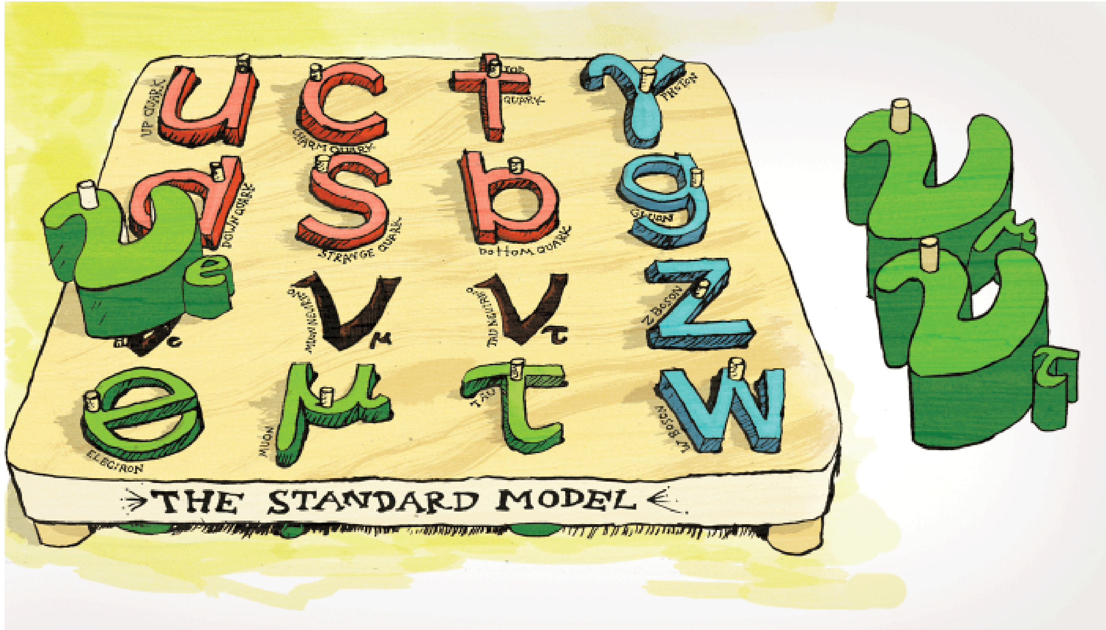
Wishlist of Neutrino Results for TAU2025



17th International Workshop on Tau Lepton Physics **(and their neutrinos!)**

University of Louisville

December 4 – 8, 2023

André de Gouvêa – Northwestern University

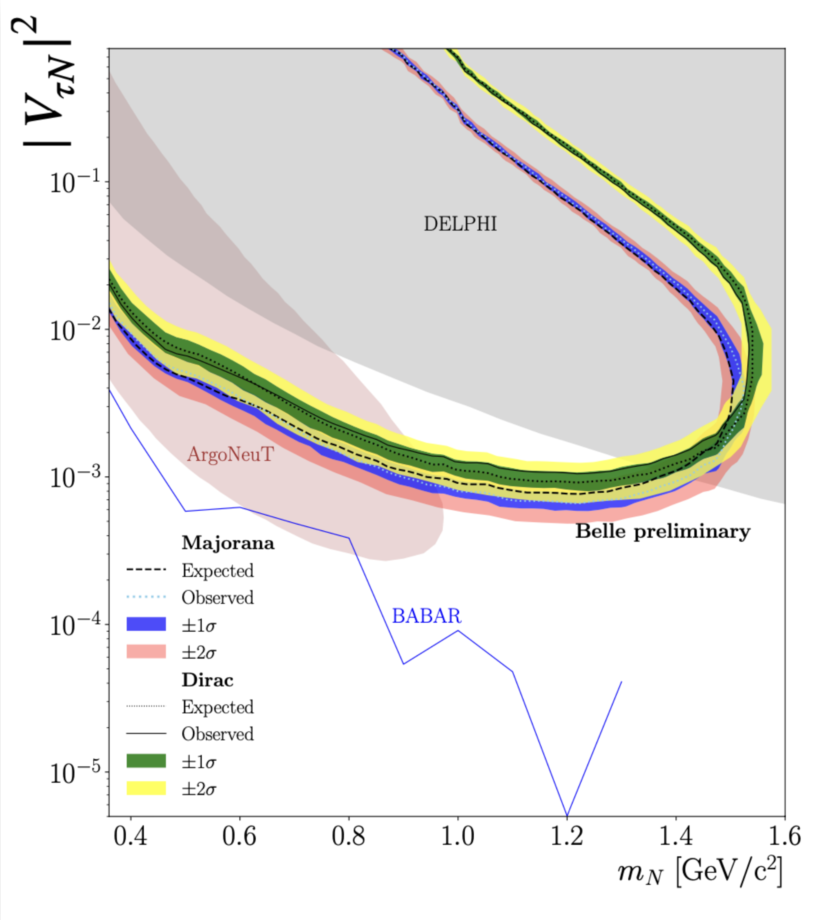
- Excluding this talk, there were around **30 presentations** related to neutrinos: three on Monday, three on Tuesday, three on Wednesday, eighteen(!) on Thursday, and three on Friday.
  - some were related to ν_τ, (but what is a ν_τ?)
  - some were related to new neutrino states that couple to the τ, $\Rightarrow$
  - some were about neutrinos and their properties,
  - some had no neutrinos at all. By design! ($\Rightarrow 0\nu\beta\beta$)
- There were theoretical and experimental talks, and we learned about results from current, near future and not-so-near future experiments.
- **I won't try to summarize all these talks.** Instead, I will use some (a small fraction) of what we heard throughout the week to color the different points I want to make. If your favorite talk was not mentioned, either directly or indirectly, I apologize in advance!

Results

- Uncertainties
  - N branching fraction
  - luminosity
  - uncertainty on the reconstruction of the two prompt tracks
  - the background yield expectations(largest)
- Handled with the nuisance parameters using CL_s prescription
- Allows for direct measurement of the N mass if a signal is observed

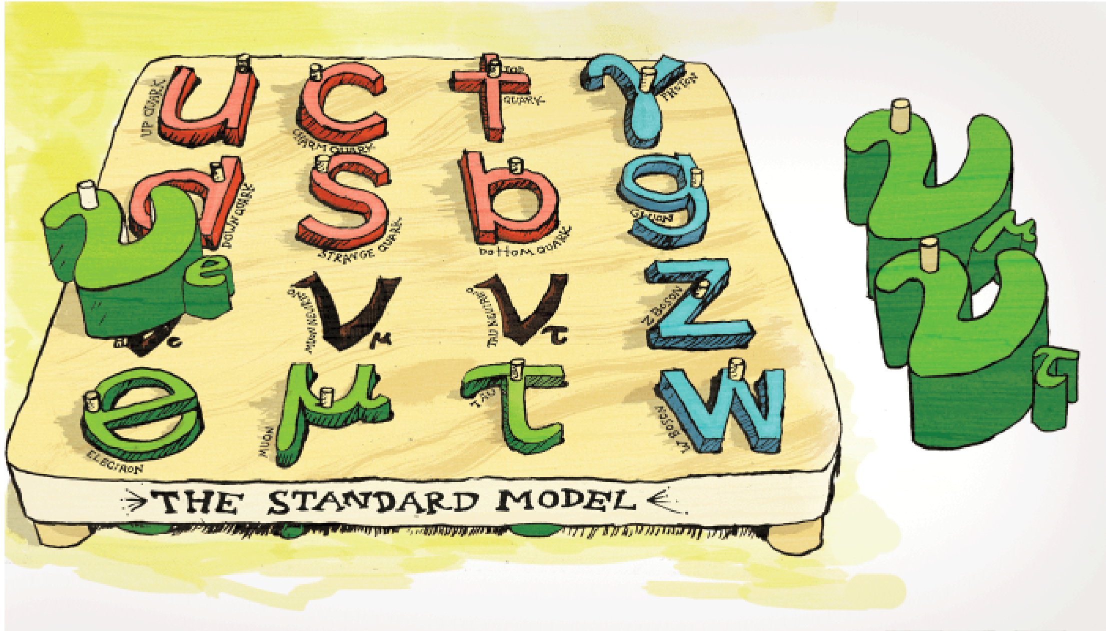
In the mass range 1.3 - 1.4 GeV/c^2, our limits are the most stringent to date

New for TAU2023



14

Wishlist of Neutrino Results for TAU2035+



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Over the last 25 years, a brand new, realistic, reasonable, and simple paradigm has emerged for neutrinos:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

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

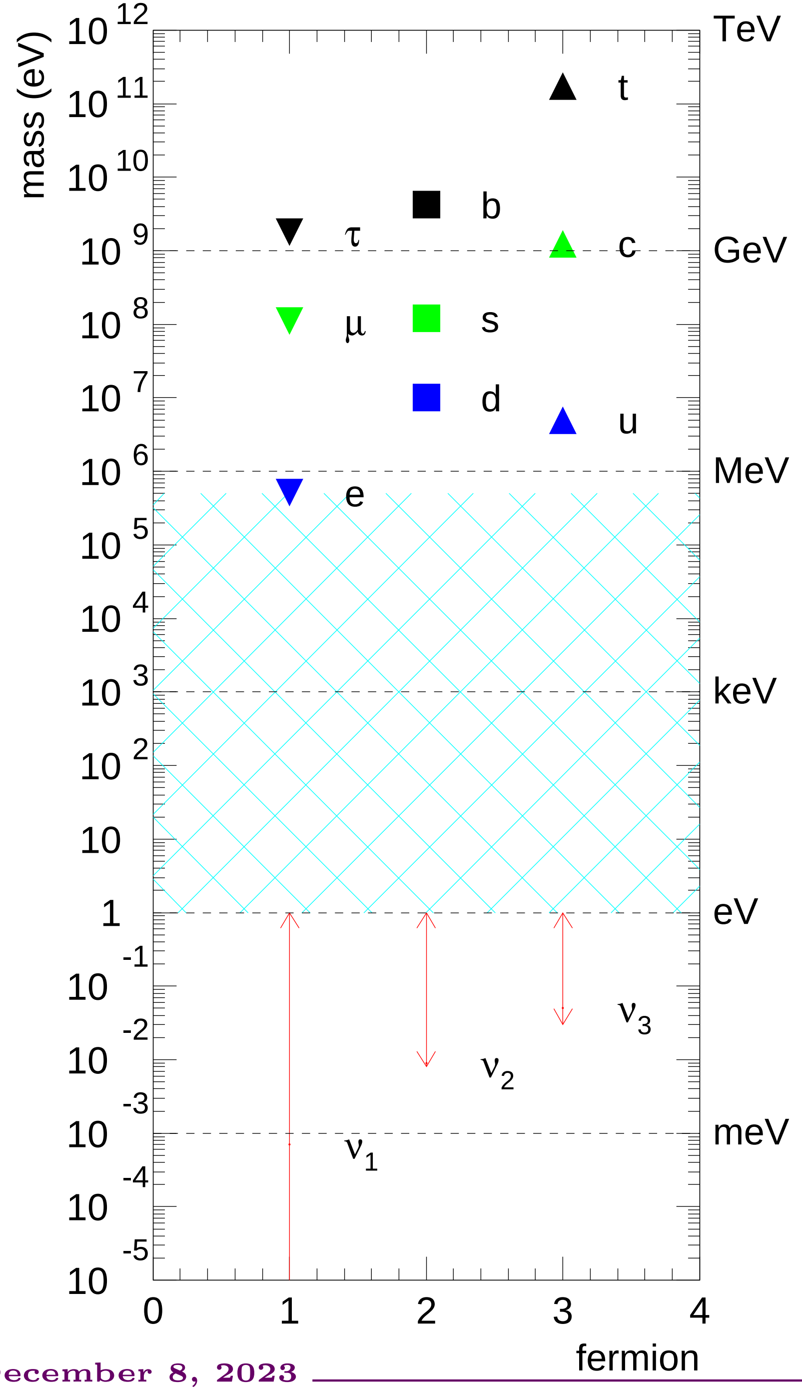
$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

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)

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

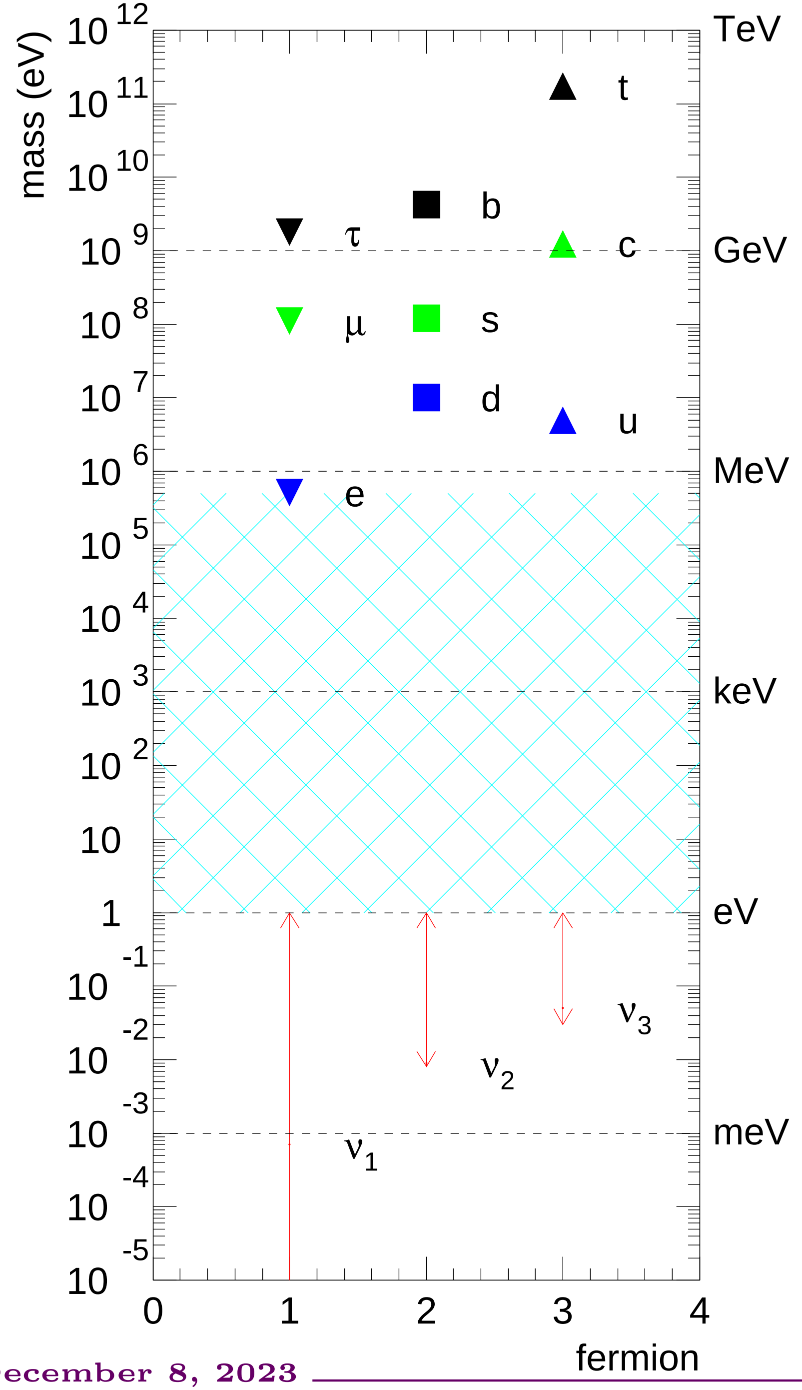
[a] Modulo the short-baseline anomalies.



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 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.

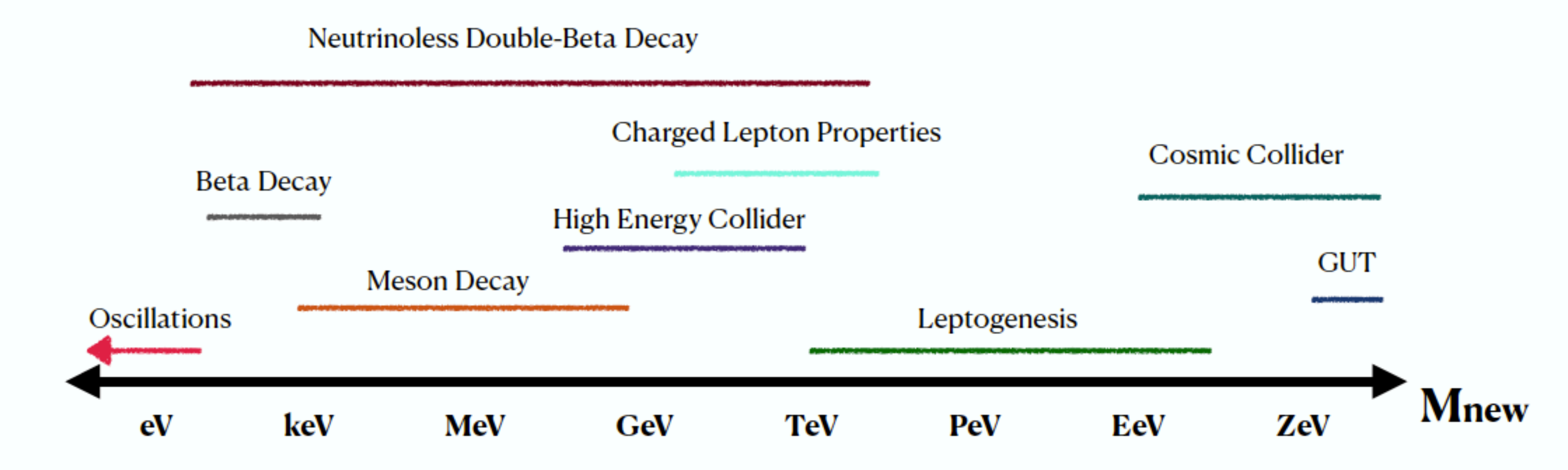
1. Neutrinos talk to the Higgs boson very, very **weakly**. And **lepton-number must be an exact symmetry** of nature (or broken very, very weakly);

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!



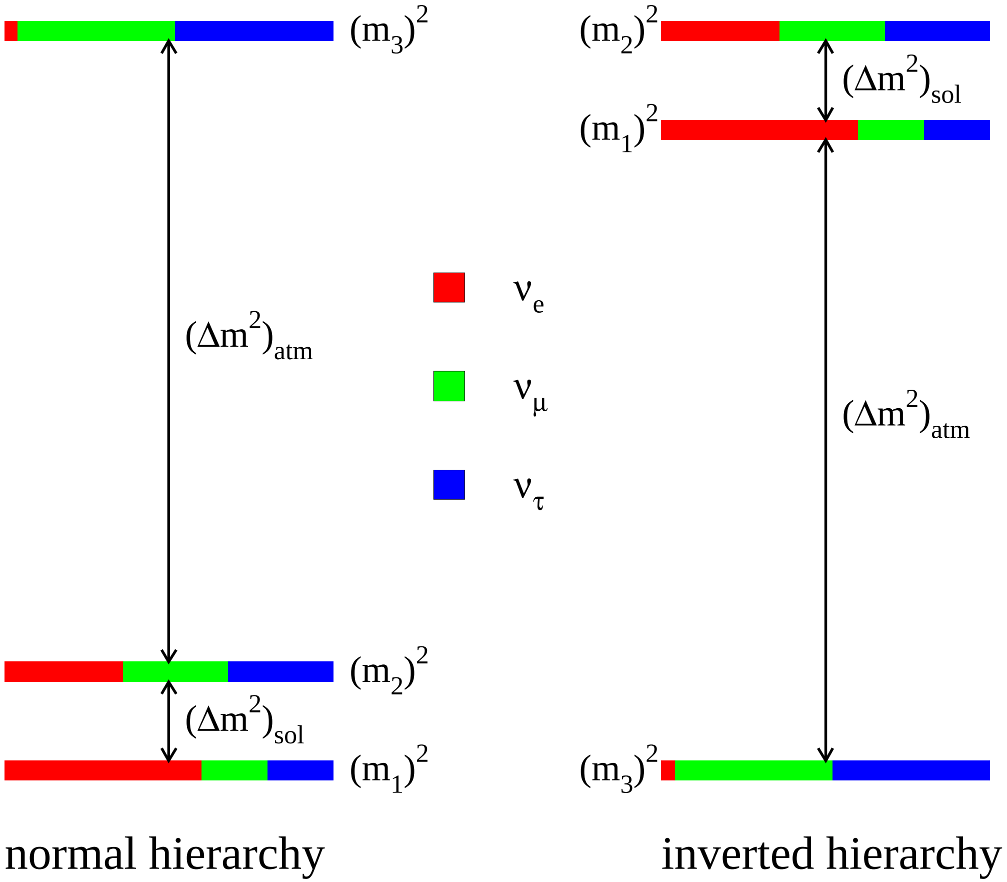
Different Mass Scales Are Probed in Different Ways, Lead to Different Consequences, and Connect to Different Outstanding Issues in Fundamental Physics.

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.

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

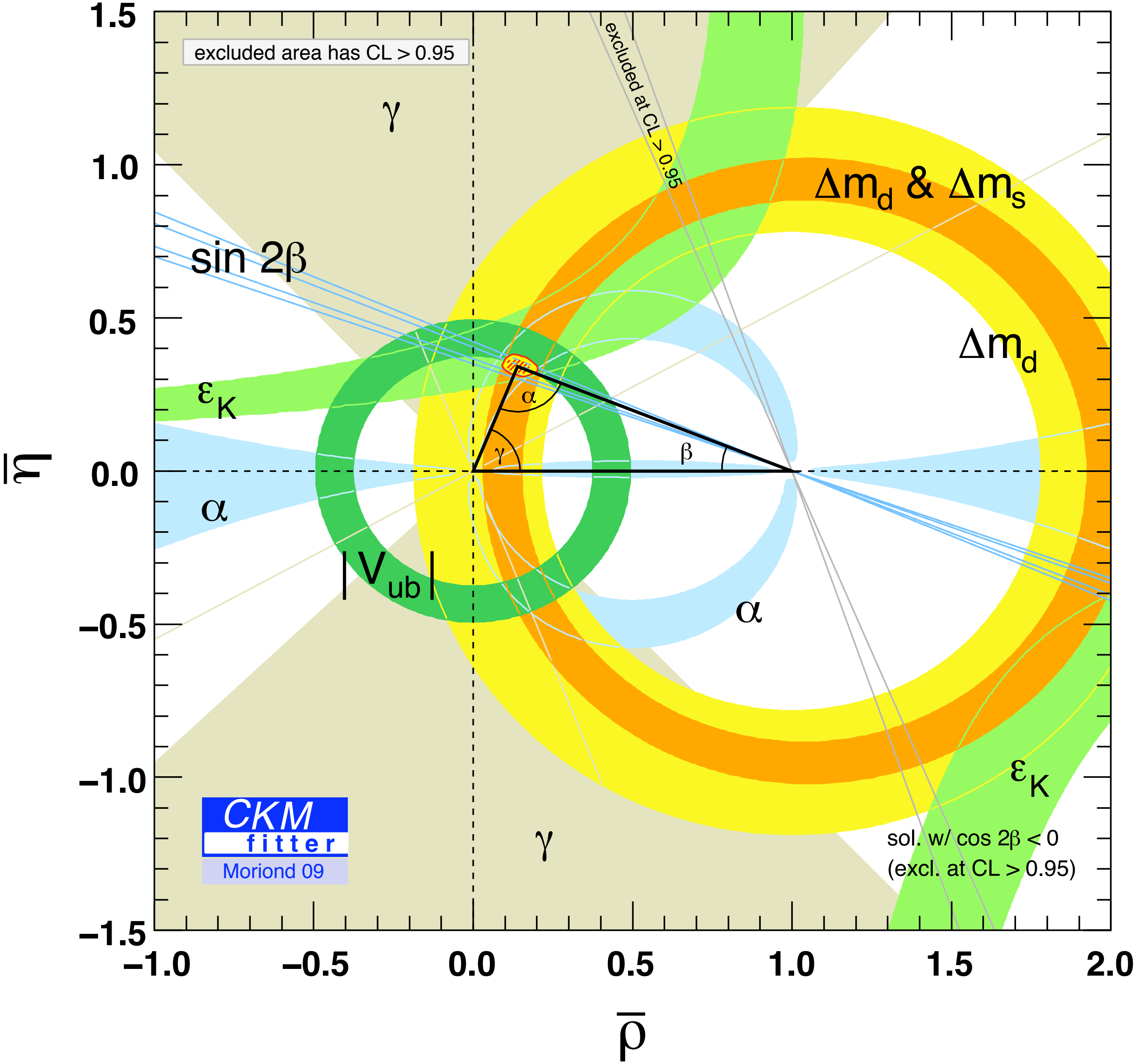


- ~~What is the ν_e component of ν_3?~~ ($\theta_{13} \neq 0$!)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13}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

$\Rightarrow$ 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!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

- Two mass-squared differences – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu 2}|^2 + |U_{\tau 2}|^2$ – solar data;
- $|U_{e2}|^2|U_{e1}|^2$ – KamLAND;
- $|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2)$ – atmospheric data, long-baseline accelerator experiments;
- $|U_{e3}|^2(1 - |U_{e3}|^2)$ – Double Chooz, Daya Bay, RENO;
- $|U_{\mu 3}|^2|U_{\tau 3}|^2$ – atmospheric, OPERA;
- $|U_{e3}|^2|U_{\mu 3}|^2$ – NOvA, T2K.

We still have a long way to go!

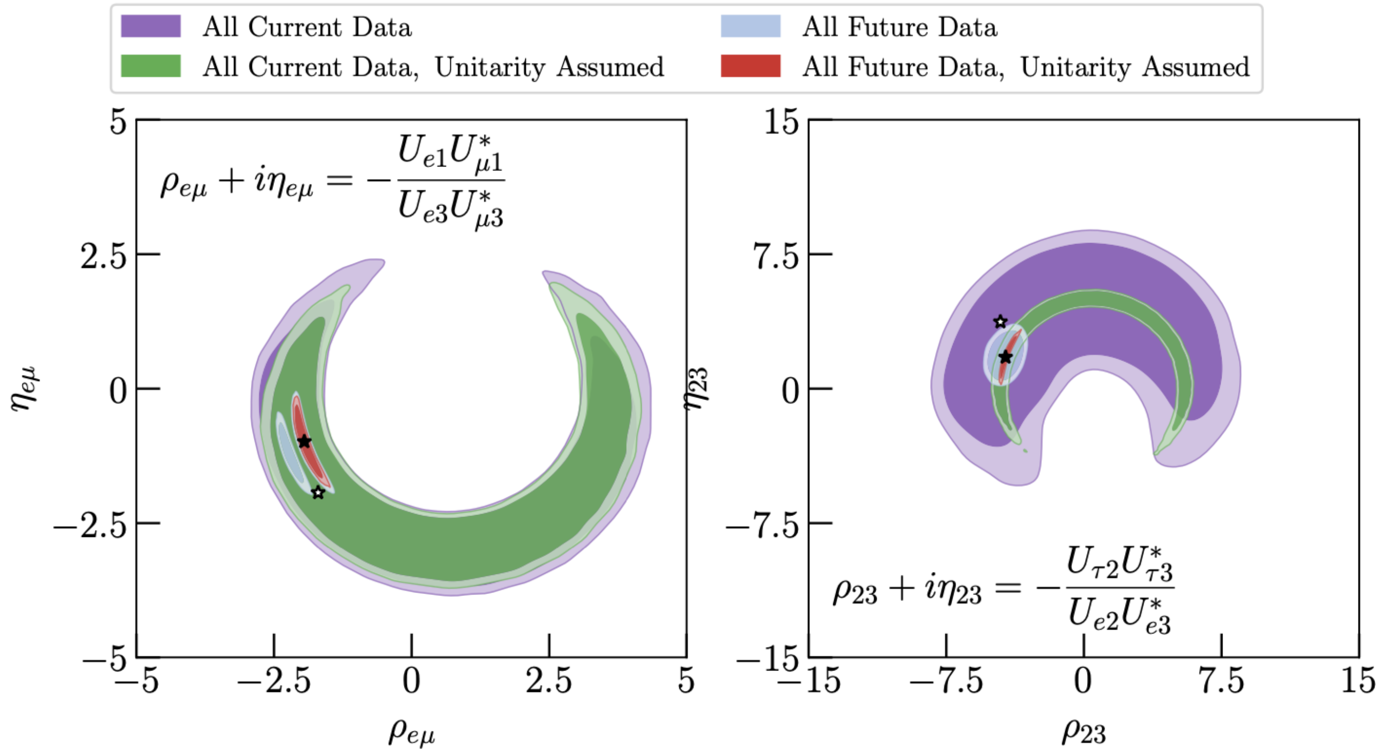


FIG. A1. Current (purple and green) and expected future (pale blue and red) measurements 95% (dark colors) and 99% confidence level (light) of two different unitarity triangles – $\rho_{e\mu}$ vs. $\eta_{e\mu}$ (left) and ρ_{23} vs. η_{23} (right). We contrast two assumptions in this figure, showing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

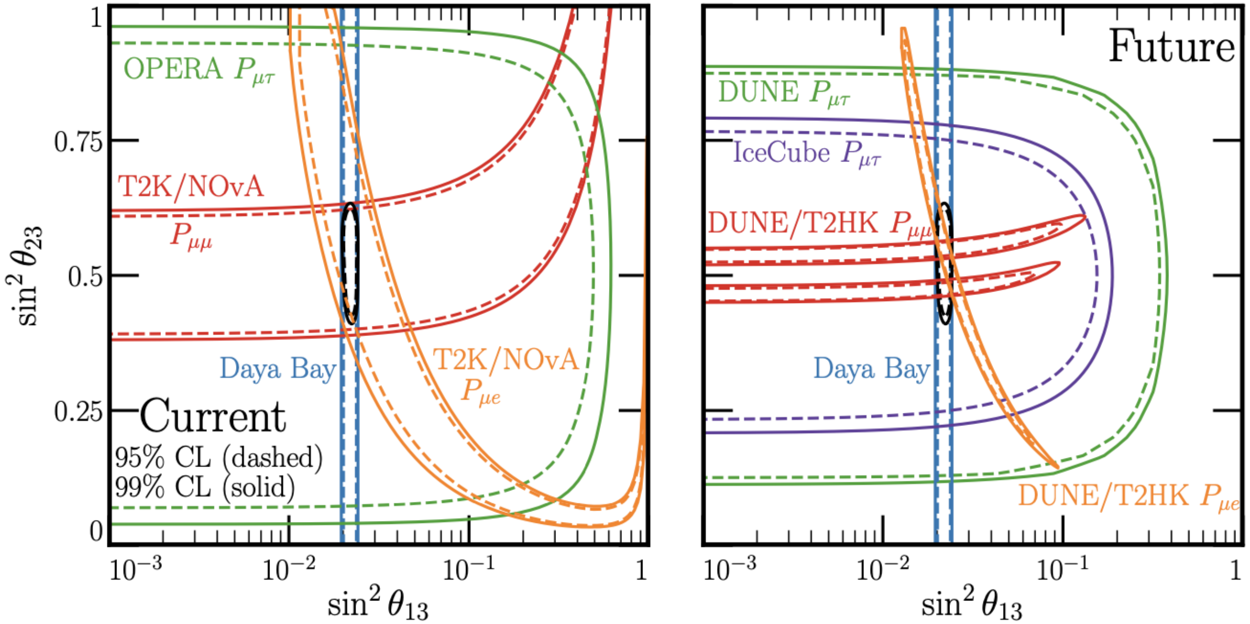


Figure 5. Current (left) and projected (right) measurements of the mixing angles $\sin^2\theta_{23}$ and $\sin^2\theta_{13}$ at 95% and 99% CL. The black contours in both panels show the joint-fit region with current data.

[Ellis, Kelly, Li, arXiv:2008.01088]

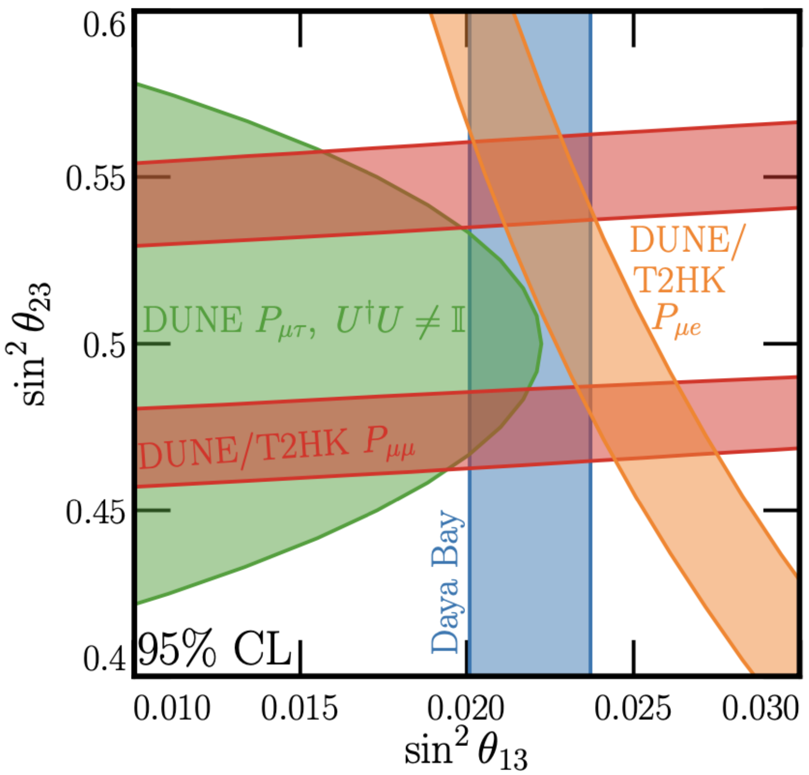


Figure 6. Projected measurements of $\sin^2\theta_{13}$ vs. $\sin^2\theta_{23}$ when unitarity is violated ($N_3 \approx 2$). For DUNE's long-baseline measurement of $P_{\mu\tau}$ (green), we simulate data assuming the underlying mixing matrix is non-unitary, and extract the measurement of these parameters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

[Ellis, Kelly, Li, arXiv:2008.01088]

Golden Opportunity to Understand Matter versus Antimatter?

The SM with massive Majorana neutrinos accommodates **five** irreducible CP-invariance violating phases.

- One is the phase in the CKM phase. We have measured it, it is large, and we don't understand its value. At all.
- One is θ_{QCD} term ($\theta G\tilde{G}$). We don't know its value but it is only constrained to be very small. We don't know why (there are some good ideas, however).
- Three are in the neutrino sector. One can be measured via neutrino oscillations. 50% increase on the amount of information.

We don't know much about CP-invariance violation. Is it really fair to presume that CP-invariance is generically violated in the neutrino sector solely based on the fact that it is violated in the quark sector? Why? Cautionary tale: "Mixing angles are small."

Indirect connection to the matter–antimatter asymmetry of the universe. The existence of new sources of CP-invariance violation is a necessary requirement.

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.

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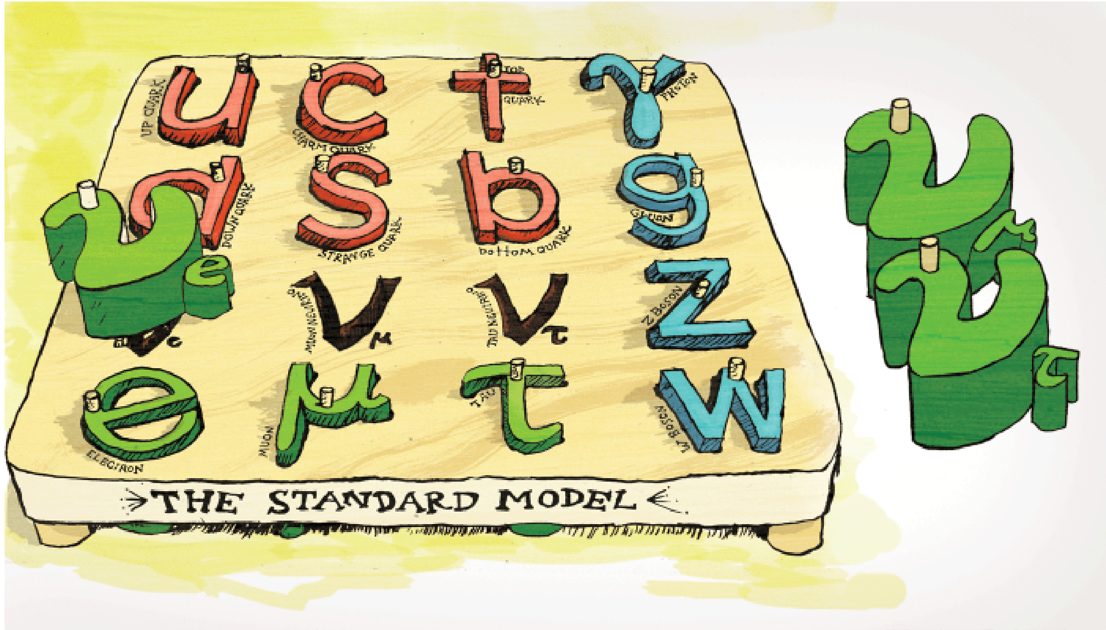

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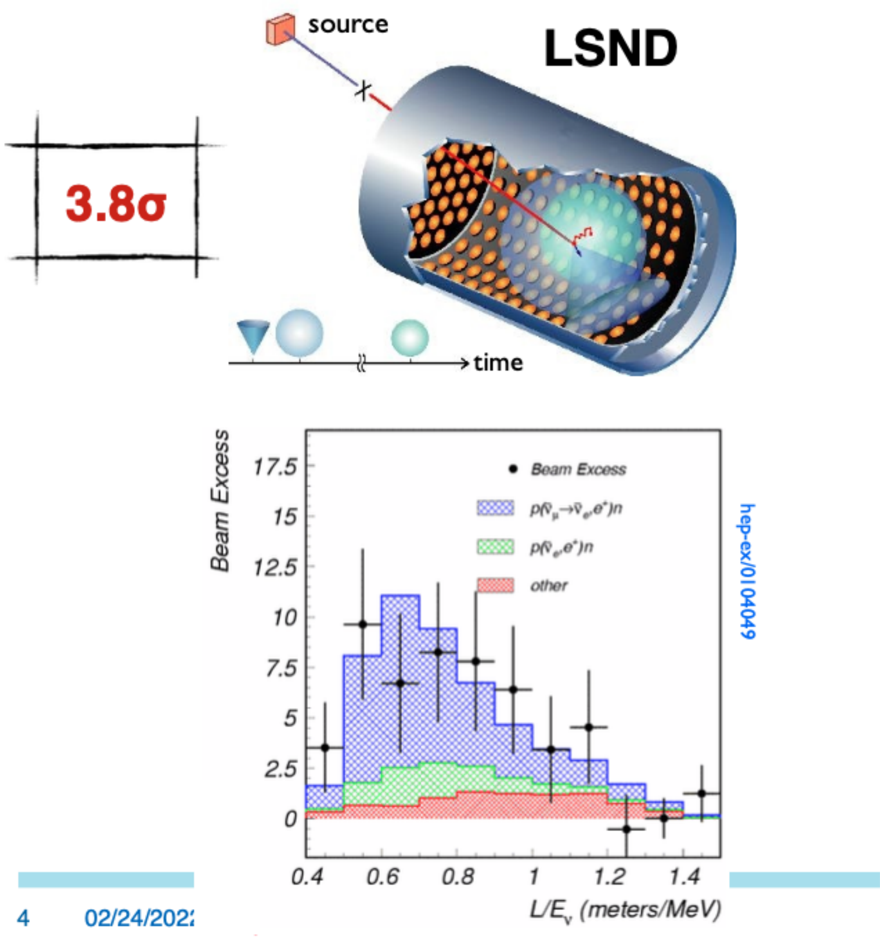
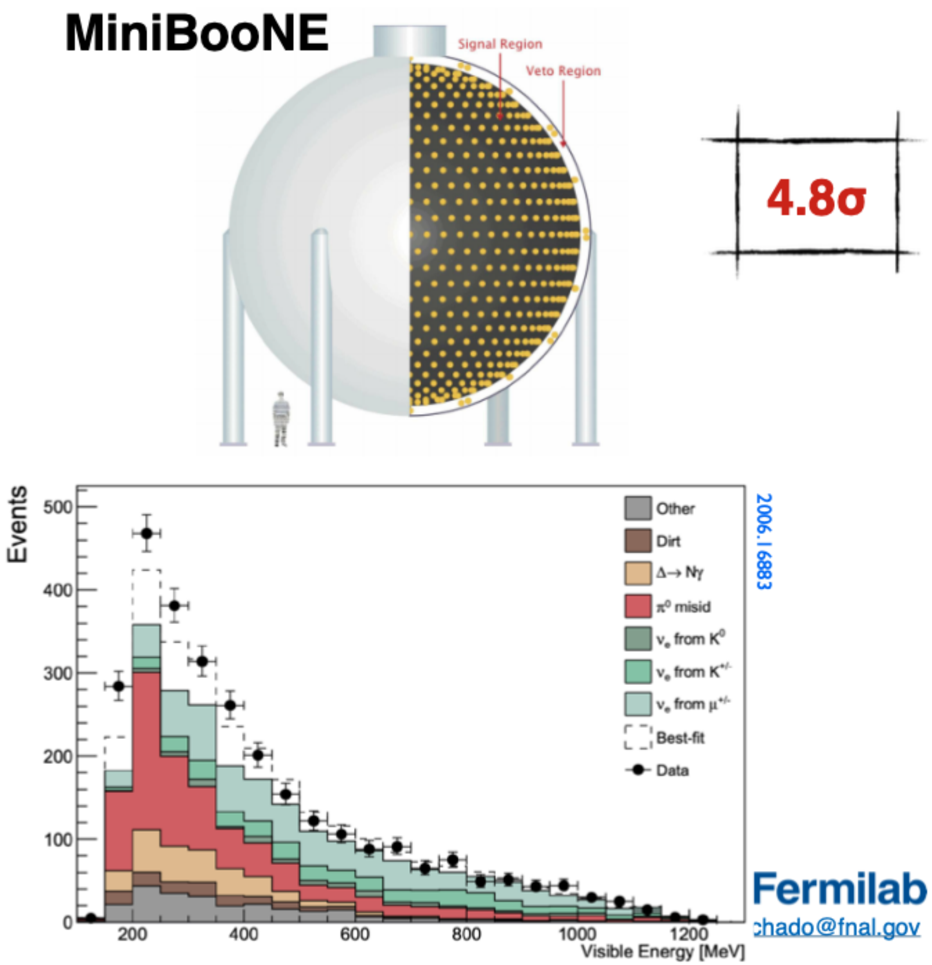
1 - Resolve the short-baseline anomalies.

Are We Sitting on More New Neutrino Physics?

3.8σ

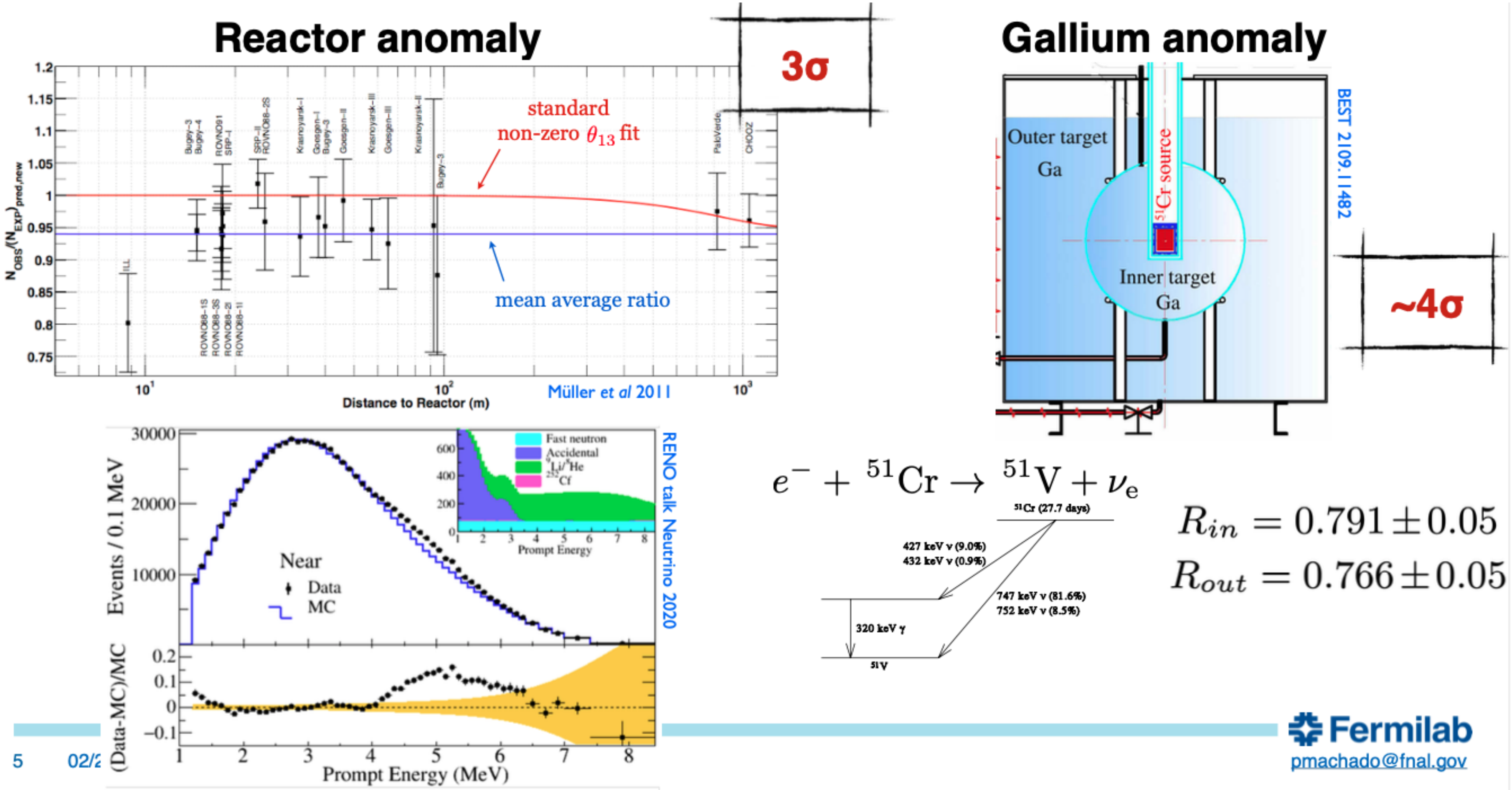




4.8σ

[courtesy of P. Machado]

Are We Sitting on More New Neutrino Physics?

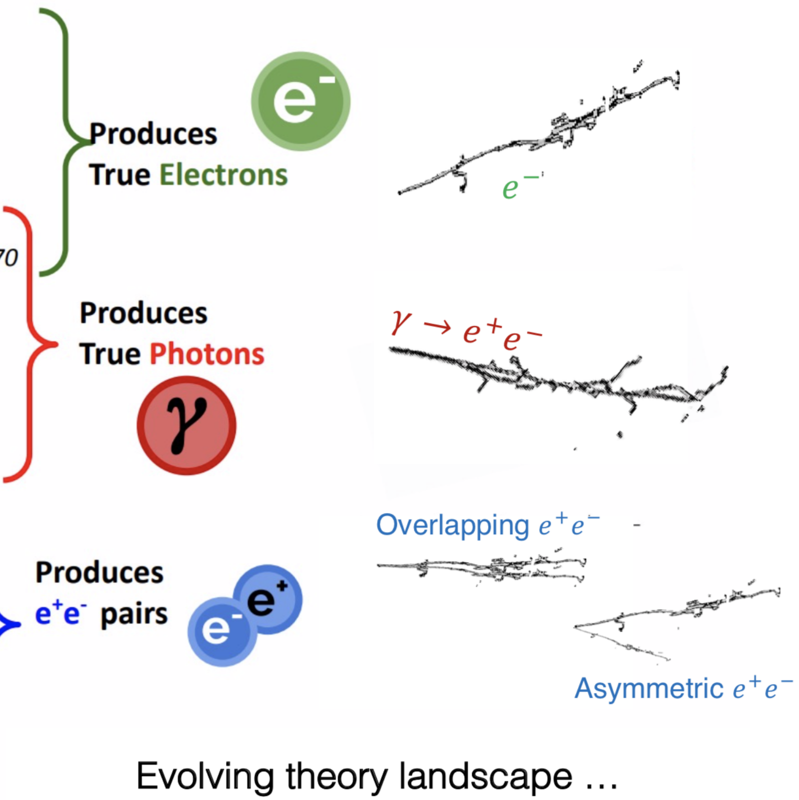


[courtesy of P. Machado]

Is it BSM? Lots of possibilities. For example...

More exploration of MiniBooNE excess

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - *[13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)*
  - *[14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141*
- New resonance matter effects
  - *[5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)*
  - *[16] Alves, Louis, deNiverville, [hep-ph]2201.00876 (2022)*
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - *[7]Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470*
- Decay of heavy sterile neutrinos produced in beam
  - *[4] Gninenko, Phys.Rev.D83:015015,2011*
  - *[12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)*
  - *[15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)*
  - *[11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)*
  - *[17] Dutta, Kim, Thompson, Thornton, Van de Water [hep-ph]2110.11944*
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - *[1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)*
  - *[2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531*
  - *[3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)*
  - *[10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)*
  - *[6] Abdallah, Gandhi, Roy,Phys. Rev. D 104, 055028 (2021)*
- Decay of axion-like particles
  - *[8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)*
- A model-independent approach to any new particle
  - *[9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)*

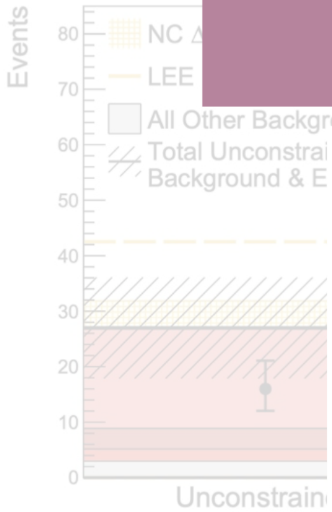


Evolving theory landscape ...
(not an exhaustive list)

[MicroBooNE talk at Neutrino 2022]

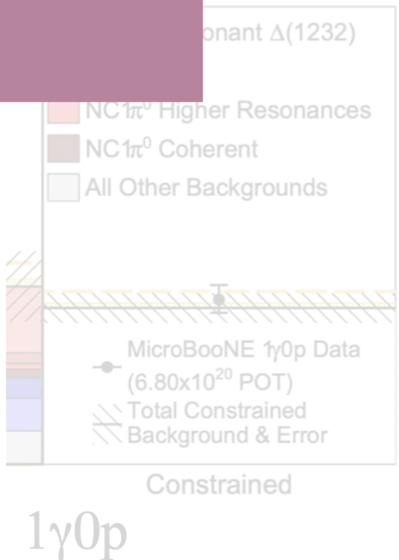
LEE Search in MicroBooNE – NC Δ→Nγ

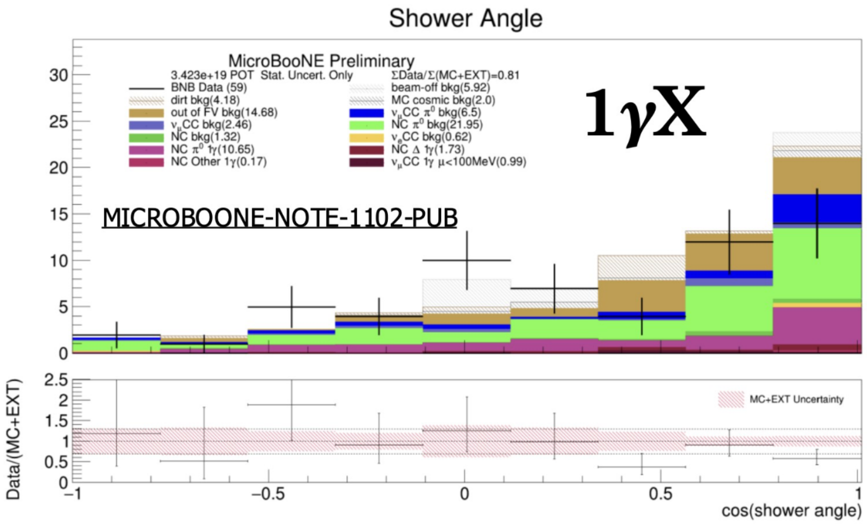
- Two ch
  - 1γ1p a
- Achieve … Δ→Nγ on any r
- Rules o … 8% C.L.



Looking ahead:
more photon searches are underway
including inclusive single-photon and
Coherent photon searches

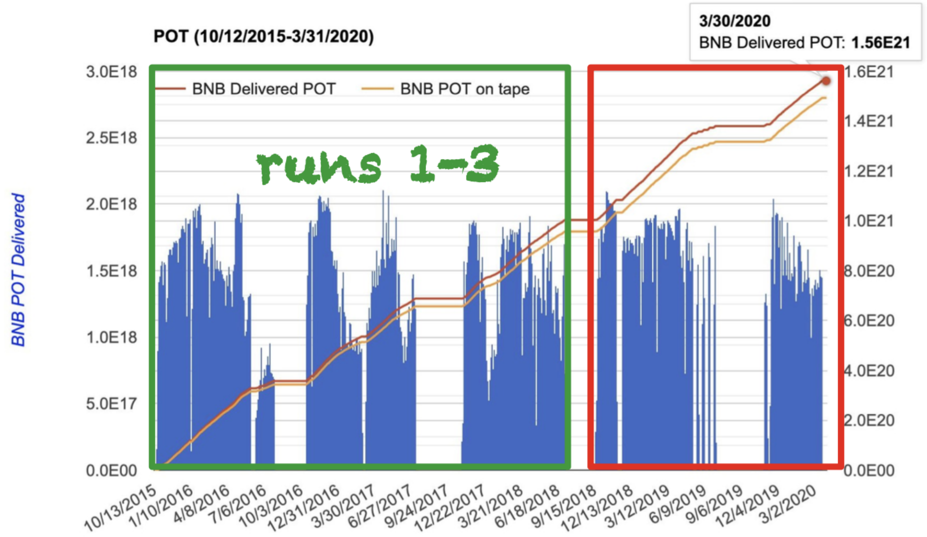
MICROBOONE-NOTE-1104-PUB
MICROBOONE-NOTE-1102-PUB
MICROBOONE-NOTE-1103-PUB

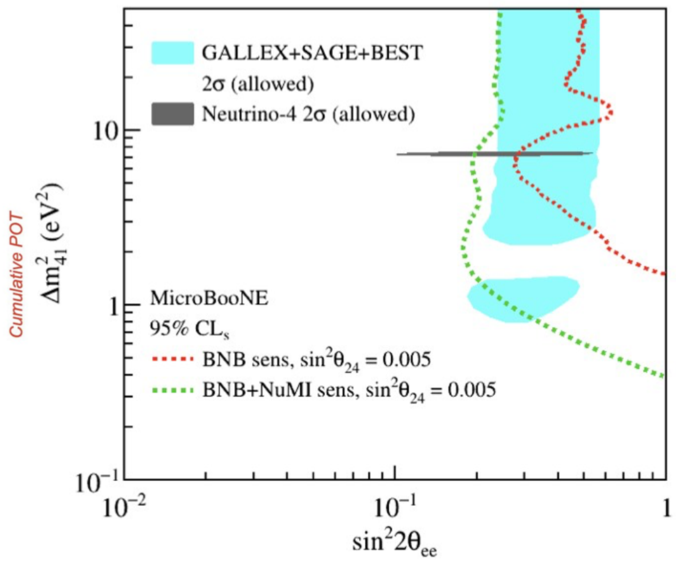




Future Prospects of the LEE Searches

- Only runs 1-3 have been explored for LEE searches so far, more results underway with the remaining data!
- A combined analysis using NuMI and BNB is underway, better sensitivity to other experimental results (mainly due to degeneracy mitigation) expected





MICROBOONE-NOTE-1116-PUB

Data Collection @ ICARUS

- ICARUS was first fully operational in June 2021 before the summer beam shutdown, and was immediately able to continue taking commissioning data when the beam resumed in November 2021
- Two successful physics runs with a combined 2.45e20 POT (BNB) and 3.42e20 POT (NuMI)

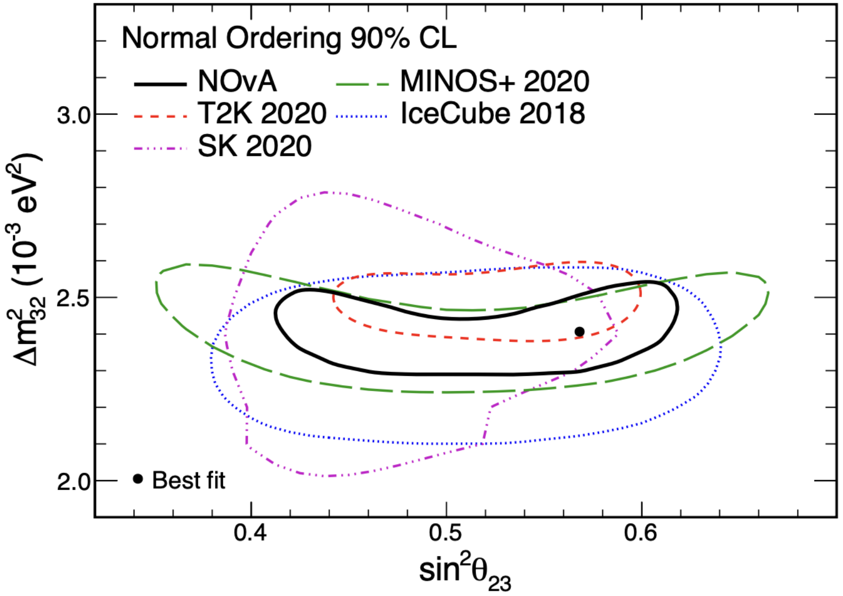
Run	Type	BNB POT	NuMI POT	BNB Eff.	NuMI Eff.
	Commissioning	2.96e20	5.03e20	88.6%	87.7%
Run 1	Physics	0.41e20	0.68e20	93.2%	92.9%
Run 2	Physics	2.04e20	2.74e20	95.0%	95.6%

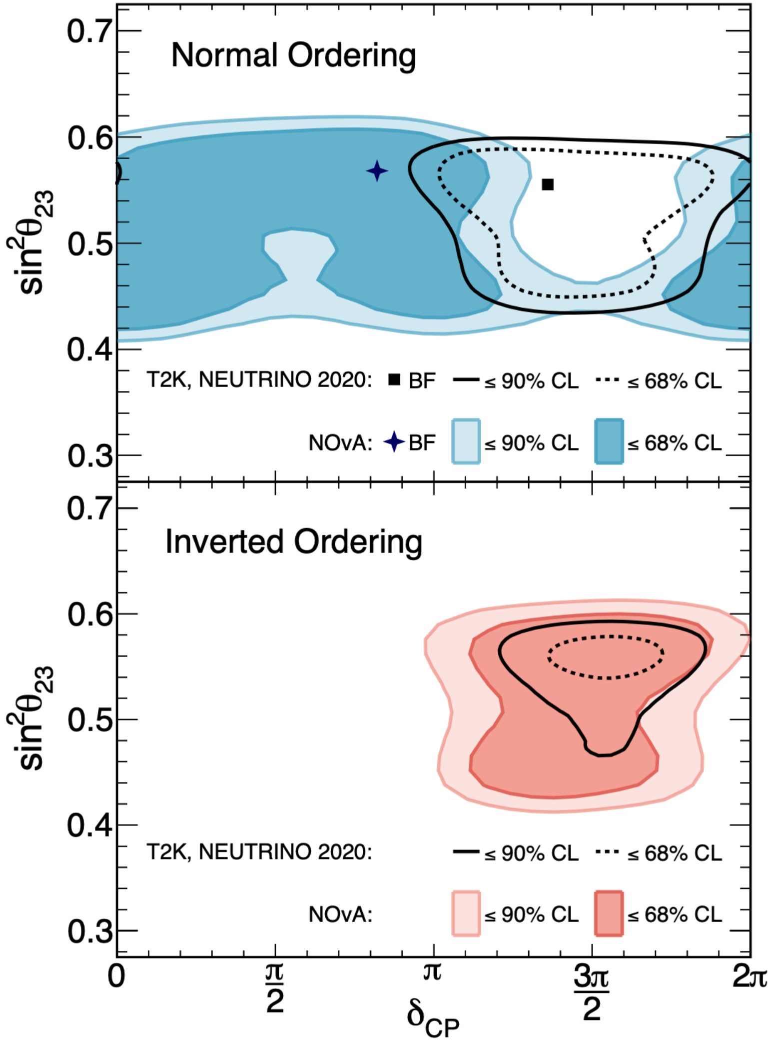
. . . and SBND will start taking data before 2025!

2 - More results from the ongoing long-baseline experiments.

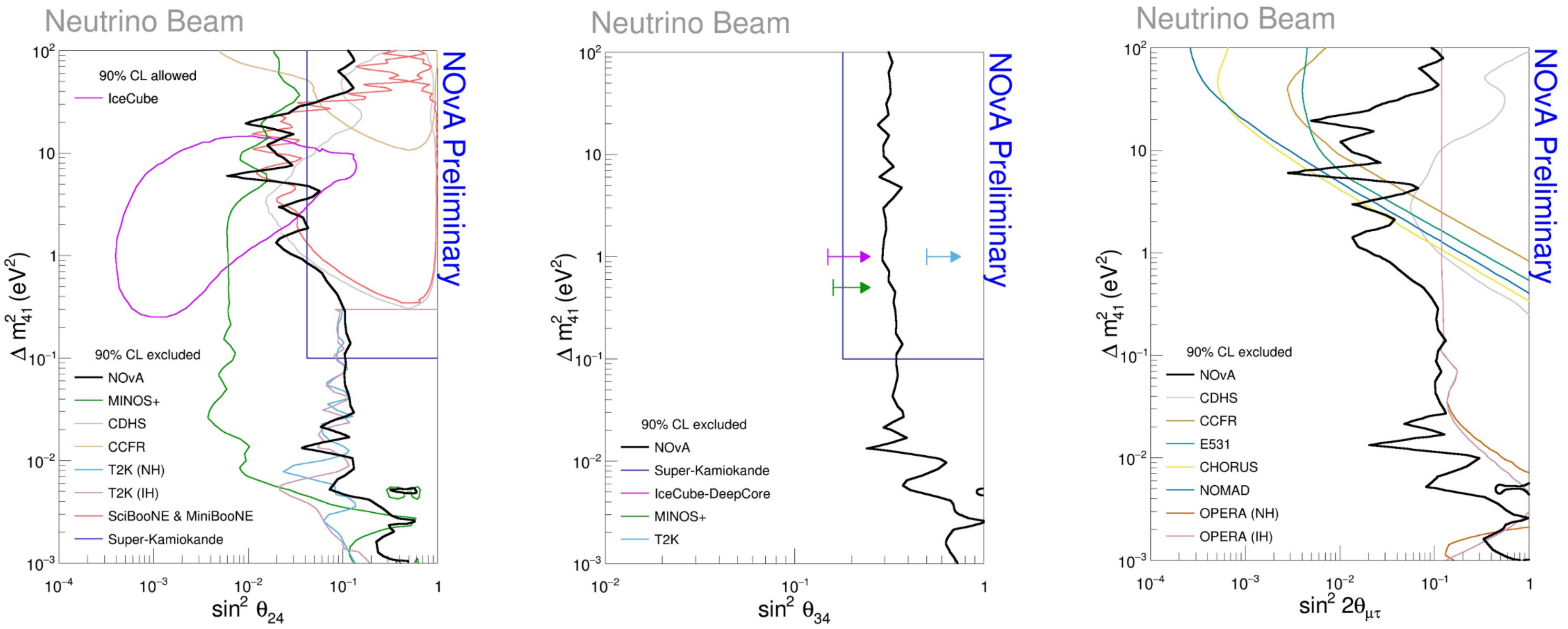
Joint Fit with T2K in progress

- NOvA and T2K have general agreement, but there are different preferences for δ_{CP} values in normal ordering.
- Results expected early next year.



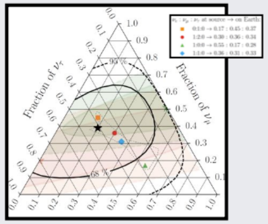


- NOvA recently searched for sterile-driven oscillations using a joint short and long baseline analysis
- Considered both ν_μ disappearance and NC disappearance
- Set limits on $\sin^2\theta_{24}$ and $\sin^2\theta_{34}$
  - Limits can be combined to set limits on effective mixing parameter controlling anomalous $\nu_\mu \rightarrow \nu_\tau$ appearance



$\nu_\tau^{\rm astro}$: What's Next?

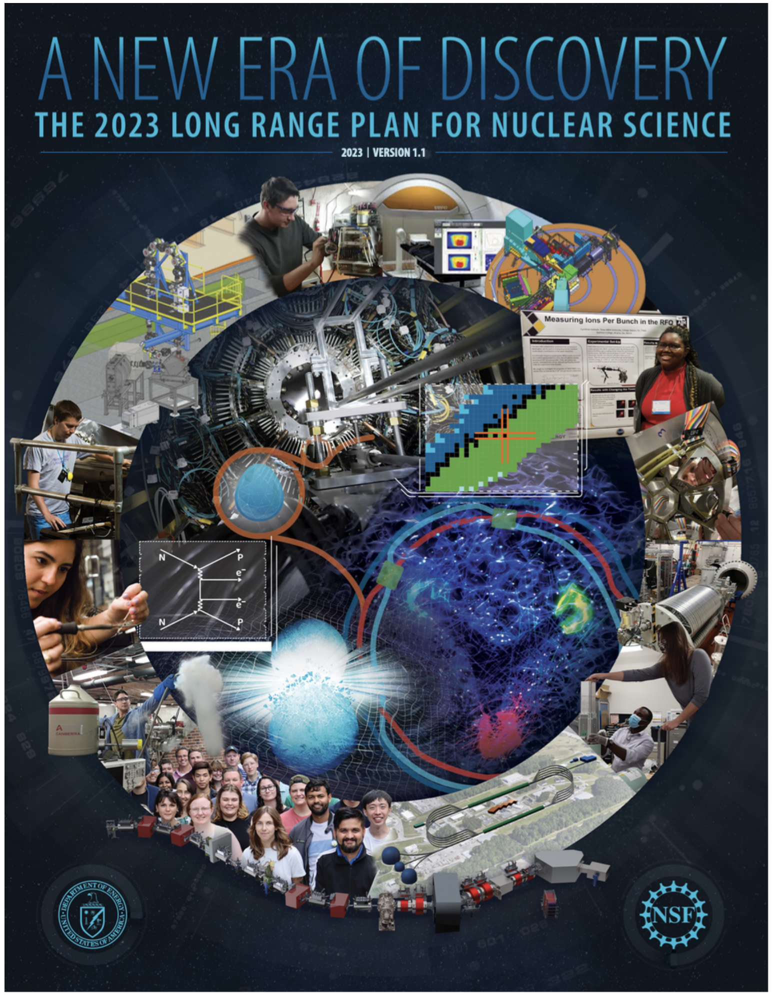
- Used just 3 (of 86) strings. Using more strings would:
  - Improve bkgd rejection, allowing for relaxation of cuts→more signal
    - Improve $\phi(\nu_\tau^{\rm astro})$ measurement
    - Update "triangle plot" with ν_τ information
      - Search for new physics (e.g., quantum gravity)
      - Identify likely astrophysical-source acceleration scenarios; maybe exclude some



- Apply a dedicated ν_τ reconstruction for direction, E,…
  - Study parameters of highest-energy ν_τ and τ ever detected
    - L_τ, energy asymmetry, …
  - Use high-astrophysical-purity ν_τ to look for point sources

3 - Steady progress on the construction of next-generation long-baseline experiments. No "surprises" would be nice. (Good surprises, however, are allowed.)

Same for searches for neutrinoless double-beta decay.



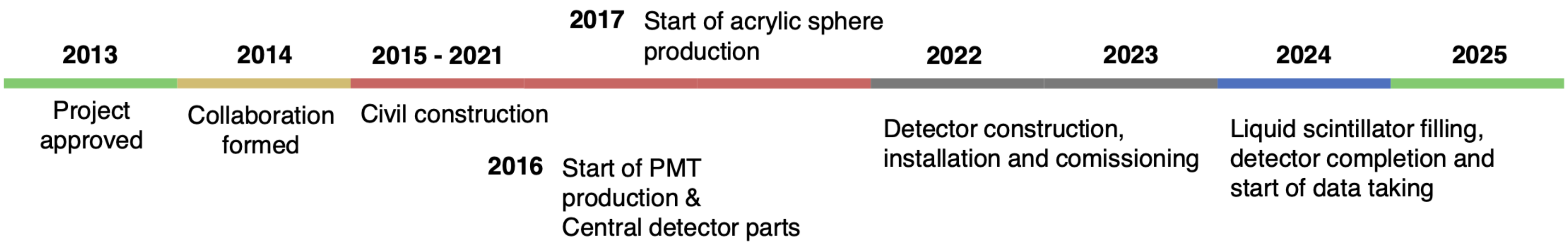
RECOMMENDATION 2

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

One of the most compelling mysteries in all of science is how matter came to dominate over antimatter in the universe. Neutrinoless double beta decay, a process that spontaneously creates matter, may hold the key to solving this puzzle. Observation of this rare nuclear process would unambiguously demonstrate that neutrinos are their own antiparticles and would reveal the origin and scale of neutrino mass. The nucleus provides the only laboratory through which this fundamental physics can be addressed.

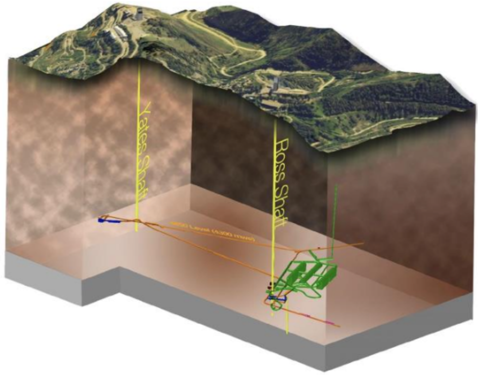
Summary

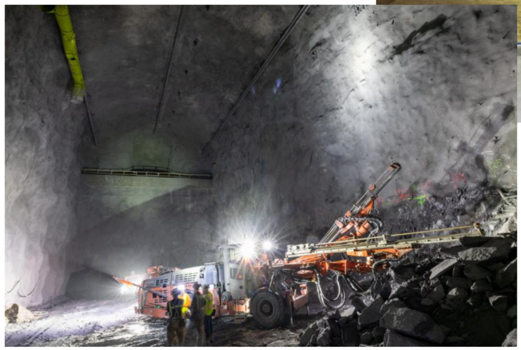
- JUNO will be the largest liquid scintillator detector in the world with unprecedented energy resolution.
- JUNO will determine the neutrino mass ordering with 3σ after 6 years of data taking using reactor antineutrinos.
- JUNO will be an observatory for geoneutrinos, atmospheric neutrinos, solar neutrinos, supernova neutrinos, proton decay, and other exotic new physics.

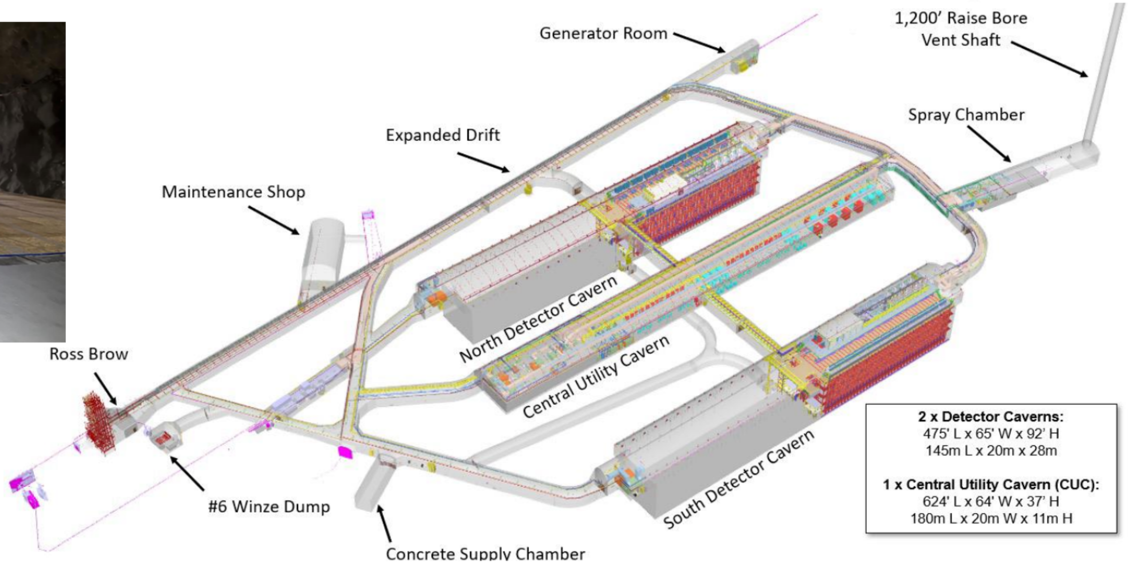


DUNE Far Site

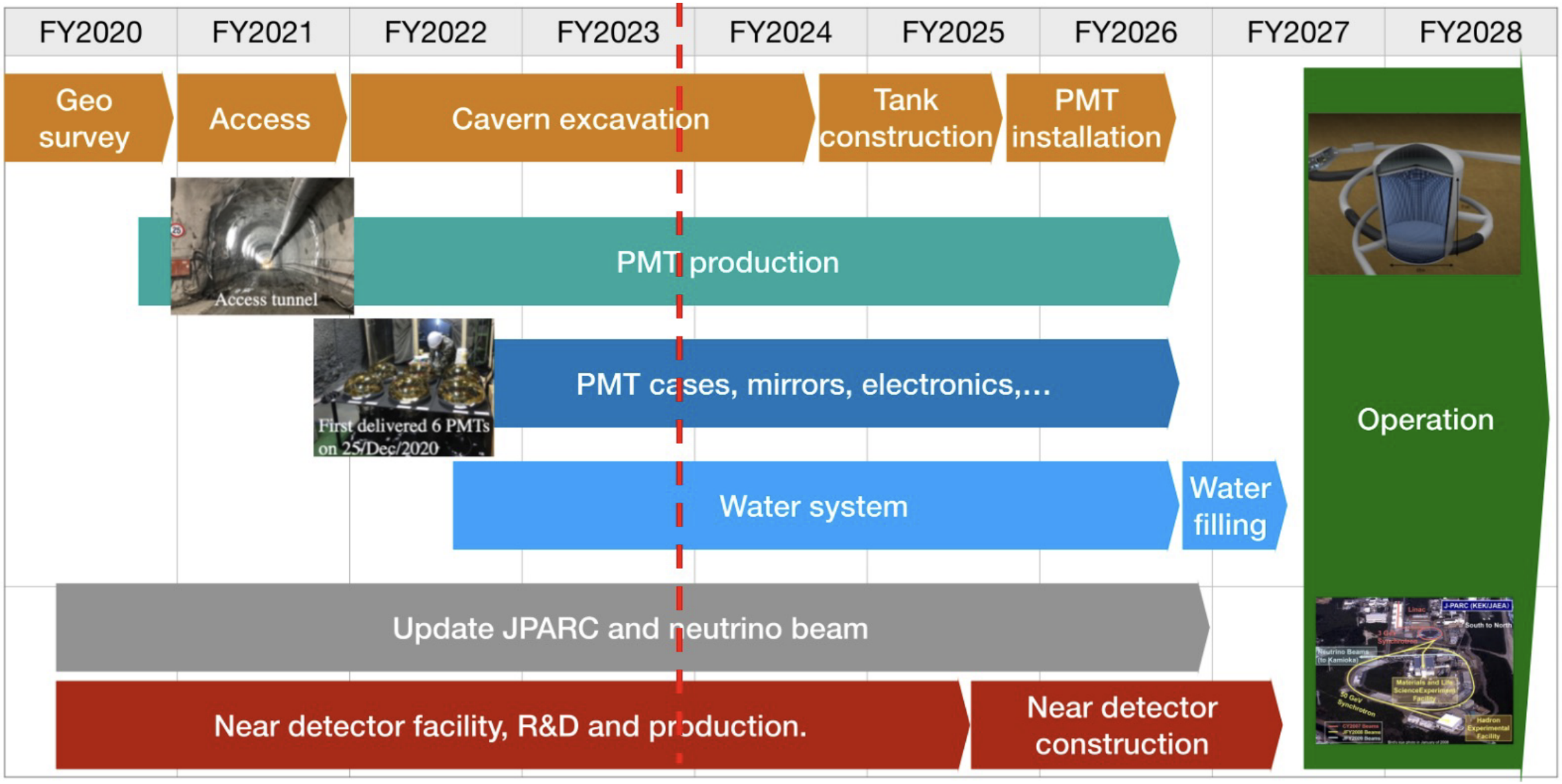
- Excavation expected to finish in 2024
- 80% done.
- Facility to be completed in 2025







Schedule



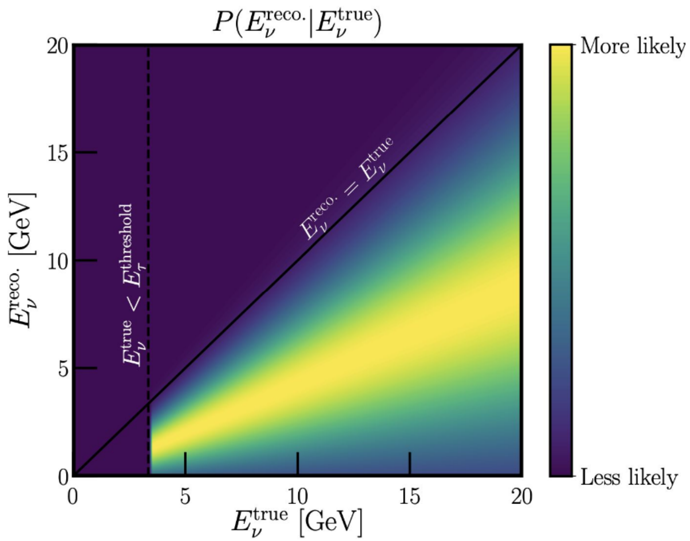
- Approved in 2019 by Japanese government.
- **7 years construction** from year 2020; **start operation in 2027**.

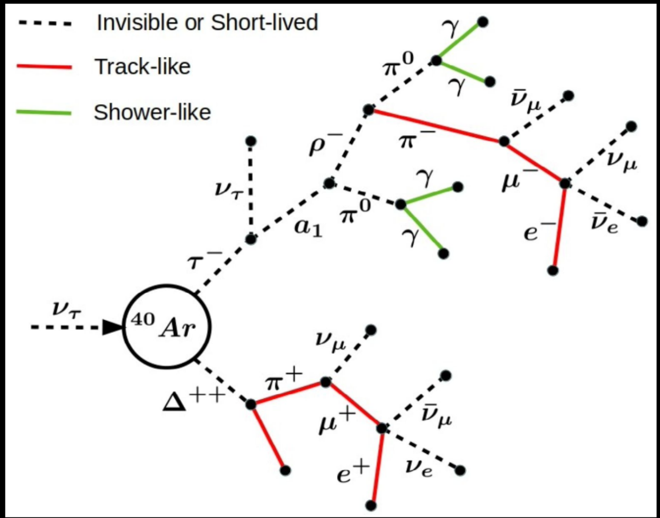
4 - More on what ν_τ is good for. And on how do we get to see ν_τ experimentally!

Challenges

- **Tau leptons have many decay modes**
- **CC-(ν_e, ν_μ) or NC events have same particle content**
  -Angular correlations due to missing neutrino(s) from τ decay is the key signature
- **Hadronic modes can be complicated**
- **Difficult to separate hadronic systems**
- **from τ decay and nucleus**

Decay mode	Branching ratio
Leptonic	35.2%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic	64.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\pi^0\nu_\tau$	9.3%
$\pi^-\pi^-\pi^+\nu_\tau$	9.0%
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.5%
other	5.7%





Barbara Yaeggy - University of Cincinnati

Tau decay length ~ 87 μm
^{40}Ar nuclear radius, ~ 3.4 fm
→ Tau decay products aren't subject to the ^{40}Ar nuclear potential

Tau lifetime (2.903±0.005) ×10^{-13} s
Mass: 1.7 GeV/c^2
→ Tau doesn't lead to observables displaced vertices

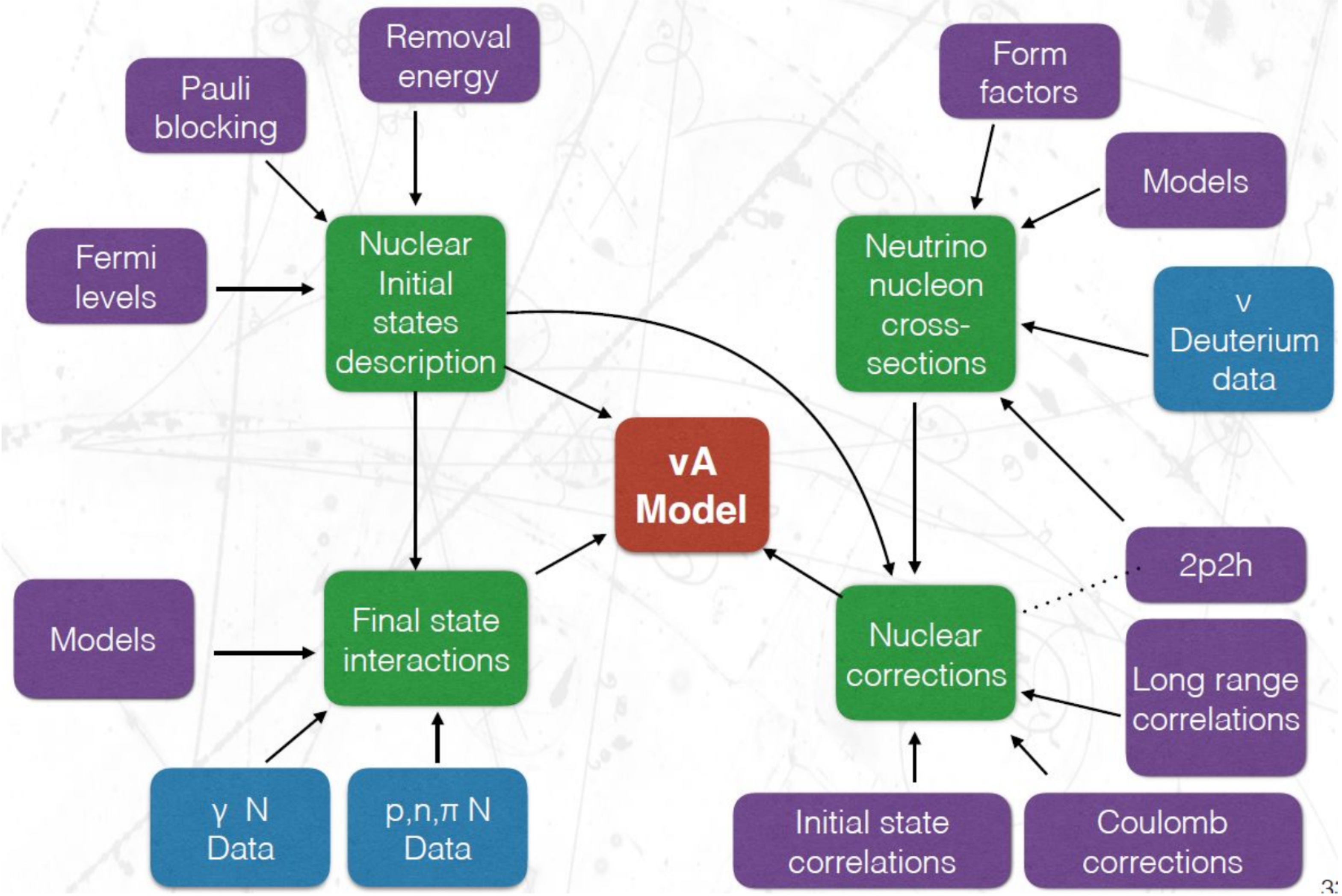
DUNE granularity is limited by a wire spacing of 3mm

Observation of Tau tracks is unlikely!

9

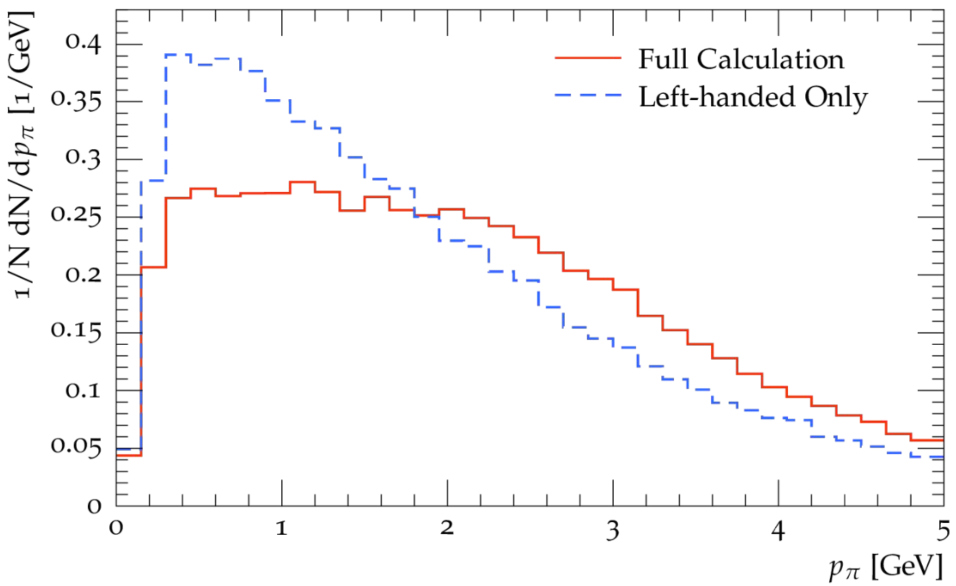
5 - Progress in our Understanding of Neutrino–Nucleus Scattering at "Low Energies" (below the DIS regime)

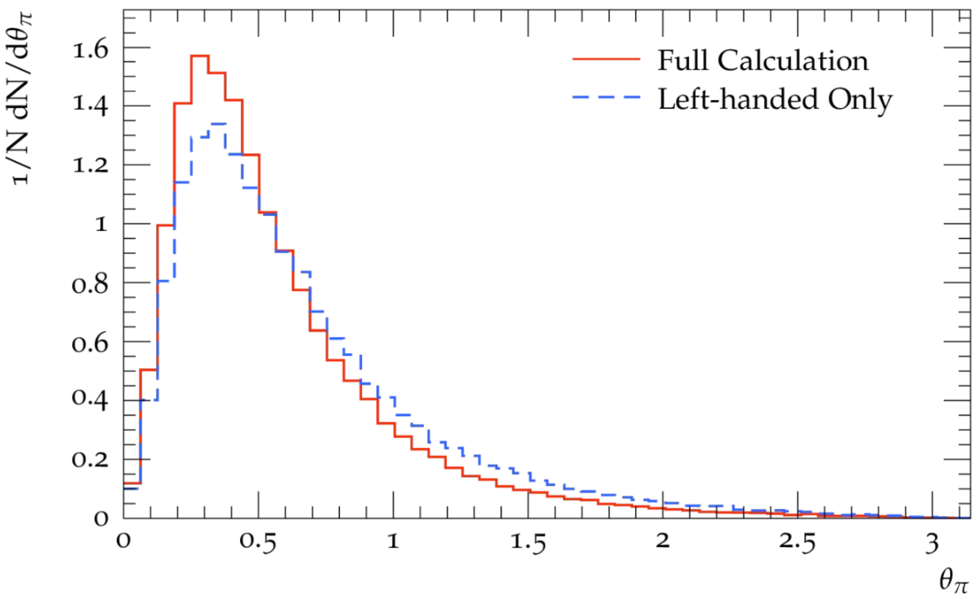
Neutrino-nuclear interactions (high energy)



DUNE Tau Optimized Flux

$$\nu_\tau A \to \tau^-(A-1)p, \quad \tau^- \to \nu_\tau \pi^-$$



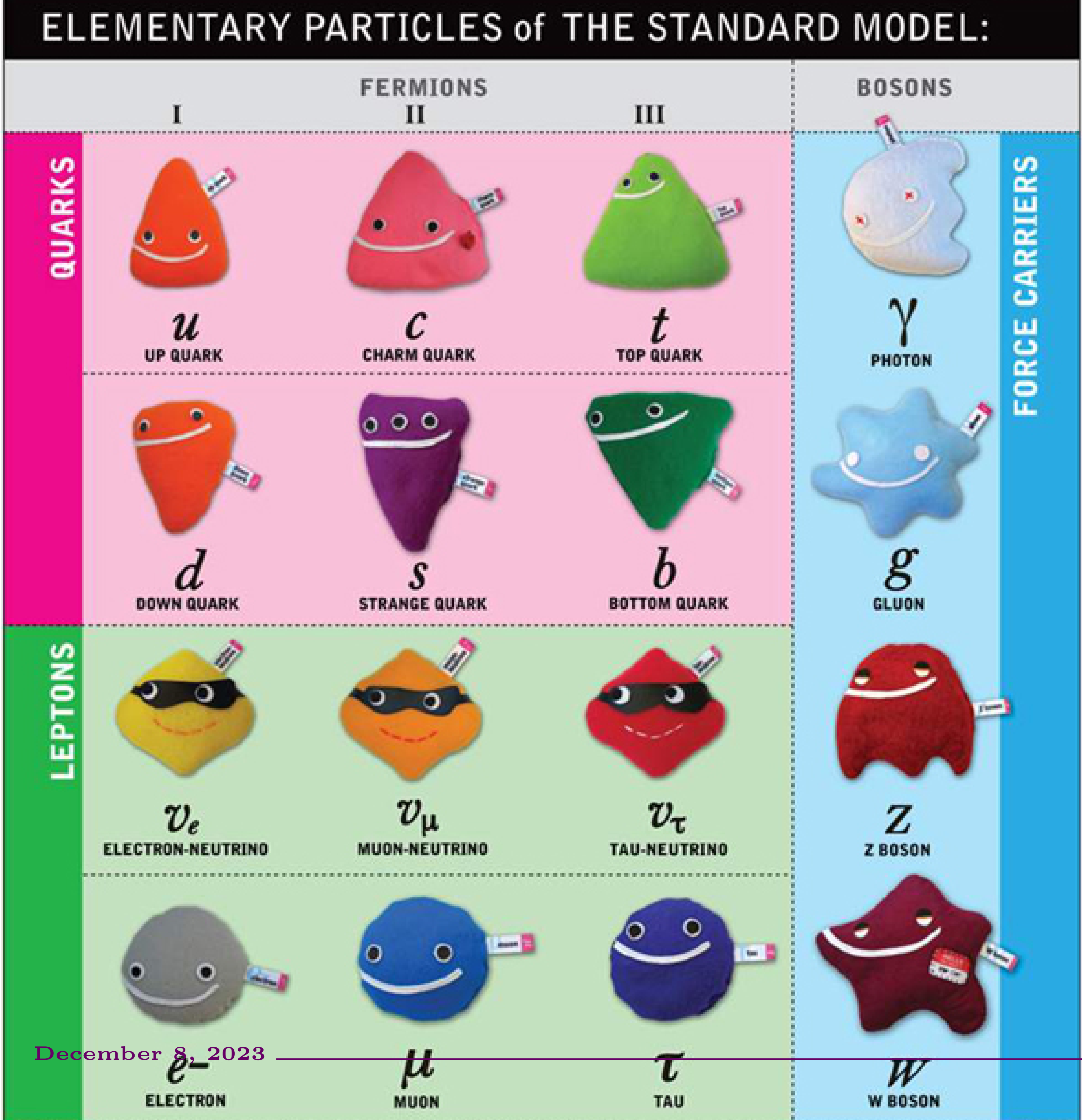


6 - SN2024A

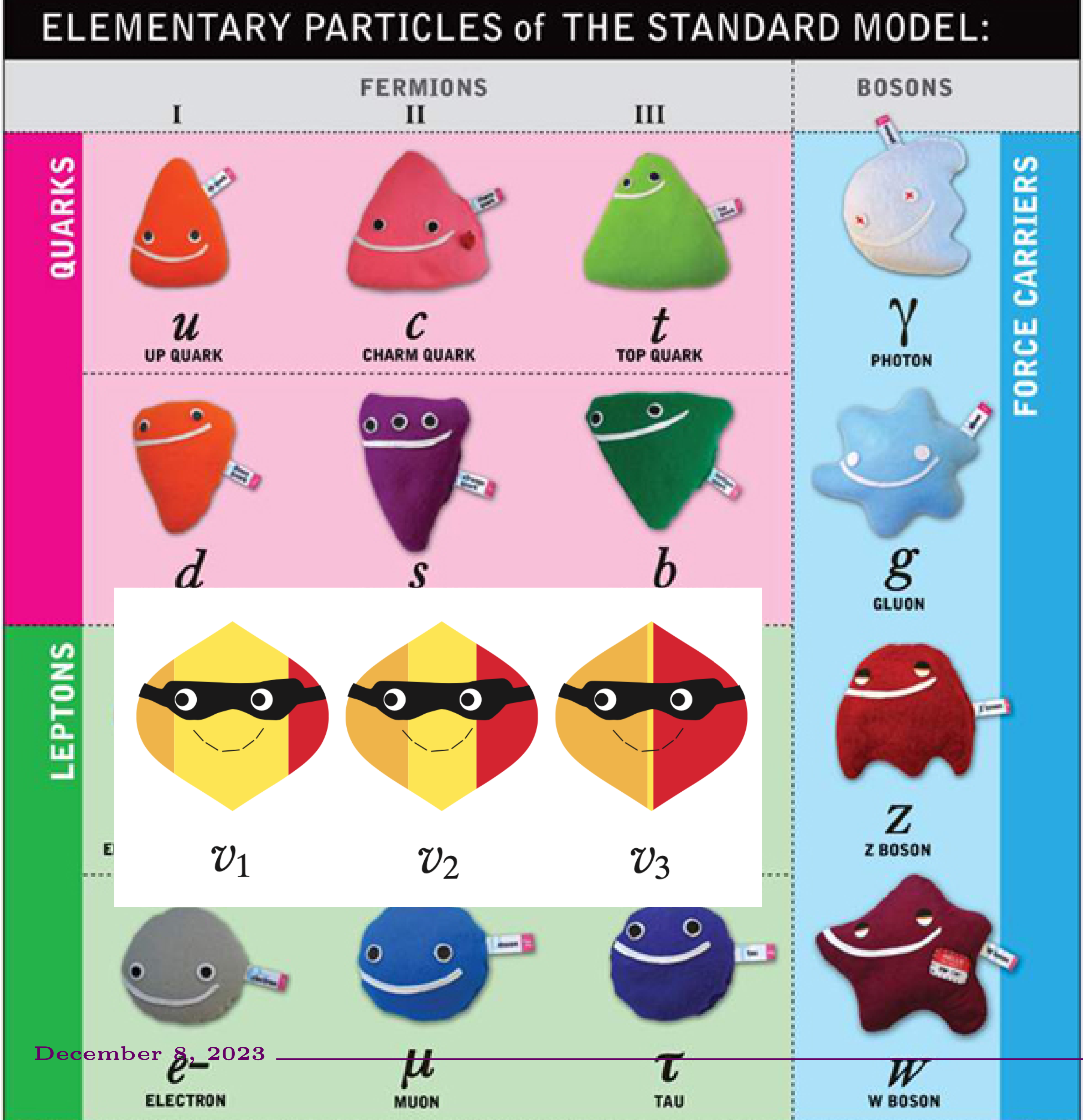
Core-collapse SN: Gravity-powered neutrino bomb

- Neutrinos carry away >99% of the energy (instantaneously, as all the stars in the universe)
  - Neutrino heating powers the expulsion of the envelope -> visible explosion
- Neutrinos are an essential ingredient in nucleosynthesis
  - Drive matter outflow from the PNS surface.
  - Set the electron fraction close to the PNS surface.
  - Drive weak processes in the entire outflow region.

In conclusion...



http://www.particlezoo.net



The Picture Changed!

http://www.particlezoo.net

- We still **know very little** about the new physics uncovered by neutrino oscillations.

- **neutrino masses are very small** – 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).

- 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" – potentially very sensitive to whatever else may be out there (e.g., $\Lambda \simeq 10^{14}$ GeV).