What we'll (hopefully) learn from Neutrino Experiments in the Next Decade

Kevin Kelly, CERN

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kjkelly@cern.ch

Outline

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- Where are we now?
  - The neutrino mass ordering
  - CP Violation in the Lepton Sector

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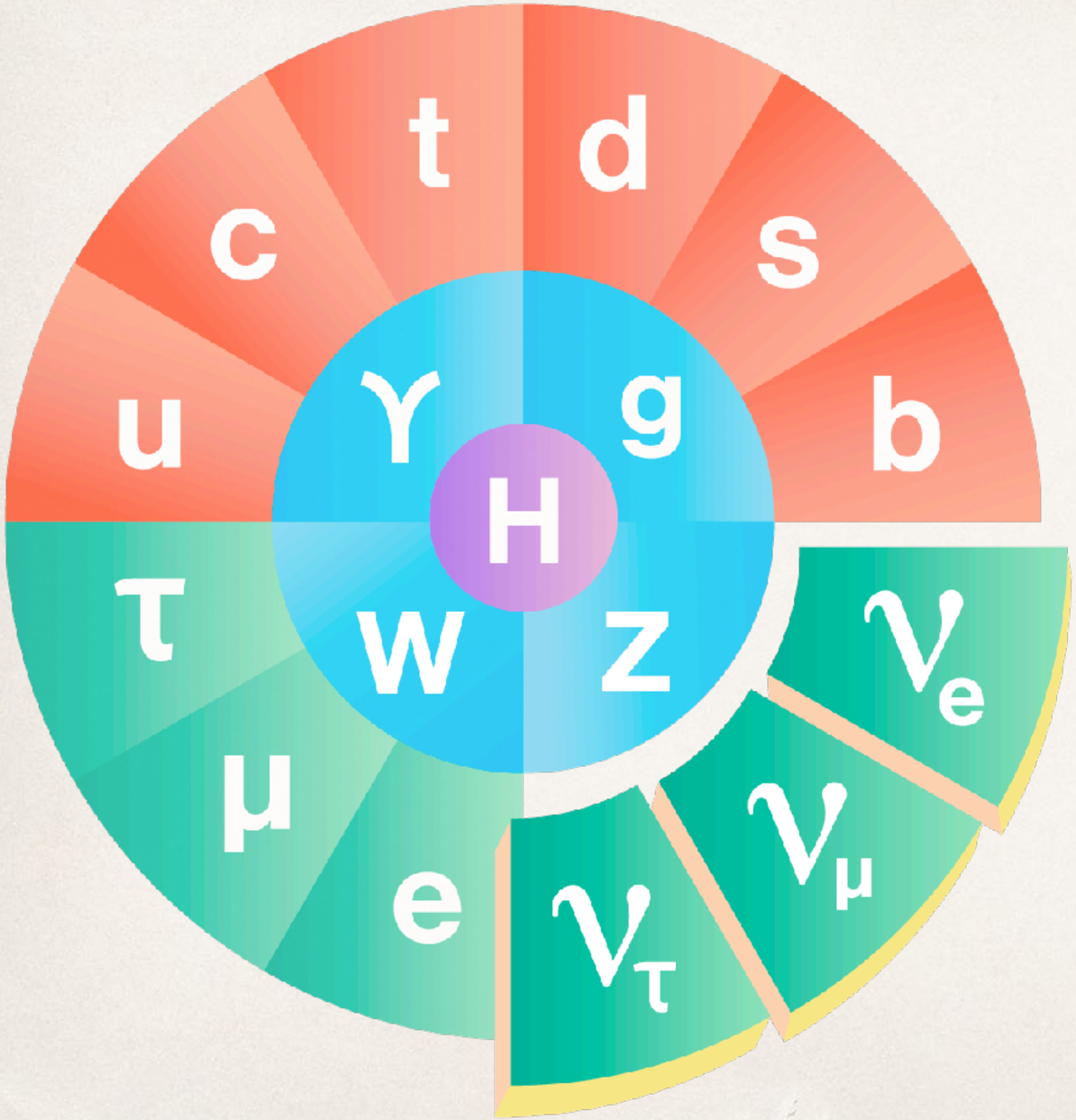
- Where are we now?
  - The neutrino mass ordering
  - CP Violation in the Lepton Sector
- Where are we going?
  - The next generation of oscillations
  - Non-neutrino prospects with upcoming experiments

(what we know now)

(what we will likely find out)

(what we will hopefully discover)

Why neutrinos for BSM?



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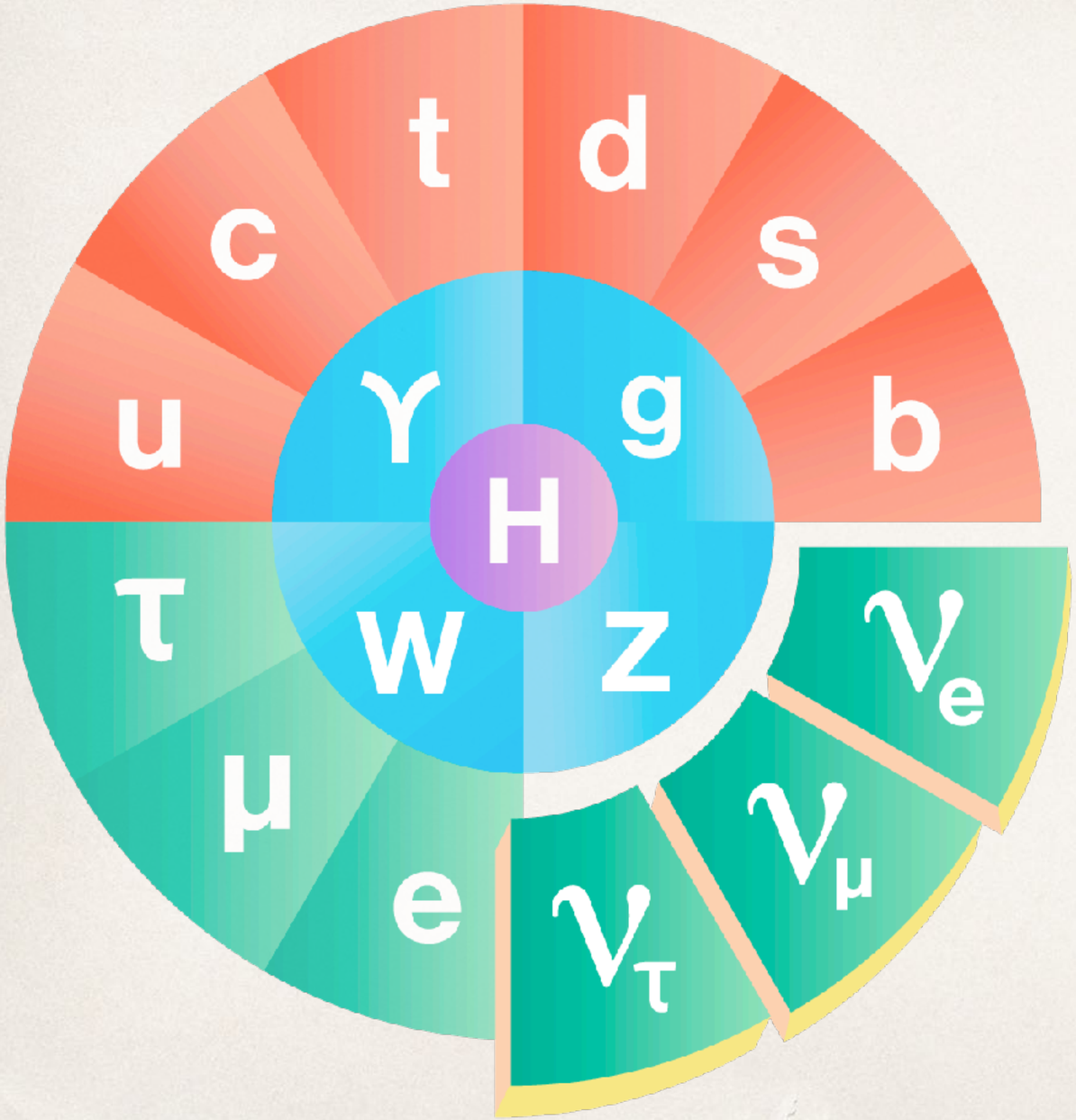

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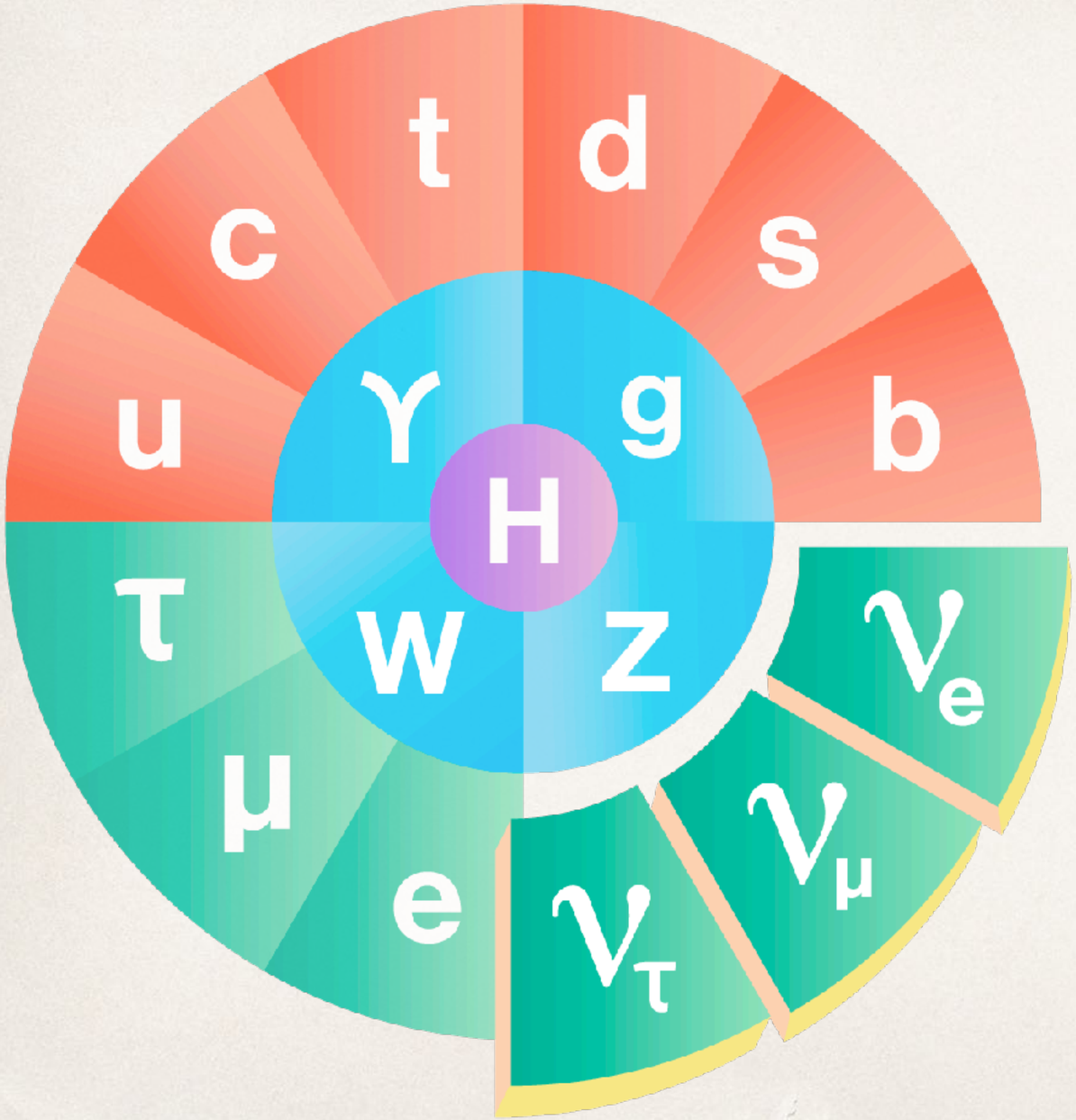

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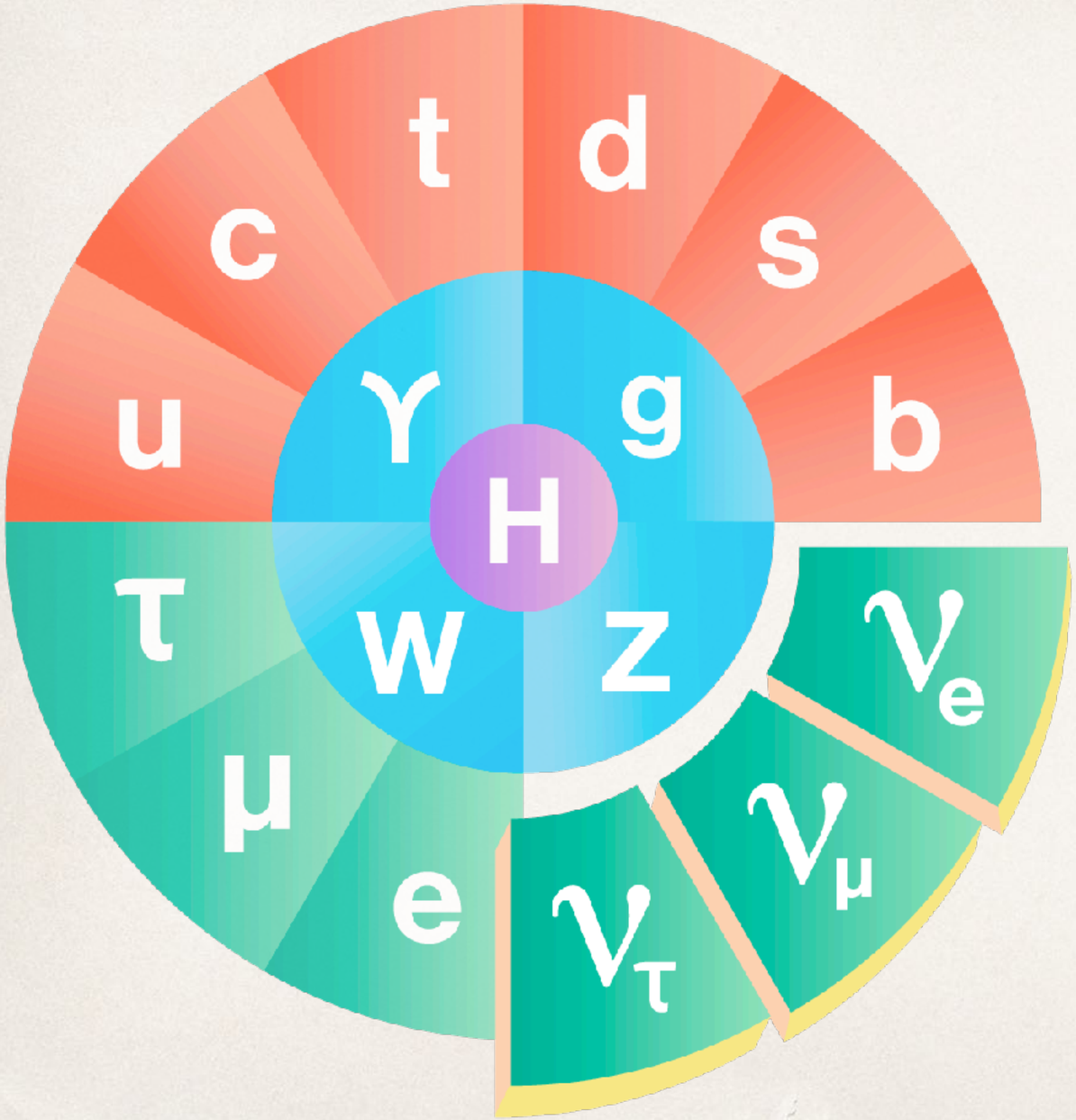

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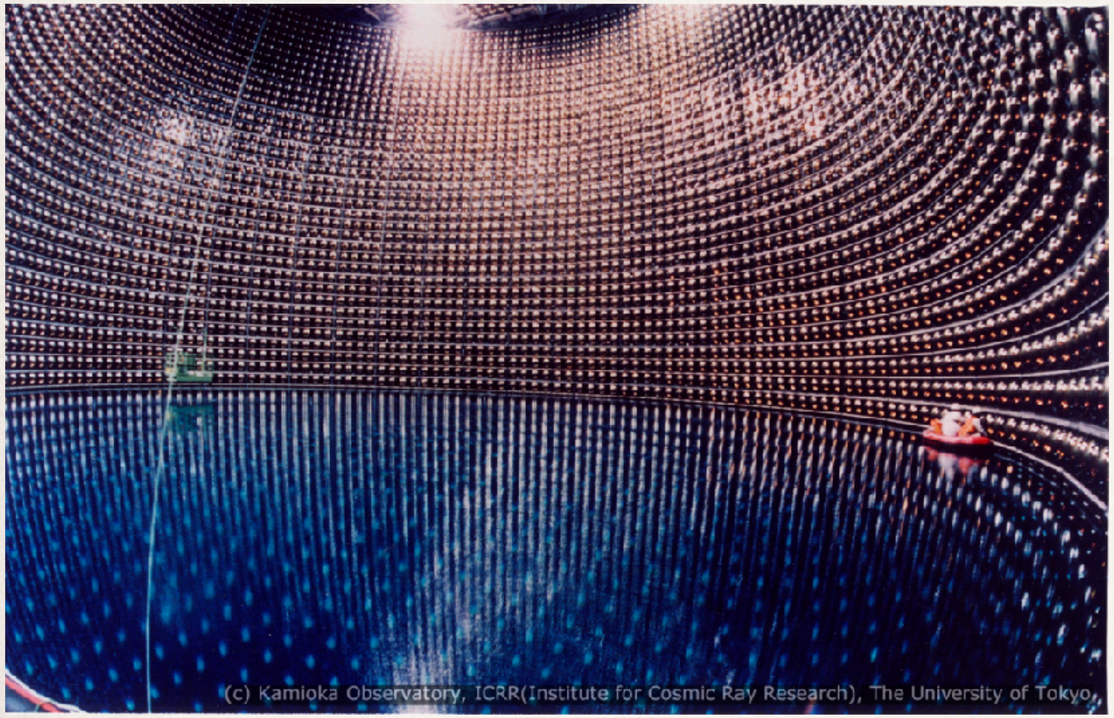
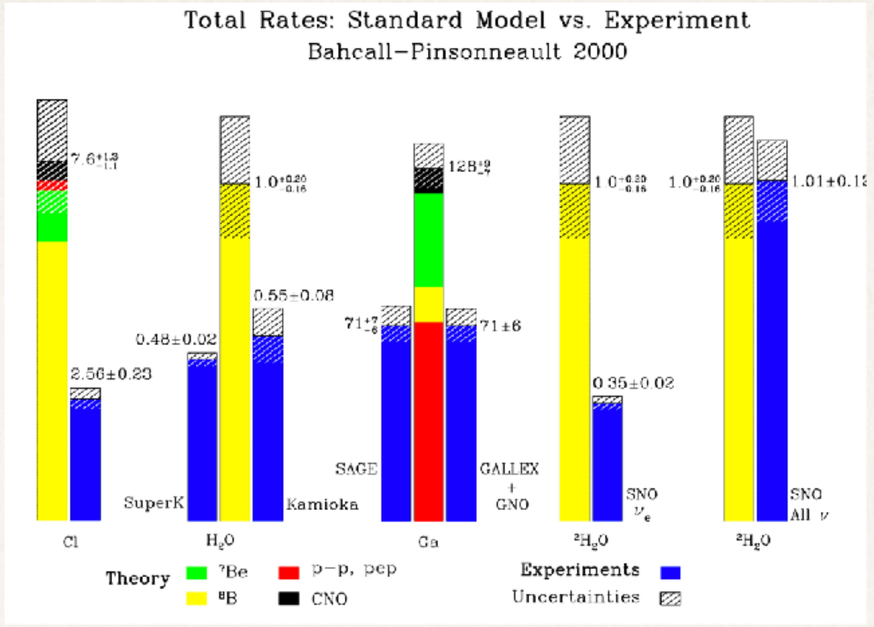
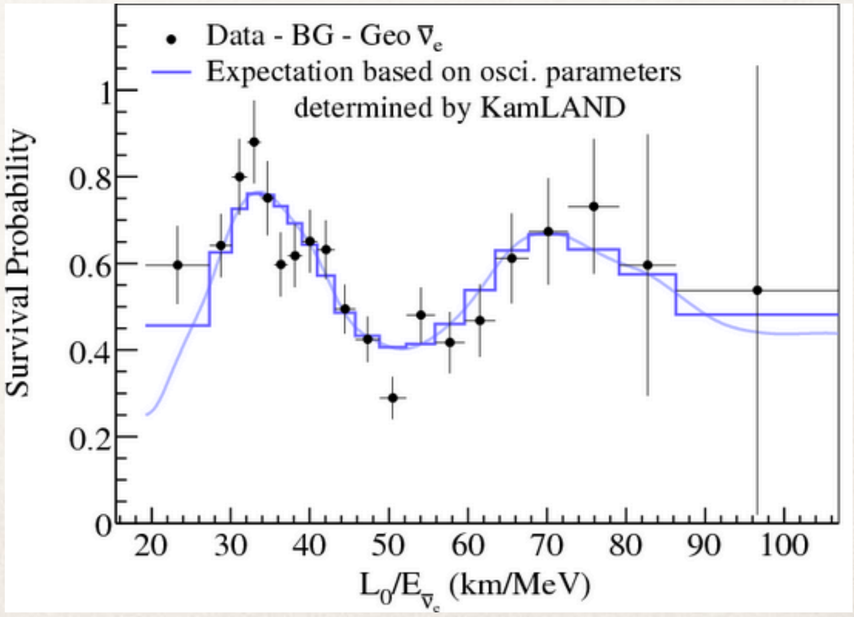
New physics (fields and/or interactions) are required to explain this.

How did we get here?







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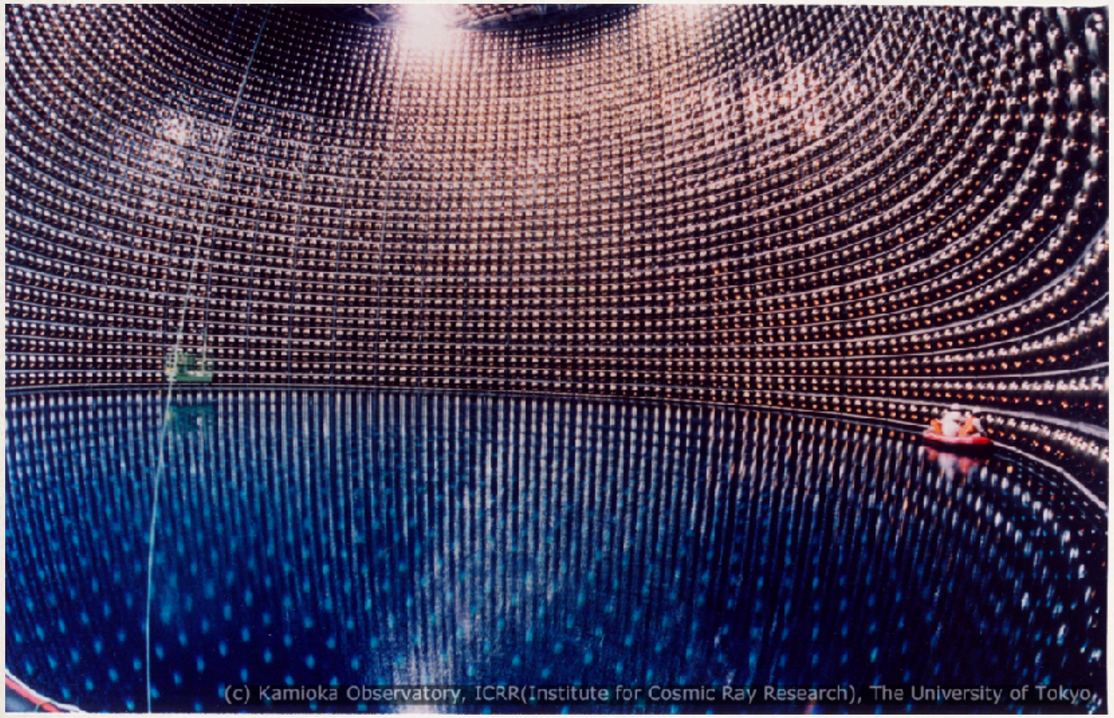
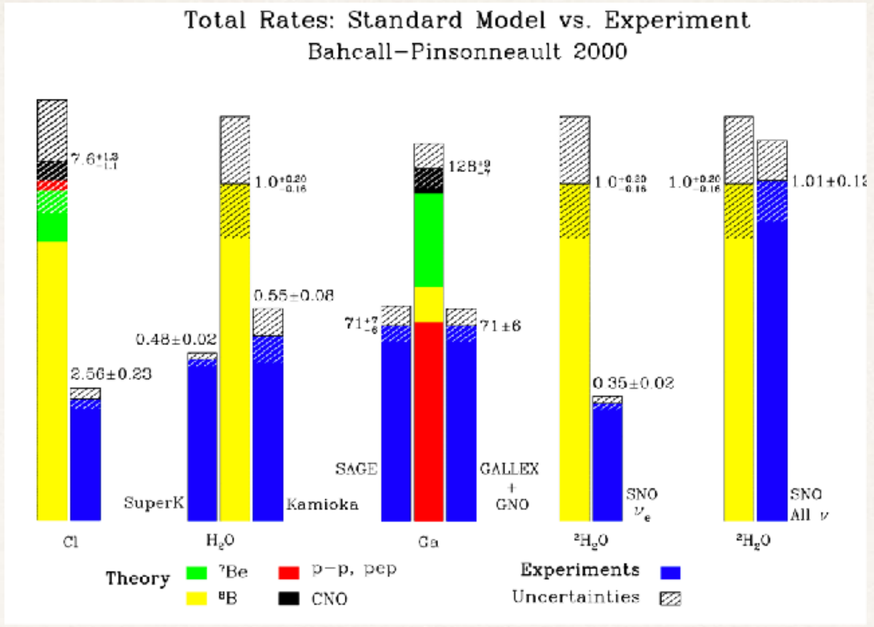
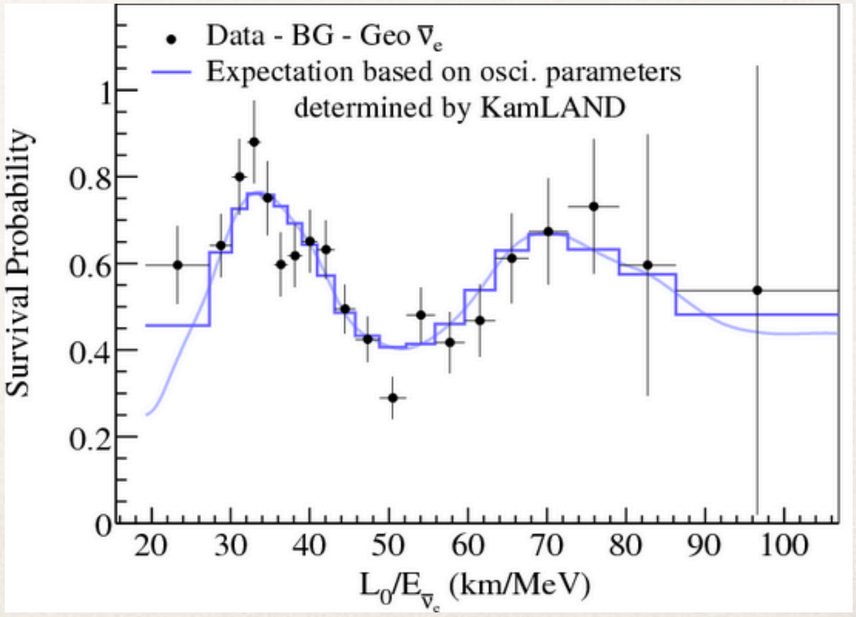




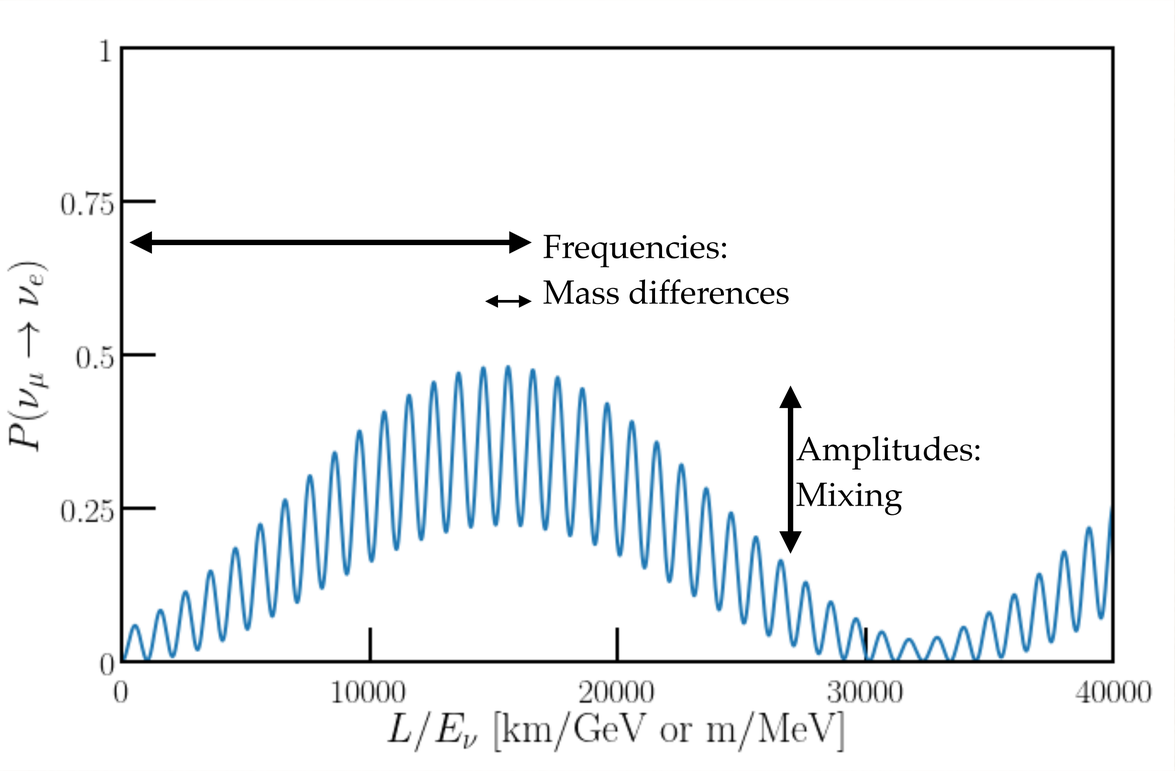


Anomalous neutrino “disappearance” in several sectors: atmospheric, solar, reactor…

Only satisfactory explanation of this and other data: neutrinos have (distinct) masses and mix.

Where are we now?

Oscillations Refresher



Oscillation probabilities depend (predominantly) on baseline length divided by neutrino energy.

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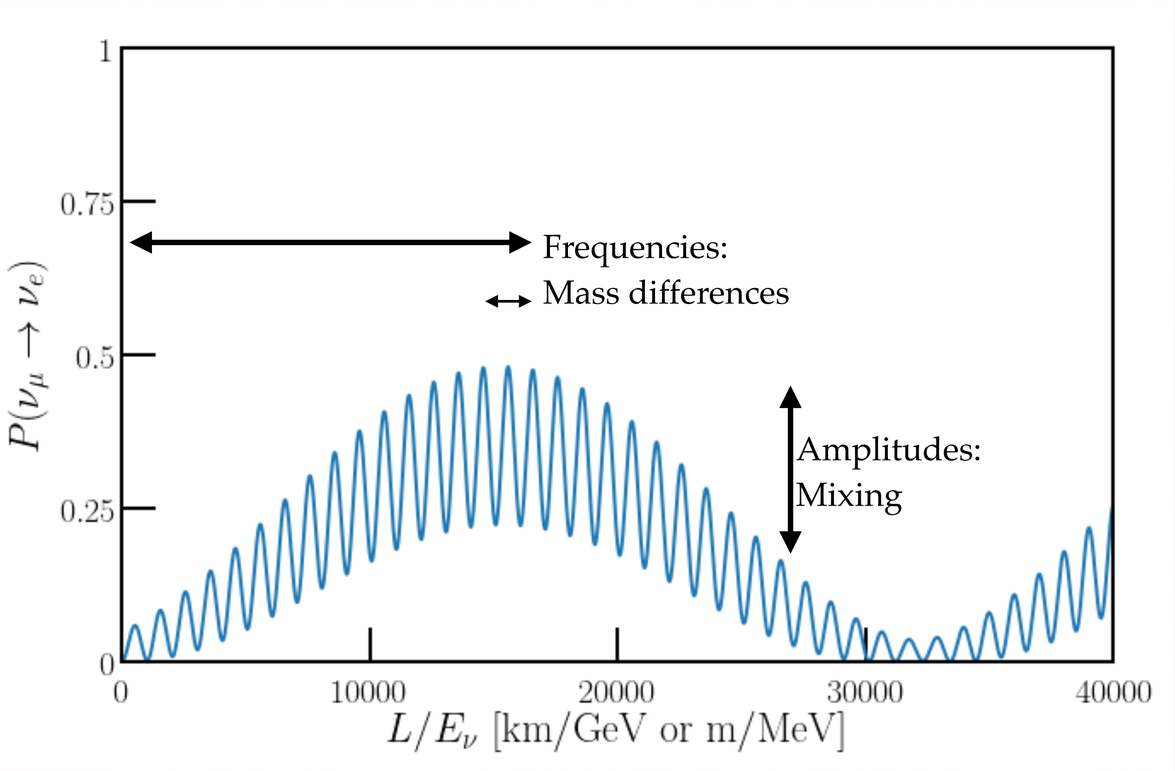

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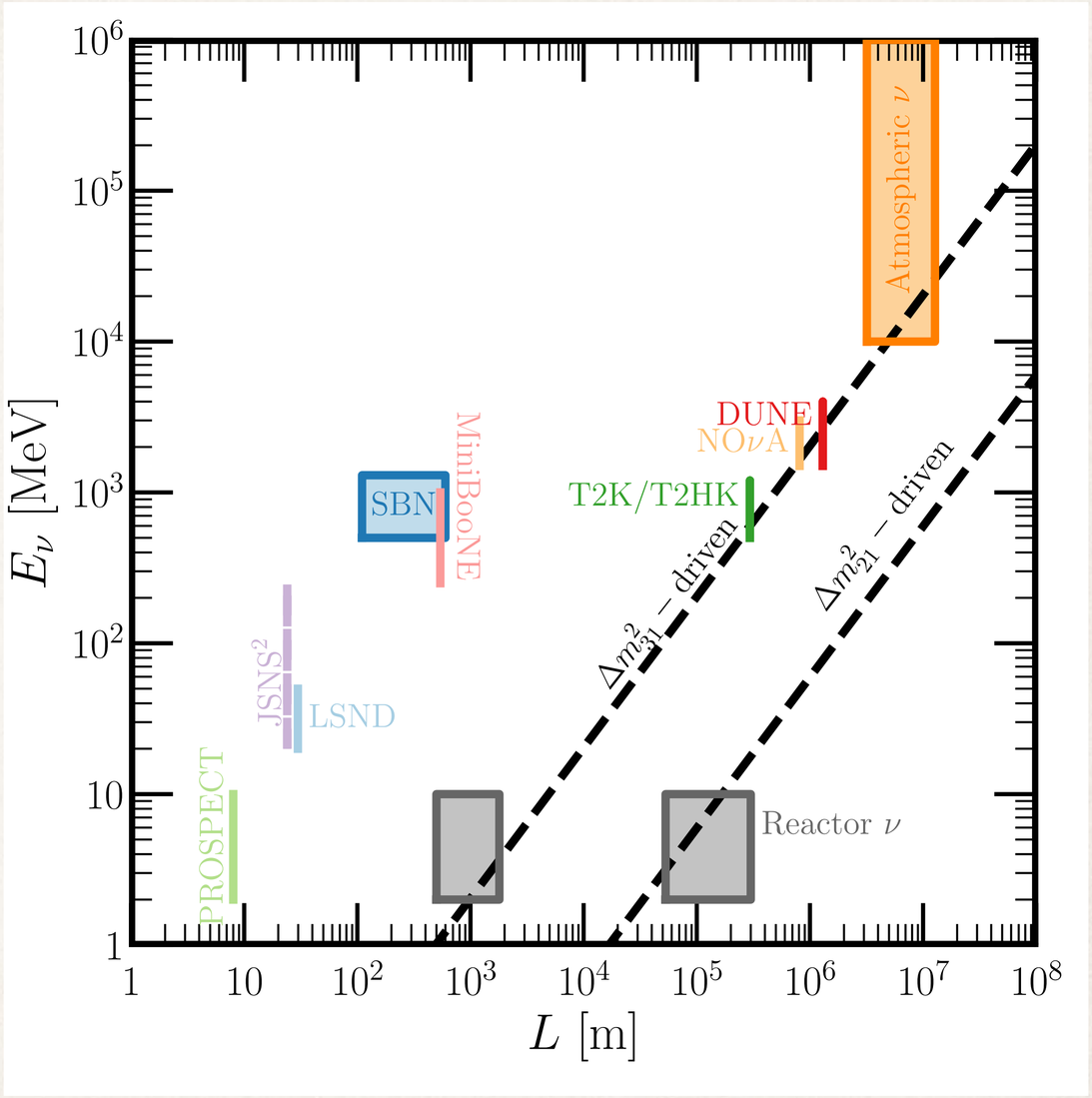

Experiments have been/will be performed for a variety of baselines and energies.

Requirements for Oscillations: Mixing and Mass Differences

Mixing between mass and flavor eigenstates: 3x3 unitary matrix (PMNS Matrix)

$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}c_{23} \end{pmatrix} \quad (c_{ij} \equiv \cos\theta_{ij},\ \ s_{ij} \equiv \sin\theta_{ij})$$

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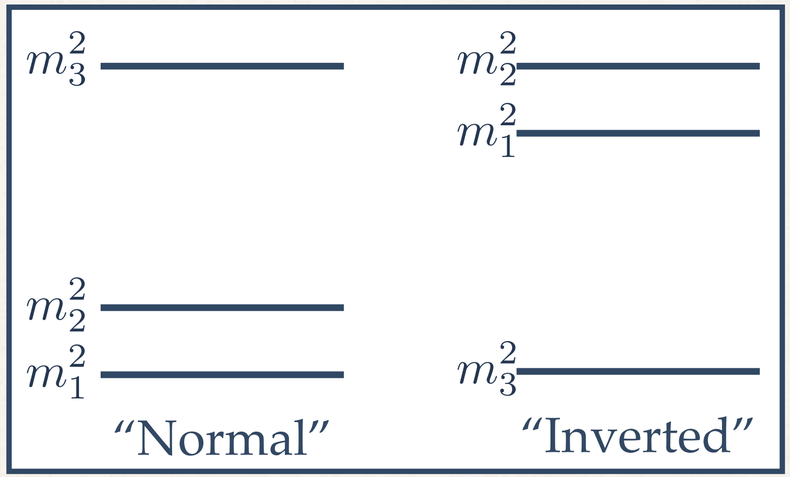
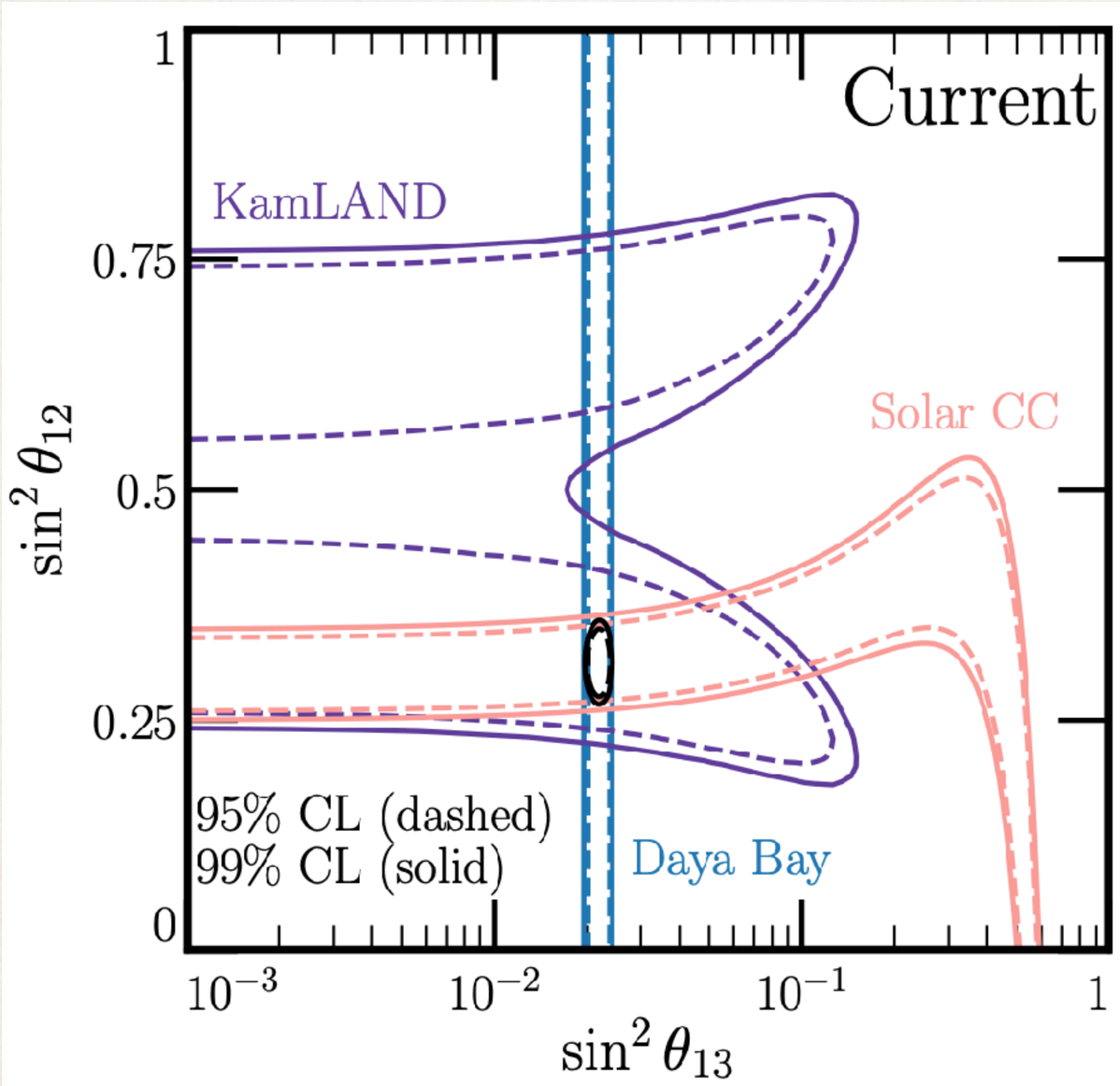
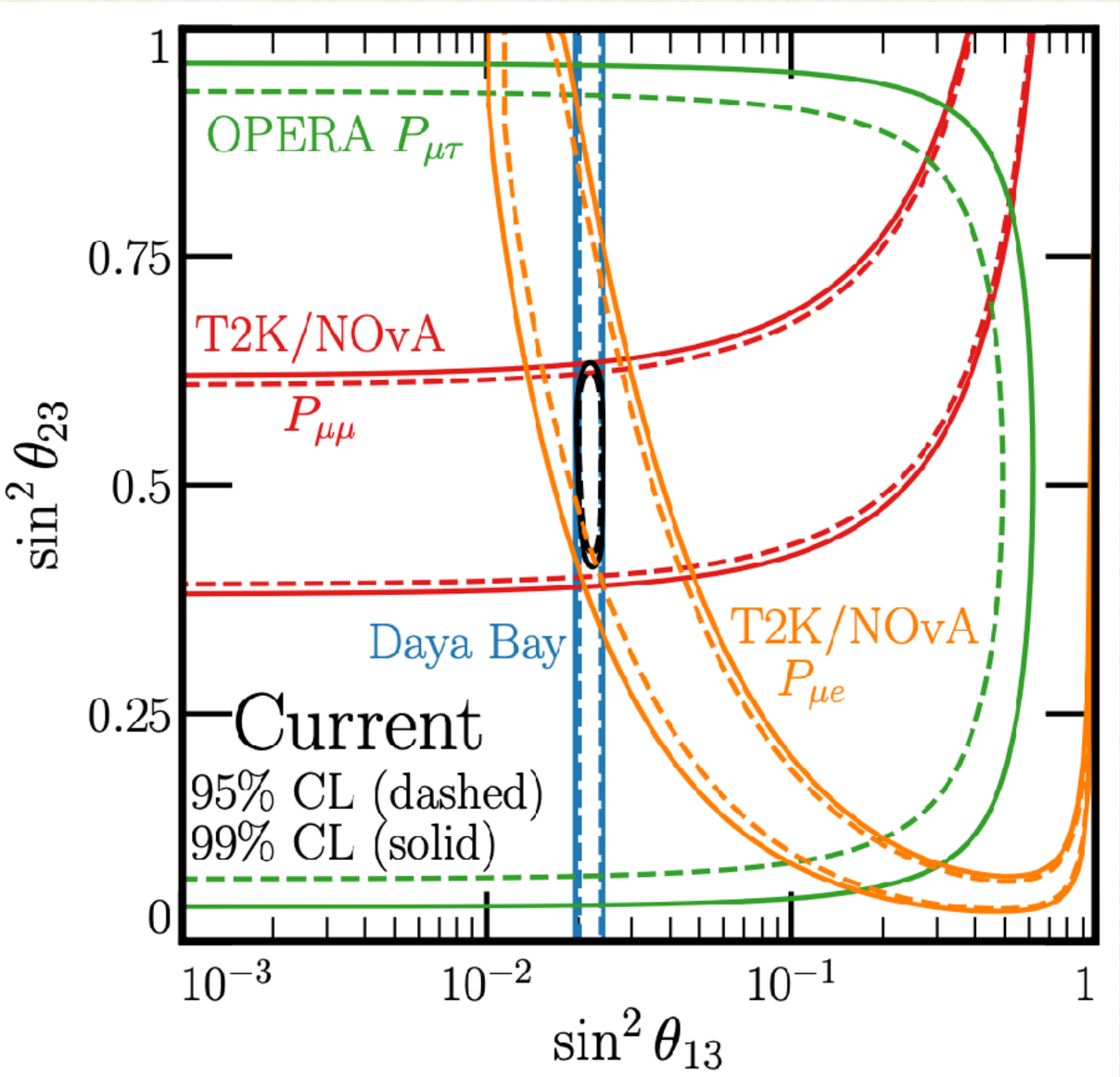
Differences between masses: relative phase acquired between different eigenstates during propagation.



- Because oscillations to date always involve ultrarelativistic neutrinos, we can only access their mass-squared differences.

Current Mixing Angle Knowledge

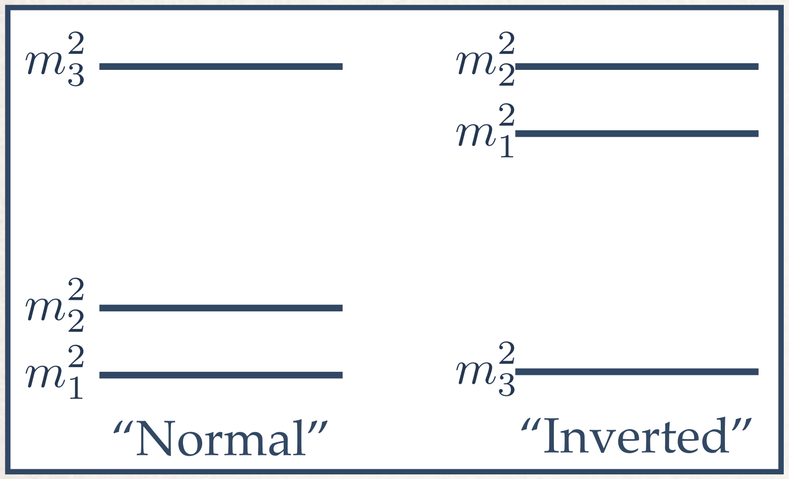




Black regions: Combined fit of current data.

Ellis, KJK, Li [2008.01088]

Masses/Mass ordering



- Combination of solar experiments/reactor antineutrino experiments measure $\Delta m^2_{21} \equiv m^2_2 - m^2_1$
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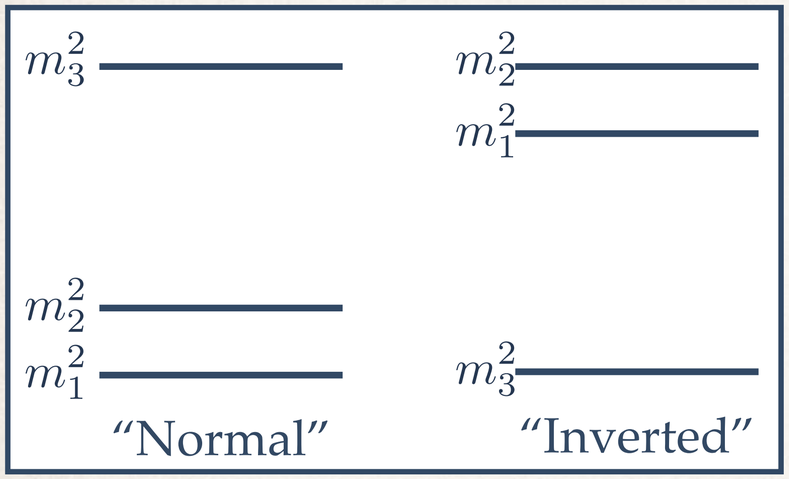

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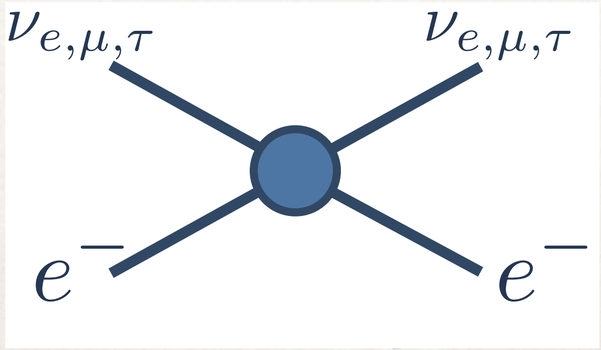
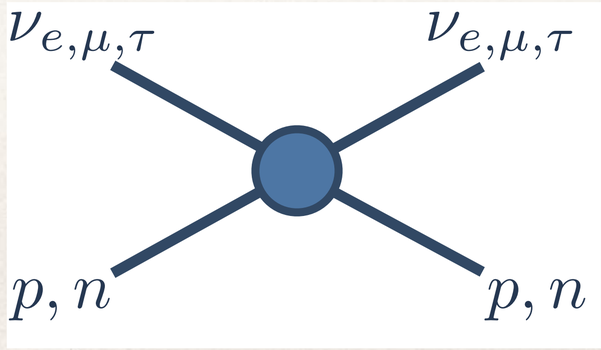
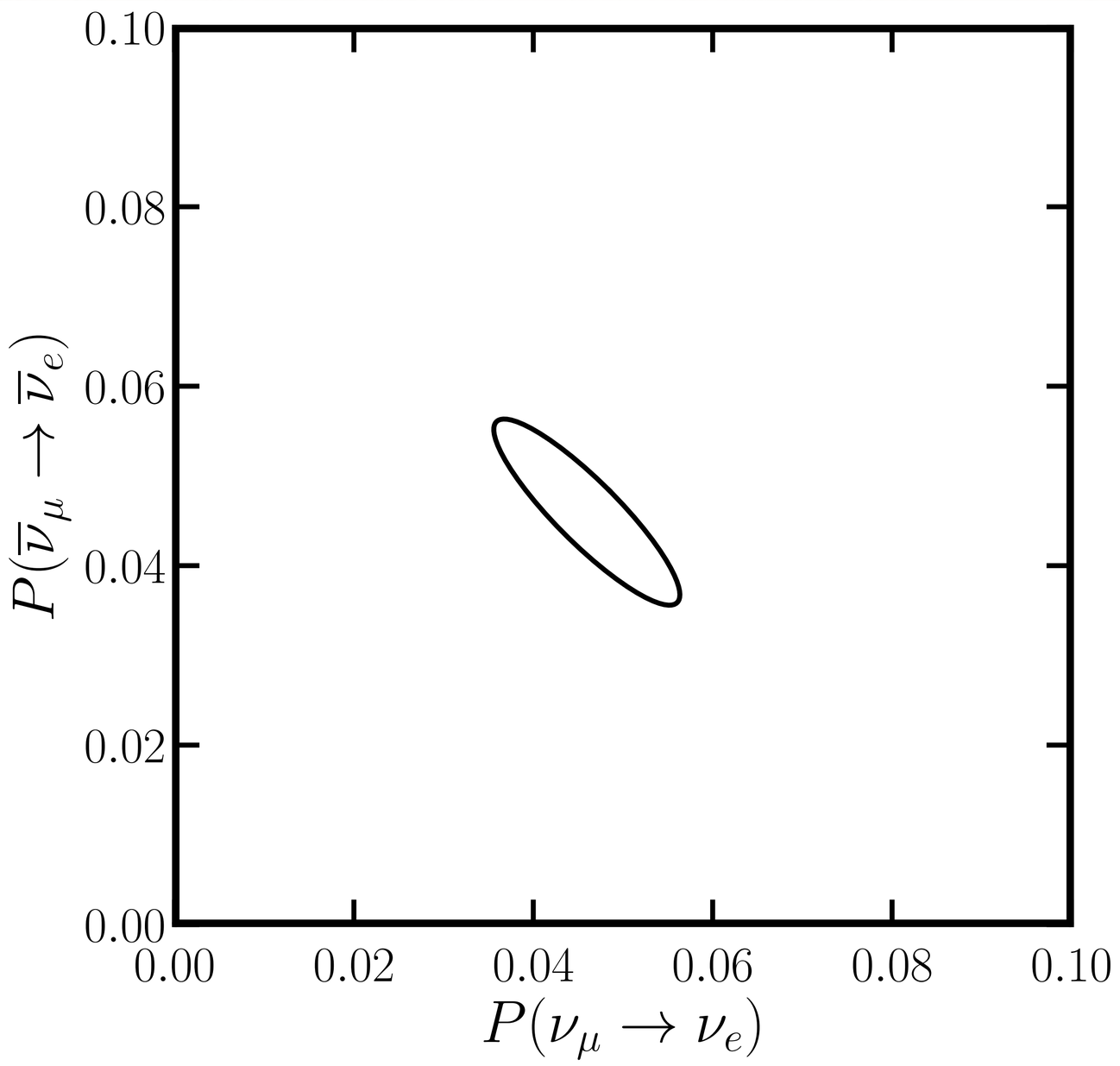
- One way to determine the mass ordering: measure electron neutrino appearance after muon neutrinos propagate through matter





Long-baseline Electron Neutrino Appearance



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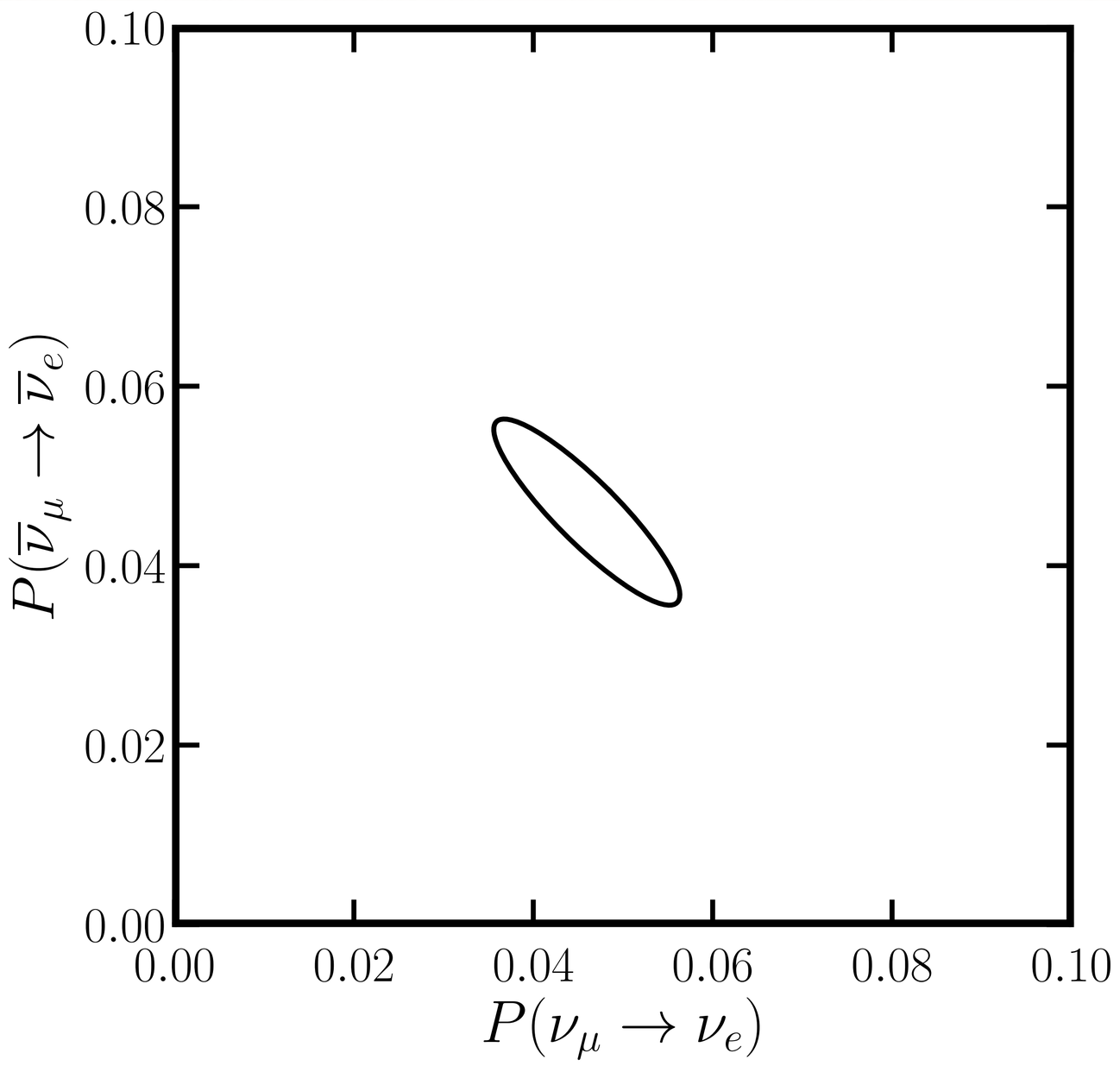

- For a fixed baseline length and neutrino energy, fix the mixing angles and mass-squared splittings to their best-fit values.
- Black line: generated by varying the CP-violating phase for vacuum oscillations.

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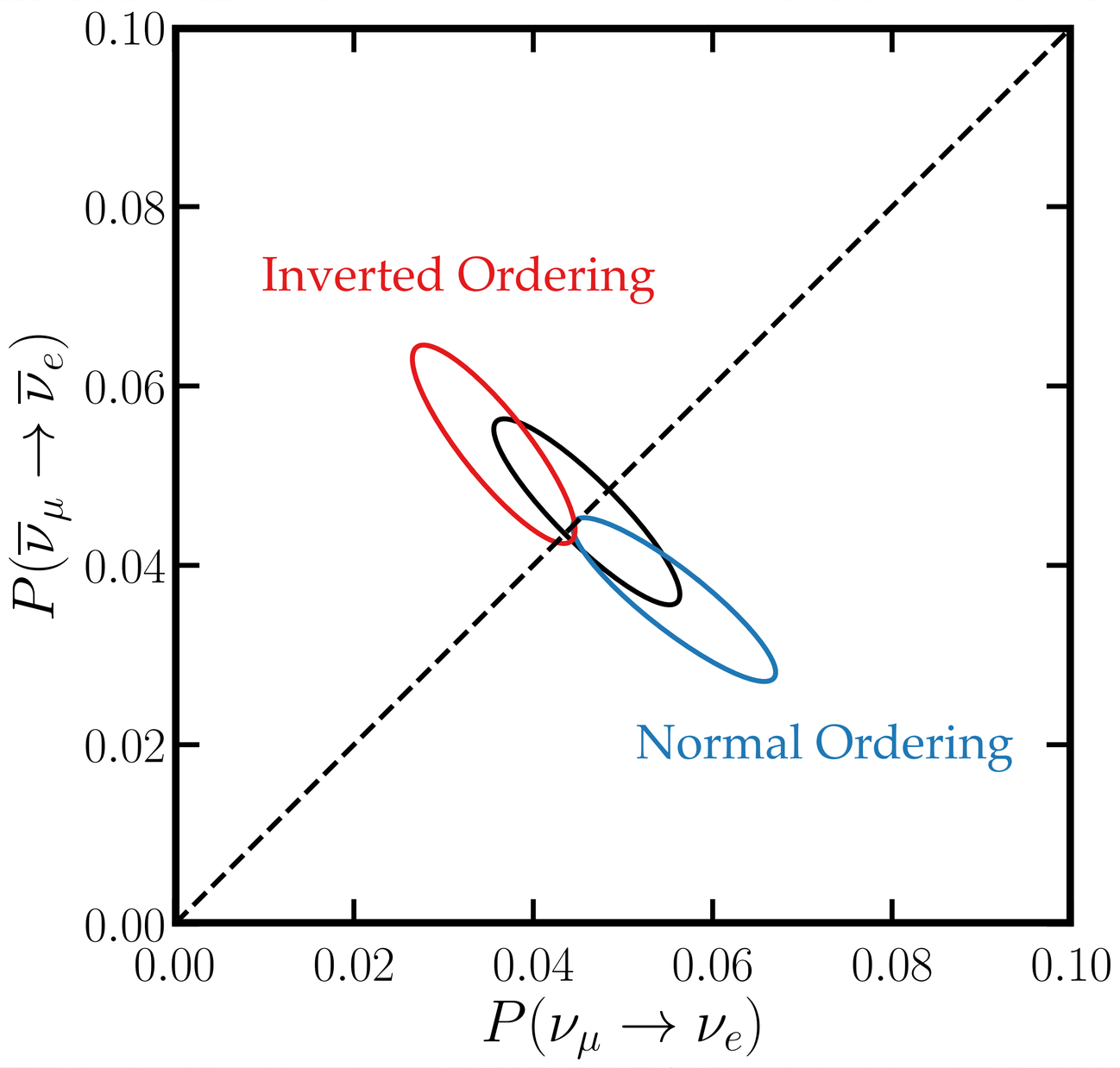
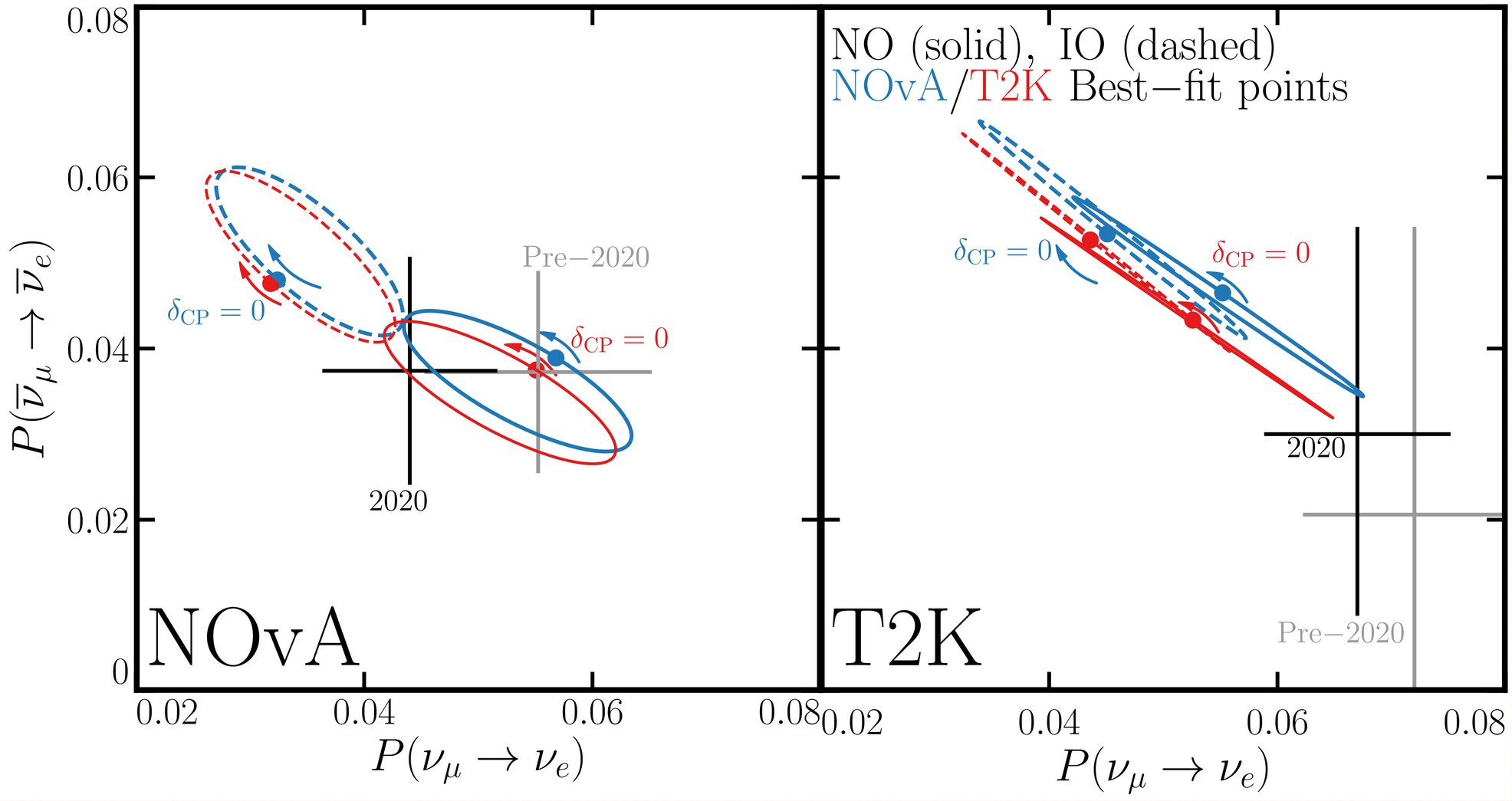


- For a fixed baseline length and neutrino energy, fix the mixing angles and mass-squared splittings to their best-fit values.
- Black line: generated by varying the CP-violating phase for vacuum oscillations.
- Red/blue lines: generated considering oscillations in matter assuming the inverted/normal orderings.
- For similar L/E, this separation increases for larger L and E.

Recent Results: T2K and NOvA

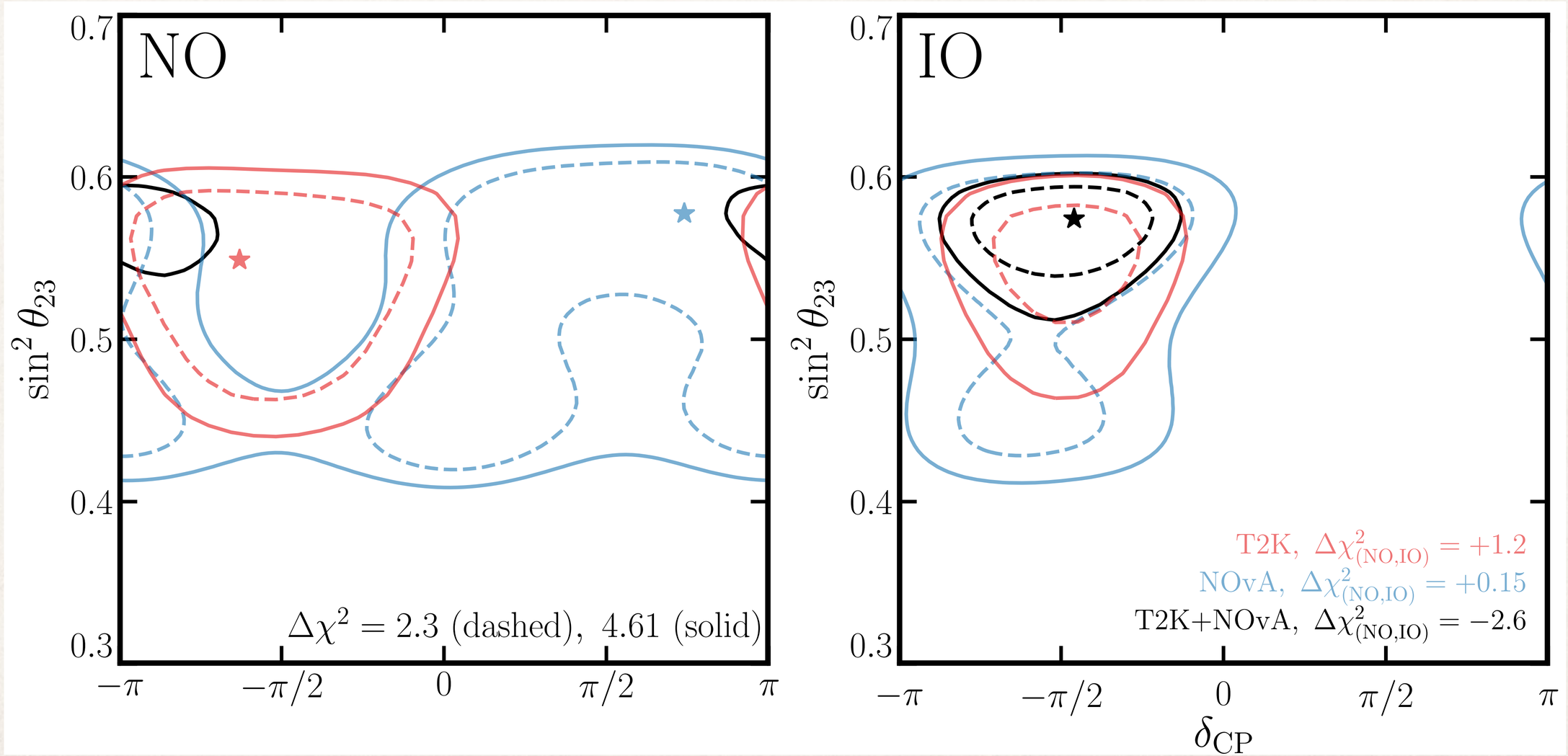
KJK et al, [2007.08526]



Previous data from T2K/NOvA preferred the NO strongly, but 2020 data have pushed the preference down significantly.

Long-baseline Preference for Mass Ordering

On their own, T2K and NOvA each prefer the Normal Ordering, but their combination prefers Inverted. Global preference for NO is now significantly reduced.



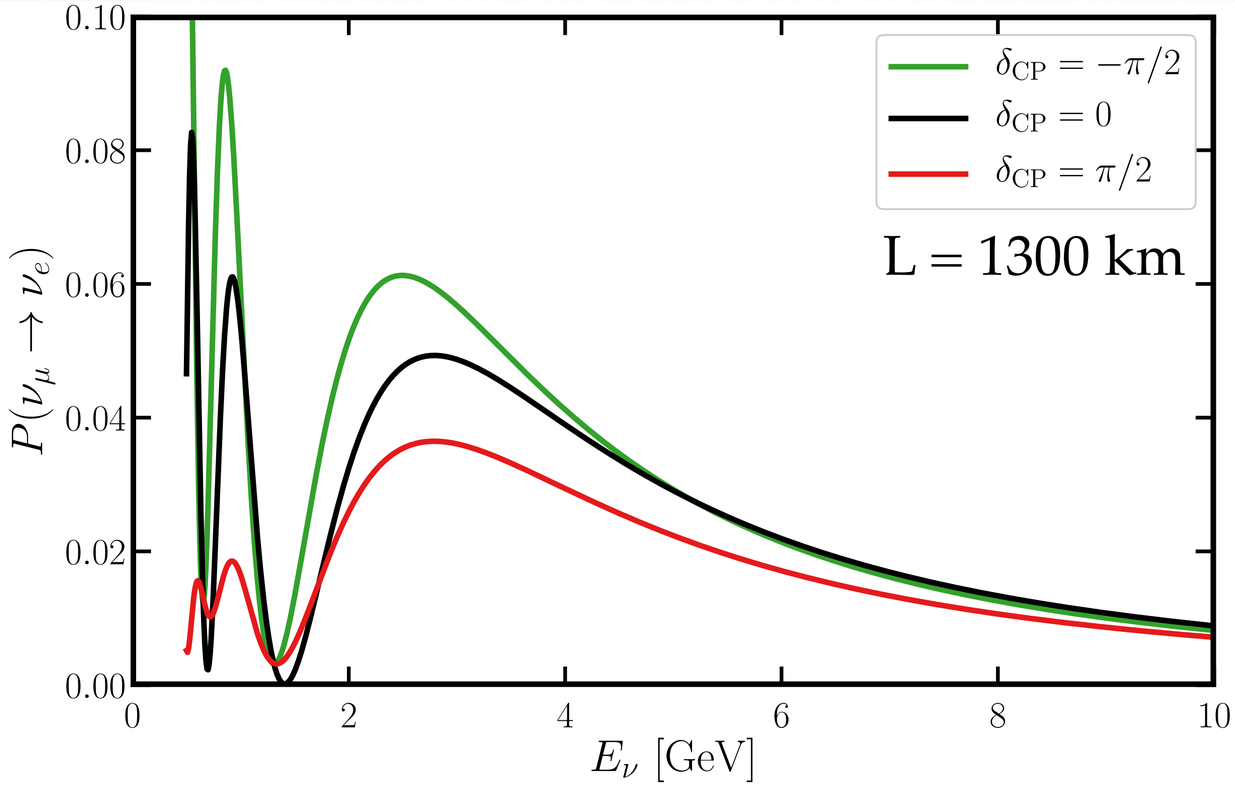
Consistent with other global fits, e.g., [2007.14792]

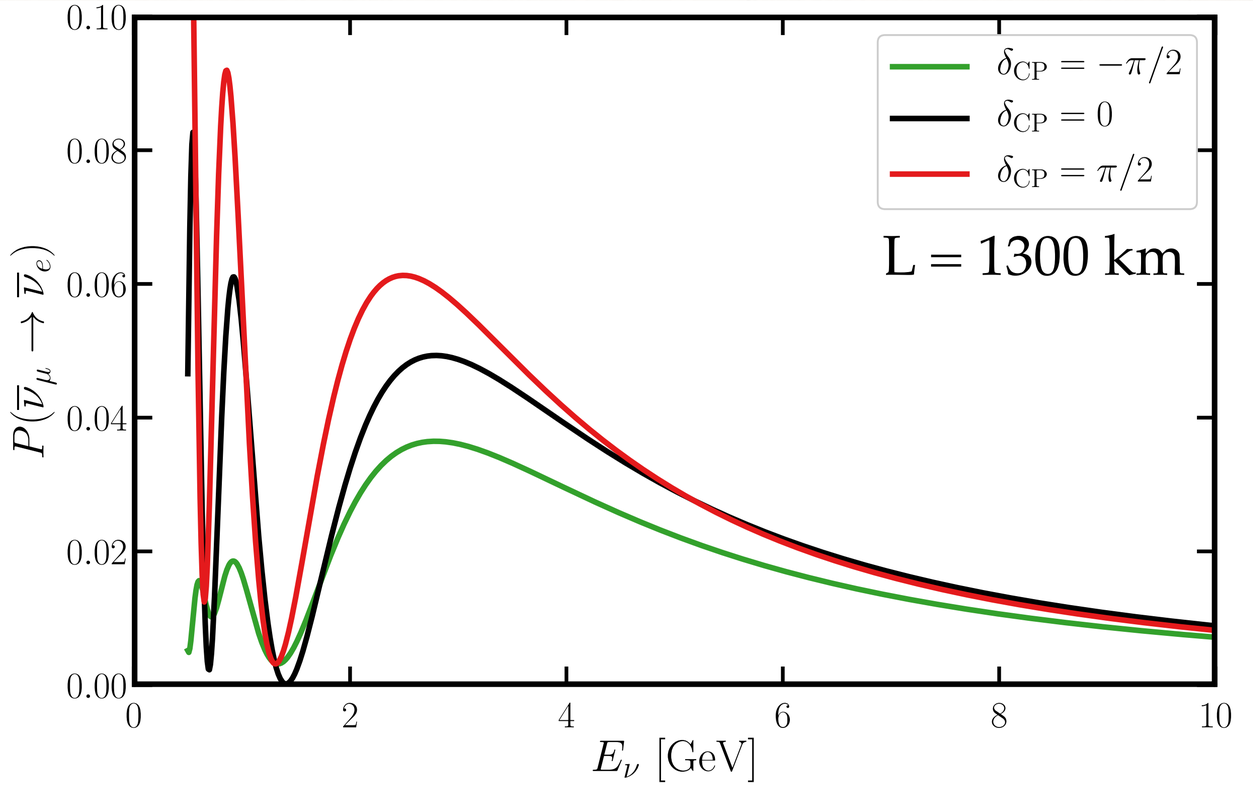
KJK et al, [2007.08526]

Other Prevailing Unknown: CP Violation

CP Violation causes

$$P(\nu_\mu \to \nu_e) \neq P(\overline{\nu}_\mu \to \overline{\nu}_e)$$





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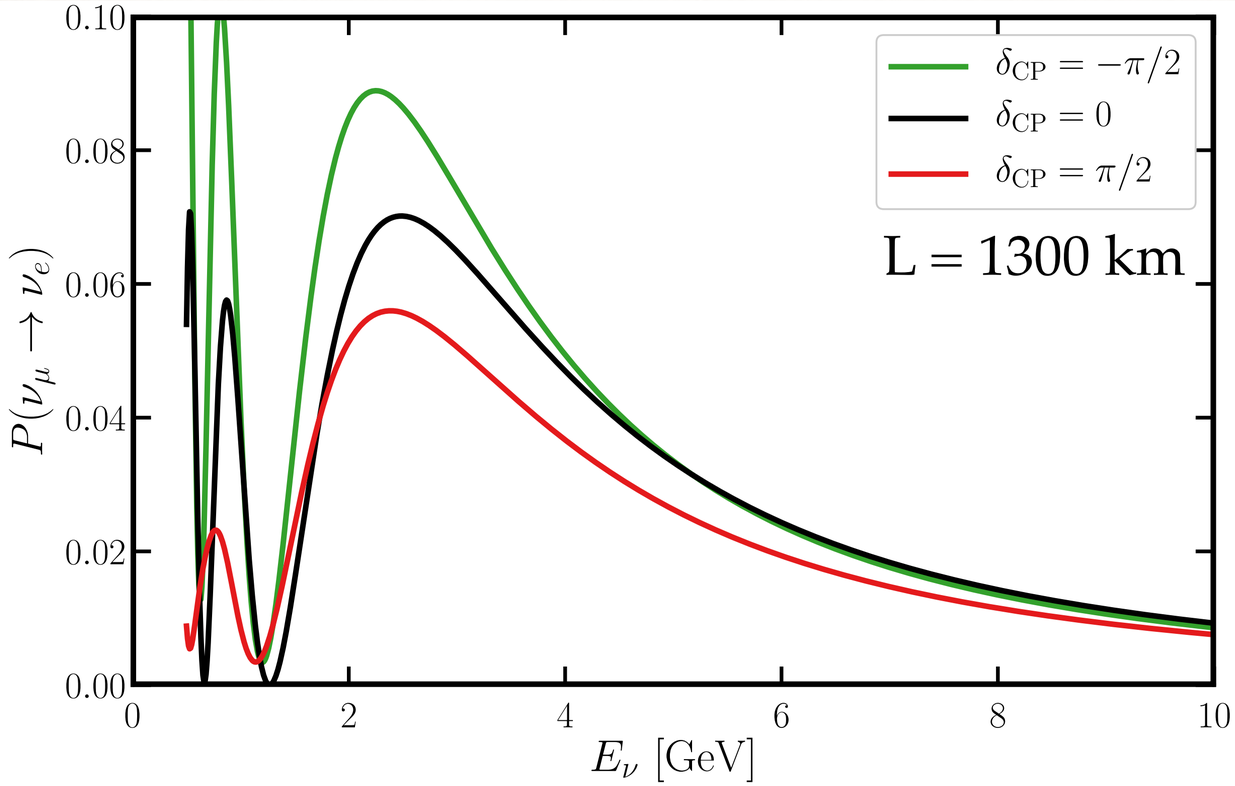

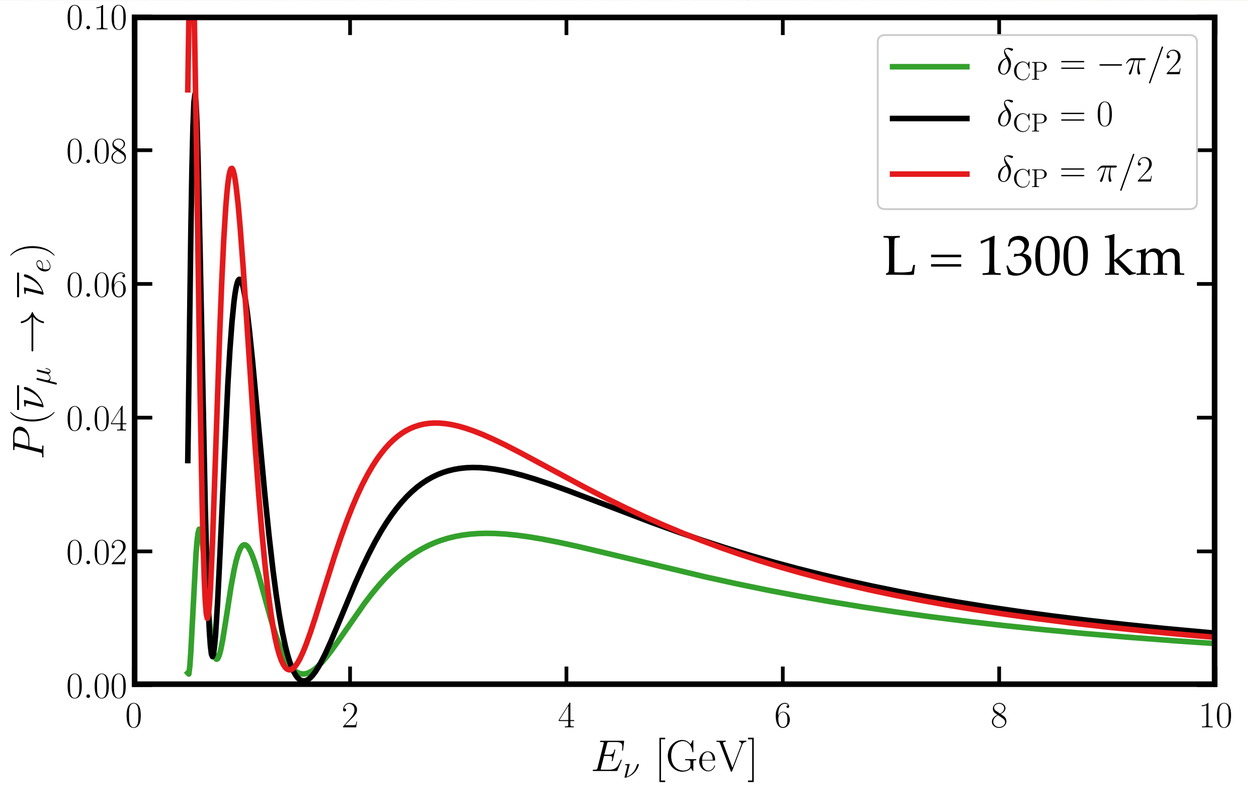

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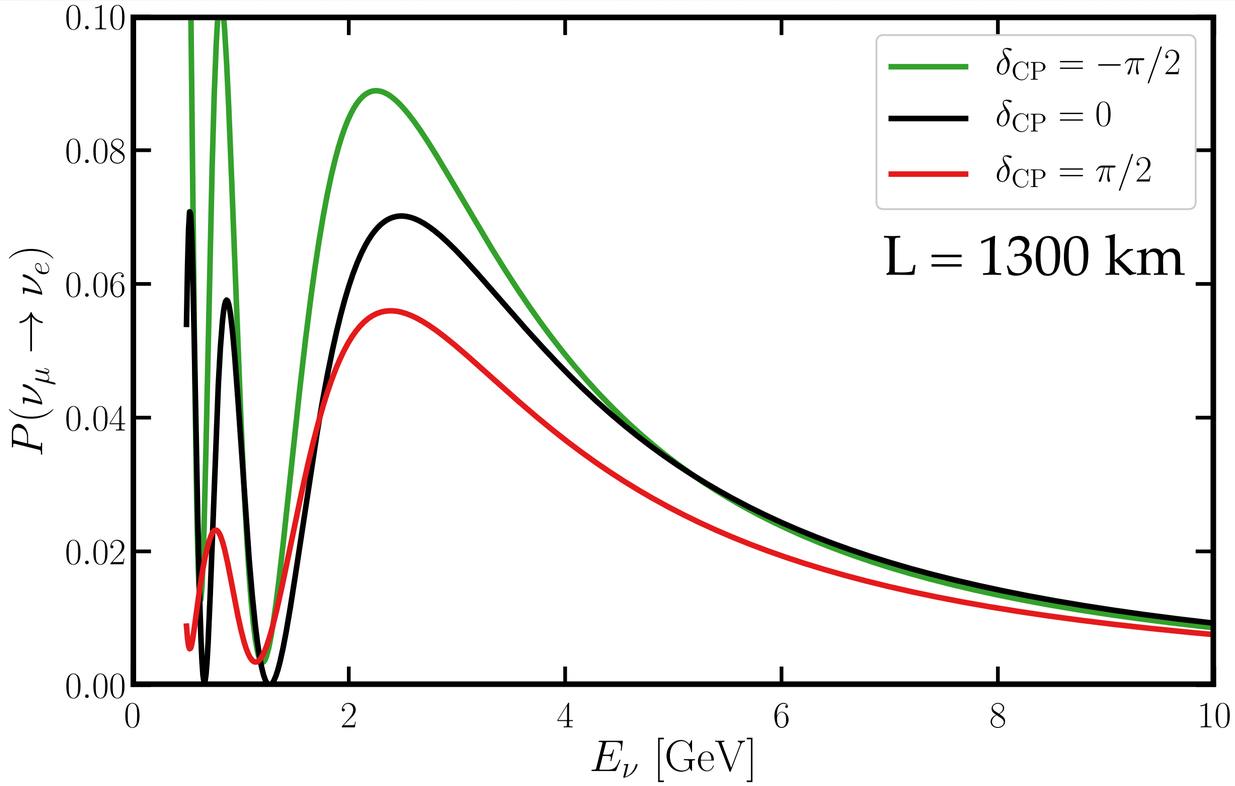
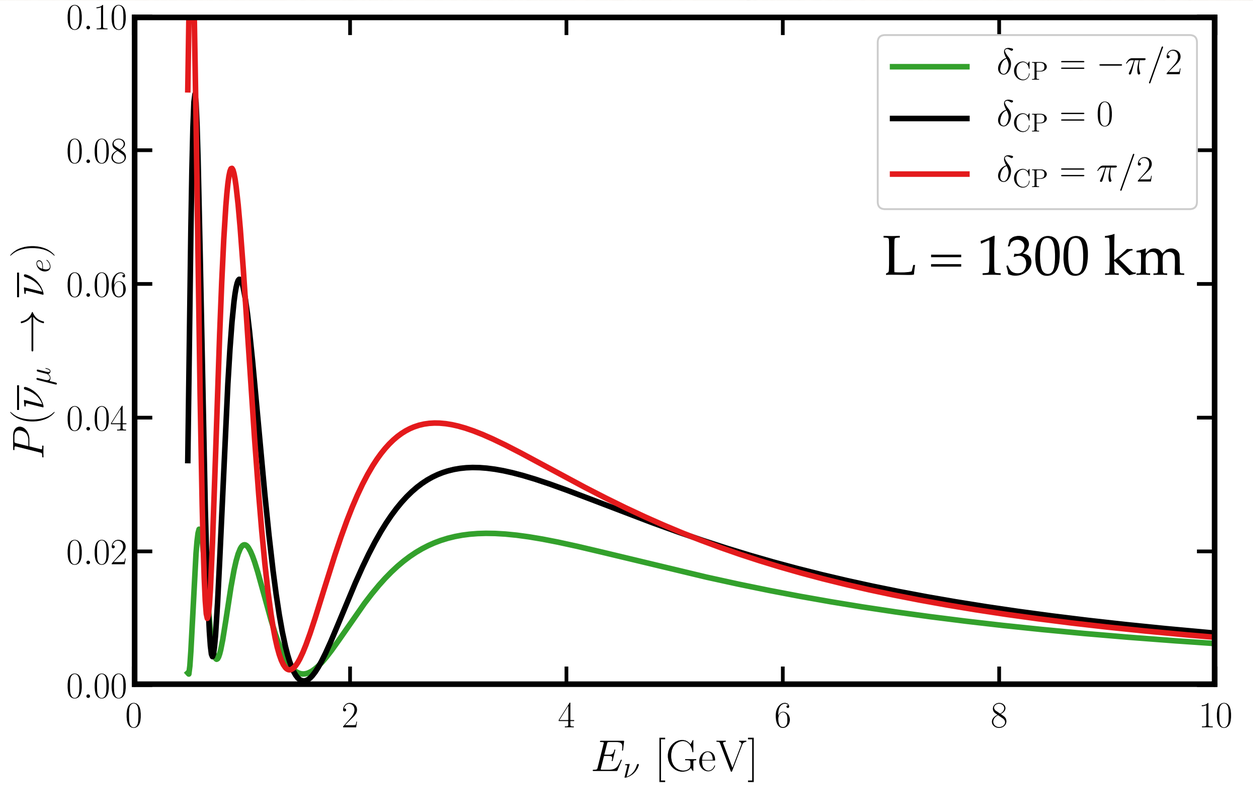
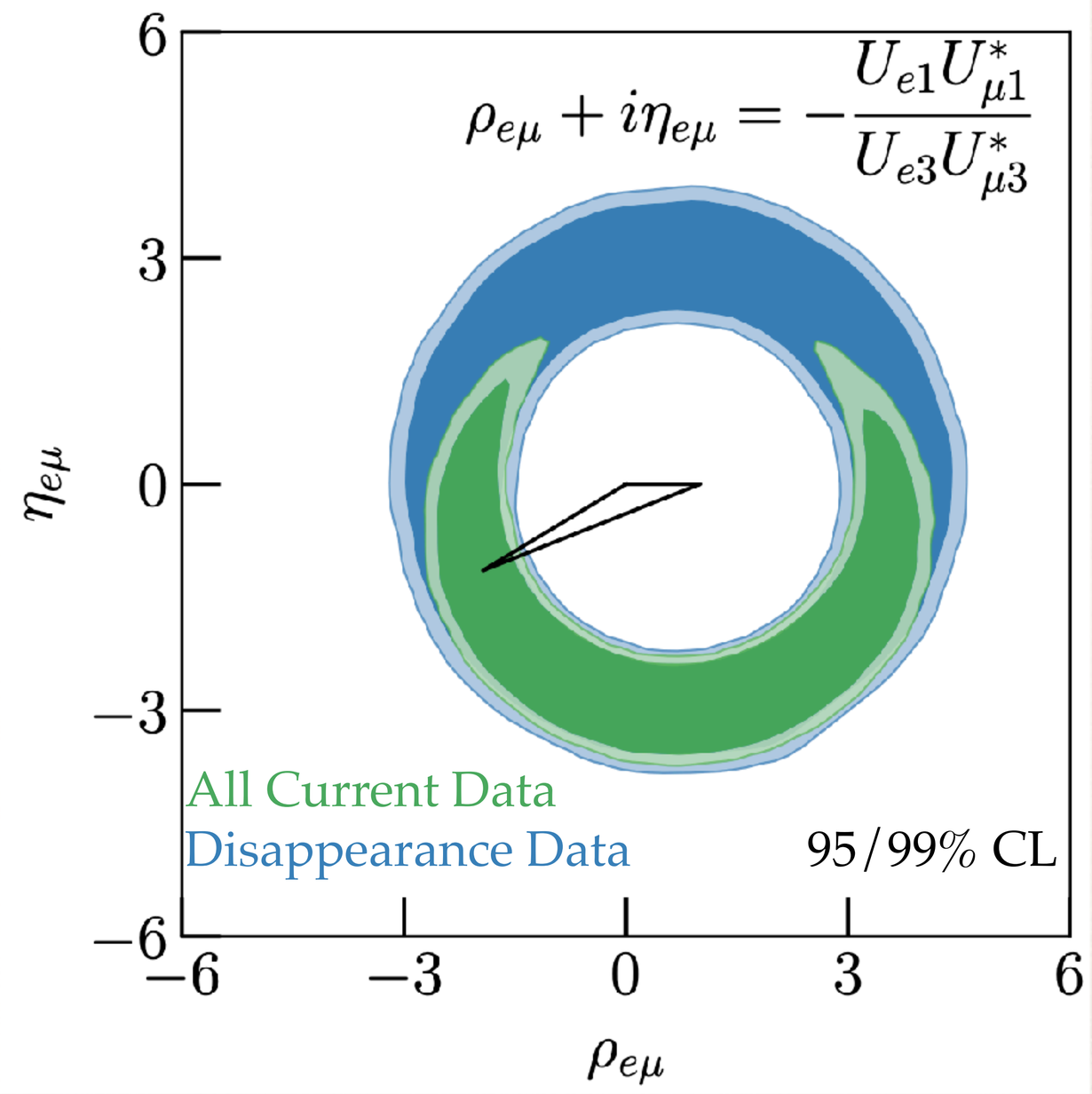




- Matter effects themselves are CP-violating. Because of this and degeneracy with other parameters, CP-violation is better measured with wide-energy beams.

Unitarity Triangles as a Probe of CP Violation



Ellis, KJK, Li [2004.13719]

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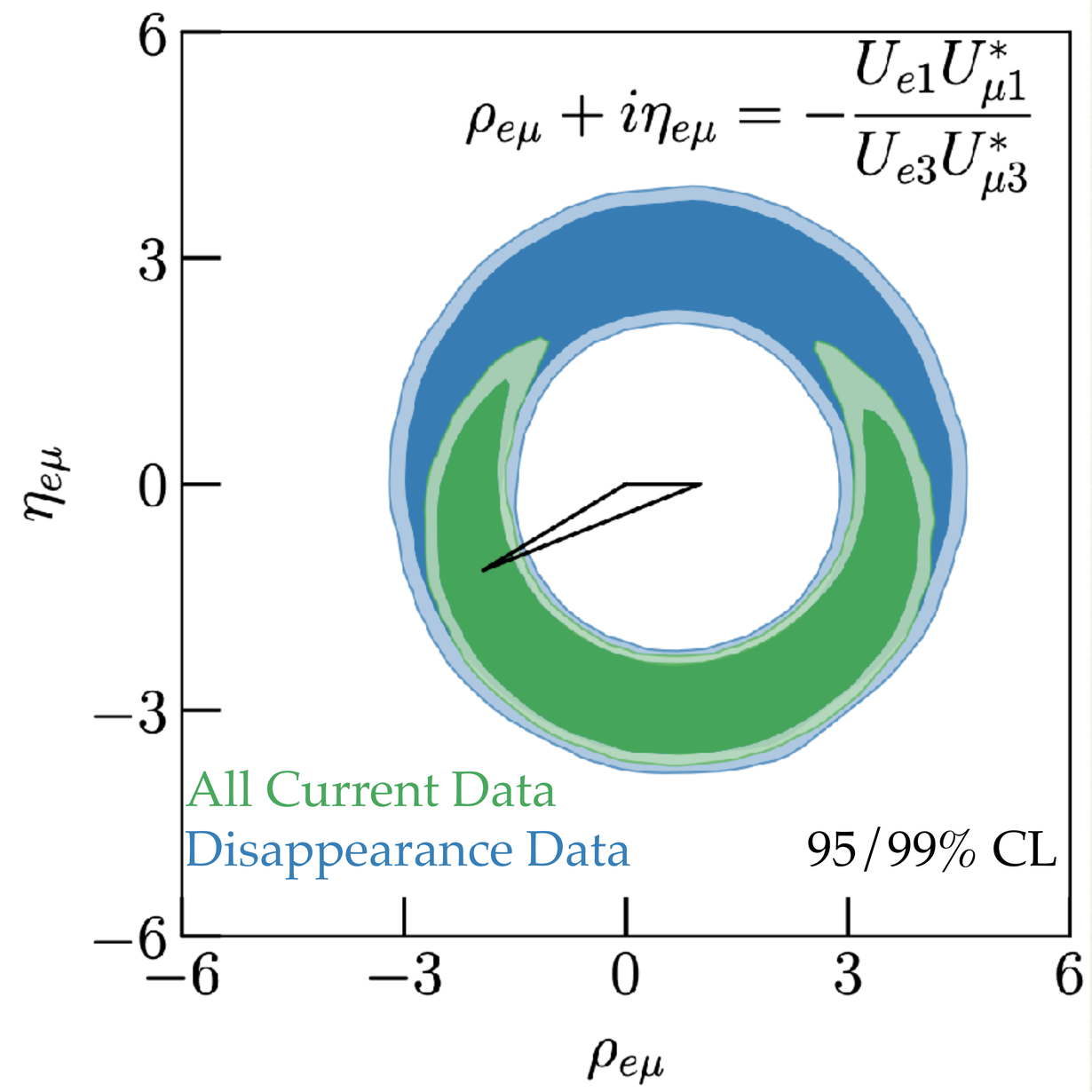


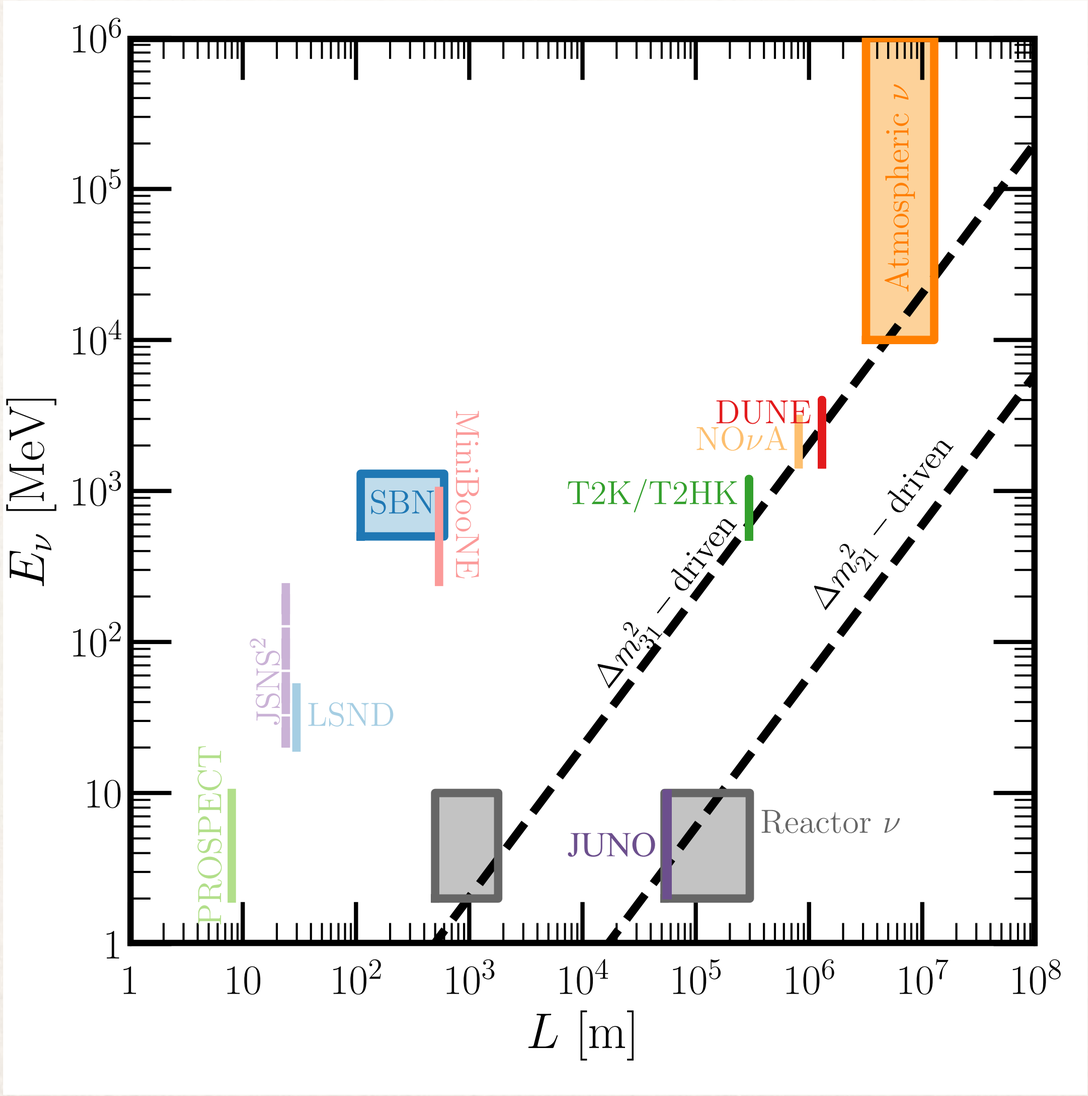
Current data: compatible with no CP violation and maximal CP violation at 95% CL.

Ellis, KJK, Li [2004.13719]

Where are we going?

Perspectives on the upcoming decade

New/Upgraded Experiments on the Horizon



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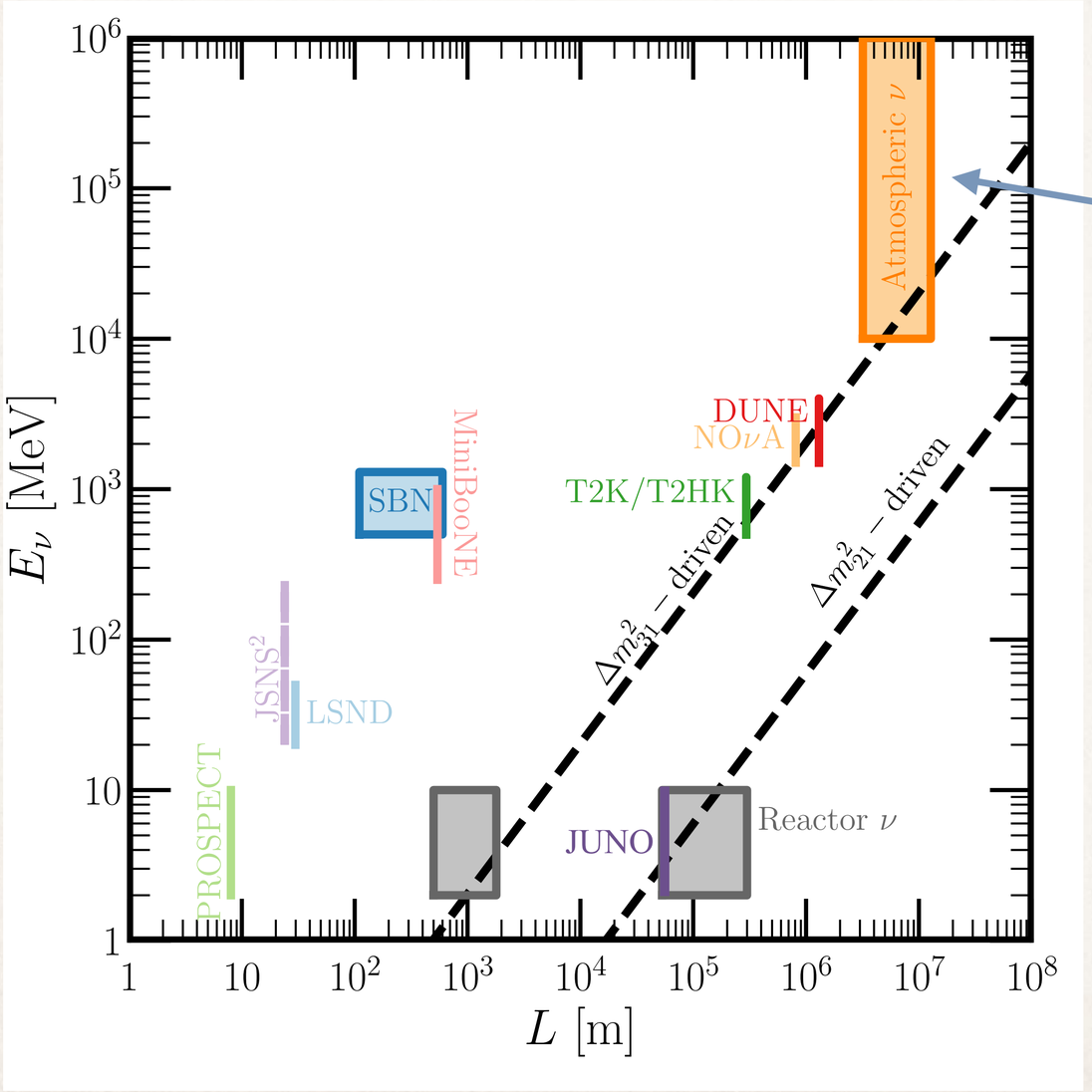

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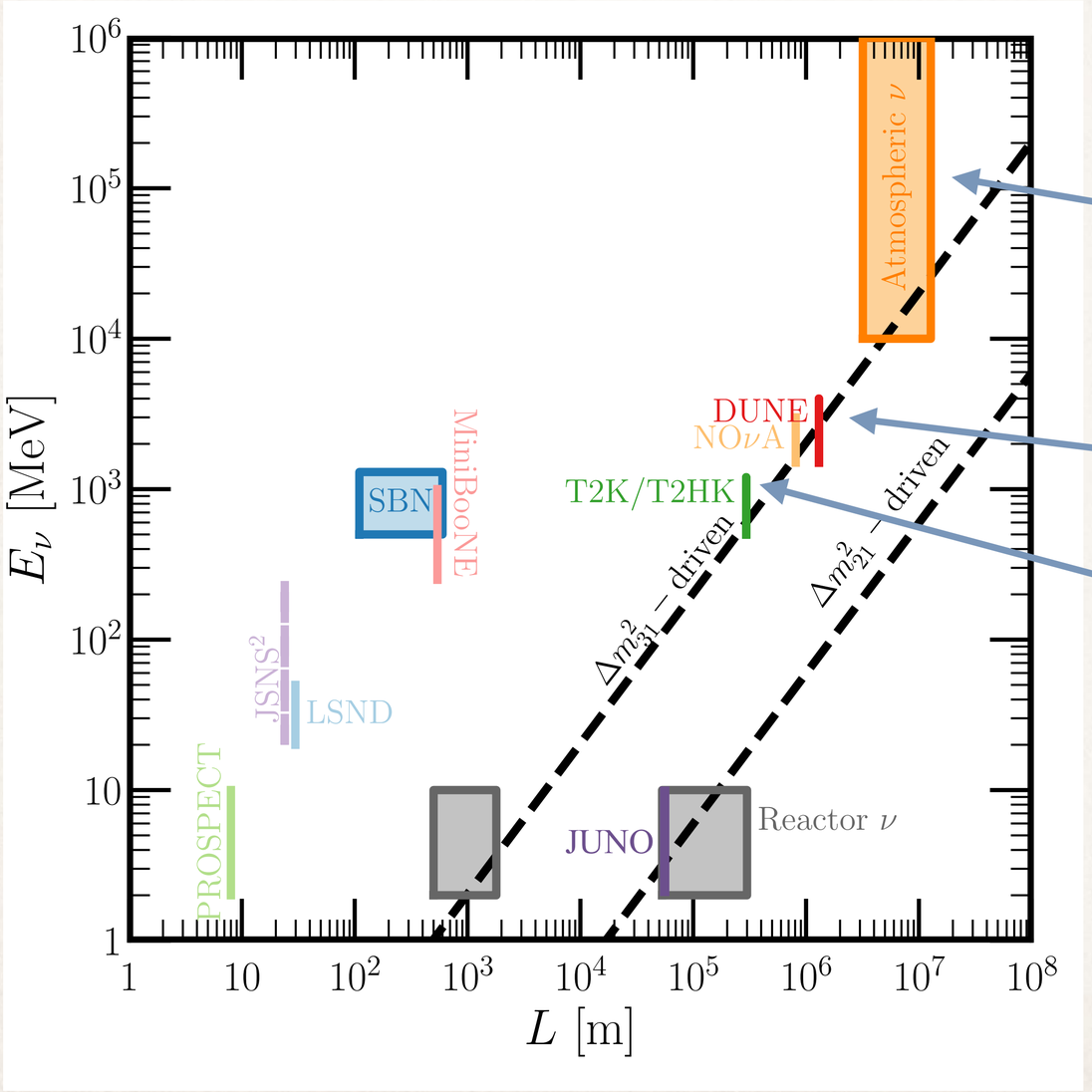

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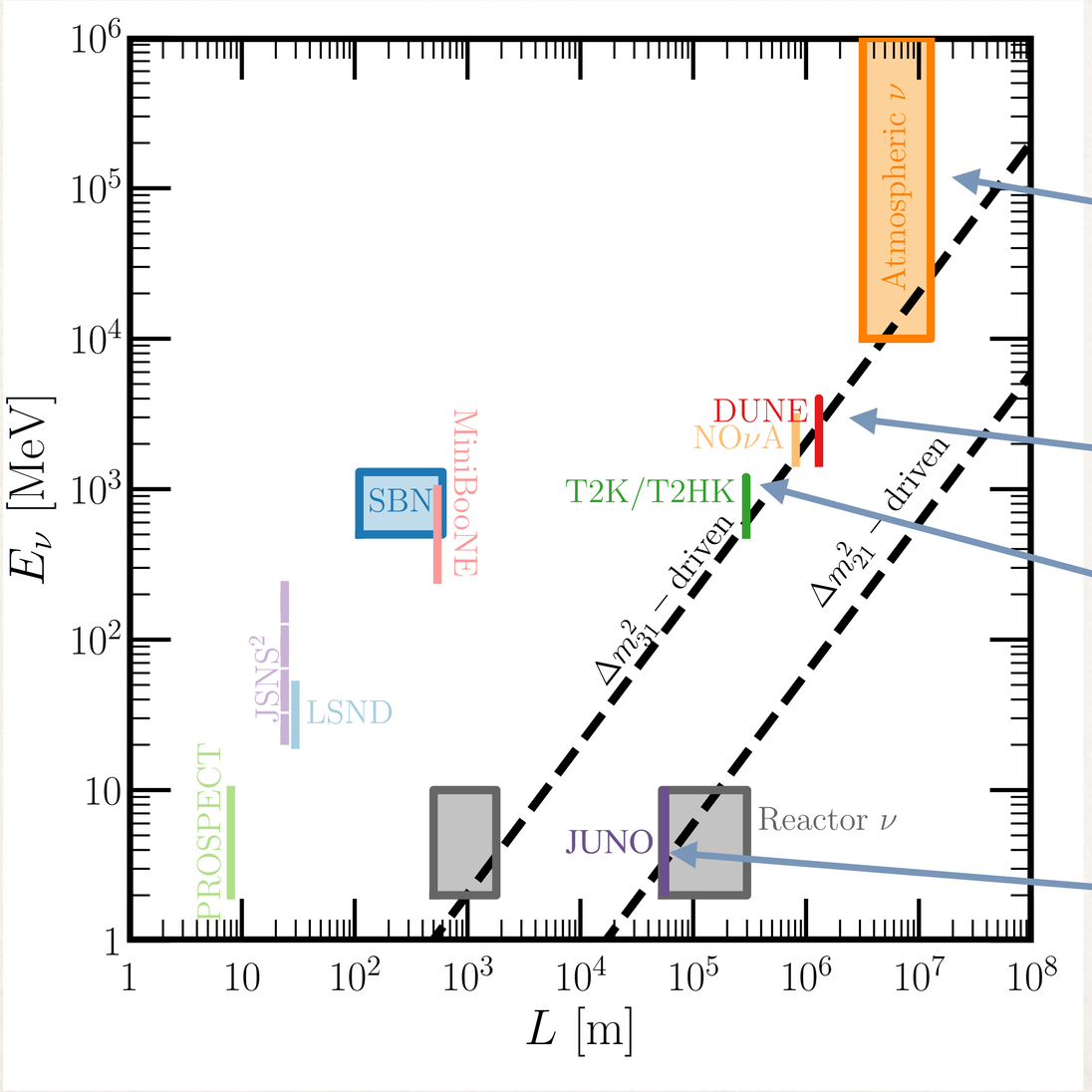

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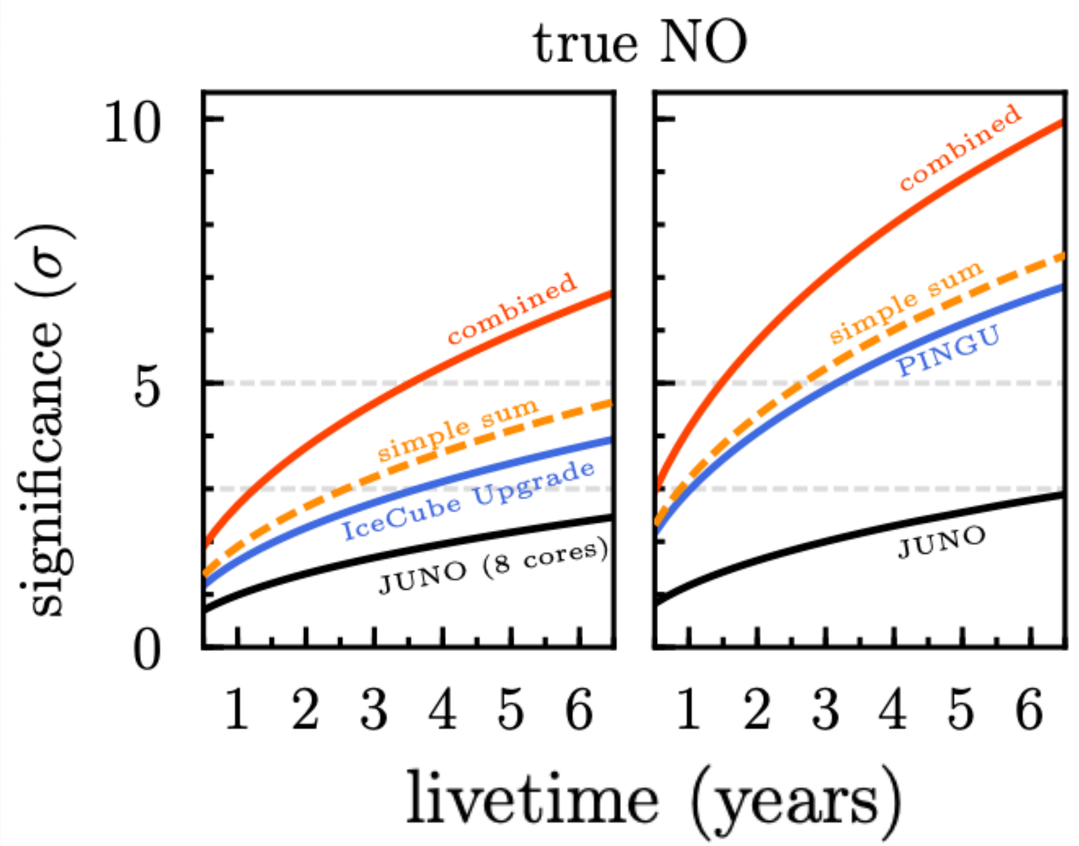
- DUNE/T2HK: Long-baseline, broad-energy beam-based experiments, suited for measuring muon disappearance/electron appearance. Both have promising atmospheric neutrino capabilities as well.
- JUNO: Medium-baseline reactor antineutrino experiment, designed to measure the mass ordering robustly.

The Next Generation and the Mass Ordering



IceCube-Gen2 & JUNO Collaborations,
[1911.06745]

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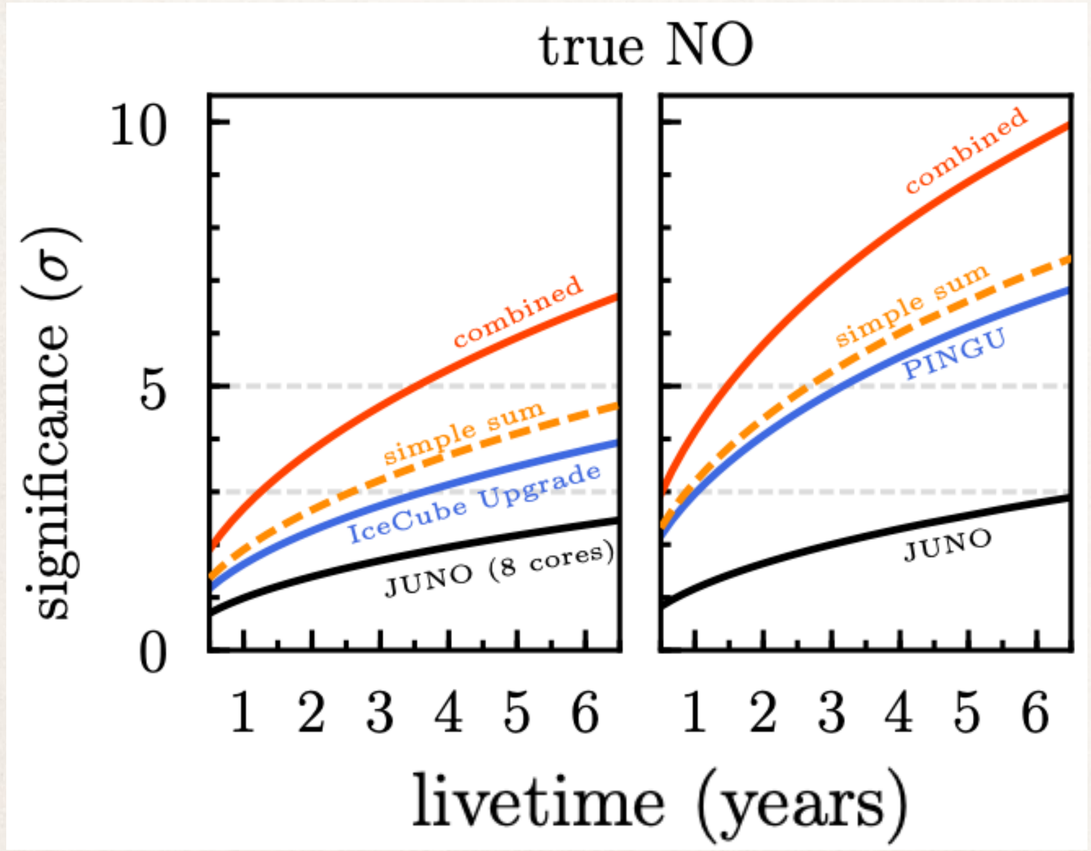

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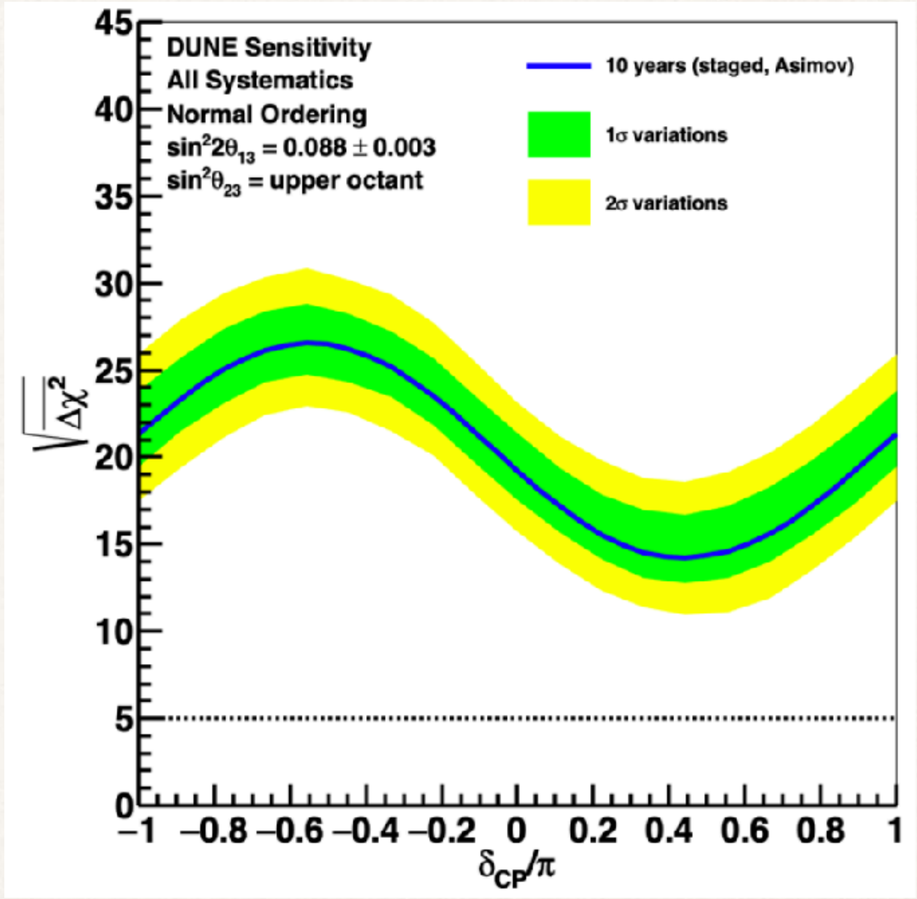
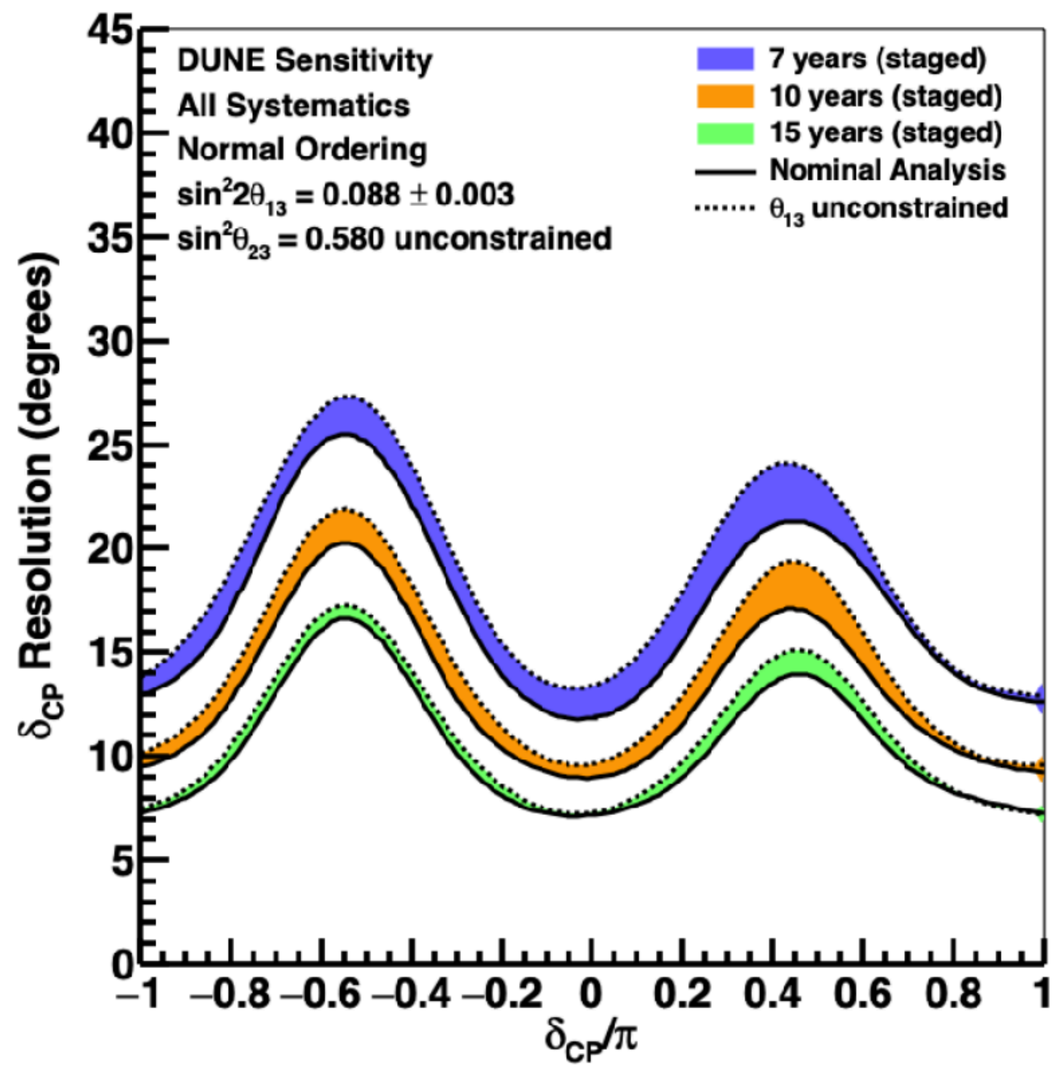


DUNE Collaboration,
[2002.03005]

The Next Generation and CP Violation



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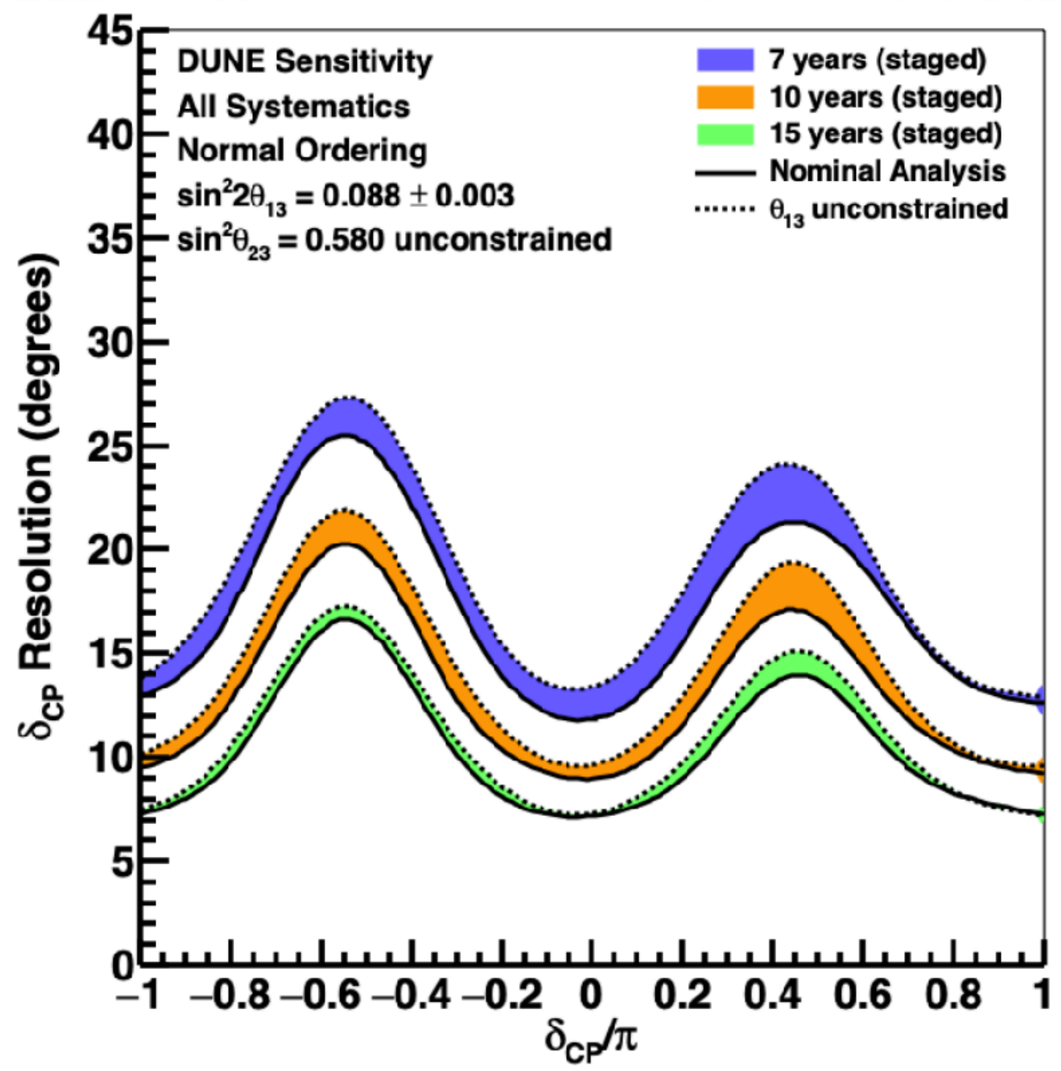

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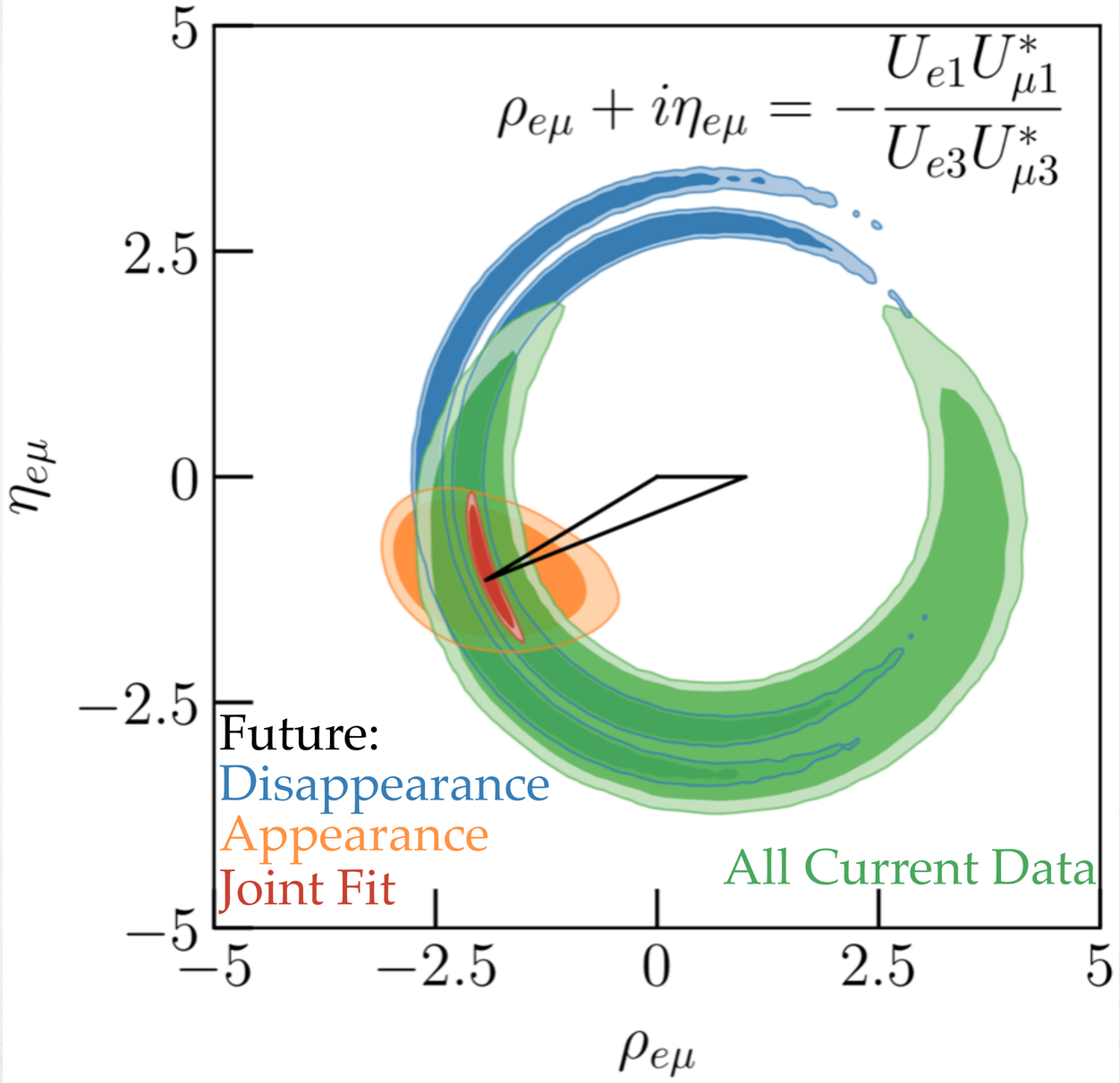

Ellis, KJK, Li [2004.13719]

Assuming “standard” oscillation physics,

DUNE, Hyper-Kamiokande, JUNO, IceCube-Gen2 will resolve all current unknowns.

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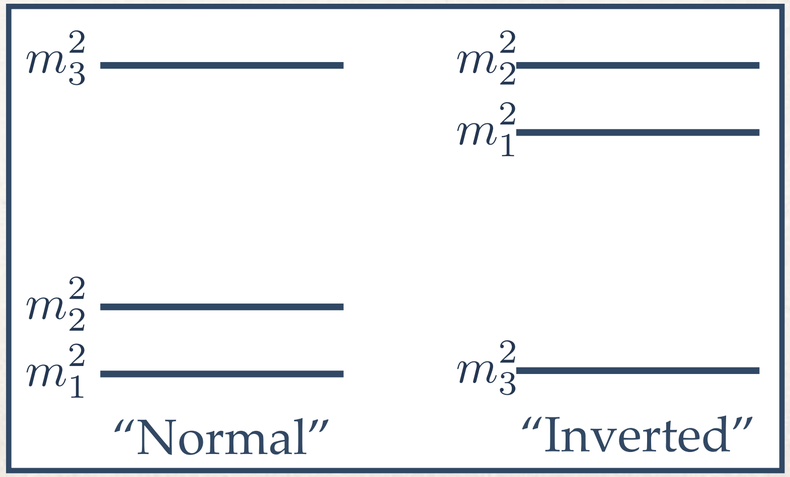
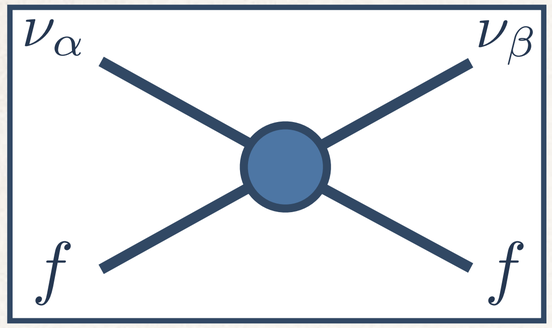


BSM with Neutrino Oscillations

What can Oscillations Teach Us?



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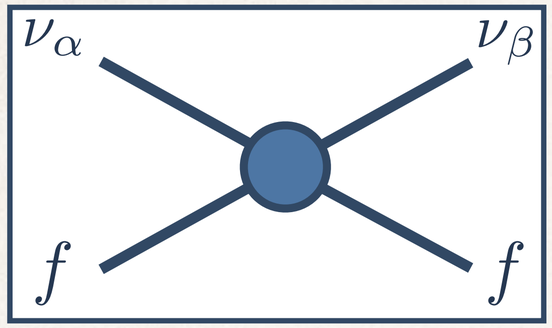

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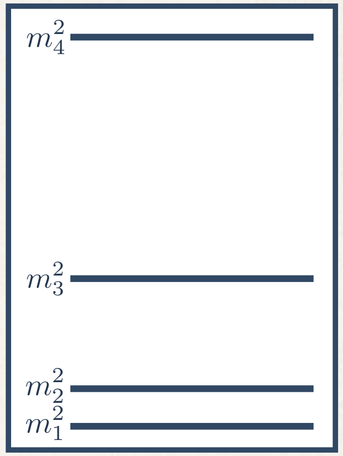

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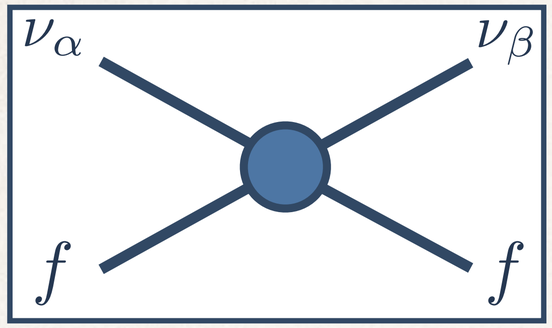

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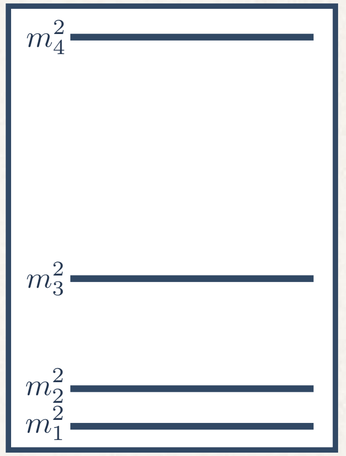

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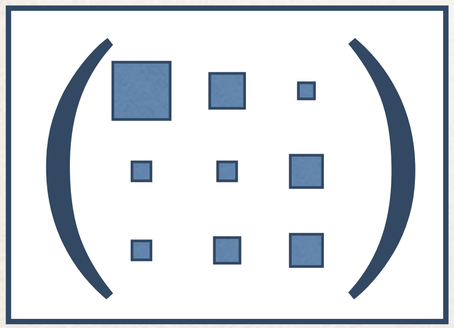

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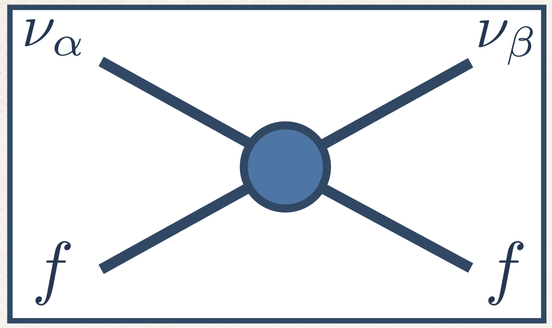

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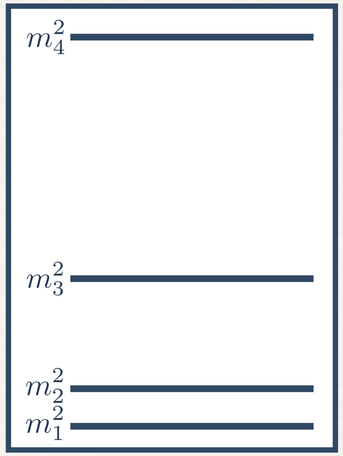

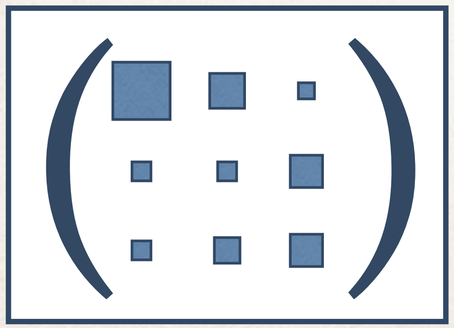

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and much, much more…

Unitarity of the Leptonic Mixing Matrix

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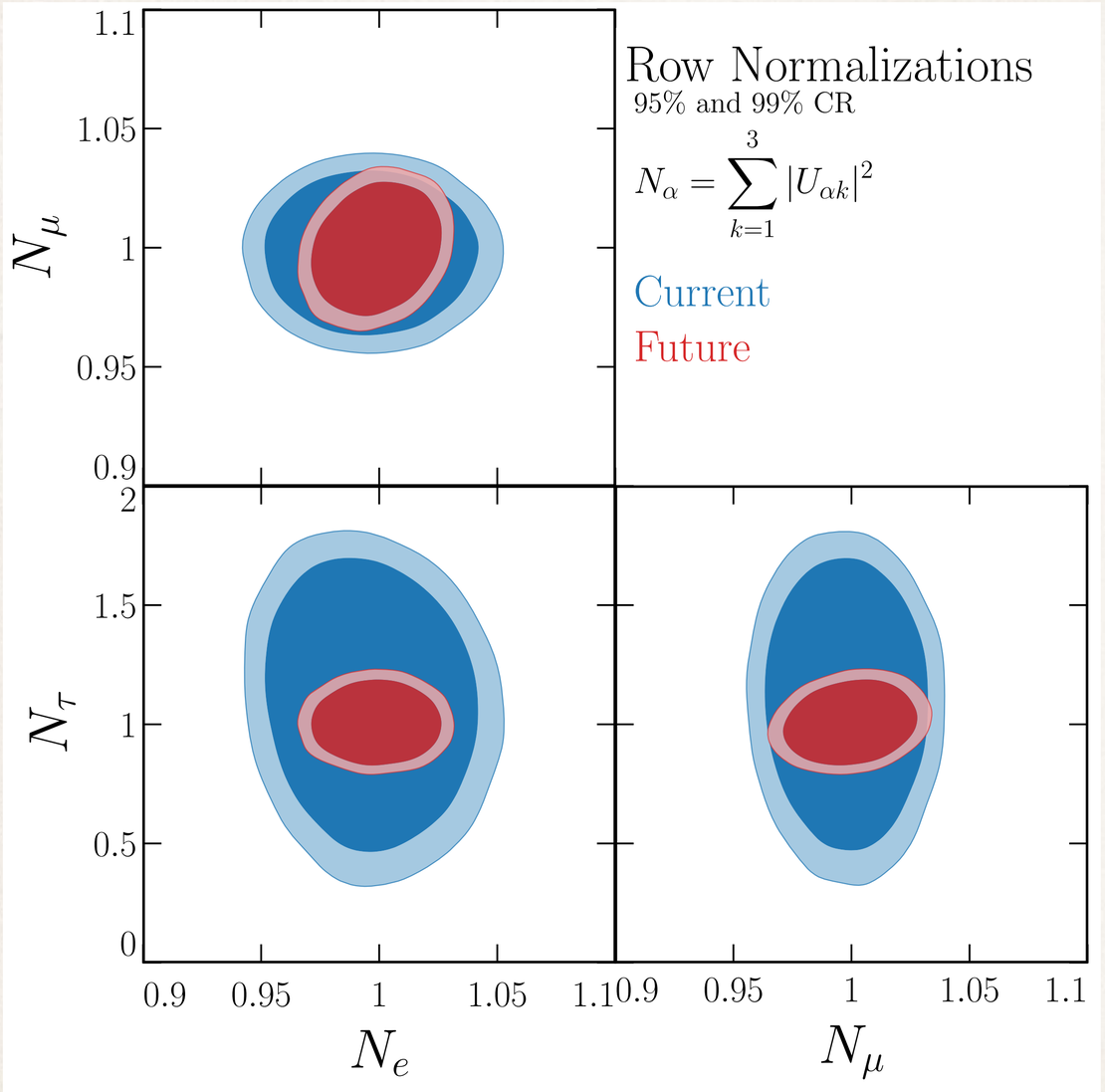
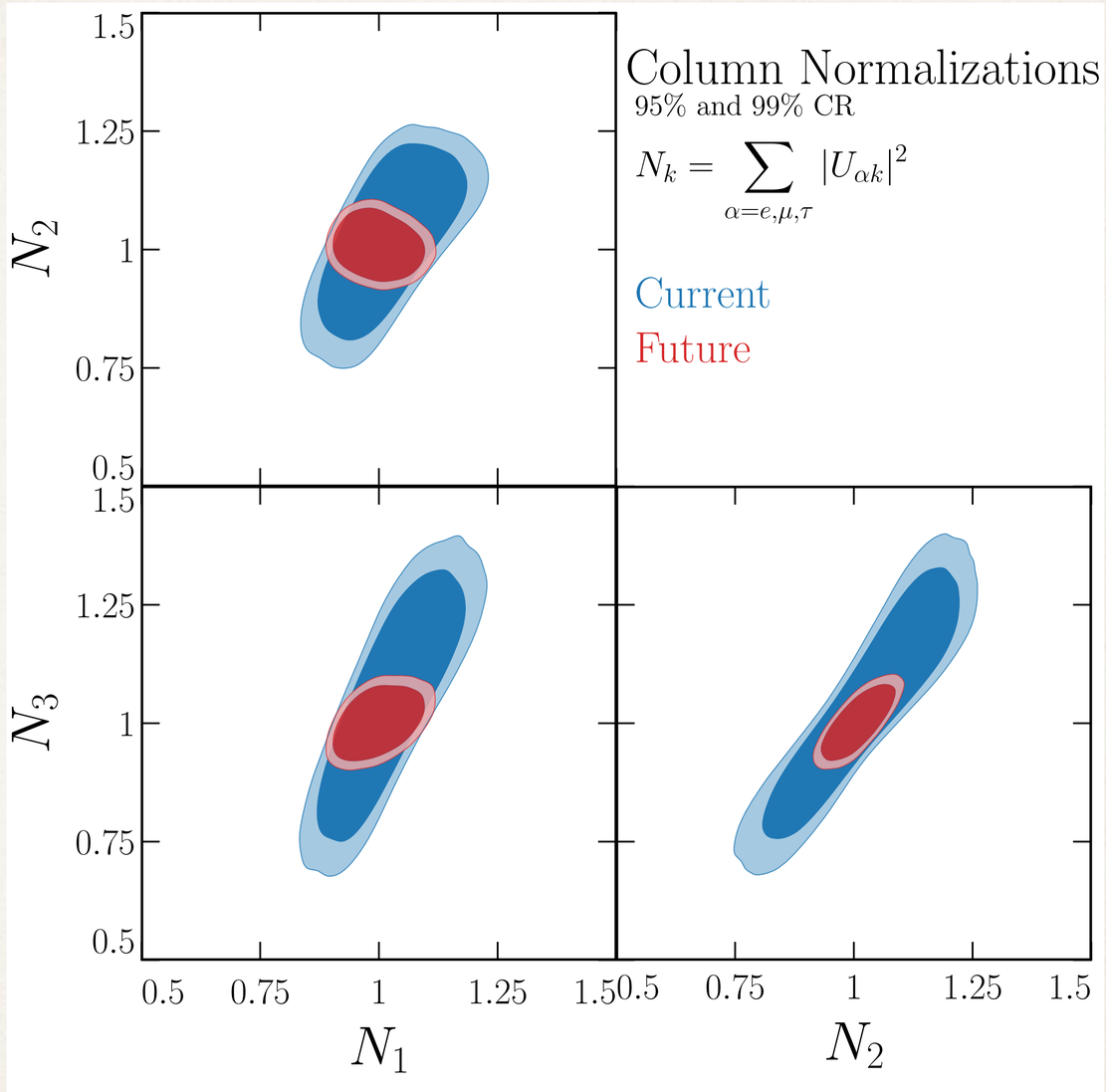
Row / Column Normalizations

Triangle Closures

How well can we constrain the Normalizations?





Ellis, KJK, Li [2008.01088]

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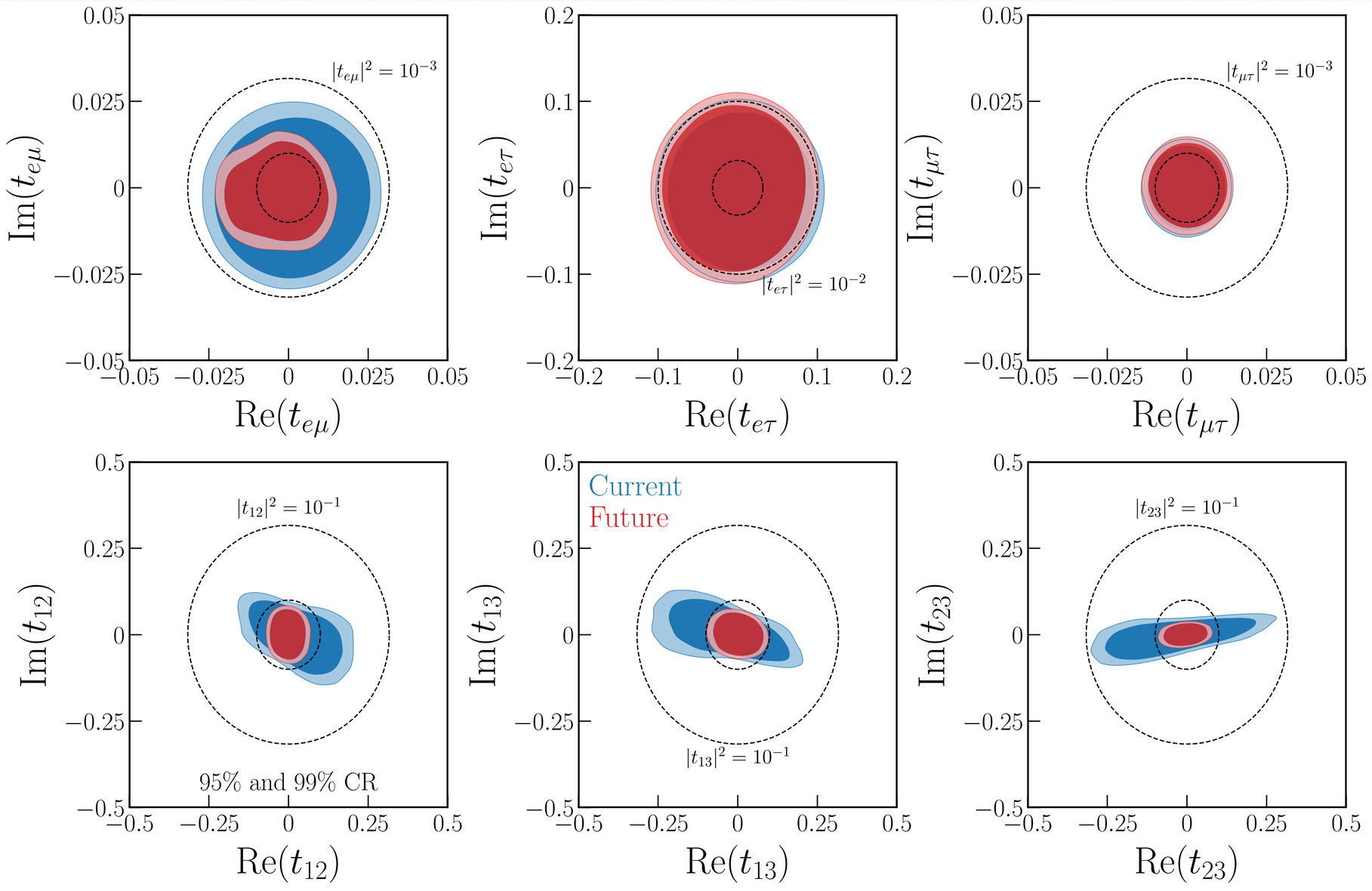
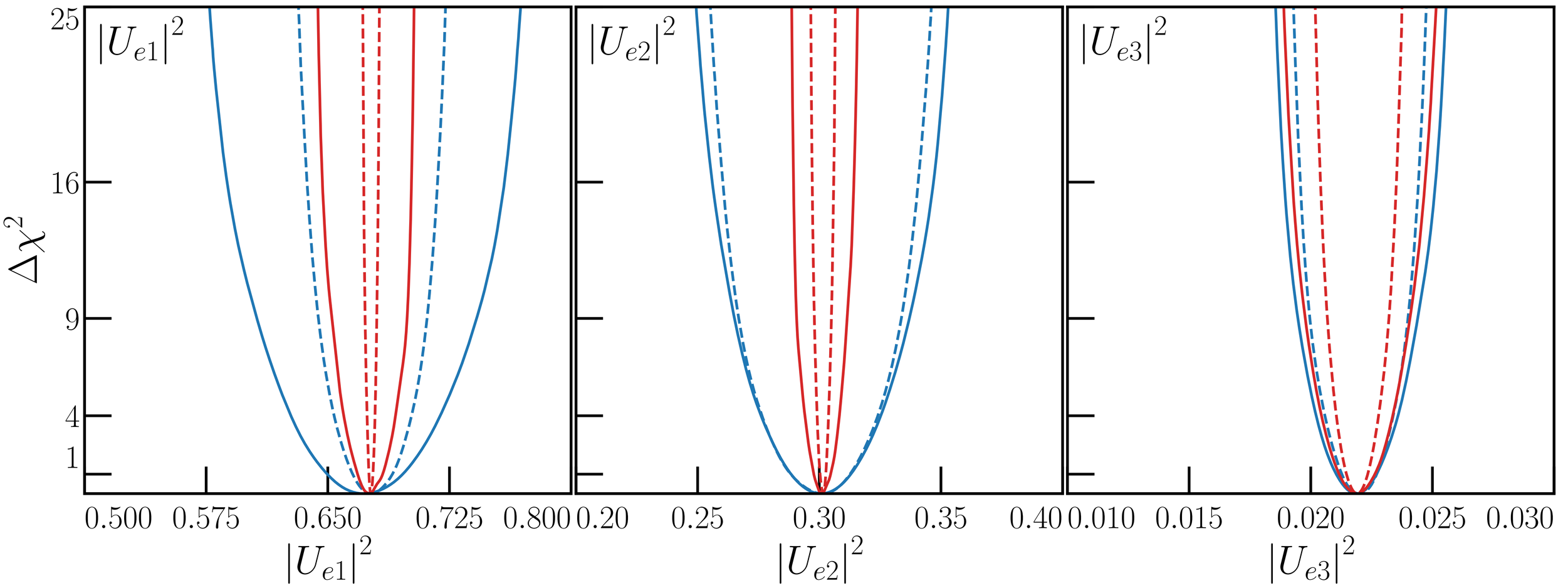


Ellis, KJK, Li [2008.01088]

Individual matrix-elements-squared?



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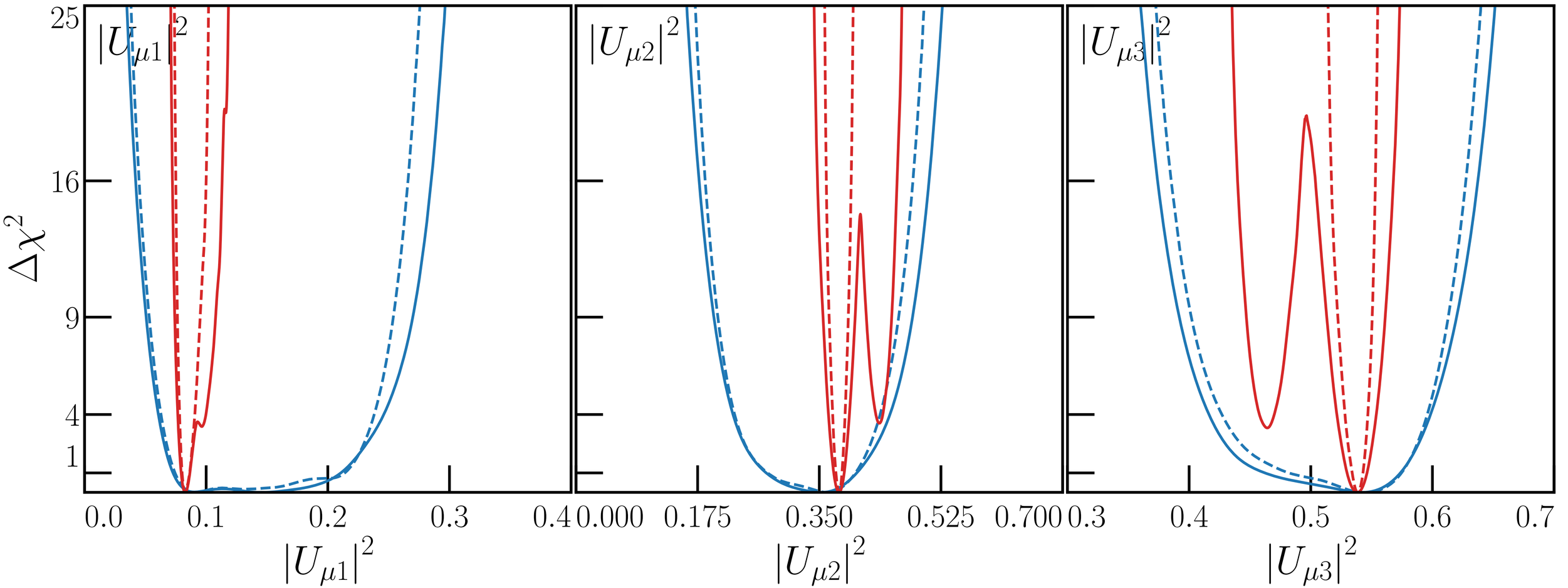

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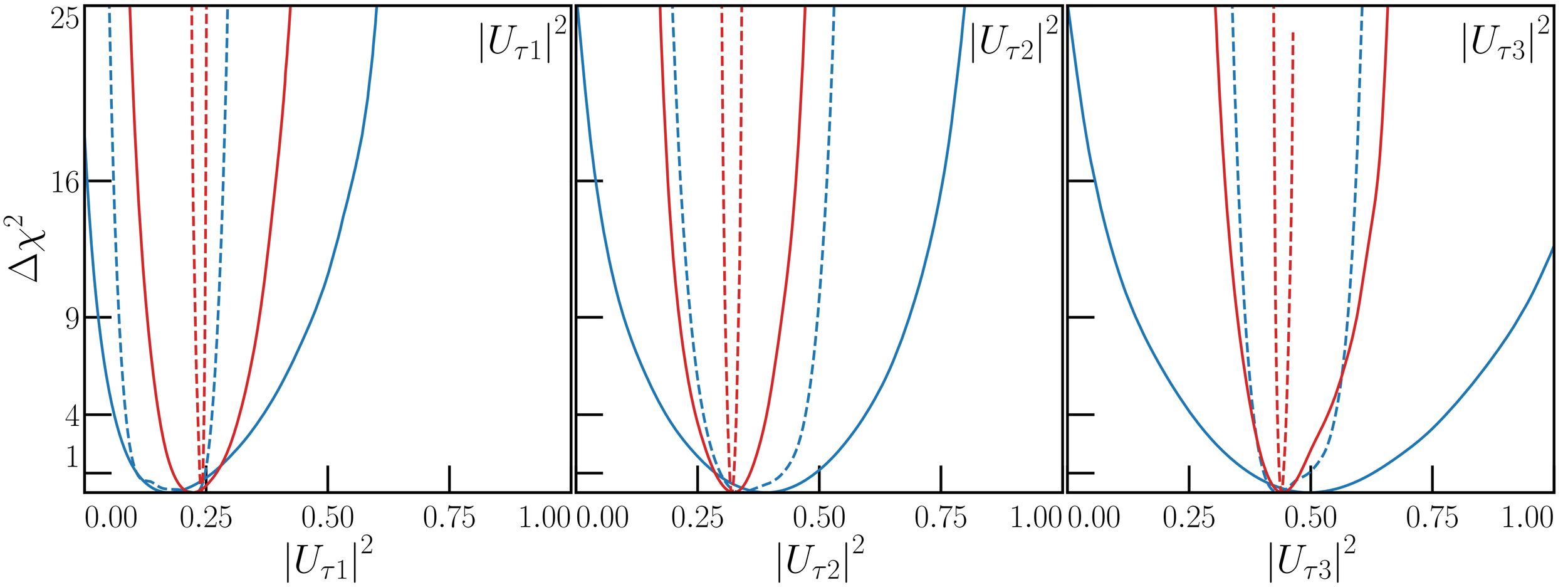

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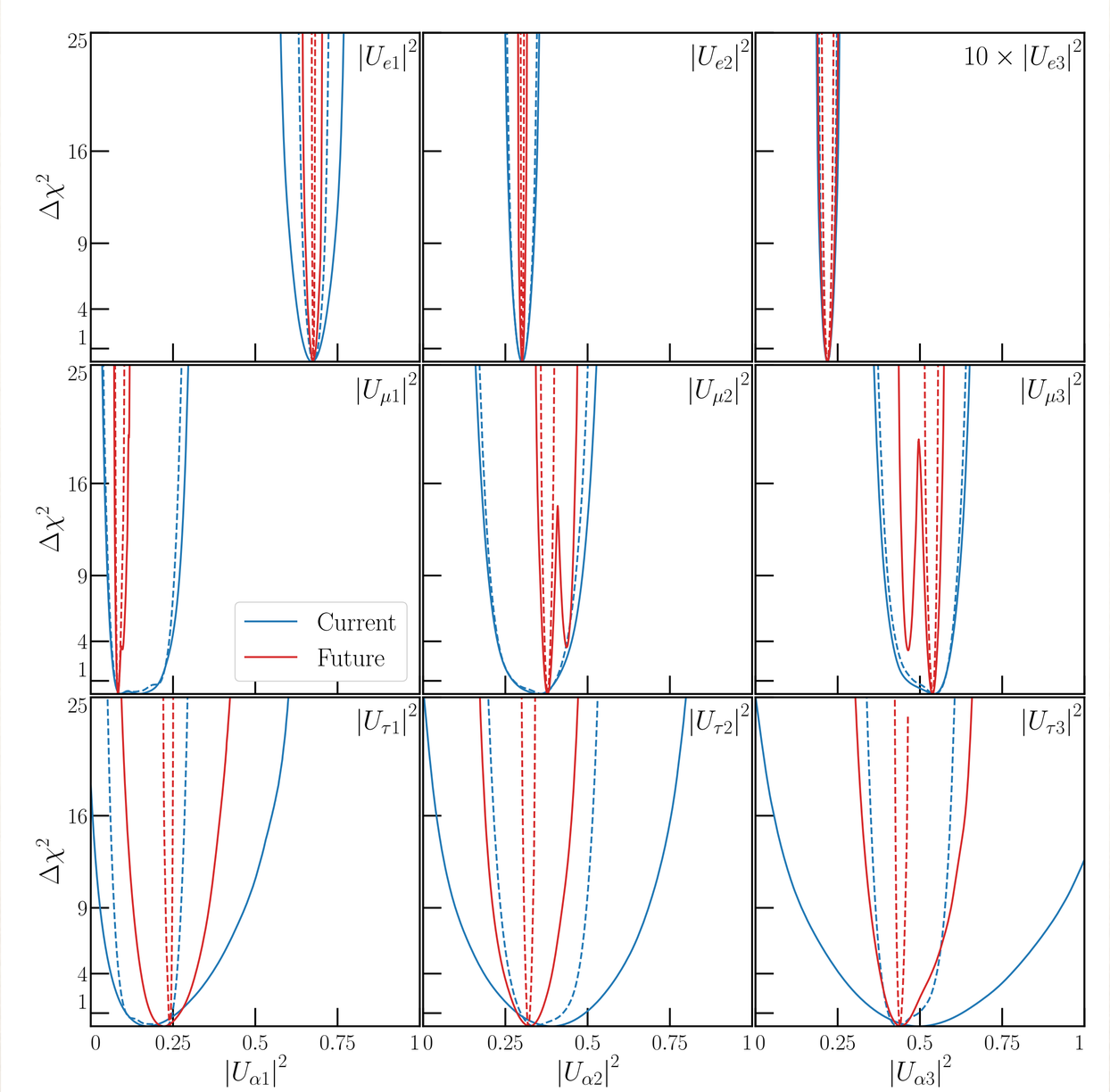
Full Comparison



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BSM with Neutrino Oscillations

BSM with Neutrino Oscillations

Experiments

Experiments

BSM with Neutrino Oscillations

White Paper on New Opportunities at the Next-Generation Neutrino Experiments

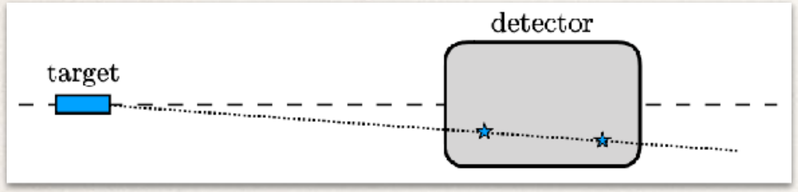
(Part 1: BSM Neutrino Physics and Dark Matter)

C.A. Argüelles[1], A.J. Aurisano[2], B. Batell[3], J. Berger[3], M. Bishai[4], T. Boschi[5], N. Byrnes[6], A. Chatterjee[6], A. Chodos[6], T. Coan[7], Y. Cui[8], A. de Gouvêa[* 9], P.B. Denton[4], A. De Roeck[* 10], W. Flanagan[11], D.V. Forero[12], R.P. Gandrajula[13], A. Hatzikoutelis[14], M. Hostert[15], B. Jones[6], B.J. Kayser[16], K.J. Kelly[16], D. Kim[17], J. Kopp[10,18], A. Kubik[19], K. Lang[20], I. Lepetic[21], P.A.N. Machado[16], C.A. Moura[22], F. Olness[6], J.C. Park[23], S. Pascoli[15], S. Prakash[12], L. Rogers[6], I. Safa[24], A. Schneider[24], K. Scholberg[25], S. Shin[26,27], I.M. Shoemaker[28], G. Sinev[25], B. Smithers[6], A. Sousa[* 2], Y. Sui[29], V. Takhistov[30], J. Thomas[31], J. Todd[2], Y.-D. Tsai[16,32], Y.-T. Tsai[33], J. Yu[* 6], and C. Zhang[4]

[1907.08311]

BSM Prospects with Neutrino Experiments

Millicharged Particles



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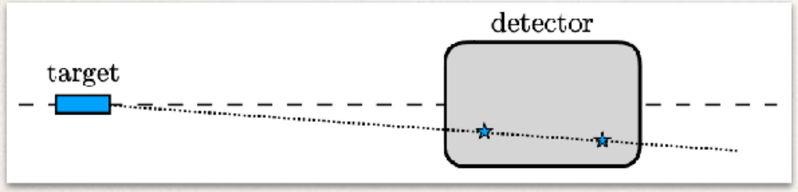

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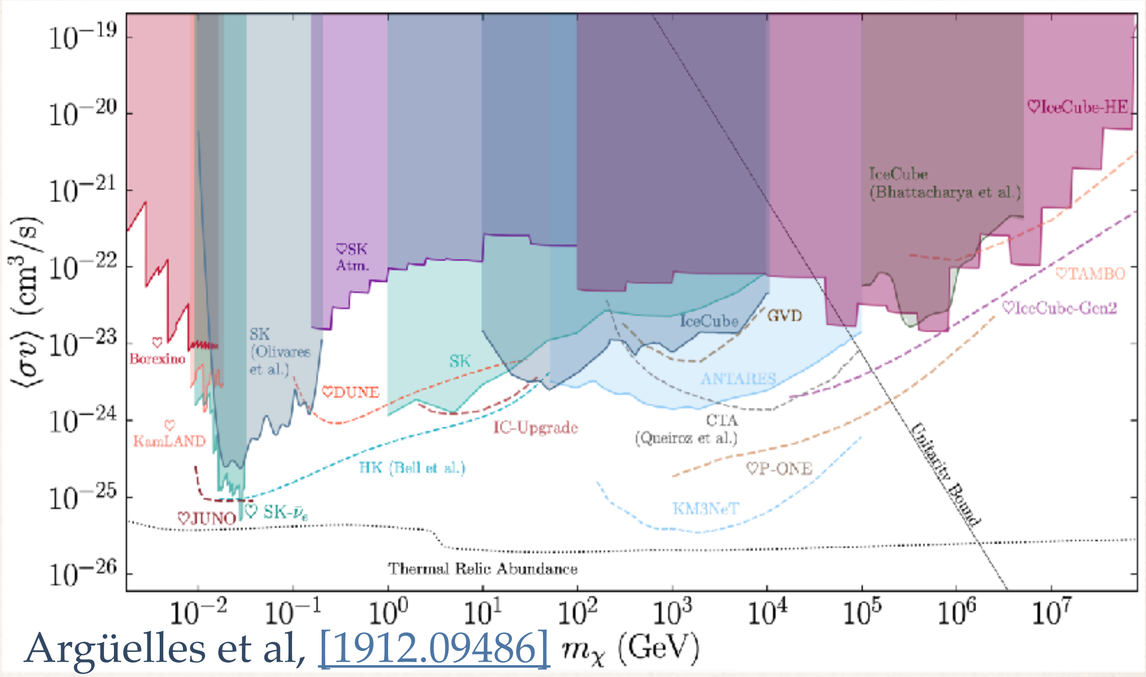

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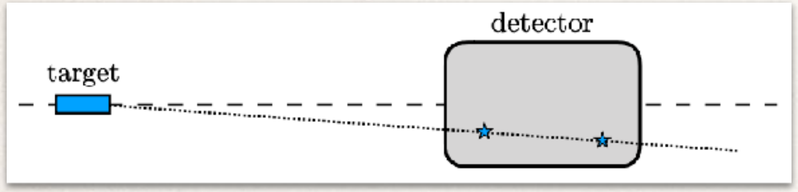

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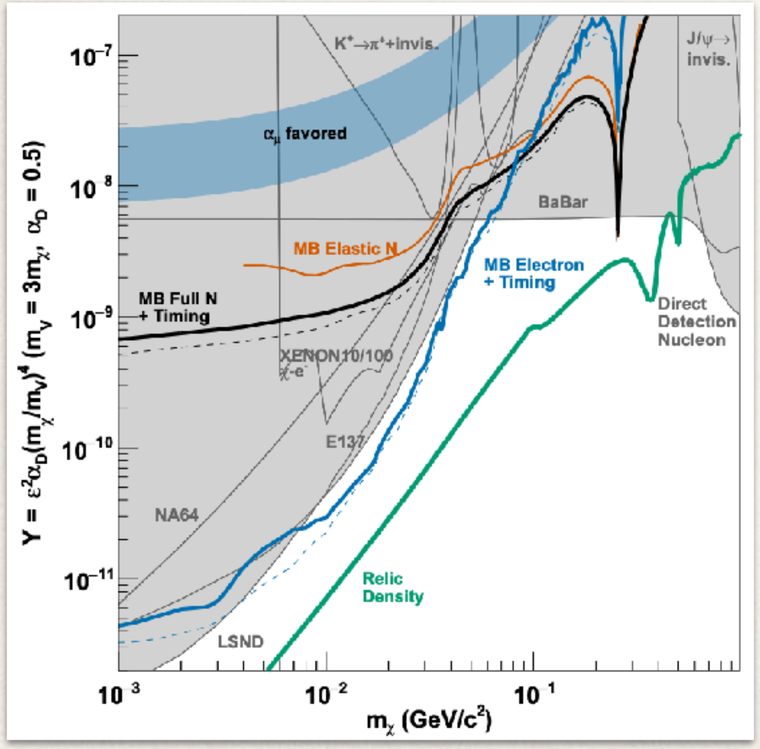

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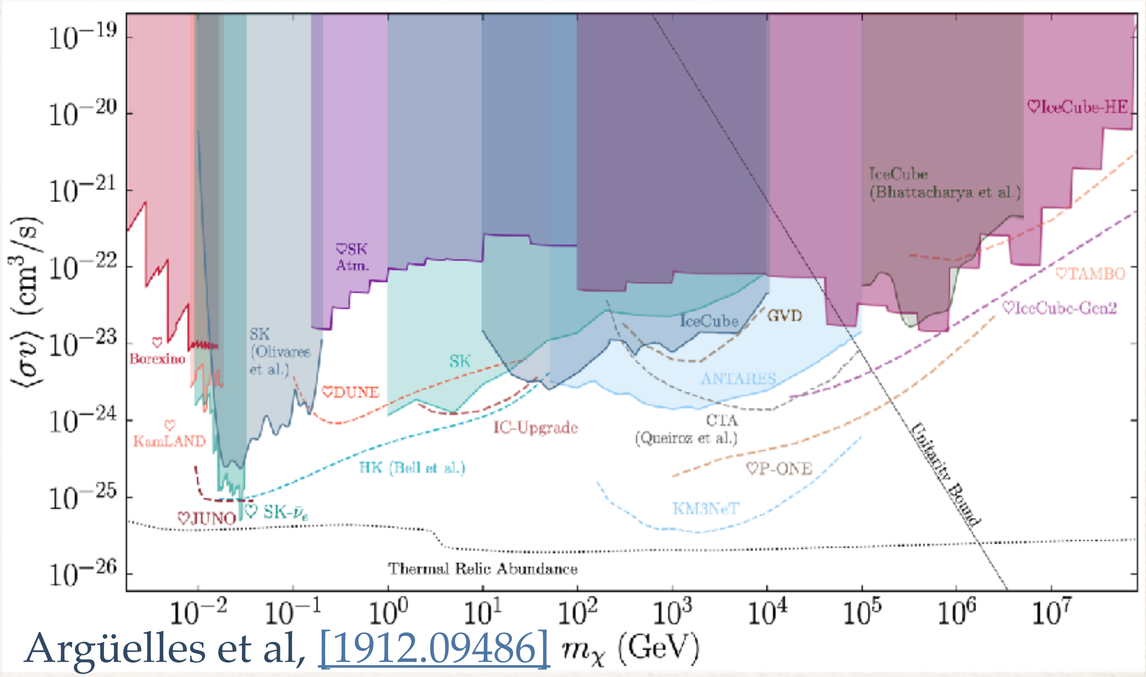

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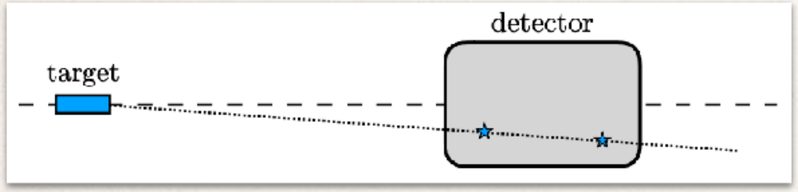

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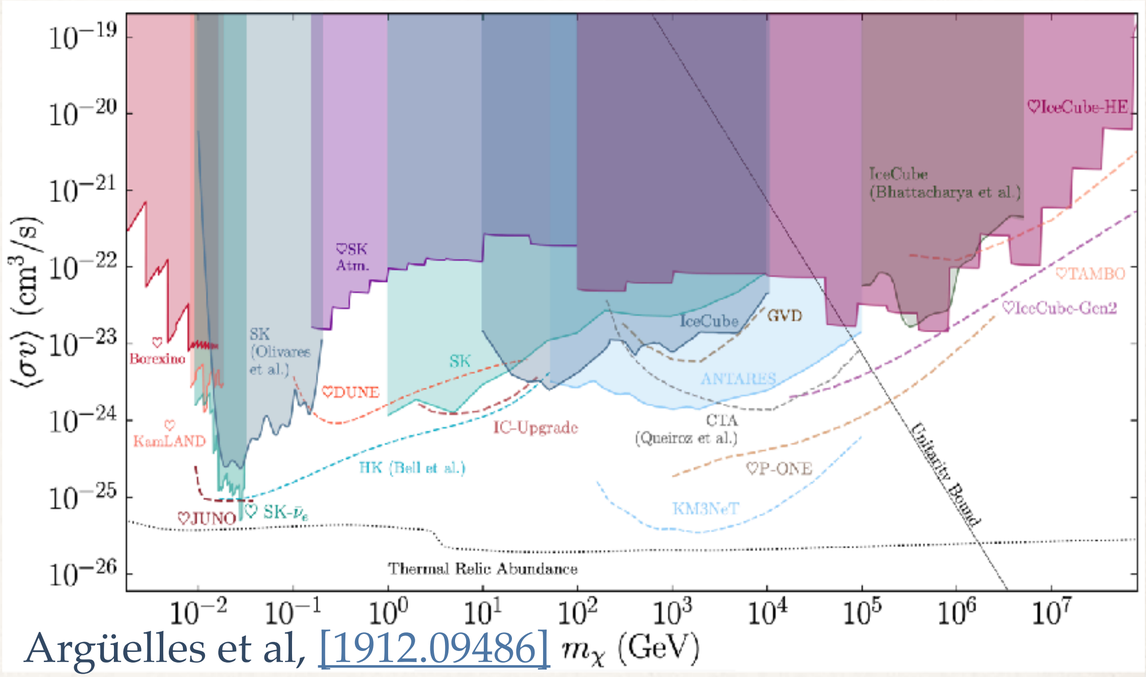

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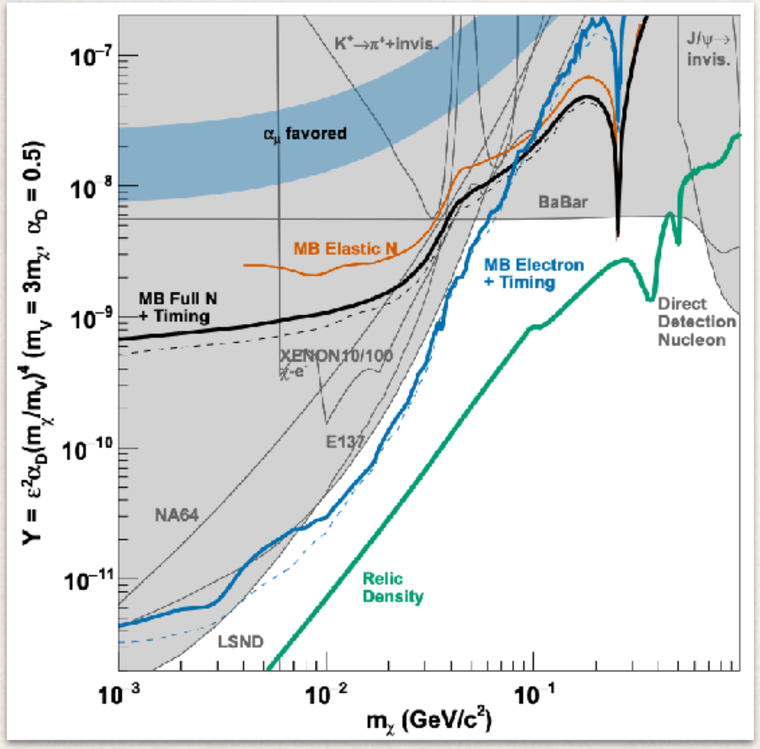

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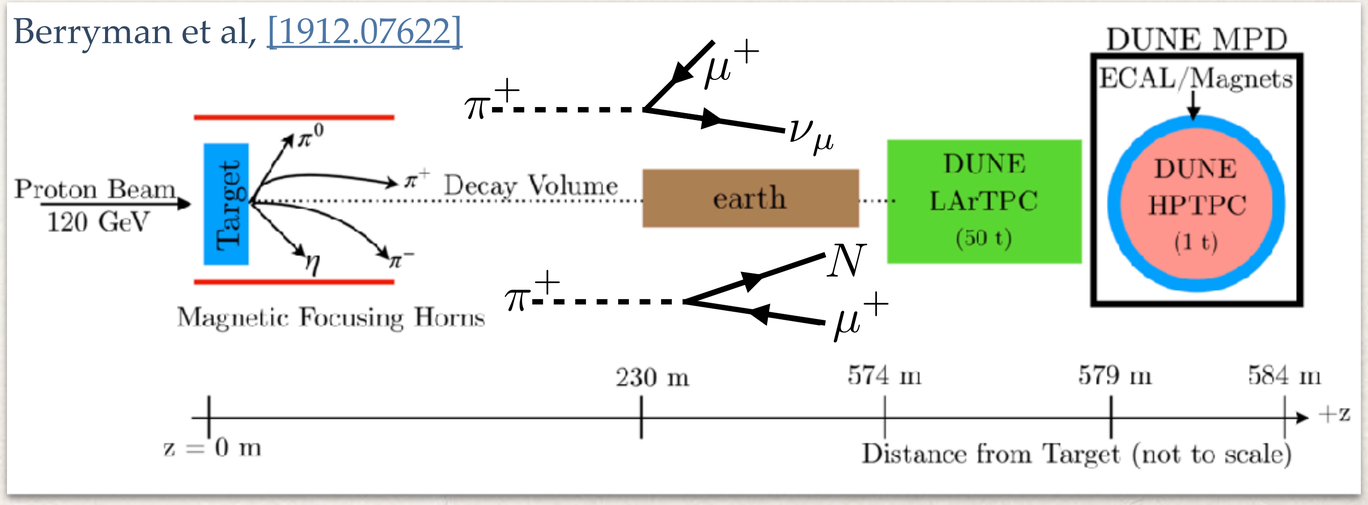
Neutrino Near Detectors as Beam Dump Facilities

Berryman et al, [1912.07622]



Neutrino Oscillation Experiments and Near Detectors

Many present-day experiments operate similar to the original method used to discover the muon neutrino:

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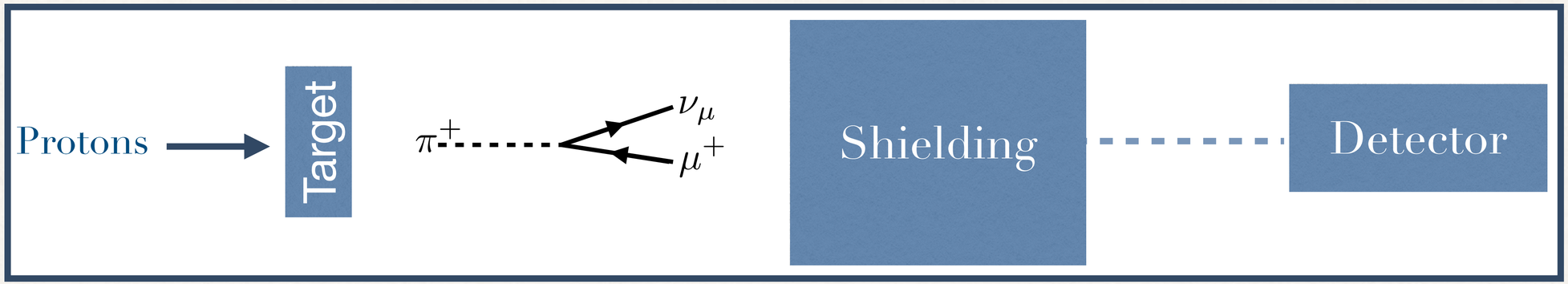

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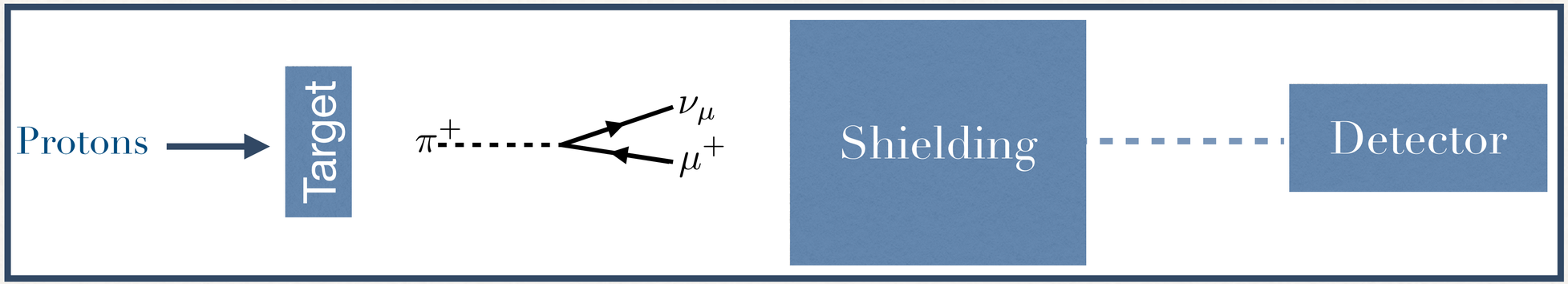
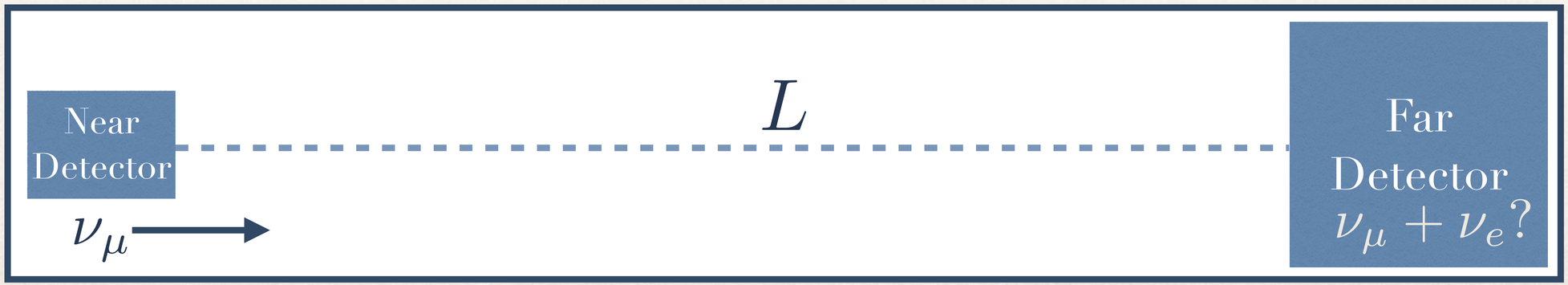


- Near detector and far detector measurements of flavor composition…



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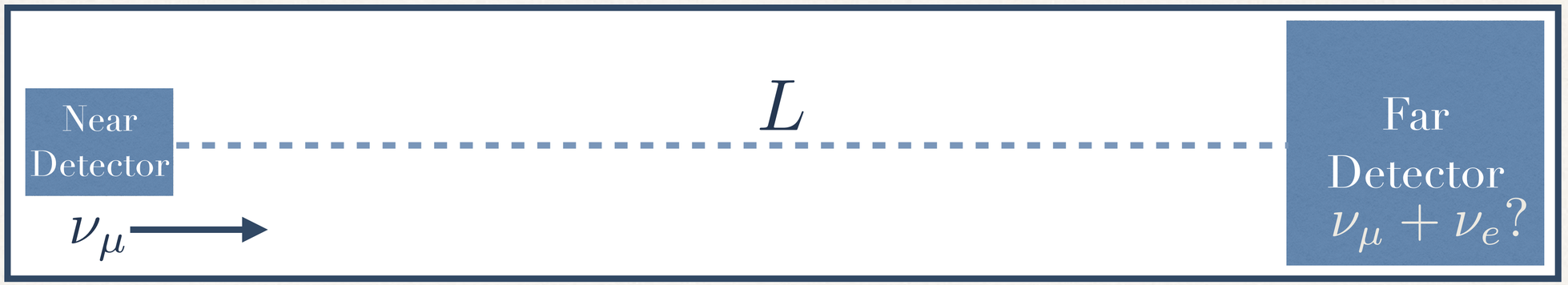

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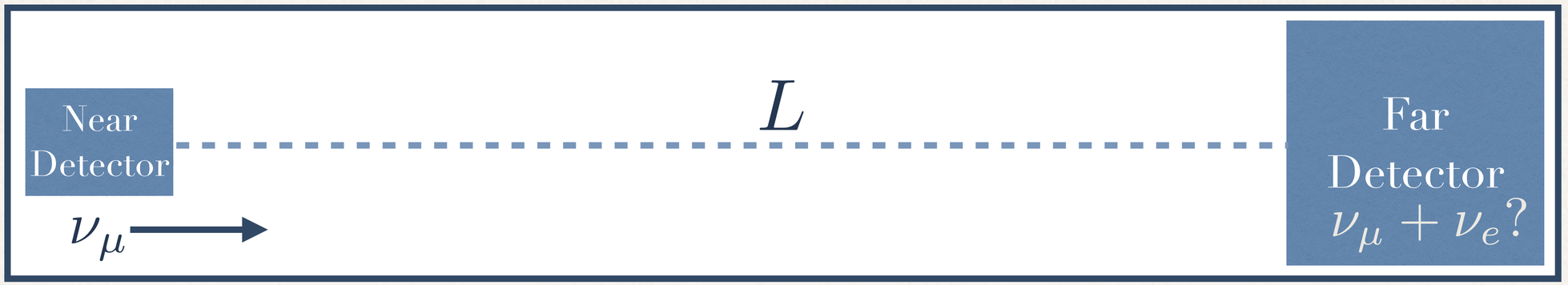
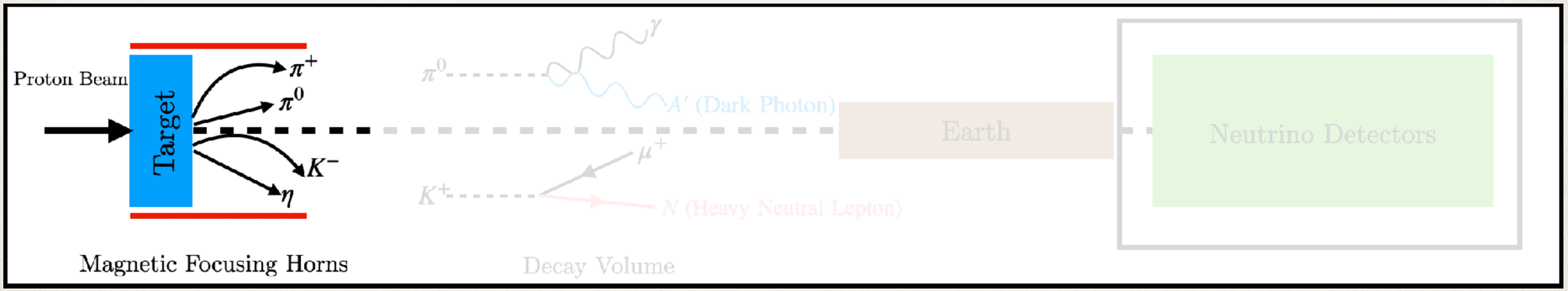


$$\frac{\Phi_{\nu_\mu}(L)}{\Phi_{\nu_\mu}(0)} = P(\nu_\mu \to \nu_\mu)$$ "Disappearance" or "Survival" Probability

$$\frac{\Phi_{\nu_e}(L)}{\Phi_{\nu_\mu}(0)} = P(\nu_\mu \to \nu_e)$$ "Appearance" Probability

✦Measure these probabilities, and extract information about oscillations.

How can these Near Detectors Search for New Physics?



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

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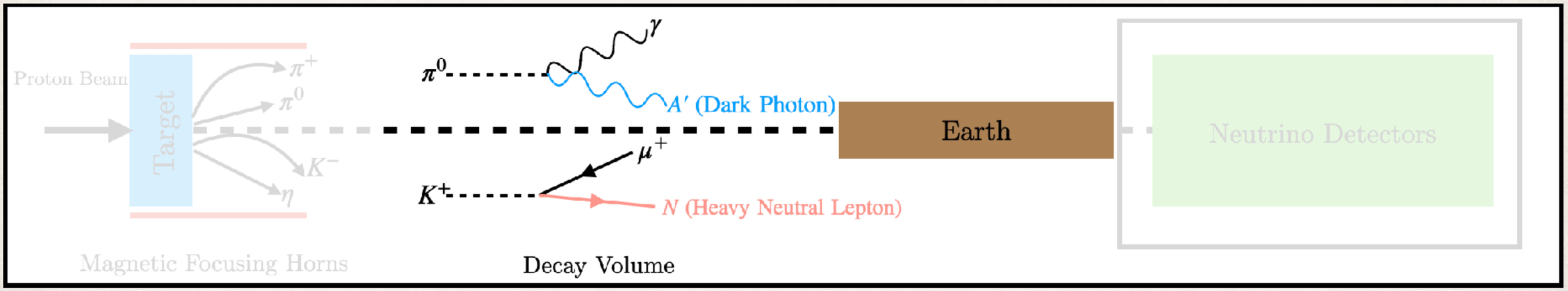

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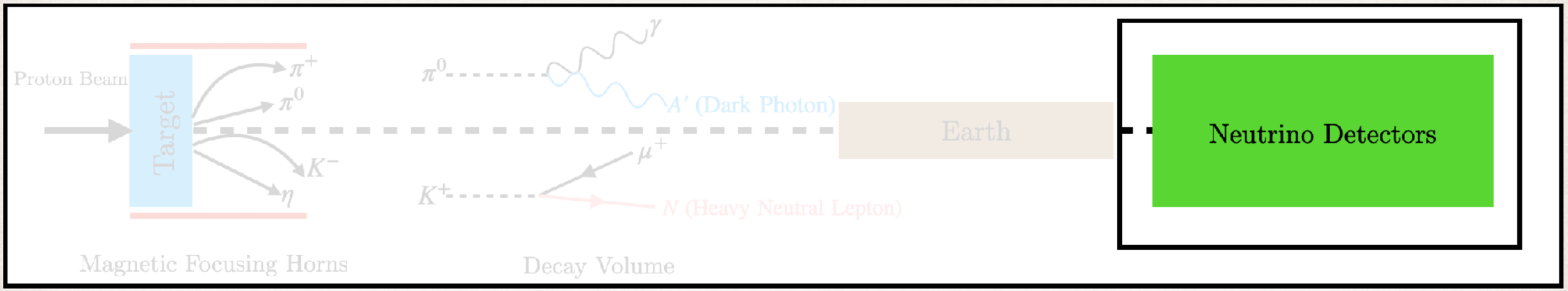

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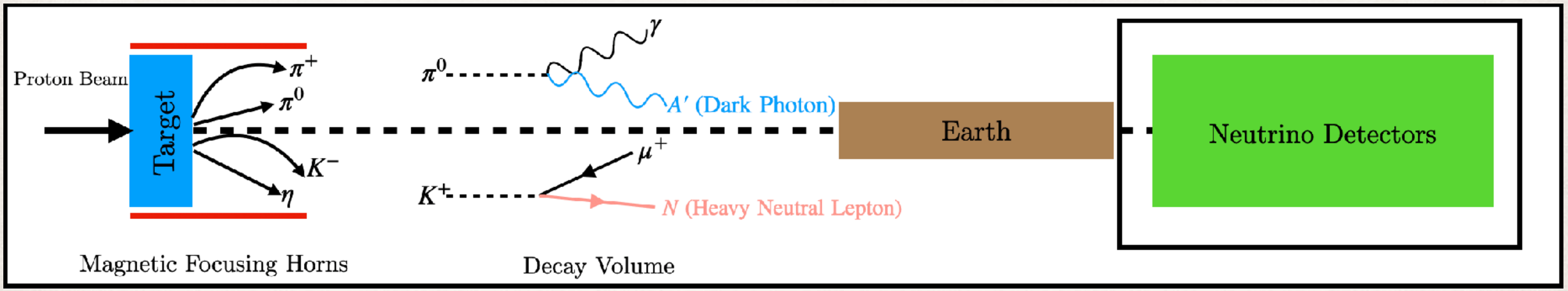

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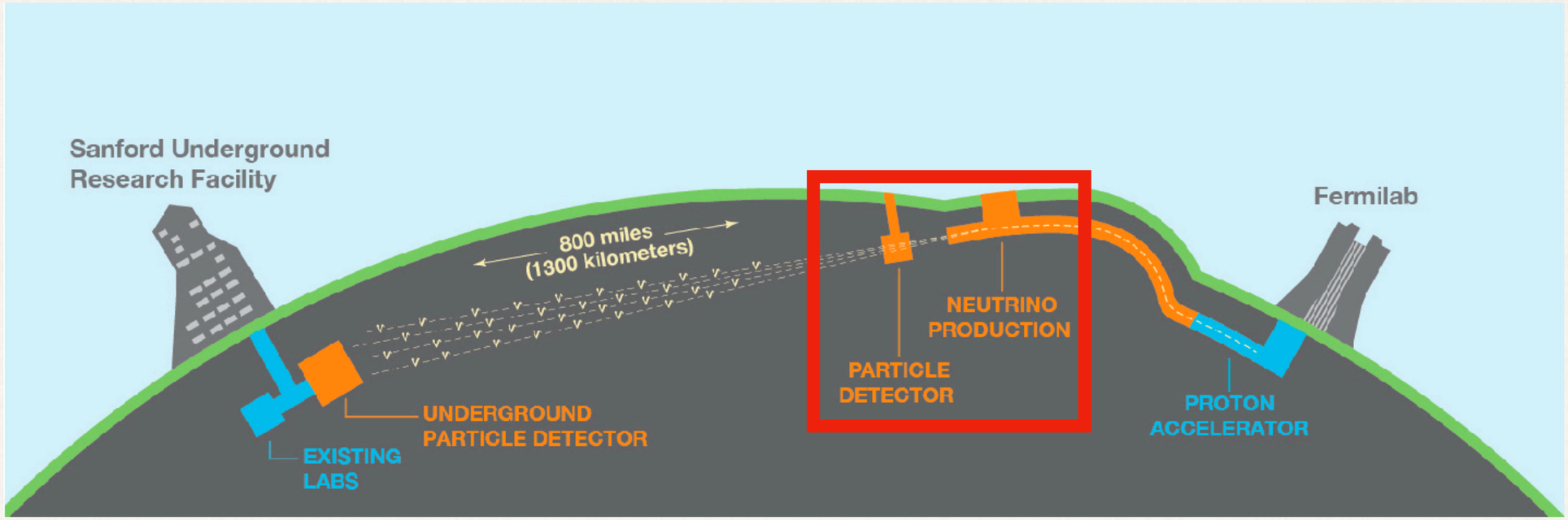
DUNE's Near Detector Complex



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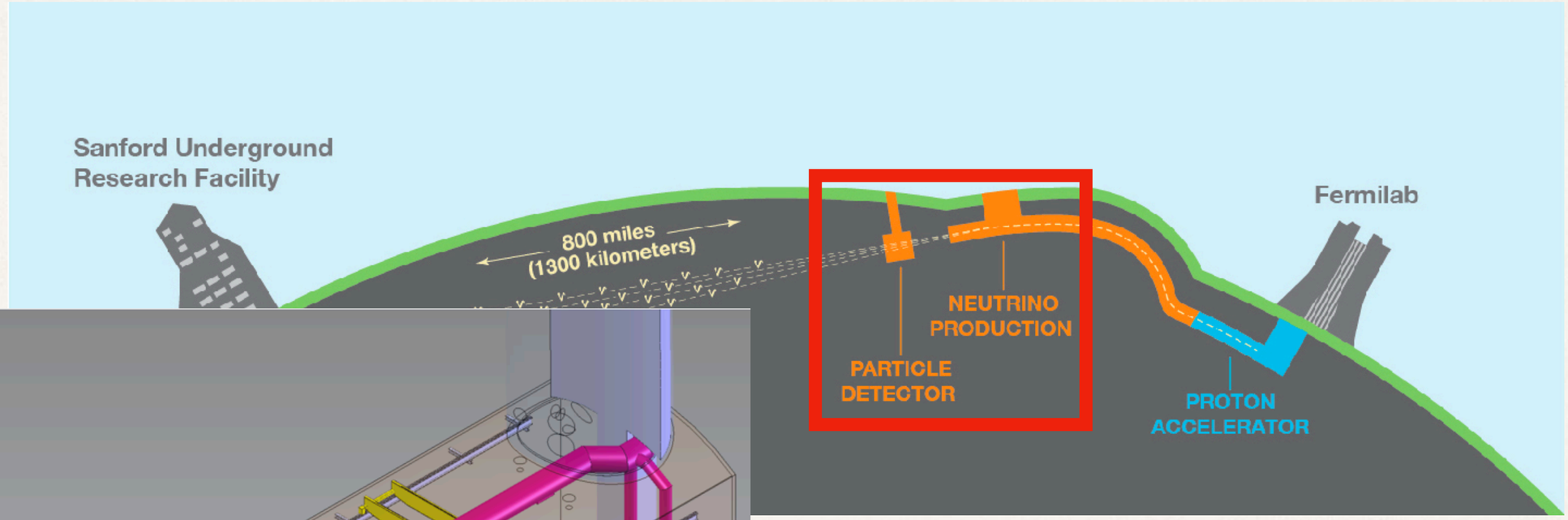
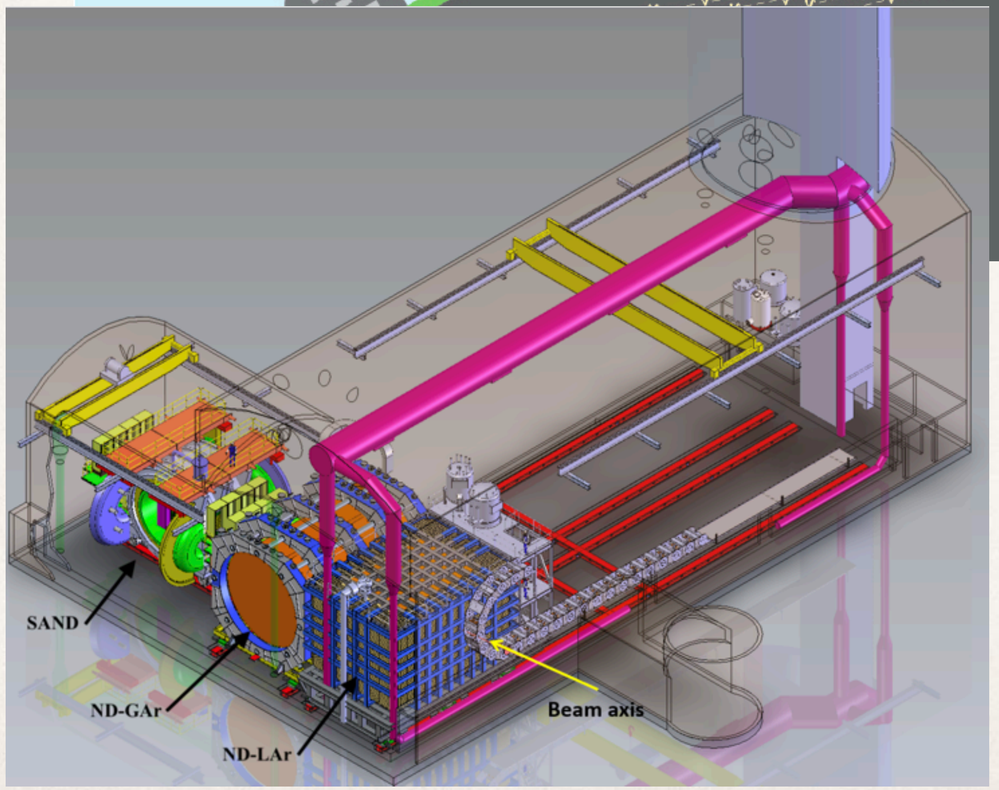
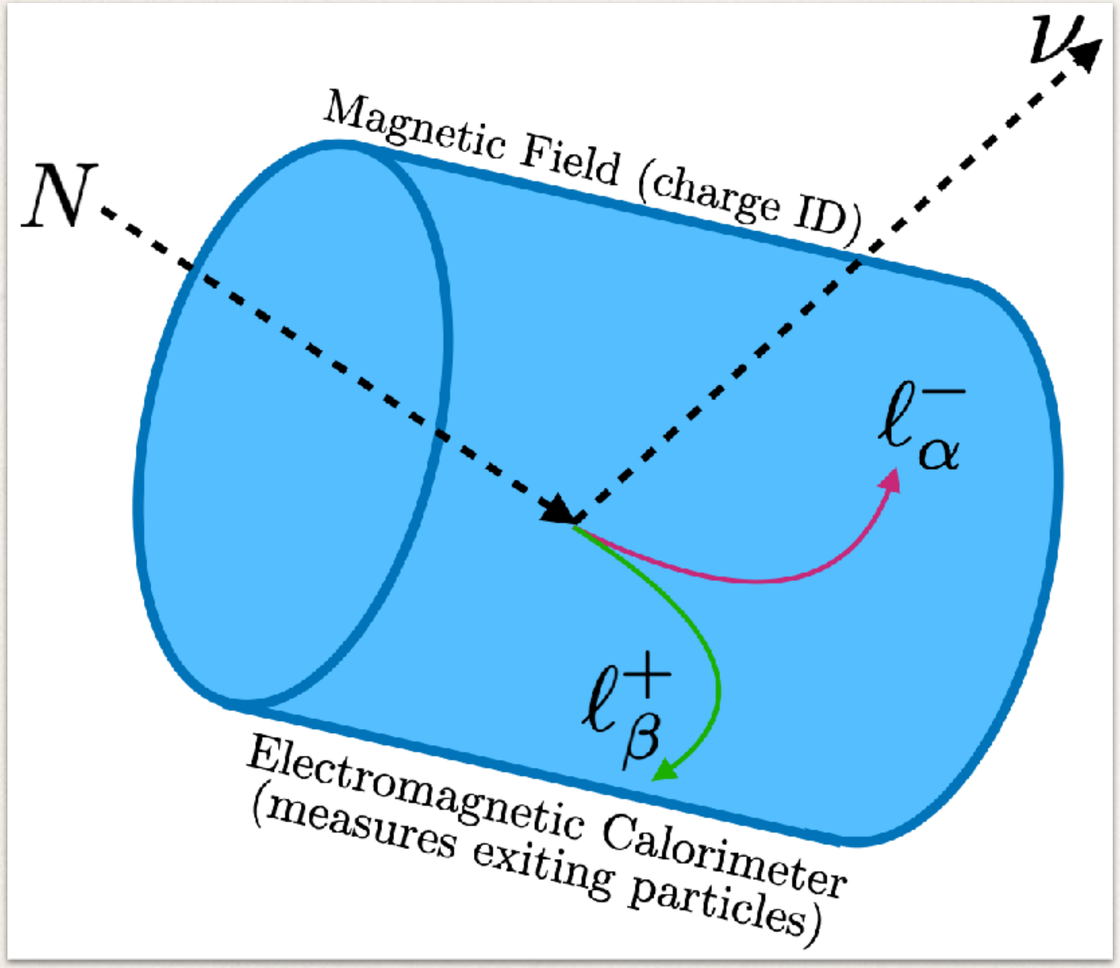




- Near Detector design is to meet neutrino oscillation-based goals.
- Various detector components can also allow for rich new physics searches.

DUNE Collaboration, [2103.13910]

Gaseous Detectors for Decays



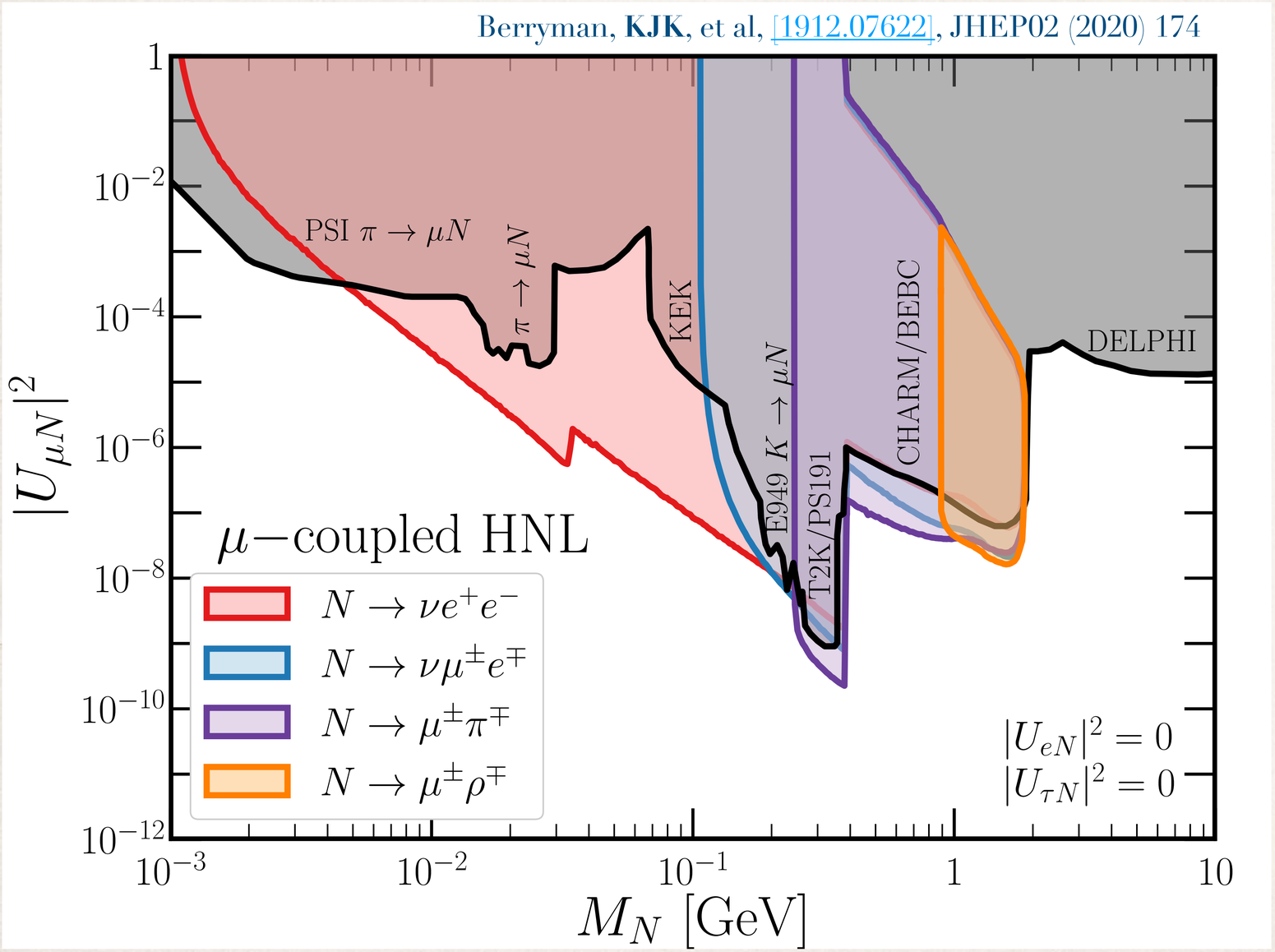
- New-physics particles can decay inside the detector, producing a signal that is difficult for neutrino scattering to mimic.
- This includes decays to charged lepton pairs, a lepton and a pion, etc.
- Low backgrounds in gaseous detectors (like at DUNE) are an ideal site for these searches.

New Physics Signal : Volume

Neutrino Scattering Backgrounds : Mass

Next-Generation Sensitivity at DUNE

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



- Tons of parameter space for a potential discovery!
- In the event of a discovery, then what?
- Search for Lepton Number Violation!

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

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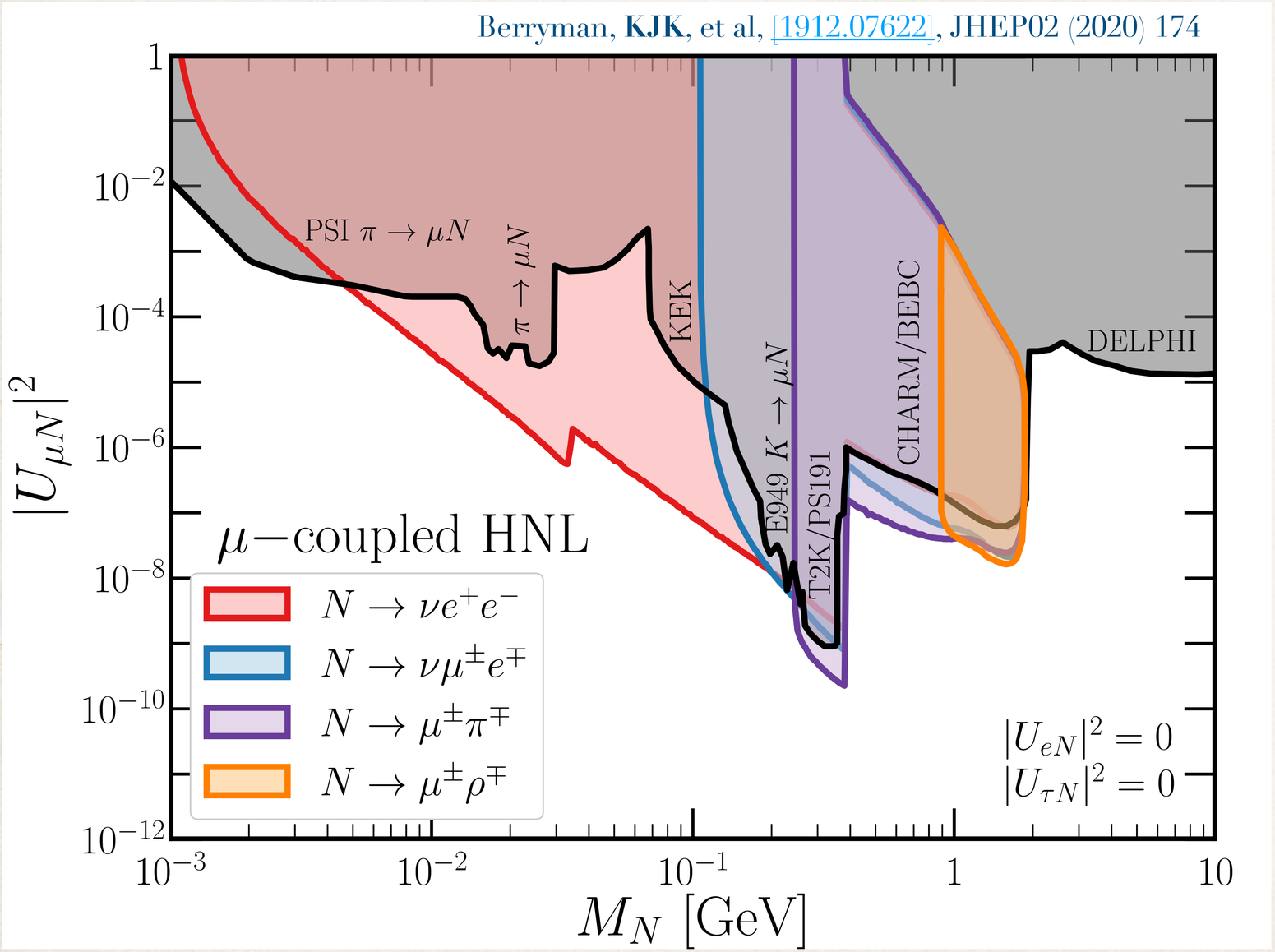

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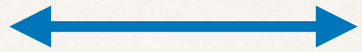
- In the event of a discovery, then what?
- Search for Lepton Number Violation!

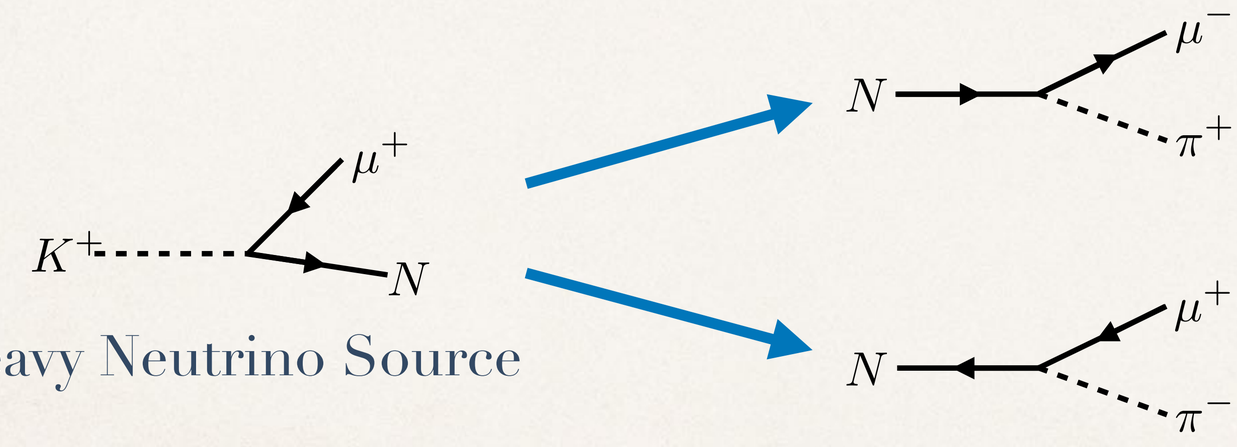
More on HNLs at DUNE? Ballett et al [1905.00284], Coloma et al [2007.03701], Breitbach et al [2102.03383]

LNV 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?

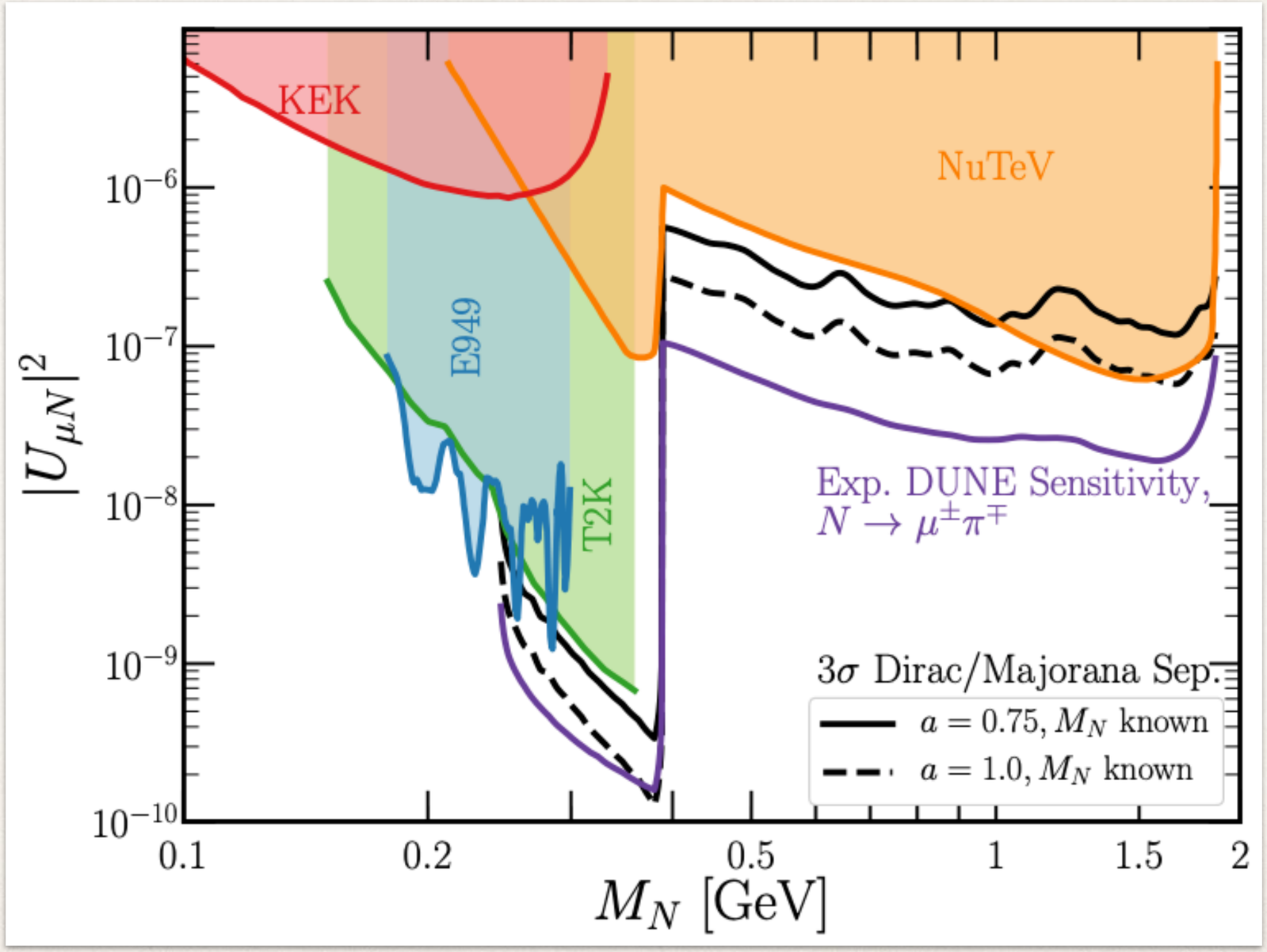


Heavy Neutrino Source

Heavy Neutrino Decay

- Do these two chains occur with equal probability?

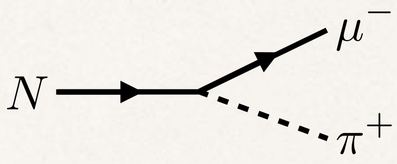
Next-Generation Prospects

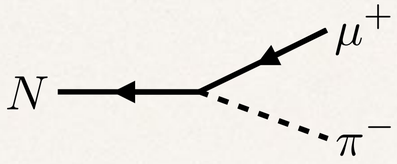


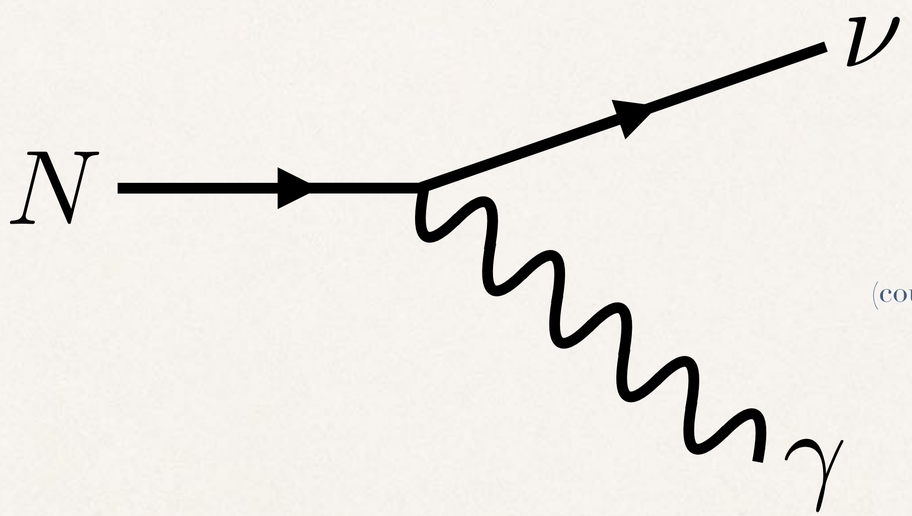
Berryman, KJK et al, [1912.07622]

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.





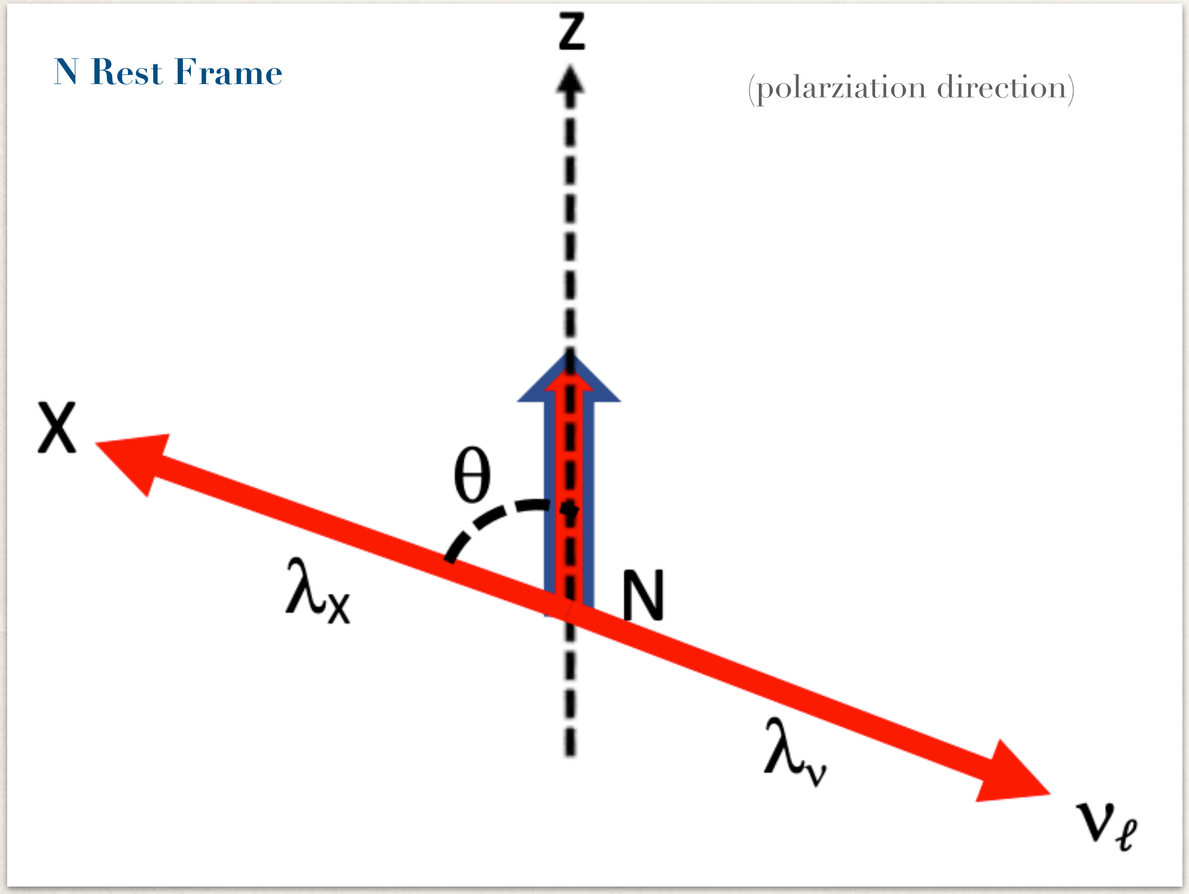


(could also be a charged-lepton pair instead of a photon, etc.)

Still, there are differences between Dirac/Majorana fermions: Measure the *distribution* of outgoing (visible) particles

Two-Body Decays

Balantekin, de Gouvêa, Kayser [1808.10518]



- 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.

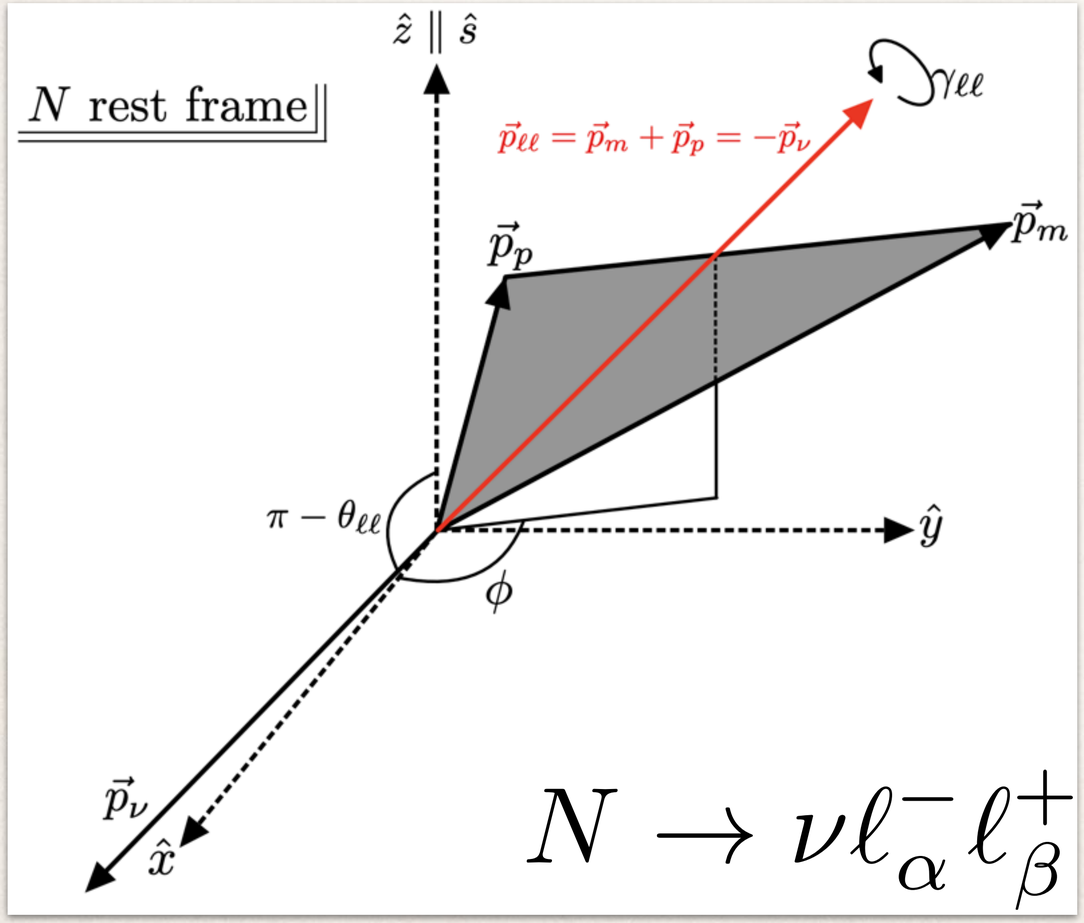
$$\frac{d\Gamma}{d\cos\theta} = \frac{\Gamma}{2}(1+\alpha\cos\theta)$$

Boson	γ	π^0	ρ^0	Z^0	H^0
α	$\frac{2\Im(\mu d^*)}{\lvert\mu\rvert^2+\lvert d\rvert^2}$	1	$\frac{m_4^2-2m_\rho^2}{m_4^2+2m_\rho^2}$	$\frac{m_4^2-2m_Z^2}{m_4^2+2m_Z^2}$	1

Extending to Three-Body Decays

de Gouvêa, Fox, Kayser, Kelly [2104.05719]

Similar CPT arguments allowed us to reach the following conclusions — if N is a Majorana fermion, its decays are forward/backward symmetric if either



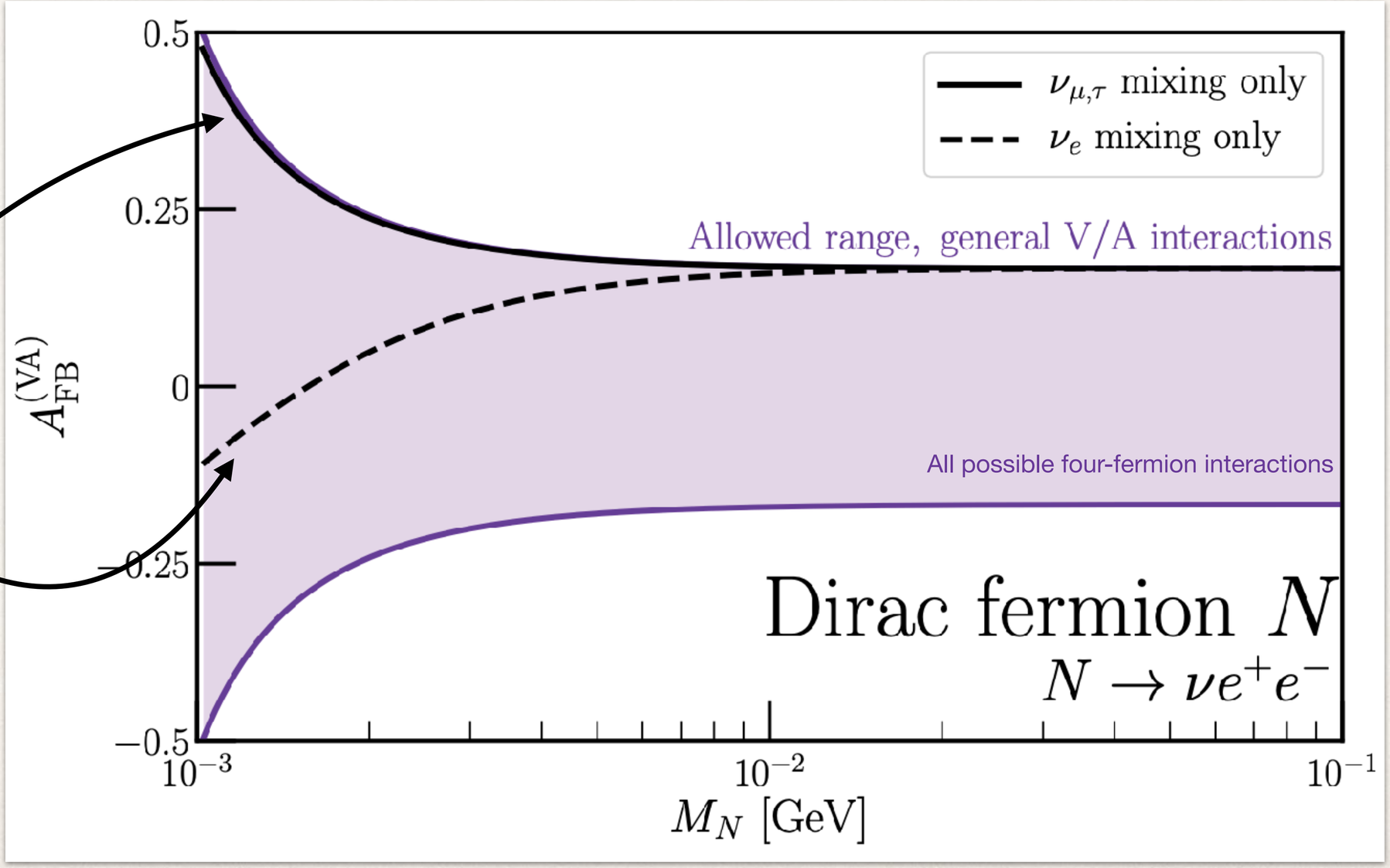
- The final-state charged leptons are identical (e.g. electron/positron pair).
- Whatever detection mechanism being used is charge-blind (can't distinguish electron from positron or muon from antimony)

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

How large can Forward/Backward Asymmetry Be?

If a non-zero asymmetry can be measured, one can prove that N is a Dirac fermion!

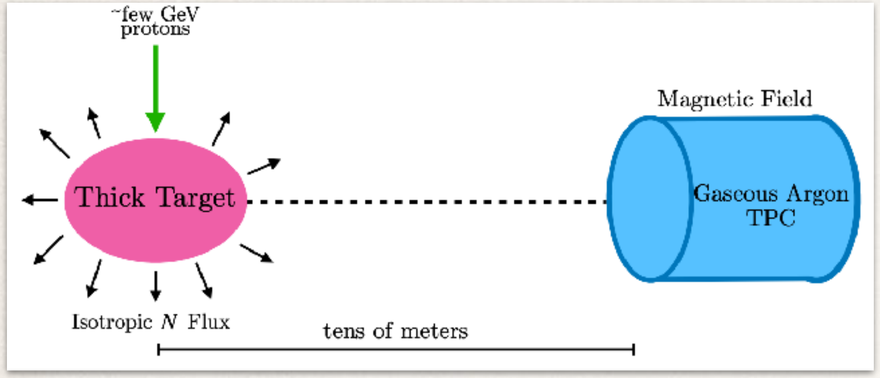
Decays mediated solely via off-shell W- and/or Z-bosons



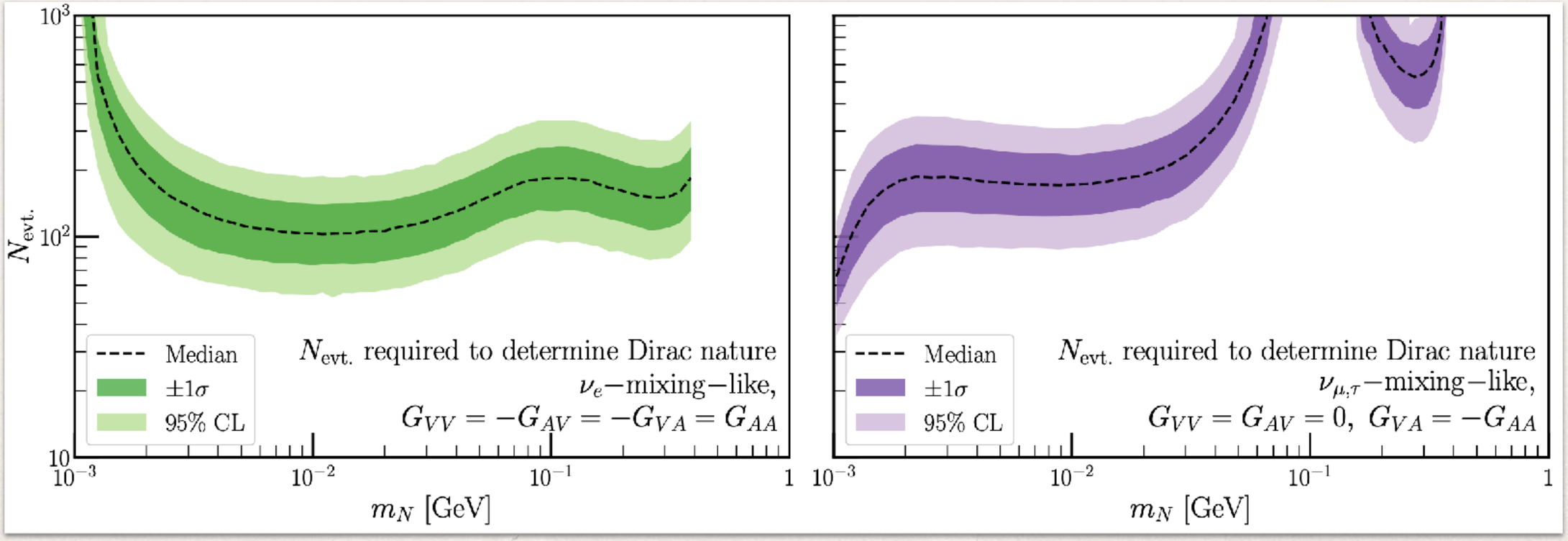
de Gouvêa, Fox, Kayser, Kelly [2104.05719]

Is this measurement feasible?

de Gouvêa, Fox, Kayser, Kelly [2109.10358]

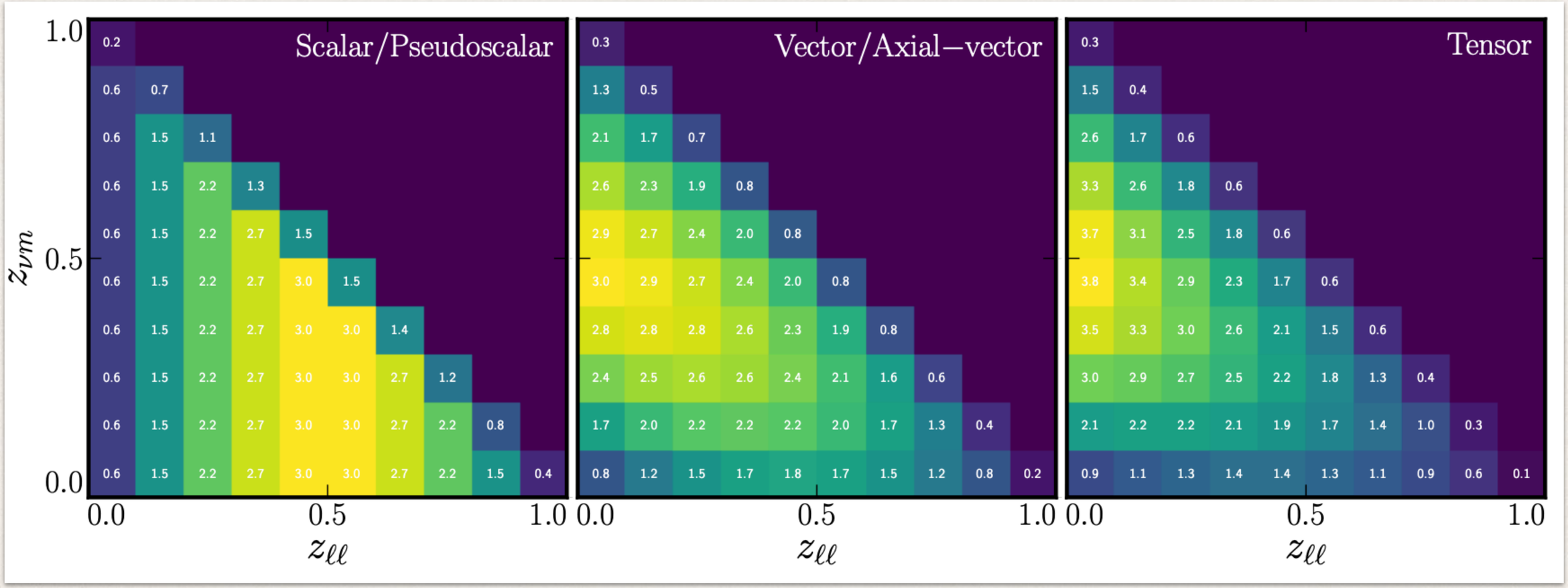


Instead of a beam environment, we envision HNL production from meson decay-at-rest (allowing us to reconstruct the N rest frame for each event). How well can we reject the Majorana hypothesis if the HNL is a Dirac fermion?



Measuring the Interaction Structure

de Gouvêa, Fox, Kayser, Kelly [2109.10358]



$$z_{\ell\ell} \equiv \left(p_{e^+} + p_{e^-}\right)^2 / m_N^2, \quad z_{\nu m} \equiv \left(p_\nu + p_{e^-}\right)^2 / m_N^2$$

Even if the N is unpolarized, we can still use its decay distributions to infer the type(s) of mediators contributing to its decay.

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  - Interesting new phenomena that impact oscillations, including non-standard interactions, sterile neutrinos, non-unitarity, etc.
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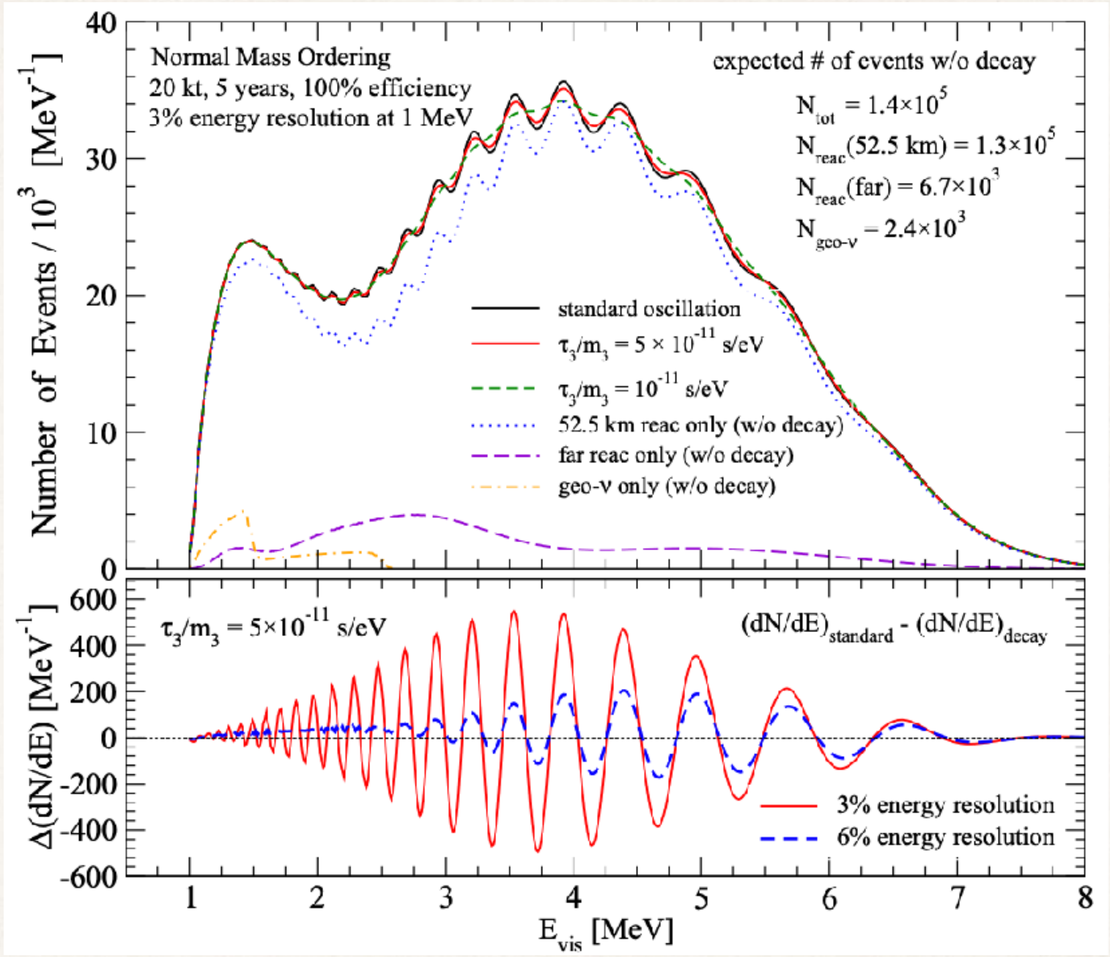
Thank you!

Backup Slides

JUNO: Jiangmen Underground Neutrino Observatory



Abrahão et al, [1506.02314]

JUNO Conceptual Design Report: [1508.07166]

JUNO Neutrino Physics Paper: [1507.05613]

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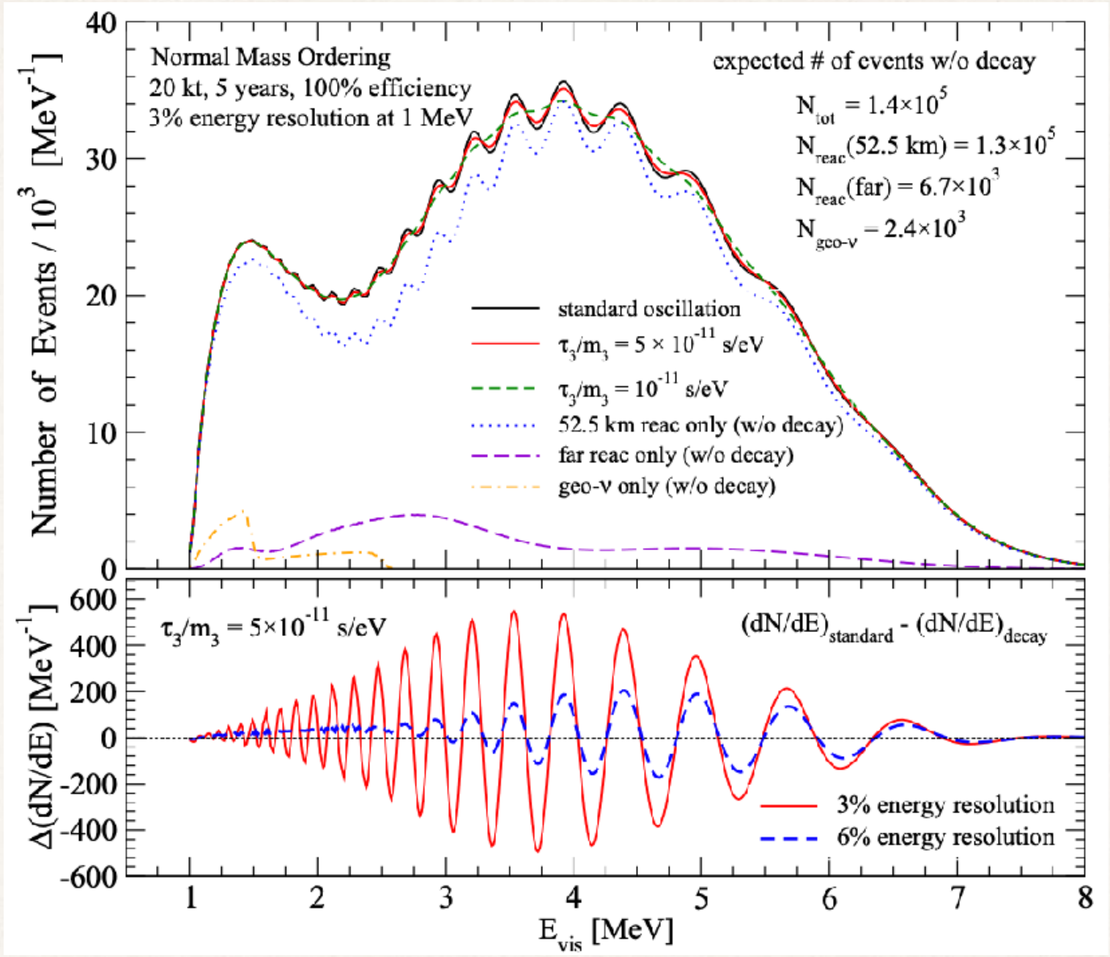

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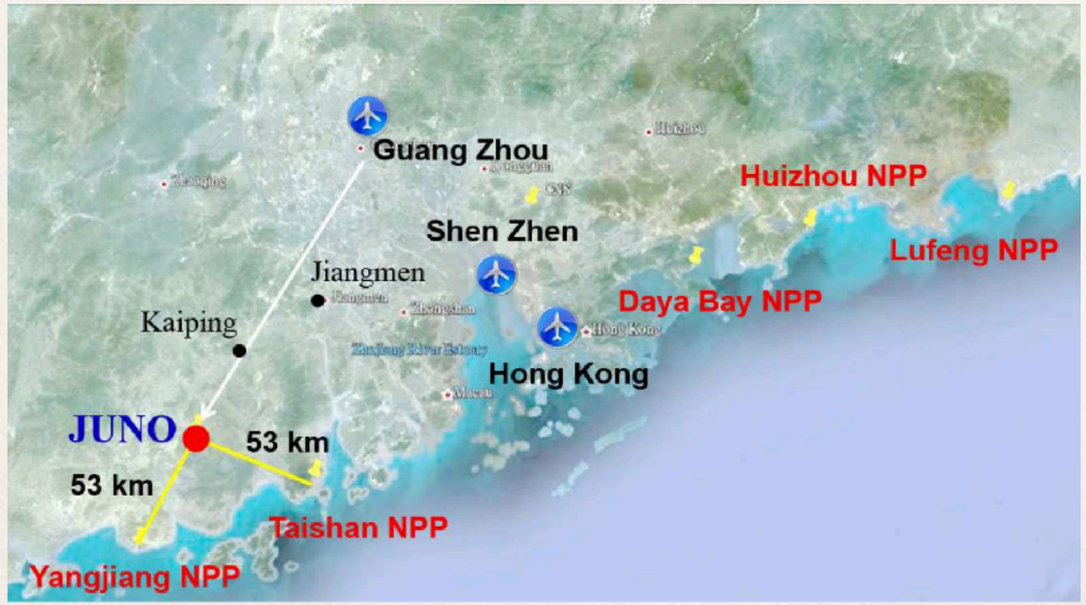

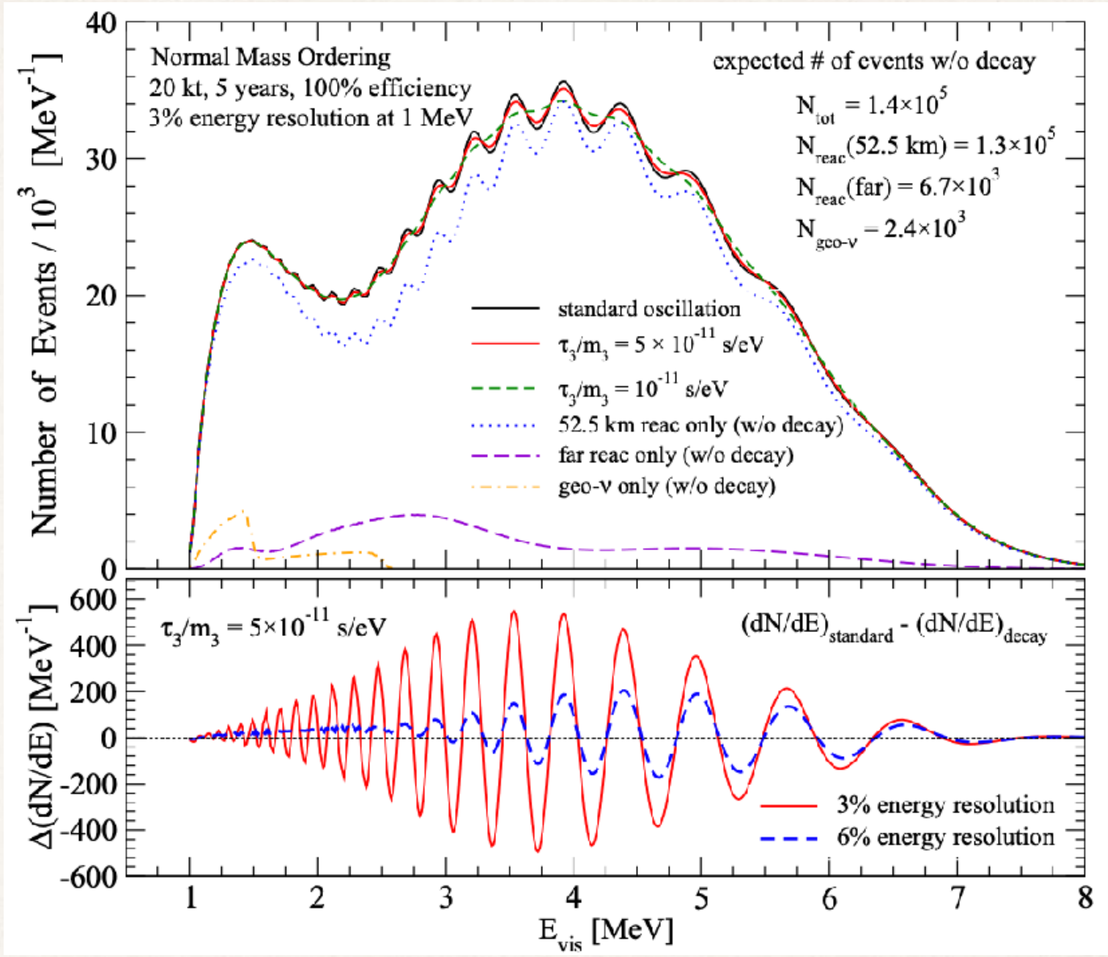

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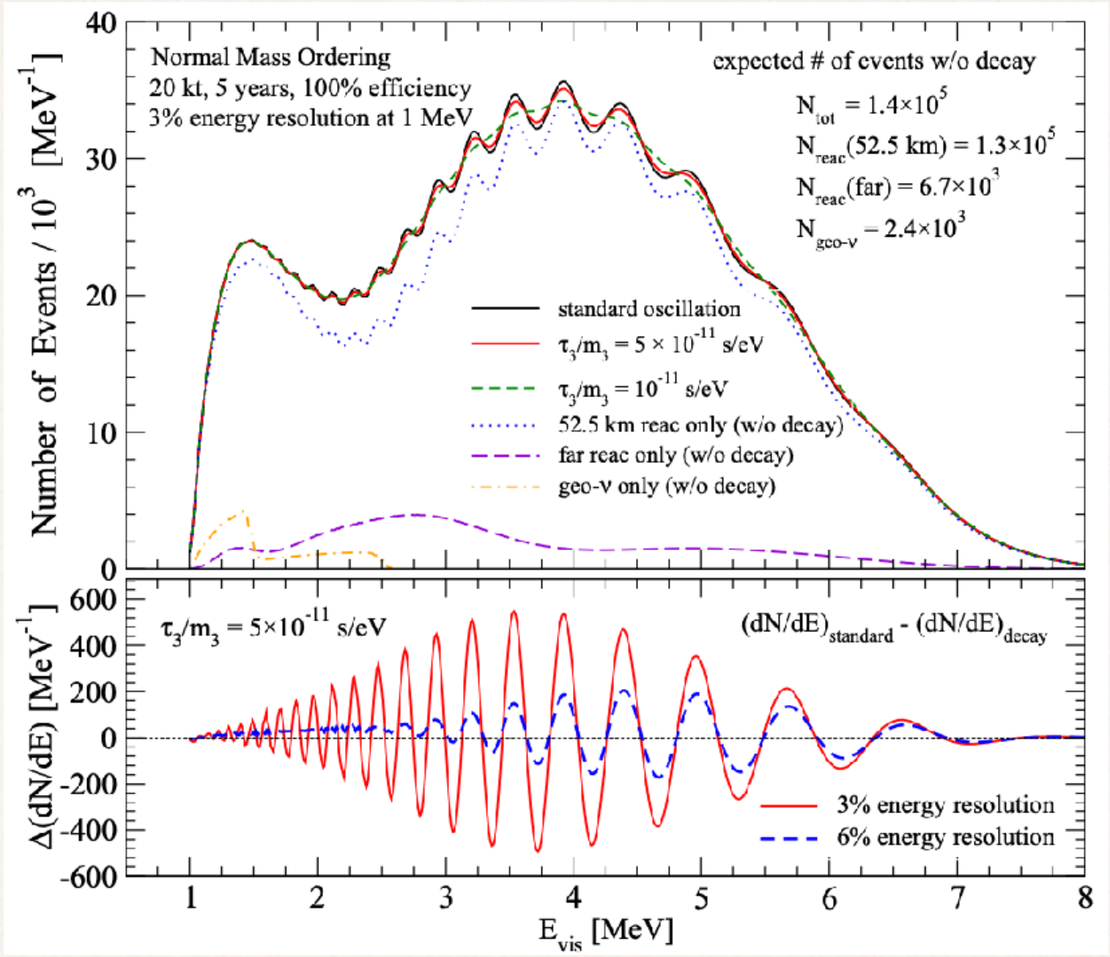

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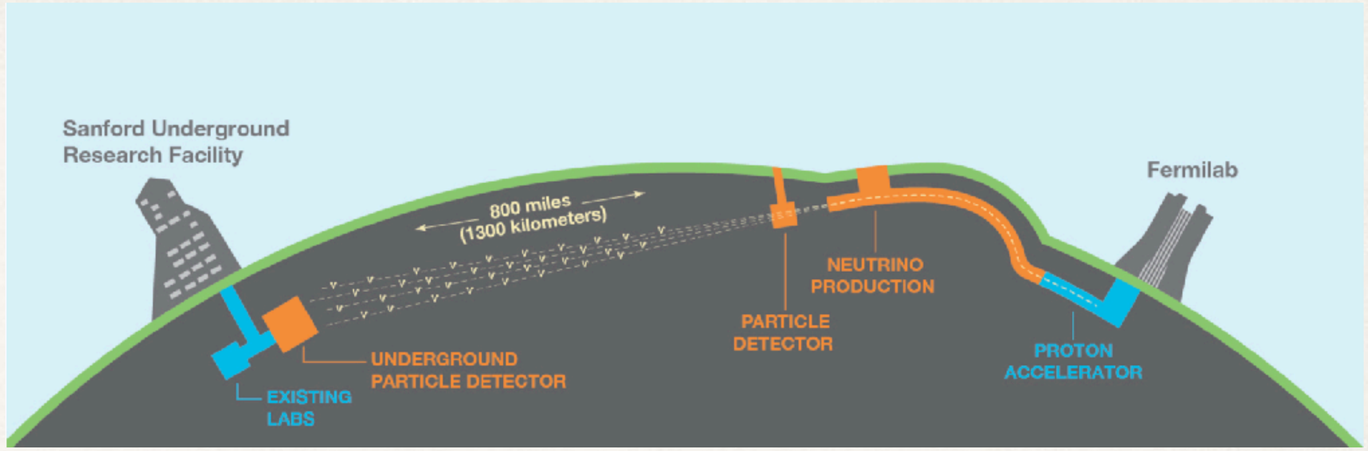
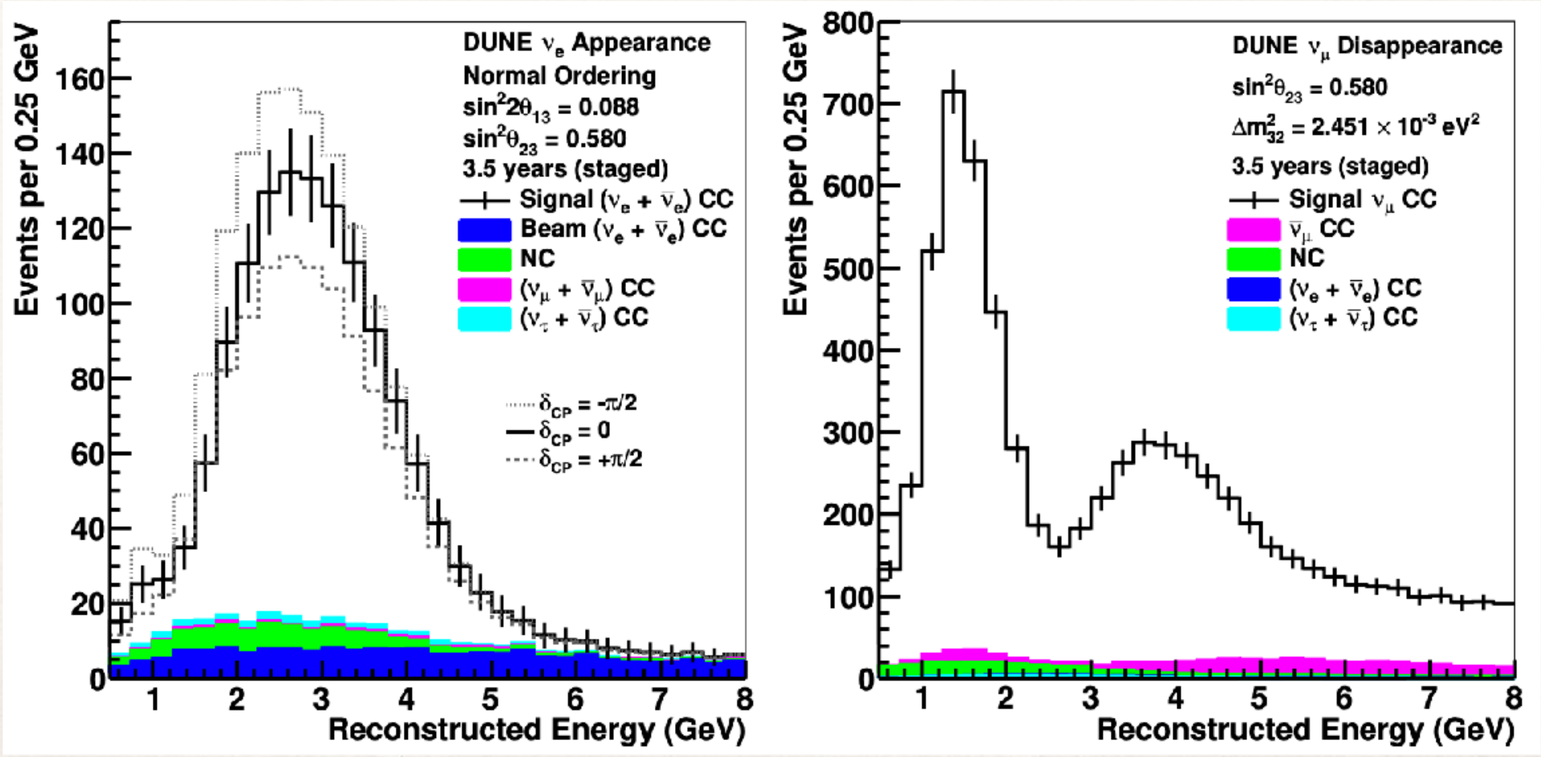
JUNO Conceptual Design Report: [1508.07166]

JUNO Neutrino Physics Paper: [1507.05613]

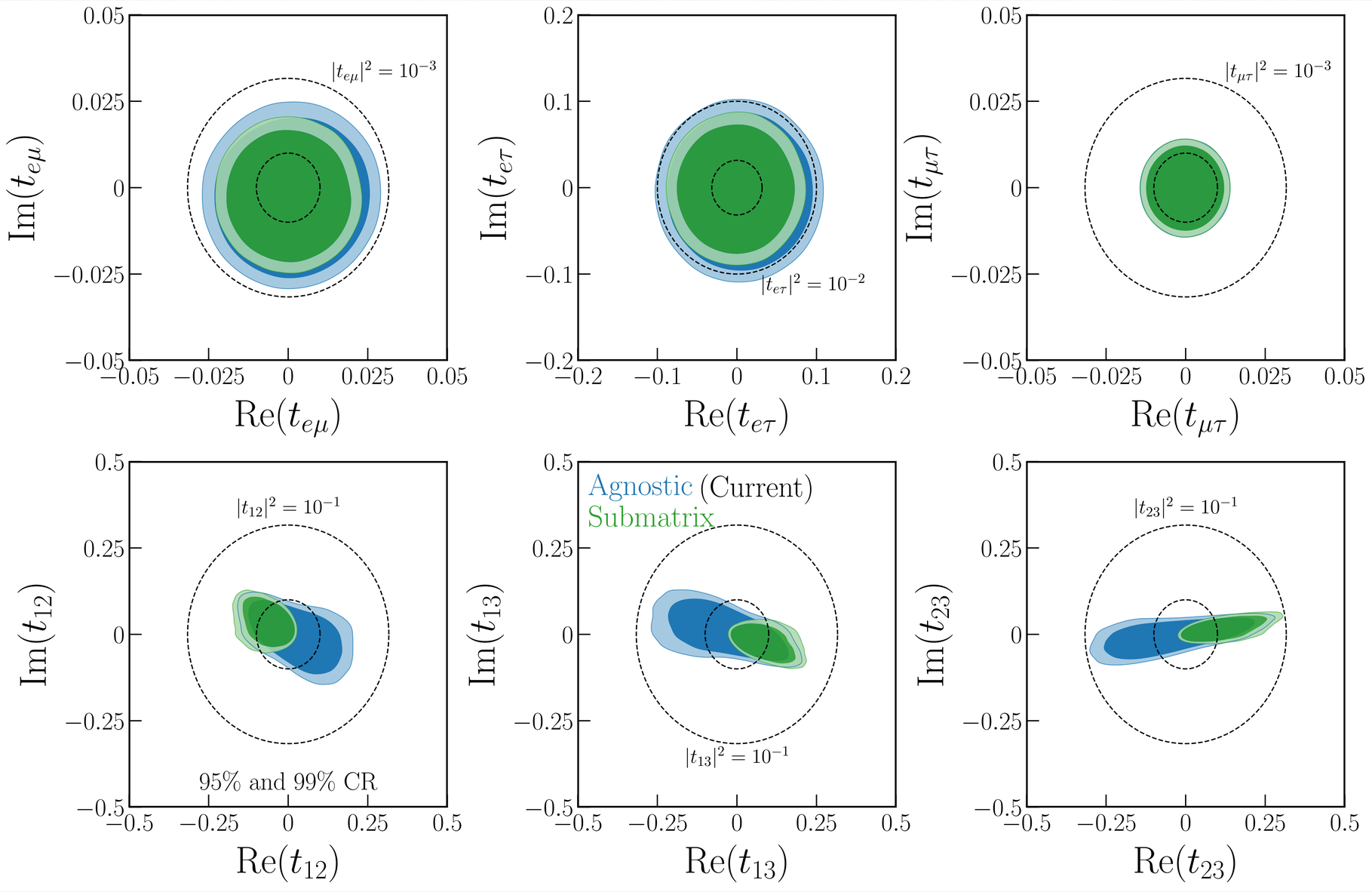
DUNE: Deep Underground Neutrino Experiment

DUNE Technical Design Report,
[2002.03005]





Triangle Closures: Agnostic vs. Submatrix Cases



Ellis, KJK, Li [2008.01088]

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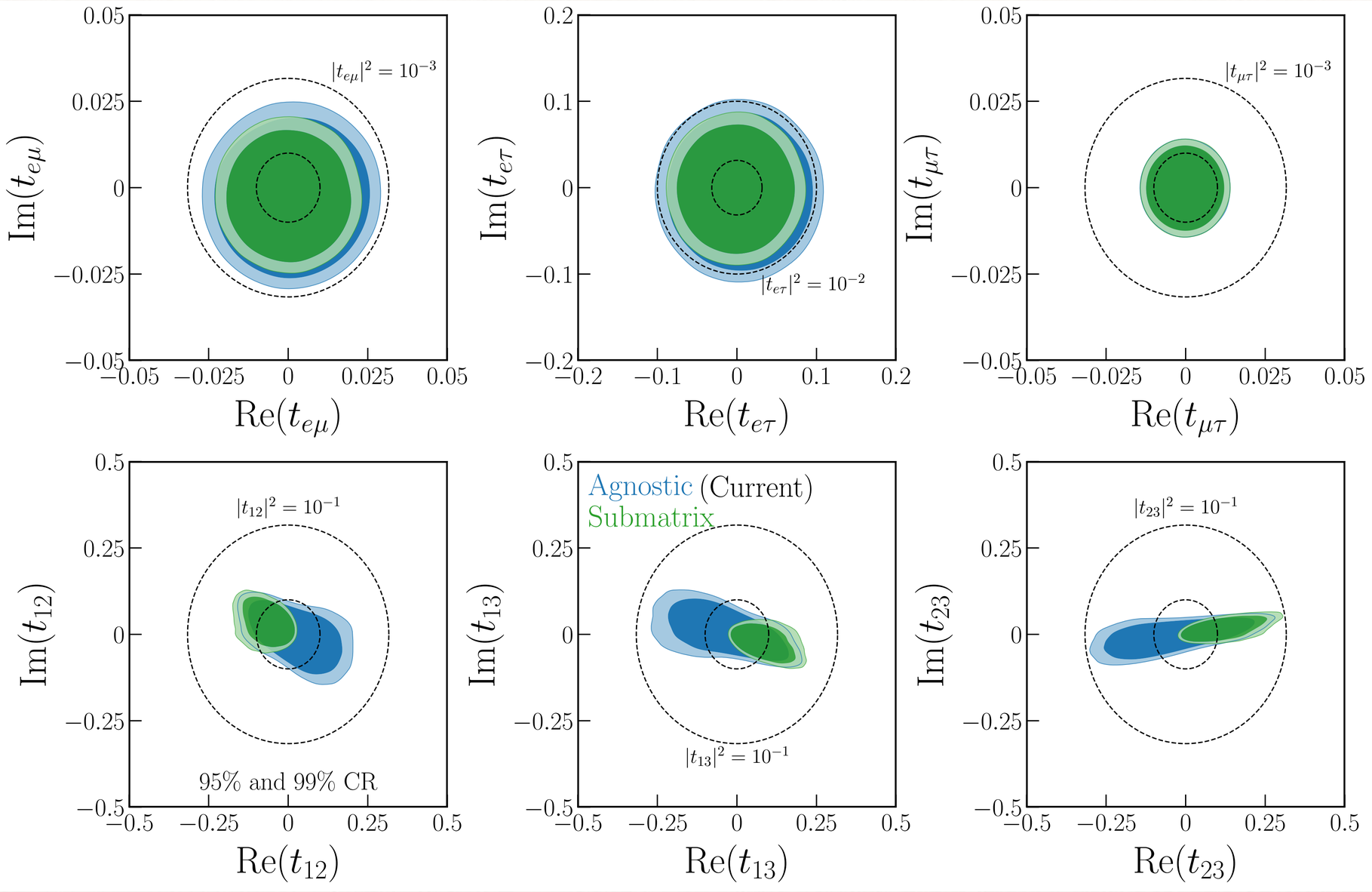

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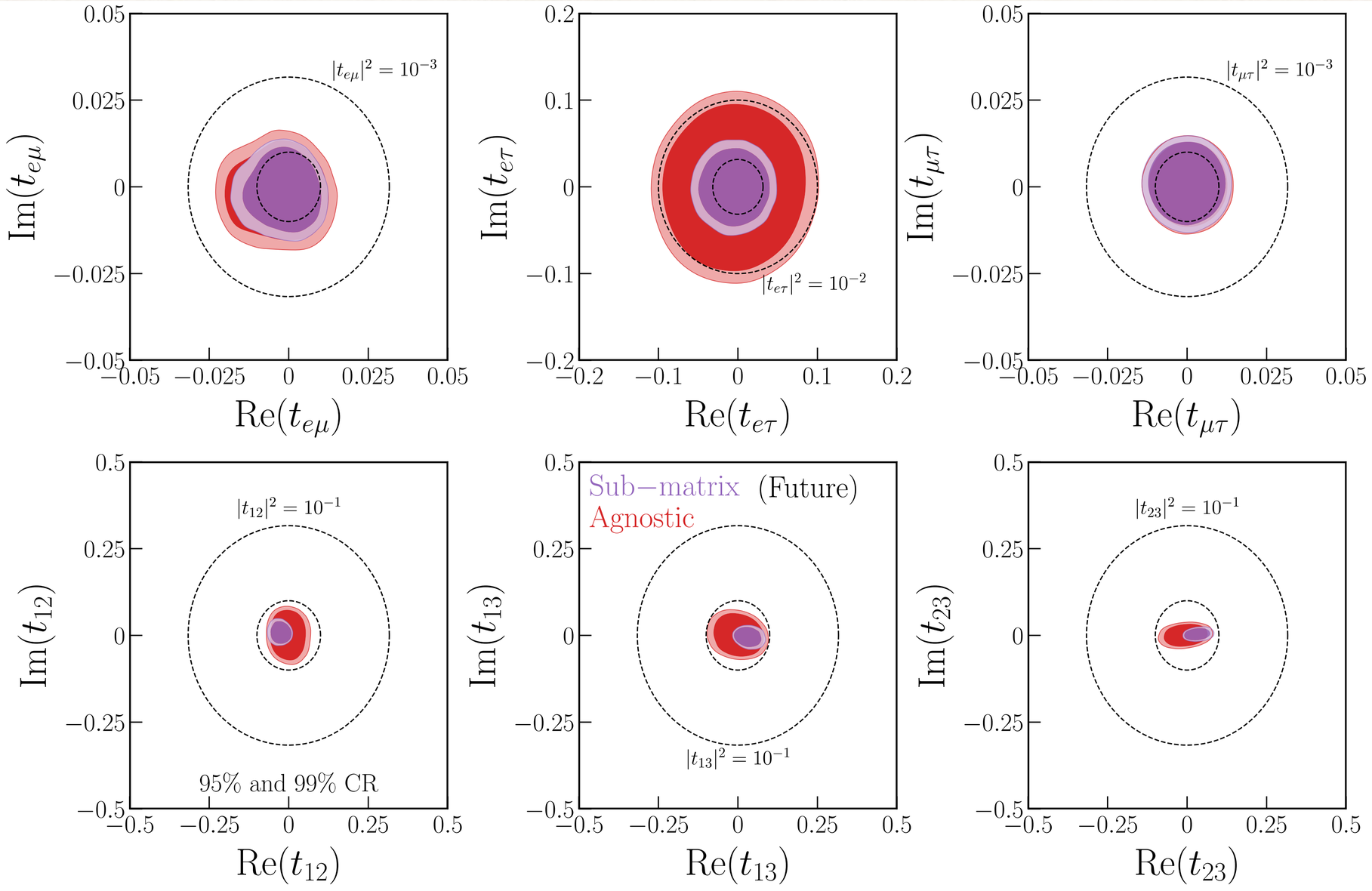

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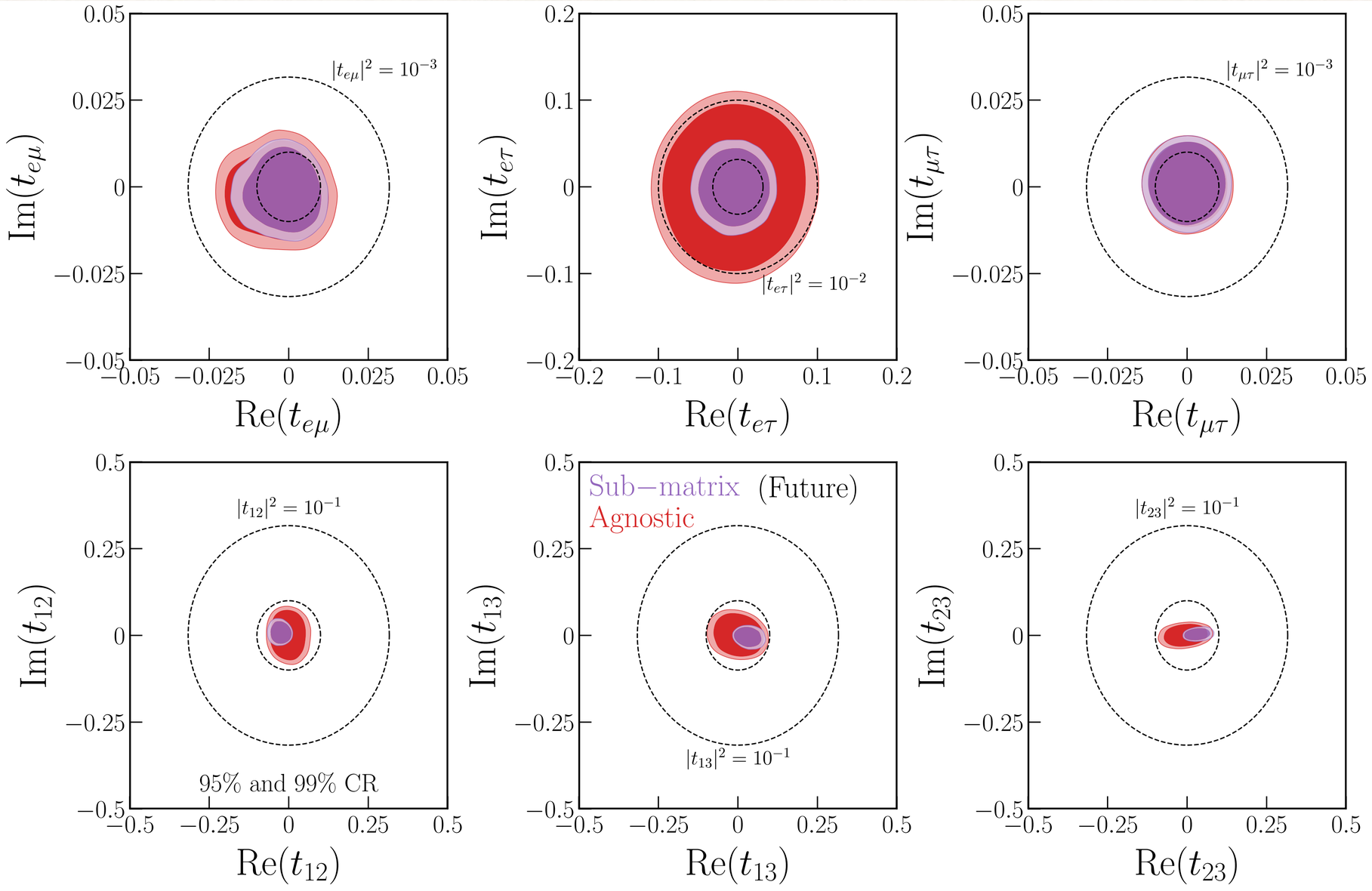


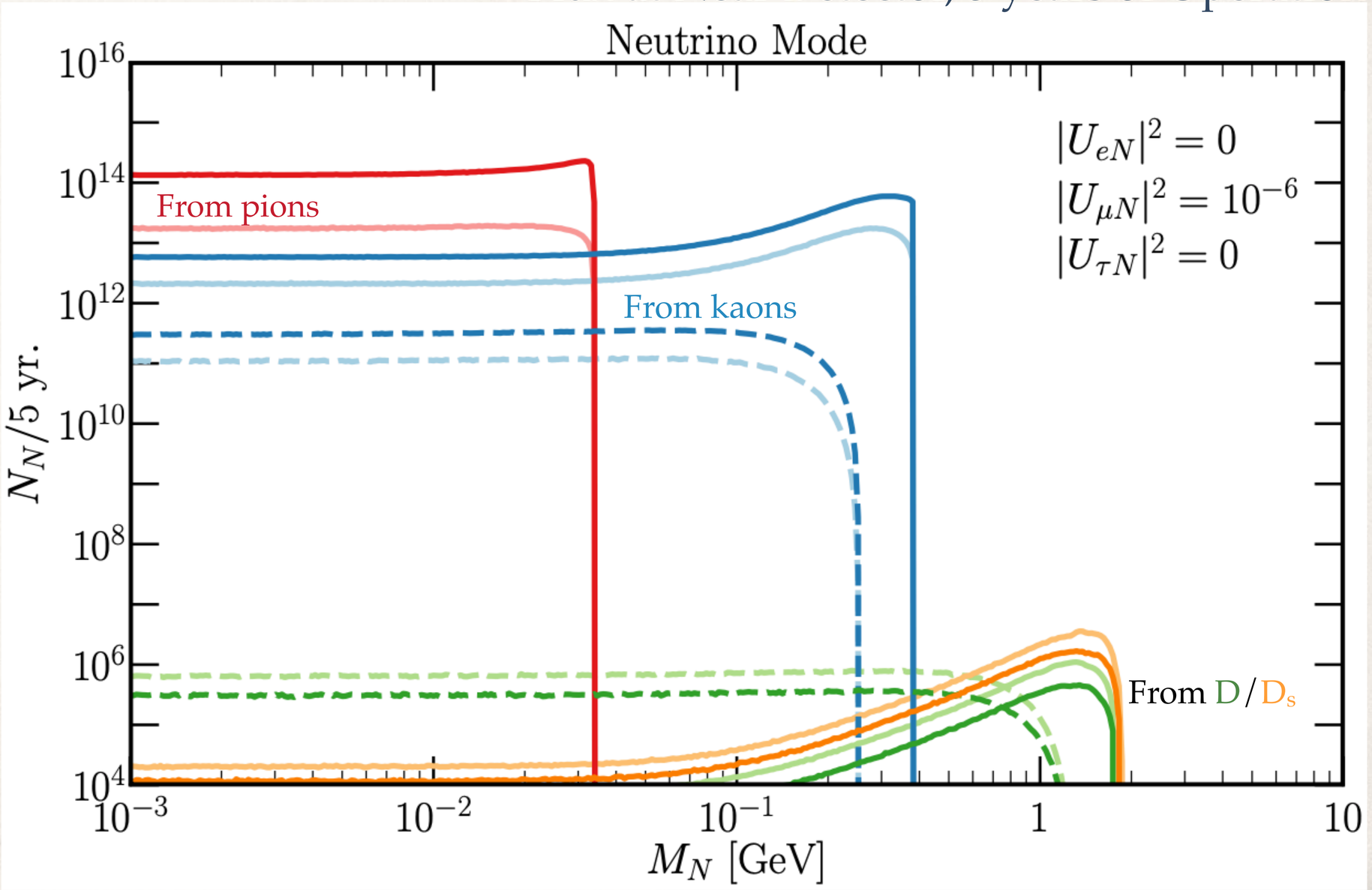
Ellis, KJK, Li [2008.01088]

Heavy Neutral Lepton Fluxes

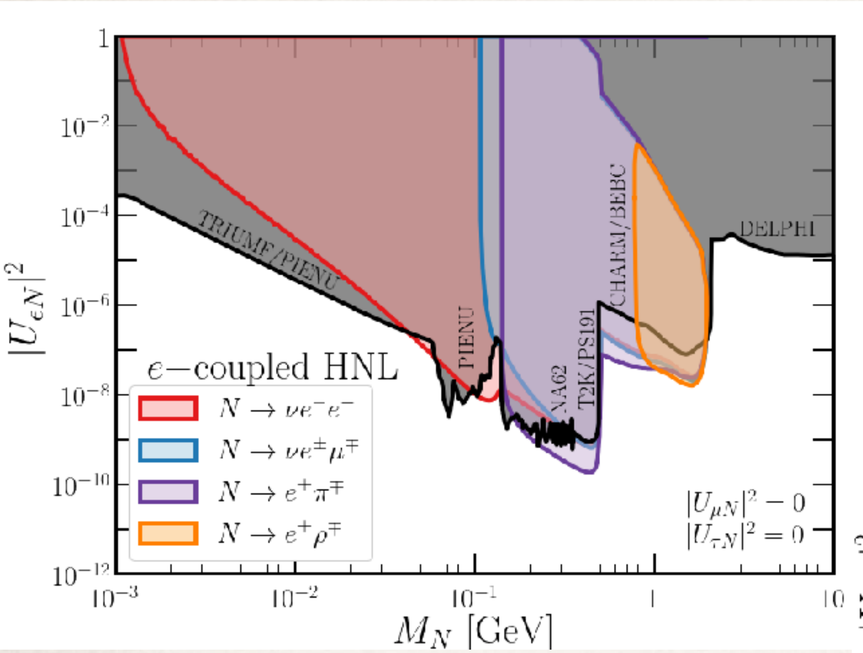
Flux at Near Detector, 5 years of Operation

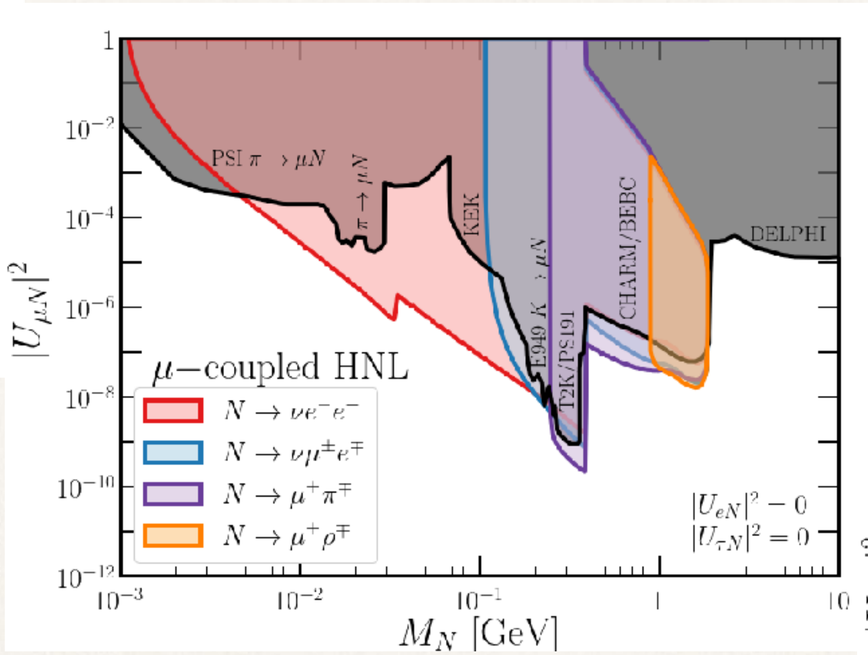
Production Modes Considered:

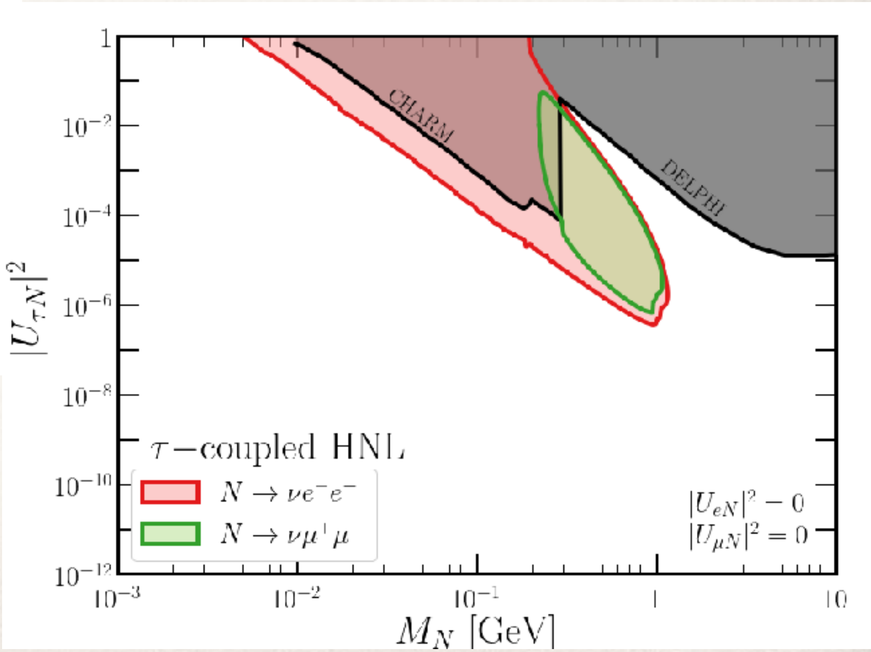
$$\pi^{\pm} \to \mu^{\pm} N$$
$$K^{\pm} \to \mu^{\pm} N$$
$$K^{\pm} \to \pi^{0} \mu^{\pm} N$$
$$D^{\pm} \to \pi^{0} \mu^{\pm} N$$
$$D^{\pm}_{(s)} \to \mu^{\pm} N$$



DUNE HNL Sensitivity, All Couplings







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