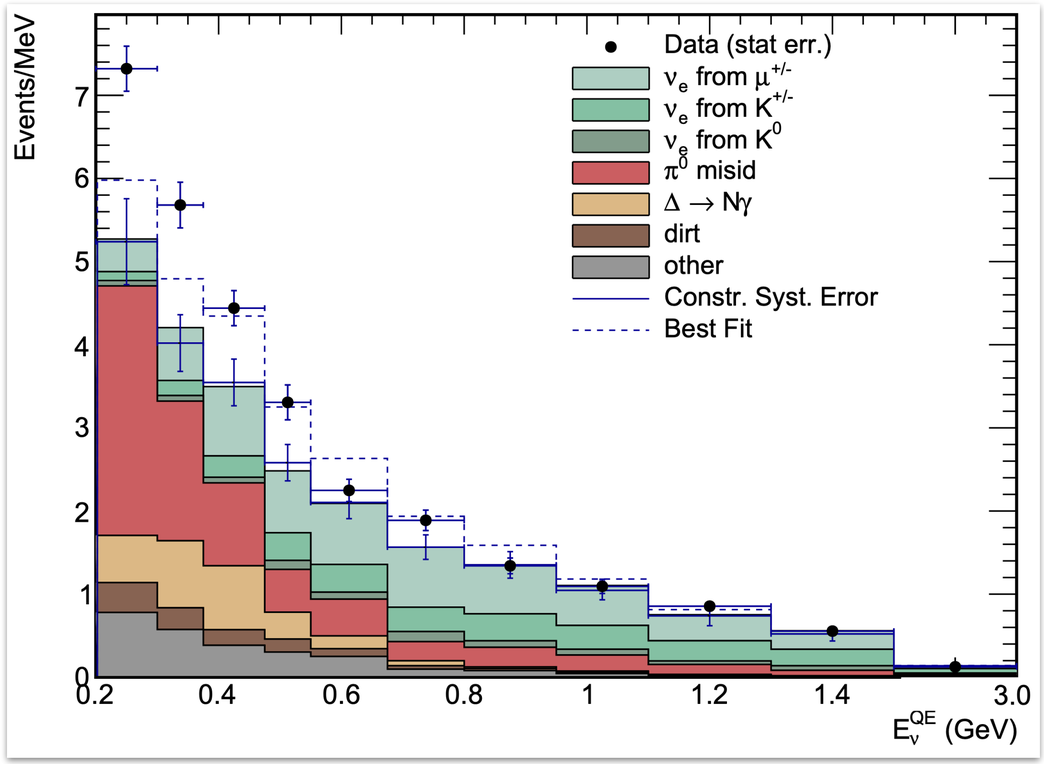
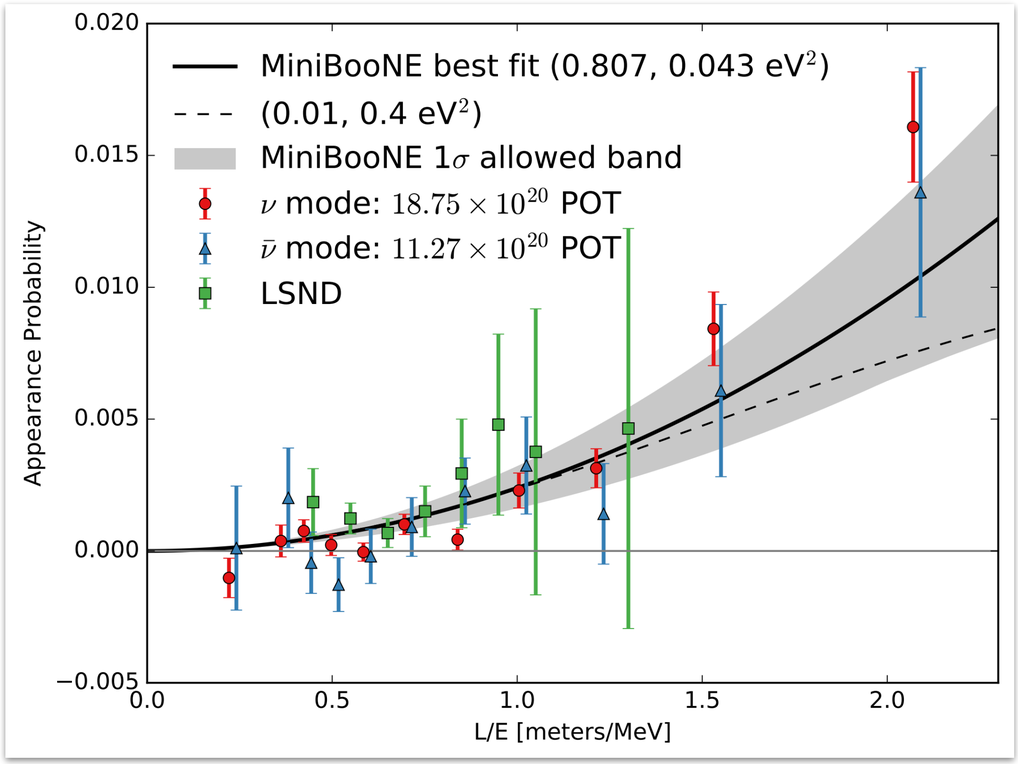
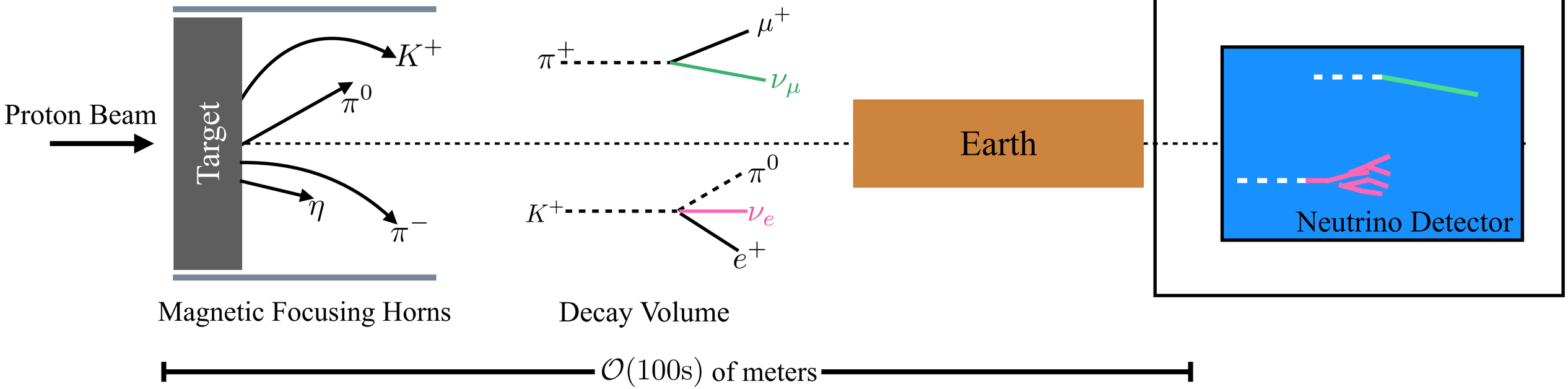


$$\nu_\mu \to \nu_e \text{ AND } \overline{\nu}_\mu \to \overline{\nu}_e ?$$

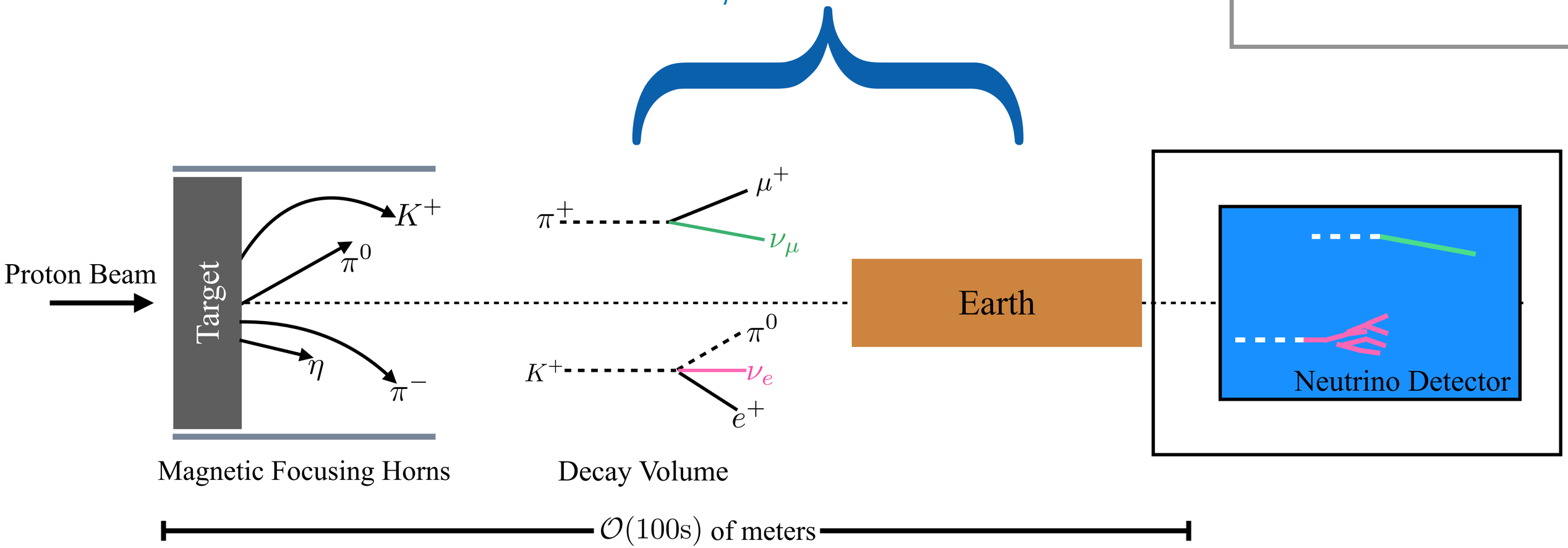
MiniBooNE Collab., [2006.16883]






Proton Beam
Target
K^+
π^0
η
π^-
π^+
μ^+
ν_μ
K^+
π^0
ν_e
e^+
Earth
Neutrino Detector
Magnetic Focusing Horns
Decay Volume
$\mathcal{O}(100\text{s})$ of meters

New neutrino physics: modify ν_e/ν_μ propagation in this regime



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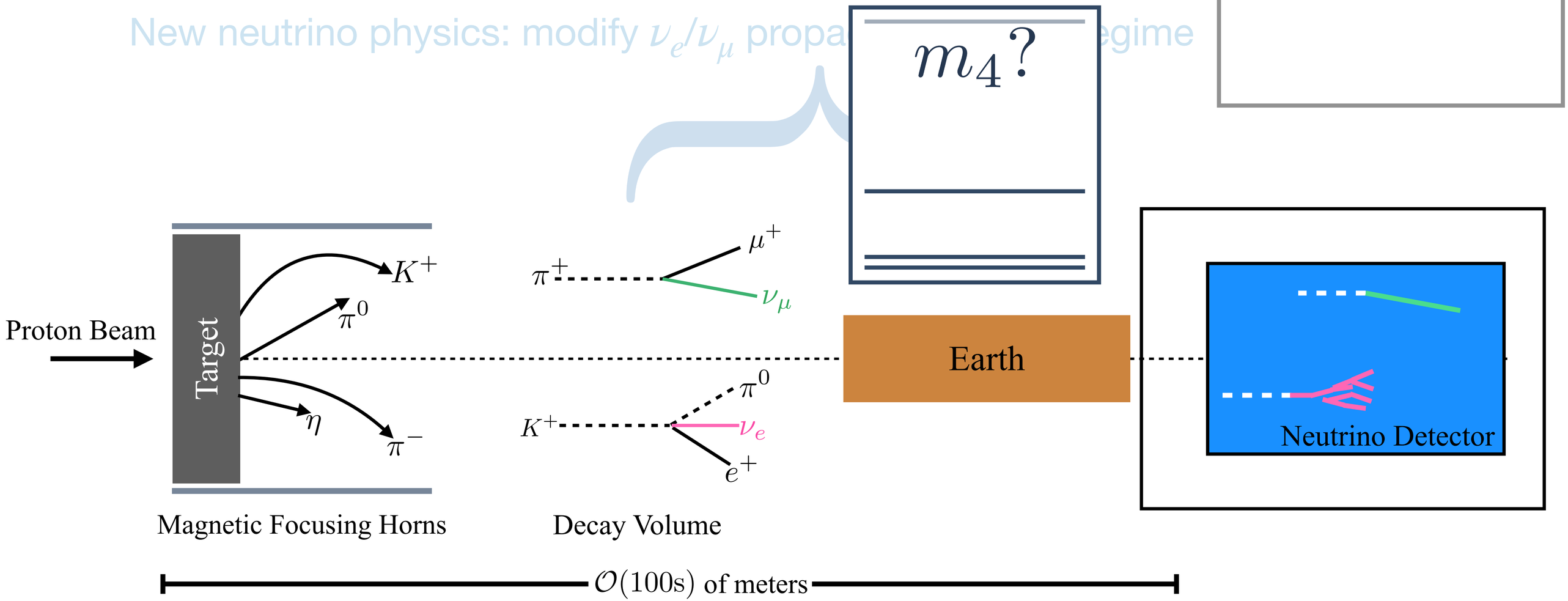
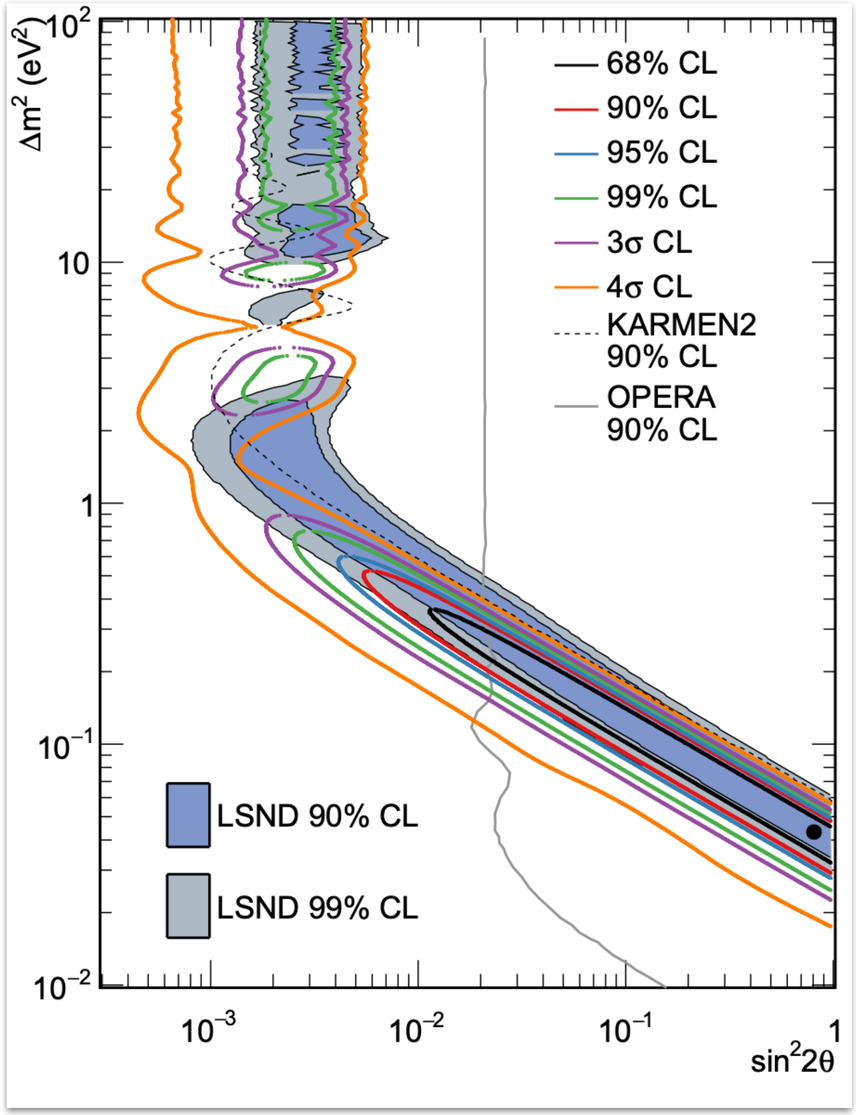


$$P_{\alpha\beta} \approx \sin^2\left(2\theta_{\alpha\beta}\right)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right) \quad \text{New mass scale } \Delta m^2 \gg \Delta m^2_{\text{SM}}$$

Fourth-neutrino interpretation



MiniBooNE Collab., [2006.16883]

If coming from oscillations, the results from LSND and MiniBooNE require a new mass eigenstate around the eV scale.

Combined with the observed invisible width of the Z-boson (LEP), any additional light neutrino(s) must be sterile — gauge singlets.

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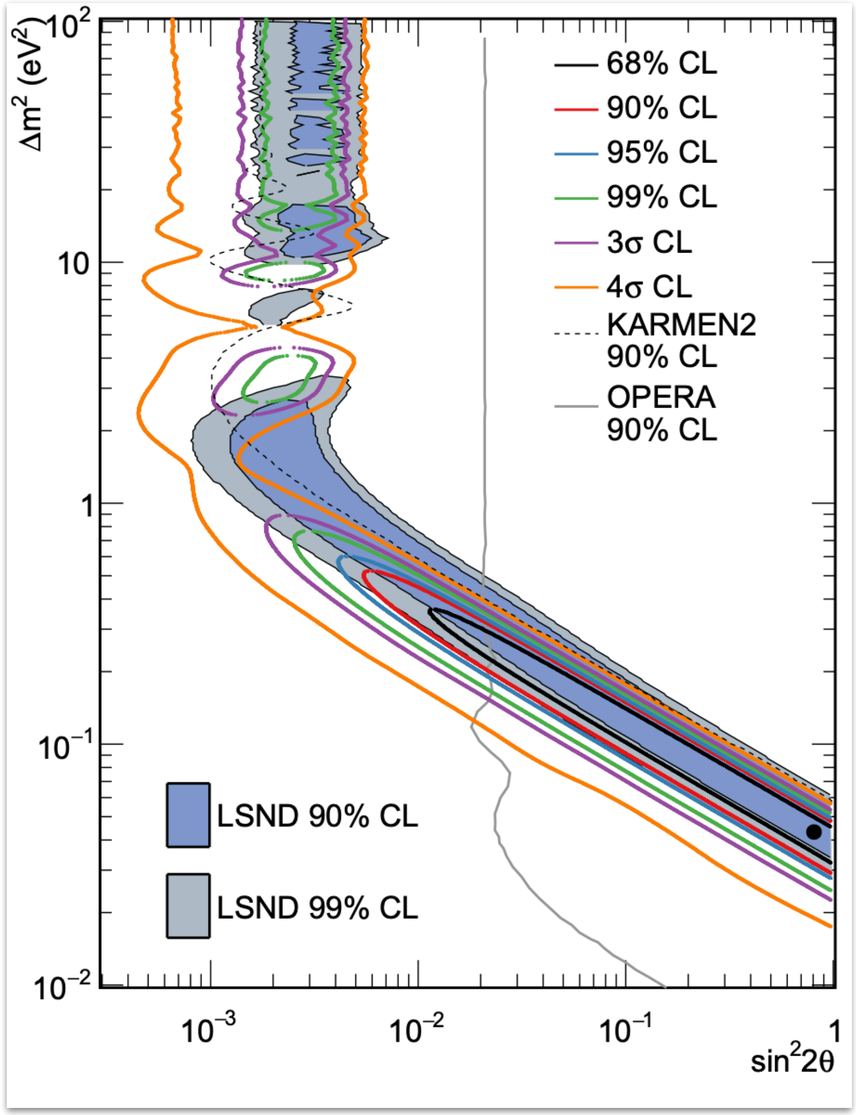

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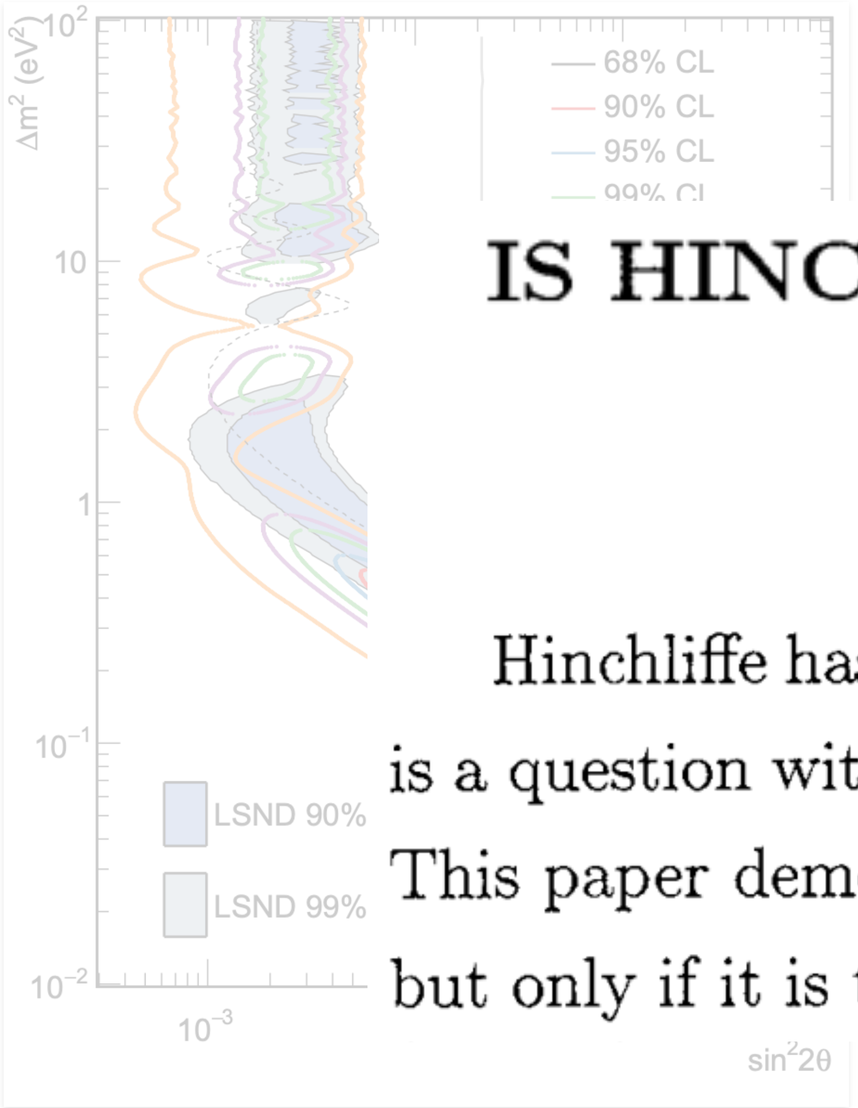
Is this 3+1 scenario compatible with global data?

Fourth-neutrino interpretation



MiniBooNE Collab., [2006.16883]

IS HINCHLIFFE'S RULE TRUE? ·

Boris Peon

Abstract

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that Hinchliffe's assertion is false, but only if it is true.

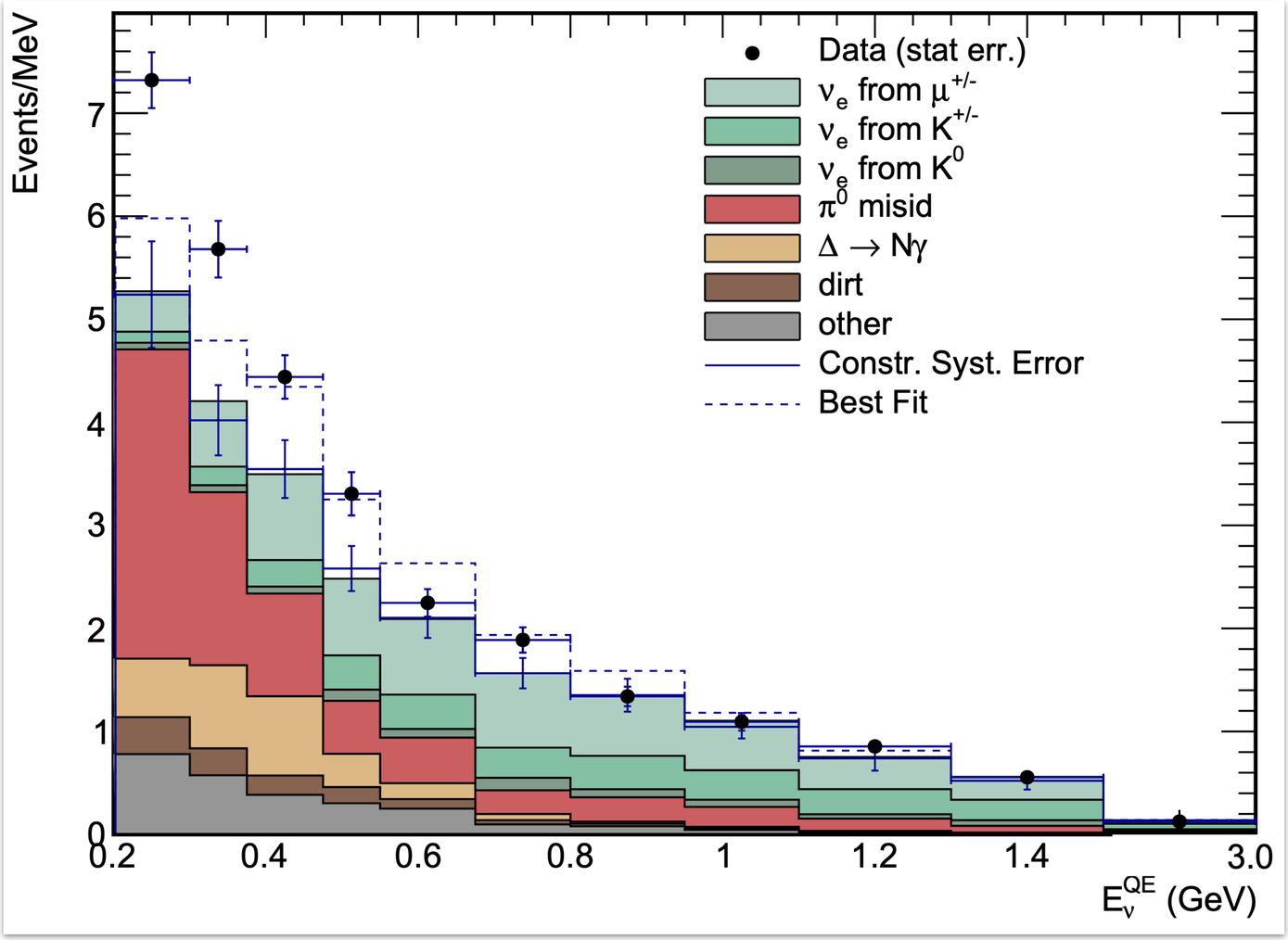
(in loving memory)

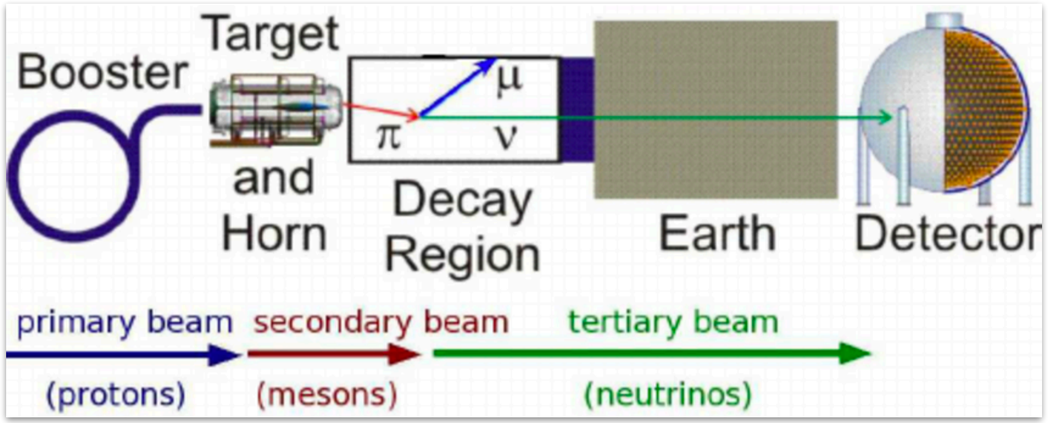
ND and
und the eV

the Z-boson
terile — gauge

al data?

The Challenge of MiniBooNE

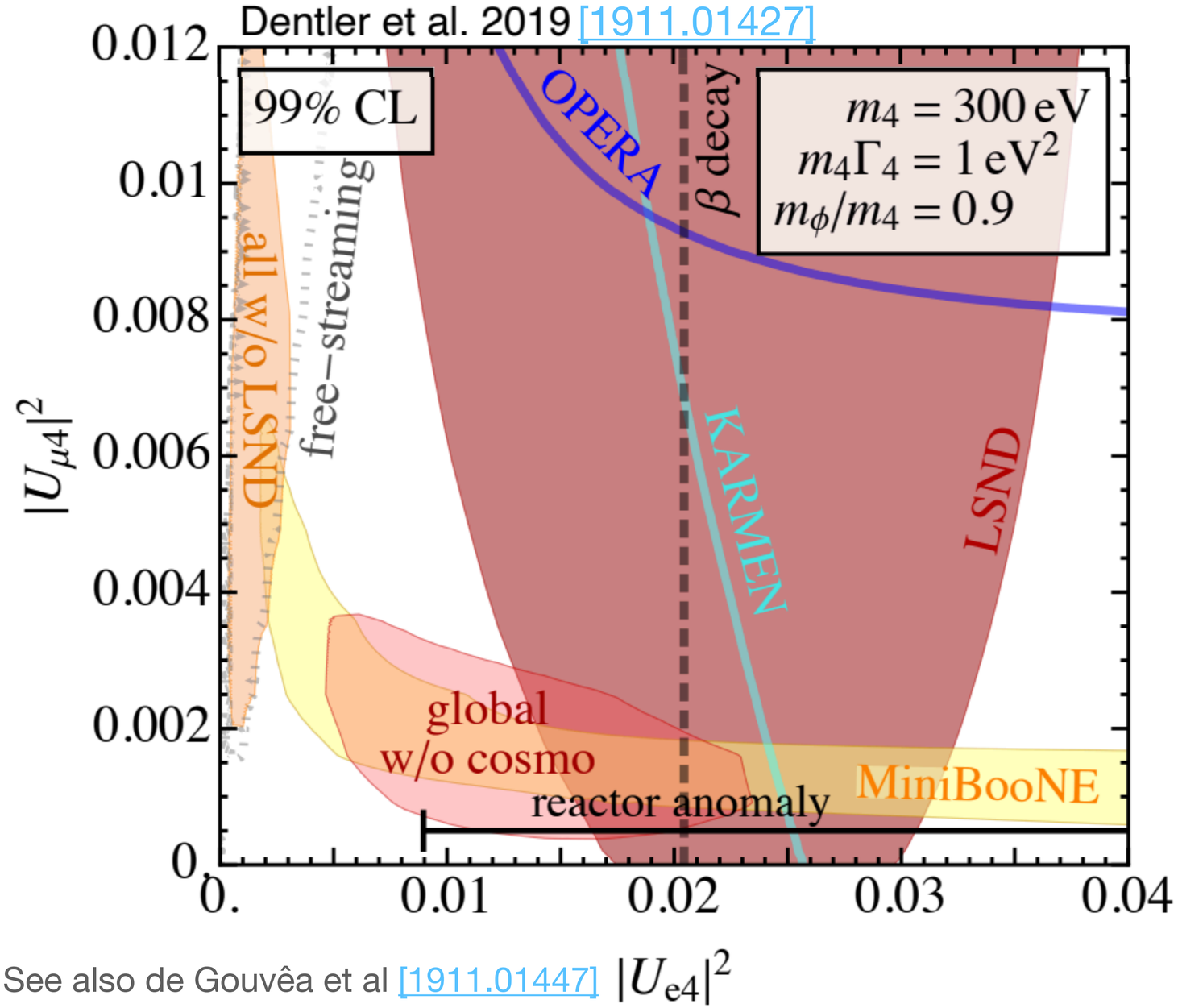


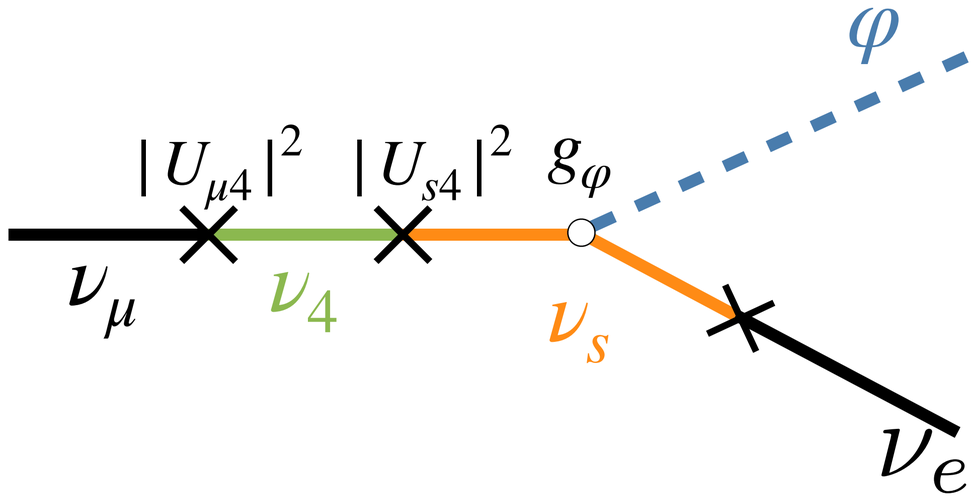


Cherenkov signatures in MiniBooNE are unable to distinguish between photons, electrons, and multiple-electron signatures.

Snowmass review on short-baseline anomalies and potential solutions: [2203.07323]

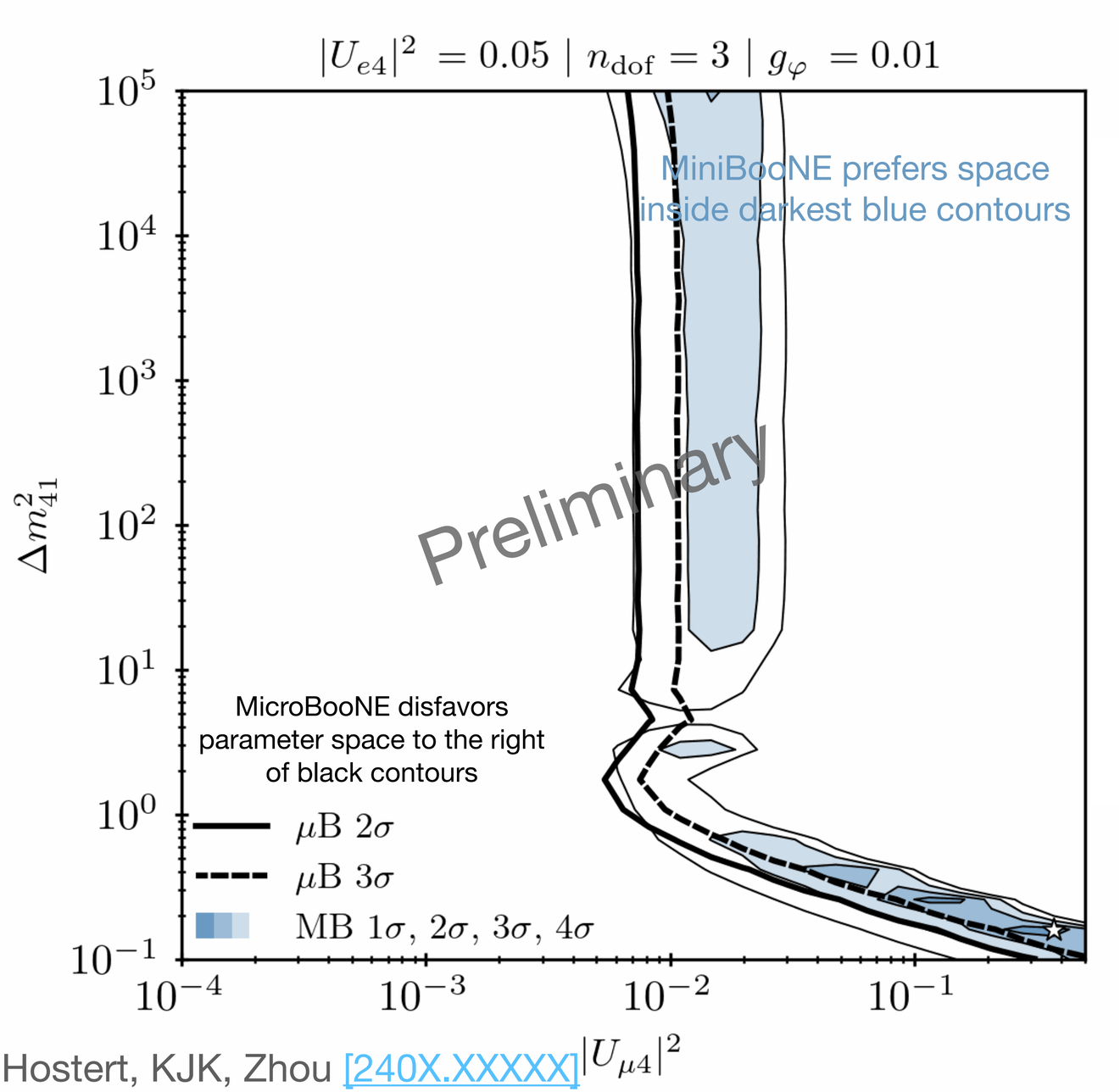
Decaying Sterile Neutrinos?



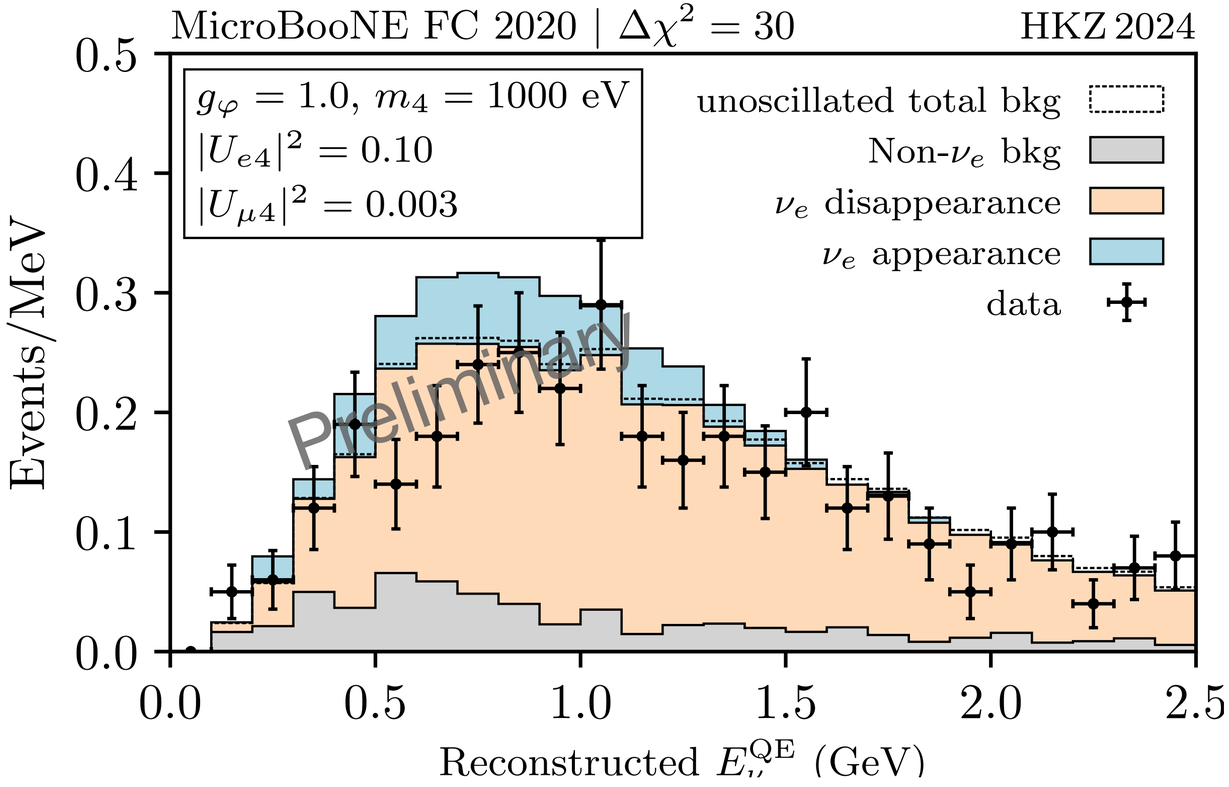


See also de Gouvêa et al [1911.01447]

Can MicroBooNE Weigh In?



Hostert, KJK, Zhou [240X.XXXXX]



Modify public MicroBooNE data release (and MiniBooNE tools) to incorporate decaying sterile neutrinos, regeneration effects, etc.

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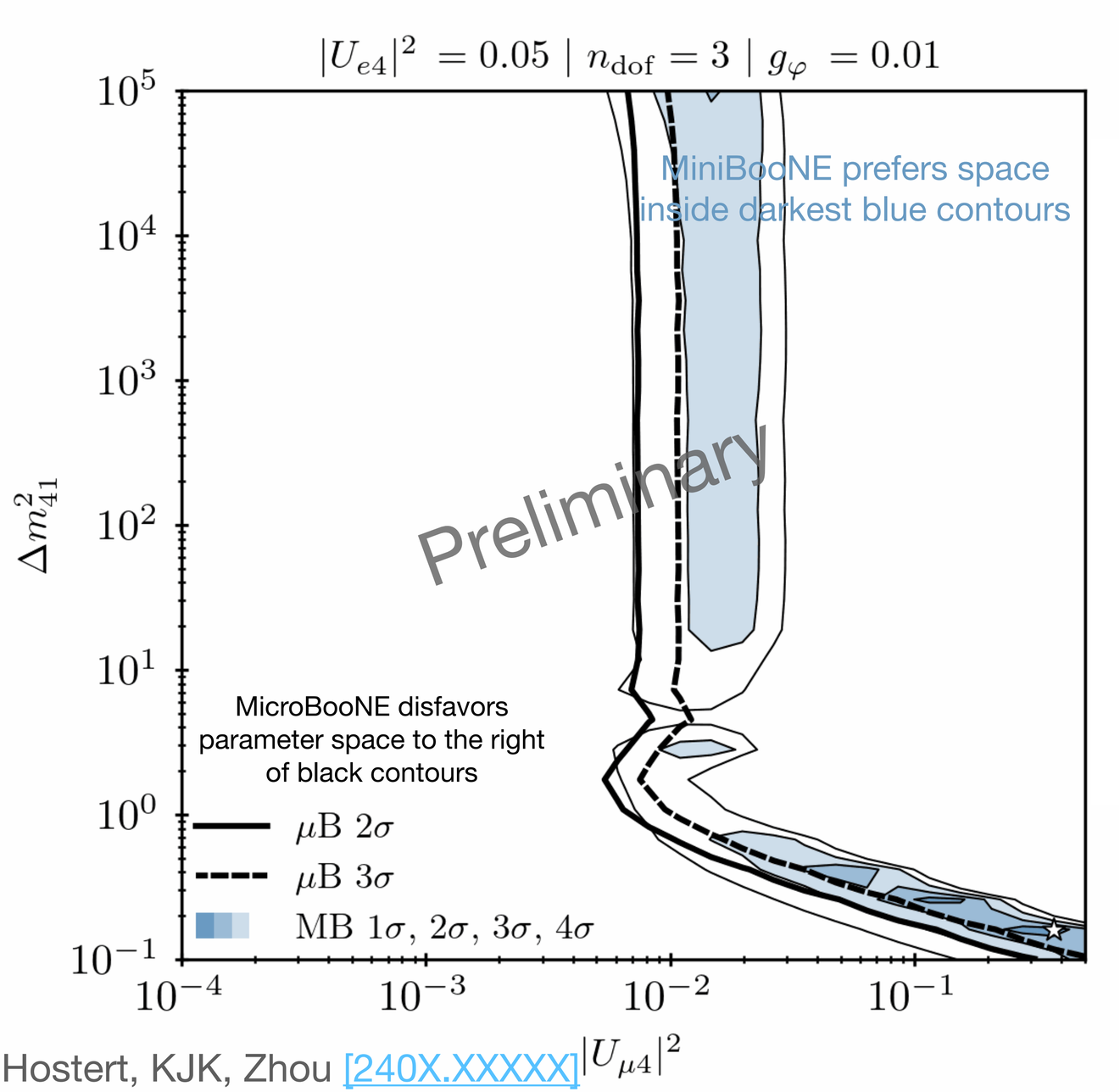

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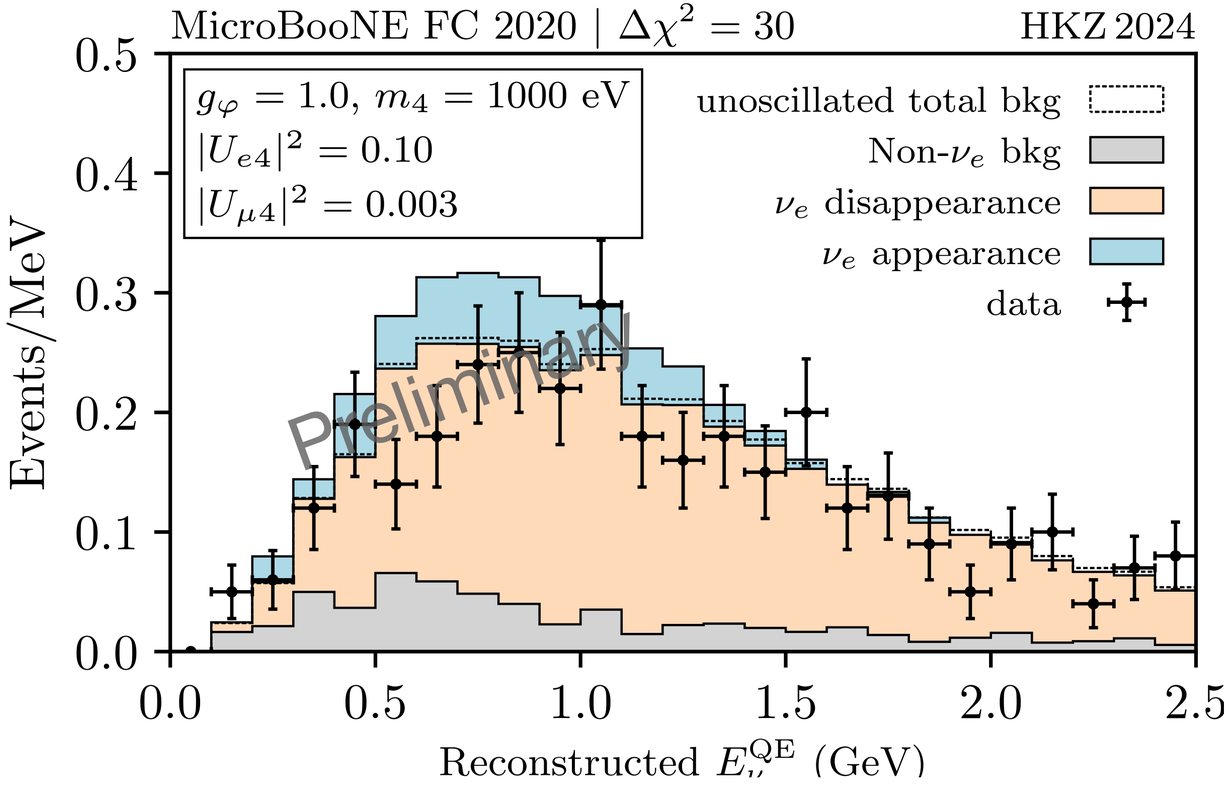

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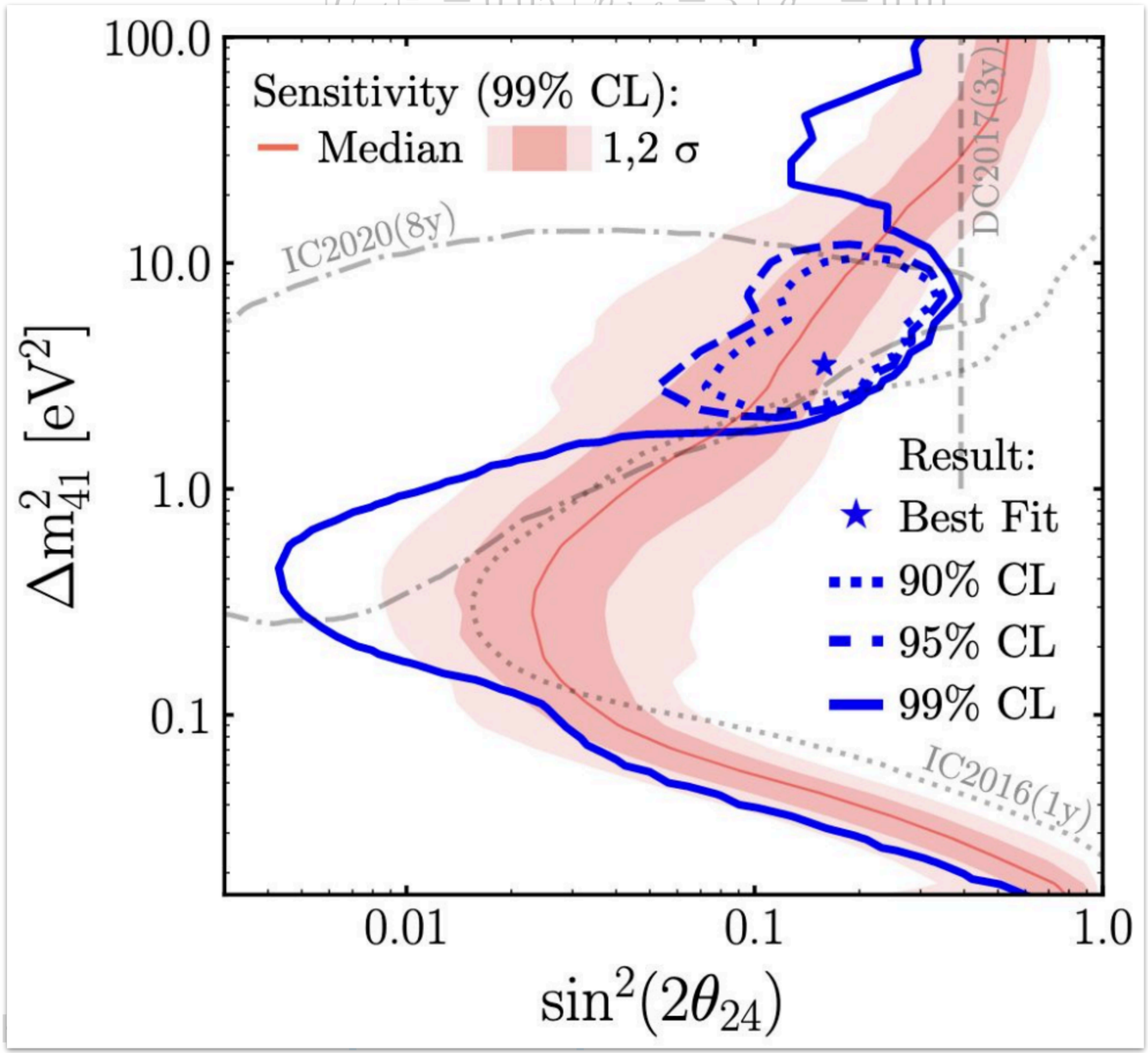
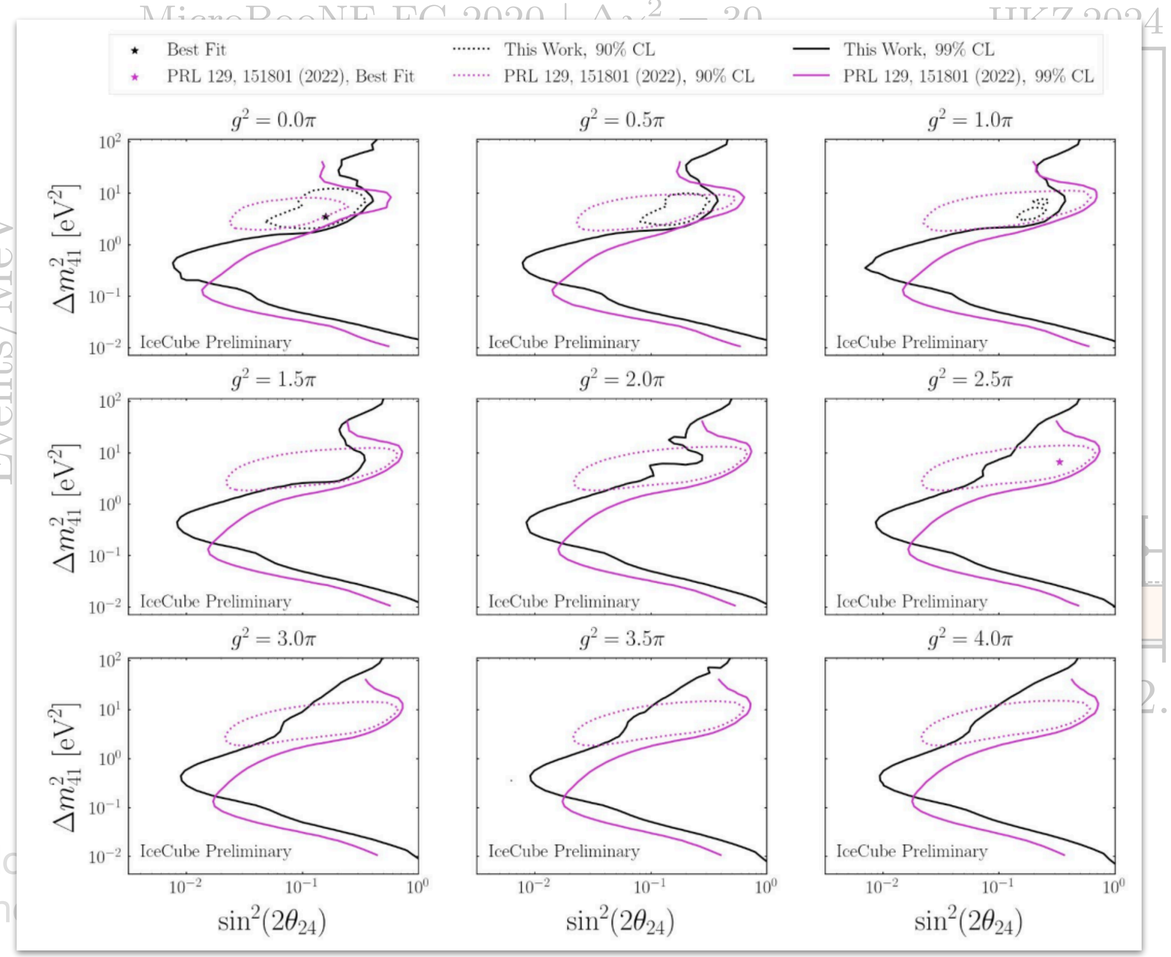
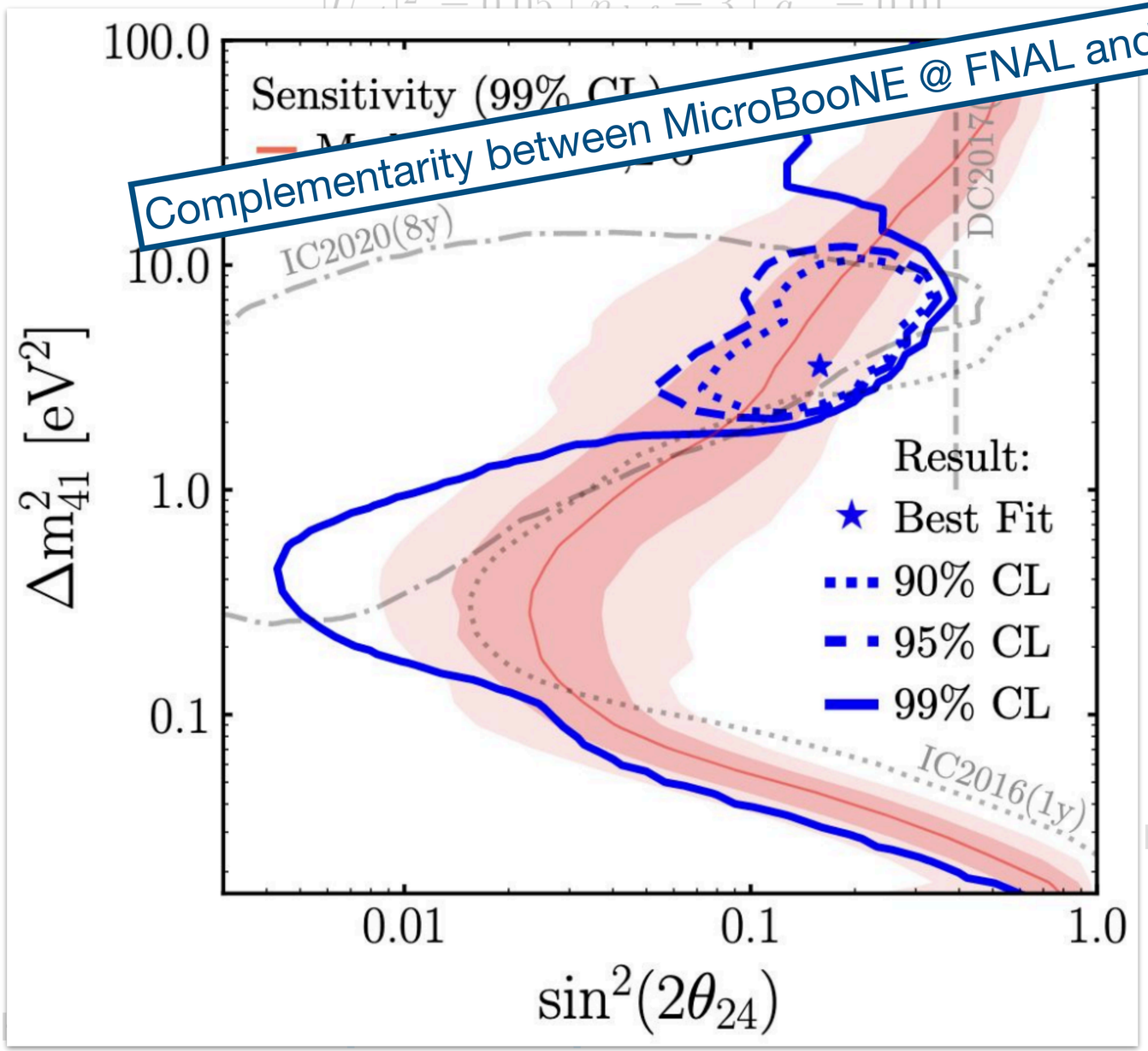


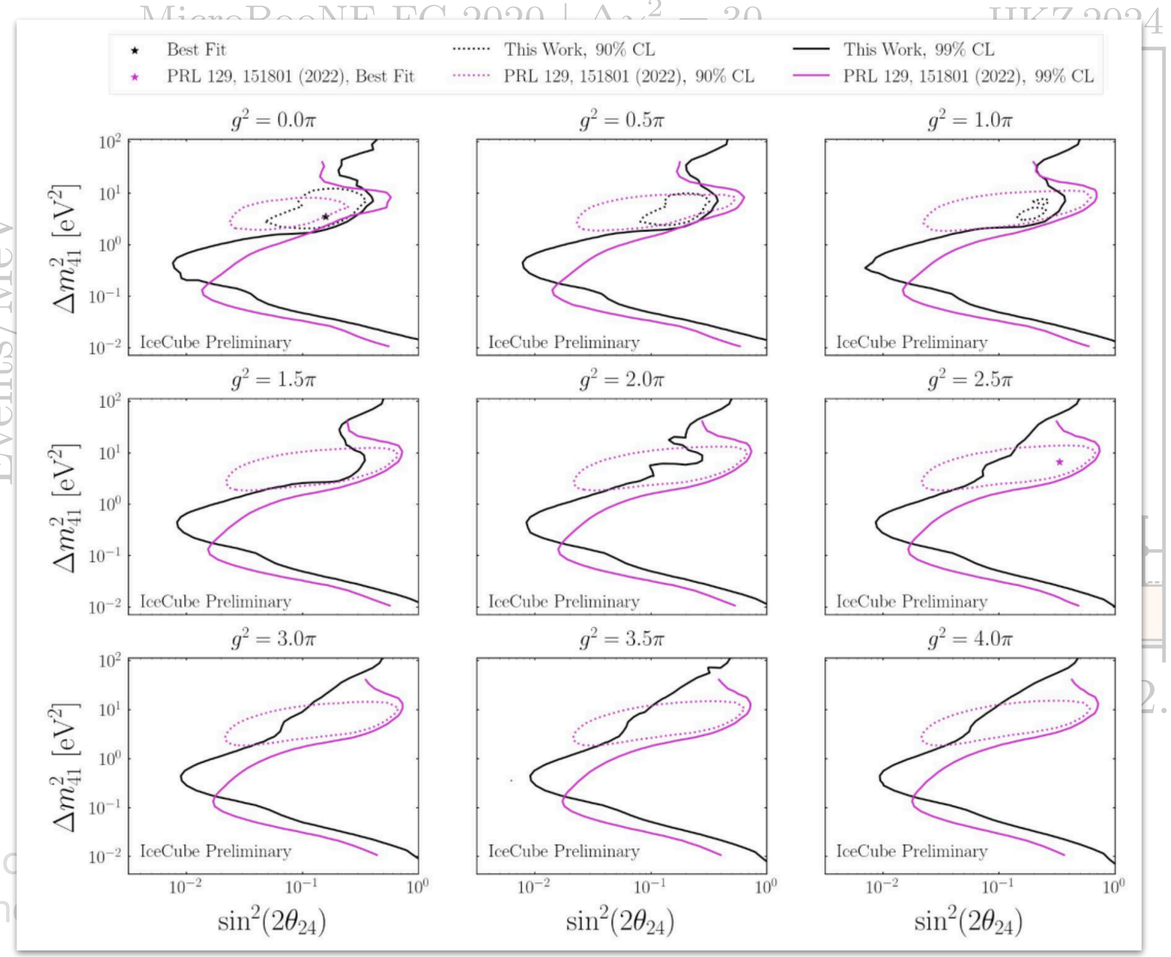


(IceCube [2405.08070] and Philip's talk Wednesday)

Can MicroBooNE Weigh In?

Complementarity between MicroBooNE @ FNAL and IceCube @ South Pole!





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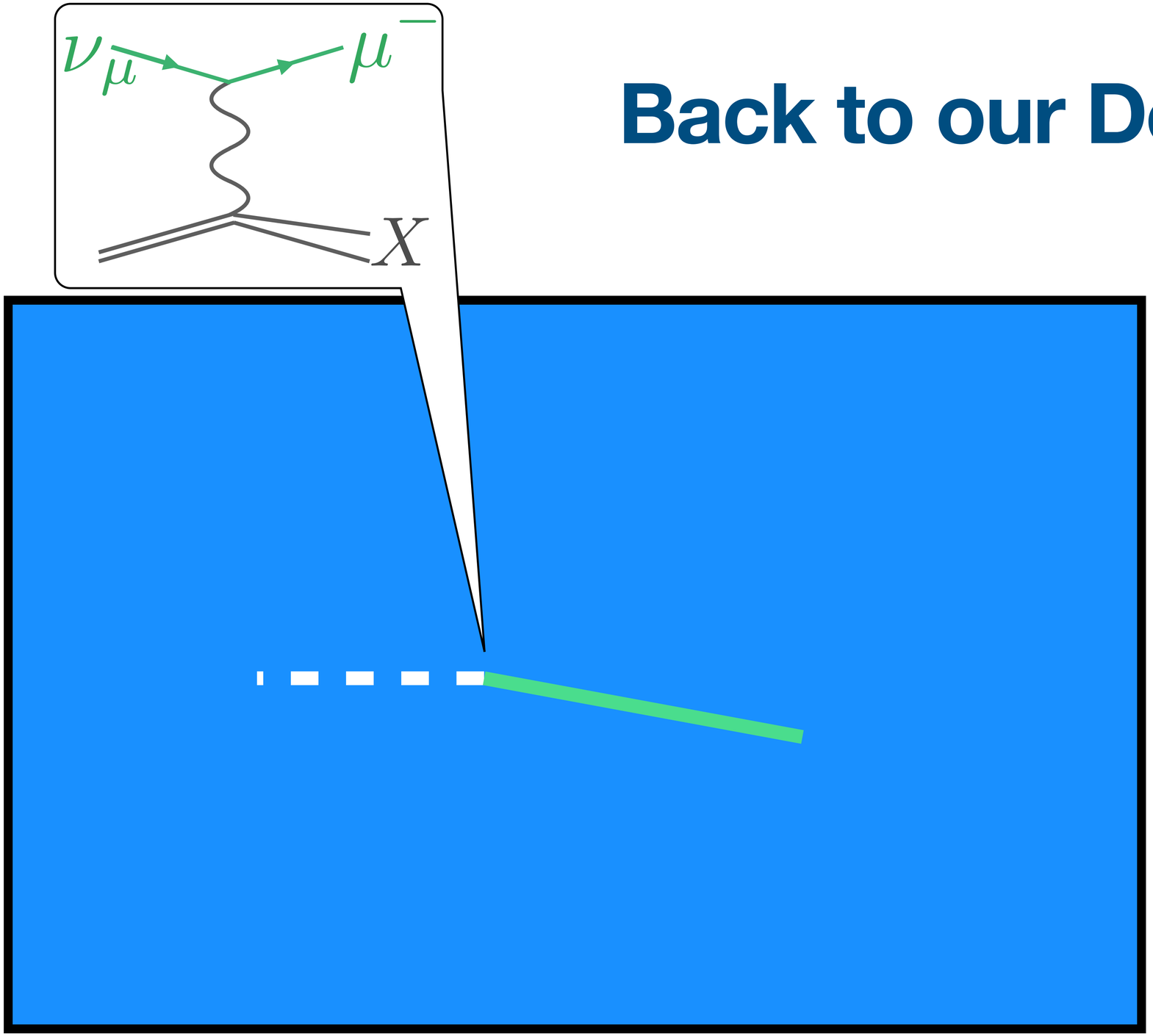
New Neutrino Interactions

Back to our Detector



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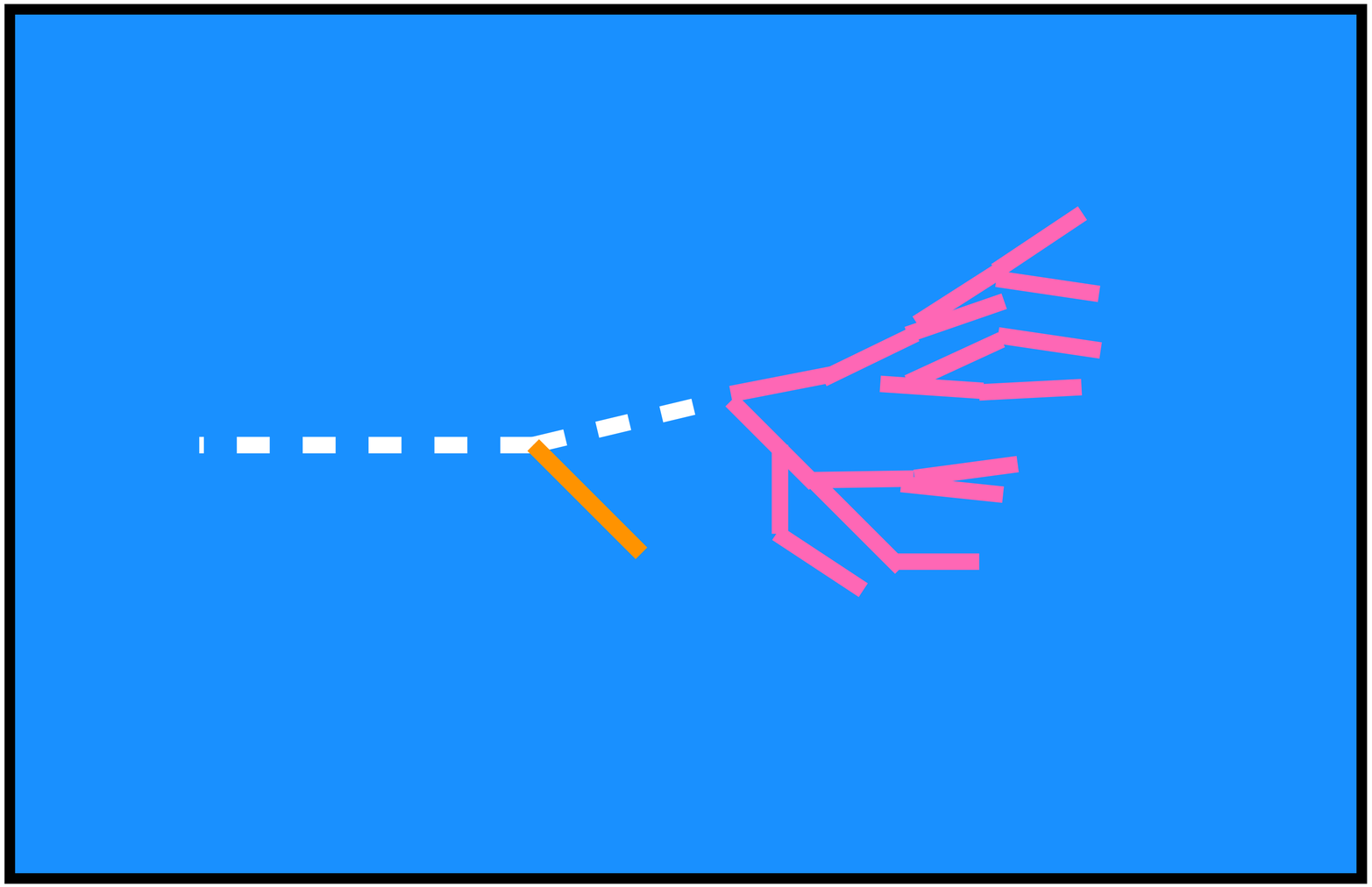
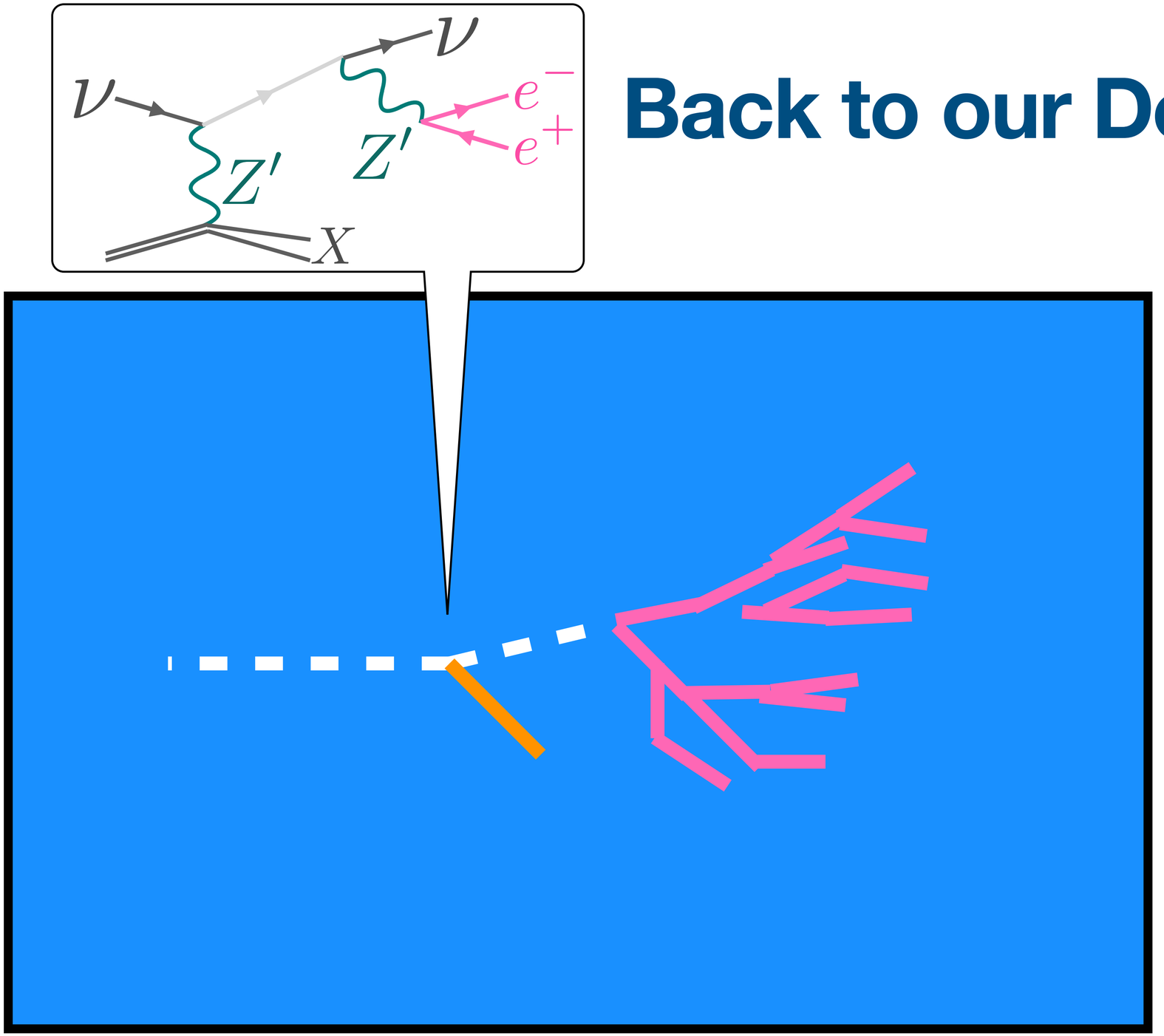


Unexpected neutrino-scattering can lead to novel signatures in the detector. Are we prepared to search for these?

Back to our Detector



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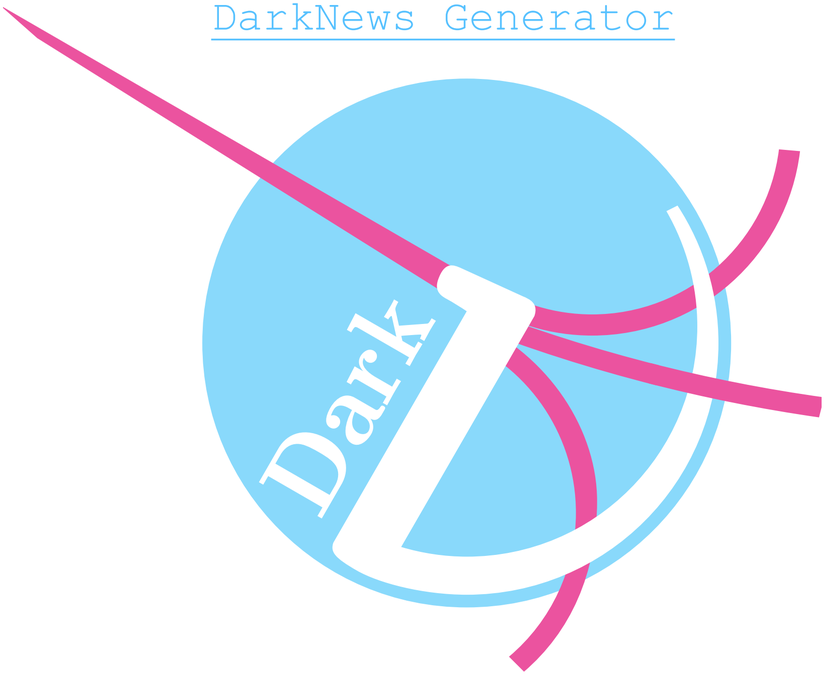
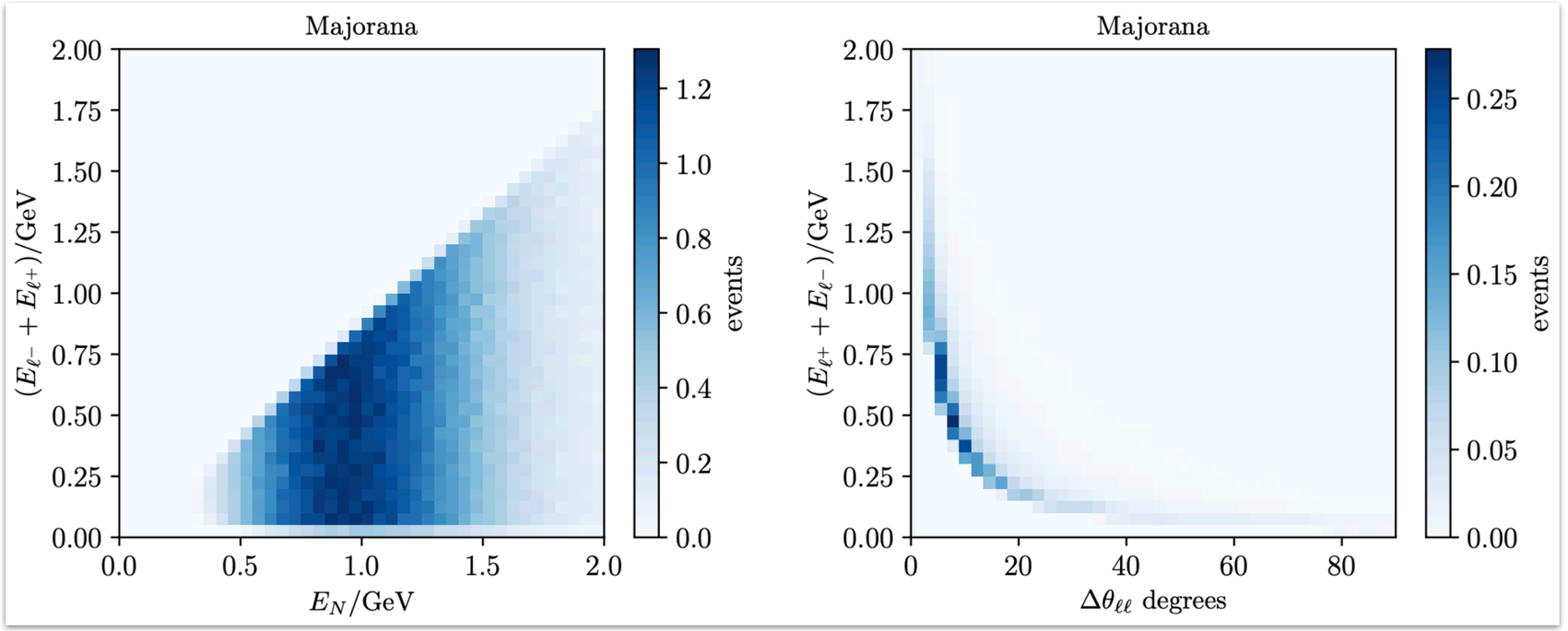
"Dark neutrinos" are a possible solution to the MiniBooNE low-energy excess (since to MiniBooNE, overlapping electron pairs look like a single electron)
Bertuzzo et al [1807.09877]
Ballett et al [1808.02915]

How do we simulate such BSM?

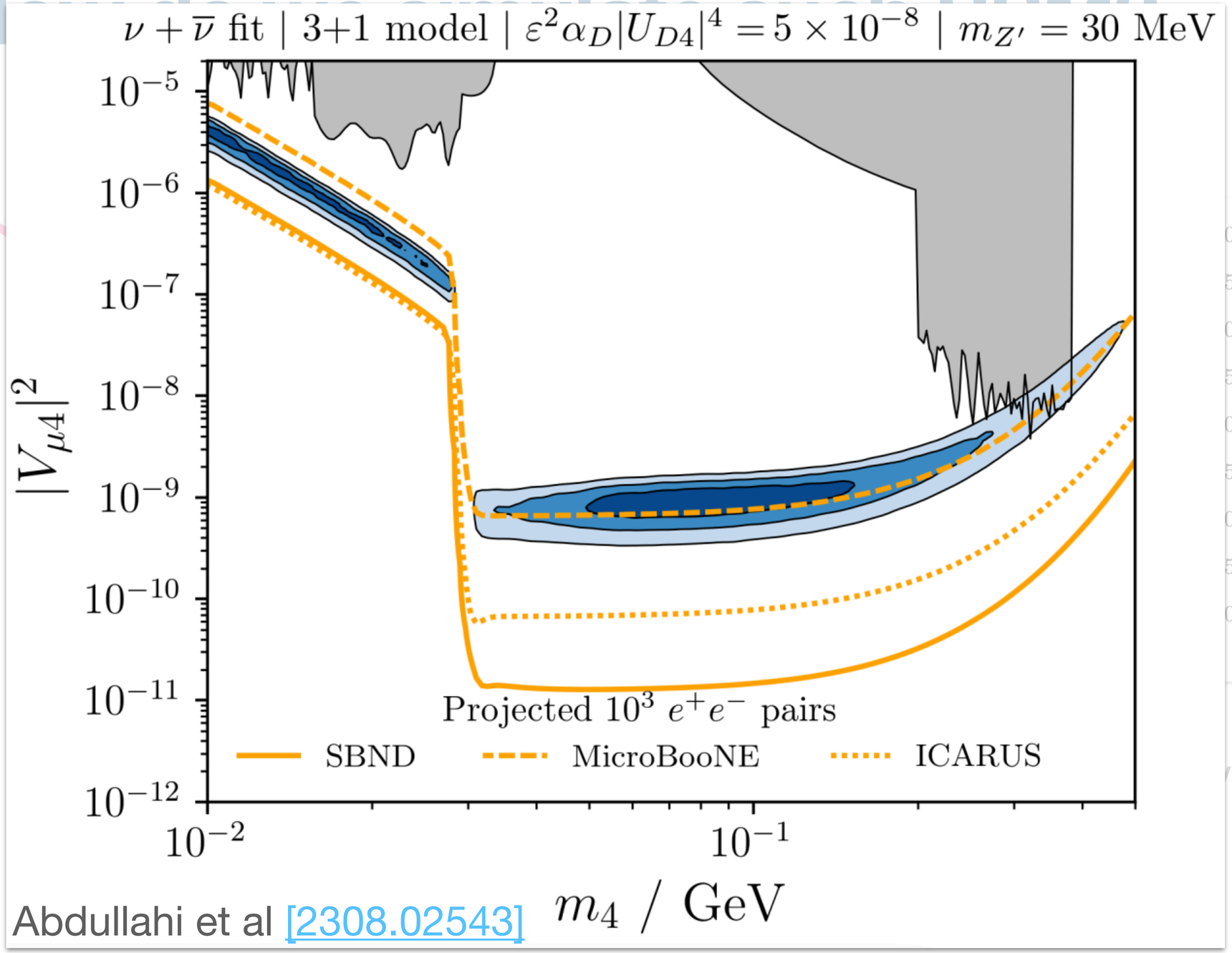
DarkNews Generator



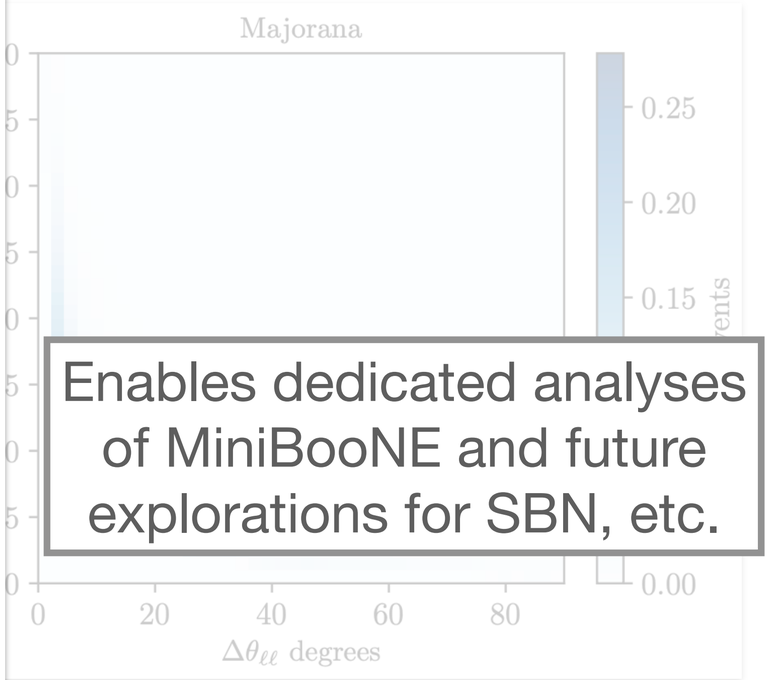
Abdullahi et al [2207.04137]



DarkNews — purpose-built tool for upscattering-type signatures.



Abdullahi et al [2308.02543]



Enables dedicated analyses of MiniBooNE and future explorations for SBN, etc.

Another approach?

Isaacson et al [2205.06378]

```
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|                                                                        |
|    .d8b.   .o88b. db   db d888888b db      db      d88888b .d8888.     |
|   d8' `8b d8P  Y8 88   88    `88'   88      88      88'     88'  YP     |
|   88ooo88 8P      88ooo88     88    88      88      88ooooo `8bo.       |
|   88~~~88 8b      88~~~88     88    88      88      88~~~~~   `Y8b.     |
|   88   88 Y8b  d8 88   88    .88.   88booo. 88booo. 88.     db   8D     |
|   YP   YP  `Y88P' YP   YP Y888888P Y88888P Y88888P Y88888P `8888Y'     |
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|                .d888888888888888888888888b.                            |
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|                `Y88888888888888888888888P  Y888888888888               |
|                  `Y88  8888  8888  88Y'       Y888888888888            |
|                 .d88888888888888888b.         Y888888888888           |
|               .d8888888888888888888888b.       888888888888           |
|              .d888888888888888888888888888b    888888888888           |
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|          d888888P'   d8888888888888888888P        888888888           |
|         8888P     .d88888888888888888888P          888888888          |
|         888P    .d88888888888888888888P            8888Y              |
|         888b  .d88888888888888888888               8888P              |
|         Y88  d8888888888888888888888888            888                |
|         `8' d8888888888888888888888888             88                 |
|             888888888888888888888888888P           8                  |
|             88888888888888P     Y8888888P                             |
|            d8888888888888       Y88888P                               |
|            888888888888888P      Y888P                                |
|           d8888888888888P         Y8P                                  |
|           888888888P               8                                   |
|          d888P                                                         |
|                                                                        |
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|                                                                        |
|    Version: 1.0.0                                                      |
|    Authors: Joshua Isaacson, William Jay, Alessandro Lovato,           |
|        Pedro A. Machado, Luke Pickering, Noemi Rocco,                  |
|        Noah Steinberg                                                  |
|                                                                        |
|    Undergraduate Student Contributions:                                |
|        Diego Lopez Gutierrez, Sherry Wang, Russell Farnsworth          |
|                                                                        |
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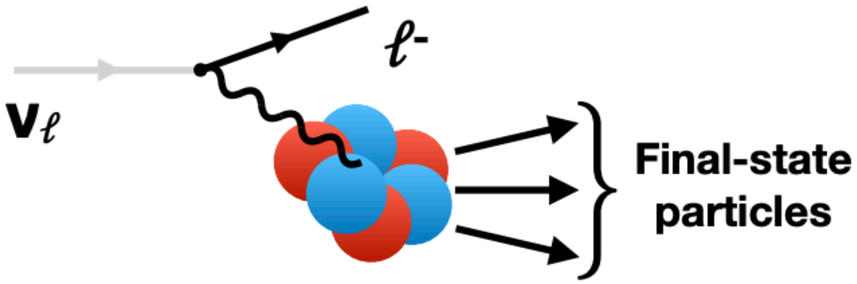
Factorizability + Modularity!

(courtesy Will Jay)



$$|\mathscr{M}|^2 = L_{\mu\nu}\,\frac{1}{P^2}\,W^{\mu\nu} \rightarrow \langle\Psi_0|J_\mu^\dagger(q)|\Psi_f\rangle\langle\Psi_f|J_\nu(q)|\Psi_0\rangle$$

Leptonic tensor: Calculable analytically in SM or BSM scenario.

Hadronic tensor: Complicated multi-scale object, encoding all the hadronic/nuclear physics

$|\Psi_0\rangle$: Initial state (say, ^{40}Ar or H_2O)

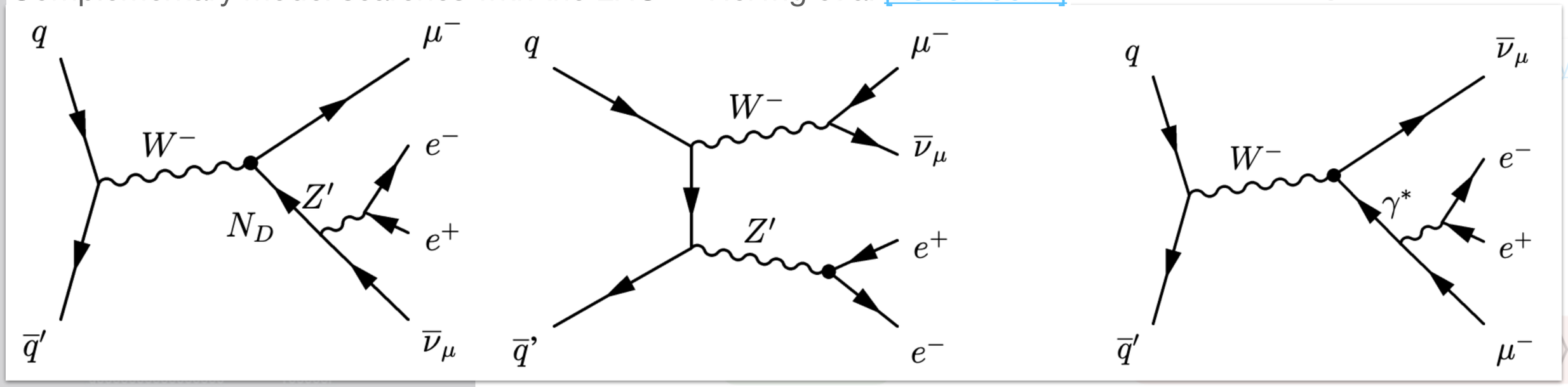
$|\Psi_f\rangle$: Final state (nuclear remnant + outgoing pions, kaons, etc…)

Interfaces well with NuHepMC event record format, Gardiner et al [2310.13211]

Another approach?

Isaacson et al [2205.06378]

Complementary model searches with the LHC — Herwig et al [2310.13042]



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New ν Physics

New  Physics

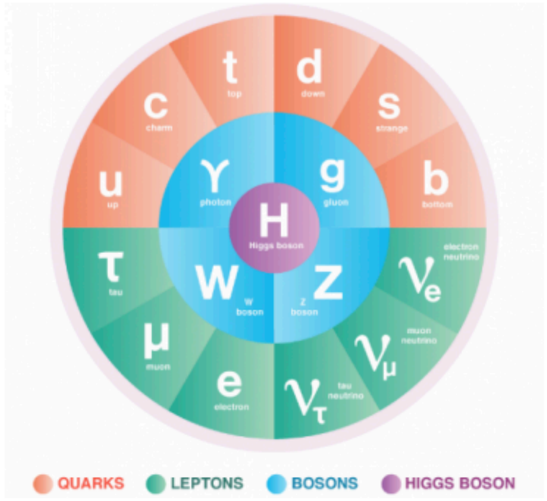
HIDDEN SECTOR / VALLEY

(from Kathryn's talk Tuesday)

"DM Candidates of a Very Low Mass," Reviews of Nuclear and Particle Physics, 2401.03025

- Theory landscape broadened; search strategies broadened

Standard Model → Connector → Dark Matter



Energy

GUT

Weak

Light

pure glue, light flavors, heavy flavors, quirky asymmetric dark matter, Strongly Interacting Massive Particle (SIMP), Wess-Zumino-Witten SIMP

Darkogenesis, Xogenesis, Hylogenesis, Cladogenesis, ADM from Leptogenesis, Dark Affleck-Dine

Dark photons, Freeze-in, WIMPless miracle

Mirror Matter, Atomic Matter, Self-Interacting Dark Matter, Magentic, Dark Anapole and EDMs

Visible Sector

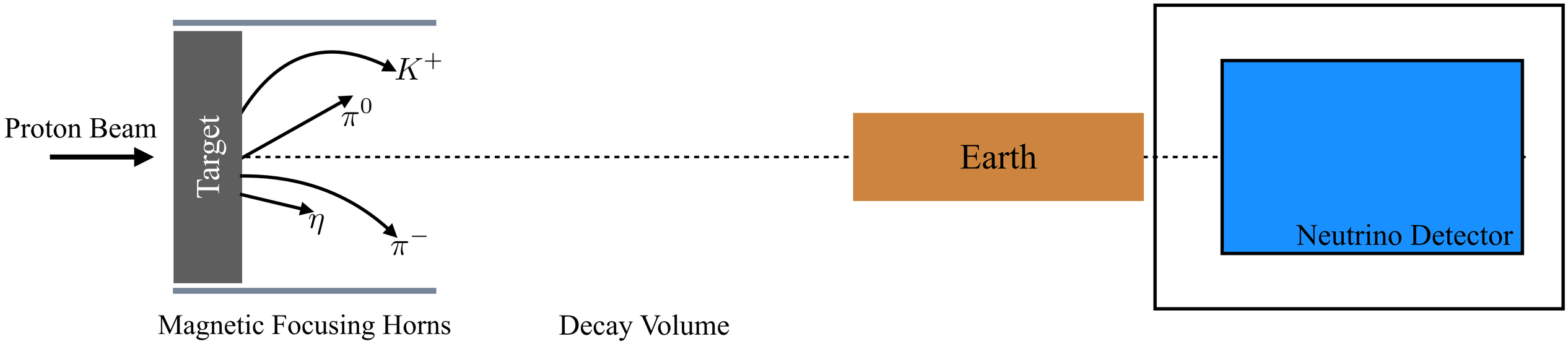
Hidden Sector

Inaccessibility

Models in mind

What else could be lurking in the beam?

Production of new states in tandem with the neutrino beam
(commonality with accelerator searches discussed in Elliot's talk Wednesday)



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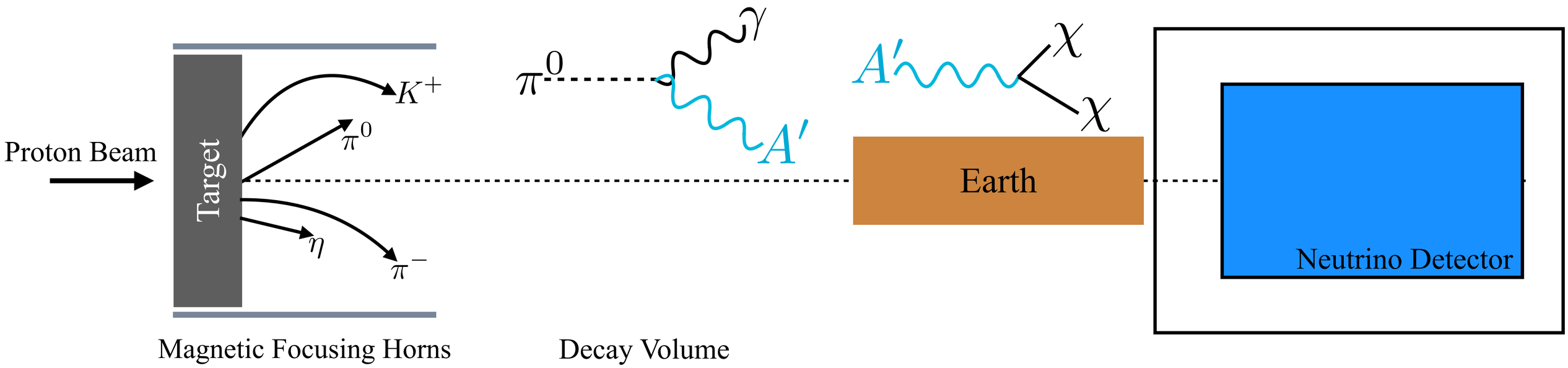

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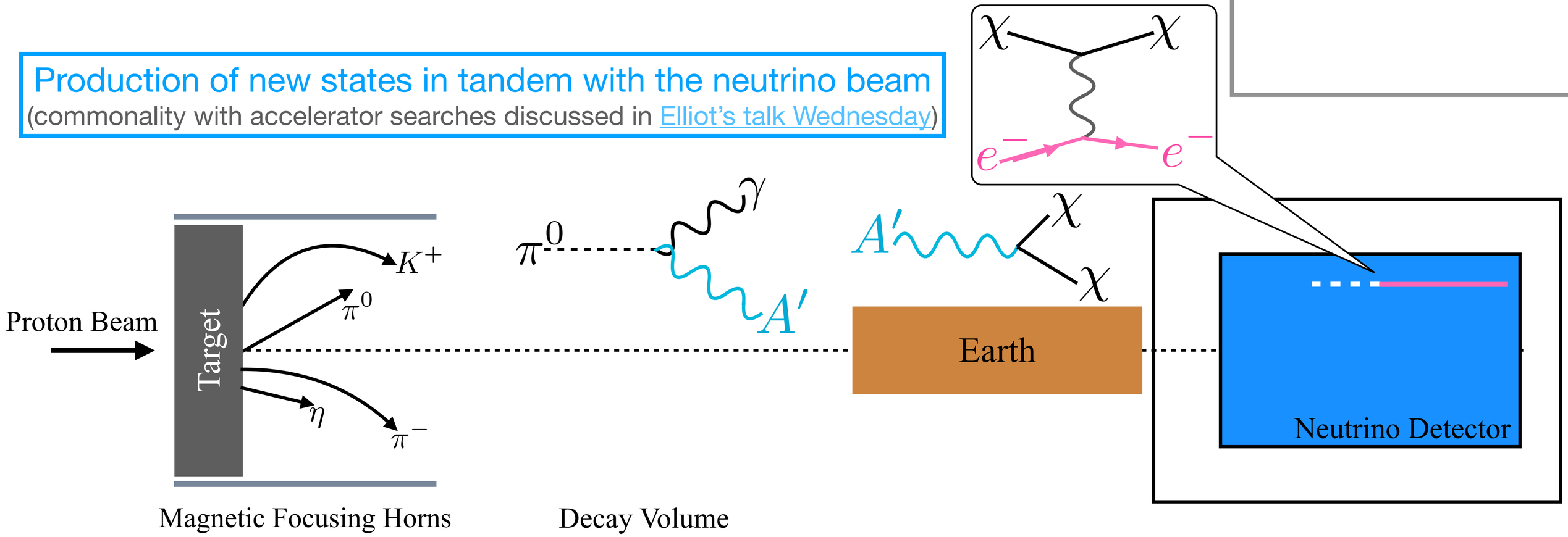

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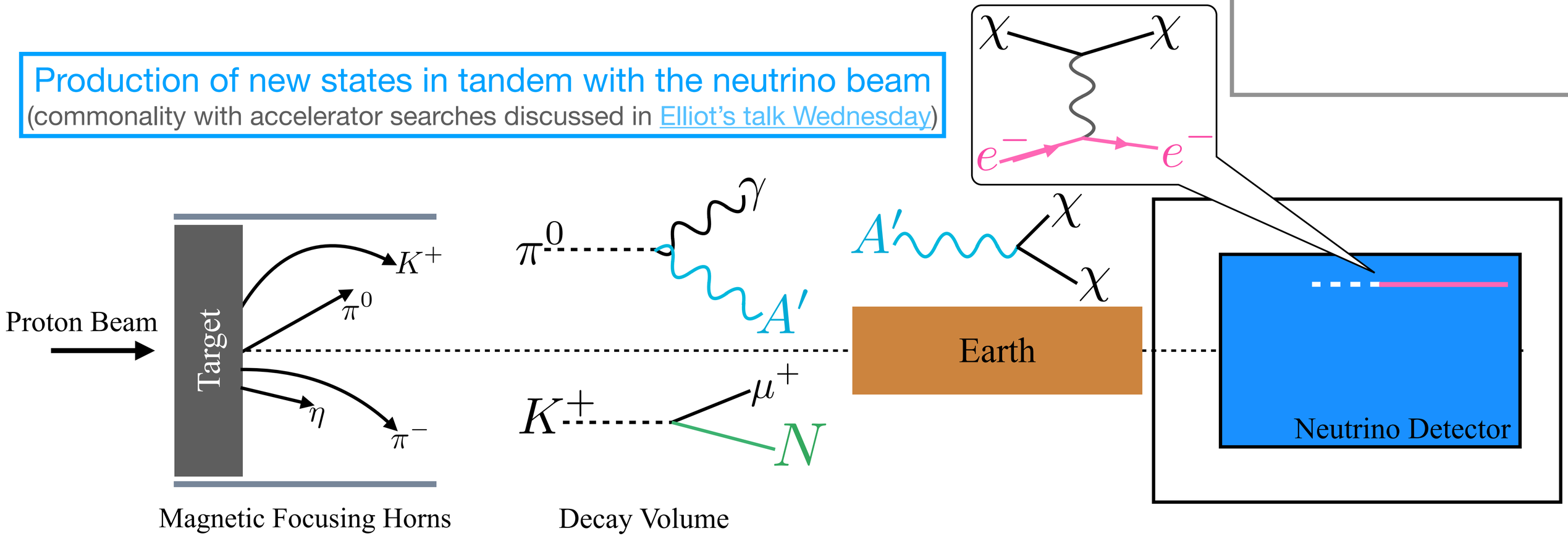

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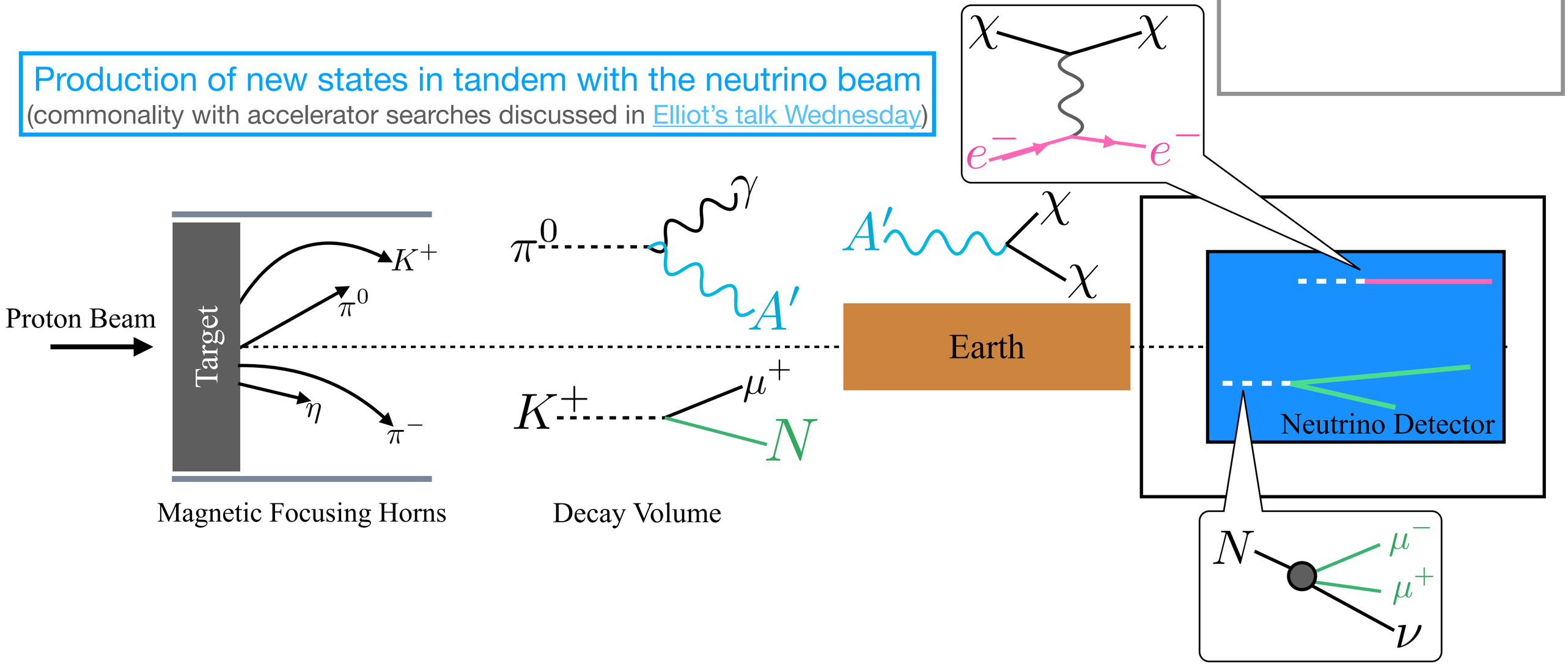

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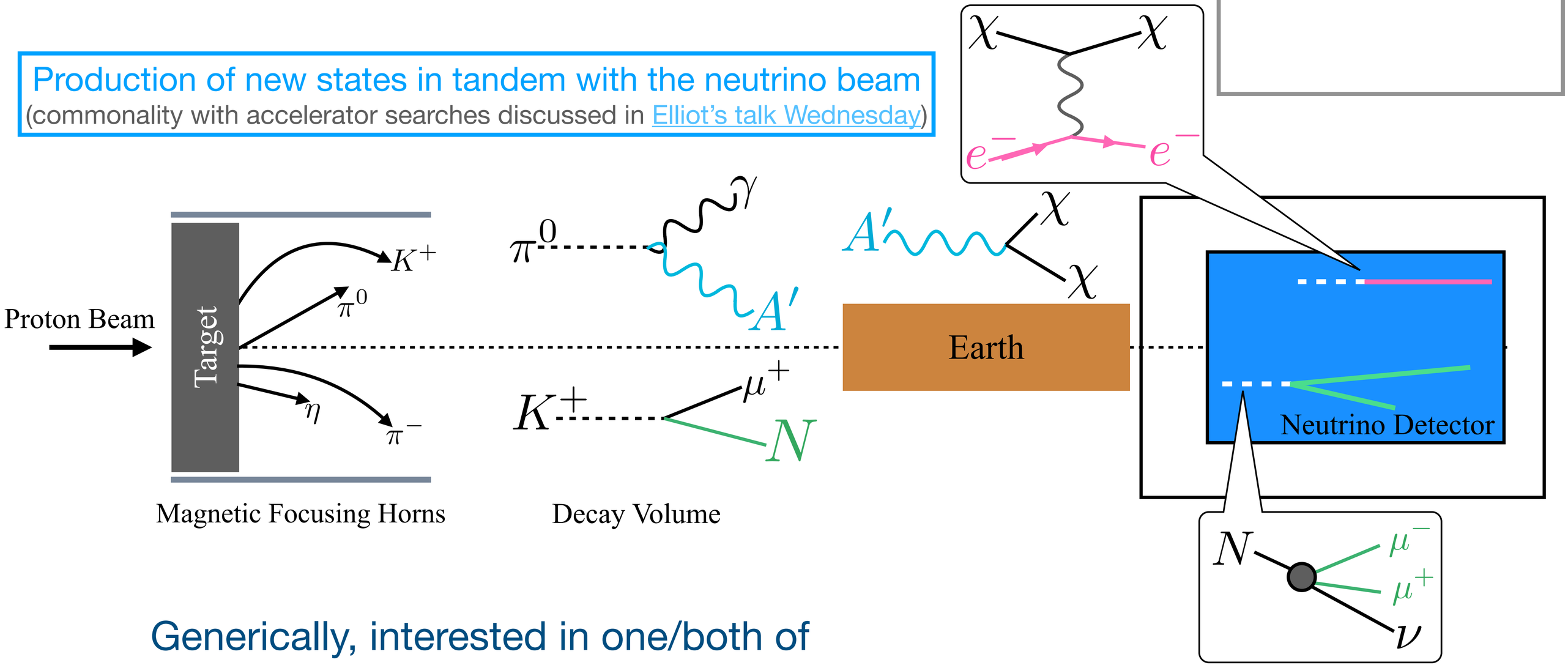
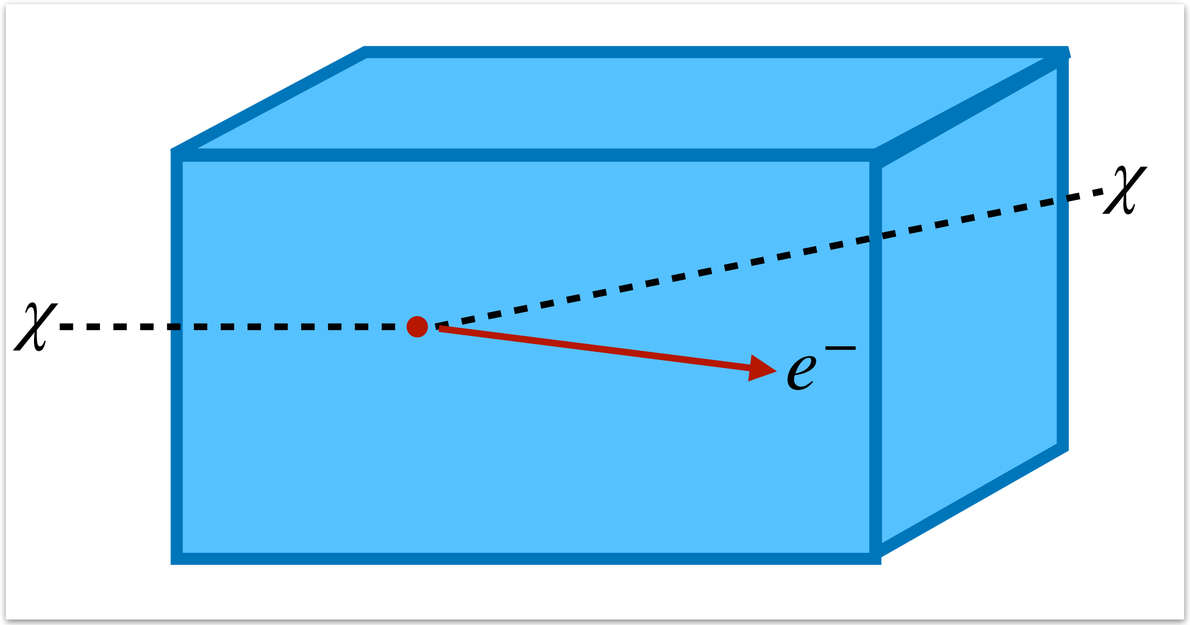


Generically, interested in one/both of

- Signal that predicts characteristically different spectrum from neutrino interactions
- Signal that is impossible/rare with SM effects

Complementarity of Neutrino Detectors

Liquid Detectors (MicroBooNE, SBND, ICARUS, etc.)



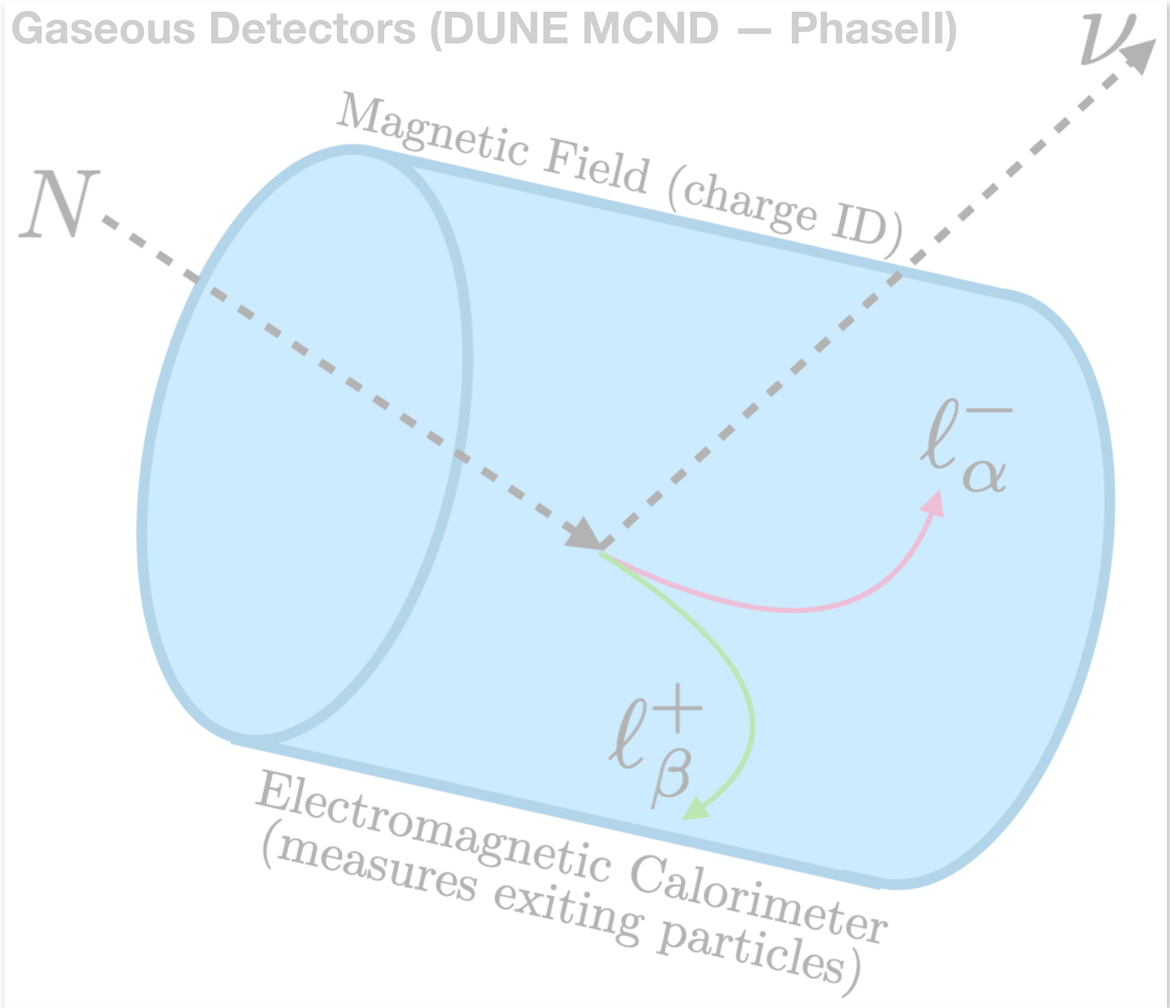
Large mass for rare-particle scattering

Excellent particle ID, energy resolution, etc.

Decay Signal $\propto$ Volume

Neutrino Scattering Backgrounds $\propto$ Mass

Gaseous Detectors (DUNE MCND — PhaseII)



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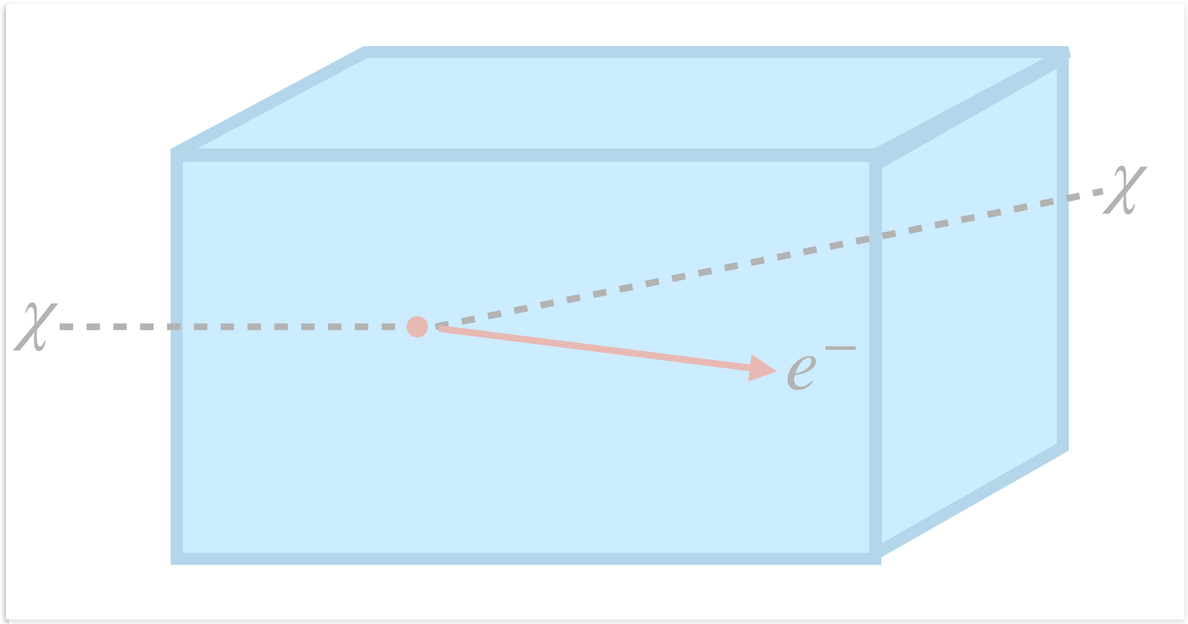

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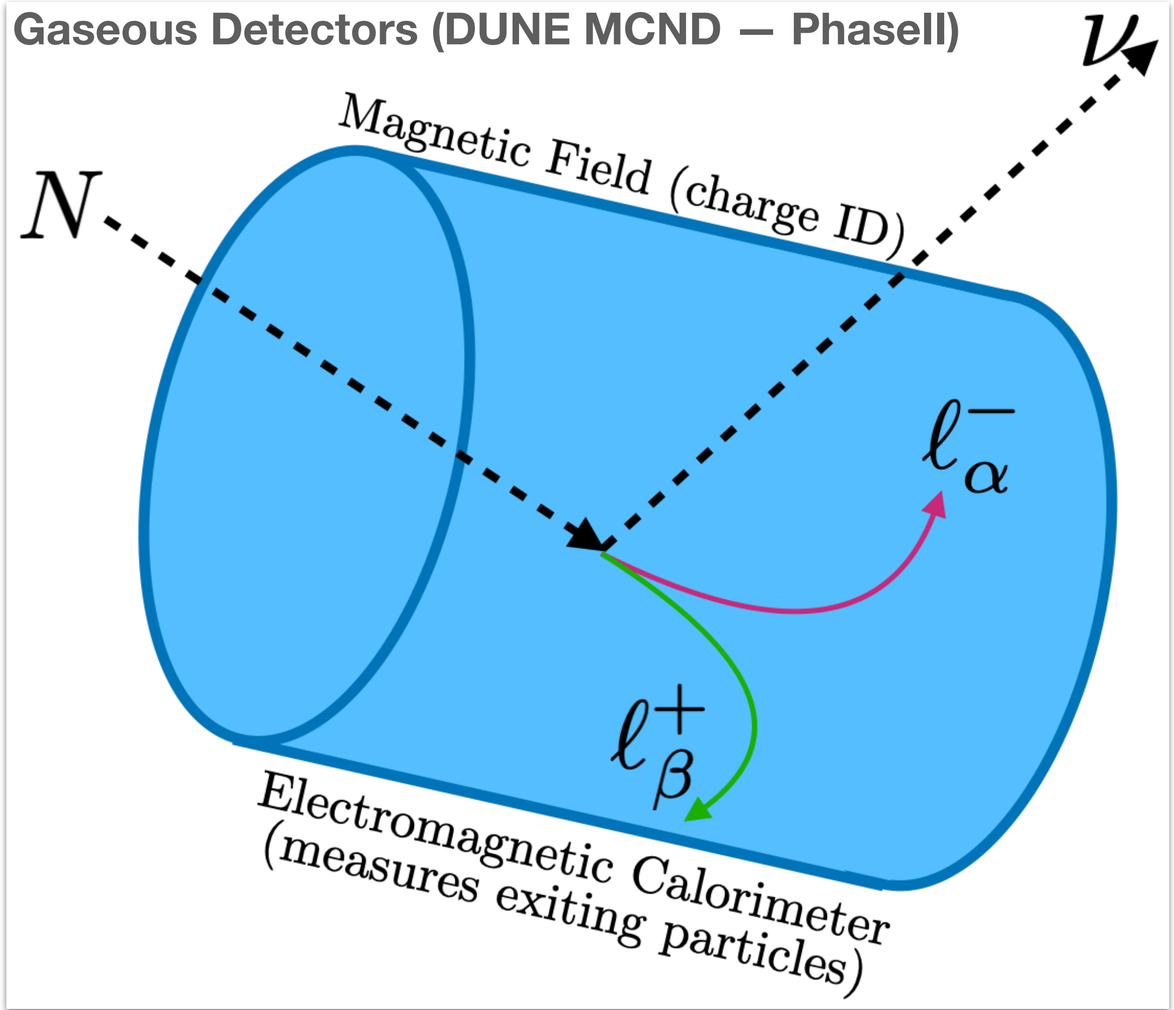
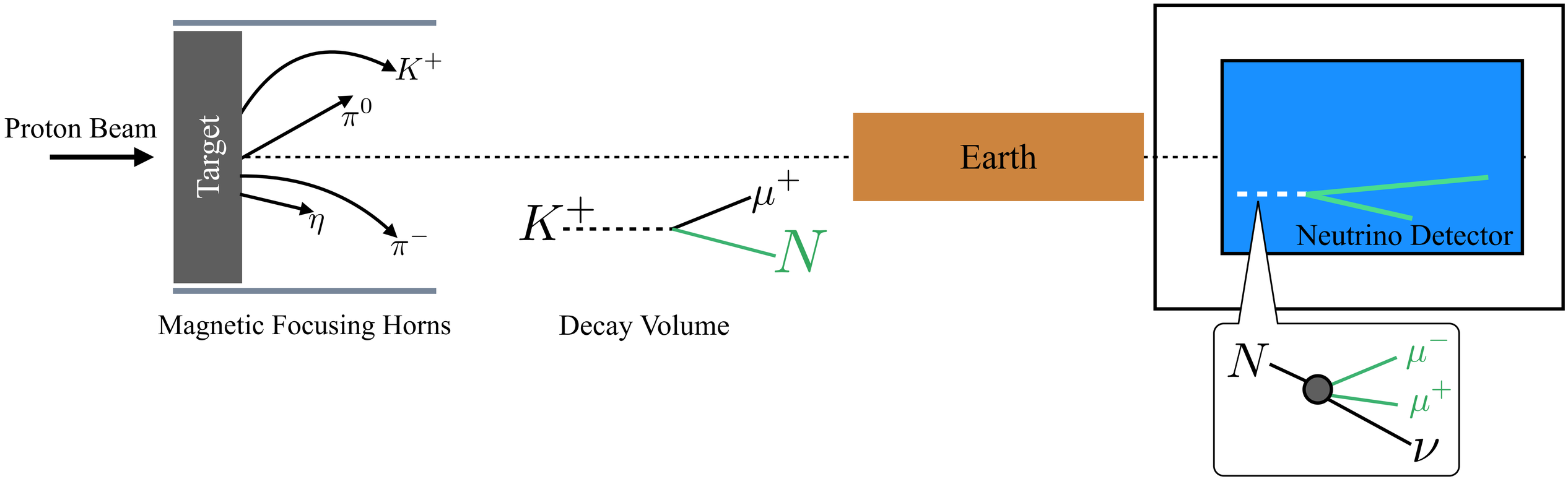
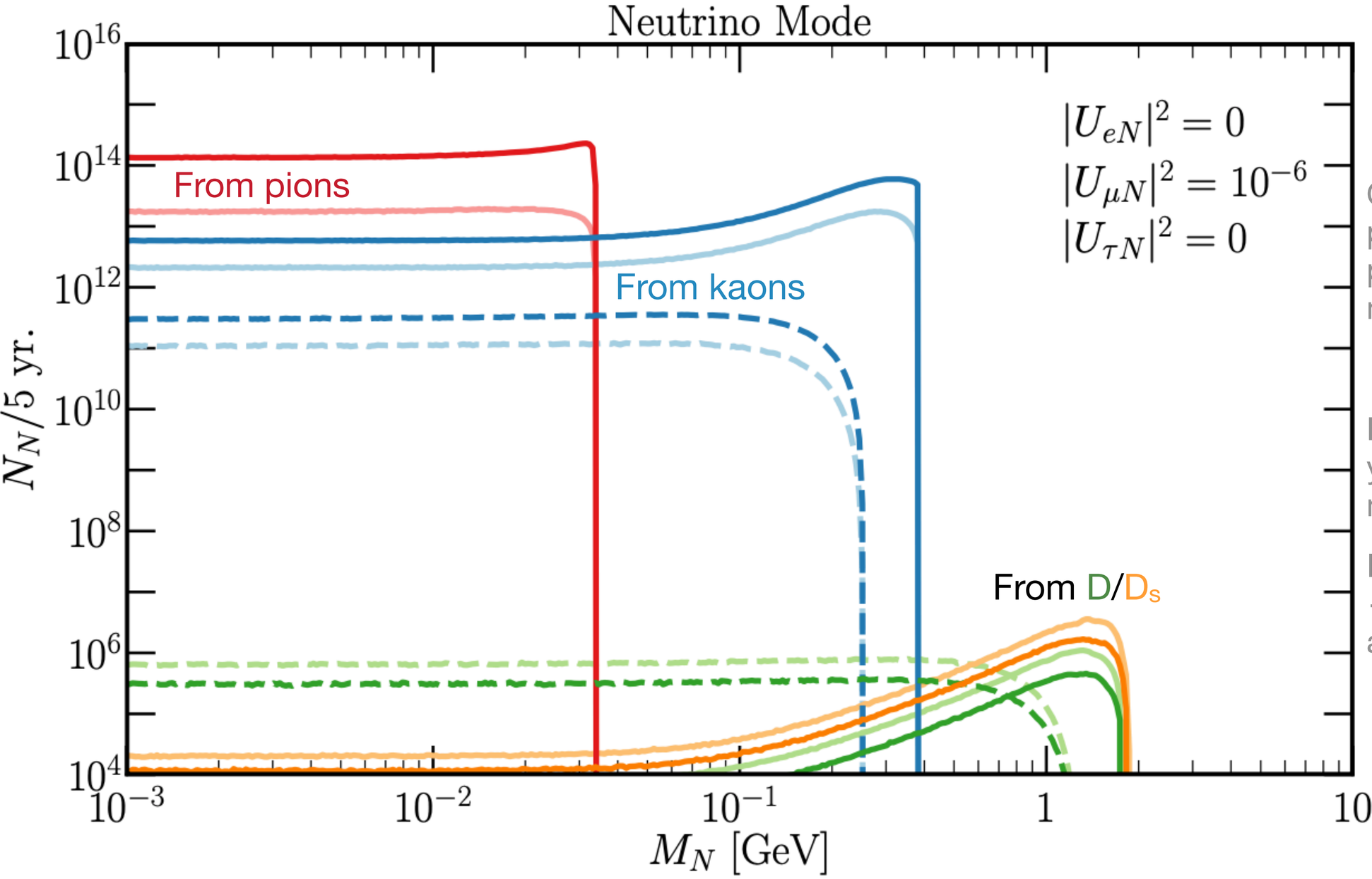


Case study — heavy neutral leptons in the DUNE beam.



HNLs in the DUNE Beam



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

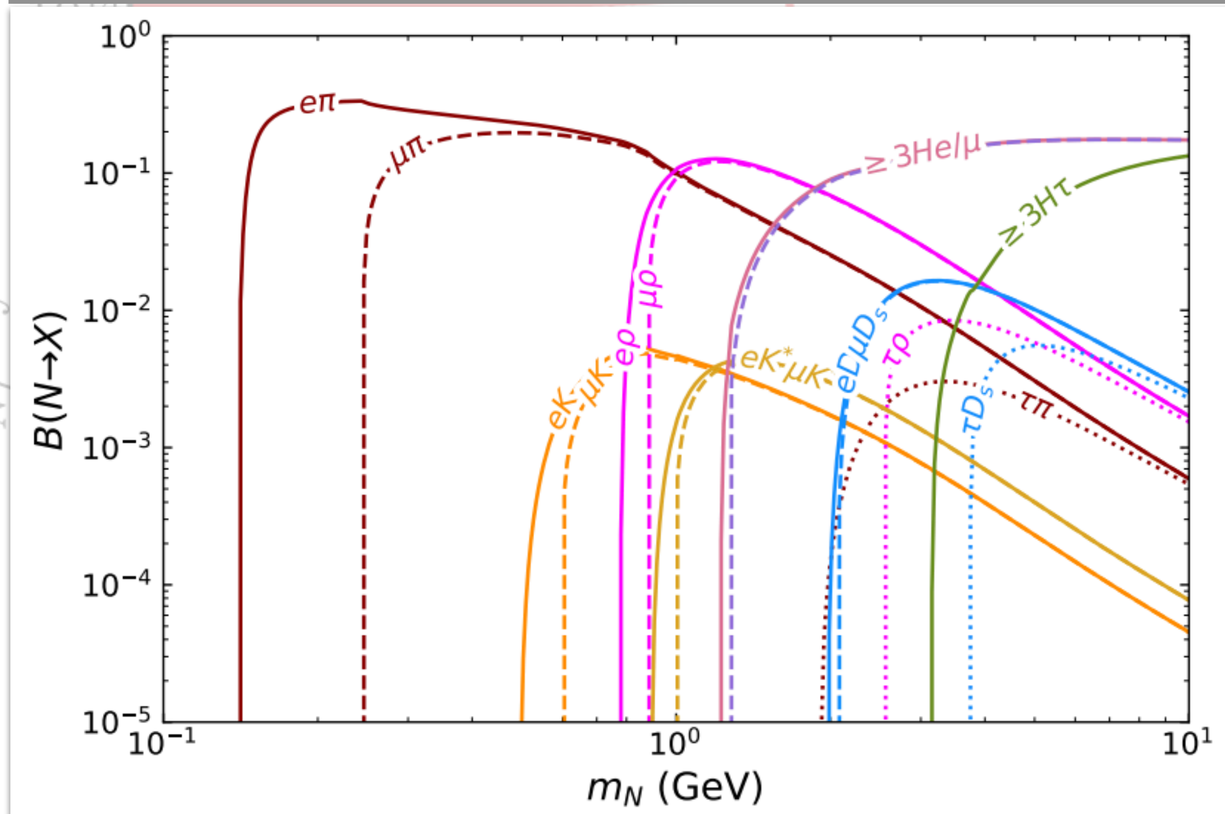
Fluxes simulated assuming 5 years of operation in neutrino mode.

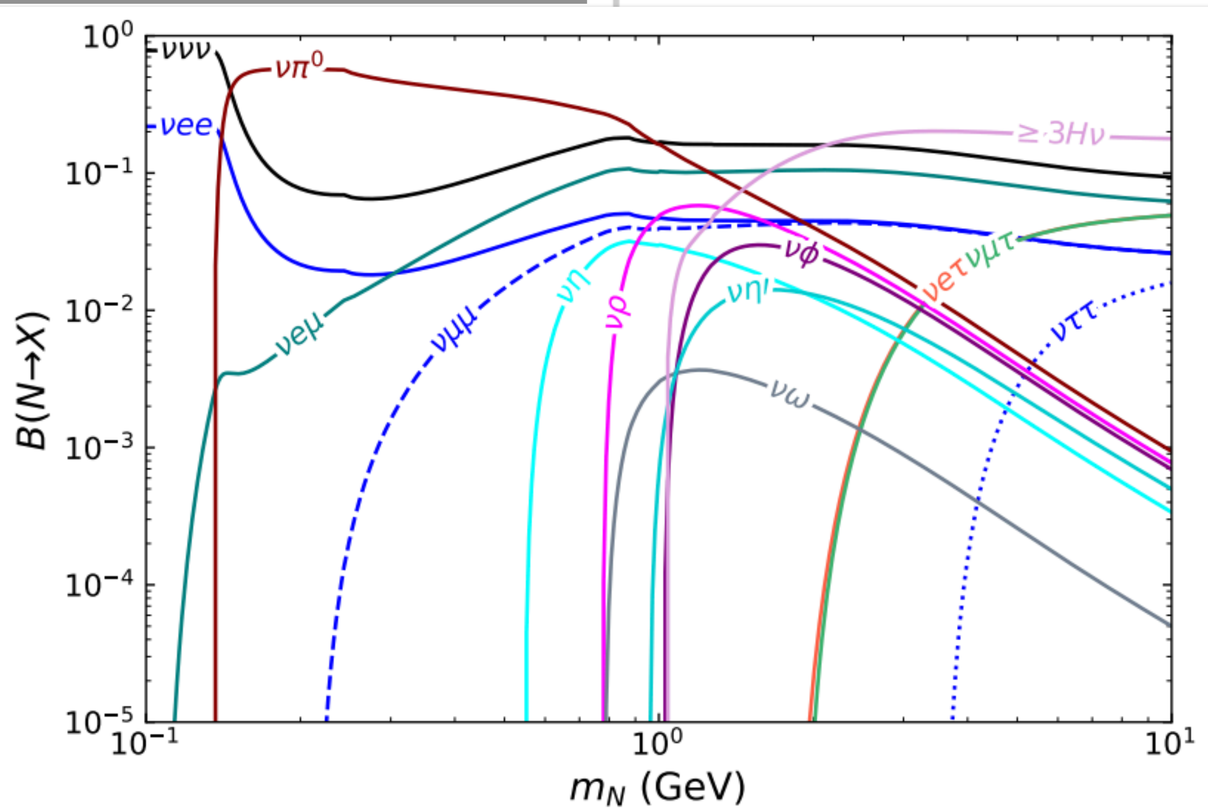
Includes acceptance efficiency — detector is 5 m in diameter at a distance of 579 m.

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

HNLs in the DUNE Beam

How do HNLs decay — into what states and how rapidly? It depends! See Alec's talk Tuesday

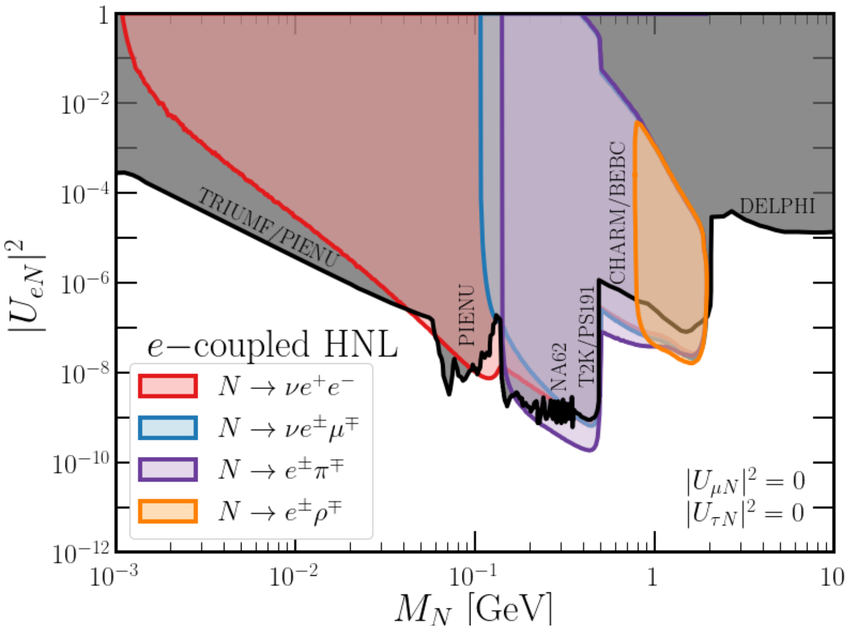


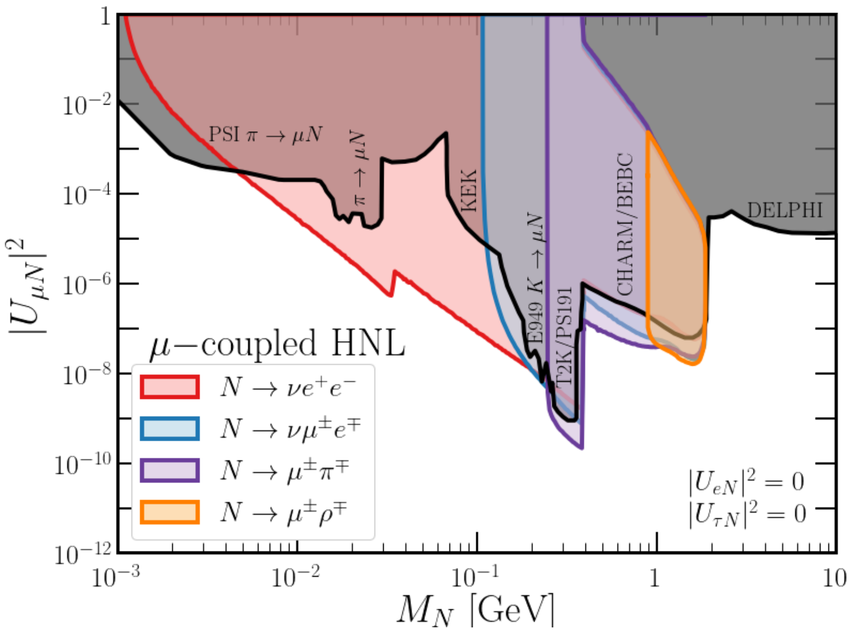


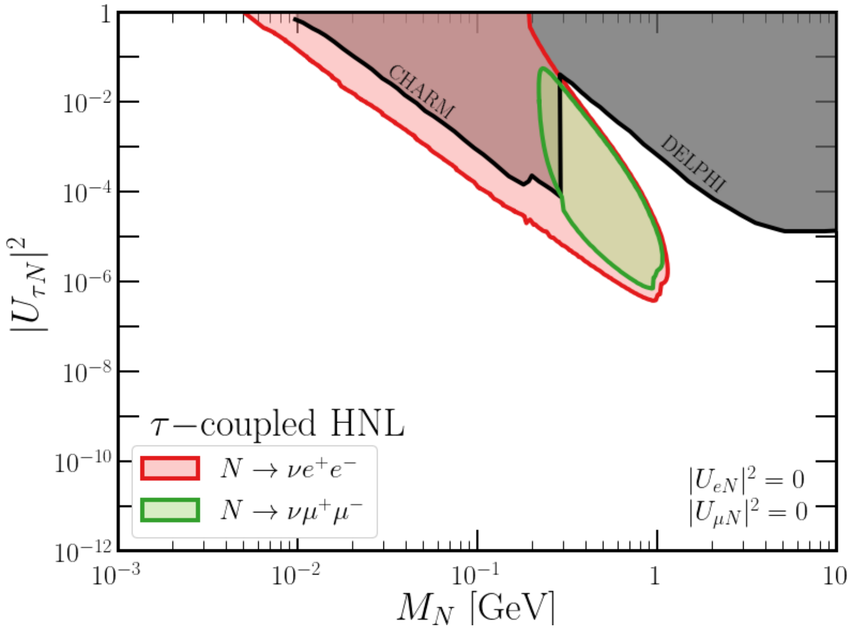
Berryman, de Gouvêa, Fox, Kayser, KJK, Raaf [1912.07622]

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

LLP @ DUNE — Heavy Neutral Leptons







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

New (ν) Physics!

New (ν) Physics! 🍾

LNV in a (Heavy) Neutrino Beam

Let's imagine that one of these facilities discovers a novel signal and the analysis points to it as a heavy neutral lepton. Follow-up studies will naturally ensue:

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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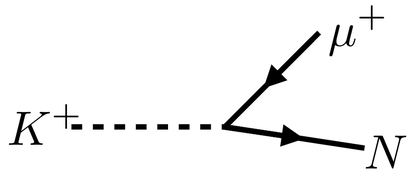

Heavy Neutrino Source

LNV in a (Heavy) Neutrino Beam

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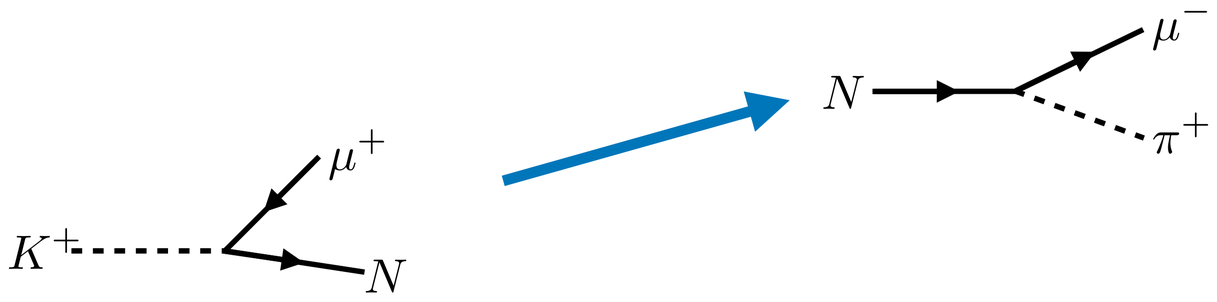

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Heavy Neutrino Decay

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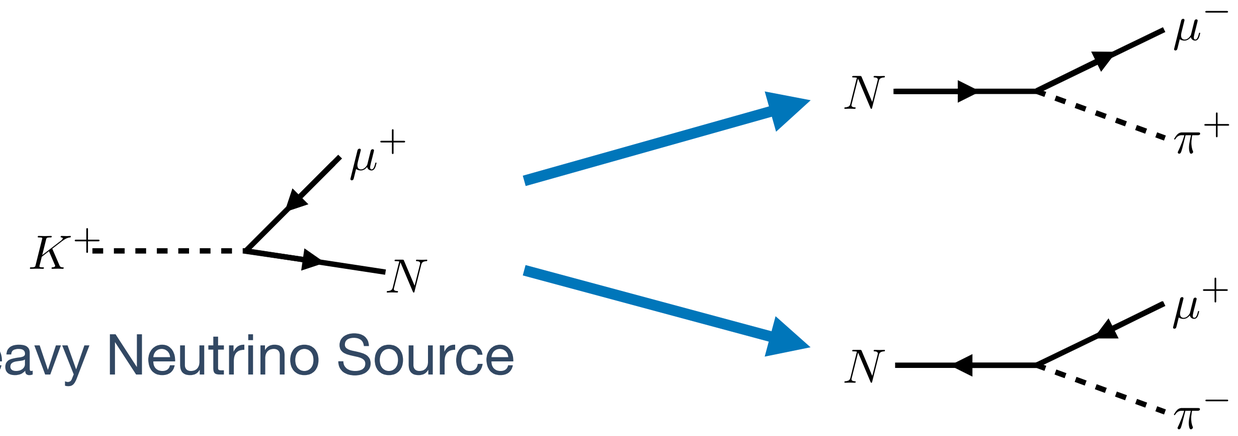

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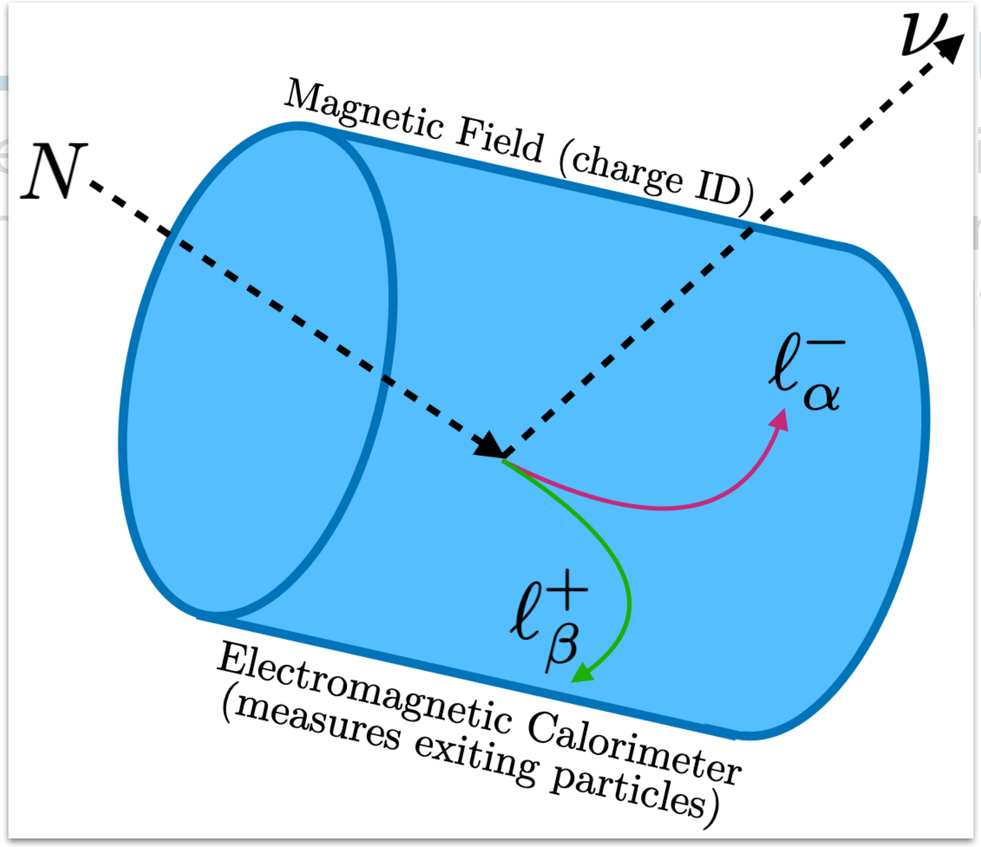

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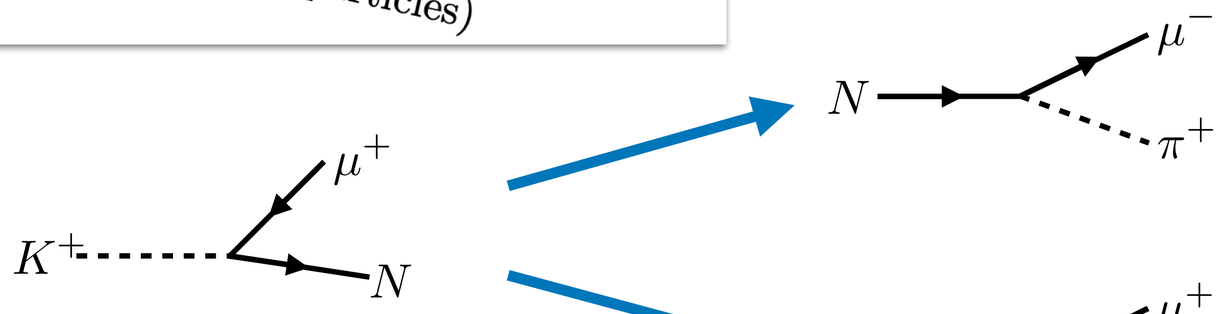

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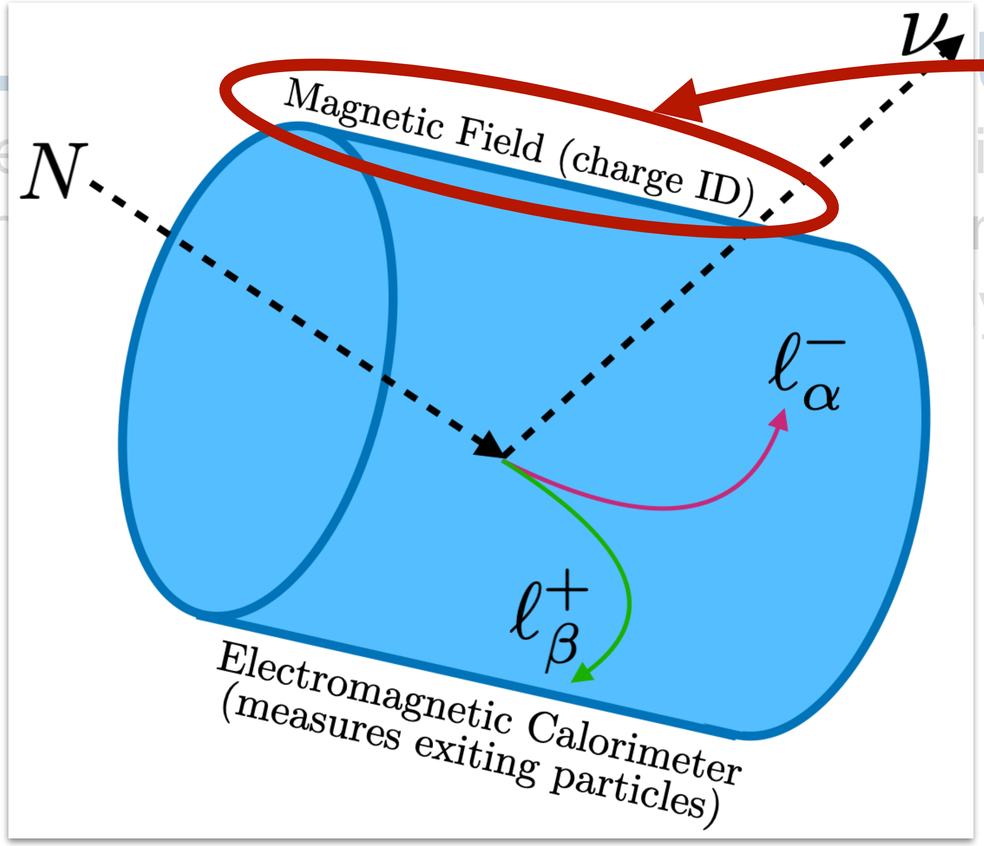
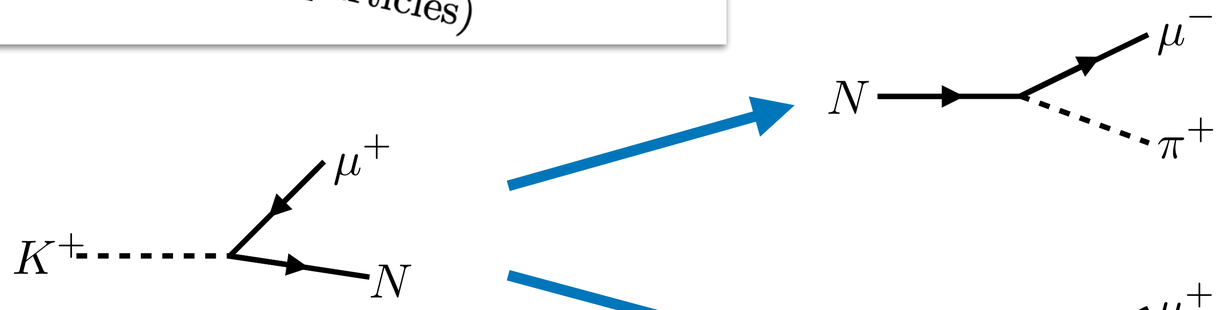


Magnetic field and particle-identification of the DUNE "more capable" Near Detector (Phase-II) *critical* for addressing this question!



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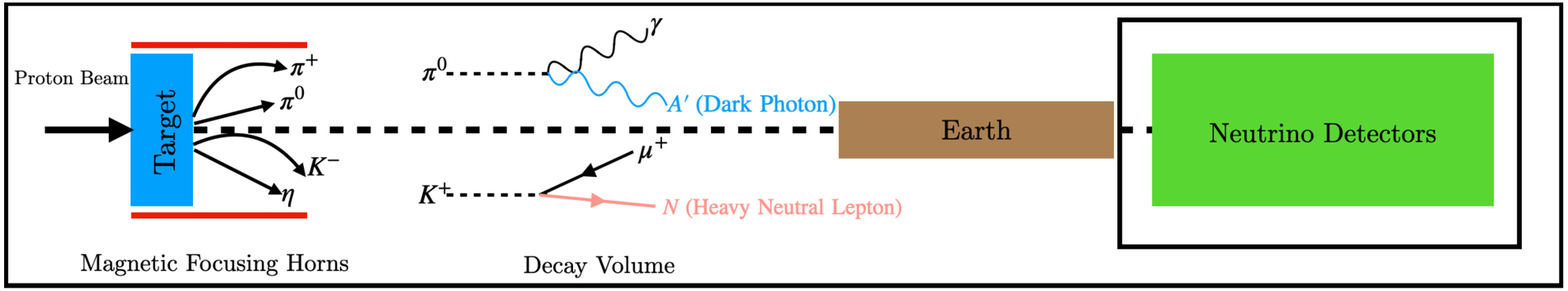
Neutrino vs. Antineutrino Mode



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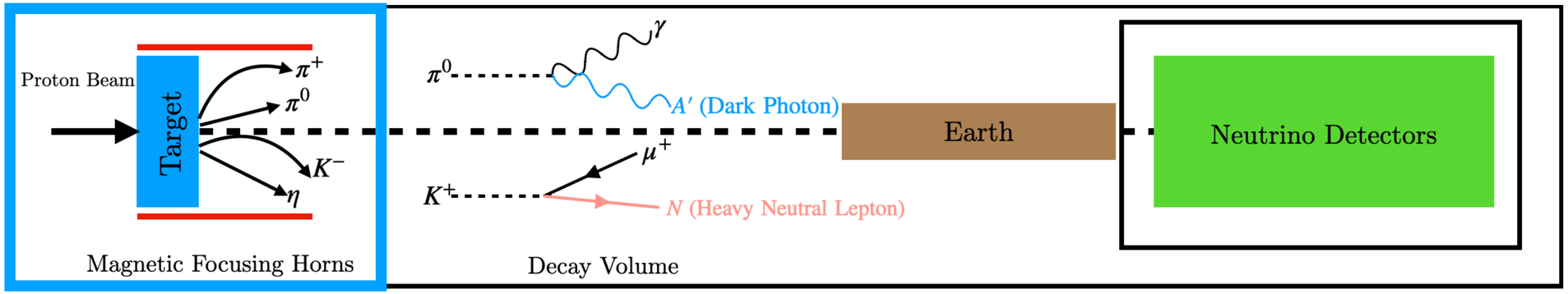

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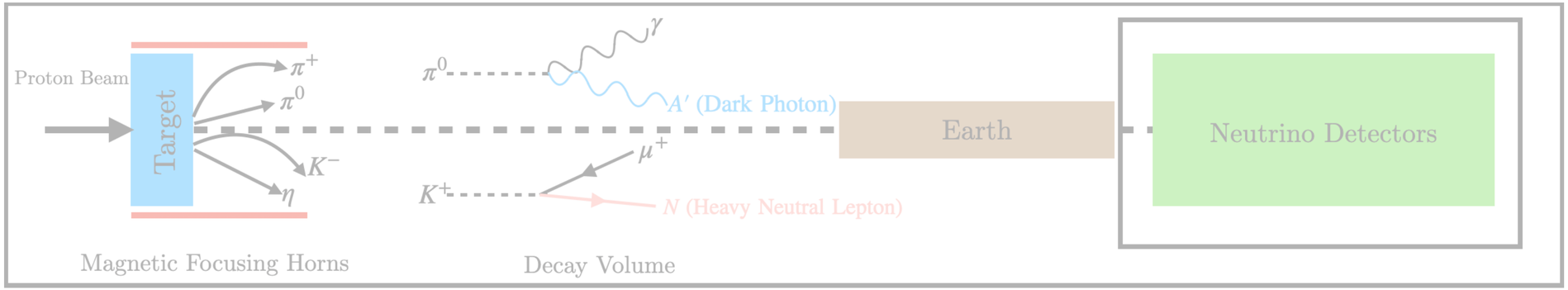

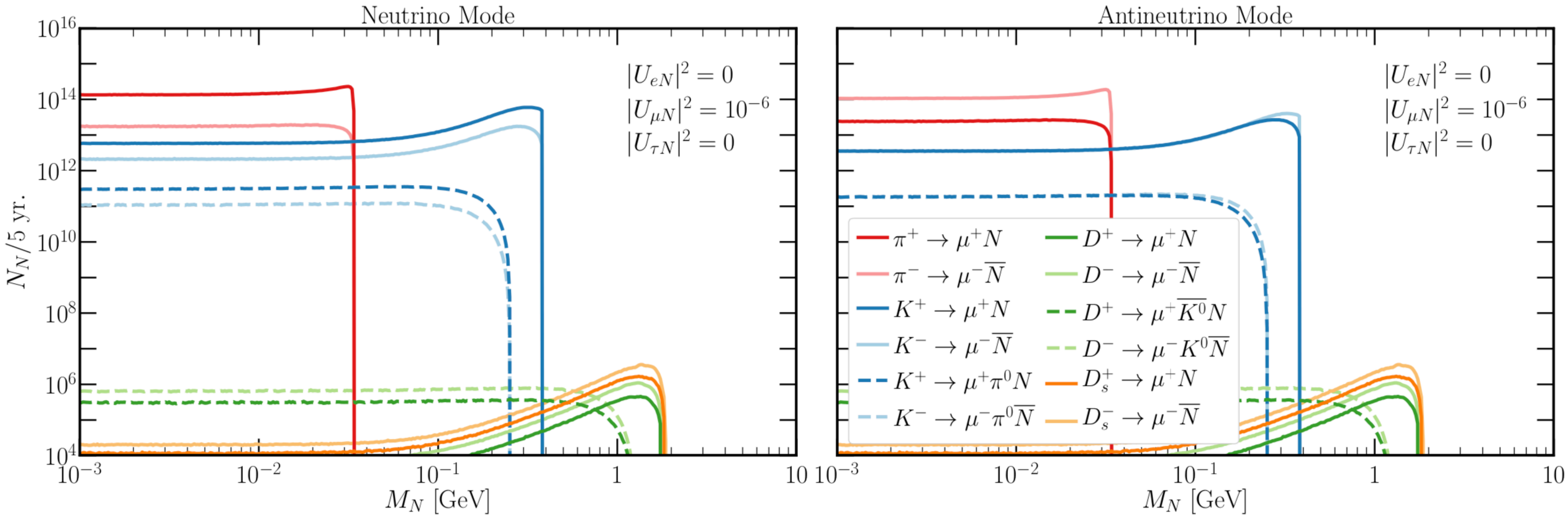

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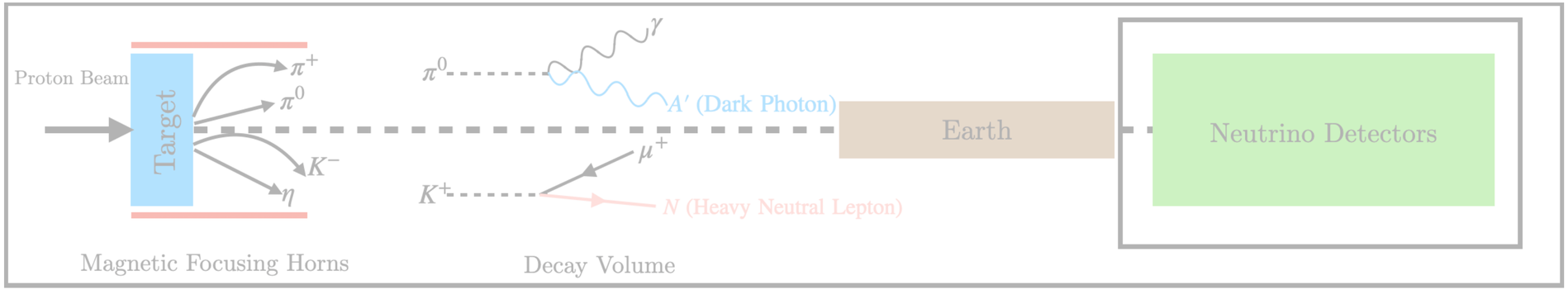

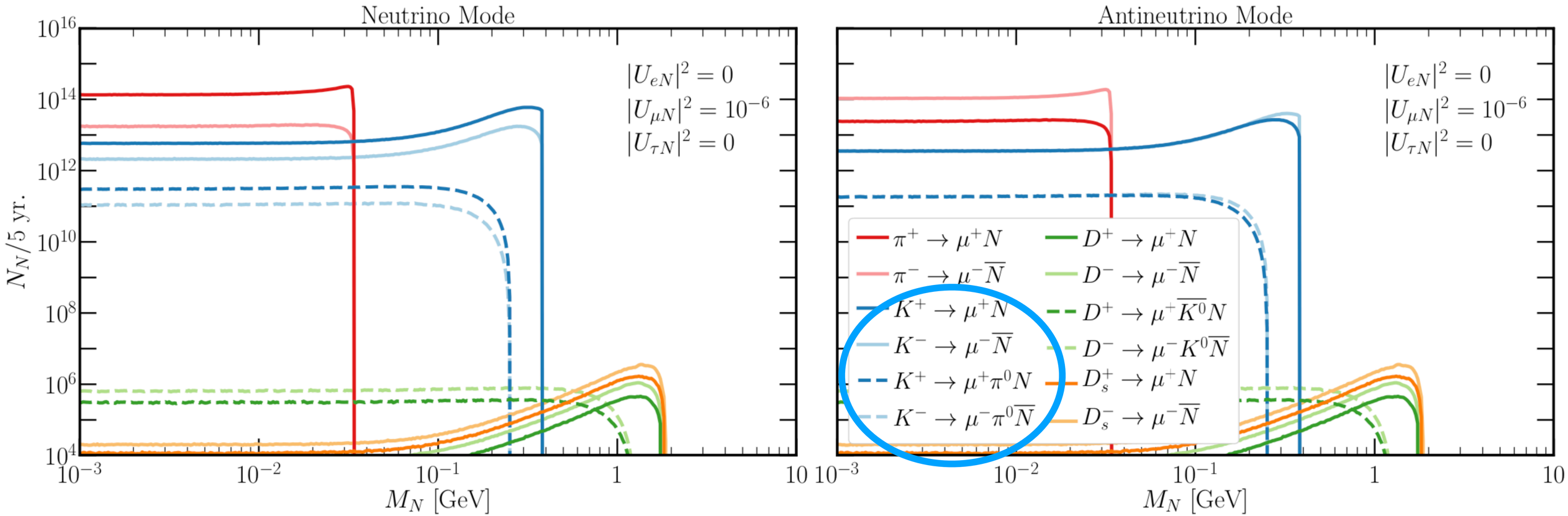

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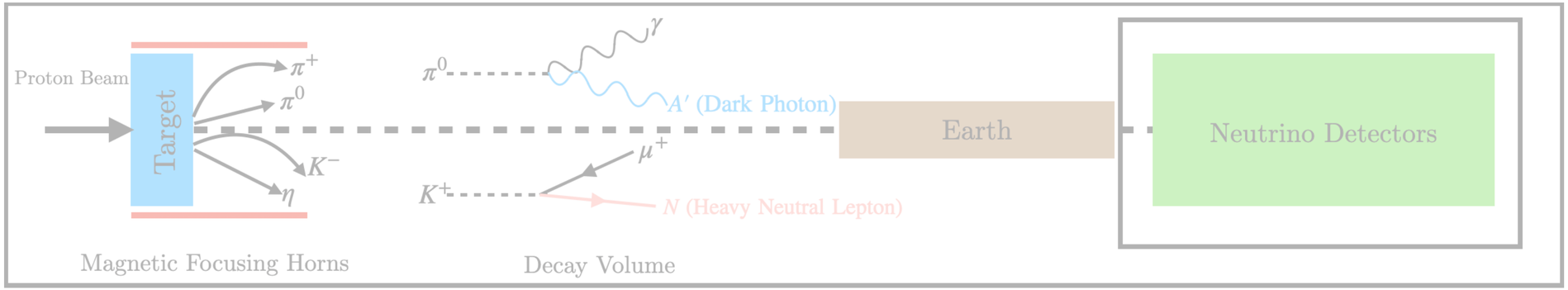

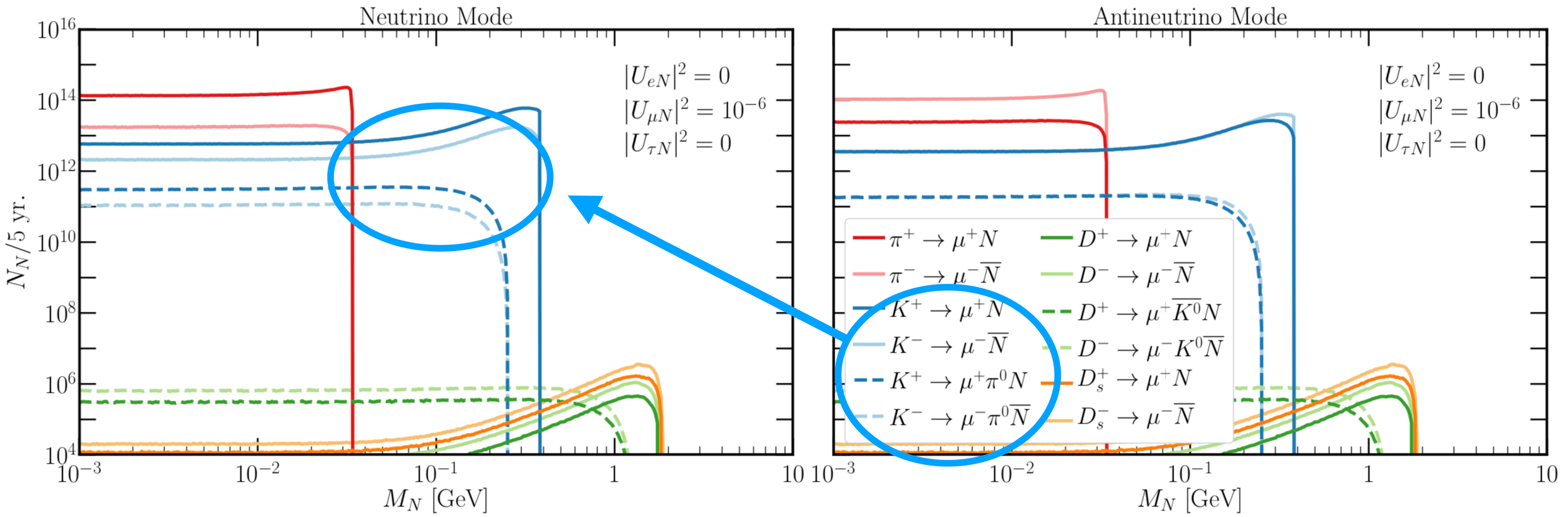

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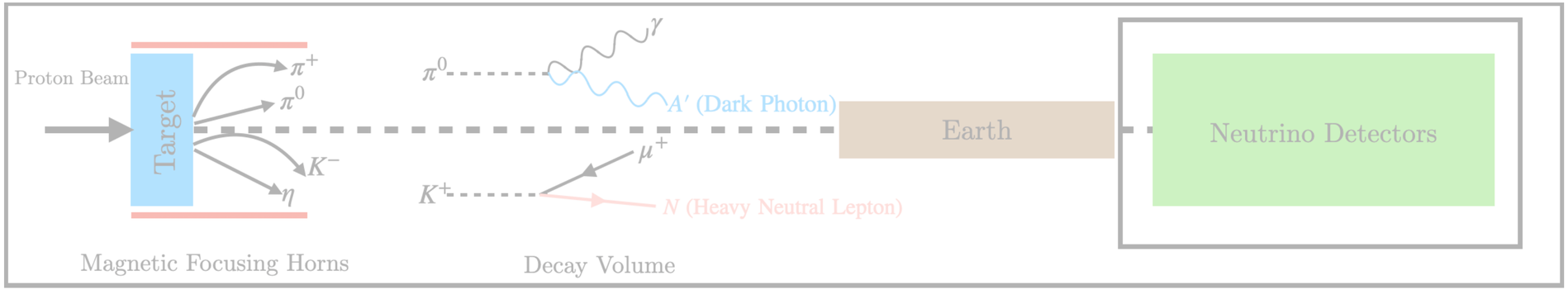
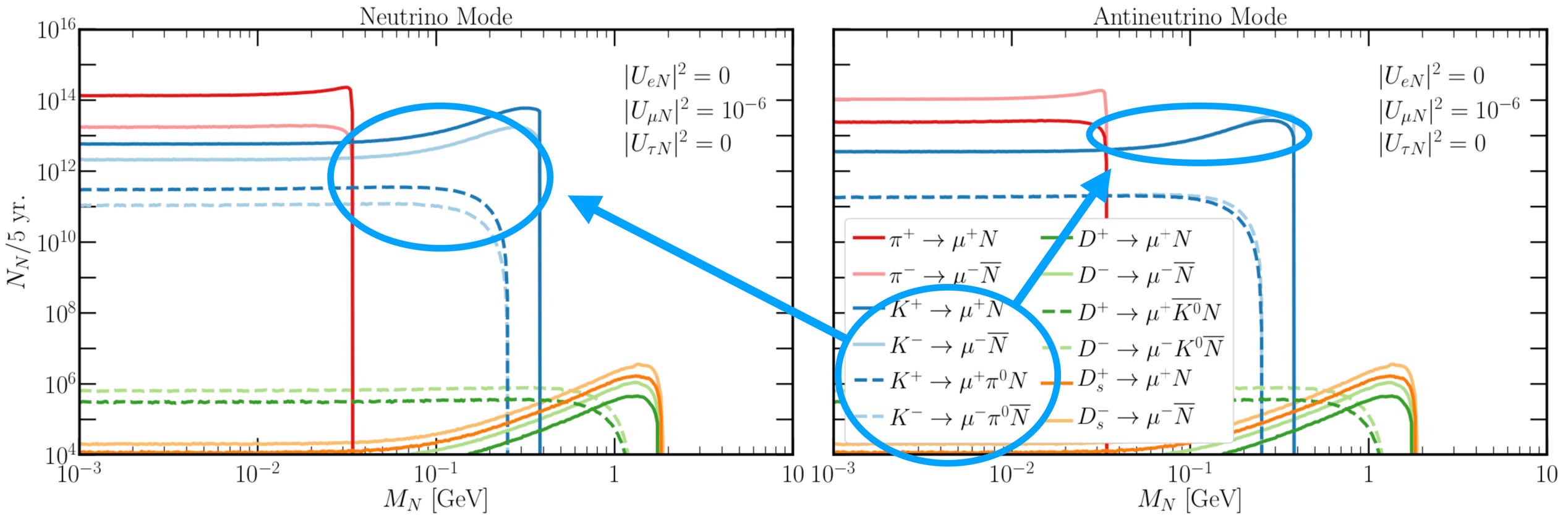
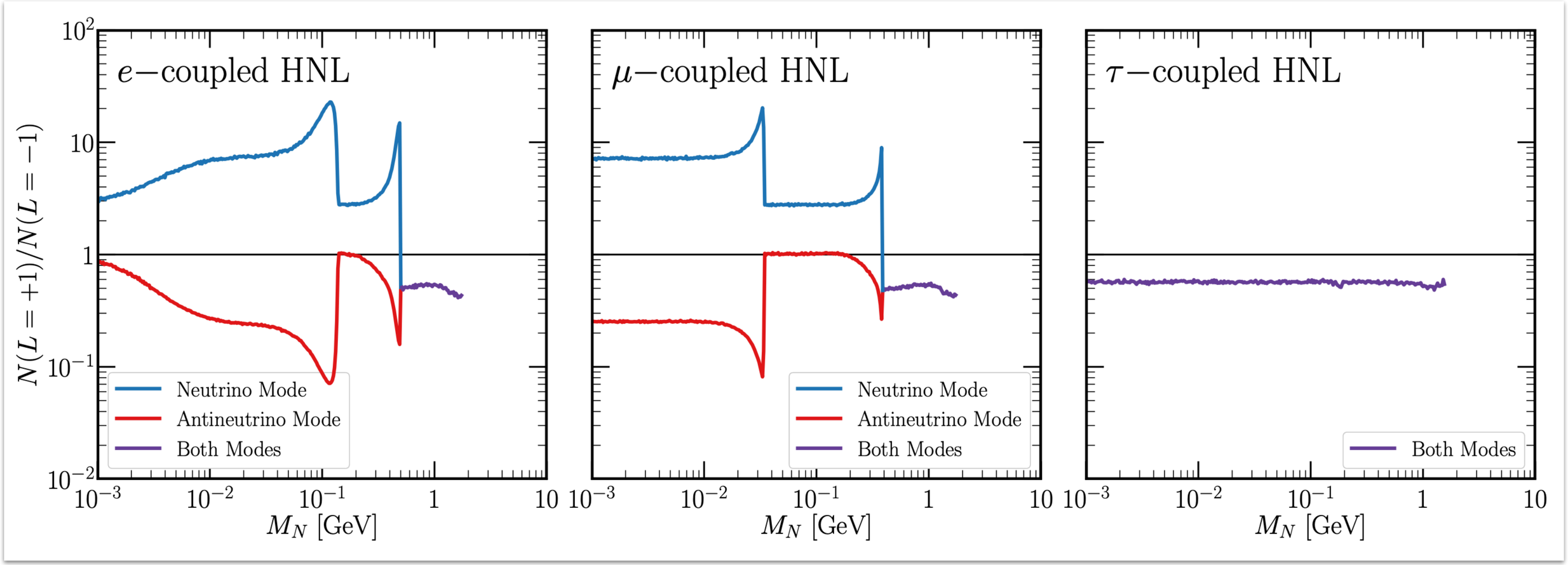


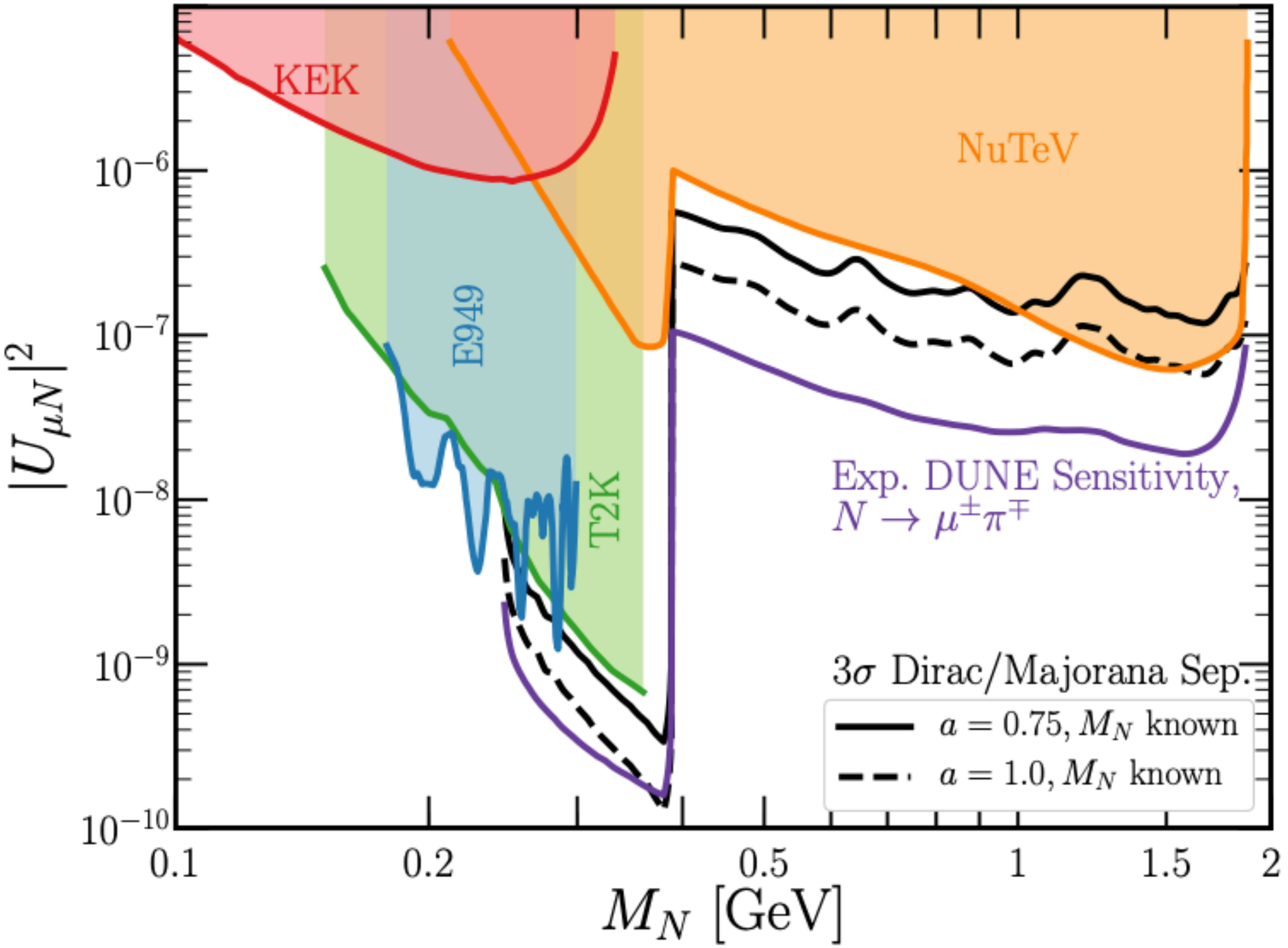


Expected Beam Purity



Next-Generation Prospects

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



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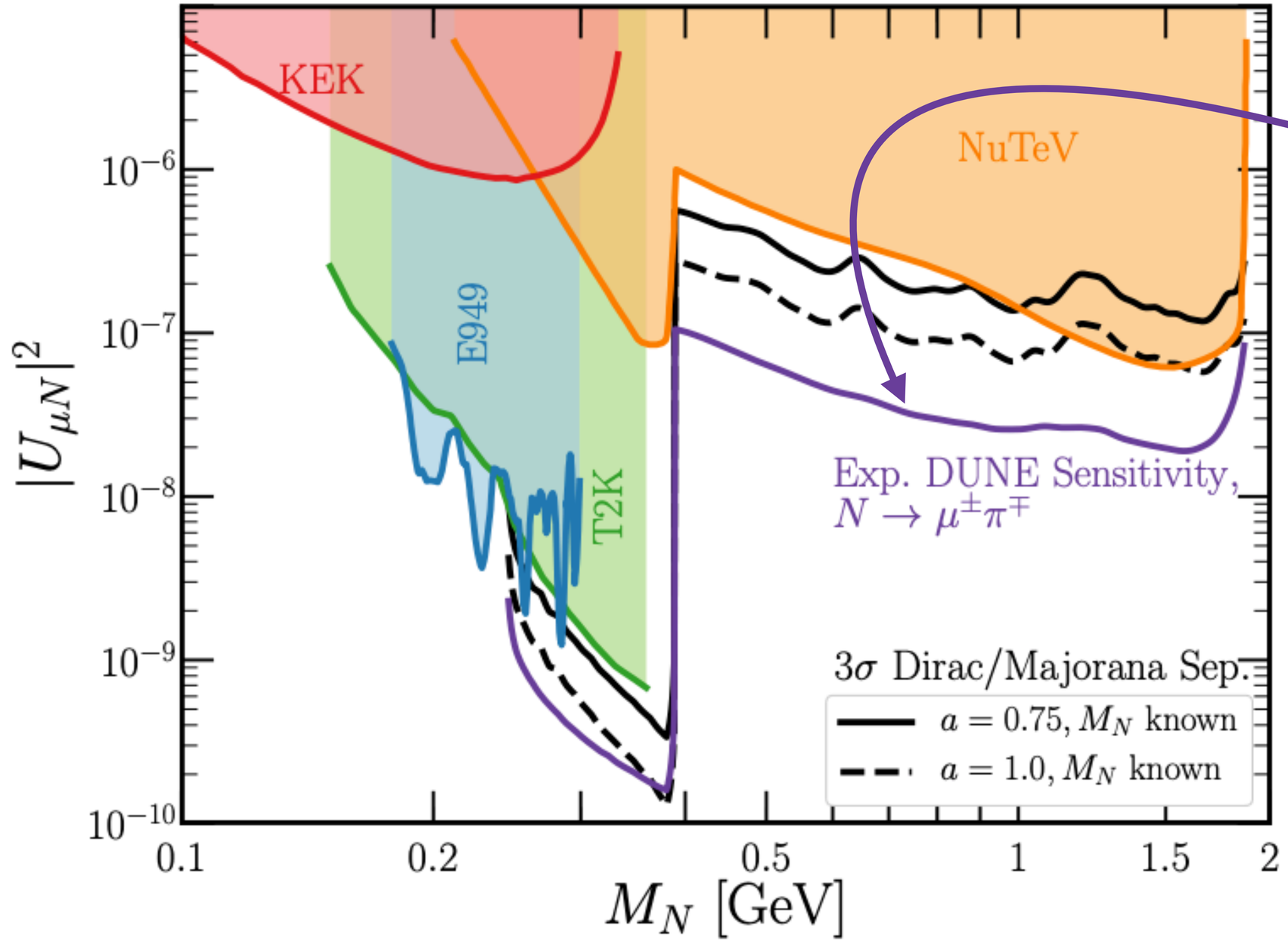

Discovery capability in DUNE-ND

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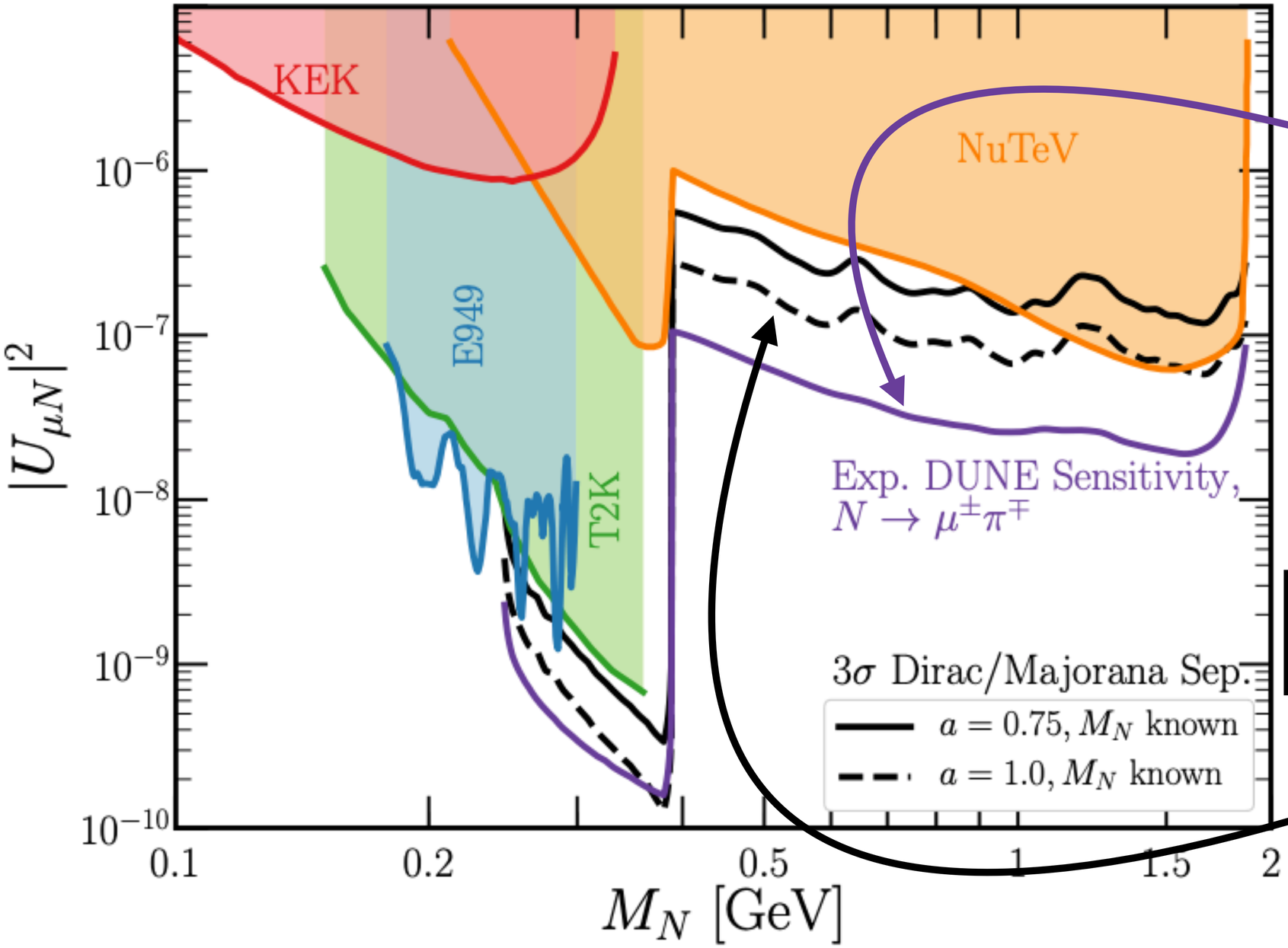

Discovery capability in DUNE-ND

Dirac vs. Majorana separation capability with DUNE MCND

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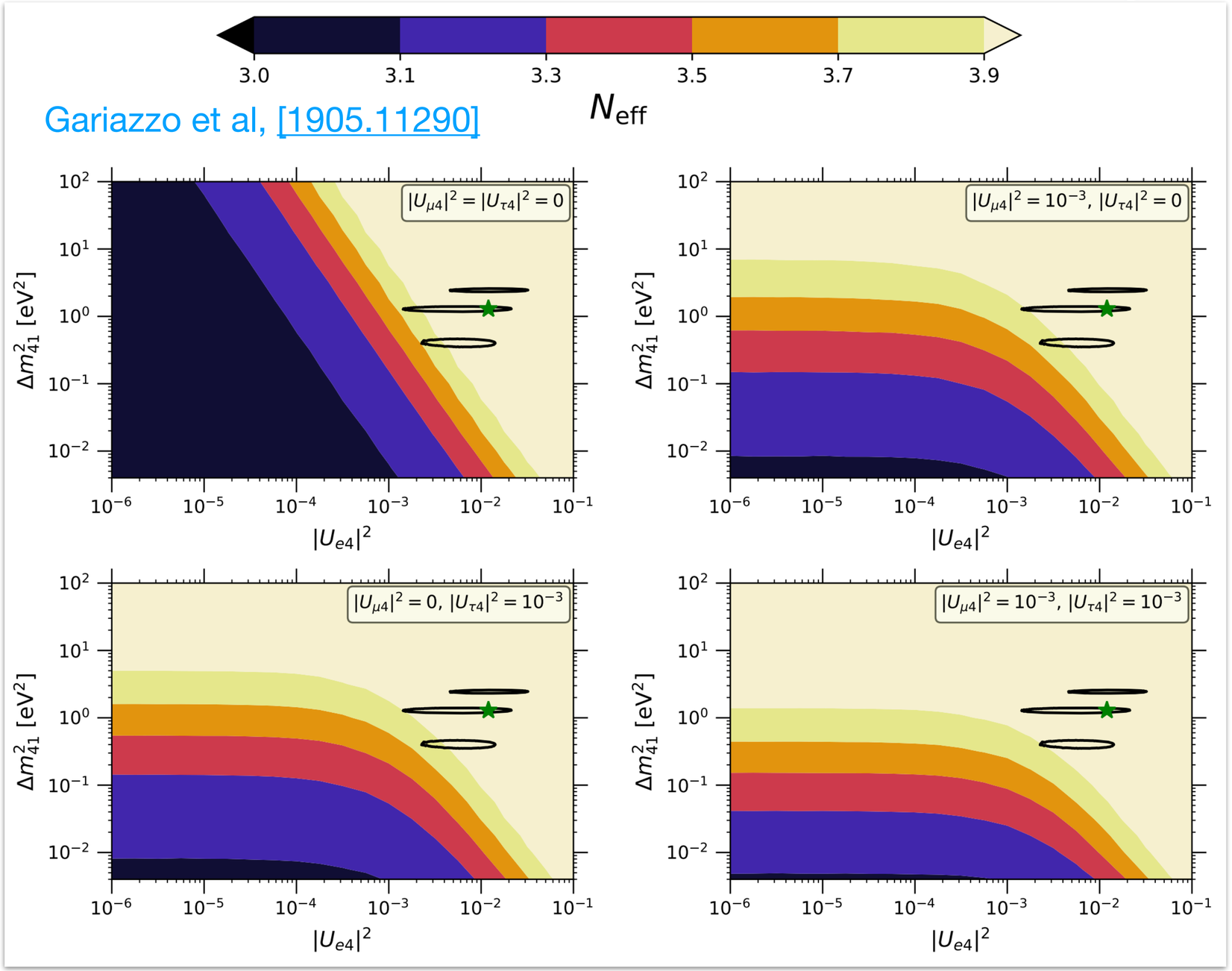
Backup

Sterile Neutrinos & Cosmology



Gariazzo et al, [1905.11290]

A new, eV-scale massive fermion that mixes (even with small mixing angles) with the SM neutrinos will be thermalized in the early universe. Cosmological probes (precision measurements of Big-Bang Nucleosynthesis and the Cosmic Microwave Background) are highly sensitive to the number of relativistic species.

Consequences of Invoking a light (sterile) Neutrino

$$P\left(\nu_\mu \to \nu_e\right) = \sin^2\left(2\theta_{\mu e}\right)\sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

- Add in a new (fourth) neutrino mass eigenstate with a significantly larger mass than the three “light” ones. This extends the Leptonic mixing matrix to 4x4 instead of 3x3.

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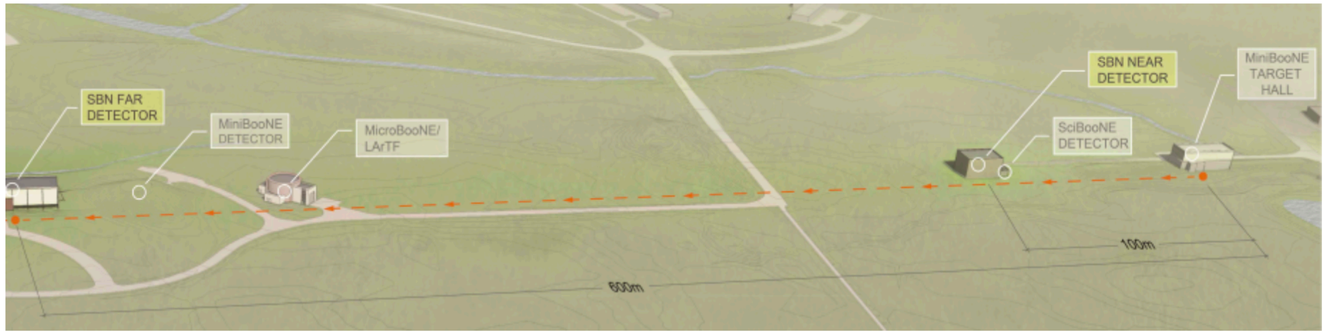
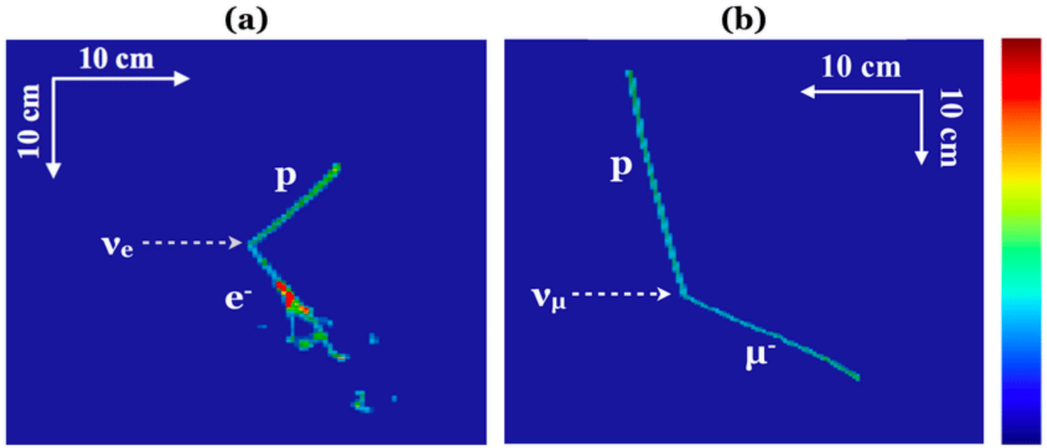
$$\sin^2\left(2\theta_{\mu e}\right) \equiv 4\left|U_{e4}\right|^2\left|U_{\mu 4}\right|^2$$

- Electron-neutrino appearance is driven by a product of the new matrix elements. Each of these being non-zero predicts electron-neutrino **and** muon-neutrino disappearance at the same neutrino energy/distance.

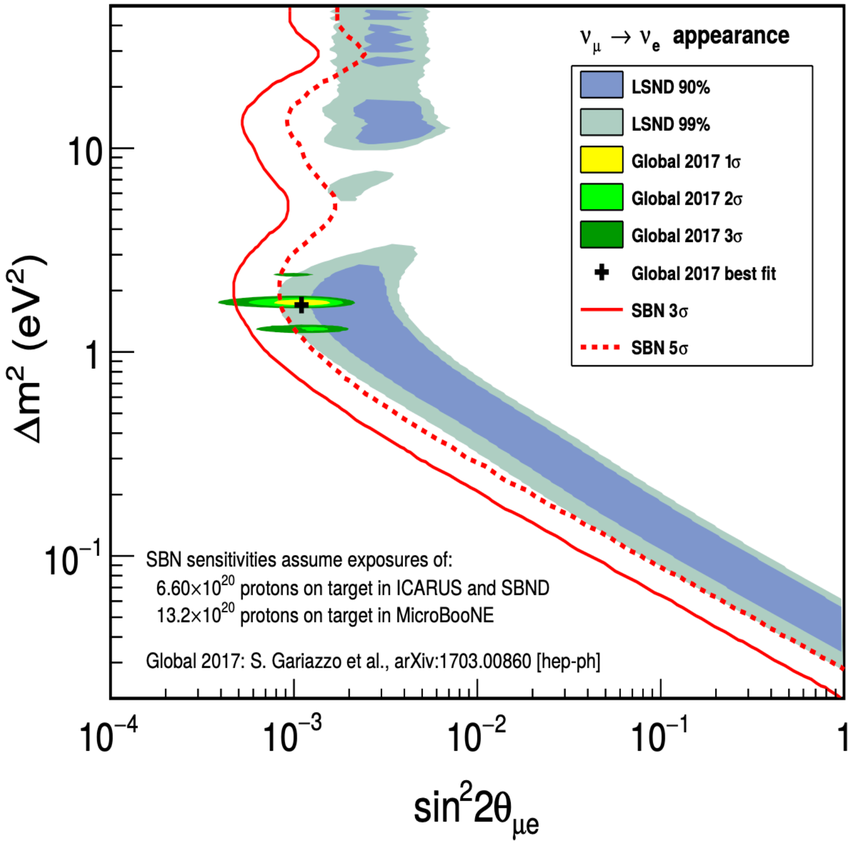
The SBN Programme

Let's solve this **once and for all**!



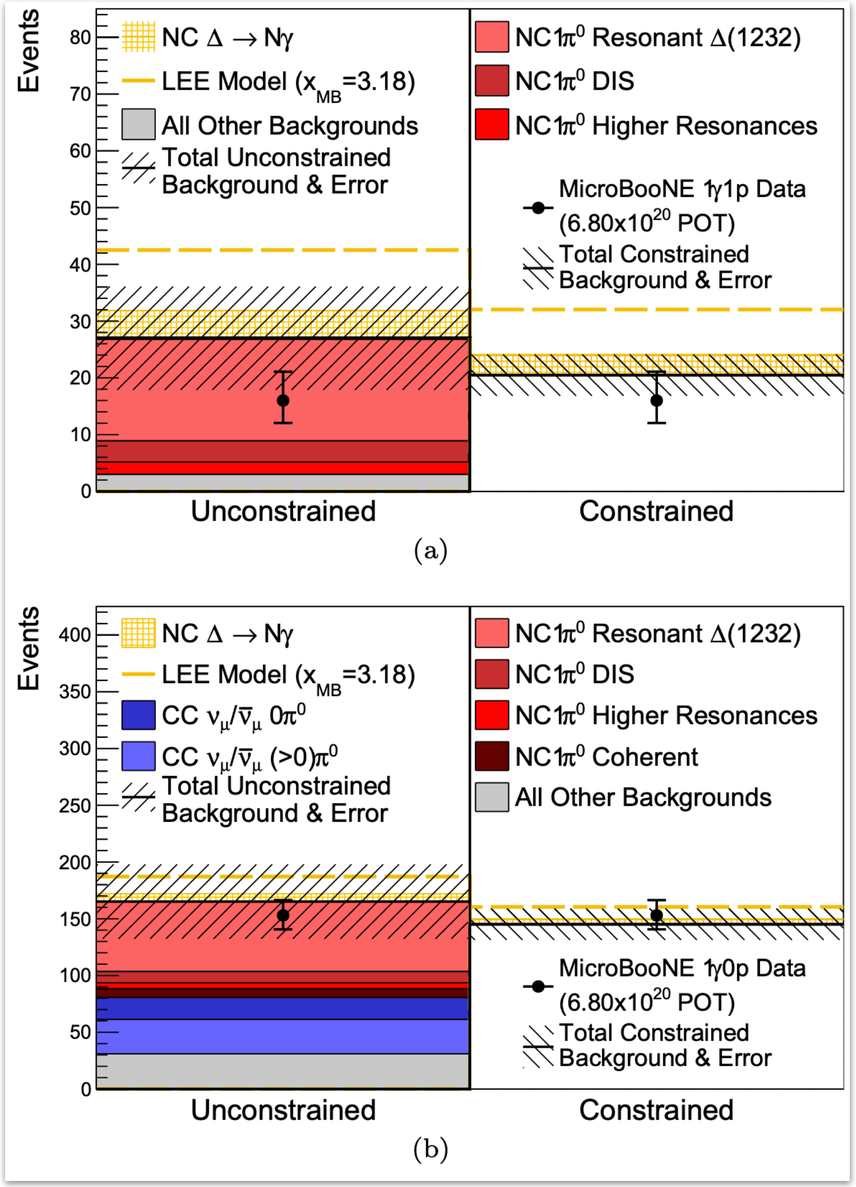


(Courtesy of Ivan Esteban)



Liquid Argon Time Projection Chambers — "Colored Bubble Chambers"

MicroBooNE Photon Analysis



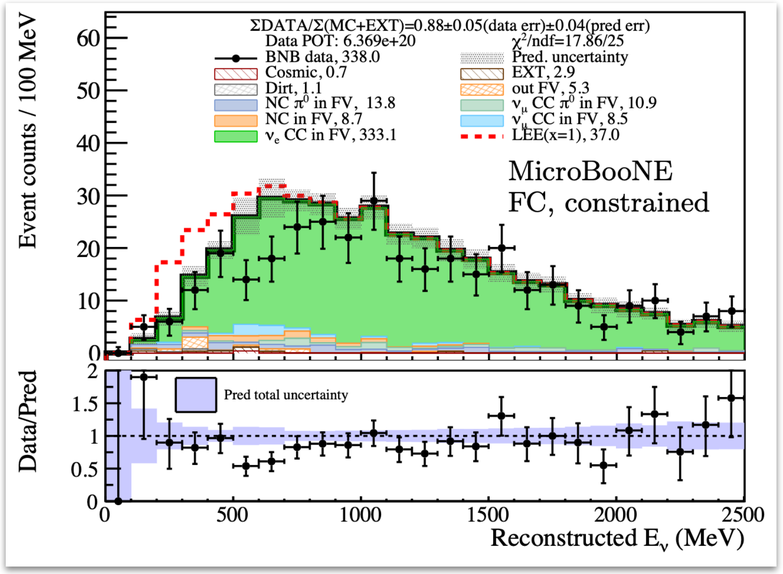
MicroBooNE Collaboration, [2110.00409]

MicroBooNE disfavors the $\Delta \to N\gamma$ explanation of the MiniBooNE anomaly at 94.8% CL.

MicroBooNE Electron Analyses

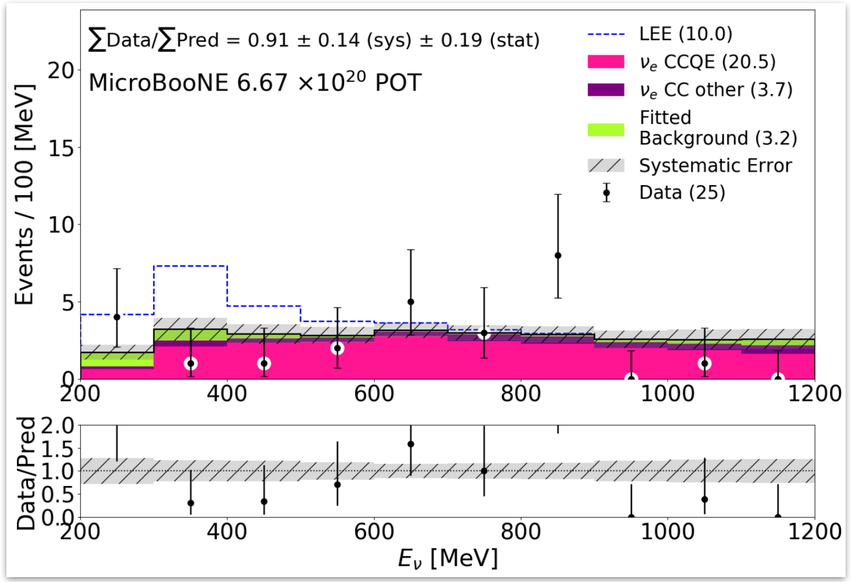
“Inclusive”

[2110.13978]

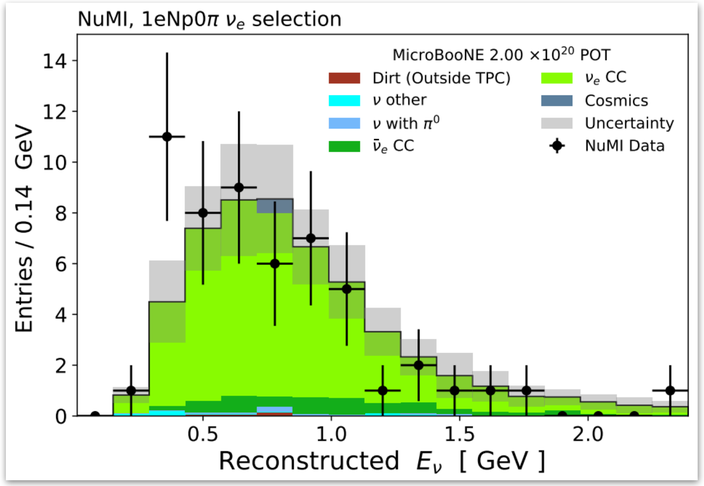


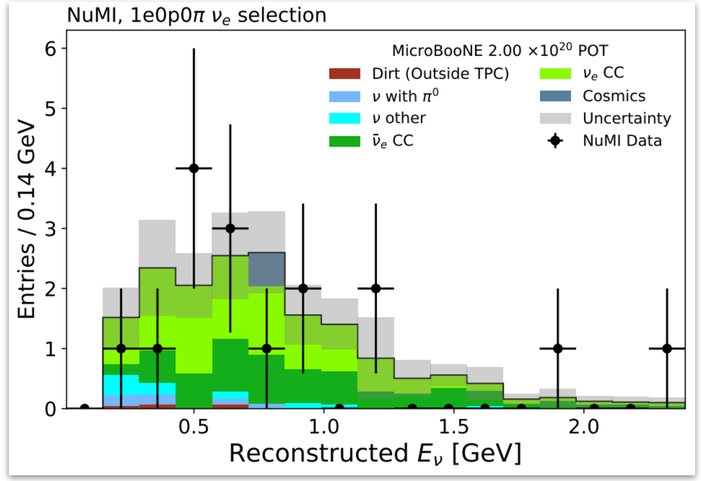
“CCQE”

[2110.14080]



“Pionless”





MicroBooNE Electron Analyses

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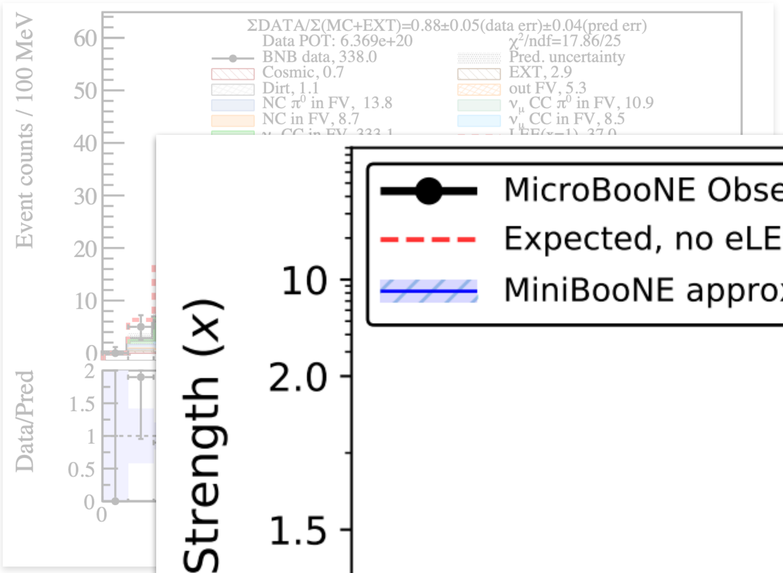

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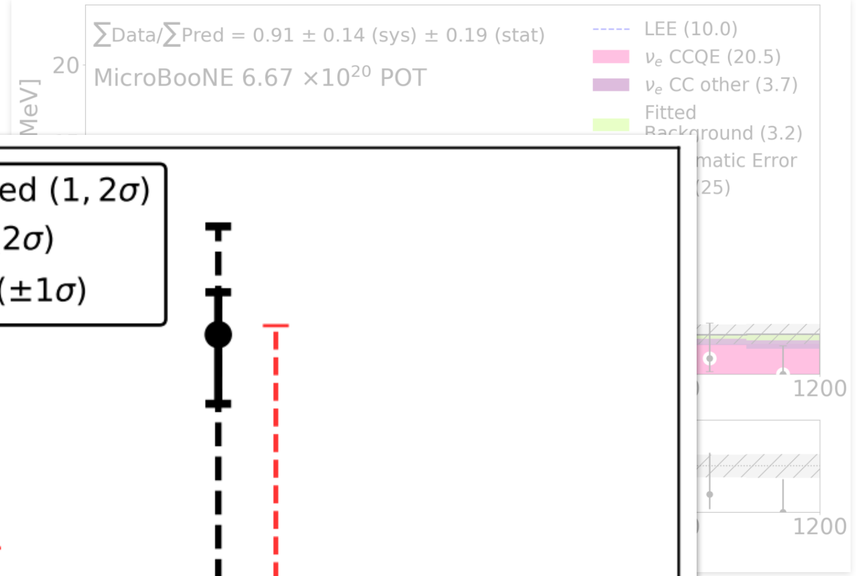
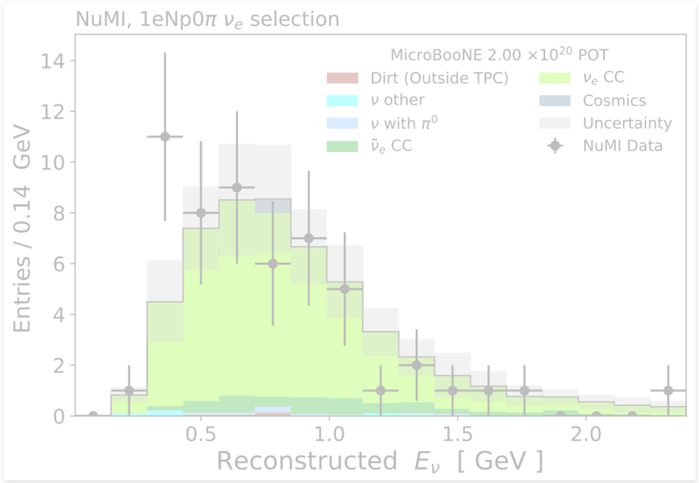
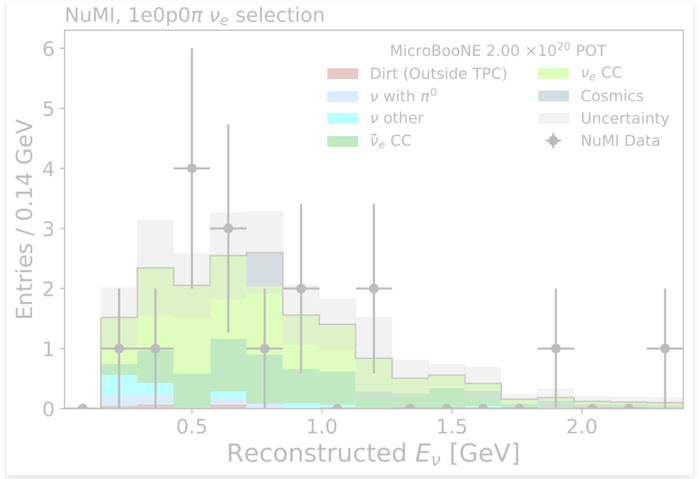


Discussion of all Results [2110.14054]

"Pionless"

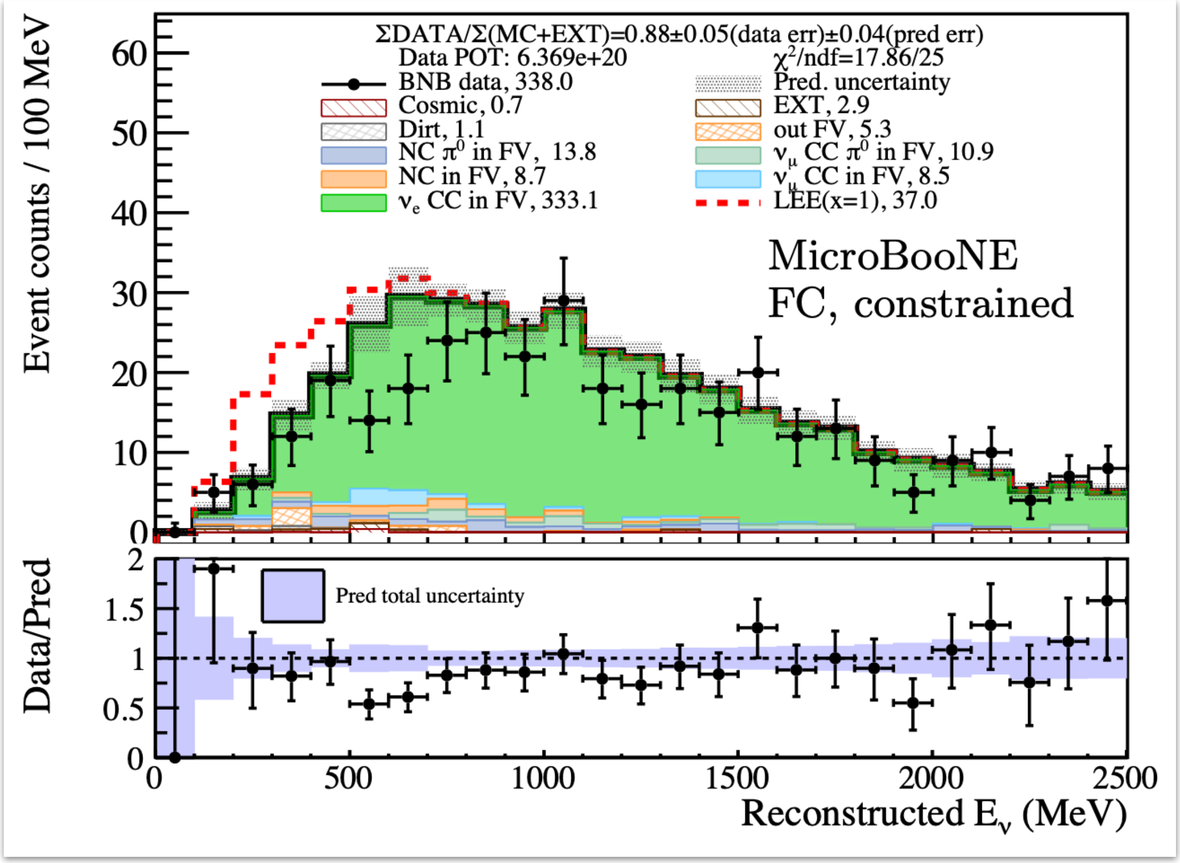




Complementarity of Inclusive/CCQE

"Inclusive"

[2110.13978]



- Large electron-neutrino and muon-neutrino (not shown) samples.
- Large (expected) excess from muon-neutrino to electron-neutrino oscillation

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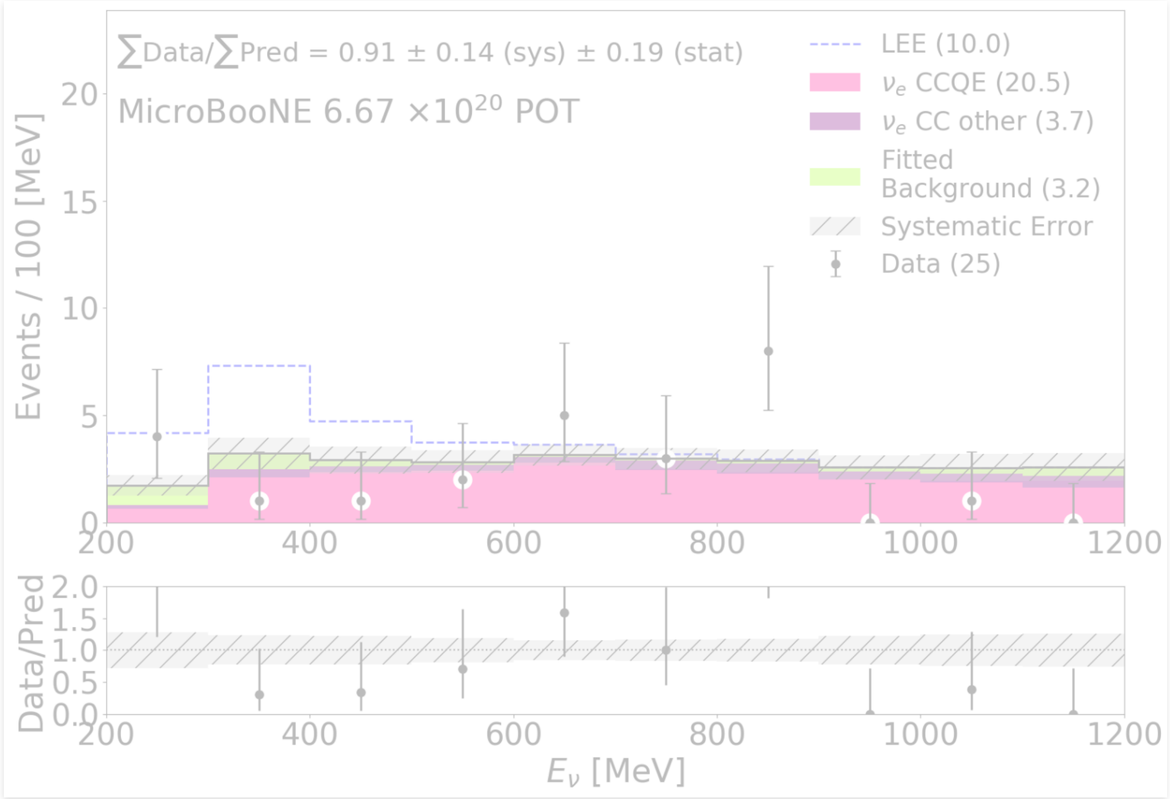

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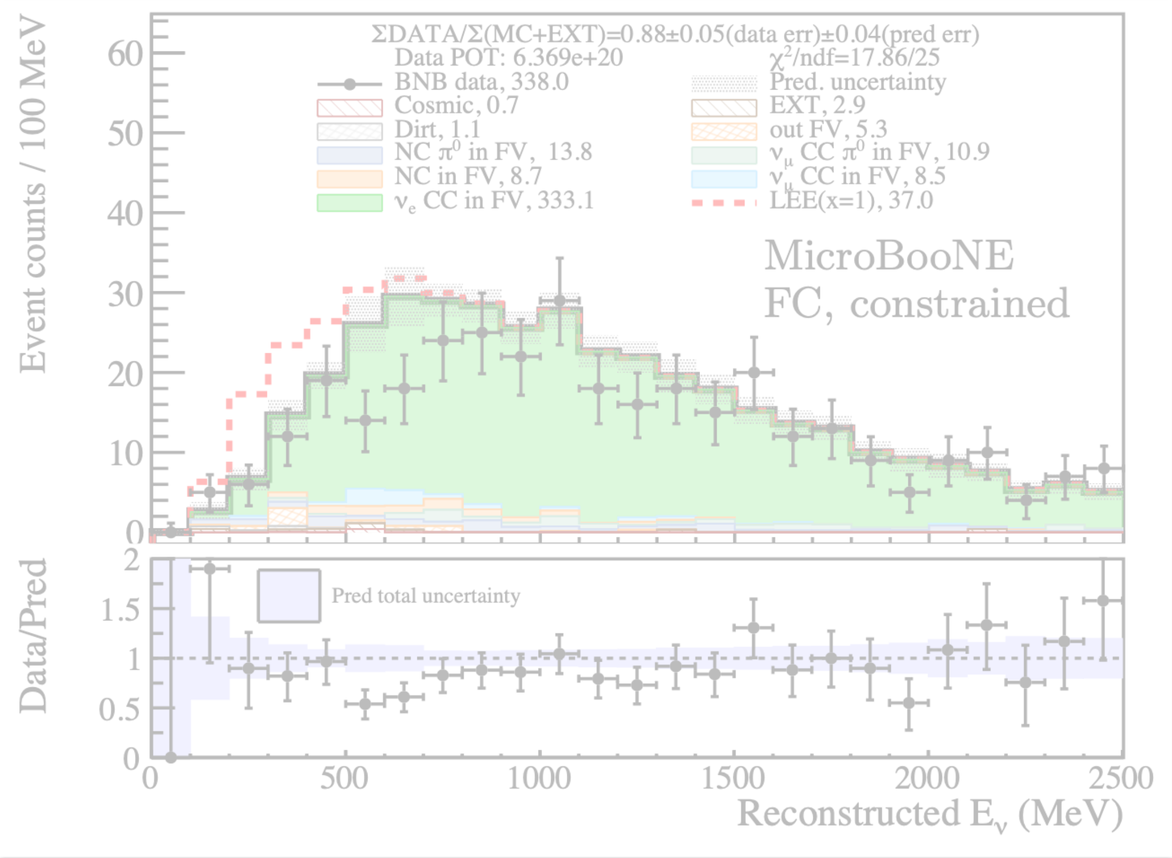

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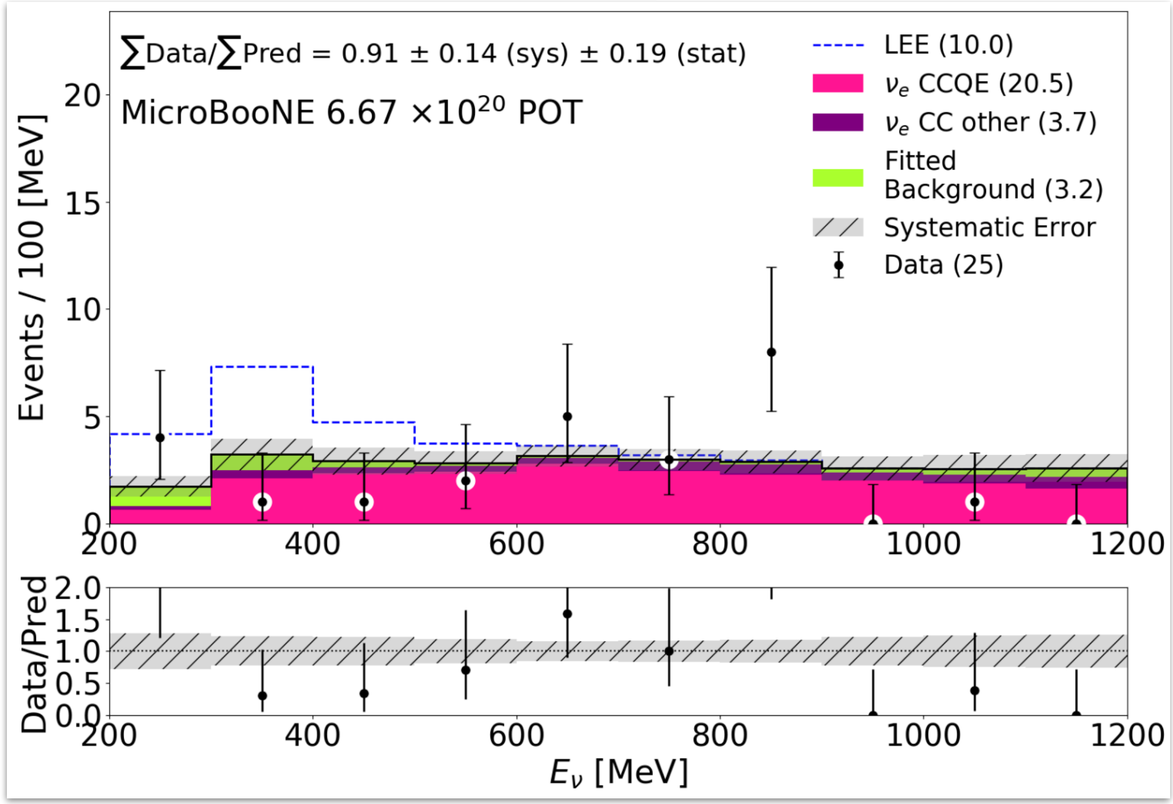

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MicroBooNE and Sterile Neutrinos

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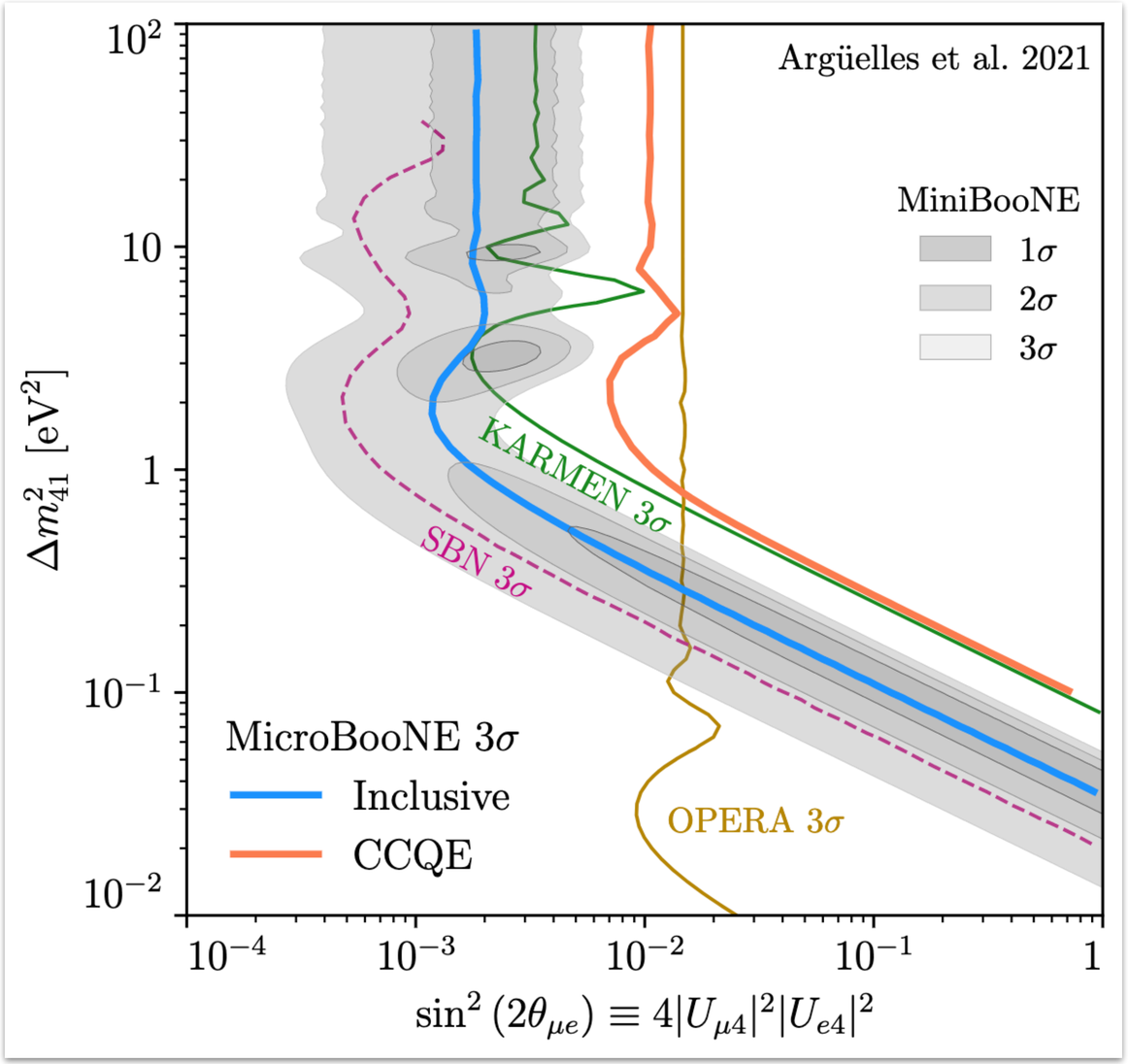
Argüelles, KJK, et al, [2111.10359]



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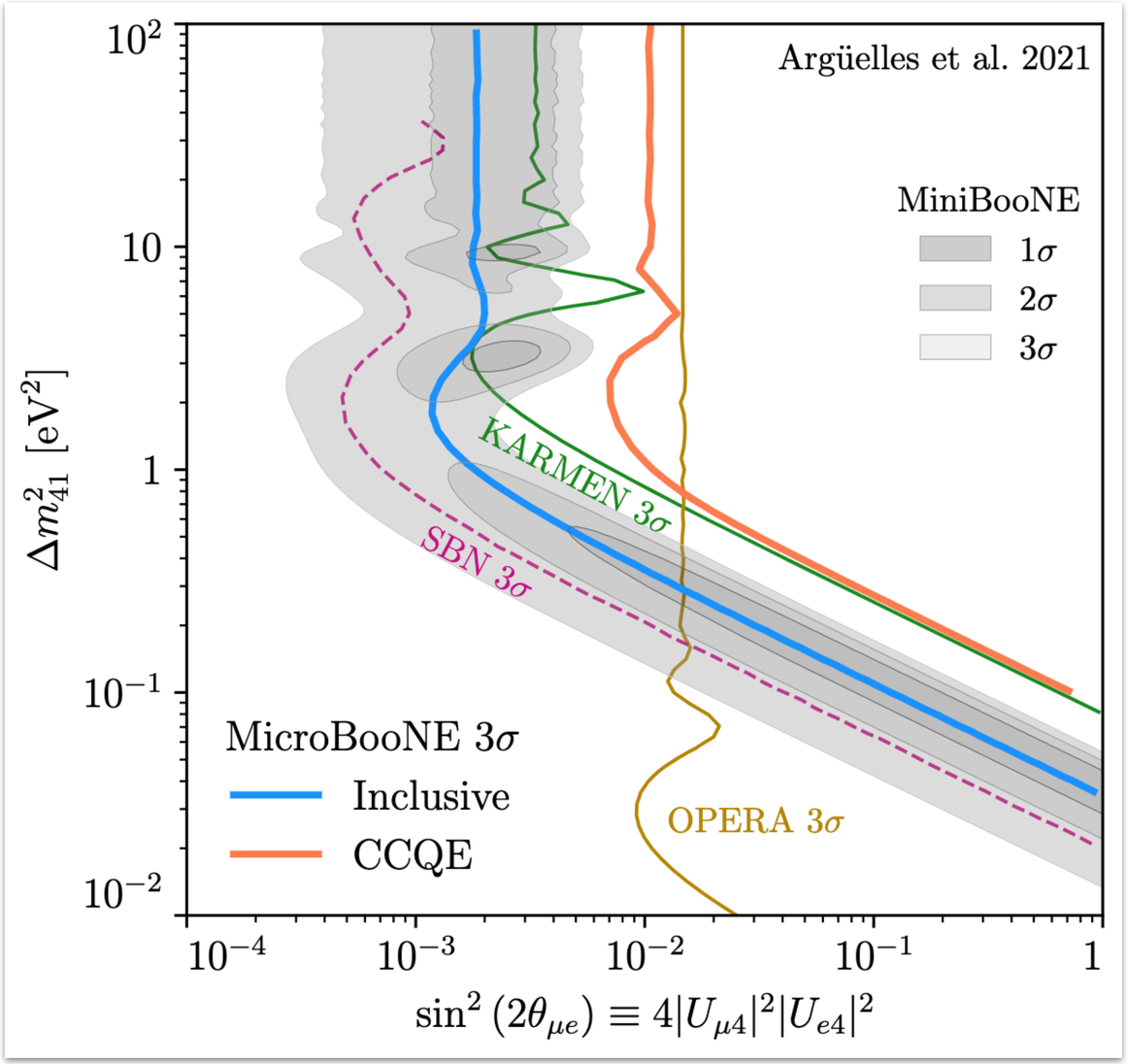

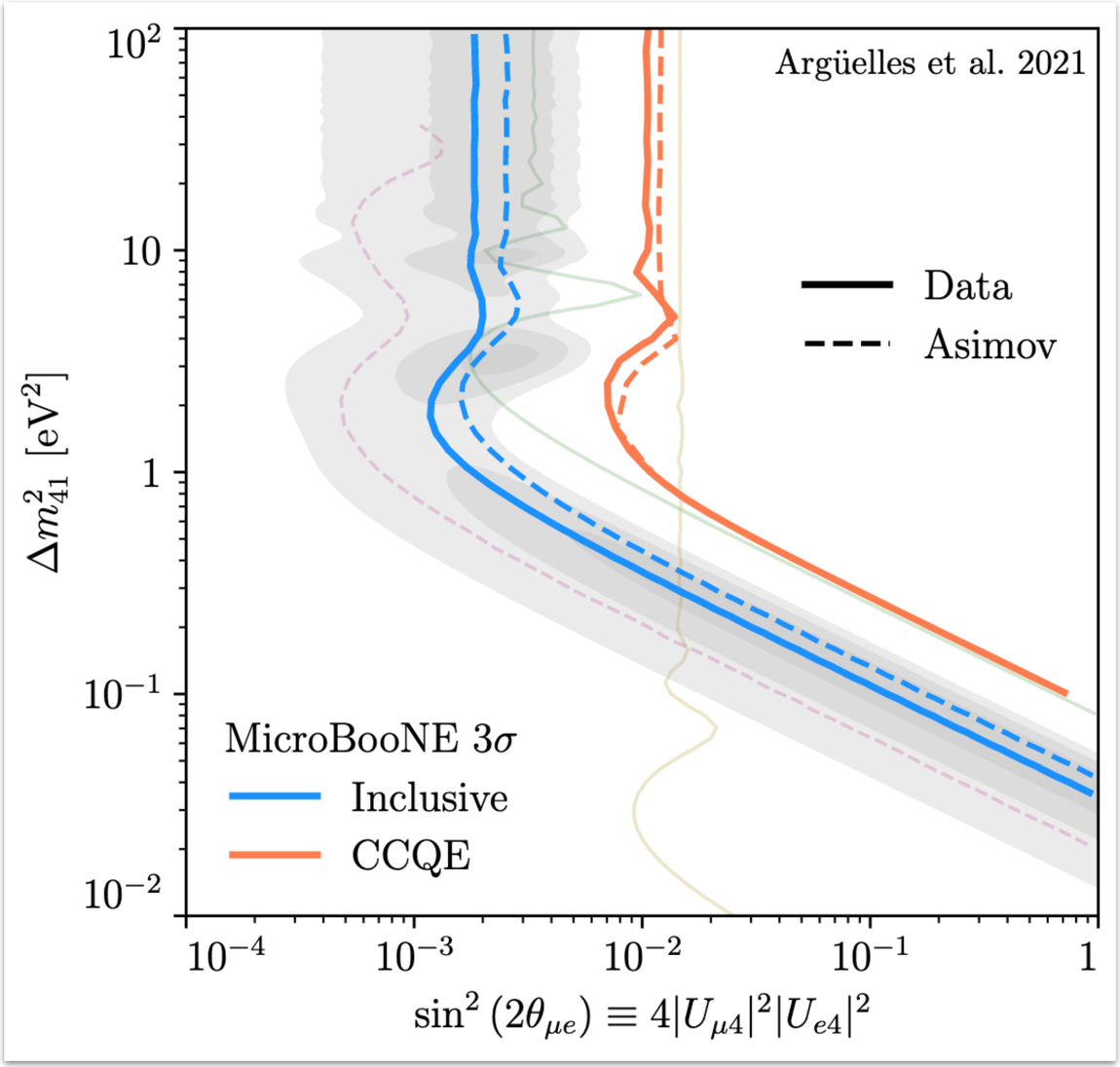

Complete 3+1 Neutrino Framework

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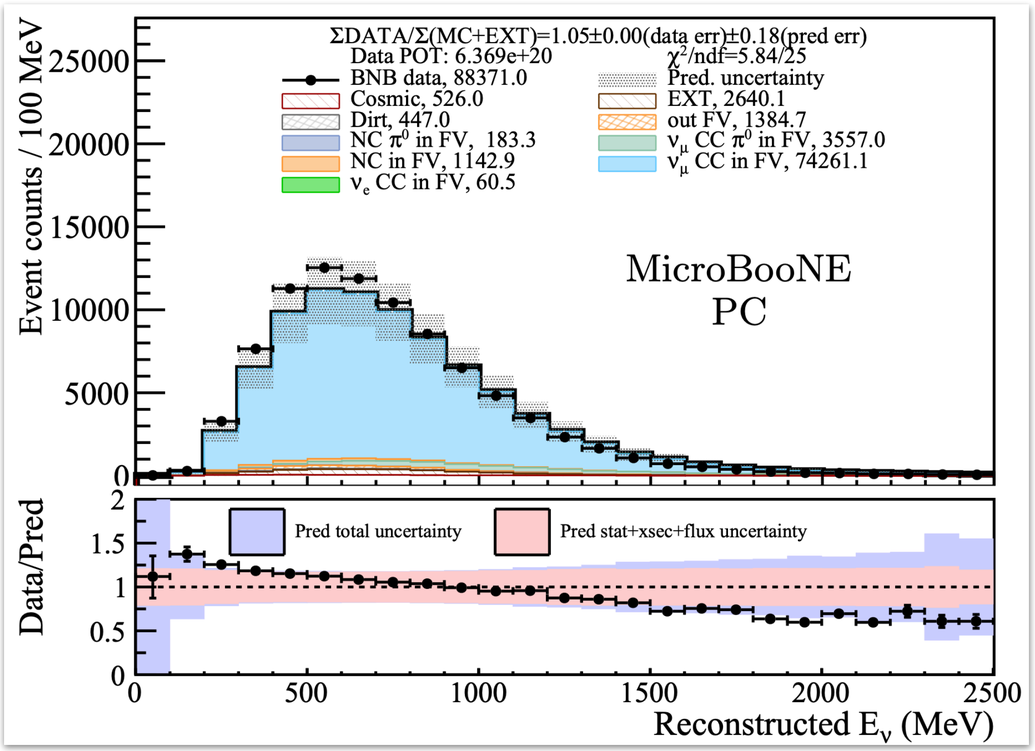

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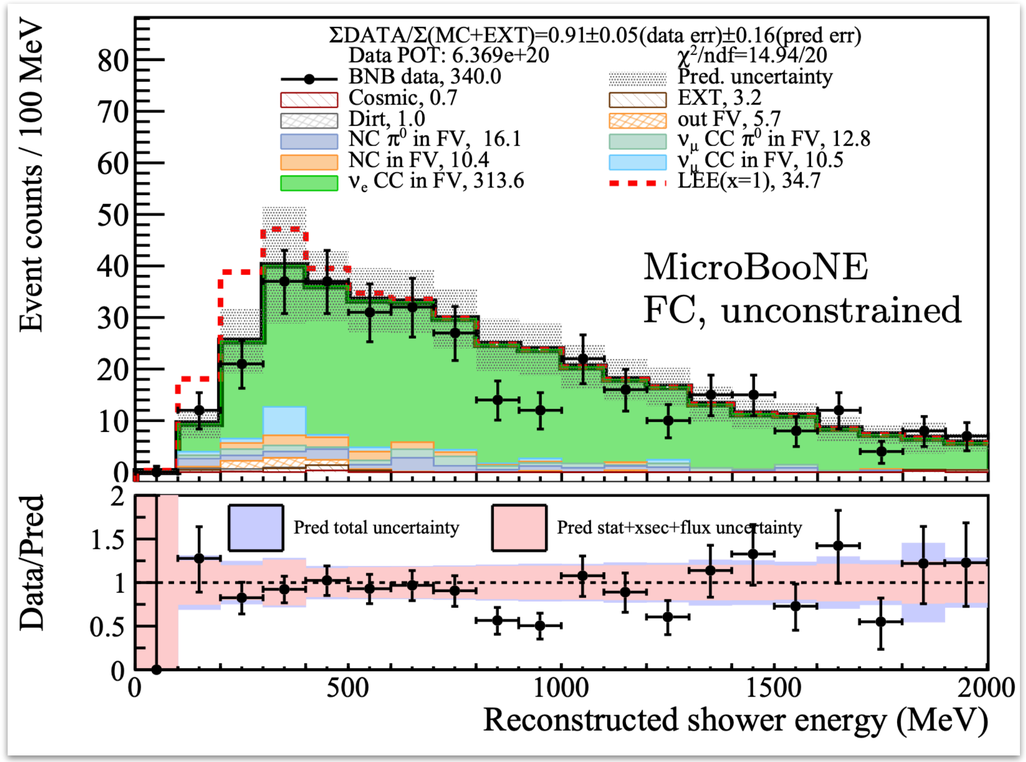
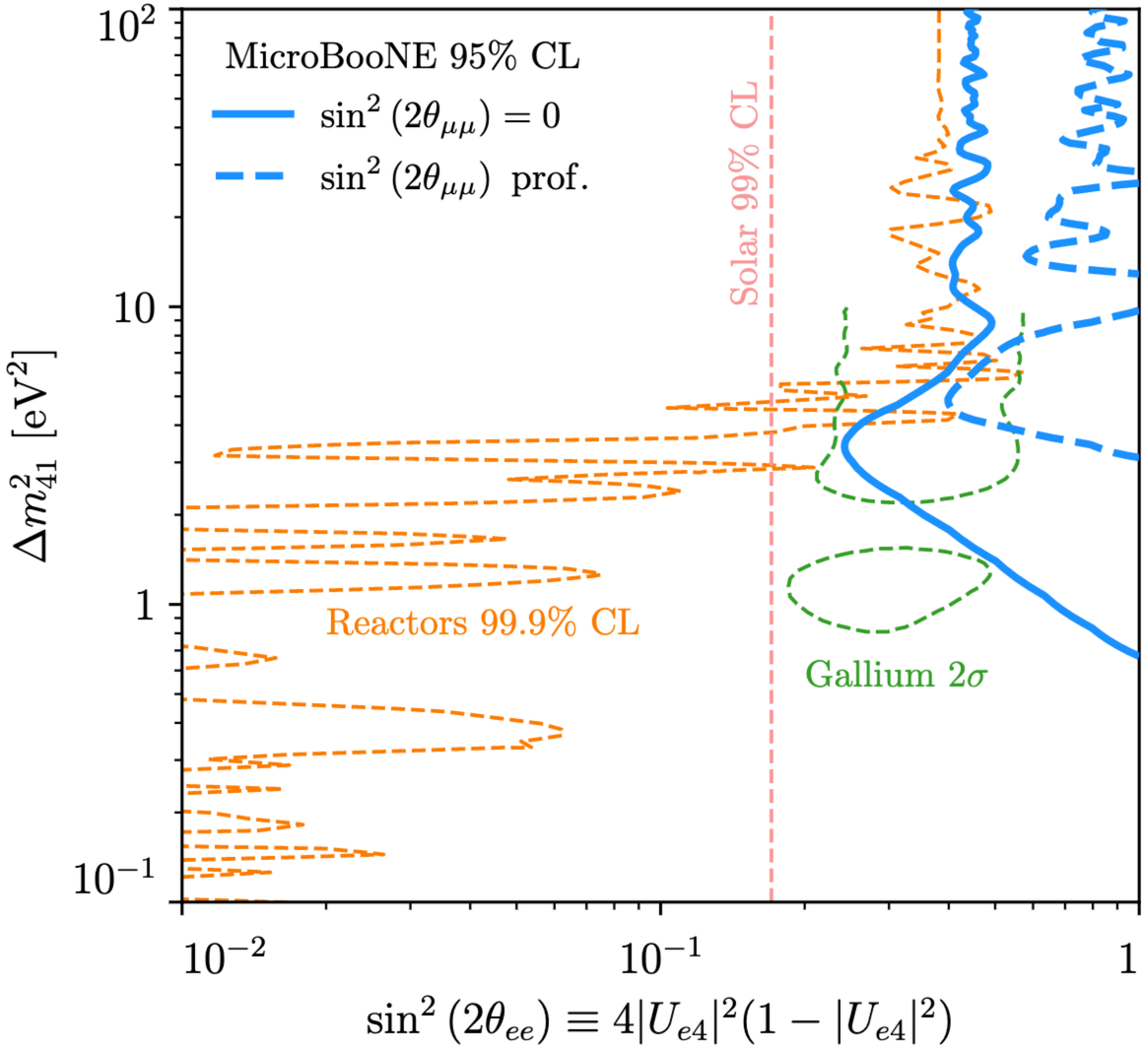
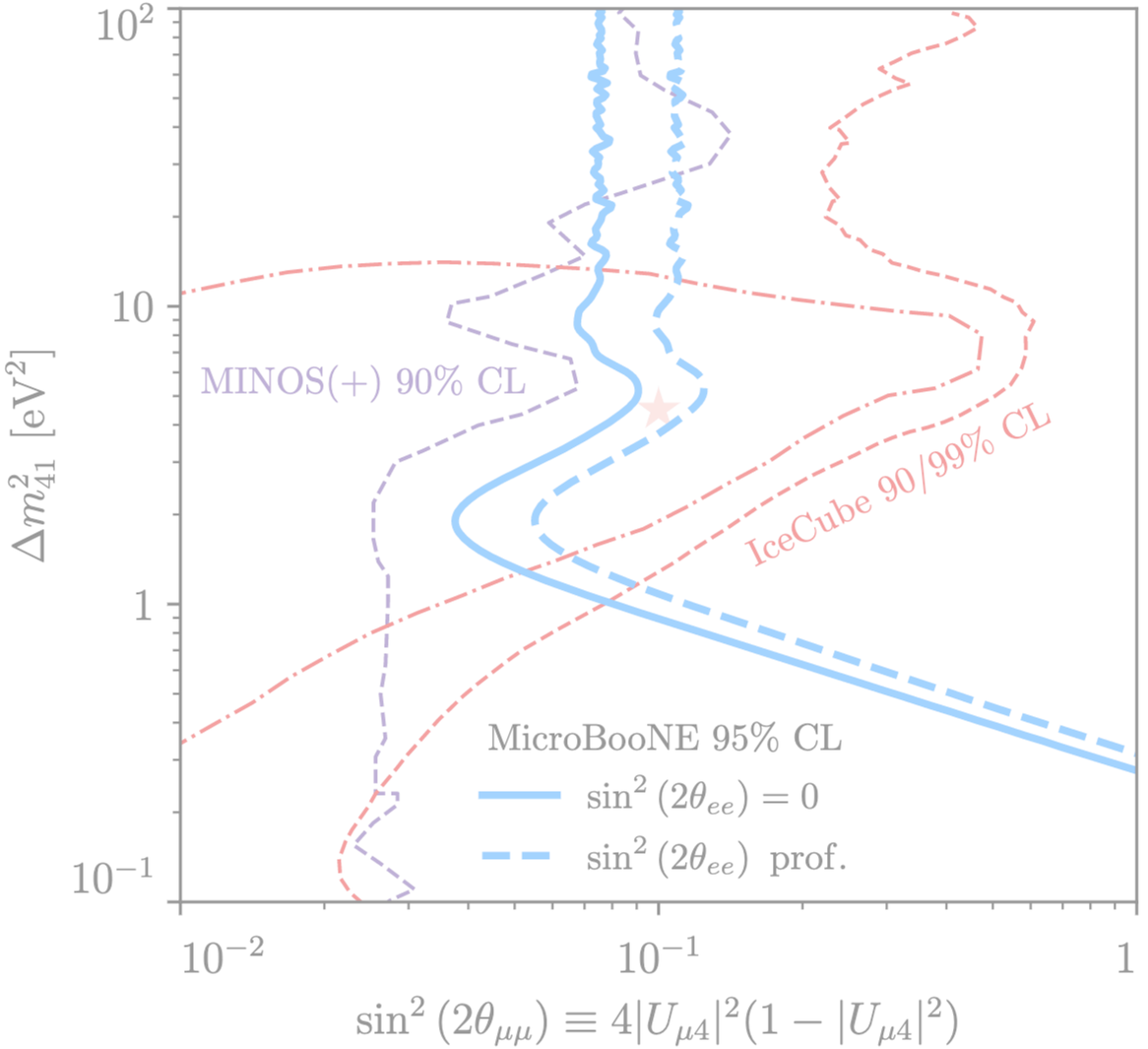


MicroBooNE, [2110.13978]

Four-Flavor Results

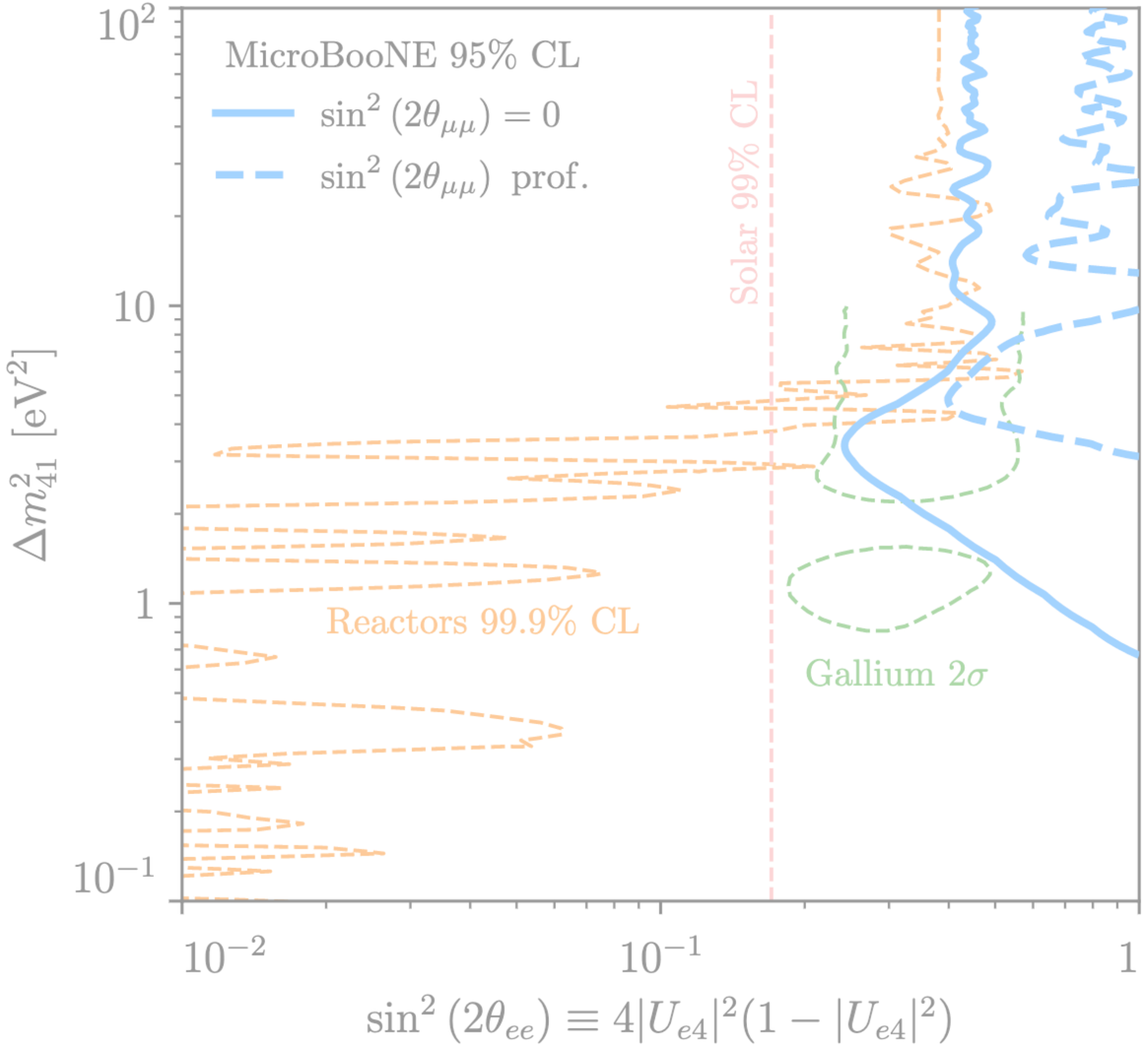
Argüelles et al, [2111.10359]
Official MicroBooNE: [2210.10216]

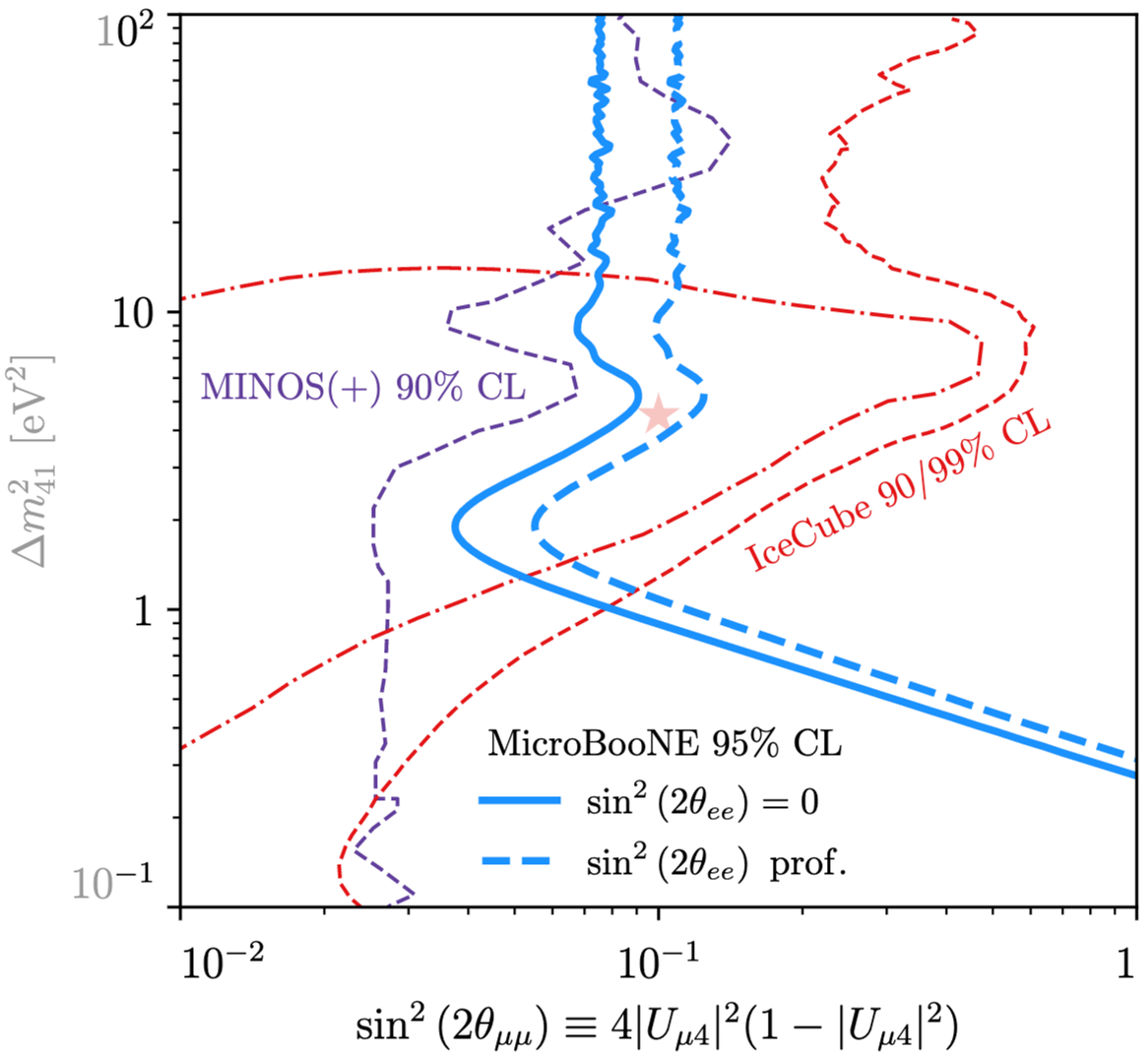




Four-Flavor Results

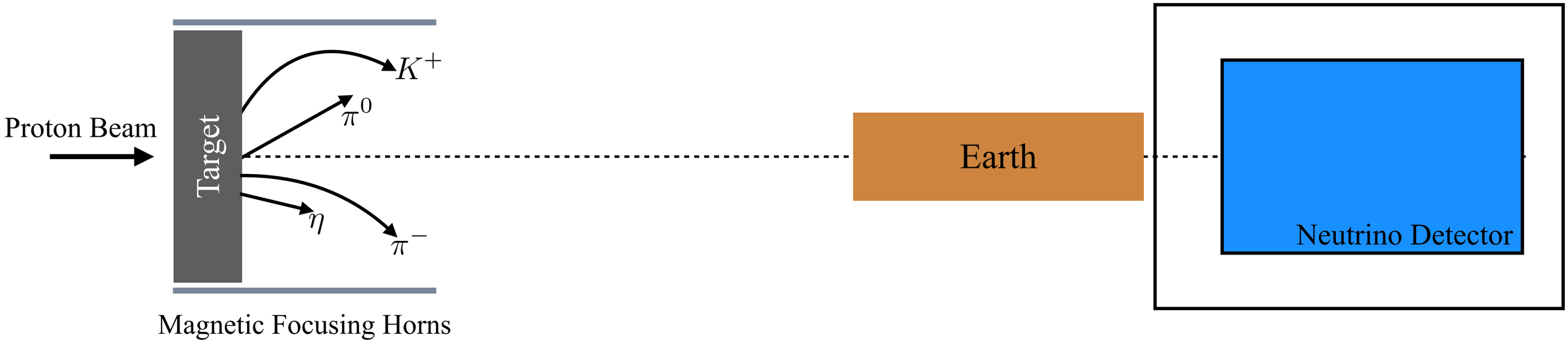
Argüelles et al, [2111.10359]
Official MicroBooNE: [2210.10216]



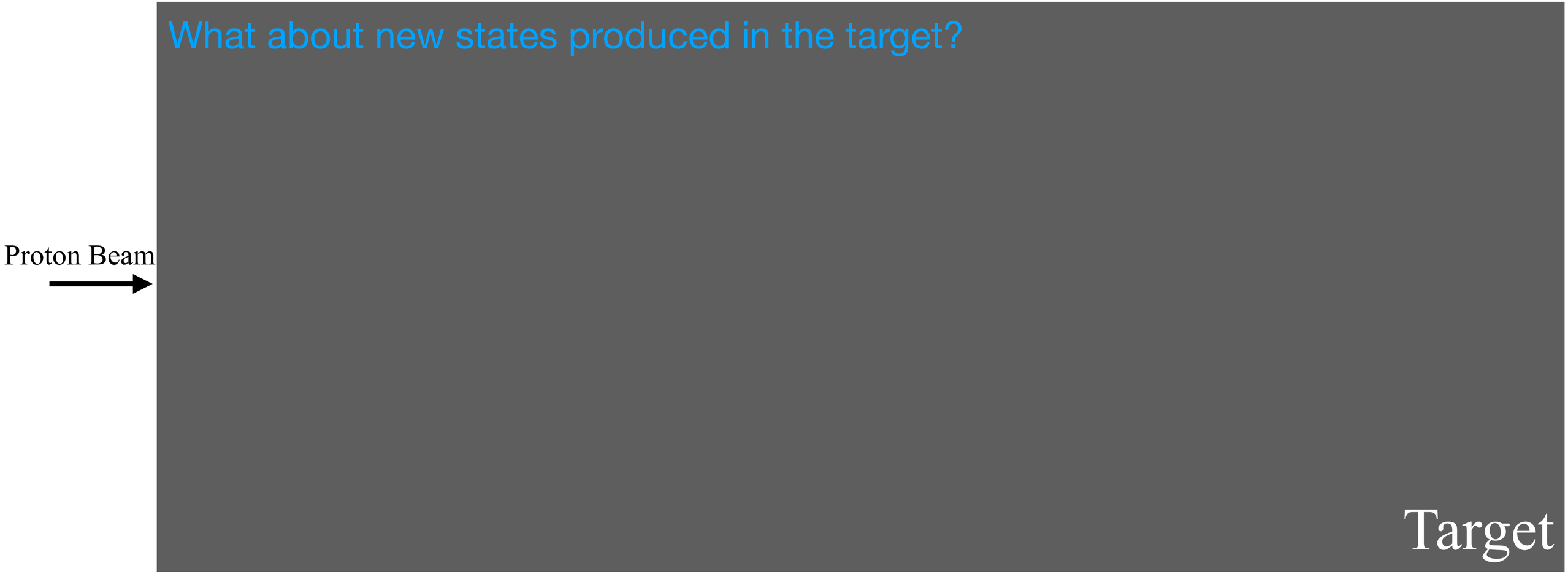


“Nonstandard” BSM Production?

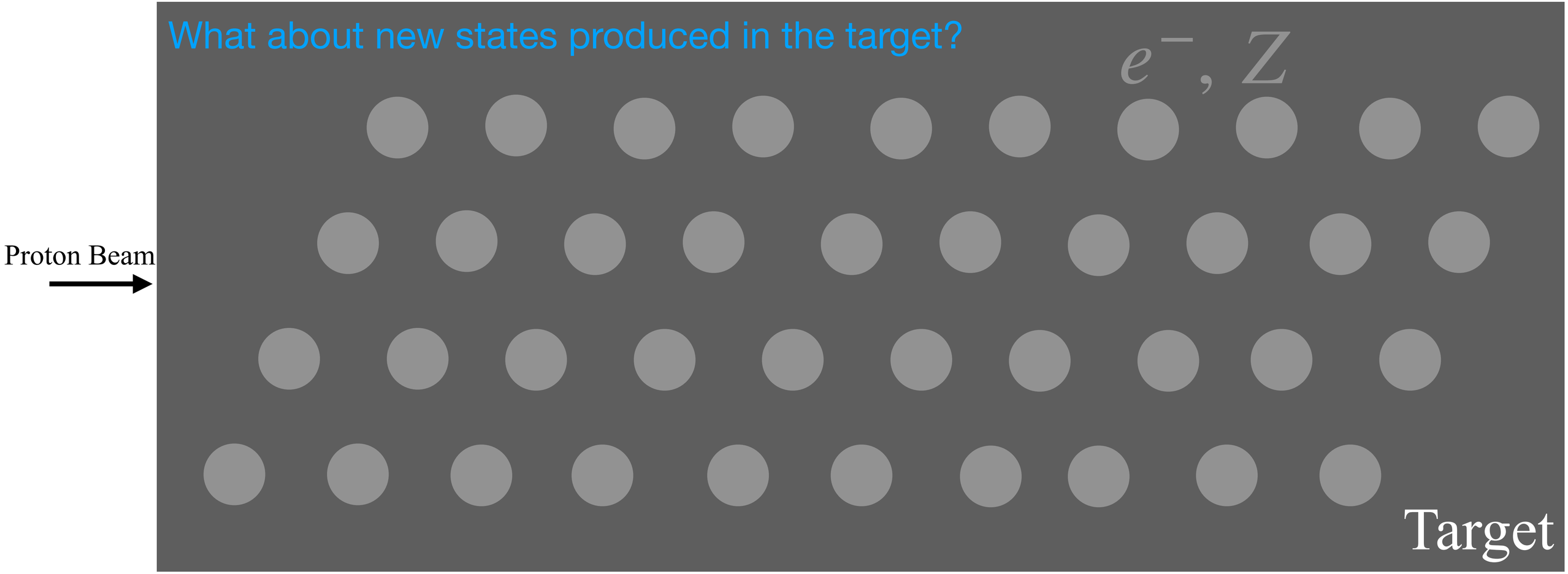
What about new states produced in the target?



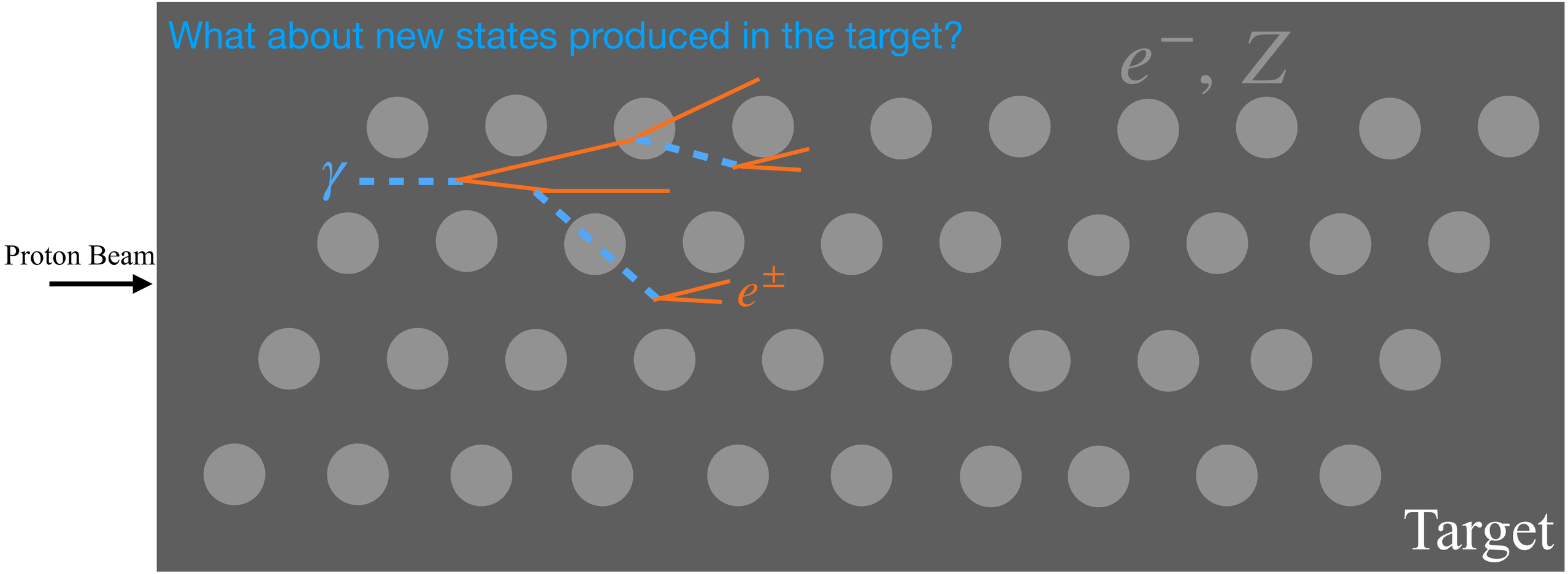
“Nonstandard” BSM Production?



“Nonstandard” BSM Production?



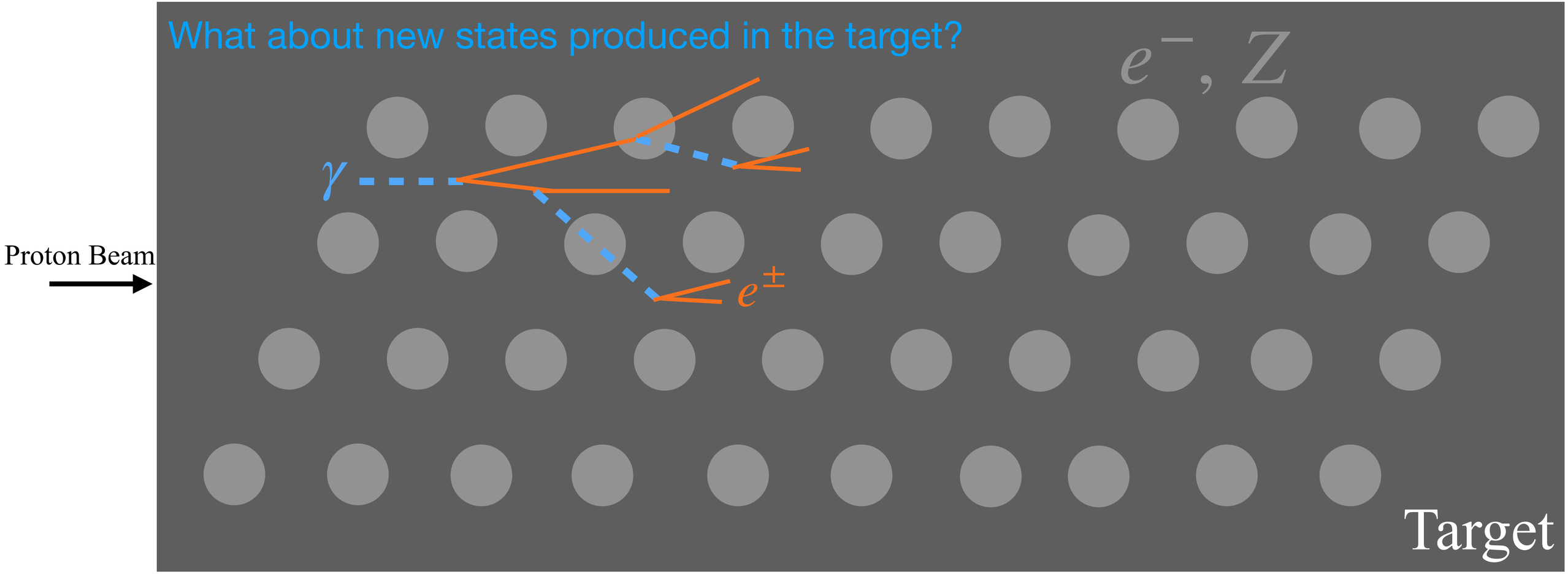
“Nonstandard” BSM Production?



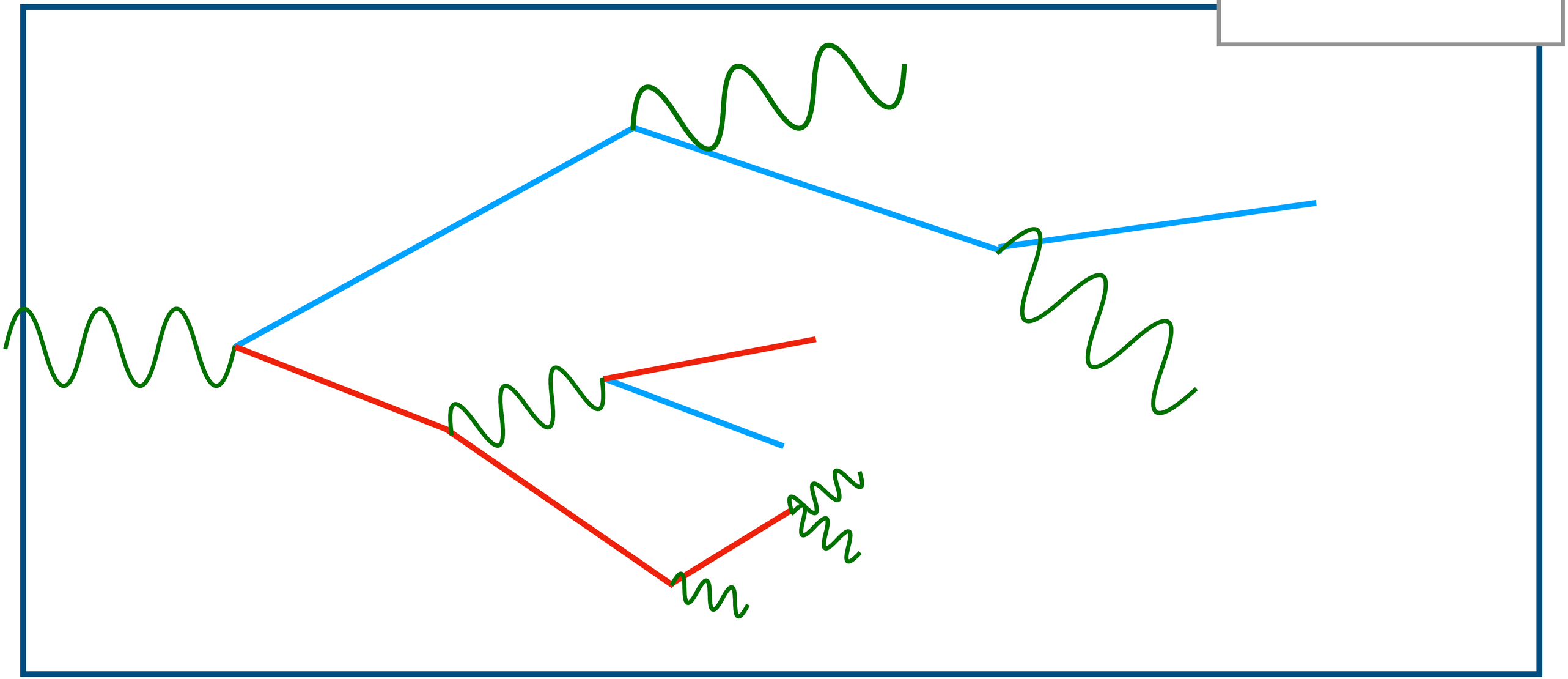
“Nonstandard” BSM Production?

Every Hadronic/Electromagnetic interaction in the target is a potential for BSM production!

many interactions = many opportunities for production



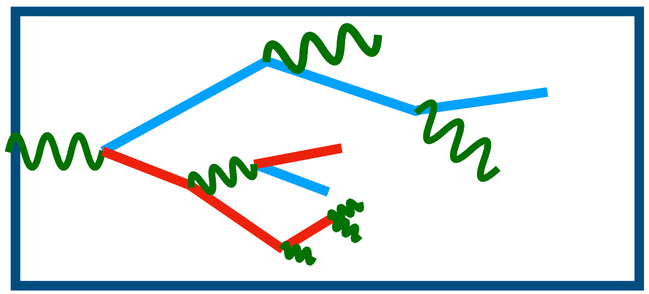
The big challenge: kinematics



The big challenge: kinematics

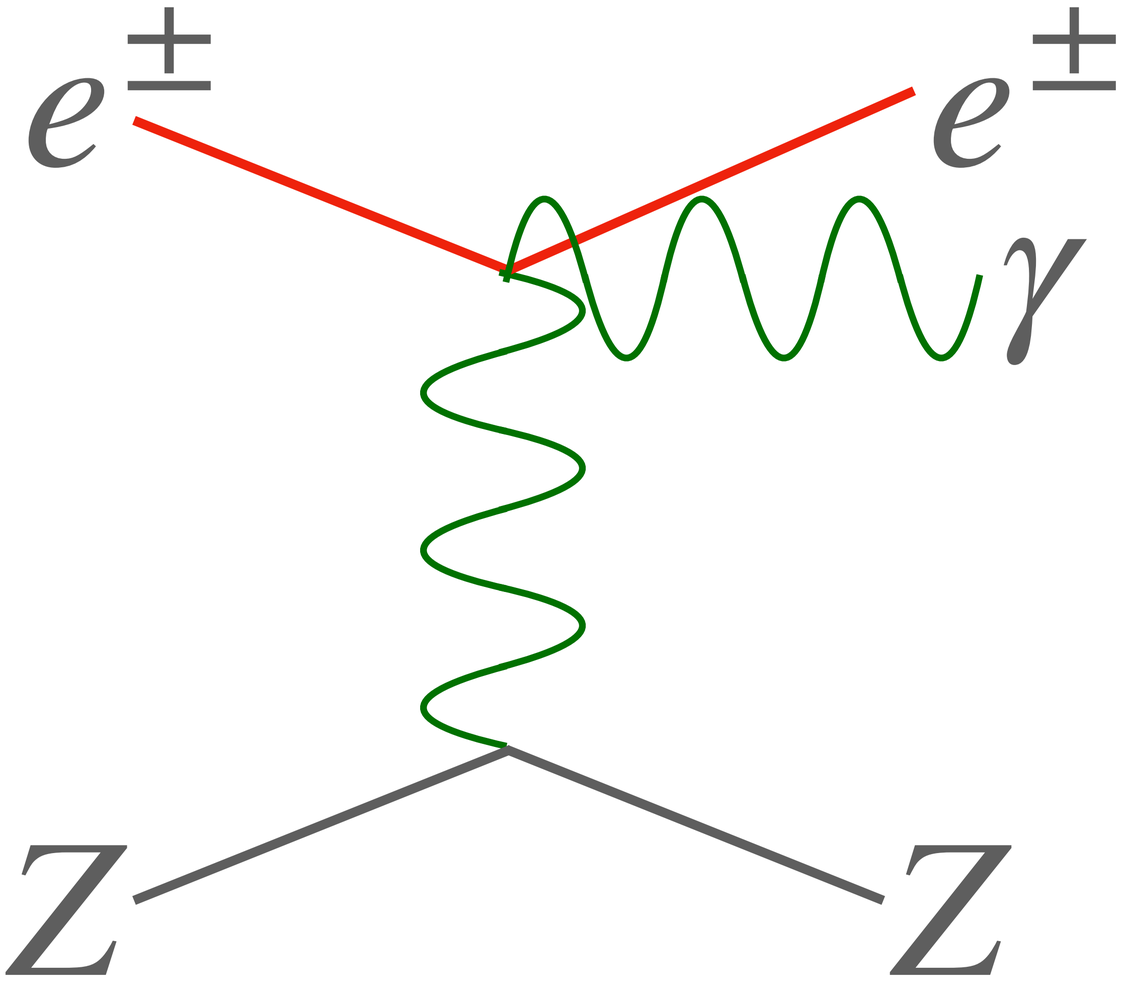
We are (often) interested in detectors in the ~forward region that have a small solid angle with respect to the incident beam.

Any small effect in *directionality* of BSM production can have a profound effect.

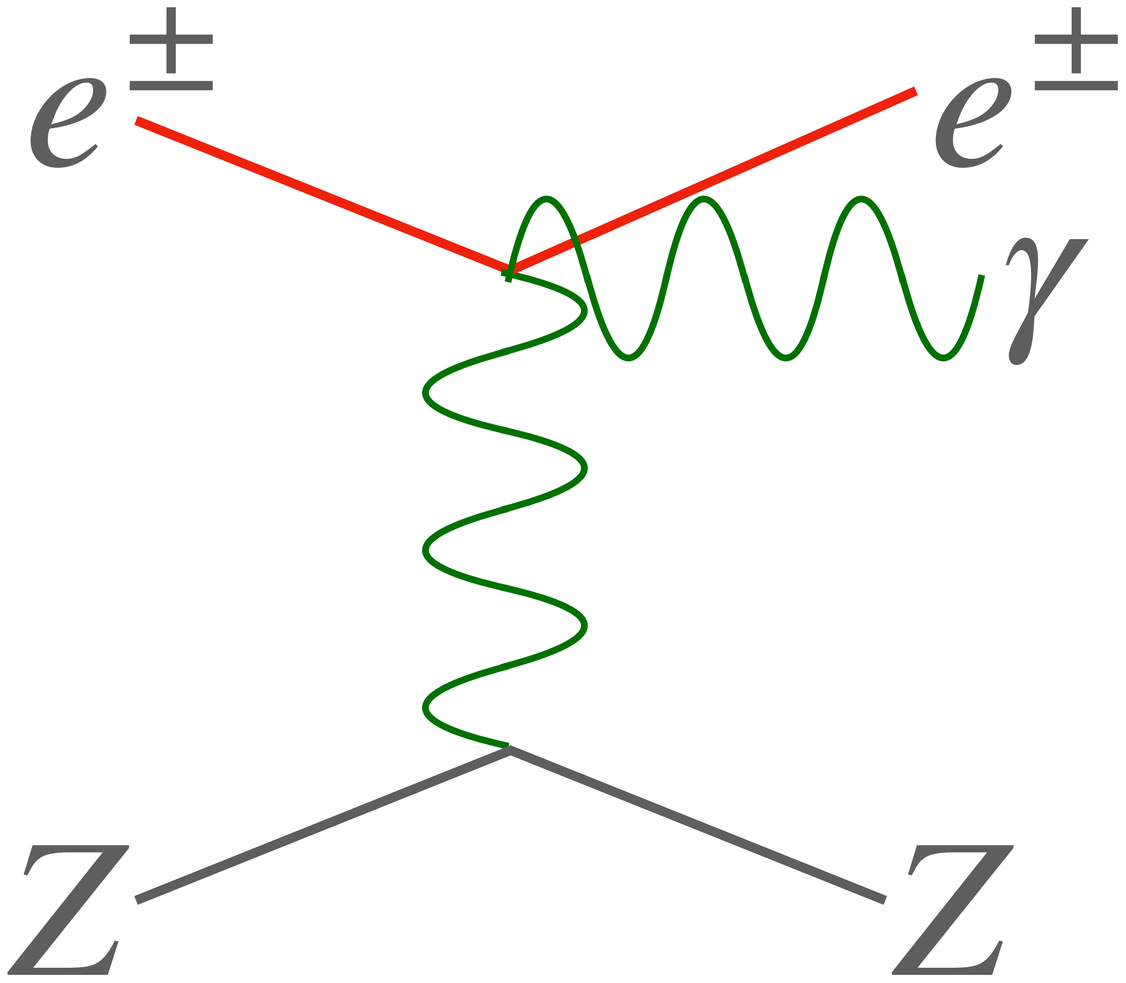


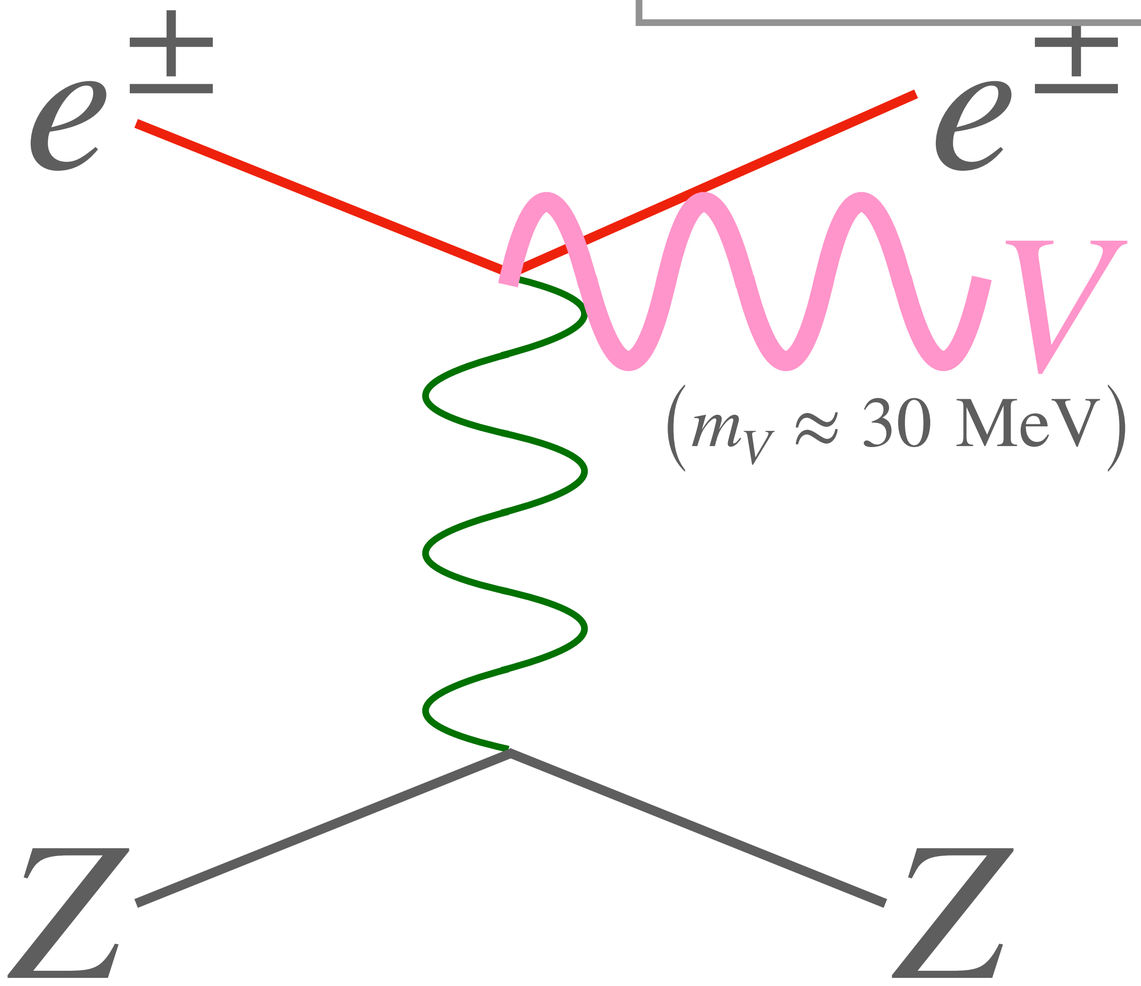
We want to
(a) Generate sample SM showers, and
(b) Resample those SM vertices to produce BSM states, tracking kinematics precisely.

SM vs. BSM Bremsstrahlung

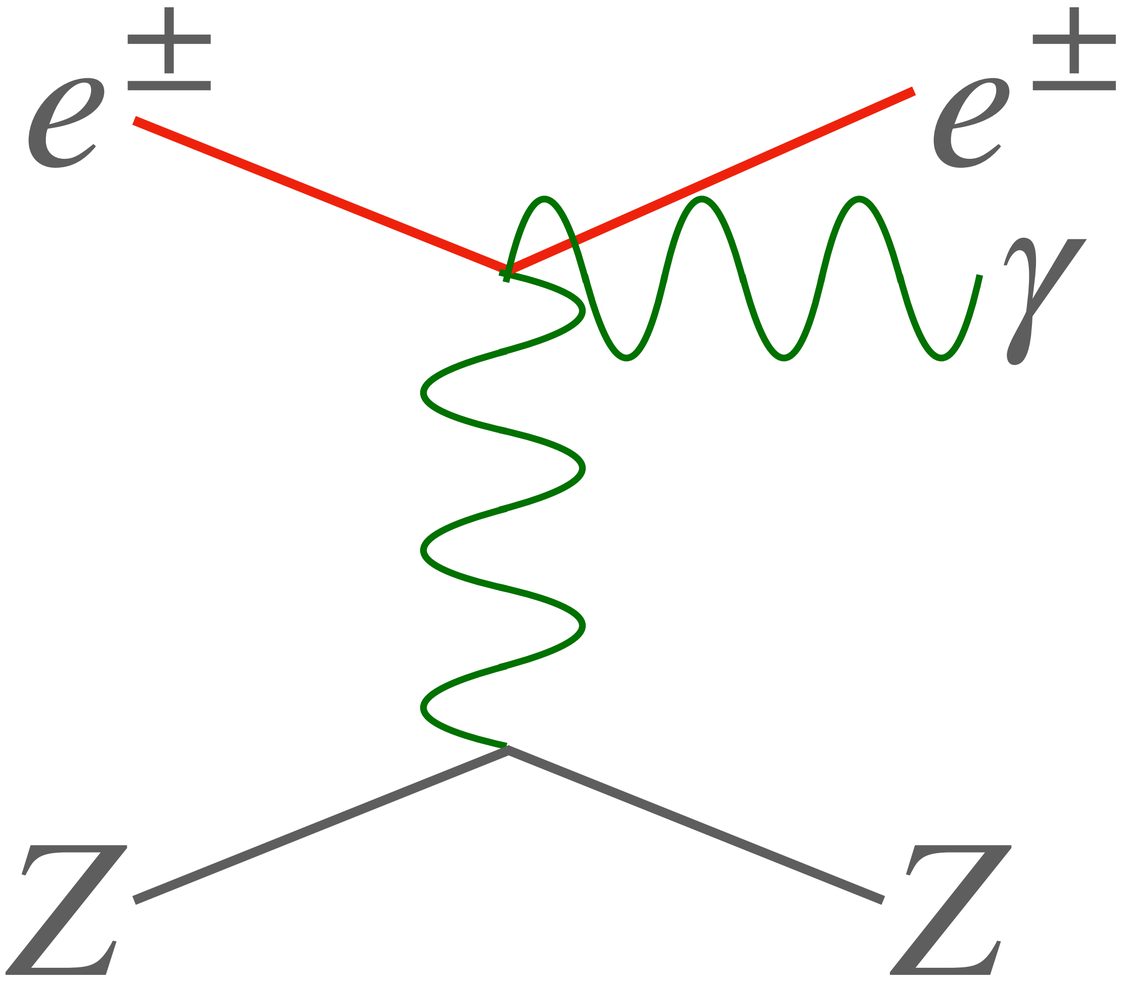


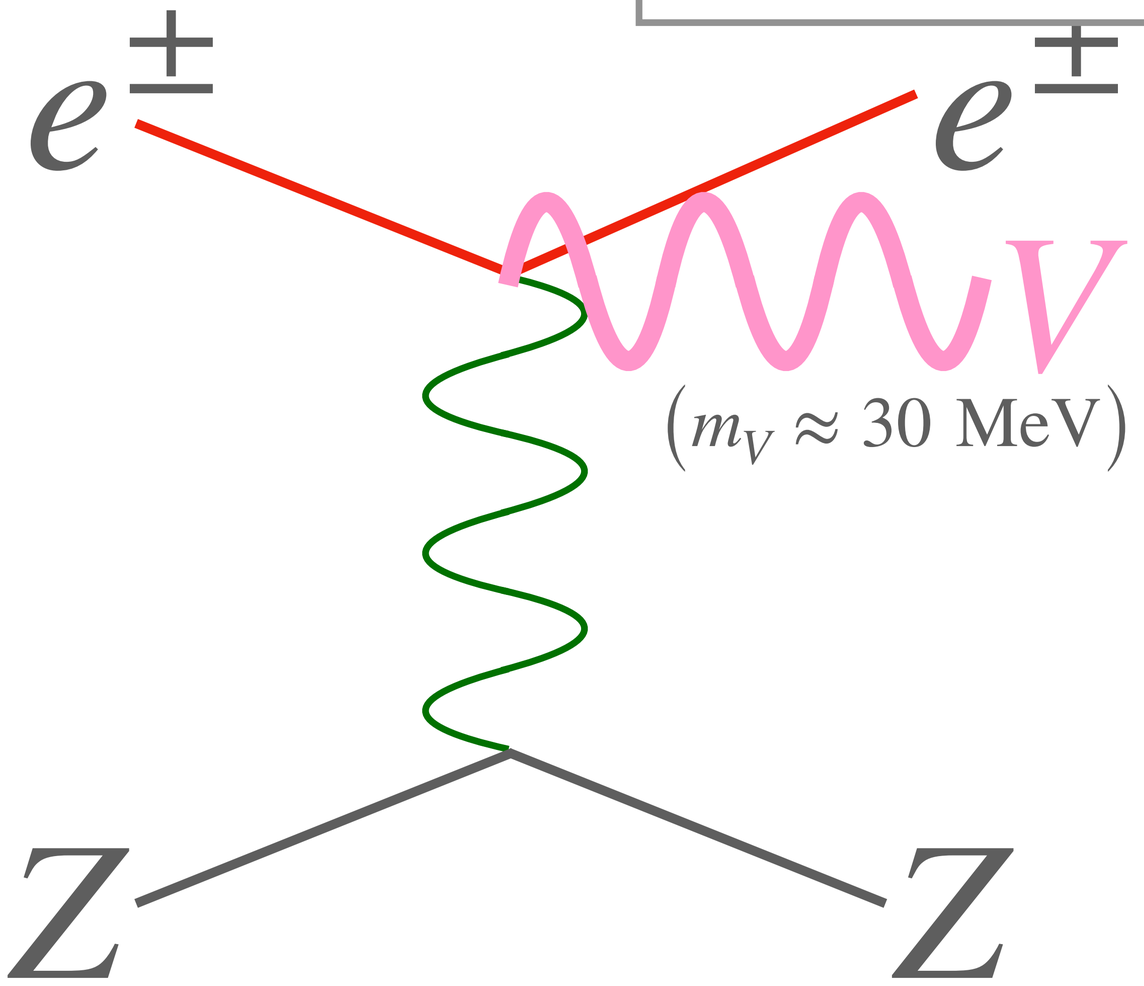
SM vs. BSM Bremsstrahlung





SM vs. BSM Bremsstrahlung

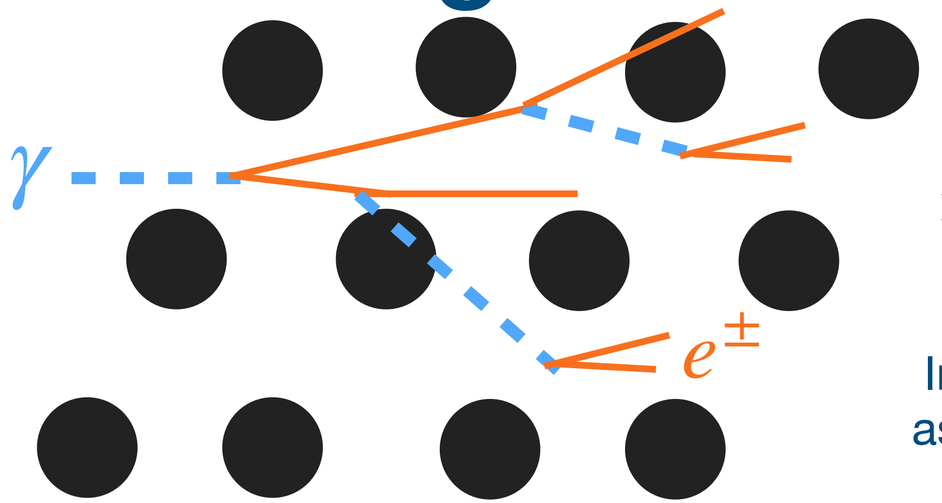




Comparing the two — big issue is kinematical distributions of outgoing particles

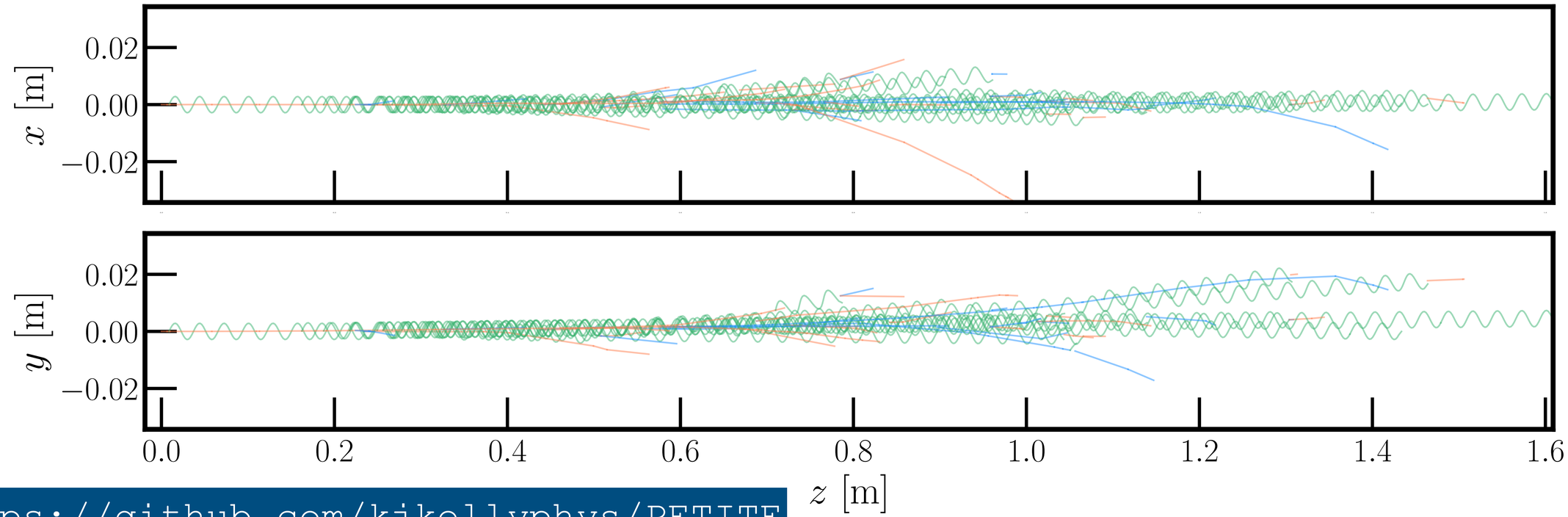
Blinov, Fox, KJK, Machado, Plestid [2401.06843]

Introducing PETITE



PETITE allows for rapid simulation of EM cascades in thick targets that can be processed for determination of BSM flux predictions

Includes SM effects for energy loss, multiple Coulomb scattering, as well as hard scattering processes. Compares extremely well against dedicated tools (e.g. GEANT-4) and analytic results (Tsai/Whitis '66)

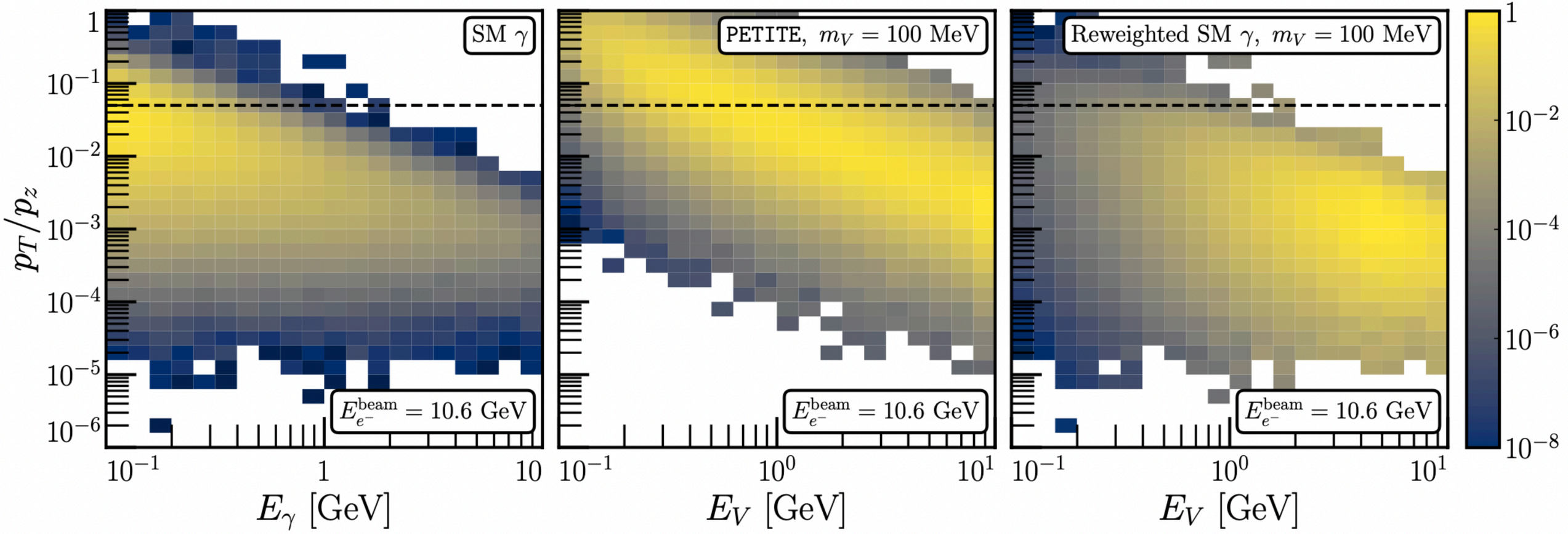


https://github.com/kjkellyphys/PETITE

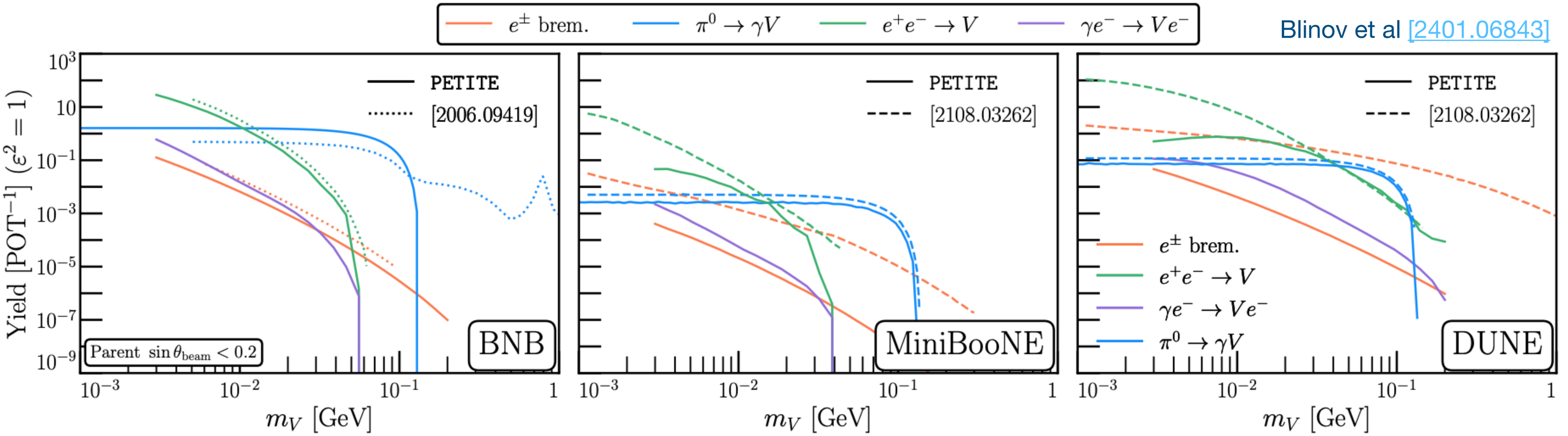
Care with Kinematics

Trying to turn daughter photons into daughter dark photons is tricky because of different kinematics. This has a significant impact, especially for very forward detectors.

Blinov, Fox, KJK, Machado, Plestid [2401.06843]



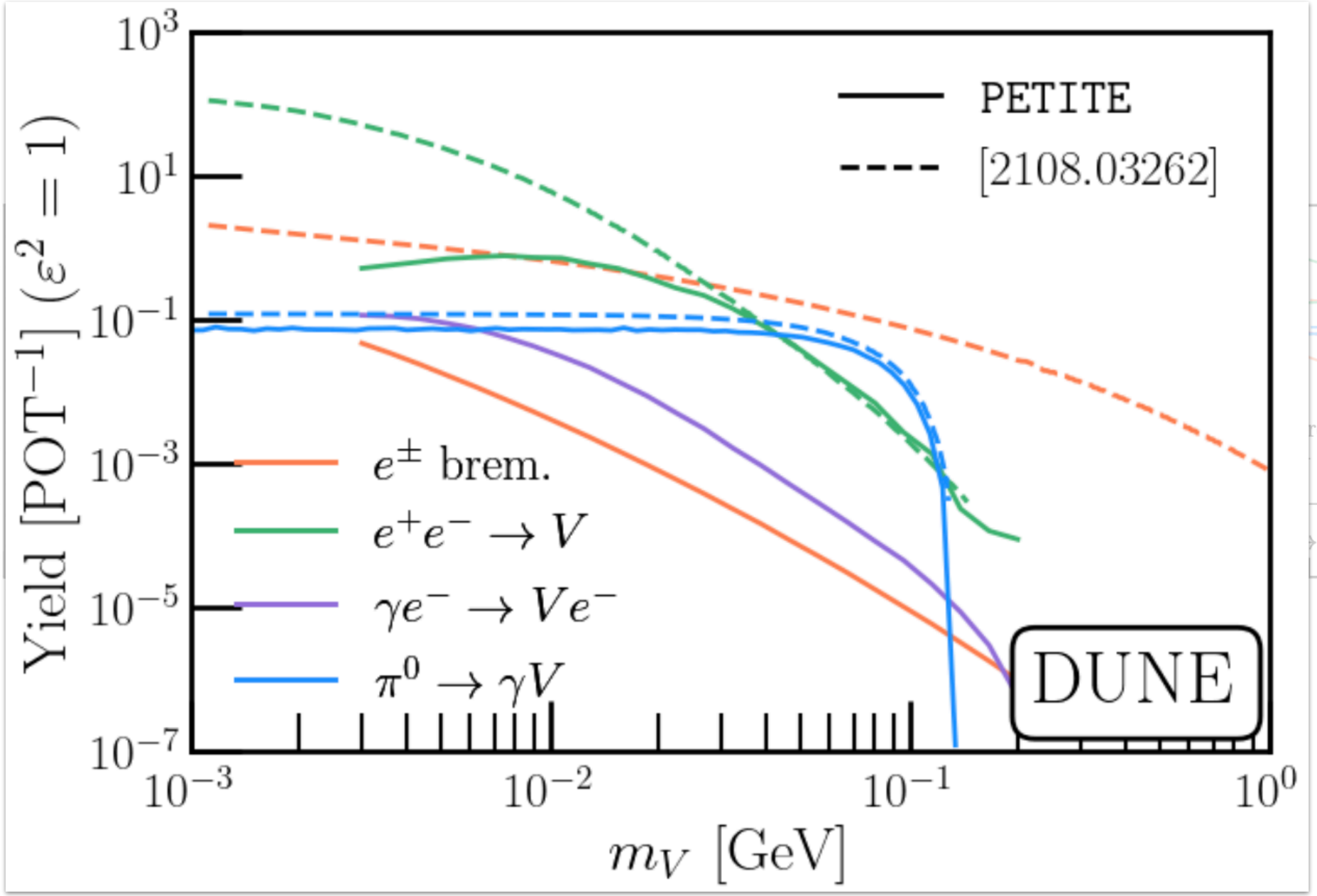
Yields from PETITE



Blinov et al [2401.06843]

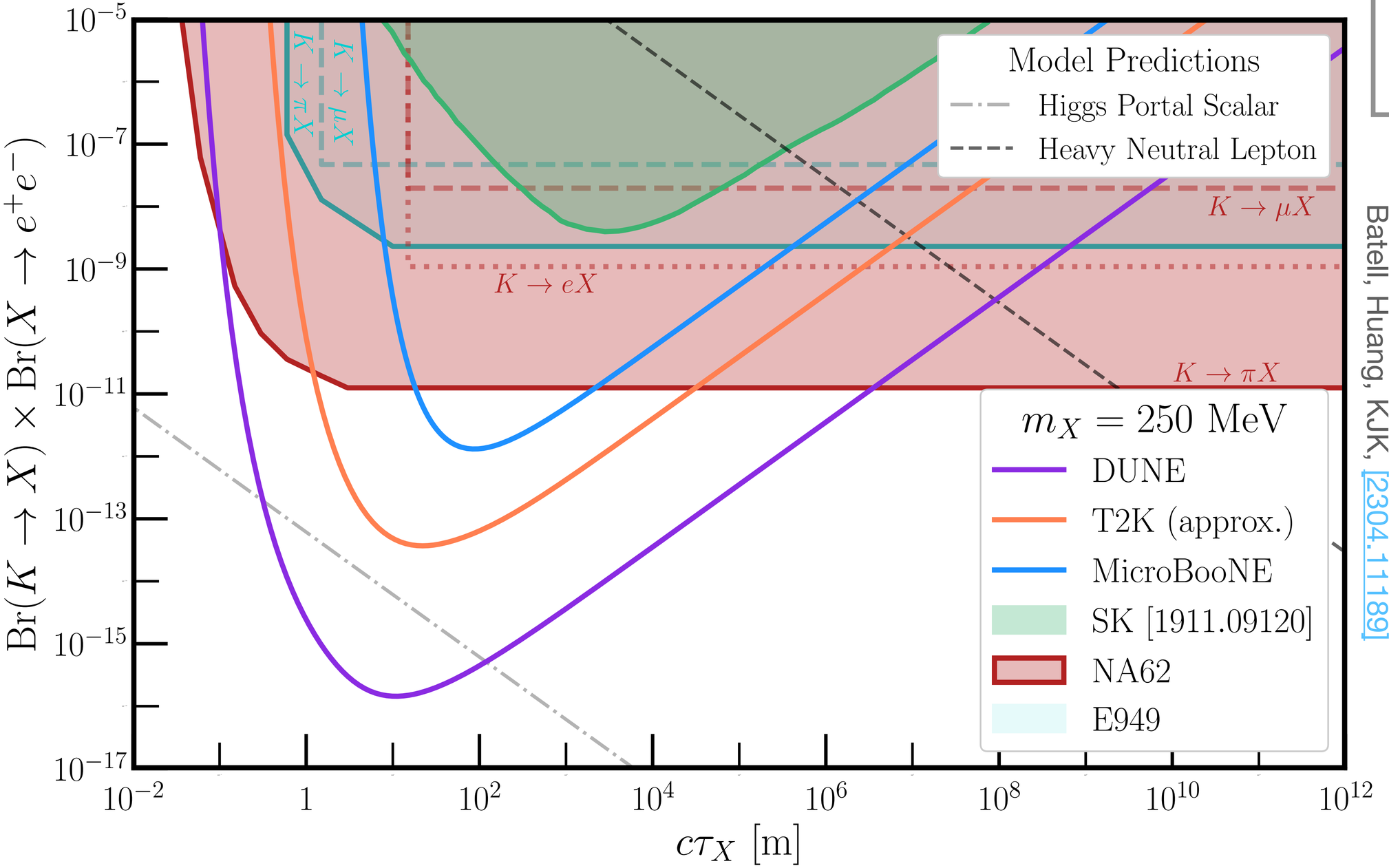
Yields from PETITE

Blinov et al [2401.06843]



Blinov et al [2401.06843]

Model-Independent LLP Search Results



Batell, Huang, KJK, [2304.11189]