ACCELERATOR-BASED NEUTRINO OSCILLATION EXPERIMENTS

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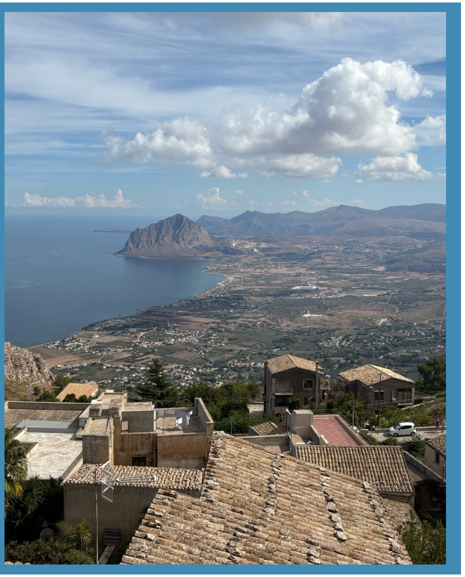
ERICE INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS, 47TH COURSE, SEPTEMBER 2026



INTRODUCTION TO THE SPEAKER

- Originally from Montpelier, Vermont, USA
- BS in physics from Georgia Tech (Atlanta)
- PhD from University of Chicago: "CP Violation in Neutral Kaon Decays" (2011)
- Studying neutrinos at BNL since 2011
- Adjunct professor at Stony Brook University
- Current experiments: DUNE, ICARUS, SBND
  - Former physics co-coordinator of DUNE
  - Physics co-coordinator of ICARUS

She/her

INTRO TO NEUTRINO OSCILLATION

NEUTRINO MIXING PARAMETERS

Neutrinos have mass ⟷ neutrinos oscillate

Flavor eigenstates — Mass eigenstates

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

NEUTRINO MIXING PARAMETERS

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

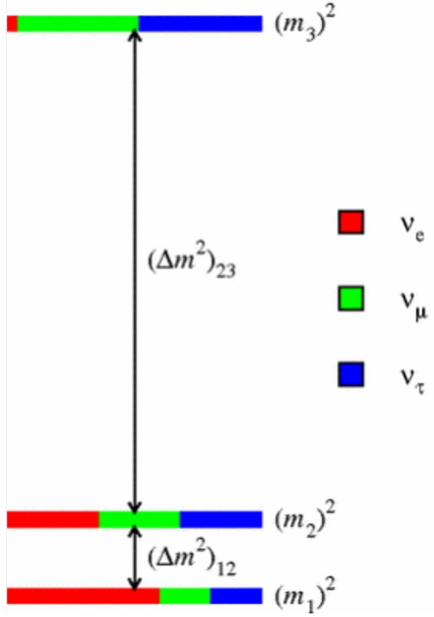
- **$\theta_{23} \approx 45^o$**
- Octant unknown (new symmetry?)

- **$\theta_{13} \approx 10^o$**
- δ_{CP} unknown (CP violation?)

- **$\theta_{12} \approx 35^o$**

Note: in the case of Majorana neutrinos, there are two additional phases, but these do not enter the neutrino oscillation probability

Normal ordering



NEUTRINO MIXING PARAMETERS

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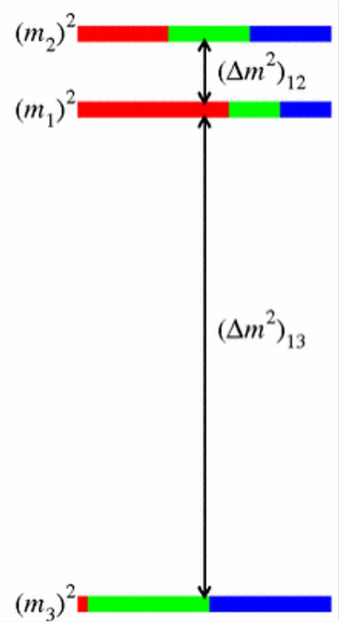
Note: in the case of Majorana neutrinos, there are two additional phases, but these do not enter the neutrino oscillation probability

Inverted ordering

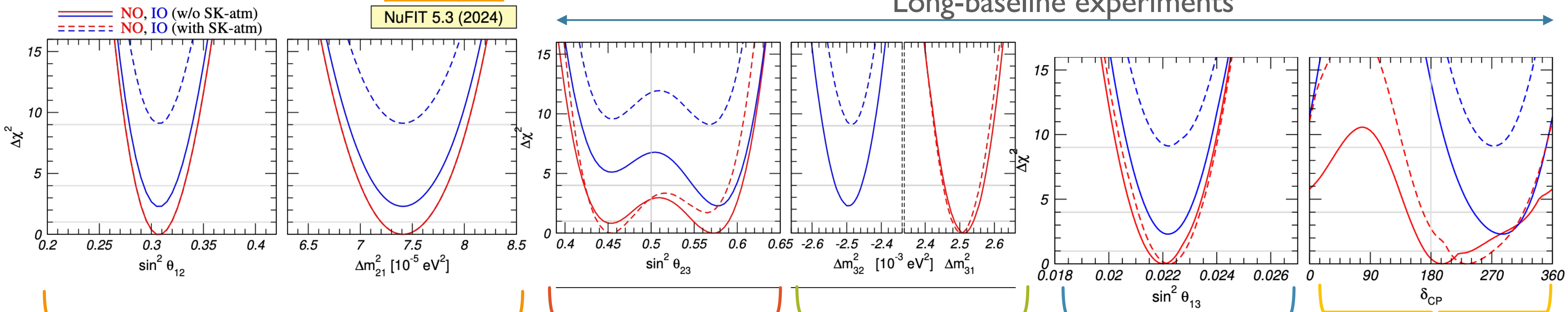


CURRENT STATUS OF MEASUREMENTS

- Example of global fit for oscillation parameters:

JHEP 09 (2020)

Long-baseline experiments



"Solar" parameters –very precise measurements from JUNO* not yet included in this fit – precision ~1-2% shown at Neutrino 2026

Octant unknown

Mass ordering unknown

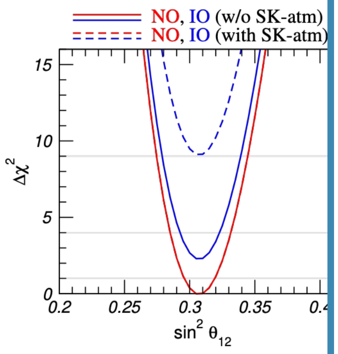
Precise measurement from reactor experiments

CP Violation?

*Reactor experiment: see L. Ludhova's talk on Sunday

CURRENT STATUS OF MEASUREMENTS

- Example of g



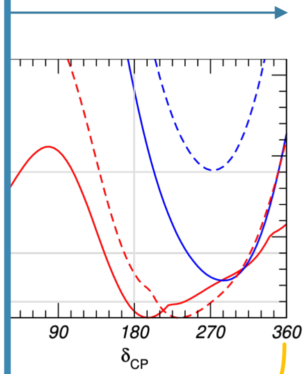
Most parameters already measured to within a few percent!

Open questions:

- Mass ordering ($\Delta m^2_{32} > 0$?)
- Octant ($\sin^2\theta_{23} = 0.5$?)
- CP violation ($\delta_{CP} \neq 0, \pi$?)
- Only 3 flavors? PMNS unitary?

Long-baseline

Long- and short-baseline



"Solar" parameter
measurements fr
not yet included in this fit – precision ~1-2% shown at Neutrino 2026

from reactor experiments

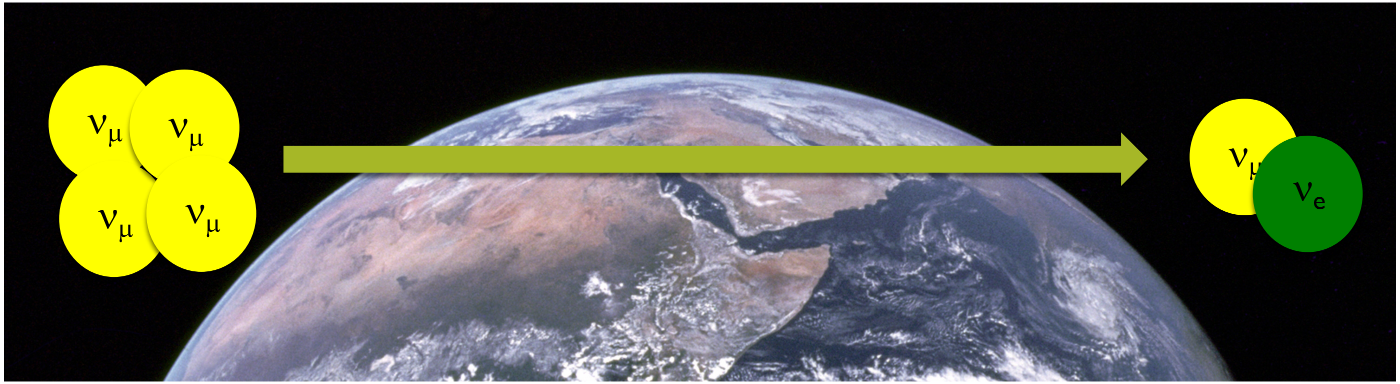
CP Violation?

*Reactor experiment: see L. Ludhova's talk on Sunday

LONG-BASELINE OSCILLATION PHYSICS

Annual Review: Experimental Considerations in Long-Baseline Neutrino Oscillation Measurements, Di Lodovico, Patterson, Shiozawa, Worcester

BASICS OF ACCELERATOR-BASED OSCILLATION EXPERIMENTS



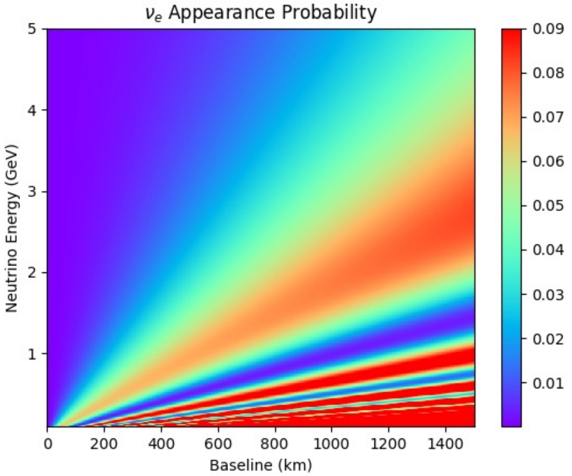
- Neutrino energies of ~few GeV
- Long-baseline: hundreds of kilometers (matter effect can be significant)
- Short-baseline: ~1 km
- Probability of oscillation depends on L/E, the neutrino mixing matrix, neutrino mass differences, and the matter effect
- Analysis of appearance and disappearance signals, combined with good understanding of the unoscillated flux and of neutrino interactions and reconstruction in the detector, can be used to precisely measure neutrino oscillation parameters

OSCILLATION PROBABILITY

- Two neutrino case: $P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$
  - Oscillation amplitude depends on θ (mixing angle)
  - Oscillation frequency depends on Δm^2 (mass difference), baseline (L), and energy (E).

OSCILLATION PROBABILITY

- Three-flavor mixing in matter:



$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

$a = G_F N_e/\sqrt{2}$

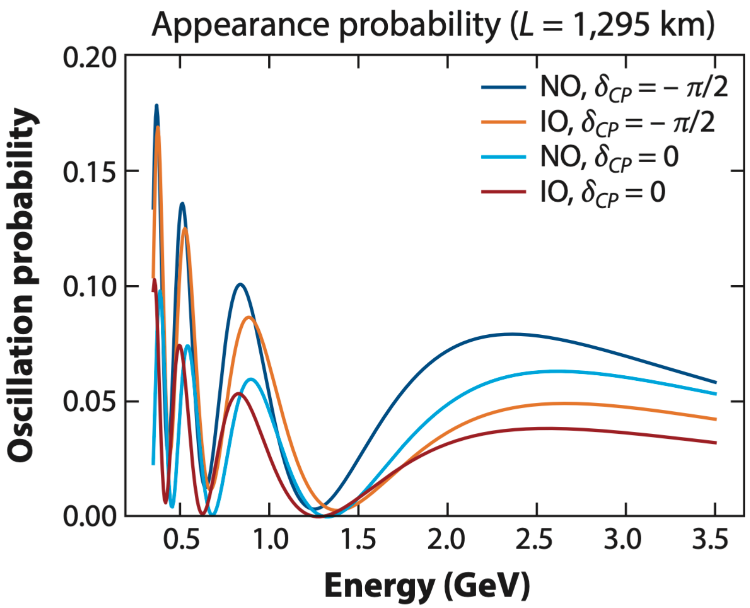
Matter effect from coherent forward scattering on electrons

CP violation

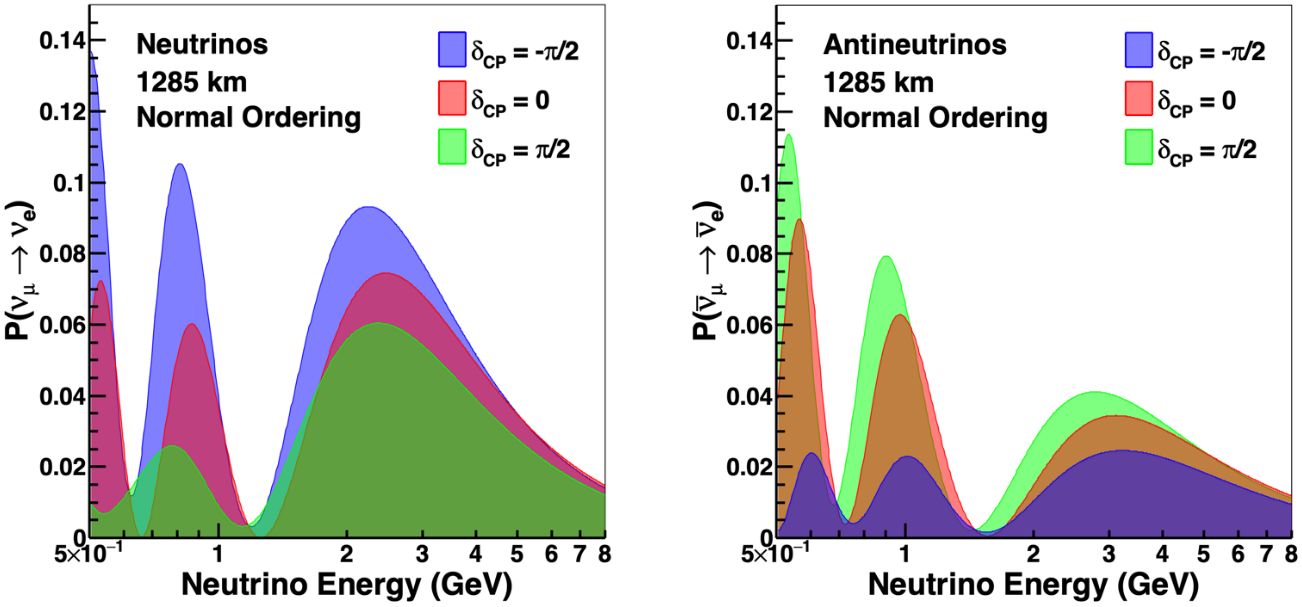
Optimize choice of baseline and energy for desired measurement (1st/2nd oscillation maxima)

MATTER EFFECT

- Matter effect occurs because there are electrons in matter, but no muons or taus:
  - Electron neutrinos can undergo coherent forward scattering in both charged-current and neutral-current interactions without a flavor change
  - Muon and tau neutrinos cannot undergo charged-current coherent forward scattering with the electrons in matter, so only the neutral-current interaction is available to them
- Effective Hamiltonian is modified in matter in a way that enhances the ν_e appearance probability for neutrinos and suppresses it for antineutrinos in normal ordering; the opposite is true for inverted ordering
- The matter effect increases with energy. Since longer-baseline experiments typically use higher energy neutrino beams (to select the desired L/E), the matter effect is in practice larger for longer baselines

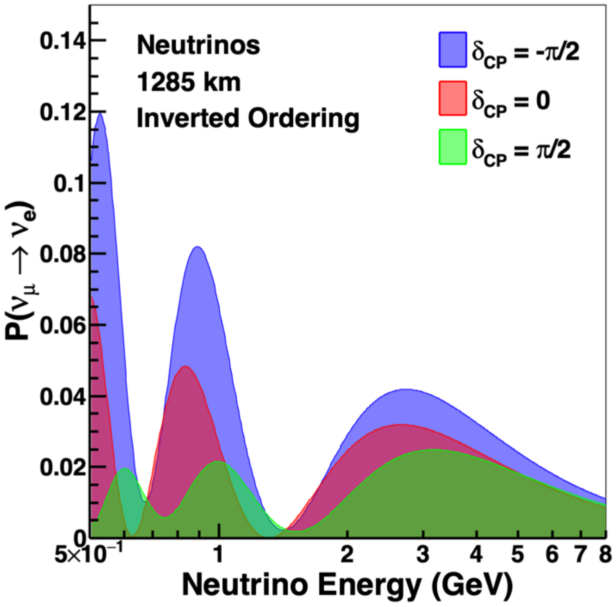


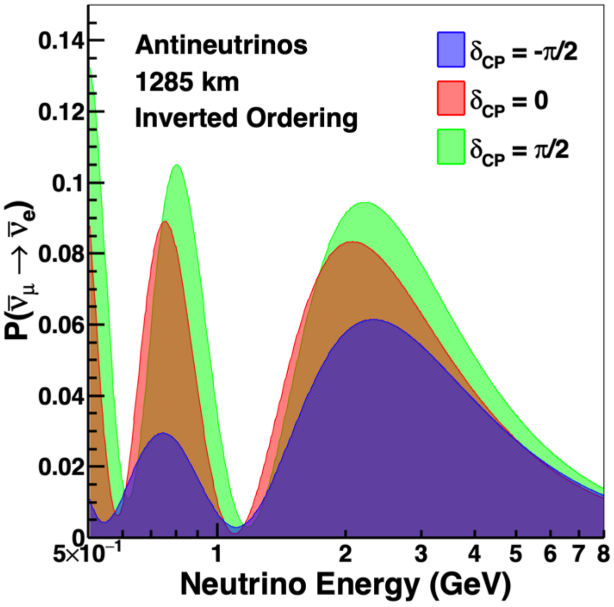
APPEARANCE PROBABILITY



- Value of δ_{CP} affects both rate and shape of appearance probability, with asymmetric impact on neutrinos and antineutrinos
- Matter effect enhances appearance probability for neutrinos and reduces it for antineutrinos if ordering is normal

APPEARANCE PROBABILITY



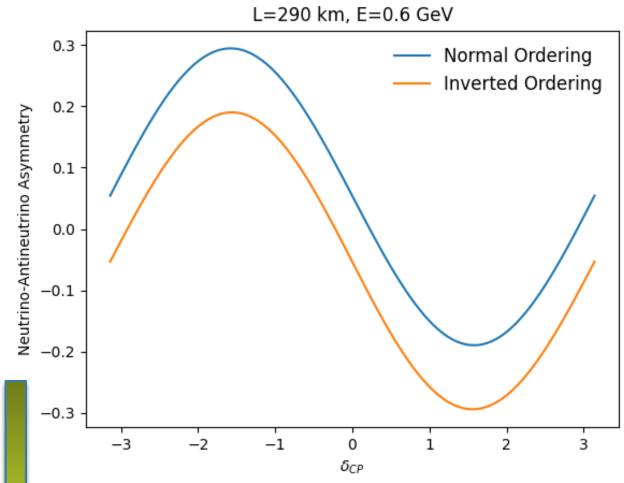


- Value of δ_{CP} affects both rate and shape of appearance probability, with asymmetric impact on neutrinos and antineutrinos
- Matter effect reduces appearance probability for neutrinos and enhances it for antineutrinos if ordering is inverted

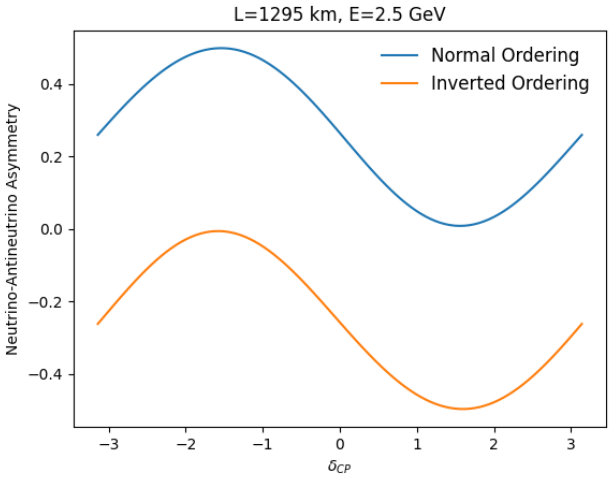
Both matter effect and δ_{CP} induce matter-antimatter asymmetry!

RESOLVING DEGENERACY

Baseline of 290 km
(very little matter effect)



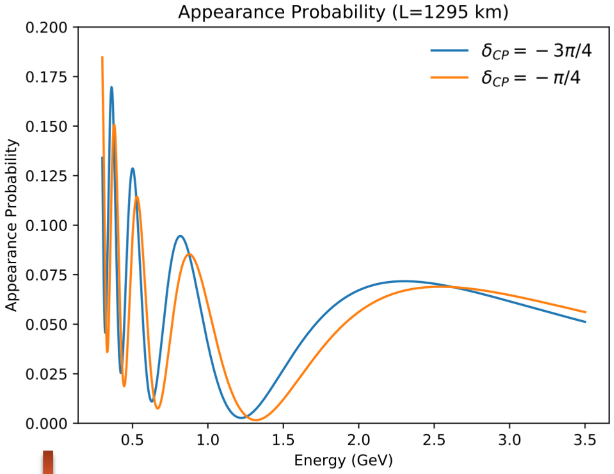
Baseline of 1295 km
(large matter effect)



Degeneracy between δ_{CP} and matter effects is lifted for baselines greater than ~1000 km because matter effect produces larger asymmetry

Matter-antimatter asymmetry

RESOLVING DEGENERACY



Baseline of 1295 km
(large matter effect)

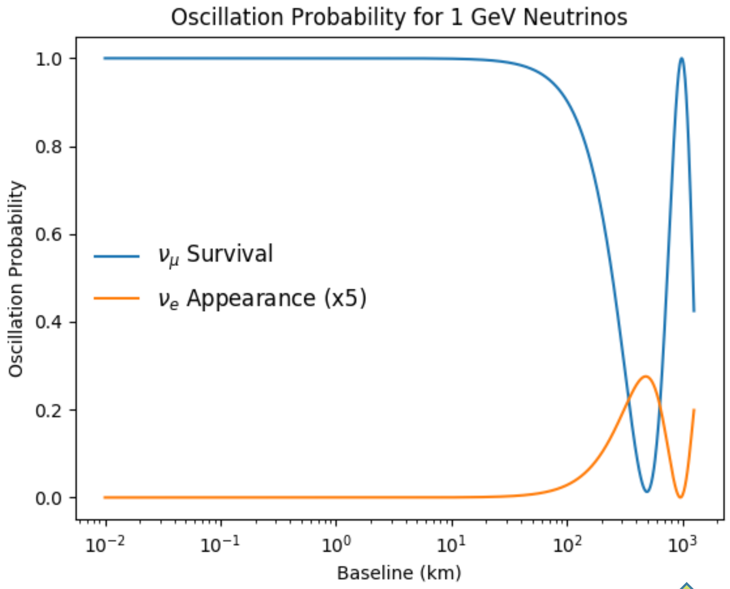
Energy dependence of oscillation can resolve δ_{CP} degeneracy

Appearance probability

SHORT-BASELINE OSCILLATION PHYSICS & STERILE NEUTRINOS

*MORE IN YESTERDAY'S TALK FROM M. MALTONI

WHY SHORT-BASELINE?



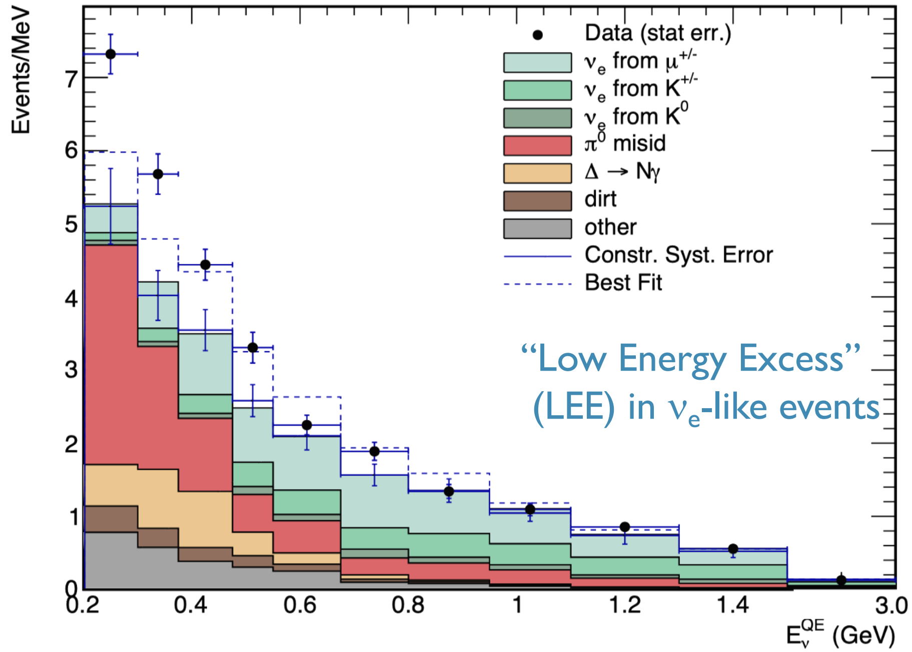
SBL Experiments

LBL Experiments

- Based on the already-measured oscillation parameters, we do not expect to see muon neutrino oscillation at small values of L/E
  - i.e.: ν_μ survival probability should be ~1 and ν_e appearance probability should be ~0 for order 1 GeV neutrinos with baselines < 10 km
- **Any ν_μ disappearance or ν_e appearance at these L/E values would require a larger mass splitting, which would require at least 1 additional neutrino mass state → new physics!**

STERILE NEUTRINOS

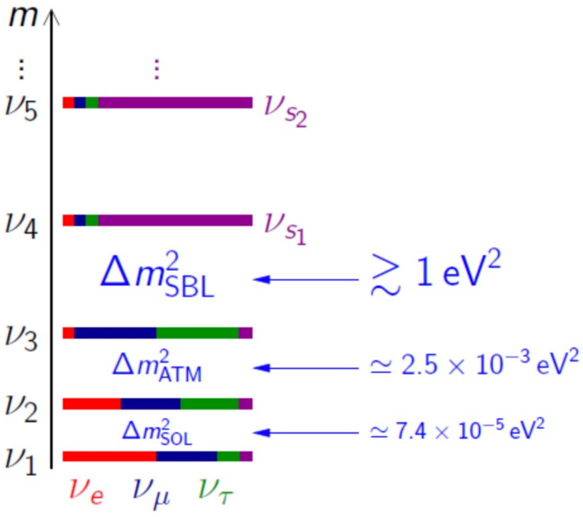
MiniBooNE (BNB)
PRD 103, 052002 (2021)



The significance of the excess observed by LSND is 3.8σ and by MiniBooNE is 4.8σ, for a combined significance of 6.1σ

- Several experiments have observations suggesting possible oscillation at L/E ~ 1
  - LSND, MiniBooNE, IceCube
  - Potential explanation is an additional "sterile" neutrino with a mass splitting of ~1 eV^2
- However, MicroBooNE does not observe LEE and there are exclusion limits in most parameter space favored by the positive hints
- Short-baseline oscillation can be probed at both short- and long-baseline accelerator experiments

STERILE NEUTRINO MODEL



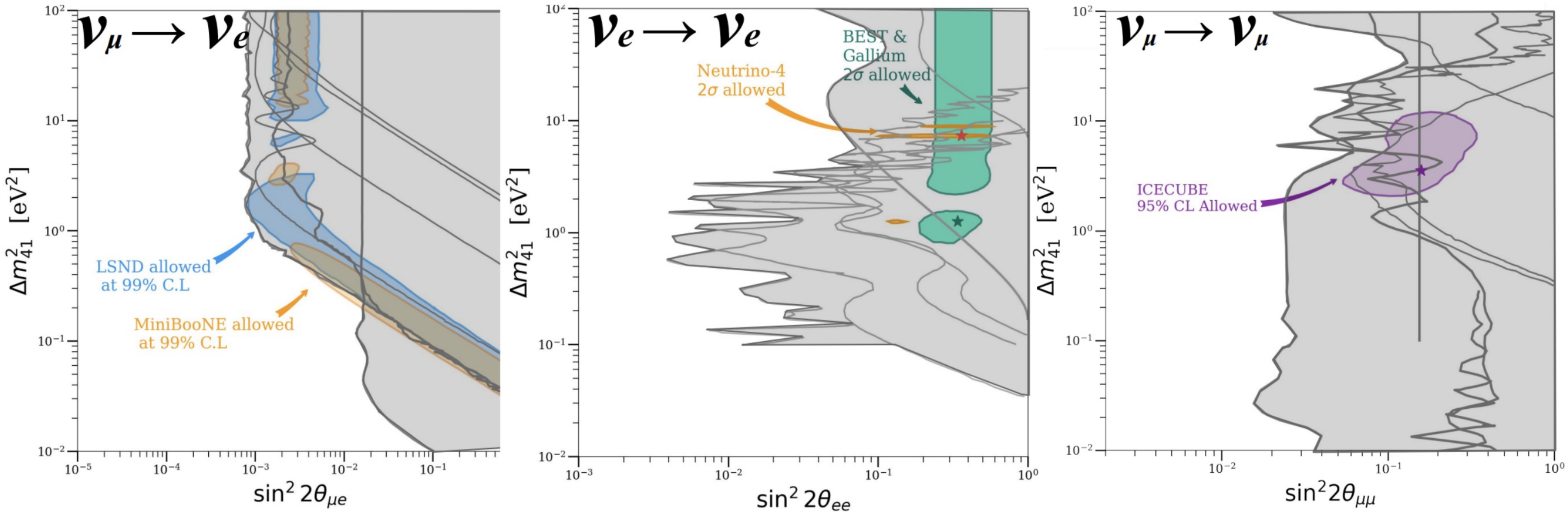
Other possible explanations for these anomalies proposed by theory community are also being explored in the same datasets

- 3 neutrino model → 3 + x neutrino model, where there are x additional, "sterile" neutrinos
- Sterile neutrinos mix with standard neutrinos (allows for additional oscillation), but do not have weak charge, (consistent with # of neutrinos from LEP/astrophysics)
- "3+1" model is simplest scenario; while this model is nearly excluded by data, we often quote sterile neutrino parameters in a simplified "2 flavor" version of this model
  - $\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$ (ν_e appearance)
  - $\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)$ (ν_μ disappearance)
  - $\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2)$ (ν_e disappearance)

2 independent matrix elements

CONFUSING STATE OF GLOBAL SEARCHES

M. Ross-Lonergan: NuPhys 2026

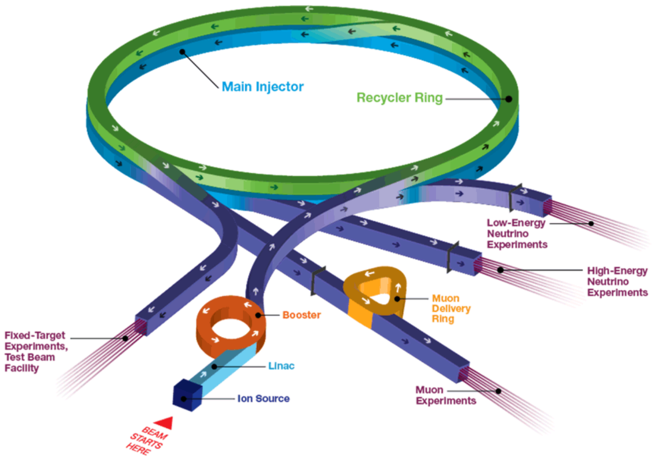


Significant tension: in each channel, there are both reported positive hints and many null results!

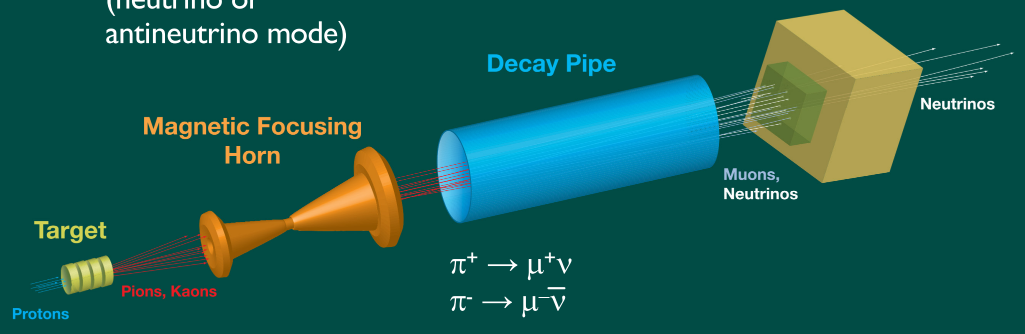
ACCELERATOR NEUTRINO EXPERIMENTAL DETAILS

NEUTRINO BEAMS

Fermilab Accelerator Complex



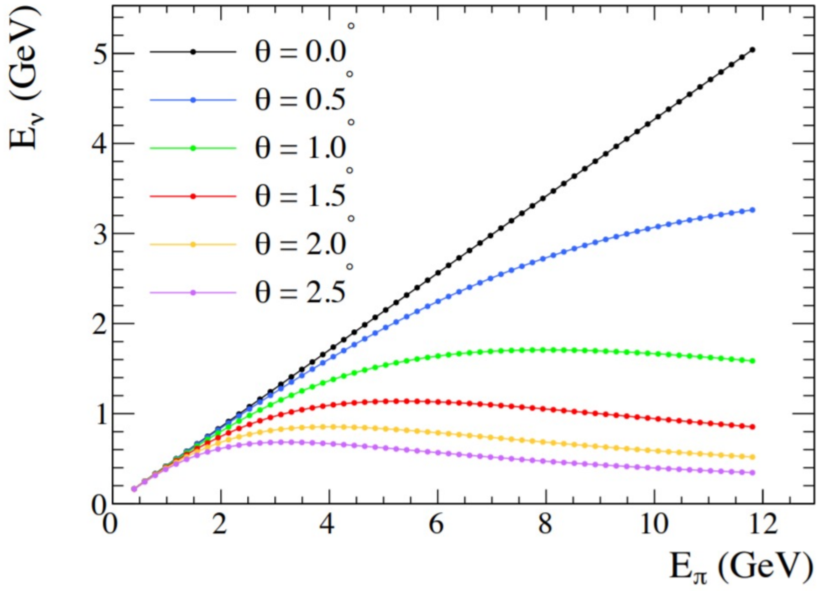
Focusing horn selects charge of mesons (neutrino or antineutrino mode)



$$\pi^+ \rightarrow \mu^+ \nu$$
$$\pi^- \rightarrow \mu^- \bar{\nu}$$

OFF-AXIS NEUTRINO BEAMS

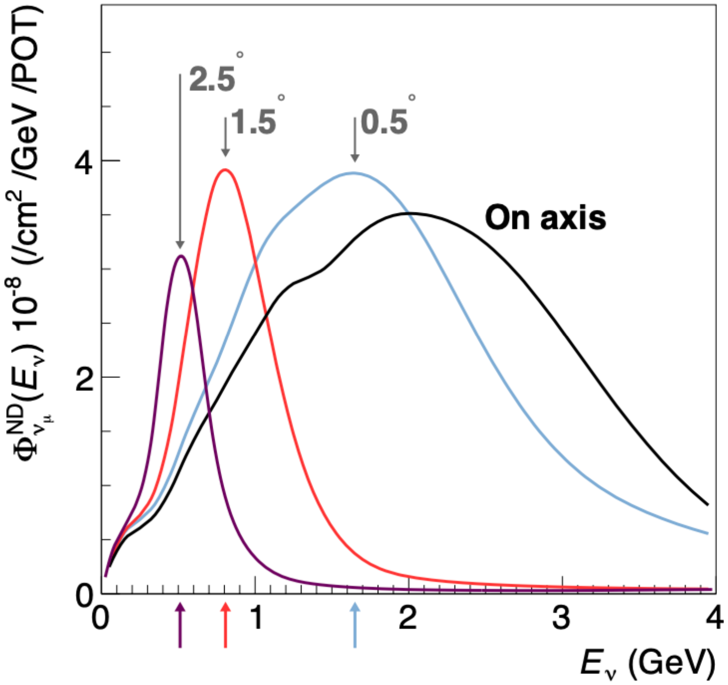
Off-axis neutrino energy:



- Kinematics of pion decay dictate flux observed at different positions with respect to the beam
- On-axis, neutrino energy is approximately linear with parent pion energy, so broad spectrum of pion energies produces broad spectrum of neutrino energies
- As you move off-axis, resulting neutrino energy becomes lower and more peaked at a particular energy regardless of parent pion energy

OFF-AXIS NEUTRINO BEAMS

Off-axis flux at DUNE ND:



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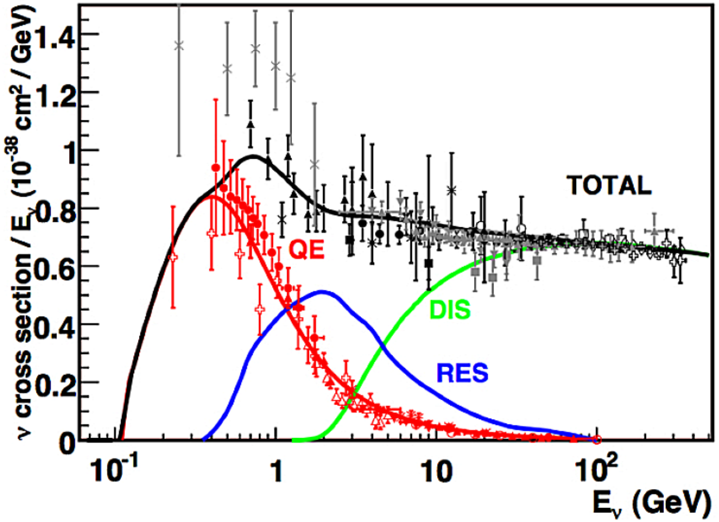
- On-axis, neutrino energy is approximately linear with parent pion energy, so broad spectrum of pion energies produces broad spectrum of neutrino energies
- As you move off-axis, resulting neutrino energy becomes lower and more peaked at a particular energy regardless of parent pion energy
- No time to discuss details, but this can be used to select near detector data with specific energies by selecting data at off-axis angles (PRISM concept) – useful for constraining systematic uncertainties

GeV-SCALE NEUTRINO INTERACTIONS

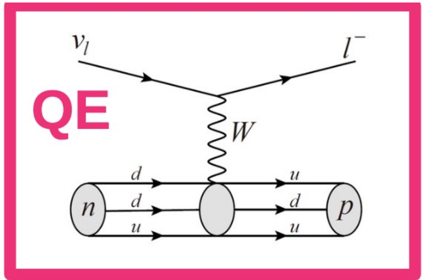
Multiple neutrino-nucleus interaction processes, including quasielastic, meson-exchange current, resonance, and deep-inelastic scattering, contribute at GeV-scale

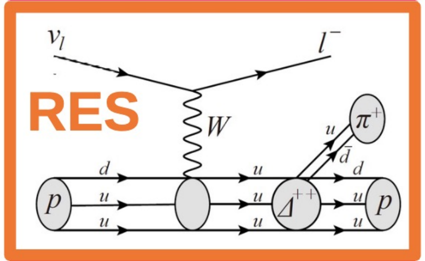


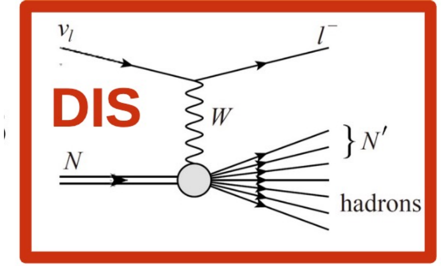
ν_μ CC Interactions

- QE: $\nu_\mu n \rightarrow \mu^- p$
- RES: $\nu_\mu N \rightarrow \mu^- N^*$, $N^* \rightarrow \pi N'$
- DIS: $\nu_\mu N \rightarrow \mu^- X$

Similar processes for ν_e and antineutrinos + neutral current interactions



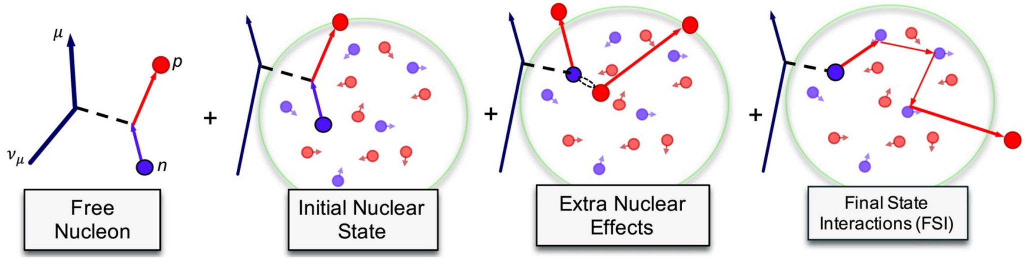




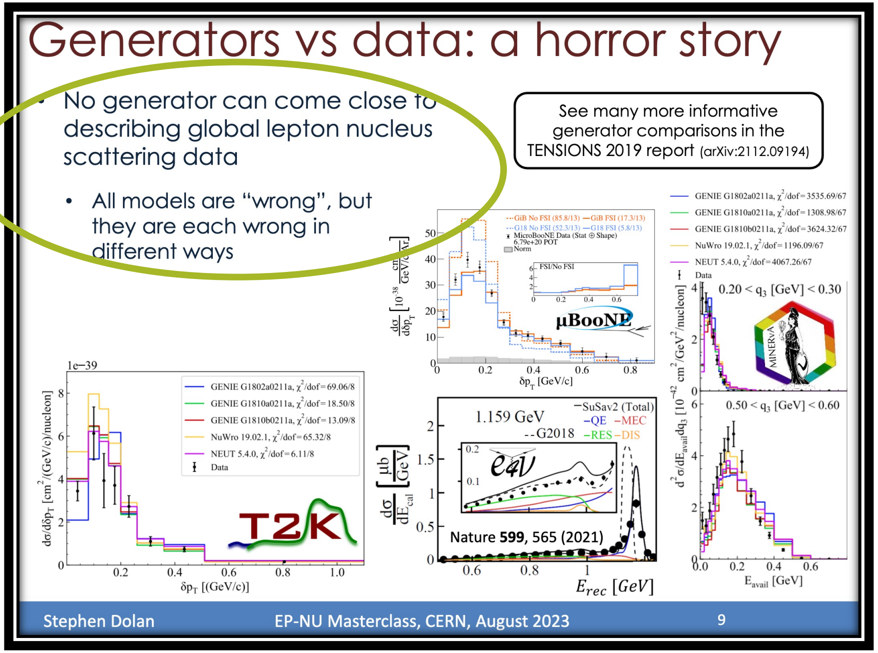
MODELING NEUTRINO-NUCLEUS INTERACTIONS

The neutrino is interacting with a nucleon inside a complex nuclear state that is historically difficult to model:

- Details of initial state and final state interactions matter



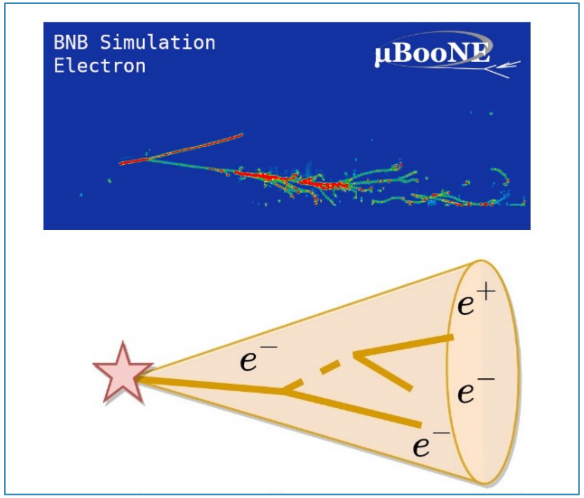
- Work constantly in progress to make better measurements and improve the modeling, but **we can not expect our generators to correctly predict our data**
- Detectors that are able to observe details of the final state should be better able to reconstruct incoming neutrino kinematics and provide constraints on model uncertainty, which is important for inferring oscillation parameters



Collaboration w/nuclear theorists critical for improving modeling and understanding uncertainty!

LARTPC FOR NEUTRINOS

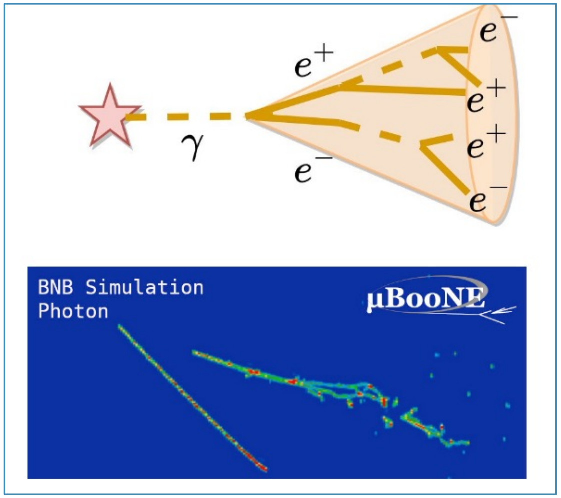
Electrons



LArTPC detectors provide good capability for distinguishing electrons from photons:

- Gap between vertex and shower start for photons (X_0 = 14 cm)
- dE/dx at shower start (e^- vs e^+e^-)

Photons

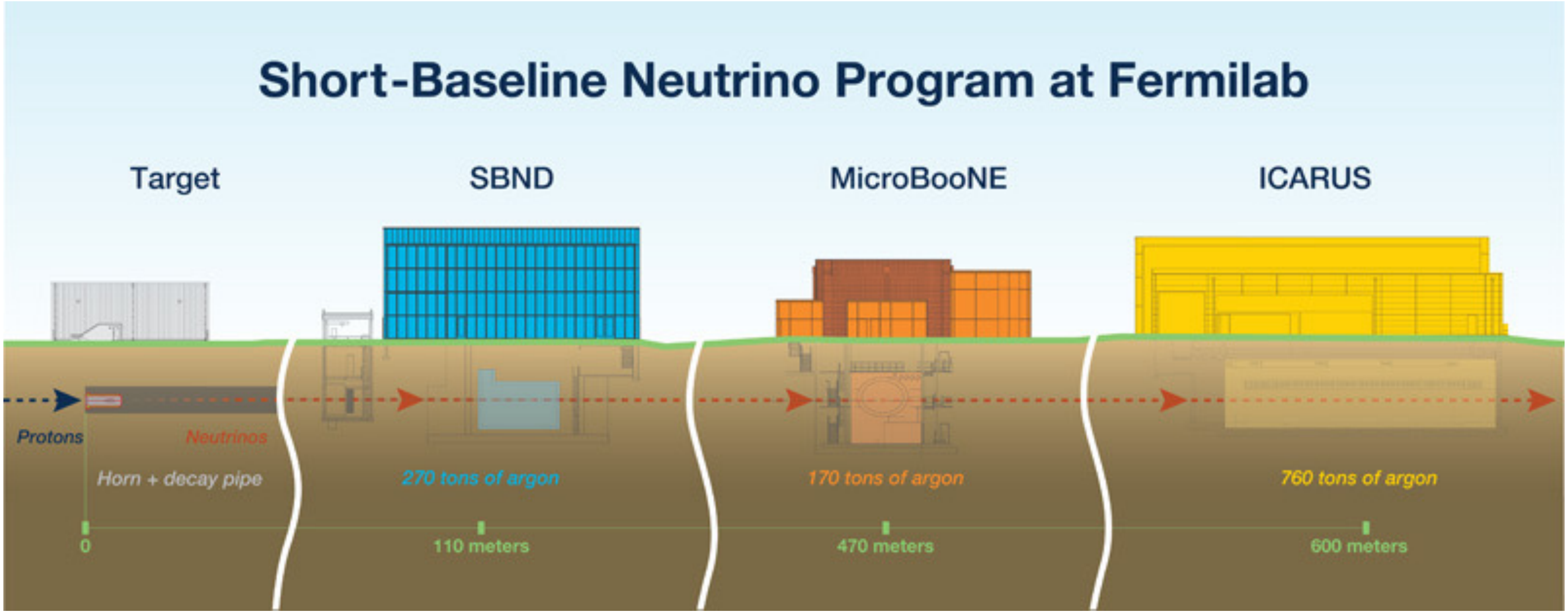


Precise imaging of final state particles (particularly the hadronic side of the interaction) is important for control of systematics associated with interaction modeling.

ACCELERATOR-BASED OSCILLATION EXPERIMENTS

SBN PROGRAM

3 LArTPC detectors in the Booster Neutrino Beam



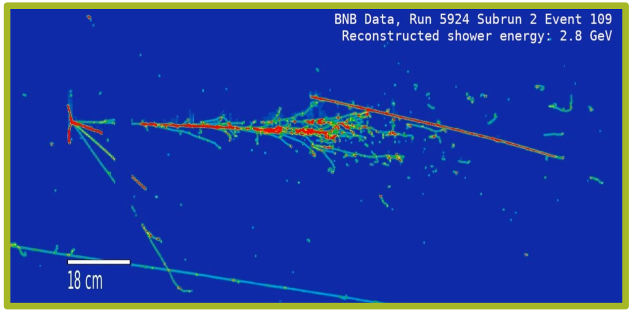
Taking physics data since 2024

Took data 2015-2022

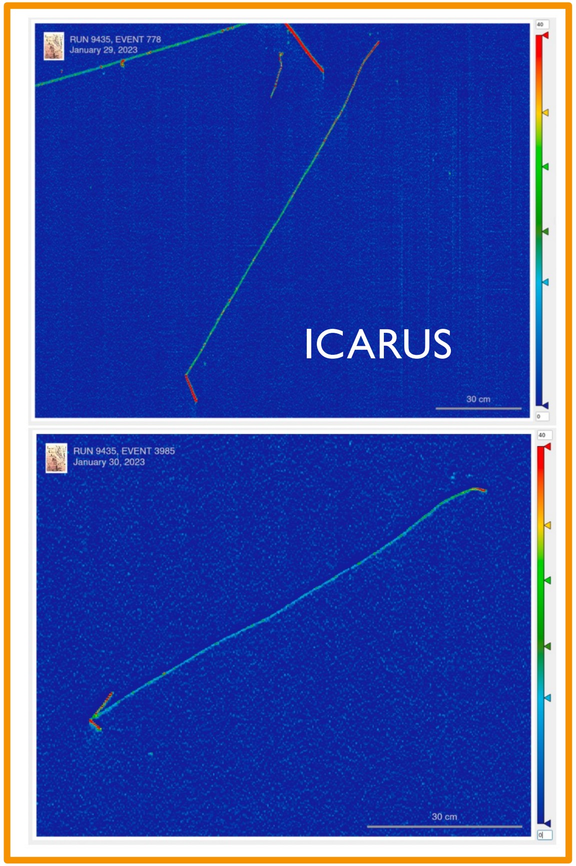
Taking physics data since 2022

SBN DATA

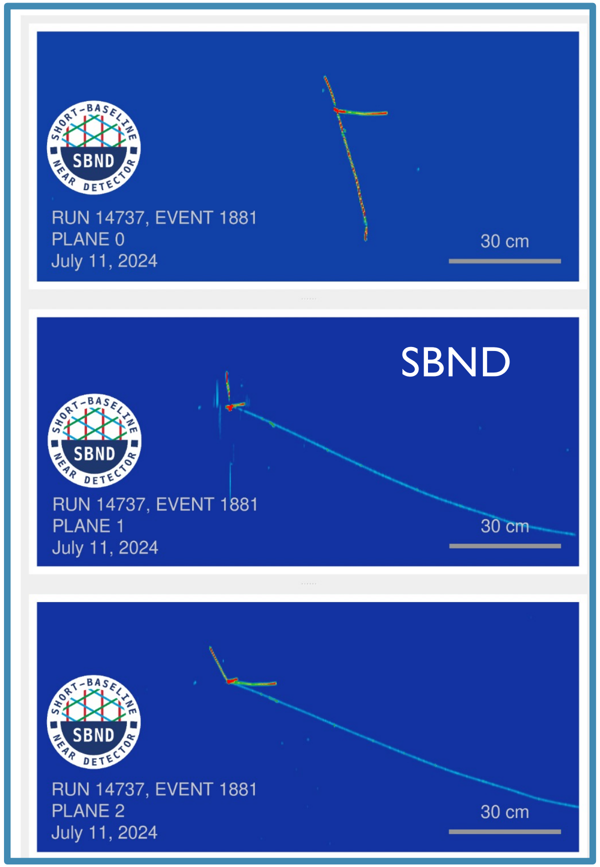
1eNp candidate data event
e
p
μBooNE
14 cm
RUN 8617 SUBRUN 46 EVENT 2328



BNB Data, Run 5924 Subrun 2 Event 109
Reconstructed shower energy: 2.8 GeV
18 cm



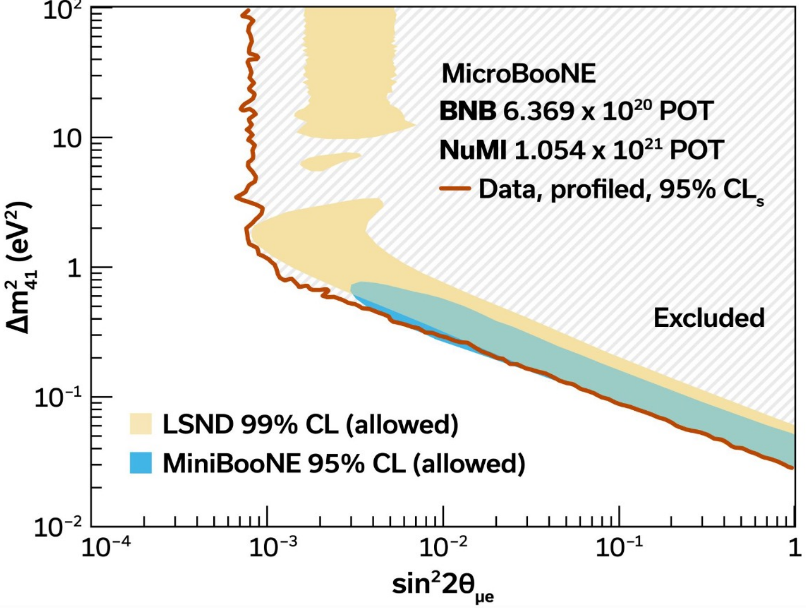
RUN 9435, EVENT 778
January 29, 2023
ICARUS
30 cm
RUN 9435, EVENT 3985
January 30, 2023
30 cm



SBND
RUN 14737, EVENT 1881
PLANE 0
July 11, 2024
30 cm
RUN 14737, EVENT 1881
PLANE 1
July 11, 2024
30 cm
RUN 14737, EVENT 1881
PLANE 2
July 11, 2024
30 cm

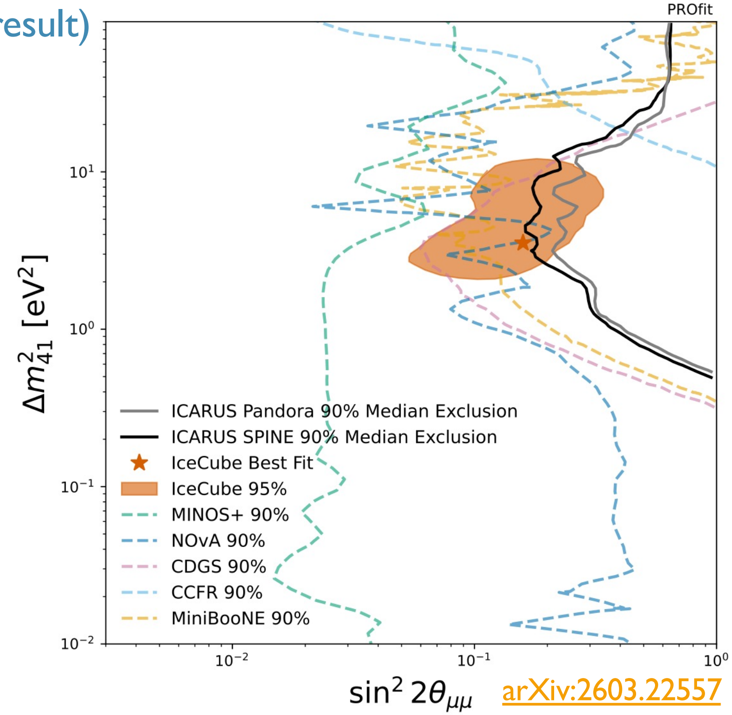
MICROBOONE & ICARUS RESULTS

Nature 648 (2025) 8092, 64-69



MicroBooNE combined appearance/disappearance analysis excludes LSND and most of MiniBooNE allowed regions at 95% CL

ICARUS ν_μ disappearance analysis excludes some of IceCube allowed region at 90% CL (systematics dominated result)

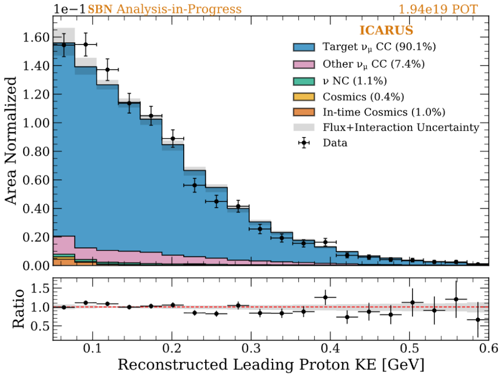


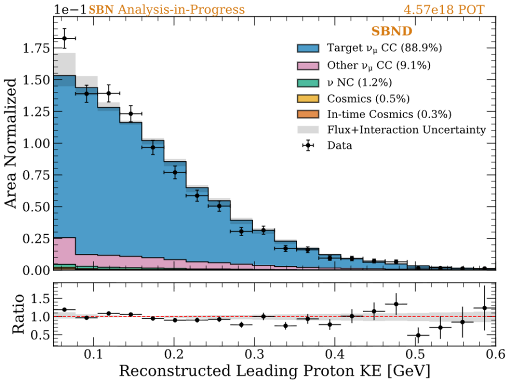
arXiv:2603.22557

SBND + ICARUS JOINT ANALYSES

- ICARUS disappearance result is systematics limited because of large unconstrained uncertainties in the flux, interaction, and detector models.
- In future SBN (ICARUS + SBND) analyses, expect systematic uncertainties to be reduced from ~20% to few percent level
  - Addition of SBND data will significantly reduce systematics by constraining flux and interaction model uncertainty
  - Already implemented improvements to detector model will significantly reduce systematics by reducing data-MC discrepancies
  - Addition of ν_e samples (BNB & NuMI) will significantly extend physics reach
- First joint disappearance analyses expected in early 2027, to be followed by analyses including ν_e appearance/disappearance

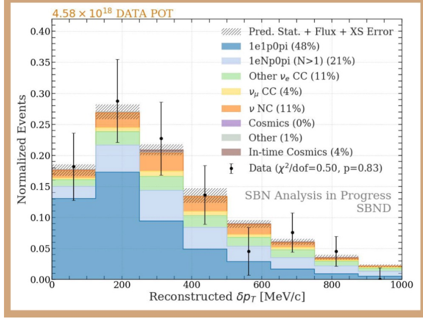
ν_μ disappearance analysis in ICARUS & SBND coming soon!

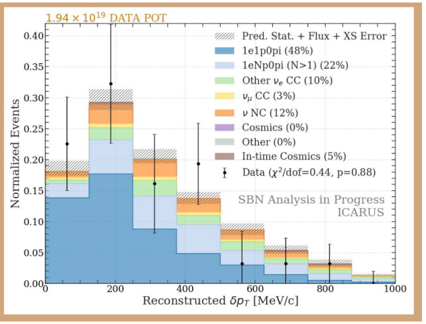




J.Mueller, Neutrino 2026

ν_e analyses in ICARUS & SBND in progress!





Oza, Xia, Neutrino 2026

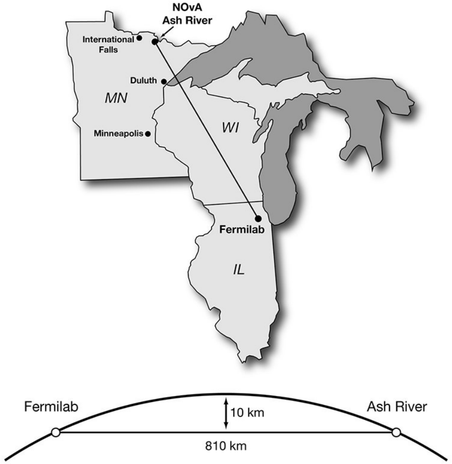
OPERATING LONG-BASELINE EXPERIMENTS: T2K & NOVA

T2K: Tokai to Kamioka

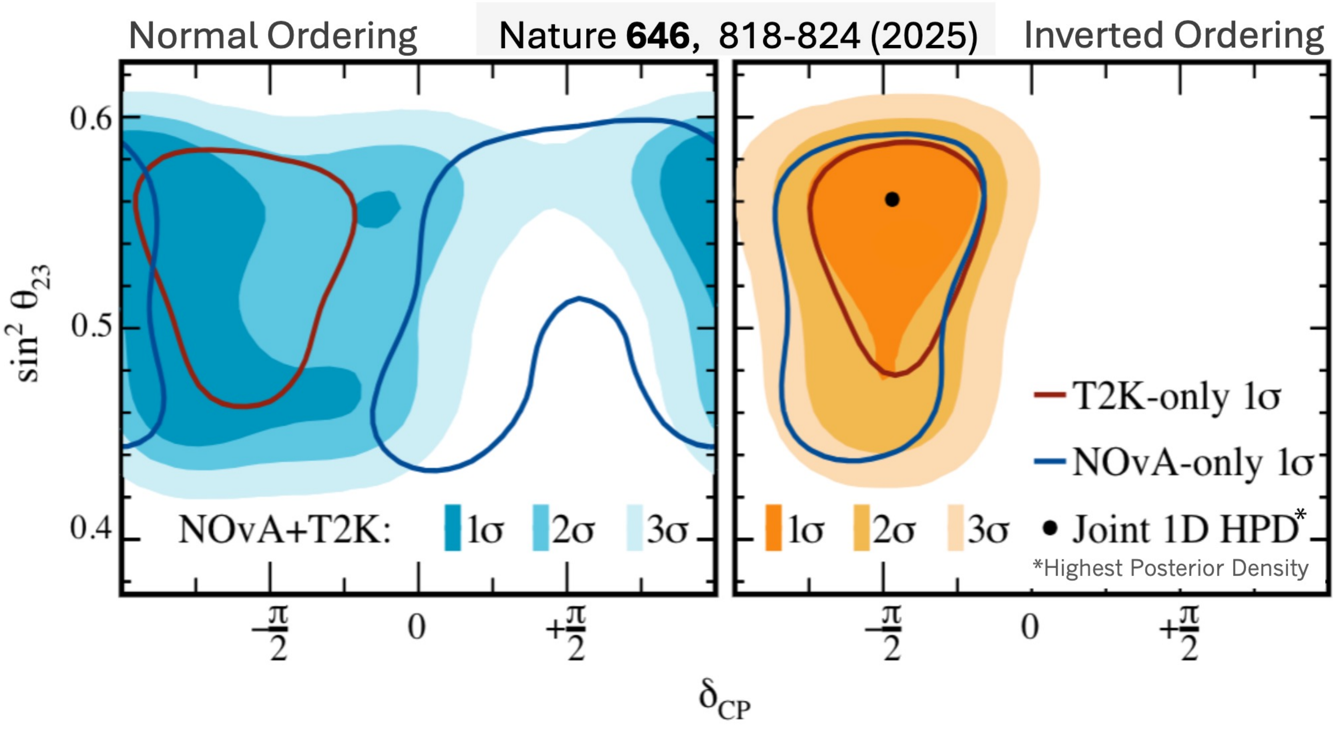
Beam: J-PARC
Far detector: SuperK WCD (50 kt)
Near detector: Suite of on- and off-axis detectors
Baseline: 295 km
Far detector located off-axis such that observed ν flux is peaked at ~600 MeV

NOvA: FNAL to Ash River

Beam: NuMI (FNAL)
Far detector: segmented liquid scintillator detector (14 kt)
Near detector: segmented liquid scintillator detector
Baseline: 810 km
Far detector located off-axis such that observed ν flux is peaked at ~2 GeV



CURRENT CPV & MASS ORDERING RESULTS

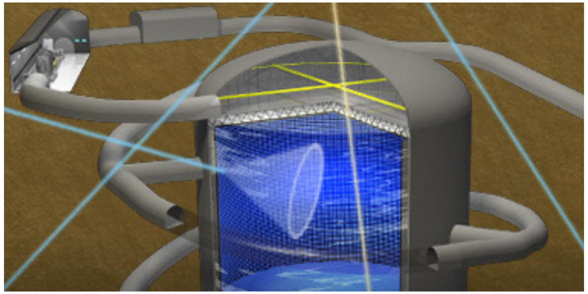


- Mild tension between NOvA and T2K
- In normal ordering, NOvA and T2K prefer different regions for δ_{CP}
- In inverted ordering, NOvA and T2K contours overlap
- Individually, NOvA and T2K both have mild preference for normal ordering
- In the joint fit, inverted ordering is preferred
- JUNO (reactor experiment) reports ~2σ preference for normal ordering when combining reactor+LBL data

FUTURE LONG-BASELINE EXPERIMENTS

Hyper-Kamiokande: Tokai to HyperK*

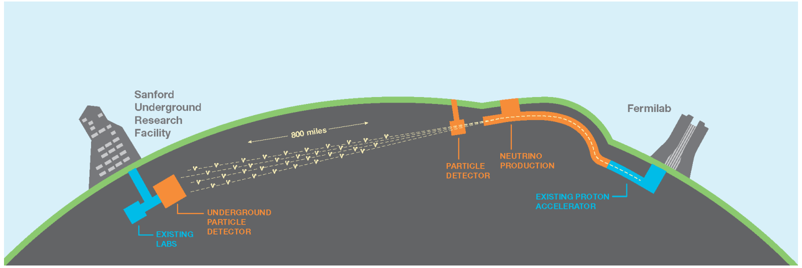
- Maximize statistics and minimize matter effect to focus on CPV discovery (short baseline, very large far detector)
  - Requires separate atmospheric neutrino sample to determine mass ordering
- Beam: J-PARC, 1.3 MW
- Far detector: WCD (187 kt fiducial)
- Near detector: upgraded T2K ND
- Baseline: 295 km
- Far detector located off-axis such that observed ν flux is peaked at ~600 MeV



*See talk from J. Wilson on Monday

DUNE: FNAL to SURF

- Measure all LBL parameters (incl. MO) in a single dataset and map oscillation pattern as a function of energy for precision measurements (long baseline, broadband beam, precision imaging far detector)
- Beam: LBNF (FNAL), ~2 MW,
- Far detector: LArTPC (>40 kt fiducial)
- Baseline: 1300 km
- Far detector located on-axis such that observed ν flux is a broad spectrum (0.5-5 GeV)



NEXT GENERATION UNDER CONSTRUCTION NOW!

R. Akutsu: Neutrino 2026

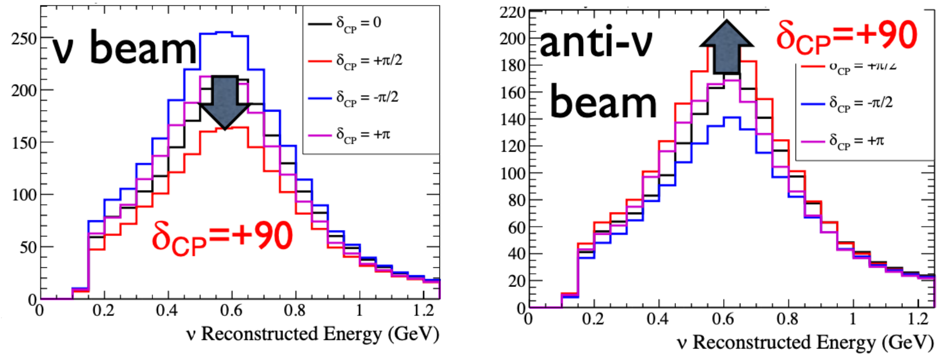
S. Gollapinni: Neutrino 2026

Hyper-Kamiokande plans to start taking data in 2028

DUNE plans to start taking data in 2030 (beam 2031)

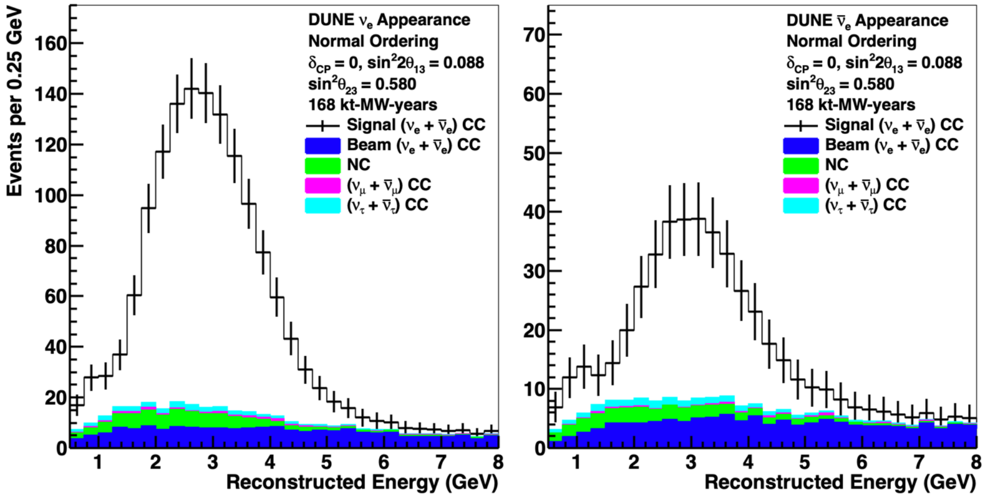
EXPECTED SPECTRA (SIMULATION)

Neutrinos Antineutrinos



Moriyama @ Neutrino 24

Neutrinos Antineutrinos



Hyper-K ν_e Appearance

>2000 events in ~10 years with $\nu/\bar{\nu}$ ratio chosen for ~equal stats

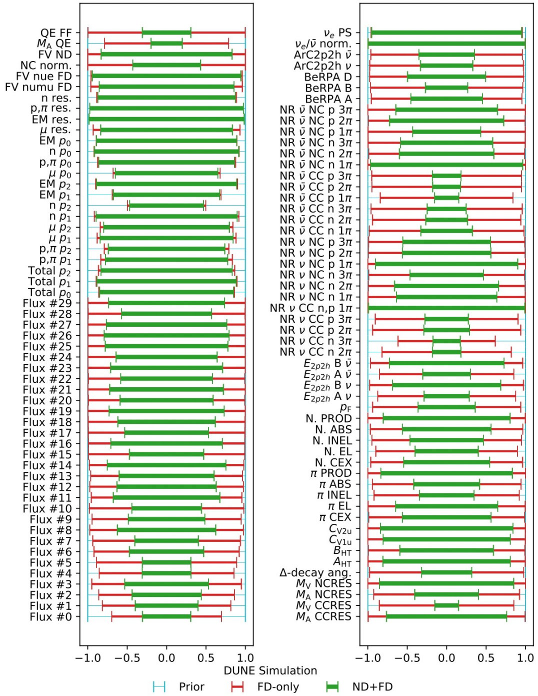
DUNE ν_e Appearance

Order 1000 events in ~7 years with $\nu/\bar{\nu}$ ratio chosen for equal exposure

SYSTEMATICS

- Order few percent uncertainty required for precision measurements
- Sources of uncertainty:
  - Neutrino flux
  - Neutrino interaction model
  - Detector effects
- Sensitivity projections must include detailed analysis of impact from individual source of systematics
- Near detectors are critical to achieve precision measurement goals! Multiple measurements (exclusive final states, different off-axis angles, etc) are required to sufficiently constrain uncertainty.

Systematics included in DUNE sensitivity projections (arXiv:2006.16043):



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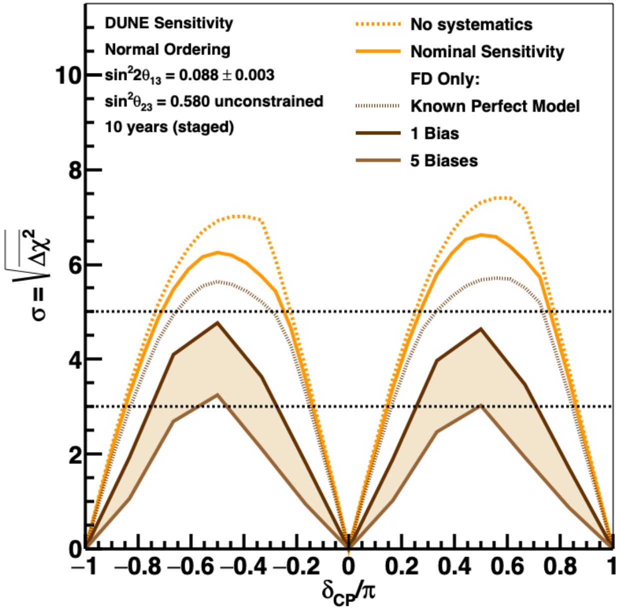
Example impact of systematics on DUNE CPV sensitivity:



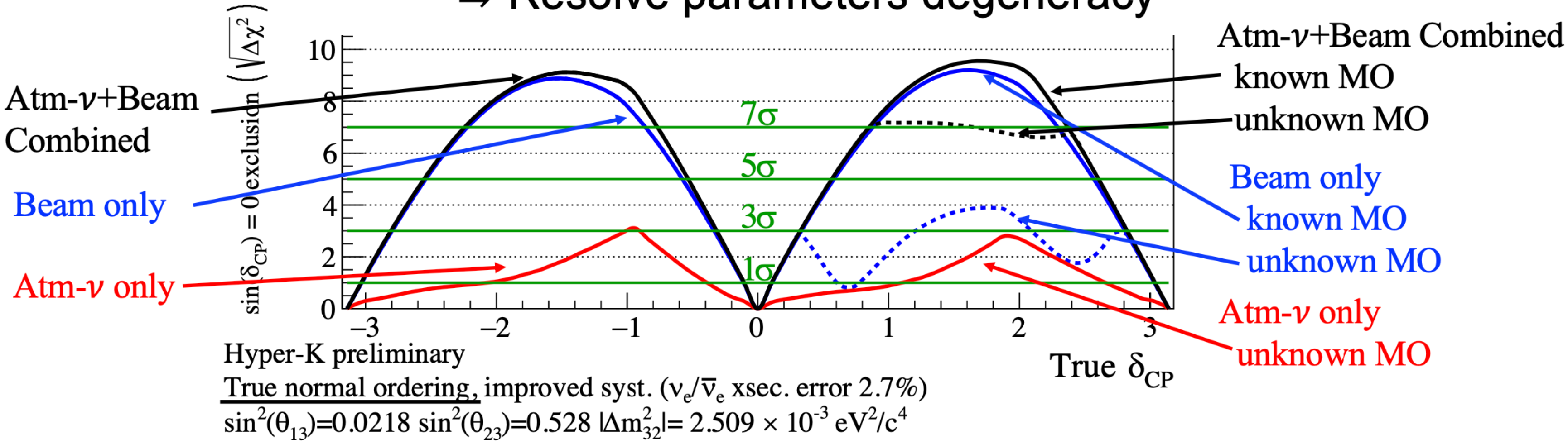
HYPER-K SENSITIVITY

Moriyama @ Neutrino 24

Strategy of oscillation measurement at Hyper-K

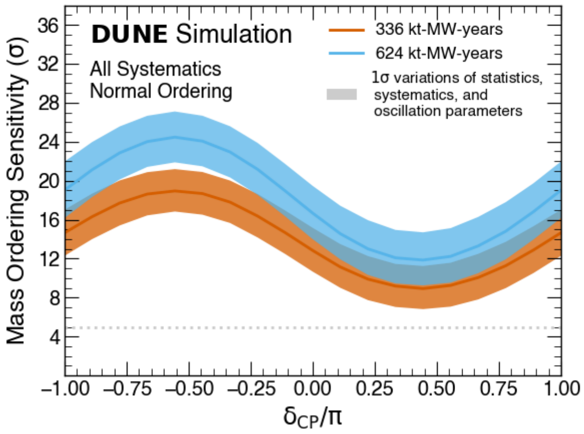
Combination of long-baseline and atm. ν observations

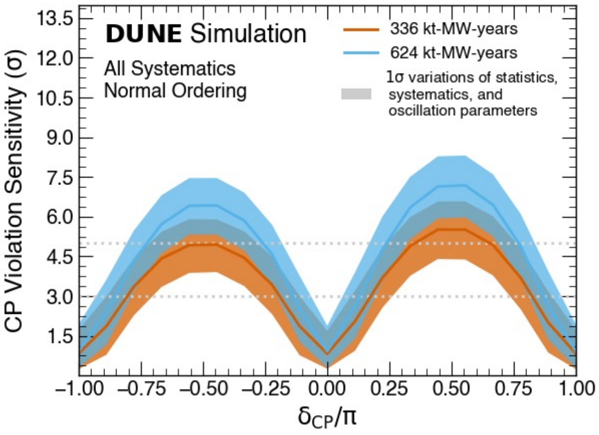
⇒ Resolve parameters degeneracy

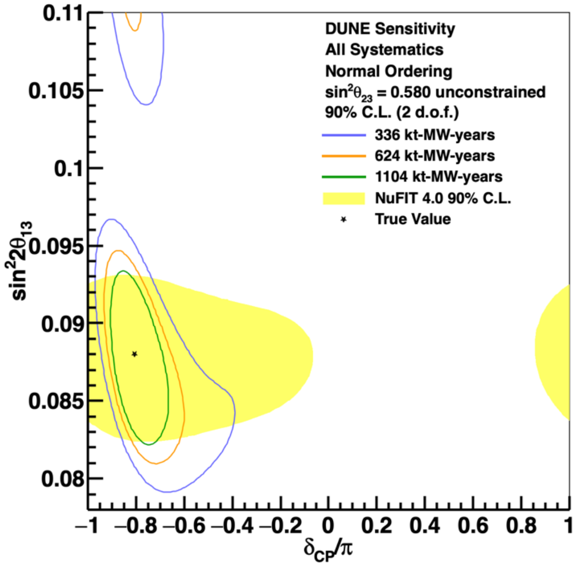


10 years exposure

DUNE SENSITIVITY







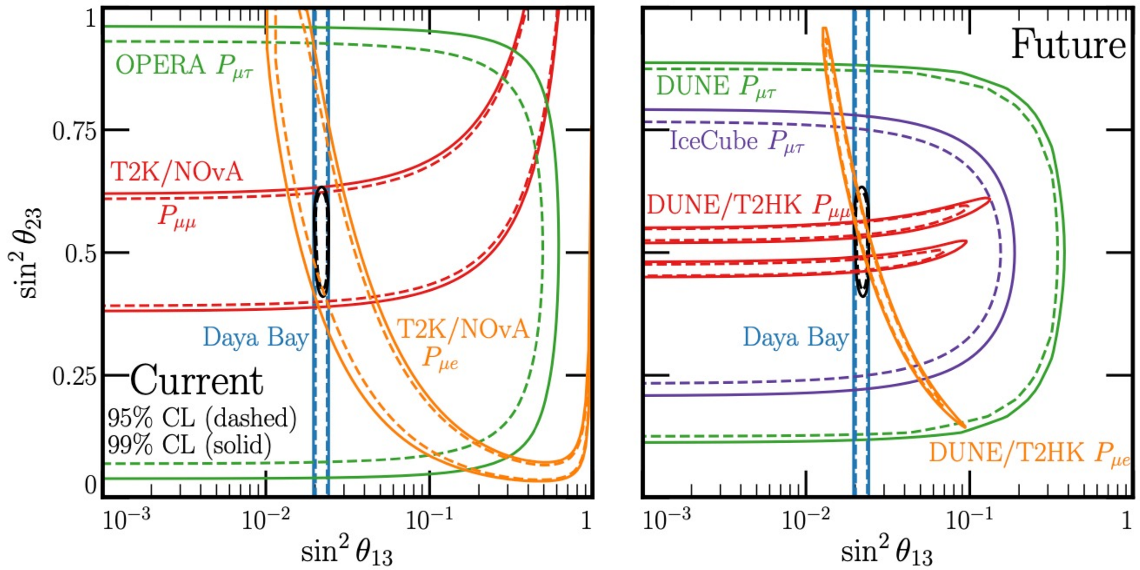
Width of band shows 1σ variations of statistics, systematic parameters, and oscillation parameters.

Unambiguous determination of neutrino mass ordering and 5σ sensitivity to δ_{CP} for a large range of parameter space.

θ_{13} precision comparable to that of reactor experiments for large exposures

TESTING PMNS UNITARITY

Ellis, Kelly, Li, *JHEP* 12 (2020) 068



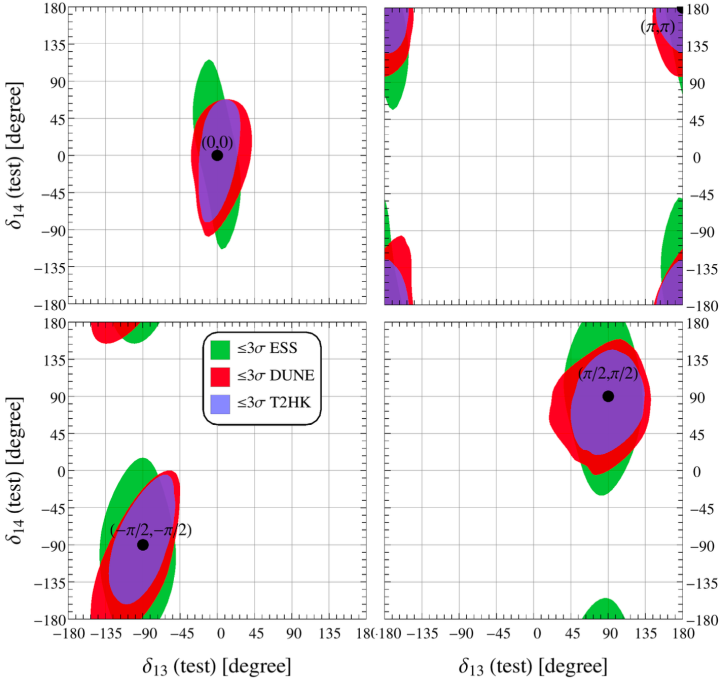
- **Current and projected** measurements in $\theta_{23} - \theta_{13}$ space: combining values obtained from long-baseline oscillation measurements (ν_μ disappearance, ν_e appearance, and ν_τ appearance) with the reactor measurement of θ_{13} to test normalization of 3rd column of mixing matrix
- Future experiments dramatically tighten long-baseline contours such that if unitarity were violated, they would not overlap with the high significance we see in current data

LIGHT STERILE NEUTRINOS AT LONG-BASELINE EXPERIMENTS

Nice review article: Palazzo (2020)

- 3+1 model of light sterile neutrinos introduces one additional mass splitting, 3 additional mixing angles, and two additional phases
  - Long-baseline experiments are uniquely sensitive to the additional CP phases
  - Oscillations in vacuum are independent of θ_{34} and δ_{34} but this is not the case in matter, so experiments with sufficient matter effect are sensitive to these parameters
- Simultaneous measurement of phases is possible in next-generation LBL experiments

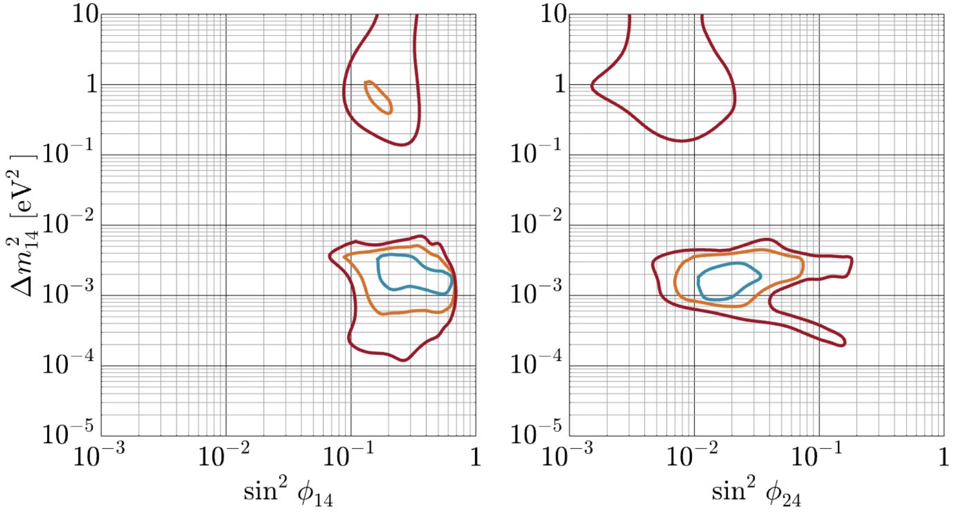
Agarwalla, et al., *JHEP* 12 (2019) 174



EXPERIMENT COMPLEMENTARITY: UNDERSTANDING BSM EFFECTS

- Fun problem to have: differentiating types of new physics observed at next-gen experiments!
- NSI vs Sterile neutrino – if we see results inconsistent with 3-flavor neutrino oscillation, could we tell whether it was more likely to come from non-standard interactions or sterile neutrinos?

Example fit to DUNE NSI "data" assuming 3+1 model



de Gouvêa and Kelly, *Nucl.Phys.B* 908 (2016) 318-335

EXPERIMENT COMPLEMENTARITY: UNDERSTANDING BSM EFFECTS

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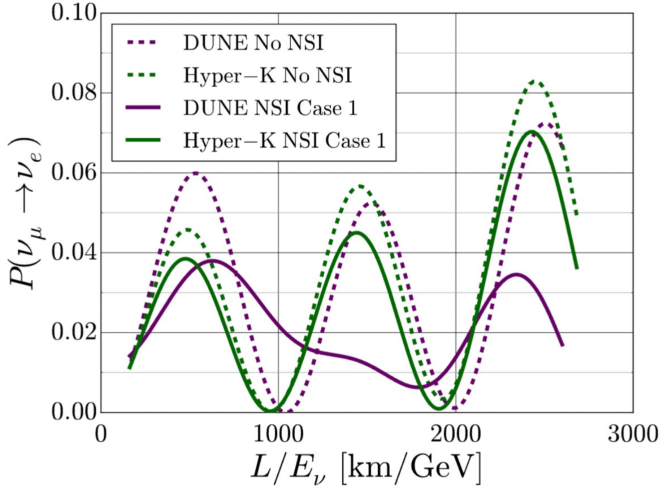
- NSI vs Sterile neutrino – if we see results inconsistent with 3-flavor neutrino oscillation, could we tell whether it was more likely to come from non-standard interactions or sterile neutrinos?
  - Sterile neutrino introduces new oscillation
  - Effects from NSI are similar to matter effect – more dramatic effect at higher energy/longer baseline
- Data at a different baselines (DUNE & Hyper-K) would observe very different oscillation probabilities for NSI

Appearance probabilities at DUNE and T2HK w/ NSI

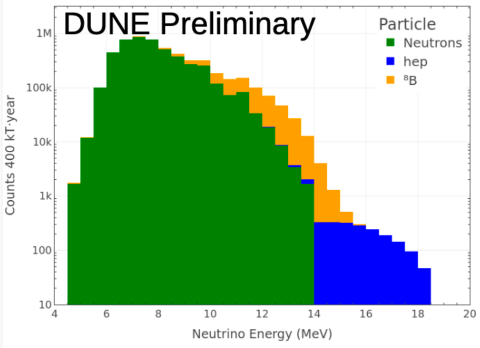


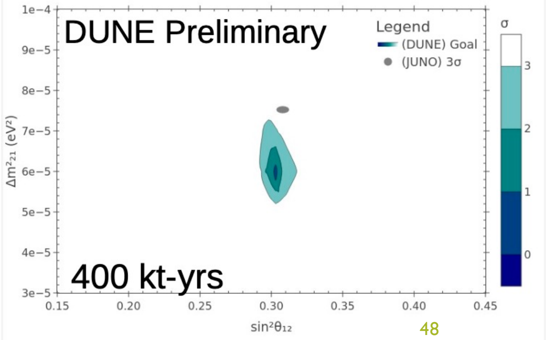
de Gouvêa and Kelly, *Nucl.Phys.B* 908 (2016) 318-335

BEYOND 3-FLAVOR OSCILLATION AT DUNE & HYPER-K

- Atmospheric neutrinos
  - Can be combined with beam measurements
- Supernova neutrinos
  - Thousands of neutrinos will be observed by DUNE and Hyper-K for a typical galactic supernova burst, allowing us to probe core collapse mechanism & supernova evolution
  - Sample at DUNE complementary to other detectors: CC absorption (ν_e) dominates while most other detectors are dominated by inverse beta decay (anti-ν_e)
  - Pointing capability (multi-messenger astrophysics)
- Physics beyond the Standard Model
  - BSM physics in oscillations (NSI, sterile neutrinos, etc)
  - Non-neutrino BSM (dark matter, other exotic particles)
  - Baryon number violation, nucleon decay

- Solar neutrinos
  - DUNE & Hyper-K will each see order 100 solar neutrinos per day
  - DUNE can observe hep solar flux at >5σ (first time!) and make measurements of solar oscillation parameters that can be compared with other experiments
  - Hyper-K expects sensitivity to new physics in the solar spectrum as well as solar oscillation parameter measurements





SUMMARY

- Accelerator-based neutrino oscillation experiments use neutrino appearance and disappearance in ν_μ-dominated beams to infer oscillation parameters – observables are neutrino and antineutrino spectra, so this requires correctly identifying the neutrino flavor and reconstructing the incoming neutrino energy from interaction products and disentangling degenerate oscillation effects
- **Important precision measurements and significant potential for new discoveries in both short- and long-baseline neutrino oscillation experiments**
  - NOvA and T2K have been producing results for the past decade+
  - SBN is producing results now! Global picture of sterile neutrino searches remains confusing…
  - DUNE and Hyper-K are under construction now!
- **Next-generation neutrino experiments represent a major experimental advance for long-baseline oscillation**: thousands of events, unambiguous determination of the neutrino mass ordering, 5σ-level sensitivity to CP violation, precision measurements of oscillation parameters – including δ_{CP} – significant sensitivity to physics beyond the Standard Model and astrophysics → the coming decade will be a very exciting time for neutrino physics!
- Measurements at DUNE and Hyper-K are **complementary** and can help differentiate among BSM scenarios if oscillations inconsistent with the standard 3-flavor model are observed