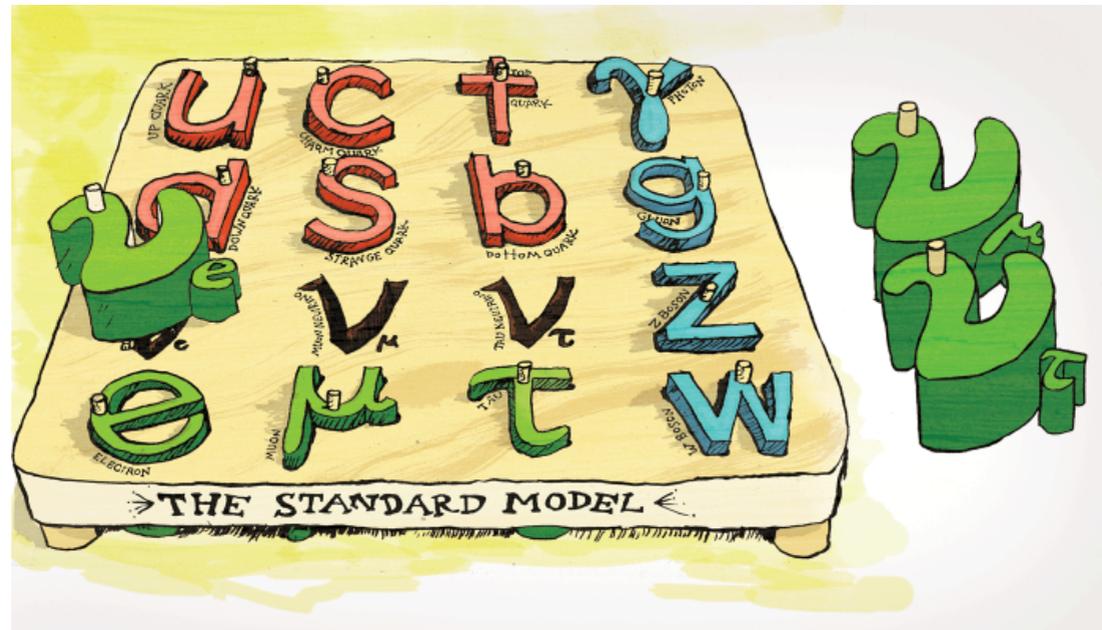


# Neutrino Theory Overview



*‘Good  $\nu$ s: Neutrino Physics at a Muon Collider’ Workshop*

*Pittsburgh – Octboer 27–29, 2025*

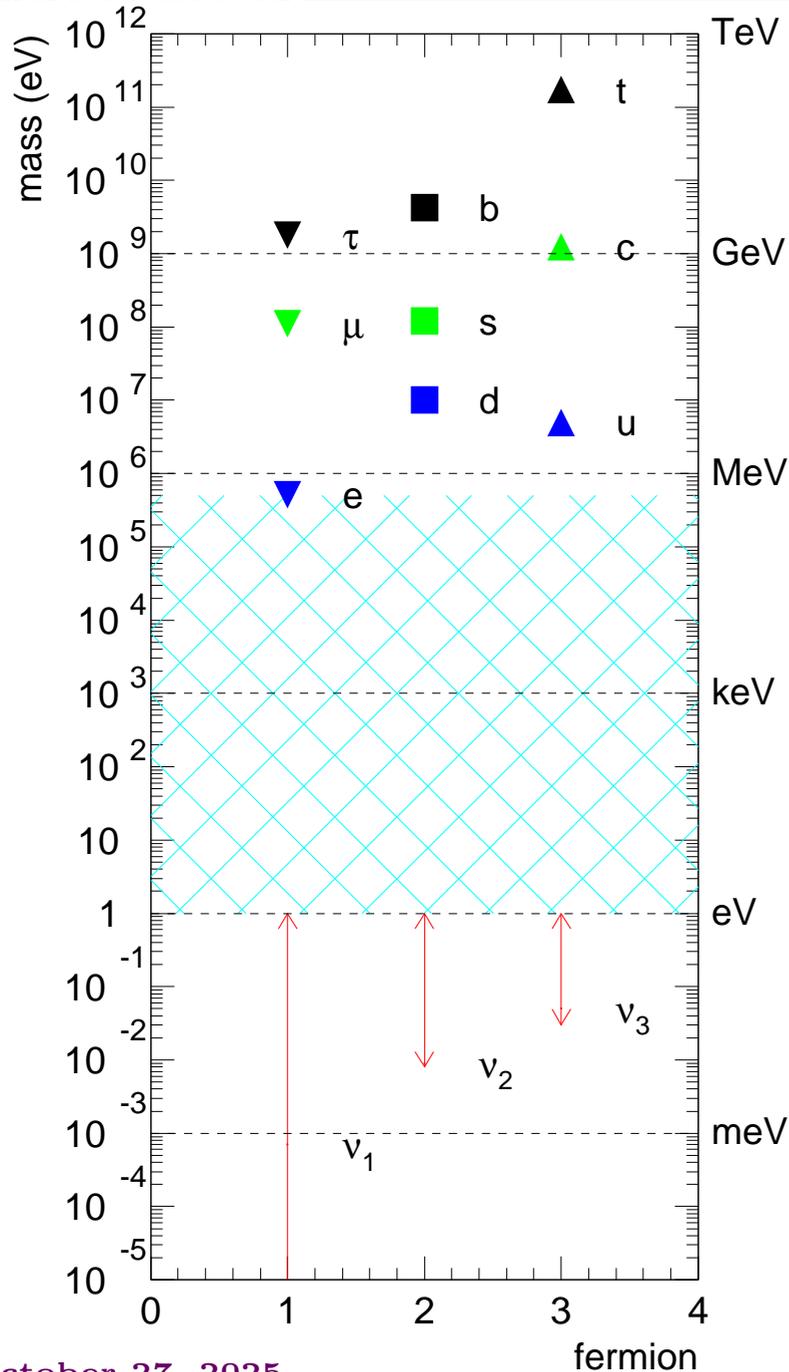
André de Gouvêa – Northwestern University

## Outline

- Neutrino Masses: What We Know We Are After;
- Neutrino Oscillation: What We Know and What We Don't Know;
- Other Questions and Opportunities.

I will try to avoid too much overlap with the many upcoming presentations.

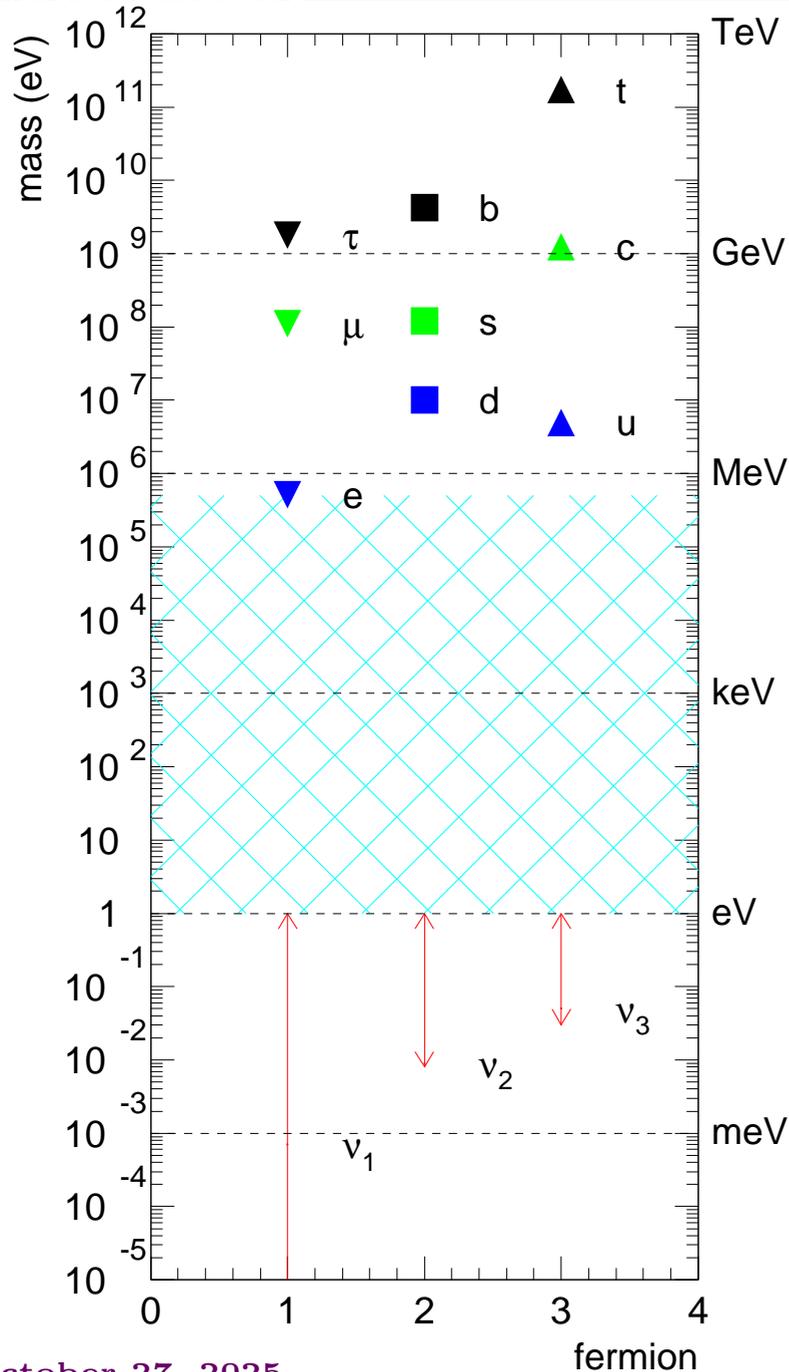
I will concentrate on neutrino oscillations. There is fascinating, unique, and very promising physics that is accessible to many other topics directly related to neutrino-associated experiments [ $0\nu\beta\beta$ ,  $\beta$ -decay and other weak, nuclear processes, UHE-neutrinos, supernova neutrinos, etc.]



# NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



# NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



NEW PHYSICS

## Nonzero neutrino masses imply the existence of new fundamental fields $\Rightarrow$ **New Particles**

We know nothing about these new particles. They can be bosons or fermions, very light or very heavy, they can be charged or neutral, experimentally accessible or hopelessly out of reach...

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There is only a handful of questions the standard model for particle physics cannot explain (these are personal. Feel free to complain).

- What is the physics behind electroweak symmetry breaking? (Higgs  $\checkmark$ ).
- What is the dark matter? (not in SM).
- Why is there so much ordinary matter in the Universe? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM).

## Neutrino Masses, Higgs Mechanism, and New Mass Scale of Nature

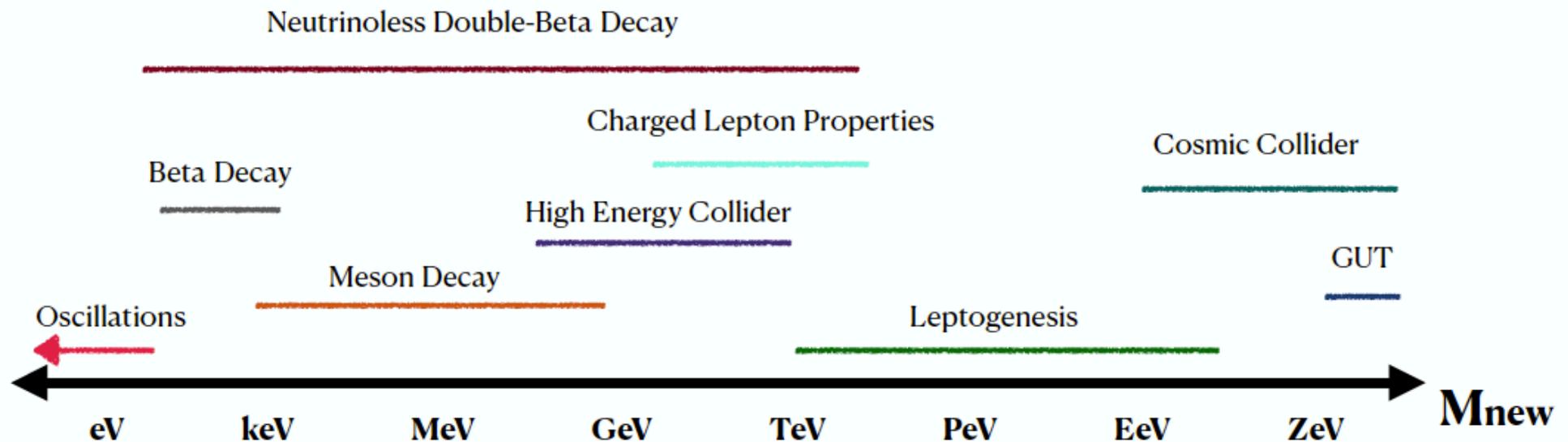
The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs doublet model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly**. And **lepton-number must be an exact symmetry** of nature (or broken very, very weakly);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking!;
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the **seesaw mechanism**.

We are going to need a lot of experimental information from all areas of particle physics in order to figure out what is really going on!

## What Is the $\nu$ Physics Scale? We Have No Idea!



Different Mass Scales Are Probed in Different Ways, Lead to Different Consequences, and Connect to Different Outstanding Issues in Fundamental Physics.

## Piecing the Neutrino Mass Puzzle

Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts . . .

- understanding the fate of lepton-number. Neutrinoless double-beta decay.
- A comprehensive long baseline neutrino program.
- Probes of neutrino properties, including neutrino scattering experiments. And what are the neutrino masses anyway? Kinematical probes.
- Precision measurements of charged-lepton properties ( $g - 2$ , edm) and searches for rare processes ( $\mu \rightarrow e$ -conversion the best bet at the moment).
- Collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- Measurements of the the large scale structure of the universe at different epochs. Neutrino properties affect, in a significant way, the history of the universe.
- Astrophysical Neutrinos – Supernovae and other Galaxy-shattering phenomena. Ultra-high energy neutrinos and correlations with not-neutrino messengers.

## HOWEVER...

We have only ever objectively “seen” neutrino masses in long-baseline oscillation experiments. It is one unambiguous way forward!

Does this mean we will reveal the origin of neutrino masses with oscillation experiments? We don’t know, and we won’t know until we try!

Furthermore, neutrino oscillation experiments are a unique environment to search for a variety of new phenomena, both neutrino-related and neutrino-not-so-related.

## Neutrino Oscillations – What We Know, Qualitative

- Solar  $\nu_e$  oscillate into  $\nu_\mu$  or  $\nu_\tau$  (large oscillation length);
- Reactor  $\bar{\nu}_e$  oscillate into  $\bar{\nu}_\mu$  or  $\bar{\nu}_\tau$ , small and large oscillation lengths;
- Atmospheric  $\nu_\mu/\bar{\nu}_\mu$  oscillate into (mostly, we suspect)  $\nu_\tau/\bar{\nu}_\tau$ , small oscillation length;
- Accelerator  $\nu_\mu/\bar{\nu}_\mu$  oscillate into (mostly, we suspect)  $\nu_\tau/\bar{\nu}_\tau$ , small oscillation length;
- Accelerator  $\nu_\mu/\bar{\nu}_\mu$  oscillate a little into  $\nu_e/\bar{\nu}_e$ , small oscillation length.

## Neutrino Oscillations – What We Don't Know, Qualitative (Agnostic View)

- Do  $\nu_\tau$  and  $\bar{\nu}_\tau$  oscillate?;
- Do  $\nu_\mu$  and  $\bar{\nu}_\mu$  oscillate with the large oscillation length?;
- Distinguish  $\nu_\mu/\bar{\nu}_\mu$  versus  $\nu_\tau/\bar{\nu}_\tau$  in  $\nu_e/\bar{\nu}_e$  oscillations.
- Are neutrinos and antineutrino oscillations “the same”? (for example,  $\nu_\mu \rightarrow \nu_e$  versus  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ ) [Is CP-invariance exact?]
- Is T-invariance exact? (for example,  $\nu_\mu \rightarrow \nu_e$  versus  $\nu_e \rightarrow \nu_\mu$ )

## The Standard Three-Massive-Active Neutrinos Paradigm fits, for the most part, all data very well<sup>a</sup>

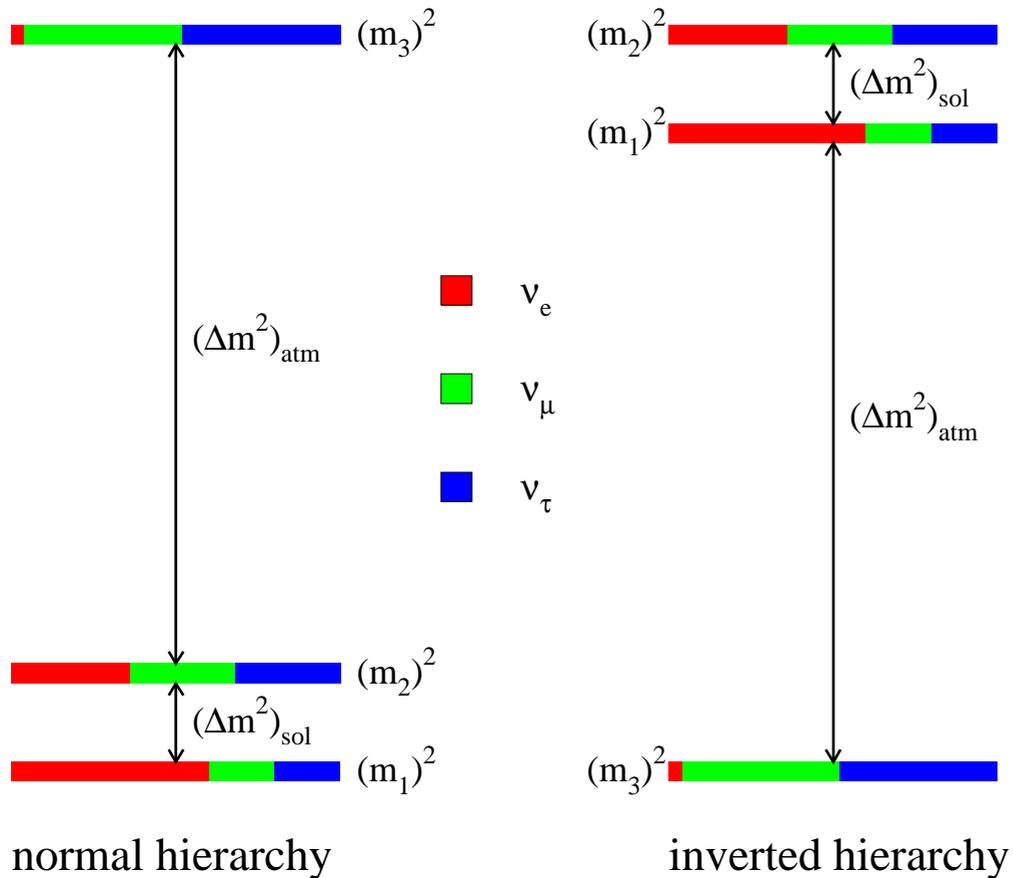
Furthermore, most of the oscillation parameters have been measured quite precisely: (see, for example, <http://www.nu-fit.org>)

$$\begin{aligned}
 \Delta m_{21}^2 &= (7.42 \pm 0.21) \times 10^{-5} \text{ eV}^2 && (3\%) \\
 |\Delta m_{31}^2| &= (2.50 \pm 0.03) \times 10^{-3} \text{ eV}^2 && (1\%) \\
 \sin^2 \theta_{12} &= 0.304 \pm 0.013 && (4\%) \\
 \sin^2 \theta_{13} &= 0.02220 \pm 0.00068 && (3\%) \\
 \sin^2 \theta_{23} &= 0.573 \pm 0.023 && (5\%) \\
 \delta_{CP} &= (105 - 405)^\circ (3\sigma) && (\text{unknown}) \\
 \text{sign}(\Delta m_{31}^2) &= +, \text{ slightly favored} && (\text{unknown})
 \end{aligned} \tag{1}$$

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<sup>a</sup>Modulo the short-baseline anomalies which I will not discuss.

# Understanding Neutrino Oscillations: Are We There Yet? [NO!]

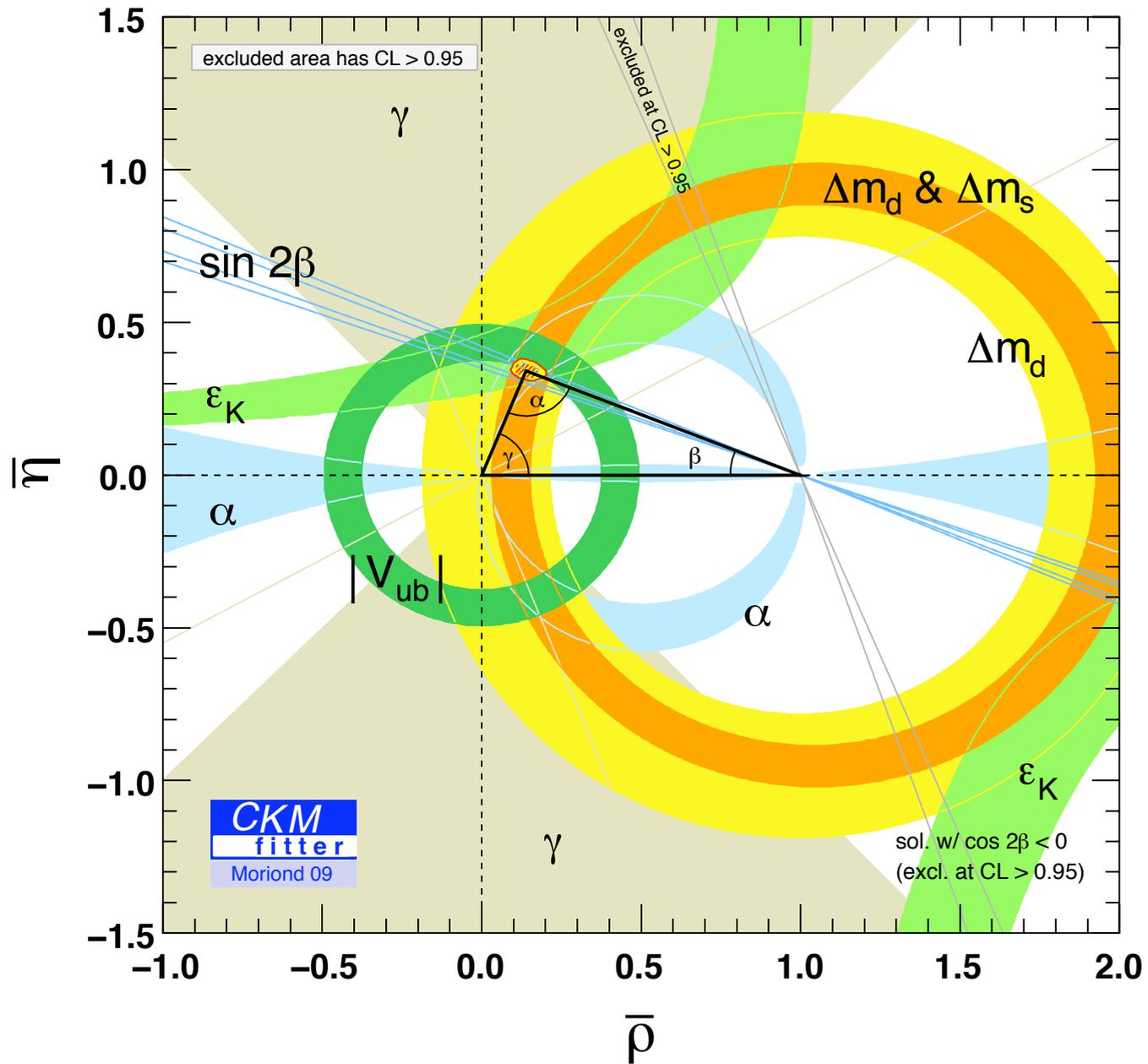


- ~~What is the  $\nu_e$  component of  $\nu_3$ ? ( $\theta_{13} \neq 0!$ )~~
- Is CP-invariance violated in neutrino oscillations? ( $\delta \neq 0, \pi?$ ) [‘yes’ hint]
- Is  $\nu_3$  mostly  $\nu_\mu$  or  $\nu_\tau$ ? [ $\theta_{23} \neq \pi/4$  hint]
- What is the neutrino mass hierarchy? ( $\Delta m^2_{13} > 0?$ ) [NH weak hint]

$\Rightarrow$  All of the above can “only” be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)

### What we ultimately want to achieve:



We need to do this in the lepton sector!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

What we have **really measured** (very roughly):

- Two mass-squared differences – many probes;
- $|U_{e2}|^2$  – solar data;
- $|U_{\mu2}|^2 + |U_{\tau2}|^2$  – solar data;
- $|U_{e2}|^2|U_{e1}|^2$  – KamLAND;
- $|U_{\mu3}|^2(1 - |U_{\mu3}|^2)$  – atmospheric data, long-baseline accelerator experiments;
- $|U_{e3}|^2(1 - |U_{e3}|^2)$  – Double Chooz, Daya Bay, RENO;
- $|U_{\mu3}|^2|U_{\tau3}|^2$  – atmospheric, OPERA;
- $|U_{e3}|^2|U_{\mu3}|^2$  – NOvA, T2K.

We still have a long way to go!

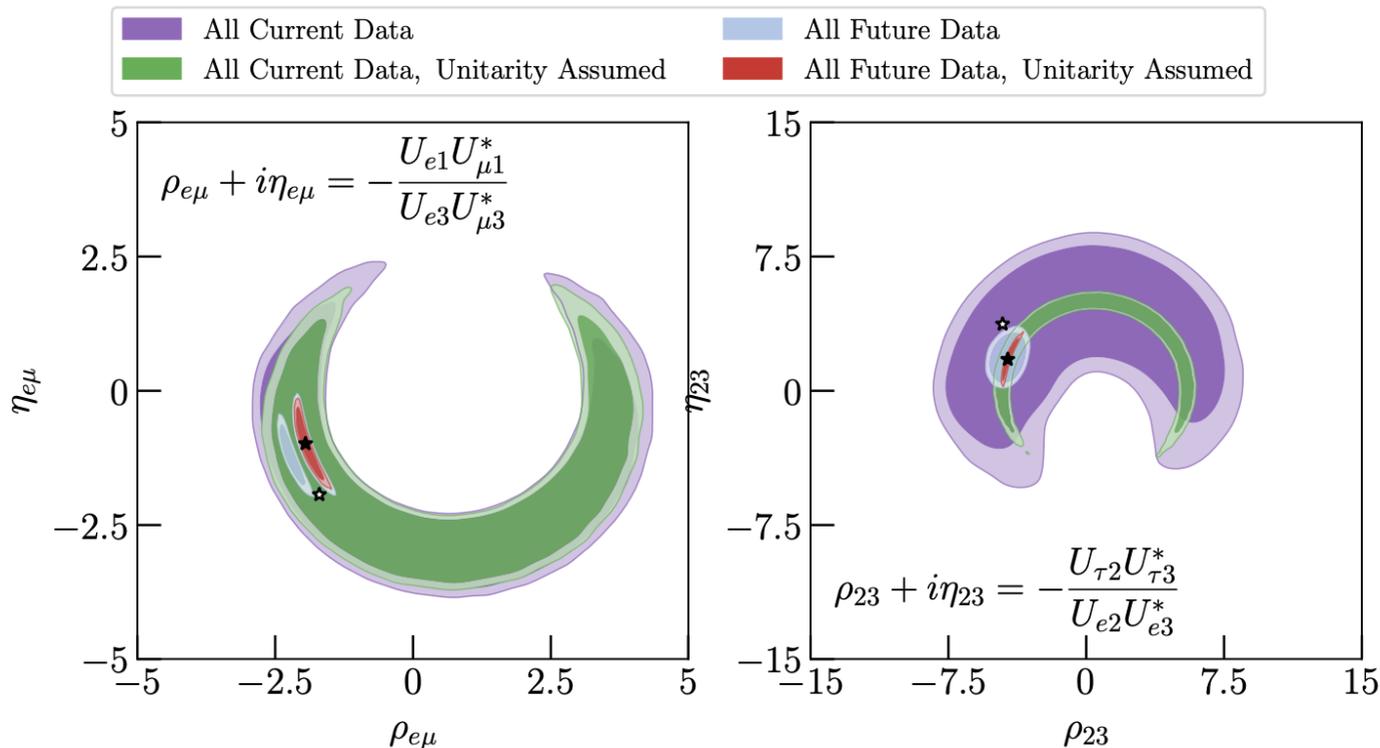
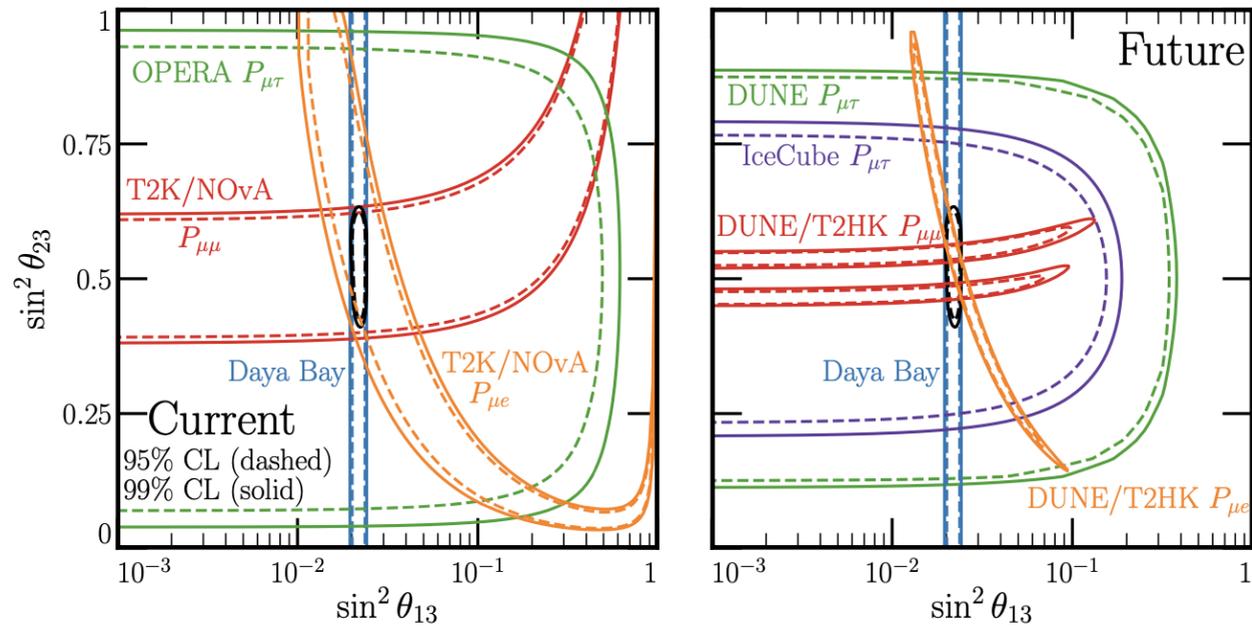


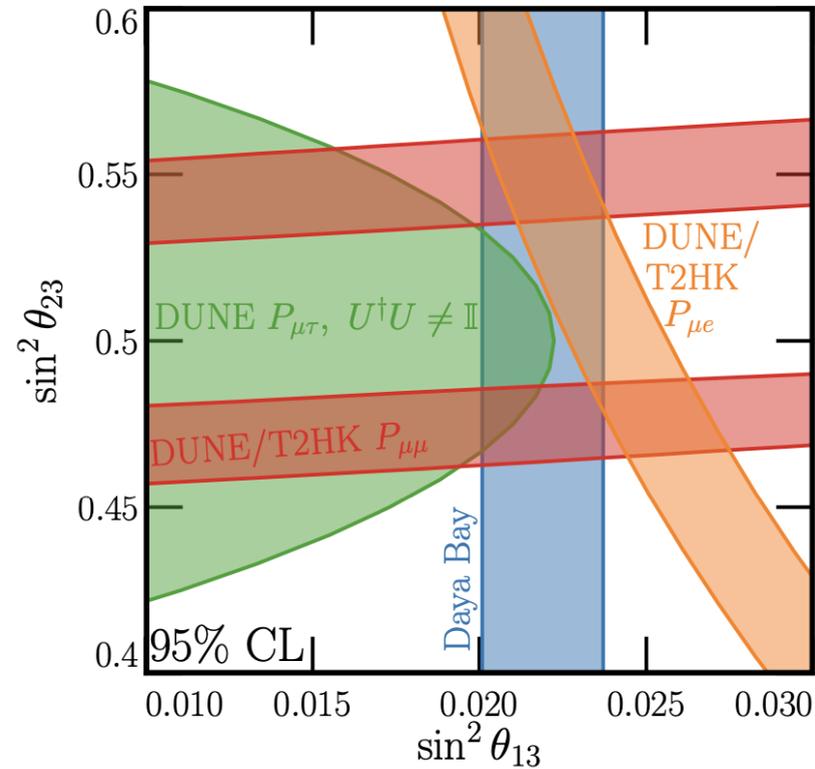
FIG. A1. Current (purple and green) and expected future (pale blue and red) measurements 95% (dark colors) and 99% confidence level (light) of two different unitarity triangles –  $\rho_{e\mu}$  vs.  $\eta_{e\mu}$  (left) and  $\rho_{23}$  vs.  $\eta_{23}$  (right). We contrast two assumptions in this figure, showing the resulting measurements when the unitarity of the leptonic mixing matrix is or is not assumed. Purple and light blue contours display the results when unitarity is not assumed, where green and red contours show the results when it is assumed. The filled-in (open) star indicates the best-fit point of the analysis of current data when unitarity is (not) assumed, corresponding to the green (purple) contours.

[Ellis, Kelly, Li, arXiv:2004.13719]



**Figure 5.** Current (left) and projected (right) measurements of the mixing angles  $\sin^2 \theta_{23}$  and  $\sin^2 \theta_{13}$  at 95% and 99% CL. The black contours in both panels show the joint-fit region with current data.

[Ellis, Kelly, Li, arXiv:2008.01088]



**Figure 6.** Projected measurements of  $\sin^2 \theta_{13}$  vs.  $\sin^2 \theta_{23}$  when unitarity is violated ( $N_3 \approx 2$ ). For DUNE's long-baseline measurement of  $P_{\mu\tau}$  (green), we simulate data assuming the underlying mixing matrix is non-unitary, and extract the measurement of these parameters assuming the matrix is unitary.

[Ellis, Kelly, Li, arXiv:2008.01088]

## Precisely Measure Oscillation Parameters. Why and How Much?

A word from flavor models:

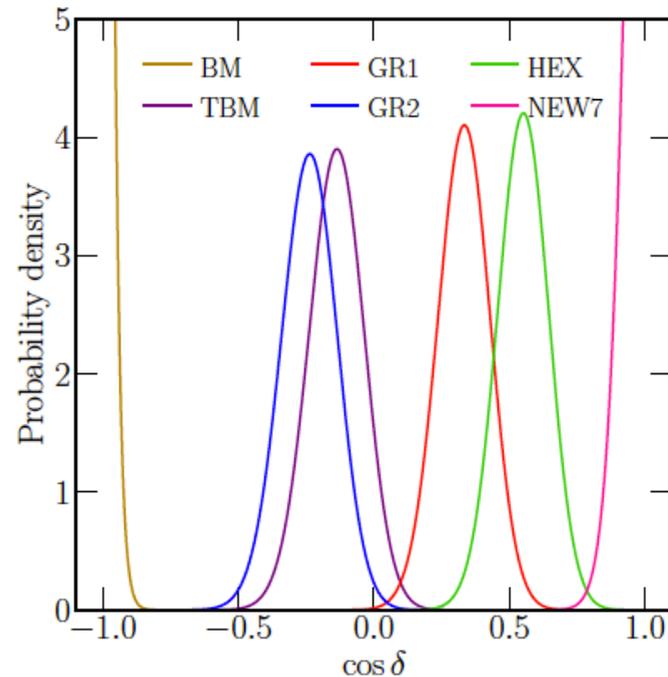


Figure 2:  $P_{\cos\delta}$  as a function of  $\cos\delta$  for various mixing patterns. Here we have assumed that  $P_z(z)$  is a Gaussian centered at the experimental best-fit value of  $z$ , with width of  $1\sigma$ .

[Everett *et al.*, arXiv:1912.10139]

## More General Comments.

If there is an underlying structure behind the values of the lepton masses and mixing angles...

- it may lead to relations among the parameters: **sum rules**.

$$f(\theta_{12}, \theta_{13}, \theta_{23}, \delta, m_1, m_2, m_3) = 0.$$

- it may lead to relations between PMNS and CKM parameters.

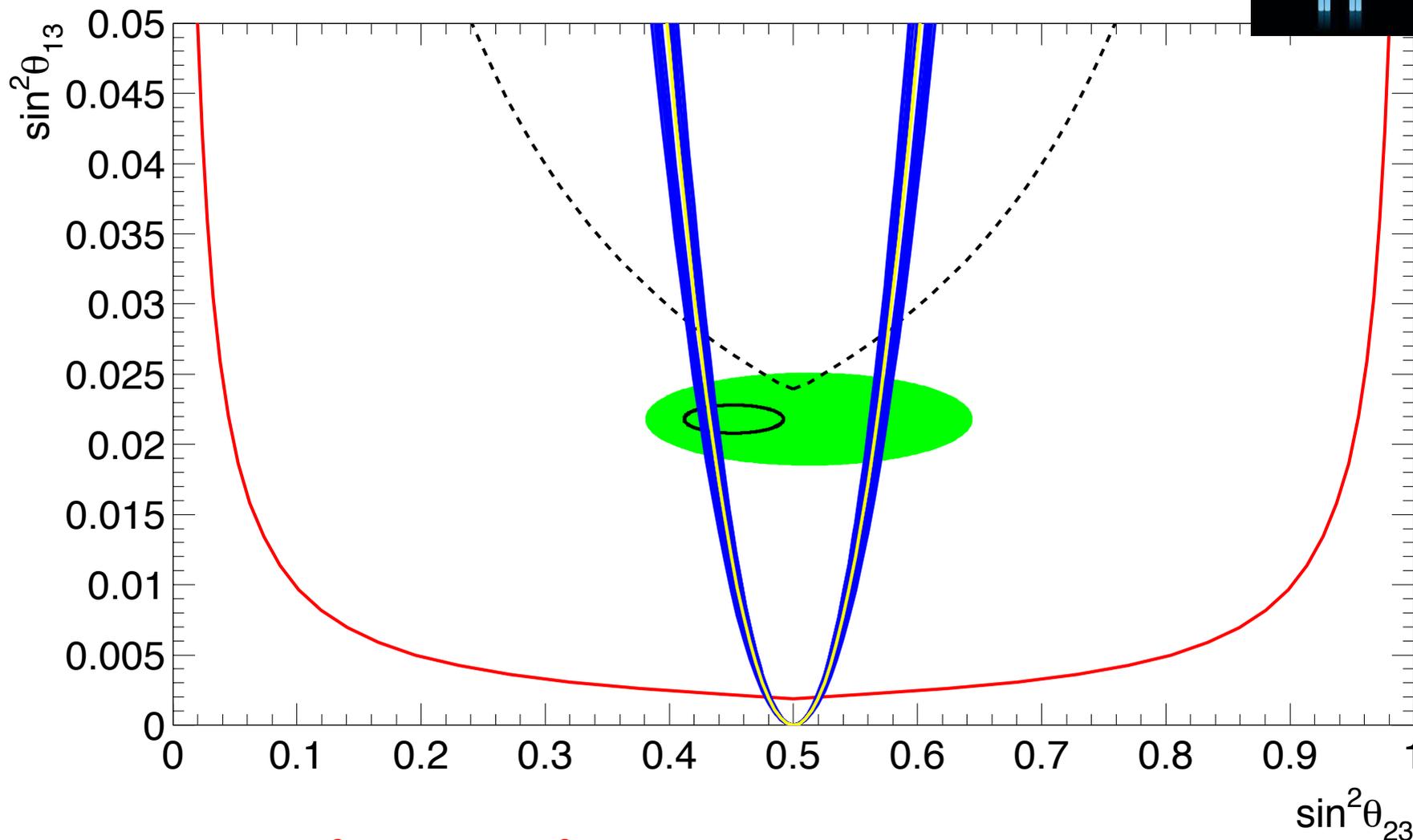
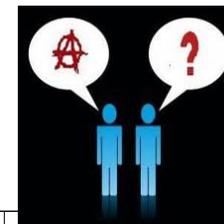
$$f(\text{PMNS}) = g(\text{CKM}).$$

- etc.

These provide guidance for precision.

- Sum rules need all oscillation parameters to be known with similar precision:  $\theta_{23}, \delta$  are the obvious outliers.
- On the CKM side,  $\theta_{12} = 13.04^\circ \pm 0.05^\circ$ ,  $\theta_{13} = 0.201^\circ \pm 0.011^\circ$ ,  $\theta_{23} = 2.38^\circ \pm 0.06^\circ$ ,  $\delta = 68.8^\circ \pm 4.5^\circ$ . (several percent to sub percent).

**Anarchy vs. Order** — more precision required!



Order:  $\sin^2 \theta_{13} = C \cos^2 2\theta_{23}$ ,  $C \in [0.8, 1.2]$

[AdG, Murayama, 1204.1249]

## Long-Baseline Experiments, Present and Future (Not Exhaustive!)

- [NOW] T2K (Japan), NO $\nu$ A (USA) –  $\nu_\mu \rightarrow \nu_e$  appearance,  $\nu_\mu$  disappearance – precision measurements of “atmospheric parameters” ( $\Delta m_{31}^2, \sin^2 \theta_{23}$ ). Pursue mass hierarchy via matter effects. Nontrivial tests of paradigm. First step towards CP-invariance violation.
- [VERY SOON] JUNO (China) –  $\bar{\nu}_e$  disappearance – precision measurements of “solar parameters” ( $\Delta m_{12}^2, \sin^2 \theta_{12}$ ). Pursue the mass hierarchy via precision measurements of oscillations.
- [SOON] km<sup>3</sup> arrays, upgraded – atmospheric neutrinos – pursue mass hierarchy via matter effects.
- [LATER] HyperK (Japan), DUNE (USA) – Second step towards CP-invariance violation. More nontrivial tests of the paradigm. Ultimate “super-beam” experiments.

## Neutrino Oscillations in the 2040s

- Limitations of the super-beams:
  - $\pi^+ \rightarrow \mu^+ \nu_\mu$ , charged-selected pions.
  - Dirty beam. Wrong-sign contamination, neutrinos from Kaons, muons lead to a beam  $\nu_e$  background.
  - Systematics will kick in by (or before) the end of the DUNE and Hyper-K runs.
  - Only initial-state  $\nu_\mu$ :  $\nu_\mu \rightarrow \nu_e$  and  $\nu_\mu \rightarrow \nu_\tau$ .
- In general, statistics will remain a challenge. (Neutrinos are only weakly interacting!)
- We can count on the questions evolving in surprising ways. E.g., short-baseline anomalies, disagreements between DUNE and Hyper-K, etc.

## Neutrino Oscillations in the 2040s



More precisely, we are going to need a **BETTER BEAM!**

Ideas include:

- Decay-at-rest beams ( $\pi$ ,  $K$ , nuclei);
- Nucleus-decay-in-flight beams ( $\beta$ -beams);
- Muon-decay-in-flight beams (neutrino factories).

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e \quad \text{and} \quad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

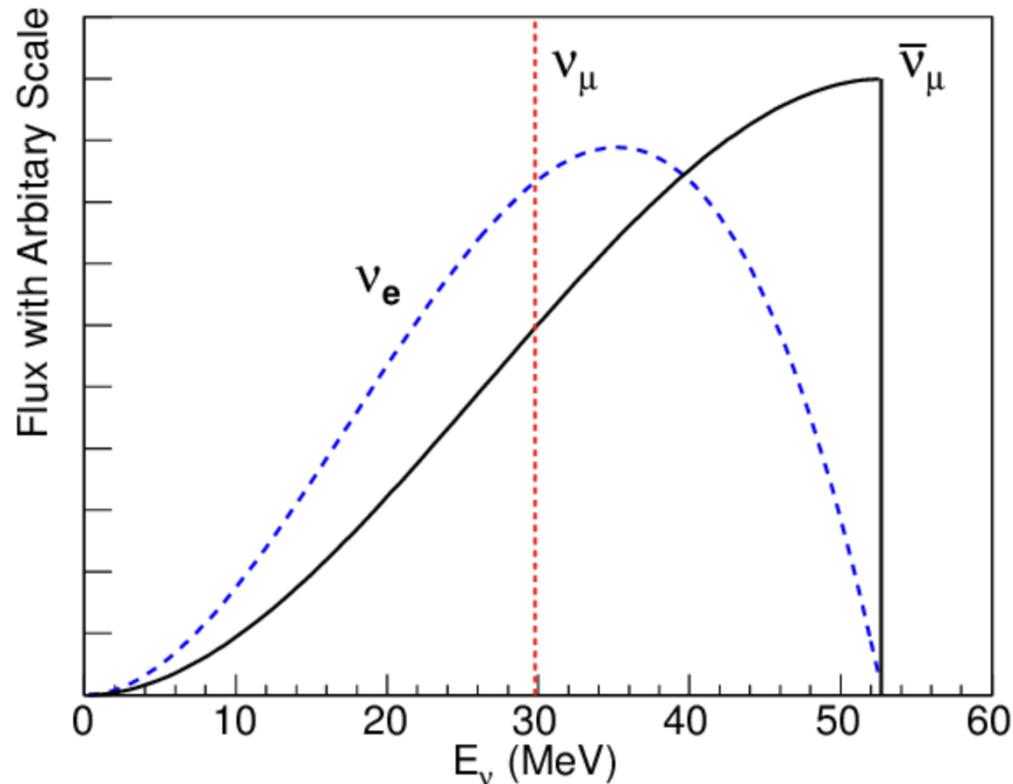
- Muon energy and charge known very well  $\rightarrow$  neutrino energy spectra known very well and neutrino beams very clean!
- Detectors with charge-ID allow one to kill the beam-background.
- High-energy  $\nu_e$  and  $\bar{\nu}_e$ -beams allow for  $\nu_e \rightarrow \nu_\mu$  and  $\nu_e \rightarrow \nu_\tau$  oscillation measurements! **New oscillation channels provide priceless opportunity for more observables.**

- 

$$\phi_{\text{osc}} \sim 3.6 \left( \frac{\Delta m^2}{3 \times 10^{-3} \text{ eV}^2} \right) \left( \frac{L}{10^4 \text{ km}} \right) \left( \frac{10 \text{ GeV}}{E} \right)$$

- Neutrino energies of (or below) tens of GeV. (or we are going to need a bigger planet!)
- Life could be very different if there were new light neutrino degrees of freedom (e.g., a new mass-squared difference).

## Muon-Collider Neutrino Beam



- Very well characterized beams. We know these shapes “perfectly” and we can modify them in a controlled way by polarizing the muons.
- There are both  $\nu_\mu$  and a  $\bar{\nu}_e$  beams. And we can separate them (different options)

## More New Physics in the Neutrino Sector?



since  $m_\nu \neq 0$  and leptons mix ...

## More New Physics in the Neutrino Sector?

- New neutrino states. In this case, e.g., the  $3 \times 3$  mixing matrix would not be unitary.
- New short-range neutrino interactions. These lead to, for example, new matter effects. If we don't take these into account, there is no reason for the three flavor paradigm to “close.”
- New, unexpected neutrino properties. Do they have nonzero magnetic moments? Do they decay? [The answer is ‘yes’ to both, but nature might deviate dramatically from expectations from the SM plus massive neutrinos.]
- Weird stuff. CPT-violation. Decoherence effects (aka “violations of Quantum Mechanics.”)
- etc.

## And There is More!

### Muon-Collider High-Energy Neutrino–Nucleus Scattering

- Neutrino Radiation can be exploited for, for example, a high-energy neutrino fixed-target experiment.
- Similar in spirit to FASER $\nu$  (arXiv:1908.02310) with several advantages:
  - Neutrino energy spectrum very well known;
  - Beam has a well-defined flavor ( $\nu_\mu$  and  $\bar{\nu}_e$  or vice-versa);
  - Perhaps very narrow beam. Is this good for something? Perhaps different, better targets and detectors?
  - May be an excellent place to do “short-baseline” oscillations. E.g.,  $\nu_\tau$  appearance. Could be a very hot topic.
- Neutrino DIS.

## And There is More!

### Neutrino Physics at the $\mu^+\mu^-$ Collision Point

- Direct test of neutrino mass models. Neutral heavy leptons, etc.
- Muon Collider as a “Neutrino Collider?” Any luminosity from the decay-daughter-neutrinos to collide?  $\nu_\mu + \bar{\nu}_\mu$ , and  $\nu_\mu + \nu_e$  collisions. Would be amazingly cool ...
- There is the possibility to study  $\mu^+ + \nu_\mu$  collisions from  $W^+$  radiation off the muon beam and  $\nu_\mu + \bar{\nu}_\mu$  from double  $W^+ + W^-$  radiation (i.e.,  $\mu^+ + \mu^- \rightarrow W^+ + W^- + (\nu_\mu + \bar{\nu}_\mu)$ ). Unique probe of “neutrino-only” forces?
- While we are at it, it may be wise to think about a  $\mu^+ + \mu^+$  collider ( $L = 2$  initial state). The LHC already has a  $B = 2$  collision, how hard can it be?

## What Could We Learn About?

- Neutrino–neutrino interactions;
- Neutrino interactions with a Dark Sector ( $LH$ -portal);
- New channels to look for lepton-number violation. E.g. Type-II Seesaw (Higgs triplet  $T = (t^{++}, t^+, t^0)$ ,  $\mu^+ \mu^+ \rightarrow t^{++} \rightarrow W^+ W^+$ ). Potential to inform a hypothetical discovery of  $0\nu\beta\beta$ ?;
- Many more interesting things I haven't thought about. There is a lot of work to do.

**In conclusion...**

- We still **know very little** about the new physics uncovered by neutrino oscillations. I have no idea how much this will change in 20 years. It could, but it doesn't have to.
- **neutrino masses are very small** – we don't know why, but we think it means something important. **neutrino mixing is “weird”** – we don't know why, but we think it means something important.
- We **need more experimental input** (neutrinoless double-beta decay, precision neutrino oscillations, UHE neutrinos, charged-lepton precision measurements, colliders, etc). This is unlikely (?) to change in 20 years.
- **Precision measurements of neutrino oscillations** are sensitive to several new phenomena. **There is at least one clear option – muon storage rings – for what to do after DUNE and Hyper-K.** And a lot of work to do to find out how much more interesting things could get.
- There is plenty of **room for surprises**, as neutrinos are potentially very deep probes of all sorts of physical phenomena. Remember that neutrino oscillations are “quantum interference devices.”

# Backup Slides . . .

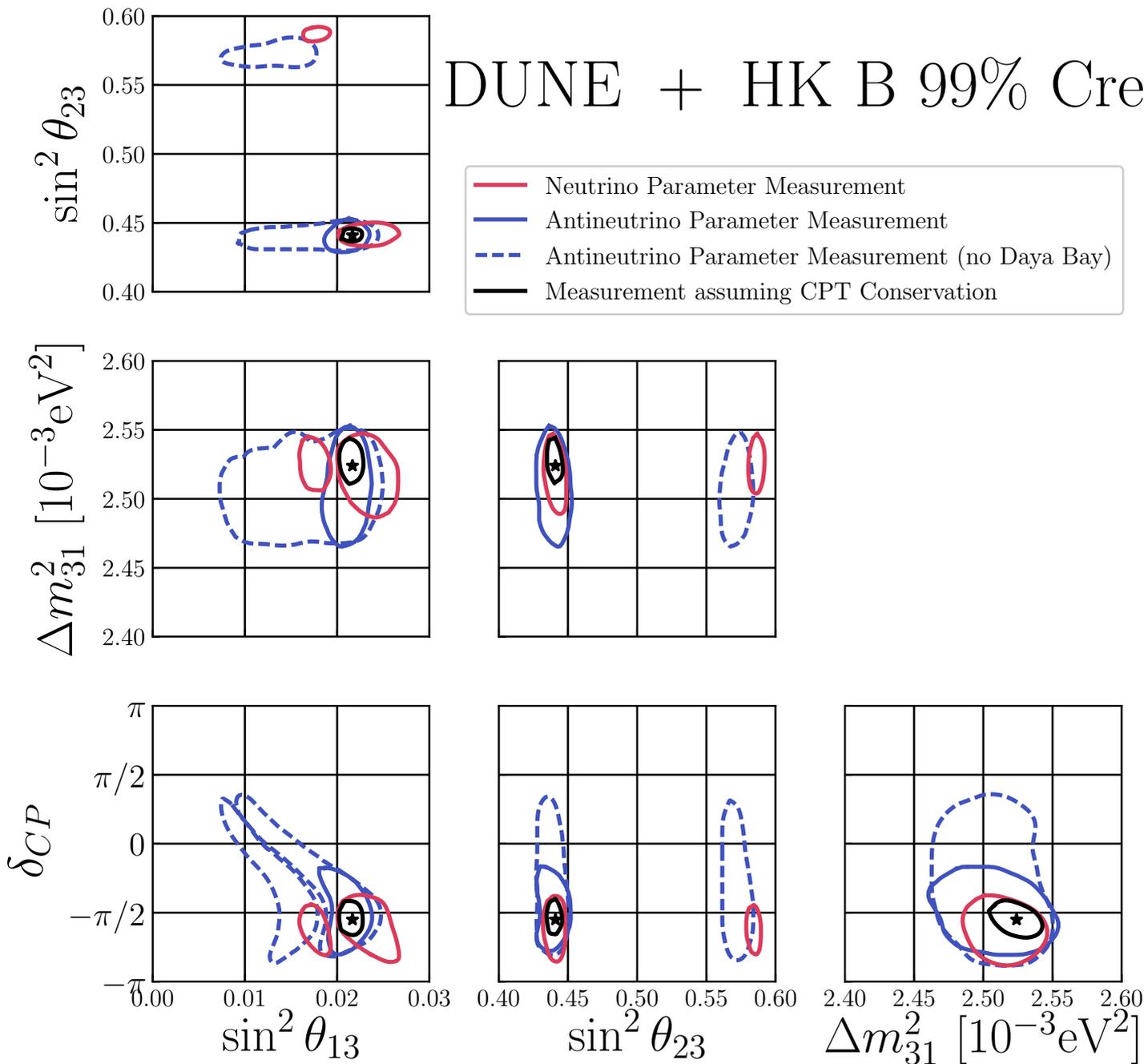
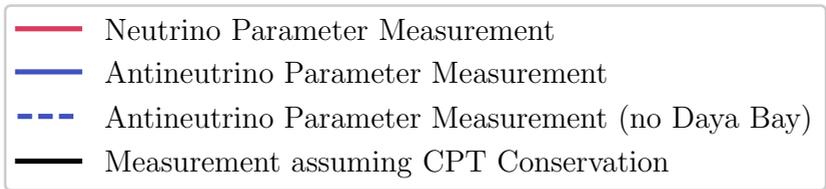


## Different Oscillation Parameters for Neutrinos and Antineutrinos?

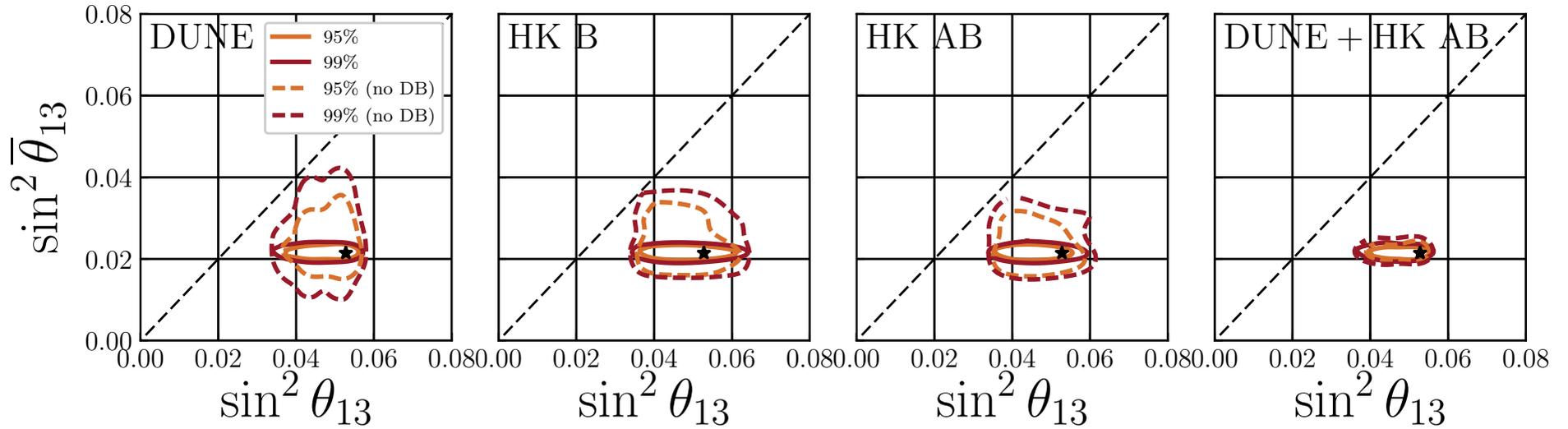
[AdG, Kelly, arXiv:1709.06090]

- How much do we know, independently, about neutrino and antineutrino oscillations?
- What happens if the parameters disagree?

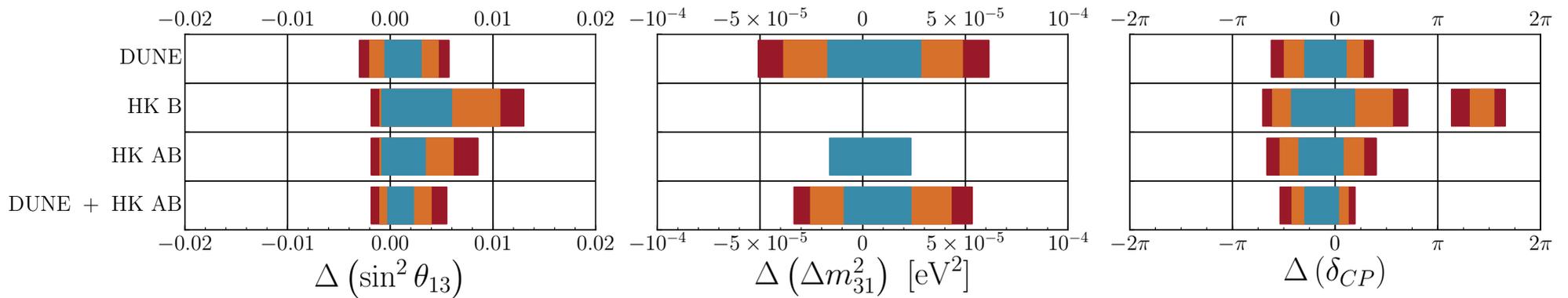
# DUNE + HK B 99% Cred.



[AdG and Kelly, arXiv:1709.06090]



[AdG and Kelly, arXiv:1709.06090]



## Some technicalities for the aficionados

- 34 kiloton liquid argon detector;
- 1.2 MW proton beam on target as the source of the neutrino and antineutrino beams, originating 1300 km upstream at Fermilab;
- 3 years each with the neutrino and antineutrino mode;
- Include standard backgrounds, and assume a 5% normalization uncertainty;
- Whenever quoting bounds or measurements of anything, we marginalize over all parameters not under consideration;
- We include priors on  $\Delta m_{12}^2$  and  $|U_{e2}|^2$  in order to take into account information from solar experiments and KamLAND. Unless otherwise noted, we assume the mass ordering is normal;
- We do not include information from past experiments. We assume that DUNE will “out measure” all experiments that came before it (except for the solar ones, as mentioned above).

## Case Study – Non-Standard Neutrino Interactions (NSI)

Effective Lagrangian (assuming new interaction is neutral-current-like):

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\rho\nu_\beta) \sum_{f=e,u,d} (\epsilon_{\alpha\beta}^{fL}\bar{f}_L\gamma^\rho f_L + \epsilon_{\alpha\beta}^{fR}\bar{f}_R\gamma^\rho f_R) + h.c.,$$

For oscillations,

$$H_{ij} = \frac{1}{2E_\nu} \text{diag} \{0, \Delta m_{12}^2, \Delta m_{13}^2\} + V_{ij},$$

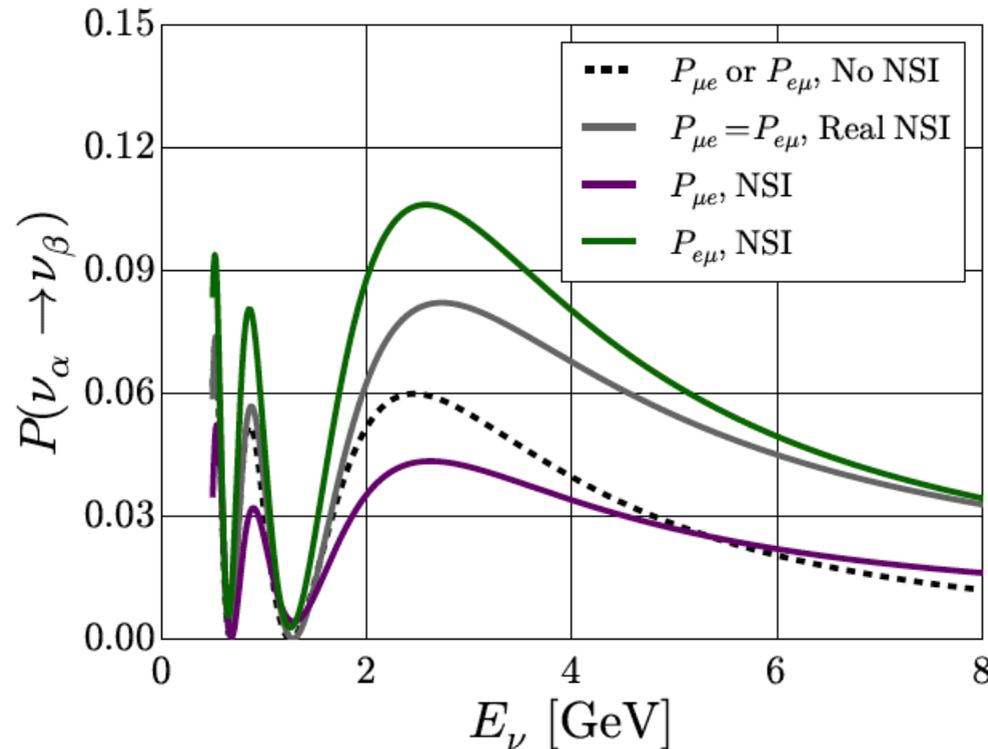
where

$$V_{ij} = U_{i\alpha}^\dagger V_{\alpha\beta} U_{\beta j},$$

$$V_{\alpha\beta} = A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix},$$

$A = \sqrt{2}G_F n_e$ .  $\epsilon_{\alpha\beta}$  are linear combinations of the  $\epsilon_{\alpha\beta}^{fL,R}$ . In the literature, it is common to consider propagation effects only and ignore NSI effects in production or detection ( $\epsilon$  versus  $\epsilon^2$ ).

There are new sources of CP-invariance violation! [easier to see T-invariance violation]



[AdG and Kelly, arXiv:1511.05562]

FIG. 2:  $T$ -invariance violating effects of NSI at  $L = 1300$  km for  $\epsilon_{e\mu} = 0.1e^{i\pi/3}$ ,  $\epsilon_{e\tau} = 0.1e^{-i\pi/4}$ ,  $\epsilon_{\mu\tau} = 0.1$  (all other NSI parameters are set to zero). Here, the three-neutrino oscillation parameters are  $\sin^2 \theta_{12} = 0.308$ ,  $\sin^2 \theta_{13} = 0.0234$ ,  $\sin^2 \theta_{23} = 0.437$ ,  $\Delta m_{12}^2 = 7.54 \times 10^{-5}$  eV<sup>2</sup>,  $\Delta m_{13}^2 = 2.47 \times 10^{-3}$  eV<sup>2</sup>, and  $\delta = 0$ , i.e., no “standard”  $T$ -invariance violation. The green curve corresponds to  $P_{e\mu}$  while the purple curve corresponds to  $P_{\mu e}$ . If, instead, all non-zero NSI are real ( $\epsilon_{e\mu} = 0.1$ ,  $\epsilon_{e\tau} = 0.1$ ,  $\epsilon_{\mu\tau} = 0.1$ ),  $P_{e\mu} = P_{\mu e}$ , the grey curve. The dashed line corresponds to the pure three-neutrino oscillation probabilities assuming no  $T$ -invariance violation (all  $\epsilon_{\alpha\beta} = 0$ ,  $\delta = 0$ ).

## Telling Different Scenarios Apart:

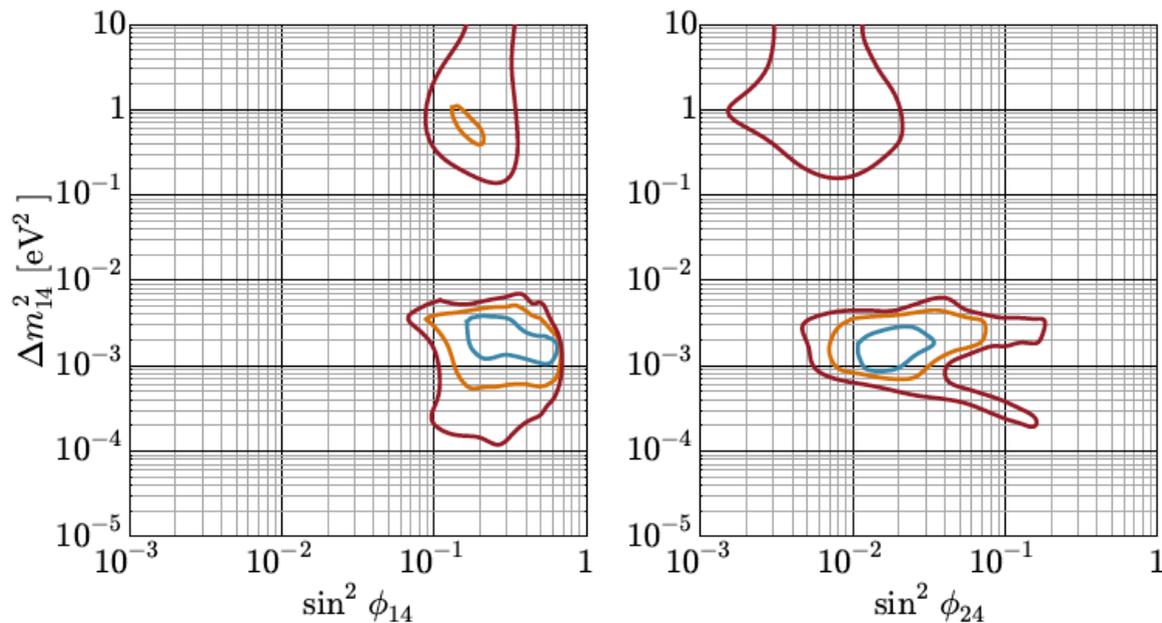
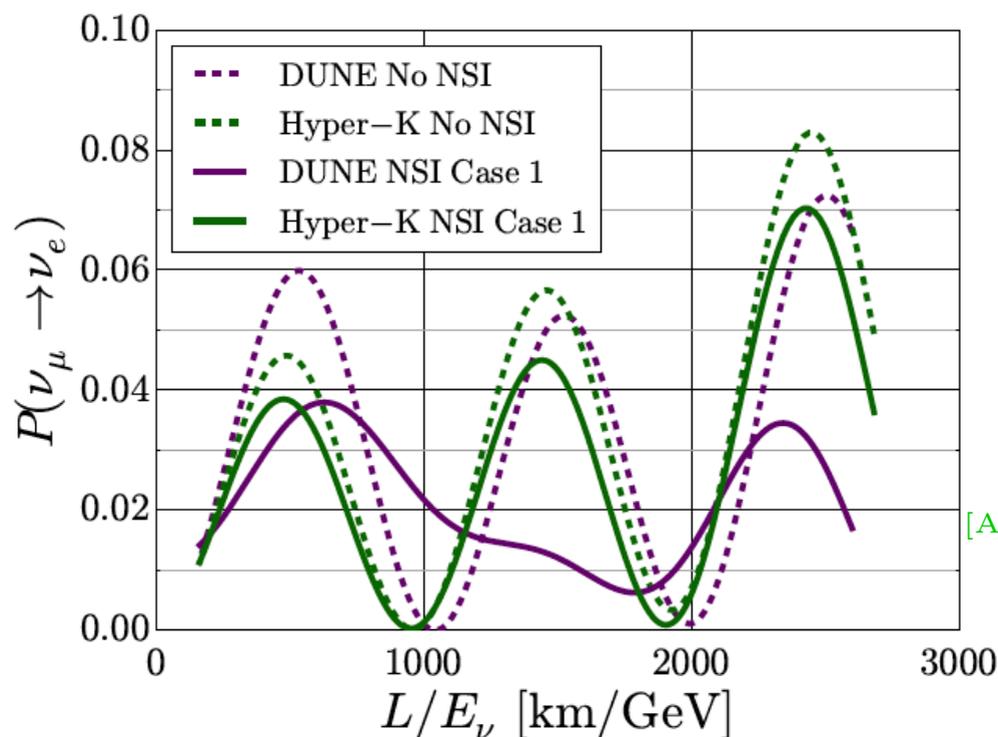


FIG. 8: Sensitivity contours at 68.3% (blue), 95% (orange), and 99% (red) for a four-neutrino fit to data consistent with Case 2 from Table I. All unseen parameters are marginalized over, and Gaussian priors are included on the values of  $\Delta m_{12}^2$  and  $|U_{e2}|^2$ . See text for details.

[AdG and Kelly, arXiv:1511.05562]

## How Do We Learn More – Different Experiments!

- Different  $L$  and  $E$ , same  $L/E$  (e.g. HyperK versus DUNE);
- Different matter potentials (e.g. atmosphere versus accelerator);
- Different oscillation modes (e.g., appearance versus disappearance,  $e$ 's,  $\mu$ 's and  $\tau$ 's).



[AdG and Kelly, arXiv:1511.05562]

FIG. 9: Oscillation probabilities for three-neutrino (dashed) and NSI (solid) hypotheses as a function of  $L/E_\nu$ , the baseline length divided by neutrino energy, for the DUNE (purple) and HyperK (green) experiments. Here,  $\delta = 0$  and the three-neutrino parameters used are consistent with Ref. [47].

## The Physics Behind NSI – Comments and Concerns

There are two main questions associated to NSI's. They are somewhat entwined.

1. Are there models for new physics that lead to large NSIs? Are these models well motivated? Are they related to some of the big questions in particle physics?
2. Are NSIs constrained by observables that have nothing to do with neutrino physics? Are large NSI effects allowed at all?

## The Physics Behind NSI – Comments and Concerns

There are two main questions associated to NSI's. They are somewhat entwined.

1. Are there models for new physics that lead to large NSIs? Are these models well motivated? Are they related to some of the big questions in particle physics?

[ans: Yes. They can be. They can be.]

2. Are NSIs constrained by observables that have nothing to do with neutrino physics? Are large NSI effects allowed at all?

[ans: Absolutely. Yes, but it is model dependent.]

See Overview by Y. Farzan and M. Tórtola, [arXiv:1710.09360 \[hep-ph\]](#)

For a concrete UV-complete model, see K.S. Babu et al, [arXiv:1705.01822 \[hep-ph\]](#)

Effective Lagrangian:

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\bar{f}\gamma^\rho f).$$

This is not  $SU(2)_L$  invariant. Let us fix that:

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{L}_\alpha\gamma_\rho L_\beta)(\bar{f}\gamma^\rho f).$$

where  $L = (\nu, \ell^-)^T$  is the lepton doublet. This is a big problem.

Charged-Lepton flavor violating constraints are really strong (think  $\mu \rightarrow e^+e^-e^+$ ,  $\mu \rightarrow e$ -conversion,  $\tau \rightarrow \mu$ +hadrons, etc), and so are most of the flavor diagonal charged-lepton effects.

There are a couple of ways to circumvent this...

## 1. Dimension-Eight Effective Operator

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\bar{f}\gamma^\rho f).$$

This is not  $SU(2)_L$  invariant. Let us fix that **in a different way**

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F\frac{\epsilon^{\alpha\beta}}{v^2}((HL)_\alpha^\dagger\gamma_\rho(HL)_\beta)(\bar{f}\gamma^\rho f).$$

where  $HL \propto H^+\ell^- - H^0\nu$ . After electroweak symmetry breaking  $H^0 \rightarrow v + h^0$  and we only get new neutrino interactions.

Sadly, it is not that simple. At the one-loop level, the dimension-8 operator will contribute to the dimension-6 operator in the last page, as discussed in detail in [\[Gavela \*et al\*, arXiv:0809.3451 \[hep-ph\]\]](#). One can, however, fine-tune away the charged-lepton effects.

## 2. Light Mediator

(Overview by Y. Farzan and M. Tórtola, arXiv:1710.09360 [hep-ph])

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\bar{f}\gamma^\rho f).$$

This may turn out to be a good effective theory for neutrino propagation but a bad effective theory for most charged-lepton processes. I.e.

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{L}_\alpha\gamma_\rho L_\beta)(\bar{f}\gamma^\rho f).$$

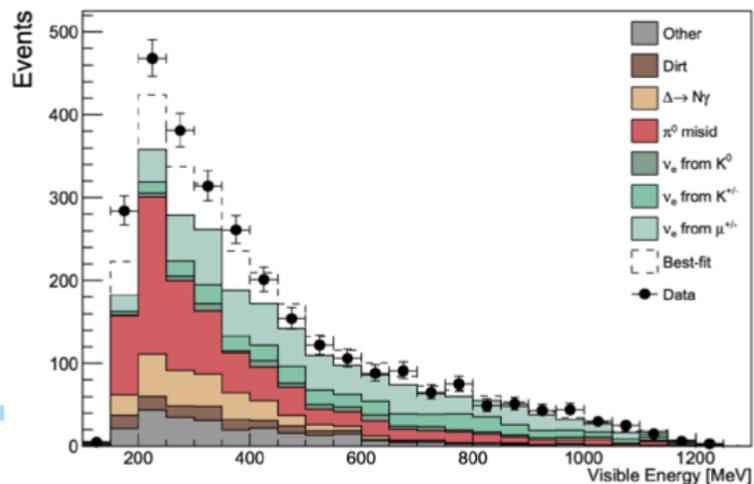
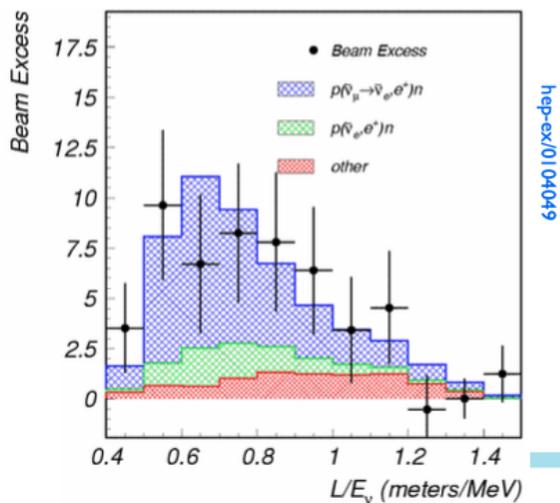
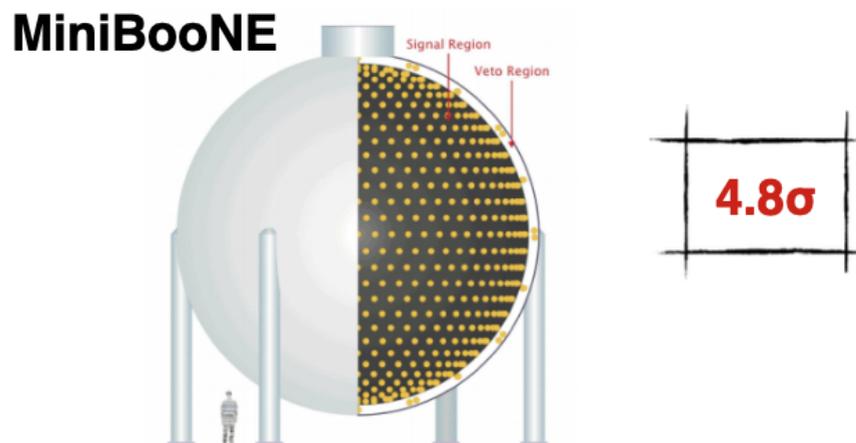
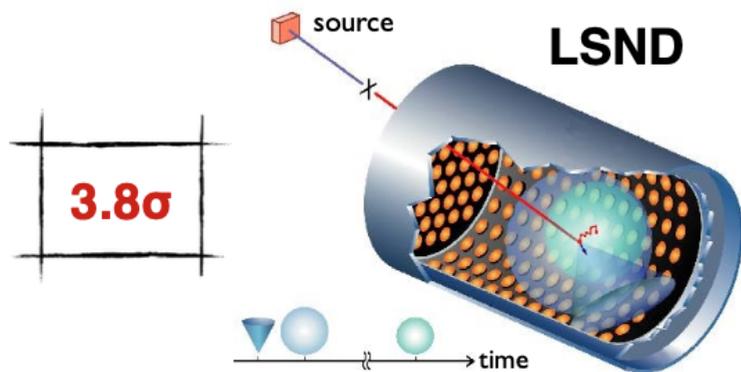
might be inappropriate for describing charged-lepton processes if the particle we are integrating out is light (as in lighter than the muon).

Charged-lepton processes are “watered down.” Very roughly

$$\epsilon \rightarrow \epsilon \left( \frac{m_{Z'}}{m_\ell} \right)^2$$

where  $m_{Z'}$  is the mass of the particle mediating the new interaction, and  $m_\ell$  is the mass associated to the charged-lepton process of interest.

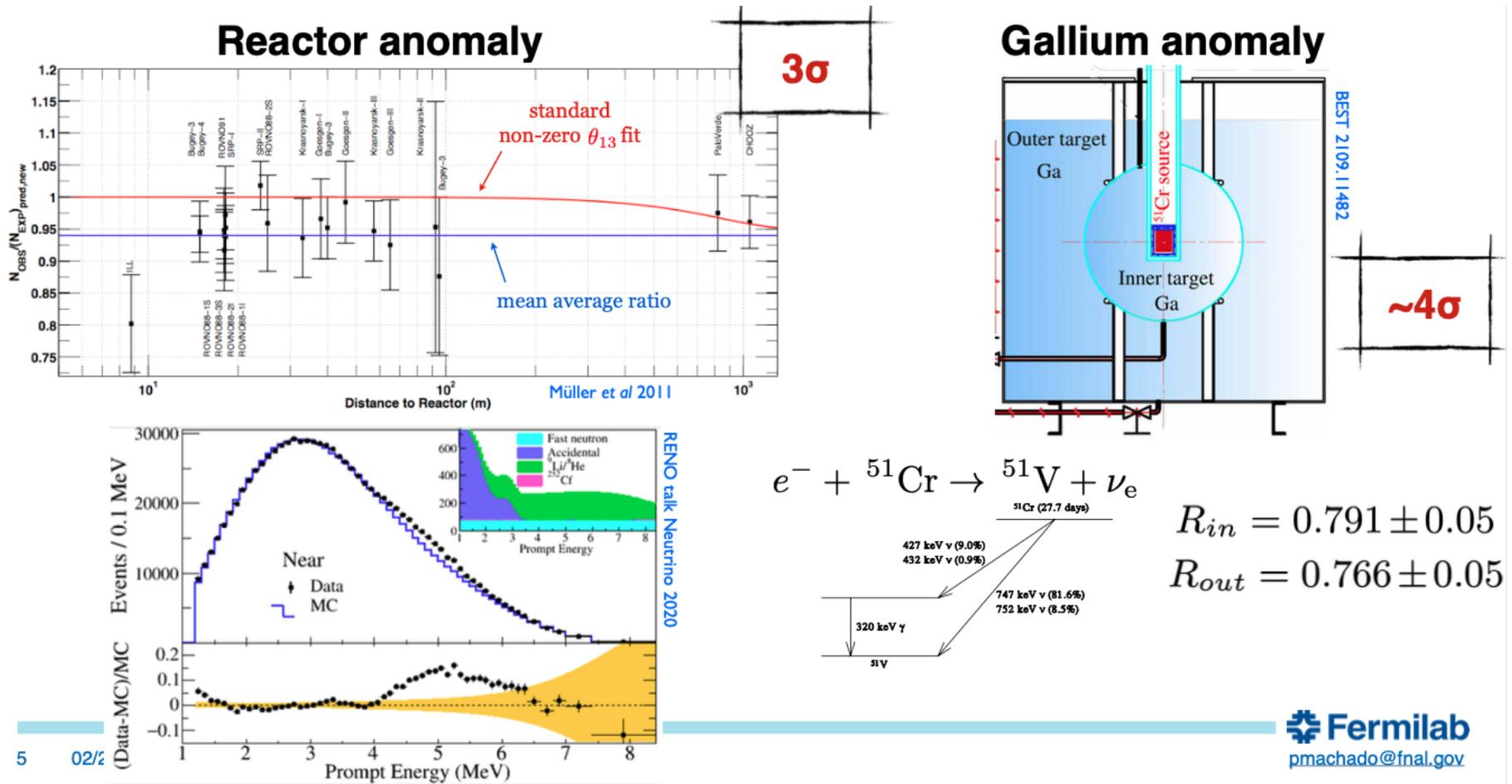
# Are We Sitting on More New Neutrino Physics?



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[P. Machado talk at TF Workshop]

# Are We Sitting on More New Neutrino Physics?



[P. Machado talk at TF Workshop]

## Case Study – Do Neutrino Mixing Parameters “Run?”

[Babu *et al* 2108.11961 [hep-ph]]

Neutrino mixing parameters are, in fact, couplings between the  $W$ -boson, the electron and the neutrino mass eigenstates  $\nu_1, \nu_2, \nu_3$ . Quantum corrections can make the mixing parameters “run,” i.e.,

$$\sin^2 \theta \rightarrow \sin^2 \theta(Q^2)$$

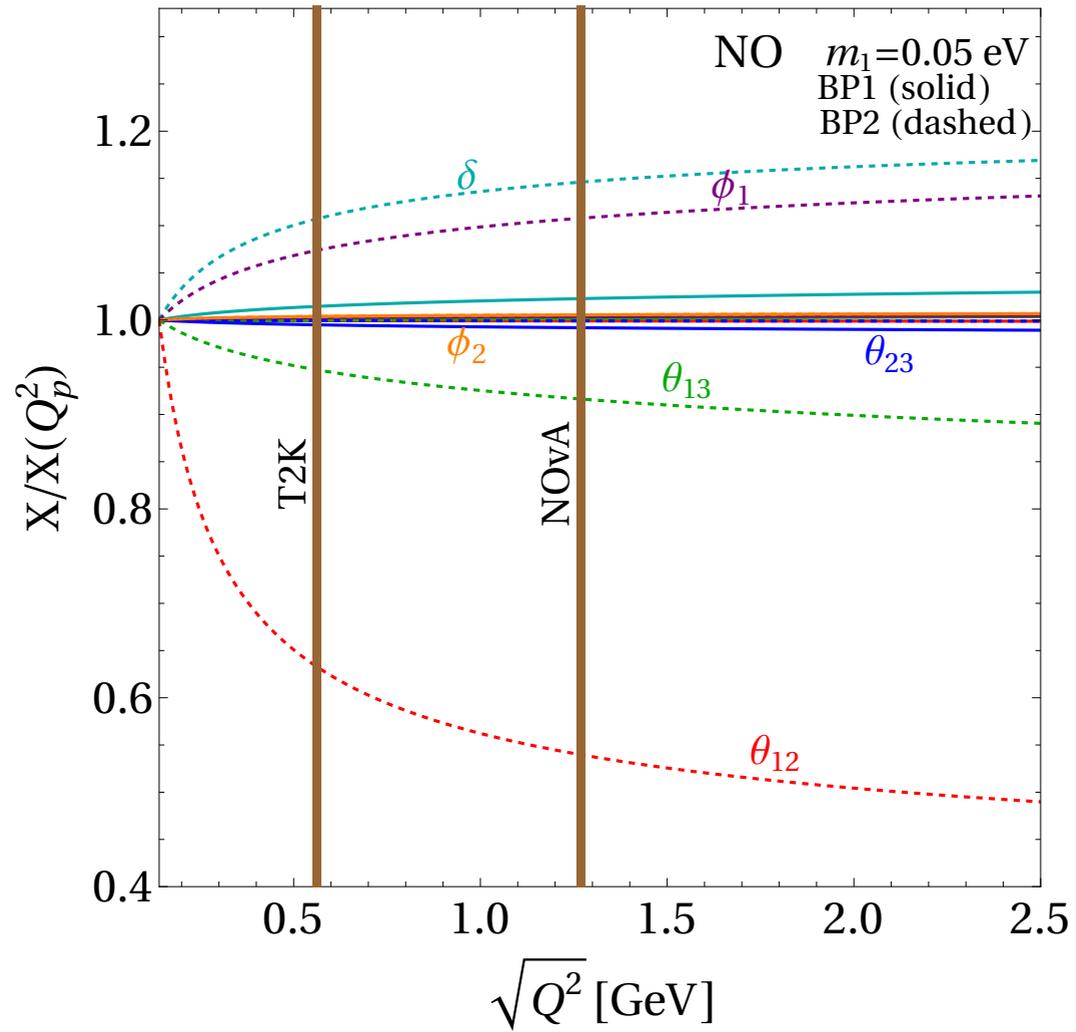
where  $Q^2$  is the momentum transfer.

If neutrino production and detection are associated to different  $Q^2$  oscillations change! E.g., assuming only two flavors and assuming CP is conserved

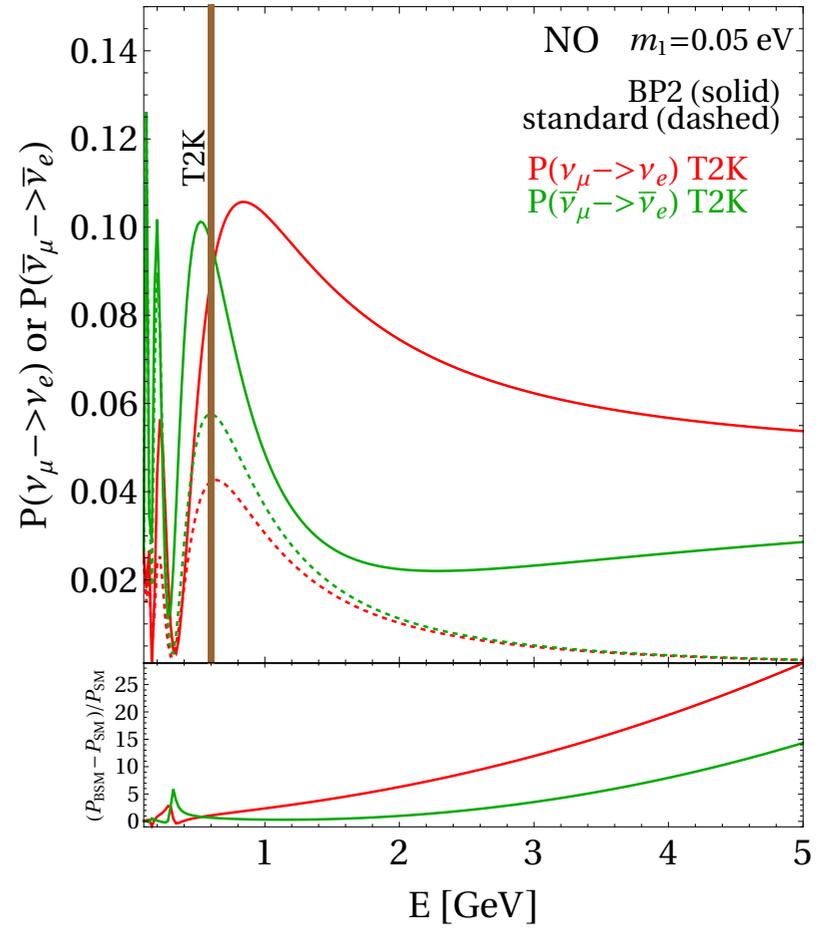
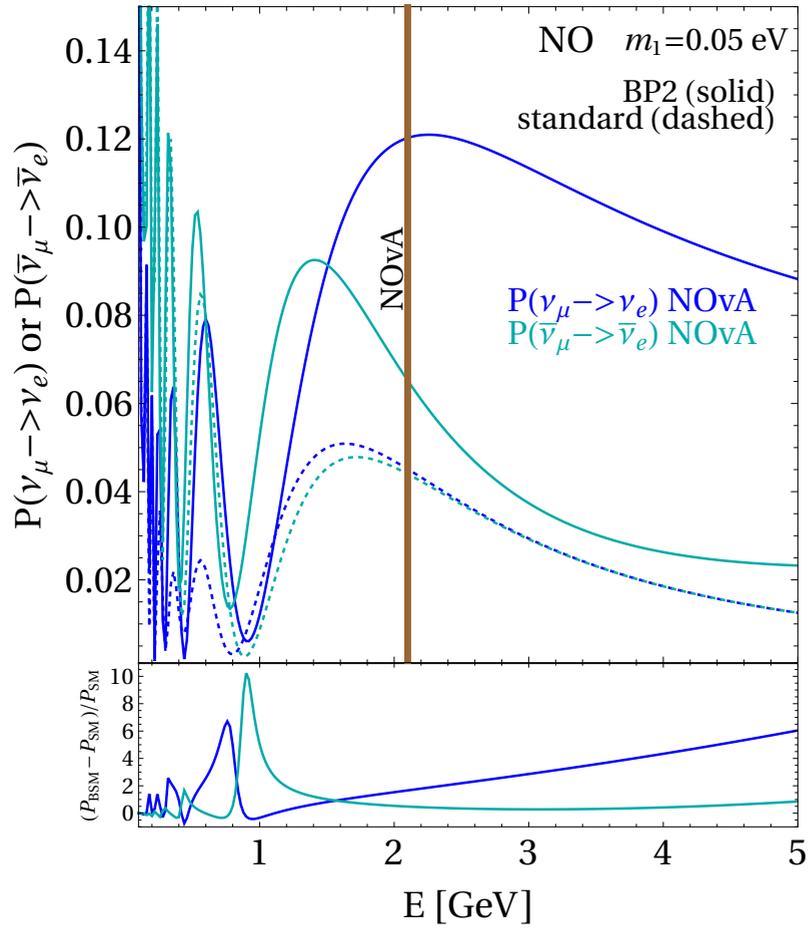
$$P_{e\mu} = P_{\mu e} = \sin^2(\theta_p - \theta_d) + \sin 2\theta_p \sin 2\theta_d \sin^2 \left( \frac{\Delta m^2 L}{4E} \right),$$

and

$$P_{ee} = P_{\mu\mu} = \cos^2(\theta_p - \theta_d) - \sin 2\theta_p \sin 2\theta_d \sin^2 \left( \frac{\Delta m^2 L}{4E} \right).$$



[Babu *et al* 2108.11961 [hep-ph]]



[Babu et al 2108.11961 [hep-ph]]