LONG-BASELINE NEUTRINO OSCILLATIONS

From Motivation to Measurements

Lecture 1 of 2

International Neutrino Summer School 2026

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hi! I am Zoya

- Assistant Professor at Ohio State University since 2025.
- Member of NOvA and DUNE experiments.
  - Physics Coordinator for NOvA. ND Prototypes Convener on DUNE.
  - DUNE: Long Baseline, ND Physics, Detector Systematics
  - NOvA: 3Flavor Oscillations, NOvA-T2K Joint Analysis
- PhD thesis on T2K experiment
  - Cross-section measurement in T2K Near Detector
- Mango, dance, books enthusiast!

Roadmap – Part I

Goal: how a long-baseline experiment is built — and why.

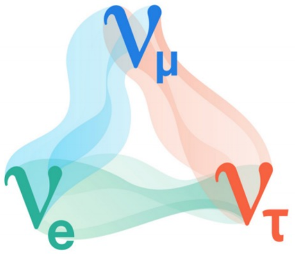
1. Framing: What we measure, what's known, what's not?
2. Accelerator beams
3. Long-baseline experiments
4. Interlude: Why a near detector?
5. From observables to analysis

Learning Outcomes – Part I

- Explain why we use accelerator neutrino beams and what "long-baseline" means
- Identify the two oscillation channels and what each one measures
- Explain why a long-baseline experiment needs a near detector
- Read an oscillation result: how event spectra become contours

1 Brief Review

Neutrino Oscillation



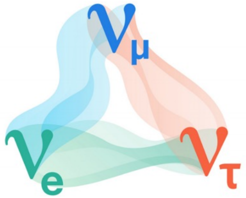
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor Eigenstates (interactions)

Leptonic Mixing Matrix

Mass Eigenstates (propagation)

Neutrino Oscillation



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

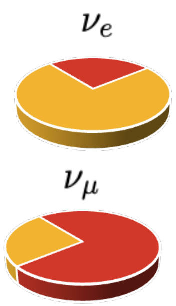
Widely used representation of the Leptonic Mixing Matrix, **assumes unitarity** and is adopted across all neutrino experiments.

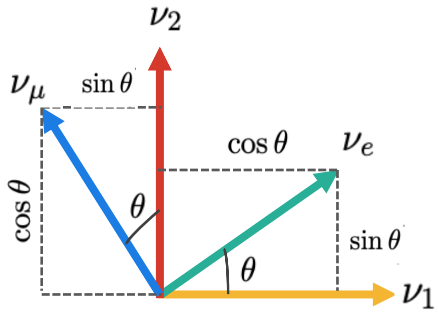
$$U_{\text{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

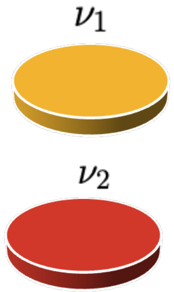
Neutrino Oscillation: Toy example

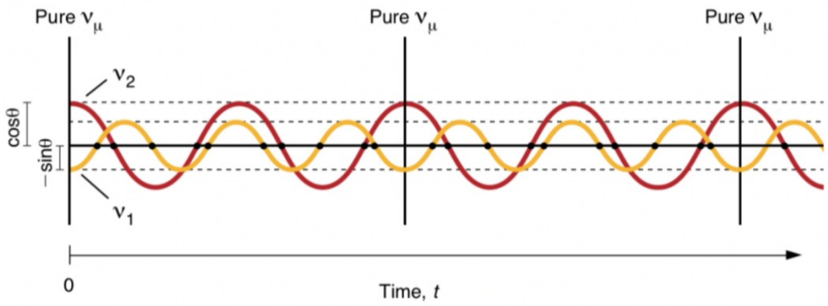
Flavor Eigenstates





Mass Eigenstates





Oscillation Probability (2-Flavor Example)

$$P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

Neutrino Oscillation

Nature's Parameters

$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2(2\theta)\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

Amplitude

$$U_{\text{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

Mixing angles θ_{12} ,θ_{13} ,θ_{23} determine the magnitude of oscillation.

$\theta_{23} \approx 45^\circ$ $\theta_{13} \approx 8.5^\circ$ $\theta_{12} \approx 34^\circ$

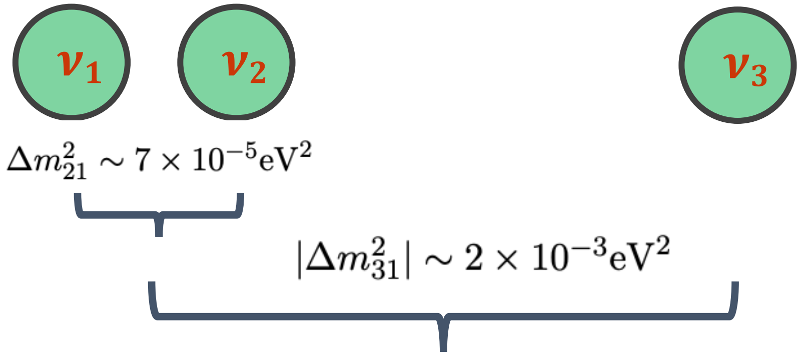
Neutrino Oscillation

Nature's Parameters

Frequency

$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

Two known mass-splitting scales determine frequency of the oscillations.

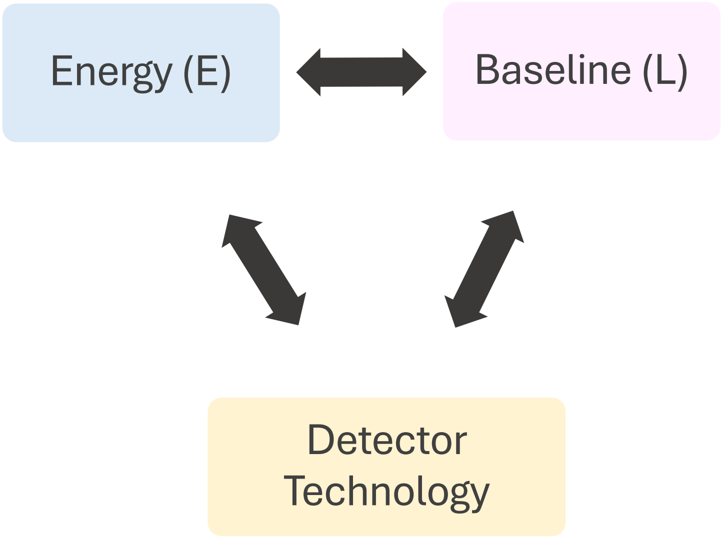


Neutrino Oscillation

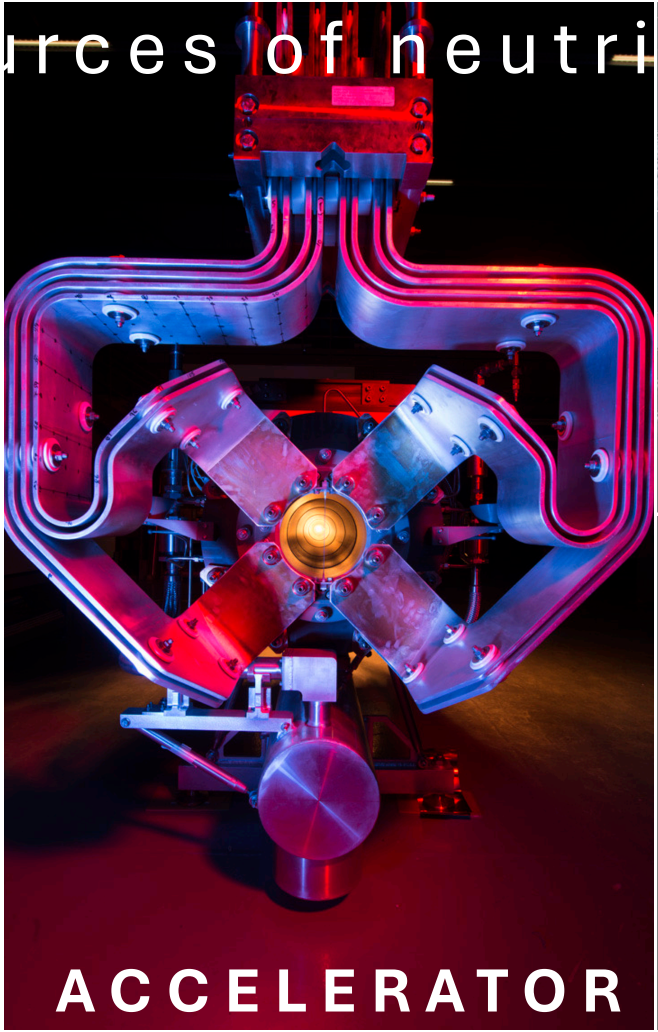
Experimental Parameters

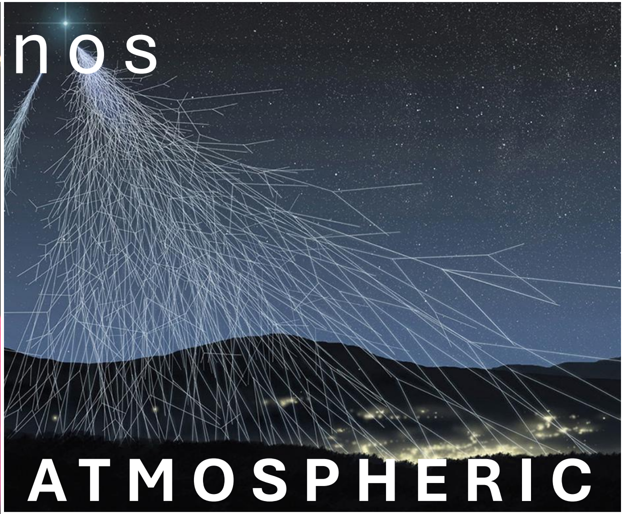
$$P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

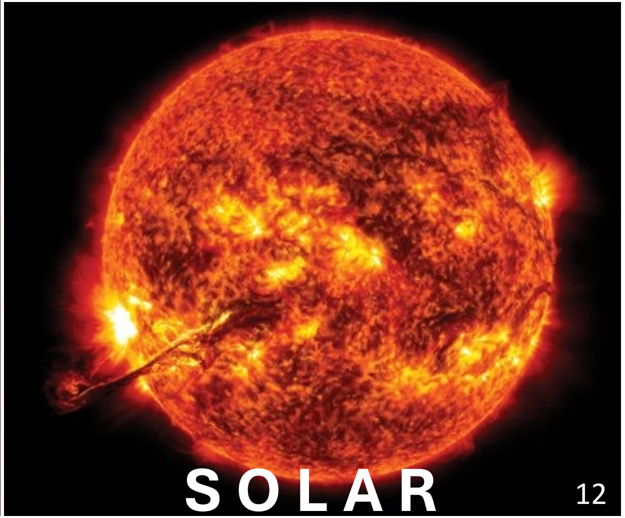
Experiments are designed with a typical L/E to optimize sensitivity to Δm^2_{ij} oscillation scales



Sources of neutrinos

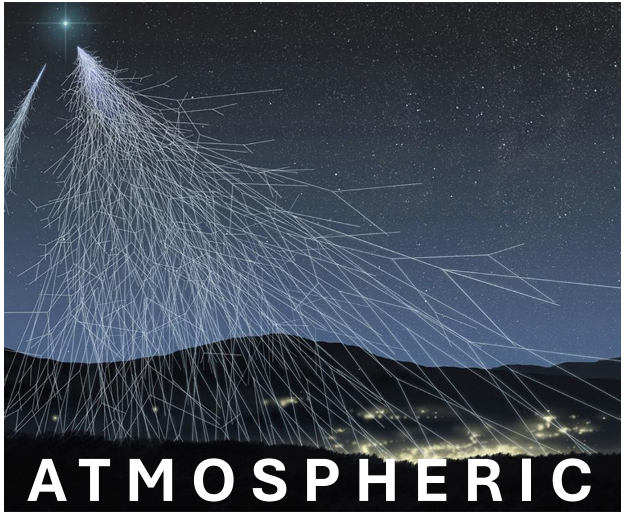


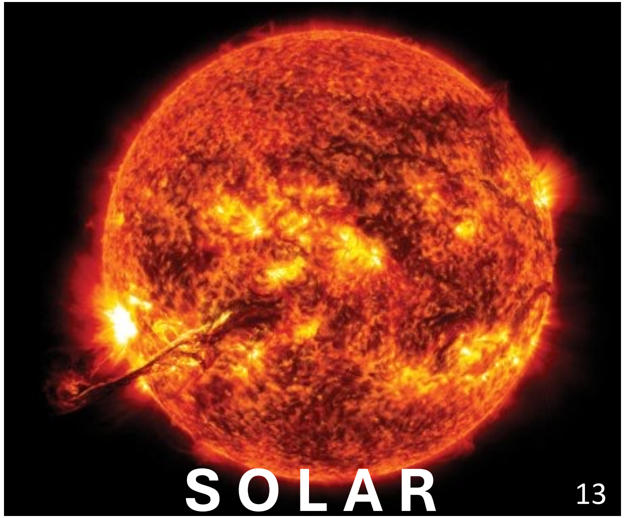


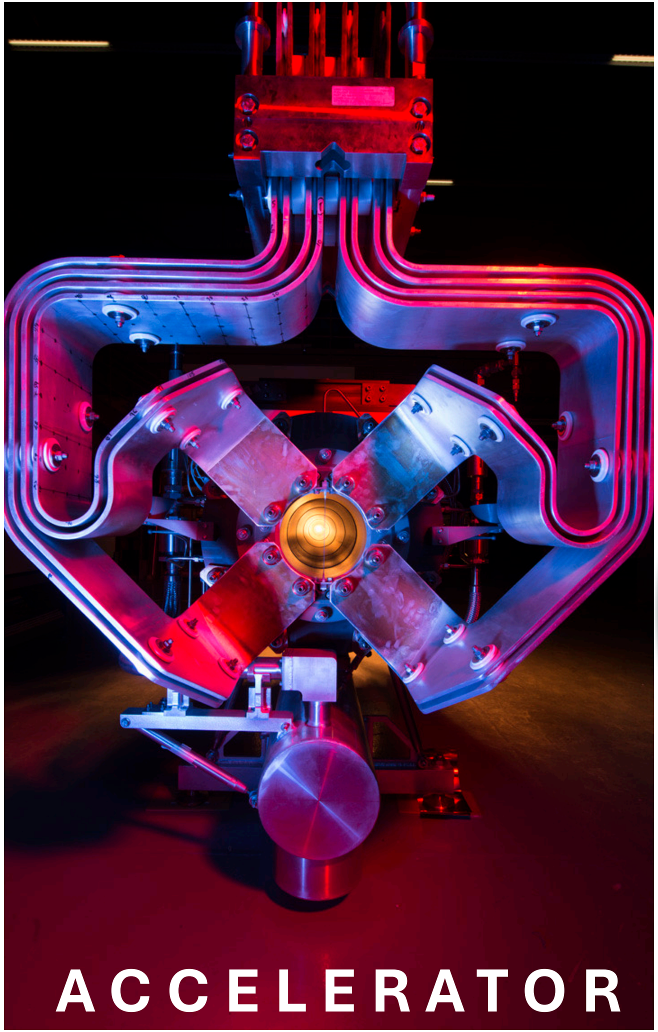


The WILD Neutrinos

Slide Inspiration: Kate Scholberg







The TAMED Neutrinos

Meet my cat : Quigley

Slide Inspiration: Kate Scholberg

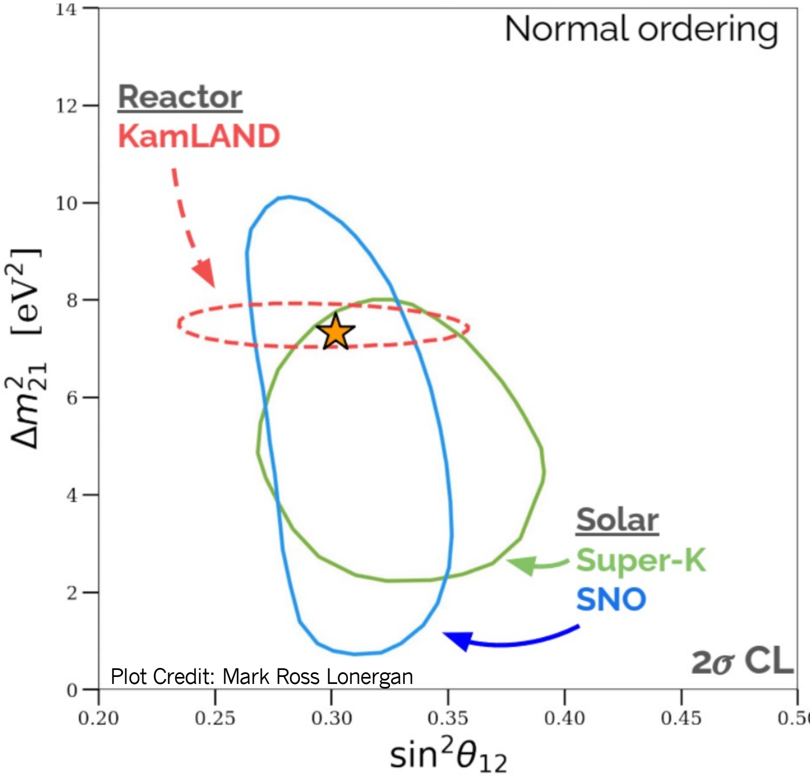
Slide Inspiration: Kate Scholberg

Discoveries in the wild…
confirmed with tame neutrinos

SOLAR

REACTOR

- Disappearance of electron neutrino from the Sun confirmed by reactor neutrino experiments!

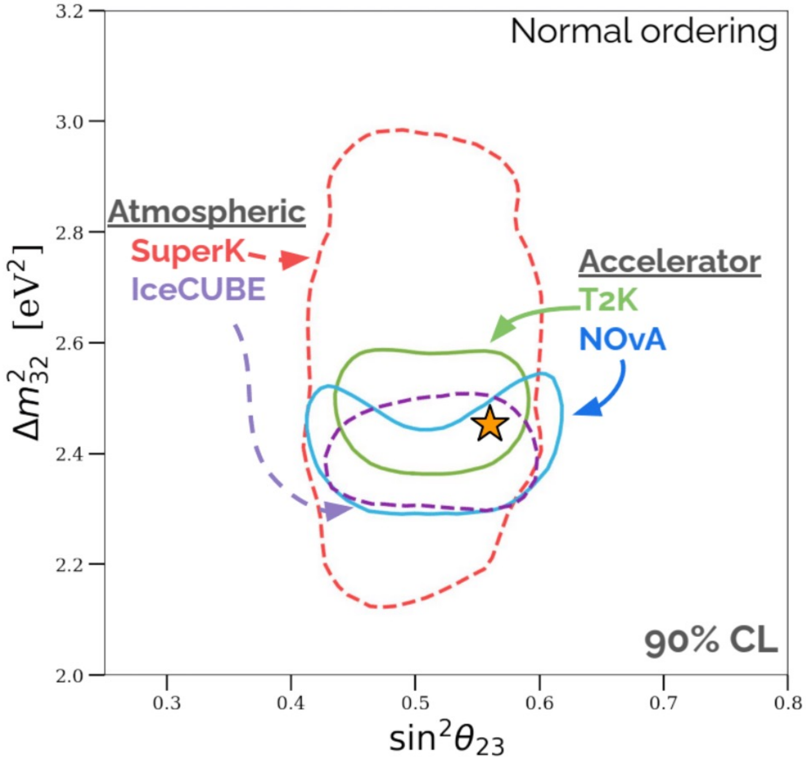


Slide Inspiration: Kate Scholberg

Discoveries in the wild... confirmed with tame neutrinos

ATMOSPHERIC

ACCELERATOR



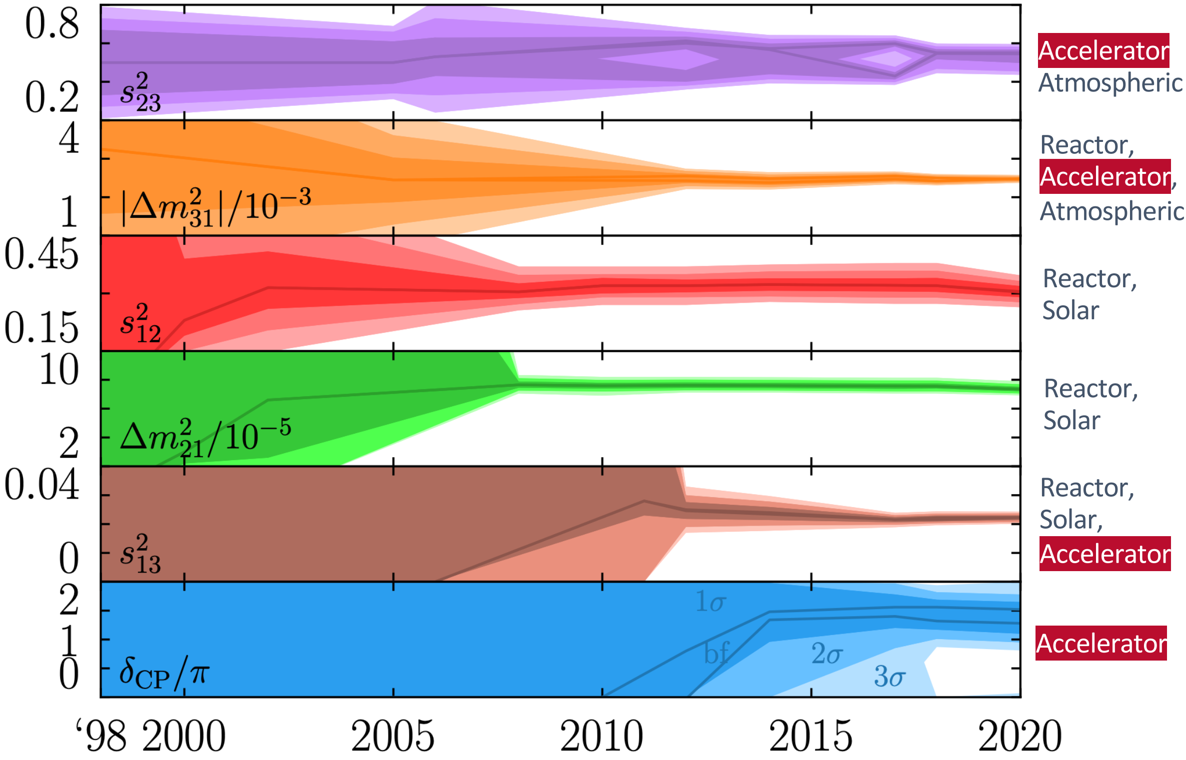
- Disappearance of muon neutrinos from the atmospheric experiments confirmed by accelerator neutrino experiments!

The Experimental Overview

A 25 years long odyssey

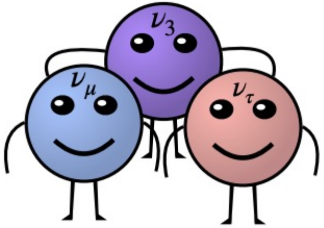
"Ultimate Goal: Not Measure Parameters but Test the Formalism": A.D. Gouvea

Snowmass NF01 report P.B. Denton et al arXiv:2212.00809



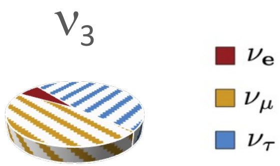
(some) open questions

Is the θ_{23} mixing maximal?

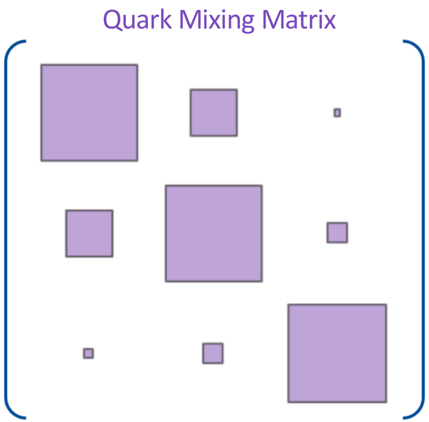


Current Measured Value : $\theta_{23} \sim 45^\circ$

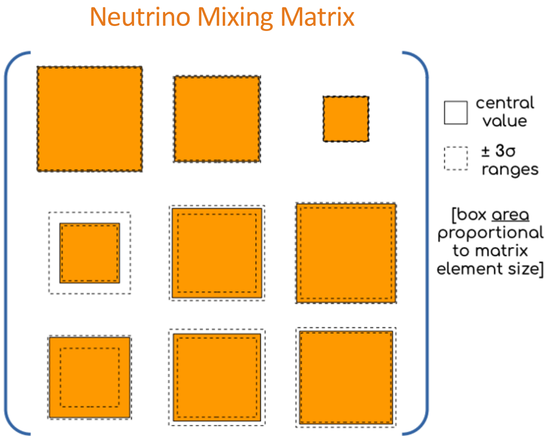
Precision : $\sin^2\theta_{23} \sim 5\%$



If $\theta_{23} = 45^\circ \rightarrow |U_{\mu 3}| = |U_{\tau 3}|$



- Values from PDG 2020



- Values from NuFIT 5.0, arXiv:2007.14792

	θ_{23}	θ_{13}	θ_{12}	δ
Leptons	$\sim 45^\circ$	8.5°	34°	?
Quarks	2.4°	0.20°	13°	69°

(some) open questions

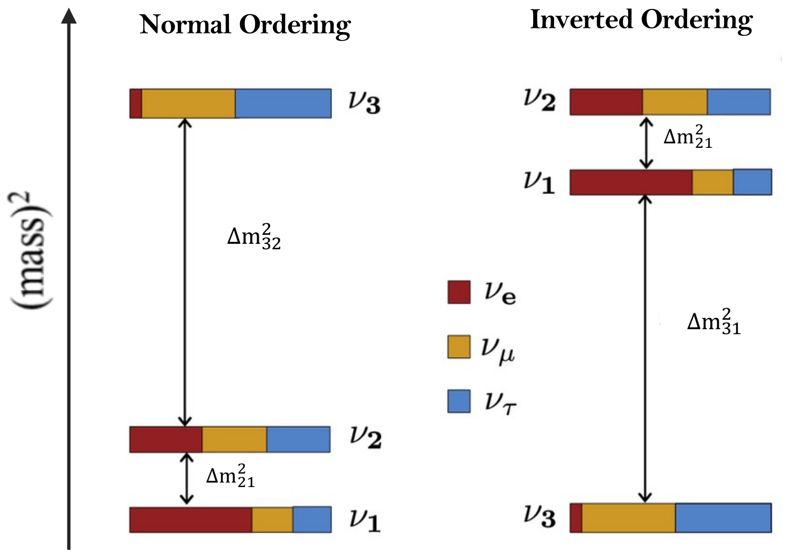
Do neutrinos violate Charge-Parity symmetry?

Do neutrinos and anti-neutrinos oscillate differently violating the CP symmetry?
Is $\sin \delta_{CP} = 0$?

Accelerator-based long-baseline oscillation experiments provide unique handle for this measurement.

(some) open questions

Which neutrino is the heaviest?

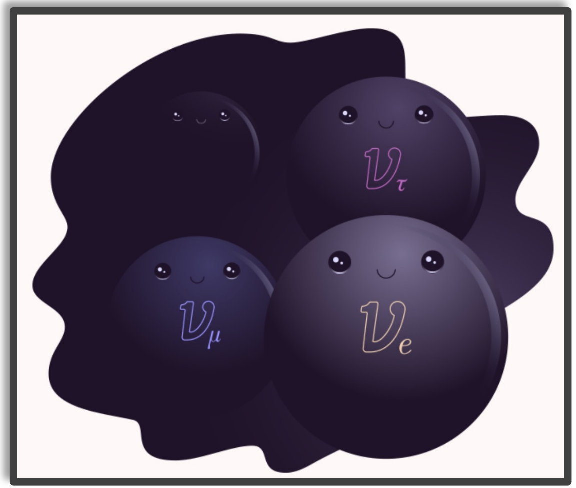


ν Mass Ordering (MO): Normal (NO) or Inverted (IO)?

Does the symmetry that determines the mass of charged leptons influences ν_1 to be the lightest neutrino or does the inverse hold?

(some) open questions

Is the 3-flavor paradigm of neutrino complete?



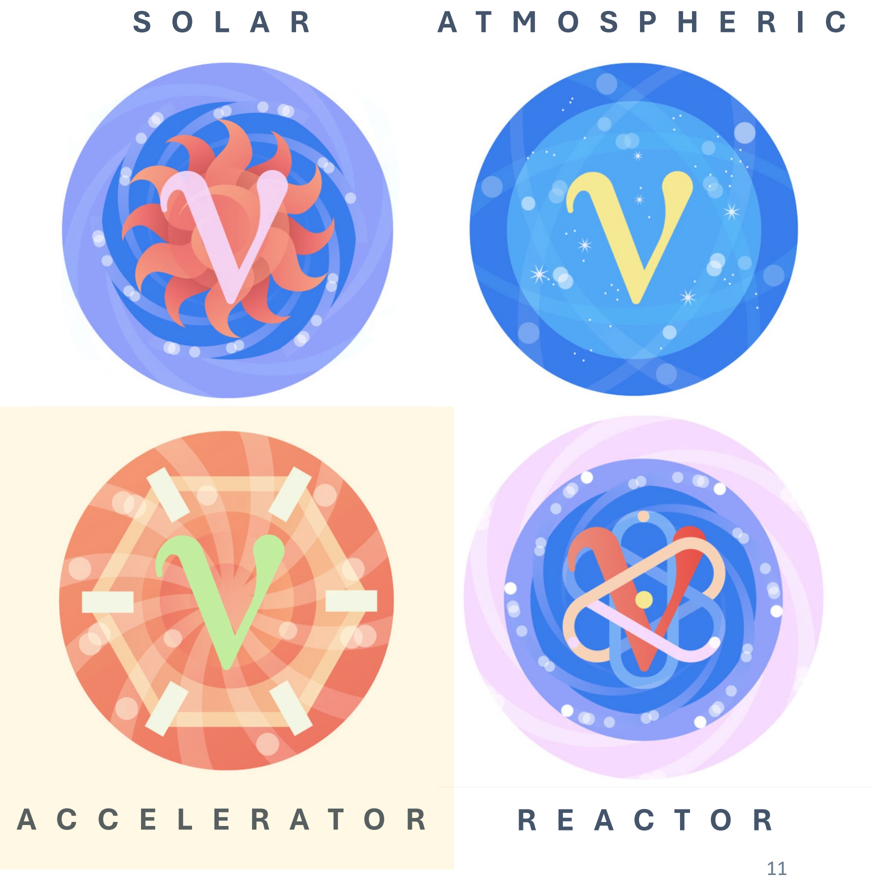
- Are there additional flavor states?
  - Heavy neutral leptons
  - Sterile neutrinos
  - Non-standard interactions
- Probing unitarity of PMNS tests robustness of 3-flavor framework!

2

Accelerator neutrinos

Why accelerator neutrino beams?

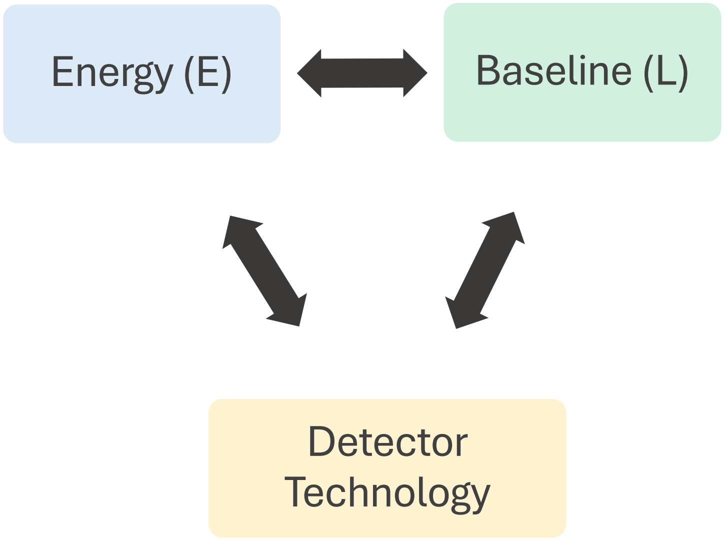
- Known flavor content (mostly $\boldsymbol{\nu_\mu}$)
- Known direction, timing, and start time
- Switchable $\nu/\,\overline{\nu}$
- Tunable energy
- High intensity → statistics



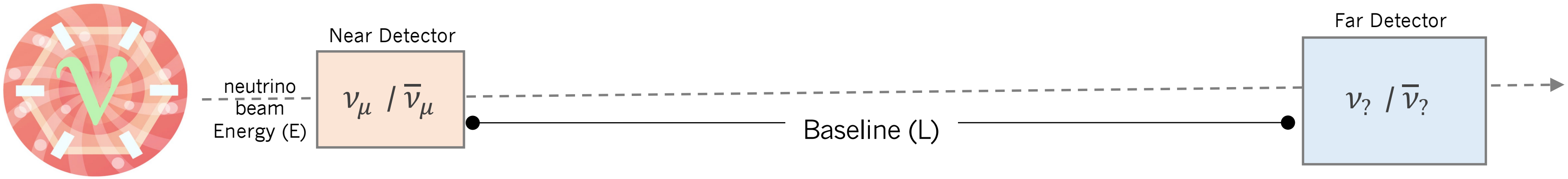
Tamest of them all

✓ CUSTOM ✗ DEFAULT

Source	Energy	Baseline	Detector Technology
Solar	✗	✗	✓
Atmospheric	✗	✗	✓
Reactor	✗	✓	✓
Accelerator	✓	✓	✓



How to build an accelerator neutrino oscillation experiment?



Items Needed

◯	One Neutrino Beam
◯	Two Neutrino Detectors

How to make a neutrino beam

STEP 1: GRAB SOME PROTONS

STEP 2: AIM

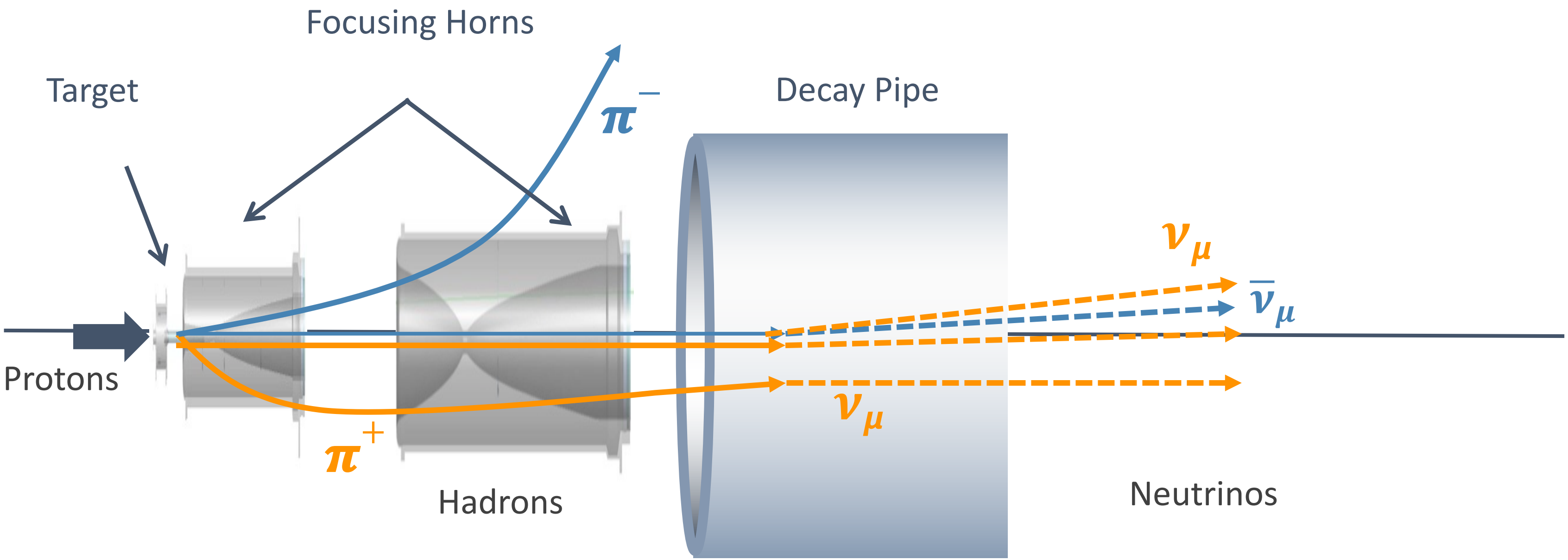
STEP 3: SMASH THINGS

STEP 4: FOCUS THE DEBRIS

STEP 5: PHYSICS HAPPENS

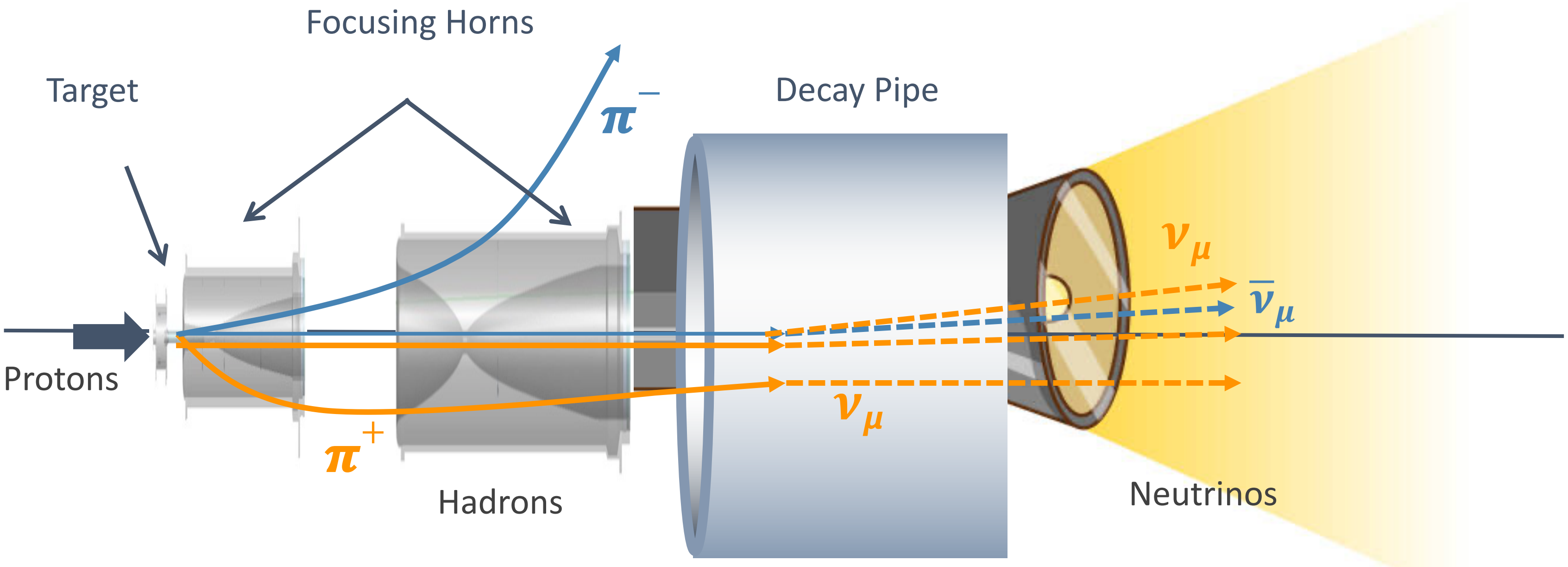
Symmetry Article YouTube how-to

How to make a neutrino beam



- Reversing the polarity of the focusing horn magnets changes the sign selection of pions, resulting in a beam enhanced in antineutrinos.

How to make a neutrino ~~beam~~ FLASHLIGHT



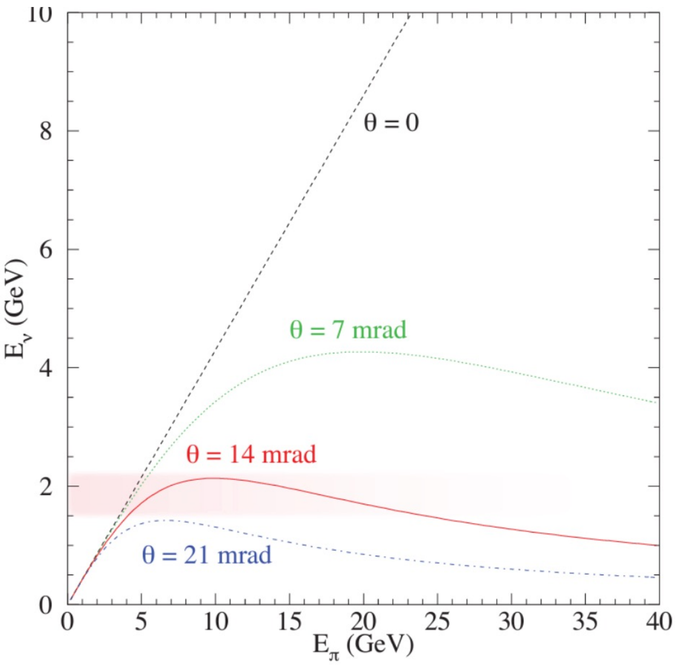
Slide inspiration Tricia Vahle

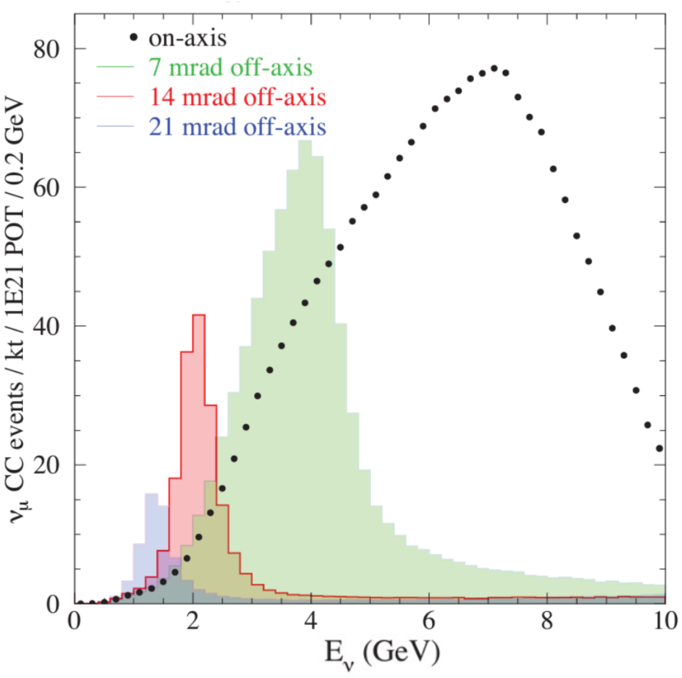
- The neutrino beam produced is analogous to a flashlight beam— spread out in space and over a range of energies, rather than being narrowly focused or monoenergetic.

The Off-Axis Beam: Tunable E

$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2} \qquad \gamma = E_\pi/m_\pi$$

$\boldsymbol{\theta}$ is the angle between the pion and neutrino direction





The Off-Axis Beam: Tunable E

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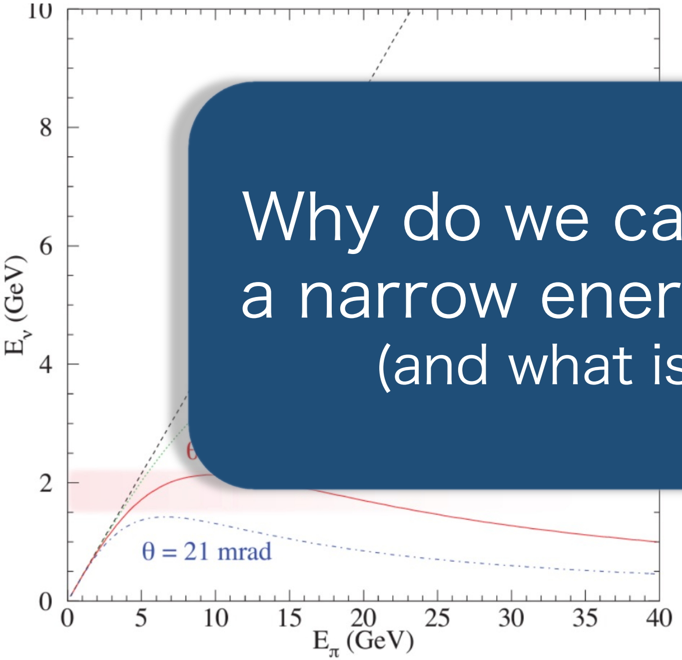
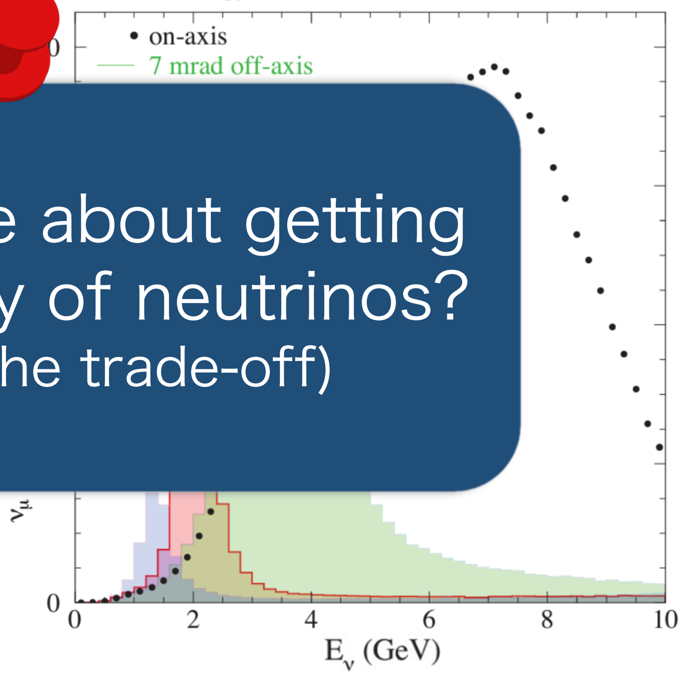


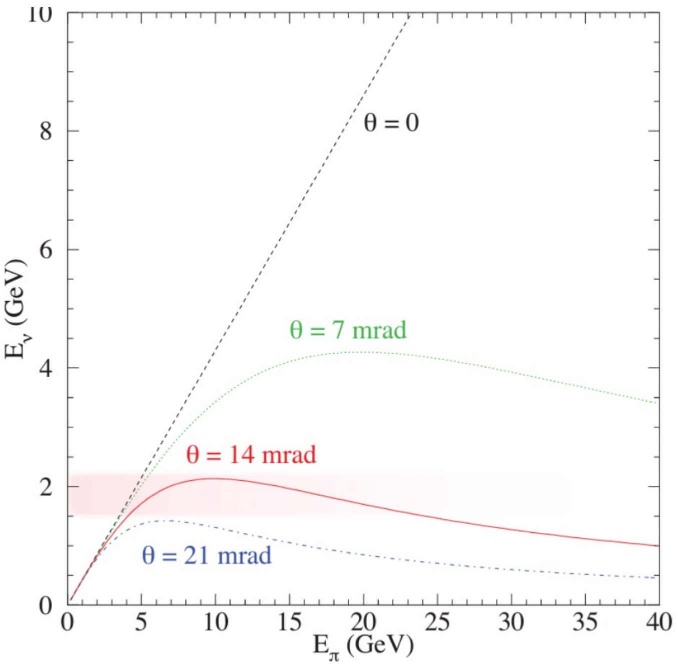


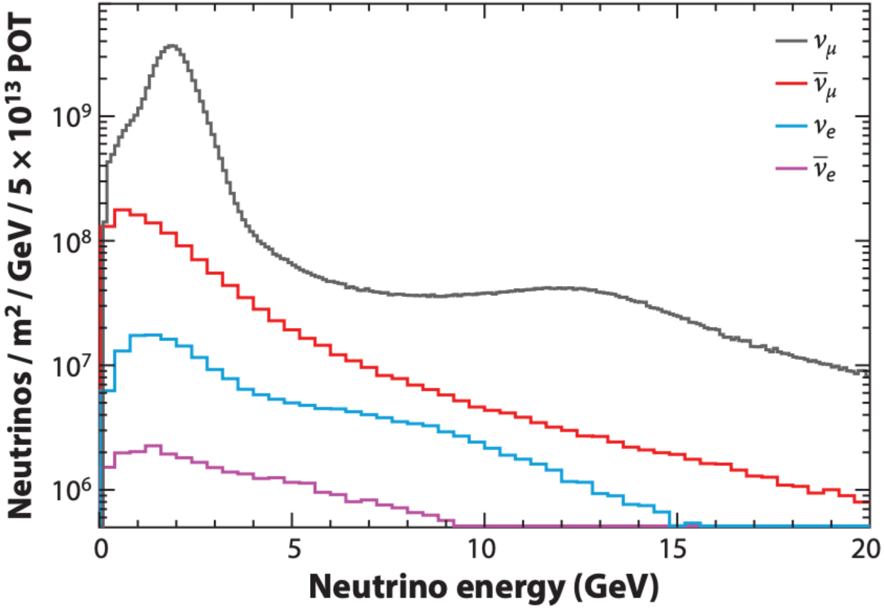
Why do we care about getting a narrow energy of neutrinos?

(and what is the trade-off)

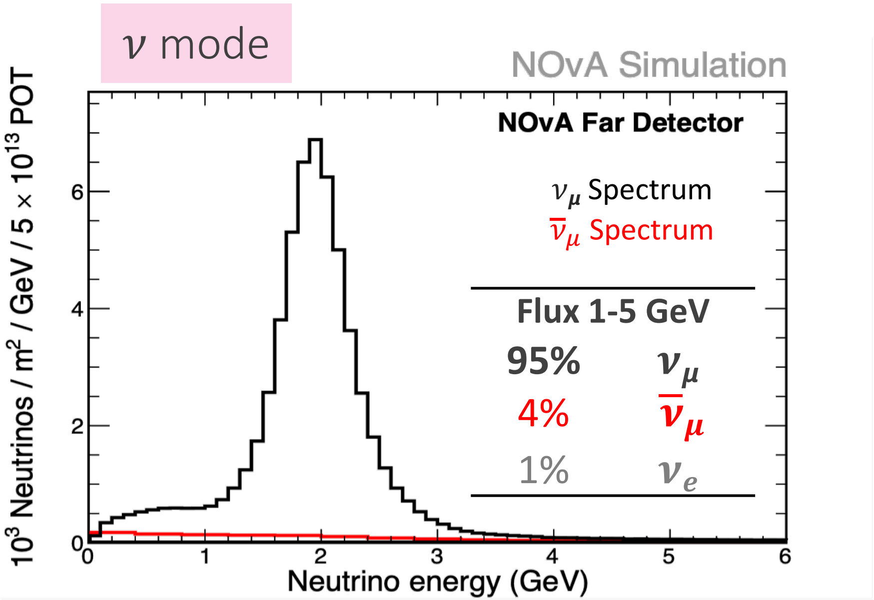
The Off-Axis Beam: Flavor Content

The off-axis angle also has a small impact on the flavor content of the beam.



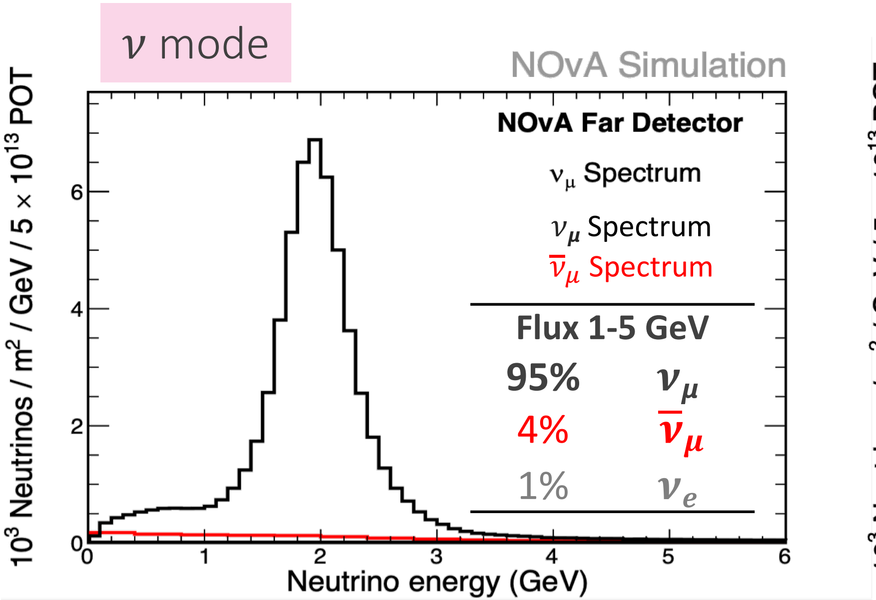


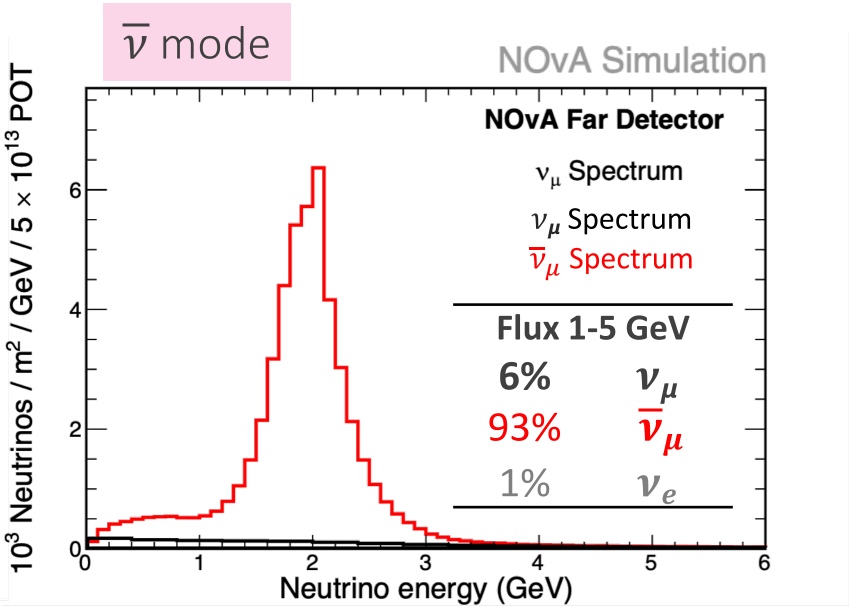
Neutrino Beam: Flavor Content



- NOvA sitting at 14 mrad off-axis to NuMI beam, gets a highly pure beam of muon neutrinos peaked at 2 GeV.

Neutrino Beam: Flavor Content

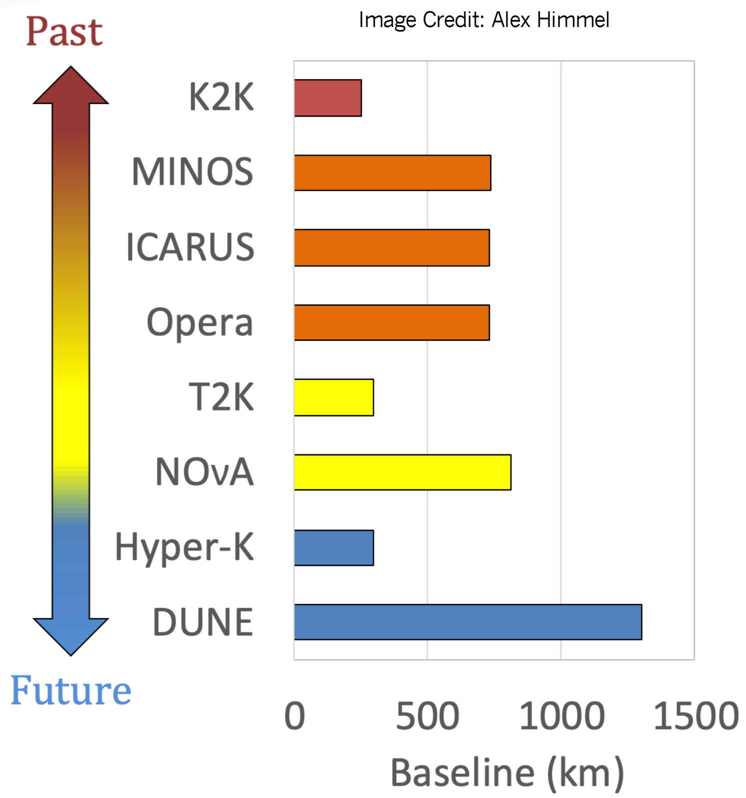




- Accelerators neutrino beams are overall highly pure, with some contamination from wrong-sign and intrinsic ν_e background.

3 Anatomy of a long-baseline experiment

How long is the "long-baseline"?



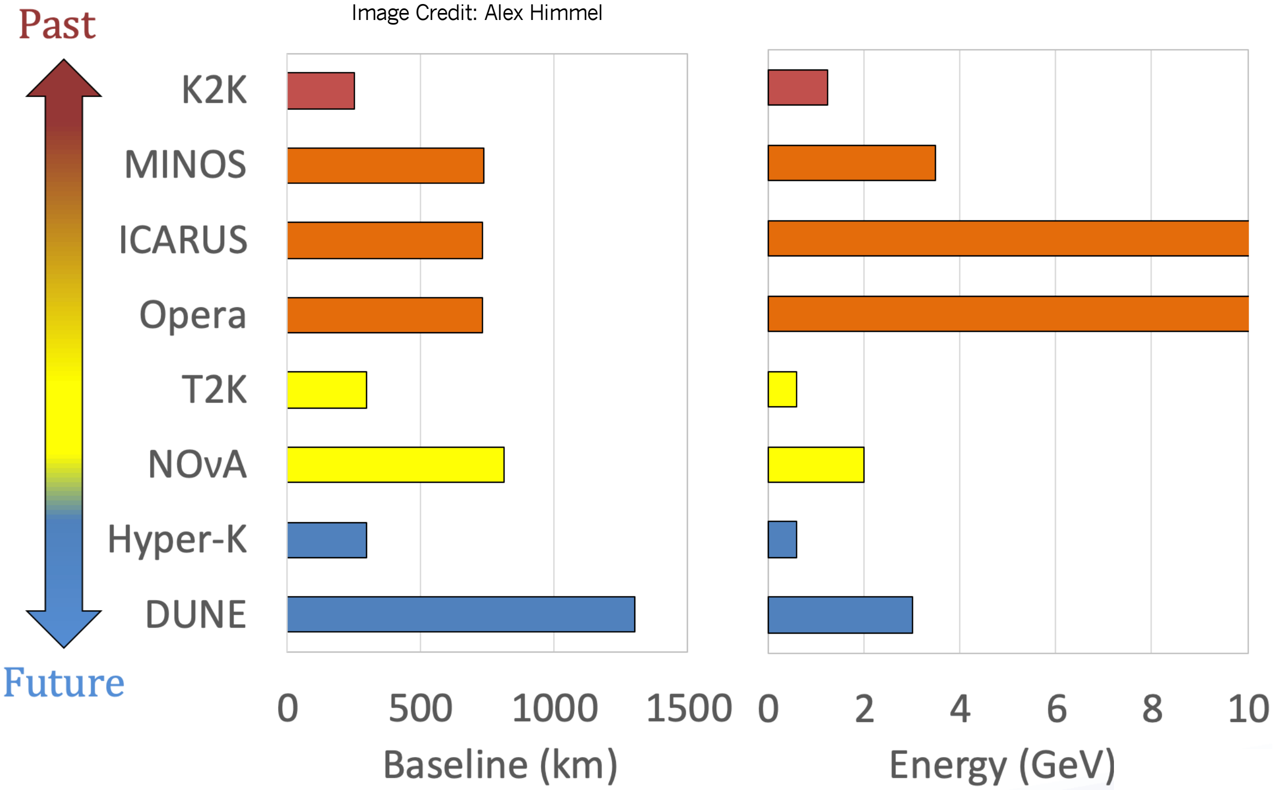
- 100-1000s of km.
- How do we pick L?

Choosing L and E:

Energy (E) ⟷ Baseline (L)

Detector Technology

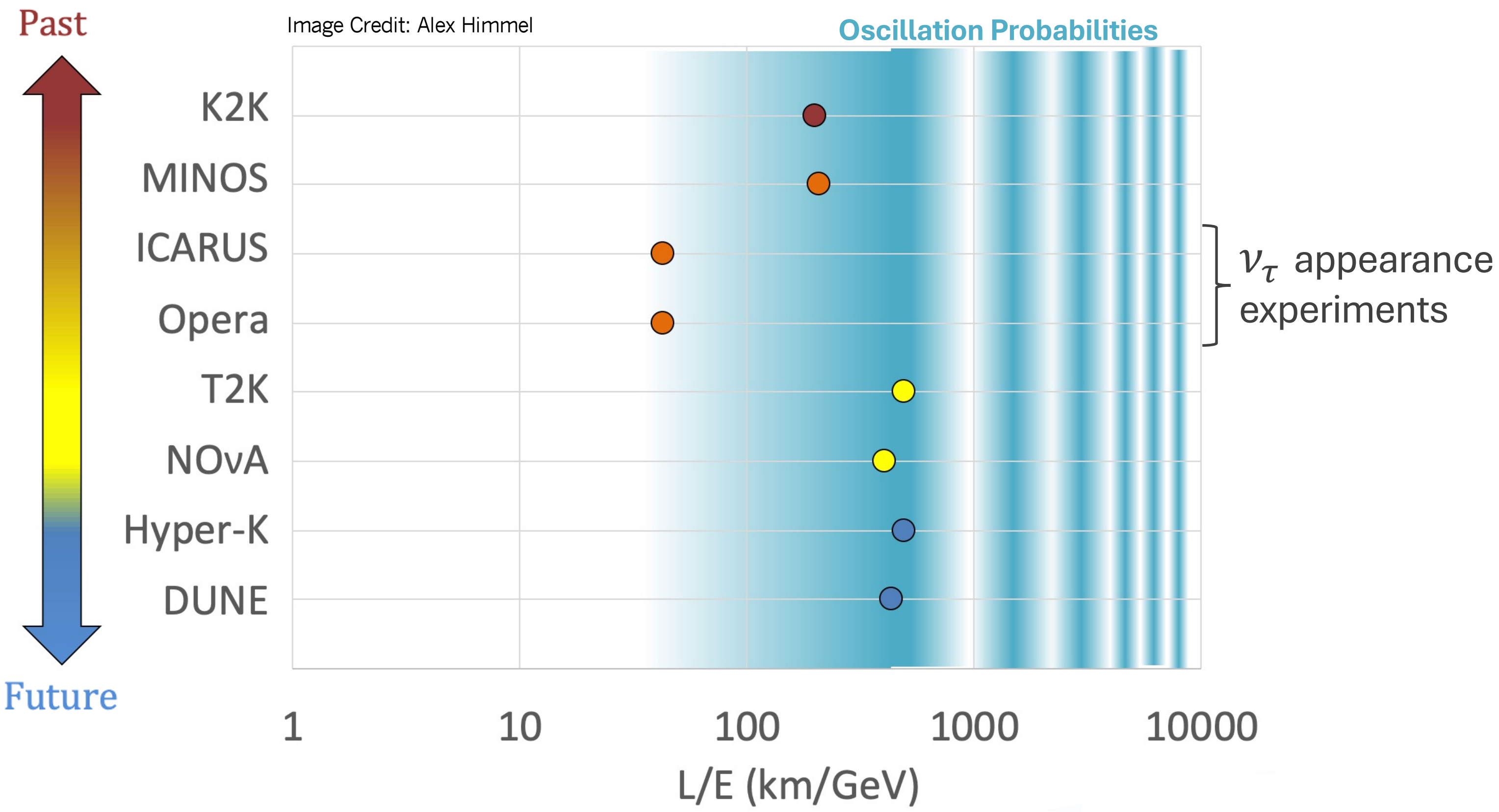
Image Credit: Alex Himmel



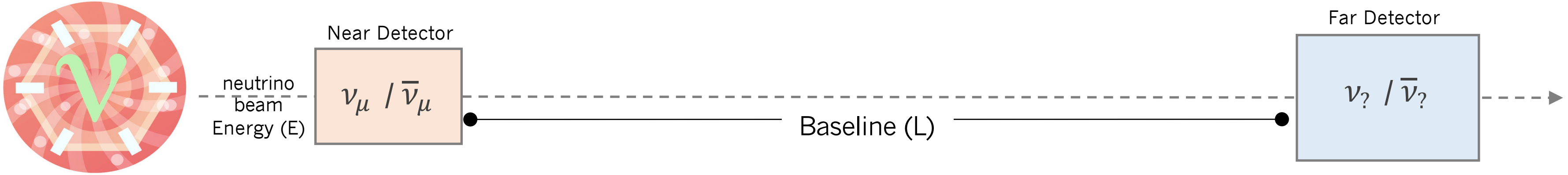
- Must pick all three together.

Choosing L/E:

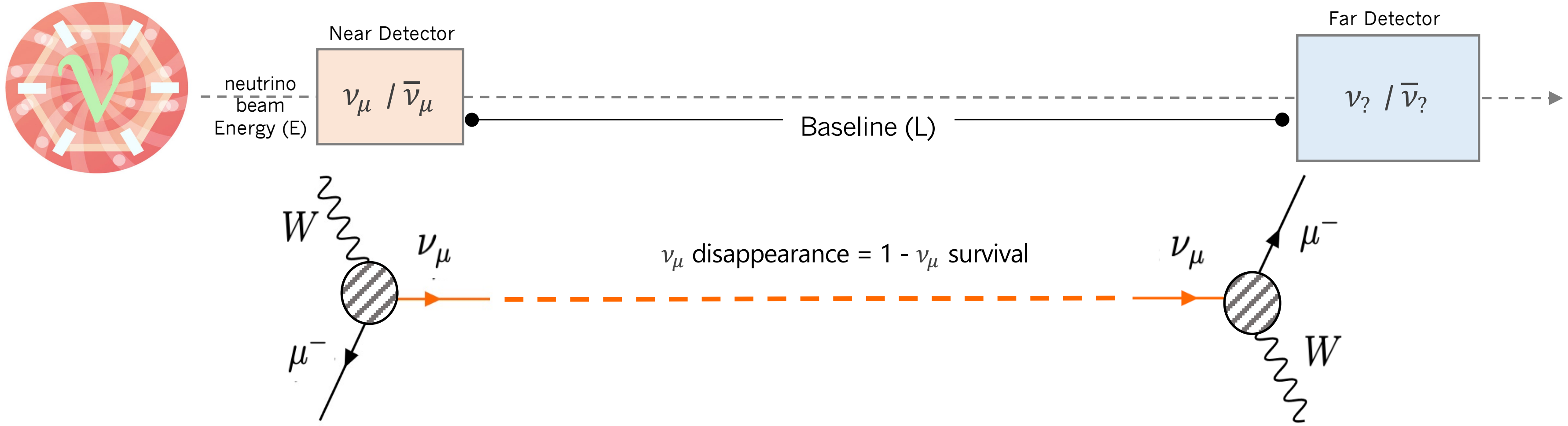
- Fix L/E at the first oscillation maximum
- Longer L → higher E at the maximum



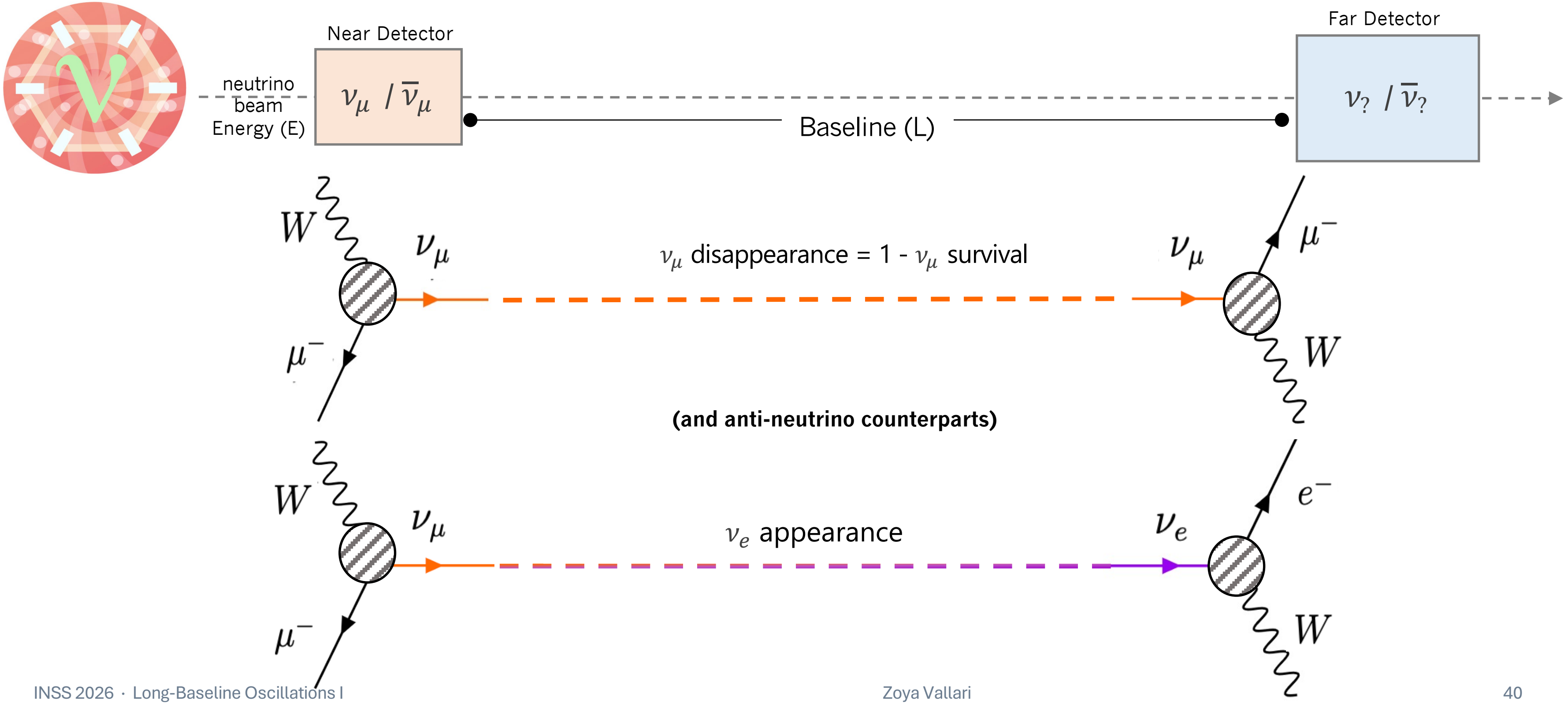
Measuring Oscillations



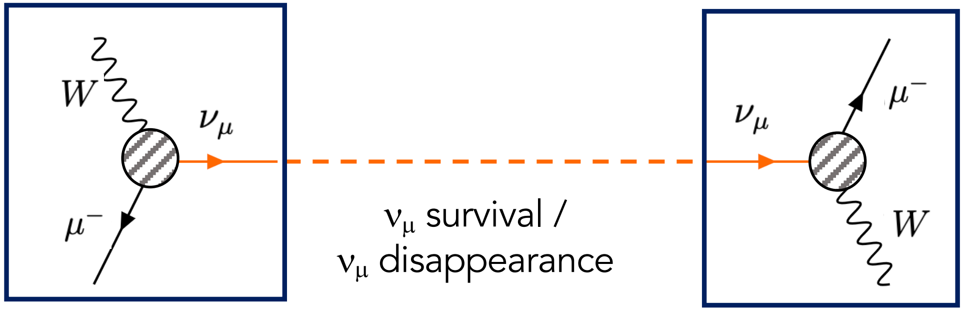
Measuring Oscillations

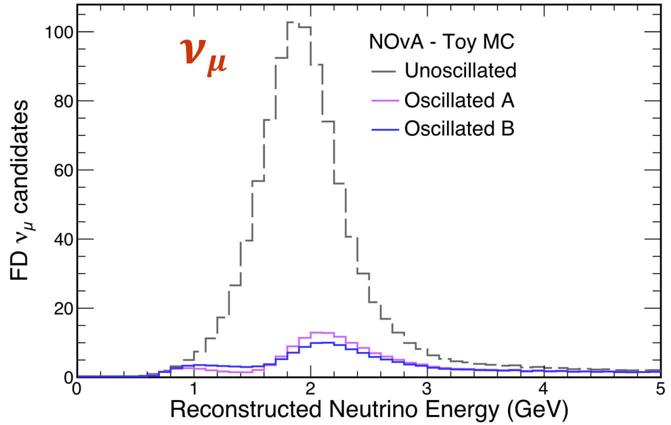


Measuring Oscillations



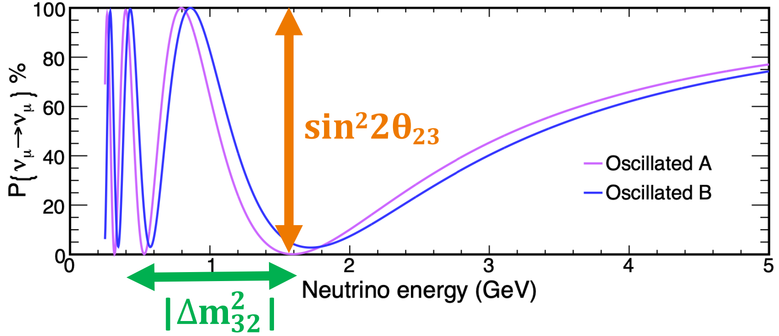
ν_μ Disappearance Channel





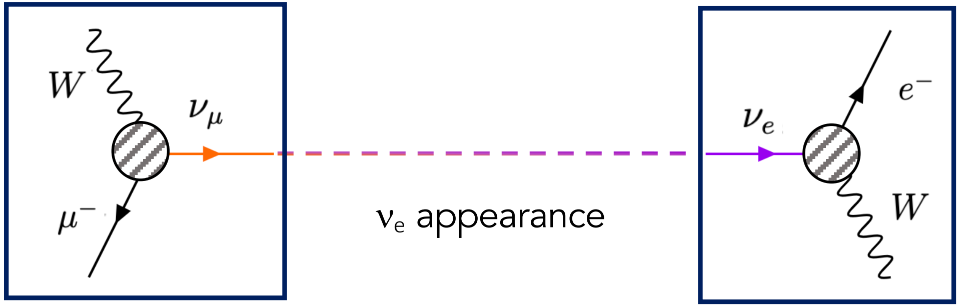
NOvA: L= 810 km

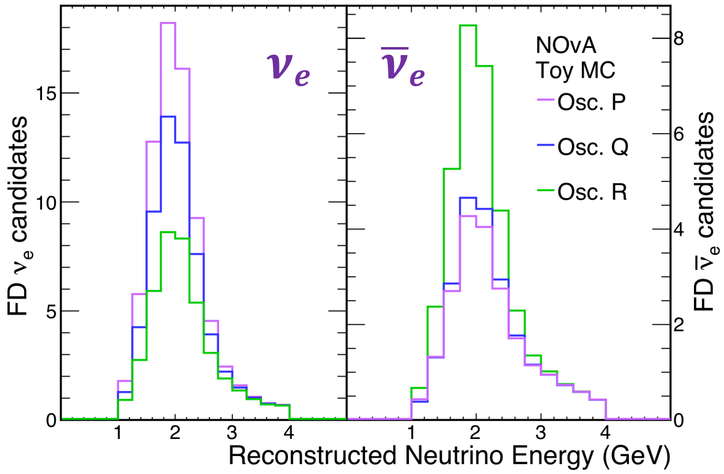
$$P\left(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu\right) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$



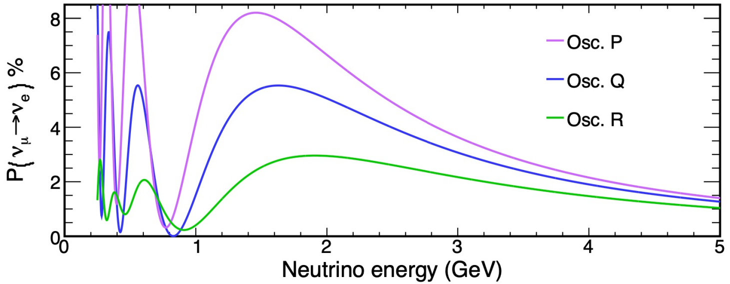
- Leading order dependence on $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$
- If $\sin^2 2\theta_{23} = 1$, then maximal ν_μ disappearance.

ν_e Appearance Channel





NOvA: L= 810 km



Mixing angles

Mass Ordering and $|\Delta m^2_{32}|$

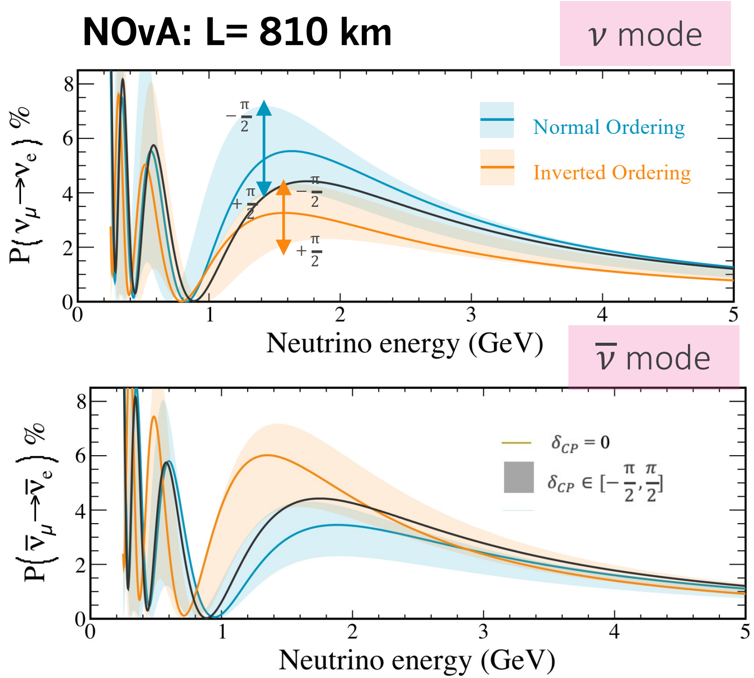
CP Phase δ_{CP}

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31} \times \frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

- Both Matter effect and $\boldsymbol{\delta_{CP}}$ term create asymmetry in ν_e vs $\bar{\nu}_e$ appearance probability.

Matter Effect matters

NOvA: L= 810 km



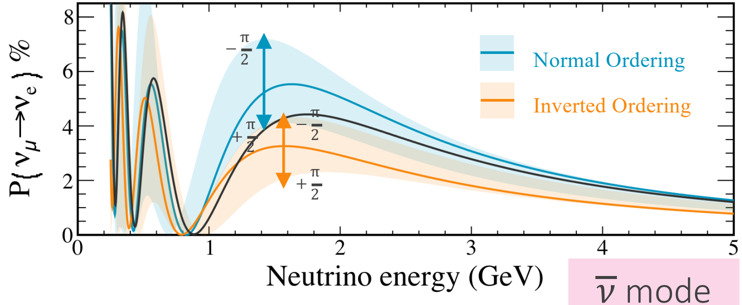
- Coherent forward scattering on electrons modifies oscillation probability
- Effect grows with E x L
  - longer baselines feel it more
- Opposite sign for ν_e vs. $\bar{\nu}_e$
- Switches based on the neutrino mass ordering

- Both Matter effect and $\boldsymbol{\delta_{CP}}$ term create asymmetry in ν_e vs $\bar{\nu}_e$ appearance probability.

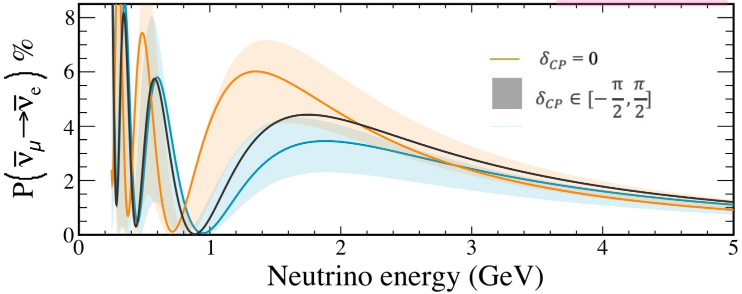
ν_e and $\bar{\nu}_e$ Appearance Channel

NOvA: L= 810 km

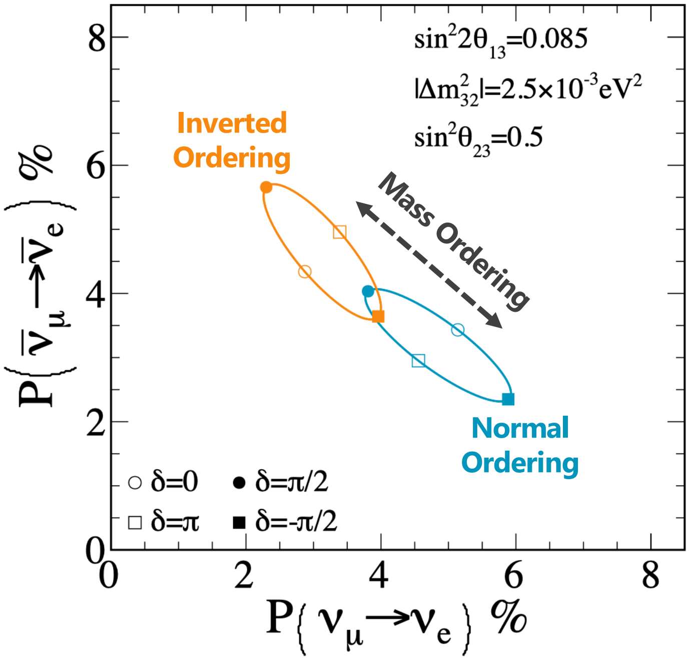
ν mode



$\bar{\nu}$ mode

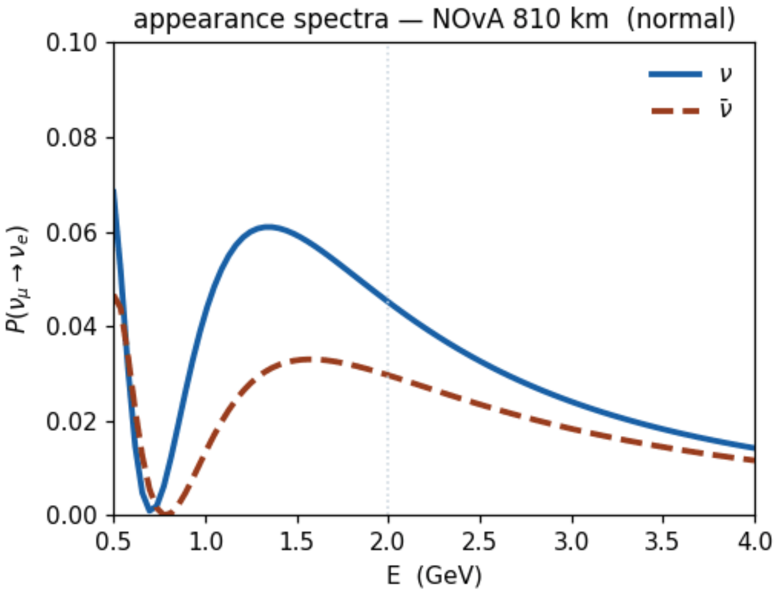


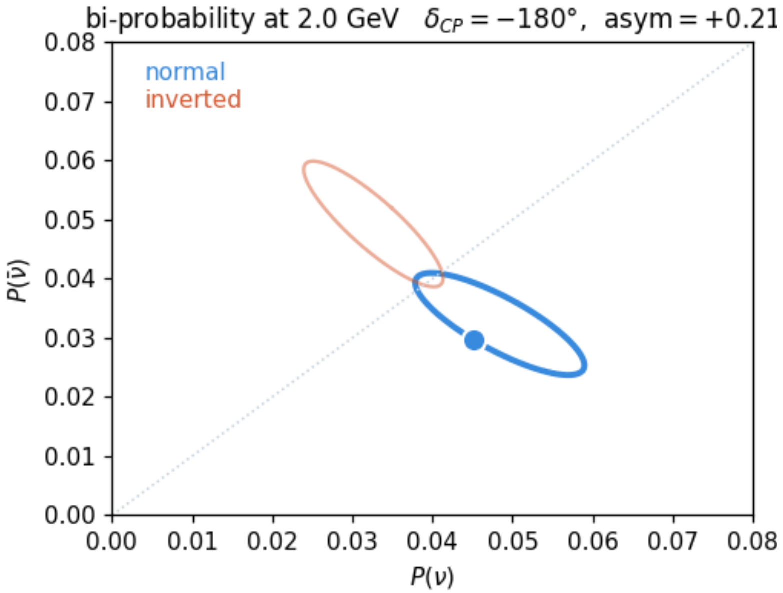
NOvA: L= 810 km, E = 2.0 GeV



- Both Mass Ordering and $\boldsymbol{\delta_{CP}}$ term create asymmetry in ν_e vs $\bar{\nu}_e$ appearance probability.

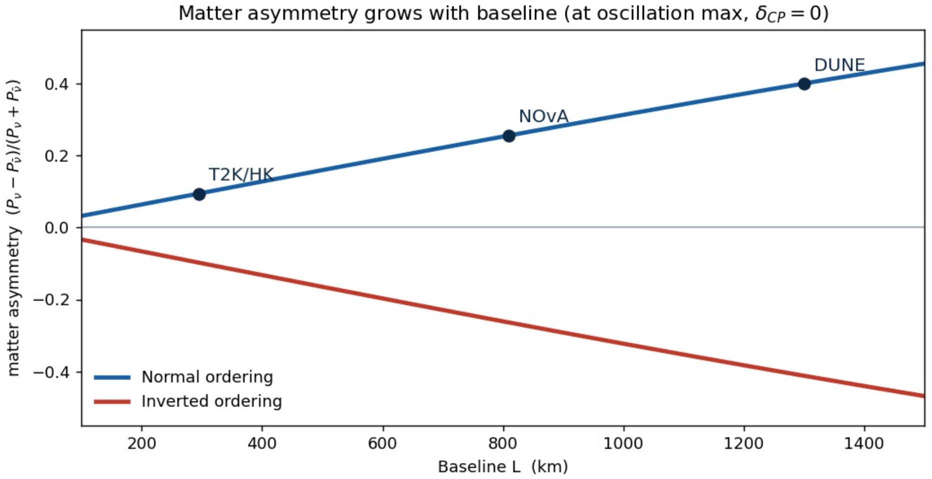
ν_e and $\bar{\nu}_e$ Appearance Channel: Degeneracies

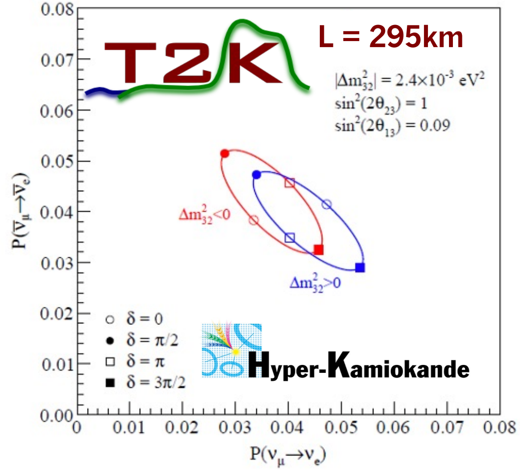


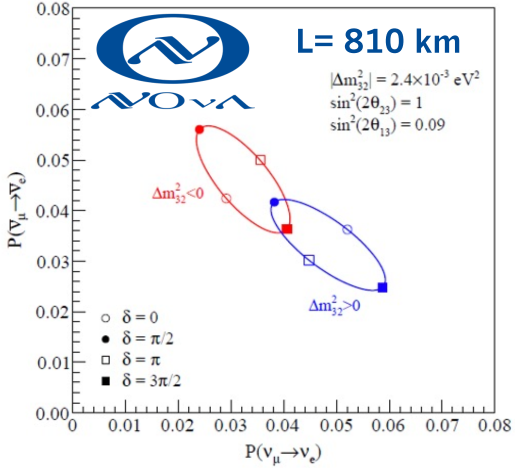


- Both Mass Ordering and $\boldsymbol{\delta_{CP}}$ term create asymmetry in ν_e vs $\bar{\nu}_e$ appearance probability.

ν_e and $\bar{\nu}_e$ Appearance Channel: Degeneracies







- Choosing L and E impacts how far away the two mass ordering ellipses are from each other.

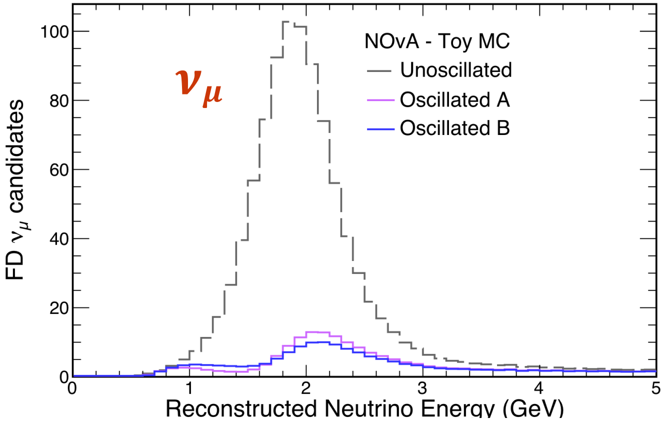
Summary: Measuring Oscillations

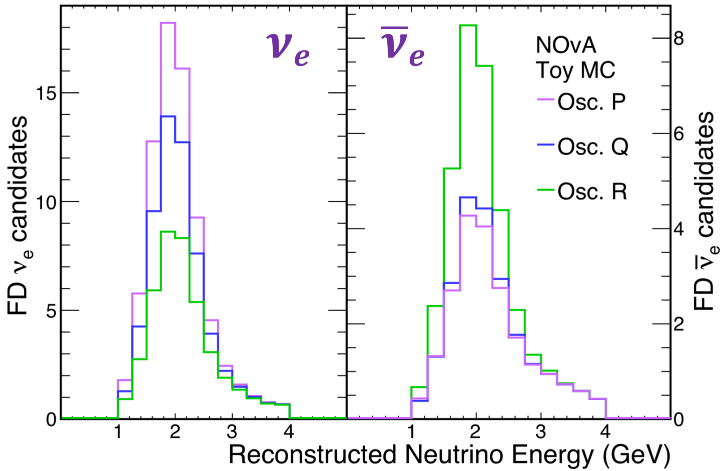
Measurement

1. **Detect** neutrino interactions.
2. **Tag** the flavor.
3. **Reconstruct** energy.

Inference

1. Compare with the no oscillation prediction.
2. Compare ν_e and $\bar{\nu}_e$ appearance rate.

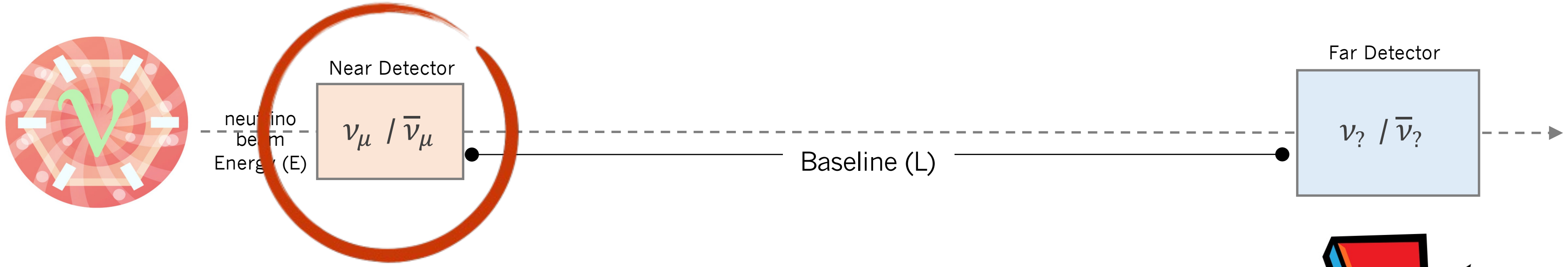




4

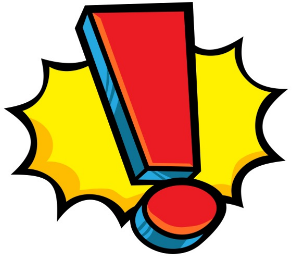
Near detector

Measuring Oscillations



Neutrino beam of Energy E

What is this detector doing here?

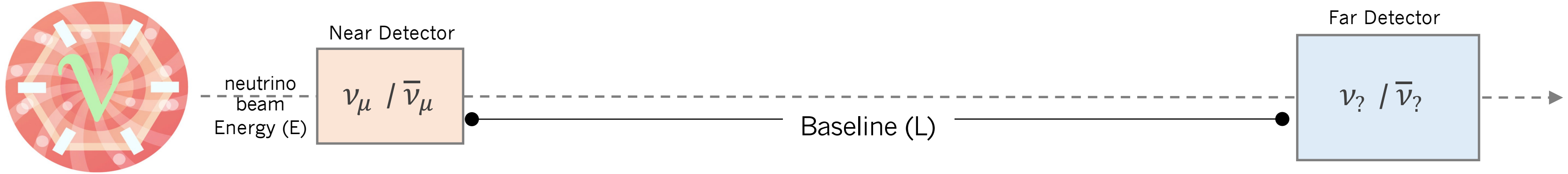


Measure oscillations at the Baseline L

Measuring Oscillations

Sample the beam before oscillations

Measure oscillations at the Baseline L



Neutrino beam of Energy E

$$P(\nu_\alpha \to \nu_\beta,\ E_\nu) = \frac{\Phi_\beta^{FD}(E_\nu,\ \vec{\theta})}{\Phi_\alpha^{ND}(E_\nu)}$$

where $\boldsymbol{\theta}$ are the oscillation parameters

Measuring Oscillations

- But detectors see neutrino events which is a product of flux, cross-section, and detector acceptance.

$$N_\beta^{FD}(E_\nu) = \Phi_\beta^{FD}(E_\nu, \vec{\theta}) \times \sigma_\beta(E_\nu) \times \epsilon_\beta^{FD}(E_\nu)$$

# of neutrino events — **neutrino flux** — **cross-section** — **detector response**

$$N_\alpha^{ND}(E_\nu) = \Phi_\alpha^{ND}(E_\nu) \times \sigma_\alpha(E_\nu) \times \epsilon_\alpha^{ND}(E_\nu)$$

Measuring Oscillations

- Moreover, experimentalists measure reconstructed energy E_{rec} which is related to E_ν by a smearing matrix S.

$$N_\beta^{FD}(E_{rec}) = \int dE_\nu \, \Phi_\beta^{FD}(E_\nu, \vec{\theta}) \times \sigma_\beta(E_\nu) \times \epsilon_\beta^{FD}(E_\nu) \times \mathbf{S}_\beta^{FD}(E_\nu \to E_{rec})$$

# of neutrino events

neutrino flux · **cross-section** · **detector response** · **detector smearing**

$$N_\alpha^{ND}(E_{rec}) = \int dE_\nu \, \Phi_\alpha^{ND}(E_\nu) \times \sigma_\alpha(E_\nu) \times \epsilon_\alpha^{ND}(E_\nu) \times \mathbf{S}_\alpha^{ND}(E_\nu \to E_{rec})$$

Role of the Near Detector

$$N_\beta^{FD}(E_{rec}) = \int dE_\nu \, \Phi_\beta^{FD}(E_\nu, \vec{\theta}) \times \sigma_\beta(E_\nu) \times \epsilon_\beta^{FD}(E_\nu) \times \mathbf{S}_\beta^{FD}(E_\nu \to E_{rec})$$

$$N_\alpha^{ND}(E_{rec}) = \int dE_\nu \, \Phi_\alpha^{ND}(E_\nu) \times \sigma_\alpha(E_\nu) \times \epsilon_\alpha^{ND}(E_\nu) \times \mathbf{S}_\alpha^{ND}(E_\nu \to E_{rec})$$

- Near Detector provides valuable data-driven cancelation and constraints on:
  - **neutrino flux**
  - **cross-section**, and
  - **detector uncertainties**

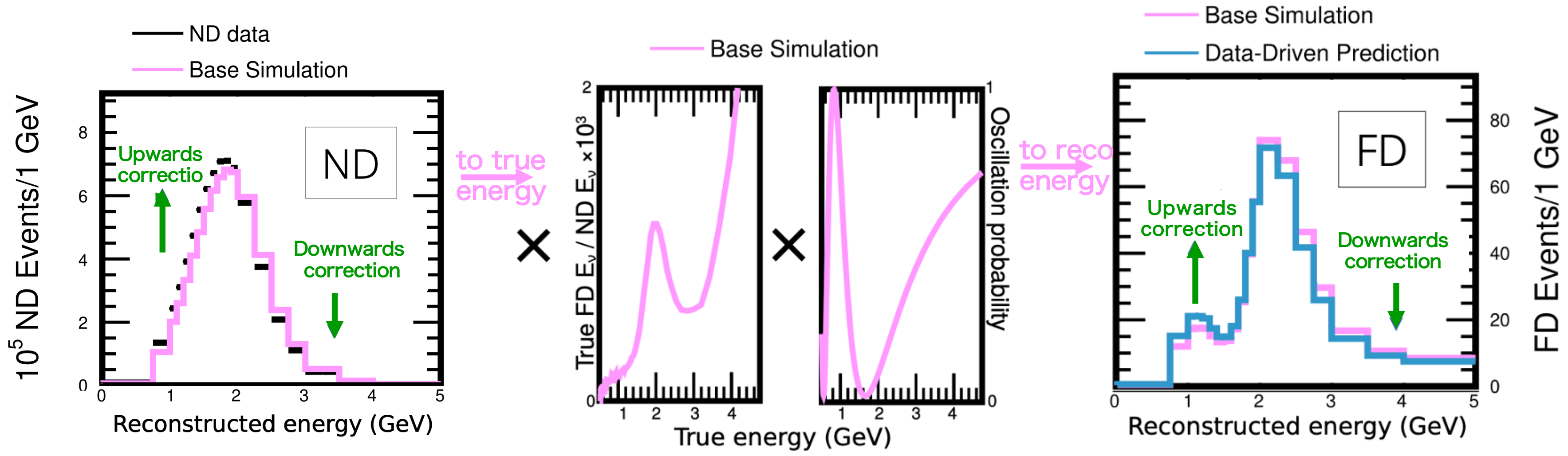
Never go on a long baseline adventure without a near detector – Anonymous.

Role of the Near Detector

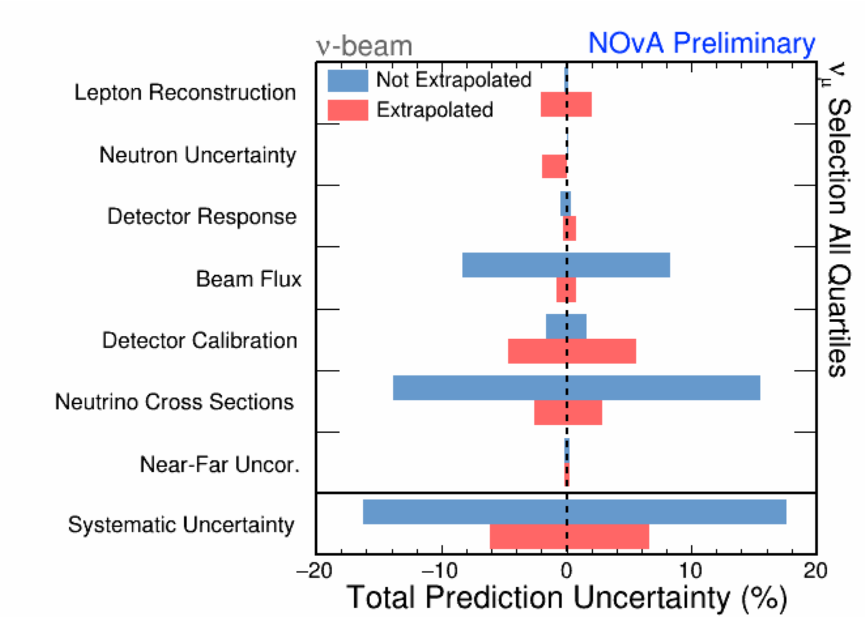
- Leverage high statistics near detector to build data-driven FD predictions
- Example: NOvA's extrapolation technique

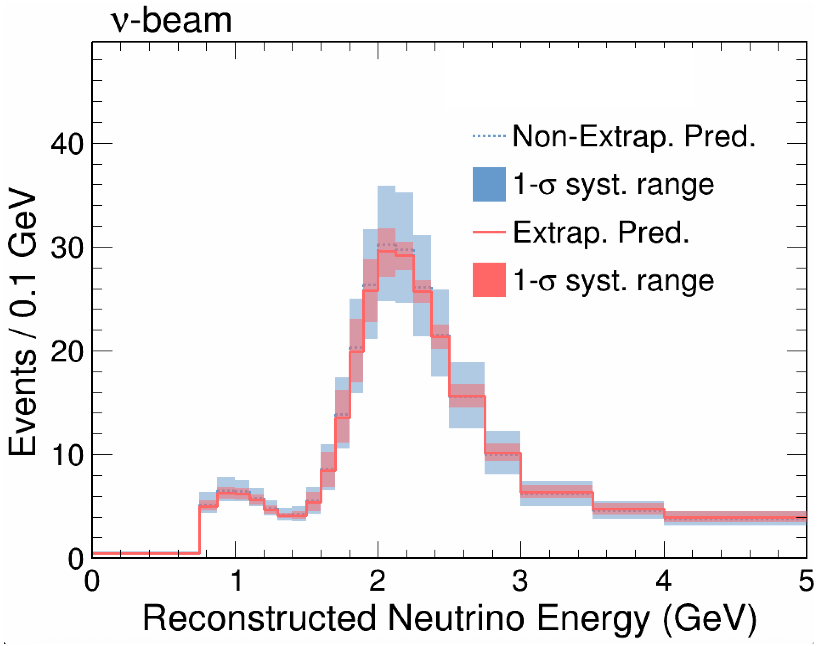
$$ND^{data}\left[\frac{\text{Far/Near}}{\text{Transformations}}\right] = FD^{pred}$$

High statistics ND data | **From simulation** | **data-driven FD predictions**



Role of the Near Detector: Systematics





Example: Systematic uncertainties on the ν_μ candidate count without ND vs with ND constraints

Measuring Oscillations

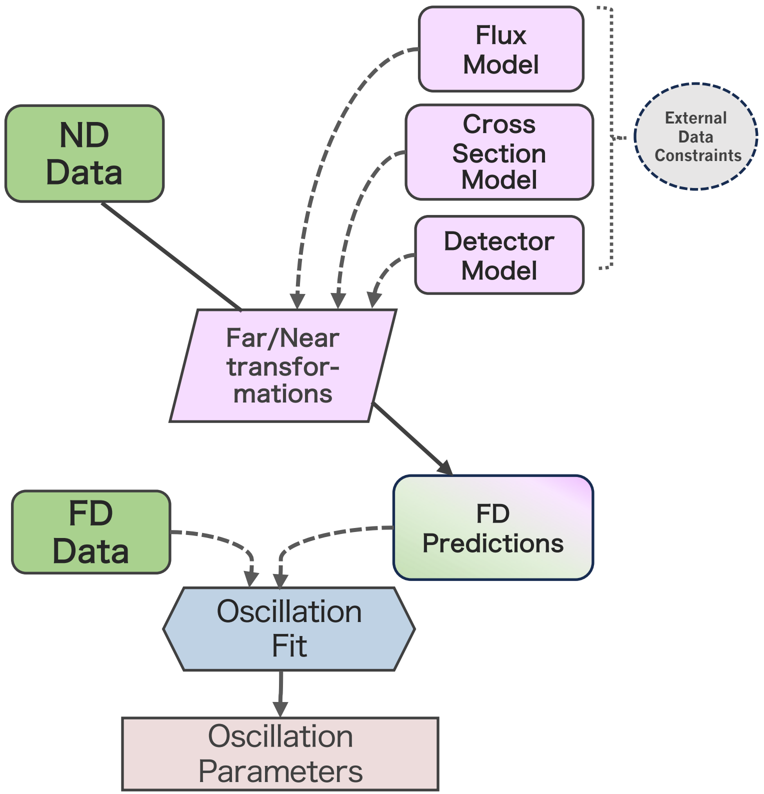
$$\mathrm{ND}^{\mathrm{data}} \left[\begin{matrix} \mathrm{Far/Near} \\ \mathrm{Transformations} \end{matrix} \right] = \mathrm{FD}^{\mathrm{pred}}$$

High statistics ND data

From simulation

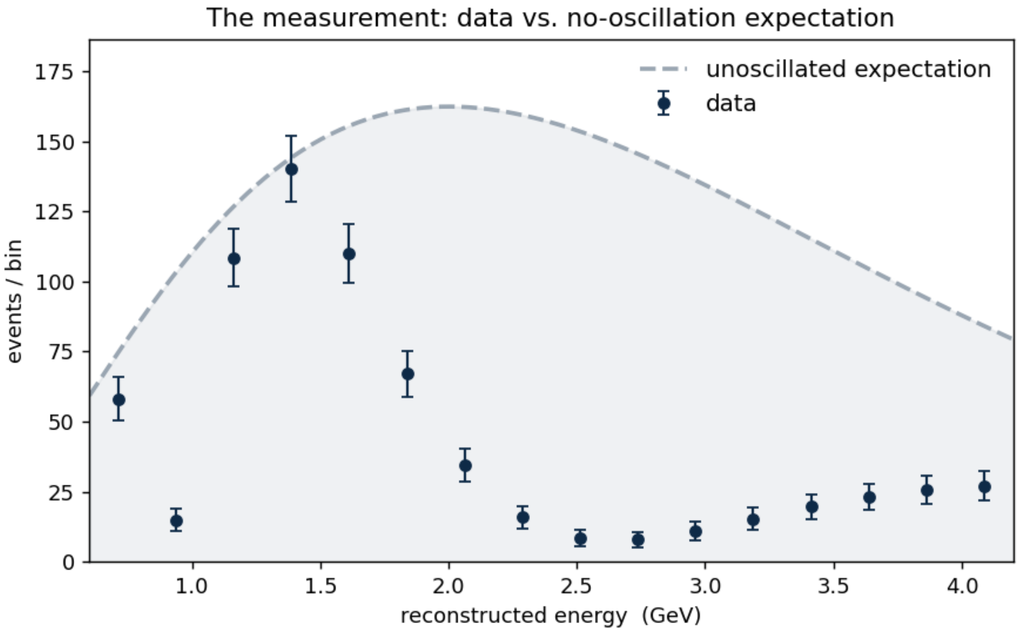
data-driven FD predictions

- The ND data anchors the FD prediction and reduces the impact of systematics.
- The fit to FD data yields the oscillation parameter measurements.



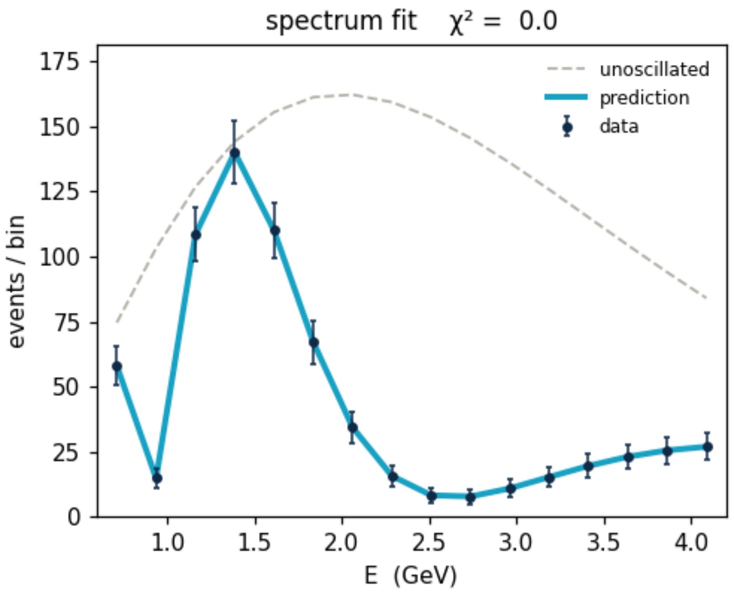
5 From datasets to contours

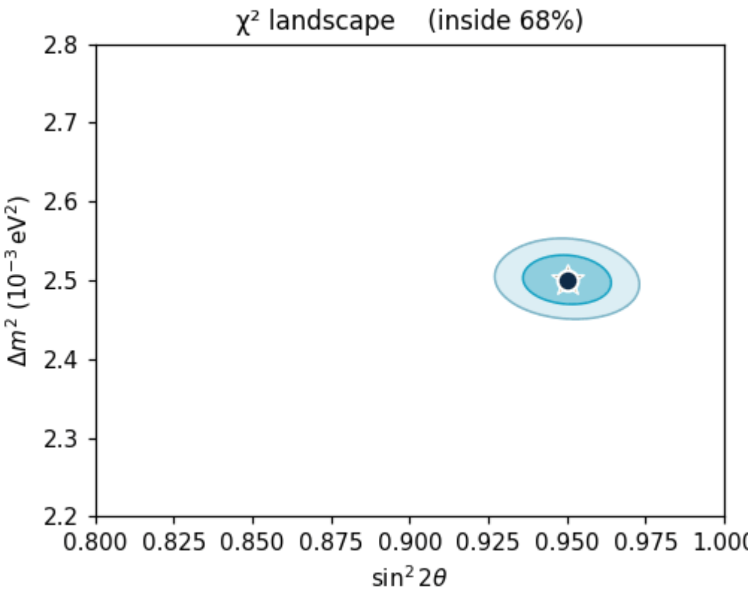
From event spectra to a measurement: toy dataset



- Vary the oscillation parameters (parameter-of-interests) and the systematics parameters (nuisance parameters) to minimize the log-likelihood.
- Two statistical methods:
  - Frequentist: χ^2 / likelihood → confidence regions
  - Bayesian: posterior → credible regions
  - Both appear in experimental results

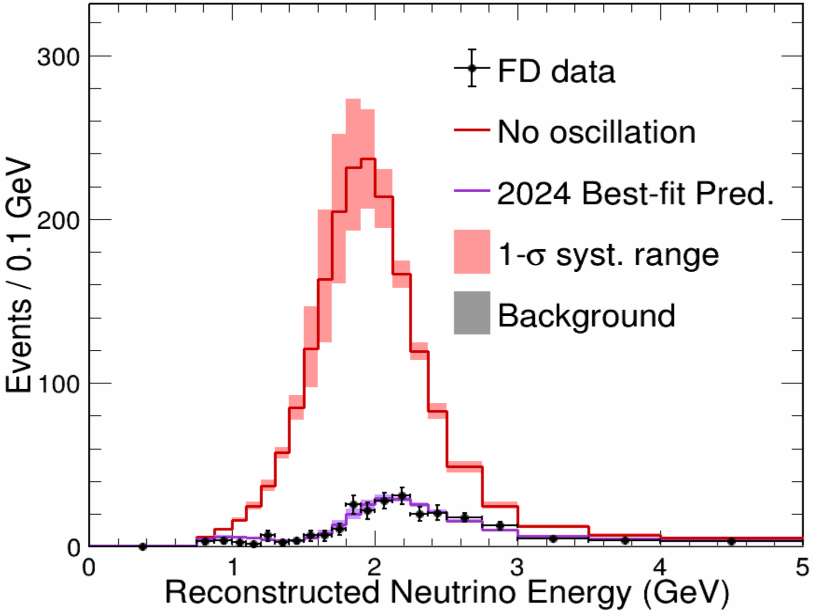
From event spectra to a measurement: toy dataset



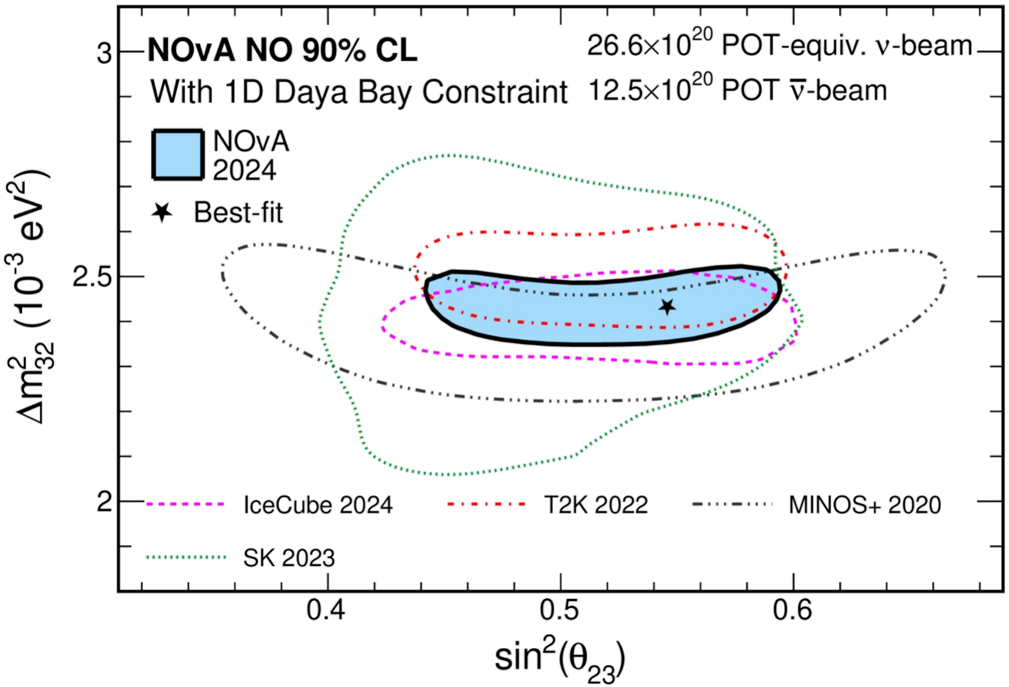


ν_μ disappearance: NOvA dataset

ν mode

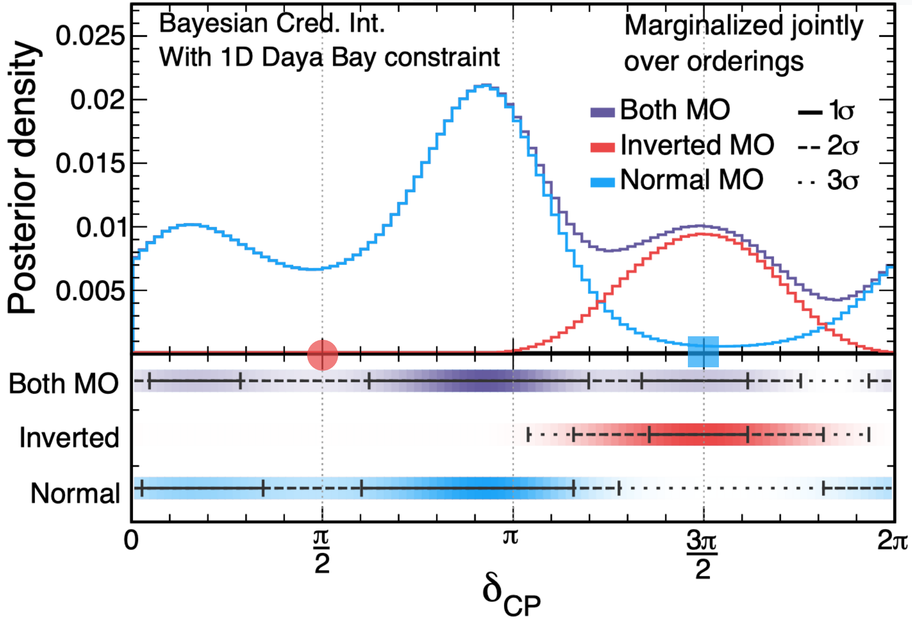


NOvA PRL 136, 01180 (2026)

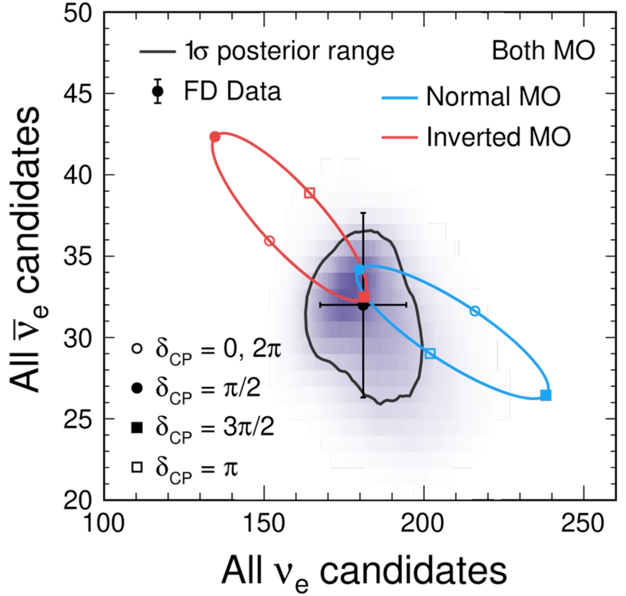


ν_e appearance: NOvA dataset

NOvA PRL 136, 01180 (2026)



181 ν_e candidates

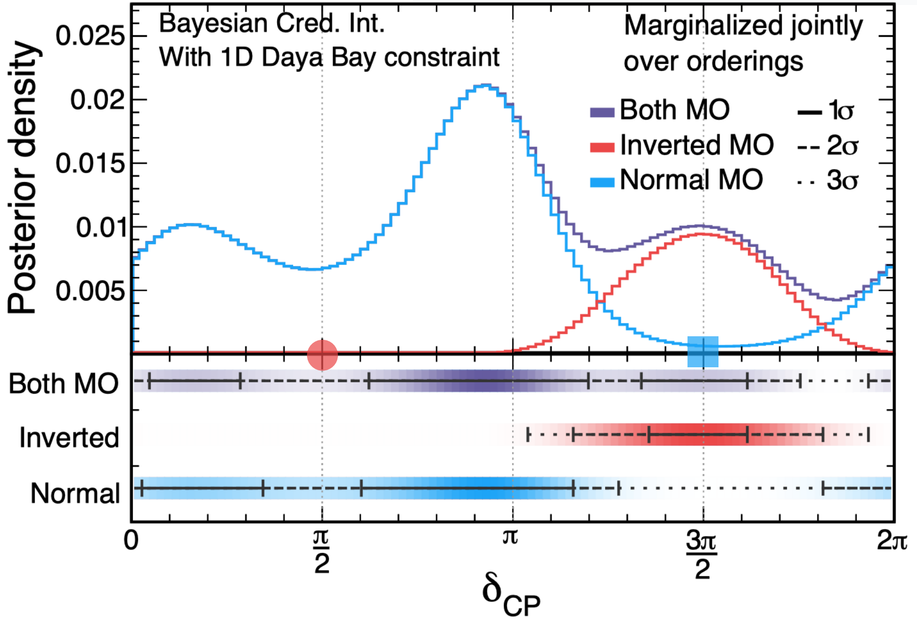


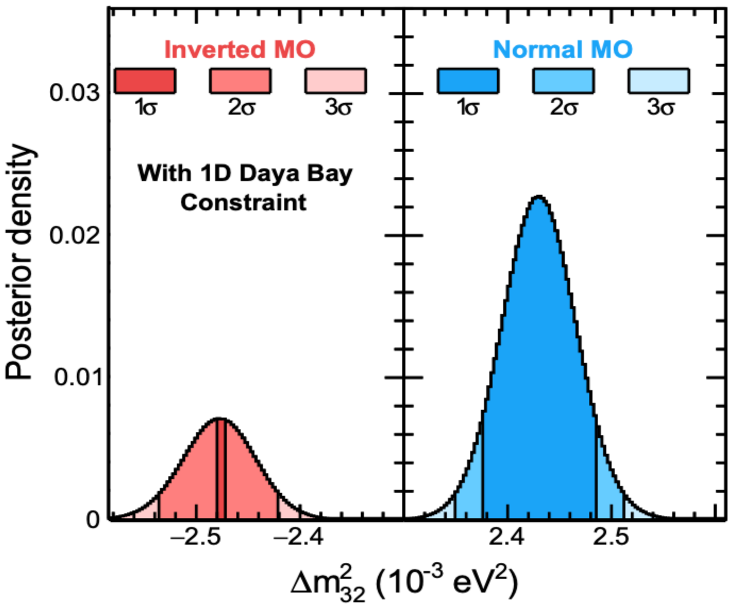
32 $\bar{\nu}_e$ candidates

- Disfavors asymmetric combinations of (MO, $\boldsymbol{\delta_{CP}}$): (NO, 3π/2) at ~2.5σ, (IO, π/2) at > 4σ

ν_e appearance: NOvA dataset

NOvA PRL 136, 01180 (2026)





- NOvA data show a preference for NO (77% posterior):IO (23% posterior)
- Gives a Bayes factor of 3.3 for NO/IO (77/23). NO ~3.3x more likely than IO.

Key takeaways

- Building a neutrino oscillation experiment is choosing where to sit on the L/E oscillation curve.
- Disappearance provides $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$
- Appearance carries δ_{CP} and mass ordering information, but degeneracy complicates it.
- Baseline sets the size of matter effect — a core design trade-off.
- Near detectors are how we keep the systematics under control.
- The end product is a **contour** in oscillation-parameter space.