# LONG-BASELINE PHENOMENOLOGY:
## AN EXPERIMENTALIST'S VIEW

ELIZABETH WORCESTER (BNL/SBU)

NEUTRINO 2024

MILAN, JUNE 2024

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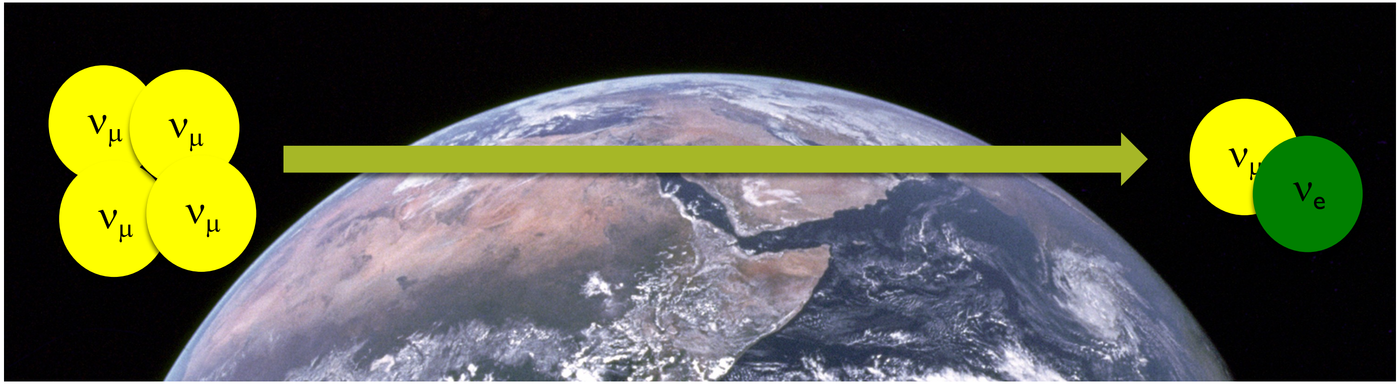
Note: I am not a phenomenologist! Goal of this presentation is to describe phenomenology that informs design and analysis of the experiments and to illustrate concepts with interesting recent work. Thanks to pheno colleagues for their input, especially P. Denton (BNL)!

# BASICS OF LONG-BASELINE OSCILLATION EXPERIMENTS



- 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

# NEUTRINO MIXING PARAMETERS

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

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

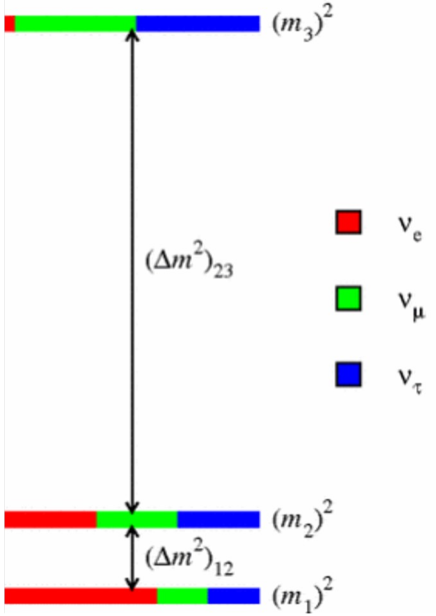
- **$\theta_{23} \approx 45^o$**
- Octant unknown (new symmetry?)

- **$\theta_{13} \approx 10^o$**
- $\delta_{CP}$ 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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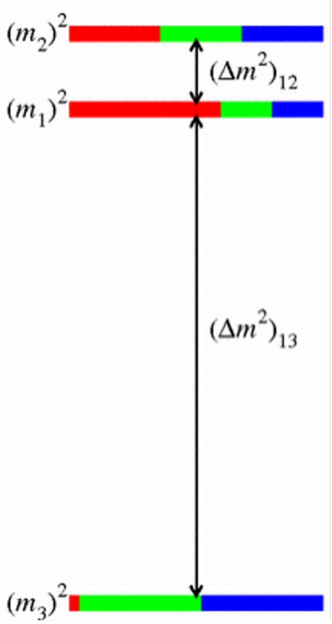
Inverted ordering



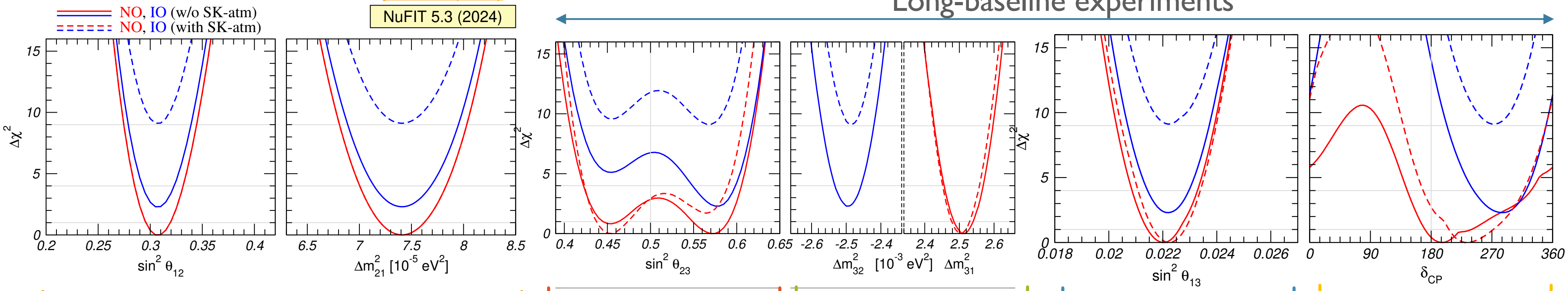
Note: in the case of Majorana neutrinos, there are two additional phases, but these do not enter the neutrino oscillation probability

# CURRENT STATUS OF MEASUREMENTS

- See yesterday's talks for details of global fits for oscillation parameters and results from operating experiments

JHEP 09 (2020)

Long-baseline experiments



"Solar" parameters – expect very precise measurements from JUNO

Octant unknown

Mass ordering unknown

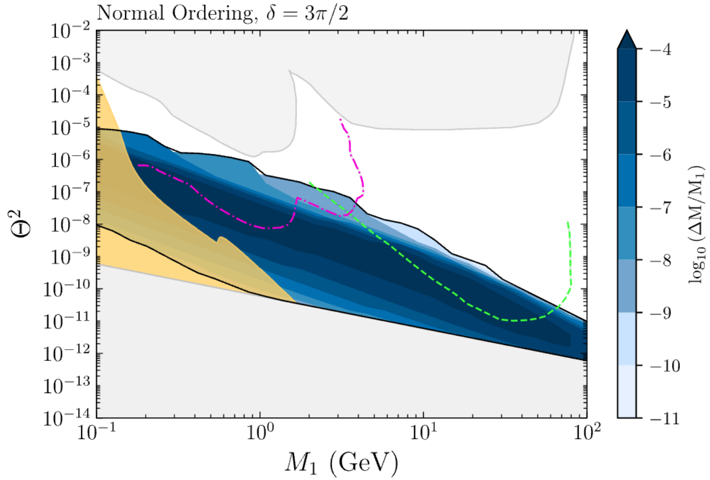
Precise measurement from reactor experiments

CP Violation?

# WHAT CAN WE LEARN FROM LONG-BASELINE OSCILLATIONS?

- What is the neutrino mass ordering?
- Is CP violated in neutrino oscillation?
  - Symmetry and symmetry violation has been a major driver of discovery in particle physics
  - Leptogenesis requires CPV in high-energy Lagrangian (incl. right-handed neutrinos)
    - No model-independent connection between low-energy (PMNS) CPV and high-energy CPV required for leptogenesis, though some models predict sufficient CPV from PMNS

Granelli, Pascoli, Petcov, *Phys.Rev.D* 108 (2023) 10, L101302

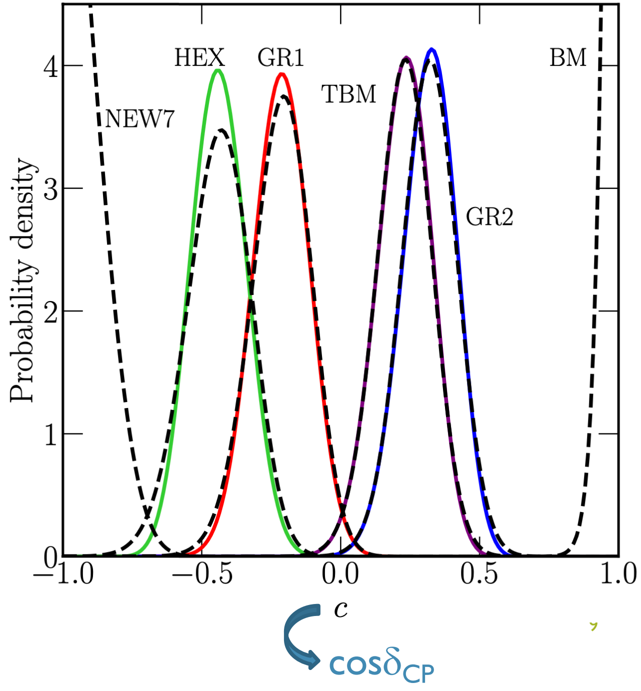


Parameter space of viable leptogenesis with CP violation coming only from $\delta_{CP}$

# WHAT CAN WE LEARN FROM LONG-BASELINE OSCILLATIONS?

- What gives rise to the neutrino flavor structure?
  - Why is the structure of the ν mixing matrix different from that of the quark mixing matrix?
  - What flavor symmetry can produce this pattern of mixing and how is it broken?
  - Is $\nu_\mu \leftrightarrow \nu_\tau$ mixing symmetric? If so, why – possible new symmetry?
- Is the neutrino mixing matrix unitary? Are there BSM effects impacting neutrino oscillation?
- Precision measurements allow model discrimination
  - Many flavor and BSM models make specific predictions for values of oscillation parameters

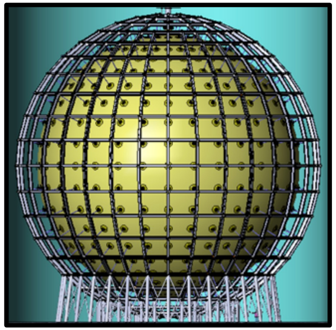
Everett, Ramos, Rock, Stuart, *Int.J.Mod.Phys.A* 36 (2021) 30, 2150228

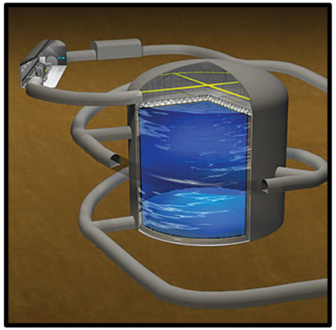


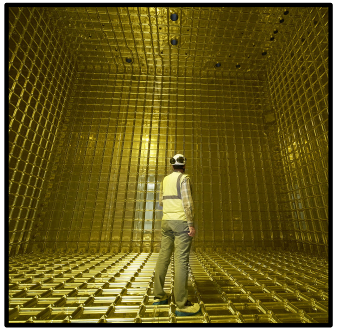
# EXPERIMENTAL OUTLOOK

- See experiment talks for experimental details and sensitivity projections – expect next generation experiments will provide unambiguous determination of the mass ordering, precise measurements of PMNS parameters including $\delta_{CP,}$ and sufficient precision to be sensitive to non-unitarity of the PMNS matrix and other BSM effects!

NOvA/T2K JUNO HyperK DUNE Next-next gen







Results now! Taking data soon! UNDER CONSTRUCTION NOW! Being designed now!

# OSCILLATION PROBABILITY

- Two-flavor mixing:

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Three-flavor mixing in matter:

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

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

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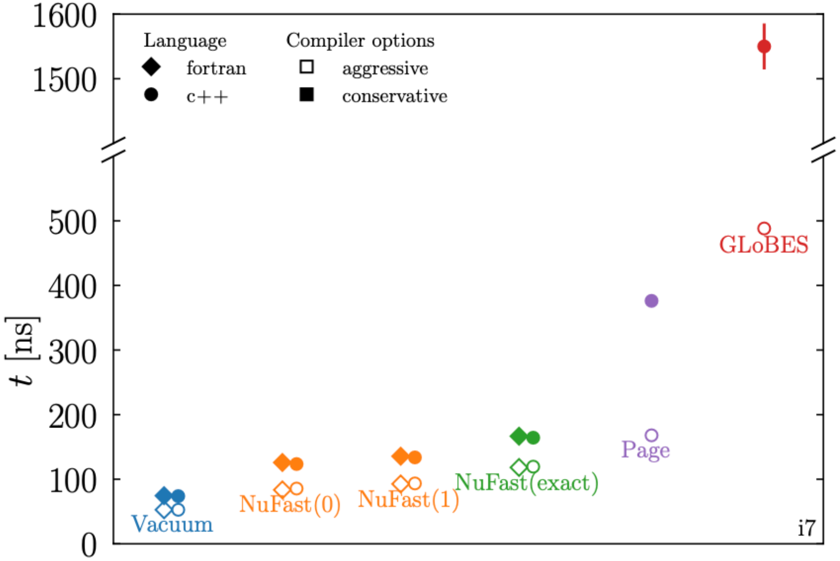
Matter effect from coherent forward scattering on electrons

CP violation

# COMPUTING OSCILLATION PROBABILITIES

- Experimental results require calculating oscillation probabilities many millions of times for fits and statistical analysis
  - Ex: NOvA frequentist oscillation analysis requires millions of Feldman-Cousins pseudoexperiment fits be performed using HPC resources
  - Computational cost of these analysis can be reduced by improving the speed of algorithms that calculate oscillation probability
- Computational advances will be critical in facilitating analysis at future experiments

Computational Time to Calculate Set of Oscillation Probabilities



Denton and Parke, arXiv: 2405.02400

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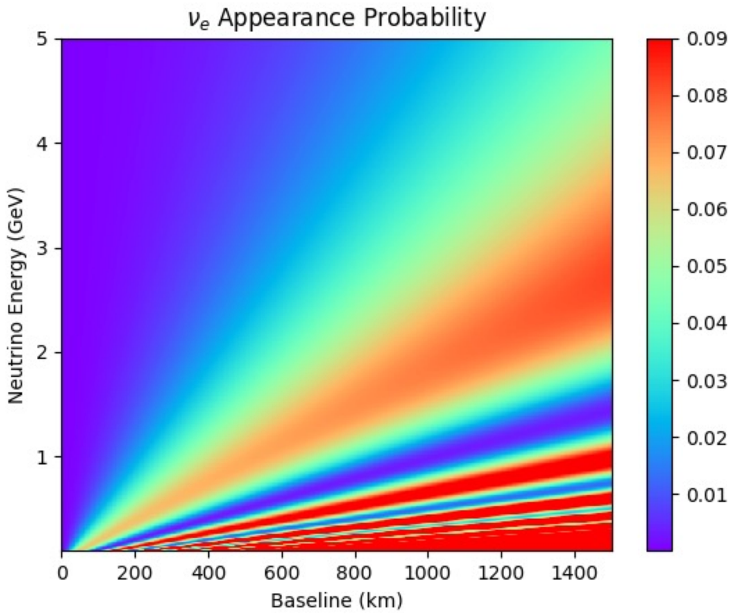

# OSCILLATION PROBABILITY

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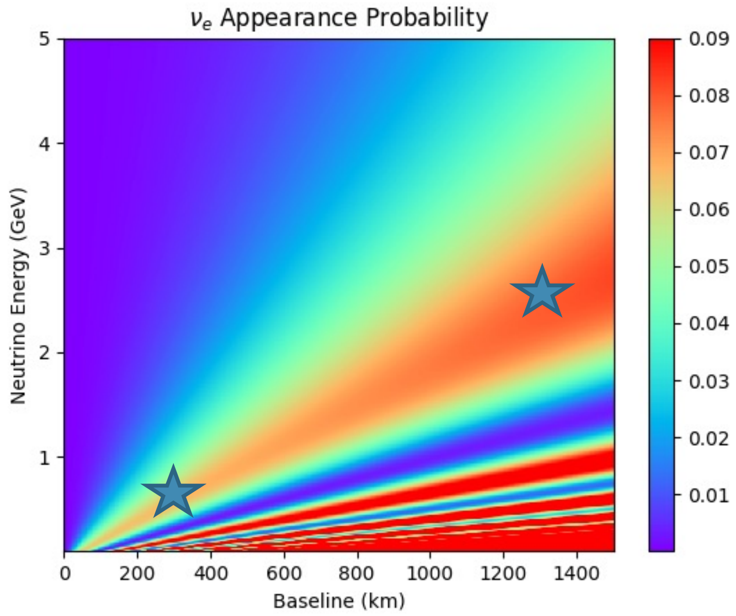


# EVENT RATES

- Accelerator-based neutrino datasets, particularly for $\nu_e$ appearance channels, are small for current experiments:

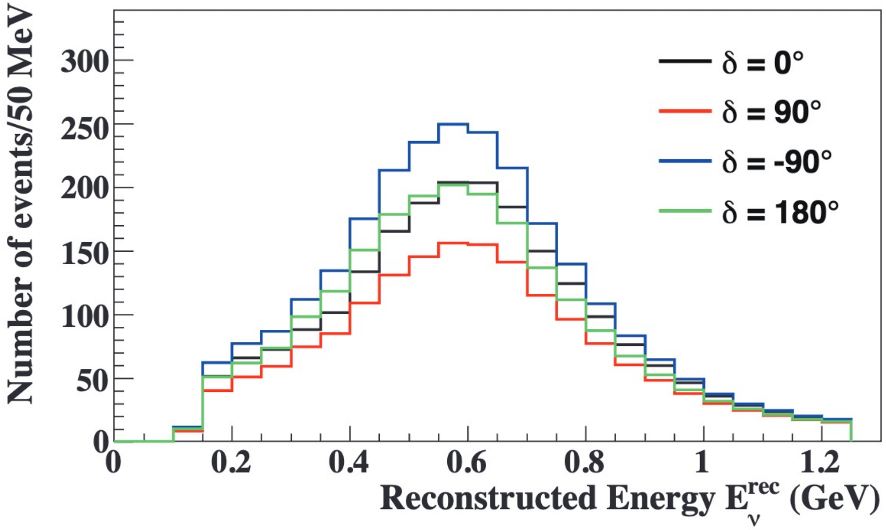
NOvA-T2K joint fit

| Channel | NOvA | T2K |
|---|---|---|
| $\nu_e$ | 82 | 94 ($\nu_e$)<br>14 ($\nu_e 1\pi$) |
| $\bar{\nu}_e$ | 33 | 16 |
| $\nu_\mu$ | 211 | 318 |
| $\bar{\nu}_\mu$ | 105 | 137 |

<250 $\nu_e$ appearance candidate events in data used for NOvA-T2K joint fit

- Higher power beams and larger detectors in next-generation experiments provide major increase in sensitivity from statistics alone (assuming uncertainties can be controlled sufficiently to take advantage of the statistics)

T2HK: Expected $\nu_e$ appearance spectrum

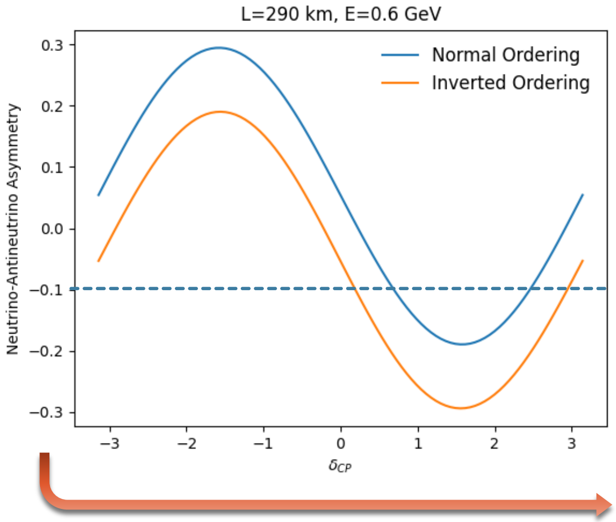


Hyper-K Design Report

Massive increase in statistical precision for next-generation experiments!

# COMPLEX PARAMETER SPACE

- Experiments are sensitive to many parameters, **if** we can resolve degenerate effects



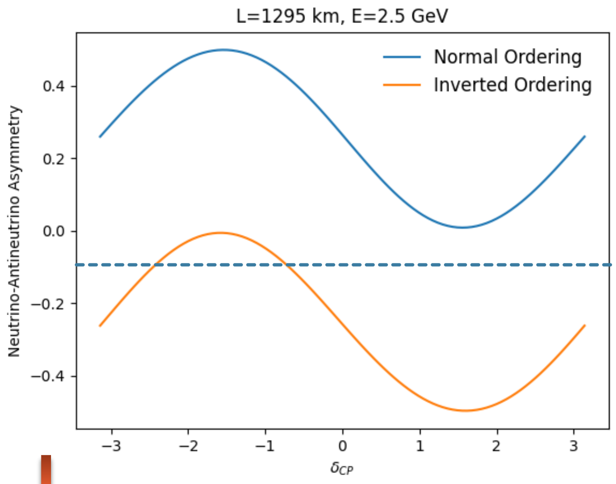
Baseline of 290 km
(very little matter effect)

Asymmetry measurement alone has degenerate possible values for both $\delta_{CP}$ and mass ordering

Matter-antimatter asymmetry

# COMPLEX PARAMETER SPACE

- Experiments are sensitive to many parameters, **if** we can resolve degenerate effects



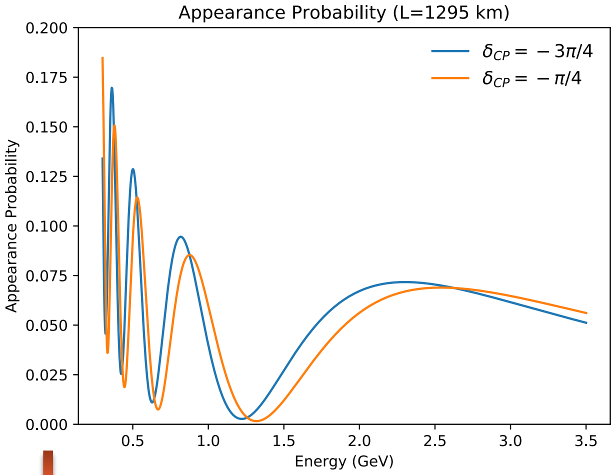
Baseline of 1295 km
(large matter effect)

Asymmetry measurement alone has degenerate possible values only for $\delta_{CP}$ -- mass ordering degeneracy lifted

Matter-antimatter asymmetry

# COMPLEX PARAMETER SPACE

- Experiments are sensitive to many parameters, **if** we can resolve degenerate effects



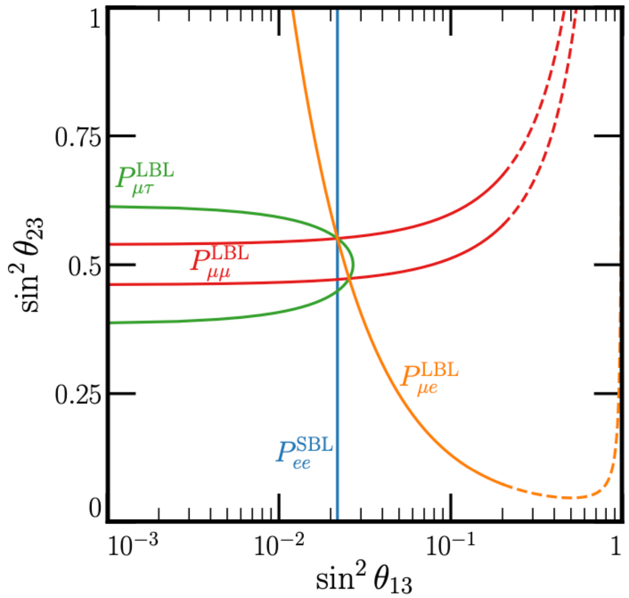
Appearance probability

Baseline of 1295 km
(large matter effect)

Energy dependence of oscillation can resolve $\delta_{CP}$ degeneracy

# TESTING PMNS UNITARITY

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



- Hypothetical **infinite precision** measurements in $\theta_{23} - \theta_{13}$ space: combining values obtained from long-baseline oscillation measurements ($\nu_\mu$ disappearance, $\nu_e$ appearance, and $\nu_\tau$ appearance) with the reactor measurement of $\theta_{13}$ to test normalization of 3rd column of mixing matrix

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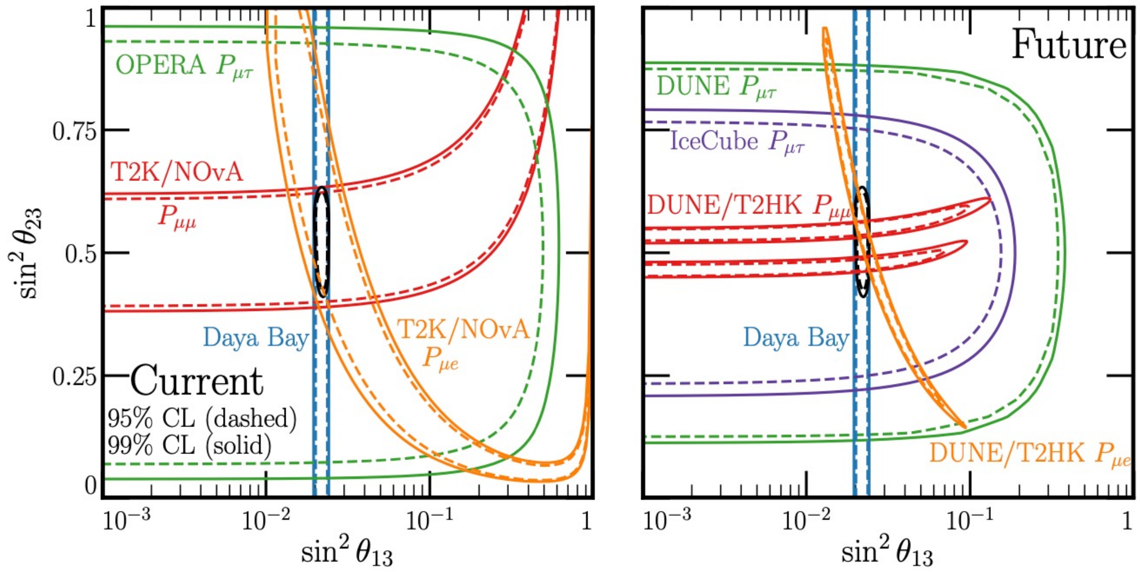
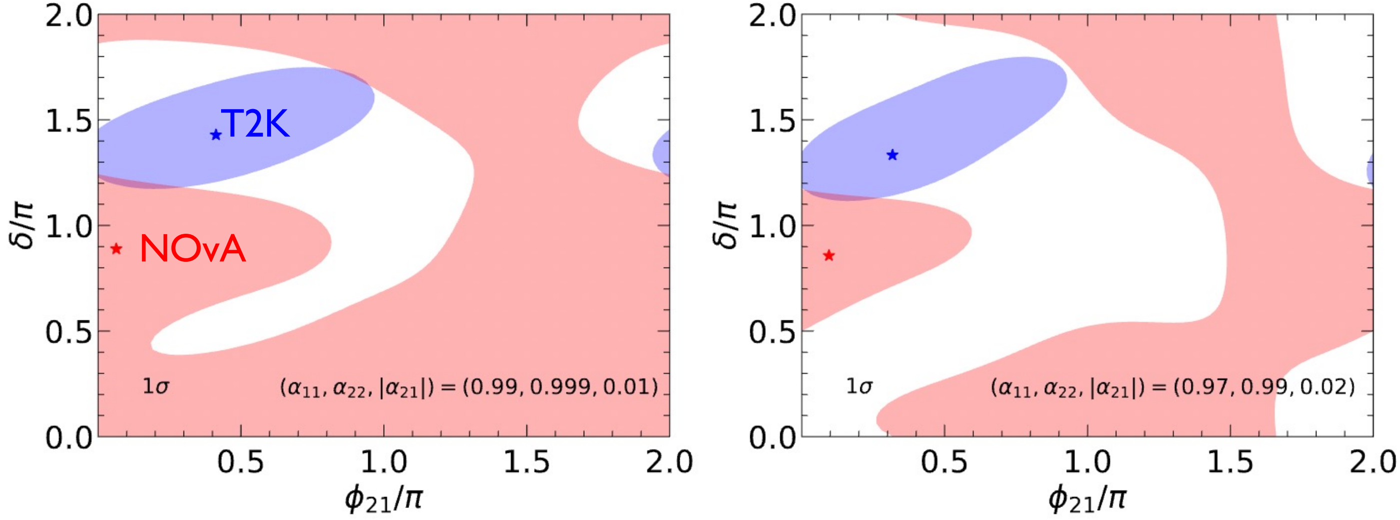
Ellis, Kelly, Li, *JHEP* 12 (2020) 068



- **Current and projected** measurements in $\theta_{23} - \theta_{13}$ space: combining values obtained from long-baseline oscillation measurements ($\nu_\mu$ disappearance, $\nu_e$ appearance, and $\nu_\tau$ appearance) with the reactor measurement of $\theta_{13}$ 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

# ANALYZING CURRENT DATA WITH NON-UNITARY PARAMETERS

Ferero, Giunti, Ternes, Tórtola, Phys.Rev.D 104 (2021) 7, 075030



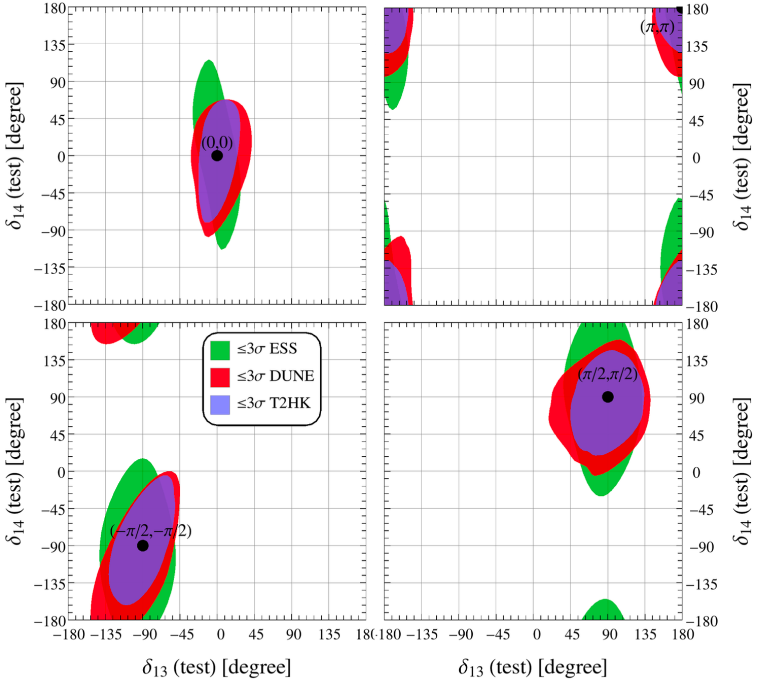
- NOvA and T2K results interpreted in the context of non-unitarity parameters in normal ordering
- No significant increase in overlap of allowed regions relative to nominal (unitary) analysis

# 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 $\theta_{34}$ and $\delta_{34}$ 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



CP Conserving

CP Violating

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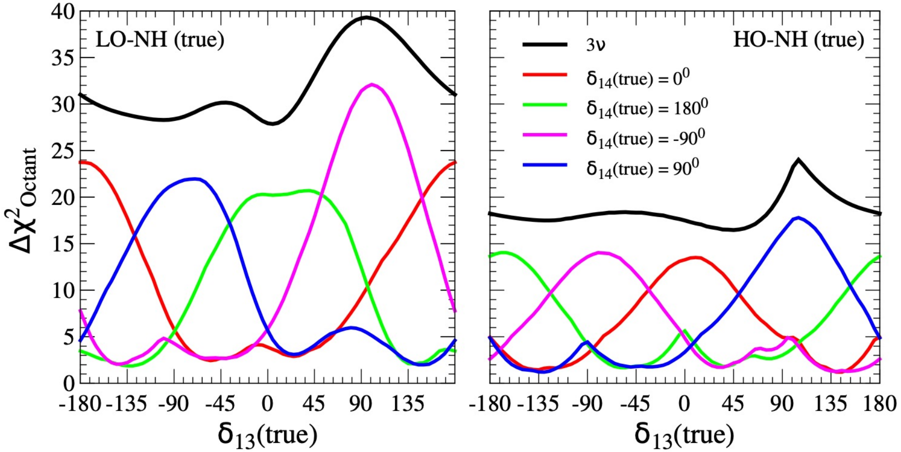
  - Oscillations in vacuum are independent of $\theta_{34}$ and $\delta_{34}$ but this is not the case in matter, so experiments with sufficient matter effect are sensitive to these parameters
- Of course, additional parameters introduce potential for degeneracies that can thwart sensitivity

## Projected Octant Sensitivity (DUNE)



True lower octant,
True normal ordering

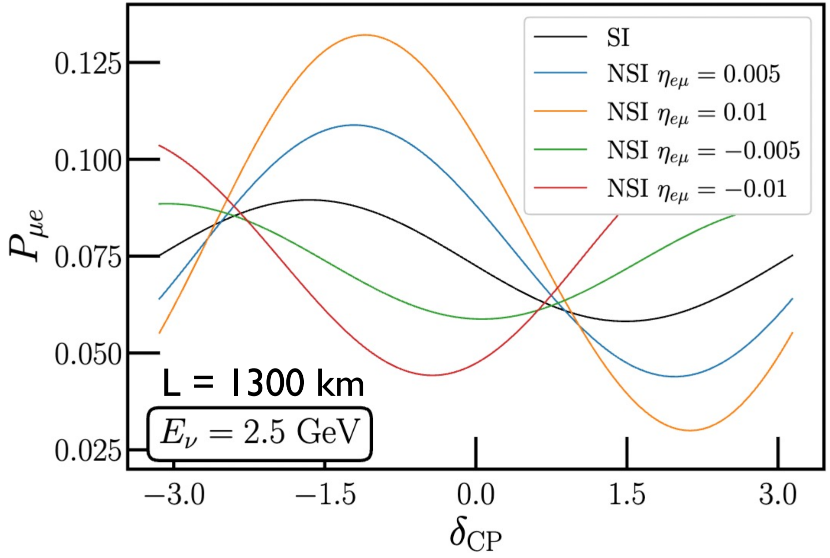
True upper octant,
True normal ordering

Agarwalla, et al., Phys.Rev.Lett. 118 (2017) 3, 031804

# NSI AT LONG-BASELINE EXPERIMENTS

- Non-standard interactions (NSI) can modify neutrino oscillation probabilities in matter, impacting measurements at long-baseline experiments (and allowing these experiments to be sensitive to NSI!)

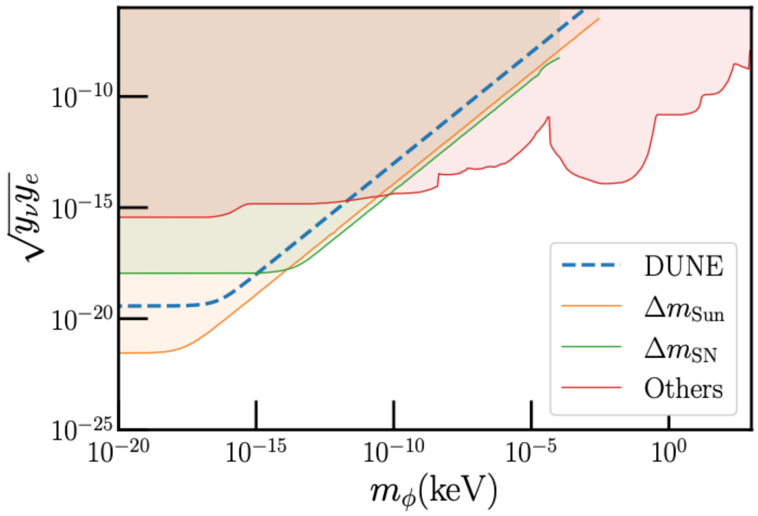
Dutta, et al., 2024



# NSI AT LONG-BASELINE EXPERIMENTS

- Non-standard interactions (NSI) can modify neutrino oscillation probabilities in matter, impacting measurements at long-baseline experiments (and allowing these experiments to be sensitive to NSI!)
- Projected DUNE limits on NSI mediated by light neutral scalar fields in this analysis appear similar to limits from astrophysical sources – complementary sensitivity! – and are based on all SNSI parameters varying separately

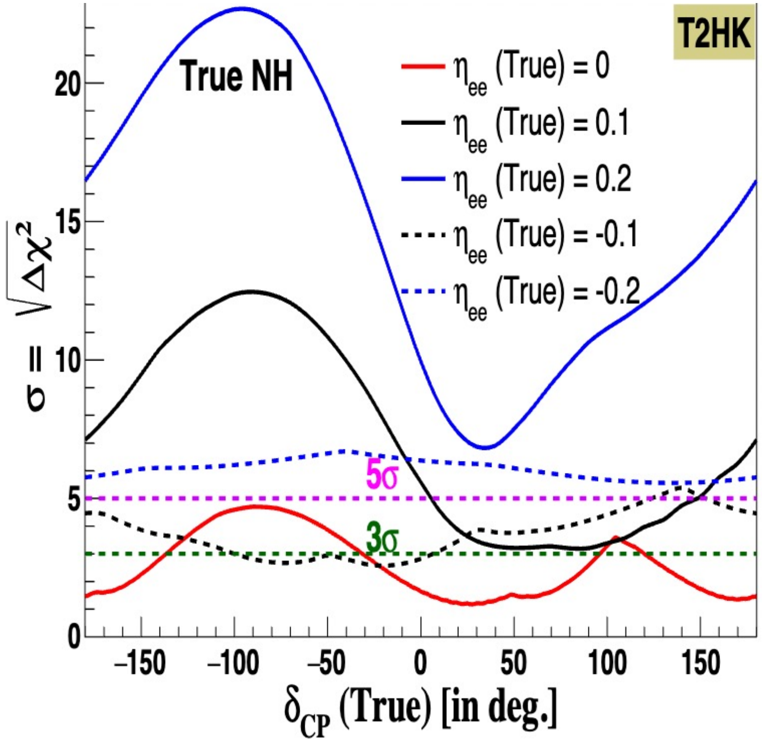
Dutta, et al., 2024



# NSI AT LONG-BASELINE EXPERIMENTS

- Non-standard interactions (NSI) can modify neutrino oscillation probabilities in matter, impacting measurements at long-baseline experiments (and allowing these experiments to be sensitive to NSI!)
- Presence of scalar NSI dramatically **enhances** the T2HK sensitivity to neutrino mass ordering in this analysis because matter-antimatter asymmetry is larger than for the SM matter effect

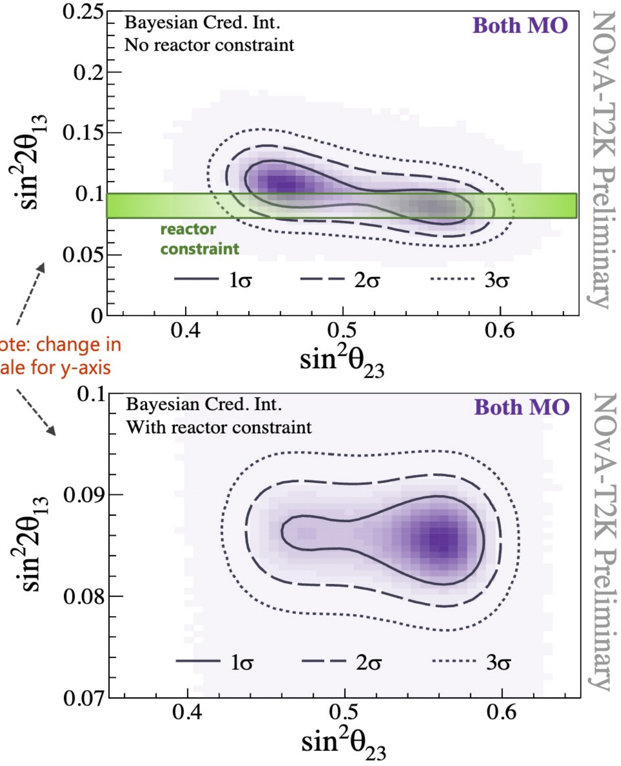
Sarker, et al., 2023, arXiv:2309.12249



# EXPERIMENT COMPLEMENTARITY: EXTERNAL CONSTRAINTS

- Precise measurements of oscillation parameters can be used to improve measurements at other experiments
- Current generation of LBL experiments typically use constraint on $\theta_{13}$ from reactor experiments

Z. Vallari, FNAL W&C Seminar

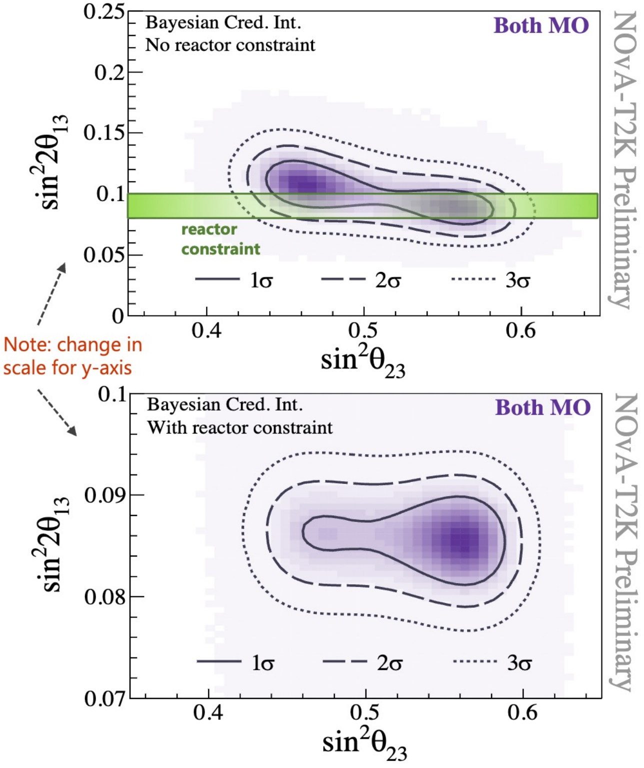


Note: change in scale for y-axis

# EXPERIMENT COMPLEMENTARITY: EXTERNAL CONSTRAINTS

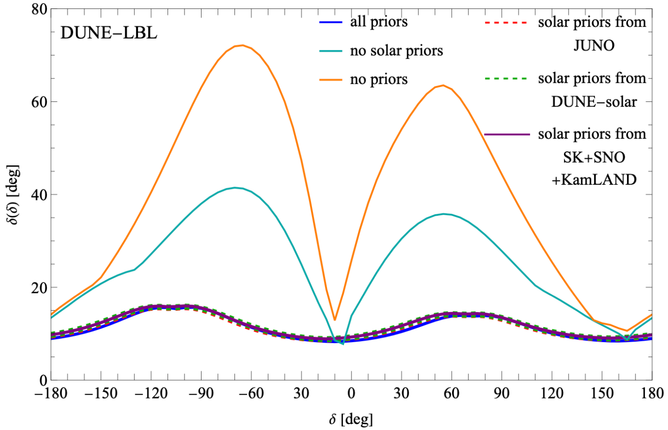
- Precise measurements of oscillation parameters can be used to improve measurements at other experiments
- Current generation of LBL experiments typically use constraint on $\theta_{13}$ from reactor experiments
- Next-gen LBL experiments can measure $\theta_{13}$ independently, but this in turn depends on knowledge of solar parameters

Z. Vallari, FNAL W&C Seminar



Note: change in scale for y-axis

Denton and Gehrlein, *HEP* 06 (2023) 090

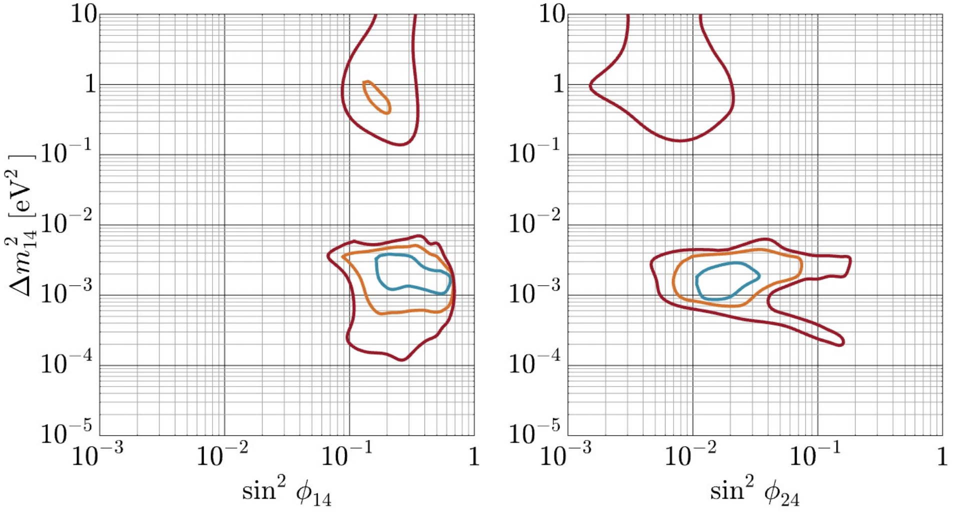


DUNE resolution on $\delta_{CP}$ significantly degraded in the absence of priors on solar oscillation parameters. This also implies that next-gen LBL experiments will have some sensitivity to these parameters in their oscillation measurements!

# EXPERIMENT COMPLEMENTARITY: UNDERSTANDING BSM EFFECTS

- Fun problem to have: differentiating types of new physics observed at next-gen experiments!
- NSI vs Sterile neutrino
  - Additional freedom in sterile model suggests the 3+1 model would likely provide a better fit to NSI data than the 3ν model, though fits tend towards large values of the additional mixing angles
  - Sterile neutrino introduces new oscillation
  - Effects from NSI typically grow with energy with no oscillatory L/E behavior

Example fit to DUNE NSI “data” assuming 3+1 model



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

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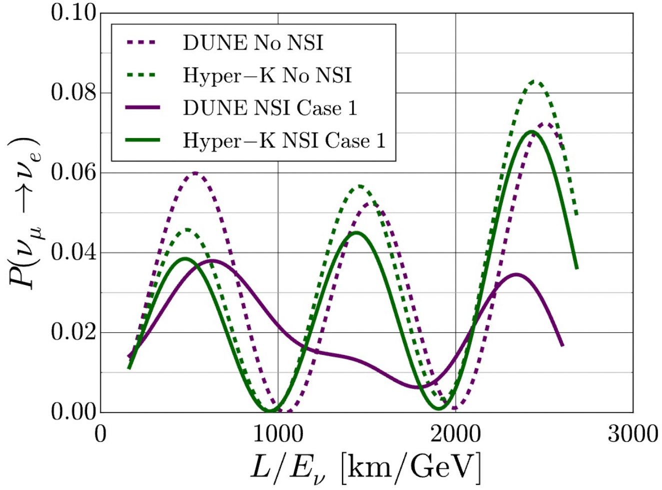
  - Sterile neutrino introduces new oscillation
  - Effects from NSI typically grow with energy with no oscillatory L/E behavior
- Data at a different baseline (T2HK) would in this case point to NSI rather than sterile neutrinos because of the very different oscillation probabilities relative to DUNE

## Appearance probabilities at DUNE and T2HK w/ NSI

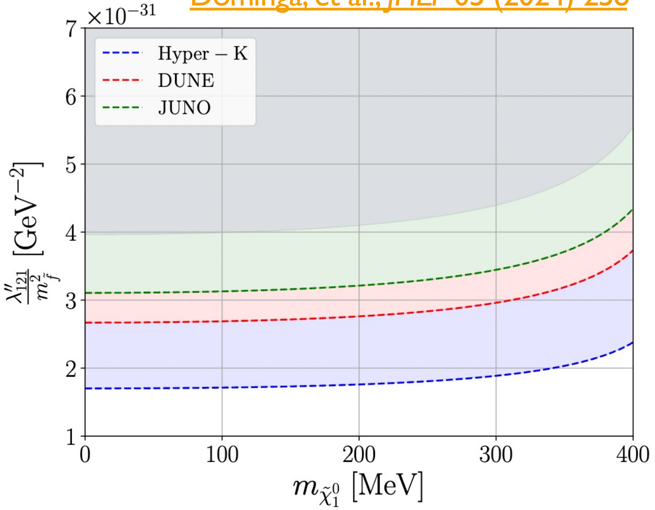


de Gouvêa and Kelly, *Nucl.Phys.B* 908 (2016) 318-335

# BSM BEYOND OSCILLATIONS

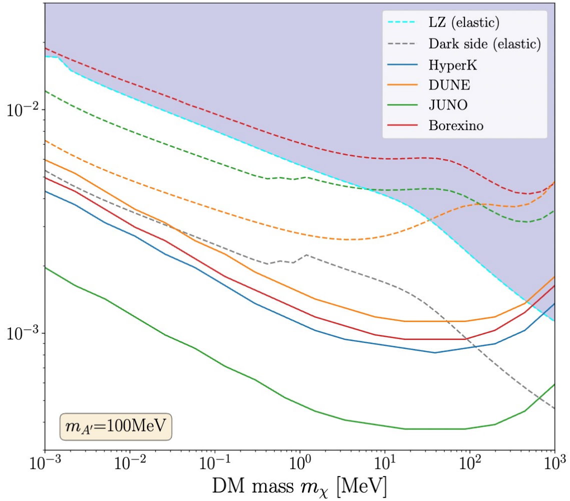
- Long-baseline oscillation experiments are also very good at detecting other (non-oscillation) BSM signatures

Dominga, et al., *JHEP* 05 (2024) 258



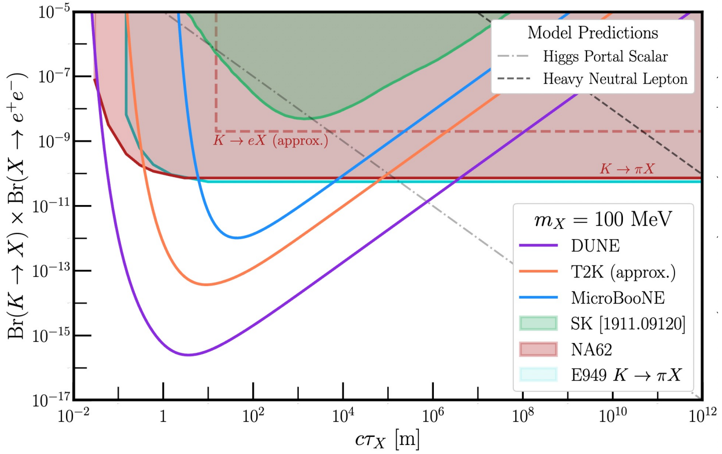
Proton Decay to an Exotic Neutral Particle

Dutta, et al., arXiv:2402.04184



Cosmic-Ray
Boosted Dark Matter

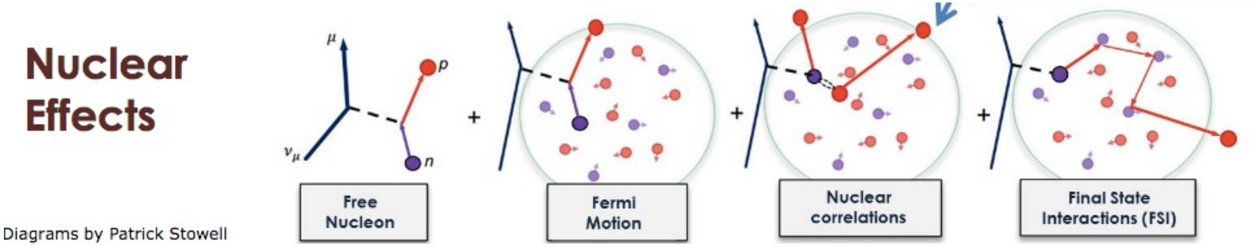
Batell, Huang, Kelly, *JHEP* 08 (2023) 092



Long-Lived Particle
(100 MeV)

# NUCLEAR PHENOMENOLOGY

- Modeling of nuclear effects in neutrino-nucleus interactions (and development of event generators that incorporate these models) is an important input to the experimental program that requires collaboration among neutrino experimentalists, nuclear experimentalists, and nuclear theorists



Diagrams by Patrick Stowell

Experimental techniques to minimize impact of uncertainty from interaction model also an important piece of this puzzle

- NuSTEC collaboration is promoting and coordinating much of this effort – too much to list here!
  - See agenda of recent NuINT 2024 workshop for the scope of work
- Also see talks on Thursday and Friday this week for details!

# CONCLUSIONS

- Long-baseline neutrino oscillation is described by a complex parameter space, providing significant experimental sensitivity to many different parameters and effects, but requiring experiments to disentangle degenerate effects
- Wealth of phenomenology investigating impact of new physics scenarios on future LBL experimental measurements – these slides provide only a few examples to give a flavor of the topics being addressed
- Degenerate effects present in both 3-flavor and BSM scenarios make complementary experiments even more critical as differences in experiment design (such as size of matter effect) can help resolve these degeneracies
- Theory efforts outside of long-baseline phenomenology also provide critical input to the LBL experimental program (eg: "other" BSM physics, neutrino-nucleus interactions)
- The LBL experimental program offers an exciting opportunity to test a wide variety of models and potentially discover new physics – the next decade (and the next talks) will be very exciting!