LONG-BASELINE NEUTRINO EXPERIMENTS

PPC 2023 Daejeon, Korea

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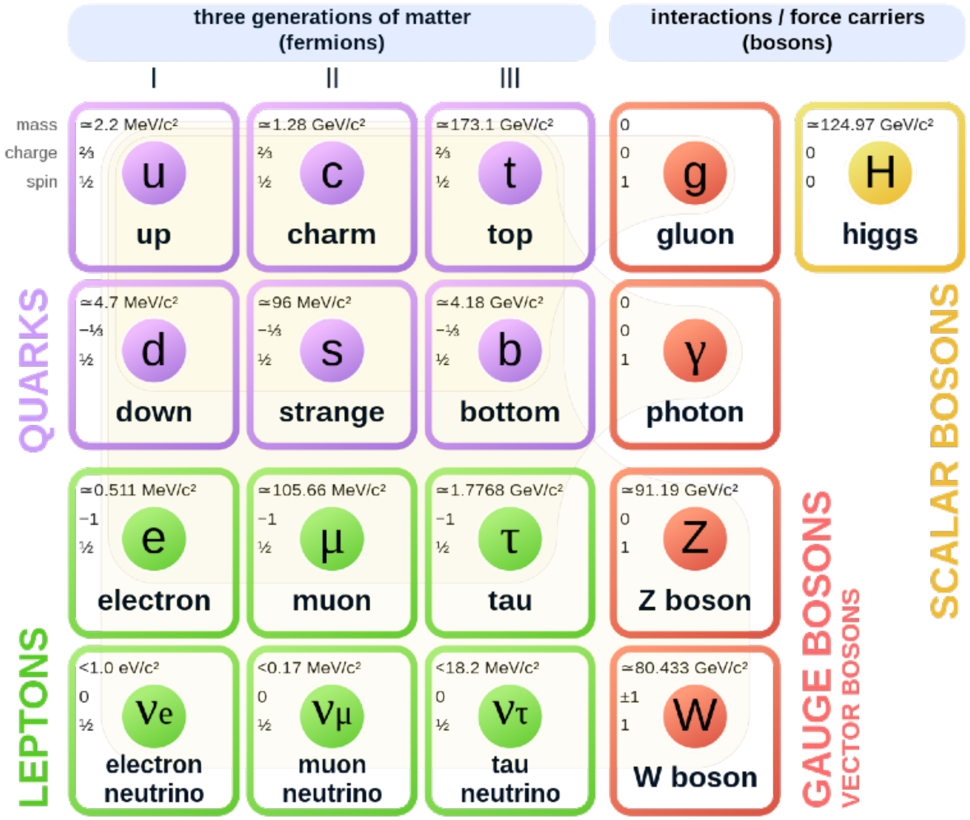
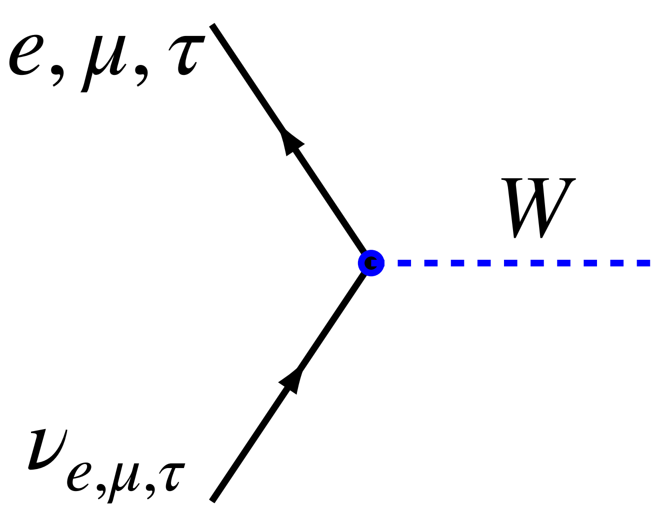
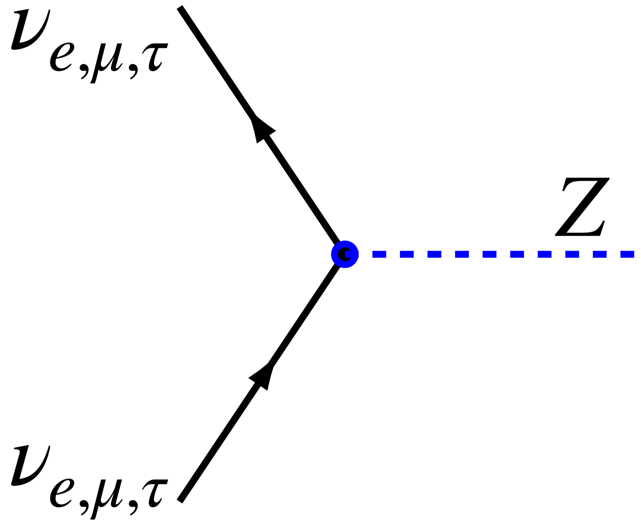
13 June 2023

THE NEUTRINO IN THE STANDARD MODEL







According to the Standard Model, neutrinos are:

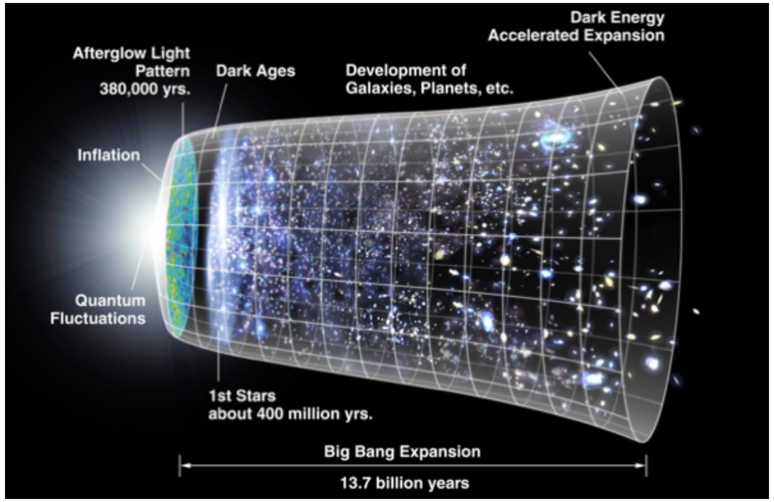
- Three fundamental spin 1/2 fermions (and their antiparticles)
- Neutral:
  - Electric charge (electromagnetism)
  - Color (strong interaction)
- Part of a "weak isospin doublet"
  - Paired to a charged fermion (e, μ, τ) through the weak interaction
- ***Have a tiny mass***

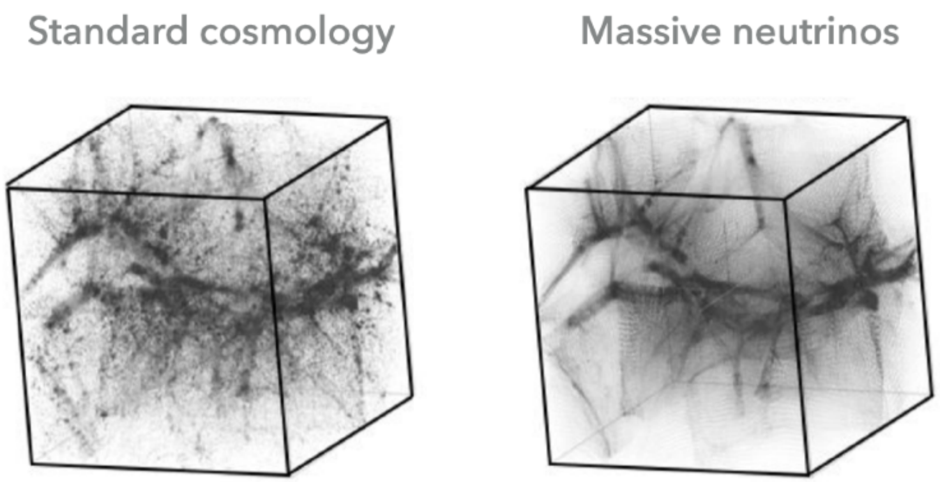
NEUTRINOS IN COSMOLOGY

The Particle Physics/Cosmology Ouroboros

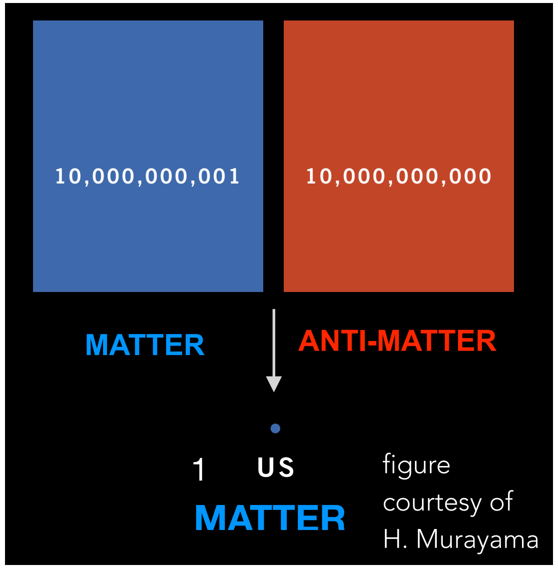
- Dynamics of the early universe are intimately connected to fundamental particles and their interactions
- As a
  - (long-lived) fundamental particle
  - Copiously produced in the early universe and in subsequent processes

It is natural that there is a very strong interplay between studying neutrino properties and their impact on cosmology

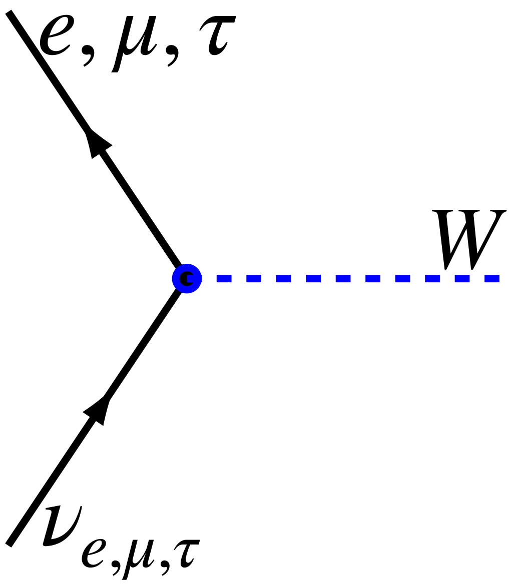


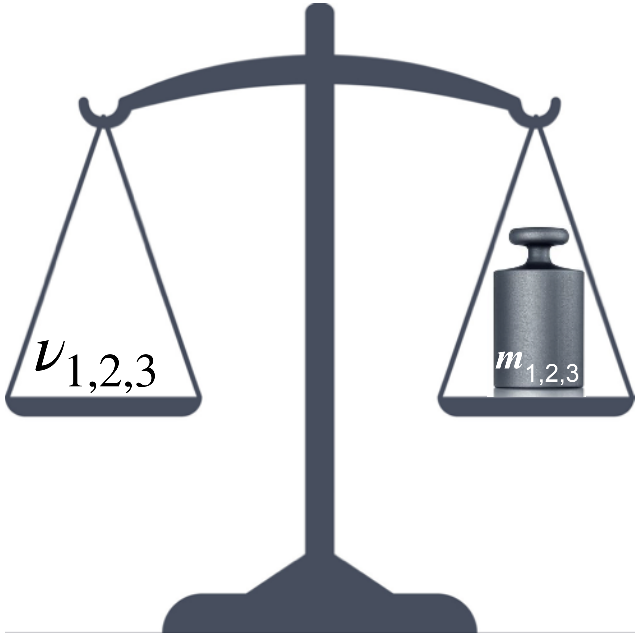


credits: Katrin Heitmann



NEUTRINO OSCILLATIONS

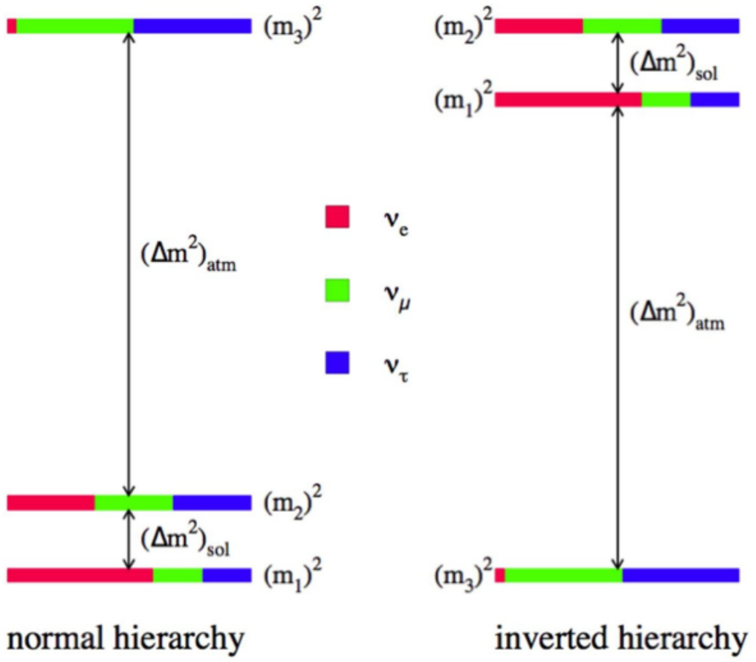




$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

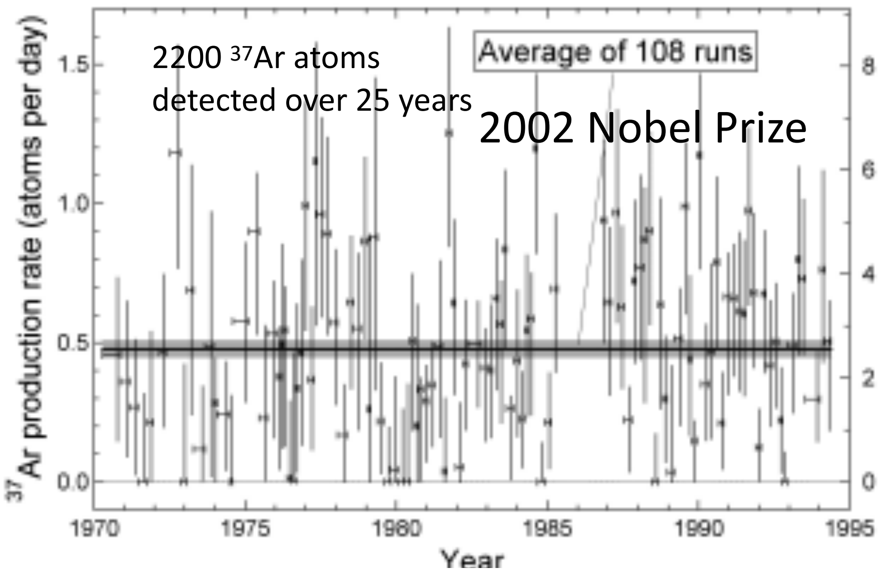
- Neutrinos are identified via their weak interaction properties
  - three weak eigenstates: $\nu_e \to e^-, \nu_\mu \to \mu^-, \nu_\tau \to \tau^-$
  - three “antineutrinos”: $\bar{\nu}_e \to e^+, \bar{\nu}_\mu \to \mu^+, \bar{\nu}_\tau \to \tau^+$
- Neutrinos can also be identified by their mass
  - three neutrino mass eigenstates $\nu_1 \to m_1, \nu_2 \to m_2, \nu_3 \to m_3$
- Flavor, mass states can “mix” via unitary transformation
  - **Allows precession of the flavor content of the neutrino with time**

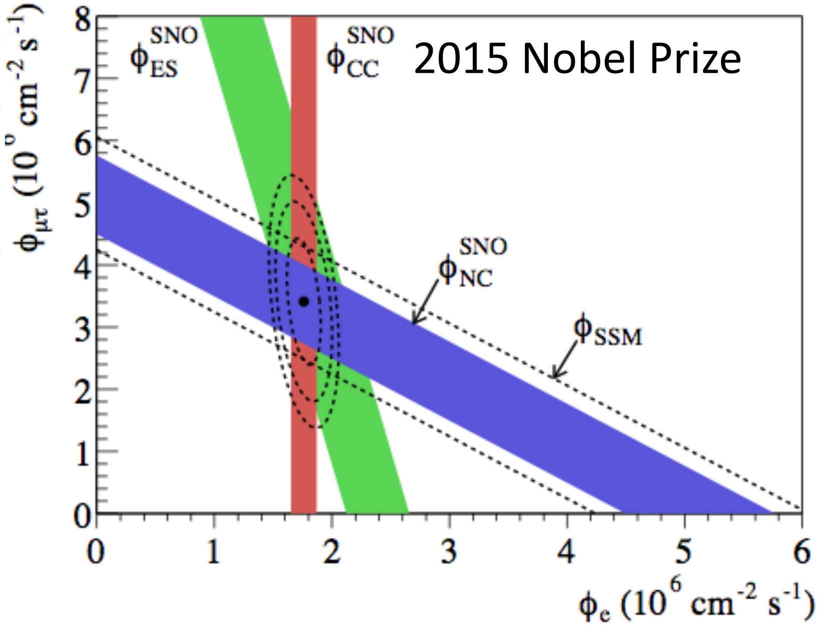


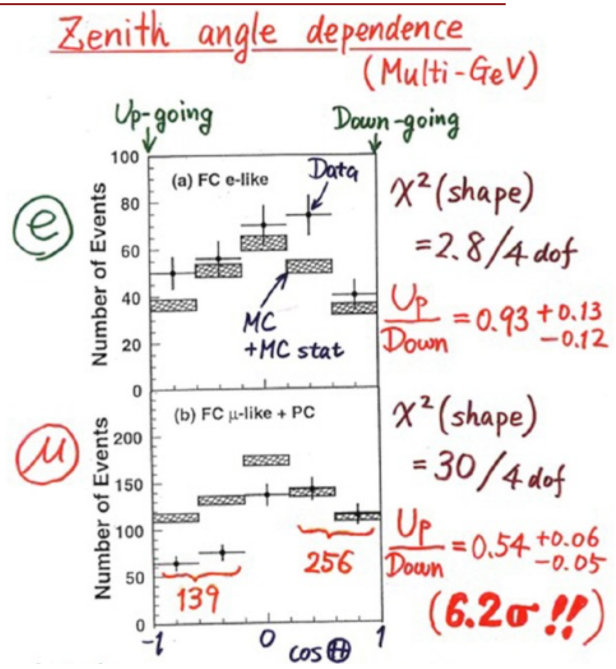
Credit: wikipedia.org

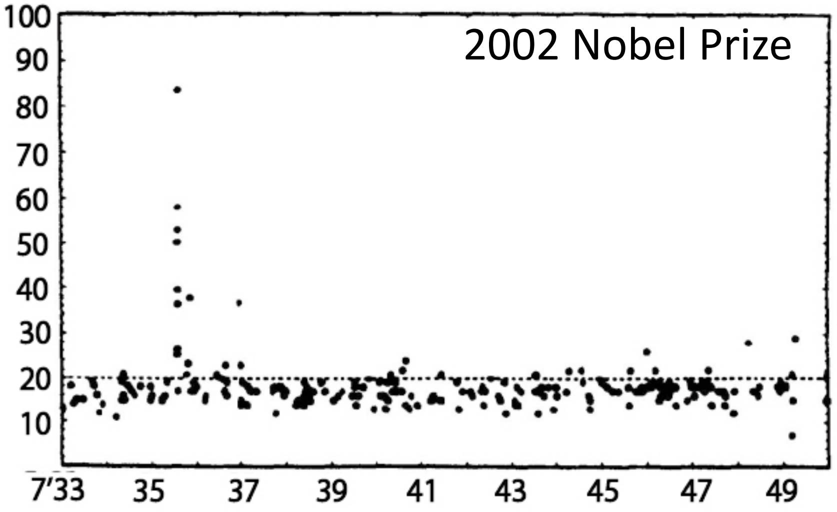
NEUTRINO ASTRONOMY/ASTROPHYSICS

2015 Nobel Prize



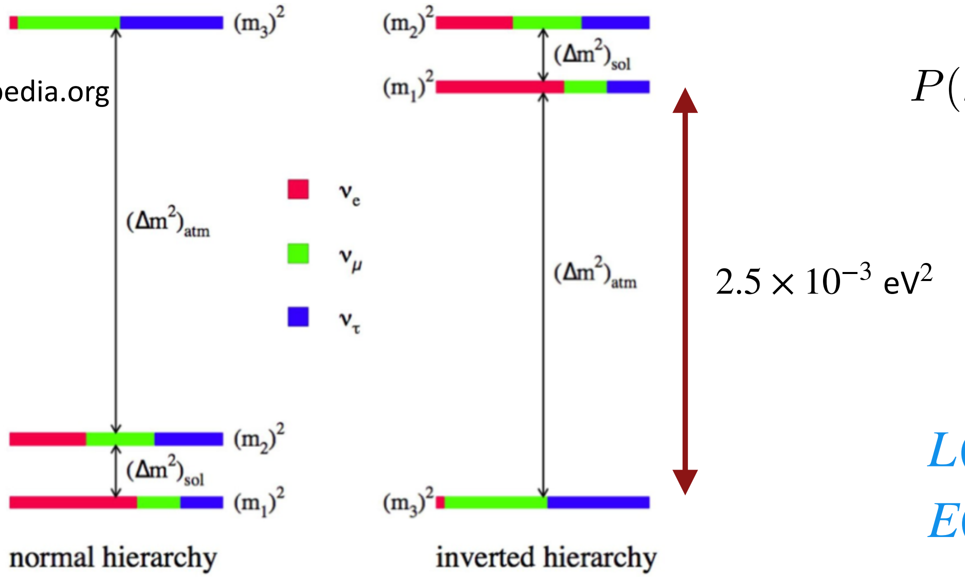






- Detection of solar neutrinos:
  - Deficit leads to inquiry into nature of the neutrino, solar model
  - Later confirmed as neutrino flavor change , solar model confirmed
  - Meanwhile neutrino flavor change also explains deficits in atmospheric ν_μ
- Detection of neutrinos from core-collapse supernova (1987a)
  - Start of a new field: implications still unfolding . . . . .
- Two-way window between universe and the neutrino
  - Story plays out over decades . . . . .

"LONG-BASELINE" NEUTRINO EXPERIMENTS



Credit: wikipedia.org

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta}$$

in vacuo

$$-4\sum_{i>j} \Re\left[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right] \sin^2\left[1.27\Delta m^2_{ij}L/E_\nu\right]$$

$$+2\sum_{i>j} \Im\left[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right] \sin\left[2.54\Delta m^2_{ij}L/E_\nu\right]$$

$\Delta m^2_{ij}(\text{eV}^2) = m_i^2 - m_j^2$

L(km) = distance between production/interaction ("baseline")

E(GeV) = energy of neutrino

- Neutrinos are **produced /interact** as **flavor eigenstates** but **propagate** as **mass (energy) eigenstates**
- Flavor precesses sinusoidally as a function of L/E (proper times)
  - Amplitudes: set by **mixing matrix U**
  - Frequency: L/E given by **difference in mass-squared eigenvalues** Δm^2_{ij}
- **"Long baseline":** observe neutrinos when kinematic phase is ~$\pi/2$ for $\Delta m^2_{atm} \sim 2.5 \times 10^{-3}$ eV^2
  - $L/E \sim 500$ km/GeV $\to L \sim \mathcal{O}(10^{2-3})$ km for ~1 GeV neutrinos
  - Observations at shorter baselines are probing non-standard oscillations (next talks)

PARAMETERS AND PHENOMENOLOGY

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

- Assuming unitarity, U is parametrized by
  - 3 "mixing angles" $(\theta_{12}, \theta_{13}, \theta_{23})$
  - complex phase (δ)

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \rightarrow \begin{matrix} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \begin{matrix} \nu_1 & \nu_2 & \nu_3 \\ \left[\begin{matrix} c_{12}c_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} \end{matrix} \right. & \begin{matrix} s_{12}c_{13} \\ c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} \\ -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} \end{matrix} & \left. \begin{matrix} s_{13}e^{-i\delta} \\ s_{23}c_{13} \\ c_{23}c_{13} \end{matrix} \right] \end{matrix}$$

$$\times \operatorname{diag}(e^{i\alpha_1/2},\ e^{i\alpha_2/2},\ 1)$$ ← doesn't impact oscillations

- $P(\nu_\mu \rightarrow \nu_\mu)$
  - Amplitude: $\sin^2 2\theta_{23}$
  - Frequency measures Δm^2_{atm}
  - $P(\nu_\mu \rightarrow \nu_\mu)$ vs. $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ tests CPT symmetry

$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}) \times \sin^2(1.27\Delta m^2_{32} L/E)$$

- $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - Equivalently impacted by $\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$ (note "octant")
  - "Oppositely" impacted by:
    - Mass ordering via matter effects: sign of x, Δm^2_{32}
    - Complex phase: δ → CP violation

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) \sim\ & \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\ & -\alpha \sin\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\ & +\alpha\cos\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\ & +\mathcal{O}(\alpha^2) \end{aligned}$$

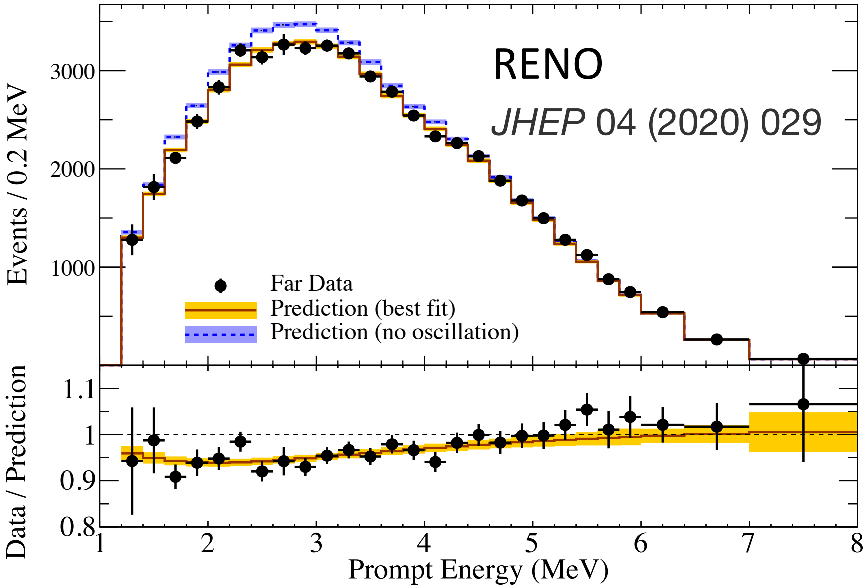
$$\alpha = \left| \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x = \pm \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m^2_{31}}$$

- $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$
  - Measures $\sin^2 2\theta_{13}$ and Δm^2_{31}

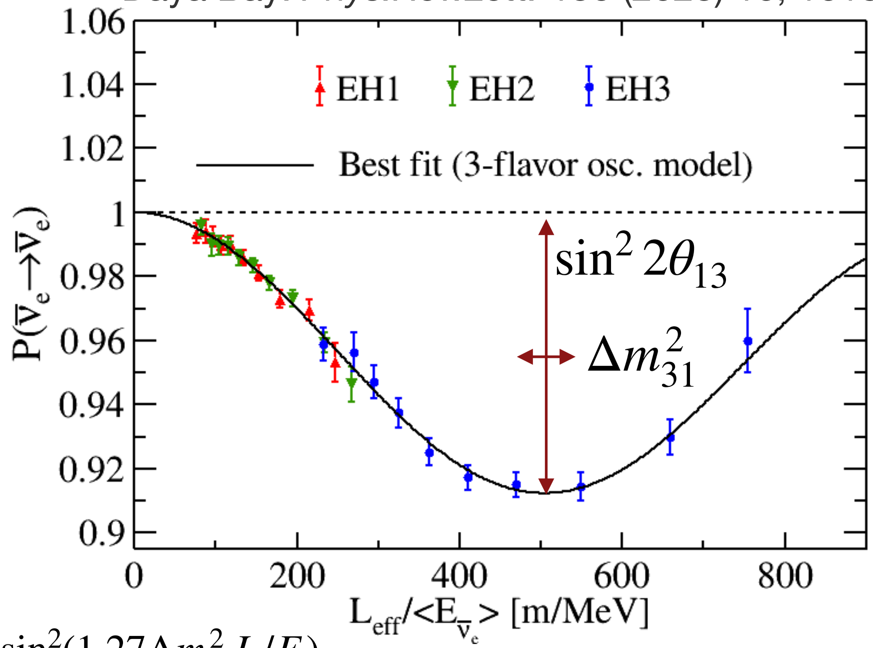
$$P(\nu_e \rightarrow \nu_e) \sim 1 - \sin^2 2\theta_{13}\ \sin^2(1.27\Delta m^2_{31} L/E) - \sin^2 2\theta_{12}\ \sin^2(1.27\Delta m^2_{21} L/E)$$

θ_{13}: DOUBLE-CHOOZ, RENO, DAYA BAY

- β decay from fission products produce O(MeV) antineutrinos
  - $n \rightarrow p + e^{-} + \bar{\nu}_e$
  - ~GW reactors produce O(10^{20}) $\bar{\nu}_e$/sec with O(MeV) energy
- Detectors ~1 km from reactor observe oscillations driven by Δm^2_{atm} with L/E ~ 0.5 km/MeV



Daya Bay: *Phys.Rev.Lett.* 130 (2023) 16, 161802



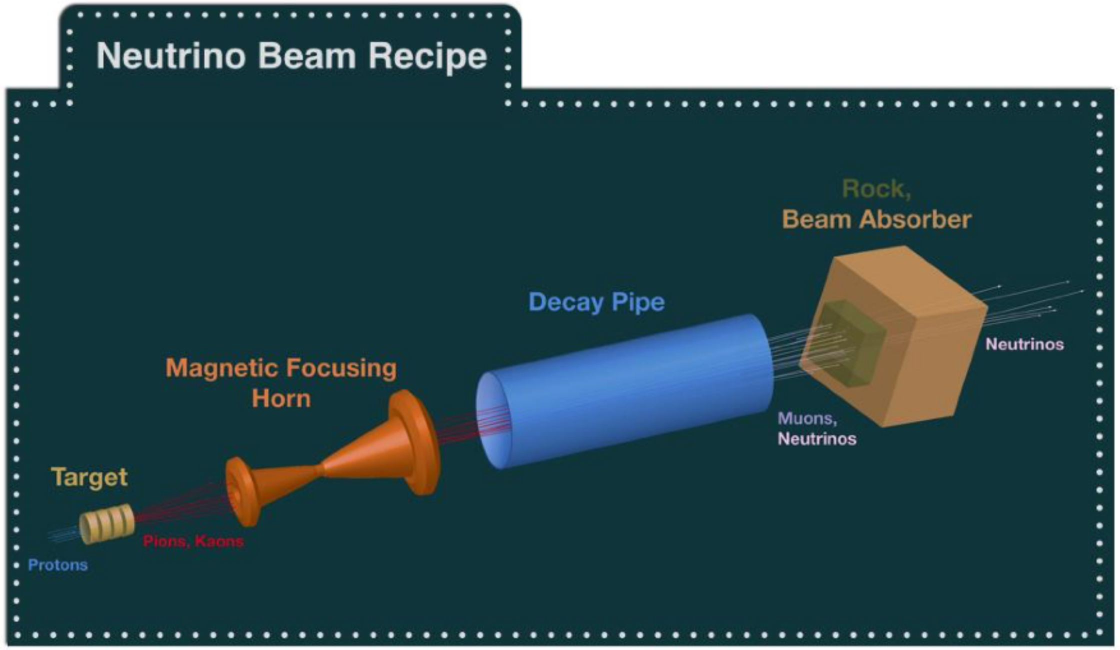
$$P(\nu_e \rightarrow \nu_e) \sim 1 - \sin^2 2\theta_{13}\ \sin^2(1.27\Delta m^2_{31} L/E)$$

- $\sin^2 2\theta_{13} = 0.0851 \pm 0.024$
- For normal ordering:
  - $\Delta m^2_{32} = \quad (2.466 \pm 0.060) \times 10^{-3}$ eV^2
- For inverted ordering
  - $\Delta m^2_{32} = -(2.571 \pm 0.060) \times 10^{-3}$ eV^2

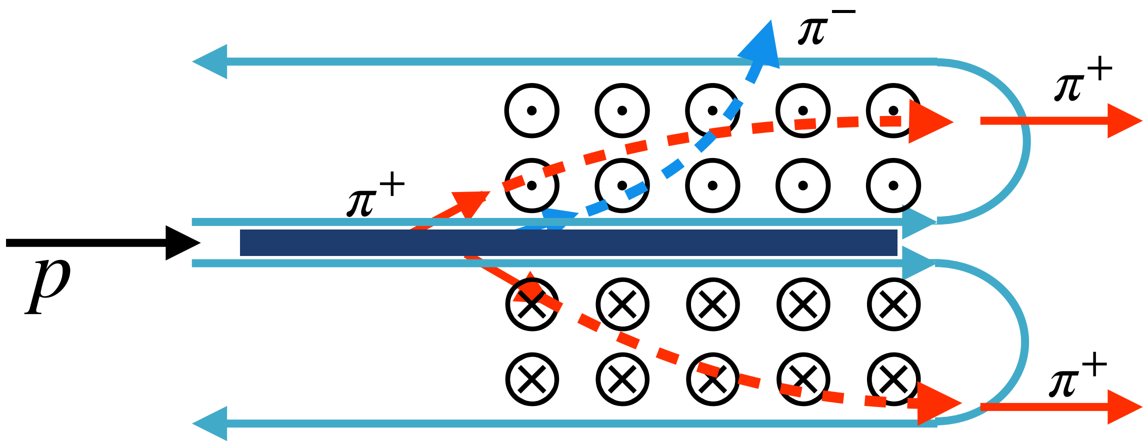
Next generation experiment:
- JUNO: "extra long baseline" 60 km
- observe oscillations driven by both $\Delta m^2_{31}, \Delta m^2_{21}$

See I. Morton-Blake from Monday ν parallel session

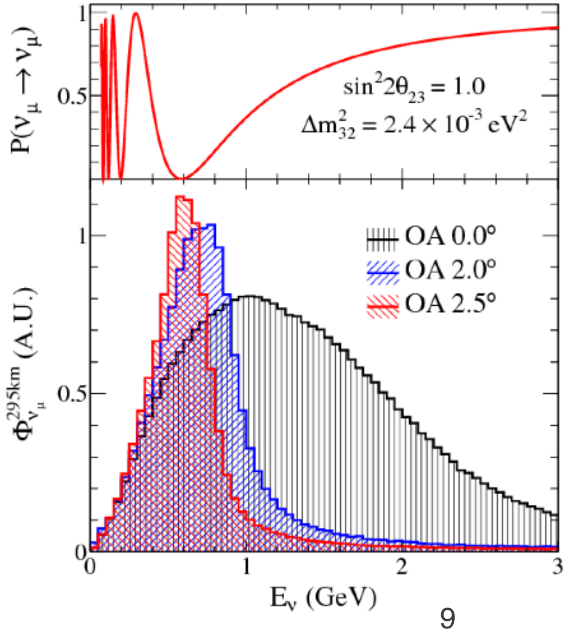
REACTORS AND ACCELERATORS



- Pion production from high energy protons
  - $\mathcal{O}(10^{12-14})$ protons per pulse
- Pions can be magnetically sign selected to produce
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$ beam
  - $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ beam
  - $\mathcal{O}(10^{5-6})$ A to produce ~1 T field

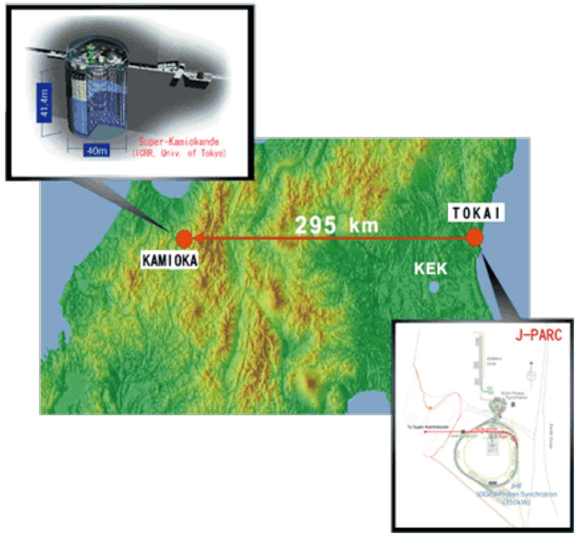


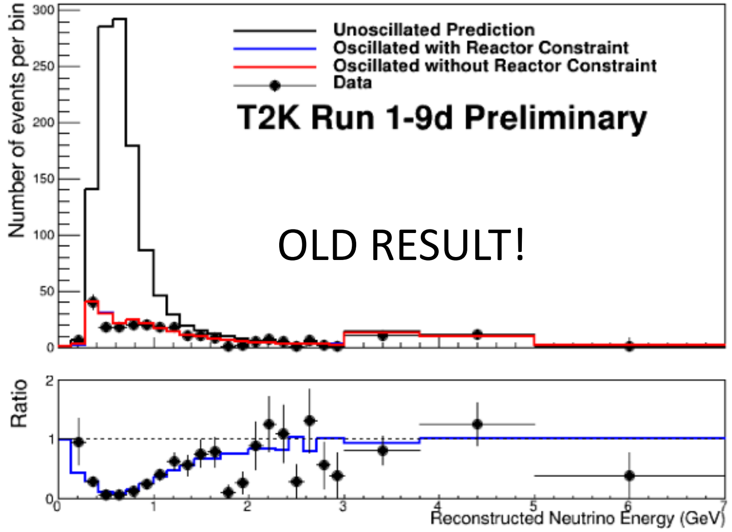
- Off-axis neutrino beam
  - Direct beam at a non-zero angle to the detector
  - Neutrino flux narrows and moves to lower energy due to pion decay kinematics

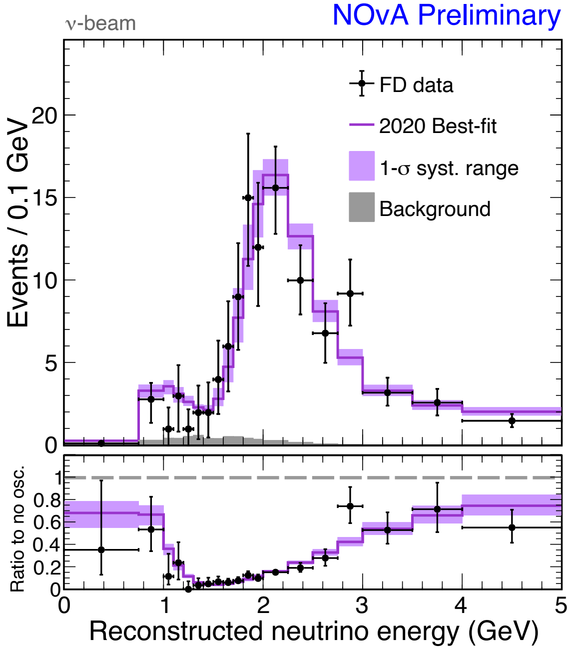


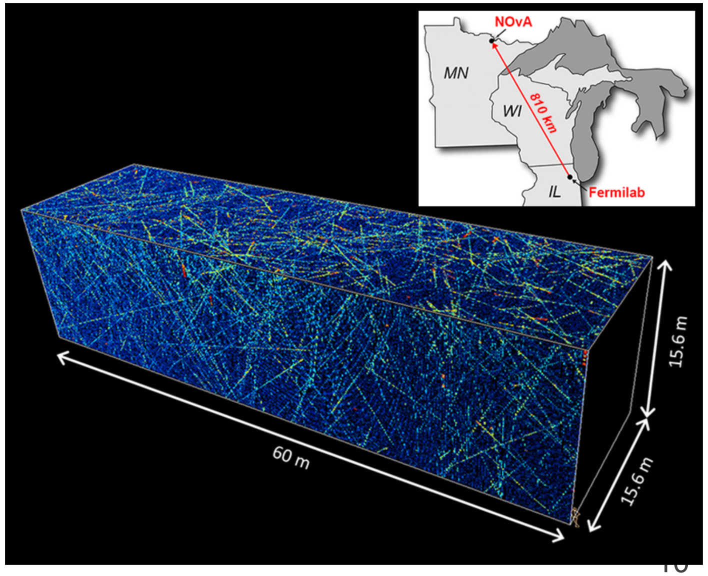
NOvA AND T2K

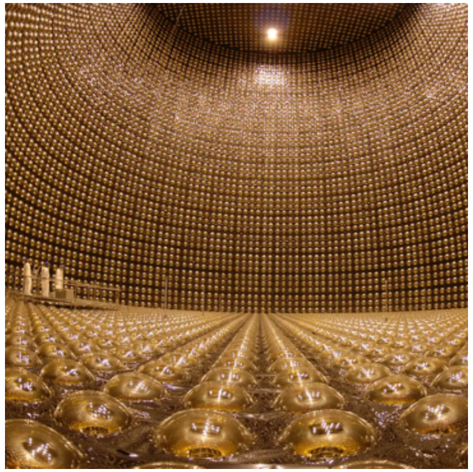
- O(1 GeV) $\nu_\mu, \bar{\nu}_\mu$ neutrinos are sent hundreds of km to large **"far" detectors**:
  - T2K: ~0.6 GeV $\nu_\mu/\bar{\nu}_\mu$ 295 km (smaller matter effect)
    - 50 kt Super-Kamiokande detector
  - NOvA: ~2 GeV $\nu_\mu/\bar{\nu}_\mu$ 810 km (larger matter effect)
    - 14 kt scintillator tracking detector
- Observe oscillation of $\nu_\mu/\bar{\nu}_\mu$ to other flavors at
  - ~500 km/GeV for $\Delta m^2_{atm} \sim 2.5 \times 10^{-5}$ eV^2







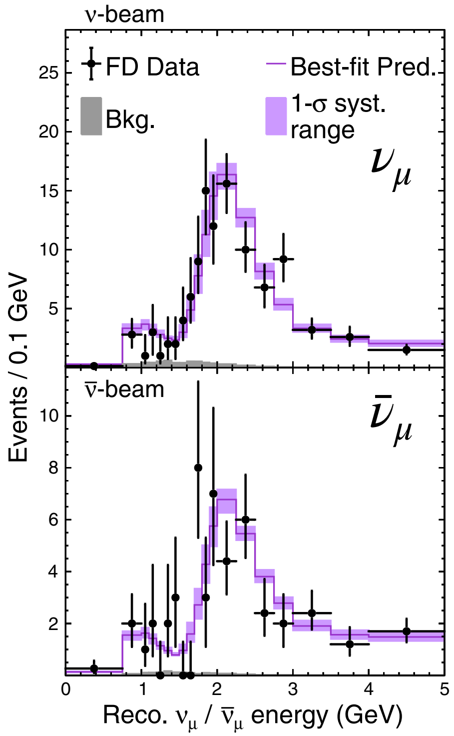


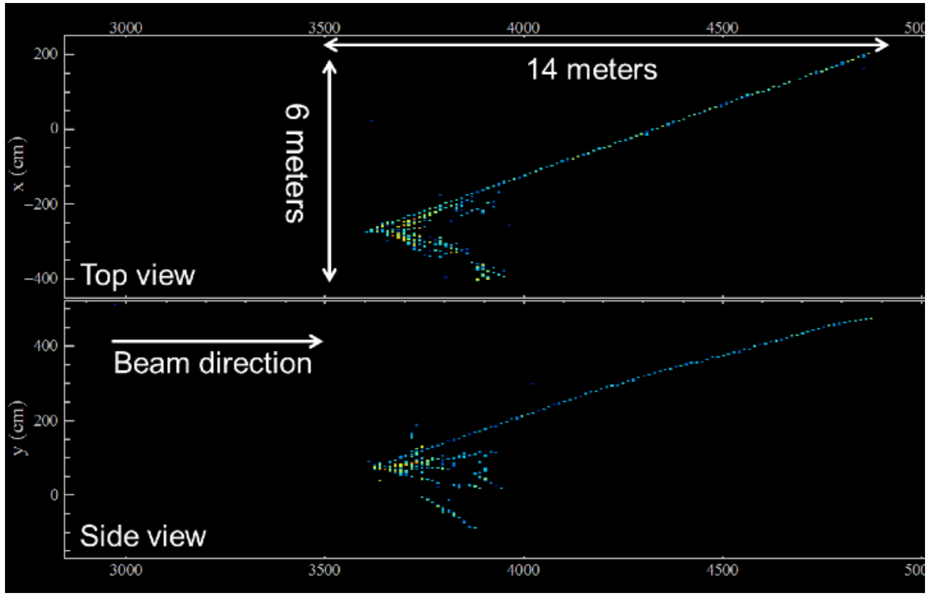


PHYSICAL REVIEW D 106, 032004 (2022)
Editors' Suggestion | Featured in Physics

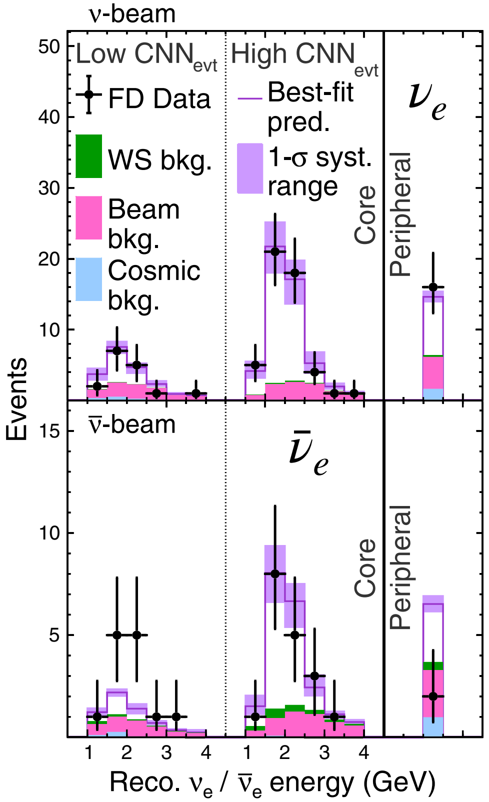
NOvA: FAR DETECTOR EVENTS

Improved measurement of neutrino oscillation parameters by the NOvA experiment

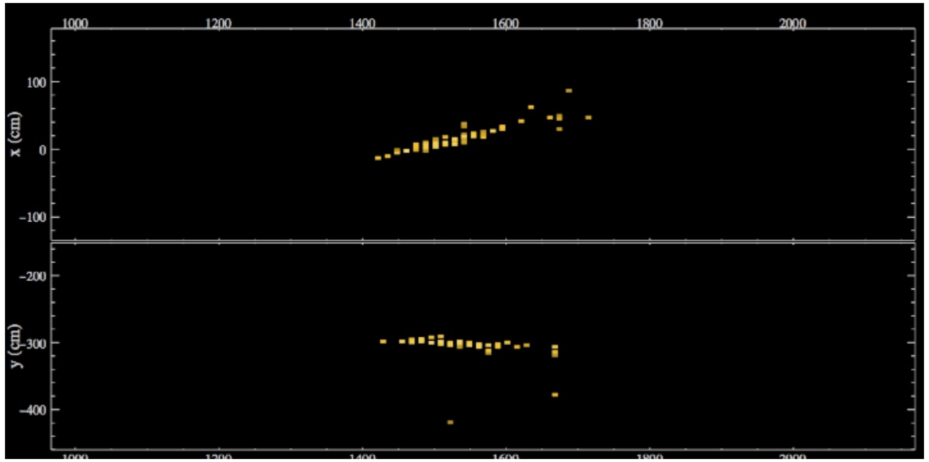




- ν_μ charged current interactions
  - muon exiting the interaction
  - Neutrino energy by adding muon and hadron energy
  - Strong "disappearance" observed for both $\nu_\mu, \bar{\nu}_\mu$ beams



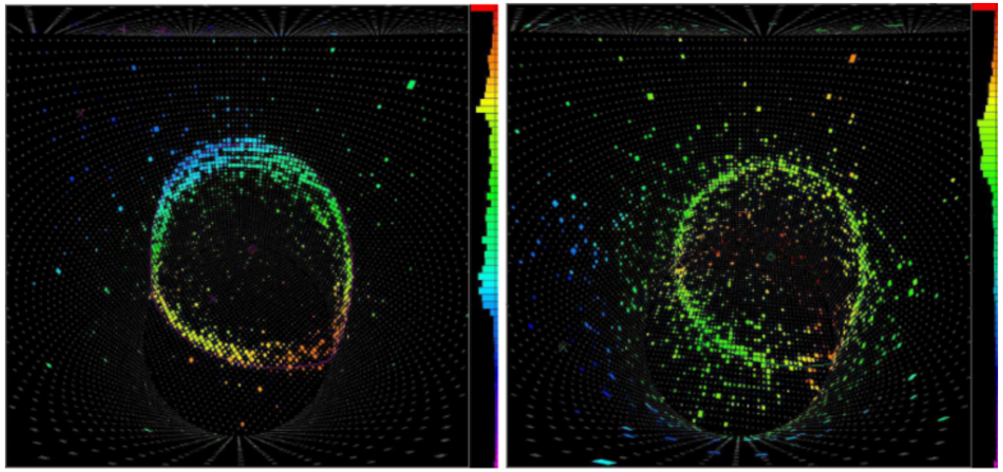
- ν_e charged current interactions
  - O(GeV) electromagnetic shower
  - Interactions from both $\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$ observed

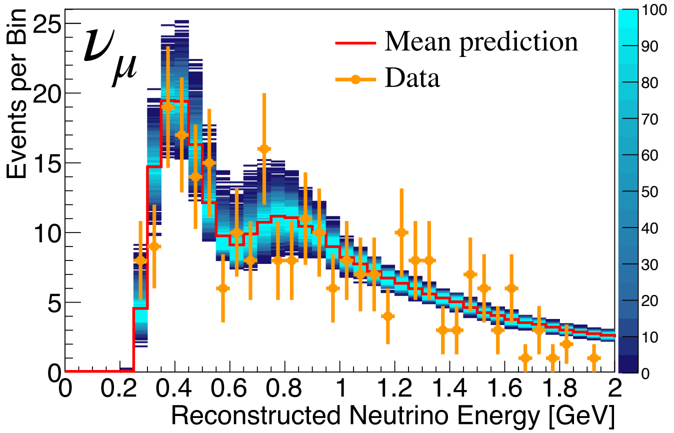


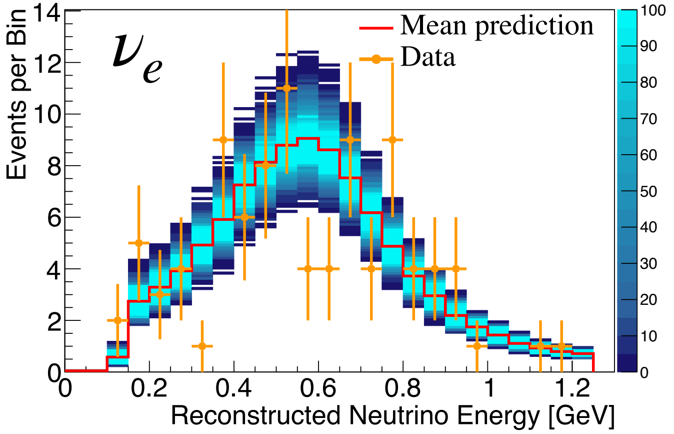
- n.b. "neutrino" vs. "antineutrino" determined by the beam configuration, not the detector

T2K

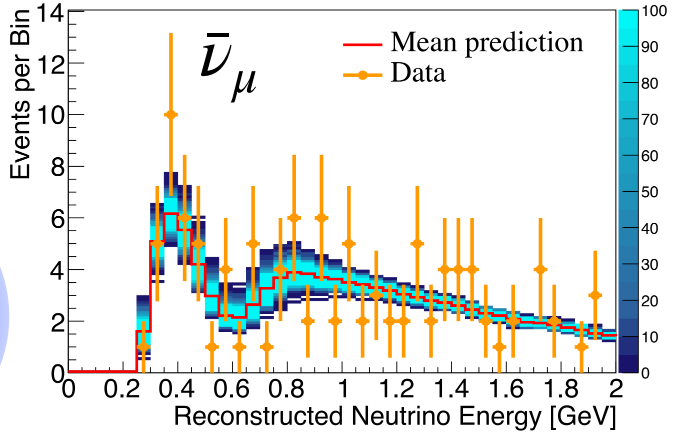
New Results! 2303.03222 [hep-ex]

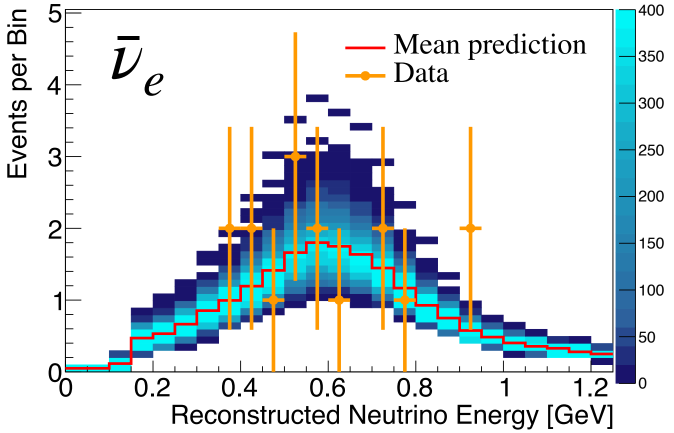


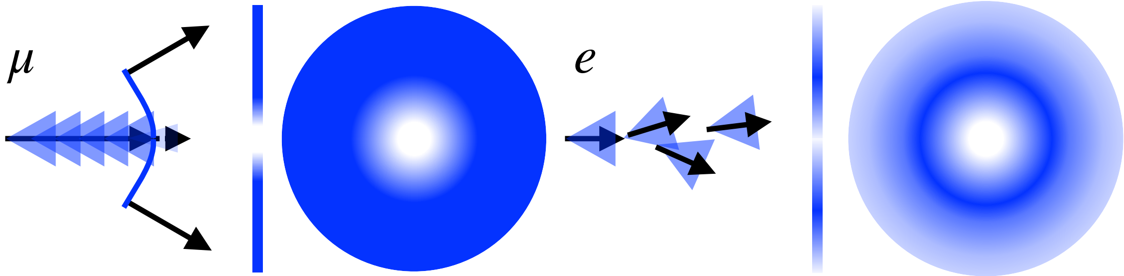




- ν_μ vs. ν_e identification via projected Cherenkov ring profile
  - Muons from ν_μ produce "clean" profiles
  - Electrons from ν_e produced "fuzzy" profiles
  - Neutrino energy assuming quasi 2-body kinematics

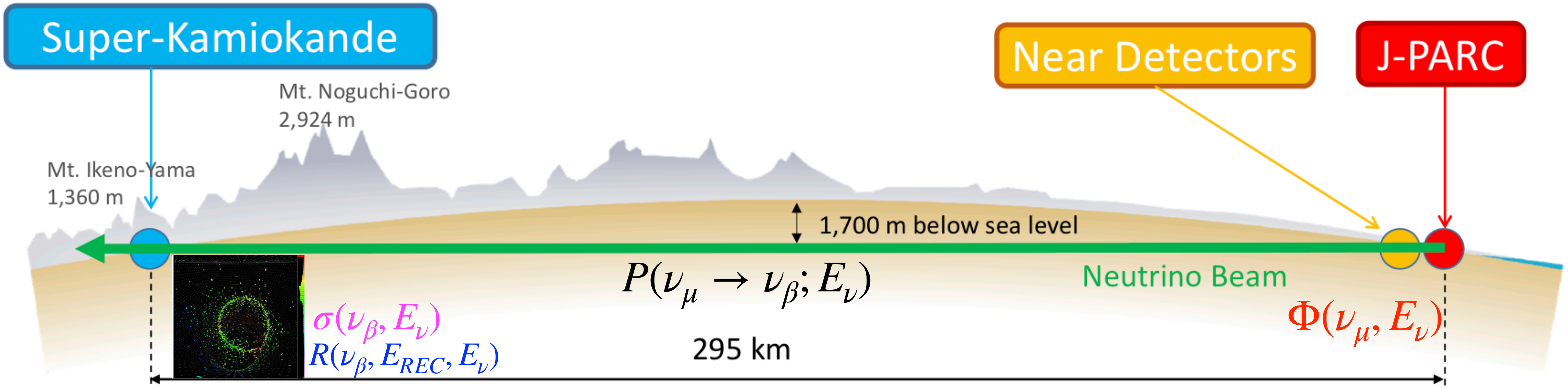


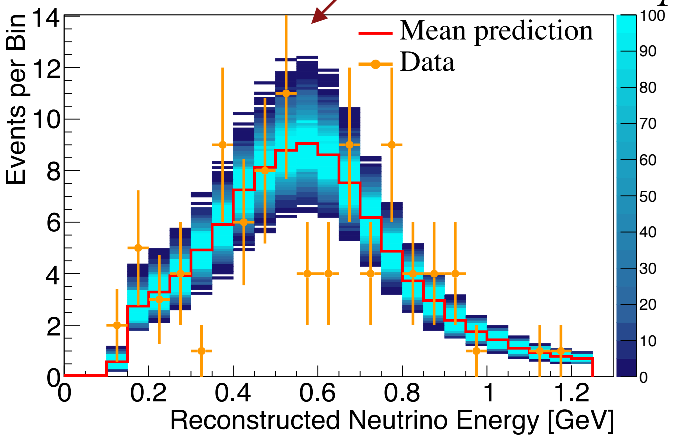




n.b. "neutrino" vs. "antineutrino" determined by the beam configuration, not the detector

NEAR DETECTOR





$$N(E_{REC}; \nu_\beta) = \int dE_\nu \, R(\nu_\beta, E_{REC}, E_\nu) \times \sigma(\nu_\beta, E_\nu) \times P(\nu_\mu \rightarrow \nu_\beta; E_\nu) \times \Phi(E_\nu, \nu_\mu)$$

We must **predict** the expected spectrum of neutrino interactions at the far detector

- $\Phi(E_\nu, \nu_\mu)$: flux of initial neutrino flavor ($\nu_\mu/\bar{\nu}_\mu$)
- $\sigma(\nu_\beta, E_\nu)$: modelling of neutrino interaction on target nucleus (^{16}O, ^{37}Ar)
- $R(\nu_\beta, E_{REC}, E_\nu)$: detector response modelling

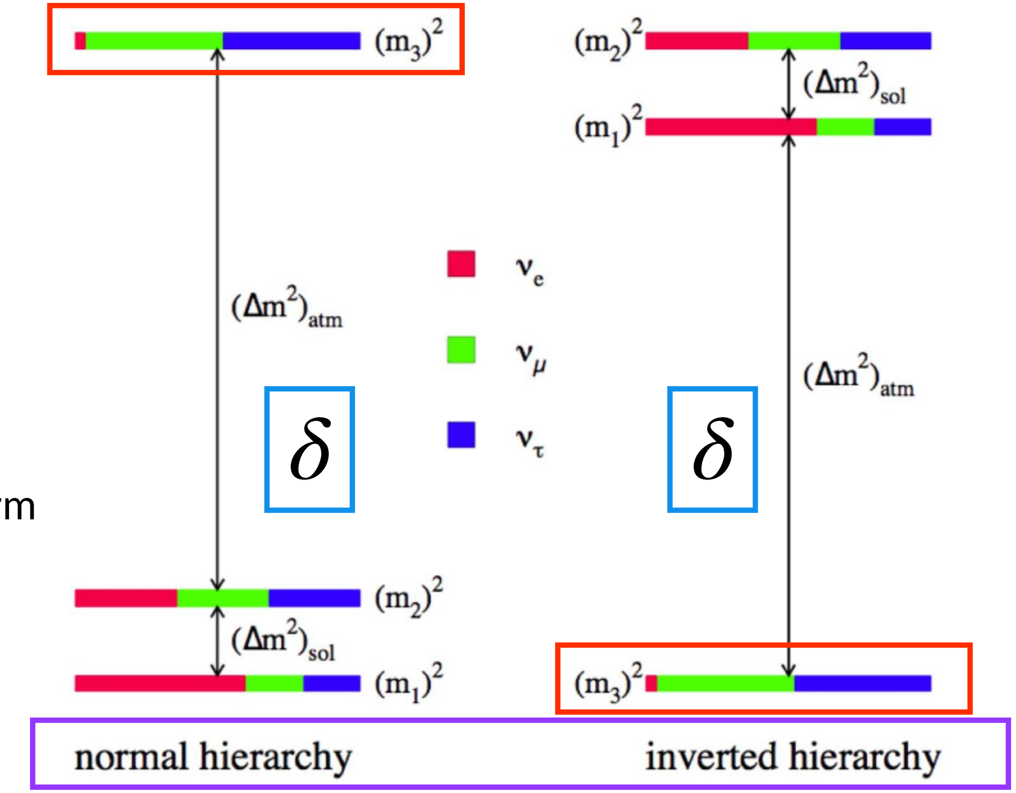
in order to **extract** the oscillation probability $P(\nu_\mu \rightarrow \nu_\beta; E_\nu)$

The **near detector** is a critical element in bringing systematic errors in each part under control

$\nu_\mu \rightarrow \nu_e$ AND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Credit: wikipedia.org

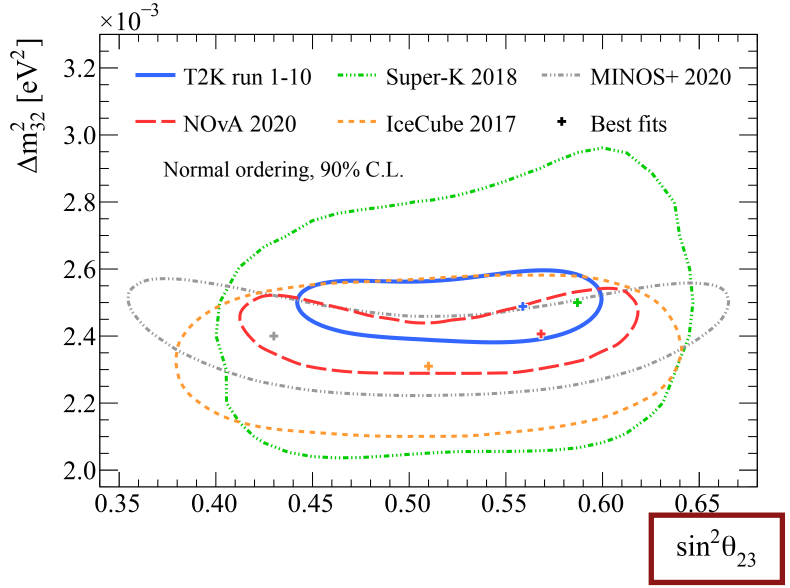
- This channel can tell us:
  - Do ν and $\bar{\nu}$ oscillate different in vacuum?
    - "CP violation" induced by a complex phase ("δ") in mixing
    - Continuous anticorrelation of ν vs. $\bar{\nu}$ oscillation probabilities
  - Is $m_3 > m_{2,1}$ or $m_3 < m_{2,1}$
    - The "ordering/hierarchy" of the mass states
    - Neutrinos traveling through **matter** have additional energy term
      - More $\nu_\mu \rightarrow \nu_e$, less $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ if ordering is "**normal**"
      - Less $\nu_\mu \rightarrow \nu_e$, more $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ if ordering is "**inverted**"
    - Discrete anti-correlation of ν vs. $\bar{\nu}$ oscillation probabilities
  - Is ν_3 more ν_μ or ν_τ (or equal parts of each)?
    - "θ_{23} octant": note $P(\nu_\mu \rightarrow \nu_\mu)$ sensitive to $2\theta_{23}$
    - More $\nu_\mu \rightarrow \nu_e$ **and** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ if ν_3 is more ν_μ
    - Continuous "common mode" scaling of $\nu, \bar{\nu}$ oscillation probabilities



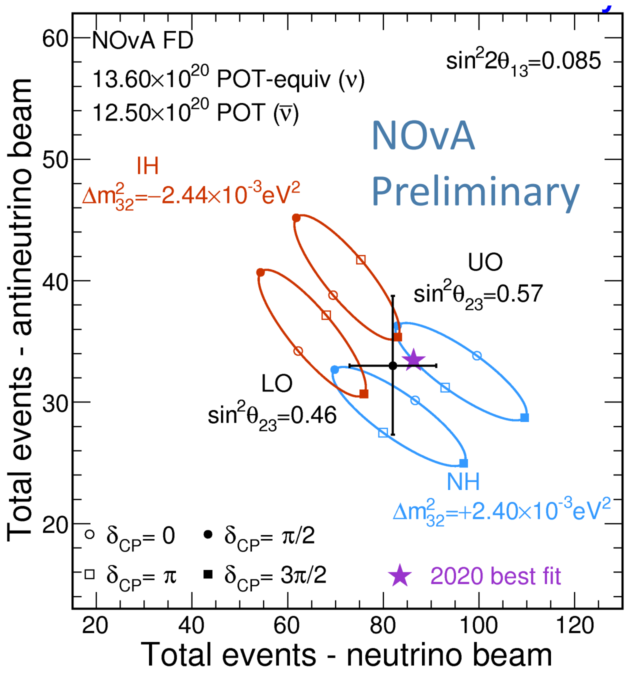
- It's complicated! Disentangle with:
  - Neutrino ($\nu_\mu \rightarrow \nu_e$) vs. antineutrino ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
  - Spectrum information
  - "Baseline" and matter effects
  - ν_μ disappearance

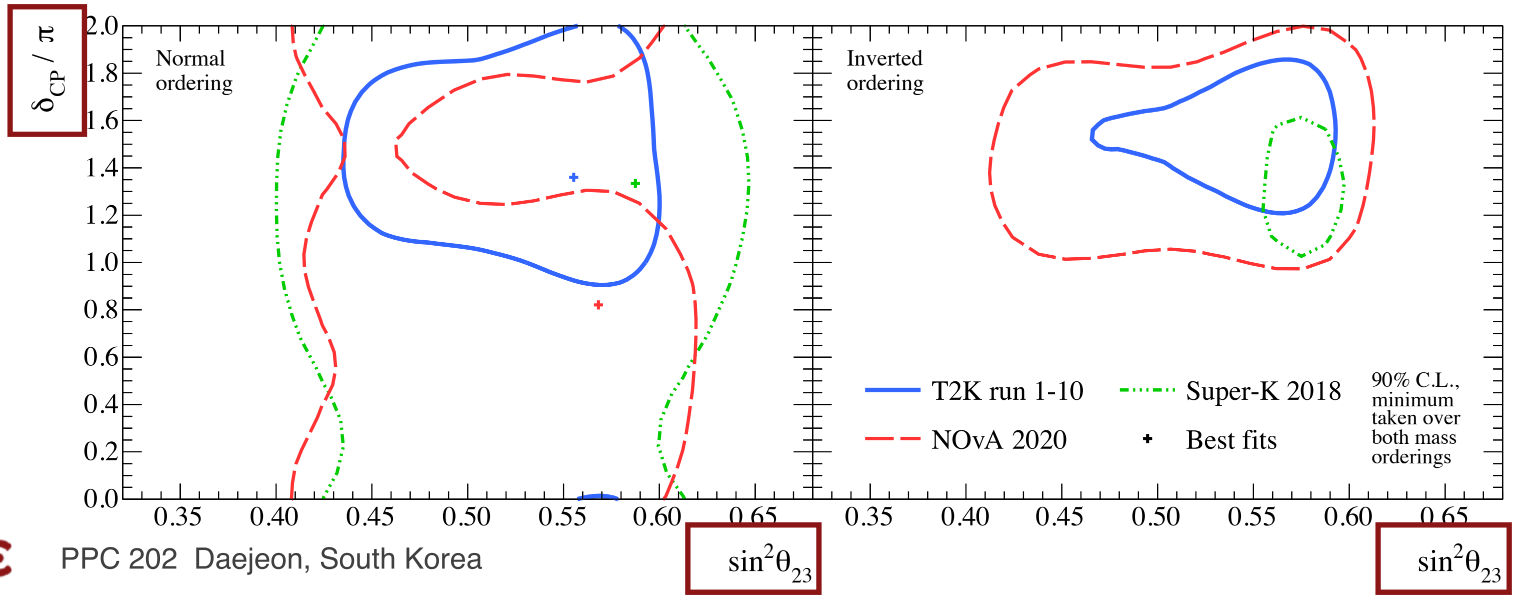
T2K AND NOVA RESULTS

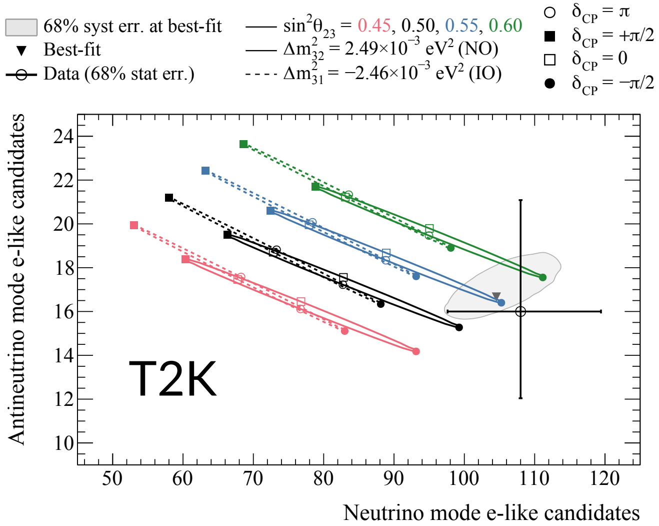
For illustration only



- T2K, NOvA: very large, possibly maximal mixing in θ_{23}:
  - $\sin^2\theta_{23} \sim 0.5$
- T2K: large $P(\nu_\mu \to \nu_e)$, small $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
  - Prefers $\delta \sim -\pi/2$ in both mass orderings
- NOvA: less asymmetry
  - Effectively all values of δ for normal ordering
  - $\delta \sim -\pi/2$ for inverted ordering

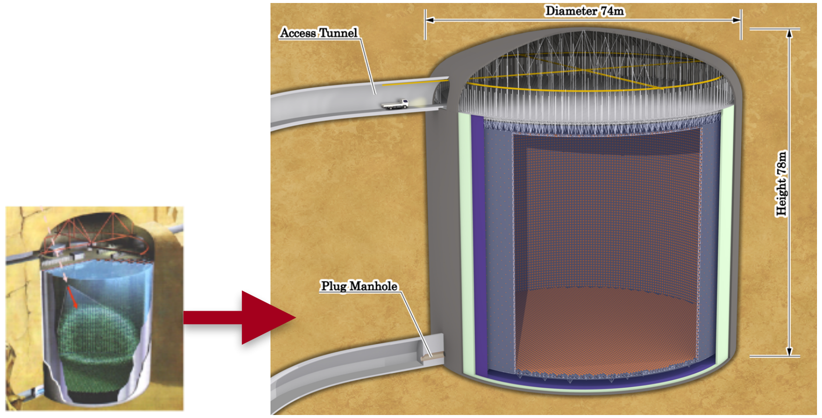




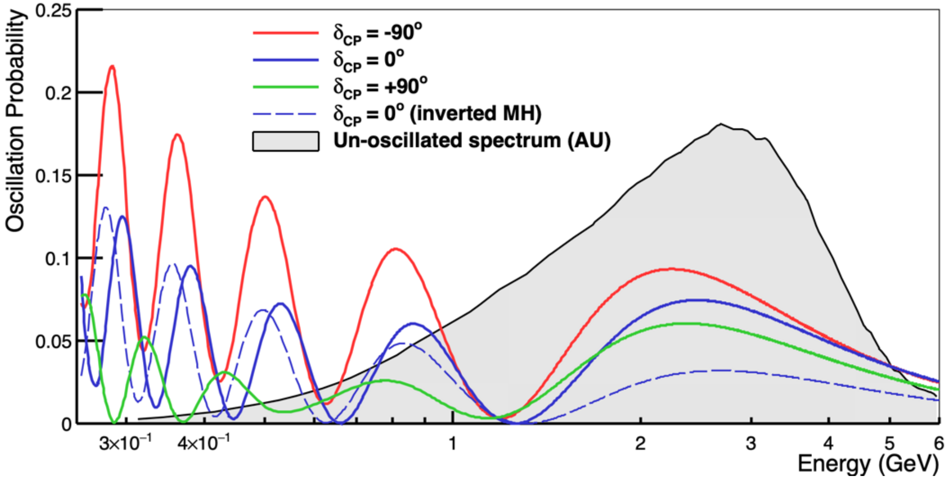


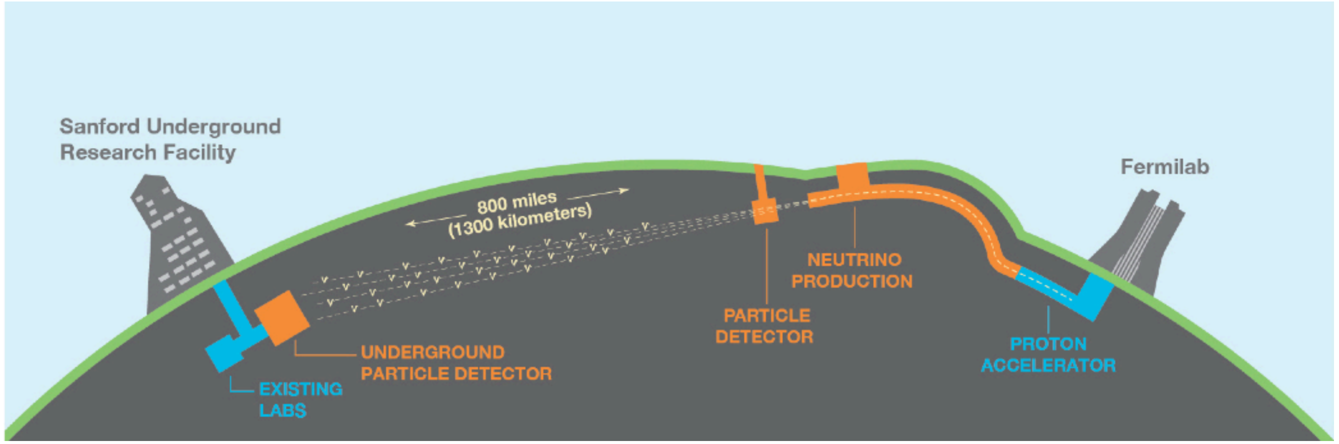
MOVING FORWARD

- NOvA and T2K will continue to take data through the decade
- A new generation of experiments will have a leap in capability, statistics, and configuration



- Hyper-Kamiokande:
  - “Upgrade” to Super-Kamiokande with 8.4 x greater volume (217 vs. 32 kton)
  - Upgraded 0.6 GeV $\nu_\mu/\bar{\nu}_\mu$ beam from J-PARC 295 km away.
- DUNE:
  - Long baseline (1285 km) with large matter effects to resolve mass ordering
  - Broad-band neutrino beam (0.5-5 GeV) to observe large range of L/E
  - Large O(10 kt) LArTPC detectors optimized for higher energy neutrino events.





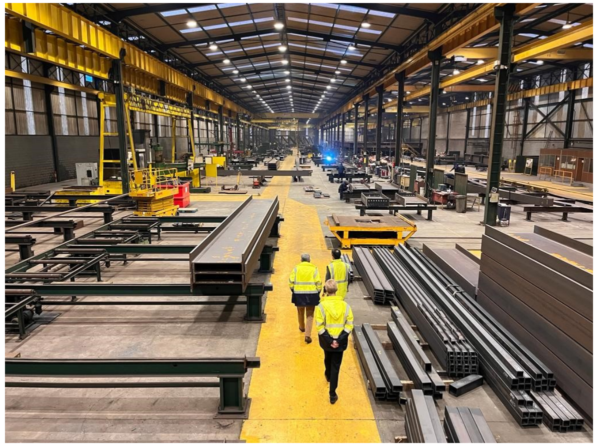
DIGGING AND BUILDING FOR THE FUTURE

Excavation of caverns for DUNE Far Detector

Tunnel for Hyper-Kamiokande

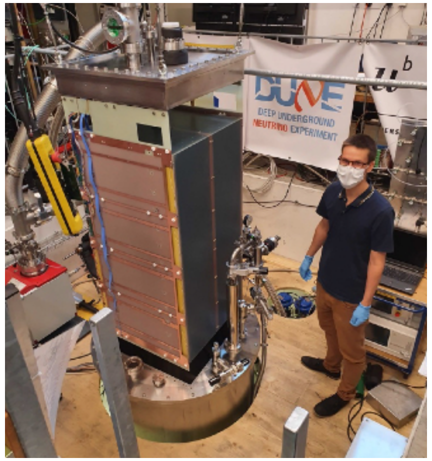
Start of cavern excavation for Hyper-K

Warm structure for DUNE cryostat

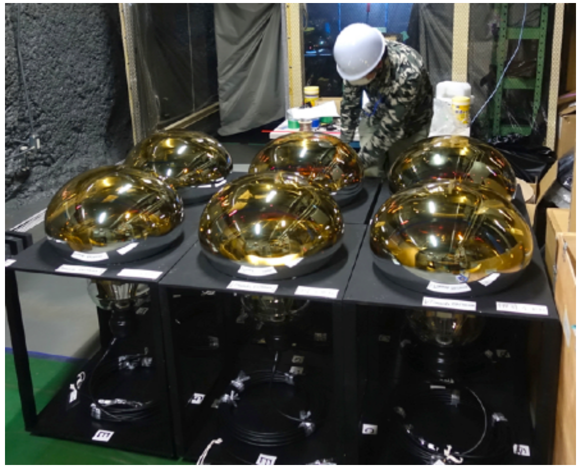


Anode wire system for DUNE Far Detector

Prototype module for DUNE Near Detector



New photosensors for Hyper-K



SUMMARY

- Neutrinos: exemplar of connections between smallest and largest scales of the universe
    - Particle physics and cosmology
- Neutrino oscillations probe fundamental properties of the neutrino
    - Essential in understanding many issues in physics from understanding particle interactions to cosmology
    - Essential questions about mass ordering and CP violation are still unresolved
- We still have fundamental questions to understand about neutrinos:
    - What are the full implications of their mass/mixing?
    - What determines the value of neutrino mixing parameters and masses?

Grojean, Day 1

- I was told that neutrino physics is “entering the golden era” 20 years ago
    - It seems the golden era will continue for at least a few more decades!
    - A new generation of ambitious experiments are under construction!