Neutrino Oscillation Physics

Current Landscape and Future Prospects

Brooke Russell

Summiting the Unknown

July 14, 2022

Outline

- 3-flavor paradigm in brief

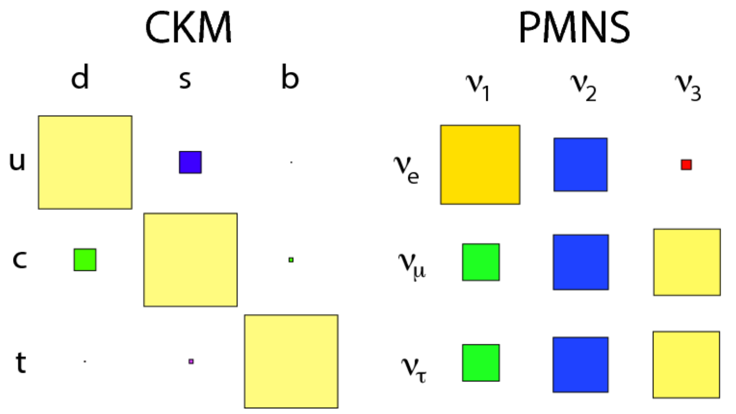
- Current picture on neutrino mass and mixings

- Next generation neutrino oscillation projected experimental reach

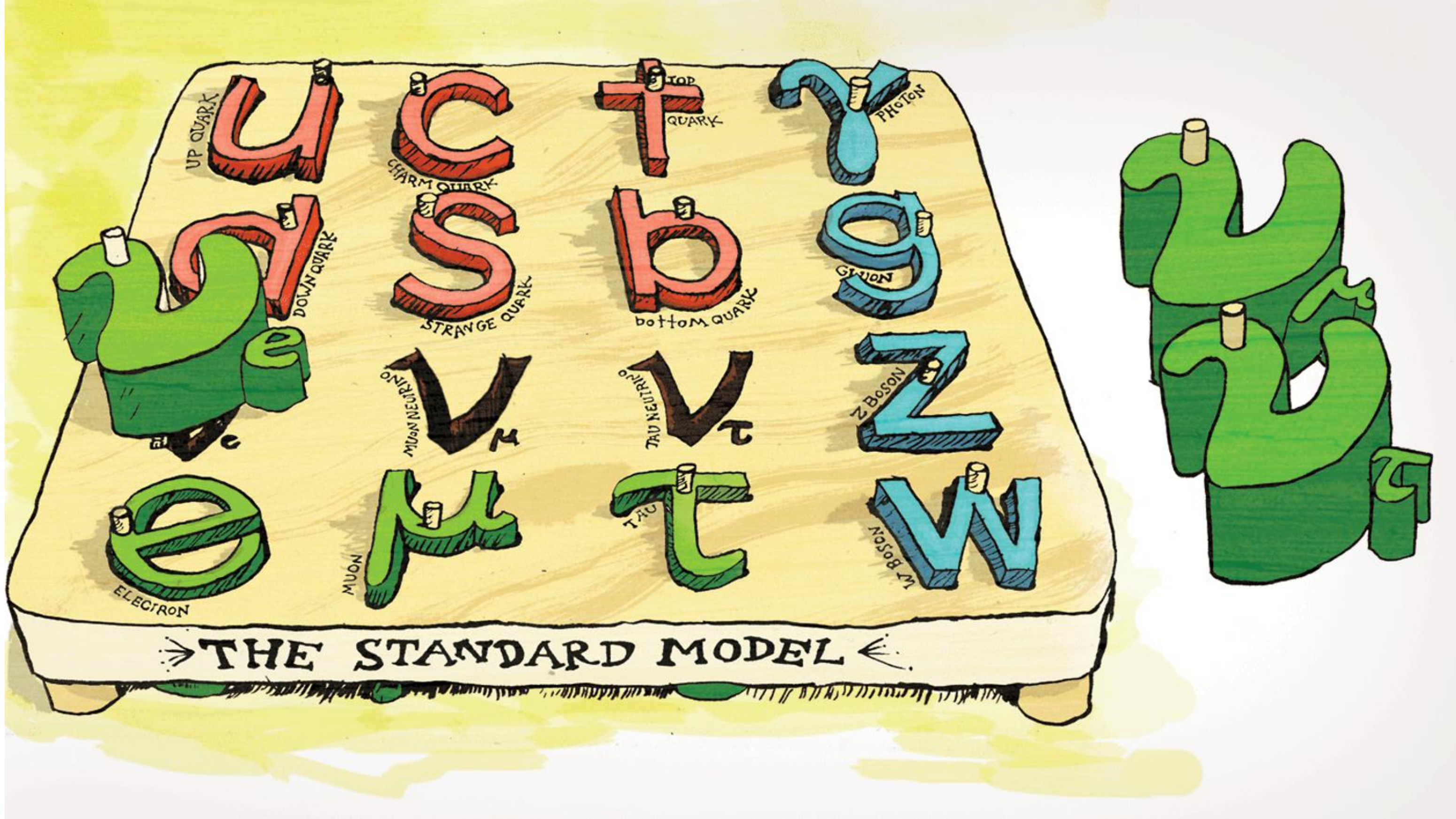
Neutrino Oscillation

In-flight transition between different neutrino flavors caused by nonzero neutrino masses and neutrino mixing

→ beyond Standard Model physics



1212.6374v2



Raymond Davis Jr. and Masatoshi Koshiba “for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos”

Takaaki Kajita and Arthur B. McDonald “for the discovery of neutrino oscillations, which shows that neutrinos have mass”

Quantifiable Known Unknowns

ν absolute mass scale

Mass ordering

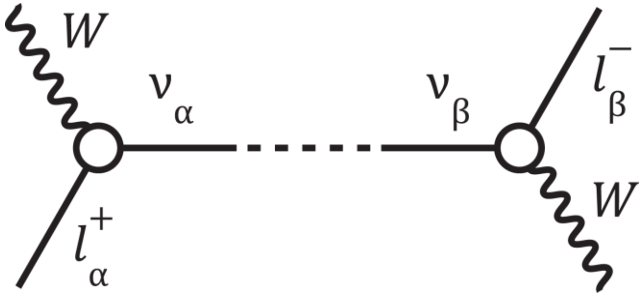
θ_{23} octant

δ complex phase

Studied through neutrino oscillation measurements

Three-neutrino Mixing Paradigm

(for oscillations in vacuum or sufficiently low densities)



Probability that a neutrino that begins as flavor α is detected in a charged-current (CC) interaction as flavor β:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \Re\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) \pm 8J\prod_{i>j}\sin\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

where $U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}\begin{pmatrix} 1 & & \\ & e^{i\frac{\alpha_{21}}{2}} & \\ & & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$,

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

L is the distance traveled, E is the neutrino energy, and $J \equiv \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})$ is the Jarlskog coefficient.

Physical parameters:

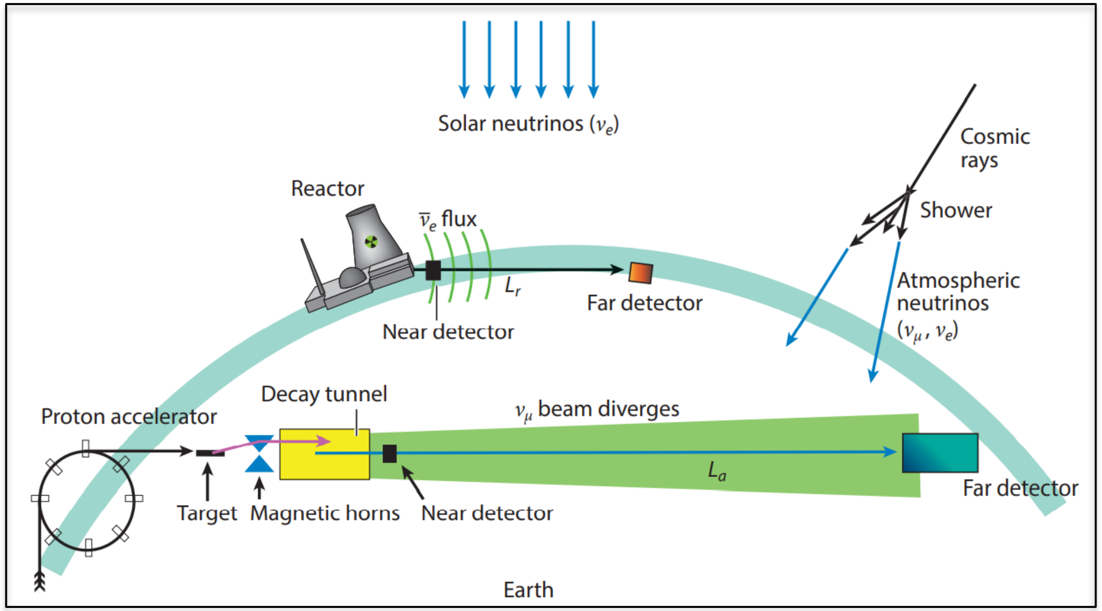
- Mixing angles θ_{ij} between mass/flavor eigenstates set oscillation amplitude
- Differences in neutrino masses Δm^2_{ji} set oscillation frequency
- Off-diagonal phase δ is a CP violating phase

Matter effect:
coherent forward CC
elastic scattering
(applicable to ν_e, $\bar{\nu}_e$ only)

Source Complementarity

Over-constrain parameter space to test 3 ν formalism

$\nu_\mu \rightarrow \nu_\tau, \bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$	atmospheric, accelerator
$\nu_e \rightarrow \nu_{\mu,\tau}$	solar
$\bar{\nu}_e \rightarrow \bar{\nu}_x$	reactor
$\nu_\mu \rightarrow \nu_x, \bar{\nu}_\mu \rightarrow \bar{\nu}_x$	atmospheric, accelerator
$\nu_\mu \rightarrow \nu_e$	accelerator



M.V. Diwan, V. Galymov, X. Qian, A. Rubbia, Annu. Rev. Nucl. Part. Sci. 2016, 66:47-71

*Adapted from A. de Gouvea

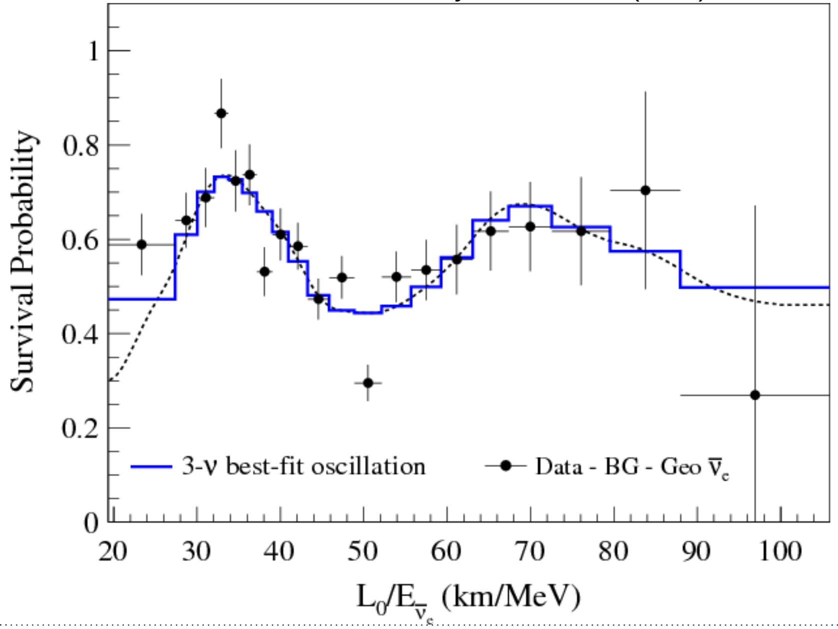
Solar

$\boldsymbol{\theta_{12}} \sim 34°$ where $\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}$

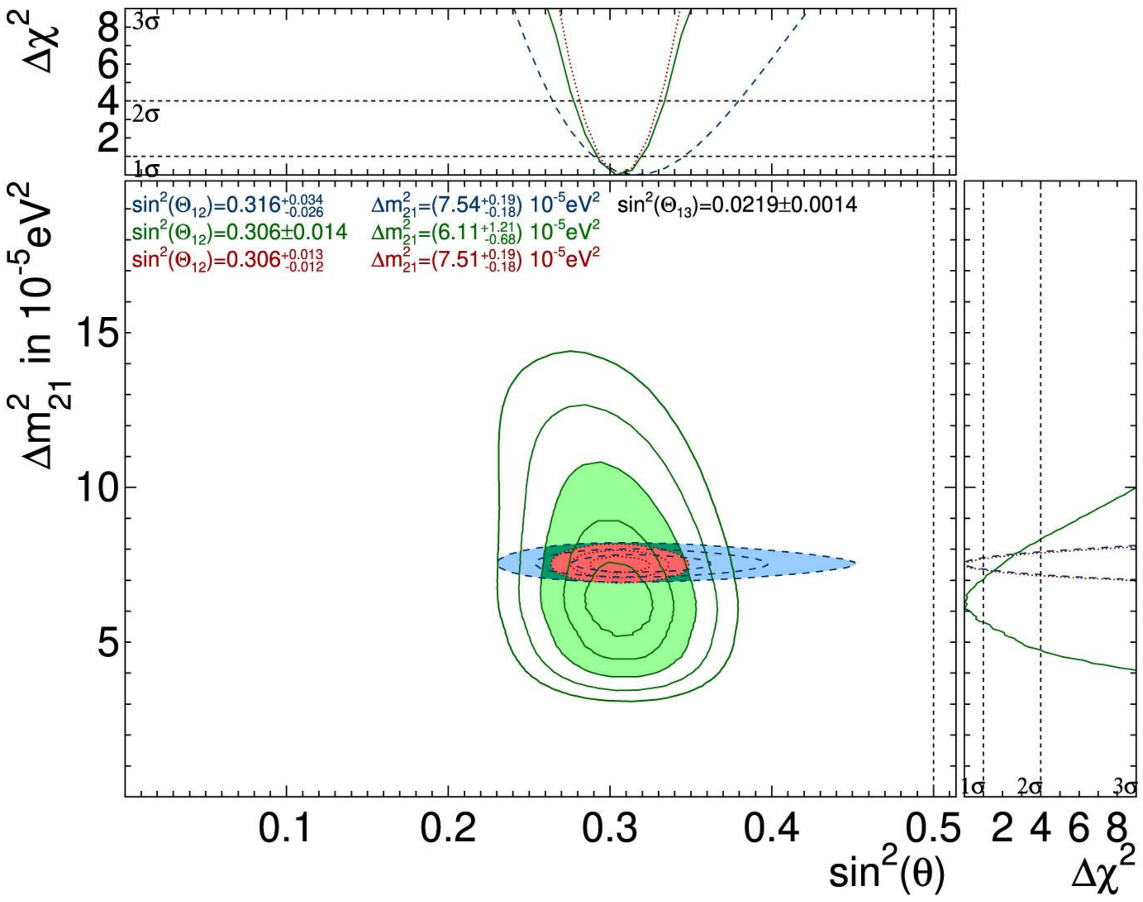
$\boldsymbol{\Delta m^2_{21}} \sim +7.5 \times 10^{-5}\ \mathrm{eV}^2$

- Absolute value determined by the KAMLAND experiment
- Slight tension between solar and reactor antineutrino measurements

Phys. Rev . D 88 (2013) 3, 033001



2111.07586

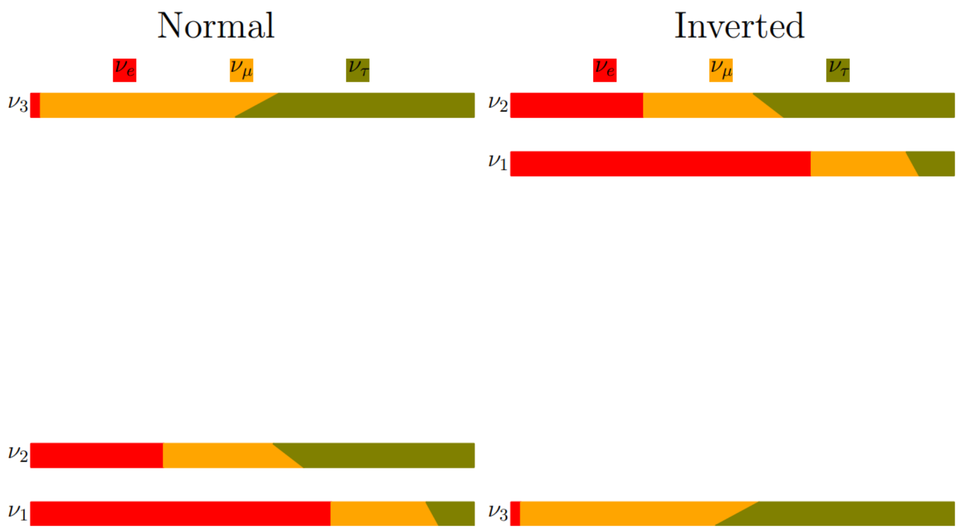


Atmospheric

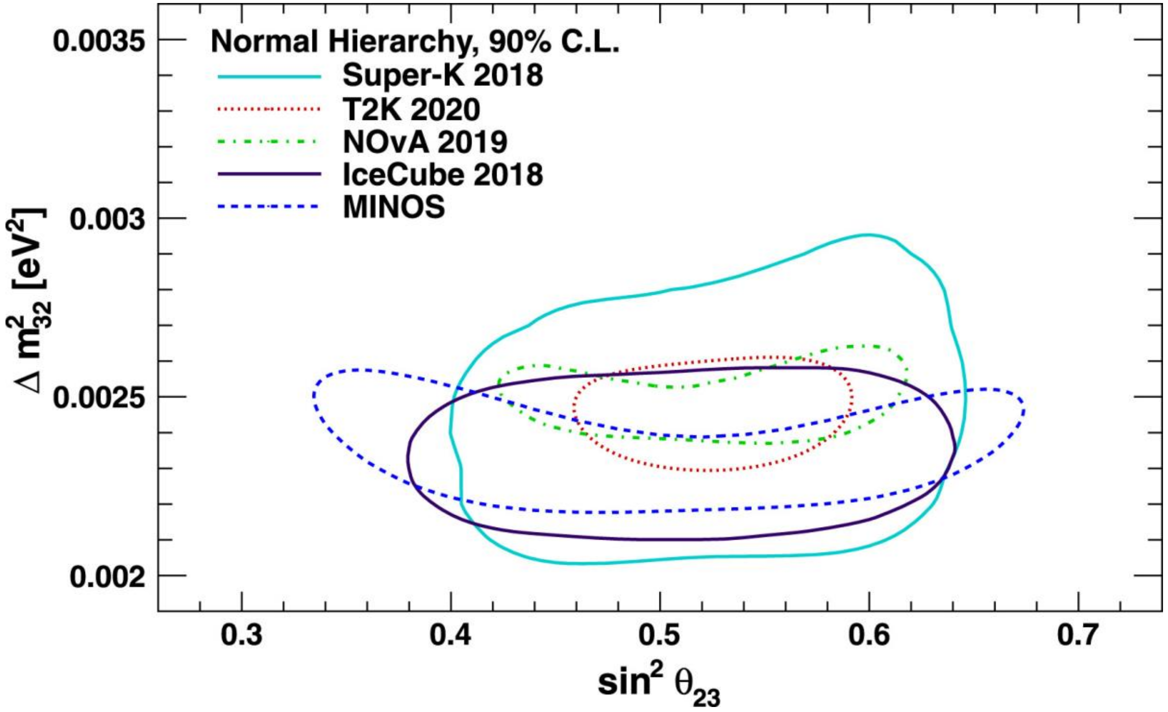
$\boldsymbol{\theta_{23}} \sim 45^\circ$ where $\tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}$

$\boldsymbol{\Delta m^2_{31}} \sim \pm 2.5 \times 10^{-3}\ \mathrm{eV}^2$

- General agreement among several ν_μ disappearance measurements indicates close to maximal ($\sim 45^\circ$)
- '*mass ordering problem*': sign of Δm^2_{31}?
- '*octant problem*': $\theta_{23} > 45^\circ$, $\theta_{23} < 45^\circ$, or $\theta_{23} = 45^\circ$



2111.07586

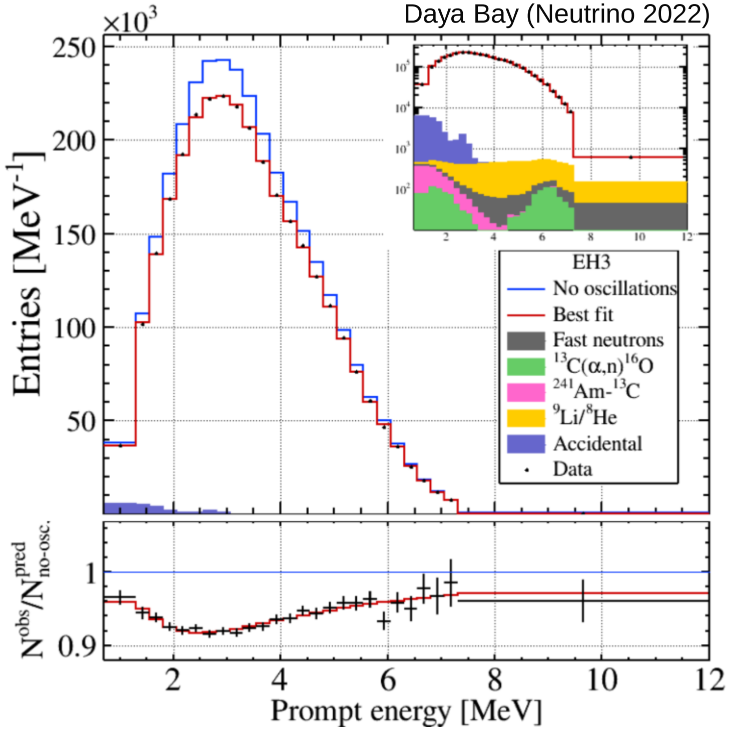


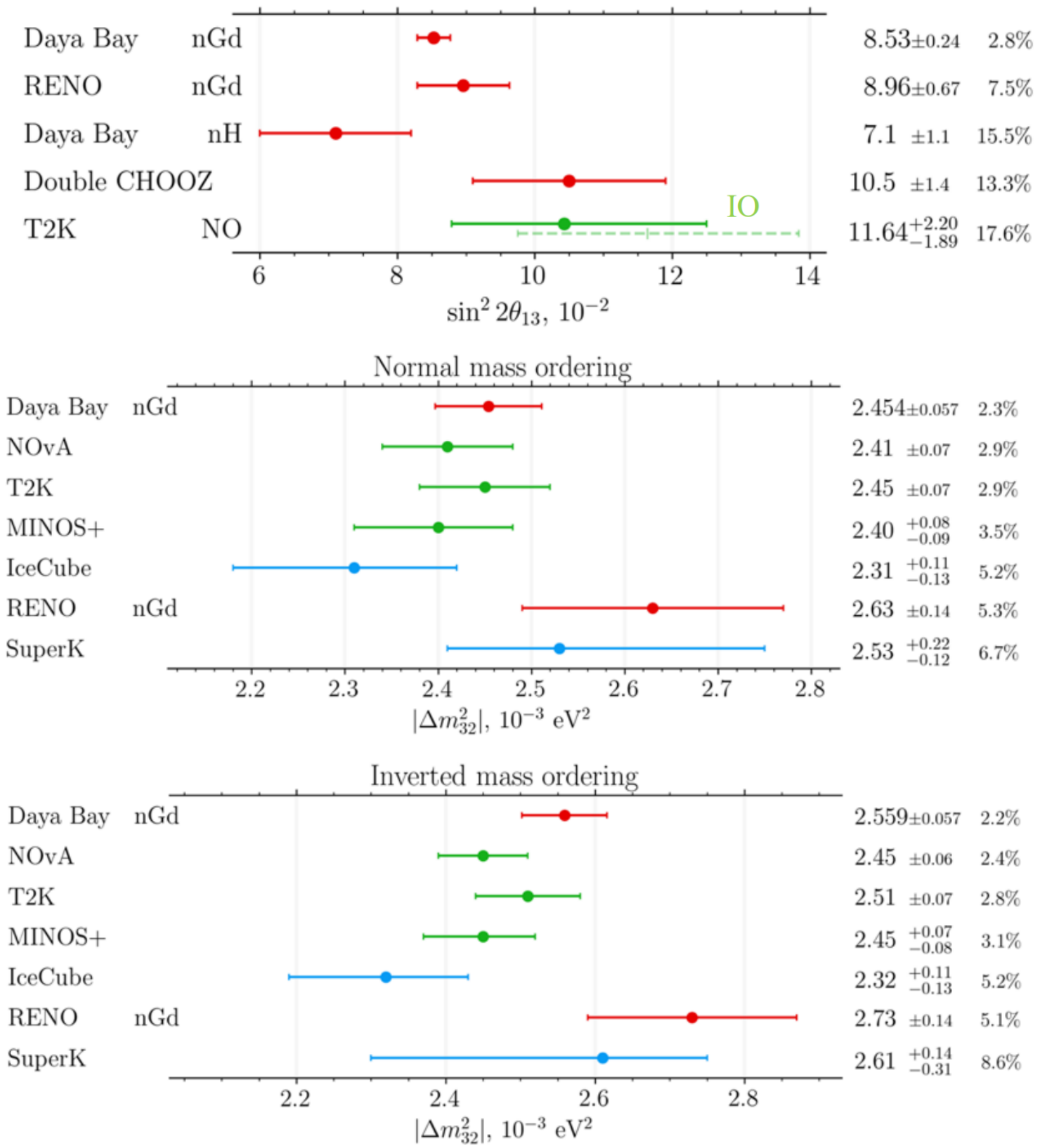
$\boldsymbol{\theta_{13}} \sim 8.5°$

where $U_{e3} \equiv sin\theta_{13}e^{-i\delta}$

Discovery of nonzero $\boldsymbol{\theta_{13}}$ makes possible the determination of $\boldsymbol{\delta}$

Daya Bay (Neutrino 2022)

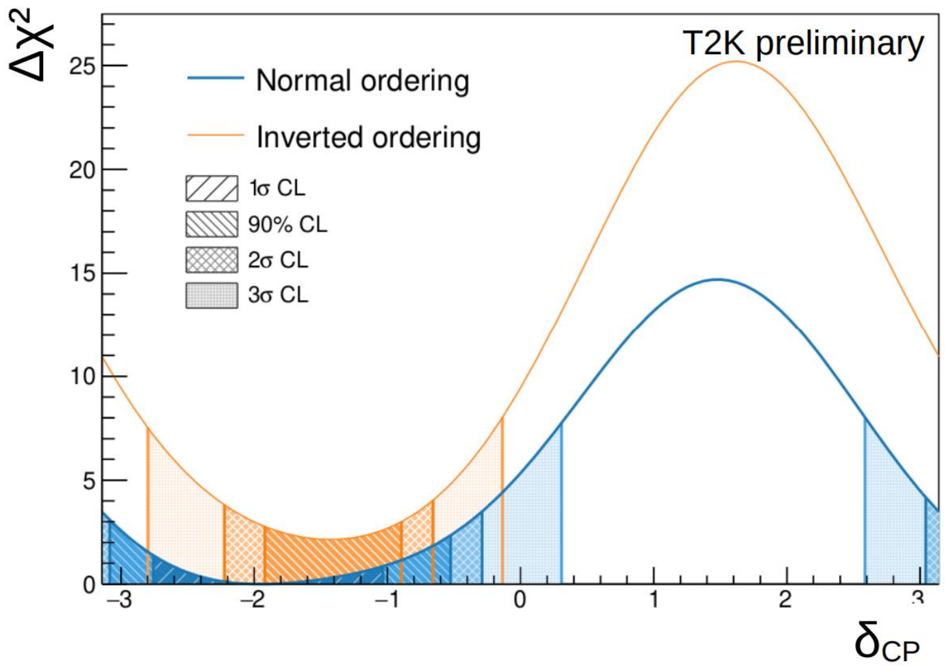




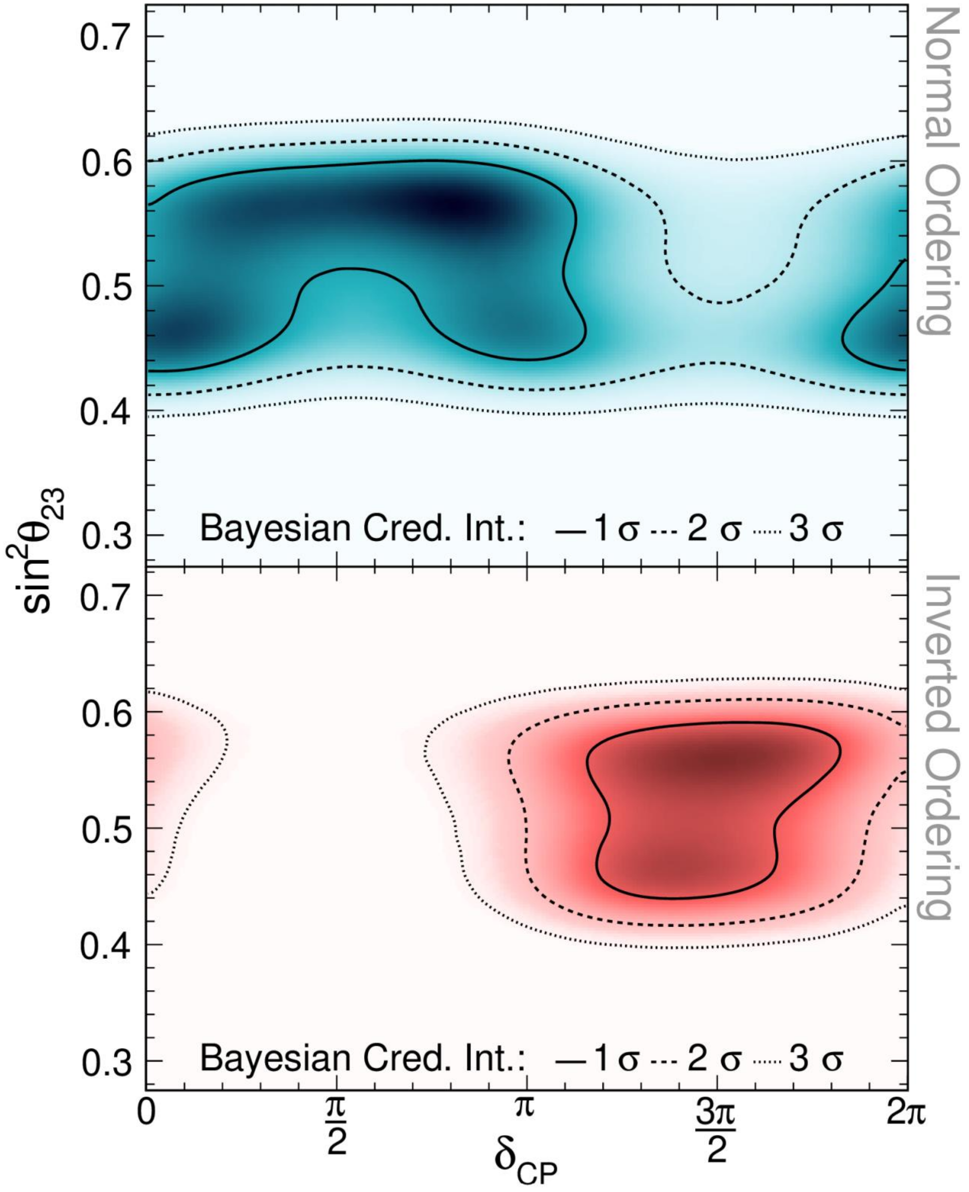
Daya Bay (Neutrino 2022)

δ

- Complex phase that governs the difference between ν and $\bar{\nu}$
- Dictates the amount of CP violation in the lepton mixing matrix
- *At present, largely undetermined*



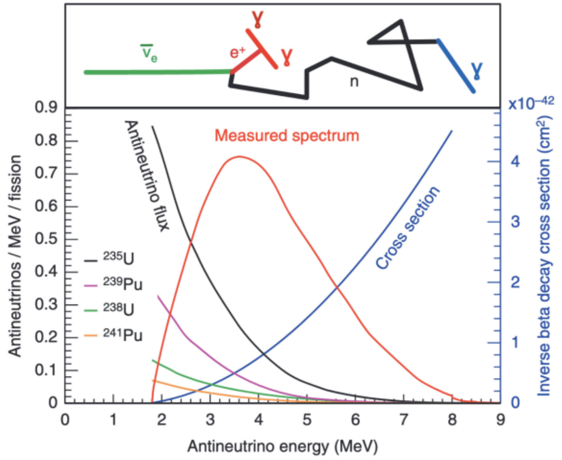
T2K (Neutrino 2022)

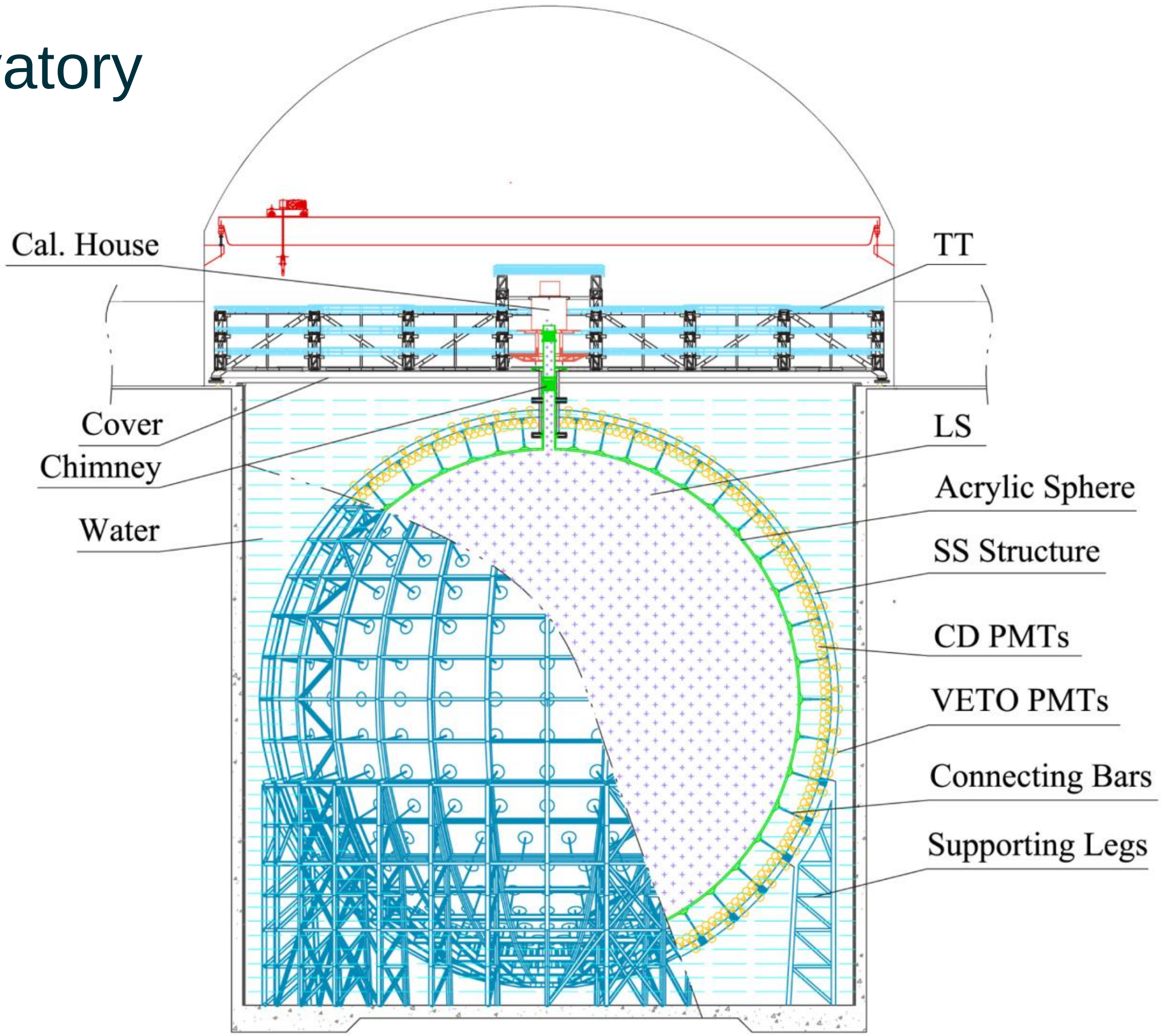


NOνA (Neutrino 2022)

JUNO
Jiangmen Underground Neutrino Observatory

- Reactor $\bar{\nu}_e$ disappearance at 53 km baseline from 2x ~20 GW reactor complexes
  - 10 kton liquid scintillator located 700-m underground
  - 75% photocathode coverage
    - 3% photodetector energy resolution at 1 MeV
- Detector construction expected to be complete at end of 2022 calendar year





BERKELEY LAB

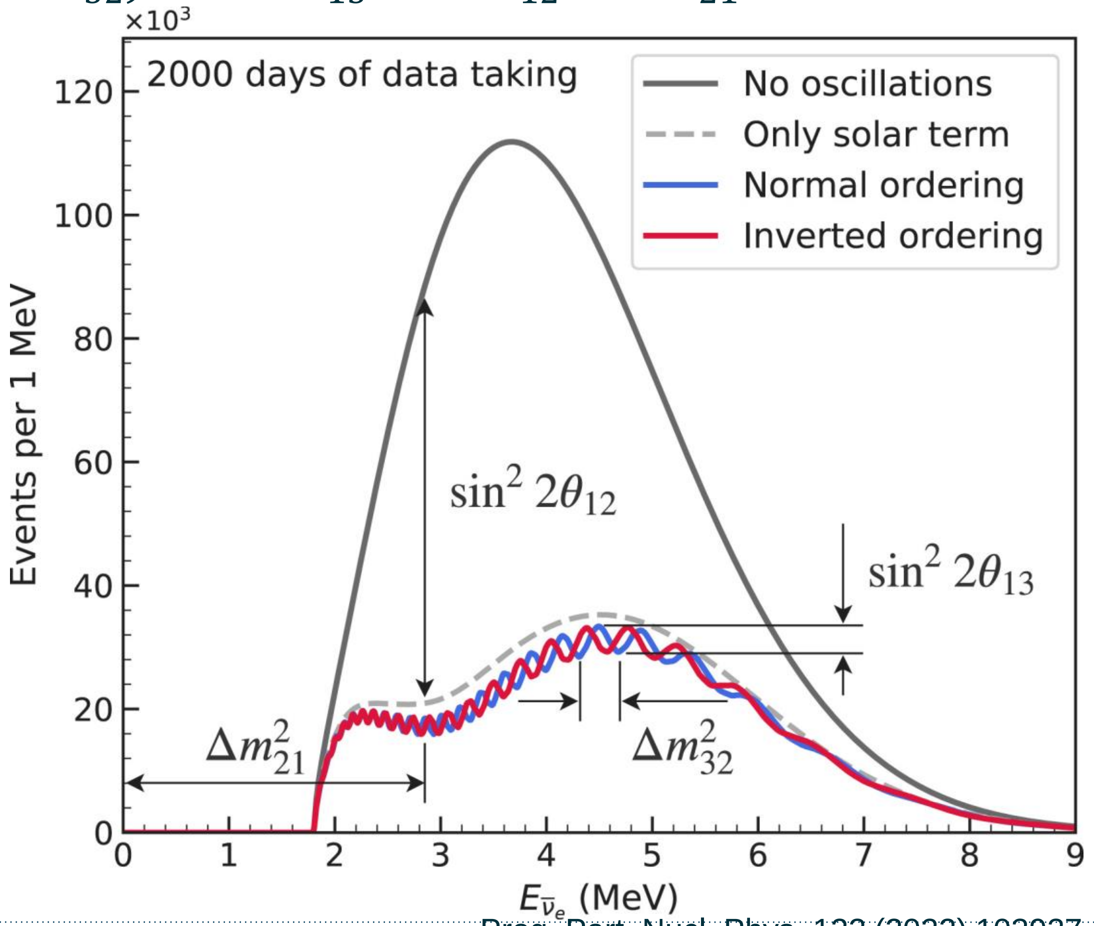
JUNO

Jiangmen Underground Neutrino Observatory

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Phi_{31} + \sin^2\theta_{12}\sin^2\Phi_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Phi_{21}$$

where $\Phi_{ji} = \frac{1.27\Delta m_{ij}^2 L}{E}$

- Sensitive to both Δm_{21}^2 and Δm_{32}^2
  - Competing Φ_{31} and Φ_{32} terms lend to differing spectra for normal versus inverted mass ordering
  - Project 6 years to determine mass hierarchy to 3σ
- High precision measurements on $\sin^2\theta_{12}$ and Δm_{21}^2



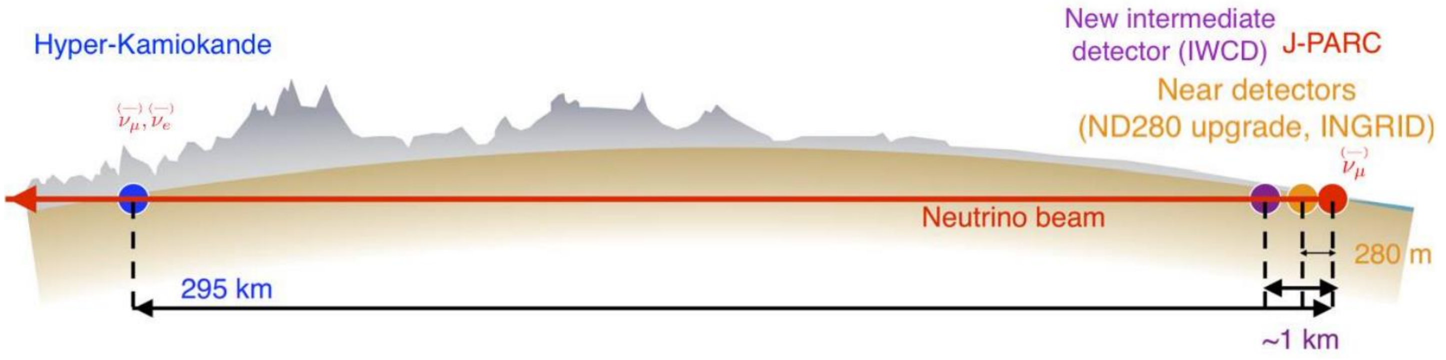
Prog. Part. Nucl. Phys. 123 (2022) 103927

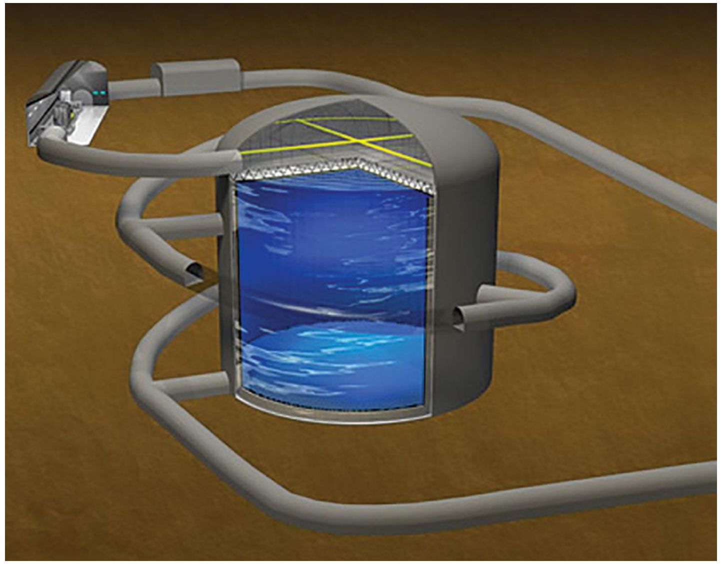
Hyper-Kamiokande

Leveraging existing JPARC/T2K infrastructure with upgrades to:

- 1.3 MW (~3x current) 0.6 GeV narrow band beam
- 188 kton fiducial volume (~7x Super-Kamiokande); 2027 projected start of data taking
- Upgraded near detector complex

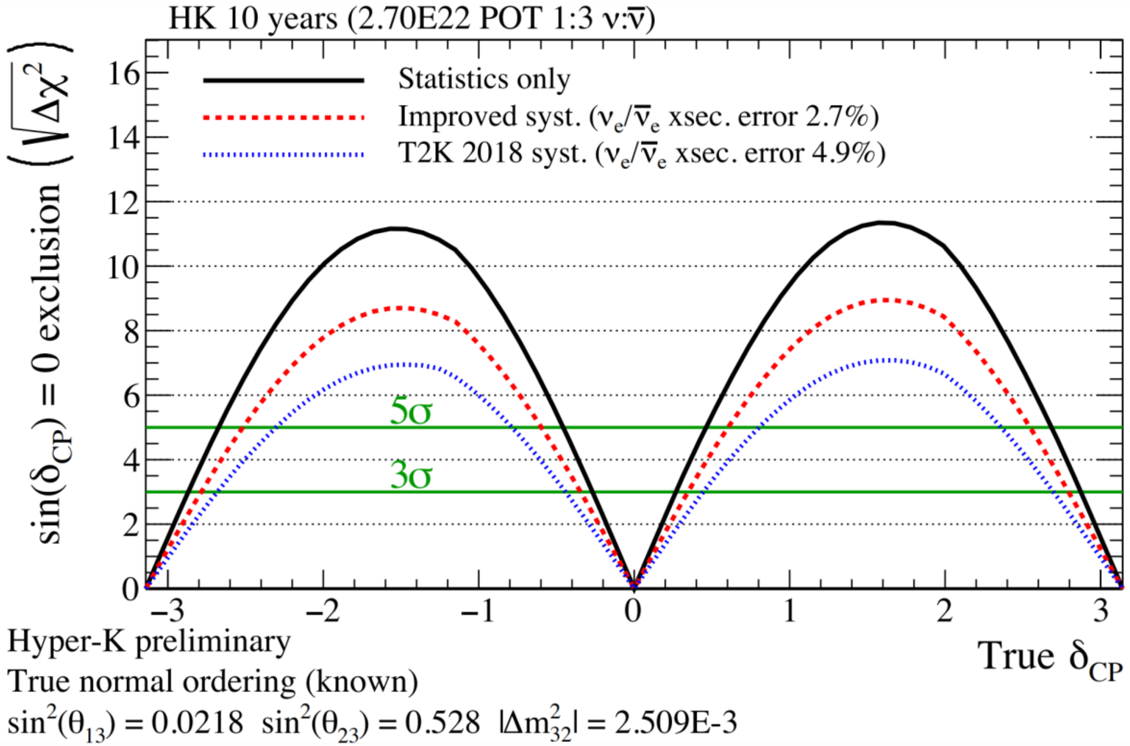
2027 projected start of data taking

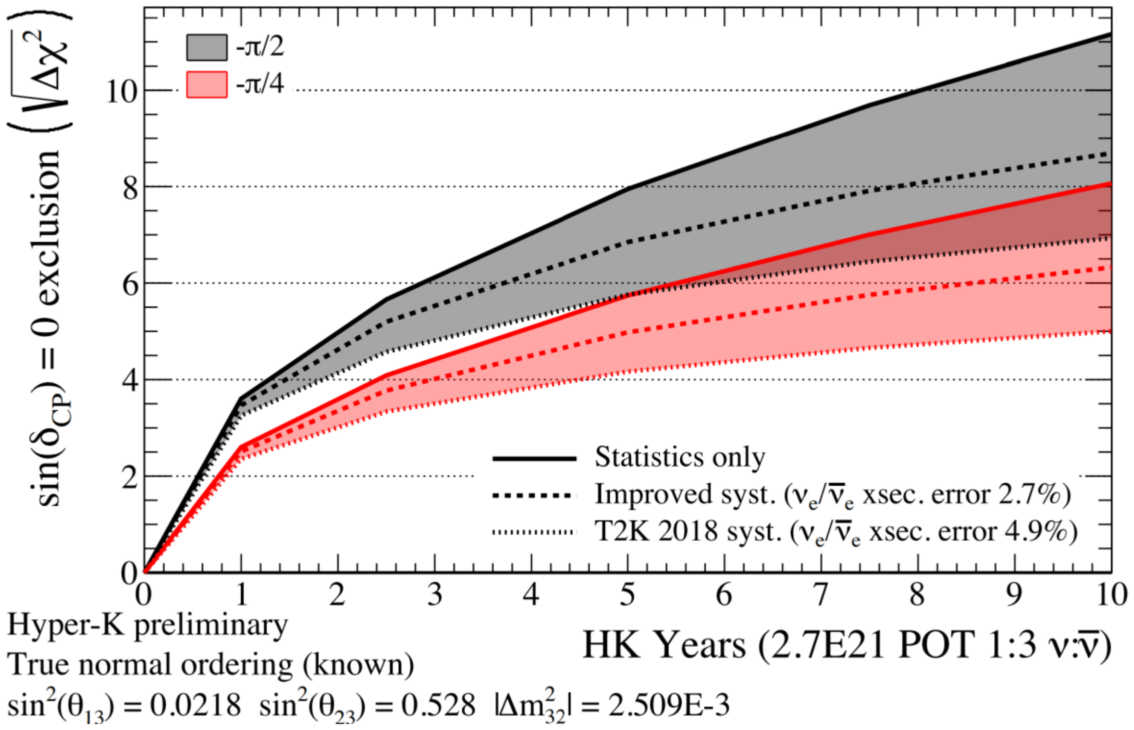




Hyper-Kamiokande

- Unable to disambiguate CPV and MO solely with beam data, although very high statistics with short baseline
- Strong constraint on δ





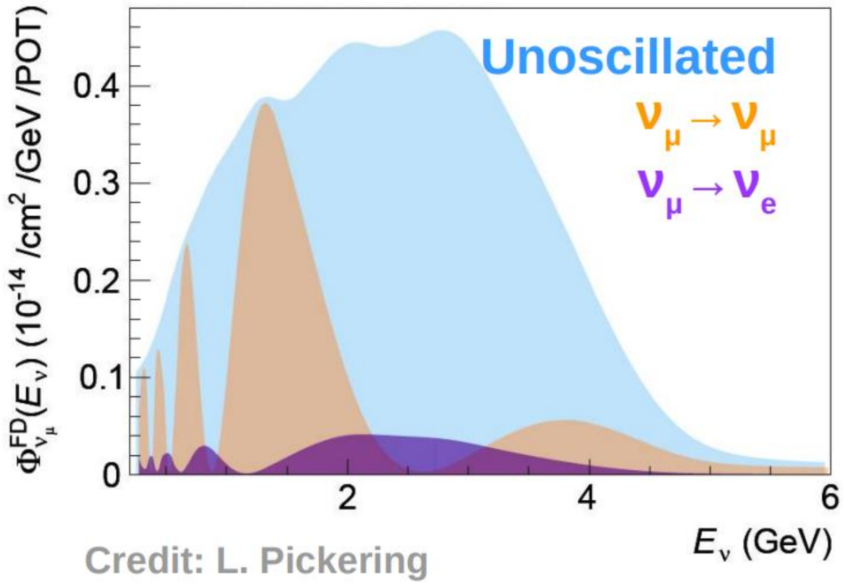
DUNE

Deep Underground Neutrino Experiment

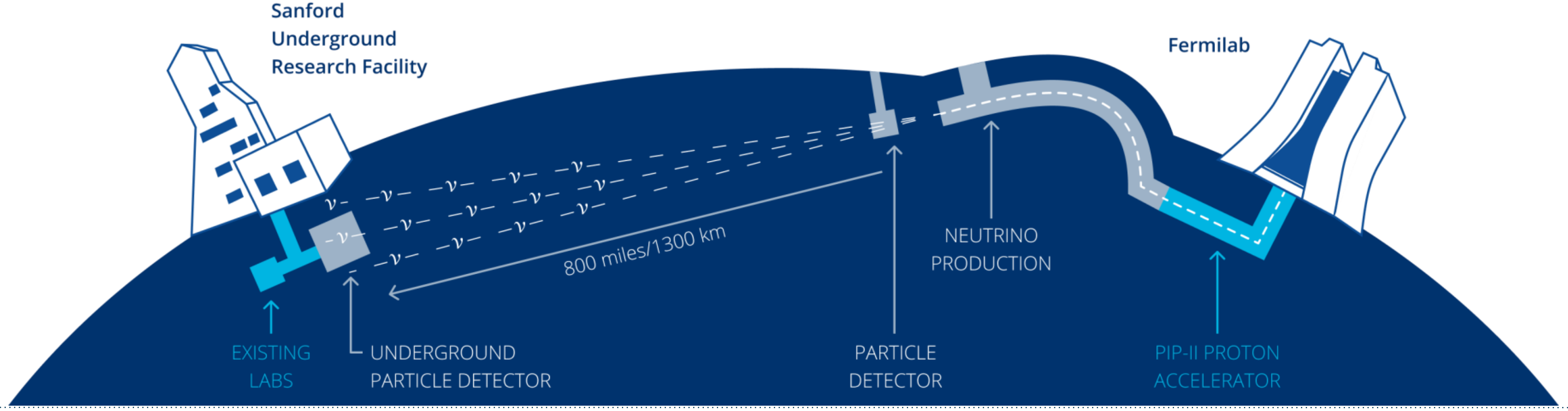
1285 km baseline with 2.5 GeV broadband beam and LAr target

Exploits the matter effect which increases as a function of baseline like $\pm\frac{2N_e}{N_e^{res}}$

Constrain all parameters with single experiment



Credit: L. Pickering



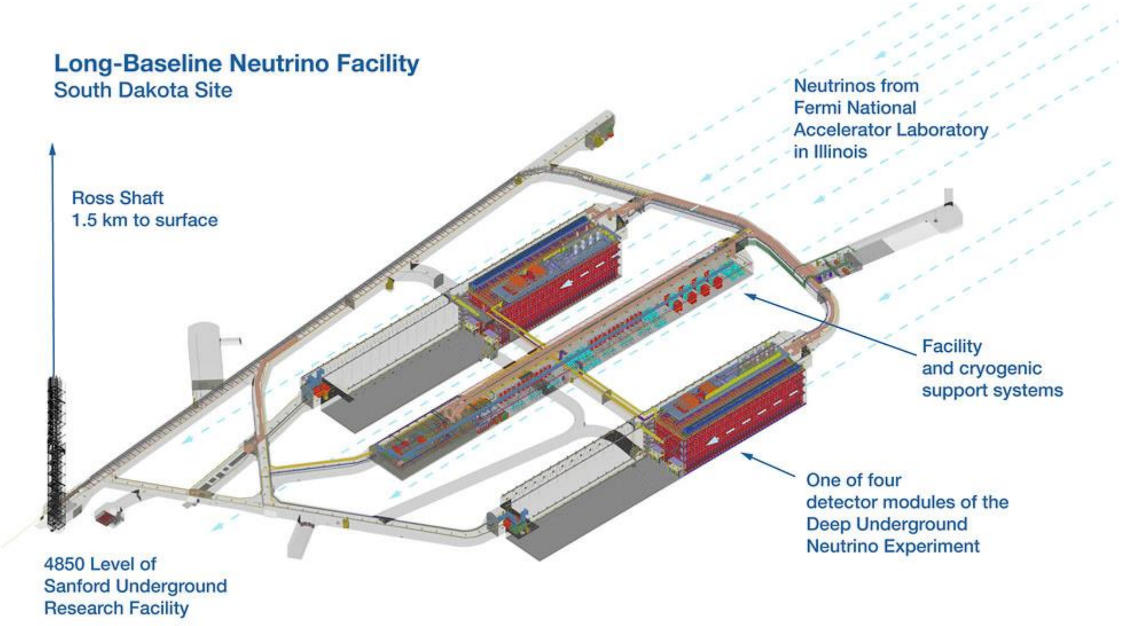
BERKELEY LAB

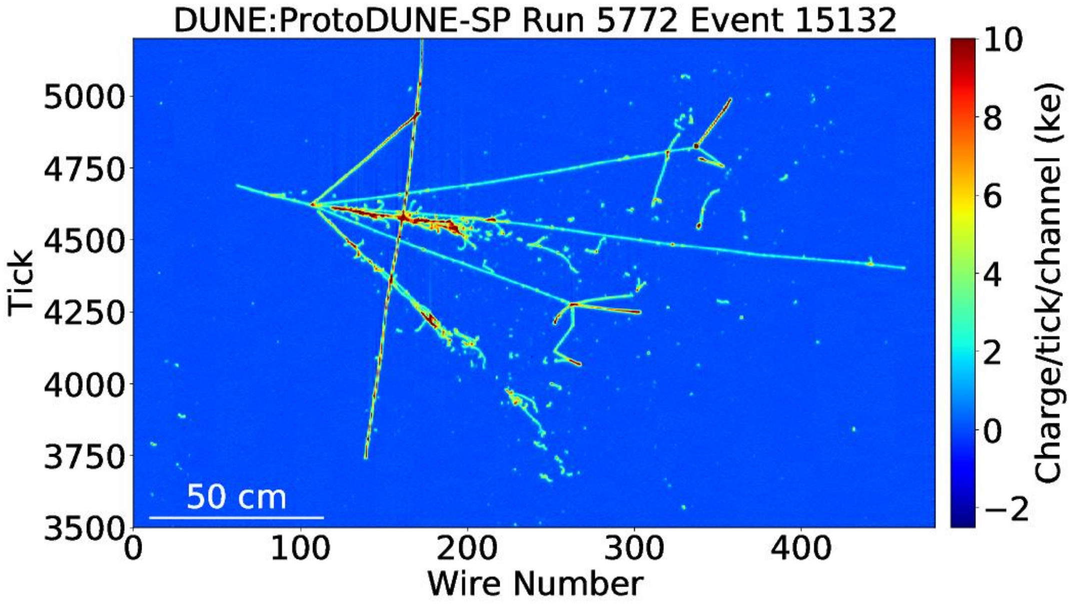
DUNE Far Detectors

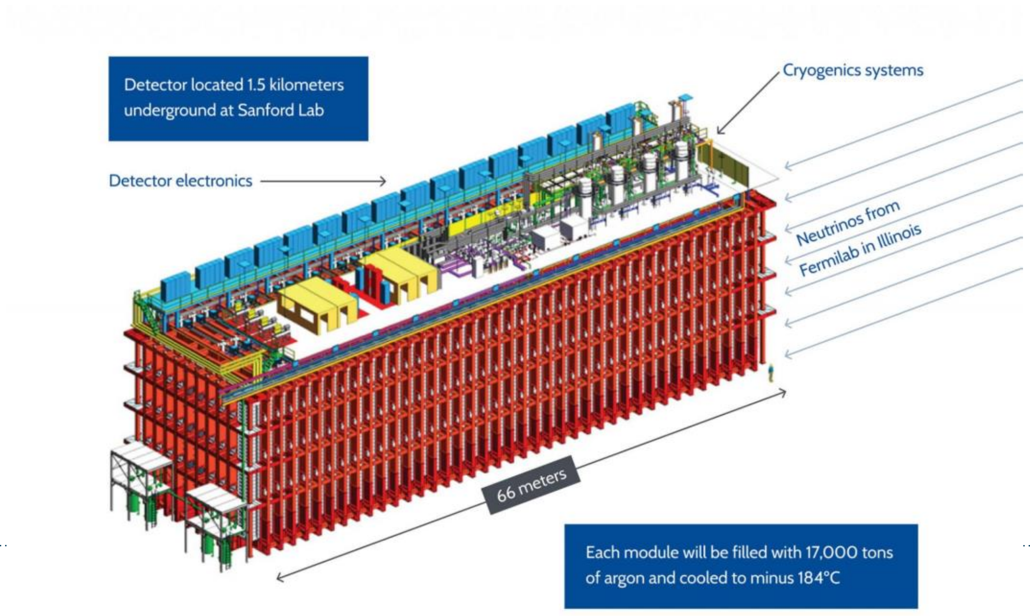
4x 17kton LArTPC ~1 mile underground

- High-fidelity calorimetric energy reconstruction from MeV-GeV
- Fine-tracking for particle ID

Cavern excavation in progress







BERKELEY LAB

DUNE Near Detector Complex

Three complementary

detector systems working

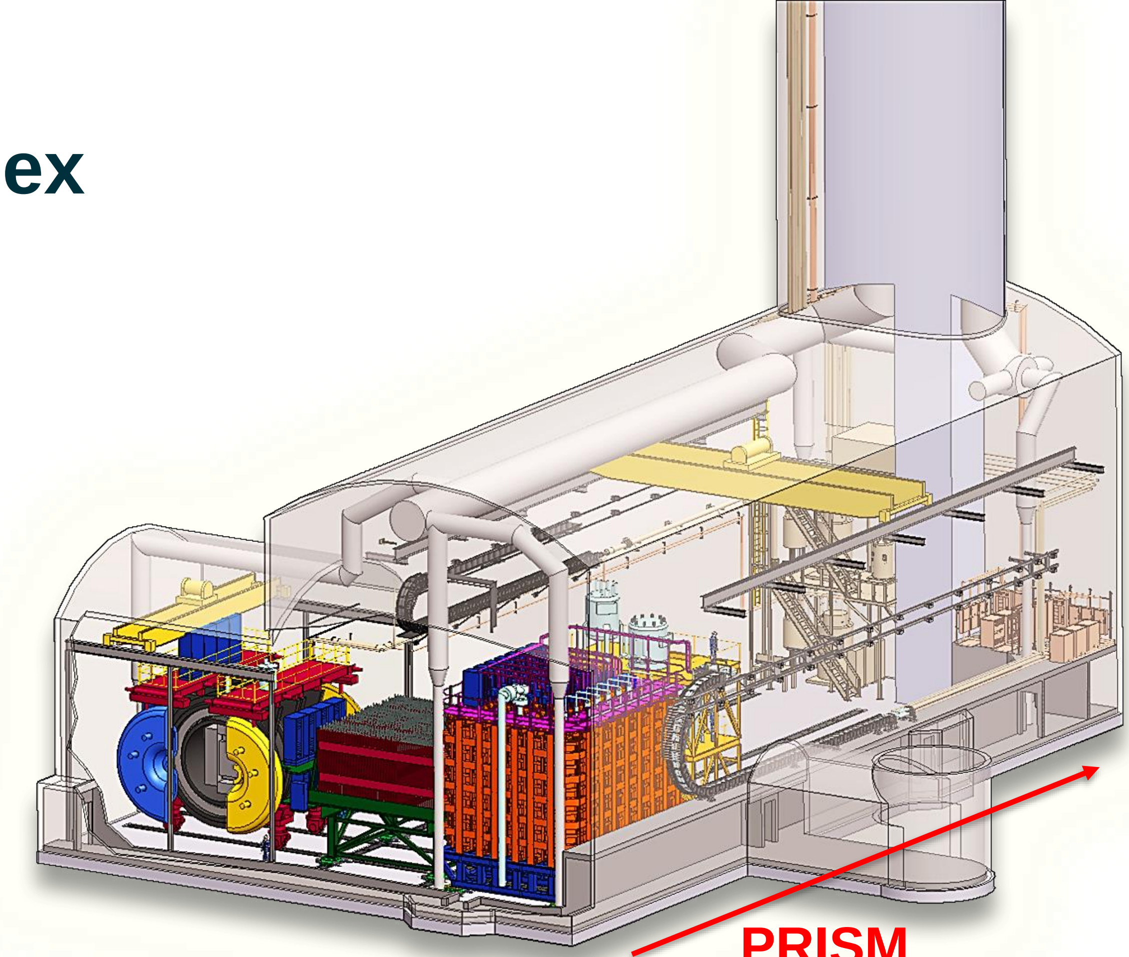
in concert to *constrain*

(1) neutrino flux,

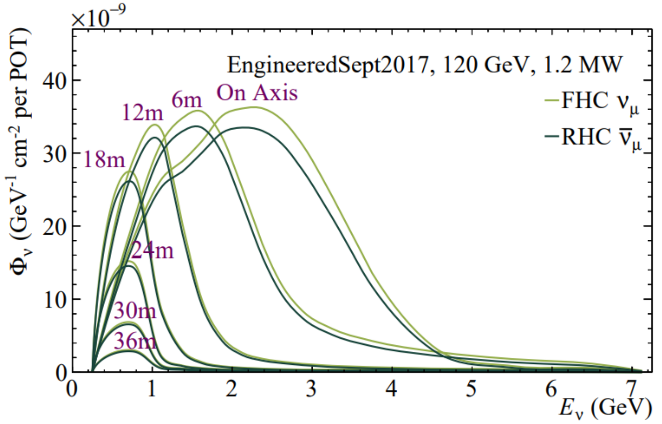
(2) interaction model,

(3) and detector response

to predict the observed neutrino spectrum at the far detector



Adapted from D. Dwyer



Far detector appearance signal:

$$\frac{dN^{far}_{\nu_e}}{dE_{rec}} = \int_{E_\nu} D^{far,inclus.}_{\nu_e-CC}(E_{rec};E_\nu)\ \sigma^{inclus.,Ar}_{\nu_e-CC}(E_\nu)\ P_{\mu e}(E_\nu)\ \Phi^{far}_{\nu_\mu}(E_\nu)\ |_{l=0}\ dE_\nu$$

Far/near difference constrained by detector model

Far/near difference constrained by theory

Far/near difference constrained by beam model and near data model

Near detector signal:

$$\frac{dN^{near}_{\nu_\mu-CC}}{dE_{rec}} = \int_{E_\nu} D^{near}_{\nu_\mu-CC,inclus.}(E_{rec};E_\nu)\ \sigma^{inclus.,Ar}_{\nu_\mu-CC}(E_\nu)\ \Phi^{near}_{\nu_\mu}(E_\nu)\ |_{l=near}\ dE_\nu$$

DUNE Near Detector Complex

Three complementary

detector systems working

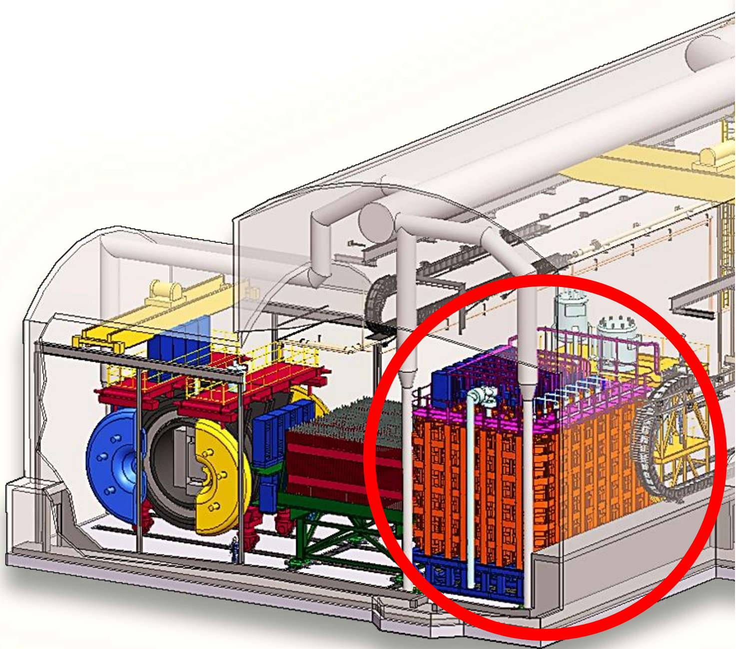
in concert to *constrain*

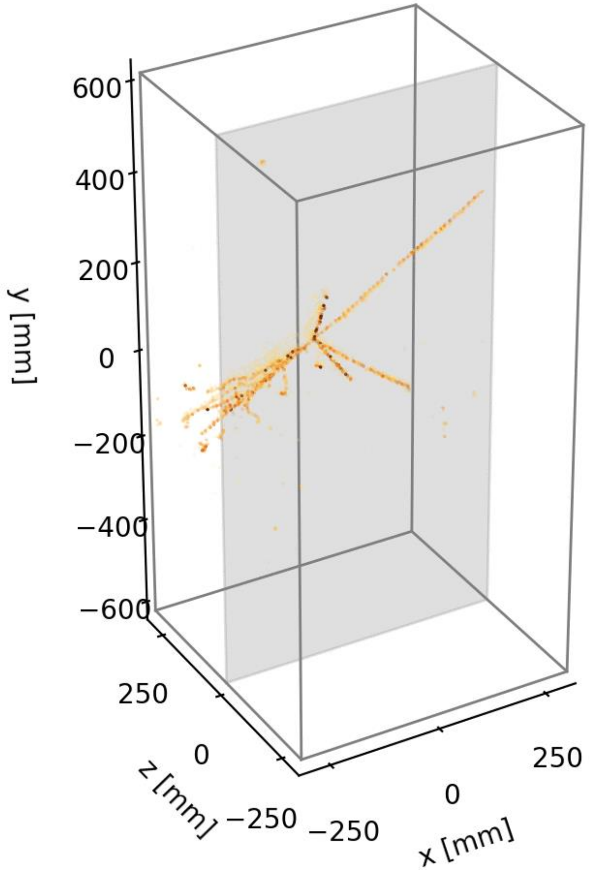
(1) neutrino flux,

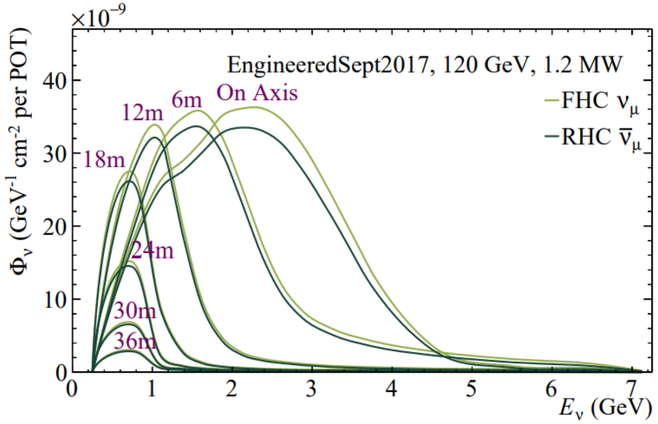
(2) interaction model,

(3) and detector response

to predict the observed neutrino spectrum at the far detector







Far detector appearance signal:

$$\frac{dN^{far}_{\nu_e}}{dE_{rec}} = \int_{E_\nu} D^{far,inclus.}_{\nu_e-CC}(E_{rec};E_\nu)\;\sigma^{inclus.,Ar}_{\nu_e-CC}(E_\nu)\;P_{\mu e}(E_\nu)\;\Phi^{far}_{\nu_\mu}(E_\nu)\;|_{l=0}\;dE_\nu$$

Far/near difference constrained by detector model

Far/near difference constrained by theory

Far/near difference constrained by beam model and near data model

Near detector signal:

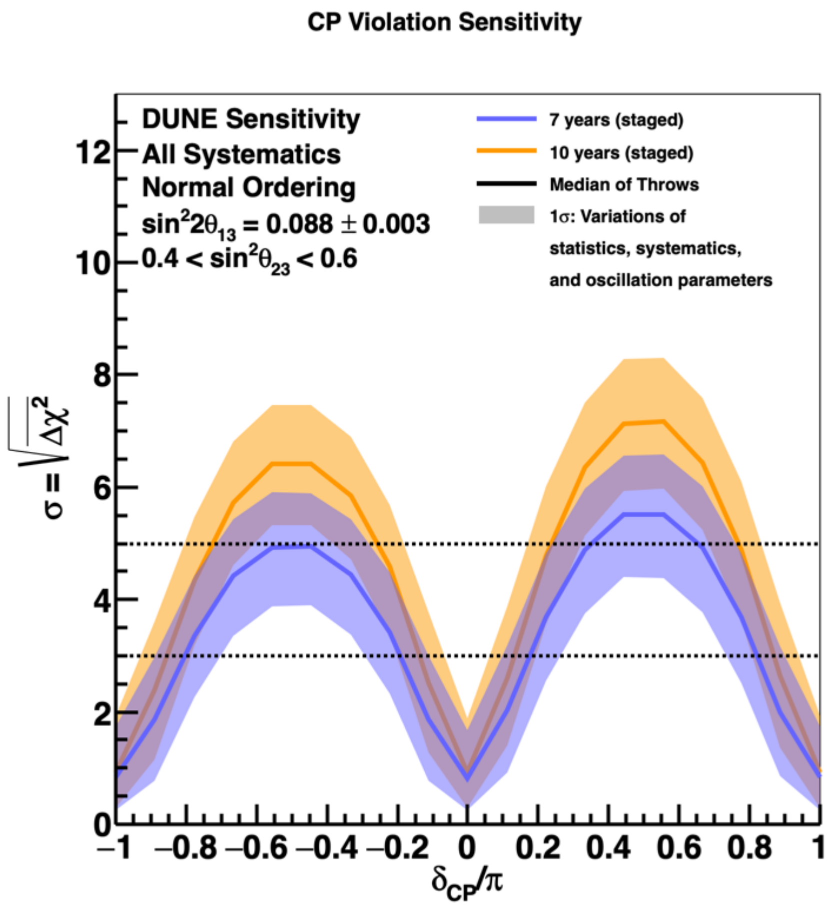
$$\frac{dN^{near}_{\nu_\mu-CC}}{dE_{rec}} = \int_{E_\nu} D^{near}_{\nu_\mu-CC,inclus.}(E_{rec};E_\nu)\;\sigma^{inclus.,Ar}_{\nu_\mu-CC}(E_\nu)\;\Phi^{near}_{\nu_\mu}(E_\nu)\;|_{l=near}\;dE_\nu$$

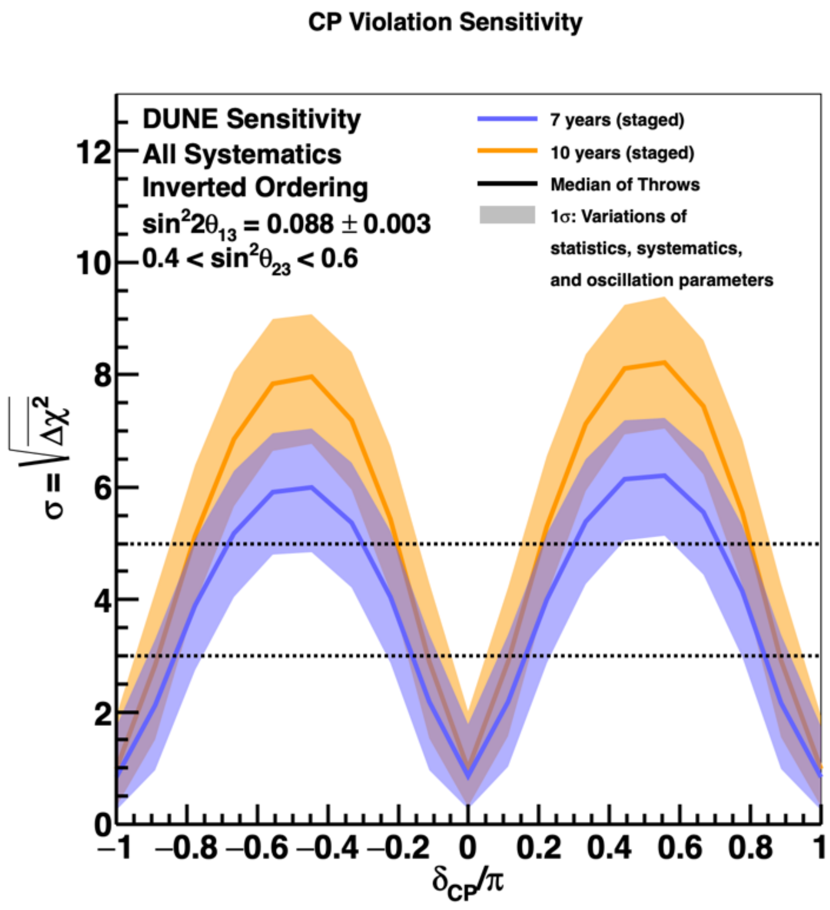
BERKELEY LAB

18

DUNE

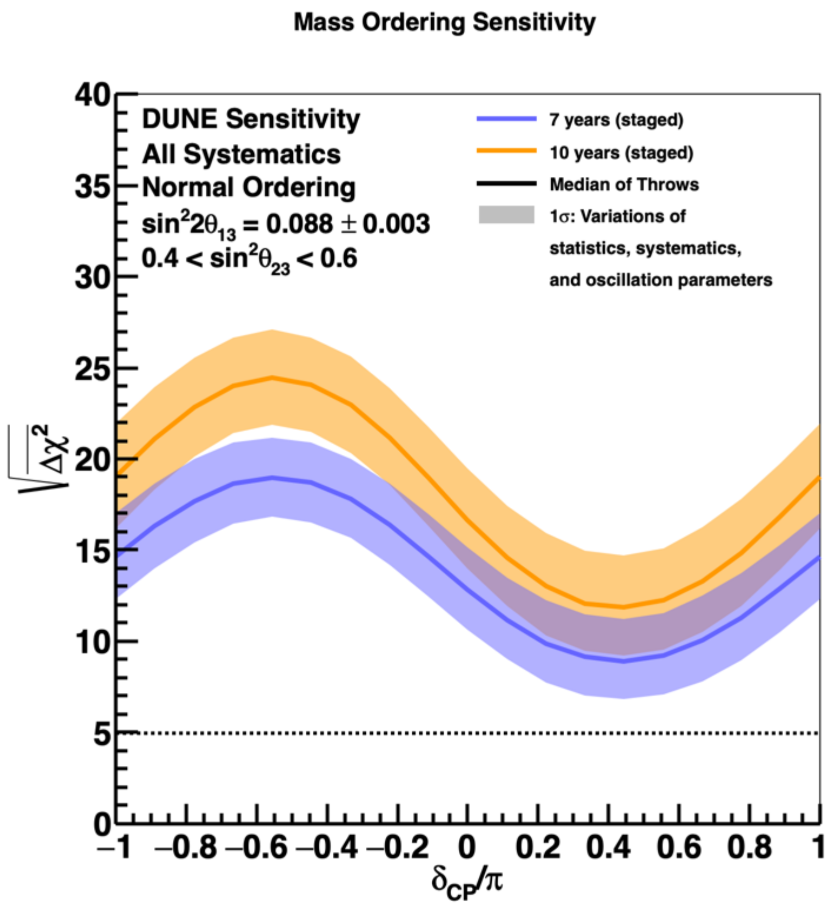
With no reliance on other experiments,
$> 5\sigma$ discovery potential for >50% of δ

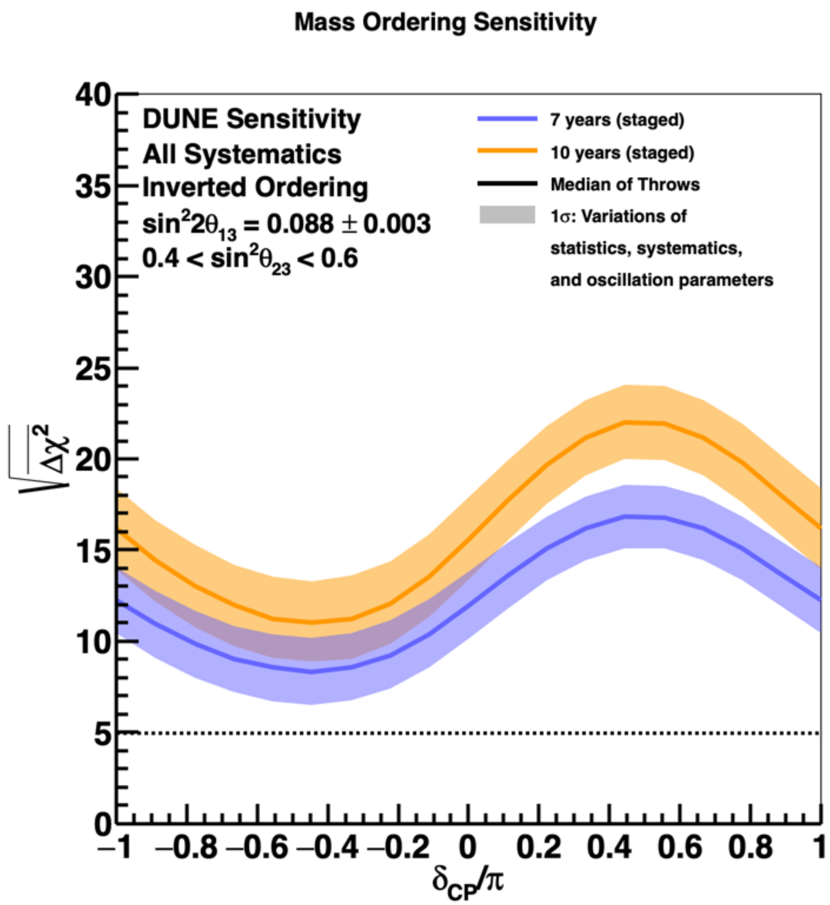




DUNE

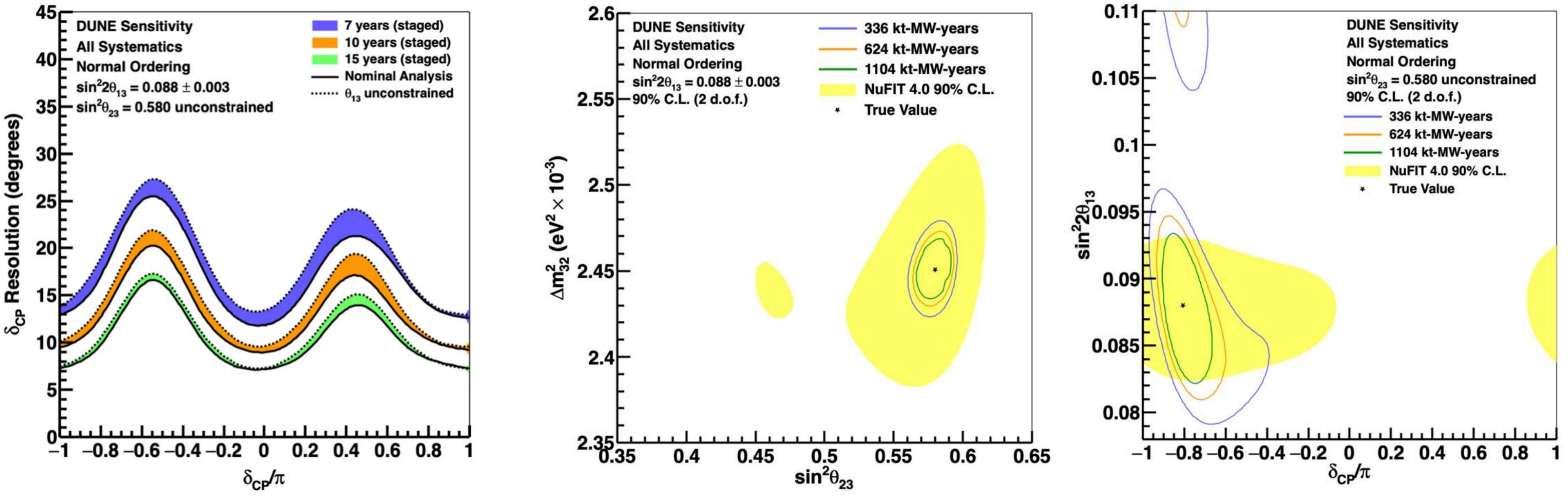
With no reliance on other experiments, definitive ability to resolve the neutrino mass ordering





DUNE

Approaching the era of precision measurements



Summary

BSM physics with neutrino oscillation phenomena

In the next 10-15 years, we expect precision measurements of all neutrino mixing parameters

- Mass ordering
- θ_{23} octant
- δ complex phase

Leveraging redundant measurements in different channels we can over constrain the parameter space
→ ultimate test of the 3 ν framework