Physics opportunities with Near and Far Detectors at long baseline neutrino experiments

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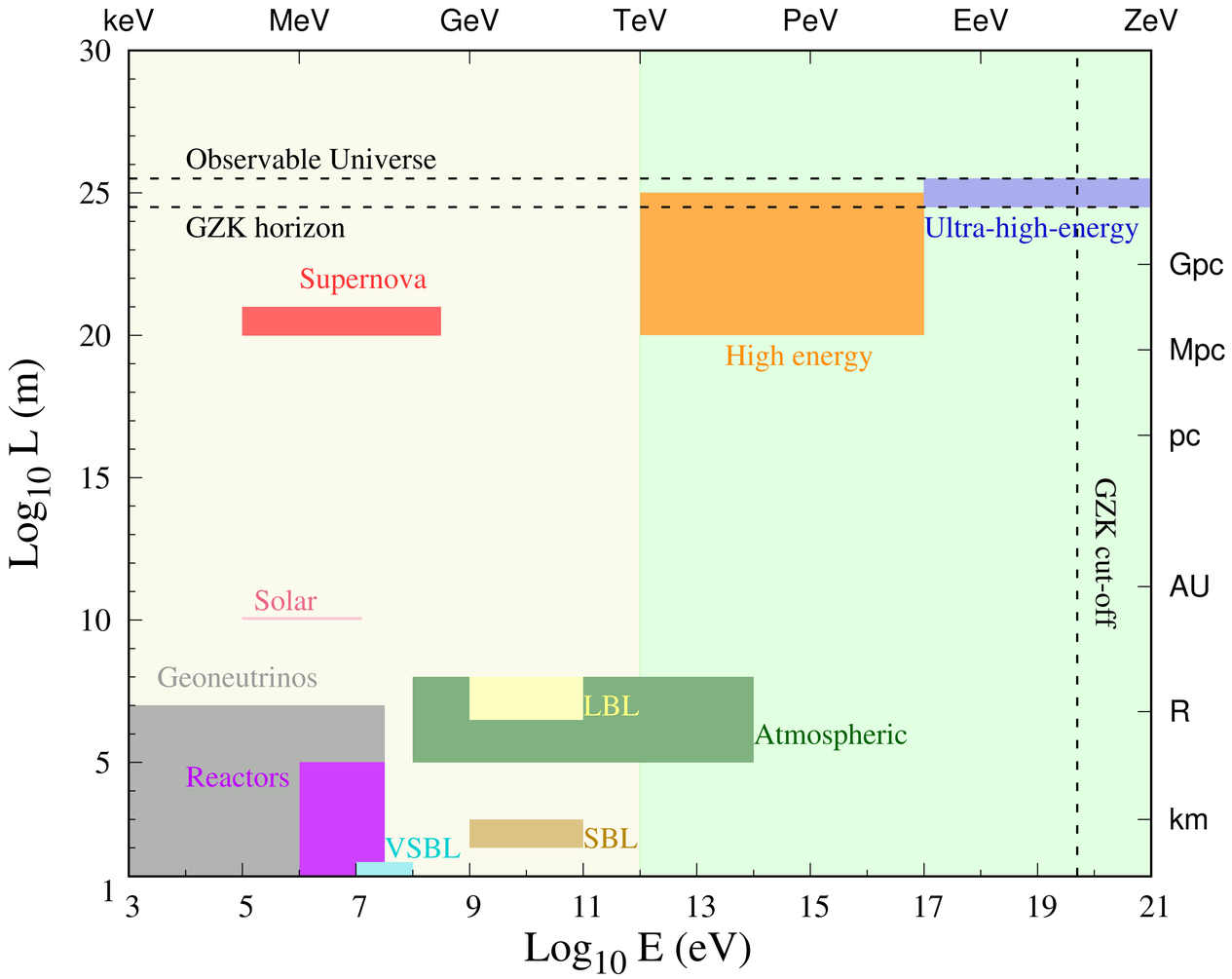
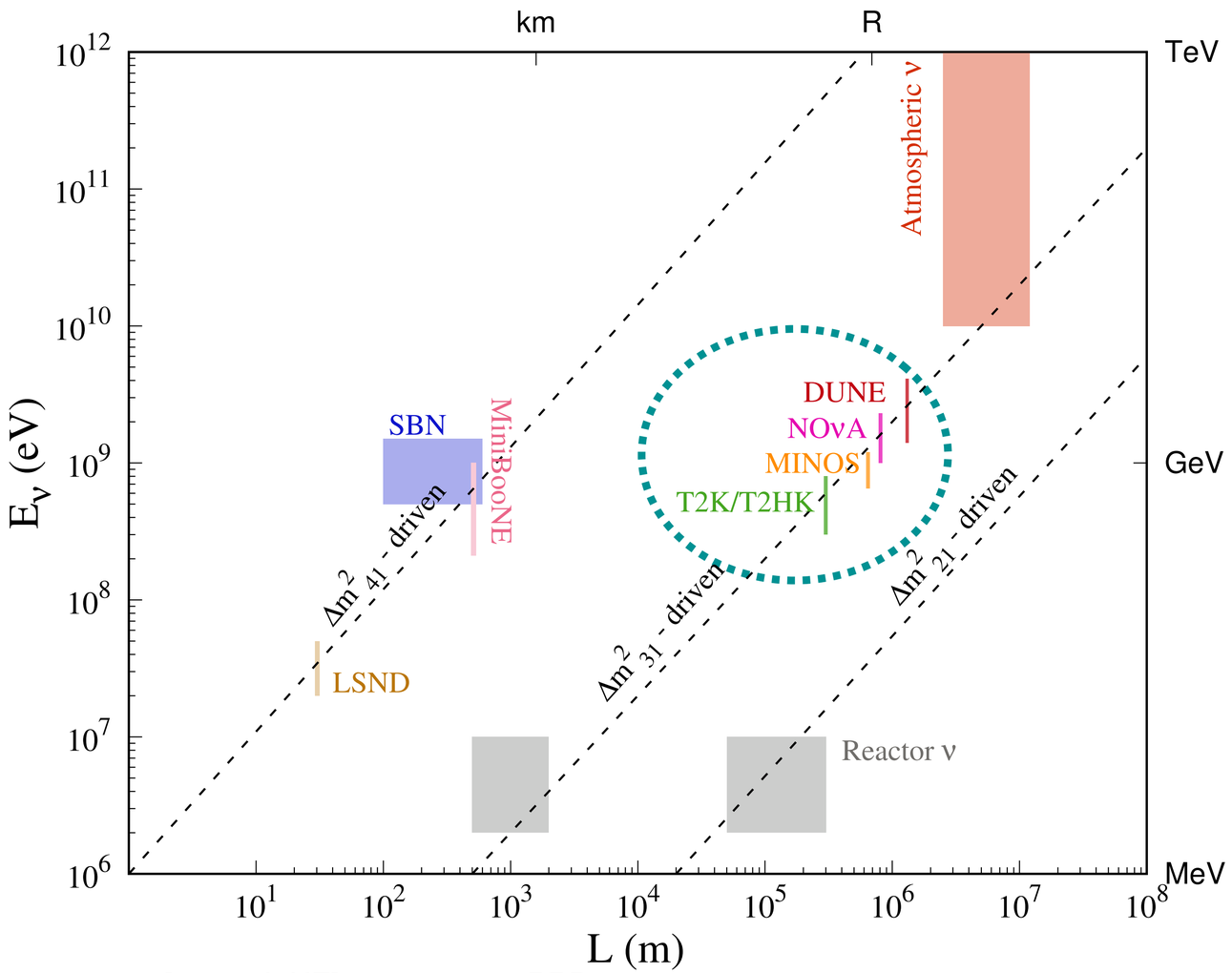
Neutrino Platform Pheno Week 2023 @ CERN, 15 March 2023

Plan

- Neutrino sources and detectors
  - Long baseline neutrino experiments
- Deep Underground Neutrino Experiment
  - Near and Far Detectors
- Neutrino oscillations in the standard three flavour paradigm and beyond
  - Non-standard Interactions
  - Sterile neutrinos
- Other possibilities

Neutrino sources





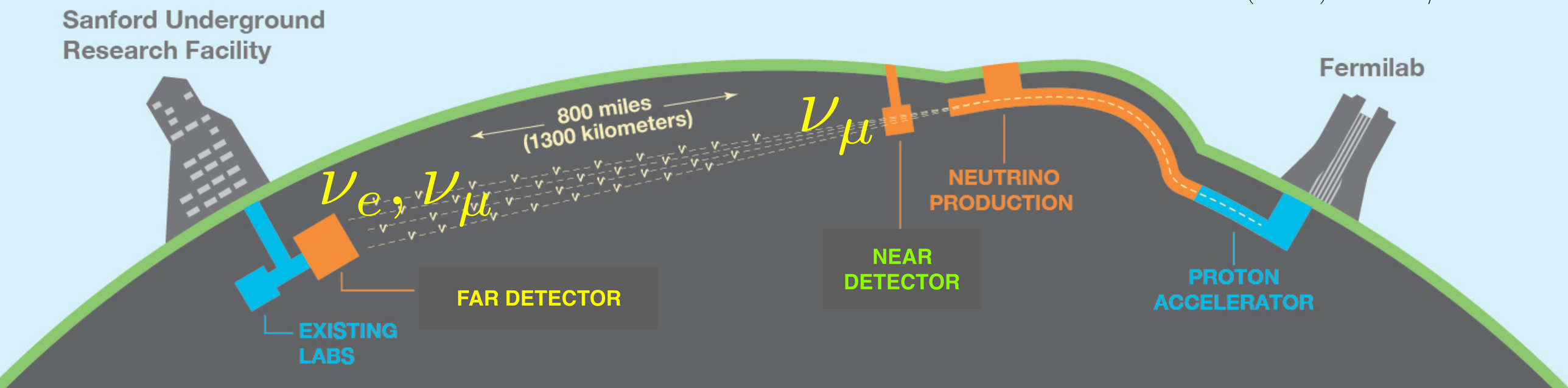
Credit : Sabila Parveen, adapted from 1903.04333 [astro-ph.HE], 1911.05088, PRD 2020

DEEP UNDERGROUND NEUTRINO EXPERIMENT

CDR, Vol 1, 1601.05471 [physics.ins-det], CDR, Vol 2, 1512.06148 [physics.ins-det], TDR vol 1, JINST 15 (2020) 08, T08008, TDR Vol 2, 2002.03005 [hep-ex]

- Beam - LBNF (FNAL), 1.2-2.4MW, Baseline 1300 km
- Far detector (LArTPC, ~ 40 kt fiducial mass) located on-axis such that observed flux is a broad spectrum (0.5-5 GeV)
- DUNE has a broad program of neutrino oscillation physics, constrain the standard three neutrino paradigm
  - Beam covers first and second oscillation maxima
  - Alternative beam tunes possible

$$\frac{L(\mathrm{km})}{E_\nu(\mathrm{GeV})} = (2n-1)\frac{\pi}{2}\frac{1}{1.27\times\Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1)\times 510\ \mathrm{km/GeV}$$

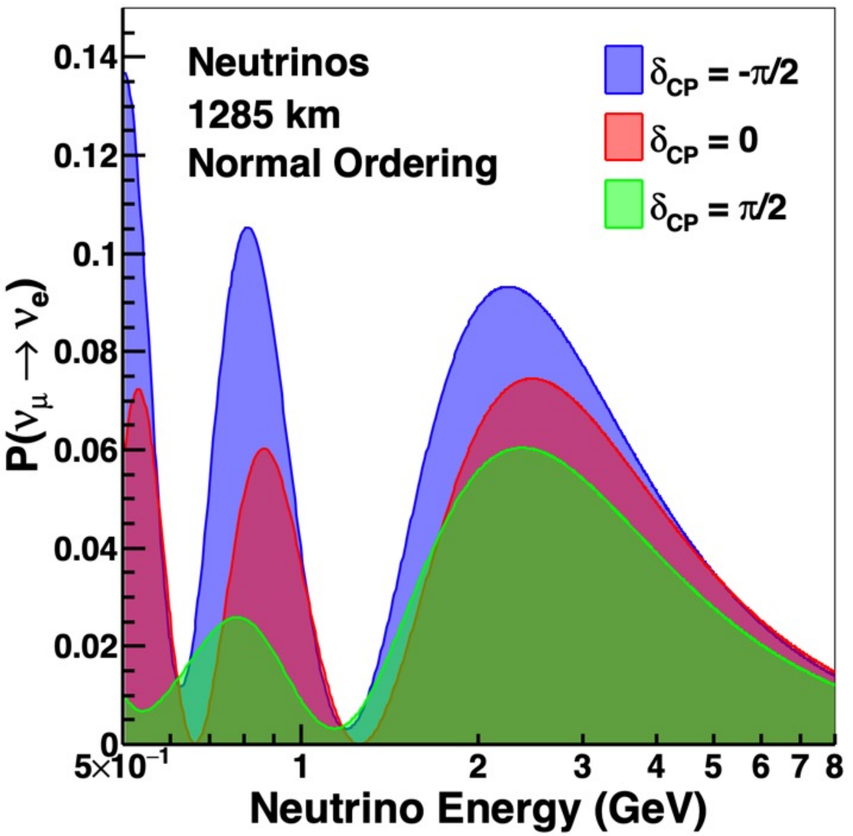


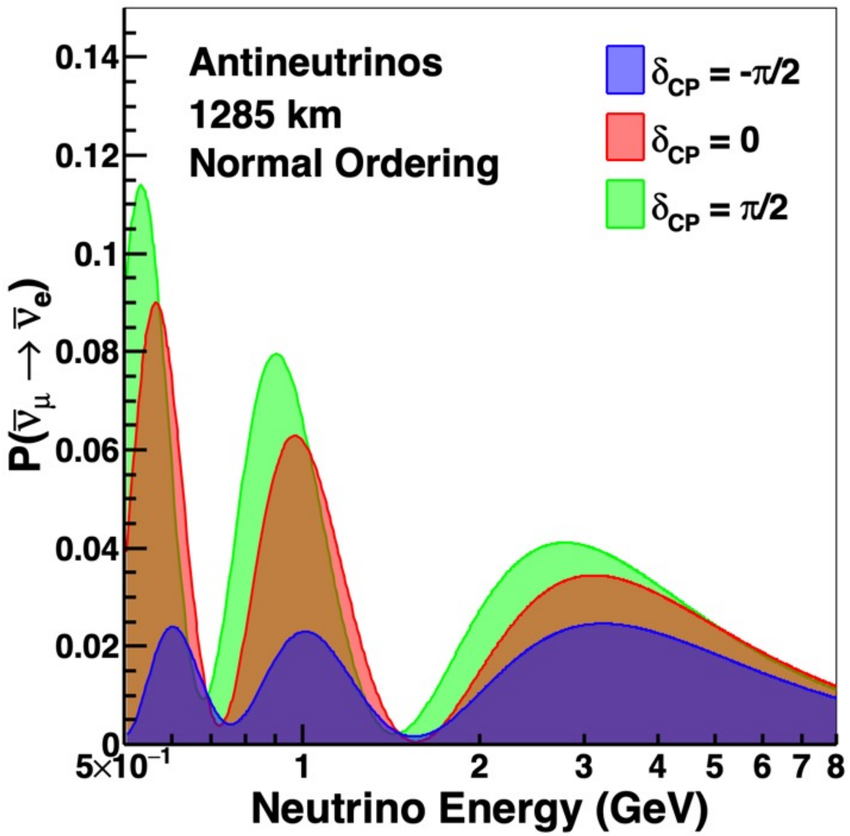
DEEP UNDERGROUND NEUTRINO EXPERIMENT

CDR, Vol 1, 1601.05471 [physics.ins-det], CDR, Vol 2, 1512.06148 [physics.ins-det], TDR vol 1, JINST 15 (2020) 08, T08008, TDR Vol 2, 2002.03005 [hep-ex]

- Muon neutrino beam
- Measure electron neutrino appearance and muon neutrino disappearance probability

$$\frac{L(\mathrm{km})}{E_\nu(\mathrm{GeV})} = (2n-1)\frac{\pi}{2}\frac{1}{1.27\times\Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1)\times 510\ \mathrm{km/GeV}$$

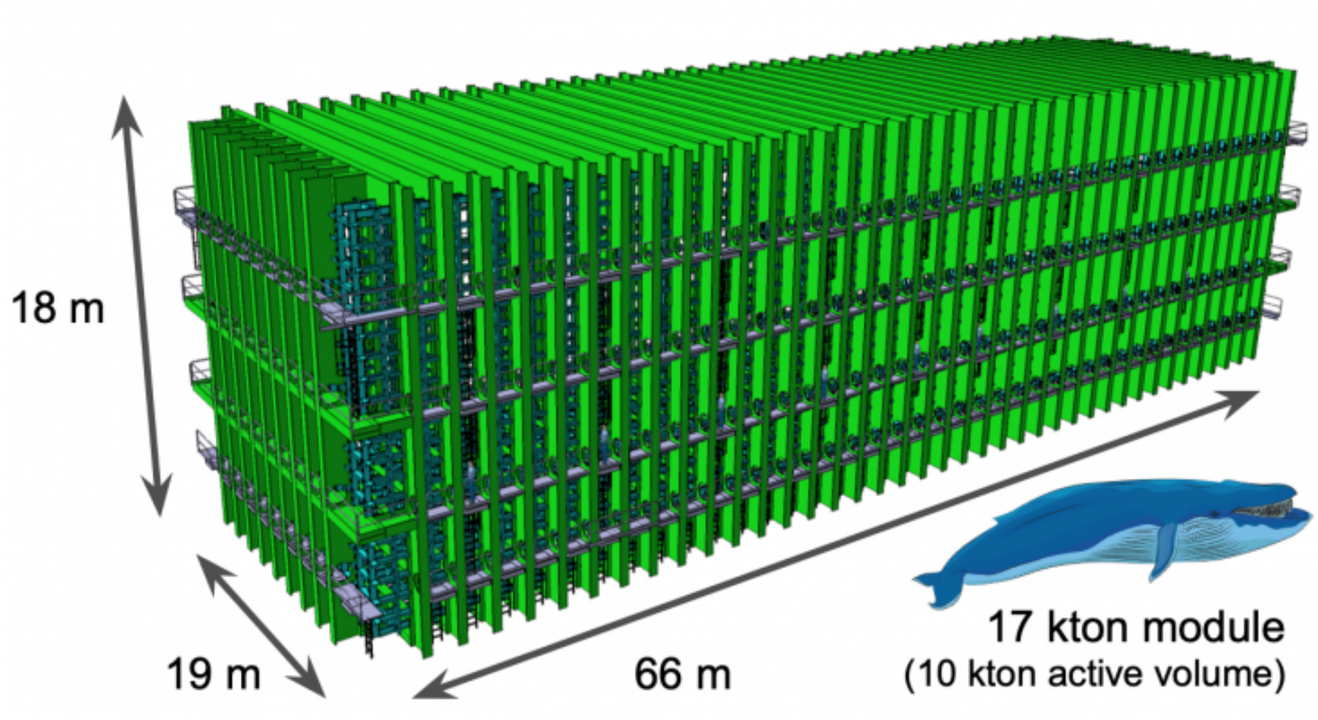




DUNE Far Detector

CDR, Vol 1, 1601.05471 [physics.ins-det], CDR, Vol 2, 1512.06148 [physics.ins-det], TDR vol 1, JINST 15 (2020) 08, T08008, TDR Vol 2, 2002.03005 [hep-ex]

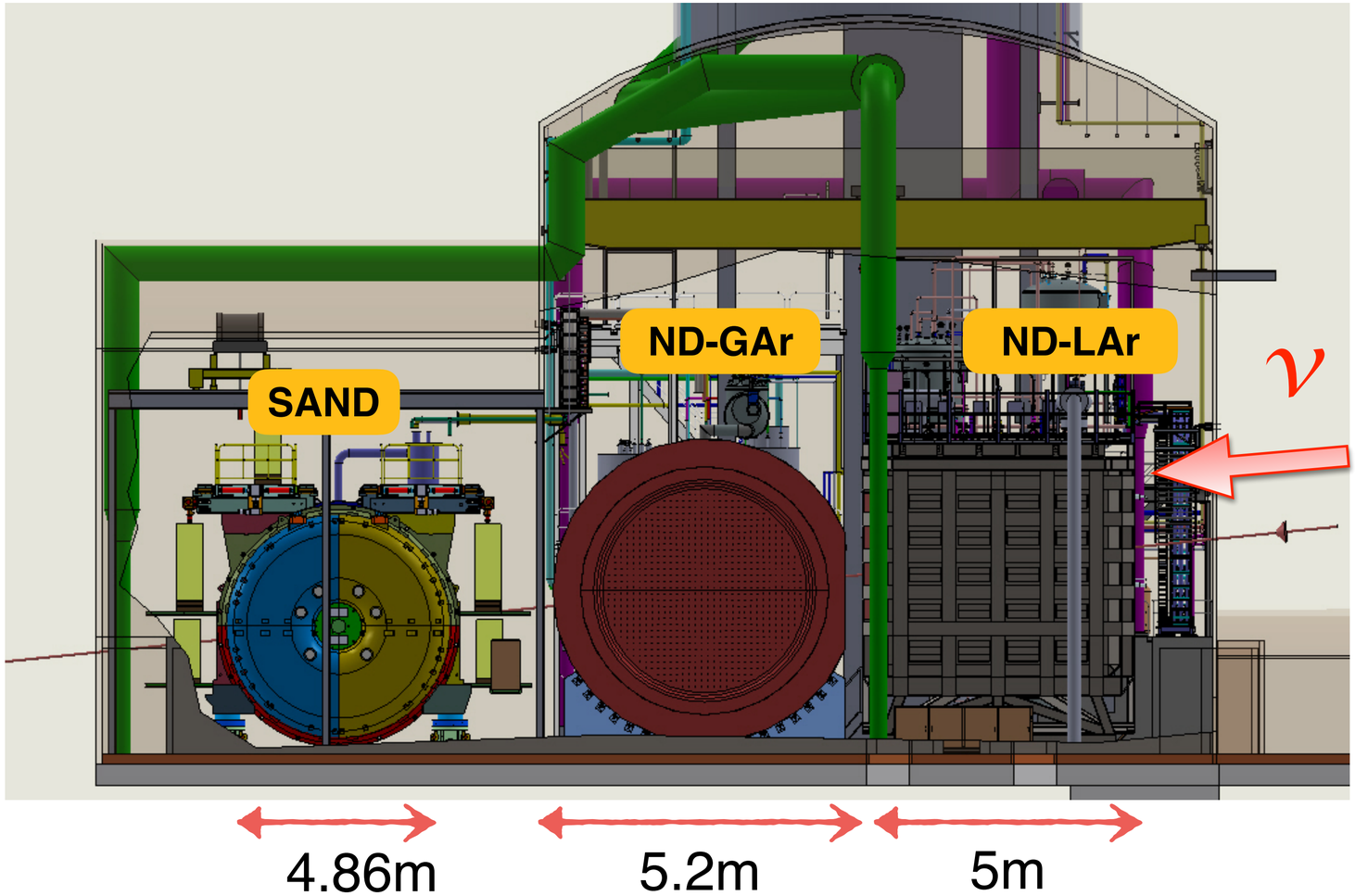
- 1300 km baseline
- Liquid Argon time projection chamber (LArTPC) - high resolution neutrino interaction imaging
- 4x17 kton LArTPC modules



DUNE Near Detector

DUNE-ND Preliminary, 2103.13910

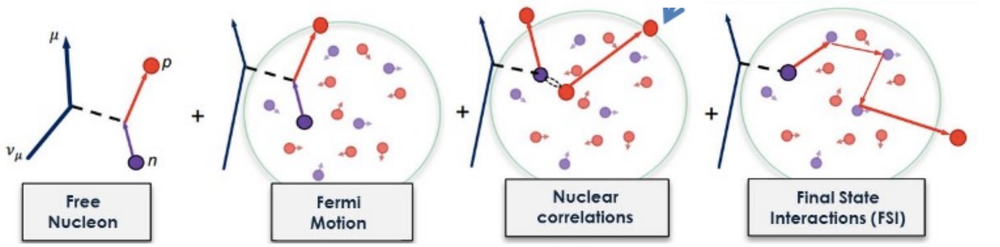
- ND Goals -
  - Constrain systematics to electron neutrino appearance measurement
  - Precision physics measurements
- Three components
  - ND-LAr - LArTPC similar to FD
  - ND-GAr - Gas Argon TPC detector
  - SAND - on-axis magnetized beam monitor
- ND-LAr and ND-GAr movable off-axis for the DUNE-PRISM program
- Each element specifically designed to fulfill requirements of oscillation measurement



Neutrino interaction modeling

Phased Construction arXiv:2203.06100, Talk by Elizabeth Worcester, NDM22

- Neutrinos in these experiments are not interacting with bare nucleons - structure of nucleus matters
- Detailed modelling of complex nuclei needed
- Interaction model affects energy reconstruction – mis-reconstructed energy can significantly bias results
- Neutrino-nucleus interaction model does not currently describe world neutrino interaction data → program of neutrino interaction experiments, model-building, and event generator development very important for precision measurements in neutrino physics
- Long-baseline experiments are being designed to provide experimental solutions to imperfect interaction model
- Improve model constraints by making precise measurements of final states
- Reduce sensitivity to details of model by making data-driven predictions



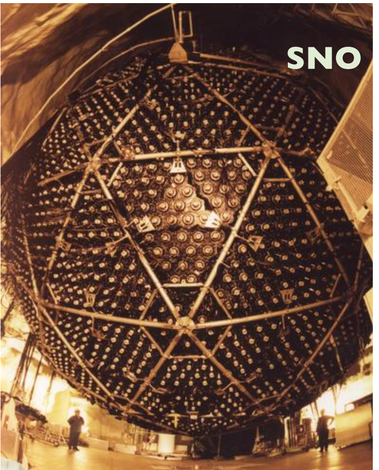
Diagrams by Patrick Stowell

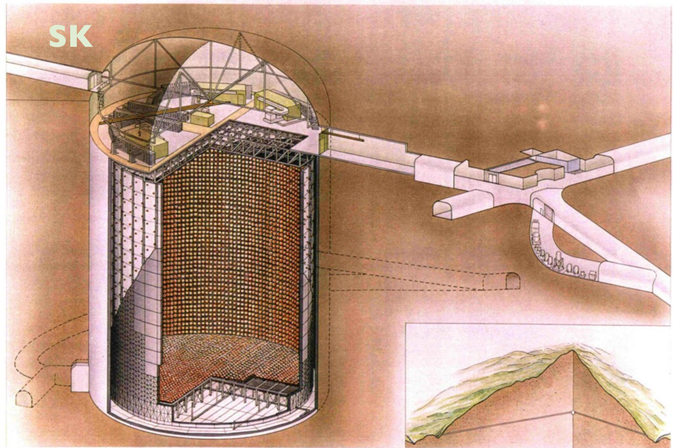
PRISM (Precision Reaction Independent Spectrum Measurement)

- Off-axis angle changes the observed near detector flux (pion decay kinematics)
- PRISM: Analysis strategy to reduce dependence on interaction modeling by using near detector data at different off-axis angles to build predicted far-detector spectrum

2015 Nobel

Neutrino oscillations





Three flavour neutrino oscillations

Pontecorvo, Sov. Phys. JETP, 6 (1957), p. 429 ; Maki, Nakagawa, Sakata, Prog. Theor. Phys., 28 (1962), p. 870

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{Atmospheric} \overbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}^{Reactor} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{Solar}$$

where $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$ and δ is the Dirac-type CP phase

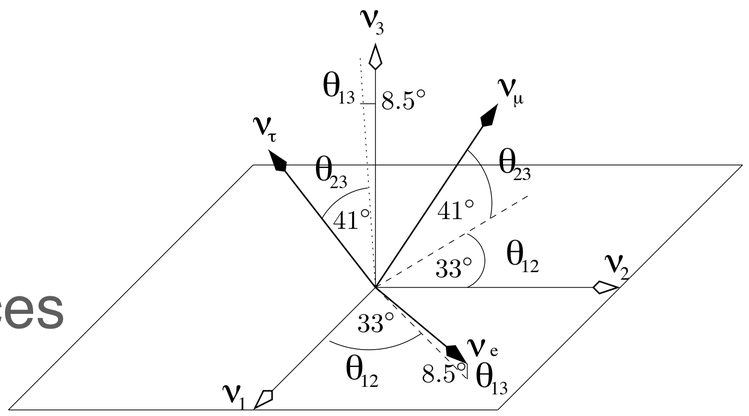
If Majorana - two additional phases appear, $U \to U\mathrm{diag}(1, e^{i\kappa}, e^{i\zeta})$

Unknowns

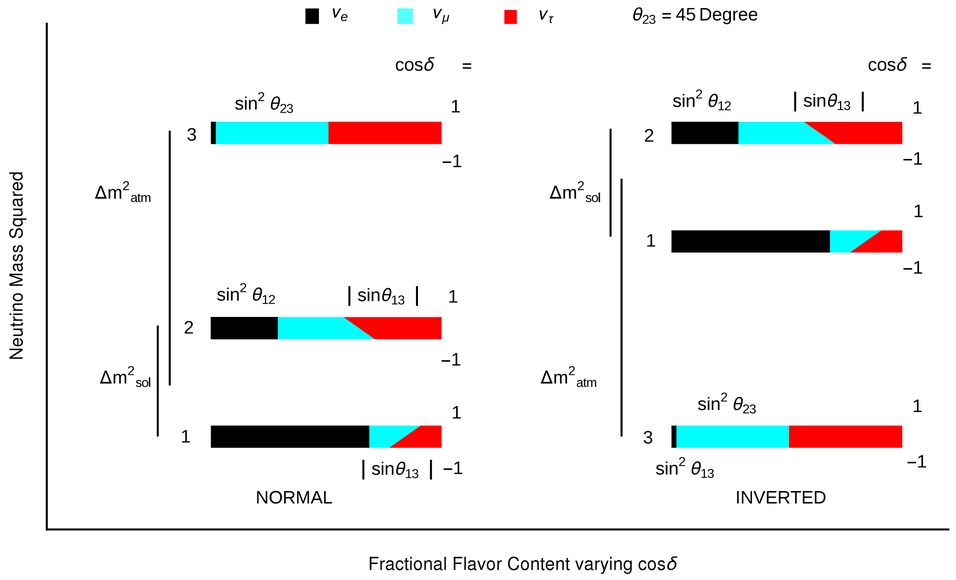
- CP violating phase
- Sign of larger mass-splitting
- Octant of theta 23

Parameters

- 3 angles
- 1 phase
- 2 mass-squared differences



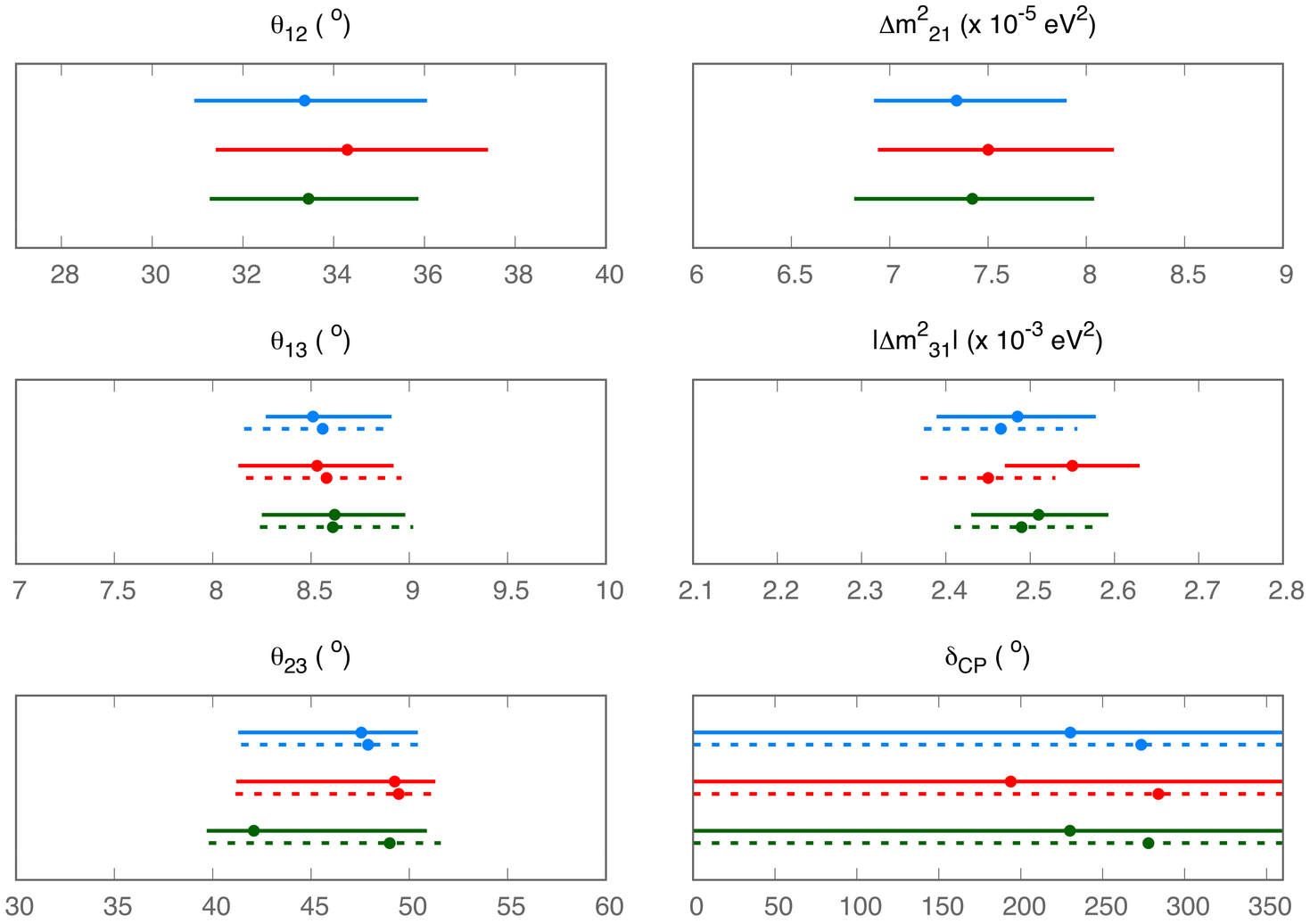
Credit : King



Credit : Mena and Parke, 2004

Current status : three flavour neutrino oscillations

NuFIT 5.0 (2020), www.nu-fit.org, JHEP 09 (2020) 178 [arXiv:2007.14792], 2003.08511, 2006.11237



- Bari group
- Spanish group
- NuFIT group
- Solid line - NH
- Dashed line - IH

Credit : Sushant Raut

Standard unknowns

Violation of discrete symmetries: C, P, T

$$A^{CP}_{\alpha\beta} = \frac{P_{\alpha\beta} - \bar{P}_{\alpha\beta}}{P_{\alpha\beta} + \bar{P}_{\alpha\beta}}, \quad A^{T}_{\alpha\beta} = \frac{P_{\alpha\beta} - P_{\beta\alpha}}{P_{\alpha\beta} + P_{\beta\alpha}}, \quad A^{CPT}_{\alpha\beta} = \frac{P_{\alpha\beta} - \bar{P}_{\beta\alpha}}{P_{\alpha\beta} + \bar{P}_{\beta\alpha}}$$

CPT Invariance

$$A^{CP}_{\alpha\beta} = -A^{CP}_{\beta\alpha}$$

$$A^{CP}_{\alpha\alpha} = 0$$

No CP asymmetry in survival probability

Unitarity

$$\sum_\beta P_{\alpha\beta} = 1 = \sum_\beta \bar{P}_{\alpha\beta}$$

$$A^{CP}_{e\mu} = A^{CP}_{\mu\tau} = A^{CP}_{\tau e} \propto \Delta P$$

$$A^{T}_{e\mu} = A^{T}_{\mu\tau} = A^{T}_{\tau e} \propto \Delta P$$

Single CP / T asymmetry

$$\begin{tikzcd}
P(\nu_\alpha \to \nu_\beta) \arrow[r, dashed, leftrightarrow, "CP"] \arrow[d, dashed, leftrightarrow, "T"'] & P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \arrow[d, dashed, leftrightarrow, "T"] \\
P(\nu_\beta \to \nu_\alpha) \arrow[r, dashed, leftrightarrow, "CP"'] \arrow[ur, dashed, leftrightarrow, "CPT"] & P(\bar{\nu}_\beta \to \bar{\nu}_\alpha)
\end{tikzcd}$$

Jarlskog factor

$$J = s_{12}c_{12}s_{23}c_{23}s_{13}c_{13}^2 \sin\delta$$

Jarlskog, PRL55, 1039 (1985)

$\nu_\mu \to \nu_e$

CP Asymmetry in vacuum

Marciano and Parsa, hep-ph/0610258

$$\mathcal{A}_{CP} = \frac{P_{\mu e} - \bar{P}_{\mu e}}{P_{\mu e} + \bar{P}_{\mu e}}$$

$$P(\nu_\mu \to \nu_e) = P_I(\nu_\mu \to \nu_e) + P_{II}(\nu_\mu \to \nu_e) + P_{III}(\nu_\mu \to \nu_e) + \text{ matter } + \text{smaller terms}$$

To leading order in small delta m^2

$$\boxed{\mathcal{A}_{CP} = \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E}\right) + \text{matter effects}}$$

$$\sim 1/\sin\theta_{13}$$

$$\sim \cot\theta_{23}$$

Grows with L and 1/E

$$P_I(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$$

$$P_{II}(\nu_\mu \to \nu_e) = \frac{1}{2}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$
$$\sin\left(\frac{\Delta m^2_{21} L}{2E_\nu}\right) \times \left[\sin\delta\sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)\right.$$
$$\left. + \cos\delta\sin\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)\cos\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)\right]$$

Interference term

$$P_{III}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12}\cos^2\theta_{13}\cos^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

Oscillation physics at DUNE

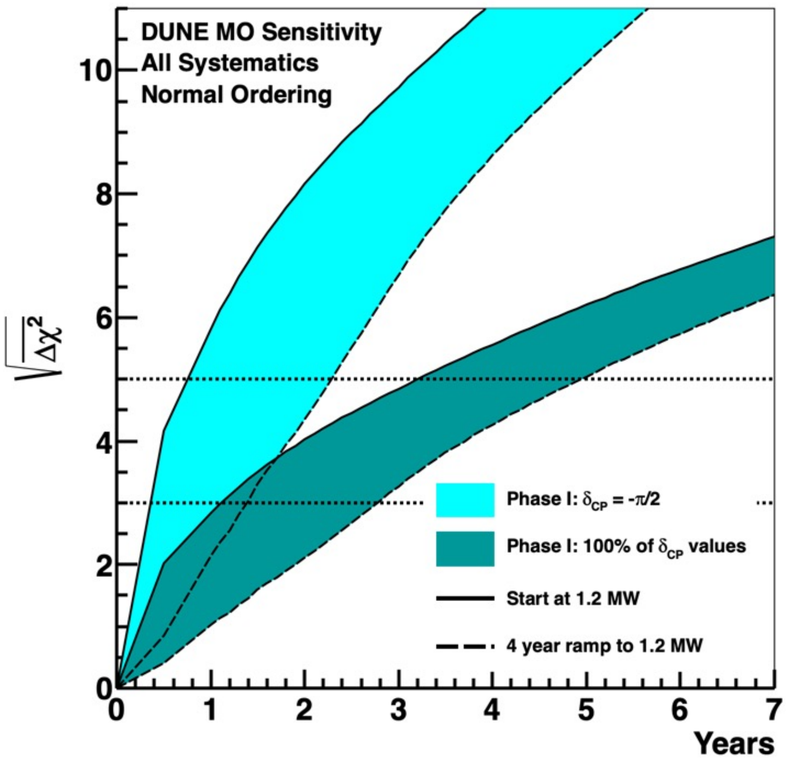
Phased Construction arXiv:2203.06100, Talk by Elizabeth Worcester, NDM22

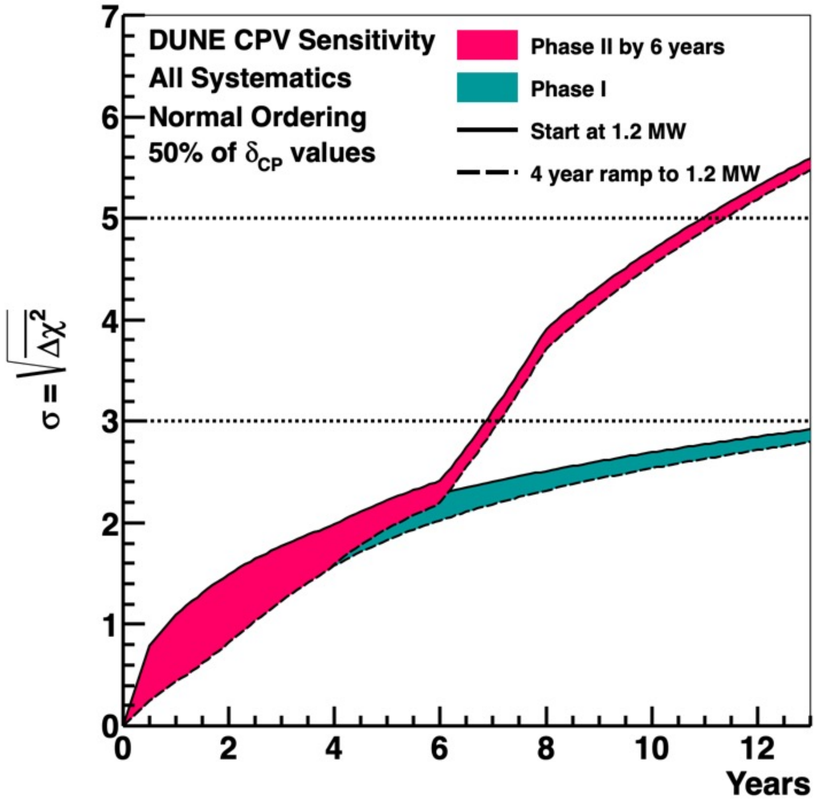
Phase I

two 17-kt (~10 kt fiducial) far detector modules, 1.2 MW proton beam, ND: ND-LAr + Temporary muon spectrometer (movable), SAND

Phase II

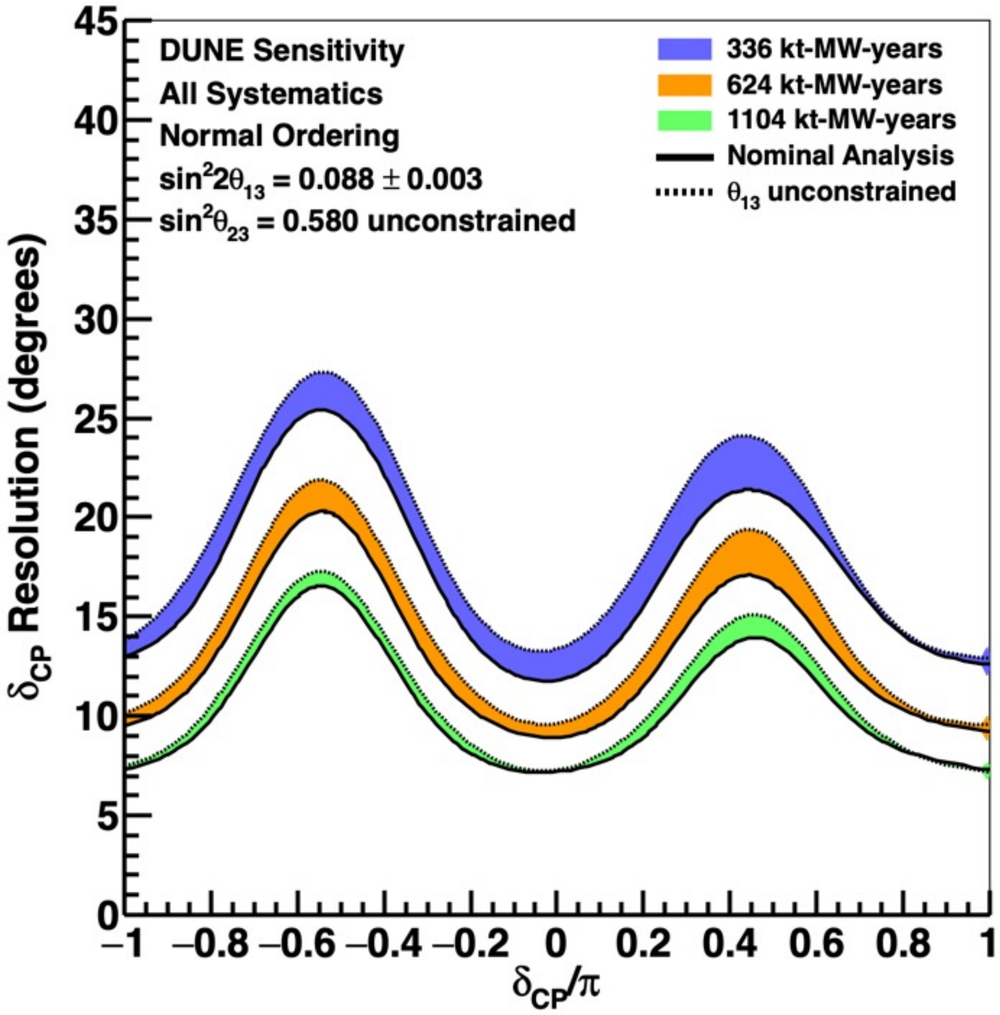
total of four far detector modules, 2.4 MW proton beam, full ND (ND-GAr replaces Temporary muon spectrometer)

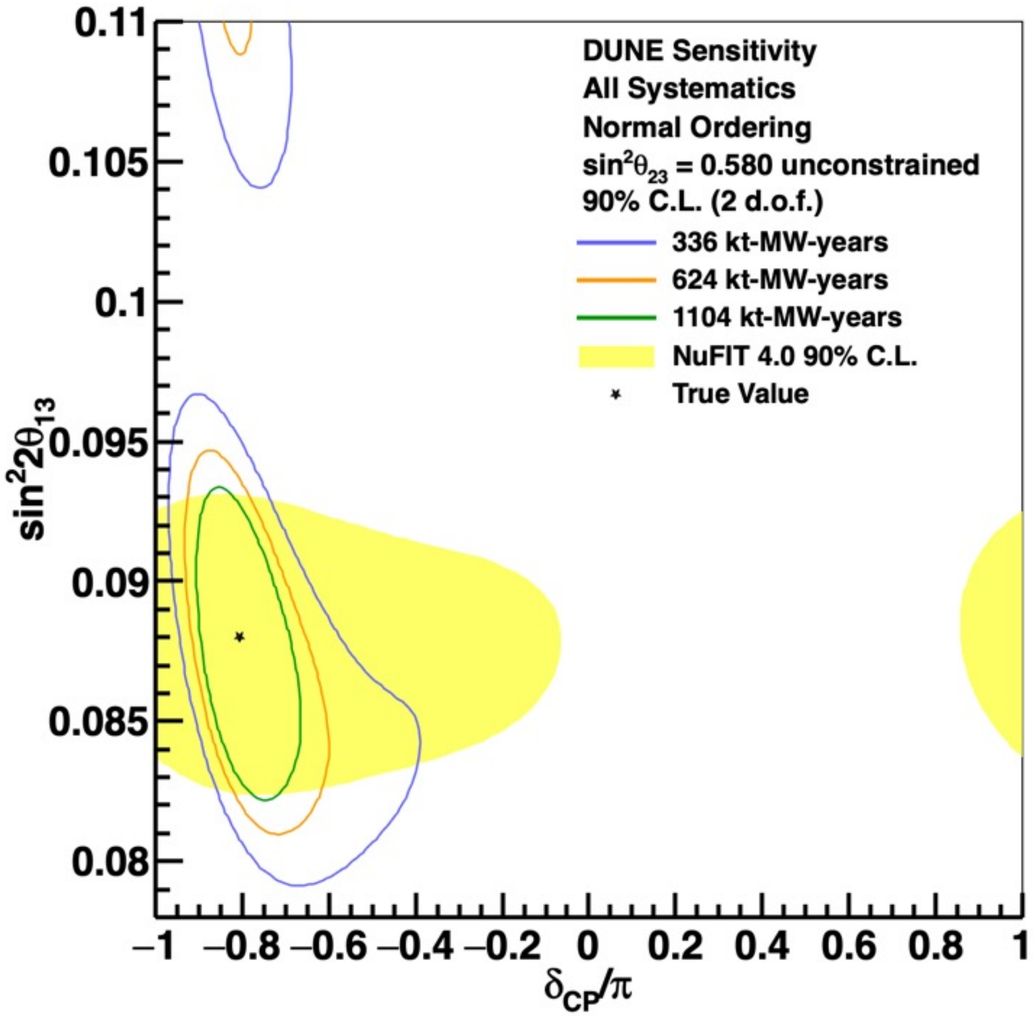




Precision measurements at DUNE

arXiv:2006.16043 arXiv:2109.01304, Talk by Elizabeth Worcester, NDM22



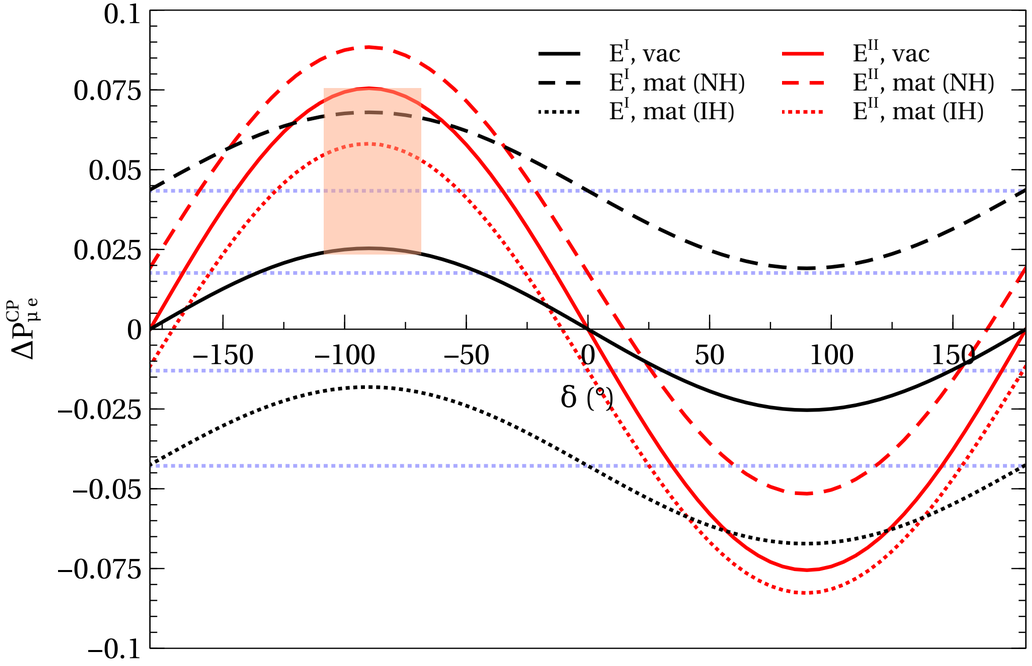


Width of band represents difference between sensitivity with and without external constraint on 13 angle.

Prospects with 2nd maxima at DUNE

Jogesh Rout, Sheeba Shafaq, Mary Bishai and PM, PRD 2021

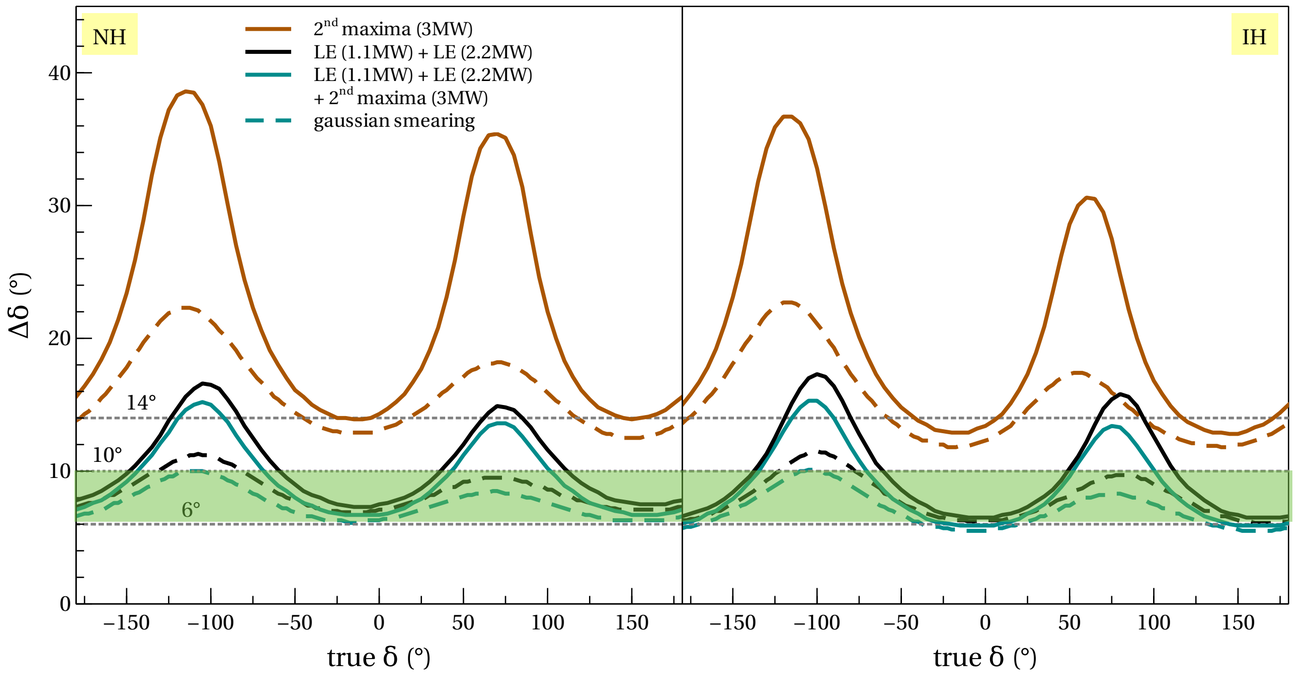
factor of ~3



$$E^I \simeq 2.6\ GeV$$

$$E^{II} \simeq 0.8\ GeV$$

CP resolution



The CP phase resolution (with improved energy resolution) is better than 10 degrees

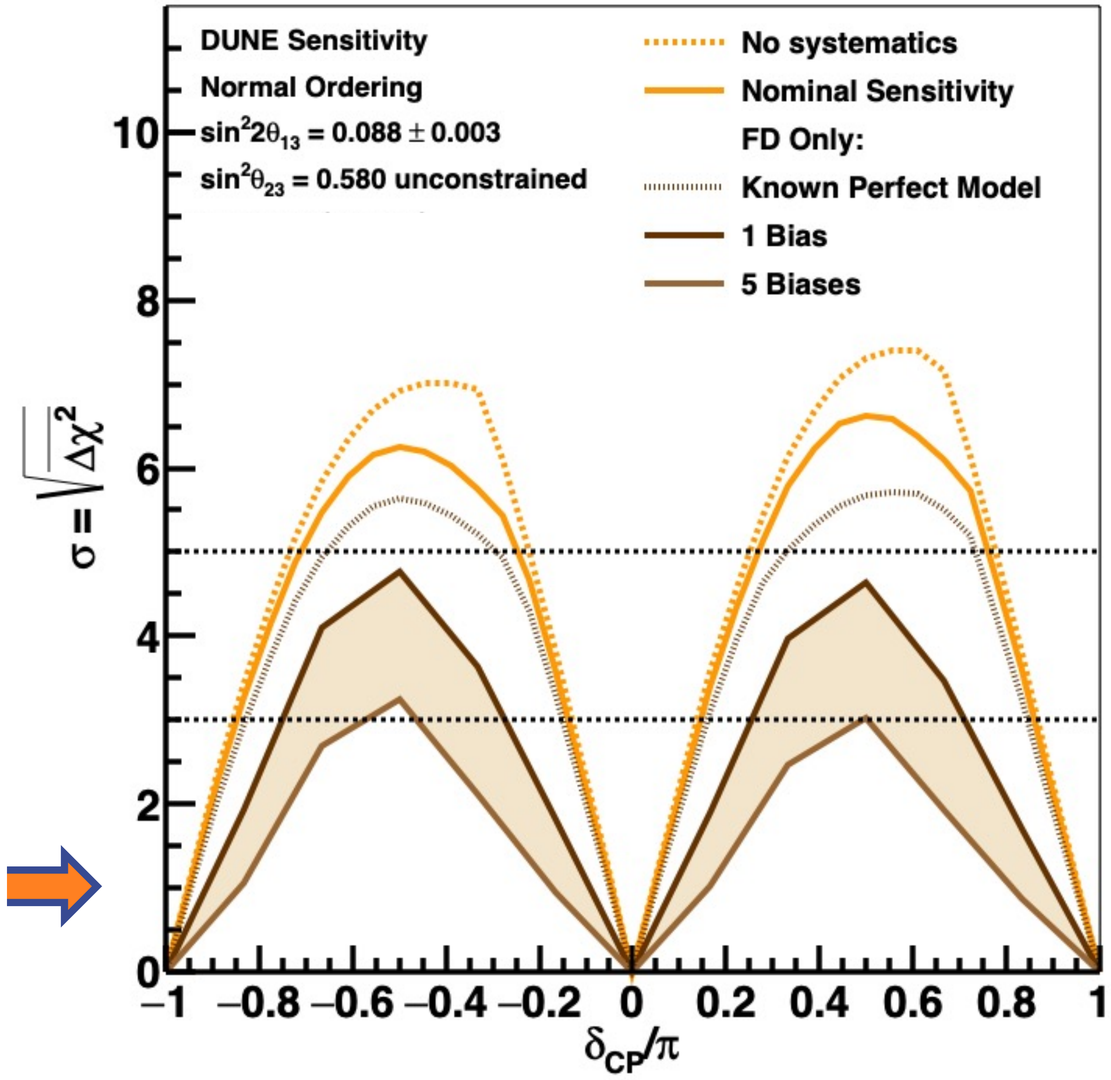
S. Choubey, M. Ghosh, D. Kempe and T. Ohlsson, Exploring invisible neutrino decay at ESSnuSB, 2010.16334.

Chakravarty, Dutta, Goswami, Pramanik, Invisible neutrino decay : First vs second oscillation maximum, 2012.04958

Systematic uncertainty

Phased Construction arXiv:2203.06100, Talk by Elizabeth Worcester, NDM22

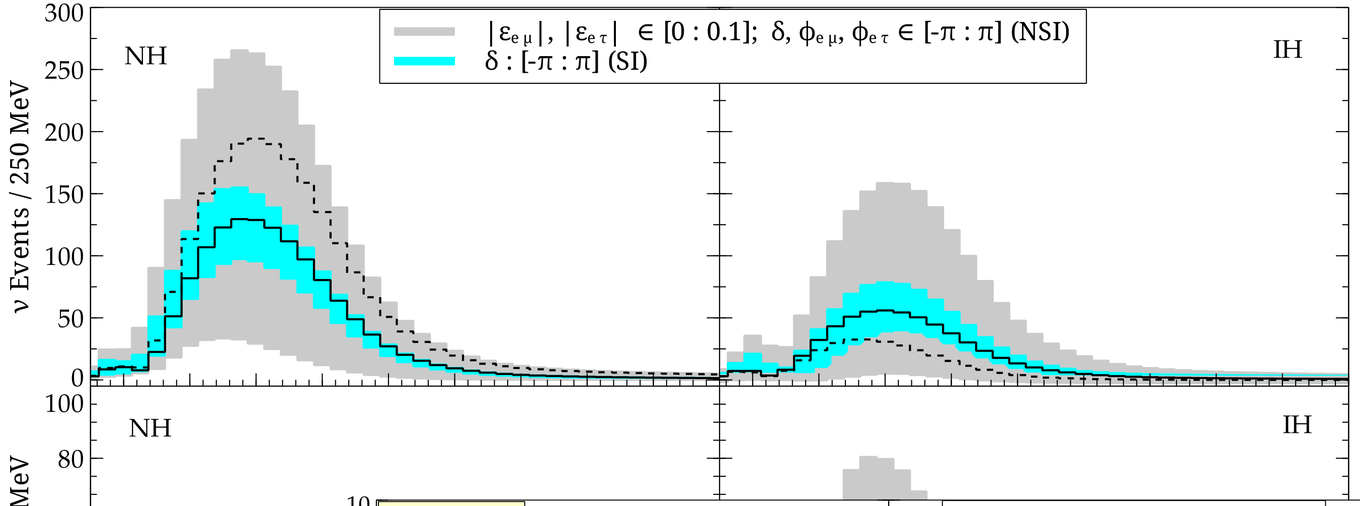
- Order few percent uncertainty required for precision measurements
- Sources of uncertainty :
  - Neutrino flux
  - Neutrino interaction model
  - Detector effects
- Impact of biases due to shortcomings in the interaction model is large
- Near detectors critical to achieve precision measurement goals

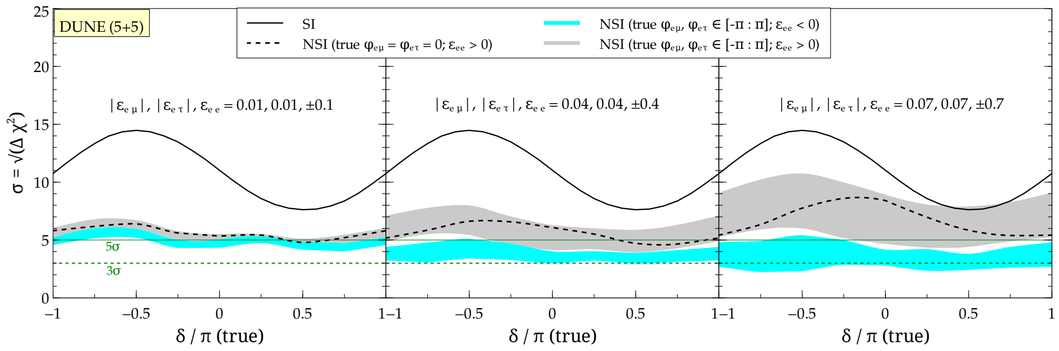


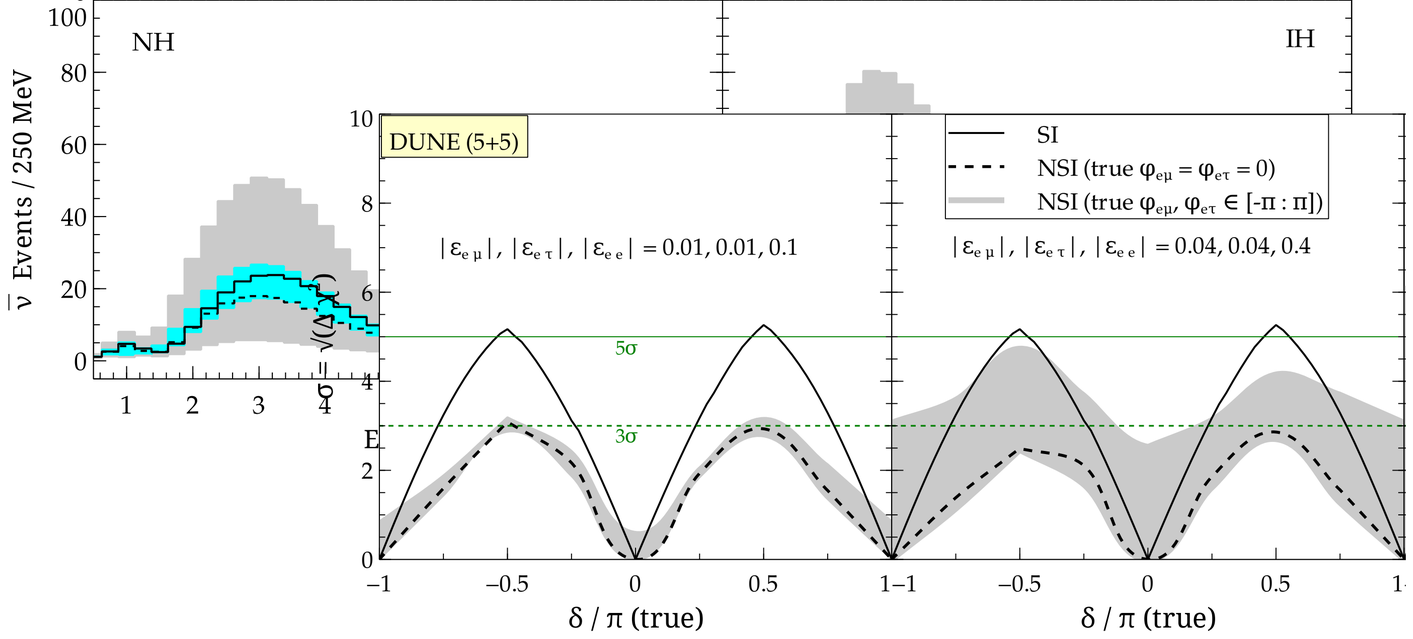
Impact of BSM physics on standard unknowns

Sensitivity to CP violation and mass hierarchy DUNE

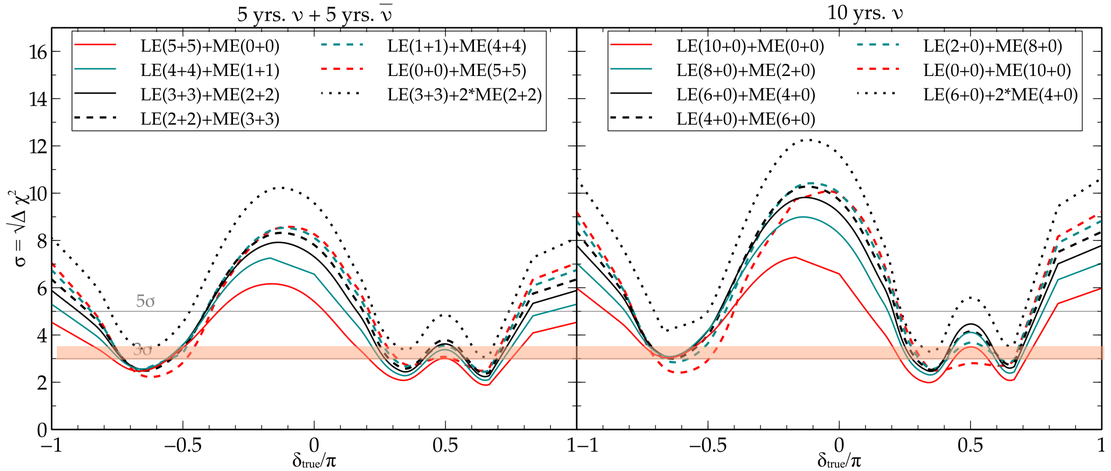
Mehedi Masud, Animesh Chatterjee, PM, J Phys G 2016, Mehedi Masud, PM, PRD 2016, Jogesh Rout, Mehedi Masud, PM, PRD 2017, M. Masud, M. Bishai and PM, Scientific Reports (2019), see also Gandhi et al, JHEP 11 (2015) 039, JHEP 11 (2016) 122, Deepthi, Goswami, Nath, PRD 96 (2017), Singha, Ghosh, Majhi and Mohanta, 2211.01816, Abinash Medhi, Debajyoti Dutta and Moon Moon Devi, 2111.12943





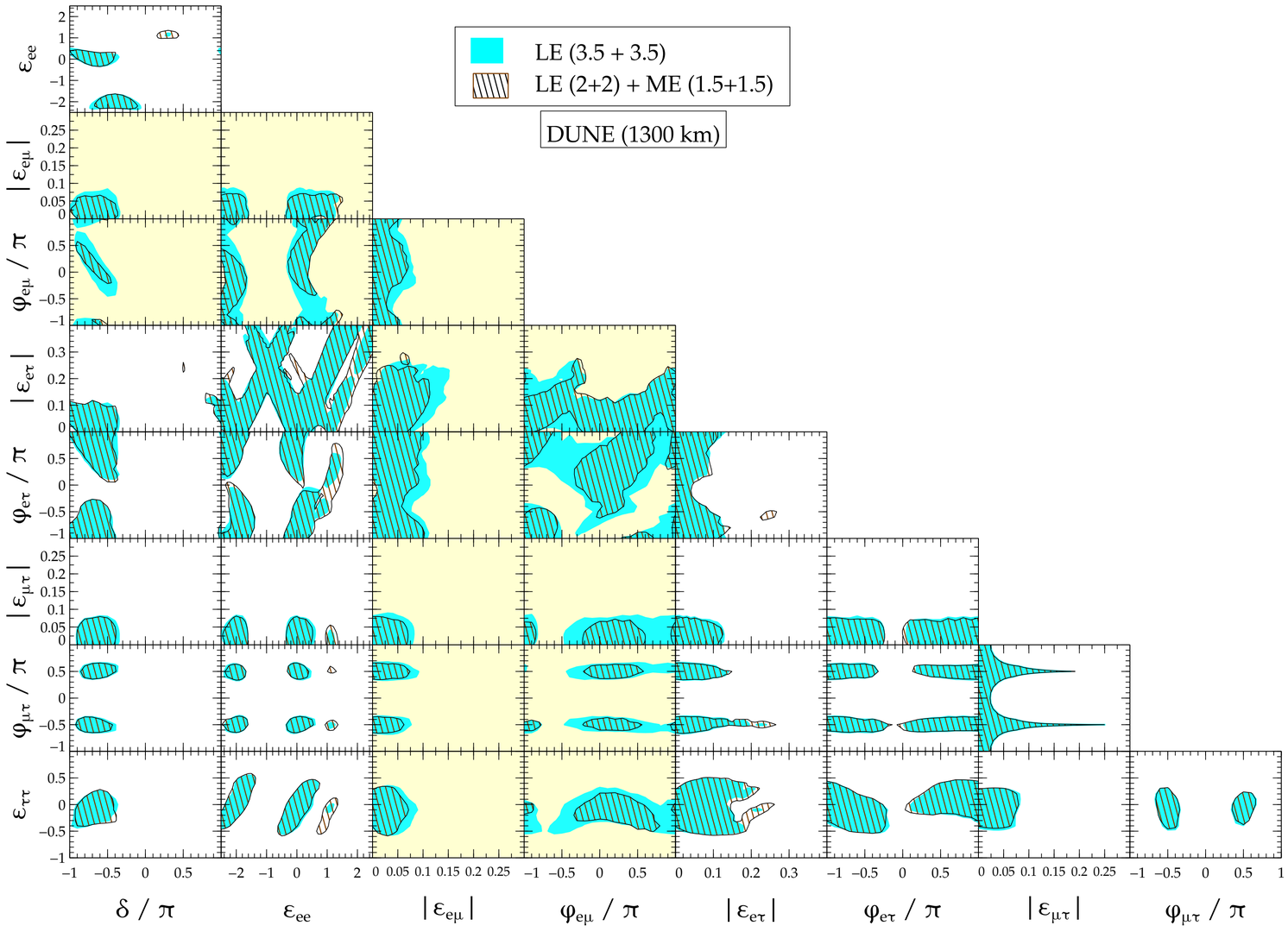


SI-NSI separation at DUNE



Correlations among NSI parameters

Mehedi Masud, Samiran Roy, PM, PRD 2019

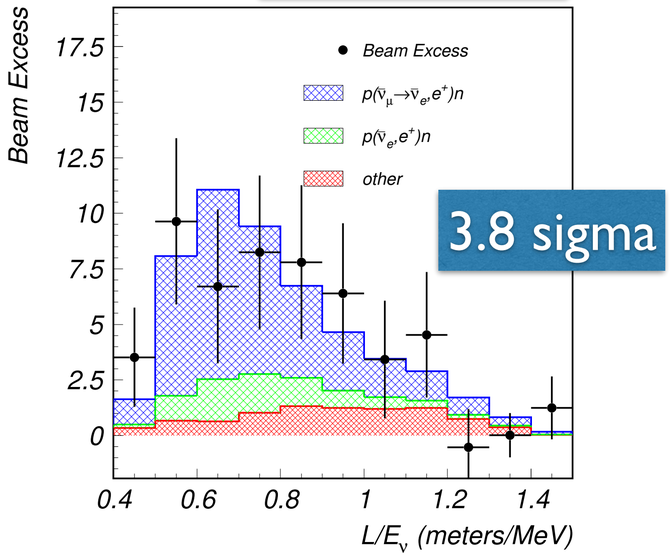


Sterile neutrino

Dasgupta and Kopp, 2106.05913

LSND

Antineutrino

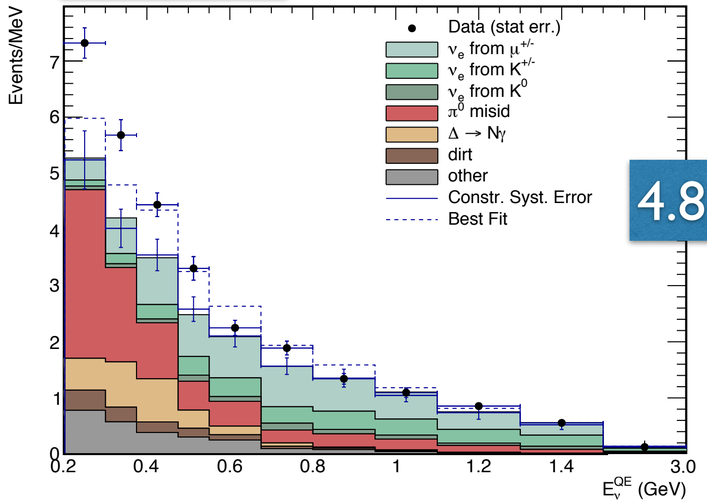


3.8 sigma

PRD64, 112007 (2001)

MiniBooNE

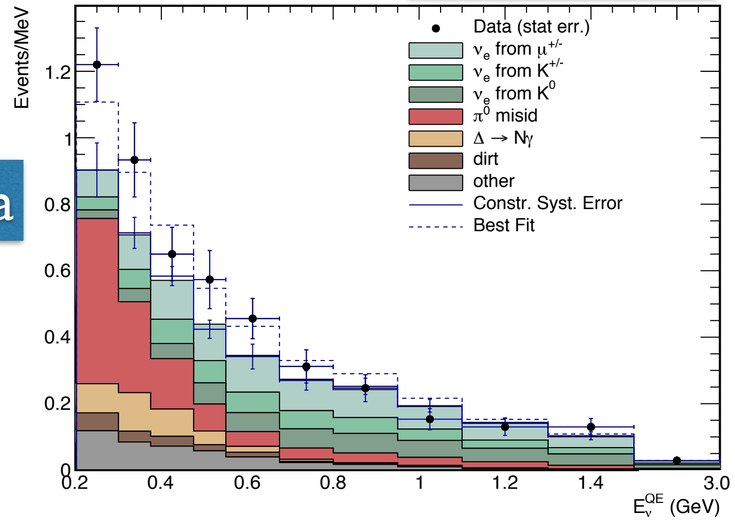
Neutrino



4.8 sigma

2006.16883

Antineutrino



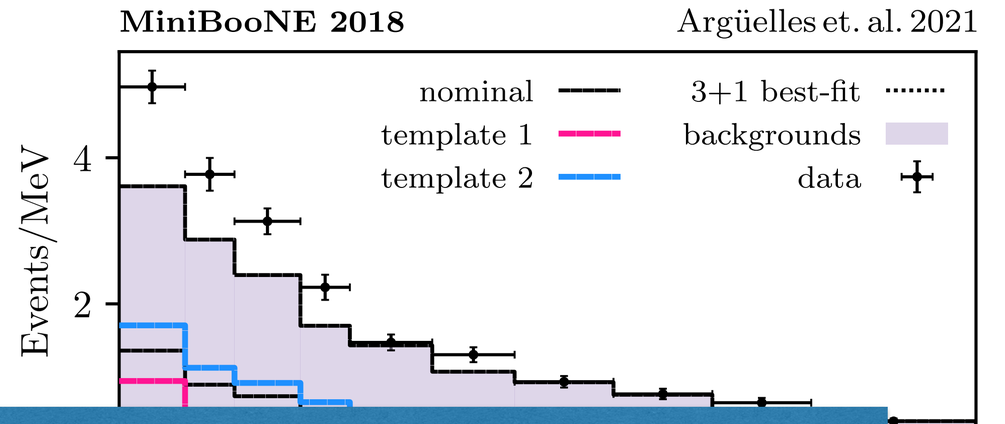
1805.12028

Experiment	L	E	Channel
LSND	30 m	20-200 MeV	Electron antinu Appearance
MiniBooNE	541 m	0.2-3 GeV	Electron anti(nu) Appearance + Disappearance
MicroBooNE	541 m	0.5-3 GeV	Appearance + Disappearance

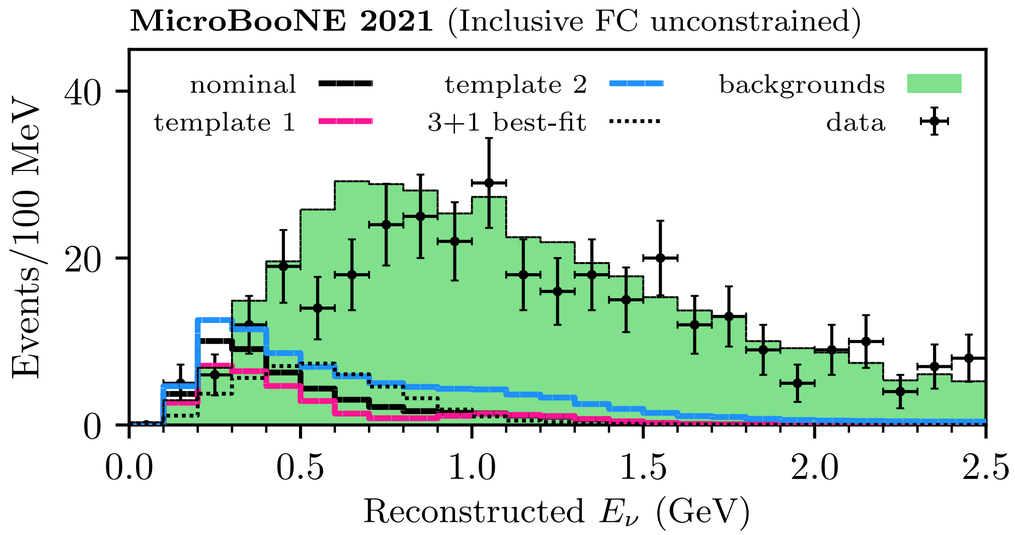
Are sterile neutrinos out ?

MicroBooNE

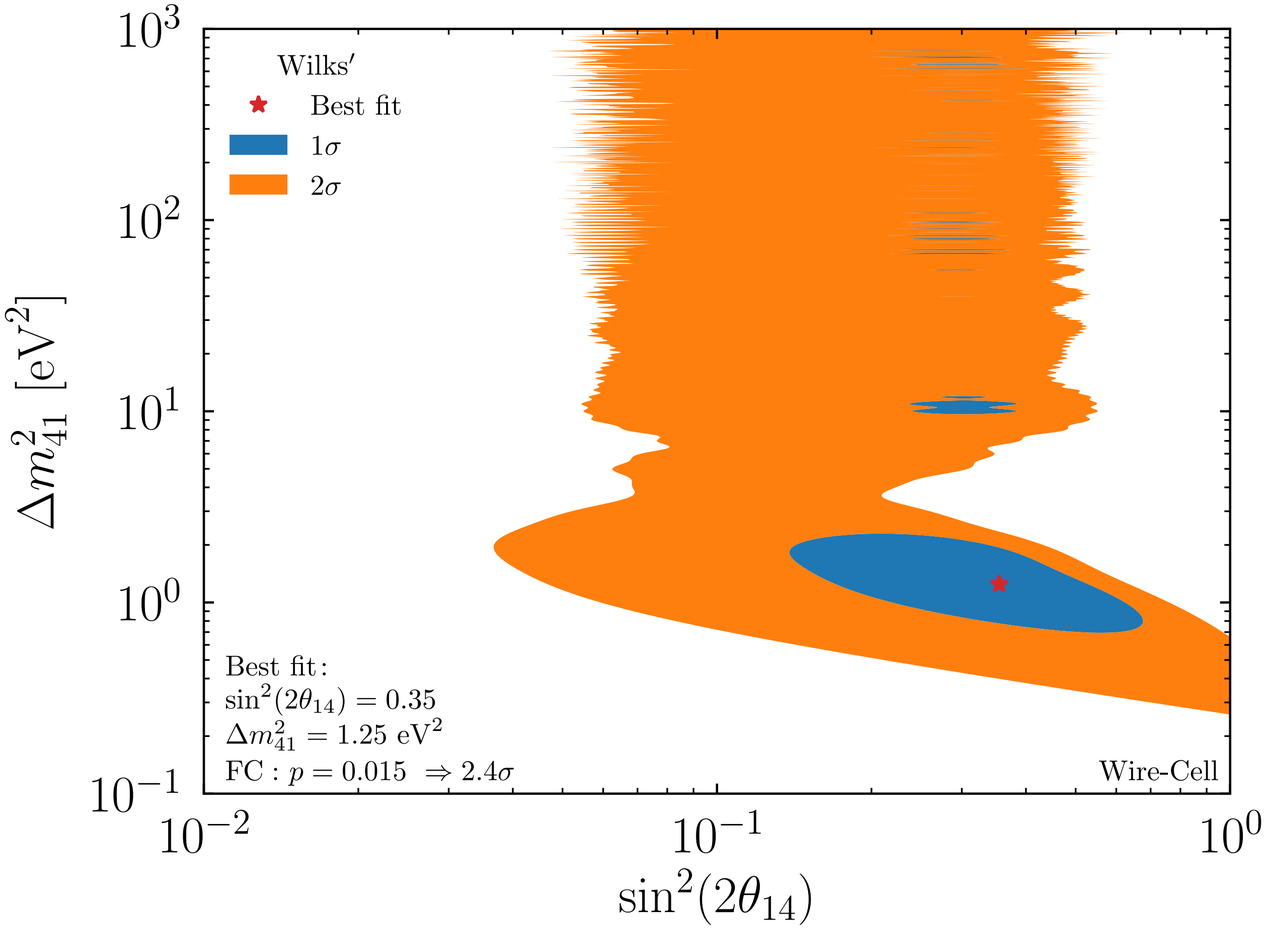
Arguelles et al, 2111.10359, see also Denton, Phys.Rev.Lett. 129 (2022) 6, 061801



Do not probe the full parameter space of sterile nu models hinted by MiniBooNE

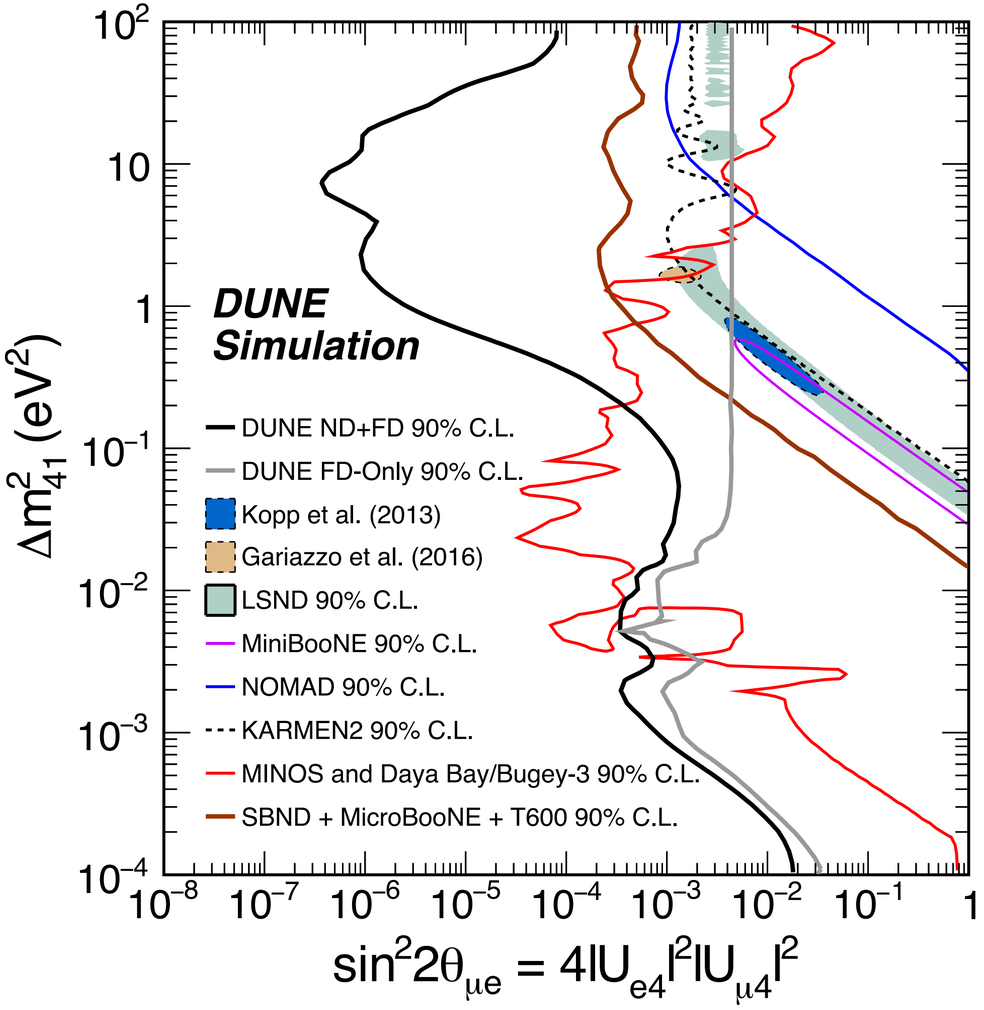


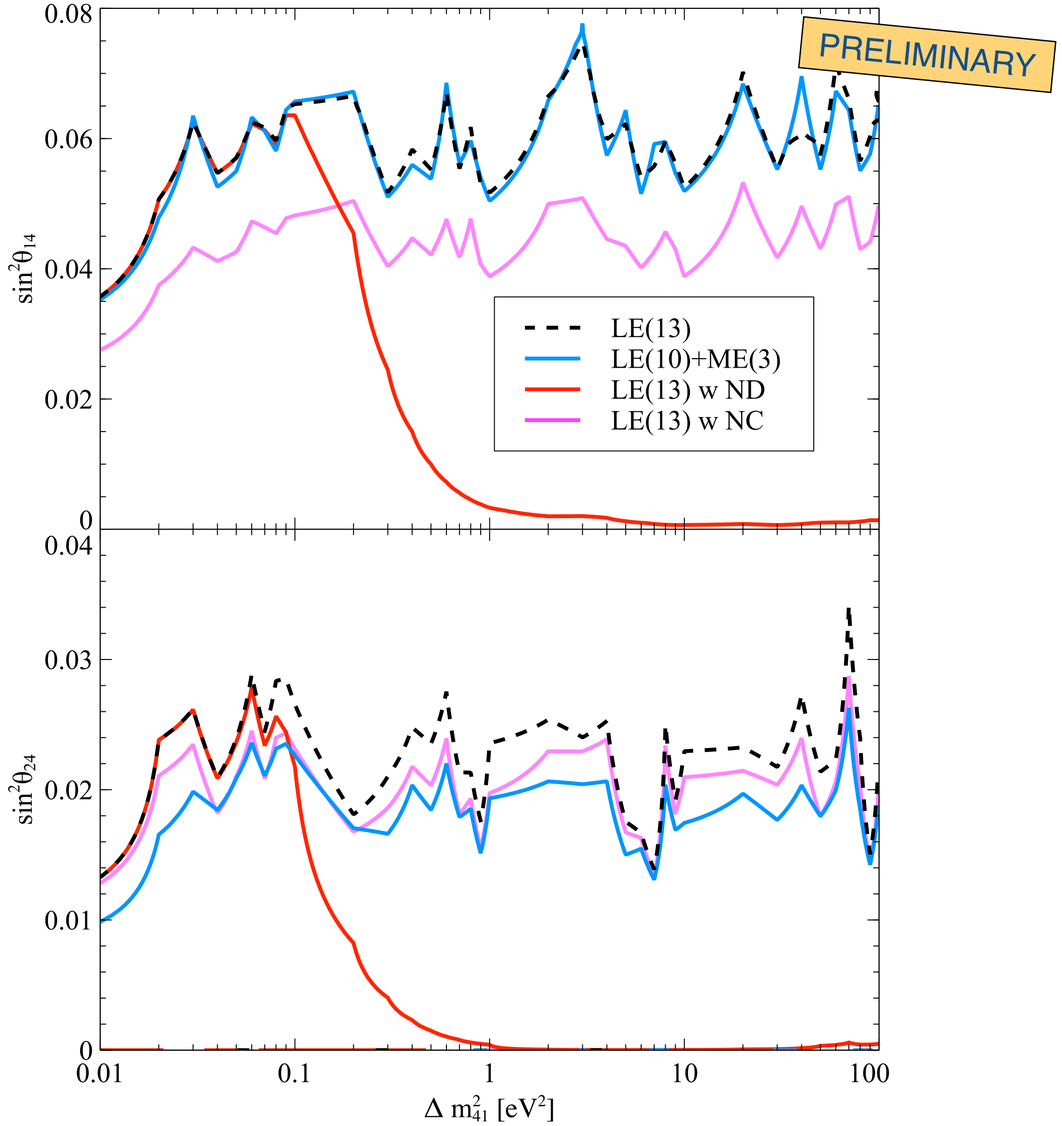
$$P^{vac}_{\mu e} = \sin^2(2\theta_{\mu e}) \sin^2 \frac{\Delta m^2_{41} L}{4E}$$



Exclusion plot in sterile case

Abi et al, Eur.Phys.J.C 81 (2021) 4, 322





Sabila Parveen, Mehedi Masud, Mary Bishai and PM, to appear

What about tau neutrinos at DUNE ?

Barbara Yaeggy, talk at NuFact 2022, 2203.05591 Snowmass white paper

- Among all fermions of the SM, tau neutrinos are least experimentally seen. Only 9 tau neutrino + tau anti neutrinos CC events seen in DONuT experiment and 10 tau neutrino CC events seen in OPERA experiment.
- Current generation of neutrino experiments provides nearly complete description of 3 flavor paradigm.
- All information about tau sector is taken from
  - Lepton universality for cross-sections
  - PMNS unitarity for oscillations
- We need to test these assumptions.

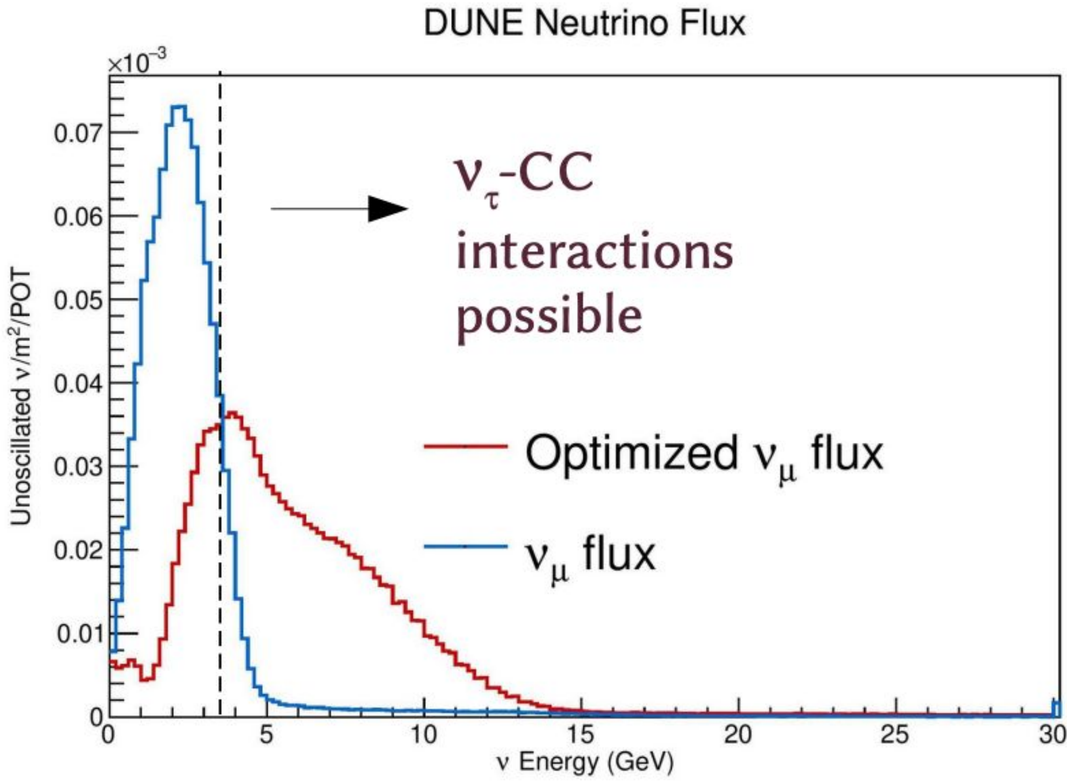
CP optimized configuration (3 horns)

~130 tau neutrino counts/year

~30 tau anti-nu counts/year

Tau optimized configuration (2 horns)

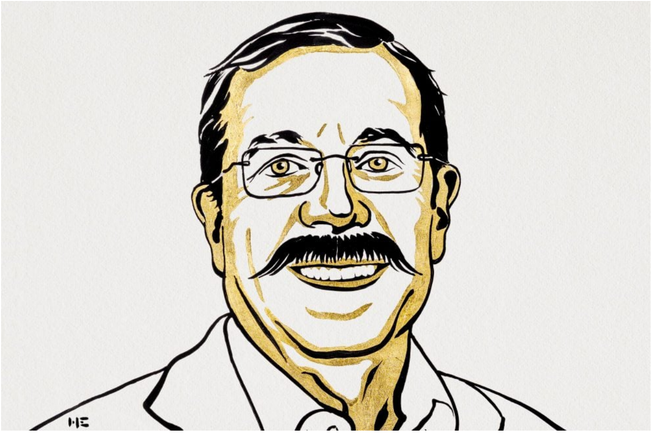
~800 tau nu counts/year



Other possibilities

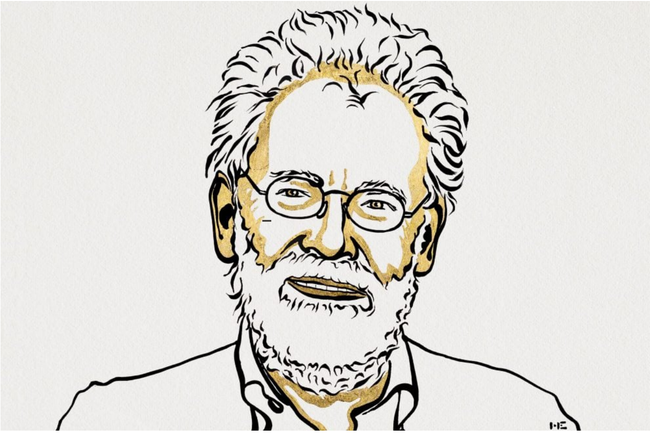
2022 Nobel

"for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"



ALAIN ASPECT

JOHN F CLAUSER



ANTON ZEILINGER

2016

Violation of Leggett-Garg Inequalities

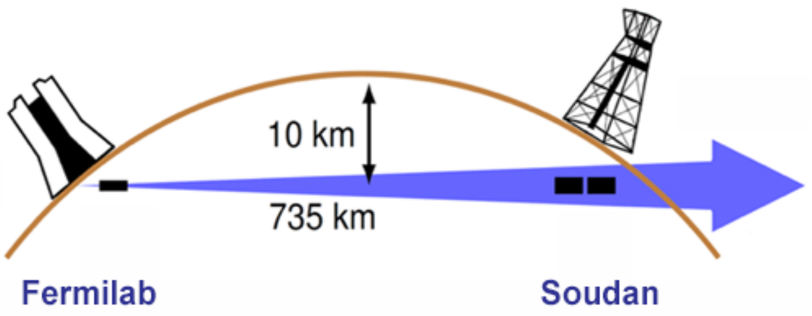
J. A. Formaggio, D. I. Kaiser, M. M. Murskyj, and T. E. Weiss, Phys. Rev. Lett. 117, 050402 (2016) ; M. Schirber, Physics 9, s81 (2016)

PRL **117,** 050402 (2016) PHYSICAL REVIEW LETTERS week ending 29 JULY 2016

Violation of the Leggett-Garg Inequality in Neutrino Oscillations

J. A. Formaggio,* D. I. Kaiser, M. M. Murskyj, and T. E. Weiss
Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
(Received 8 February 2016; published 26 July 2016)

The Leggett-Garg inequality, an analogue of Bell's inequality involving correlations of measurements on a system at different times, stands as one of the hallmark tests of quantum mechanics against classical predictions. The phenomenon of neutrino oscillations should adhere to quantum-mechanical predictions and provide an observable violation of the Leggett-Garg inequality. We demonstrate how oscillation phenomena can be used to test for violations of the classical bound by performing measurements on an ensemble of neutrinos at distinct energies, as opposed to a single neutrino at distinct times. A study of the MINOS experiment's data shows a greater than 6σ violation over a distance of 735 km, representing the longest distance over which either the Leggett-Garg inequality or Bell's inequality has been tested.



- MINOS measures the survival probabilities of oscillating muon neutrinos produced in the NuMI accelerator complex.
- The accelerator provides a source of neutrinos with a fixed baseline and an energy spectrum that peaks at a point corresponding to δL/Ev ~ 250 km/GeV, close to the region where the survival probability Pμμ reaches its first minimum.
- This experimental design provides an ideal phase space to test for LGI violations.

2016

LGI test at MINOS

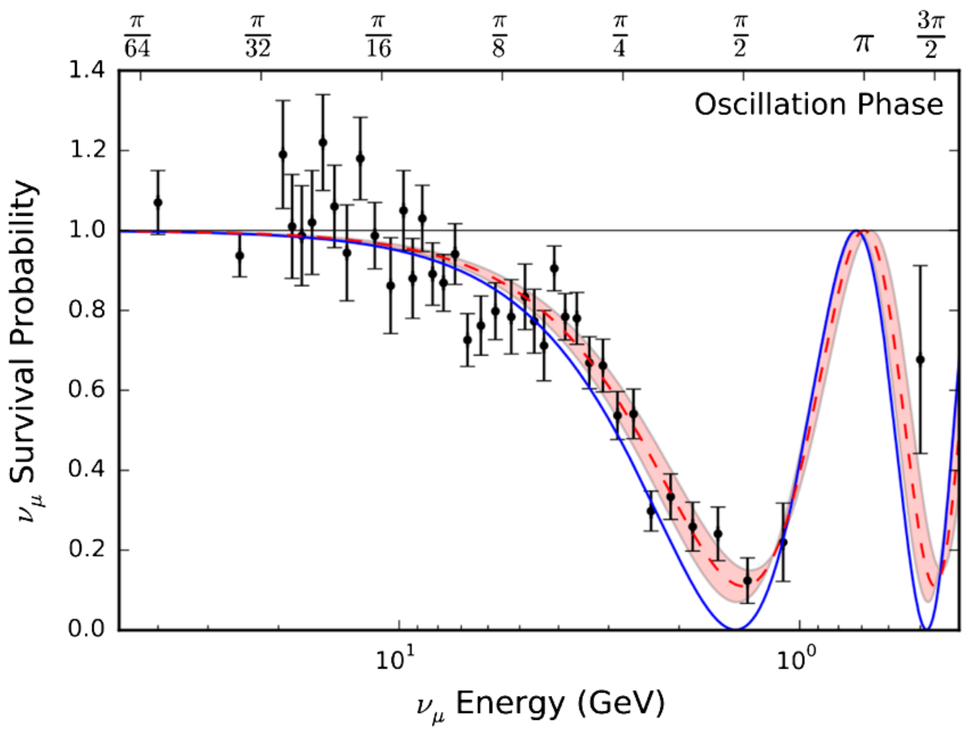
J. A. Formaggio, D. I. Kaiser, M. M. Murskyj, and T. E. Weiss, Phys. Rev. Lett. 117, 050402 (2016) ; M. Schirber, Physics 9, s81 (2016)

$$\psi_{a;ij} \simeq \frac{\omega_a}{2}(t_j - t_i) = \frac{1}{4E_a}(m_2^2 - m_1^2)(t_j - t_i).$$

$$\sum_{i=1}^{n-1} \psi_{a;i,i+1} = \psi_{a;1n}$$

$$\mathcal{C}_{ij}(\omega_a) = 1 - 2\sin^2 2\theta \sin^2 \psi_{a;ij}.$$

$$K_n^Q = (2-n) + 2\sum_{a=1}^{n-1} P_{\mu\mu}(\psi_a) - 2P_{\mu\mu}\left(\sum_{a=1}^{n-1}\psi_a\right)$$



- This violation occurs over a distance of 735 km, providing the longest range over which a Bell-like test of quantum mechanics has been carried out to date.

LGI in two flavour case

Gangopadhyay, Home and Sinha Roy , Phys. Rev. A 88, 022115 (2013)

$$C_{12} = \mathbb{P}_{\nu_e\nu_e}(t_1,t_2) - \mathbb{P}_{\nu_e\nu_\mu}(t_1,t_2) - \mathbb{P}_{\nu_\mu\nu_e}(t_1,t_2) + \mathbb{P}_{\nu_\mu\nu_\mu}(t_1,t_2)$$

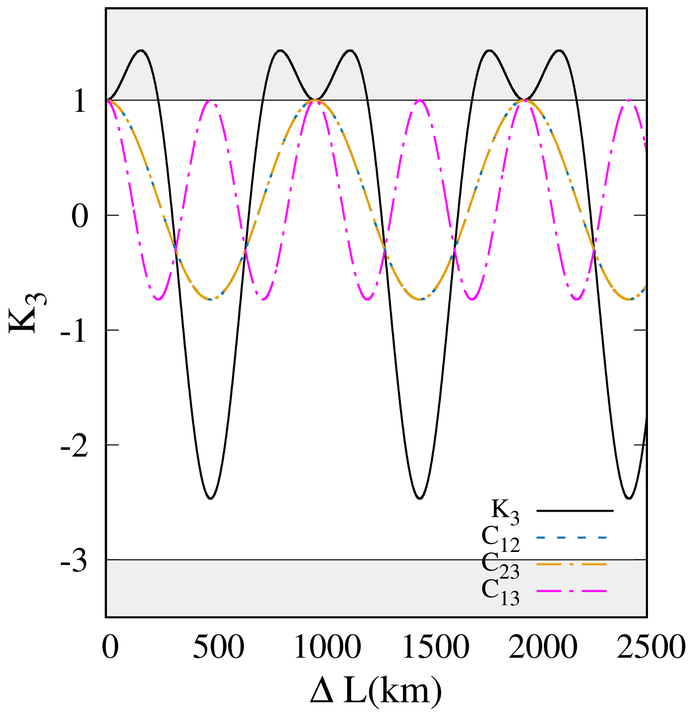
$$Q = \begin{cases} +1 & \text{for } \nu_\mu \\ -1 & \text{for } \nu_e \text{ or } \nu_\tau \end{cases}$$

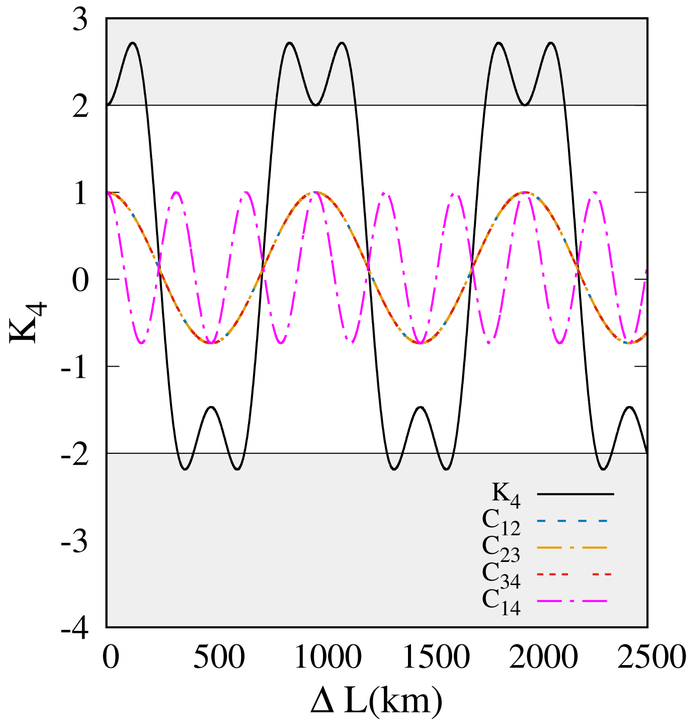
$$\mathbb{P}_{\nu_\alpha\nu_\beta}(t_1,t_2) = P_{\mu\alpha}(t_1)P_{\alpha\beta}(t_2)$$ Joint Probabilities

$$C_{12} = 1 - 2\sin^2 2\theta \sin^2\left(\frac{\Delta m^2 \Delta L}{4E}\right)$$

$$K_3 = 1 - 2\sin^2 2\theta\left[2\sin^2\frac{\Delta m^2\tau}{4E} - \sin^2\frac{2\Delta m^2\tau}{4E}\right]$$

$$K_4 = 2 - 2\sin^2 2\theta\left[3\sin^2\frac{\Delta m^2\tau}{4E} - \sin^2\frac{3\Delta m^2\tau}{4E}\right]$$





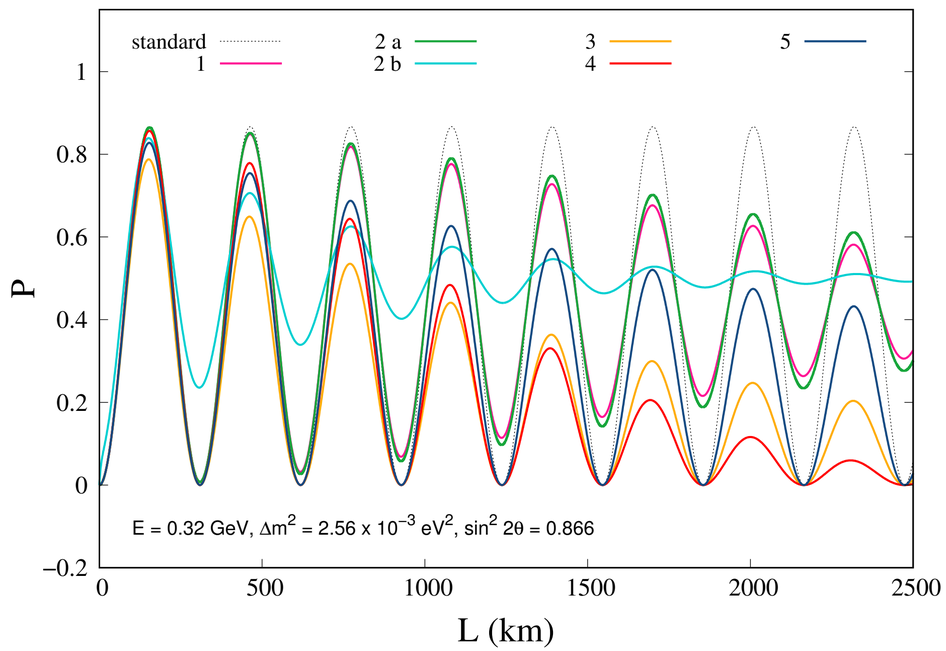
Shafaq and Mehta, J Phys. G 48, 085002 (2021)

Damped oscillations and LGI

Blennow, Ohlsson and Winter, JHEP (2005)

$$P_{\alpha\beta} = \sum_{i,j=1}^{3} U_{\alpha j}\, U^*_{\beta j}\, U^*_{\alpha i}\, U_{\beta i}\, \exp(-\mathrm{i}2\Delta_{ij}) D_{ij}$$

$$= \sum_{i=1}^{3} J^{\alpha\beta}_{ii} D_{ii} + 2 \sum_{1\le i<j\le 3} |J^{\alpha\beta}_{ij}| D_{ij} \cos(2\Delta_{ij} + \arg J^{\alpha\beta}_{ij})$$



S. No.	Damping Scenario	$D_{ij} = \exp\left(-\kappa_{ij} \frac{\lvert\Delta m^2_{ij}\rvert^{\xi} L^{\beta}}{E^{\gamma}}\right)$	κ (units)
	Decoherence like $\xi \neq 0$		
1	Intrinsic wave packet decoherence	$\exp\left(-\sigma_E^2 \frac{(\Delta m^2_{ij})^2 L^2}{8E^4}\right)$	$\frac{\sigma_E^2}{8}$ (GeV^2)
2	Quantum decoherence	$\exp\left(-\kappa \frac{(\Delta m^2_{ij})^2 L^2}{E^2}\right)$	κ (dimensionless)
	Decay like $\xi = 0$		
3	Invisible neutrino decay	$\exp\left(-\kappa \frac{L}{E}\right)$	κ (GeV $\cdot$ km^{-1})
4	Oscillations into sterile neutrino	$\exp\left(-\epsilon \frac{L^2}{(2E)^2}\right)$	ϵ (eV^4)
5	Neutrino absorption	$\exp\left(-\kappa L E\right)$	κ (GeV^{-1} $\cdot$ km^{-1})

Shafaq, Kushwaha and Mehta, 2021

See also Shafaq and Mehta, J Phys. G 48, 085002 (2021)

Non-standard Neutrino Oscillations :

description in terms of unitarity triangles

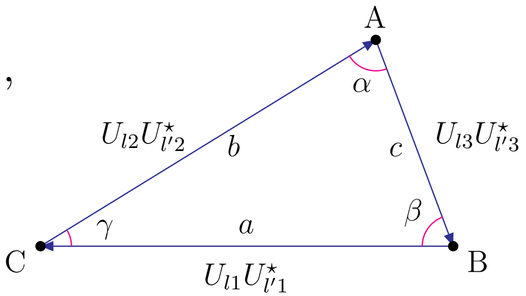
Masud, PM, Ternes and Tortola, JHEP 05 (2021) 171

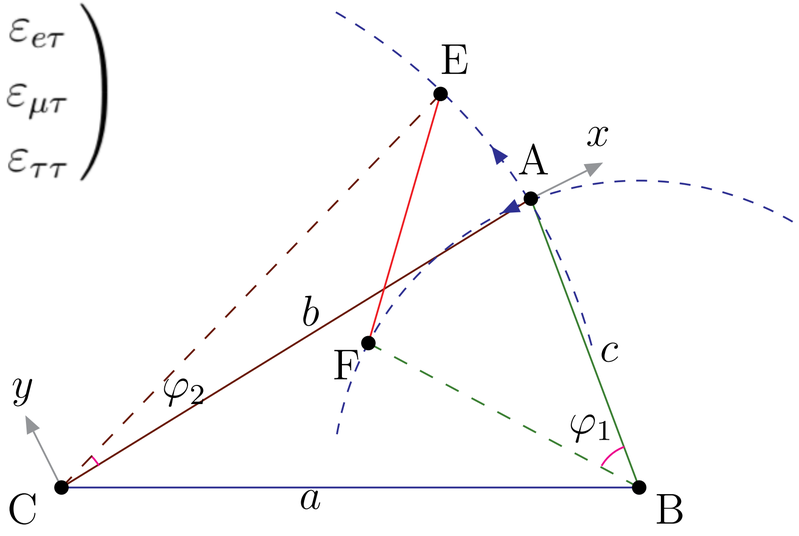
$$H = H_0 + H_{SI} + H_{NSI}$$

$$= \frac{1}{2E} U \begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix} U^\dagger + \sqrt{2} G_F N_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} + \sqrt{2} G_F N_e \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

vacuum term — standard matter term — NSI term

$$= \frac{\Delta m_{31}^2}{2E} U^m \left[K_{\rm diag} + A\tilde{\varepsilon} \right] (U^m)^\dagger ,$$





Approximate expression for appearance probability depends on 3 parameters of the triangle

$$P_{\ell\ell'} = 4(c_{\ell\ell'}^N)^2 \sin^2 \Delta_{31}^N - 8 b_{\ell\ell'}^N c_{\ell\ell'}^N \sin \Delta_{31}^N \sin \Delta_{21}^N \cos[\Delta_{32}^N + \alpha_{\ell\ell'}^N] + 4(b_{\ell\ell'}^N)^2 \sin^2 \Delta_{21}^N .$$

$$b_{\mu e}^N = |U_{22}^N U_{12}^{N*}| , \qquad c_{\mu e}^N = |U_{23}^N U_{13}^{N*}| , \qquad \alpha_{\mu e}^N = \arg\left(-\frac{U_{23}^N U_{13}^{N*}}{U_{22}^N U_{12}^{N*}} \right)$$

CP Violation

Same form as vacuum case and standard matter case

THANK YOU