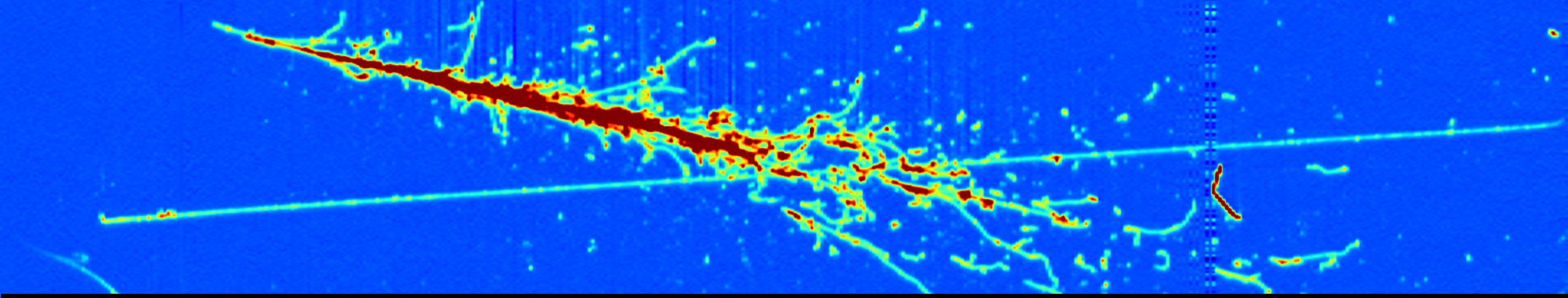
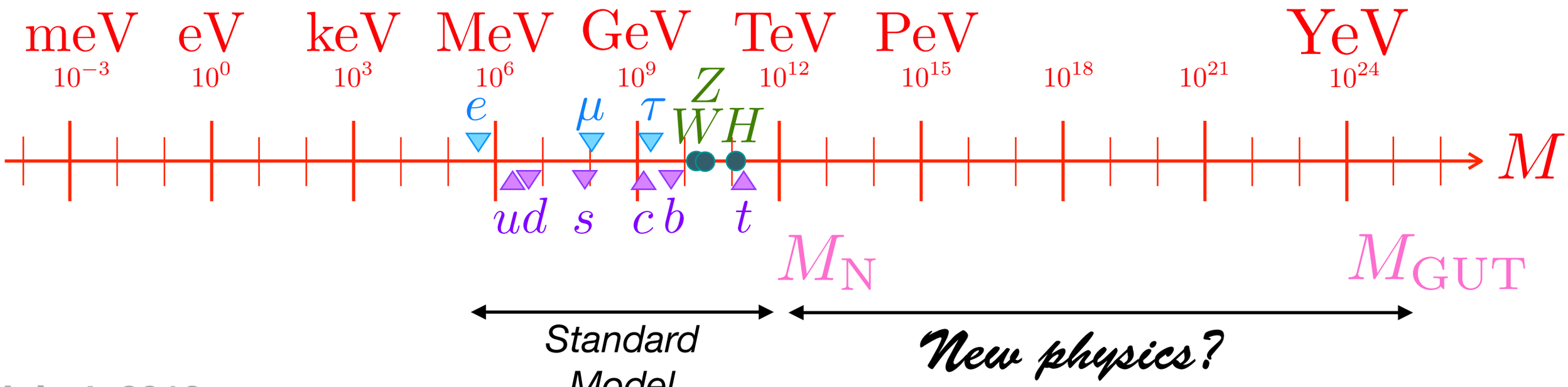
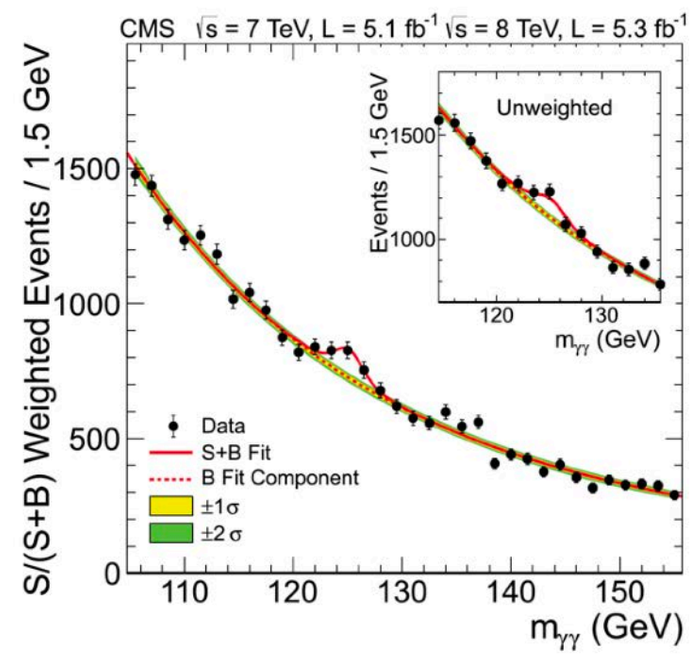


Neutrino Oscillations
Three-Flavor and Beyond

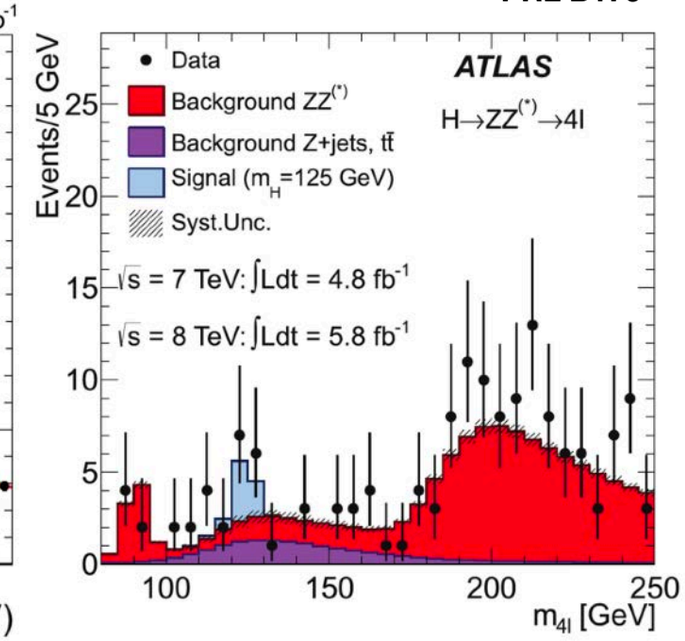
Mark Messier
Indiana University



July 4, 2012



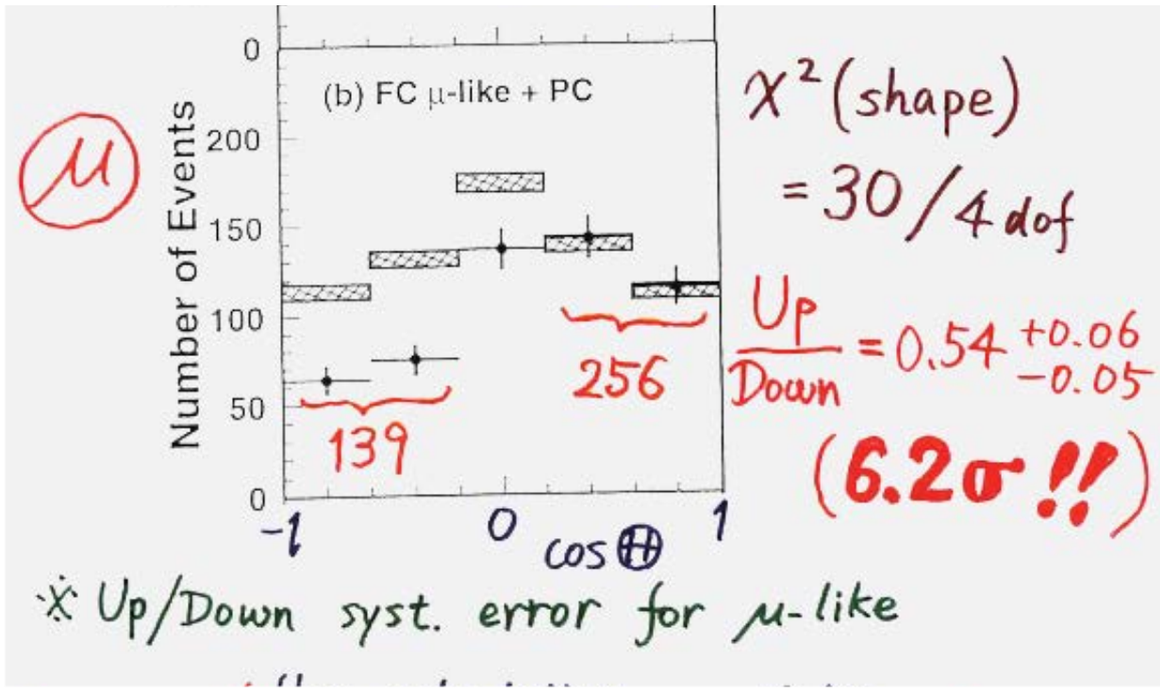
PRL B176

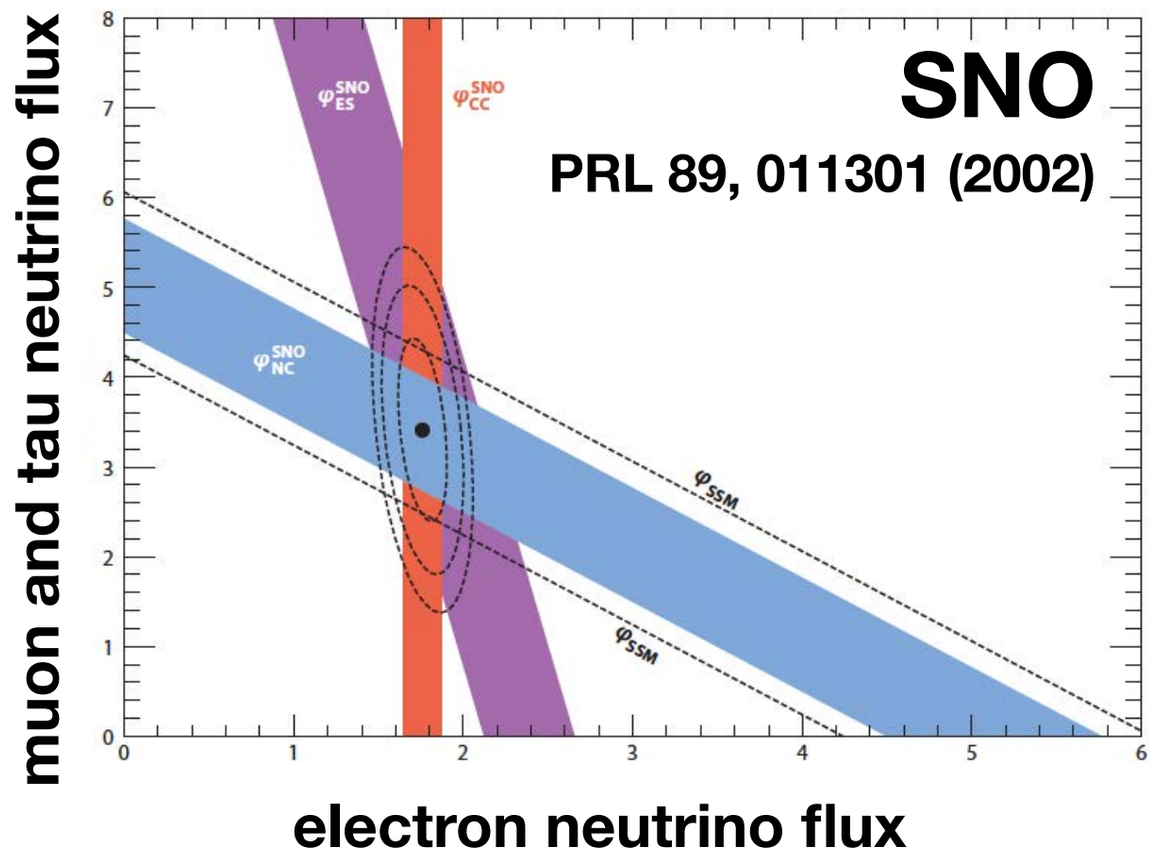


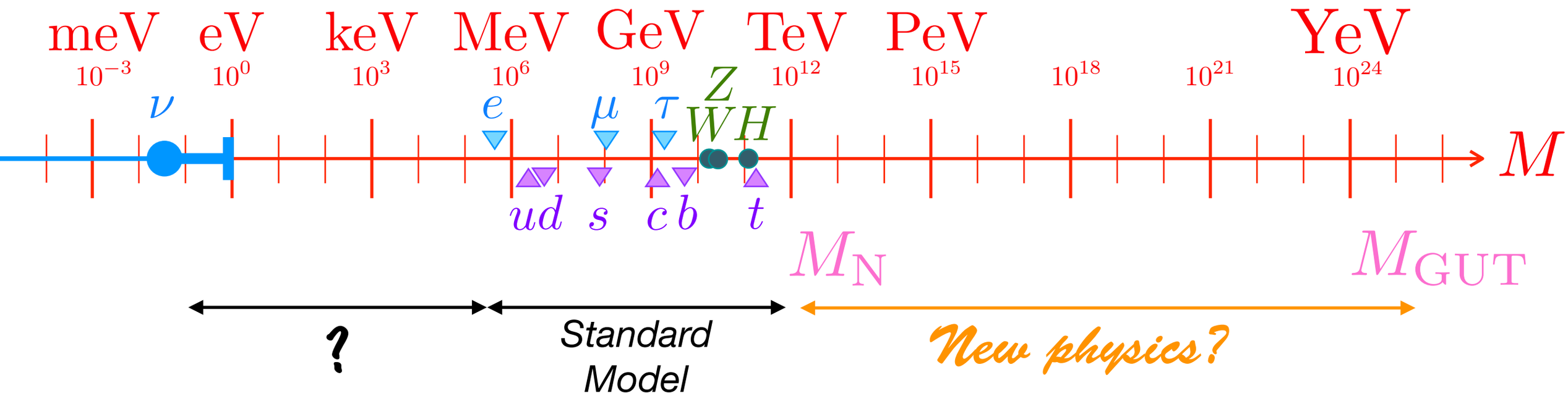
$$\mathcal{L}_{\mathrm{mass}} = \begin{bmatrix} \bar{\psi}_{\mathrm{L}} & \bar{\psi}_{\mathrm{R}} \end{bmatrix} \begin{bmatrix} 0 & m_{\mathrm{D}} \\ m_{\mathrm{D}} & 0 \end{bmatrix} \begin{bmatrix} \psi_{\mathrm{L}} \\ \psi_{\mathrm{R}} \end{bmatrix}$$

2015 Nobel Prize in physics “for the discovery of neutrino oscillations, which shows that neutrinos have mass”

T. Kajita June 5th, at Neutrino 1998







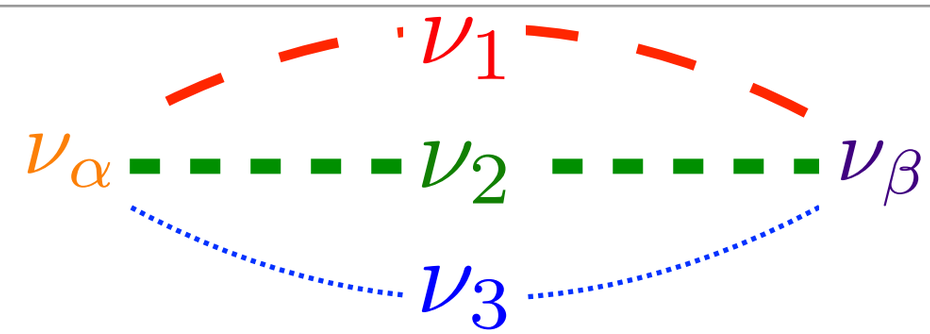
$$\mathcal{L}_{\rm mass} = \begin{bmatrix} \bar{\nu}_{\rm L} & \bar{\nu}_{\rm R} \end{bmatrix} \begin{bmatrix} 0 & m_{\rm D} \\ m_{\rm D} & M_{\rm M} \end{bmatrix} \begin{bmatrix} \nu_{\rm L} \\ \nu_{\rm R} \end{bmatrix}$$

$$\lambda \simeq \frac{m_{\rm D}^2}{M_{\rm M}}$$

$$10^{-1}\ {\rm eV} \simeq \frac{(10^6 ... 10^{11})^2 {\rm eV}^2}{(10^{13} ... 10^{23})\ {\rm eV}}$$

Neutrino mass requires new physics possibly approaching the GUT scale

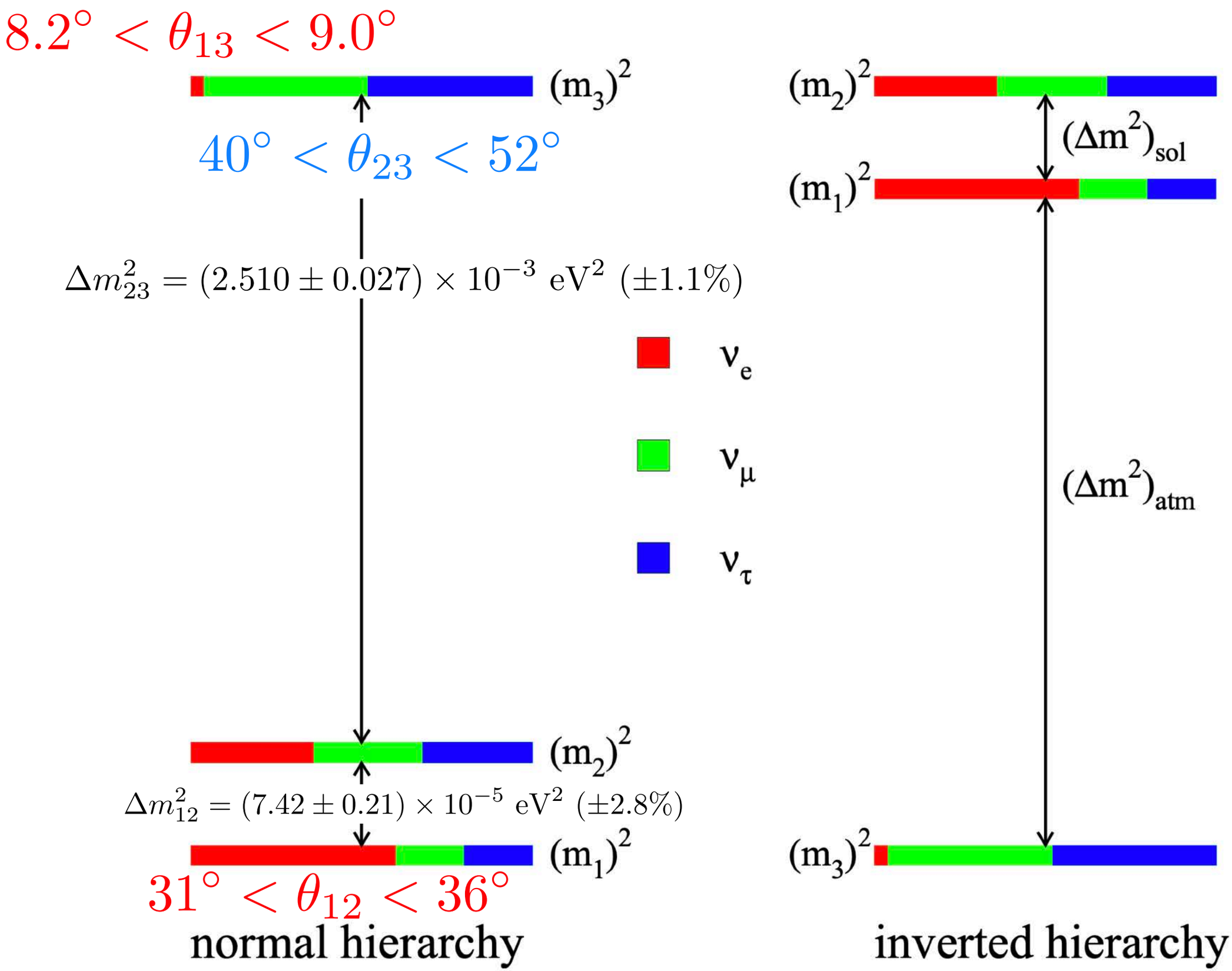
Neutrino oscillations



$$\left| \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \left| \begin{array}{c} \nu_1 \\ \nu_2 \\ \nu_3 \end{array} \right\rangle$$

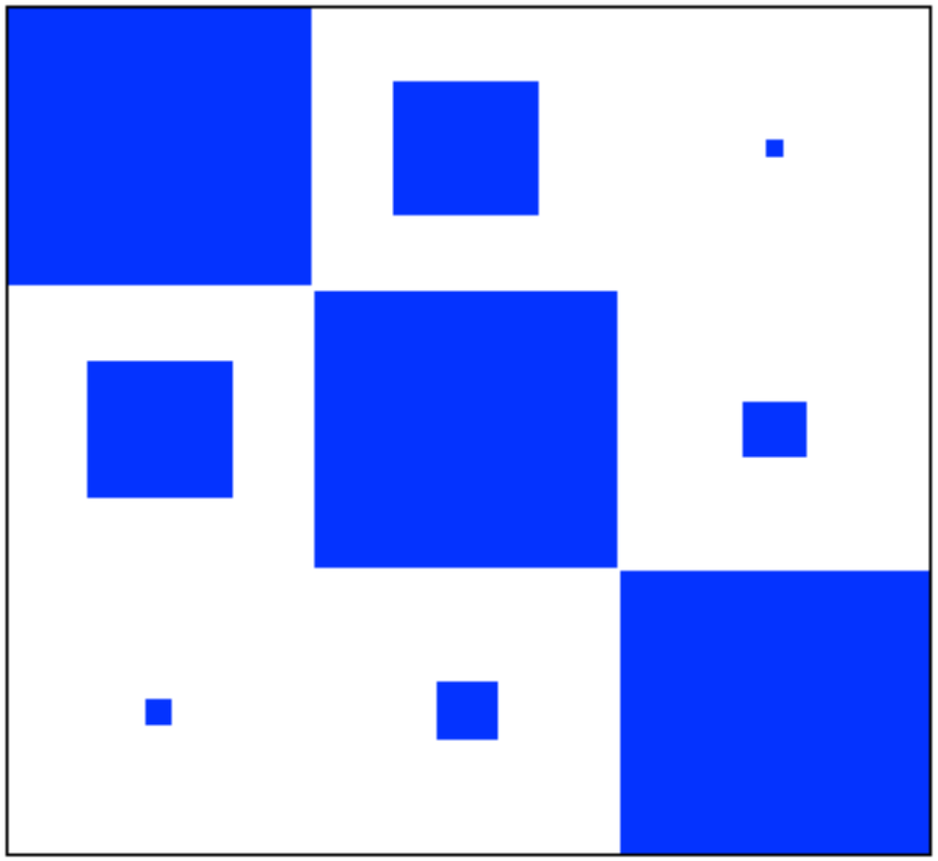
$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

$\lvert\Delta m^2_{32}\rvert \equiv \lvert m_3^2 - m_2^2\rvert$ $\simeq 2\times 10^{-3}\ \mathrm{eV}^2$	$\Delta m^2_{31} \simeq \Delta m^2_{32}$	$\Delta m^2_{21} \simeq 8\times 10^{-5}\ \mathrm{eV}^2$
$\nu_\mu \longrightarrow \nu_\mu$	$\nu_e \longrightarrow \nu_e$	$\nu_e \longrightarrow \nu_e$
$\nu_\mu \longrightarrow \nu_\tau$	$\nu_\mu \longrightarrow \nu_e$	$\nu_e \longrightarrow \nu_\mu + \nu_\tau$
atmospheric and long baseline	reactor and long baseline	solar and reactor

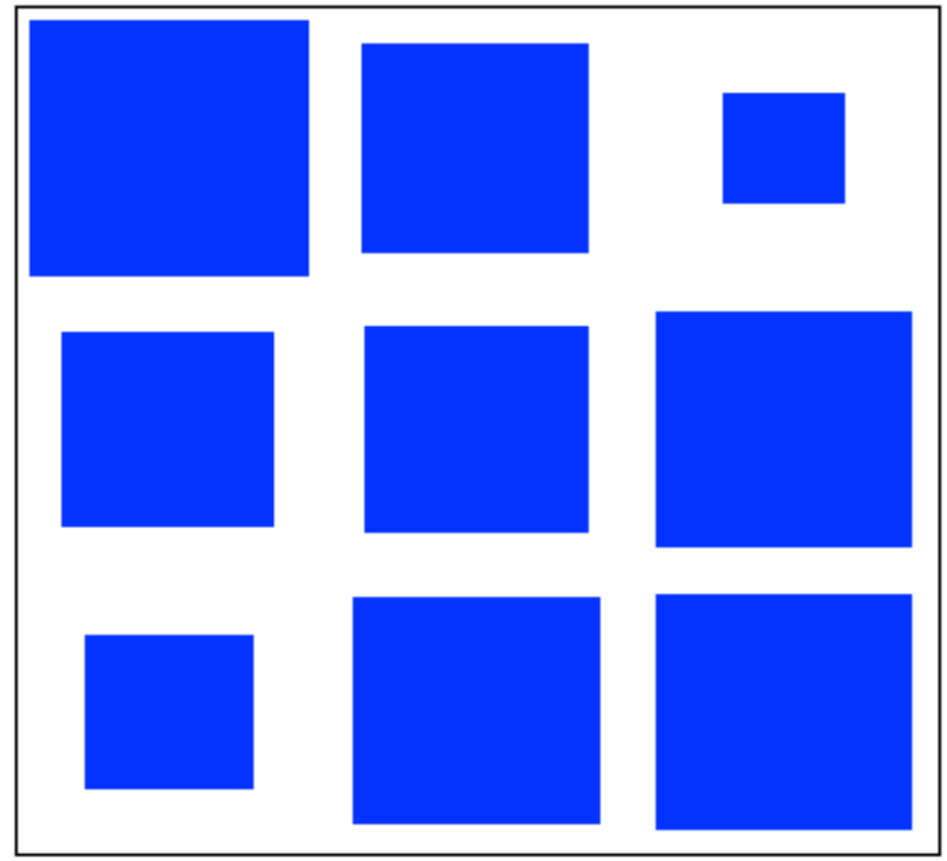


arXiv:2102.00594 NuFit, arXiv:2111.03086

Quark mixing

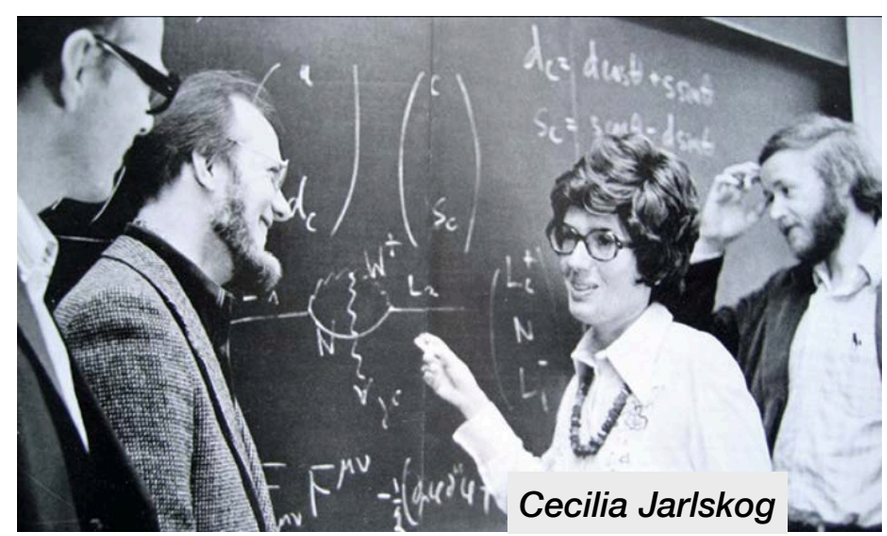


Neutrino mixing



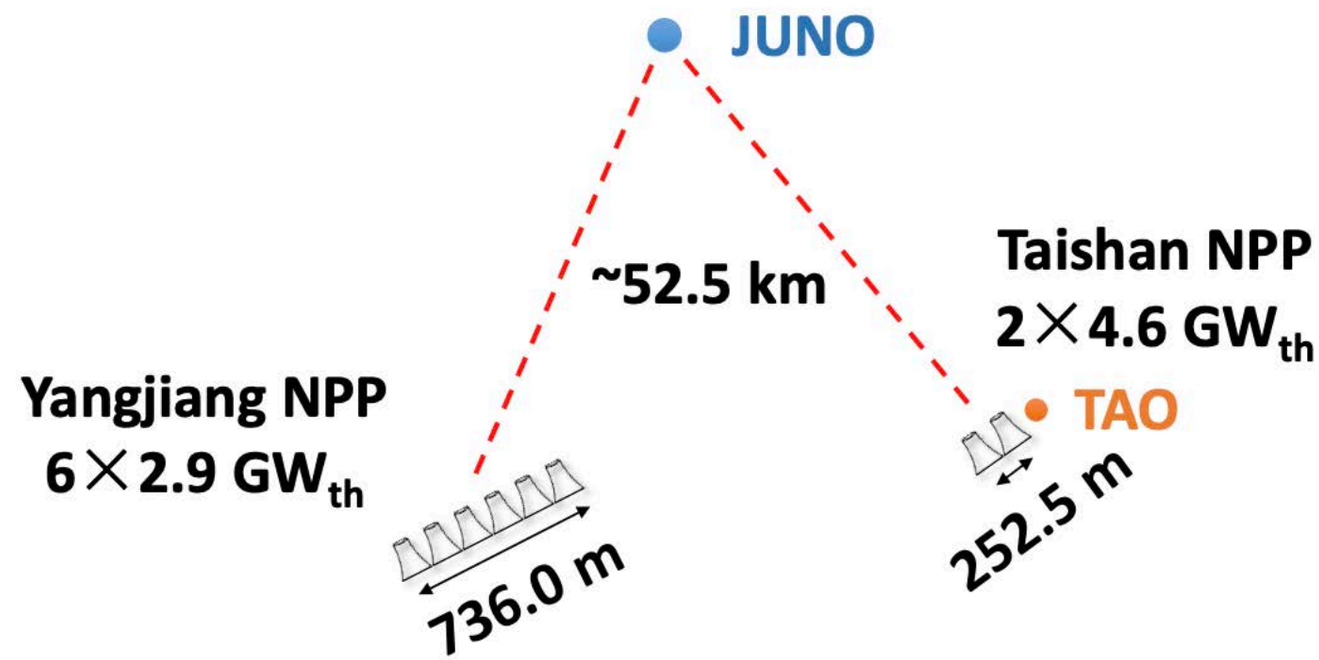
$$\frac{J_{\mathrm{PMNS}}}{J_{\mathrm{CKM}}} = \frac{3 \times 10^{-2}}{3 \times 10^{-5}} \sin(\delta_{\mathrm{PMNS}})$$

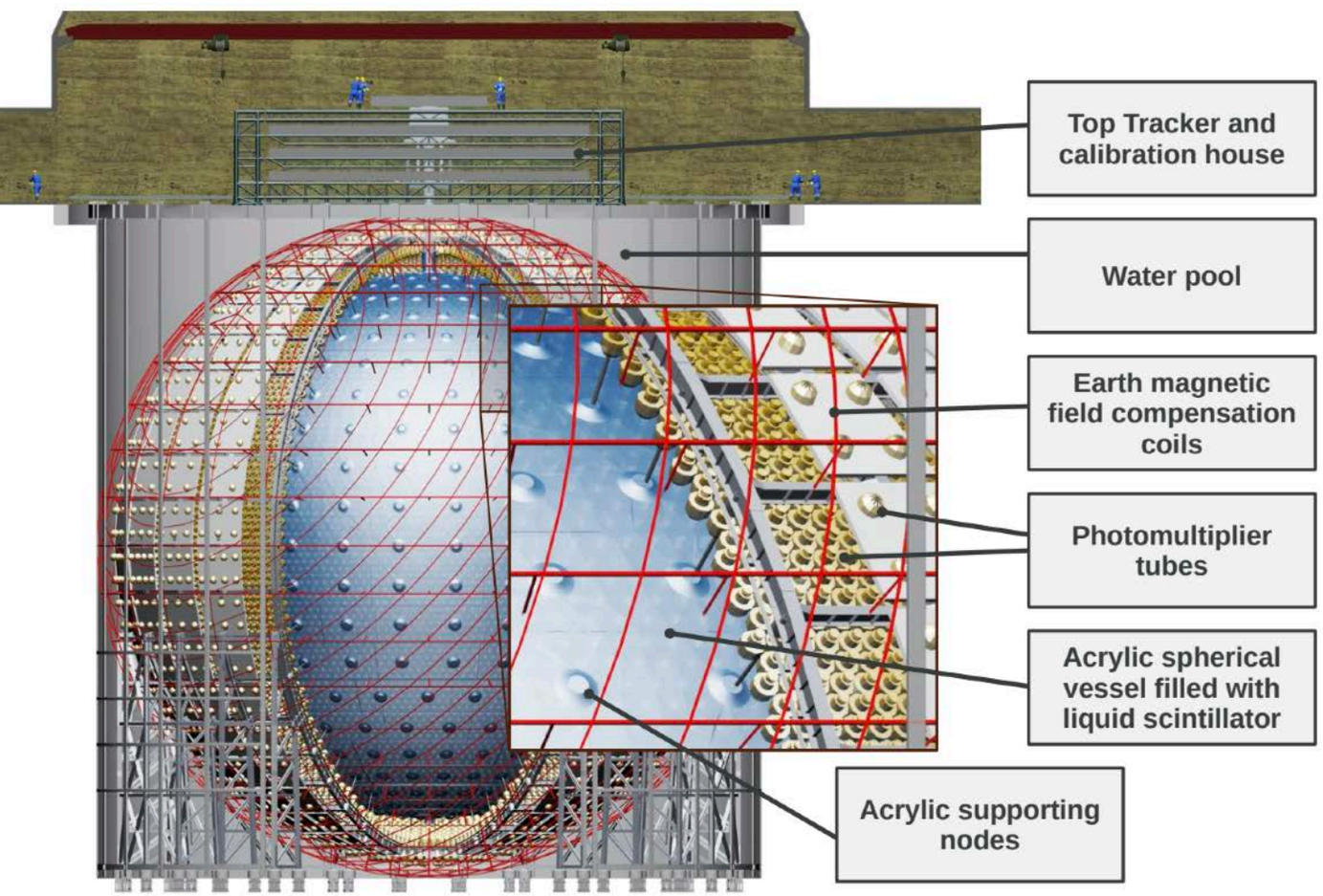
CP violation in neutrinos could be 1000x larger than in quarks

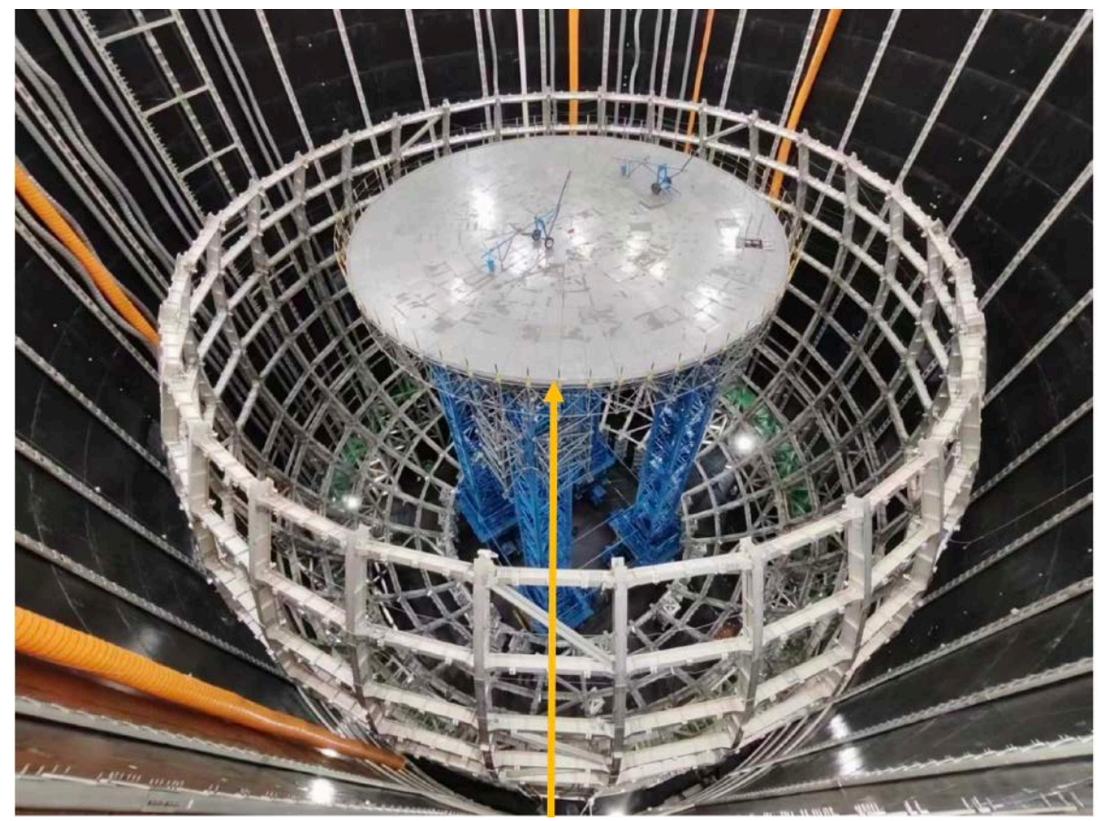


Cecilia Jarlskog

JUNO





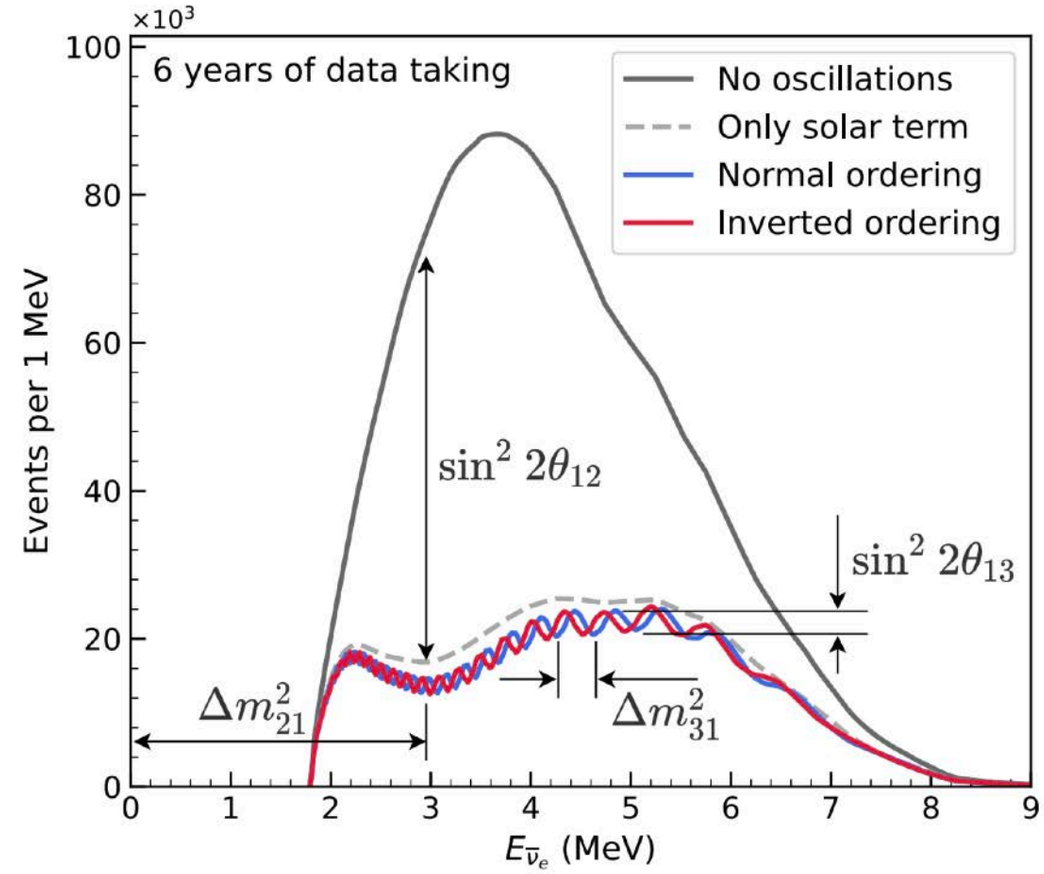


20 kt liquid scintillator

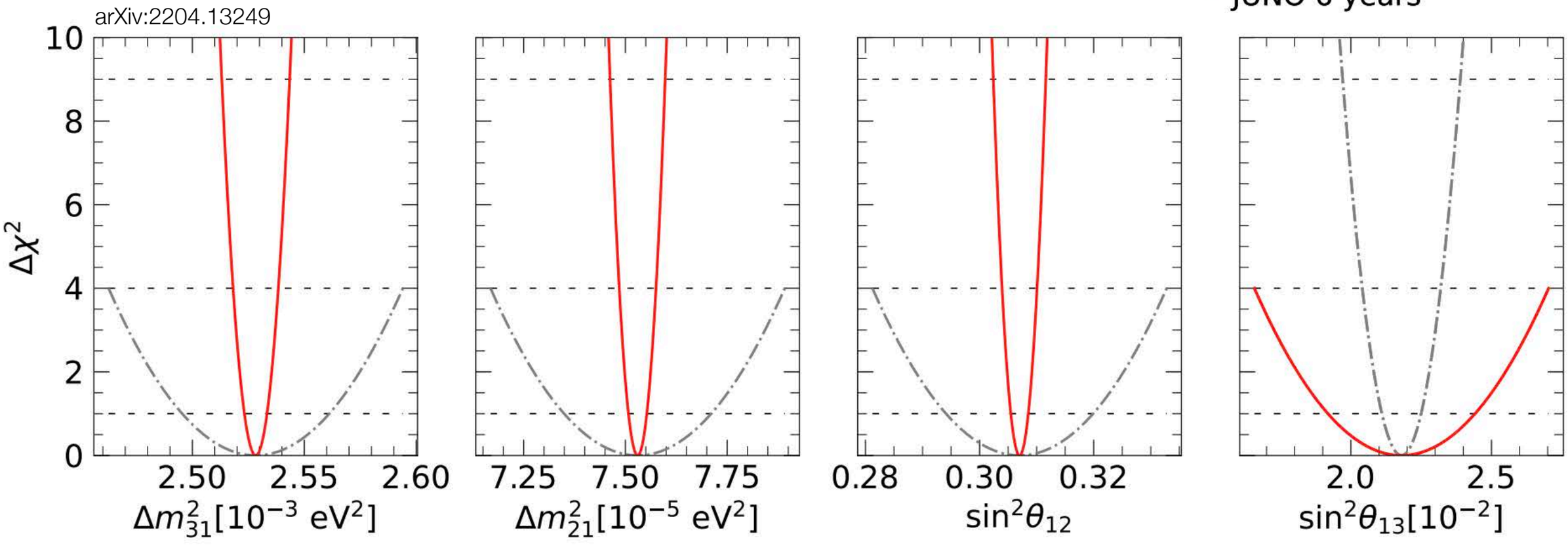
JUNO

Operations begin in 2023

Order of magnitude improvement in Δm^2_{31}, Δm^2_{21}
θ_{12} precision in 6 years

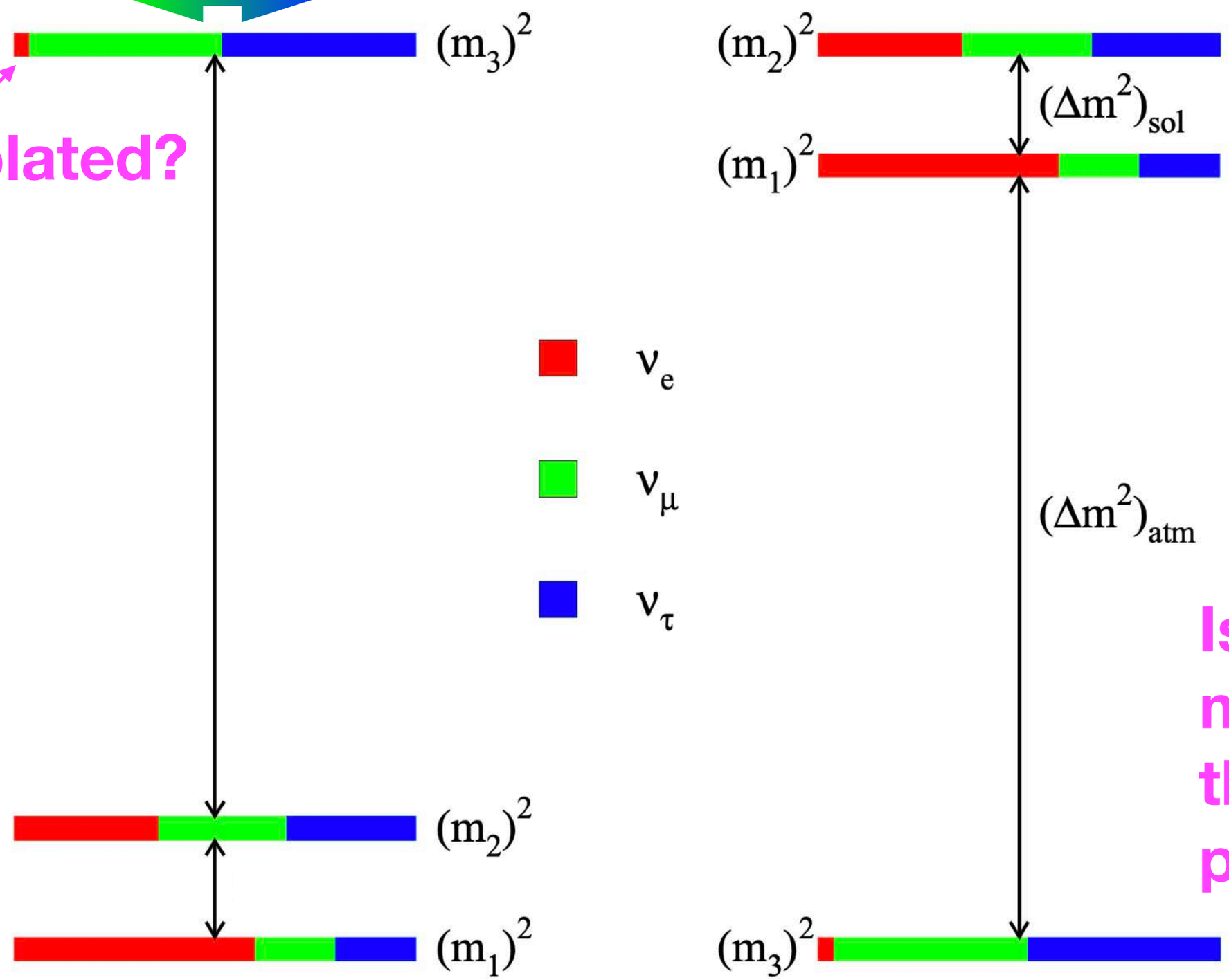


arXiv:2204.13249



Is this symmetry real?

Is CP violated?



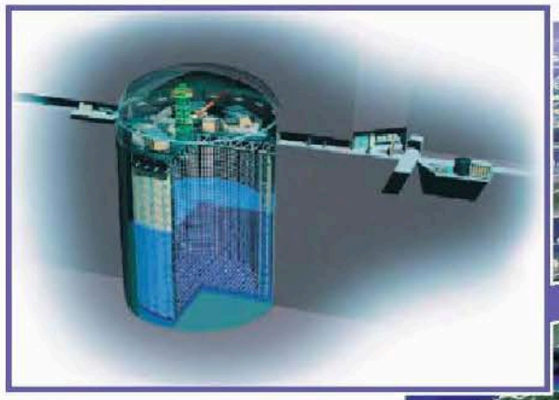
Is there more to this picture?

normal hierarchy ⟷ inverted hierarchy

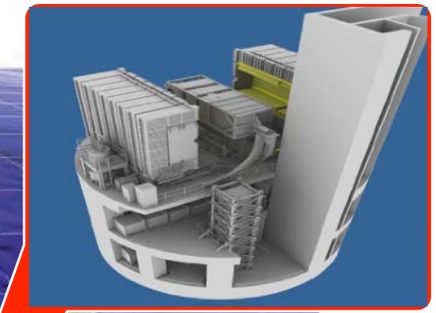
Which ordering is the correct one?

arXiv:2102.00594 NuFit v5.1

T2K



Super-Kamiokande
(ICRR, Univ. Tokyo)



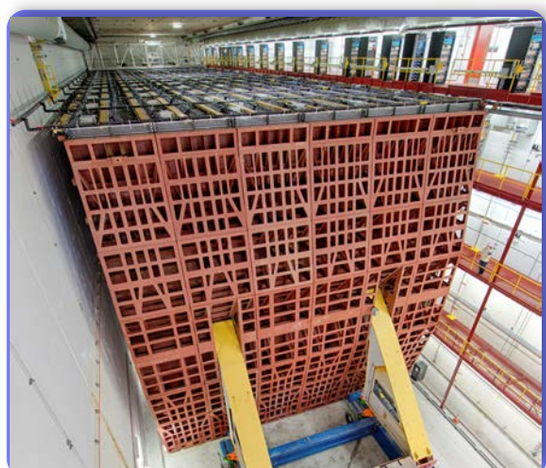
INGRID + ND280

J-PARC Main Ring
(KEK-JAEA, Tokai)

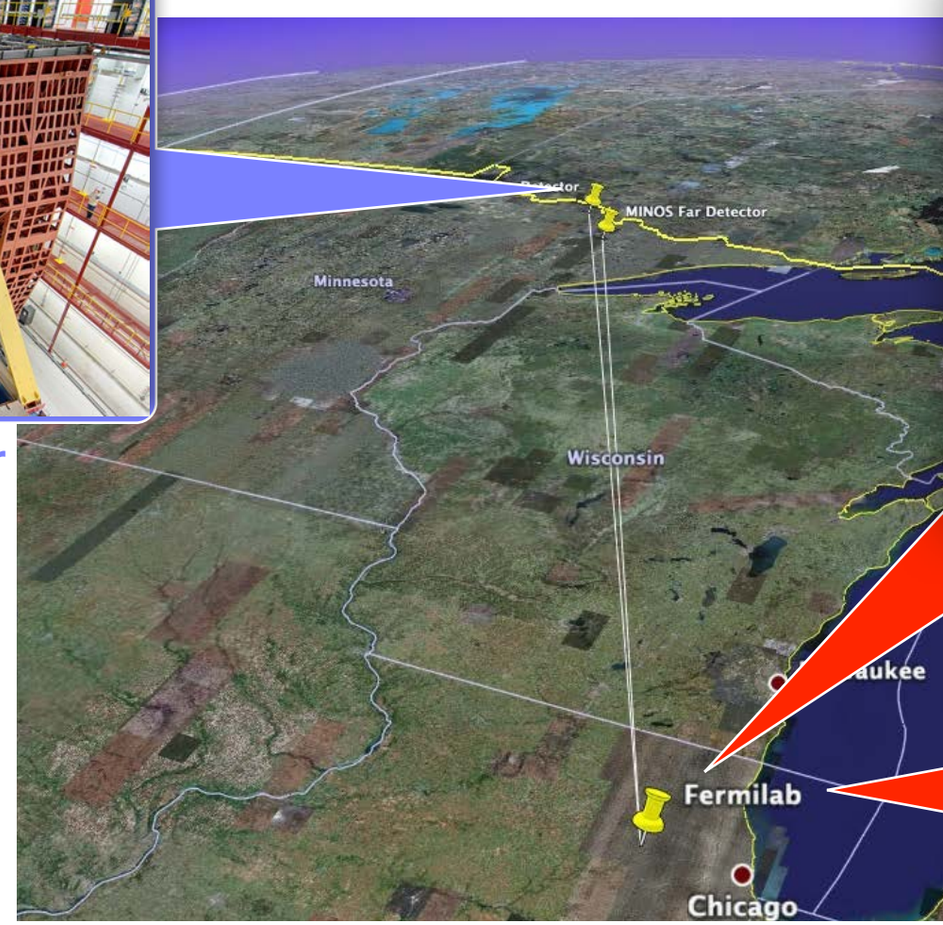
$$E_\nu \simeq 0.7 \text{ GeV},$$

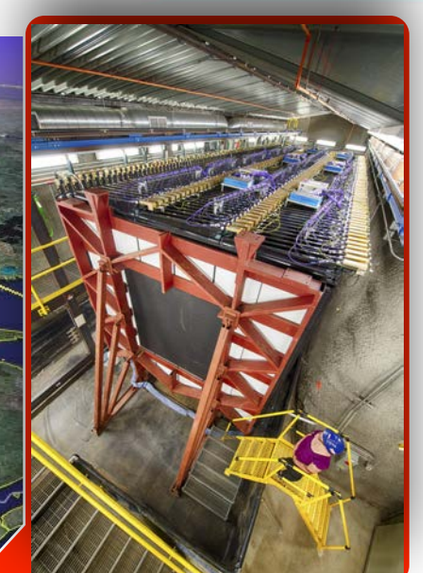
$$\Delta \equiv \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 295 \text{ km}}{0.7 \text{ GeV}} \simeq \frac{\pi}{2}$$

NOvA



NOvA Far Detector





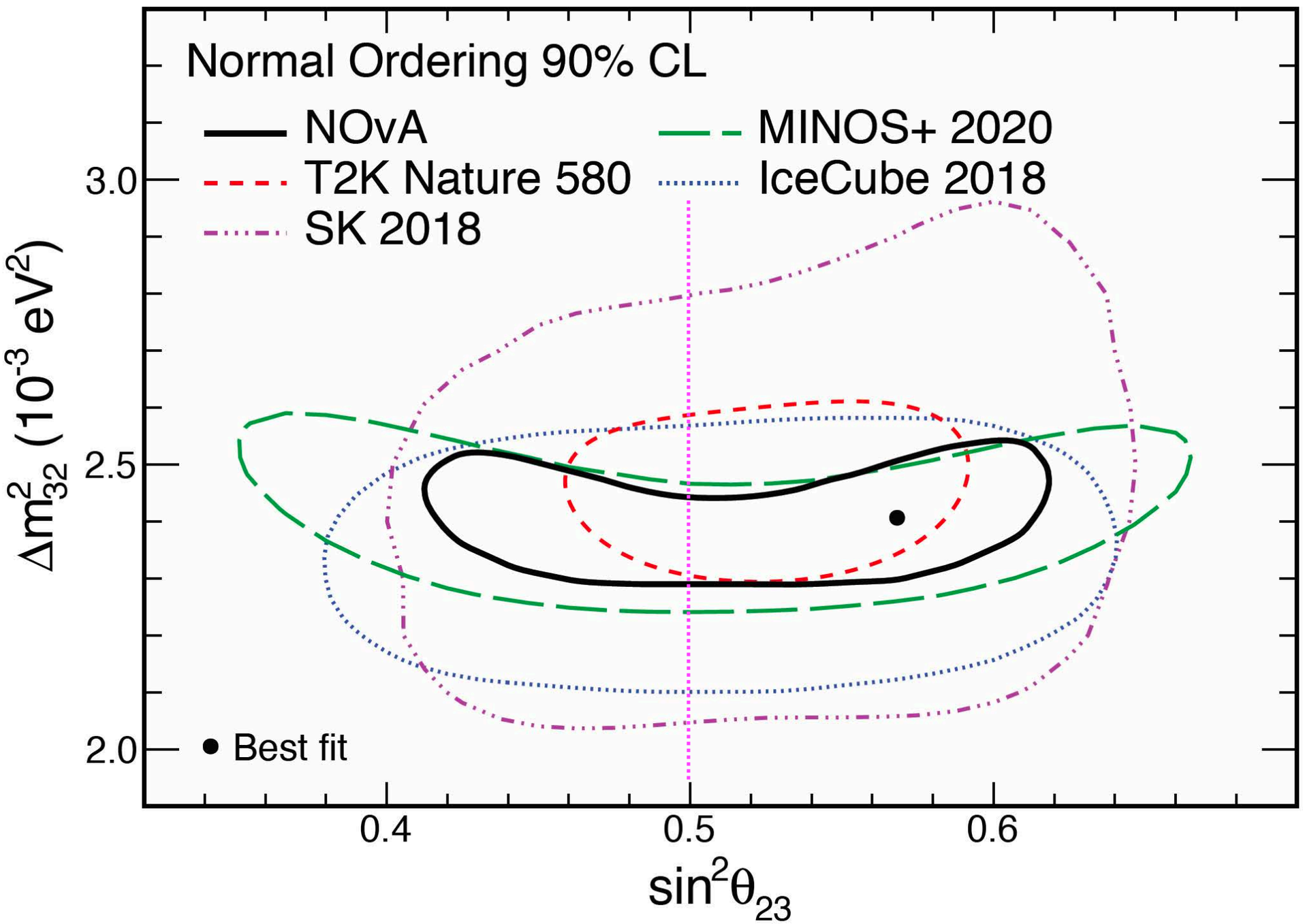
NOvA Near Detector

Fermilab Main Injector

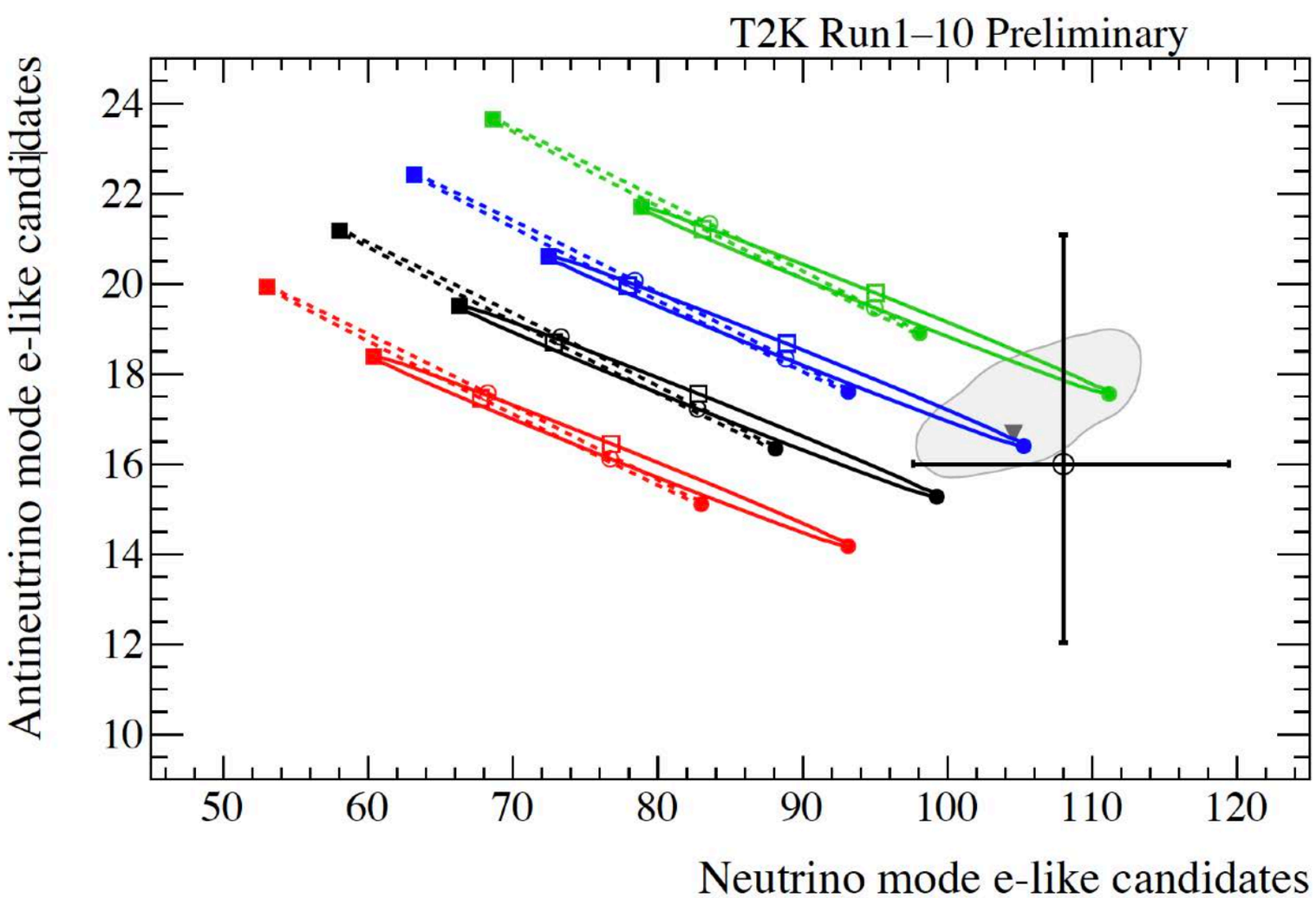
$$E_\nu \simeq 2 \text{ GeV},$$

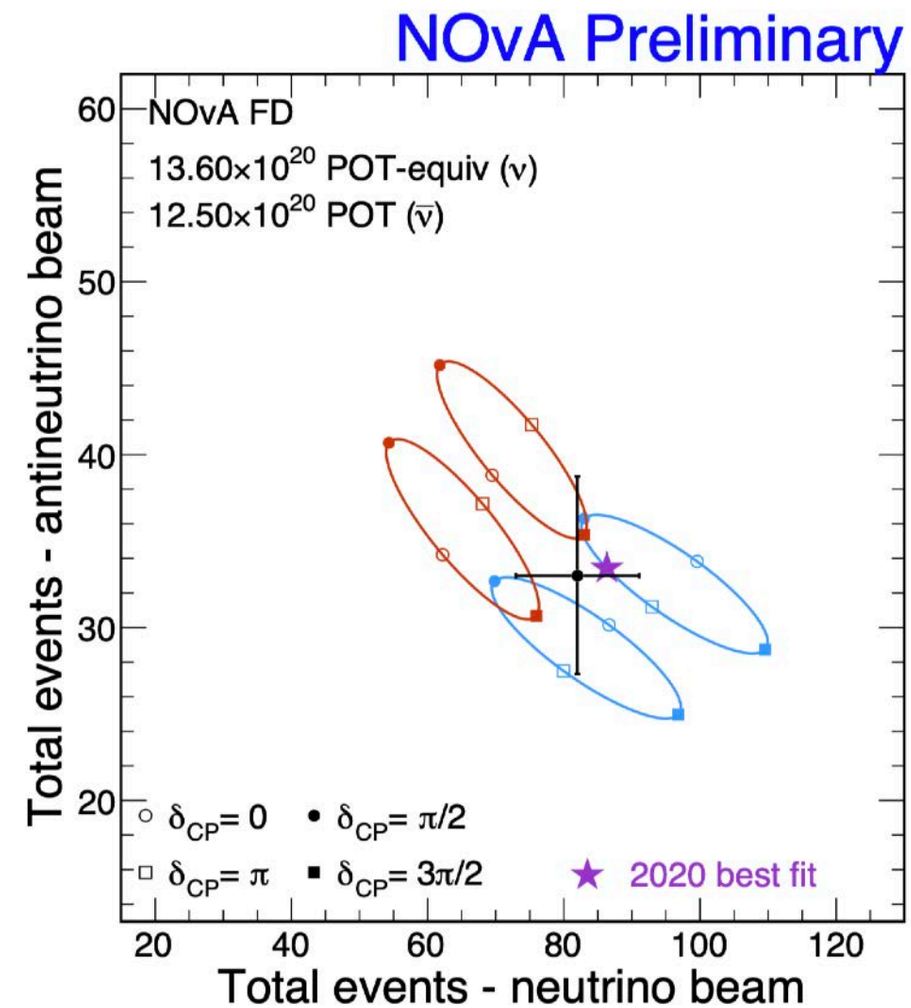
$$\Delta \equiv \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 810 \text{ km}}{2 \text{ GeV}} \simeq \frac{\pi}{2}$$

μ-τ Symmetry in Neutrino Mixing?



Mass ordering and CP violation





T2K sees a large difference between $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

NOvA does not. CPV and mass ordering remain to be resolved.

$$\frac{P_{\bar{\nu}_\mu \to \bar{\nu}_e}}{P_{\nu_\mu \to \nu_e}} \stackrel{?}{=} 1$$

To answer this question we count events:

$$N_e = \mathcal{F}(E) \cdot \sigma(E) \cdot \epsilon(E) \cdot P_{\nu_\mu \to \nu_e}(E)$$
$$\bar{N}_e = \bar{\mathcal{F}}(E) \cdot \bar{\sigma}(E) \cdot \bar{\epsilon}(E) \cdot P_{\bar{\nu}_\mu \to \bar{\nu}_e}(E)$$

counts *flux* *cross-section* *detection* *oscillations*

…and solve:

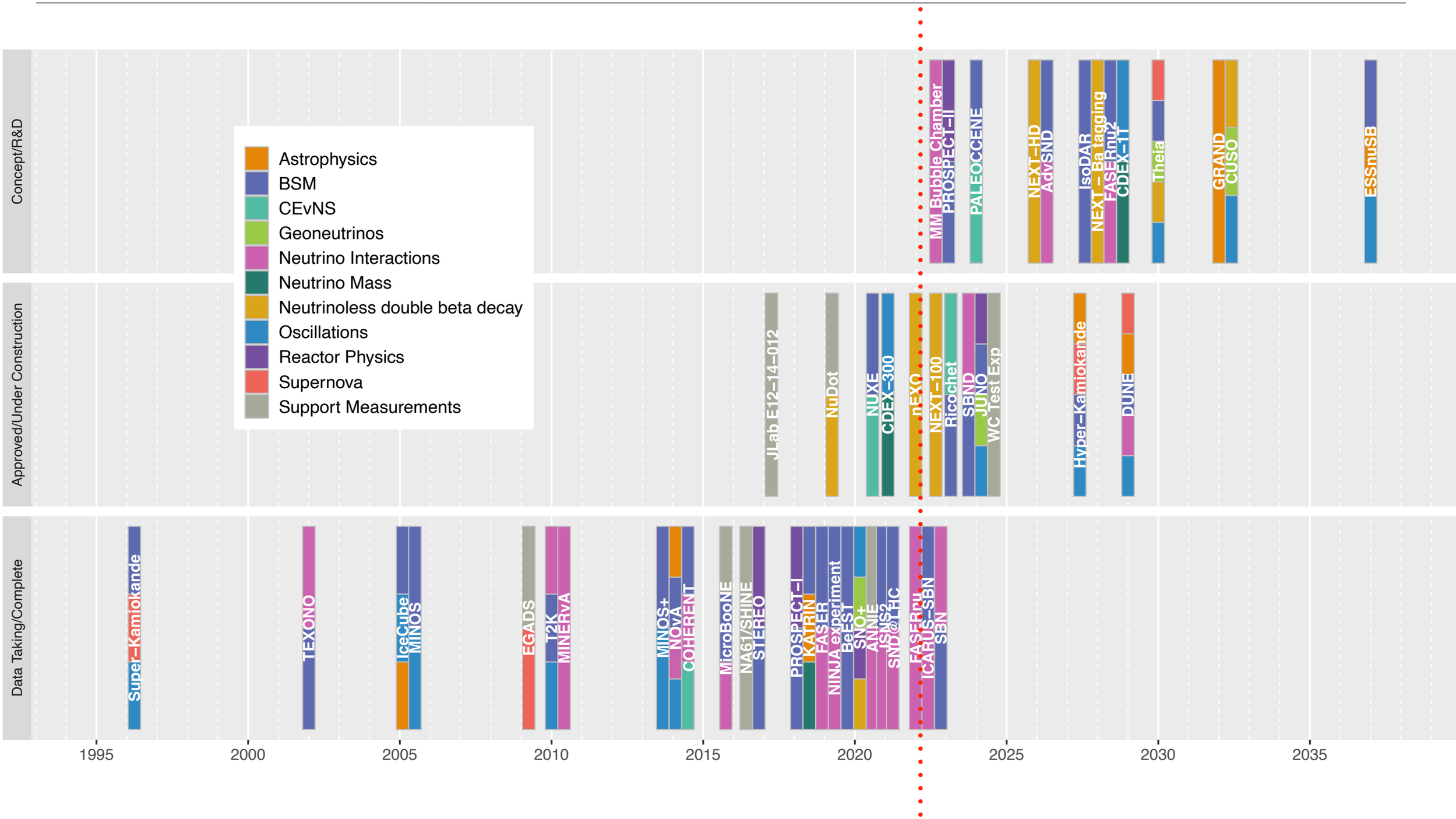
$$\frac{\mathcal{F}}{\bar{\mathcal{F}}} \cdot \frac{\sigma}{\bar{\sigma}} \cdot \frac{\epsilon}{\bar{\epsilon}} \cdot \frac{\bar{N}_e}{N_e} \stackrel{?}{=} 1$$

To reach our goals, the uncertainties in each of these must be below 1%

$$\frac{\mathcal{F}}{\bar{\mathcal{F}}} \cdot \frac{\sigma}{\bar{\sigma}} \cdot \frac{\epsilon}{\bar{\epsilon}} \cdot \frac{\bar{N}_e}{N_e} \stackrel{?}{=} 1$$

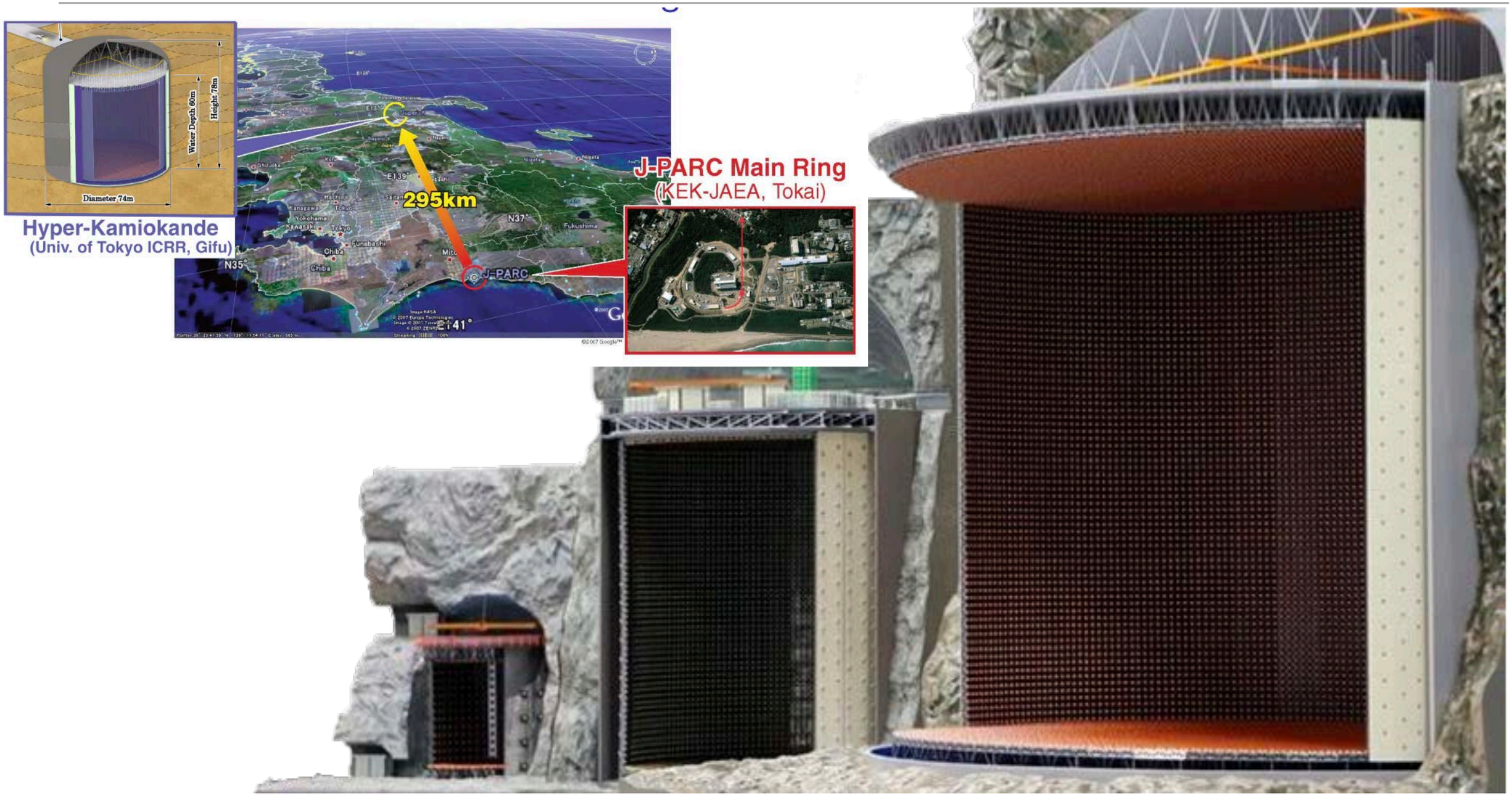
Factor	Note	a priori difference	What's needed		
$\bar{N}_e / N_e$	Event counts		Large far detectors	Intense beams	
$\epsilon / \bar{\epsilon}$	Detection efficiency	~20%	Highly capable far detectors	Highly capable near detectors	Test Beams
$\mathcal{F} / \bar{\mathcal{F}}$	Neutrino flux	~15…30%	Highly capable near detectors	Dedicated measurements	
$\sigma / \bar{\sigma}$	Neutrino-nucleus cross-sections	x 2 to 3	Highly capable near detectors	Dedicated measurement and theory program	Test Beams

Neutrino Experiments Past Current, and Future



(…still work in progress - contact NF conveners if you don't see you experiment!)

T2 Hyper-Kamiokande



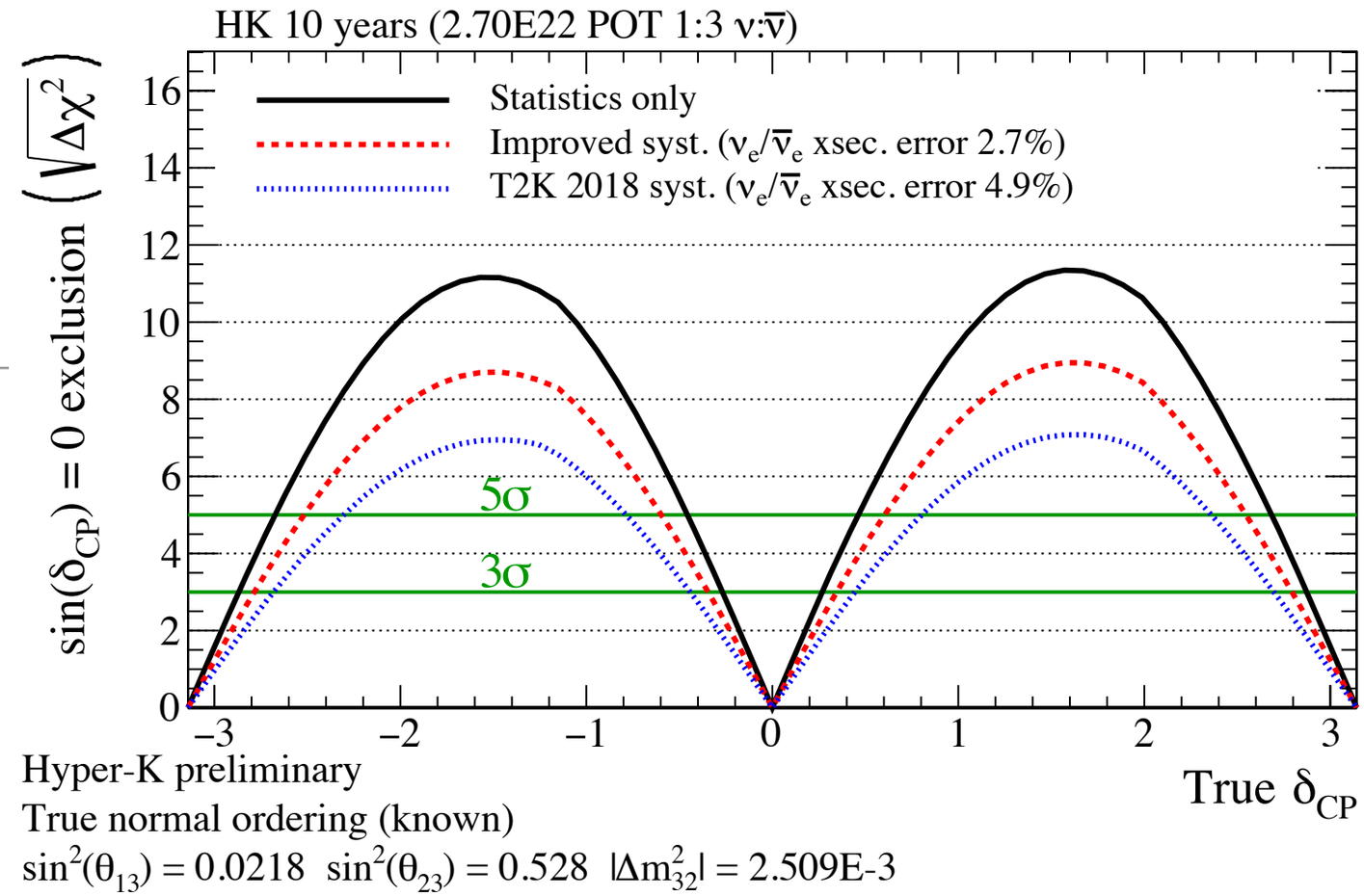
Kamiokande	Super-Kamiokande	Hyper-Kamiokande
3 kton	22.5 kton	188 kton

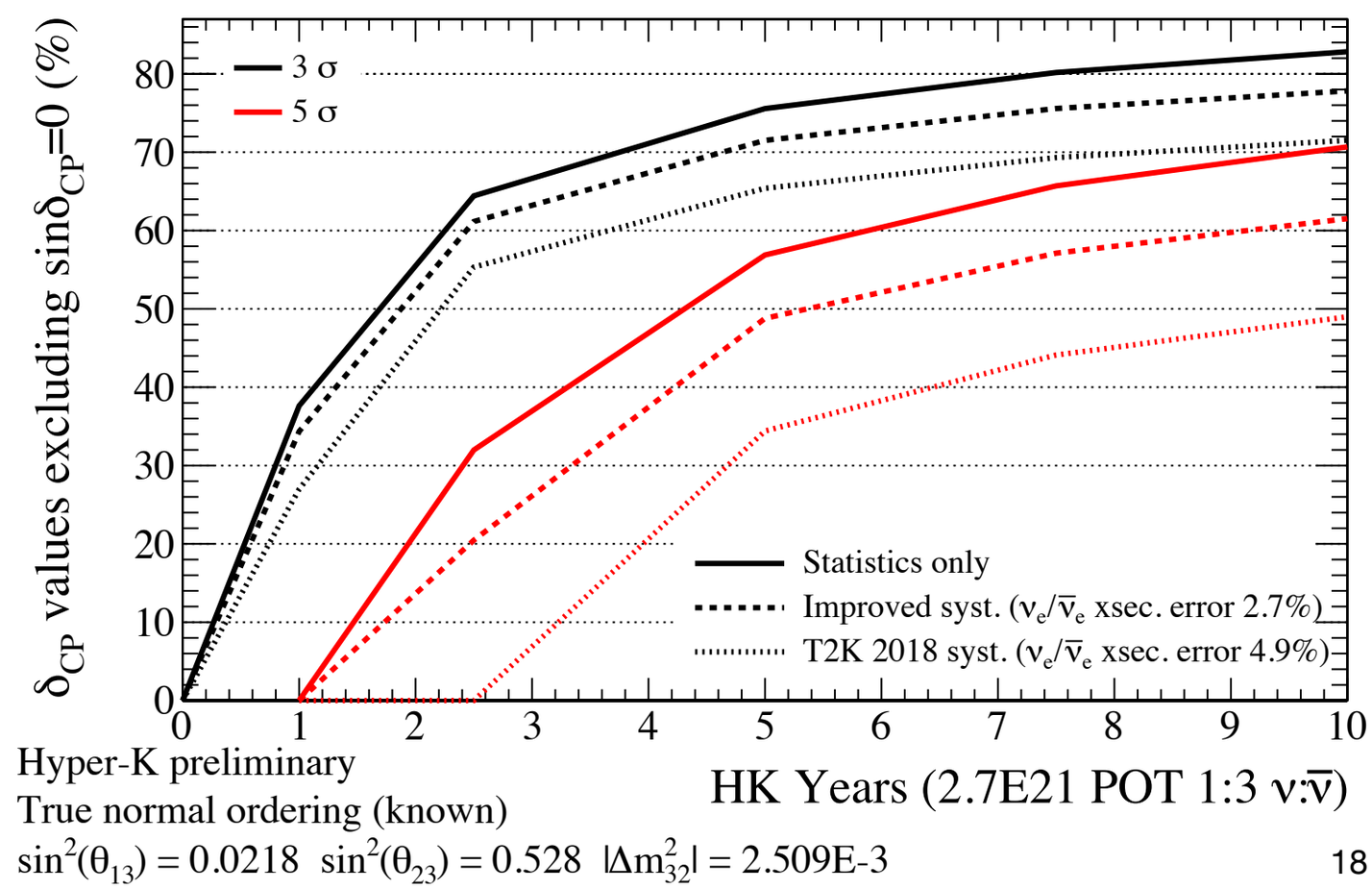
T2HK

Data taking expected to begin in 2027

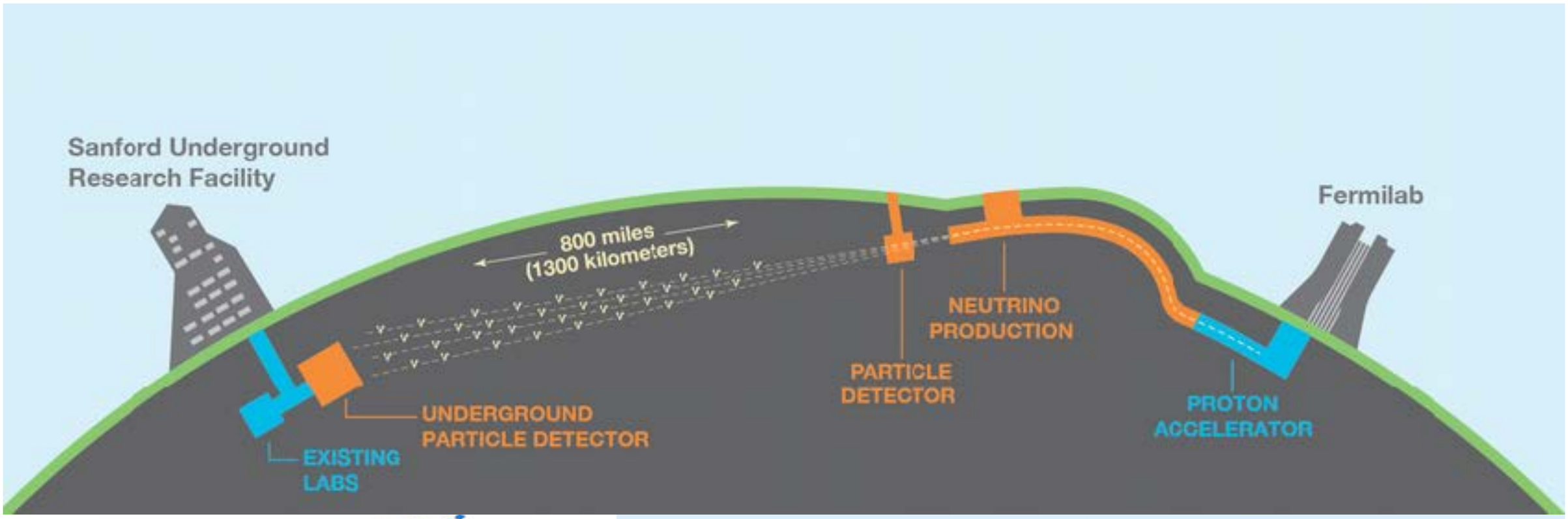
5σ discovery of CP violation in 10 years for 60% of δ_{CP} values

The search depends strongly on resolving the mass ordering and controlling systematic uncertainties

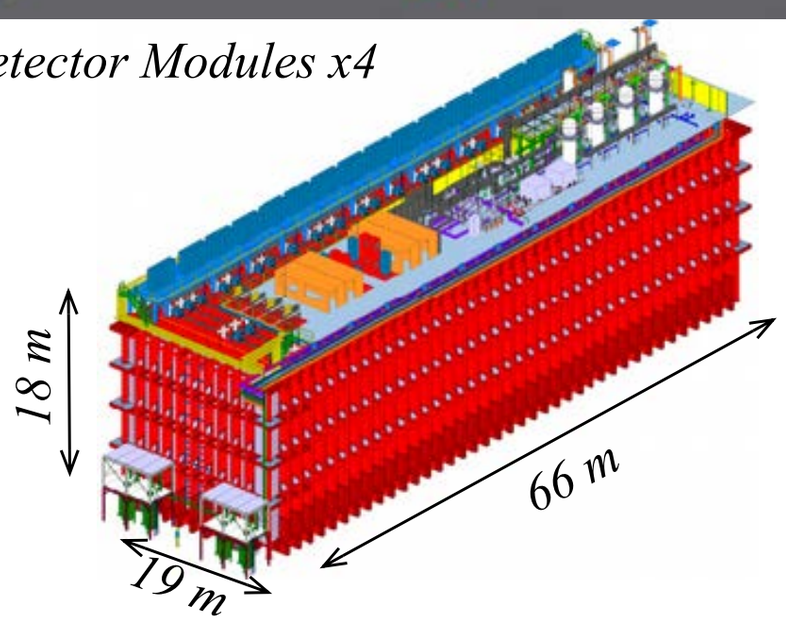




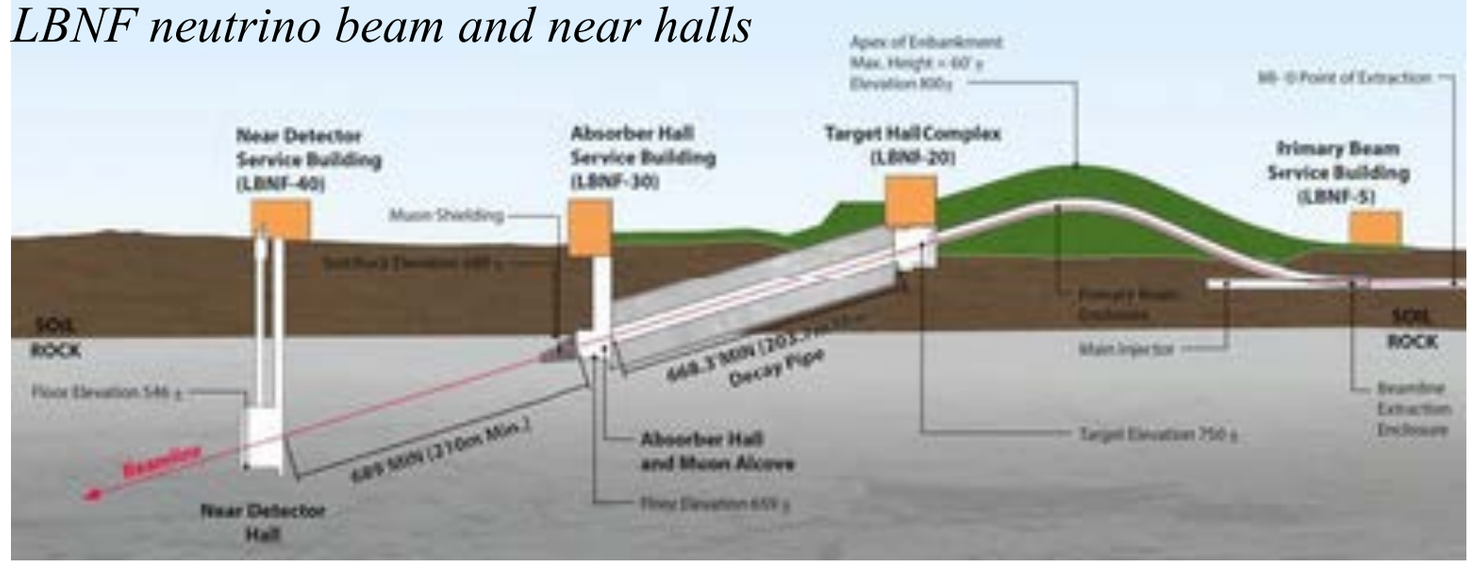
DUNE

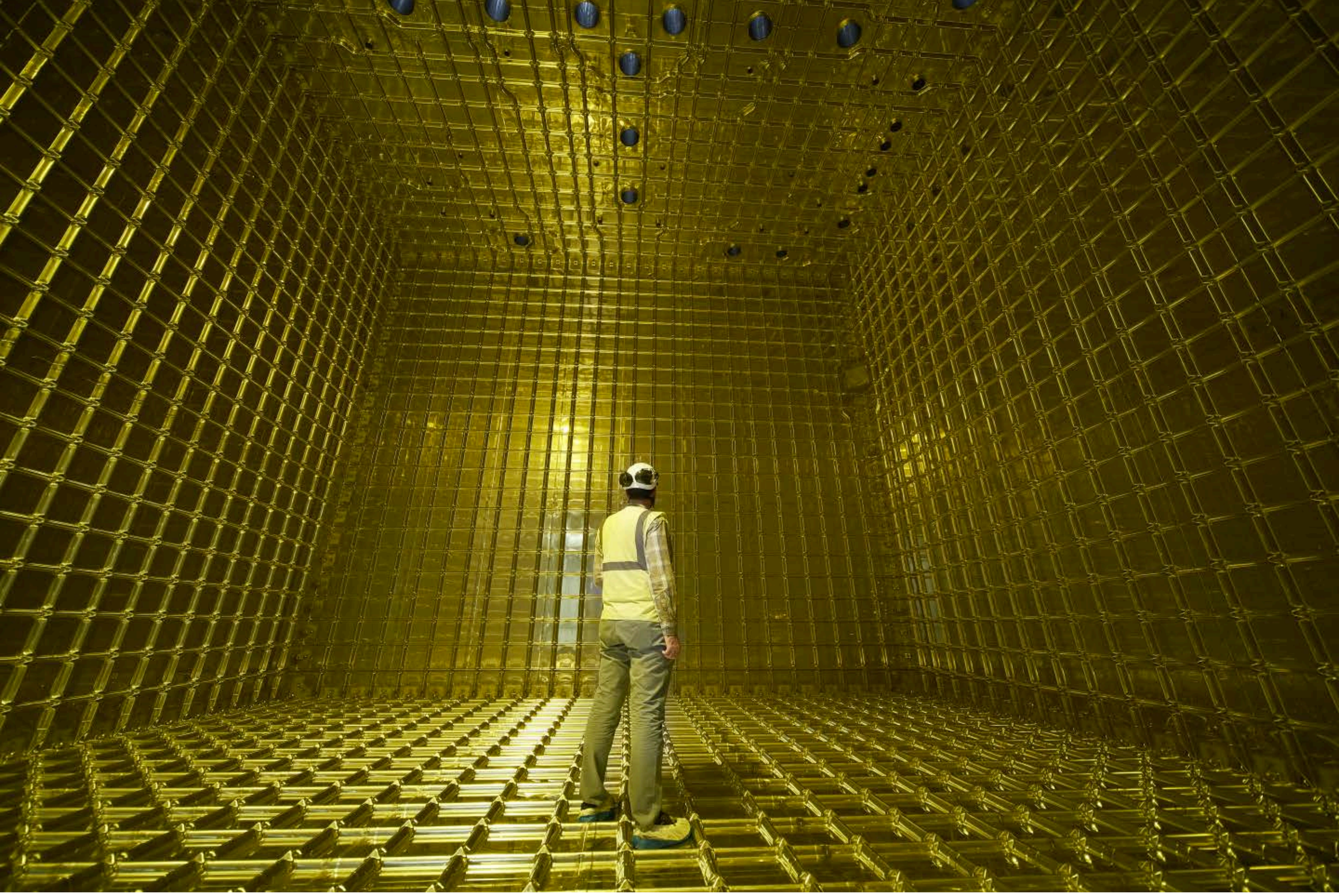


Detector Modules x4



LBNF neutrino beam and near halls

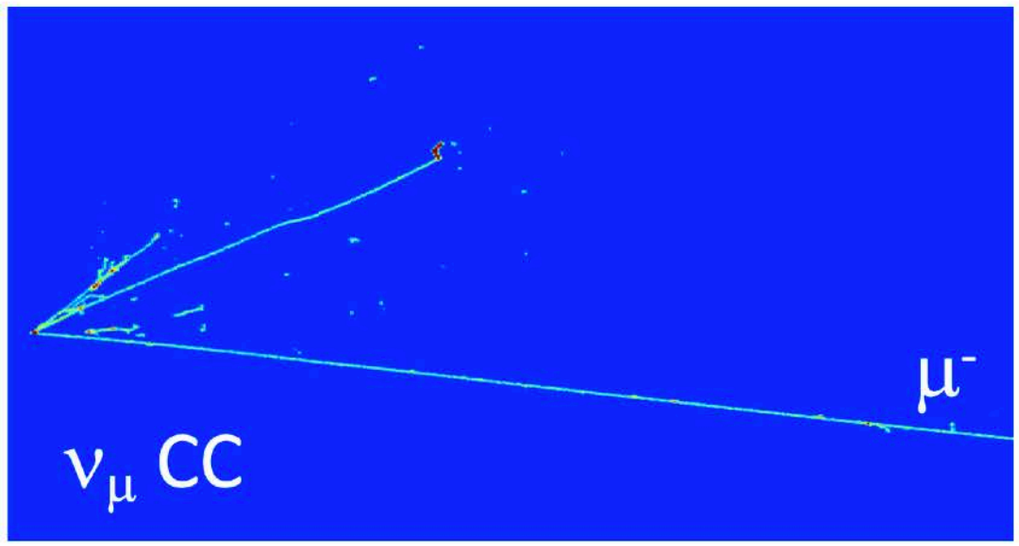




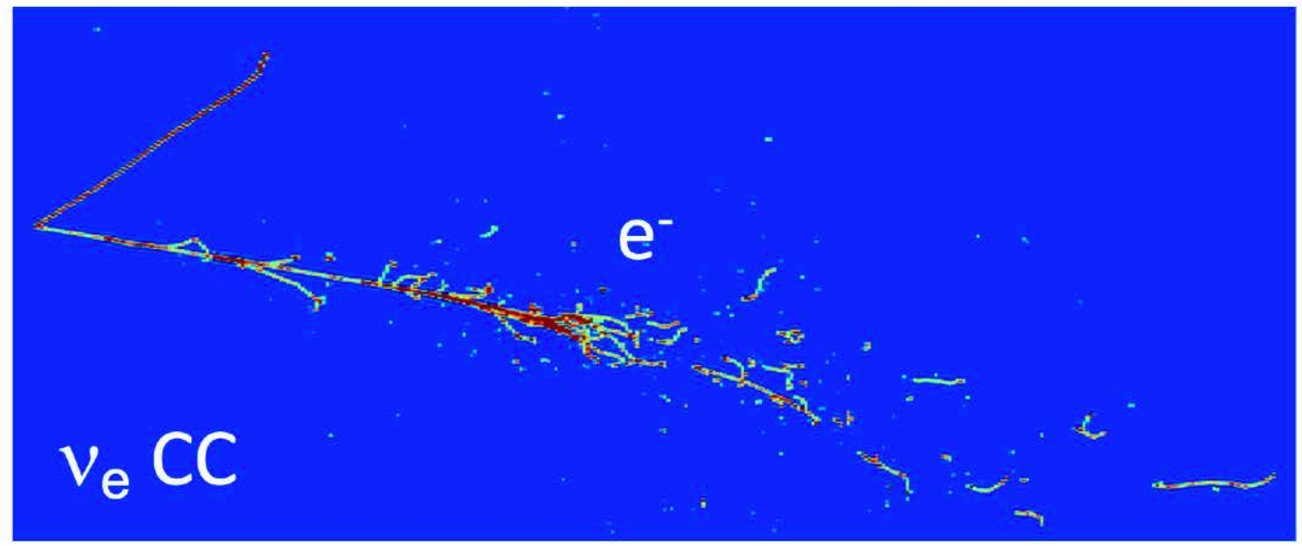
DUNE Prototype at CERN

Events in DUNE

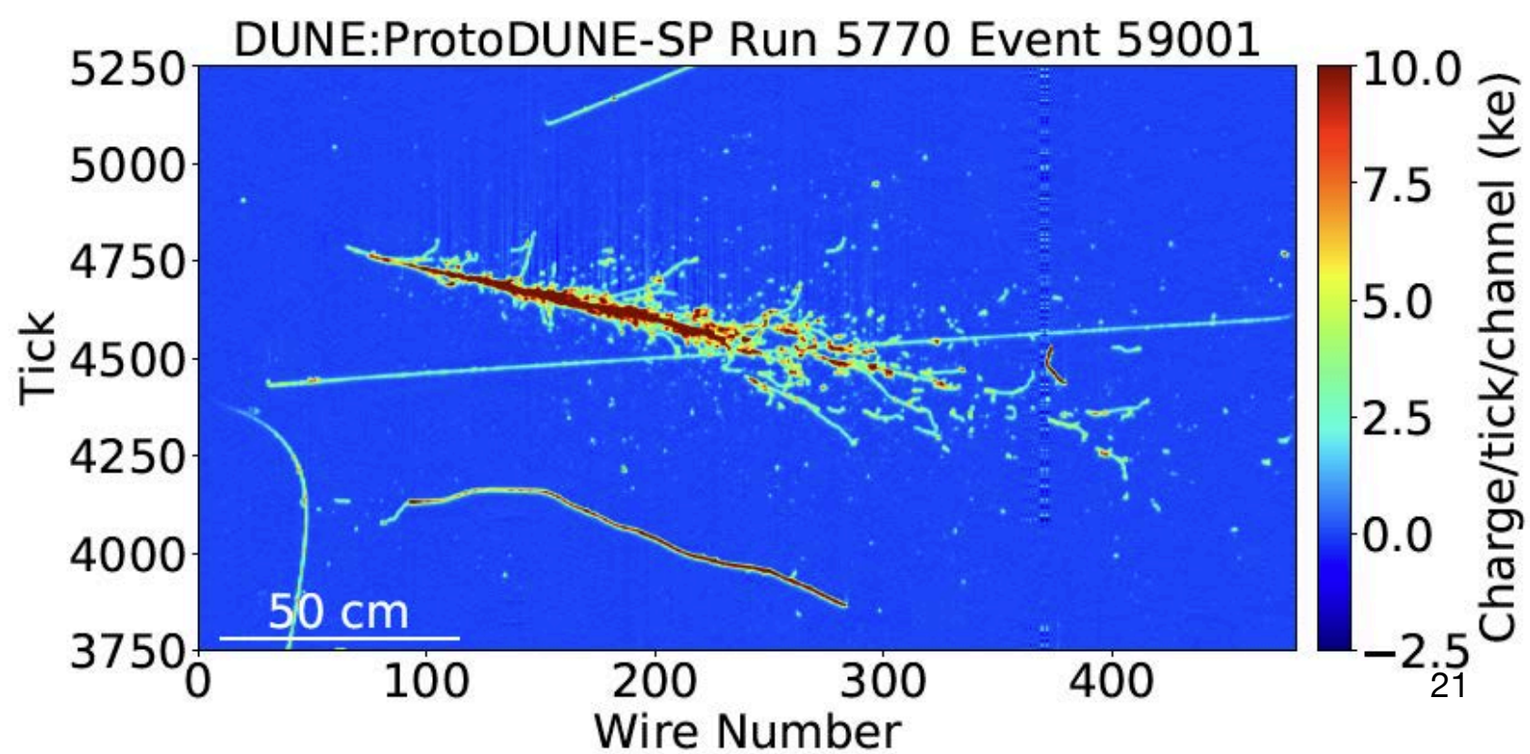
DUNE-MC



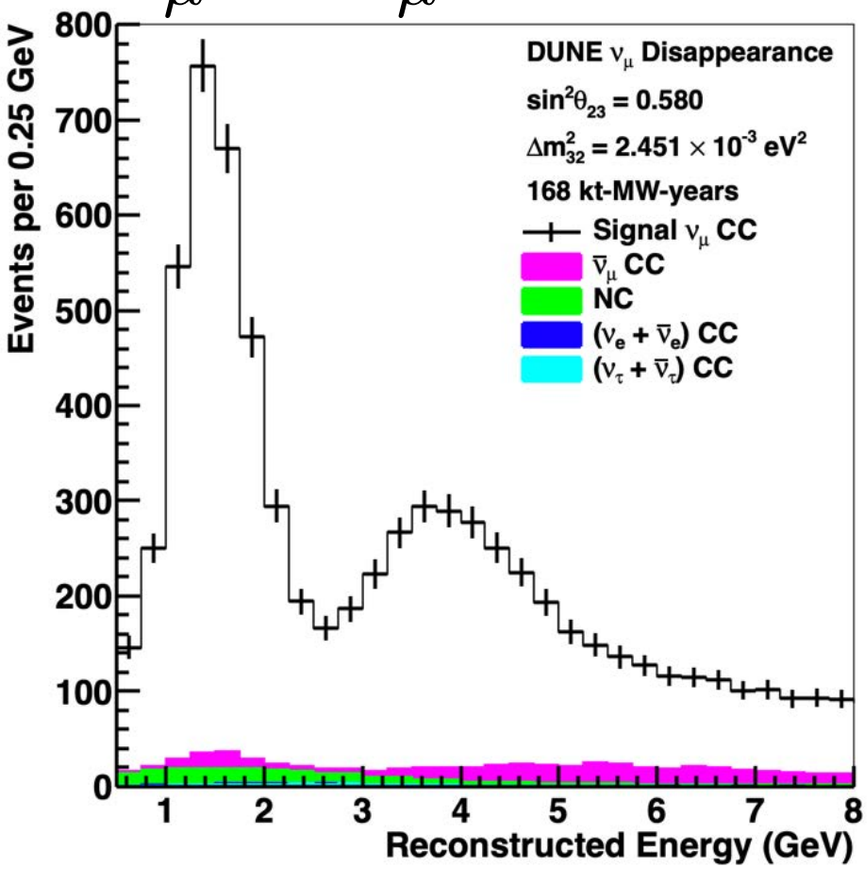
DUNE-MC



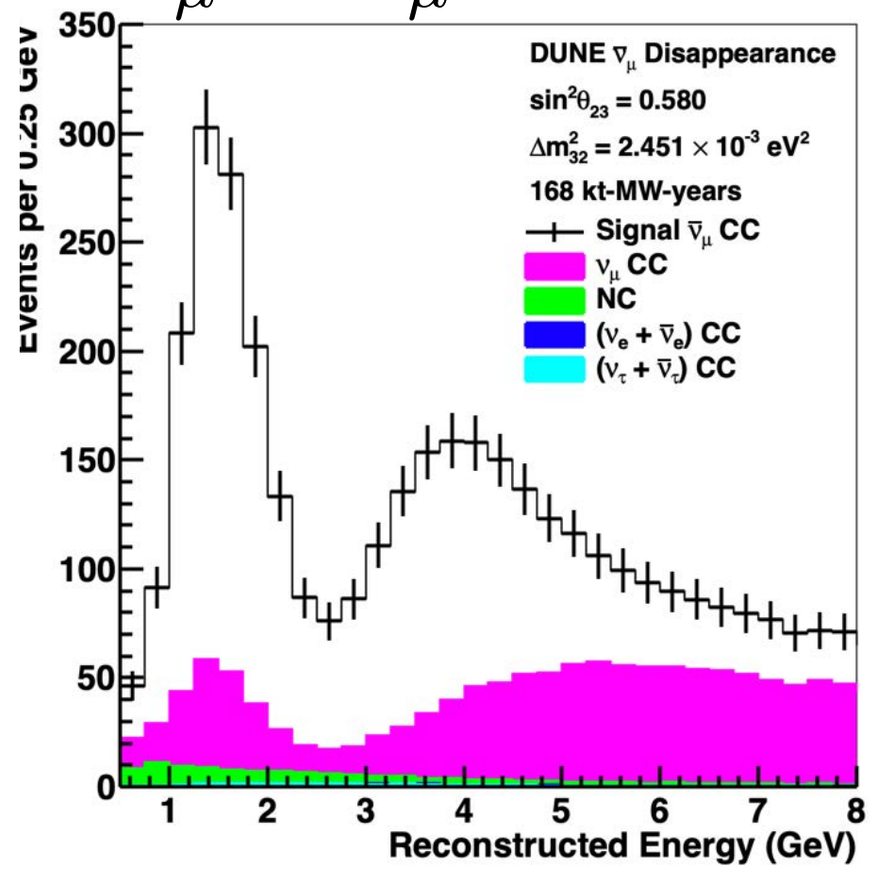
A 6 GeV electron recorded by DUNE prototype at CERN



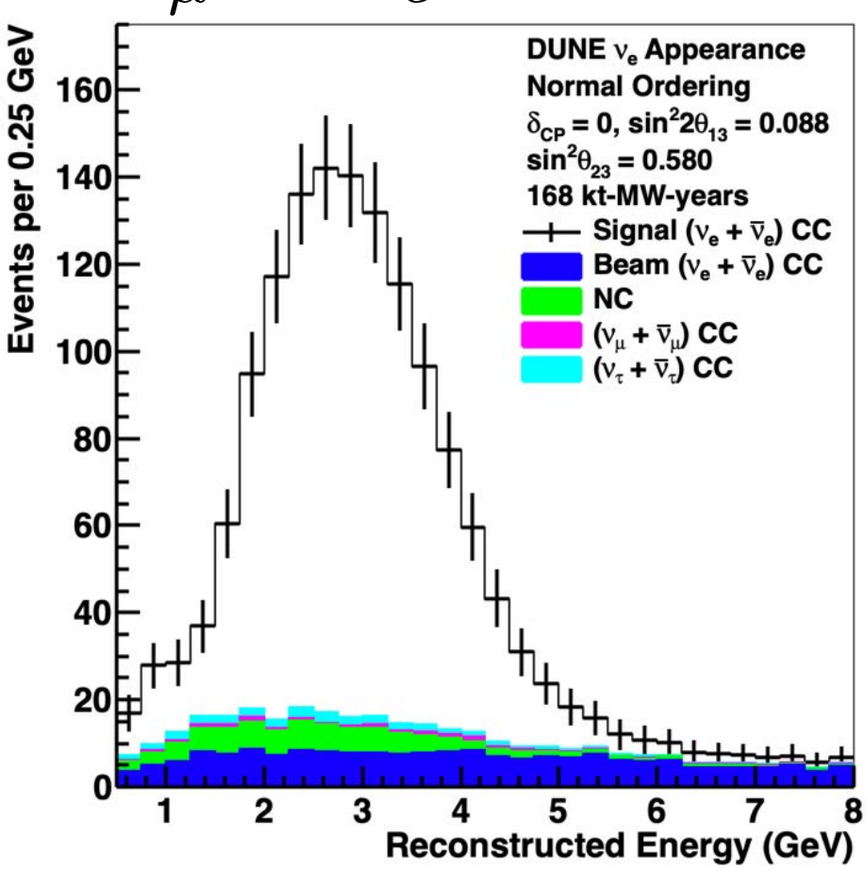
$\nu_\mu \to \nu_\mu$



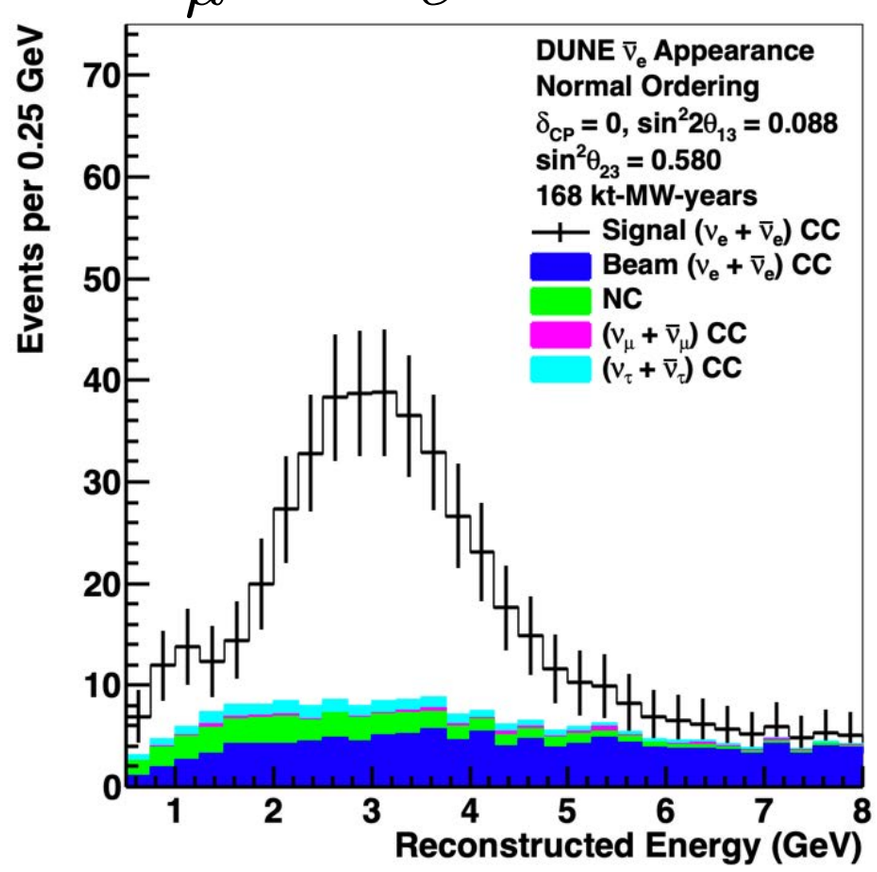
$\bar{\nu}_\mu \to \bar{\nu}_\mu$



$\nu_\mu \to \nu_e$



$\bar{\nu}_\mu \to \bar{\nu}_e$



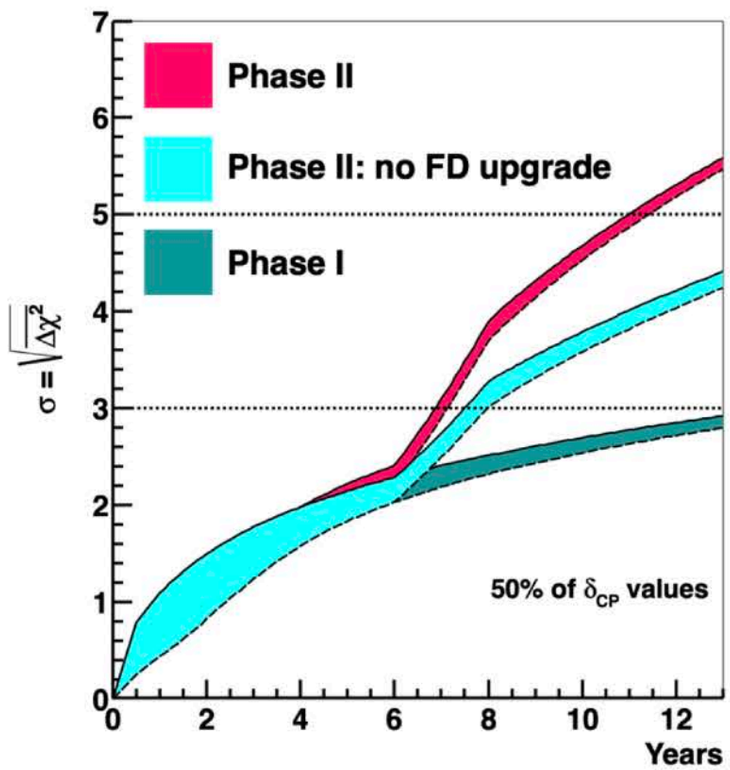
DUNE will measure
$P(\nu_\mu \to \nu_\mu)$,
$P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$,
$P(\nu_\mu \to \nu_e)$, and,
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$,
at very long baseline and over a wide energy range.

Phase 1
Begins in 2029:
5σ resolution of mass ordering

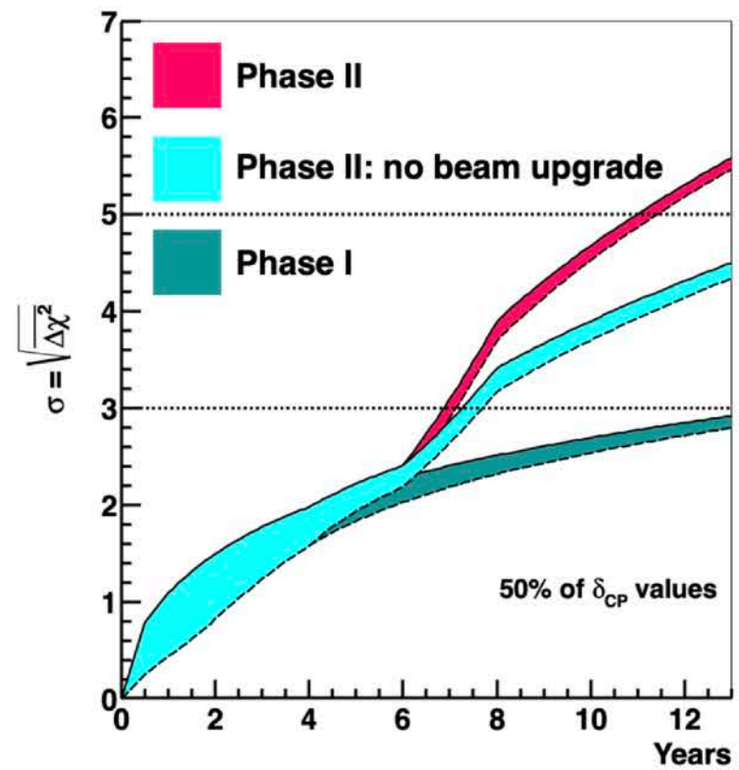
Phase 2
Begins mid 2030's:
5σ discovery of CP violation

Combination of high energy and long baseline gives unique sensitivity to physics beyond PMNS

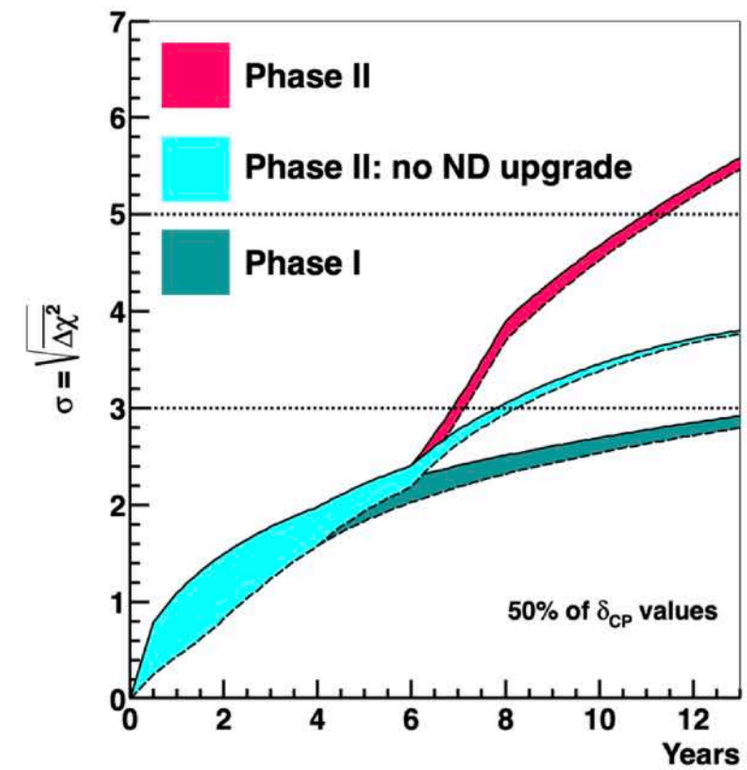
DUNE discovery potential for CP Violation and beyond



Start data taking with **2** detector modules then **4**



Fermilab proton power **1.2 MW** then **2.4 MW**



Phase one near detector and **Phase two near detector**

Discerning Neutrino Mass Models

$$U_{e3} = \sqrt{\frac{\Delta m^2_{12}}{\Delta m^2_{13}}}$$

$$\frac{\sqrt{\Delta m^2_{31}}}{2}\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix}$$

normal mass ordering

$$\sqrt{\Delta m^2_{31}}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

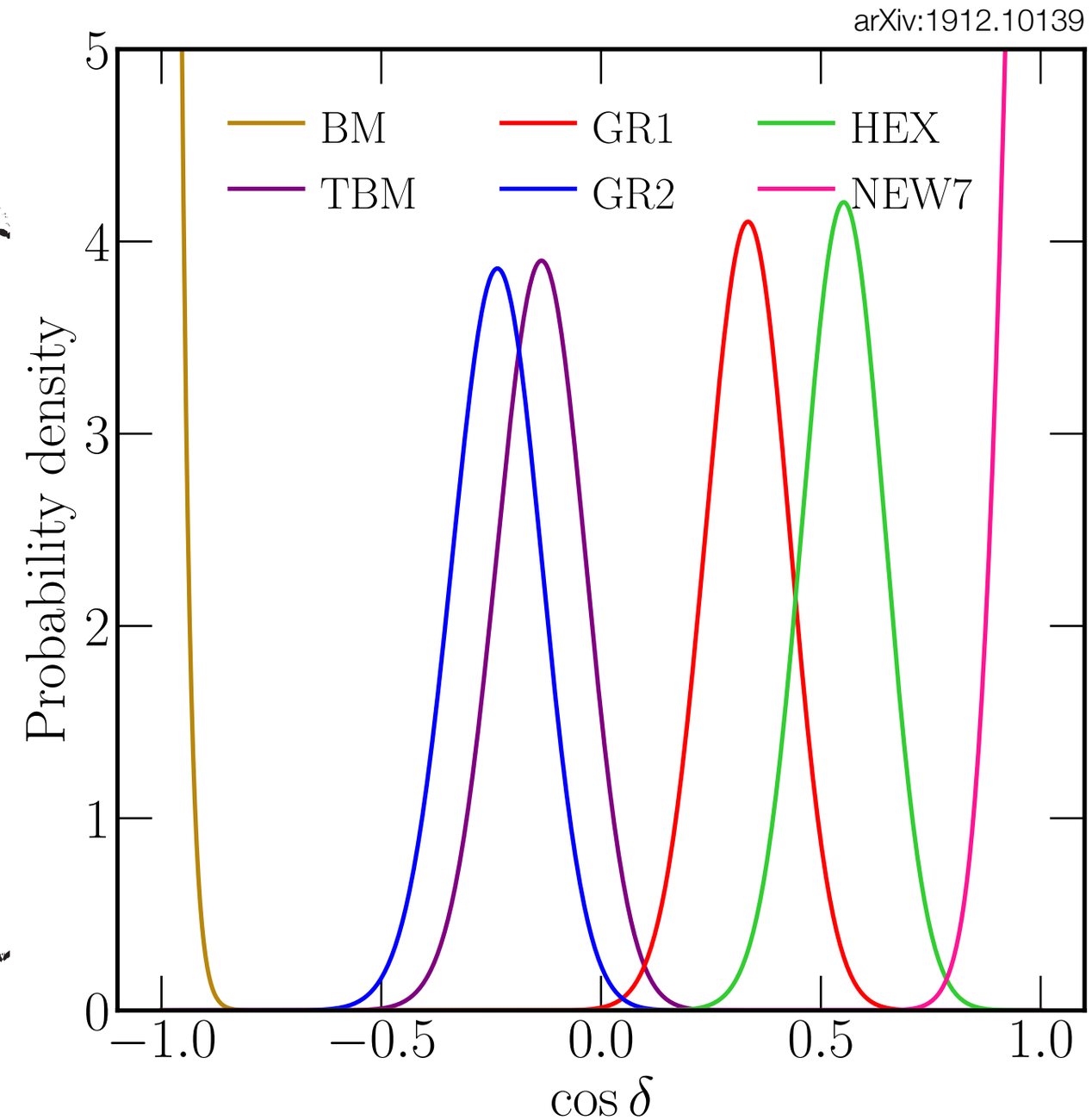
$$\sqrt{\Delta m^2_{31}}\begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

$$\sqrt{\frac{\Delta m^2_{31}}{2}}\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

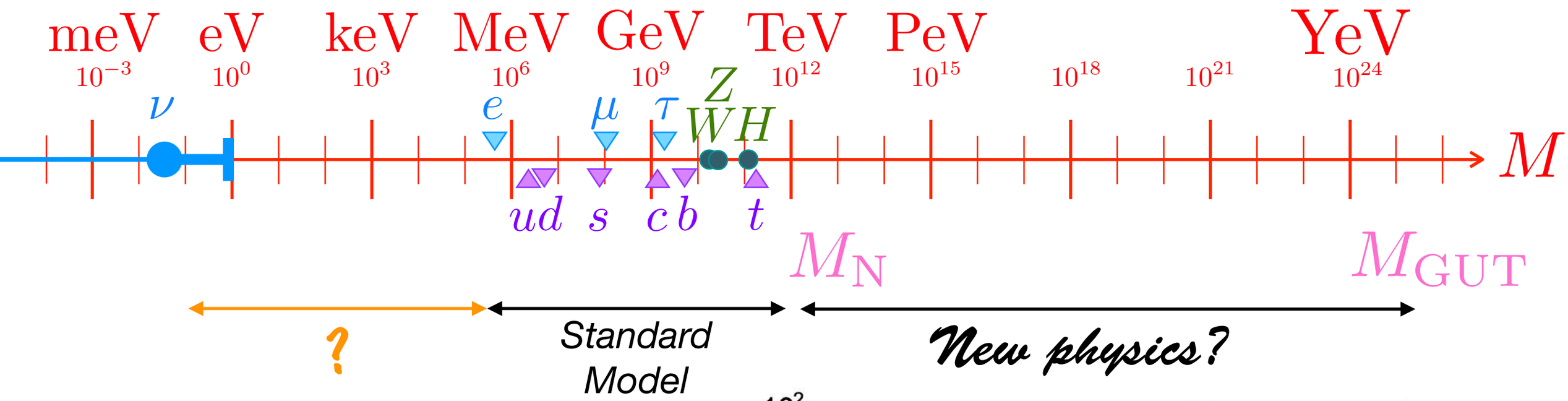
$$U_{e3} = \frac{\Delta m^2_{12}}{\Delta m^2_{13}}$$

inverted mass ordering

After arXiv:hep-ph/0510213

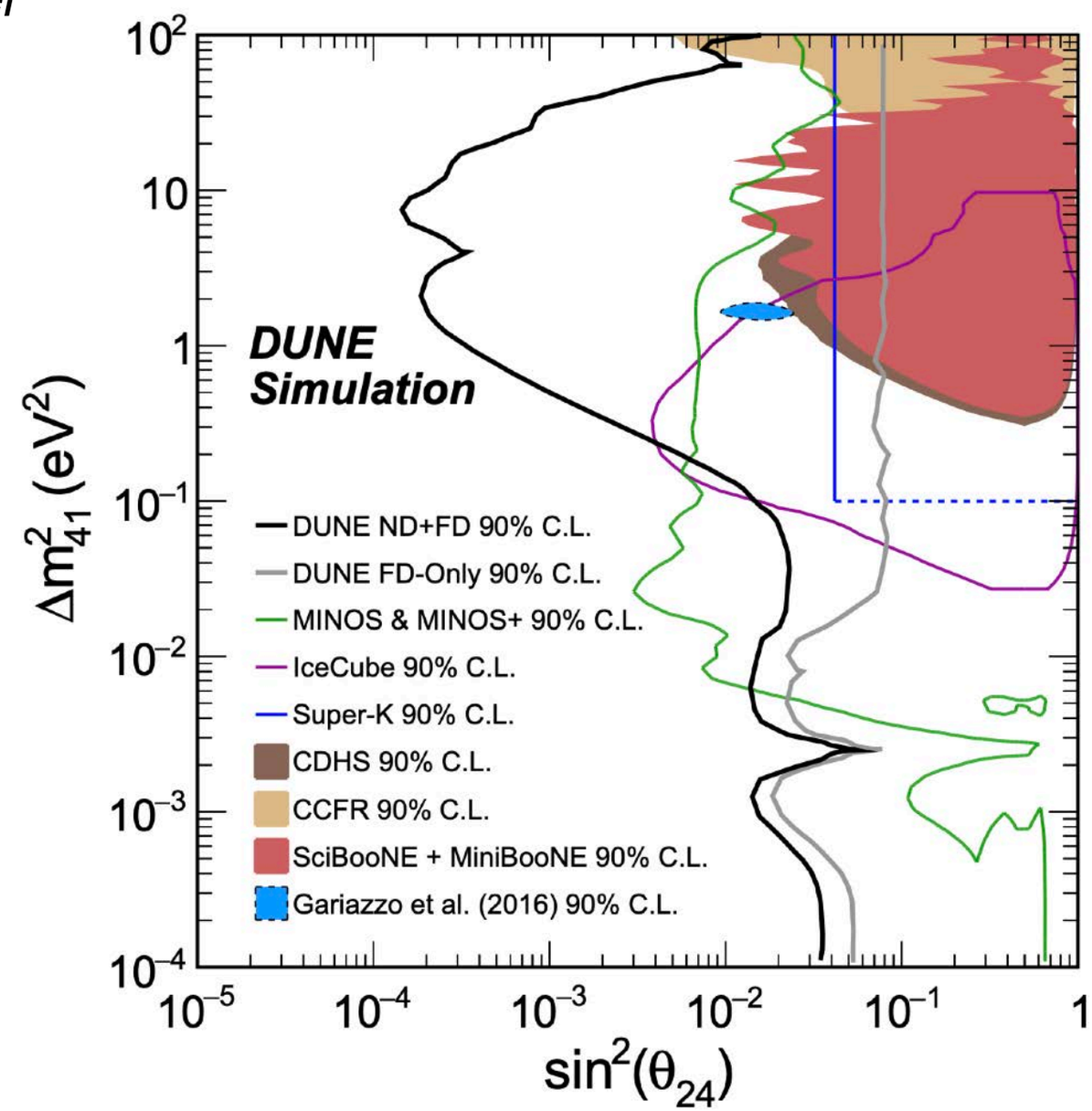


With precision, we can discern among neutrino mass models



Any new particles here?

With precision, we will be prepared for the next steps when PMNS oscillations are the backgrounds for other beyond the standard model searches



Summary

- Neutrino oscillations are an open window on new physics
- Big questions remain to be resolved: μ-τ symmetry, Mass ordering, CP violation
- Precision will be key to answering these questions and to make searches for new physics
- The future program is a world-wide endeavor and will require a diverse experimental program. In the U.S., the program will be anchored by DUNE.