# Precision Neutrino Physics: Experiments

Kendall Mahn, Michigan State University

Office of Science
U.S. Department of Energy

# Disclaimers

Thank you to the organizers for the support to be here!

I often get excited and speak too fast…

1. Feel free to ask me to repeat or slow down
2. I’ll be here for the rest of the week - *feel free to ask questions anytime*
3. It’s OK to raise your hand or to interrupt me for either of these

Feedback and comments welcome: mahn@msu.edu

# Outline - *and goals for learning*

What do we know about neutrinos experimentally?

What do we want to learn next?

How do we do precision neutrino experiments?

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What do we know about neutrinos experimentally?

What do we want to learn next?

~~How do we do precision neutrino experiments?~~

*Behind all of this awesome physics are some really incredible detectors, and I found I didn't have time to talk about them in any detail at all…*

# Outline - *and goals for learning*

What do we know about neutrinos experimentally?

Broadly, three topics:

Neutrino oscillation - *implies neutrino mass and mass ordering, may imply flavor*

Mass mechanism - Dirac vs. Majorana

(absolute) neutrino mass scale

# Outline - *and goals for learning*

What do we know about neutrinos experimentally?

Broadly, three topics:

**Neutrino oscillation** - *implies neutrino mass and mass ordering, may imply flavor*

Mass mechanism - Dirac vs. Majorana

(absolute) neutrino mass scale

# What do we know about neutrino oscillation?

$$\begin{bmatrix} \nu_\mathrm{e} \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Flavor states

Mass states

*Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS)*

# What do we know about neutrino **flavor**?

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}$$

Flavor states

*How do we know there are 3 flavors of neutrino?*

Aside: helpful resource is Particle Data Group “Particle Listings”, reviews

Particle Listings

R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022) and 2023 update

*Cut-off date for Listings/Summary Tables was Jan. 15, 2023. Files can be downloaded directly by clicking on the icon: PDF. For a key to the listings click here.*

https://pdg.lbl.gov/

# What do we know about neutrino **flavor?**

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}$$

Flavor states

*How do we know there are 3 flavors of neutrino?*

"Invisible width of the Z" - *the cross section changes based on number of NC coupling to Z boson*

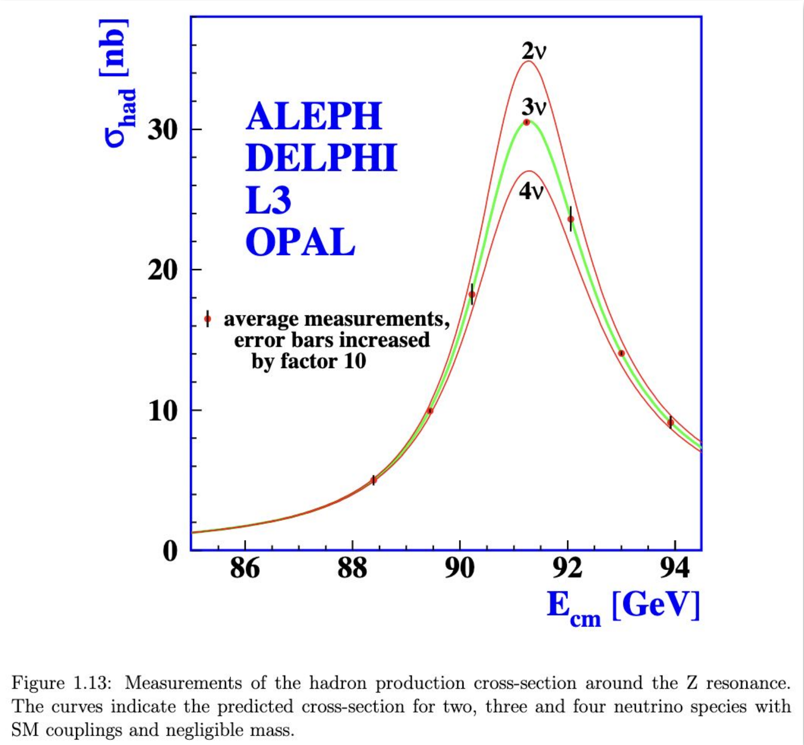


Figure 1.13: Measurements of the hadron production cross-section around the Z resonance. The curves indicate the predicted cross-section for two, three and four neutrino species with SM couplings and negligible mass.

ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, and LEP Electroweak Working Group, and SLD Group, and SLD Heavy Flavour Group, Phys. Reports 427, 257 (2006)

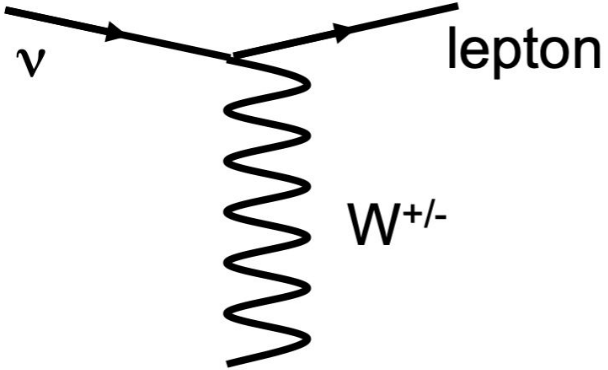
# What do we know about neutrino flavor **and interactions?**

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}$$

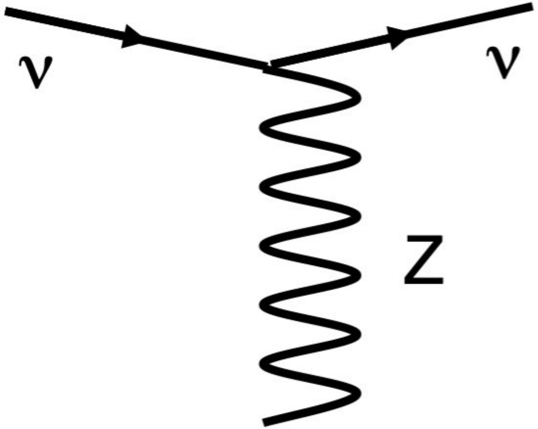
Flavor states

Charged Current (CC)

$$\boxed{\begin{array}{l} \nu_e \longrightarrow e \\ \nu_\mu \longrightarrow \mu \\ \nu_\tau \longrightarrow \tau \end{array}}$$



Neutral Current (NC)



*Neutrinos interact in two ways*

# What do we know about neutrino flavor **and interactions?**

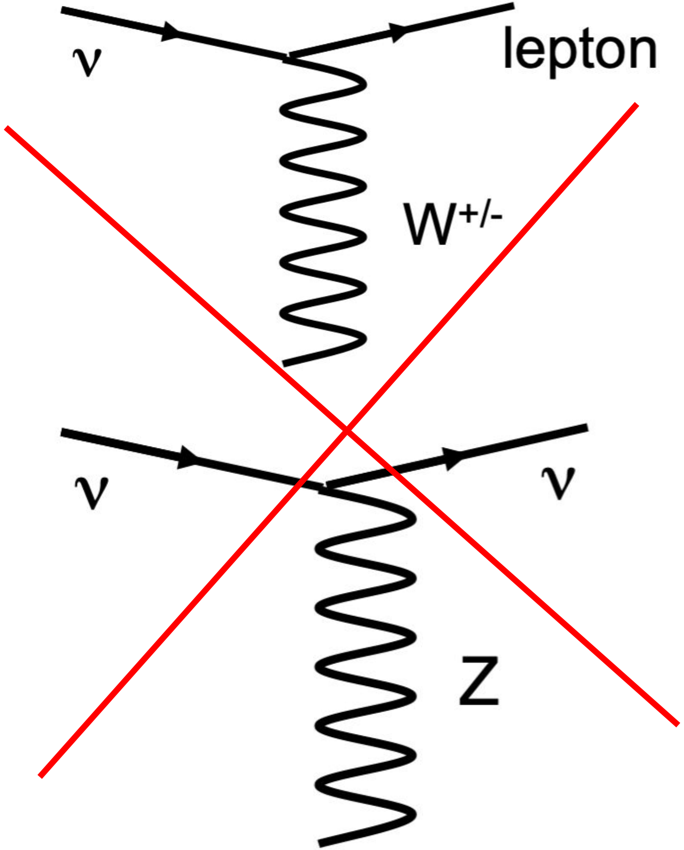
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}$$

$$\nu_S$$

Charged Current (CC)

$$\boxed{\begin{array}{l}\nu_e \longrightarrow e\\ \nu_\mu \longrightarrow \mu\\ \nu_\tau \longrightarrow \tau\end{array}}$$

Neutral Current (NC)



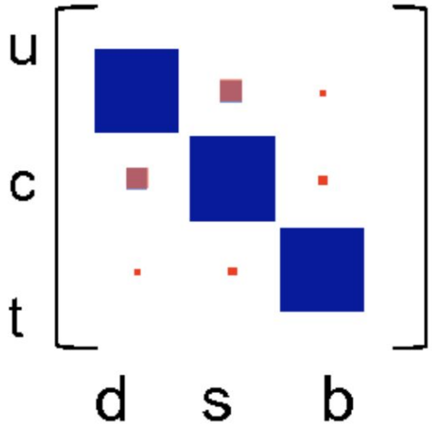
*What about a sterile flavor?*
It won’t interact via W or Z

# What do we know about neutrino oscillation? **Mixing matrix**

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

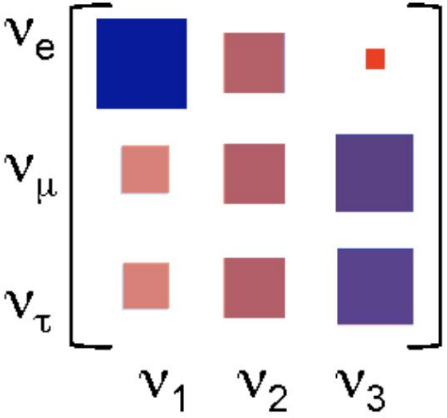
**Quarks**

*CKM*



**Leptons**

*PMNS*



*Graphic: J.Phys. G45 (2018) no.1, 013001*

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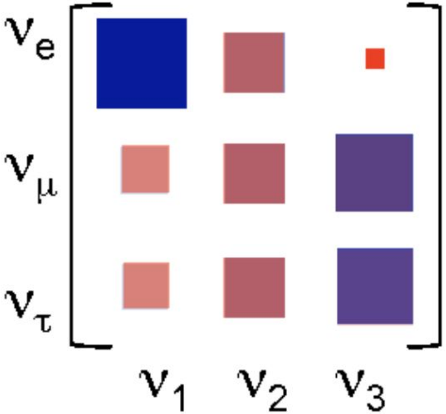
If U is unitary, 3 mixing angles ($\theta_{12}$ $\theta_{23}$ $\theta_{13}$ ) and one phase* ($\delta_{CP}$)

**Leptons**

*PMNS*



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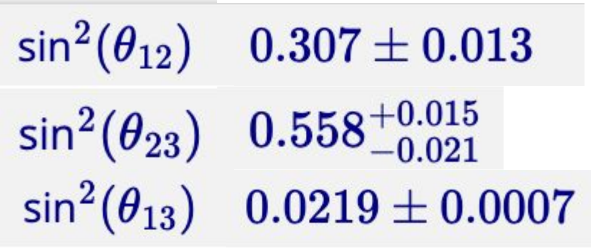
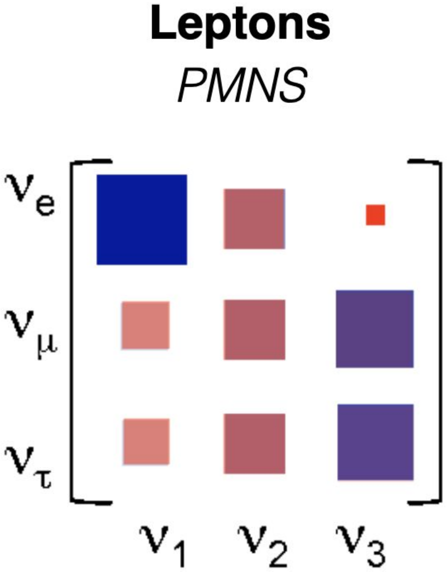
If U is unitary, 3 mixing angles ($\theta_{12}$ $\theta_{23}$ $\theta_{13}$ )

Mixing angles are large. From PDG2023:



| | |
|---|---|
| $\sin^2(\theta_{12})$ | $0.307 \pm 0.013$ |
| $\sin^2(\theta_{23})$ | $0.558^{+0.015}_{-0.021}$ |
| $\sin^2(\theta_{13})$ | $0.0219 \pm 0.0007$ |



**Leptons**

*PMNS*

# What do we know about neutrino oscillation? **Probabilty**

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

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[\boxed{U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}}\right]\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) + 2\sum_{i>j} \mathrm{Im}\left[\boxed{U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}}\right]\sin\left(\frac{2.54\Delta m^2_{ij}L}{E}\right)$$

Probability to oscillate from flavor $\nu_\alpha$ to $\nu_\beta$ and depends on:

- U elements (and therefore $\theta_{12}$ $\theta_{23}$ $\theta_{13}$, $\delta_{CP}$)

# What do we know about neutrino oscillation? **L and E**

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

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Probability to oscillate from flavor $\nu_\alpha$ to $\nu_\beta$ and depends on:

- U elements
- L - ‘baseline’ - *in meters or kilometers*
- E - neutrino energy - *in MeV or GeV*

# What do we know about neutrino oscillation? **Mass splitting**

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

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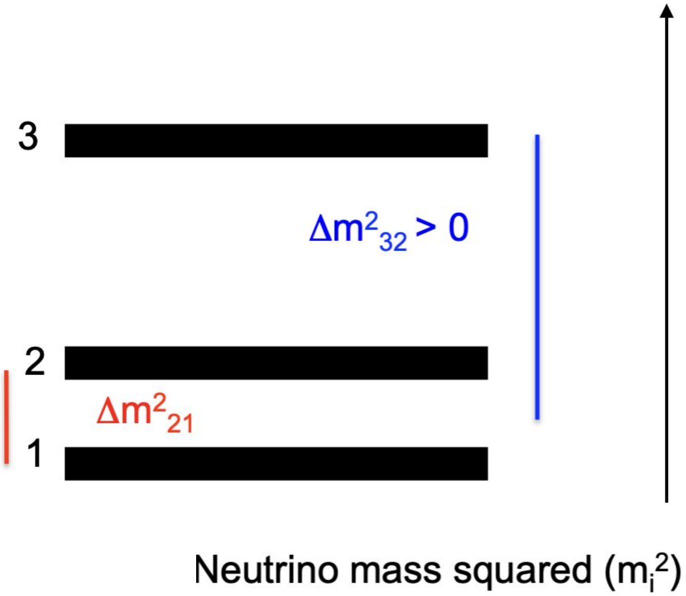
Probability to oscillate from flavor $\nu_\alpha$ to $\nu_\beta$ and depends on:

- U elements
- L - ‘baseline’
- E - neutrino energy
- mass splitting $\Delta m^2_{ij} = m^2_i - m^2_j$

# Mass splitting and mass ordering



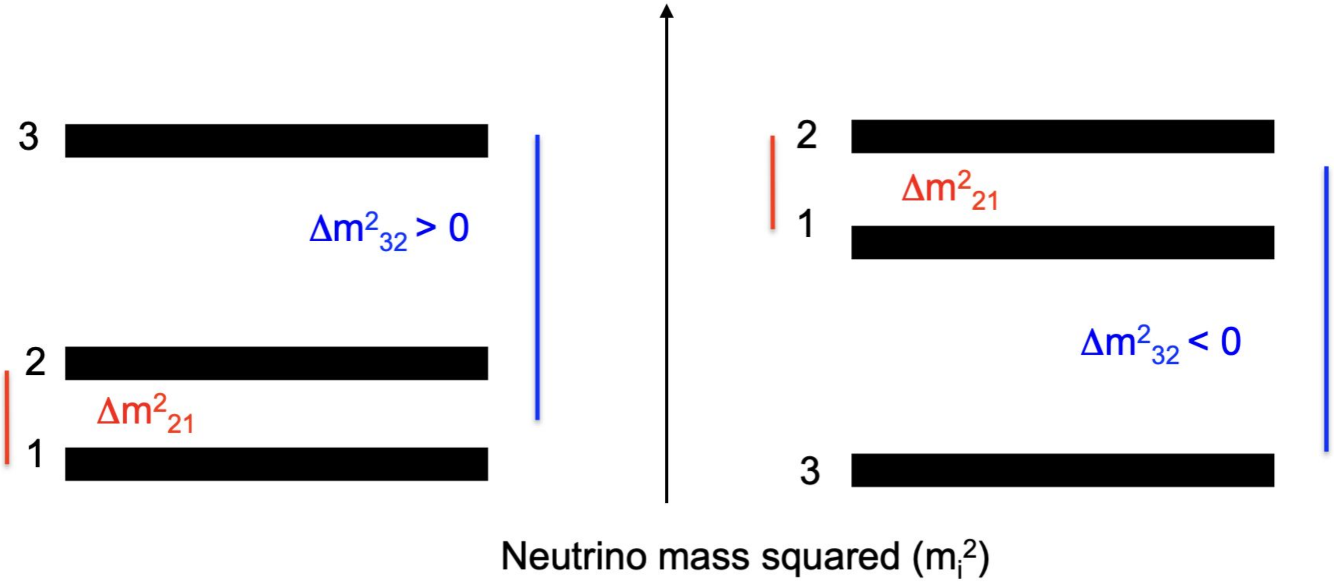
$$\begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Mass states

Three masses means two independent mass splittings ( $\Delta m^2_{ij} = m^2_i - m^2_j$ )

- $\Delta m^2_{21}$ ~$10^{-5}$ eV$^2$ - *known to be positive from solar neutrino experiments*
- $\Delta m^2_{32}$ ~$10^{-3}$ eV$^2$

# Mass splitting and mass ordering



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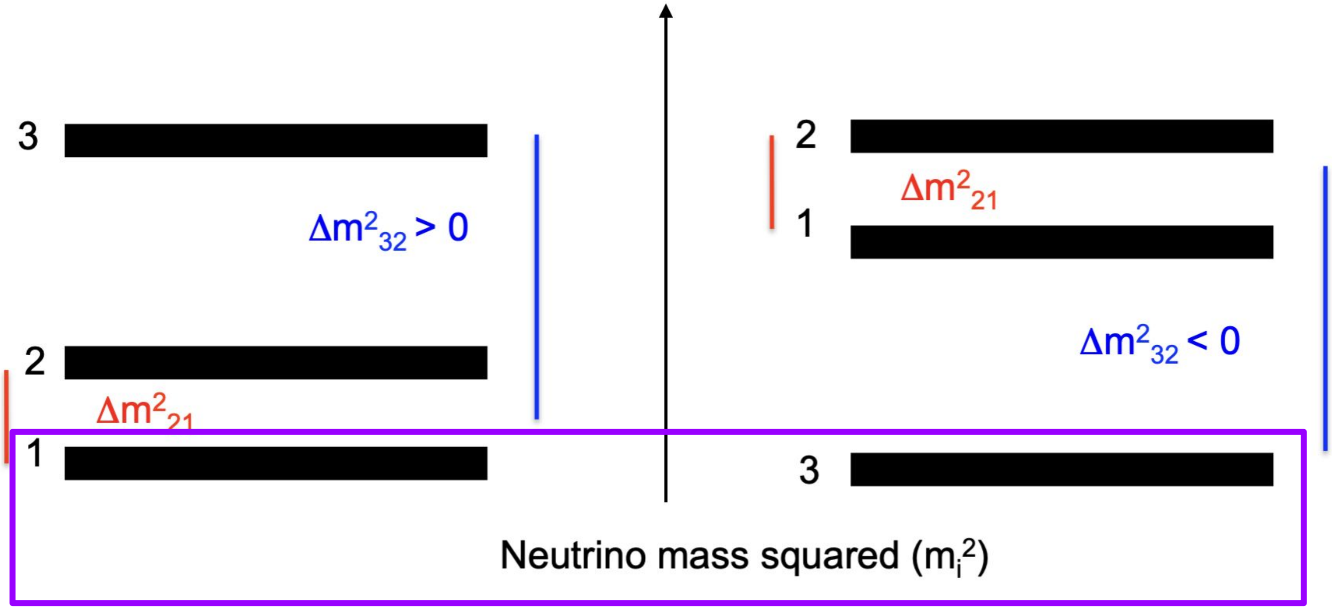
- $\Delta m^2_{21}$ ~$10^{-5}$ $\mathrm{eV}^2$
- $\Delta m^2_{32}$ ~$10^{-3}$ $\mathrm{eV}^2$ - **open question!** *Is $\Delta m^2_{32} > 0$ (normal mass ordering) or $< 0$ (inverted MO, or 'hierarchy')*

# Mass splitting and mass ordering



$$\begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Mass states

Three masses means two independent mass splittings ( $\Delta m^2_{ij} = m^2_i - m^2_j$ )

- $\Delta m^2_{21}$ ~$10^{-5}$ $eV^2$ - *known to be positive from solar neutrino experiments*
- $\Delta m^2_{32}$ ~$10^{-3}$ $eV^2$ - *normal or inverted?*
- **Open question:** What's the absolute mass scale?

# Measuring absolute neutrino mass - KATRIN example

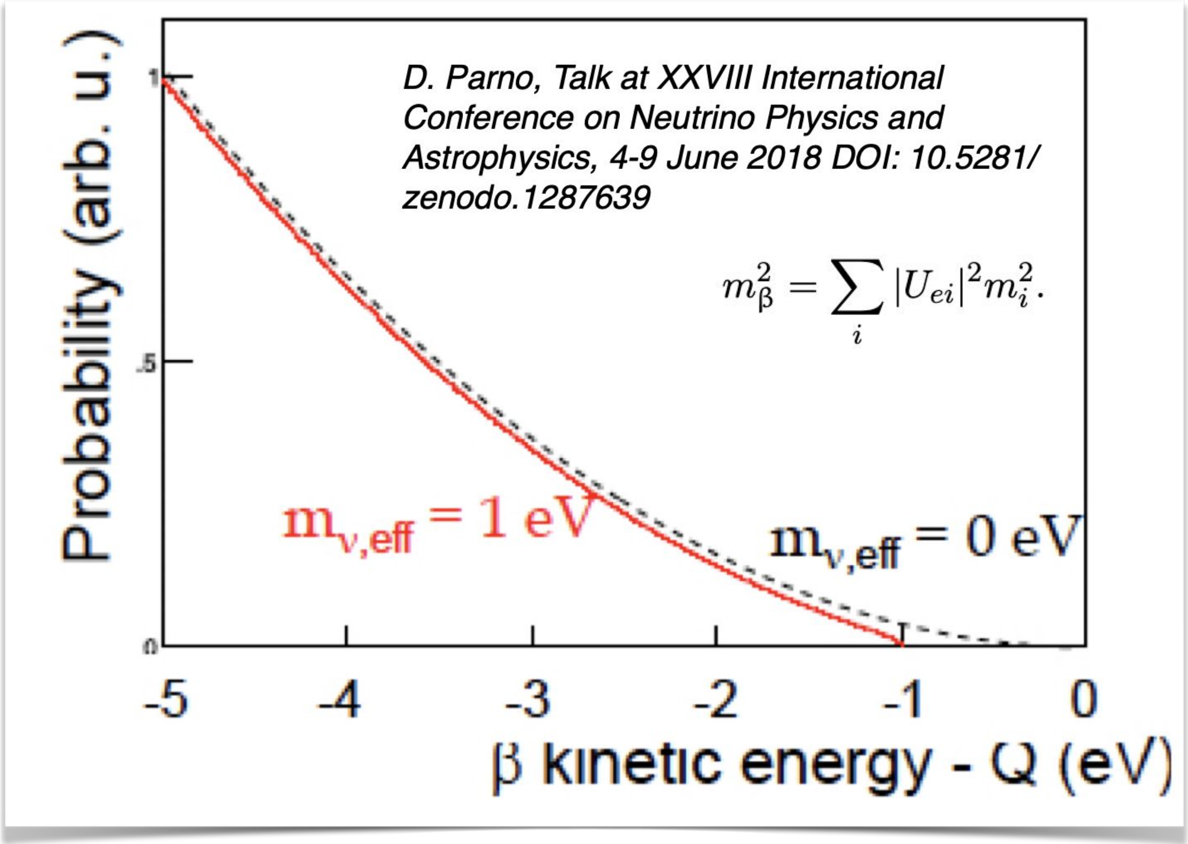
KATRIN

Karlsruhe Tritium Neutrino Experiment

1. Tritium source decays
2. Electrons are channeled to a high resolution spectrometer
3. Measure endpoint energy for neutrino mass

phys.org

# Measuring absolute neutrino mass - KATRIN example



*D. Parno, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI: 10.5281/zenodo.1287639*

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2 .$$

1. Tritium source decays
2. Electrons are channeled to a high resolution spectrometer
3. Measure endpoint energy for neutrino mass

# Measuring absolute neutrino mass - *now and future*

Latest KATRIN result - $m_\nu < 0.45$ eV (90% C.L.)

Other techniques - *see Snowmass topical group on neutrino properties*, *NSAC report*

- Cyclotron radiation tritium spectrometer - Project 8 - *R&D, toward 40meV scale*
- Holmium experiments - ECHo and HOLMES - *R&D toward sub eV scale*
    - *Decay of $^{163}$Ho, $\nu$ mass inferred from de-excitation energy (temperature or calorimetry)*

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Complementarity with astrophysics:

- Neutrino mass inferred from time of flight of supernova bursts
- Sum of neutrino mass probed with CMB, dark energy experiments:
  - DESI results - sum of neutrino masses < 0.072
  - Normal ordering implies sum of neutrino masses $\geqq$ 0.059 eV
  - Some tension with inverted ordering (sum of nu mass $\geqq$ 0.10 eV)
- Search for Cosmic Neutrino Background neutrinos - PTOLEMY

# Back to oscillation

$$\begin{bmatrix} \nu_{\mathrm{e}} \\ \nu_{\mu} \\ \nu_{\tau} \end{bmatrix} = \begin{bmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

*Alternative way to show U uses cos $\theta_{ij}$ = c and sin $\theta_{ij}$ = s*

# Back to oscillation

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*Alternative way to show U uses cos $\theta_{ij}$ = c and sin $\theta_{ij}$ = s*

If Majorana, there are two extra phases

# Back to oscillation

But, phases cancel in oscillation probabilities - *alternate probe of Dirac/Majorana?*

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\boxed{\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]}\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) + 2\sum_{i>j} \mathrm{Im}\boxed{\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]}\sin\left(\frac{2.54\Delta m^2_{ij}L}{E}\right)$$

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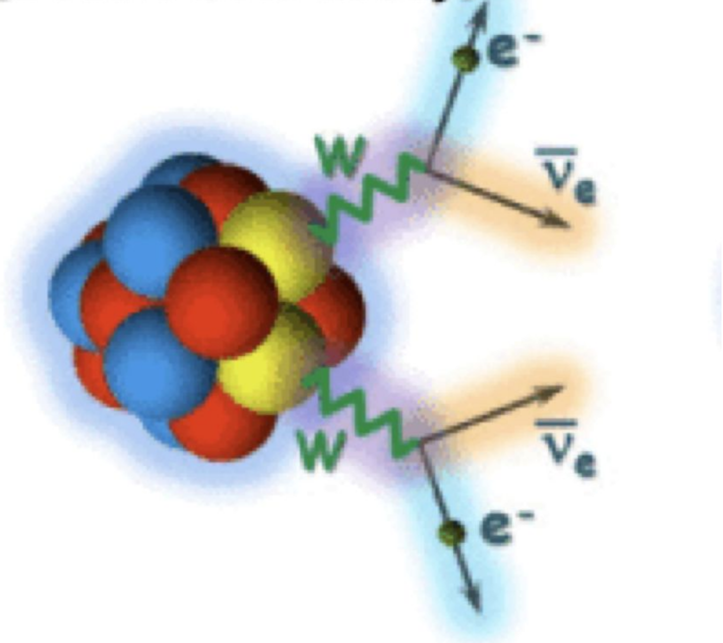
*Alternative way to show U uses cos $\theta_{ij}$ = c and sin $\theta_{ij}$ = s*

If Majorana, there are two extra phases

# Neutrinoless double beta decay and Majorana particles

[Double beta decay]

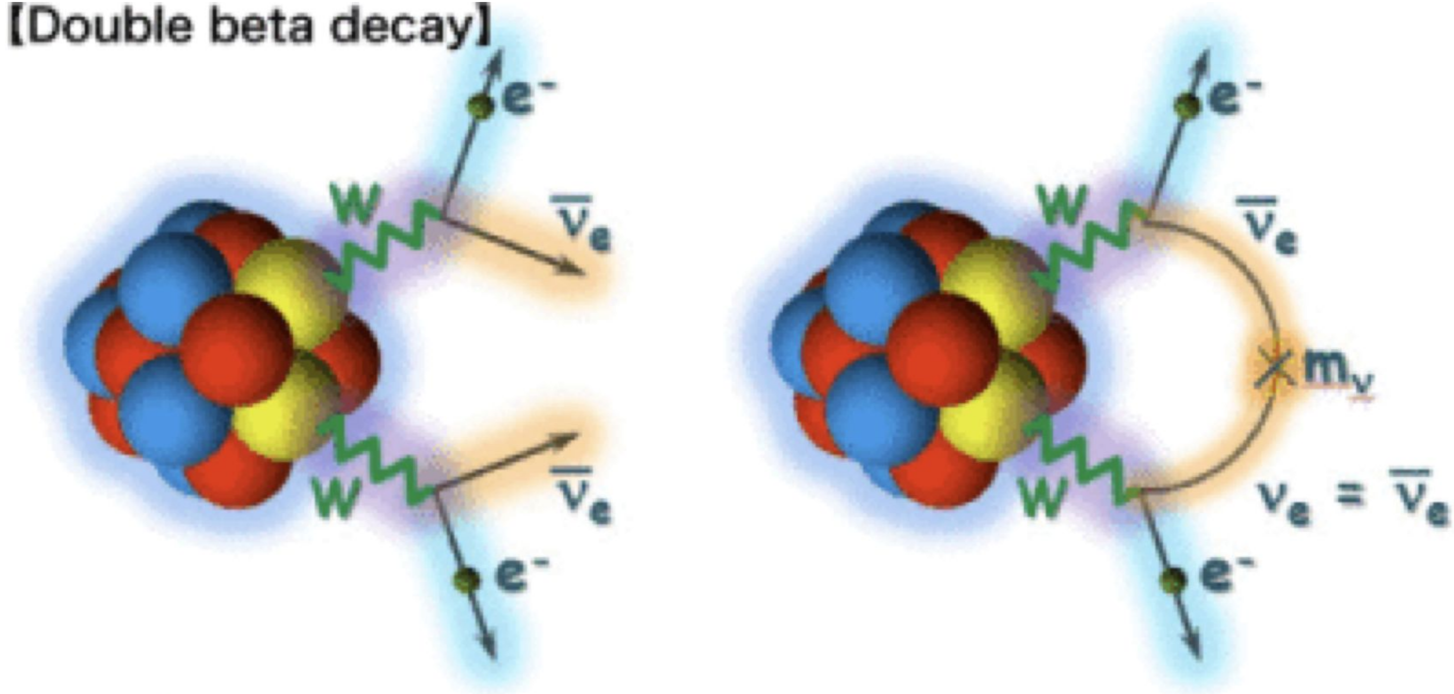


Double beta decay
which emits anti-neutrinos

Beta decay: two neutrinos, two electrons emitted

*credit: CANDLES experiment*

# Neutrinoless double beta decay and Majorana particles



Double beta decay which emits anti-neutrinos

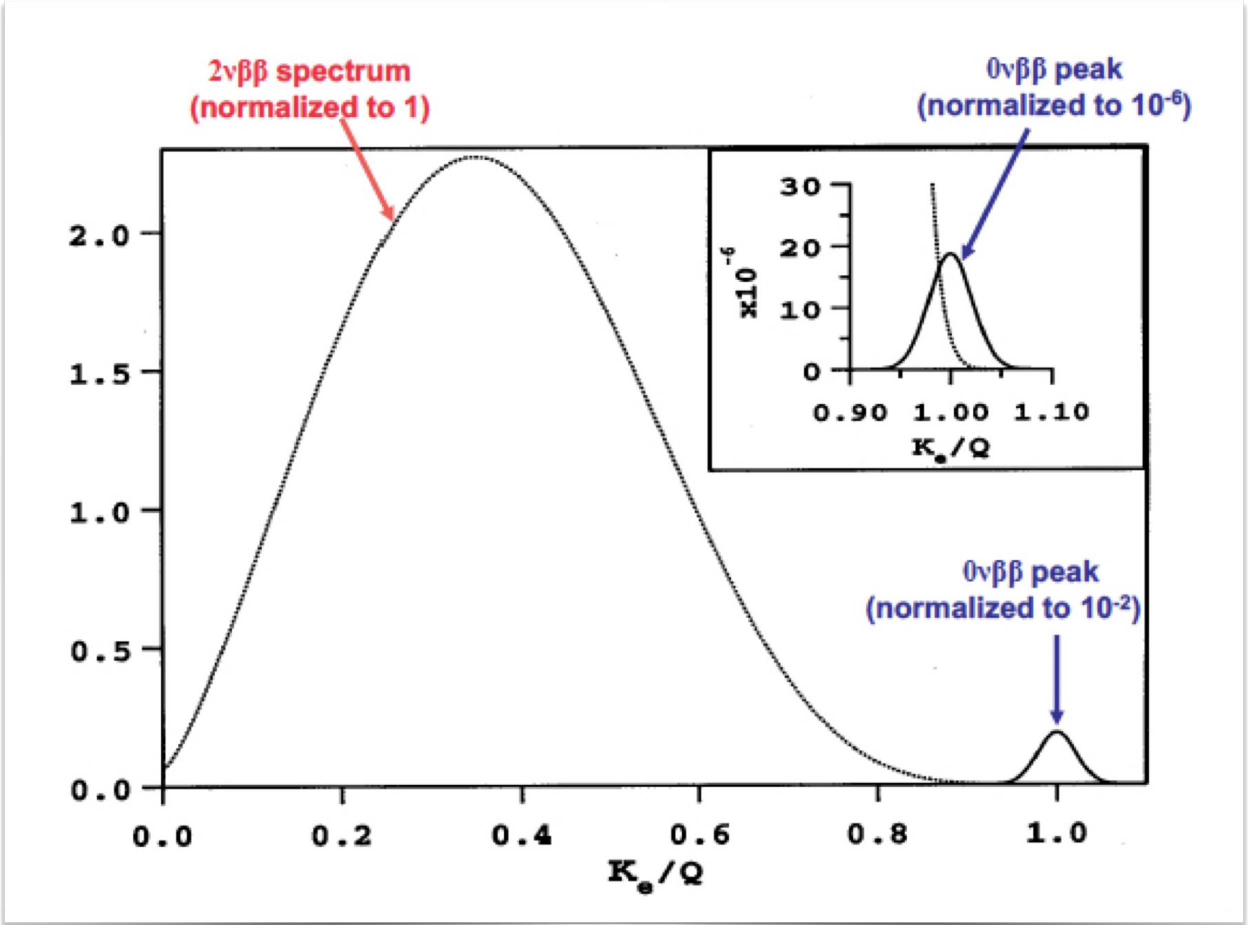
Neutrinoless double beta decay

*credit: CANDLES experiment*

Neutrinoless double beta decay - *only possible if neutrinos are Majorana particles*

# How do you measure $0\nu\beta\beta$ - *neutrinoless double beta decay*

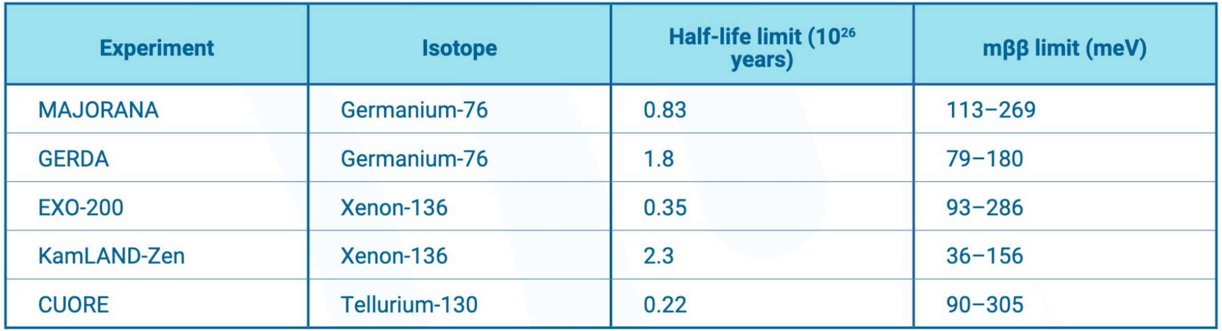
Look past the endpoint of $2\nu\beta\beta$ for the bump of $0\nu\beta\beta$



*credit: M. Dolinkski, INSS2017*

# How do you measure $0\nu\beta\beta$ - *neutrinoless double beta decay*

If you observe $0\nu\beta\beta$, you measure its half life, $T_{1/2}$



| Experiment | Isotope | Half-life limit ($10^{26}$ years) | mββ limit (meV) |
|---|---|---|---|
| MAJORANA | Germanium-76 | 0.83 | 113–269 |
| GERDA | Germanium-76 | 1.8 | 79–180 |
| EXO-200 | Xenon-136 | 0.35 | 93–286 |
| KamLAND-Zen | Xenon-136 | 2.3 | 36–156 |
| CUORE | Tellurium-130 | 0.22 | 90–305 |

*NSAC report*

Half life infers effective neutrino mass, $m\beta\beta$:

$$\langle m_{\beta\beta}\rangle^2 = |\textstyle\sum_i U_{ei}^2 \; m_{\nu i}|^2$$

Interpretation requires:

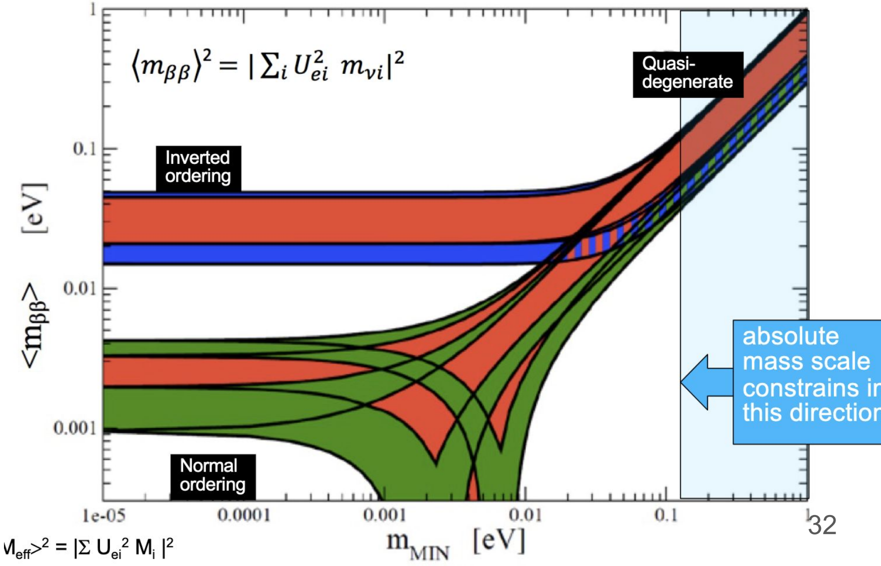
- Nuclear Theory: determine relevant nuclear matrix elements
- Oscillation experiments: U elements
- Experimental precision: large scale x exquisite control of backgrounds, radiopurity, and noise

# Current and future programs of $0\nu\beta\beta$

From: K. Scholberg Snowmass neutrino frontier summary

A complete picture of neutrinos can emerge with a combination of direct mass measurements, oscillation and $0\nu\beta\beta$ experiments:

- Future experiments plan to cover inverted ordering
- Allowed regions correspond to Majorana phases + oscillation matrix uncertainties



# Back to oscillation: three ‘sectors’

‘Atmospheric’
~100 km/GeV

‘Reactor’
~1 km/MeV

Solar
$10^{10}$ m / MeV

$$U = \boxed{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \cdot \boxed{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix}} \cdot \boxed{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \cdot$$

*Alternative way to show U uses cos $\theta_{ij}$ = c and sin $\theta_{ij}$ = s*

# Back to oscillation: three ‘sectors’

‘Atmospheric’
~100 km/GeV

‘Reactor’
~1 km/MeV

Solar
$10^{10}$ m / MeV

Accelerator - *predominantly atm, but sensitive to* $\delta_{CP}$

*And reactor experiments have been used to probe solar oscillation as well*

$$U = \boxed{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \cdot \boxed{\begin{pmatrix} c_{13} & 0 & s_{13}\boxed{e^{-i\delta_{\mathrm{CP}}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix}} \cdot \boxed{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \cdot$$

*Alternative way to show U uses cos* $\theta_{ij}$ *= c and sin* $\theta_{ij}$ *= s*

# Back to oscillation: three ‘sectors’ leads to simpler life

*Reminder: probability to oscillate from flavor* $\nu_\alpha$ to $\nu_\beta$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin^2\left(\frac{1.27\,\Delta m^2_{ij}L}{E}\right) + 2\sum_{i>j}\mathrm{Im}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin\left(\frac{2.54\,\Delta m^2_{ij}L}{E}\right)$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot$$

*Alternative way to show U uses cos* $\theta_{ij}$ *= c and sin* $\theta_{ij}$ *= s*

# Back to oscillation: three ‘sectors’ leads to simpler life

$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\,\Delta m^2_{32} L}{E}\right) + \ldots$$

$\Delta m^2{}_{32} >> \Delta m^2{}_{21}$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}\right] \sin^2\left(\frac{1.27\,\Delta m^2_{ij} L}{E}\right) + 2\sum_{i>j} \mathrm{Im}\left[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}\right] \sin\left(\frac{2.54\,\Delta m^2_{ij} L}{E}\right)$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot$$

*Alternative way to show U uses cos $\theta_{ij}$ = c and sin $\theta_{ij}$ = s*

# Back to oscillation: three ‘sectors’ leads to simpler life

$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 \boxed{2\theta_{23}} \sin^2\left(\frac{1.27\boxed{\Delta m^2_{32}}L}{E}\right) + \ldots$$

“$\nu_\mu$ disappearance” now is “just”* a function of $\Delta m^2_{32}$ and $\theta_{23}$ parameters - *only one sector*

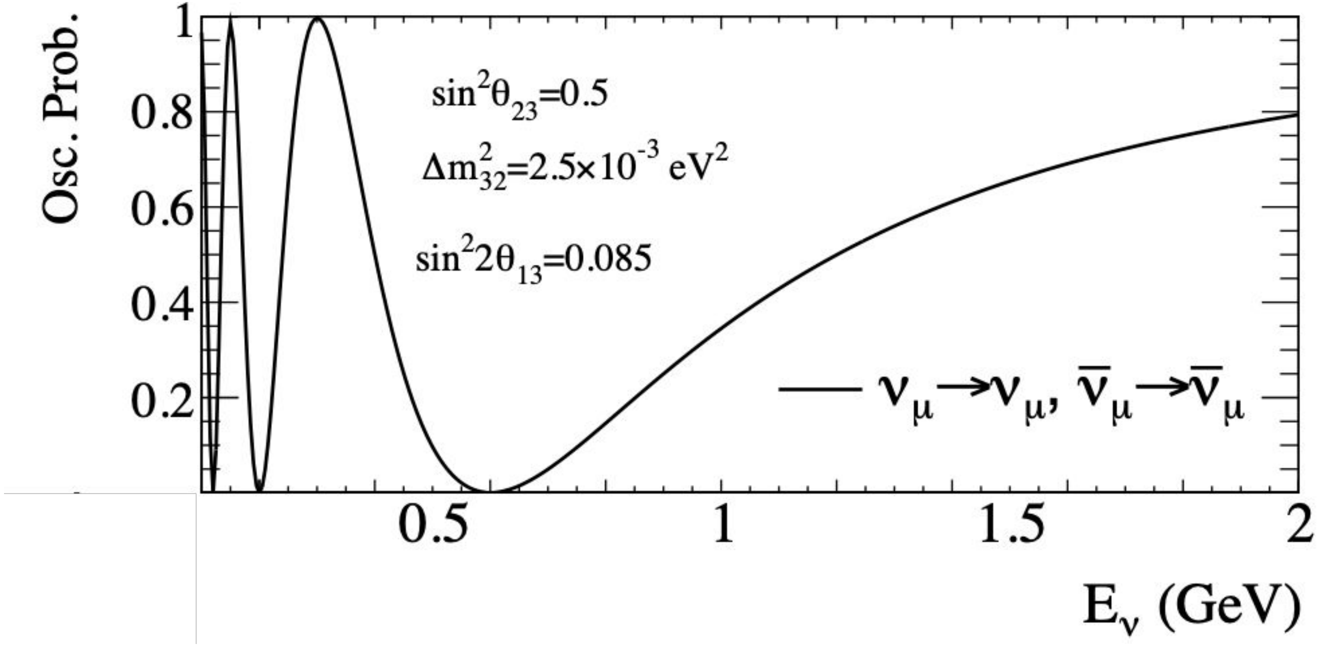
$$U = \boxed{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \cdot$$

**subleading terms, experiments consider the full oscillation probability*

# Back to oscillation: muon neutrino disappearance

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\,\Delta m^2_{32} L}{E}\right) + \ldots$$

"$\nu_\mu$ disappearance", for fixed L=295km vs. E:



# Back to oscillation: muon neutrino disappearance

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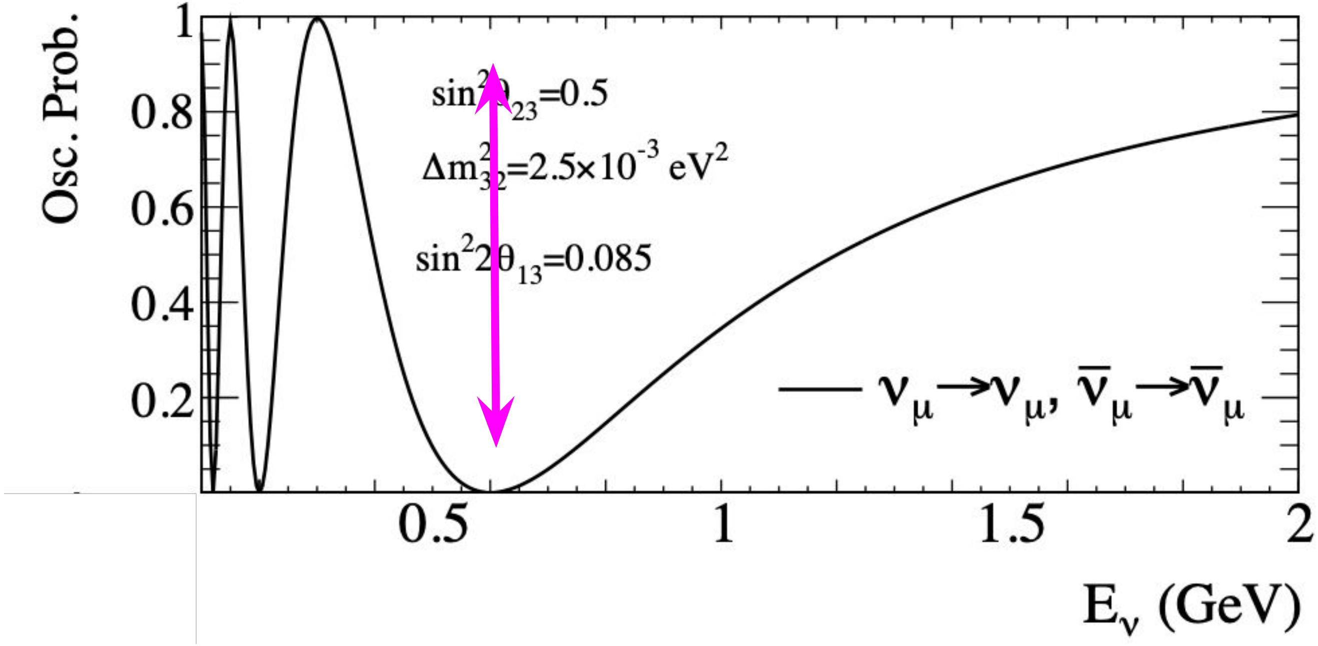

**Amplitude** given by $\sin^2(2\theta_{23})$

# Back to oscillation: muon neutrino disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\,\Delta m^2_{32} L}{E}\right) + \ldots$$

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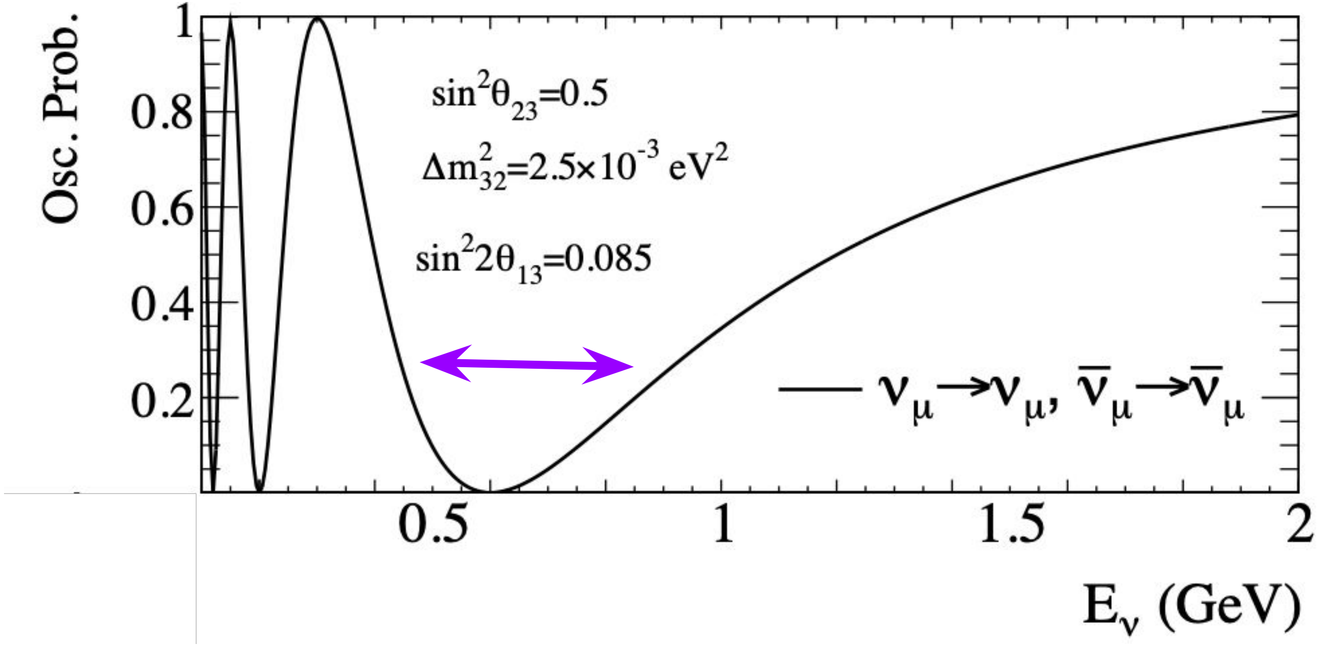
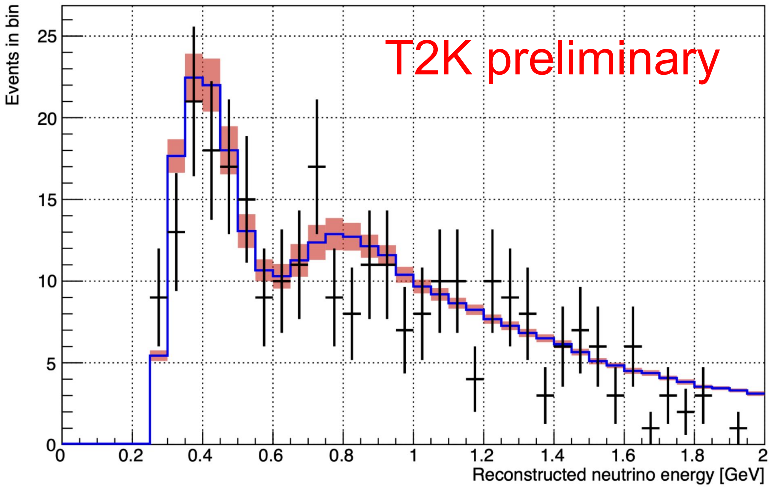
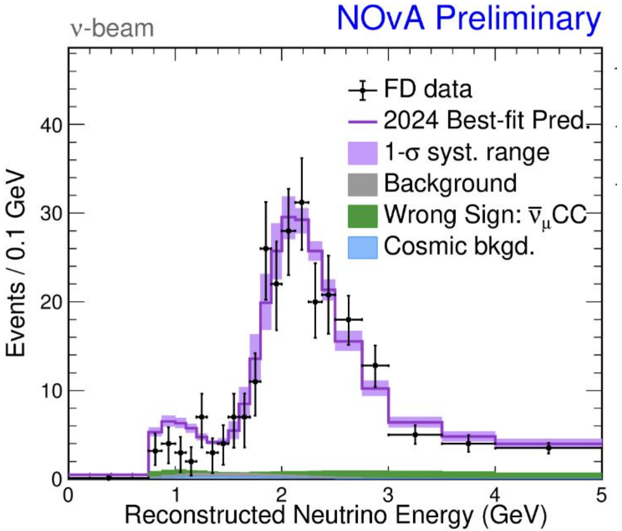


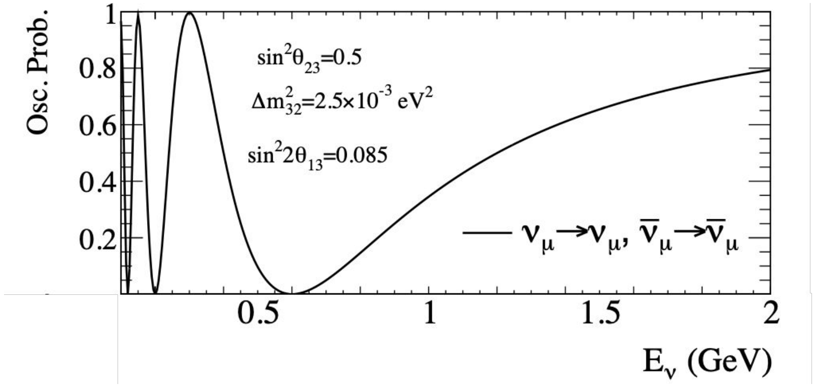
Amplitude given by $\sin^2(2\theta_{23})$

**Frequency** given by $\Delta m^2_{32}$

# Back to oscillation: muon neutrino disappearance



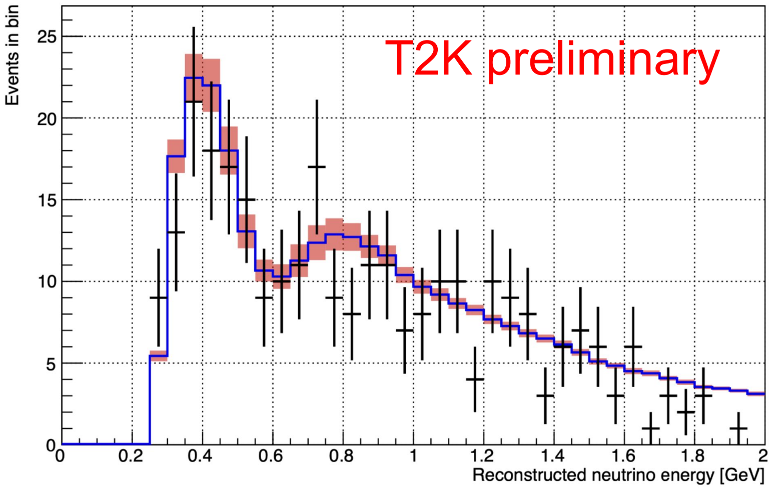


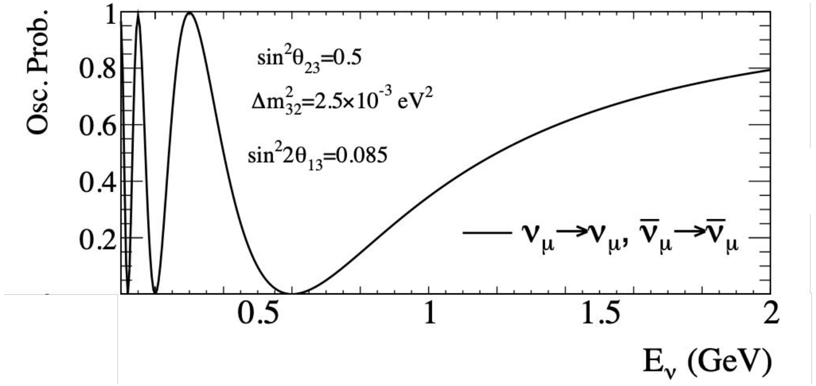


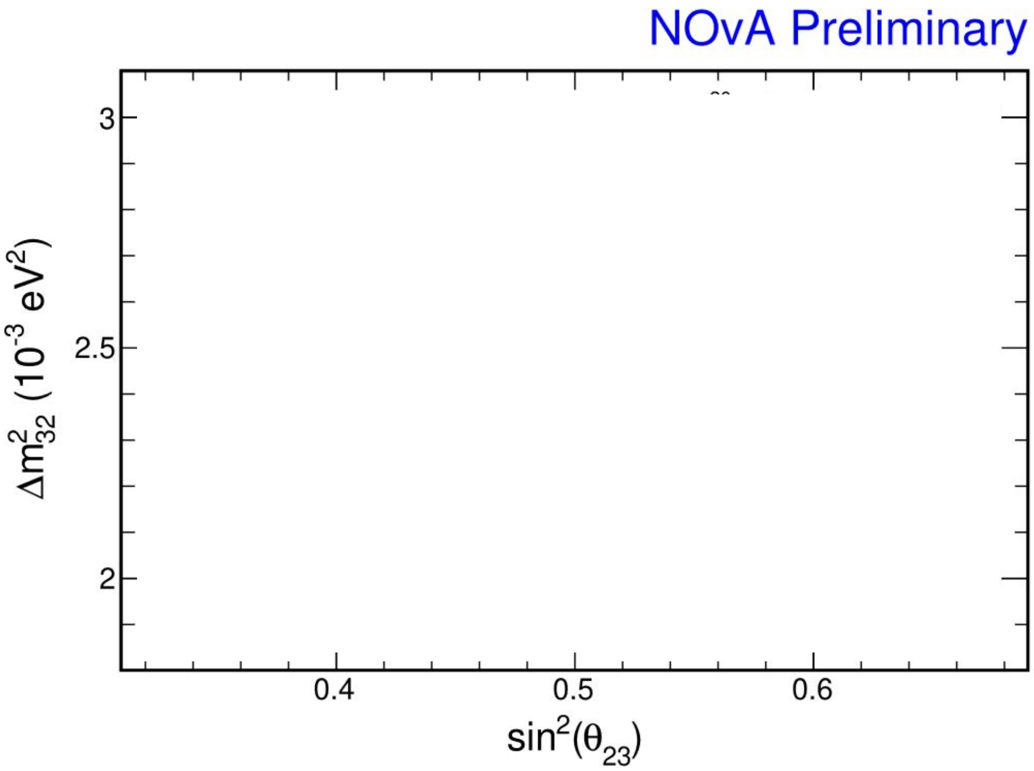
Now, adding realistic backgrounds, energy estimator, flux and cross section

Examples from Tokai-to-Kamioka and NOvA - *current accelerator based experiments from Neutrino2024*

# Back to oscillation: muon neutrino disappearance

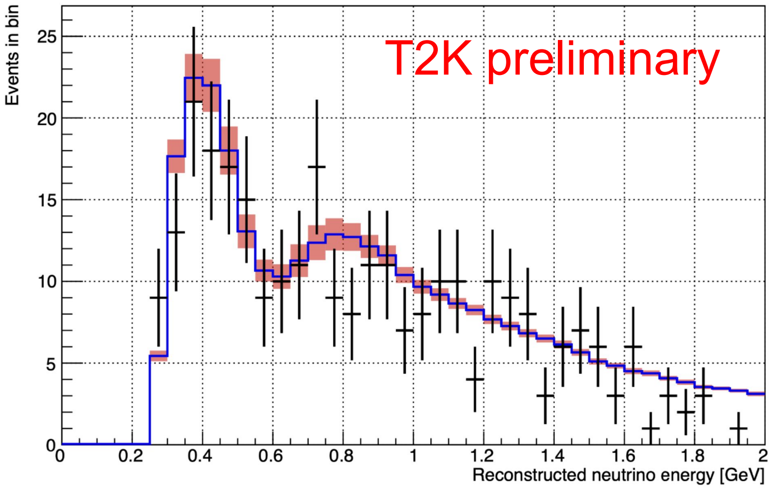


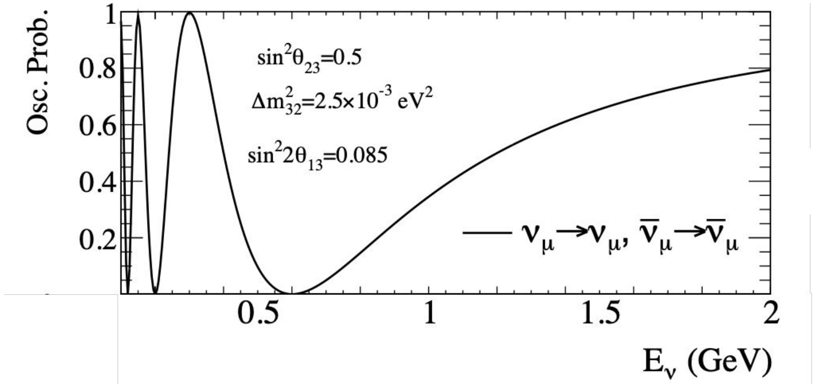


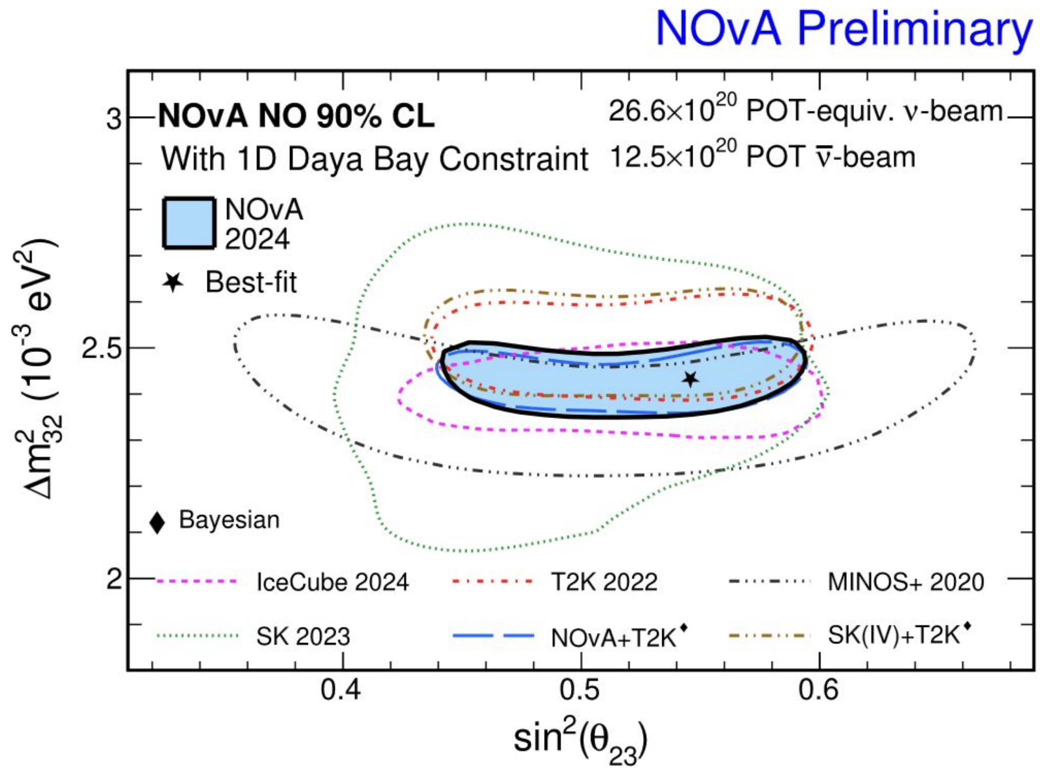


Data provides closed contour constraints on $\Delta m^2_{32}$ and $\sin^2(\theta_{23})$

# Back to oscillation: muon neutrino disappearance







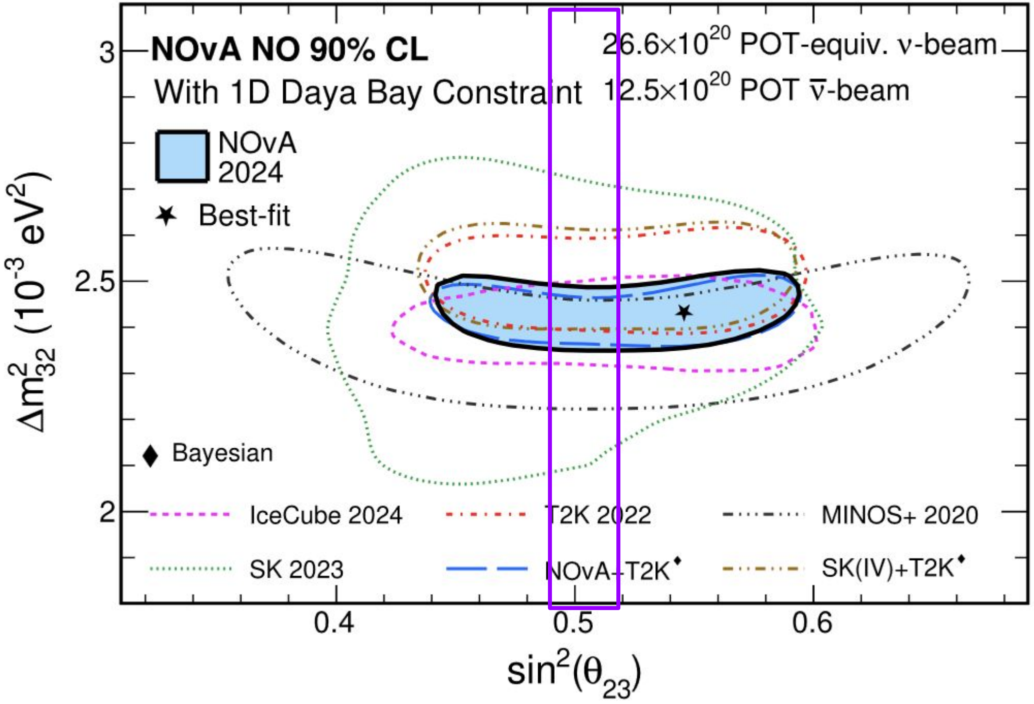
Data provides closed contour constraints on $\Delta m^2_{32}$ and $\sin^2(\theta_{23})$

# Why is muon neutrino disappearance interesting?

Open question: Is $\nu_3$ mostly $\nu_\mu$ or $\nu_\tau$?

- Balance set by $\theta_{23}$
- $\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$? - “octant”
- If maximal, then implies an underlying symmetry in U
- Can also test CPT by comparing neutrino to antineutrino disappearance

NOvA Preliminary



# Back to oscillation: muon neutrino disappearance

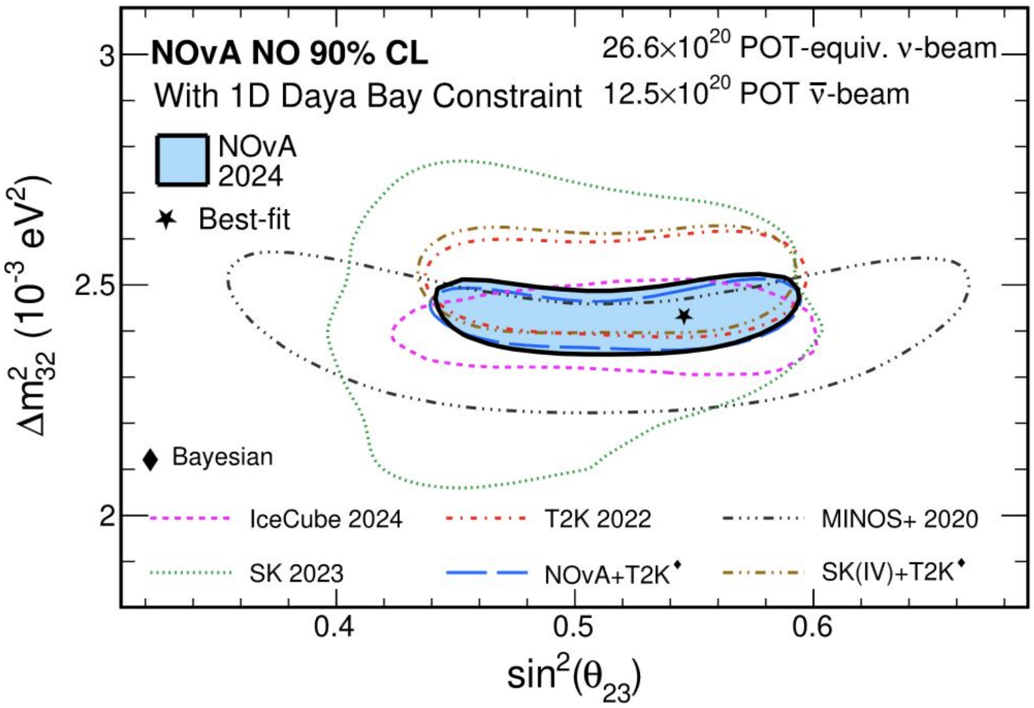
Open question: Is $\nu_3$ mostly $\nu_\mu$ or $\nu_\tau$?

- Balance set by $\theta_{23}$
- $\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$? - "octant"
- If maximal, then implies an underlying symmetry in U

Current data: mild preference for upper octant, still consistent with maximal mixing

Future program (DUNE, Hyper-Kamiokande) programs can determine octant

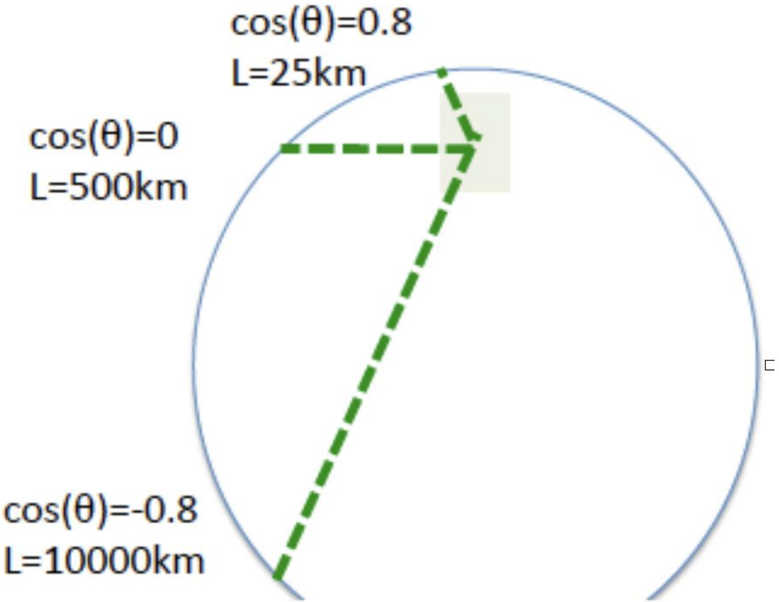
NOvA Preliminary



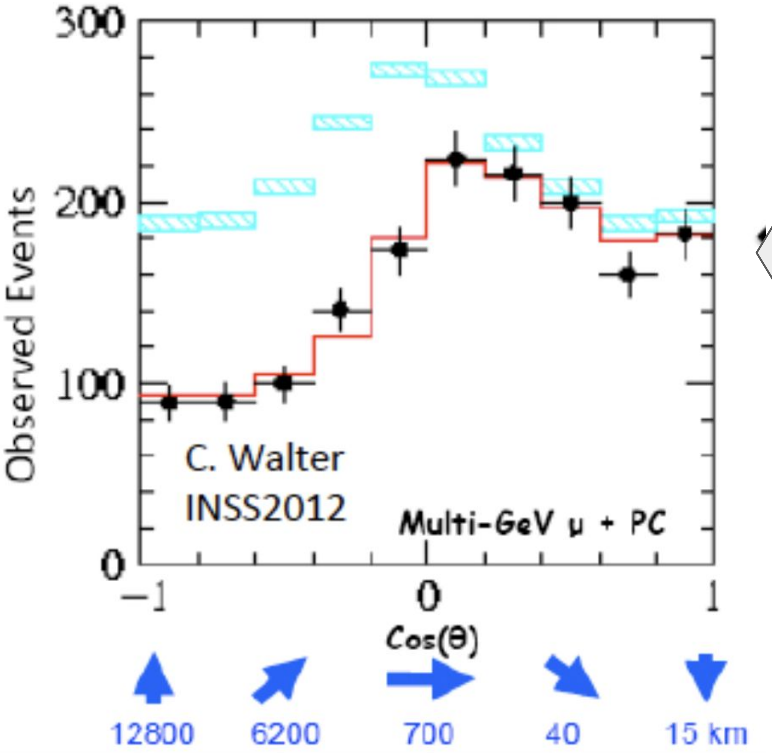
# Muon neutrino disappearance: atmospherics

Global data picture also includes atmospheric experiments (IceCube, Super-Kamiokande) and MINOS (previous era accelerator based experiment)

Atmospheric experiments use **changing L**, fixed E

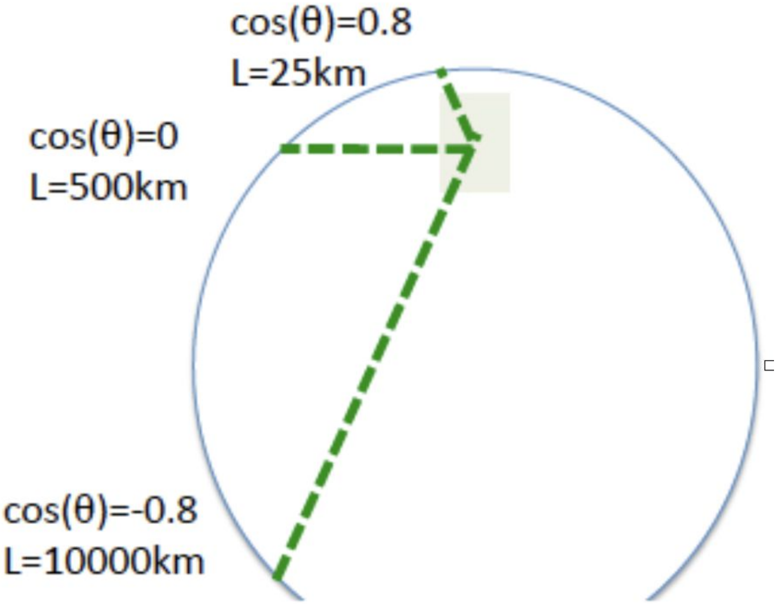


# Muon neutrino disappearance: atmospherics



C. Walter
INSS2012

Atmospheric experiments use **changing L**, fixed E



# What about appearance?

Most of the $\nu_\mu$ disappear into $\nu_\tau$, but a small fraction transition to $\nu_e$:

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{32}} \ll 1$$

$$\Delta = \frac{\Delta m^2_{32} L}{4E_\nu}$$

$$A = 2\sqrt{2} G_F N_e \frac{E_\nu}{\Delta m^2_{32}}$$

$$\begin{aligned}
P_{\nu_\mu \to \nu_e} = & \frac{1}{(A-1)^2} \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2[(A-1)\Delta] \\
& -(+)\frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times \\
& \sin\delta_{CP} \sin\Delta \sin A\Delta \sin[(1-A)\Delta] \\
& +\frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times \\
& \cos\delta_{CP} \cos\Delta \sin A\Delta \sin[(1-A)\Delta] \\
& +\frac{\alpha^2}{A^2} \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2 A\Delta
\end{aligned}$$

Approximation from M. Freund, PRD 64, 053003 -
*if you use my formula, doublecheck the subscripts…*

# Key features of appearance channels

Sign of sin($\delta_{CP}$) term switches for neutrinos and antineutrinos

*Comparison of neutrino to antineutrino oscillation tests CP violation in neutrino sector*

$$\begin{aligned}
P_{\nu_\mu\to\nu_e} = & \frac{1}{(A-1)^2}\sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2[(A-1)\Delta] \\
& -(+)\frac{\alpha}{A(1-A)}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\times \\
& \sin\delta_{CP}\sin\Delta\sin A\Delta\sin[(1-A)\Delta] \\
& +\frac{\alpha}{A(1-A)}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\times \\
& \cos\delta_{CP}\cos\Delta\sin A\Delta\sin[(1-A)\Delta] \\
& +\frac{\alpha^2}{A^2}\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2 A\Delta
\end{aligned}$$

Approximation from M. Freund, PRD 64, 053003 -
*if you use my formula, doublecheck the subscripts…*

# Key features of appearance channels

Sensitive to all oscillation parameters at once, and sensitive to the octant directly ($\sin^2(\theta_{23})$ terms)

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} = & \frac{1}{(A-1)^2} \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2[(A-1)\Delta] \\
& -(+)\frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times \\
& \sin\delta_{CP} \sin\Delta \sin A\Delta \sin[(1-A)\Delta] \\
& +\frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times \\
& \cos\delta_{CP} \cos\Delta \sin A\Delta \sin[(1-A)\Delta] \\
& +\frac{\alpha^2}{A^2} \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2 A\Delta
\end{aligned}
$$

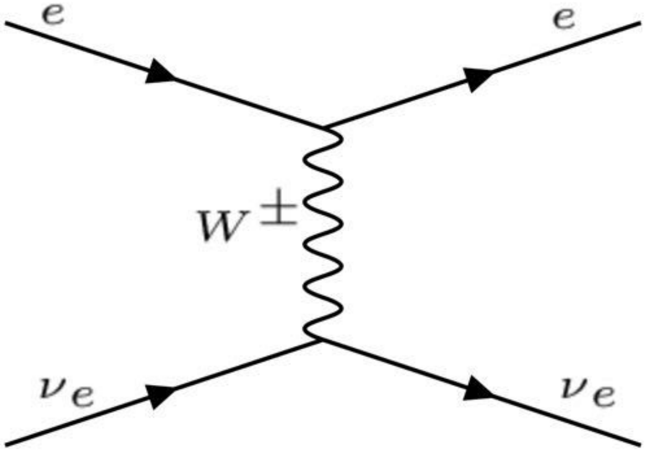
Approximation from M. Freund, PRD 64, 053003 -
*if you use my formula, doublecheck the subscripts…*

# Key features of appearance channels - matter effects

Sensitive to sign of $\Delta m^2_{32}$ - *mass ordering through "matter effects", A terms:*

$$A = 2\sqrt{2} G_F N_e \frac{E_\nu}{\Delta m^2_{32}}$$

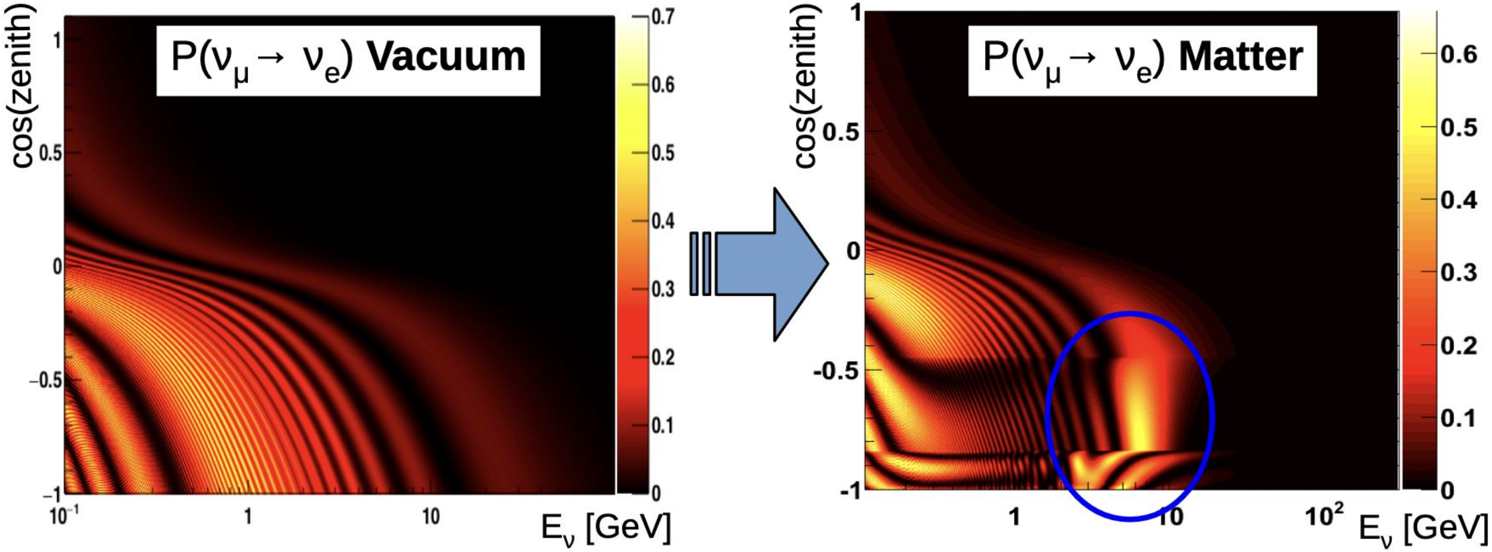
$\nu_e$ interact in matter with an extra CC interaction ($\nu_e$ - e scattering) *- doesn't happen for* $\nu_\mu$, $\nu_\tau$



# Key features of appearance channels - matter effects

Matter effects manifest differently for atmospheric neutrinos

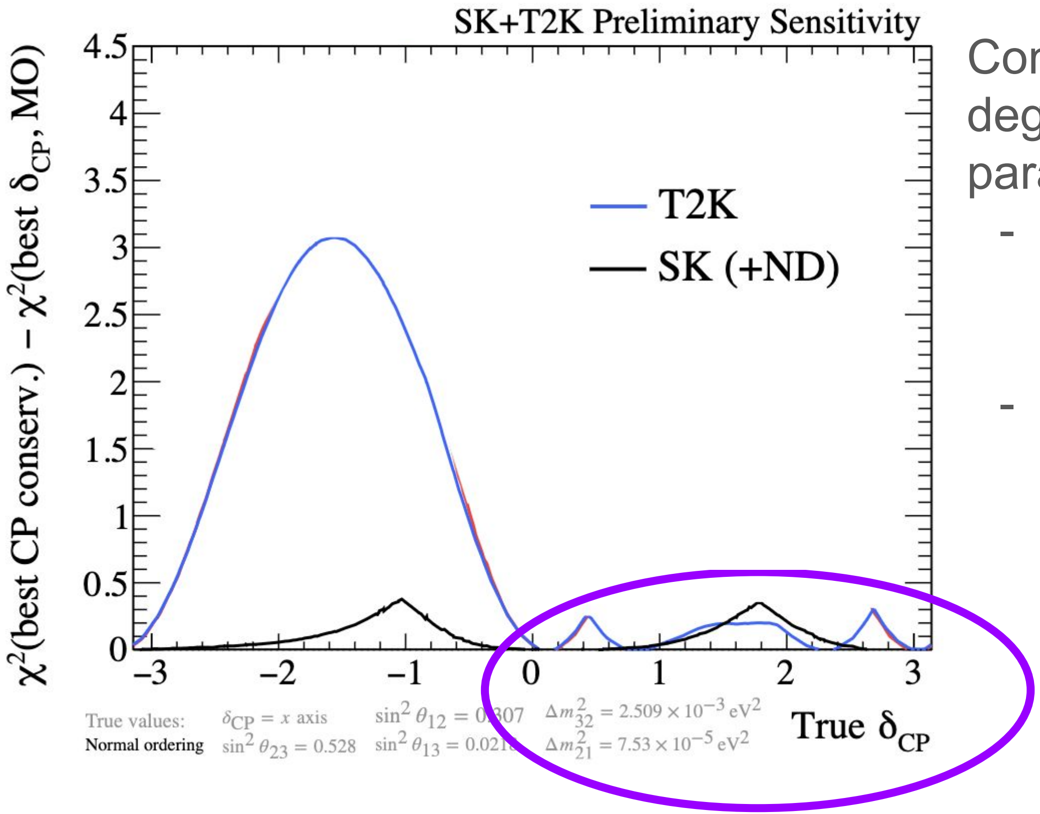
[C. Bronner, PANE2018]



Presence of a resonance driven by $\theta_{13}$ induced matter effects between 2 and 10 GeV

- Only for $\nu$ in NH and $\bar{\nu}$ in IH → sensitivity to the mass hierarchy
- Size of the effect depends on $\sin^2(\theta_{23})$ → sensitive to $\theta_{23}$ octant

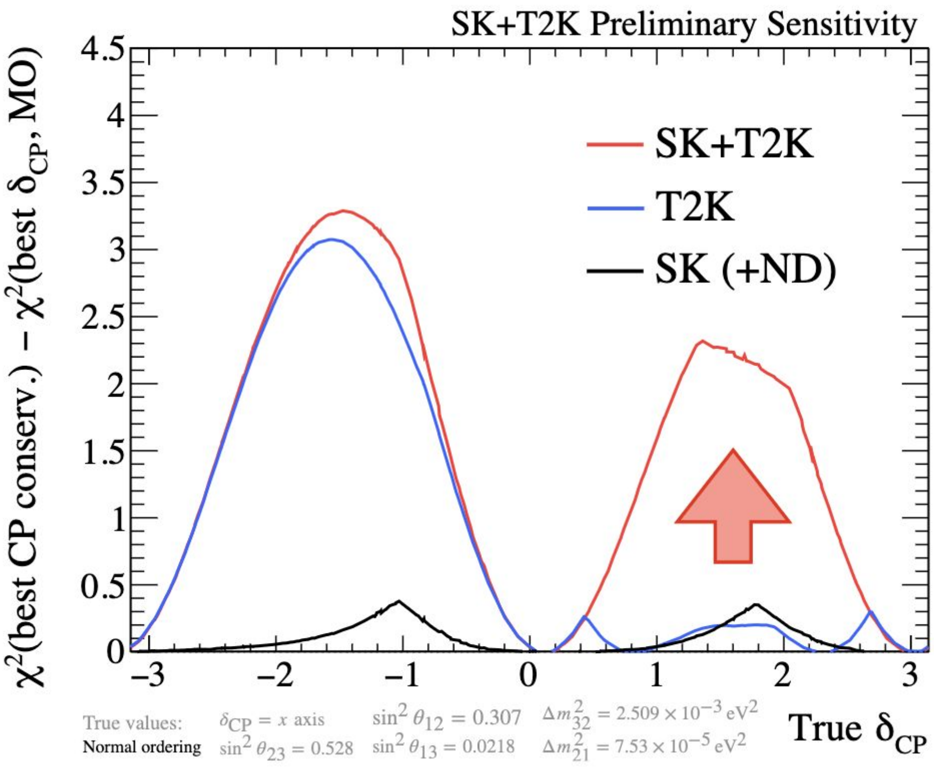
# Disentangling neutrino oscillation through combinations



Combinations of experiments resolve degeneracies between unknown parameters

- Experiments have different L, E different oscillation probabilities break degeneracies
- Example: **degeneracy with mass ordering** results in poor sensitivity to $\delta_{CP}$ for T2K and SK alone

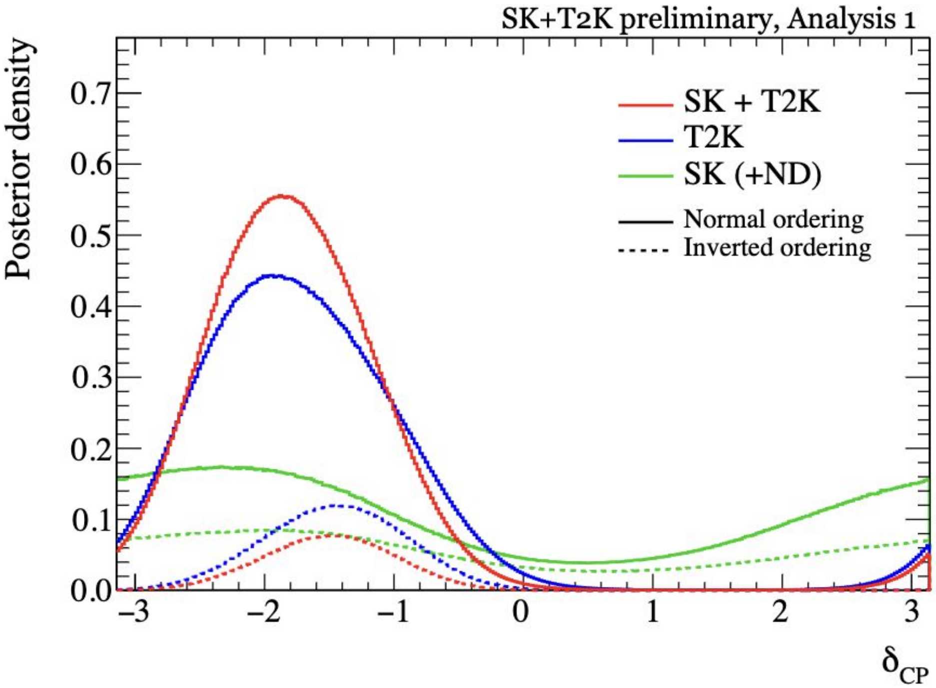
# Disentangling neutrino oscillation through combinations



Combinations of experiments resolve degeneracies between unknown parameters

- Experiments have different L, E different oscillation probabilities break degeneracies
- Example: degeneracy with mass ordering results in poor sensitivity to $\delta_{CP}$ for T2K and SK alone
- **Together, sensitivity to $\delta_{CP}$** through information about mass ordering

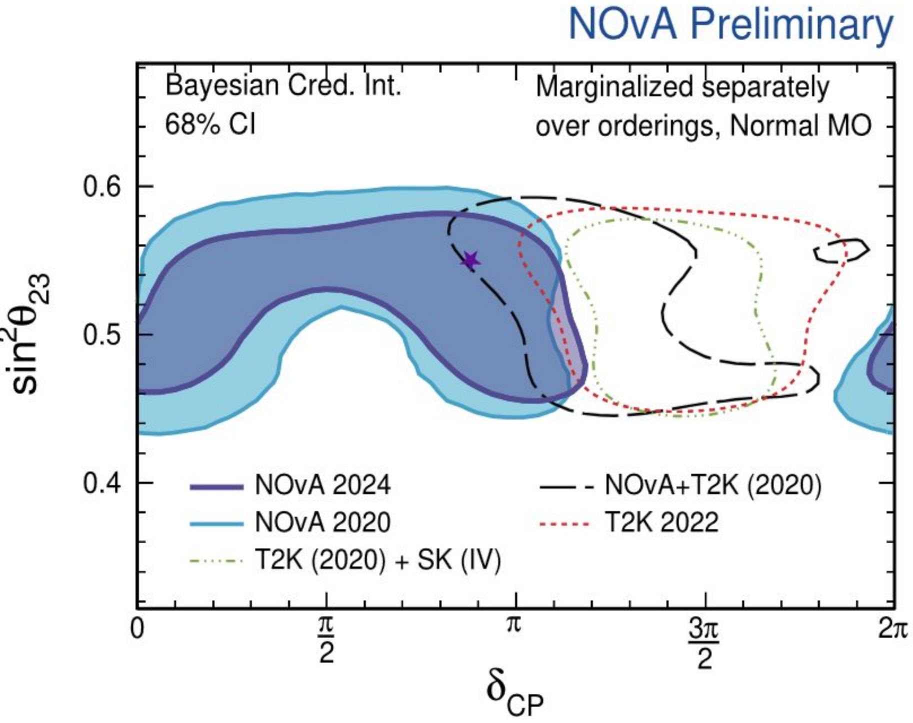
# Current status of CPV, mass ordering

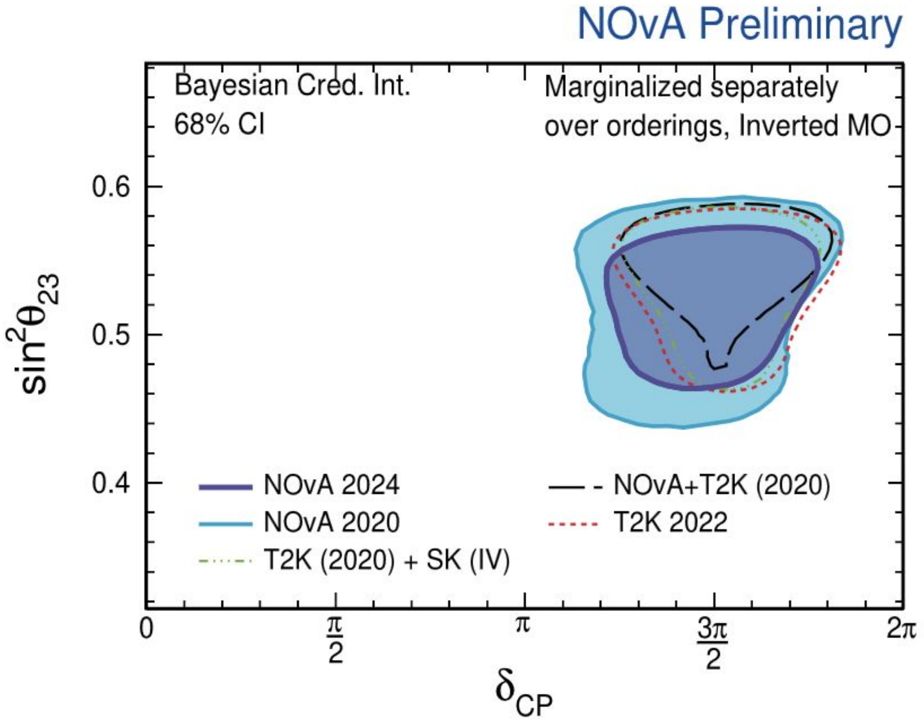


Combined SK+T2K results favor maximum CPV, consistent with T2K

- Weak preference for normal mass ordering MO (Bayes factor is ~9.0, 1.6$\sigma$)

# Current status of CPV, mass ordering

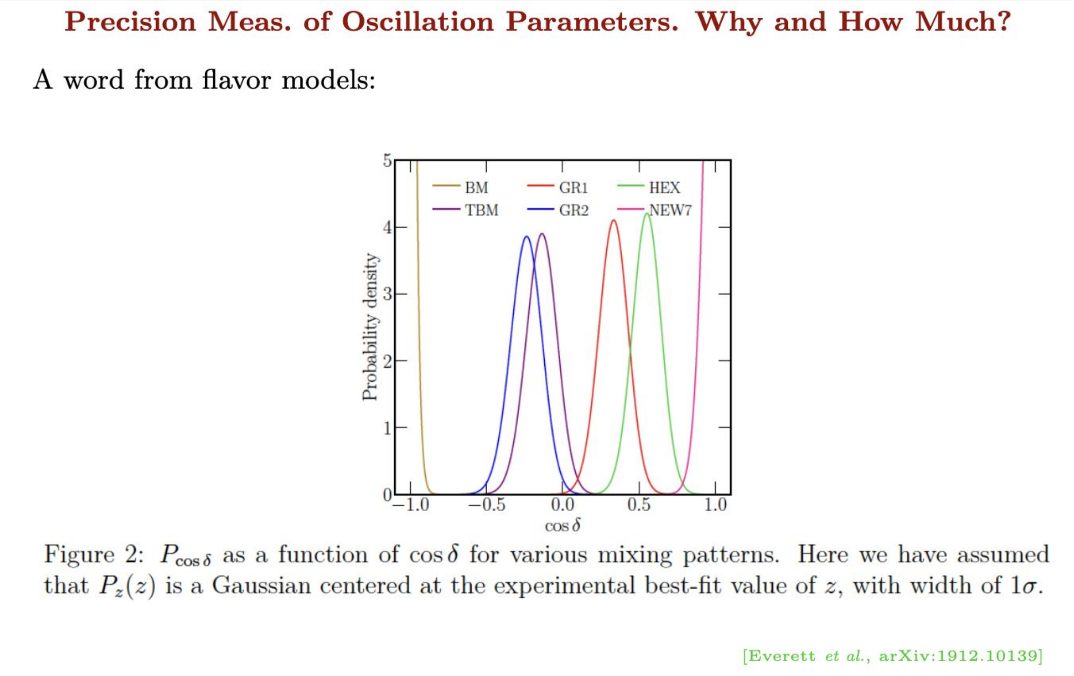




However, NOvA favors different parameter space assuming normal ordering

- Also, weak preference for normal mass ordering MO (frequentist, also 1.6$\sigma$, 87% when Daya Bay reactor constraint is used)

# A word on CPV



**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 $1\sigma$.

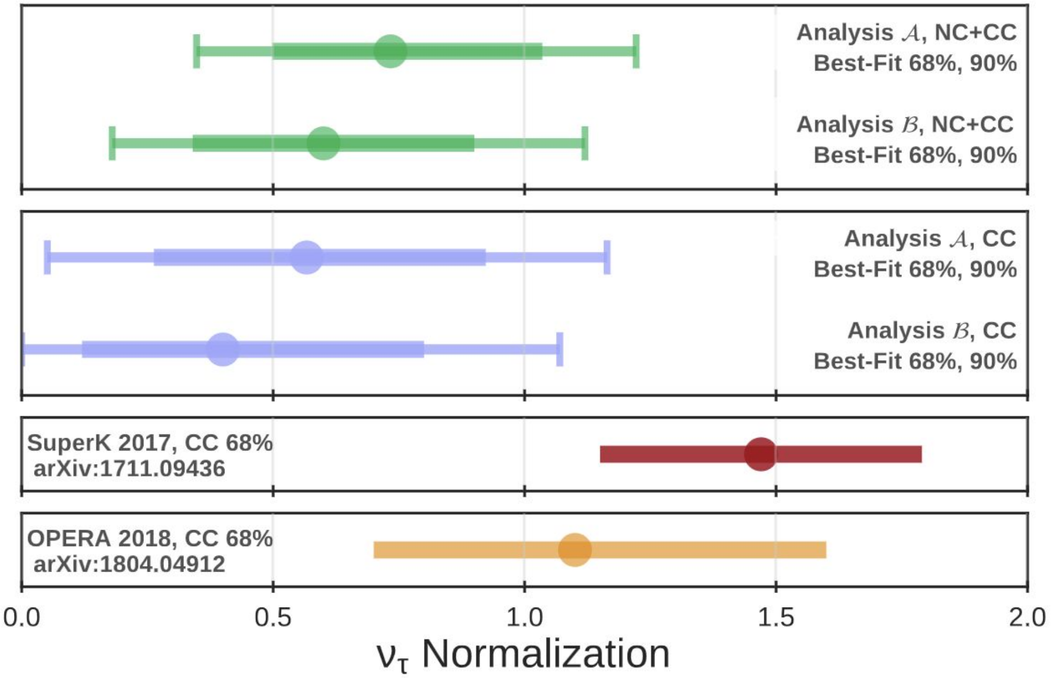
[Everett *et al.*, arXiv:1912.10139]

Precision depends on:

1. Sufficient ability to resolve a param of interest ($\delta_{CP}$ =0?) and distinguish models
2. André de Govêa - “*Ultimate Goal:* Not Measure Parameters but Test the Formalism (*Over-Constrain Parameter Space)*” Snowmass Neutrino Colloquium

Important feature of future (DUNE and HK) program - *diversity and redundancy to get at the same physics robustly*

# More appearance: taus!



IceCube, SK search for $\nu_\tau$ - consistent with standard model oscillation

- Complementary to a dedicated beam experiment (OPERA), DUNE will have tau appearance capability from the beam as well
- Recent workshop write up on all things tau (NuTau2021)

# Back to oscillation: now to reactor results

‘Atmospheric’
~100 km/GeV

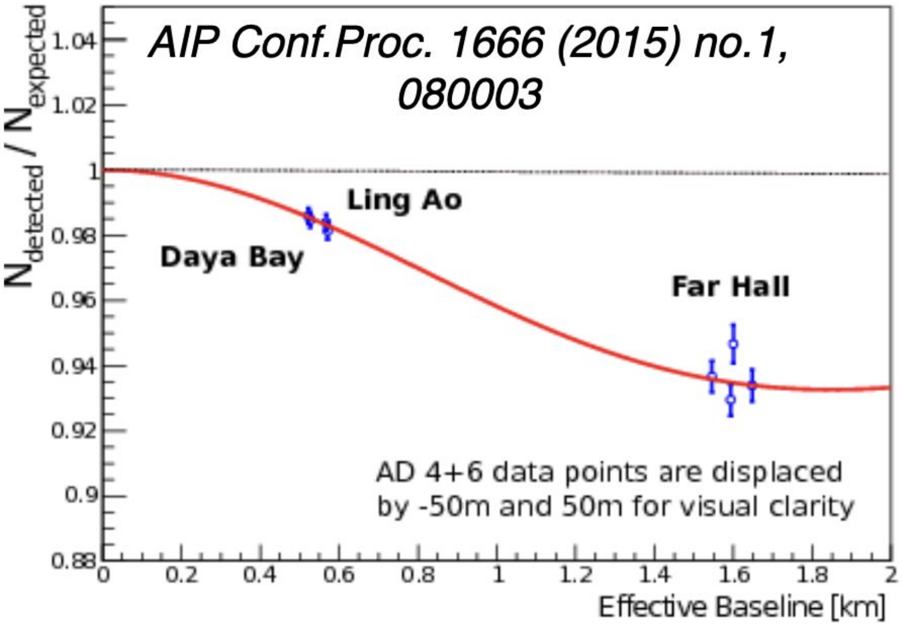
‘Reactor’
~1 km/MeV

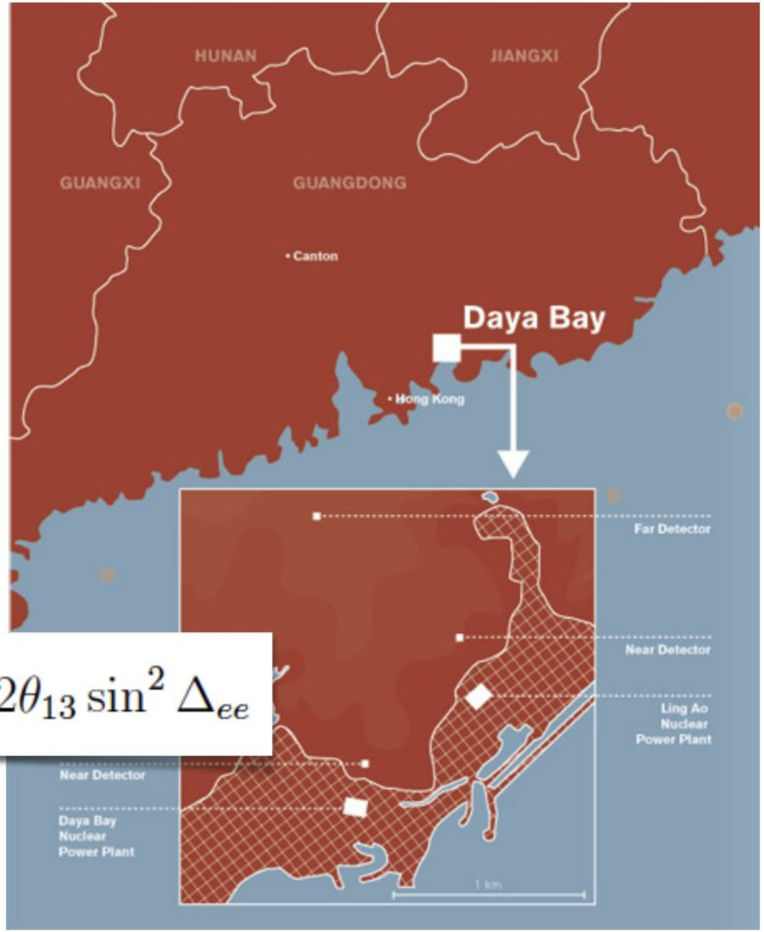
Solar
$10^{10}$ m / MeV

Reactors have provided key measurements of $\theta_{13}$, which were included in the previous results shown - *degeneracy breaking precision*

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \boxed{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix}} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot$$

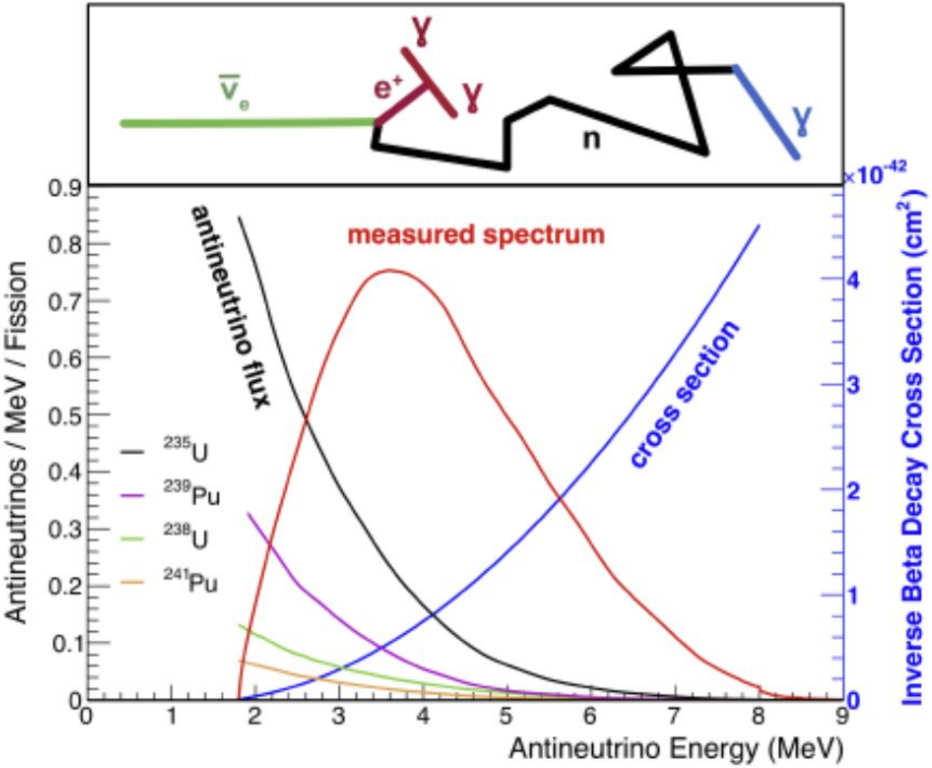
# Example: Daya Bay experiment

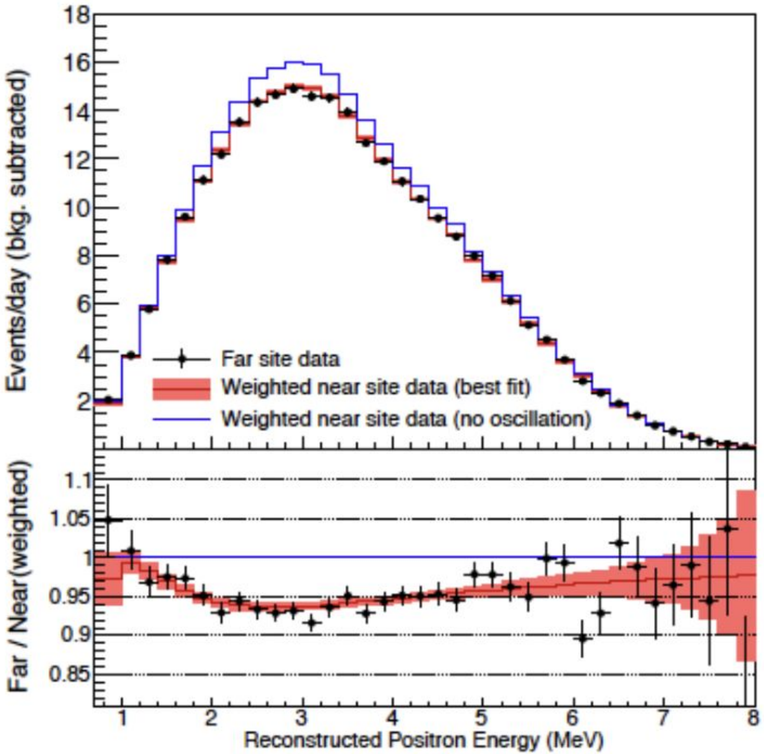

AIP Conf.Proc. 1666 (2015) no.1, 080003



$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$

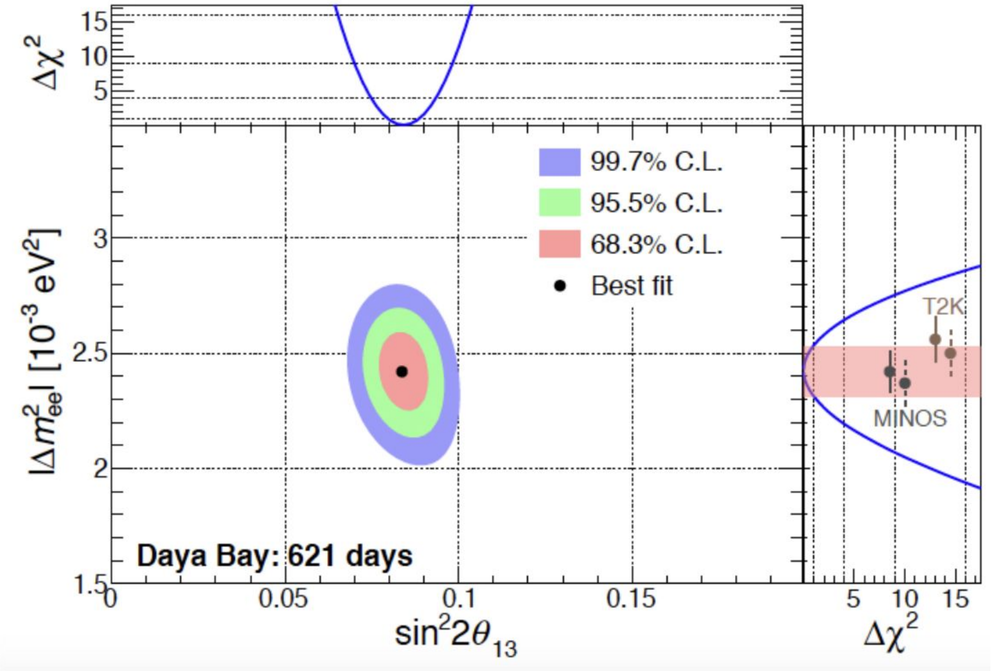
# Example: Daya Bay experiment





*Phys. Rev. Lett. 115, 111802 (2015)*

# Example: Daya Bay experiment



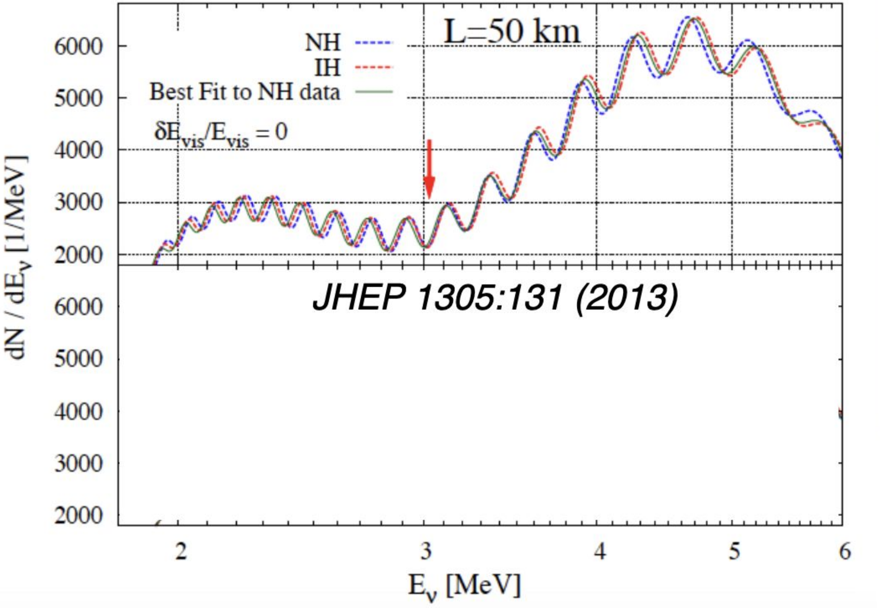
$$\Delta m^2_{\rm eff}|_e = \cos^2\theta_{12}|\Delta m^2_{31}| + \sin^2\theta_{12}|\Delta m^2_{32}|$$
$$= |\Delta m^2_{32}| \pm \cos^2\theta_{12}\Delta m^2_{21}.$$

*Phys. Rev. Lett. 115, 111802 (2015)*

Daya Bay, Double Chooz and RENO provided precision measurements of $\theta_{13}$

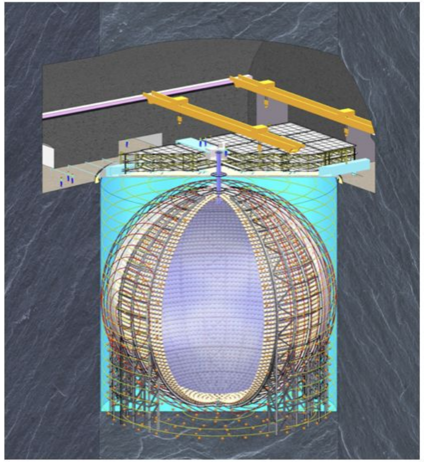
Comparisons between $\Delta m^2_{ee}$ measured at Daya Bay and $\Delta m^2_{32}$ at accelerators may also provide indications of mass ordering

# Future of reactors: JUNO



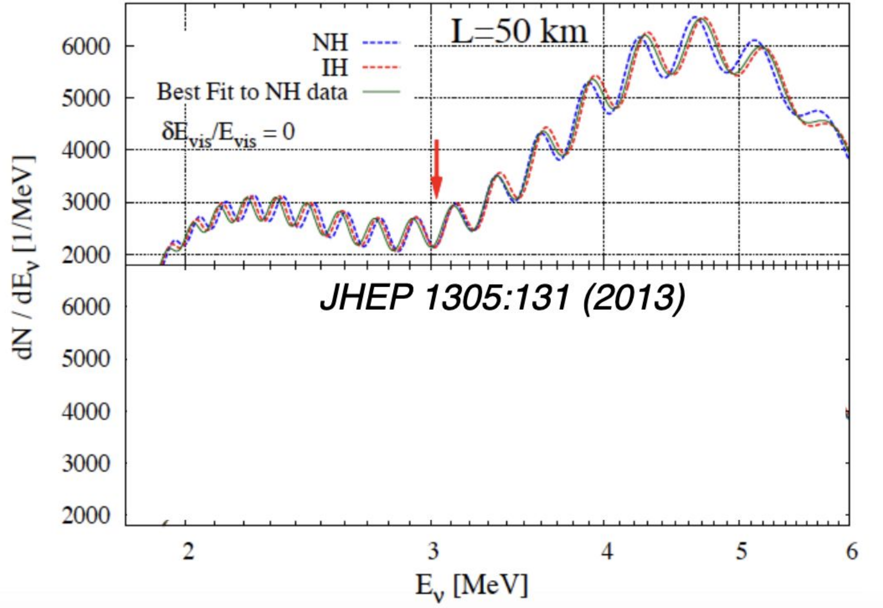
*JHEP 1305:131 (2013)*

At baselines of 50km for reactor neutrino energies, novel sensitivity to hierarchy choice

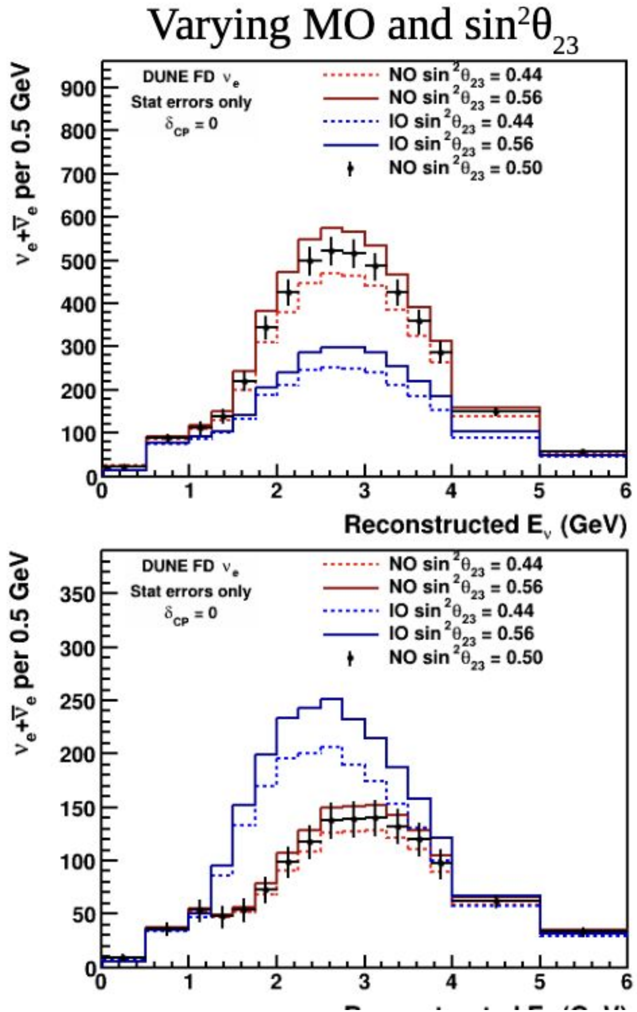


*Concept design report: arXiv:1508.07166*

# Complementarity of JUNO and DUNE



JHEP 1305:131 (2013)



DUNE is sensitive to mass ordering through matter effects, but JUNO measures it in vacuum - *comparison between the two is important to understand Non Standard Interactions (NSI)*

# Back to oscillation: last but not least, solar

‘Atmospheric’
~100 km/GeV

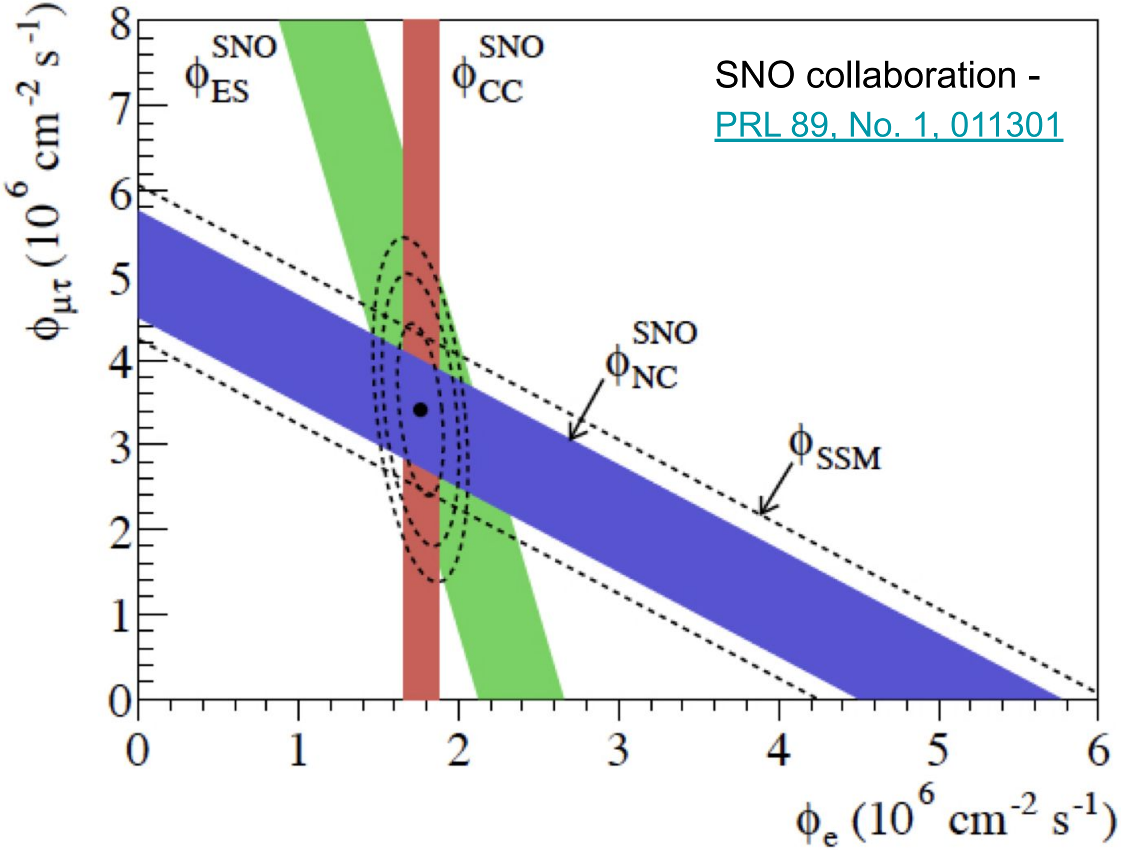
‘Reactor’
~1 km/MeV

Solar
$10^{10}$ m / MeV

Solar (and reactor) measurements - *original precision trendsetters in neutrinos*
*Not covered today: work by Borexino to measure MSW, new solar ν channels*

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \boxed{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \cdot$$

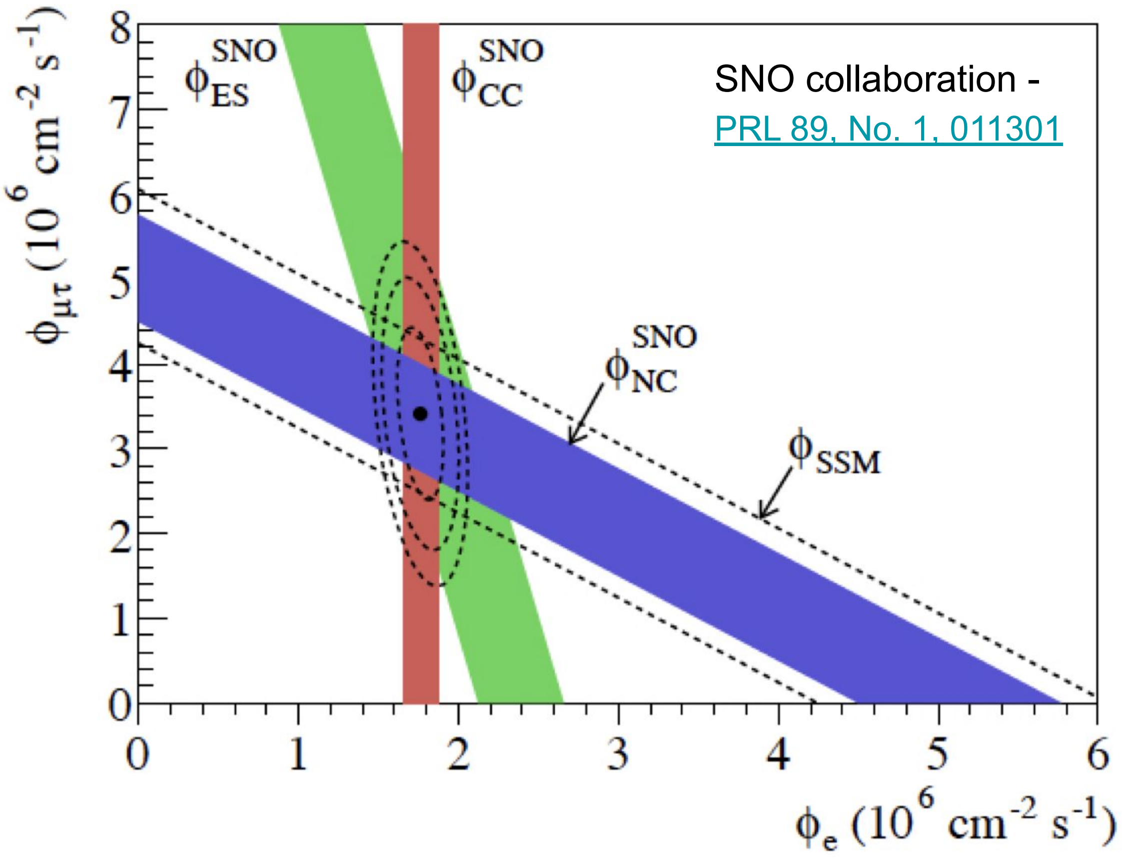
# Back to oscillation: last but not least, solar



SNO collaboration - [PRL 89, No. 1, 011301]()

Consistency between Standard Solar Model - *oscillation wasn't a mismodelling of sun*

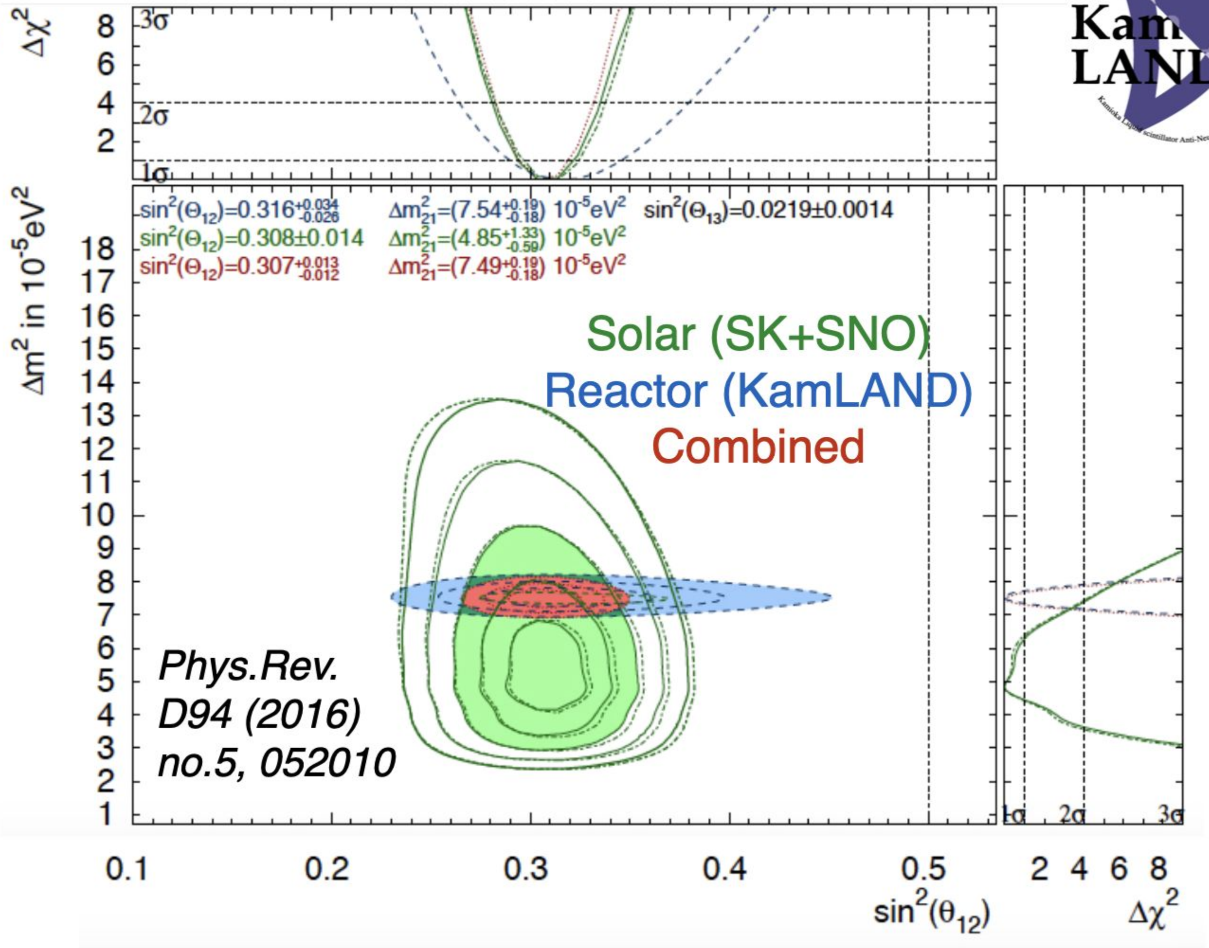
# Back to oscillation: last but not least, solar



SNO collaboration -
[PRL 89, No. 1, 011301](PRL 89, No. 1, 011301)

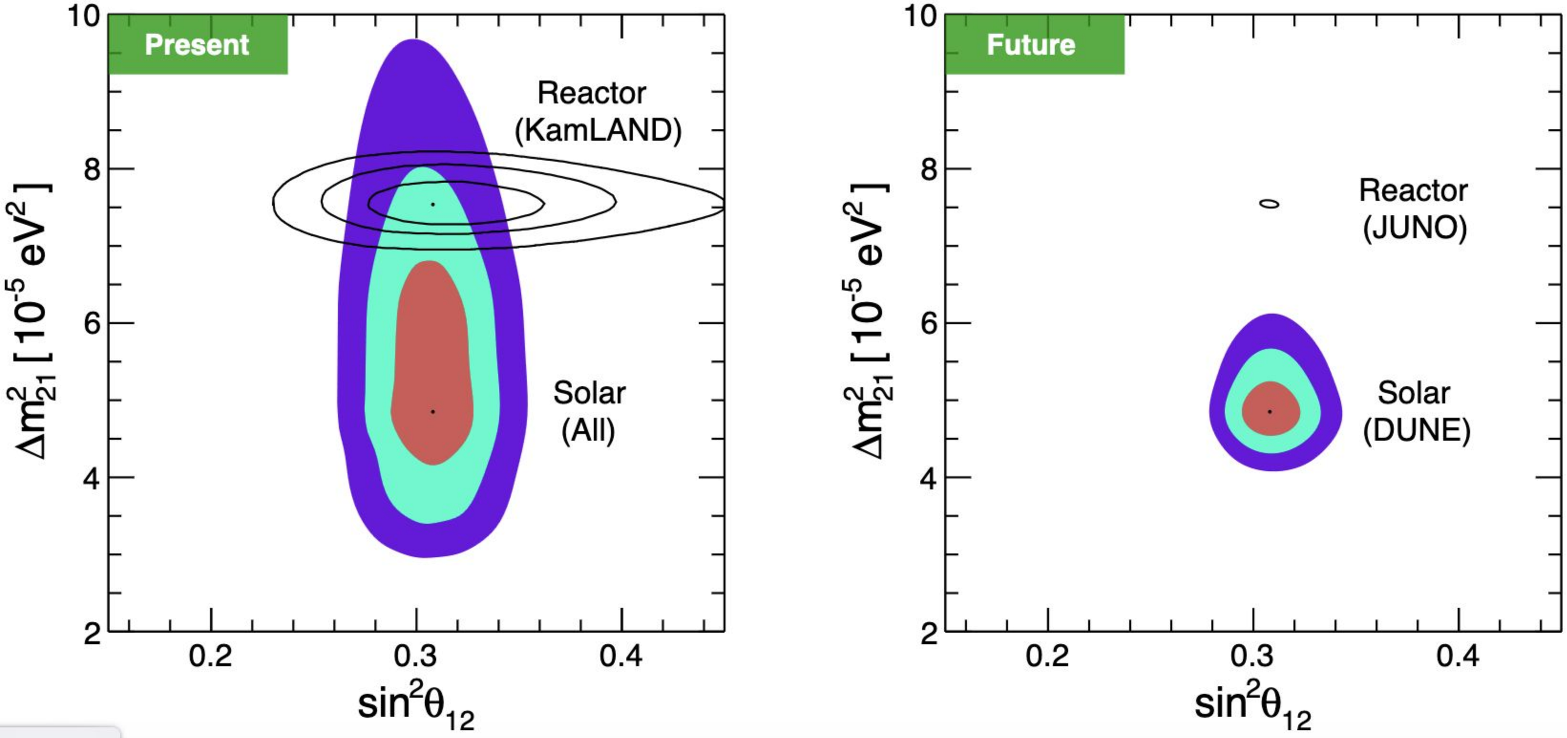
Consistency between NC and electron neutrino CC, and electron elastic scattering (ES) channels - *conserved total number of all neutrino flavors, but transitioned out of electron flavor*

# Solar and reactor comparison



A host of reactors at solar L/E provided complementary information (KamLAND experiment)

# The future of solar



DUNE and JUNO again may provide precision solar parameter information

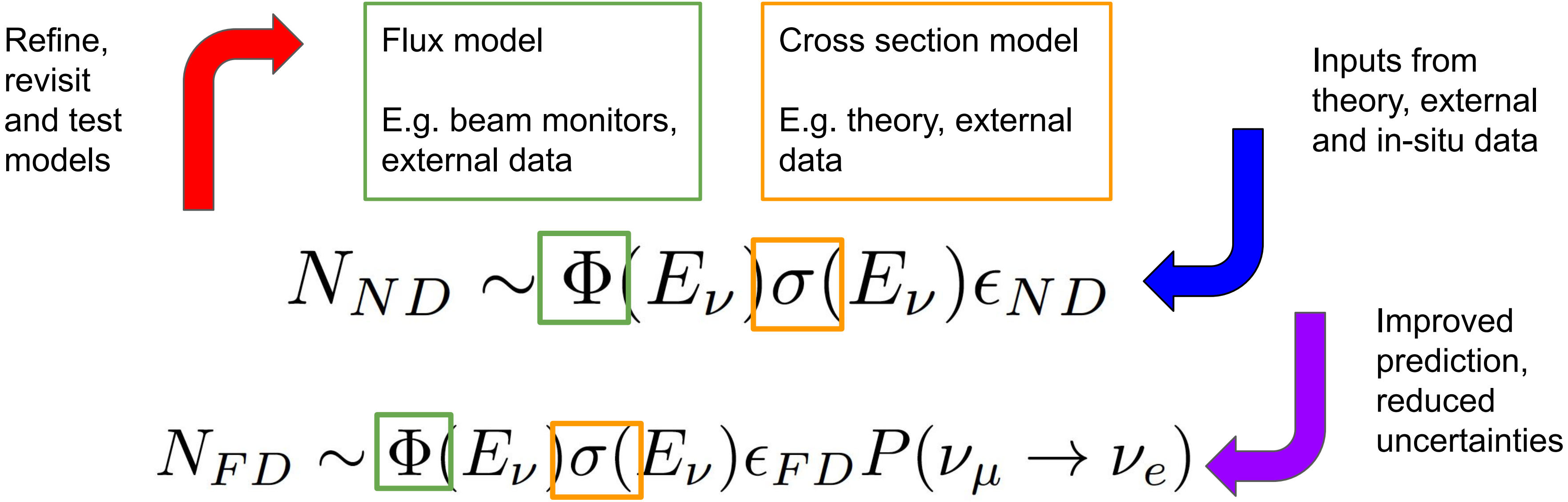
# Precision requires a lot of detail - *example from T2K*

$$N_{FD} \sim \boxed{\Phi}(E_\nu)\boxed{\sigma}(E_\nu)\epsilon_{FD}P(\nu_\mu \rightarrow \nu_e)$$

We determine oscillation parameters from event rates (at our ‘far’ detector)

- Uses neutrino source (flux, $\boldsymbol{\Phi}$), cross section ($\boldsymbol{\sigma}$), and detector (efficiency) models

# Precision requires a lot of detail - *example from T2K*



Refine, revisit and test models

Flux model

E.g. beam monitors, external data

Cross section model

E.g. theory, external data

Inputs from theory, external and in-situ data

$$N_{ND} \sim \boxed{\Phi}(E_\nu)\boxed{\sigma}(E_\nu)\epsilon_{ND}$$

Improved prediction, reduced uncertainties

$$N_{FD} \sim \boxed{\Phi}(E_\nu)\boxed{\sigma}(E_\nu)\epsilon_{FD}P(\nu_\mu \rightarrow \nu_e)$$

We determine oscillation parameters from event rates (at our ‘far’ detector, SK)

- Uses neutrino source (flux, **Φ**), cross section (**σ**), and detector (efficiency) models
- Model tested against near detector data to enable cancellation
- Models built from theory, beam monitors and key external measurements for flux parameters (e.g. NA61) and cross section theory and experiment (e.g. MINERvA)

# Precision experiments enable more physics

Oscillation programs are able to do plenty of physics - *searches for exotic particles, beyond standard model, rare processes etc*

Far detectors may contribute to astrophysics, or searches for proton decay

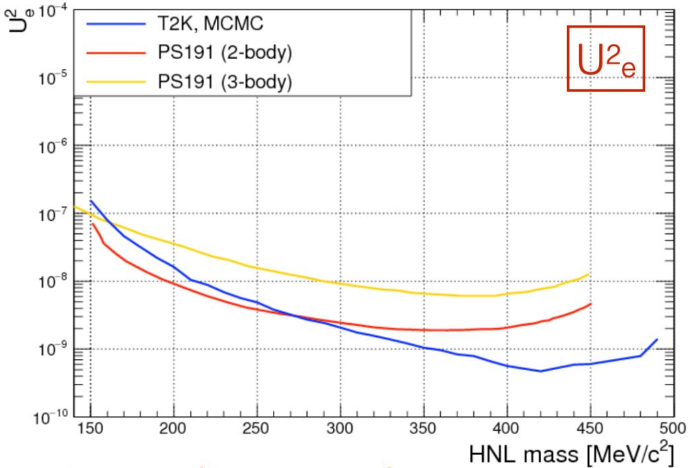
# Precision experiments enable more physics - *example T2K*

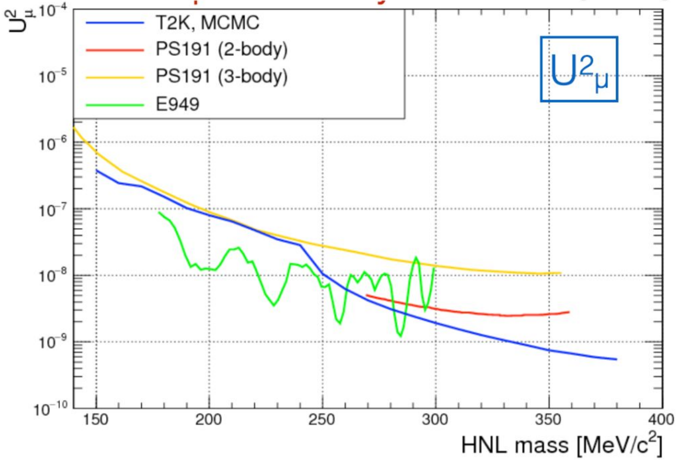
$$K^+ \to \ell^+ N$$

$$N \to \ell^\pm \pi^\mp, \ell^\pm \ell^\mp \nu$$

Production of heavy neutral leptons (N) from kaon decay

- Uses large volume, low mass TPCs for signal selection
- Best high-mass limits on coupling to N to μ, e
- Phys.Rev.D 100 (2019) 5, 052006



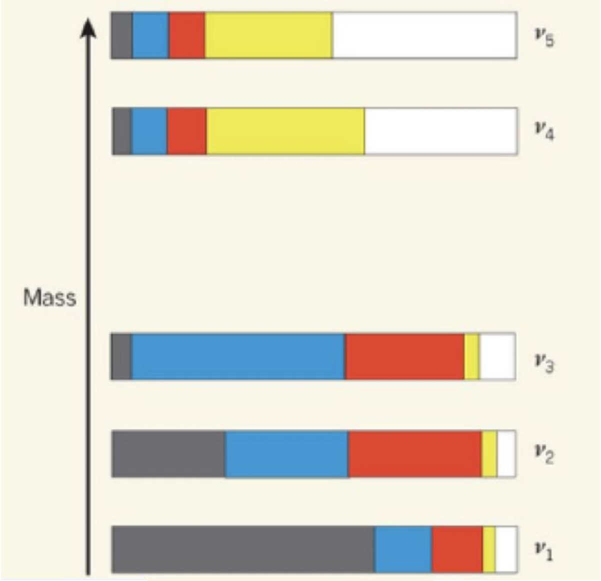


# Precision experiments enable more physics: sterile neutrinos

Daya Bay, MINOS, and other programs have searched for anomalous oscillation consistent with a light sterile* neutrino:

- Mass splitting ~1-10eV$^2$

$$U_{\alpha i} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \nu_s \end{pmatrix} \begin{pmatrix} U_{e1} & U_{e2} & \cdots & U_{eN} \\ U_{\mu 1} & U_{\mu 2} & \cdots & U_{\mu N} \\ U_{\tau 1} & U_{\tau 1} & \cdots & U_{\mu N} \\ \vdots & \vdots & \ddots & \vdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_N \end{pmatrix}$$



W.C. Louis,
Nature, Volume: 478,
Pages: 328–329

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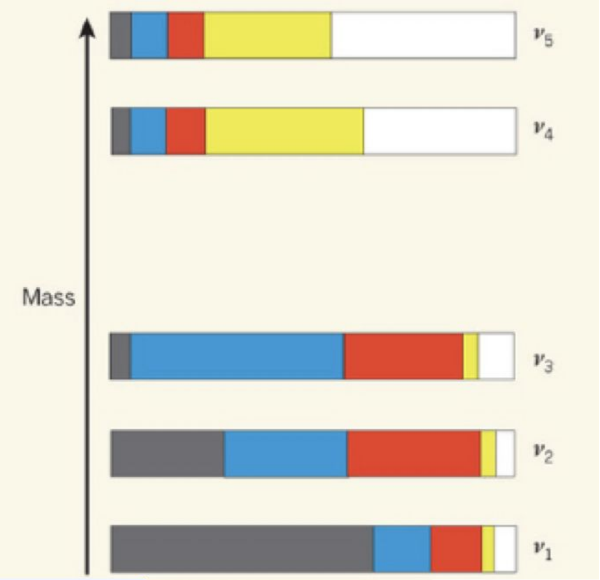
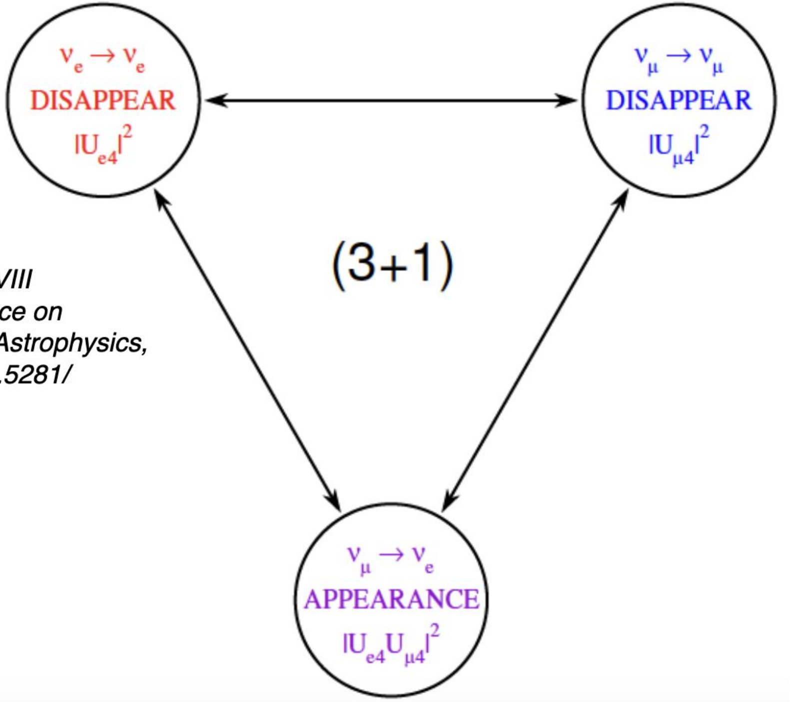


W.C. Louis,
Nature, Volume: 478,
Pages: 328–329

**sterile neutrinos can be very heavy, or keV scale, and can be tested by a variety of programs, including direct mass measurements and cosmology*

# Unclear picture around sterile neutrinos

Reactor $\nu_e$ disappearance results, from Daya Bay, neutral current results from MINOS, MINOS+ and T2K, and short baseline $\nu_\mu$ disappearance results are at odds with a sterle $\nu_e$ appearance signal



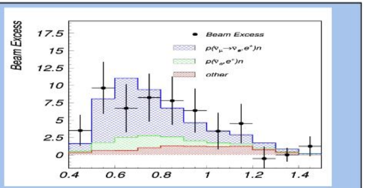
*M. Maltoni, Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018 DOI:10.5281/ zenodo.1287014*

Tension doesn't abate with adding extra steriles (3+2, etc)

# Sterile neutrino status and… PROSPECT(s) ;)

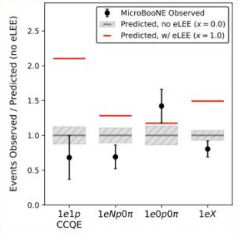
### LSND @ LANL (~30 MeV, 30 m)

Unresolved... JSNS$^2$ will test



### MiniBooNE @ FNAL ($\nu,\overline{\nu}$ ~1 GeV, 0.5 km)

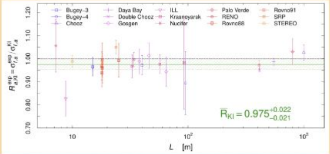
Unresolved.... Results from MicrobooNE rule out specific electron/gamma final state explanations for LEE so far ....**more data from FNAL SBN program soon**



### "Reactor flux anomaly"

Resolved (probably?) with new input $\beta$-decay spectra from 235-U fission

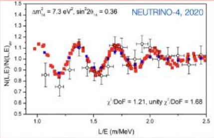
J. Kopp, Nu2022



### "Reactor spectral anomaly"

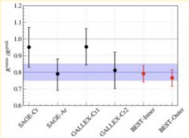
~Unresolved... new data disfavor.. more data coming...

PROSPECT, SoLid, STEREO, NEOS, DANSS, CHANDLER, Neutrino-4,....



### "Gallium anomaly"

Unresolved... new BEST results (5$\sigma$) confirm...no baseline dependence

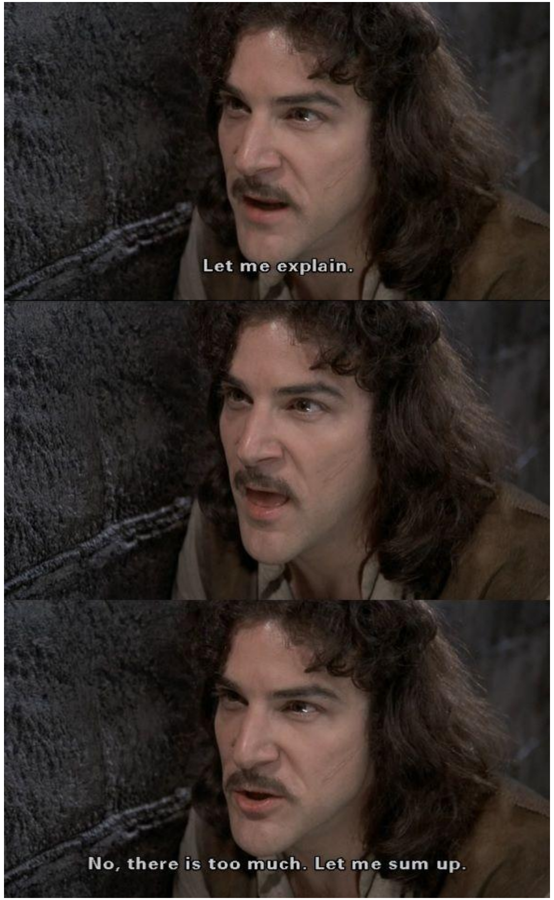


Anomalous indications so far to be addressed with current generation program

Future program also has unique capabilities and constraints to add

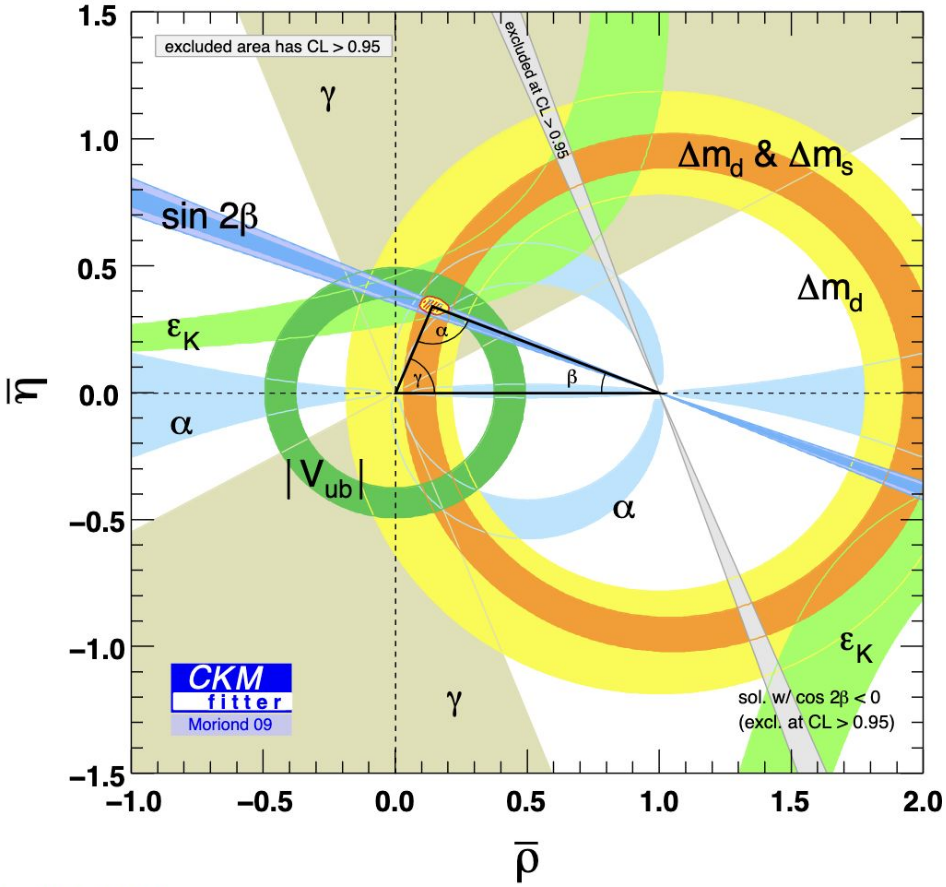
From: K. Scholberg Snowmass neutrino frontier summary

# Closing thoughts on precision



Credit: The Princess Bride

# Closing thoughts on precision neutrino physics

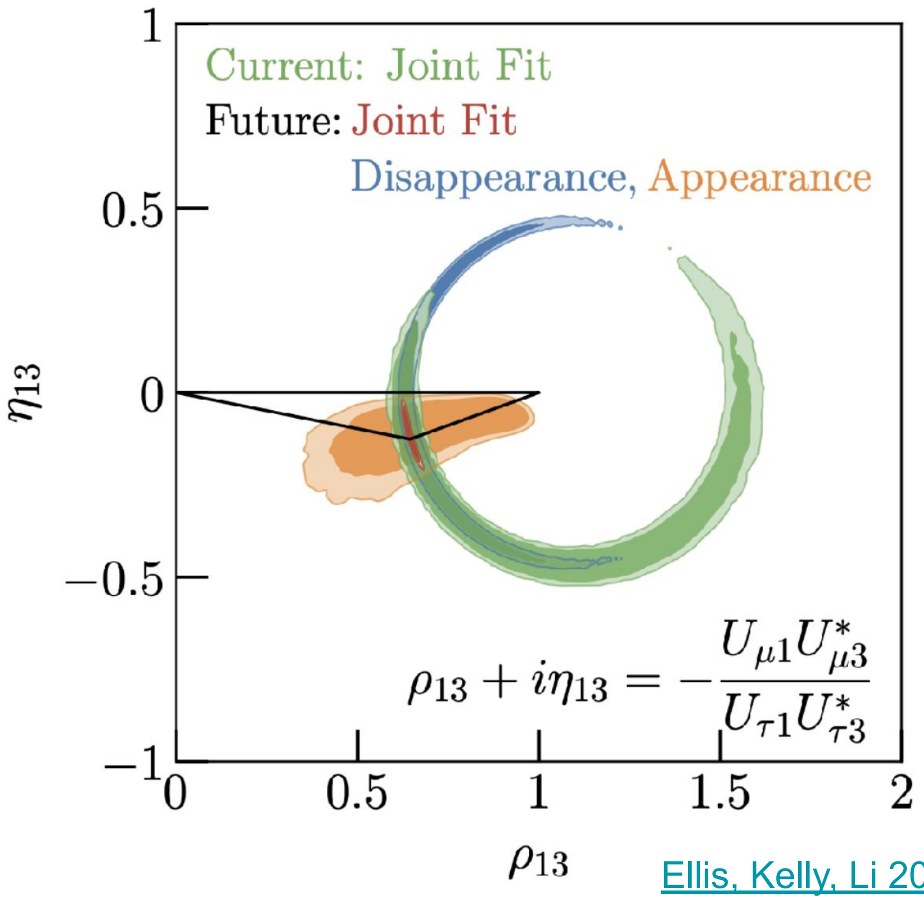


André de Govêa - “*we need this in the lepton sector*”

[Snowmass Neutrino Colloquium]

Unitarity ‘triangle’ built from elements of quark mixing matrix

# Closing thoughts on precision neutrino physics



Ellis, Kelly, Li 2004.13719

Pedro Machado at the P5 town hall at Fermilab

*“DUNE, HK, JUNO and IceCube will enable a bona fide precision physics program in the neutrino sector”*

# Closing thoughts on precision neutrino physics

Key features of precision:

1. Ability for multiple experiments to get at the same physics, in different ways
2. Each experiment is pushing the physics as far as it can:
    a. Well built, exquisite detectors
    b. Careful attention to detail and fundamentals - *checking, rechecking, sometimes back to basics*
    c. Creative new approaches in existing or with new technologies

Precision doesn’t happen overnight - *it takes decades long patience*

Precision happens because of you - *we are so lucky, as a field, to have such wonderful students as you!*

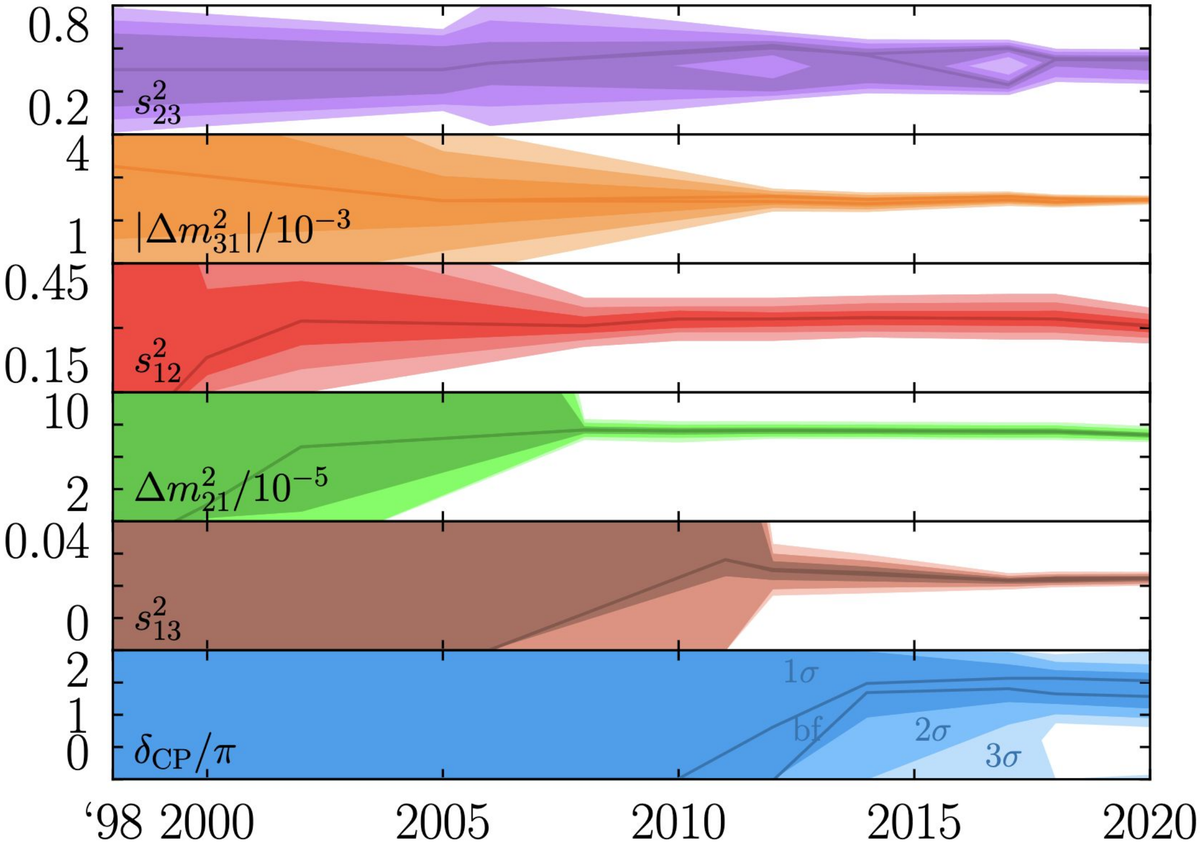
# Closing thoughts on precision neutrino physics

We have learned so much, so recently, about neutrinos

Next up: $\delta_{CP}$ and the mass ordering, new direct mass measurements, and neutrinoless double beta decay searches

Precision experiments also afford new measurements on NSI, exotica

Complementary to major advances from CMB, dark energy efforts



Snowmass Neutrino Oscillation Report

# Backups

# Neutrino Theory 101 - *thanks to Michael Peskin!*

How to write a Lagrangian for neutrino mass:

Begin with

$$\mathcal{L} = \sum_j \overline{\psi}_j (i \not\partial) \psi_j - \quad ?$$

What terms without derivatives are allowed ?

# Neutrino Theory 101 - *thanks to Michael Peskin!*

Recall that the 4-component Dirac fermion is a reducible representation of the Lorentz group,

$$\Psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} \qquad S^{\mu\nu} = \frac{i}{4}[\gamma^\mu, \gamma^\nu] = \begin{pmatrix} \sigma^{\mu\nu} & 0 \\ 0 & \overline{\sigma}^{\mu\nu} \end{pmatrix}$$

so $\psi_L, \psi_R$ are independent fields. The kinetic term splits

$$\mathcal{L} = \psi_L^\dagger i\overline{\sigma}^\mu \partial_\mu \psi_L + \psi_R^\dagger \sigma^\mu \partial_\mu \psi_R$$

The two representations are complex conjugates of one another, that is

$\psi_L' = i\sigma^2 \psi_R^*$ transforms like $\psi_L$

In this language, the usual Dirac mass term is

$$\overline{\Psi}\Psi = \psi_R^\dagger \psi_L + h.c. = \epsilon_{ab} \psi_a' \psi_b + h.c.$$

x

# Neutrino Theory 101 - *thanks to Michael Peskin!*

If $\Psi$ has lepton number L = 1, $\psi_L$ has L = 1, but $\psi'_L$ has L = -1. Then the usual Dirac mass term conserves L.

The most general fermion mass term is

$$M_{jk}\epsilon_{ab}\psi_a^j\psi_b^k + h.c.$$

where $M_{ij}$ is a symmetric matrix. If $M_{ij}$ pairs L = 1 fields with L = -1 fields, this is a "Dirac mass" and L is conserved. However, there is another possibility. The most striking case is with one chiral fermion

$$m\epsilon_{ab}\psi_a\psi_b + h.c.$$

This is the "Majorana mass". The physical fermion has 2 states, with +1/2 and -1/2 helicity. The -1/2 state is (mostly) a fermion, but the +1/2 state is mostly its antiparticle, an antifermion. L is not conserved.

# Neutrino Theory 101 - *thanks to Michael Peskin!*

In the Standard Model, $\nu_R$ has zero quantum numbers and can be omitted from the theory.

If neutrinos are massive, there are 3 possibilities:

1. $\nu_R$ does not exist; then all neutrino masses are Majorana. Also L is not conserved. The neutrino mass term needs 2 Higgs fields.

2. Neutrino masses are Dirac and and L is conserved. The mass term can come, as for quarks, from the Yukawa coupling to the Higgs.

3. $\nu_R$ has both Majorana $M$ and Dirac mass terms. The Majorana mass violates L but does not violate the SM gauge symmetries, so it can be very large: $M \gg m$ . Then the masses are effectively Majorana, with

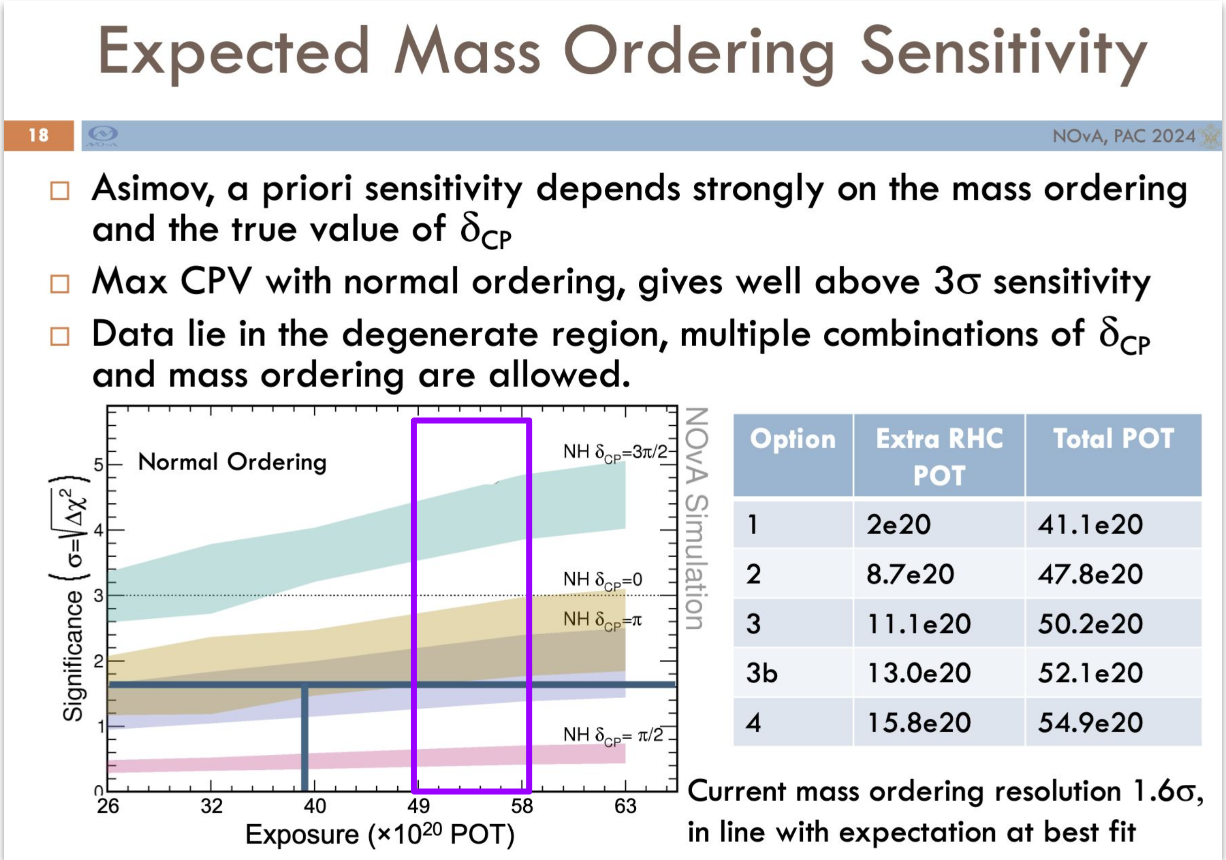
$$m(\nu_L) \sim m^2/M$$

This is the seesaw mechanism of Yanagida and Gell-Mann, Ramond, and Slansky.

# Neutrino Theory 101 - *thanks to Michael Peskin!*

The “Majorana phases” in the neutrino mass matrix appear only in chirality-violating processes. In long-baseline experiments, the production and detection of neutrinos both occur by weak current, which are chirality conserving. Thus, these phases must cancel out. To detect these phases, it is essential to have a chirality-violating process, such as neutrino-neutrino annihilation thorough the Majorana mass.

# How well will NOvA do at the mass ordering?



## Expected Mass Ordering Sensitivity

18

NOvA, PAC 2024

- ☐ Asimov, a priori sensitivity depends strongly on the mass ordering and the true value of $\delta_{CP}$
- ☐ Max CPV with normal ordering, gives well above $3\sigma$ sensitivity
- ☐ Data lie in the degenerate region, multiple combinations of $\delta_{CP}$ and mass ordering are allowed.

| Option | Extra RHC POT | Total POT |
|---|---|---|
| 1 | 2e20 | 41.1e20 |
| 2 | 8.7e20 | 47.8e20 |
| 3 | 11.1e20 | 50.2e20 |
| 3b | 13.0e20 | 52.1e20 |
| 4 | 15.8e20 | 54.9e20 |

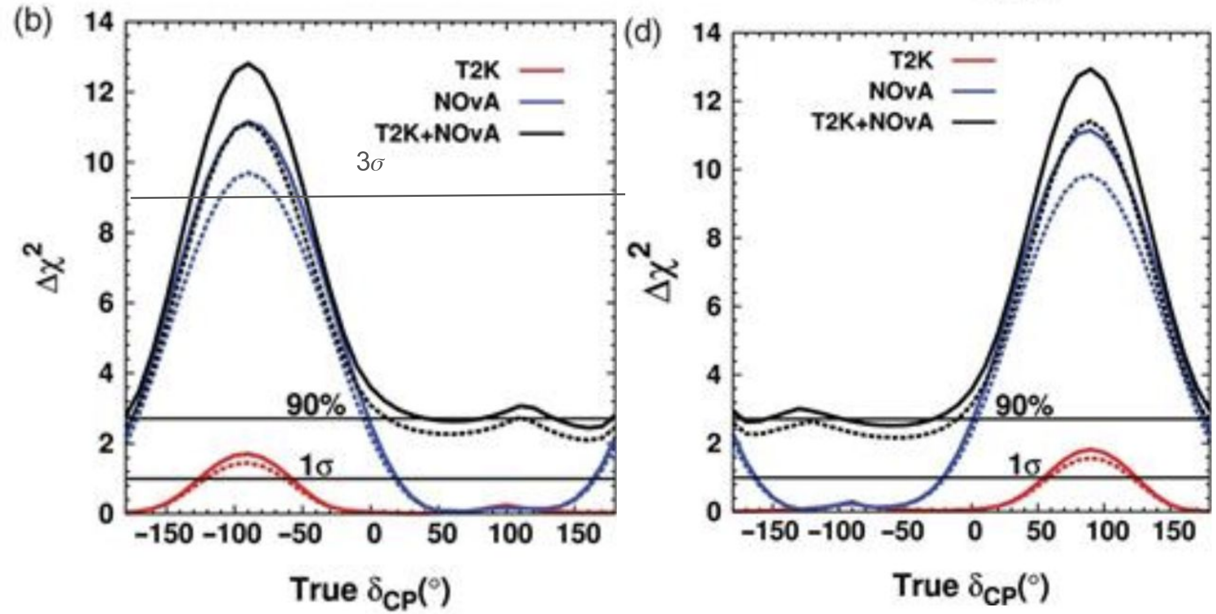
Current mass ordering resolution $1.6\sigma$, in line with expectation at best fit

**Sensitivity varies based on underlying parameters;** statistics limited experiment

- Assuming T2K values, then favorable resolution of MO ($3\sigma$)
- Current NOvA MO sensitive "in line with expectation at best fit"

NOvA slides to Fermilab Program Advisory Committee

# How well will NOvA and T2K do at the mass ordering?

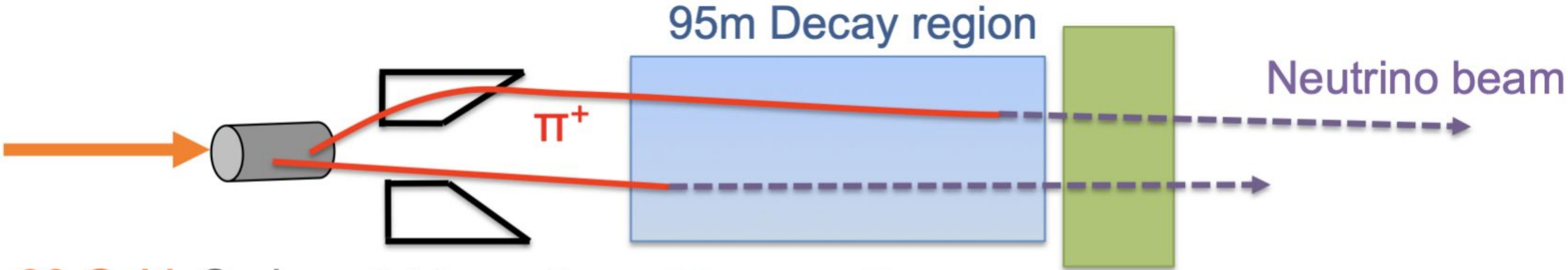


PTEP Volume 2015, Issue 4, April 2015, 043C01

**Sensitivity varies based on underlying params**; assumes equal nu/nubar running

- Note: see how there’s three different conventions in this talk? T2K’s, NOvA, and this T2K paper? Sorry…
- Sensitivity boosted by combination in ‘weak’ region, so expect NOvA sensitivity boosted when we include T2K

# Accelerator-based neutrino beams vs. dedicated K beam?



30 GeV Proton beam

Carbon Target

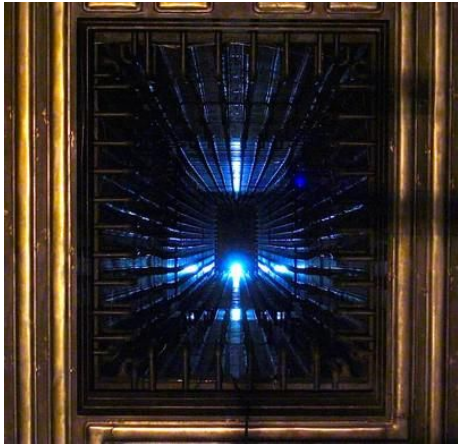
3 Magnetic focusing ``horns”

Pions and kaons decay to neutrinos

Beam dump

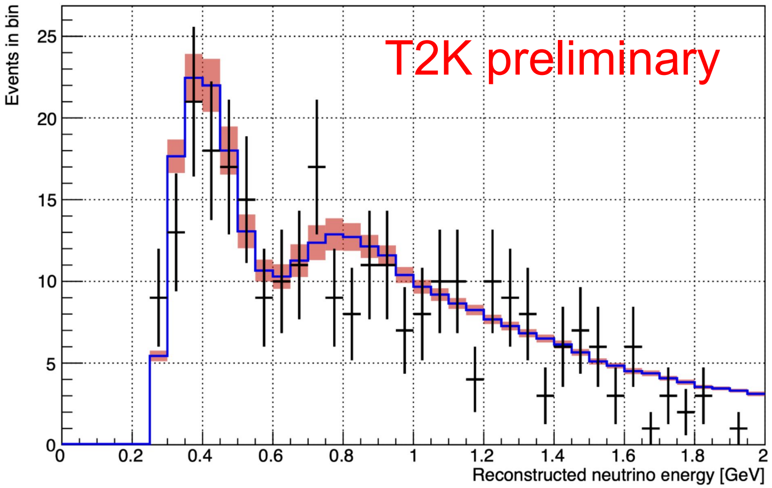
Our beam is one of the most intense in the world - *not necessarily true that dedicated experiments are more intense*

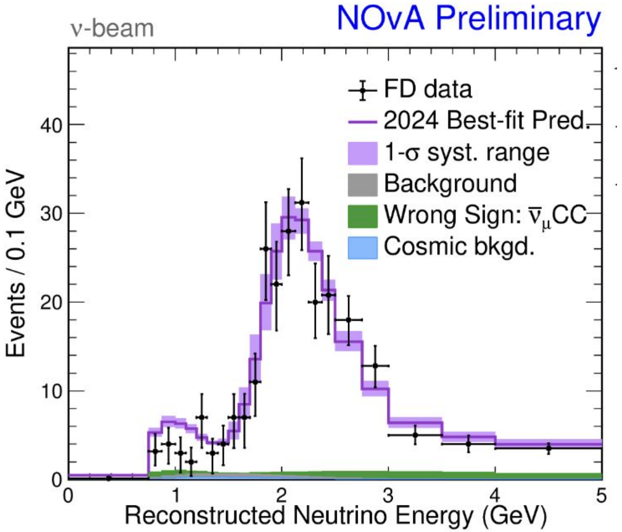
Decay volume is water cooled

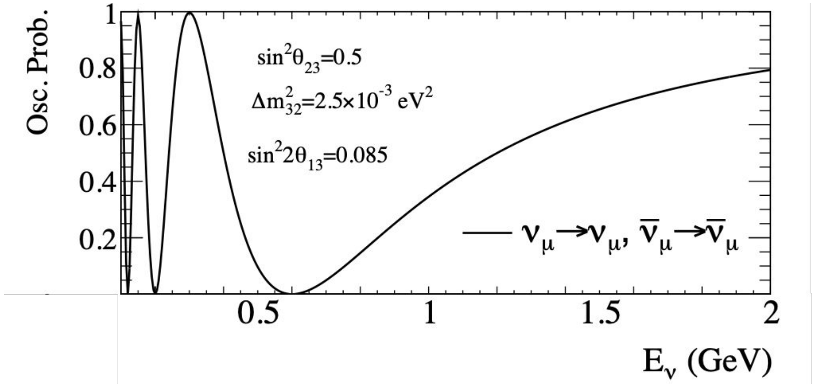


We also have a low density detector in a magnetic field - *excellent sign selection + particle separation helps for competitive limits*

# Should these two things be the same? *Nope*

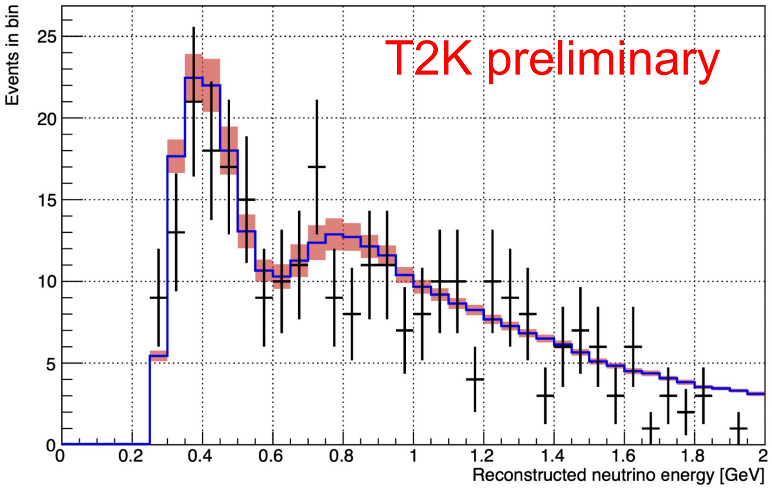


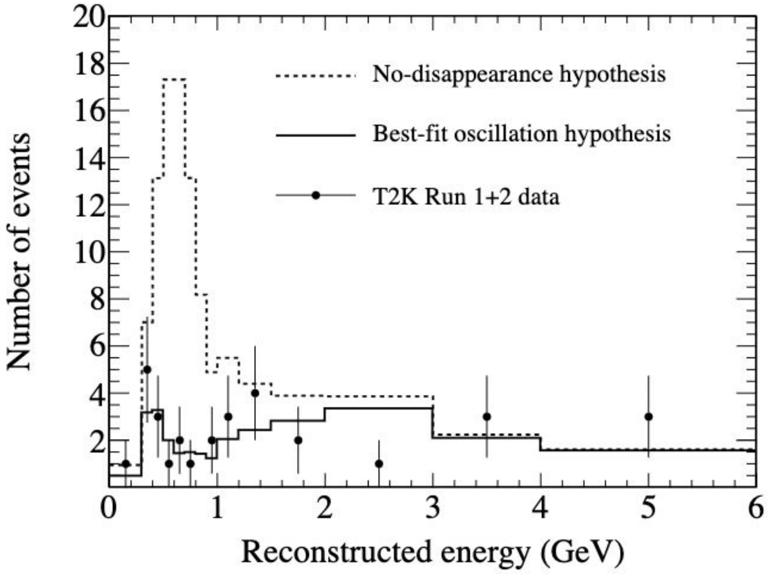


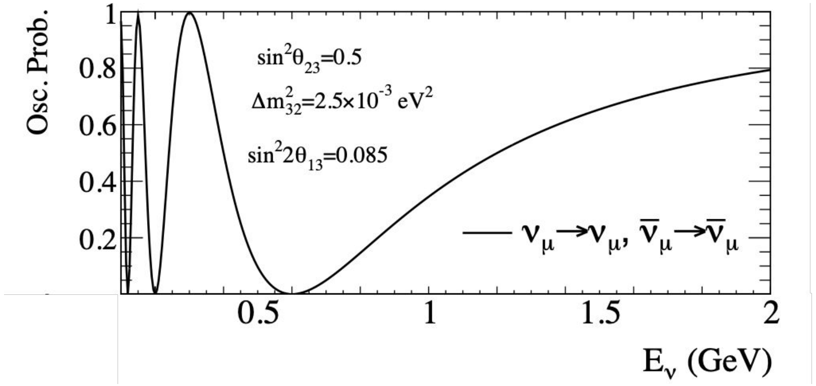


Different backgrounds, flux and cross section

# Should these two things be the same? *Nope*

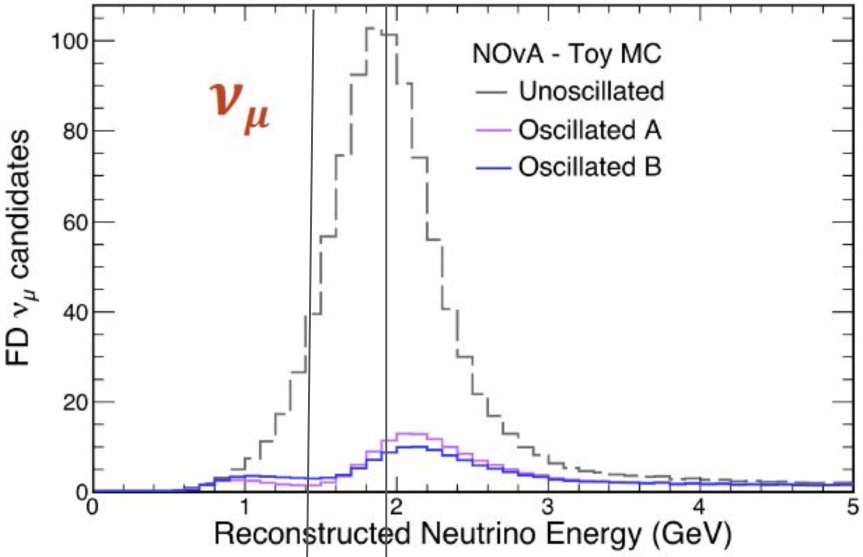


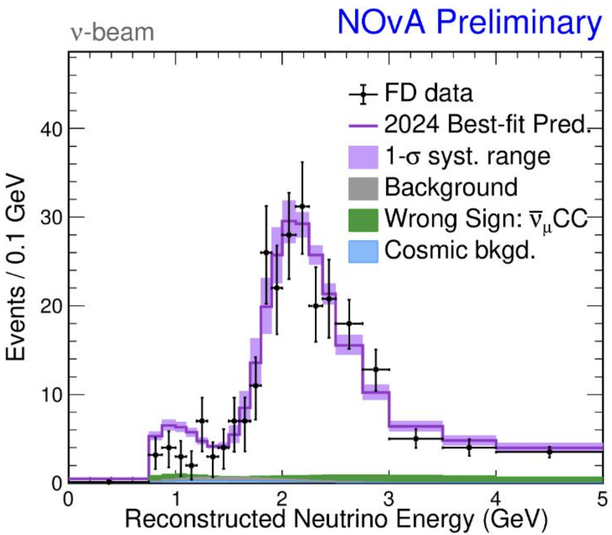




T2K peak flux is riiiight on top of the oscillation peak - *didn't have to be that way*

# Should these two things be the same? *Nope*

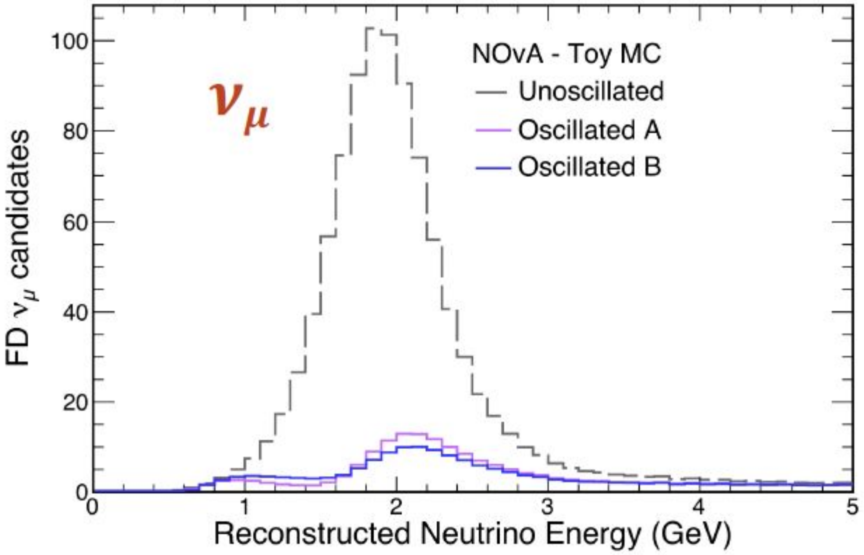


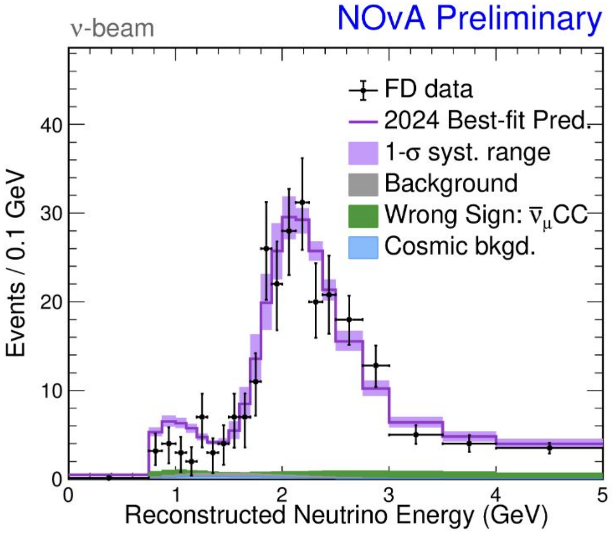


Peak of flux for NOvA is different

Than the max disappearance value

# Should these two things be the same? *Nope*





Cross section rises with energy, too, so enhanced rate at higher energies

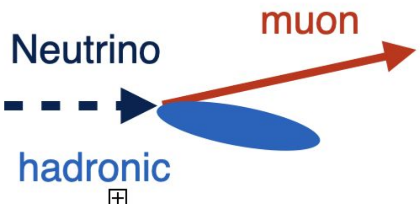
The two experiments also have different energy estimators

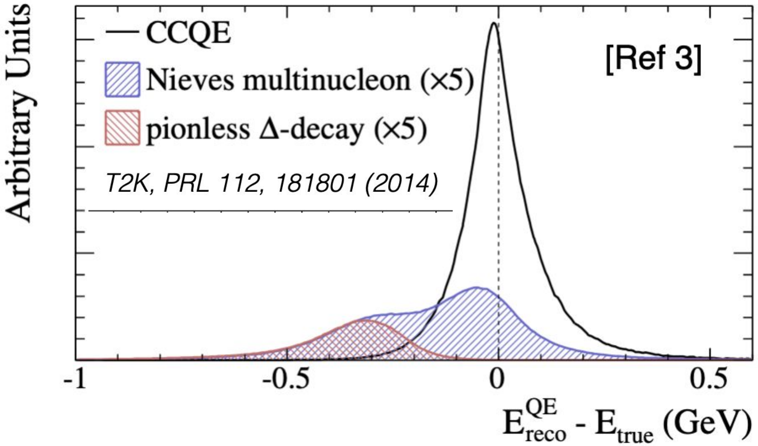
# Energy estimators - *are also different*

- Oscillation depends on energy
  - Estimate from hadronic and/or leptonic information

$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)} \qquad E_\nu = E_\mu + \sum E_{hadronic}$$

- Nuclear effects bias true and estimated neutrino energy





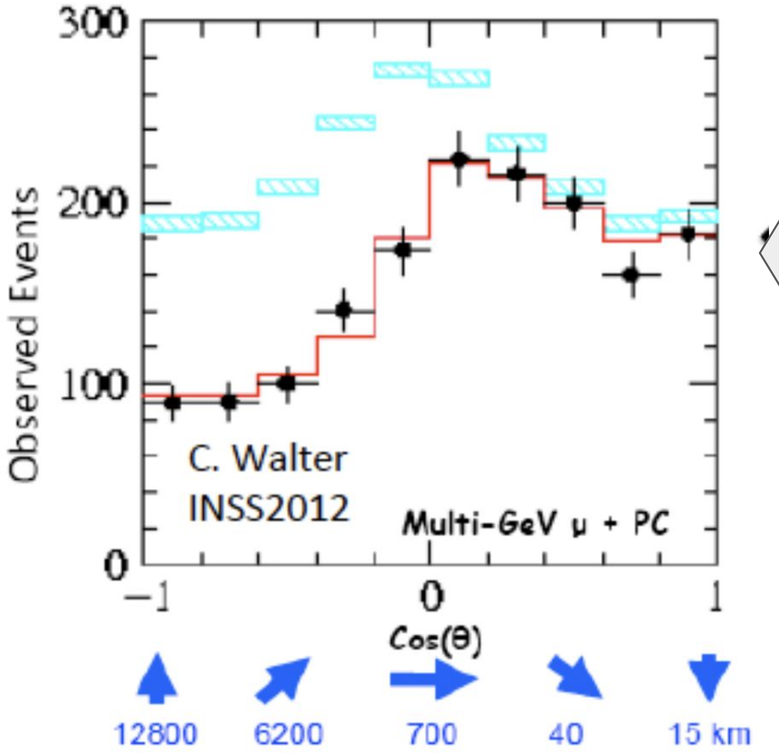
*T2K, PRL 112, 181801 (2014)*

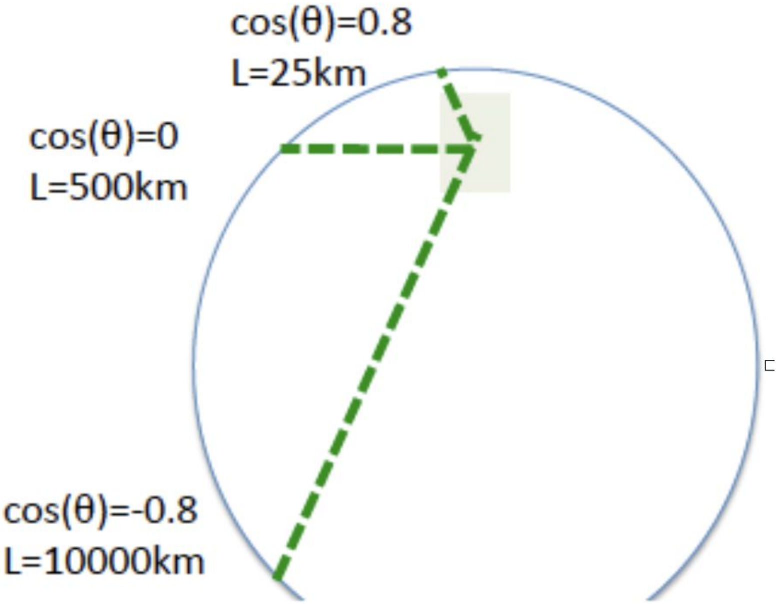
T2K uses E(QE)

NOvA uses Enu (w/ hadronic)

# Why the rapid change near cos(th) = 0?

Wild guess: baseline is changing rapidly for small angle change in detector -> big osc prob changes?





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