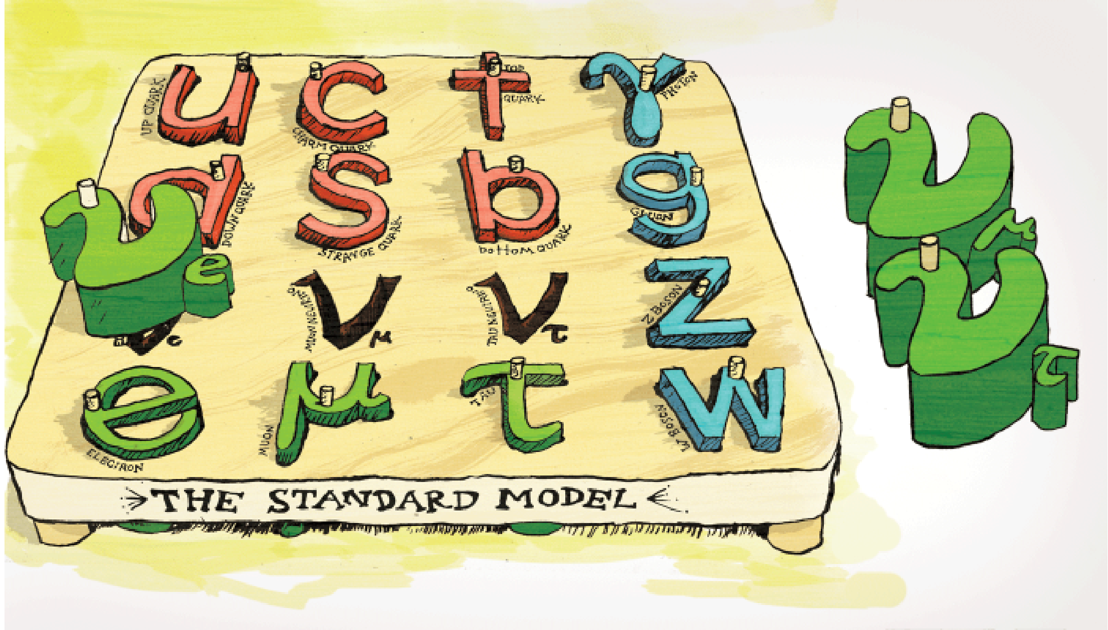
Neutrino Physics In (And Towards) the Muon Collider Era



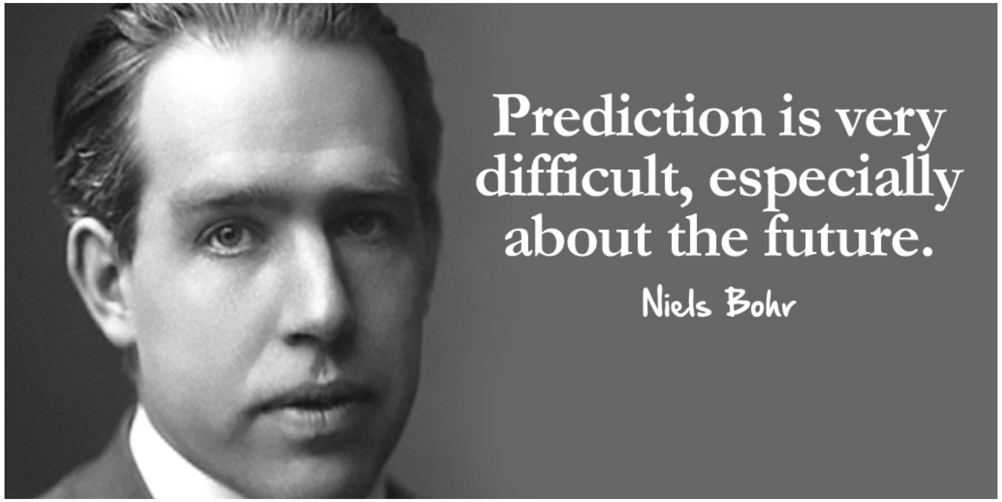
Hokkaido Workshop on Particle Physics at Crossroads

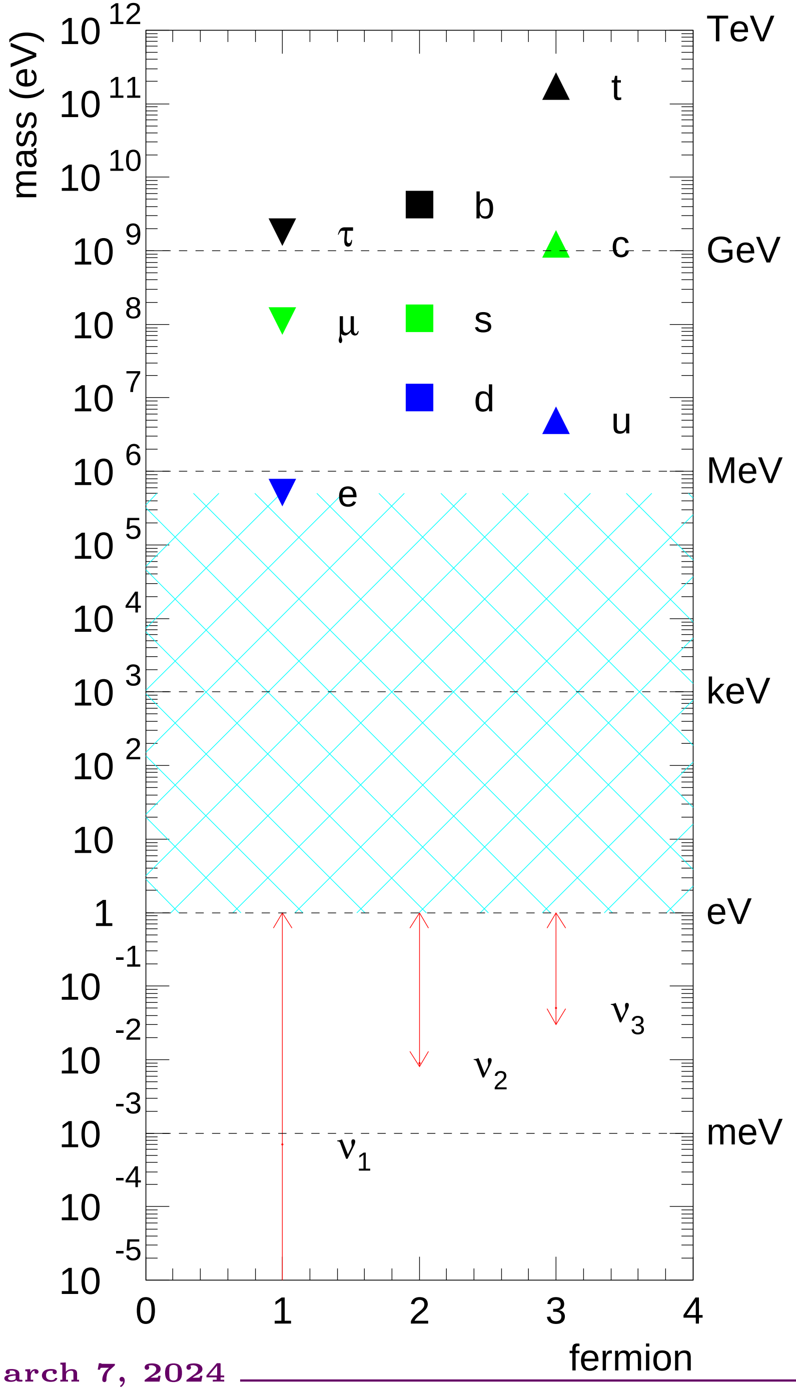
Sapporo, Japan, March 7–10, 2024

André de Gouvêa – Northwestern University

DISCLAIMERS

- These are My Personal Impressions.
- Neutrino Physics Today: There is a Lot Going On Now, Many Thinks Can Change and We Hope They Will!
- There is No Way I Can Explore All Corners of Possibility Space Here. I will Concentrate on a Few Topics.

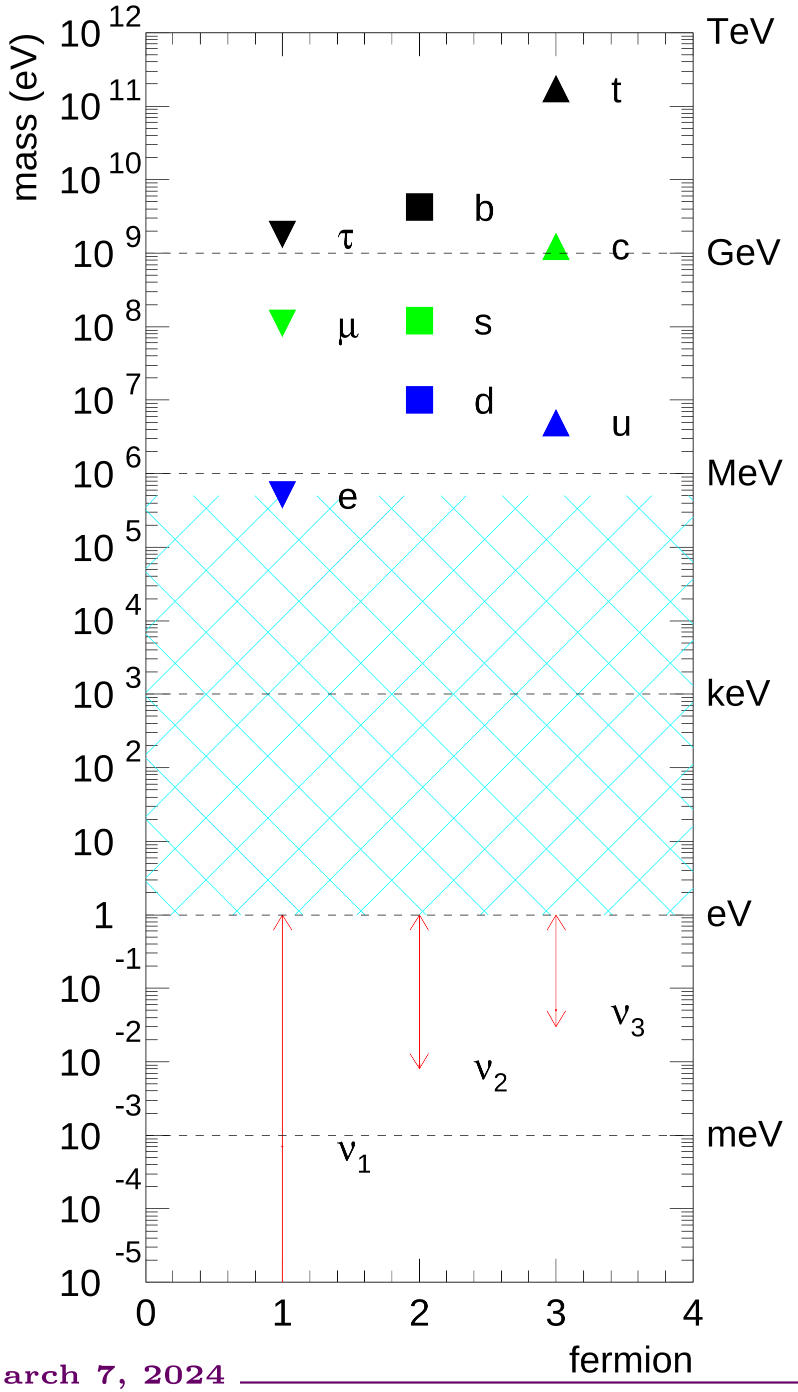




NEUTRINOS HAVE MASS

[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 ⇒ 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…

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 ✓).
- 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 a 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.

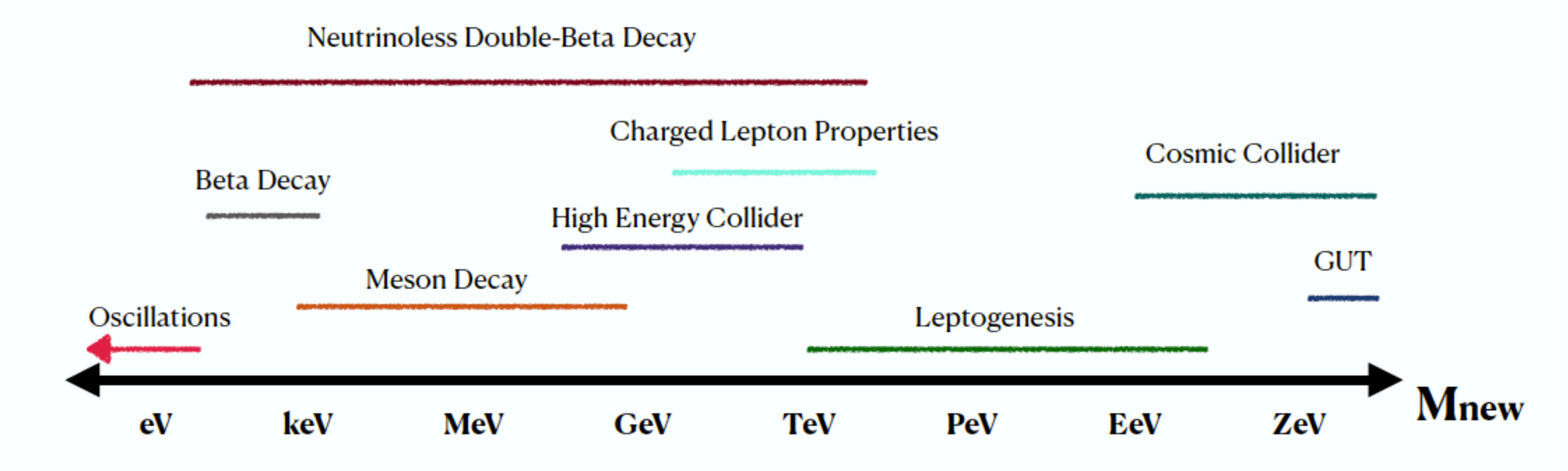
1. Neutrinos talk to the Higgs boson very, very **weakly**. And **lepton-number must be an exact symmetry** of nature (or broken very, very weakly);

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 ν 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

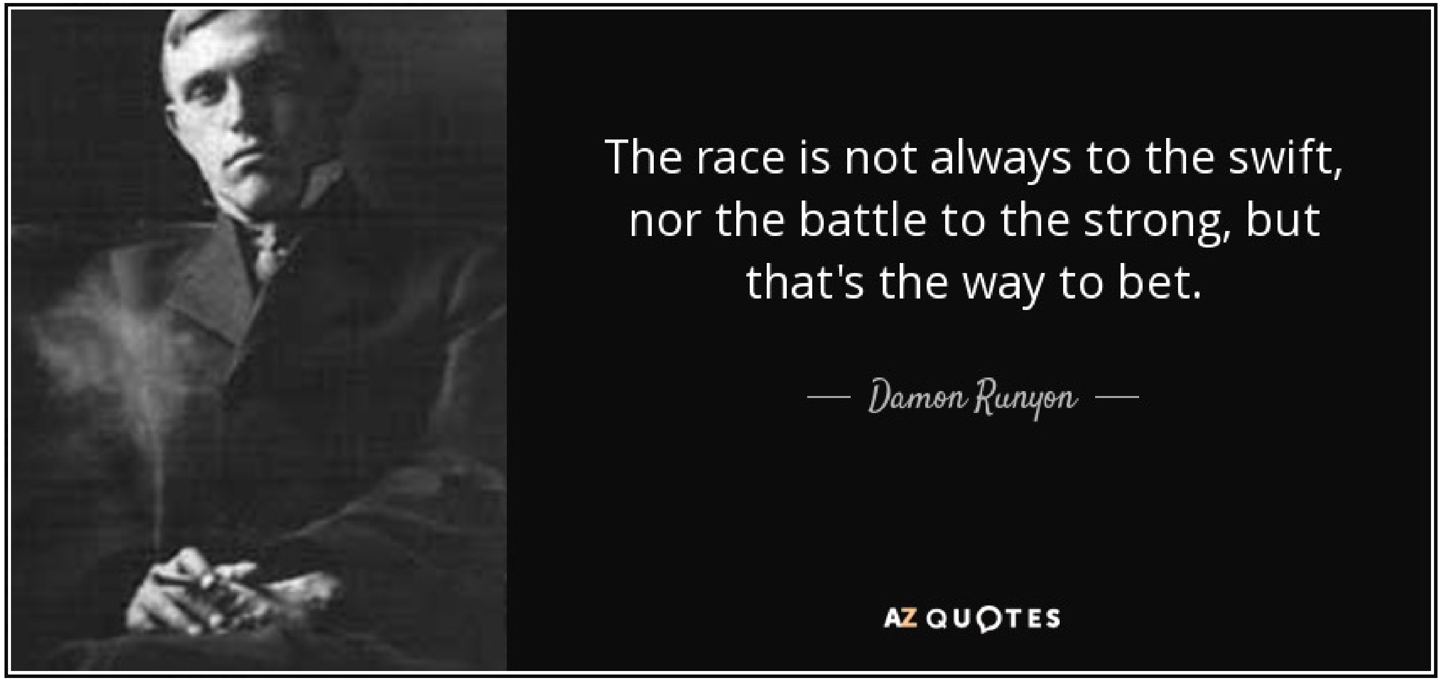
Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts . . .

- 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 ($\mu \to e$-conversion the best bet at the moment).
- Collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- Neutrino properties affect, in a significant way, the history of the universe. These can be “seen” in cosmic surveys of all types.
- 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!



The race is not always to the swift, nor the battle to the strong, but that's the way to bet.

— Damon Runyon —

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

- [NOW] T2K (Japan), NOνA (USA) – $\nu_\mu \to \nu_e$ appearance, ν_μ disappearance – precision measurements of “atmospheric parameters” $(\Delta m^2_{31}, \sin^2\theta_{23})$. Pursue mass hierarchy via matter effects. Nontrivial tests of paradigm. First step towards CP-invariance violation.

- [SOON] JUNO (China) – $\bar{\nu}_e$ disappearance – precision measurements of “solar parameters” $(\Delta m^2_{12}, \sin^2\theta_{12})$. Pursue the mass hierarchy via precision measurements of oscillations.

- [SOON] km^3 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.

A Realistic, Reasonable, and Simple Paradigm:

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

Definition of neutrino mass eigenstates (who are ν_1, ν_2, ν_3?):

- $m_1^2 < m_2^2$ $\Delta m_{31}^2 < 0$ – Inverted Mass Hierarchy
- $m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$ $\Delta m_{31}^2 > 0$ – Normal Mass Hierarchy

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu3}|^2}{|U_{\tau3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

This Standard Three-Massive-Active Neutrinos Paradigm fits, for the most part, all data very well[a]

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

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

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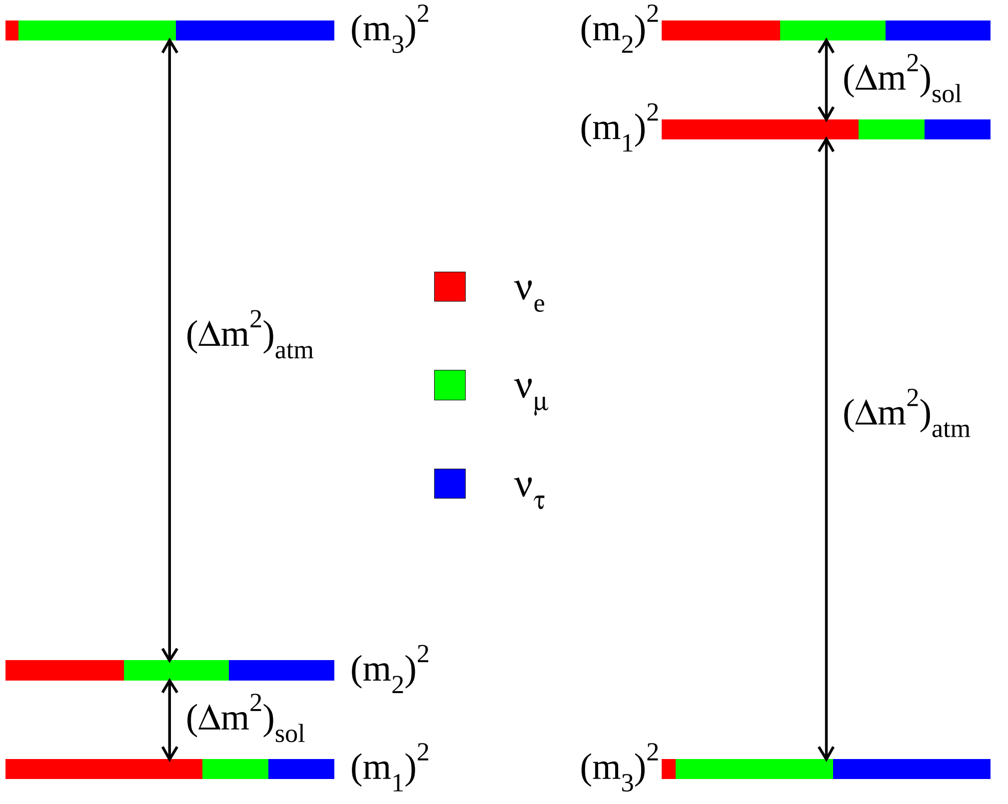
[a] Modulo the short-baseline anomalies which I will not discuss.

Missing Oscillation Parameters: Are We There Yet? (NO!)



normal hierarchy

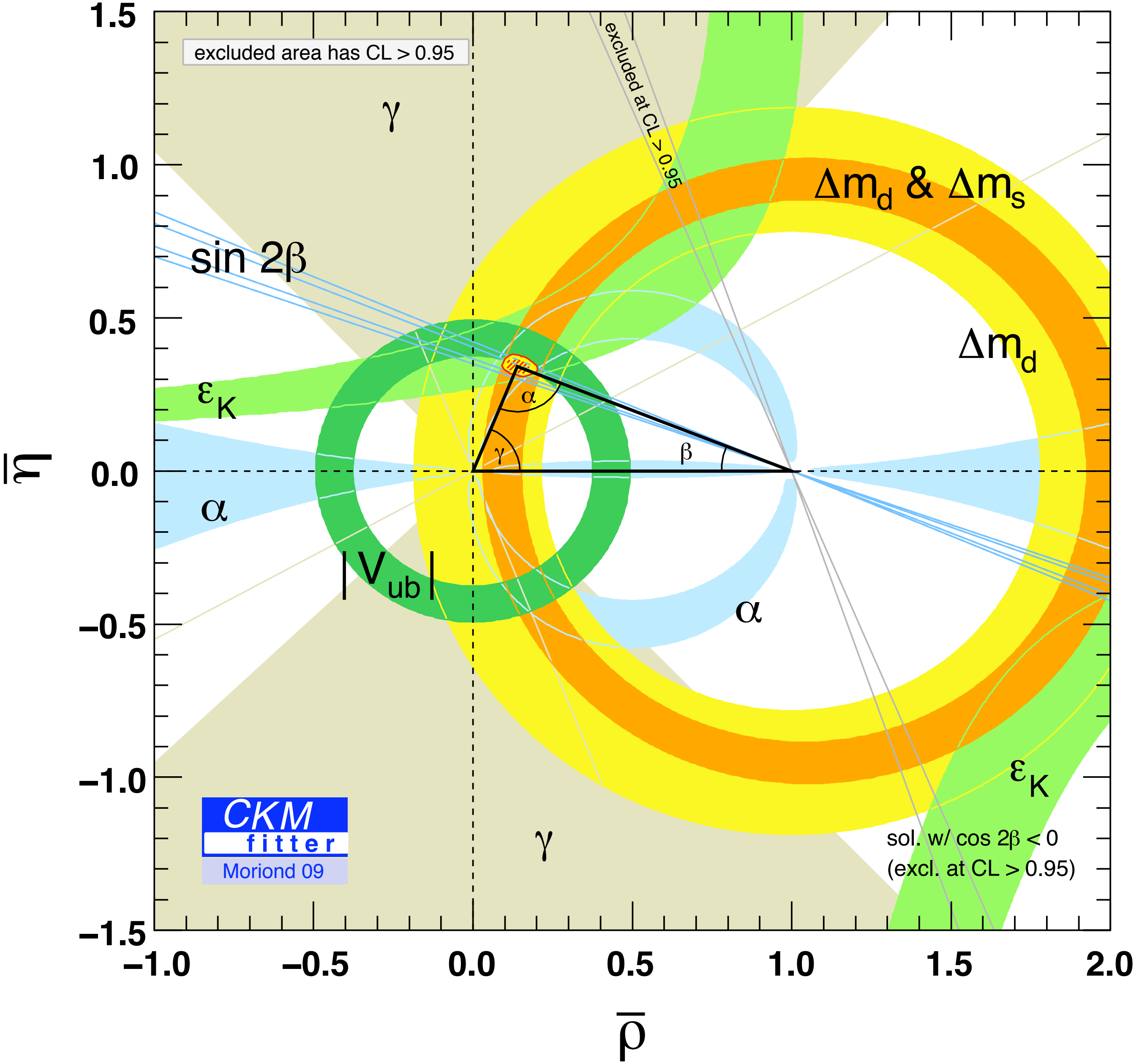
inverted hierarchy

- ~~What is the ν_e component of ν_3?~~ ($\theta_{13} \neq 0$!)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

⇒ 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!

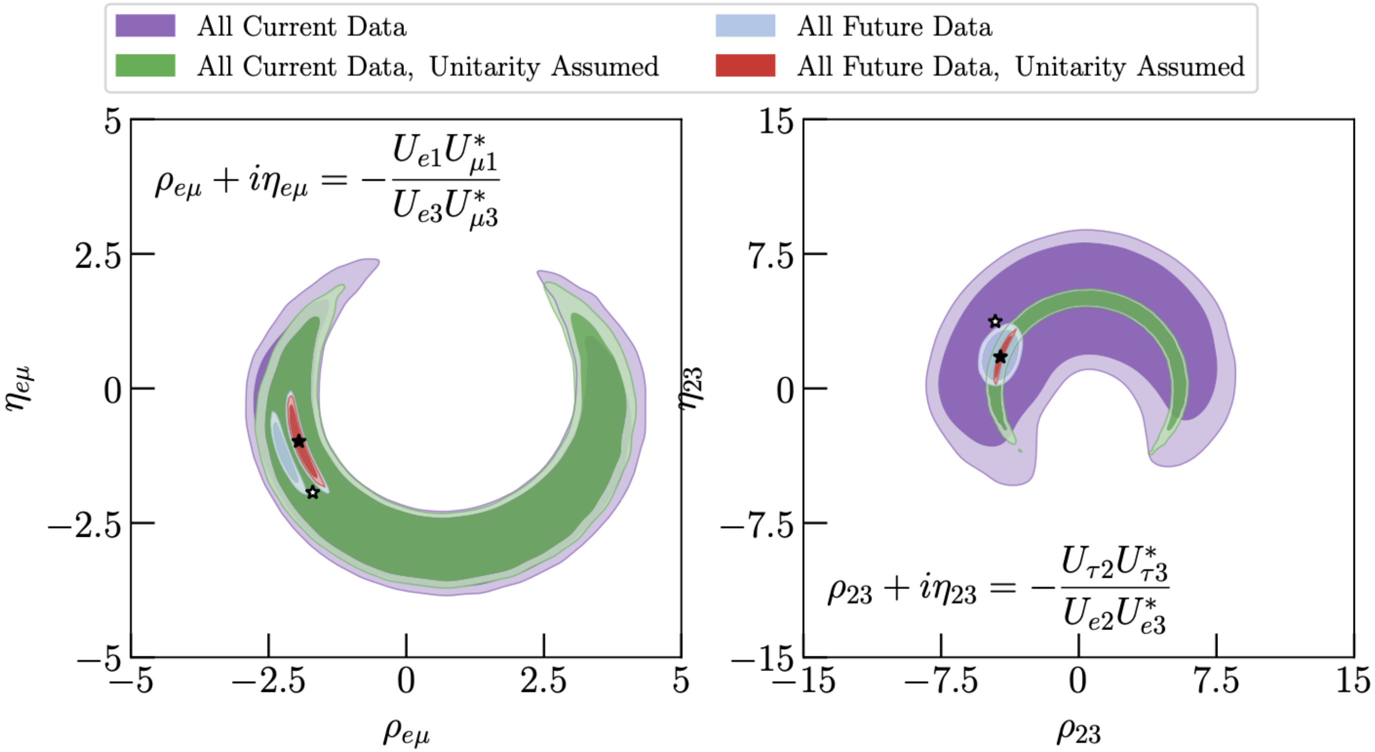


FIG. A1. Current (purple and green) and expected future (pale blue and red) measurements 95% (dark colors) and 99% confidence level (light) of two different unitarity triangles – $\rho_{e\mu}$ vs. $\eta_{e\mu}$ (left) and ρ_{23} vs. η_{23} (right). We contrast two assumptions in this figure, showing 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]

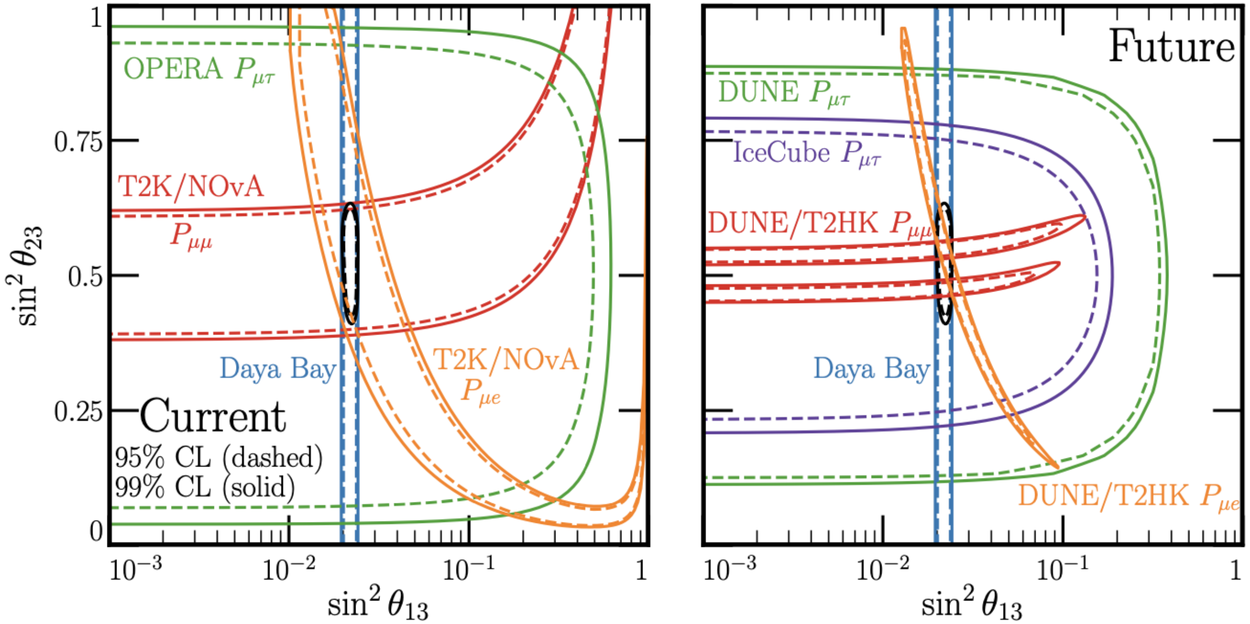


Figure 5. Current (left) and projected (right) measurements of the mixing angles $\sin^2\theta_{23}$ and $\sin^2\theta_{13}$ at 95% and 99% CL. The black contours in both panels show the joint-fit region with current data.

[Ellis, Kelly, Li, arXiv:2008.01088]

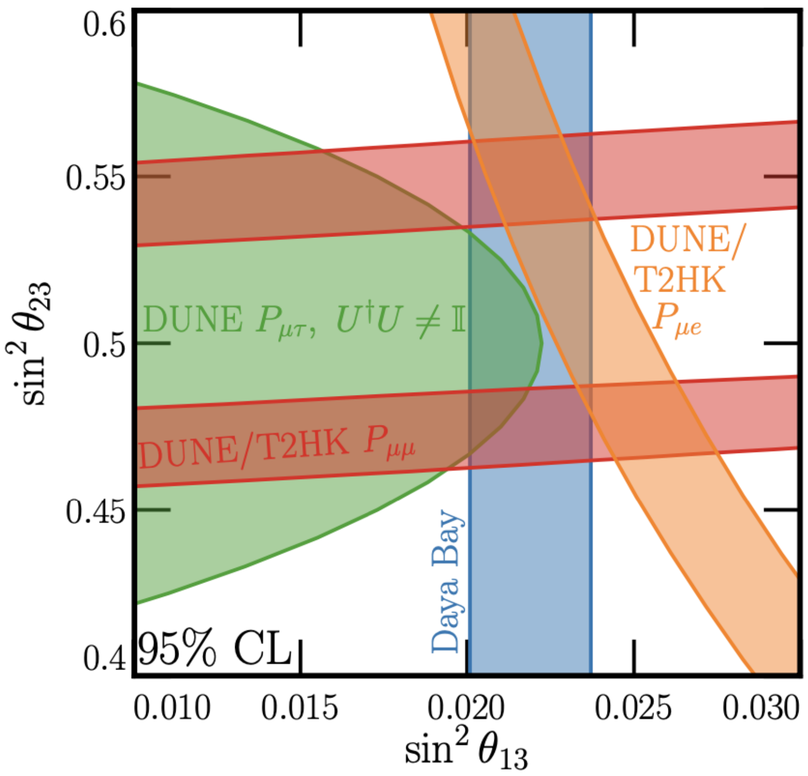


Figure 6. Projected measurements of $\sin^2\theta_{13}$ vs. $\sin^2\theta_{23}$ when unitarity is violated ($N_3 \approx 2$). For DUNE's long-baseline measurement of $P_{\mu\tau}$ (green), we simulate data assuming the underlying mixing matrix is non-unitary, and extract the measurement of these parameters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

[Ellis, Kelly, Li, arXiv:2008.01088]

What Could We Run Into?

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

What Could We Run Into?

- New neutrino states. In this case, the 3×3 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 νSM expectations.
- Weird stuff. CPT-violation. Decoherence effects (aka "violations of Quantum Mechanics.")
- etc.

Understanding Fermion Mixing

One of the puzzling phenomena uncovered by the neutrino data is the fact that Neutrino Mixing is Strange. What does this mean?

It means that lepton mixing is very different from quark mixing:

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

$\boxed{\text{WHY?}}$

(They certainly look VERY different, but which one would you label as “strange”?)

Precision Meas. of Oscillation Parameters. Why and How Much?

A word from flavor models:

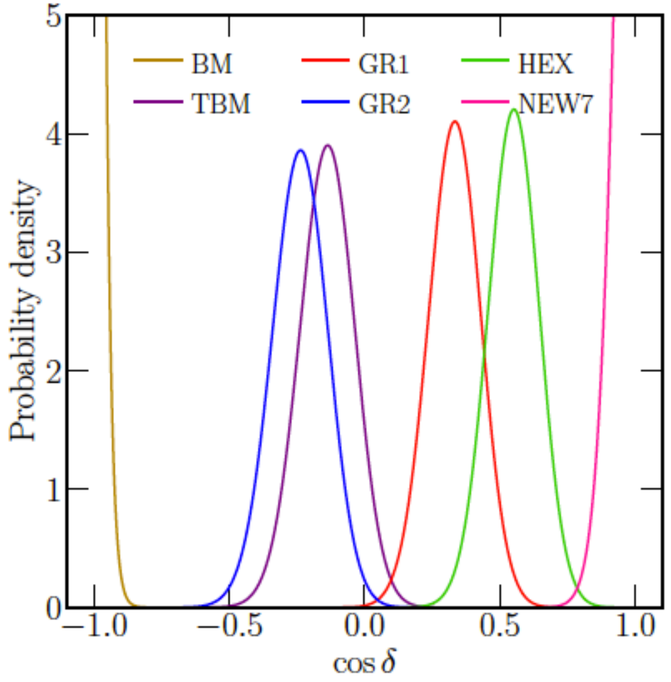


Figure 2: $P_{\cos\delta}$ as a function of $\cos\delta$ for various mixing patterns. Here we have assumed that $P_z(z)$ is a Gaussian centered at the experimental best-fit value of z, with width of 1σ.

[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.

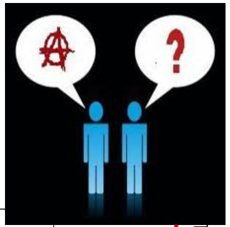
$$f(\text{PMNS})=g(\text{CKM}).$$

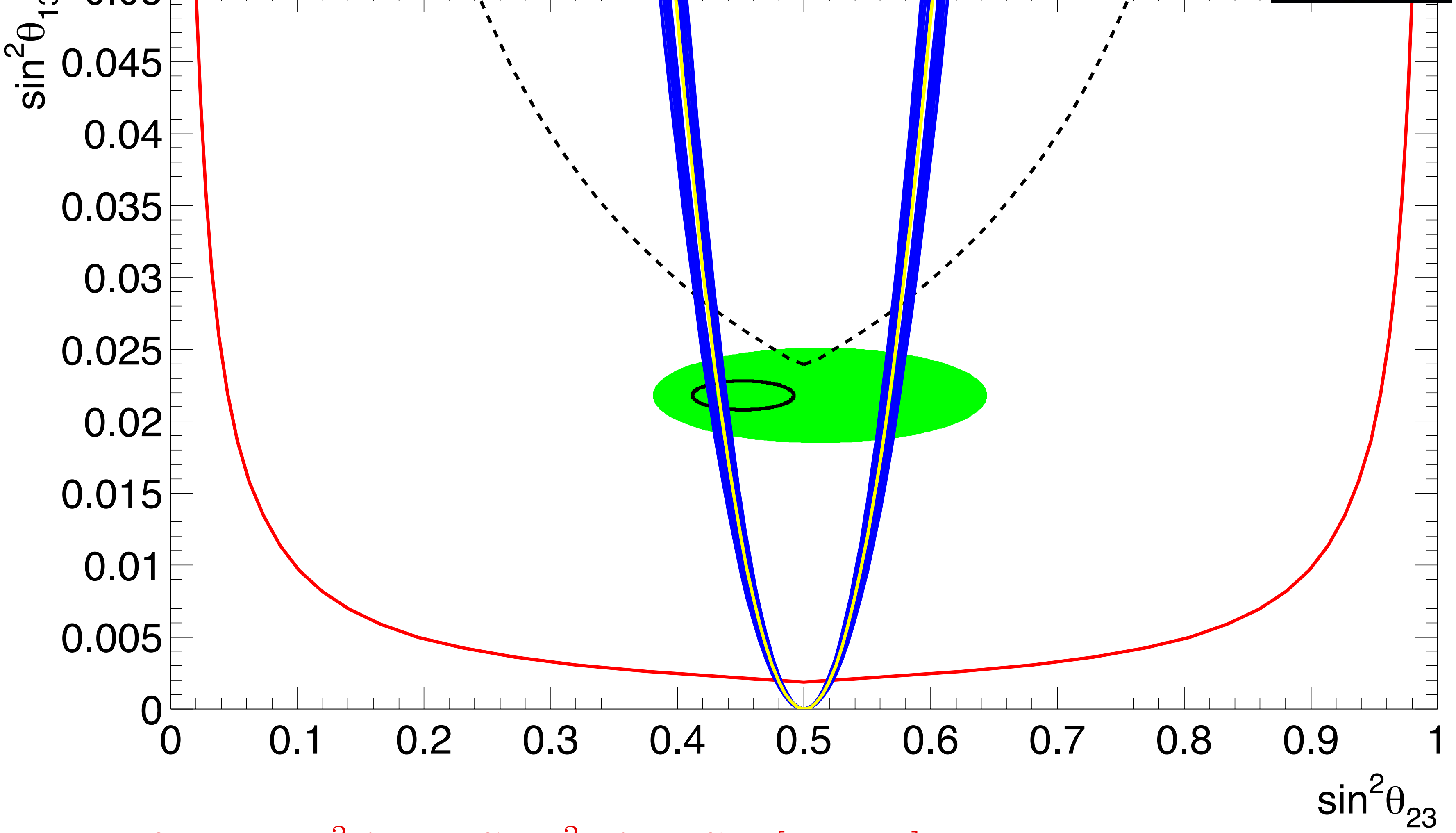
- etc.

These provide guidance for precision.

- Sum rules need all oscillation parameters to be known with similar precision: θ_{23},δ are the obvious outliers.
- On the CKM side, $\theta_{12}=13.04^\circ\pm0.05^\circ$, $\theta_{13}=0.201^\circ\pm0.011^\circ$, $\theta_{23}=2.38^\circ\pm0.06^\circ$, $\delta=68.8^\circ\pm4.5^\circ$. (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]

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 ν_e background.
  - Systematics will kick in by (or before) the end of the DUNE and Hyper-K runs.
  - Only initial-state ν_μ: $\nu_\mu \rightarrow \nu_e$ 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 (π, K, nuclei);
- Nucleus-decay-in-flight beams (β-beams);
- Muon-decay-in-flight beams (neutrino factories).

The Muon Path to the Energy Frontier is Intense

If we are ever to build a weak-scale(+) muon collider, we will need to learn how to build, for a finite amount of money, . . .

. . . a multi MW proton source

. . . muon beams

. . . muon storage rings

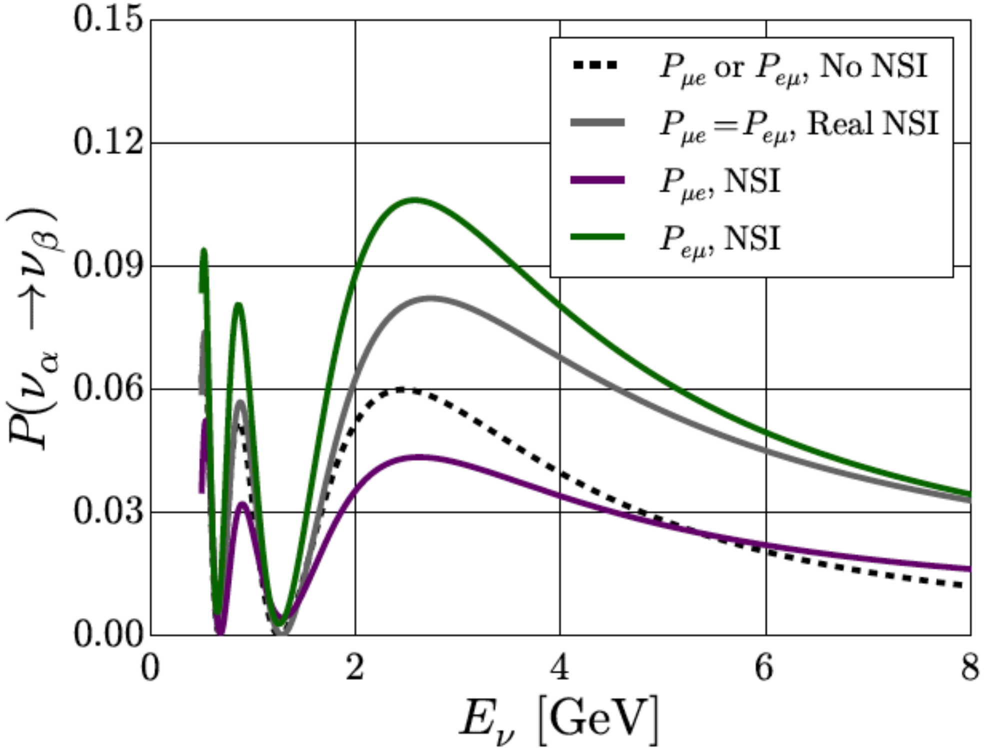
. . . etc.

The physics case for every one of these components is quite strong in its own right. [IMHO]

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

- Muon energy and charge known very well → neutrino energy spectra known very well and neutrino beams very clean!
- Detectors with charge-ID allow one to kill the beam-background.
- High-energy ν_e and $\bar{\nu}_e$-beams allow for $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$ oscillation measurements! **New oscillation channels provide priceless opportunity for more observables.**
- $$\phi_{\rm osc} \sim 3.6 \left(\frac{\Delta m^2}{3\times 10^{-3}~{\rm eV}^2}\right)\left(\frac{L}{10^4~{\rm km}}\right)\left(\frac{10~{\rm GeV}}{E}\right)$$
- 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).

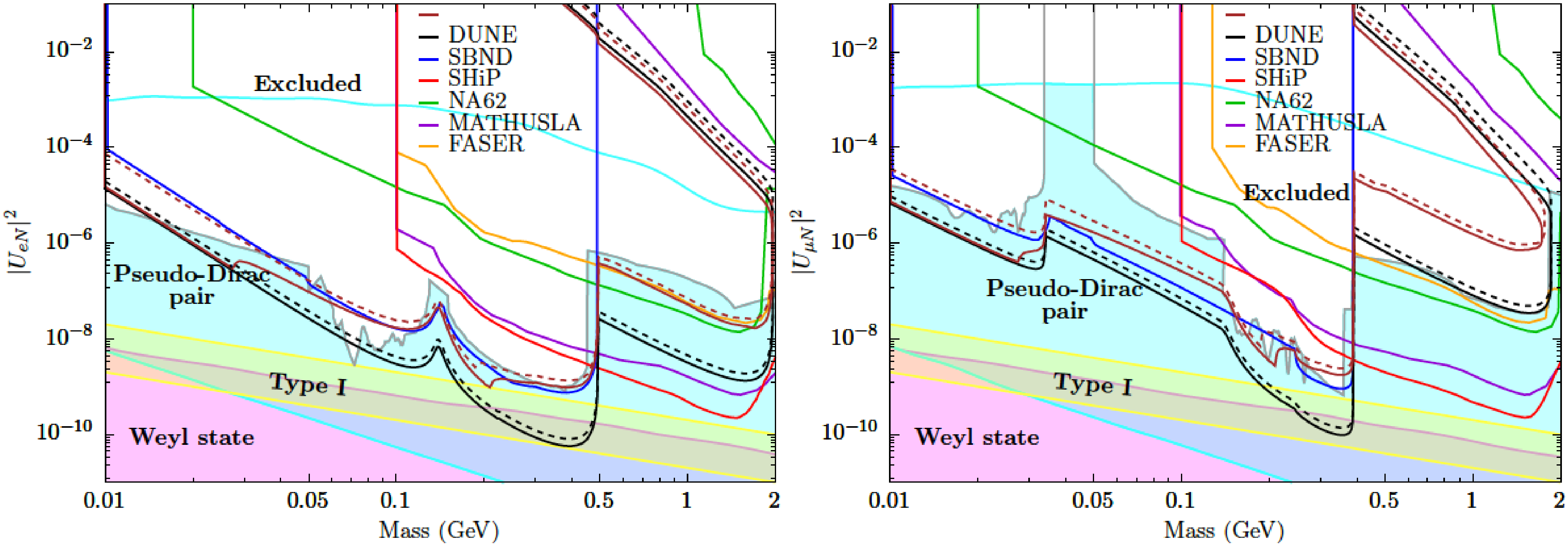
One simple example: T-invariance violation **[see Joe Sato (next talk)]**



[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 $\sin^2\theta_{12} = 0.308$, $\sin^2\theta_{13} = 0.0234$, $\sin^2\theta_{23} = 0.437$, $\Delta m^2_{12} = 7.54 \times 10^{-5}$ eV^2, $\Delta m^2_{13} = 2.47 \times 10^{-3}$ eV^2, 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 $\epsilon_{\alpha\beta} = 0$, $\delta = 0$).

Beyond Oscillations: Testing the Seesaw Mechanism. There is a lot of room to cover

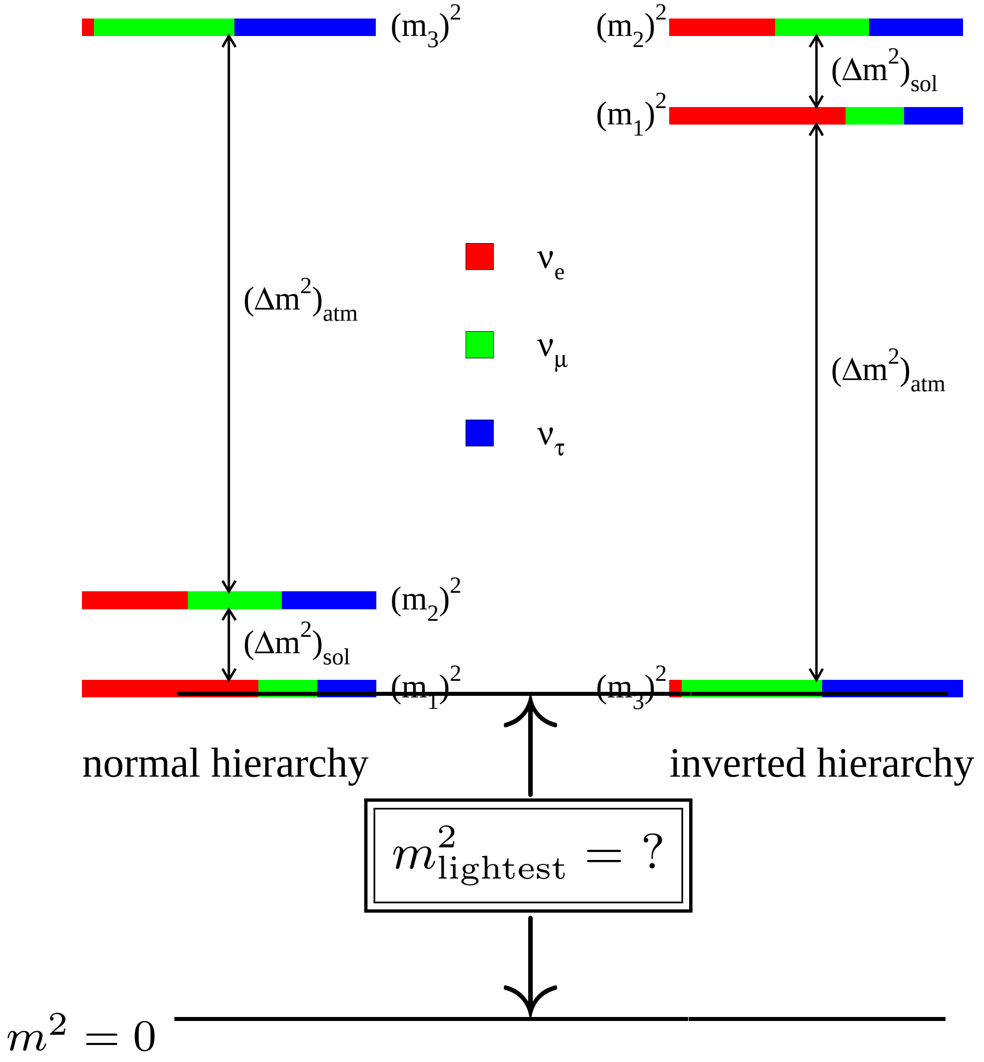


[Ballett et al, arXiv:1905.00284]

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 FASERν (arXiv:1908.02310) with several advantages:
  - Neutrino energy spectrum very well known;
  - Beam has a well-defined flavor (ν_μ 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., ν_τ appearance. Could be a very hot topic.
- Neutrino DIS.

What We Know We Don't Know: How Light is the Lightest Neutrino?



So far, we've only been able to measure neutrino mass-squared differences.

The lightest neutrino mass is only poorly constrained: $m^2_{\text{lightest}} < 1\ \text{eV}^2$

qualitatively different scenarios allowed:

- $m^2_{\text{lightest}} \equiv 0$;
- $m^2_{\text{lightest}} \ll \Delta m^2_{12,13}$;
- $m^2_{\text{lightest}} \gg \Delta m^2_{12,13}$.

Need information outside of neutrino oscillations:

→ cosmology, β-decay, $0\nu\beta\beta$

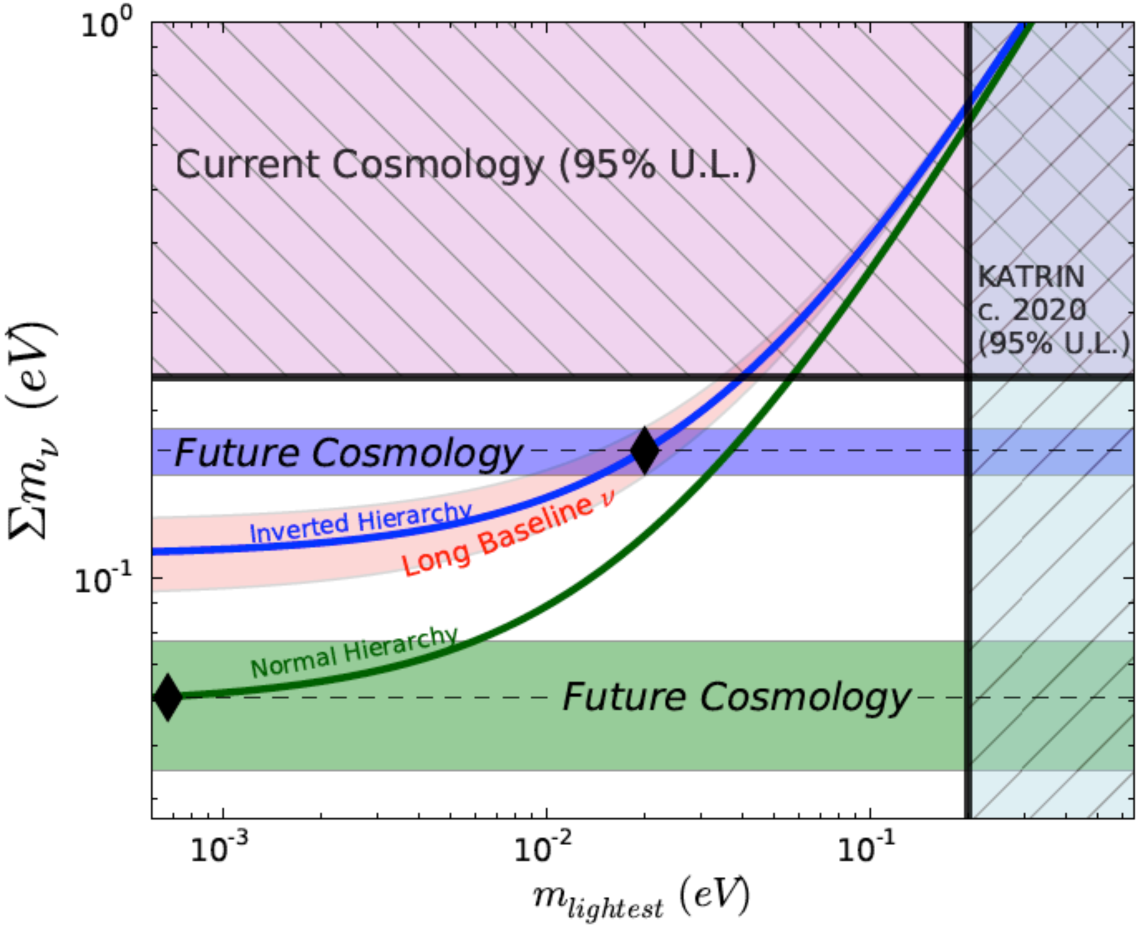


Figure 7. *Current constraints and forecast sensitivity of cosmology to the sum of neutrino masses. In the case of an "inverted hierarchy," with an example case marked as a diamond in the upper curve, future combined cosmological constraints would have a very high-significance detection, with 1-σ error shown as a blue band. In the case of a normal neutrino mass hierarchy with an example case marked as diamond on the lower curve, future cosmology would still detect the lowest $\sum m_\nu$ at greater than 3-σ.*

[K. Abazajian *et al.* arXiv:1309.5386]

And there is a lot of hope for life after this (Project 8?). What would come next-next?

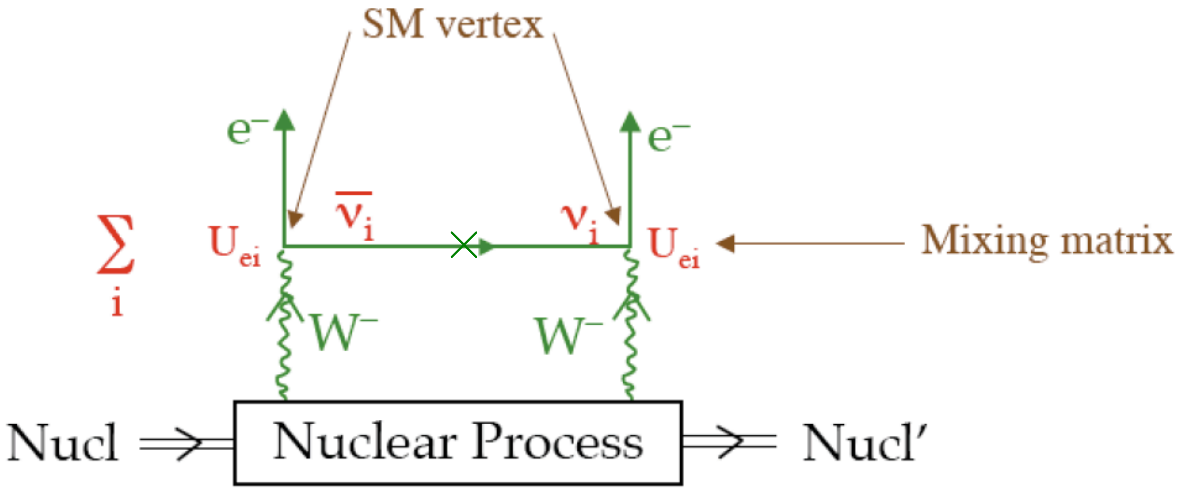
sensitivity $m^2_{\nu_e} > (0.2\text{ eV})^2$

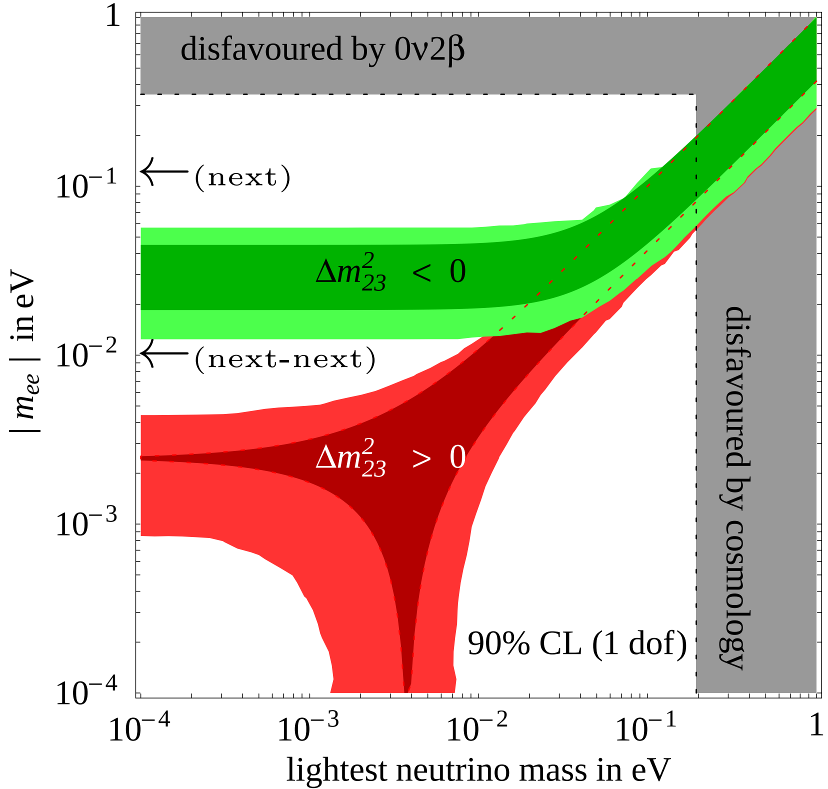
What We Know We Don't Know: Are Neutrinos Dirac or Majorana Fermions?

Best Bet: search for

Neutrinoless Double-Beta

Decay: $\boxed{Z \to (Z+2)e^-e^-}$





Helicity Suppressed Amplitude $\propto \frac{m_{ee}}{E}$

Observable: $m_{ee} \equiv \sum_i U_{ei}^2 m_i$

⇐ **no longer lamp-post physics!**

- What if we end up not observing neutrinoless double-beta decay? Is it possible we can conclude something? Tempting, but it would be a "plausibility-type" of discovery.
- And what if they are Dirac fermions? How do we find out?
- Can they be Dirac fermions? What about quantum gravity?
- And what if the neutrinos are pseudo-Dirac fermions (seems to be good with our quantum gravity friends)? We could discover that via very-long-wavelength oscillations! (this requires neutrinos coming from very far away. SN neutrinos? The CνB?)
- And what if we discover lepton number violation? Neutrinos are Majorana fermions, but how do we learn 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., $\mu^+ + \mu^- \to W^+ + W^- + (\nu_\mu + \bar{\nu}_\mu)$). 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 $T = (t^{+}+, t^{+}, t^{0})$, $\mu^{+}\mu^{+} \to t^{++} \to W^{+}W^{+}$). 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."