SEARCHING FOR PHYSICS BEYOND THE STANDARD MODEL IN NEUTRINO OSCILLATIONS

She/her

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BNL NUSTEAM/NUPUMAS LECTURE

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INTRODUCTION

- Originally from Montpelier, VT
- BS in physics from Georgia Tech
- PhD from University of Chicago: "CP Violation in Neutral Kaon Decays"
- Studying neutrinos at BNL since 2011
- Adjunct professor at Stony Brook University
- Experiments: DUNE, ICARUS, SBND
- Hobbies include running, climbing/bouldering, guitar




SUMMARY

- We have quite specific expectations of how neutrino oscillations behave in the 3-neutrino paradigm based on existing measurements of neutrino oscillation parameters
- The existence of neutrino mass already means there must be new physics – we just don't know yet exactly what it looks like
- Several models of new physics predict specific distortions of neutrino oscillation spectra, allowing us to search for those specific effects and place limits on the parameters of those models
- Some new physics may affect the observed spectra in ways that are semi-degenerate with the 3-neutrino oscillation parameters or with other new physics models – experiments with different energies and baselines can disentangle these effects
- We can search for new physics more generically , eg: by studying whether the PMNS matrix is unitary
- Searches for new physics in neutrino oscillation are intrinsically tied to study of 3-neutrino oscillation

INTRO TO NEUTRINO OSCILLATION

AGAIN!

In many cases we look for BSM physics by looking for deviations in observed oscillation effects from what is expected in the standard 3-neutrino paradigm. So, we have to understand 3-flavor oscillation to understand how BSM may affect those oscillations.

NEUTRINO MIXING PARAMETERS

Neutrinos have mass ⟷ neutrinos oscillate (already BSM physics!)

Flavor eigenstates Mass eigenstates

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

NEUTRINO MIXING PARAMETERS

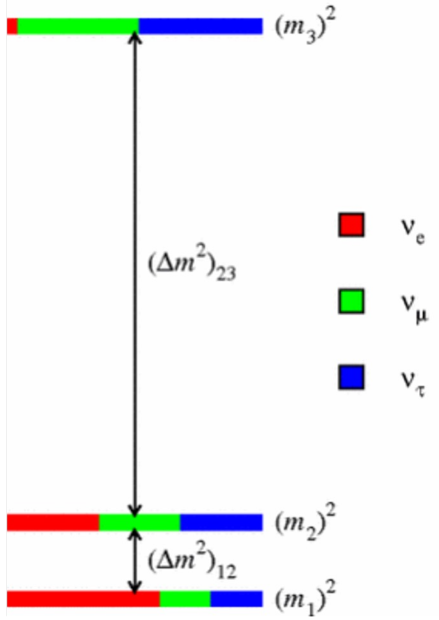
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times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

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

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

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

Normal ordering



NEUTRINO MIXING PARAMETERS

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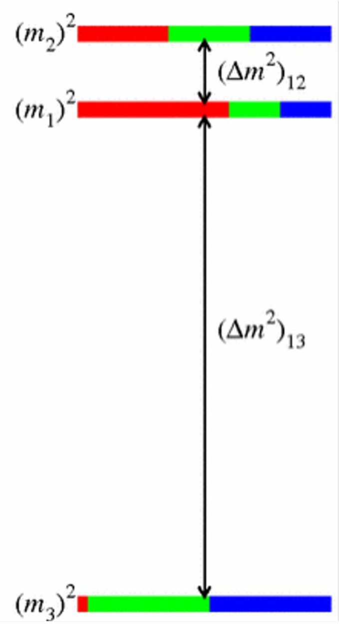
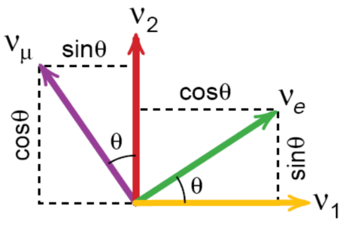
Inverted ordering



NEUTRINO OSCILLATION PROBABILITY: BONUS HOMEWORK

- In the two-flavor approximation, derive the ν_μ to ν_e oscillation probability



$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Step 1: Write $|\nu_\mu\rangle$ and $|\nu_e\rangle$ in terms of ν_1 and ν_2
Step 2: Apply the Schrodinger equation to get the time evolved $|\nu_\mu(t)\rangle$ state in terms of ν_1 and ν_2
Step 3: Use natural units, assume a common momentum for both mass states, and assume $E=p>>m$ to write ΔE in terms of m_1, m_2, and E
Step 4: Square the inner product of the $|\nu_e\rangle$ and $|\nu_\mu(t)\rangle$ states to get the probability of oscillation from ν_μ to ν_e

Slides 15-16 in this lecture will walk you through the calculation more fully:
https://indico.cern.ch/event/305391/contributions/701285/attachments/580248/798873/ZZ_NeutrinoPhysics_L2.pdf

NEUTRINO OSCILLATION PROBABILITY

- Two neutrino case: $P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

  - Oscillation amplitude depends on θ (mixing angle)
  - Oscillation frequency depends on Δm^2 (mass difference), baseline (L), and energy (E).

NEUTRINO OSCILLATION PROBABILITY

- Three-flavor mixing in matter:

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

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

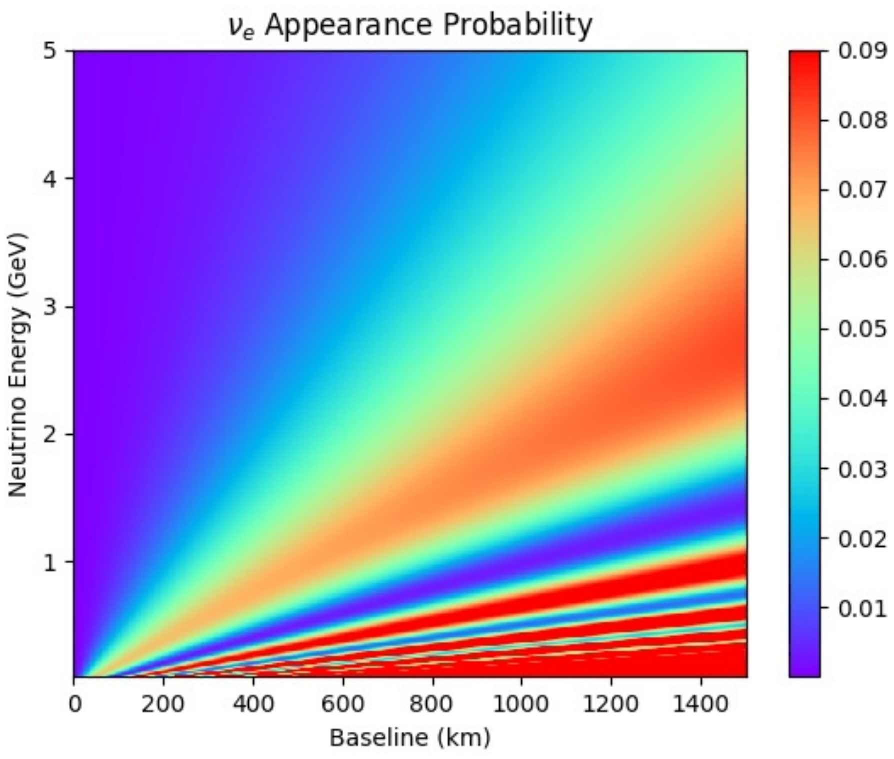
Matter effect from coherent forward scattering on electrons, couples to baseline

CP violation

$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$$

Same basic dependence as two-flavor case

NEUTRINO OSCILLATION PROBABILITY



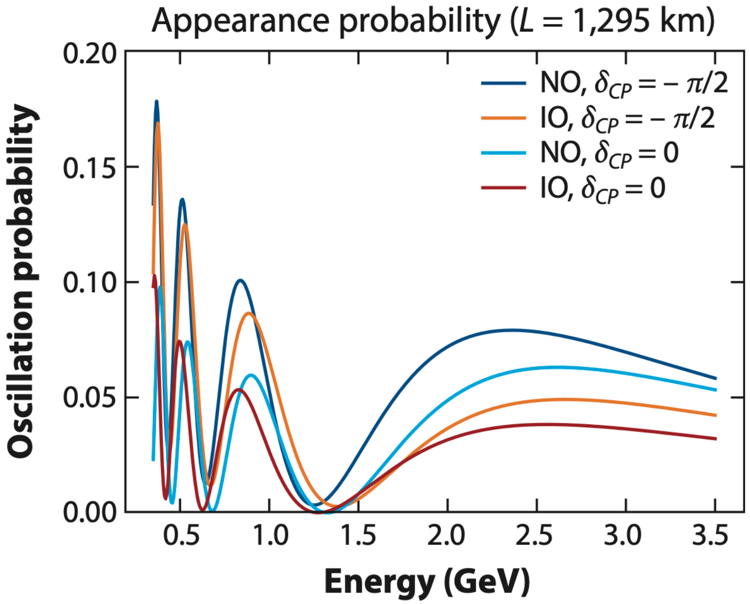
Optimize choice of baseline and energy for desired measurement (1st/2nd oscillation maxima)

Questions:

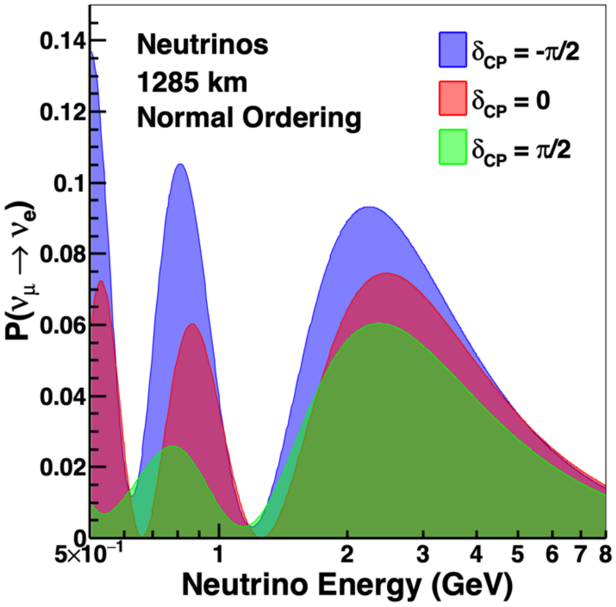
- I want to place a detector at a baseline of 600 km and observe the first oscillation maximum. What neutrino energy should I target in designing the beam?
- I have a neutrino beam energy of 750 MeV and I'd like to observe the 2nd oscillation maximum. Where should I place my detector?

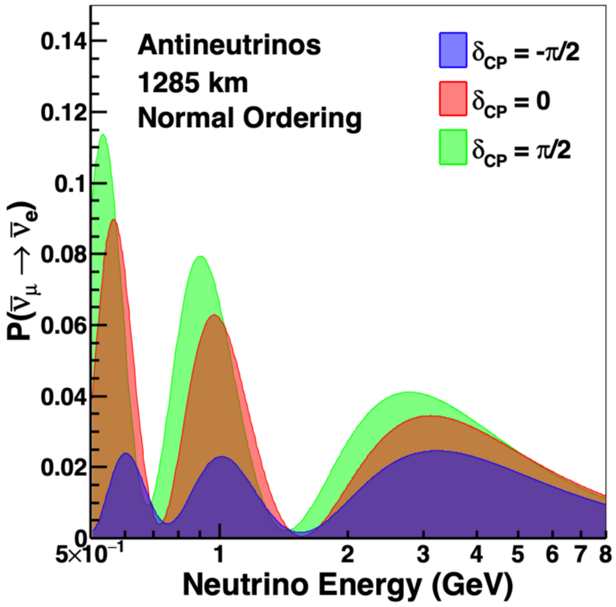
MATTER EFFECT

- 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



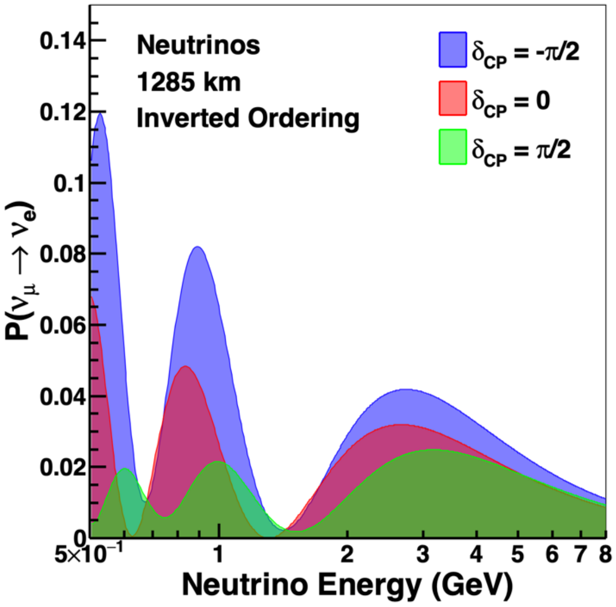
APPEARANCE PROBABILITY

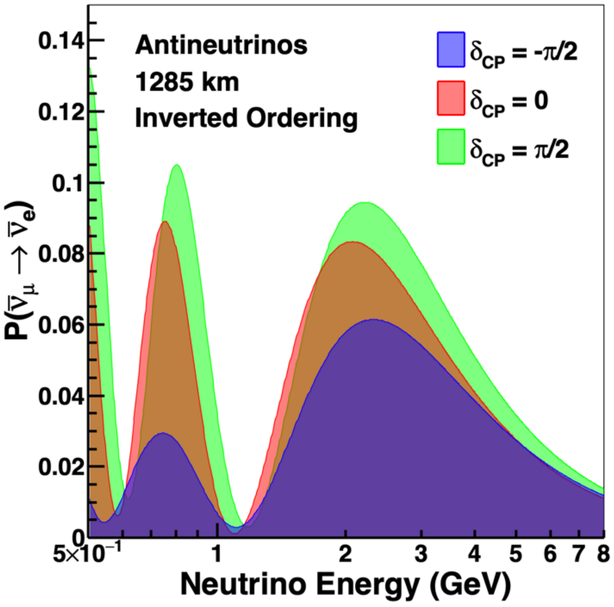




- Value of δ_{CP} affects both rate and shape of appearance probability, with asymmetric impact on neutrinos and antineutrinos
- Matter effect enhances appearance probability for neutrinos and reduces it for antineutrinos if ordering is <u>normal</u>

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!

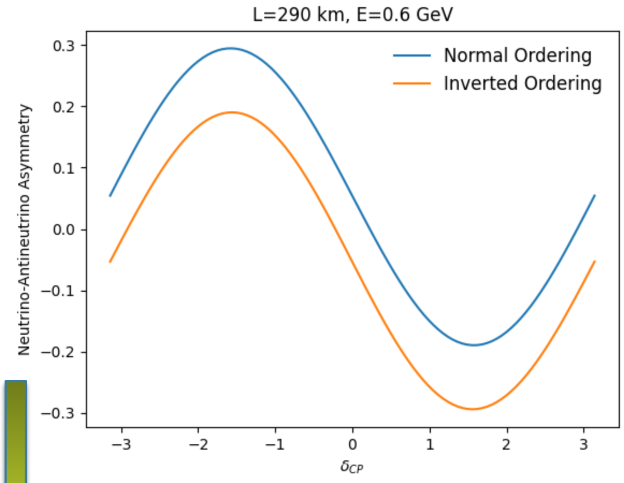
QUESTIONS

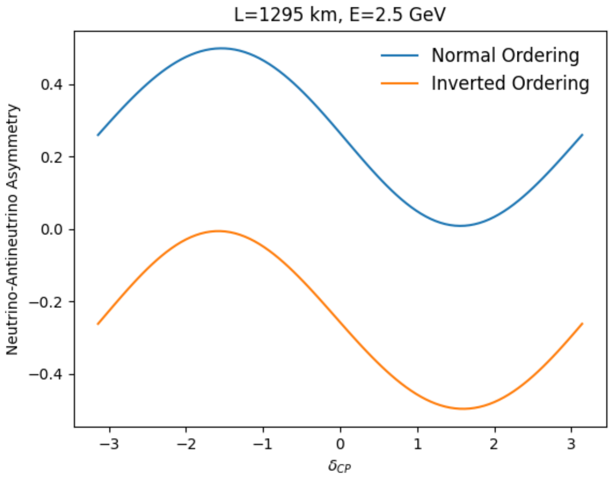
- What combination of neutrino/antineutrino, normal/inverted ordering, and δ_{CP} values gives the largest appearance probability?
- What combination of neutrino/antineutrino, normal/inverted ordering, and δ_{CP} values gives the smallest appearance probability?
- Can you find a combination of neutrino/antineutrino, normal/inverted ordering that have similar appearance probabilities for different values of δ_{CP}?

RESOLVING DEGENERACY

Baseline of 290 km
(very little matter effect)

Baseline of 1295 km
(large matter effect)

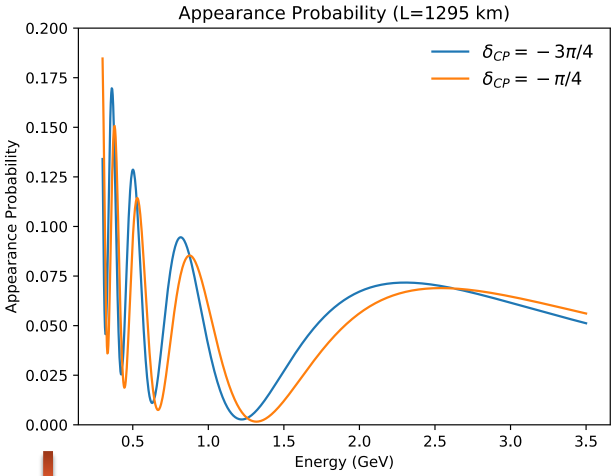




Degeneracy between δ_{CP} and matter effects is lifted for baselines greater than ~1000 km because matter effect produces larger asymmetry

Matter-antimatter asymmetry

RESOLVING DEGENERACY



Baseline of 1295 km
(large matter effect)

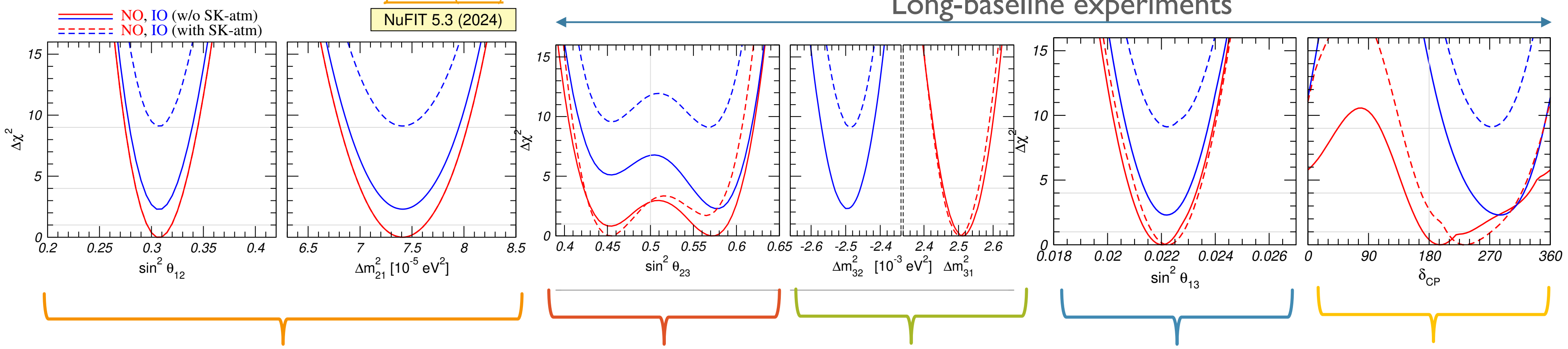
Energy dependence of oscillation can resolve δ_{CP} degeneracy

Appearance probability

CURRENT STATUS OF MEASUREMENTS

- Example of global fit for oscillation parameters:

JHEP 09 (2020)



"Solar" parameters – expect very precise measurements from JUNO (reactor experiment coming soon)

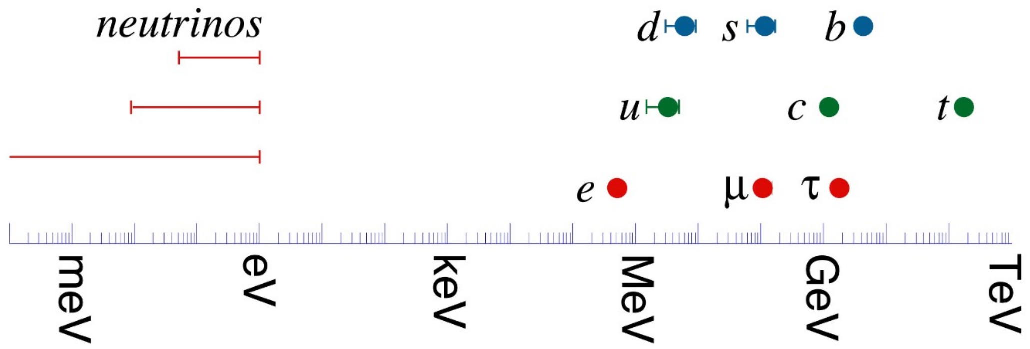
Octant unknown

Mass ordering unknown

Precise measurement from reactor experiments

CP Violation?

NEUTRINOS MASS → BSM PHYSICS



- Neutrino masses (still unmeasured) are very light compared to all other known particles – suggests that perhaps their mass is generated in a different way from other particles or that they couple extremely weakly to the Higgs
- To generate neutrino mass with the Higgs mechanism would require additional (right-handed) neutrinos that are not yet observed
- Whether through a new mass-generation mechanism, new particles, or both, the currently known neutrino masses imply there must be new physics

NEW PHYSICS SCENARIOS

NON-STANDARD INTERACTIONS (NSI)

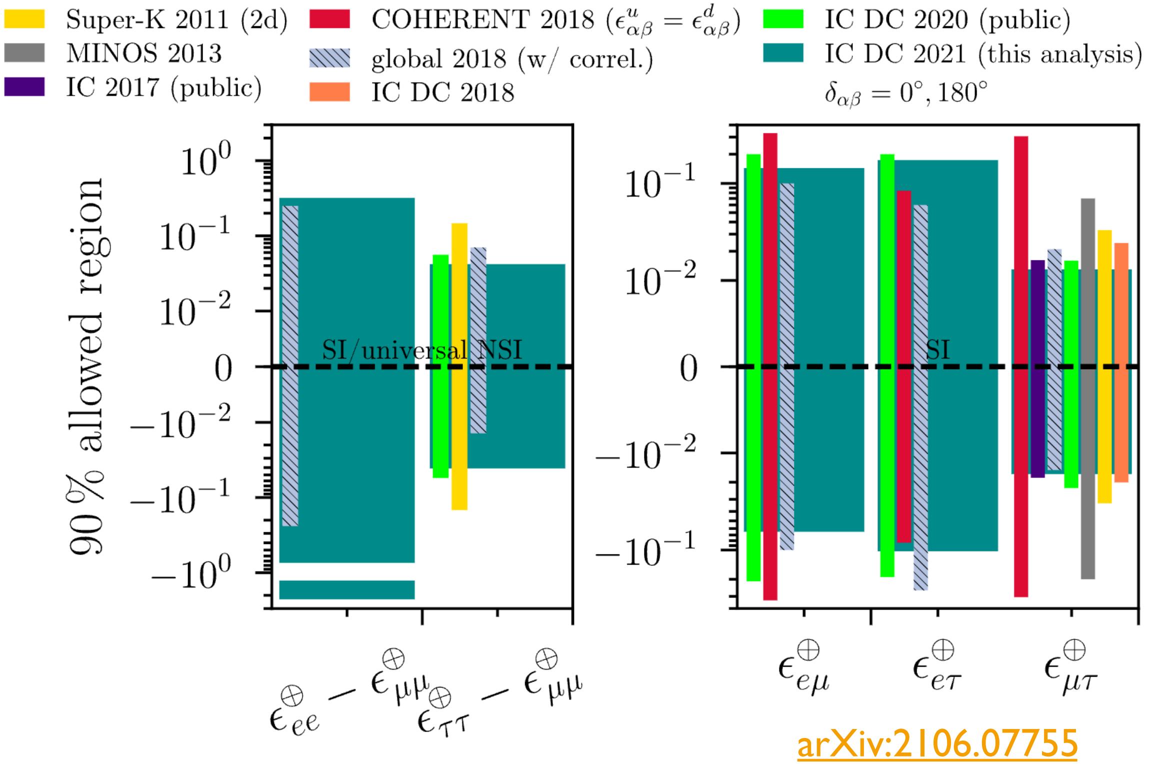
- New neutrino interactions
- While the new interactions could affect neutrino production, interaction, or propagation, typically we focus on propagation effects, leading to perturbations of the matter effect, eg: vector NSI

$$H = \frac{1}{2E}\left[U_{\mathrm{PMNS}} \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger_{\mathrm{PMNS}} + a \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix} \right]$$

Standard oscillations — Non-standard oscillations

NSI SEARCHES

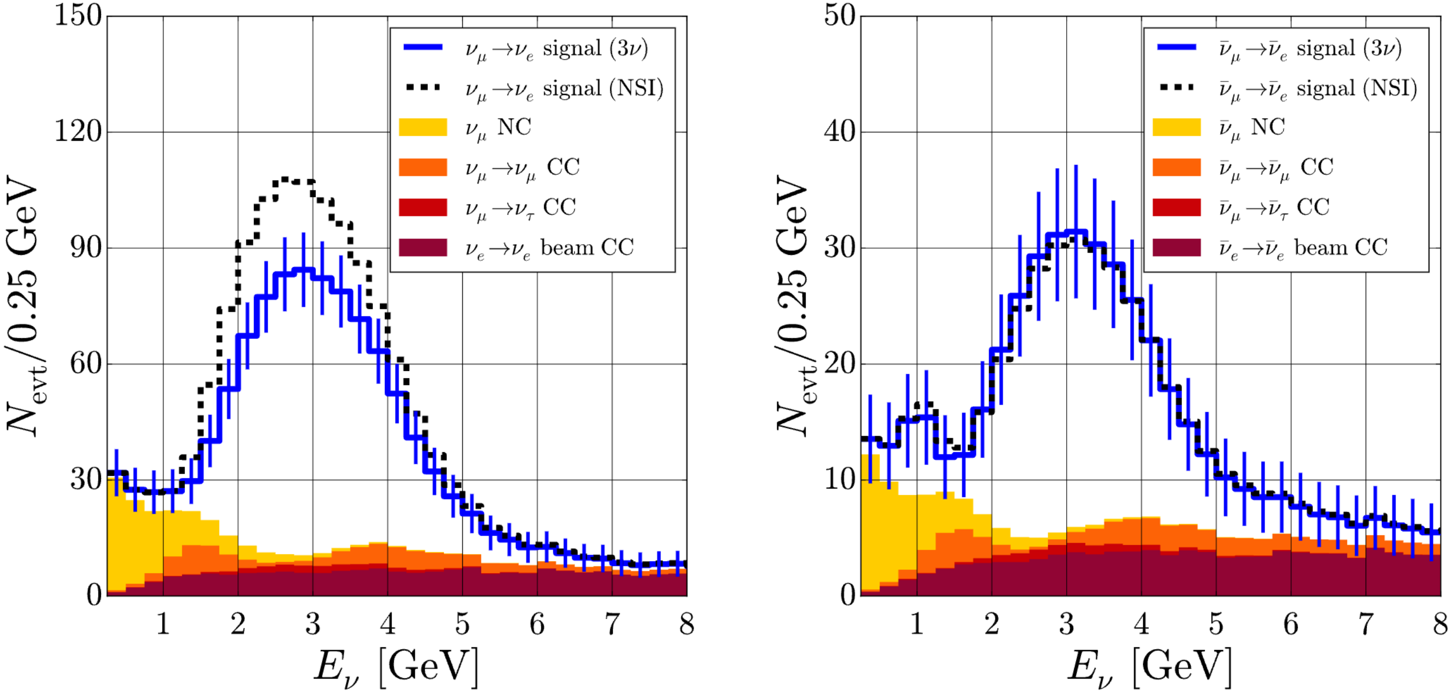
- Compare observed oscillation spectra to those expected for standard 3-flavor mixing and for values of various NSI parameters
- So far experiments have set limits, ie: "if NSI were present with parameter value x, we would have seen it – since we did not see it, we know that parameter must be smaller than x"



arXiv:2106.07755

NSI AT DUNE

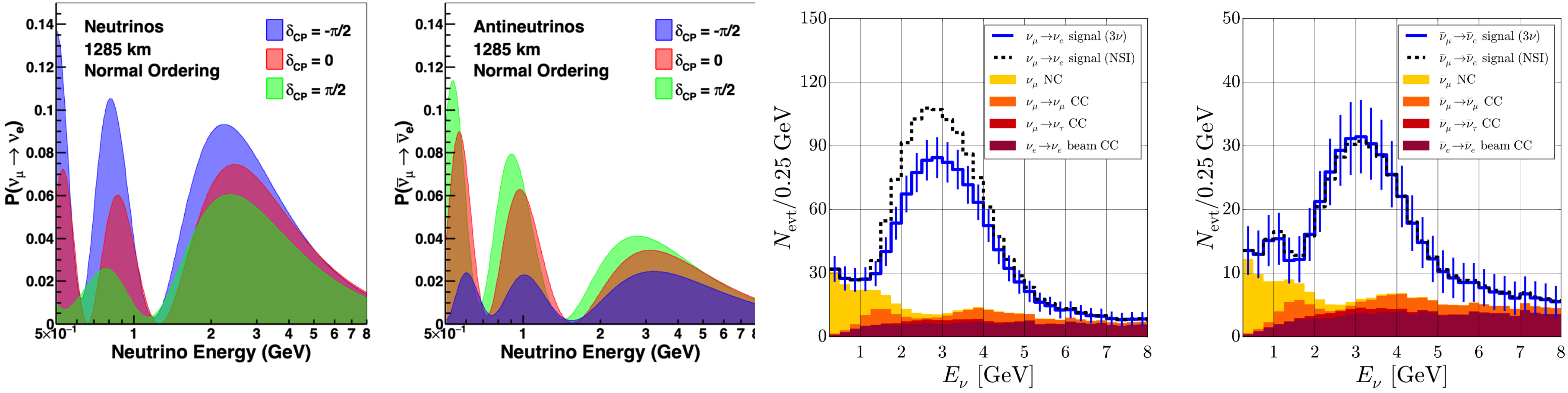
arXiv:1511.05562



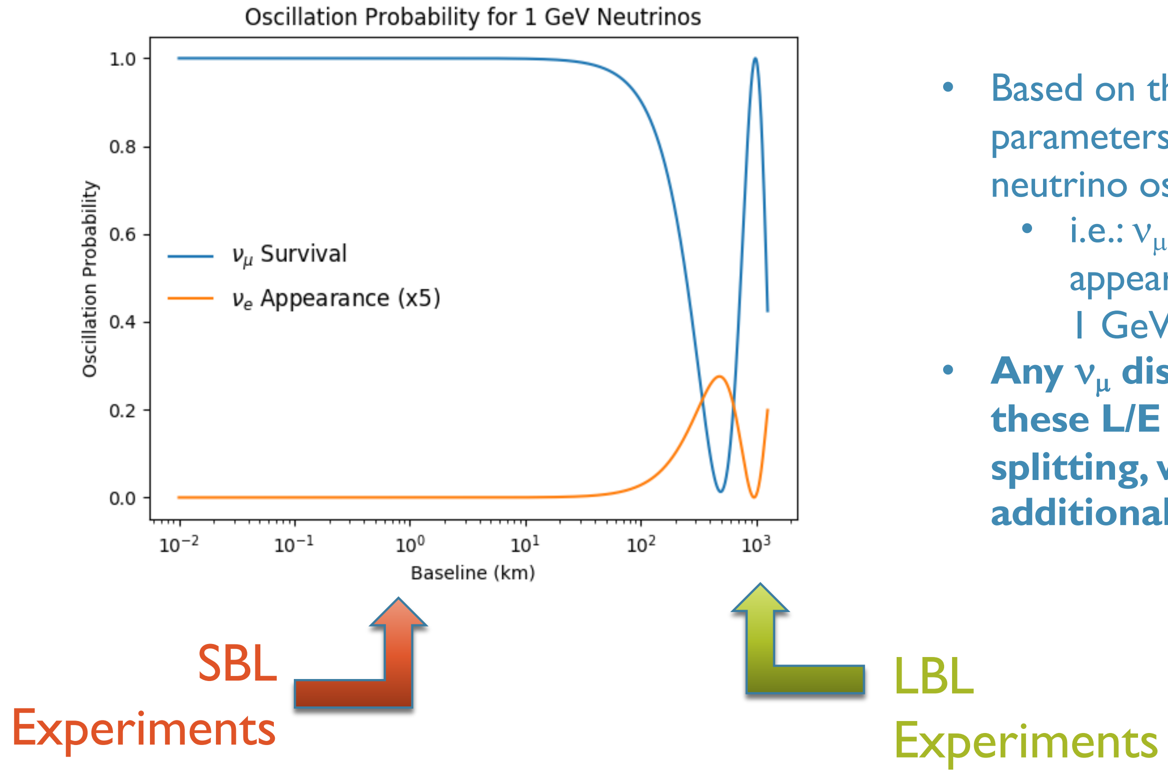
Neutrino and antineutrino appearance samples for a particular set of NSI parameters, compared to standard 3-neutrino mixing

Question: how does this compare to the impact of δ_{CP} from slide 13?

CPV VS NSI


Neutrinos
1285 km
Normal Ordering
$\delta_{CP} = -\pi/2$
$\delta_{CP} = 0$
$\delta_{CP} = \pi/2$
$P(\nu_\mu \to \nu_e)$
Neutrino Energy (GeV)
Antineutrinos
1285 km
Normal Ordering
$\delta_{CP} = -\pi/2$
$\delta_{CP} = 0$
$\delta_{CP} = \pi/2$
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
Neutrino Energy (GeV)
$\nu_\mu \to \nu_e$ signal (3ν)
$\nu_\mu \to \nu_e$ signal (NSI)
ν_μ NC
$\nu_\mu \to \nu_\mu$ CC
$\nu_\mu \to \nu_\tau$ CC
$\nu_e \to \nu_e$ beam CC
$N_{evt}/0.25$ GeV
E_ν [GeV]
$\bar{\nu}_\mu \to \bar{\nu}_e$ signal (3ν)
$\bar{\nu}_\mu \to \bar{\nu}_e$ signal (NSI)
$\bar{\nu}_\mu$ NC
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC
$\bar{\nu}_\mu \to \bar{\nu}_\tau$ CC
$\bar{\nu}_e \to \bar{\nu}_e$ beam CC
$N_{evt}/0.25$ GeV
E_ν [GeV]

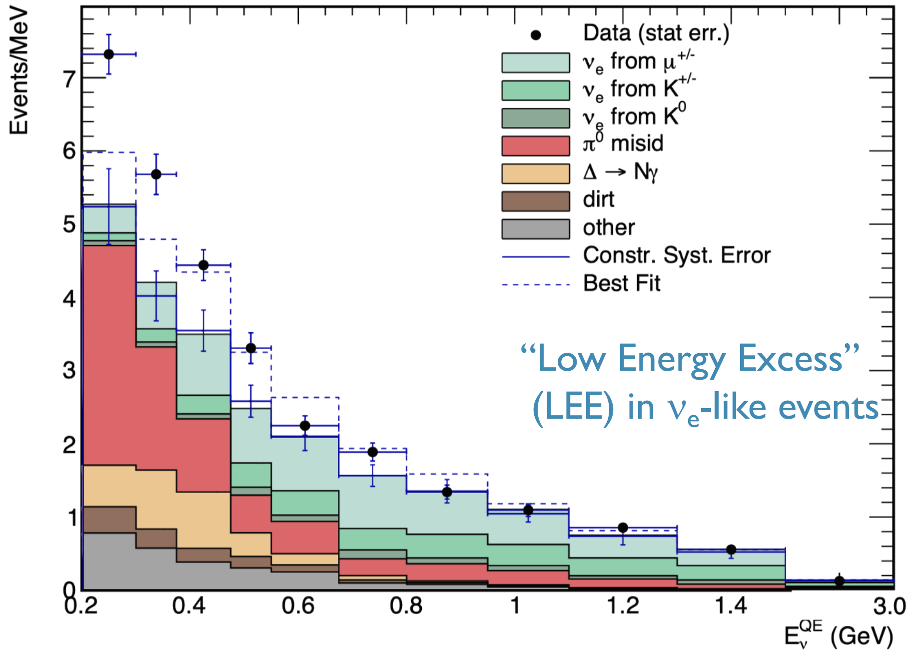
STERILE NEUTRINOS



- 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**

STERILE NEUTRINOS

MiniBooNE (BNB)
PRD 103, 052002 (2021)



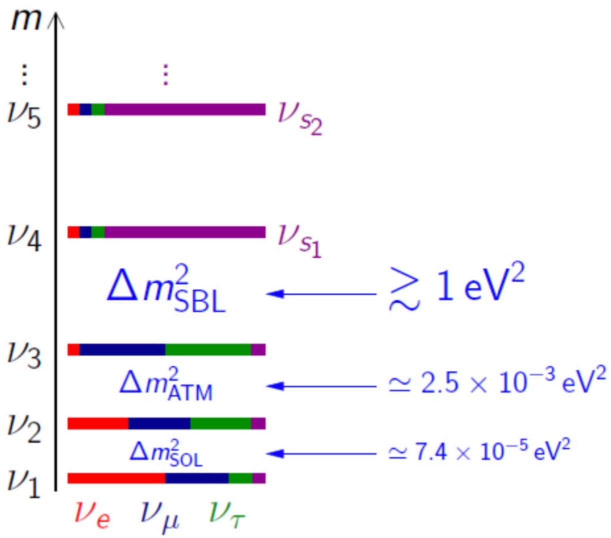
The significance of the excess observed by LSND is 3.8σ and by MiniBooNE is 4.8σ, for a combined significance of 6.1σ

- Several experiments have observations suggesting possible ν_e appearance at L/E ~ 1
  - LSND, MiniBooNE
  - Potential explanation is an additional "sterile" neutrino with a mass splitting of ~1 eV^2
- However, MicroBooNE does not observe LEE and there is no evidence for ν_μ disappearance at L/E~1

STERILE NEUTRINOS

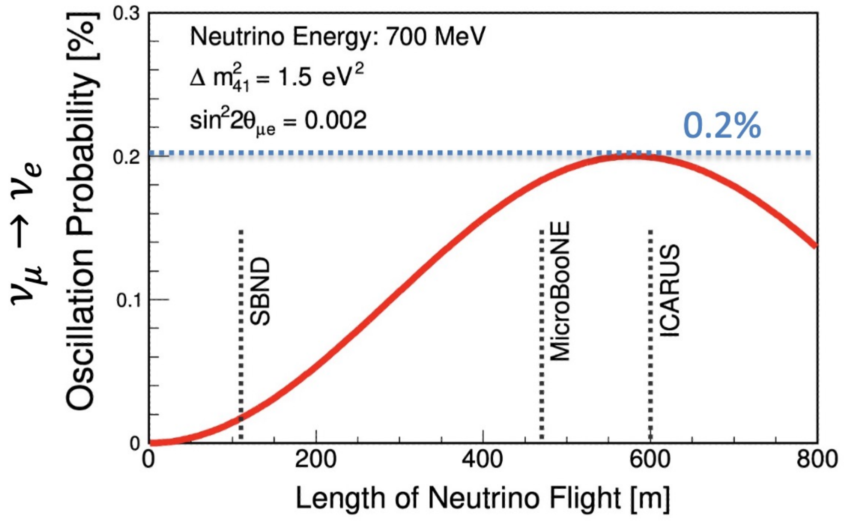
- 3 neutrino model → 3 + x neutrino model, where there are x additional, "sterile" neutrinos
- Sterile neutrinos mix with standard neutrinos (allows for additional oscillation), but do not have weak charge, (consistent with # of neutrinos from LEP/astrophysics)
- "3+1" model is simplest scenario; while 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

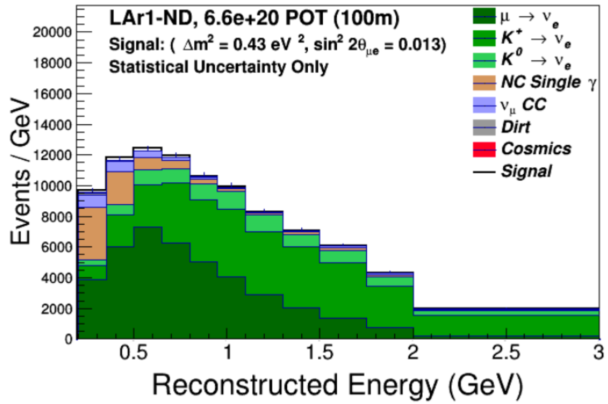


STERILE NEUTRINOS AT OSCILLATION EXPERIMENTS: SHORT BASELINE

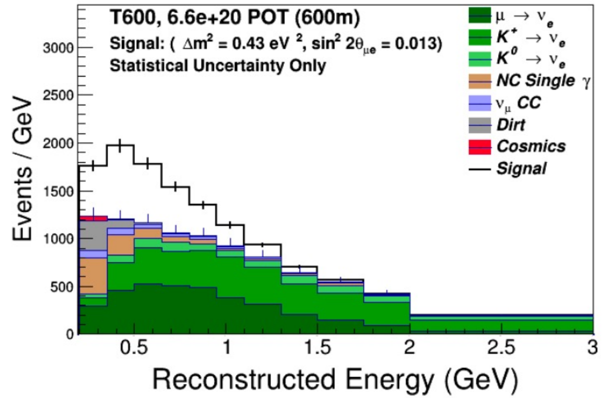
Example oscillation at BNB peak energy



Also sensitive to ν_μ disappearance at same baseline



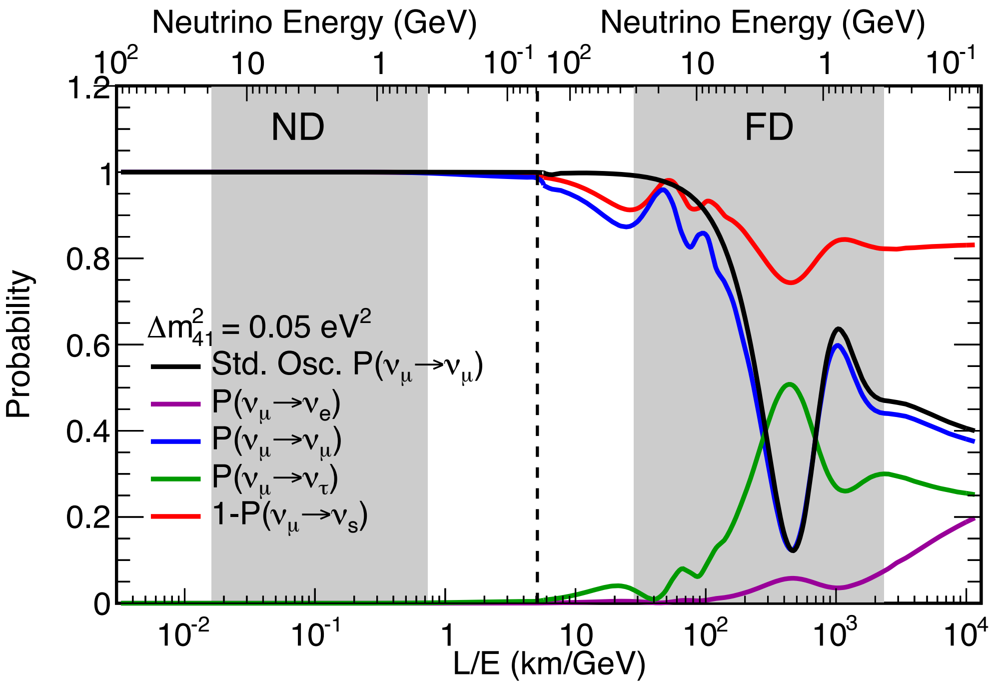
For these oscillation parameters, very little ν_e appearance at SBND



For these oscillation parameters, large ν_e appearance at ICARUS

STERILE NEUTRINOS AT OSCILLATION EXPERIMENTS: LONG BASELINE

Sensitive to ν_μ disappearance at far detector in NC & CC channels



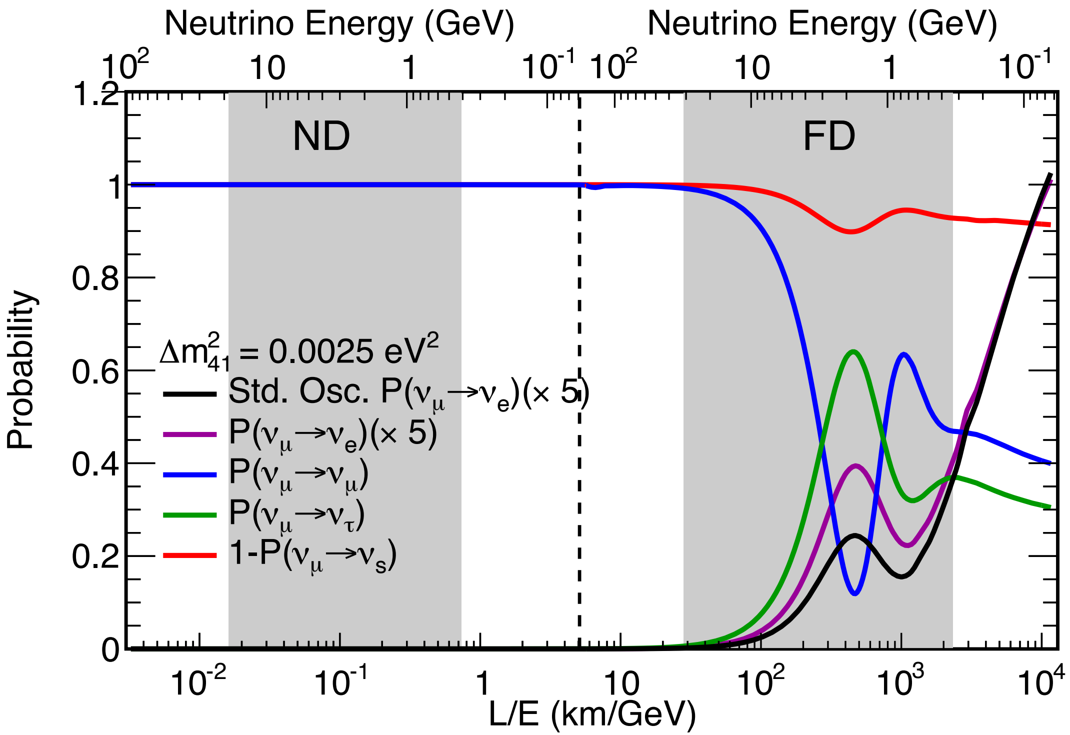
NC disappearance

3-flavor ν_μ CC disappearance

Distortion to ν_μ CC disappearance

STERILE NEUTRINOS AT OSCILLATION EXPERIMENTS: LONG BASELINE

Sensitive to ν_e appearance at far detector (degenerate w/ PMNS)



3-flavor ν_e CC appearance

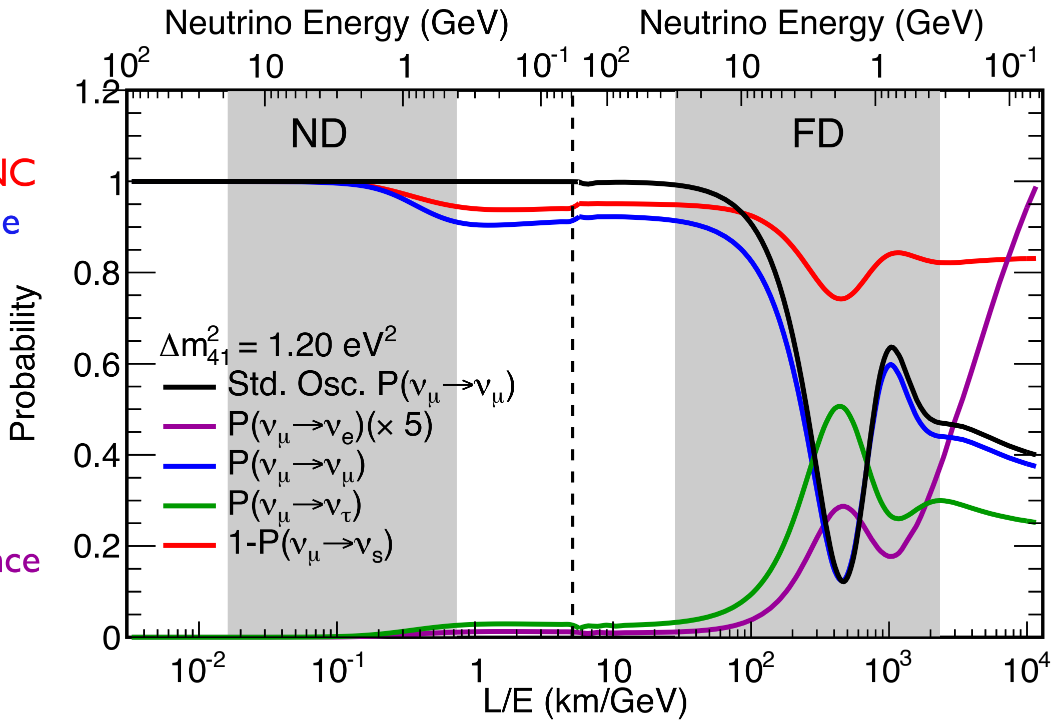
3+1 ν_e CC appearance

STERILE NEUTRINOS AT OSCILLATION EXPERIMENTS: LONG BASELINE

Sensitive to ν_μ disappearance and ν_e appearance at near detector

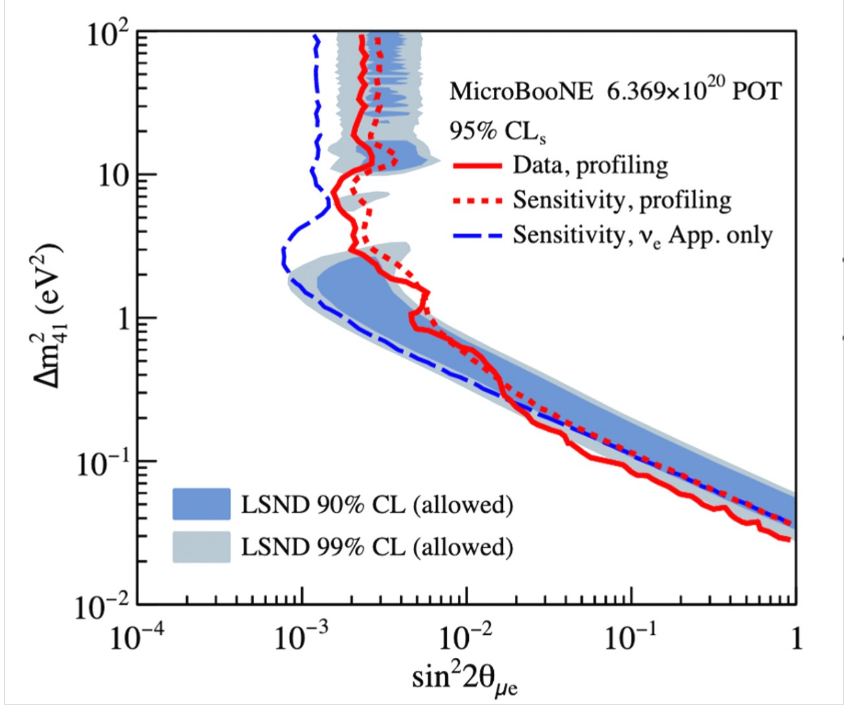
ν_μ CC and NC disappearance at ND

ν_e CC appearance at ND

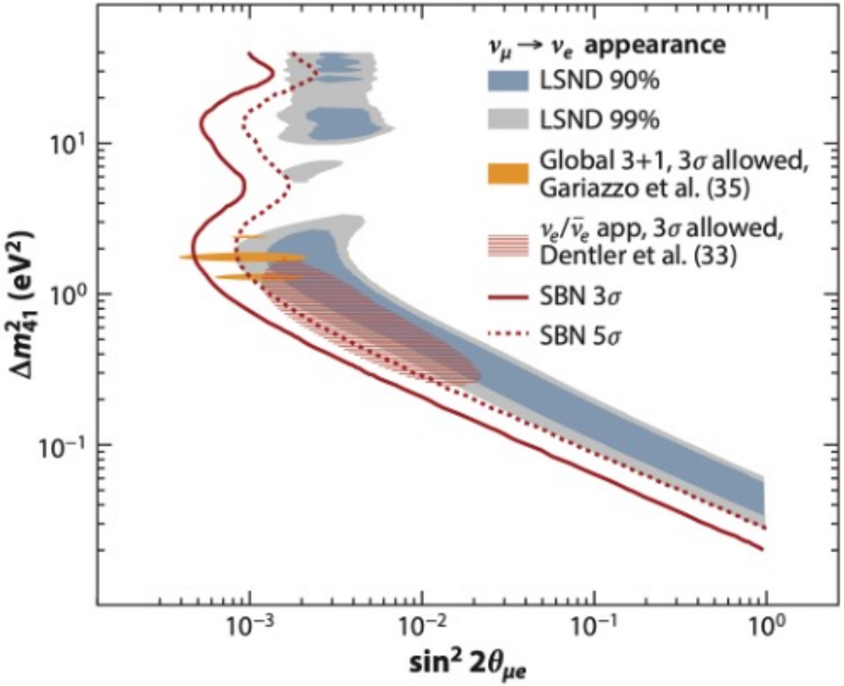


(SOME) STERILE NEUTRINO LIMITS & SENSITIVTY PROJECTIONS

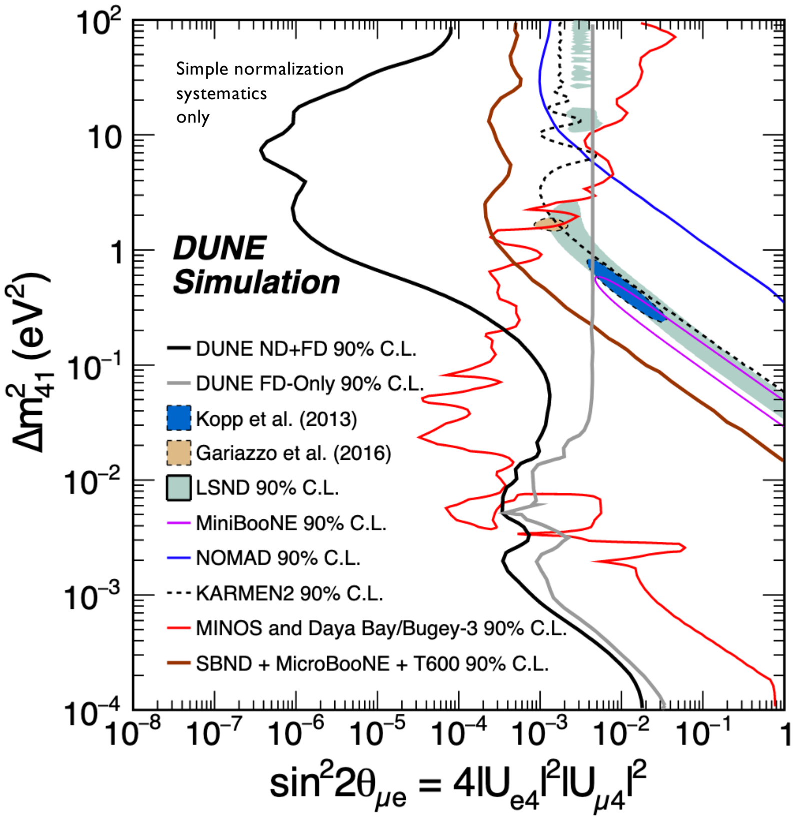
MicroBooNE (BNB)
Phys.Rev.Lett. 130 (2023) 1, 011801



SBN sensitivity projection



(SOME) STERILE NEUTRINO LIMITS & SENSITIVTY PROJECTIONS



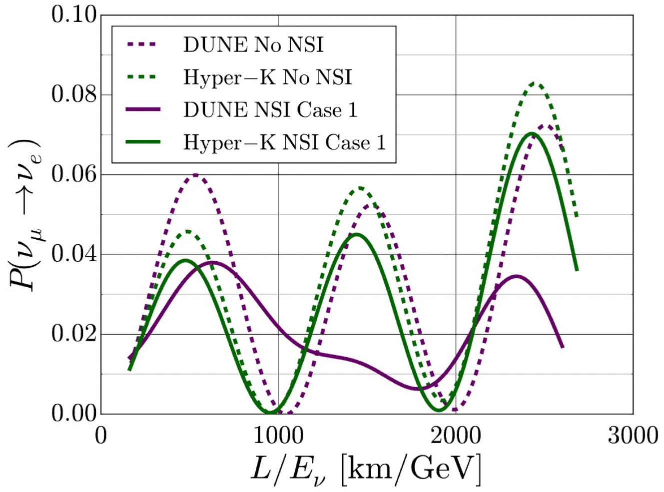
Questions:

- Why are these sensitivity/exclusion contours so wiggly?
- Compare the DUNE ND+FD and FD-only curves on this plot and the DUNE oscillation probabilities from a few slides back. Where do you think the DUNE sensitivity in the 1-10 eV^2 range is coming from?
- Do you think the "simple normalization systematics only" comment is important? Why?

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?
  - 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

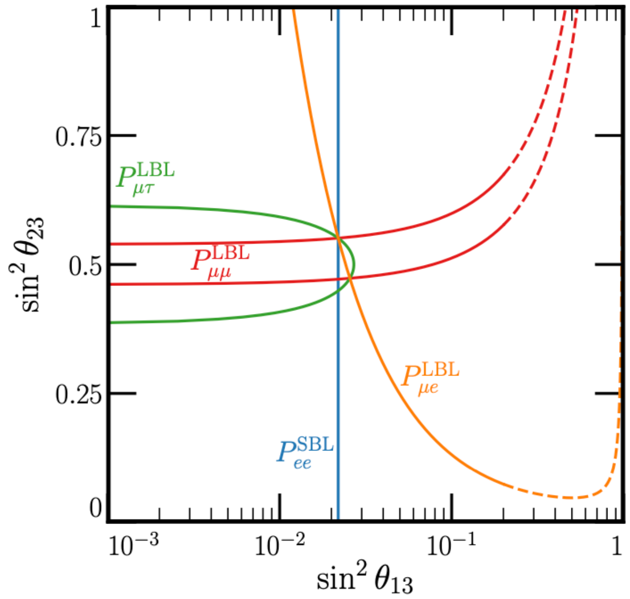


de Gouvêa and Kelly, *Nucl.Phys.B* 908 (2016) 318-335

Question: If we saw deviations from 3-flavor oscillation that behave similarly at DUNE and HyperK, what might we conclude about the new physics?

TESTING PMNS UNITARITY

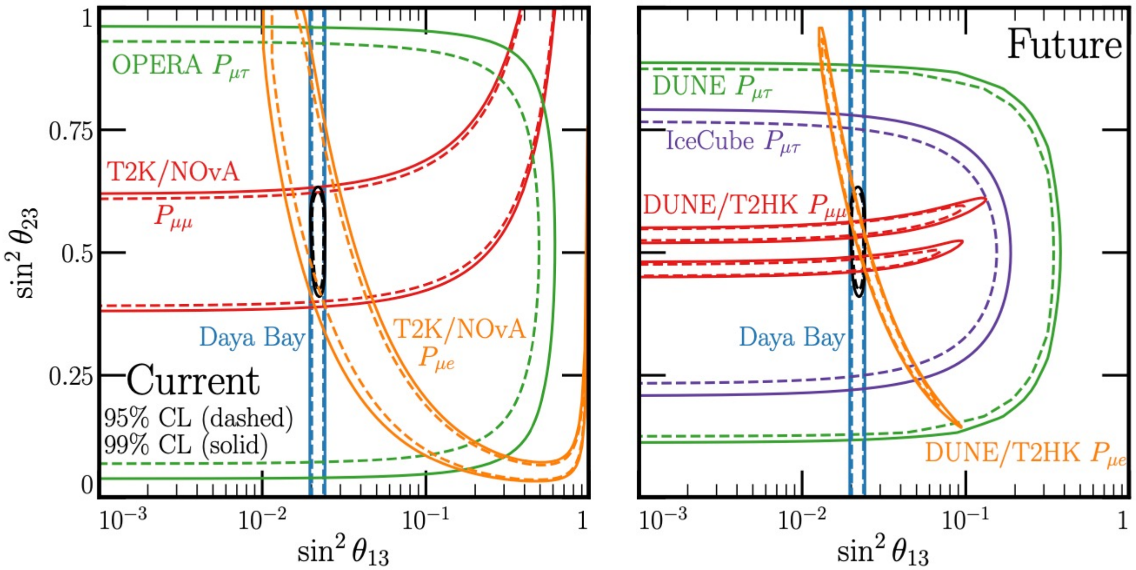
Ellis, Kelly, Li, *JHEP* 12 (2020) 068



- Hypothetical **infinite precision** measurements in $\theta_{23} - \theta_{13}$ space: combining values obtained from long-baseline oscillation measurements (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

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

SUMMARY

- We have quite specific expectations of how neutrino oscillations behave in the 3-neutrino paradigm based on existing measurements of neutrino oscillation parameters
- The existence of neutrino mass already means there must be new physics – we just don't know yet exactly what it looks like
- Several models of new physics predict specific distortions of neutrino oscillation spectra, allowing us to search for those specific effects and place limits on the parameters of those models
- Some new physics may affect the observed spectra in ways that are semi-degenerate with the 3-neutrino oscillation parameters or with other new physics models – experiments with different energies and baselines can disentangle these effects
- We can search for new physics more generically, eg: by studying whether the PMNS matrix is unitary
- Searches for new physics in neutrino oscillation are intrinsically tied to study of 3-neutrino oscillation