# Neutrino Oscillations
# Three-Flavor and Beyond

***DRAFT 15 JULY 2022***

***Comments welcome here:***

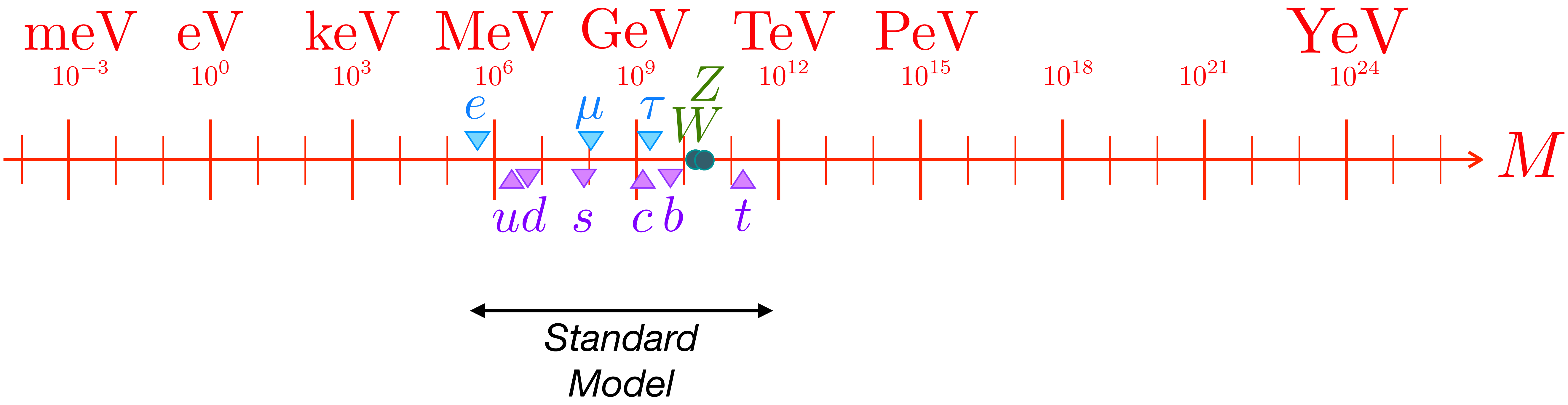
***https://forms.gle/qndm3xgZ8WhaAcKP9***

Mark Messier
Indiana University

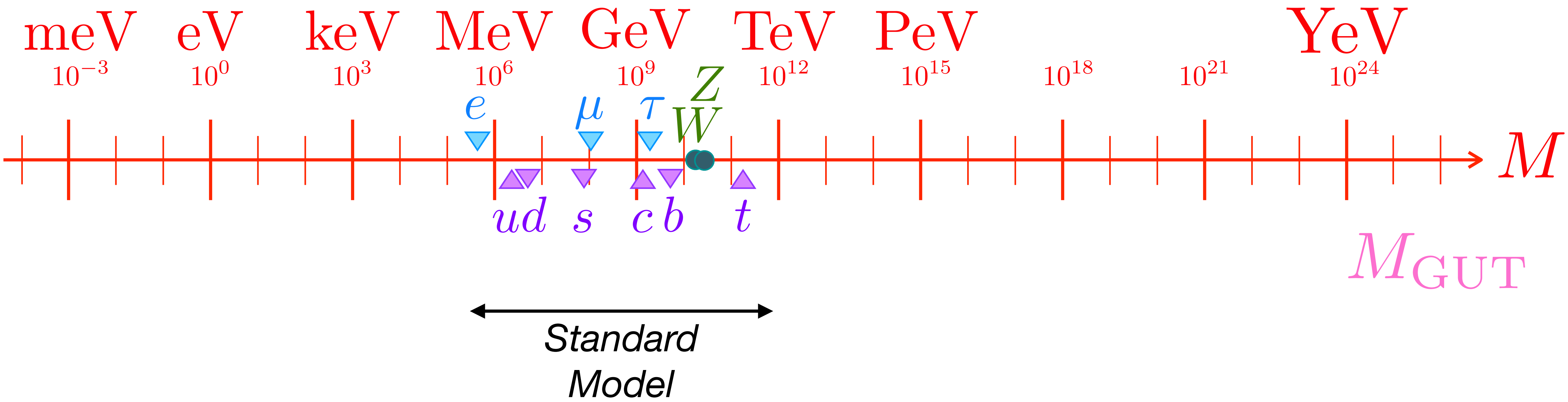
ZOOM
https://virginiatech.zoom.us/j/85314872899?pwd=UlI4ZTdtbkRNb2FWZlVpaE0yZlV4dz09

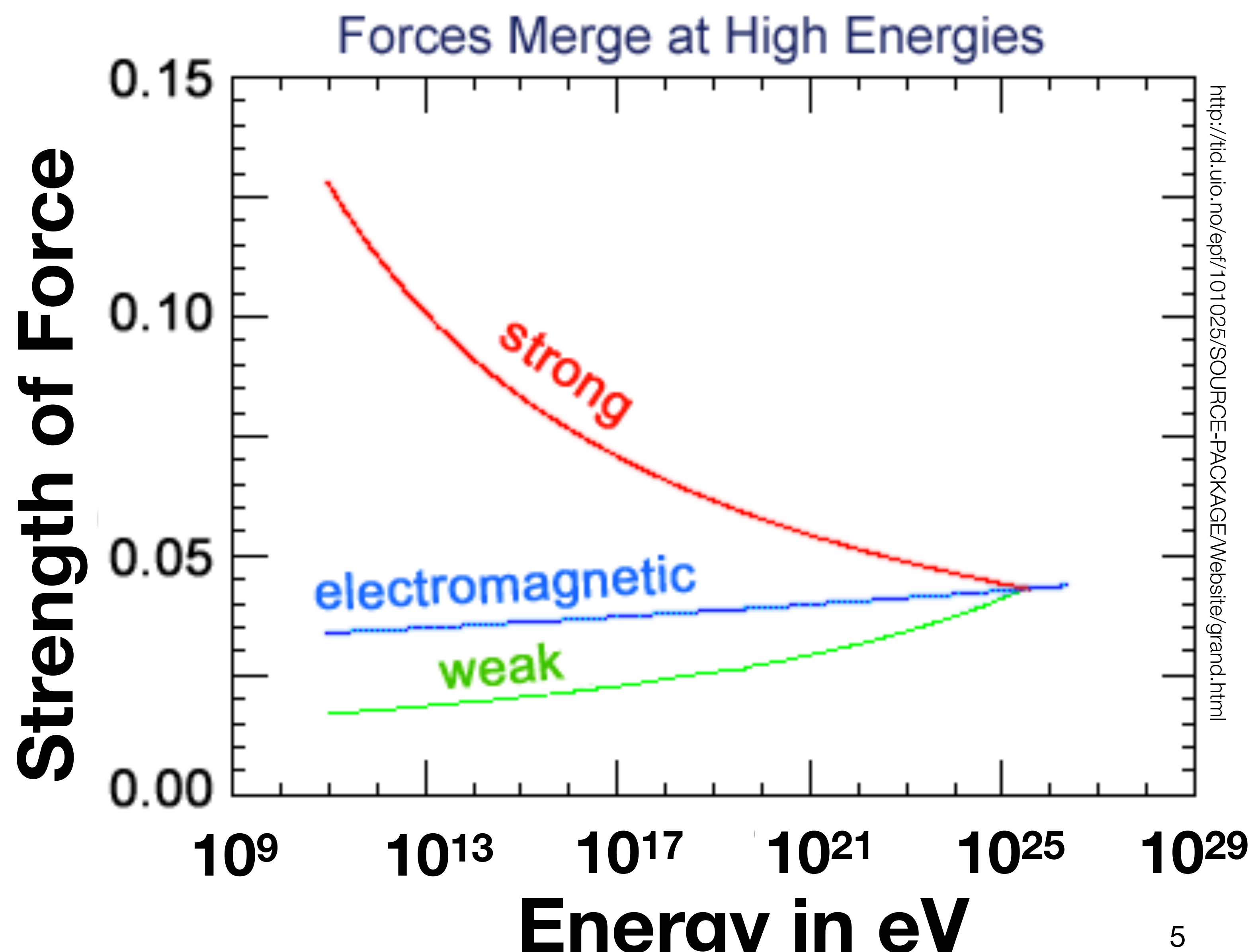
1. Why we love neutrinos
2. Neutrino oscillations
    1. What do we know?
    2. What do we want to know?
3. The future
4. What the future demands
5. The payoff

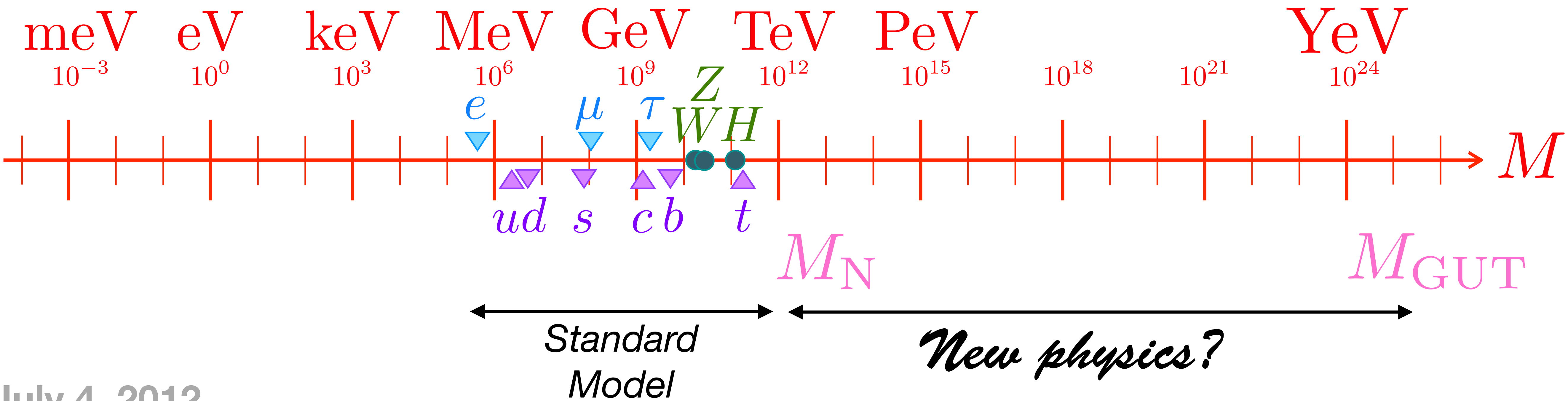
1. **Why we love neutrinos**
2. Neutrino oscillations
    1. What do we know?
    2. What do we want to know?
3. The future
4. What the future demands
5. The payoff



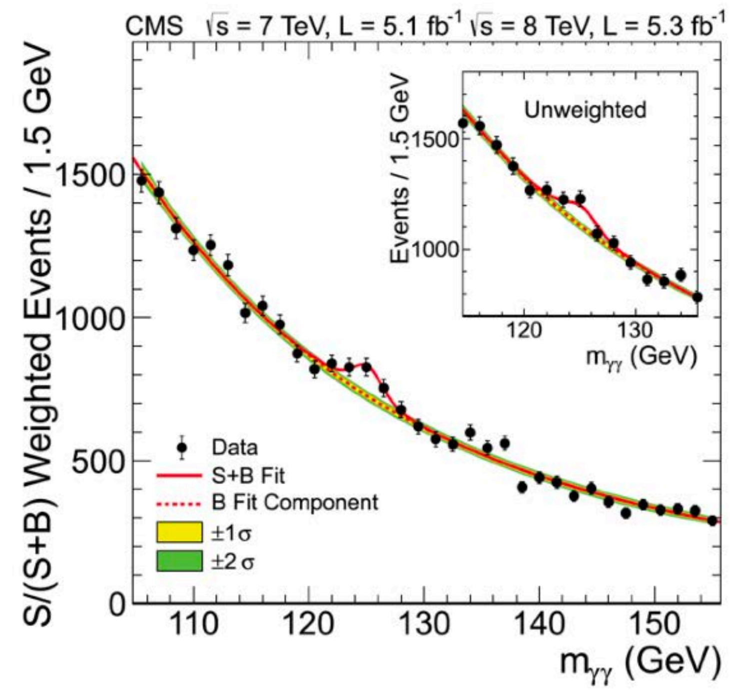

*follows A. de Gouvêa*
*https://indico.cern.ch/event/1011452*


meV
eV
keV
MeV
GeV
TeV
PeV
YeV
$10^{-3}$
$10^{0}$
$10^{3}$
$10^{6}$
$10^{9}$
$10^{12}$
$10^{15}$
$10^{18}$
$10^{21}$
$10^{24}$
$e$
$\mu$
$\tau$
$Z$
$W$
$M$
$u\,d$
$s$
$c\,b$
$t$
$M_{\rm GUT}$
Standard Model

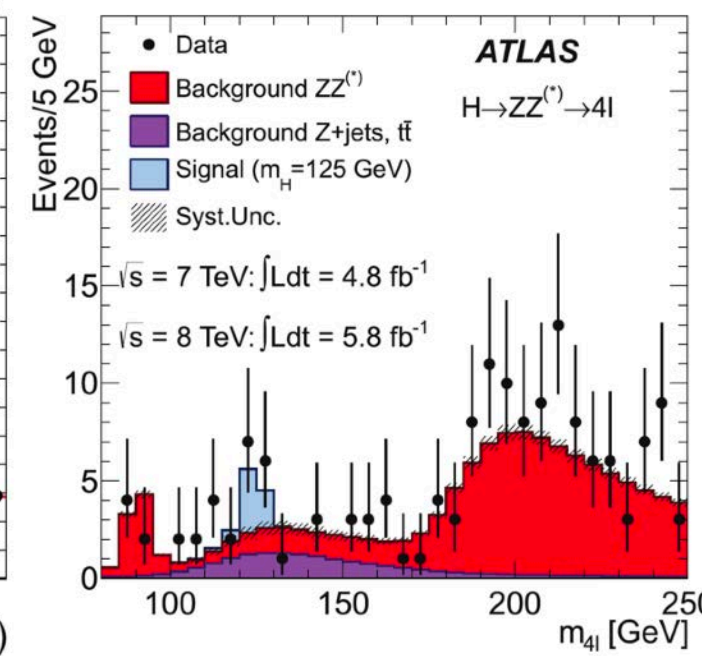

Forces Merge at High Energies
Strength of Force
0.15
0.10
0.05
0.00
strong
electromagnetic
weak
$10^{9}$
$10^{13}$
$10^{17}$
$10^{21}$
$10^{25}$
$10^{29}$
Energy in eV
http://tid.uio.no/epf/101025/SOURCE-PACKAGE/Website/grand.html




July 4, 2012


PRL B176



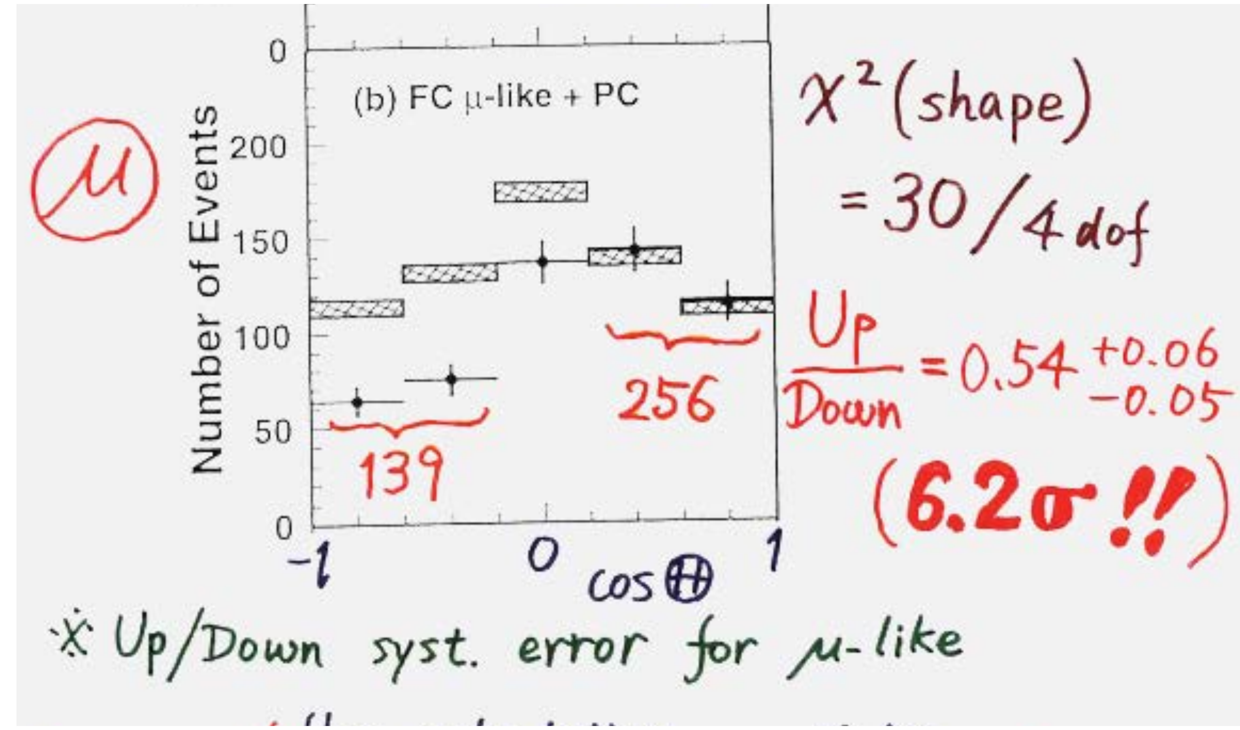

$$\mathcal{L}_{\text{mass}} = \begin{bmatrix} \bar{\psi}_{\mathrm{L}} & \bar{\psi}_{\mathrm{R}} \end{bmatrix} \begin{bmatrix} 0 & m_{\mathrm{D}} \\ m_{\mathrm{D}} & 0 \end{bmatrix} \begin{bmatrix} \psi_{\mathrm{L}} \\ \psi_{\mathrm{R}} \end{bmatrix}$$

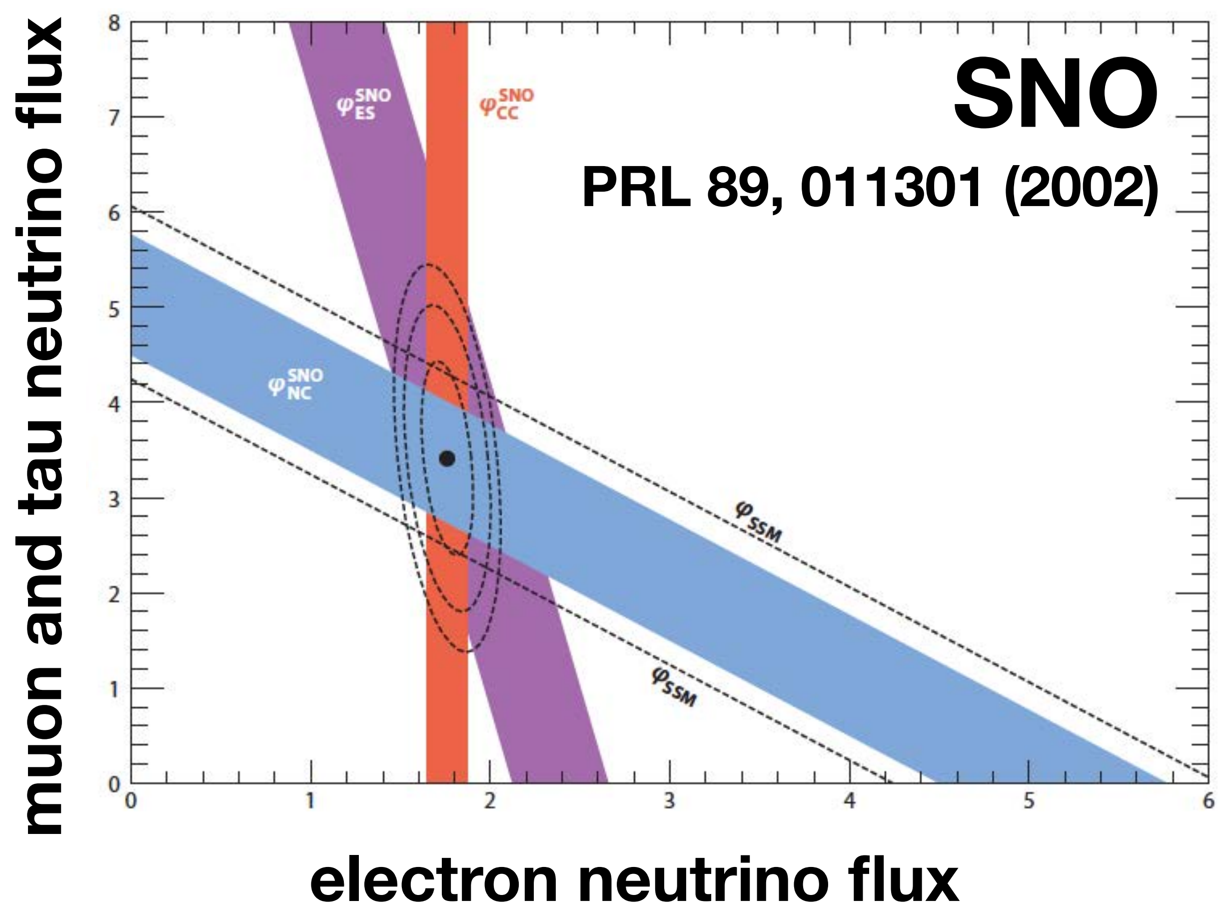
**Takaaki Kajita**
**Super-Kamiokande Collaboration**
University of Tokyo, Kashiwa, Japan

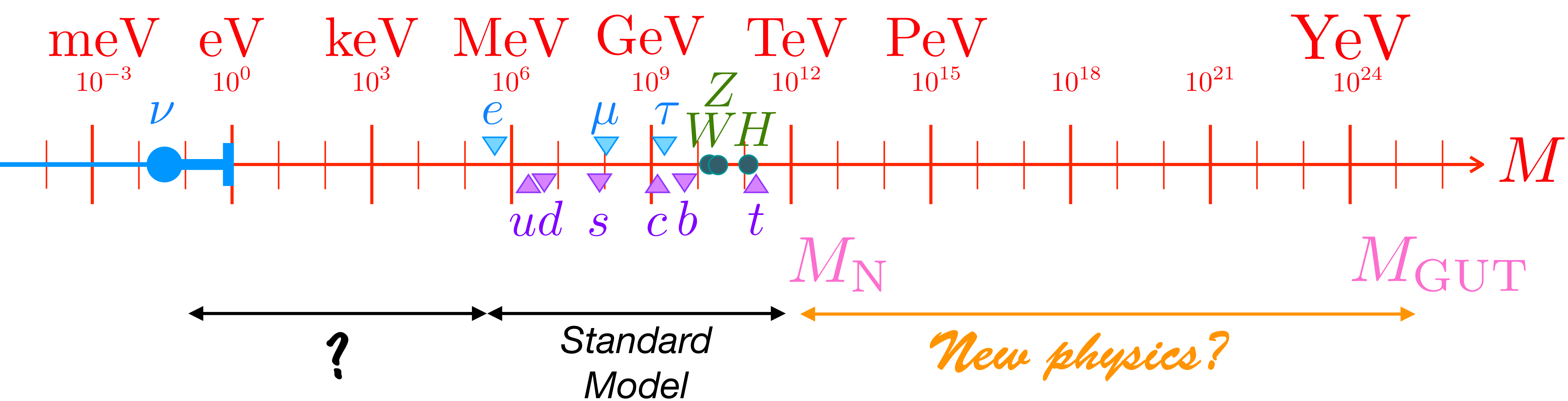
**Arthur B. McDonald**
**Sudbury Neutrino Observatory Collaboration**
Queen's University, Kingston, Canada

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

**T. Kajita June 5th, at Neutrino 1998**





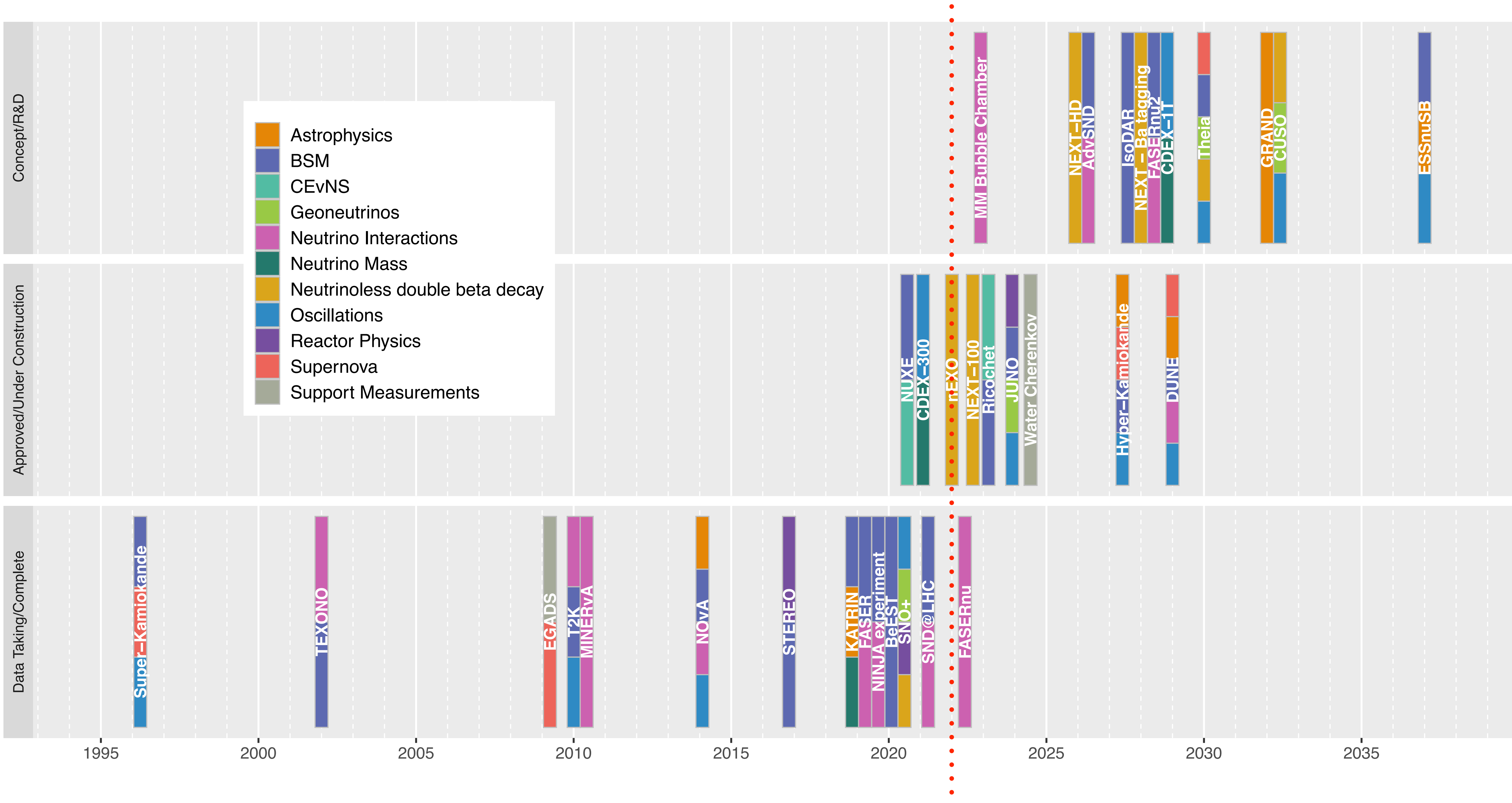

$$\mathcal{L}_{\text{mass}} = \begin{bmatrix} \bar{\nu}_{\text{L}} & \bar{\nu}_{\text{R}} \end{bmatrix} \begin{bmatrix} 0 & m_{\text{D}} \\ m_{\text{D}} & M_{\text{M}} \end{bmatrix} \begin{bmatrix} \nu_{\text{L}} \\ \nu_{\text{R}} \end{bmatrix}$$

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

$$10^{-2}\ \text{eV} \simeq \frac{(10^6 \ldots 10^{11})^2\ \text{eV}^2}{(10^{14} \ldots 10^{24})\ \text{eV}}$$

***Neutrino masses may probe physics approaching the GUT scale***

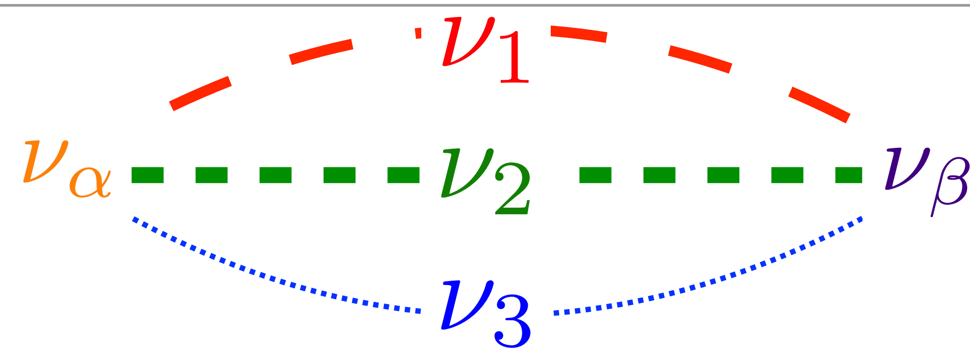
# Neutrino Experiments Past Current, and Future




*(NB: will need to update and add link to form….)*

1. Why we love neutrinos
2. **Neutrino oscillations**
    1. **What do we know?**
    2. **What do we want to know?**
3. The future
4. What the future demands
5. The payoff

# Neutrino oscillations




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

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

$|\Delta m^2_{32}| \equiv |m^2_3 - m^2_2|$
$\simeq 2 \times 10^{-3}\ \mathrm{eV}^2$

$\nu_\mu \longrightarrow \nu_\mu$
$\nu_\mu \longrightarrow \nu_\tau$

atmospheric and
long baseline

$\Delta m^2_{31} \simeq \Delta m^2_{32}$

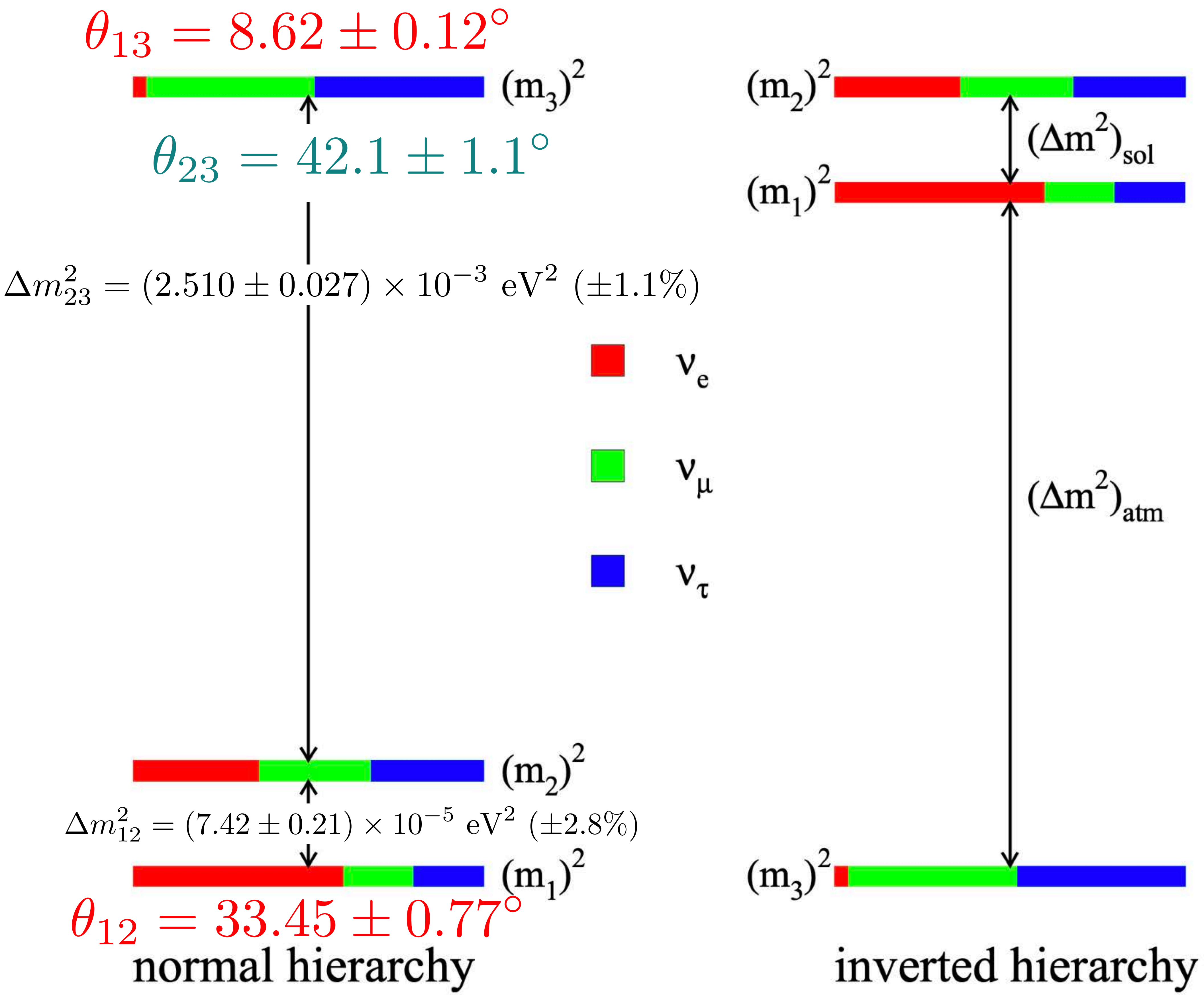
$\nu_e \longrightarrow \nu_e$
$\nu_\mu \longrightarrow \nu_e$

reactor and
long baseline

$\Delta m^2_{21} \simeq 8 \times 10^{-5}\ \mathrm{eV}^2$

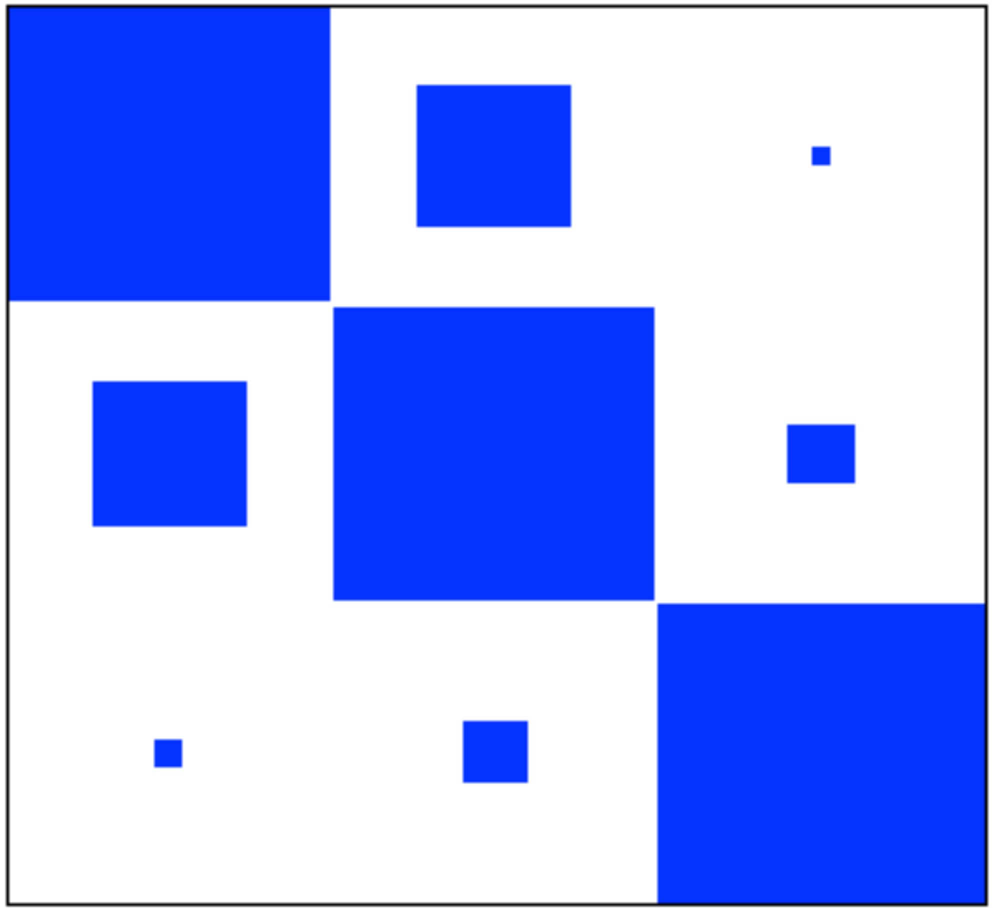
$\nu_e \longrightarrow \nu_e$
$\nu_e \longrightarrow \nu_\mu + \nu_\tau$

solar and
reactor

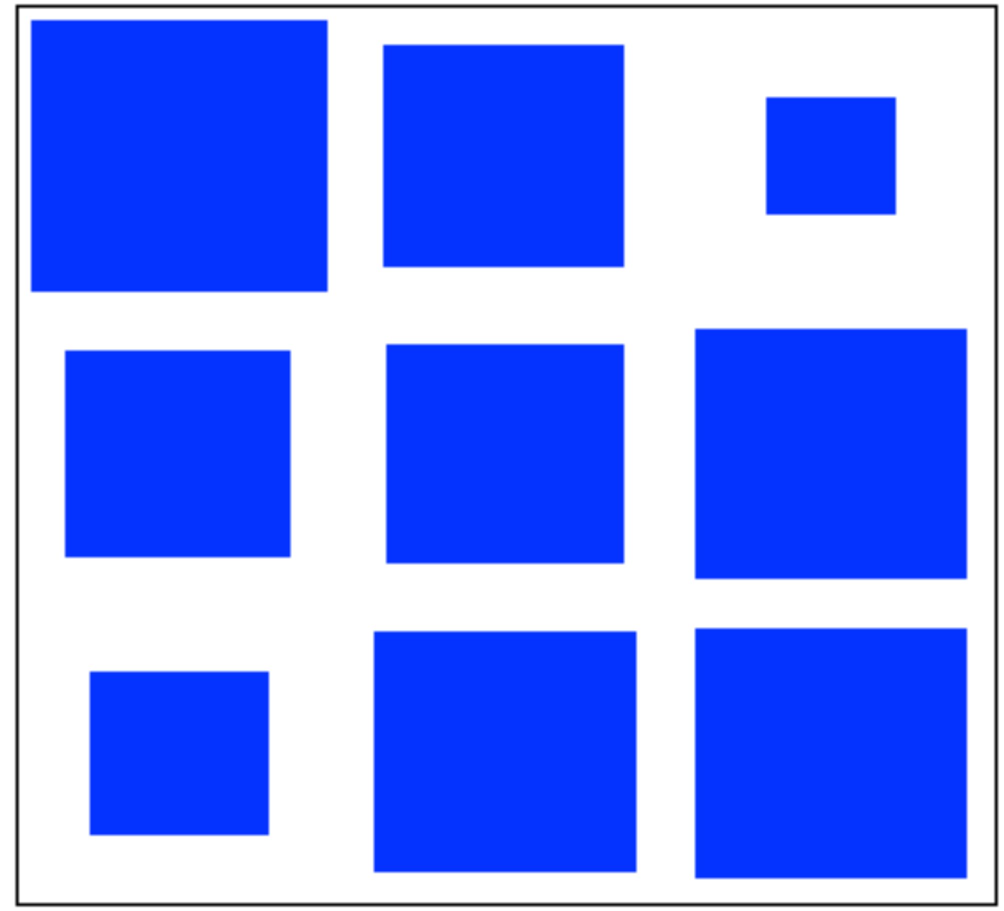



arXiv:2102.00594 NuFit v5.1

Quark mixing

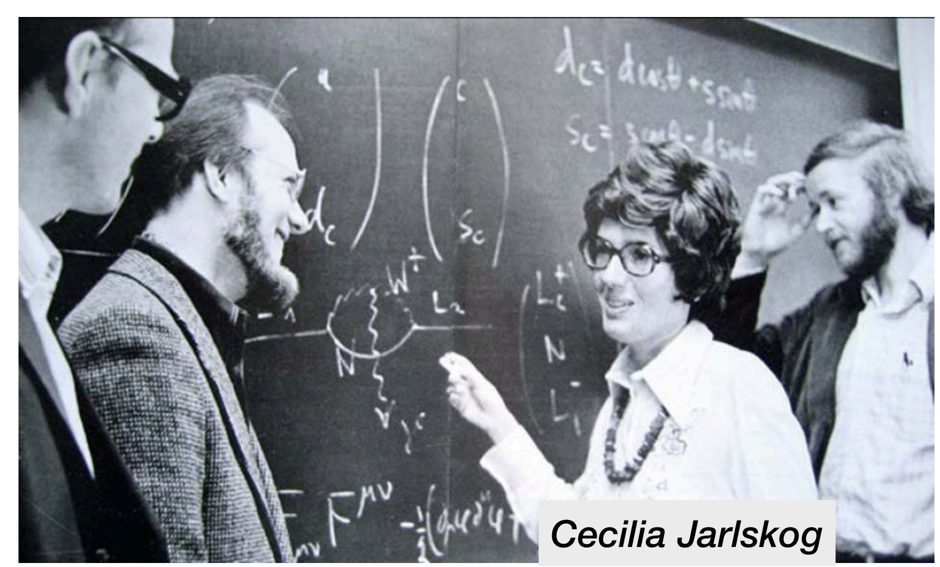


Neutrino mixing

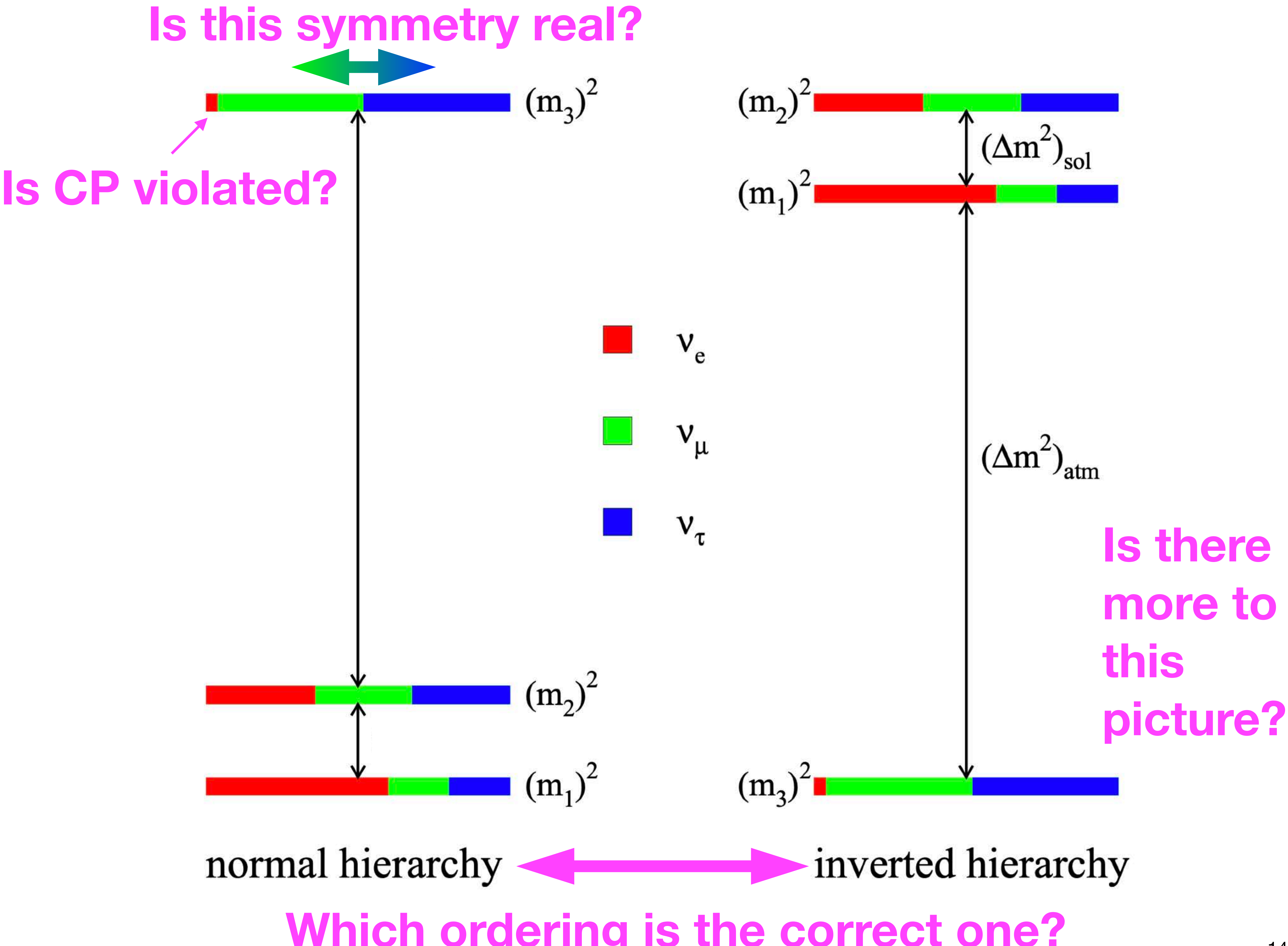


$$\frac{J_{\text{PMNS}}}{J_{\text{CKM}}} = \frac{3 \times 10^{-2}}{3 \times 10^{-5}} \sin(\delta_{\text{PMNS}})$$

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



*Cecilia Jarlskog*






arXiv:2102.00594 NuFit v5.1

# T2K


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

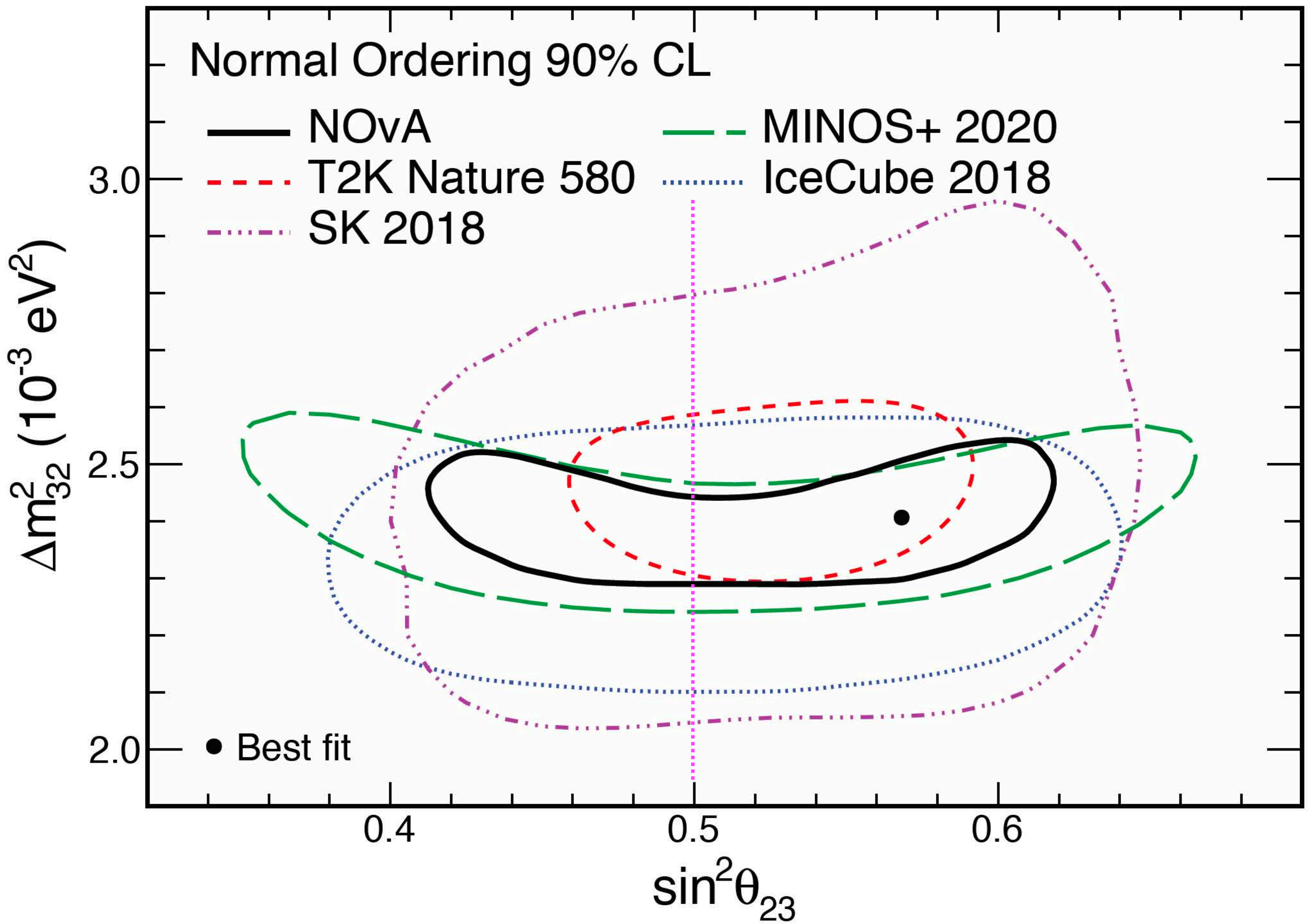
$$\Delta \equiv \frac{1.27 \cdot 0.0025\ \text{eV}^2 \cdot 295\ \text{km}}{0.7\ \text{GeV}} \simeq \frac{\pi}{2}$$

# NOvA


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

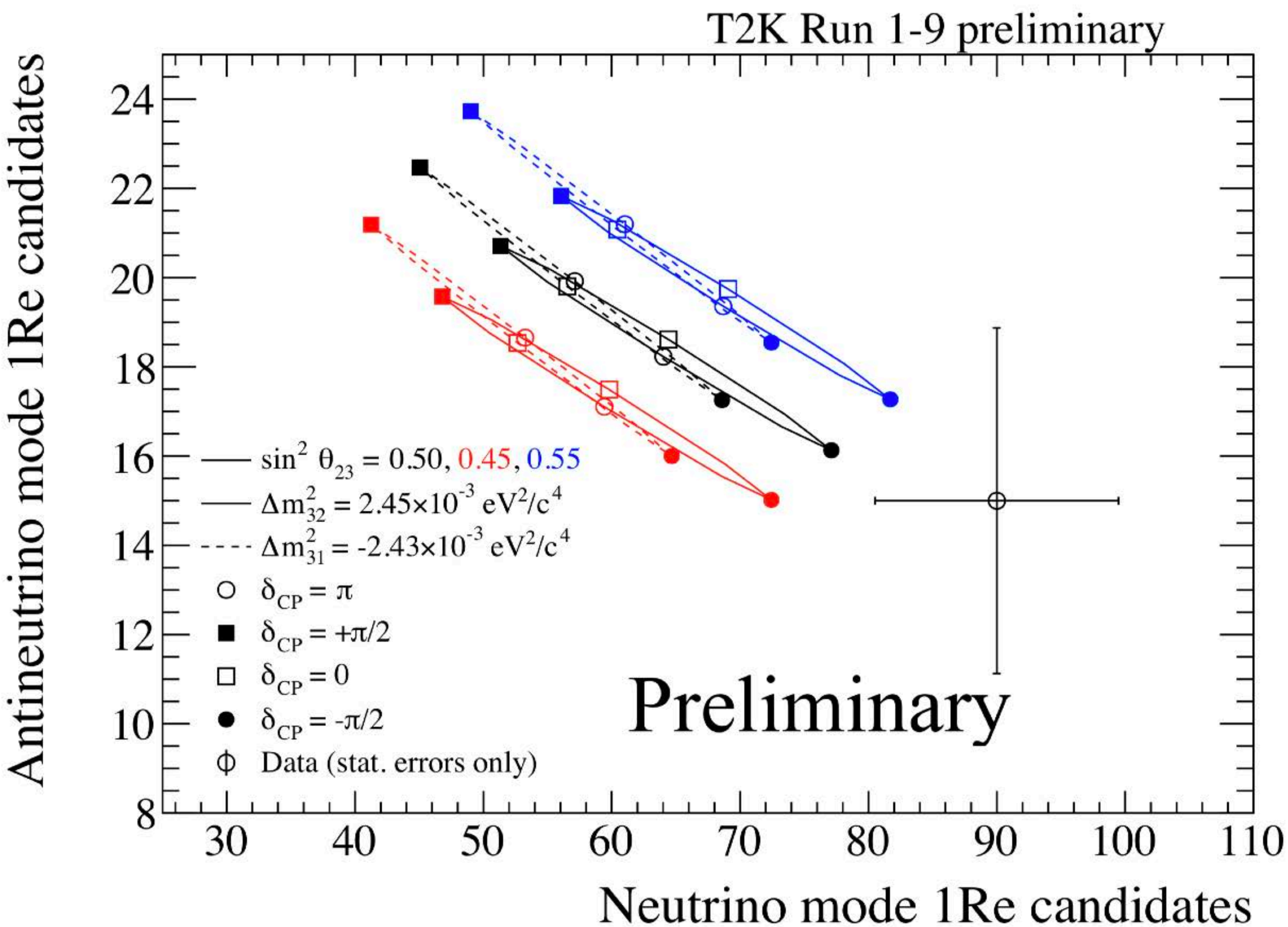
$$\Delta \equiv \frac{1.27 \cdot 0.0025\ \text{eV}^2 \cdot 810\ \text{km}}{2\ \text{GeV}} \simeq \frac{\pi}{2}$$

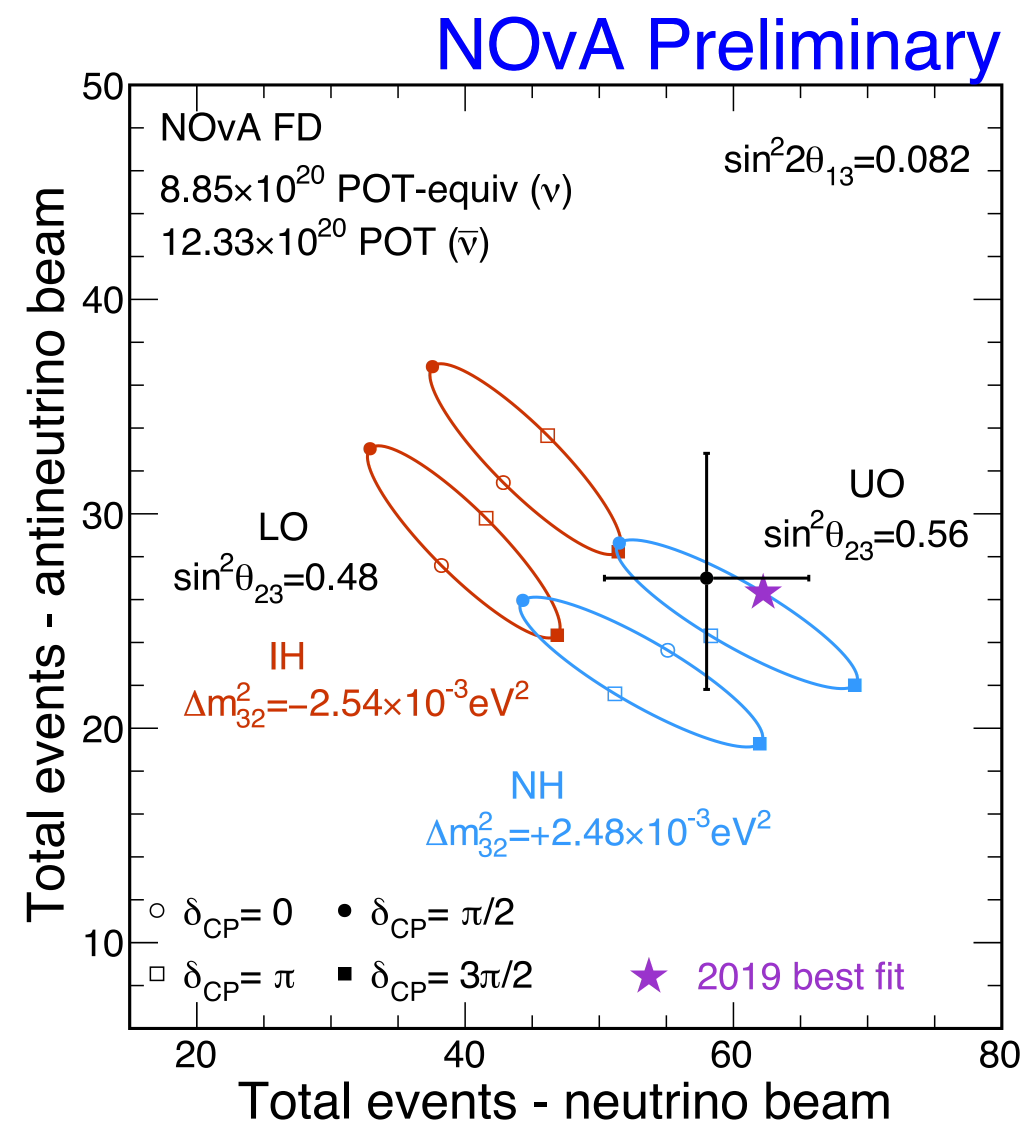
# μ-τ Symmetry in Neutrino Mixing?



*(needs updating to latest results)*

# Mass ordering and CP violation



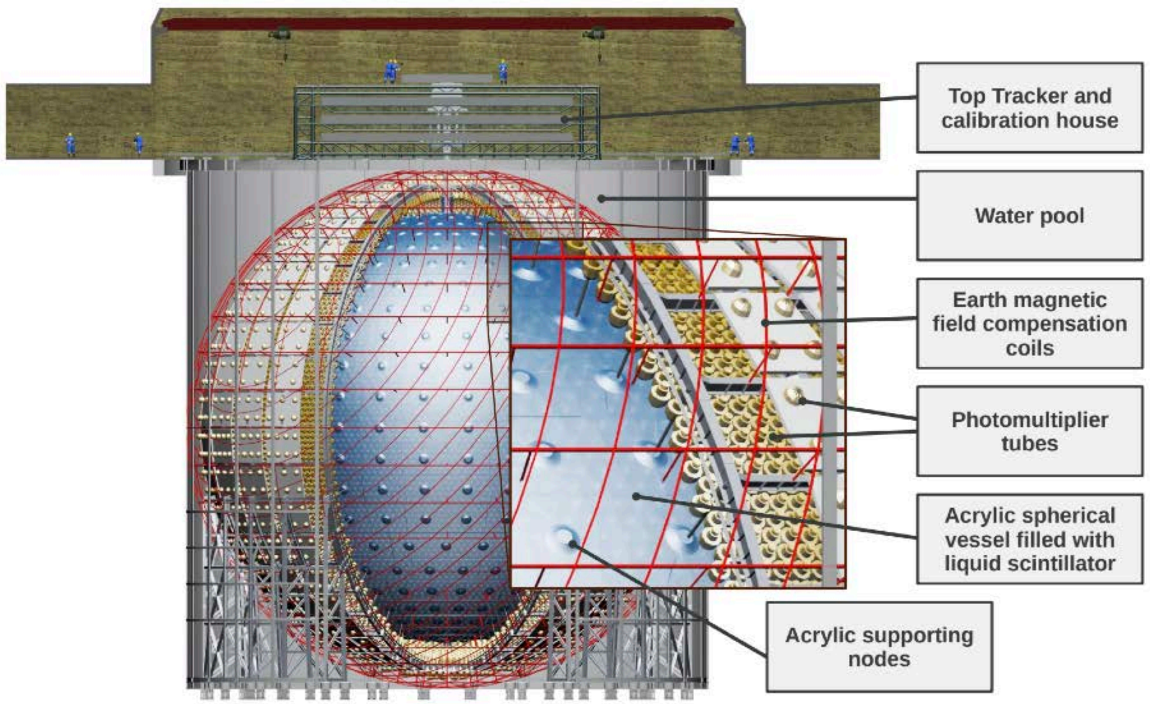



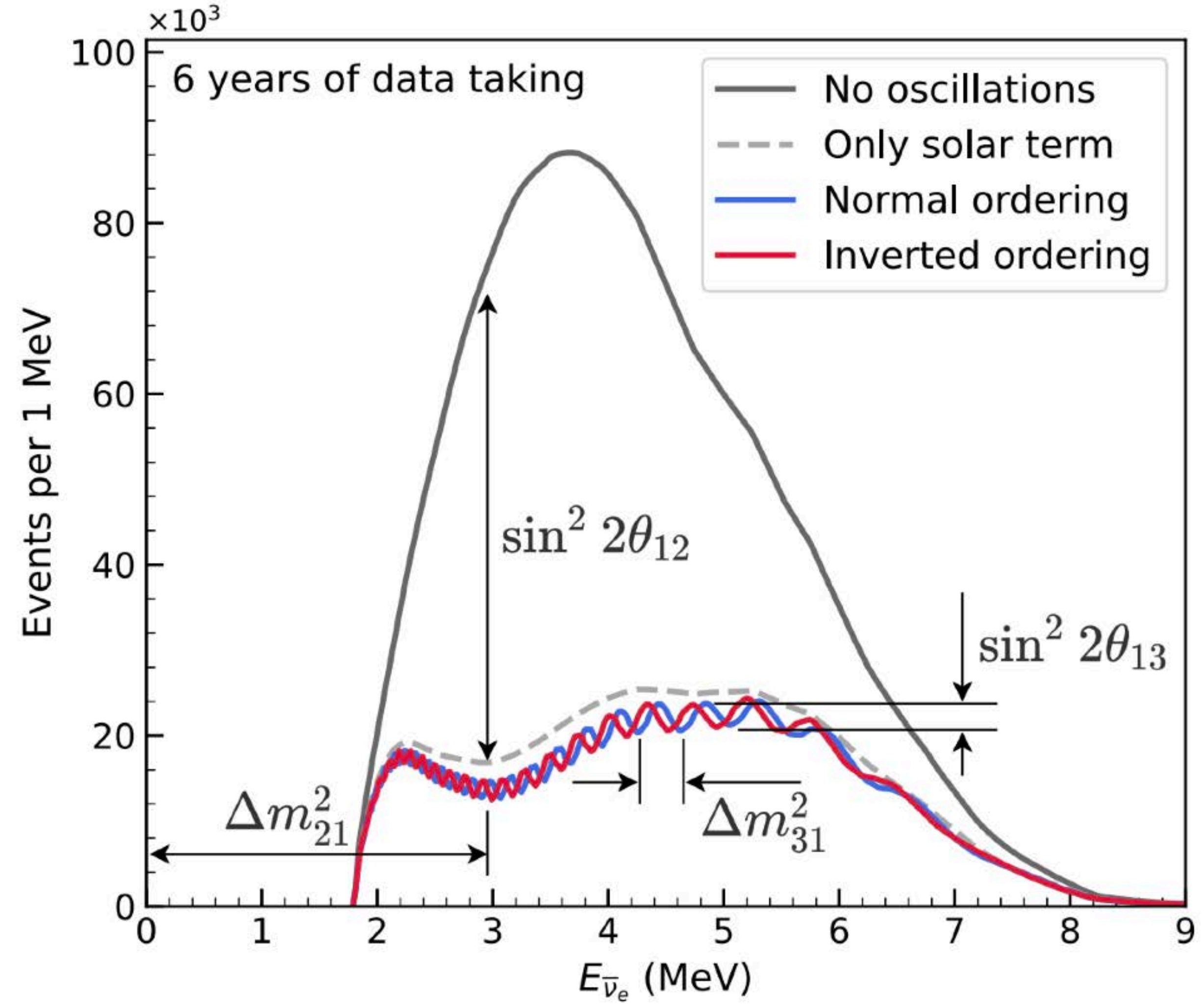

T2K sees a large difference between $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

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

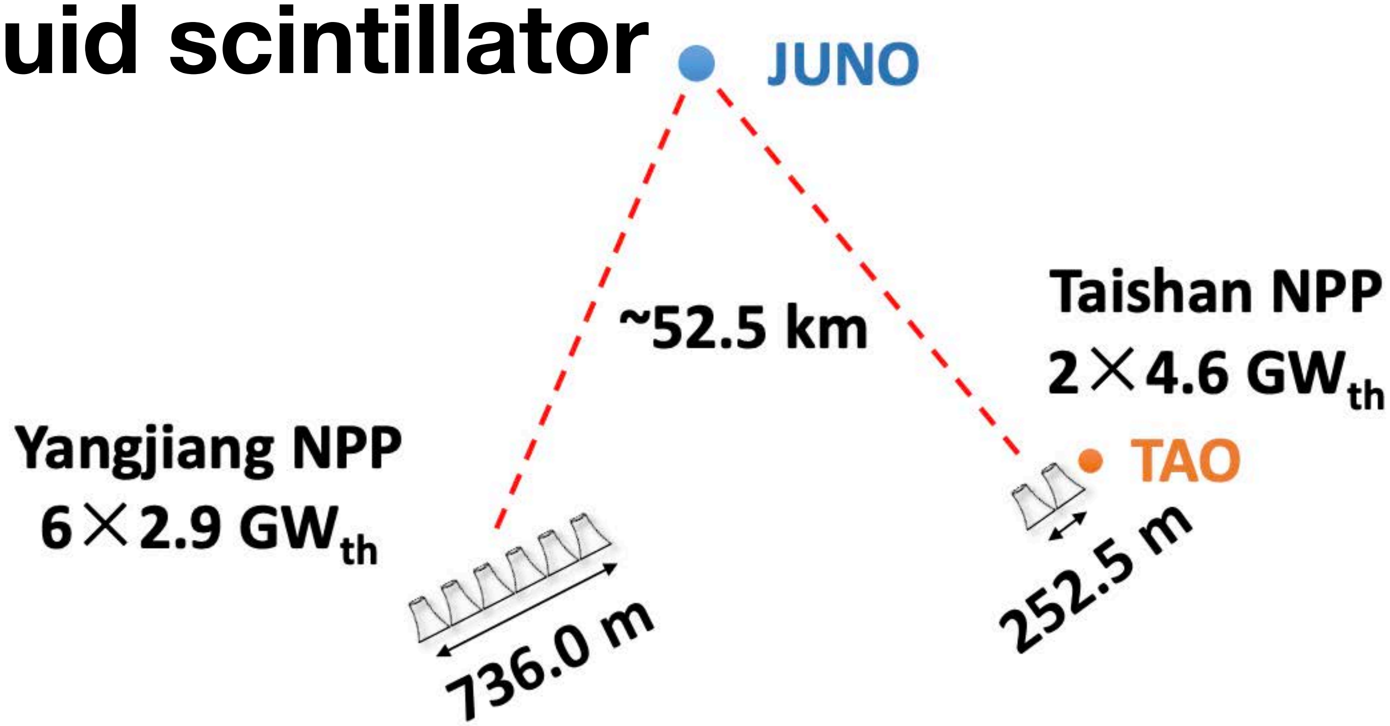
1. Why we love neutrinos
2. Neutrino oscillations
    1. What do we know?
    2. What do we want to know?
3. **The future**
4. What the future demands
5. The payoff

# JUNO

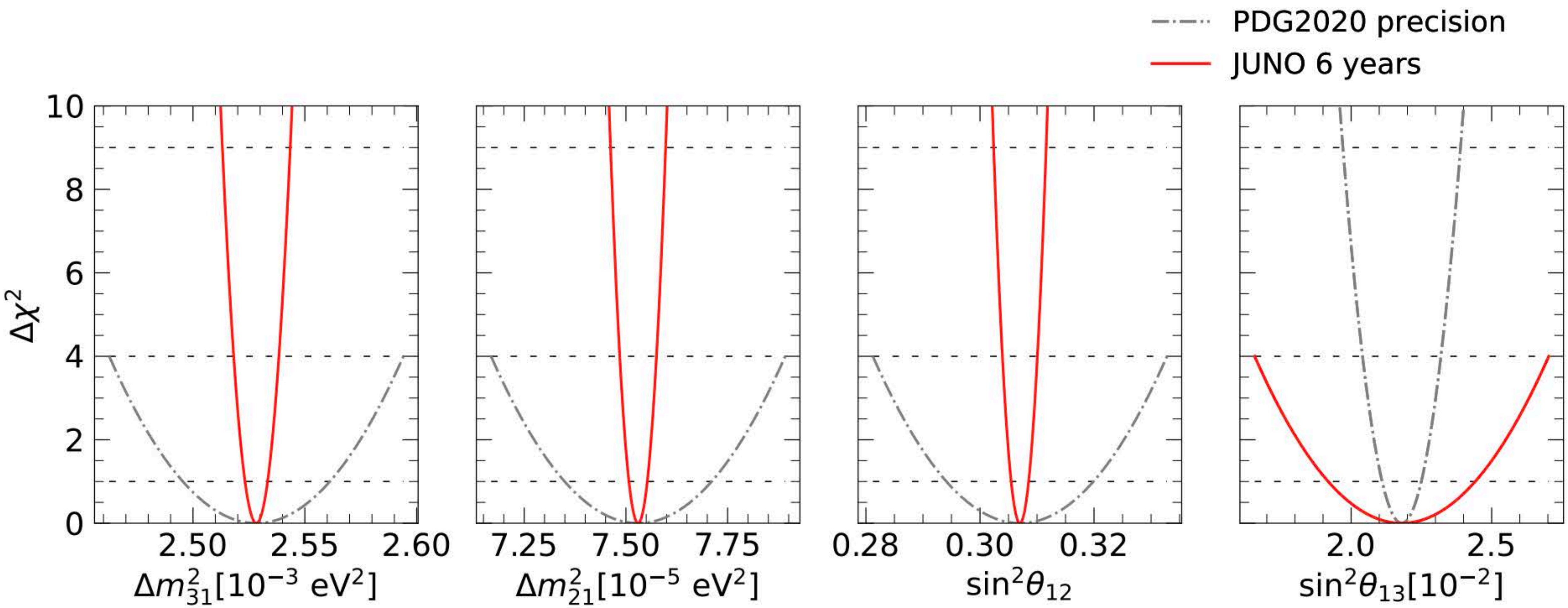



**20 kt liquid scintillator**

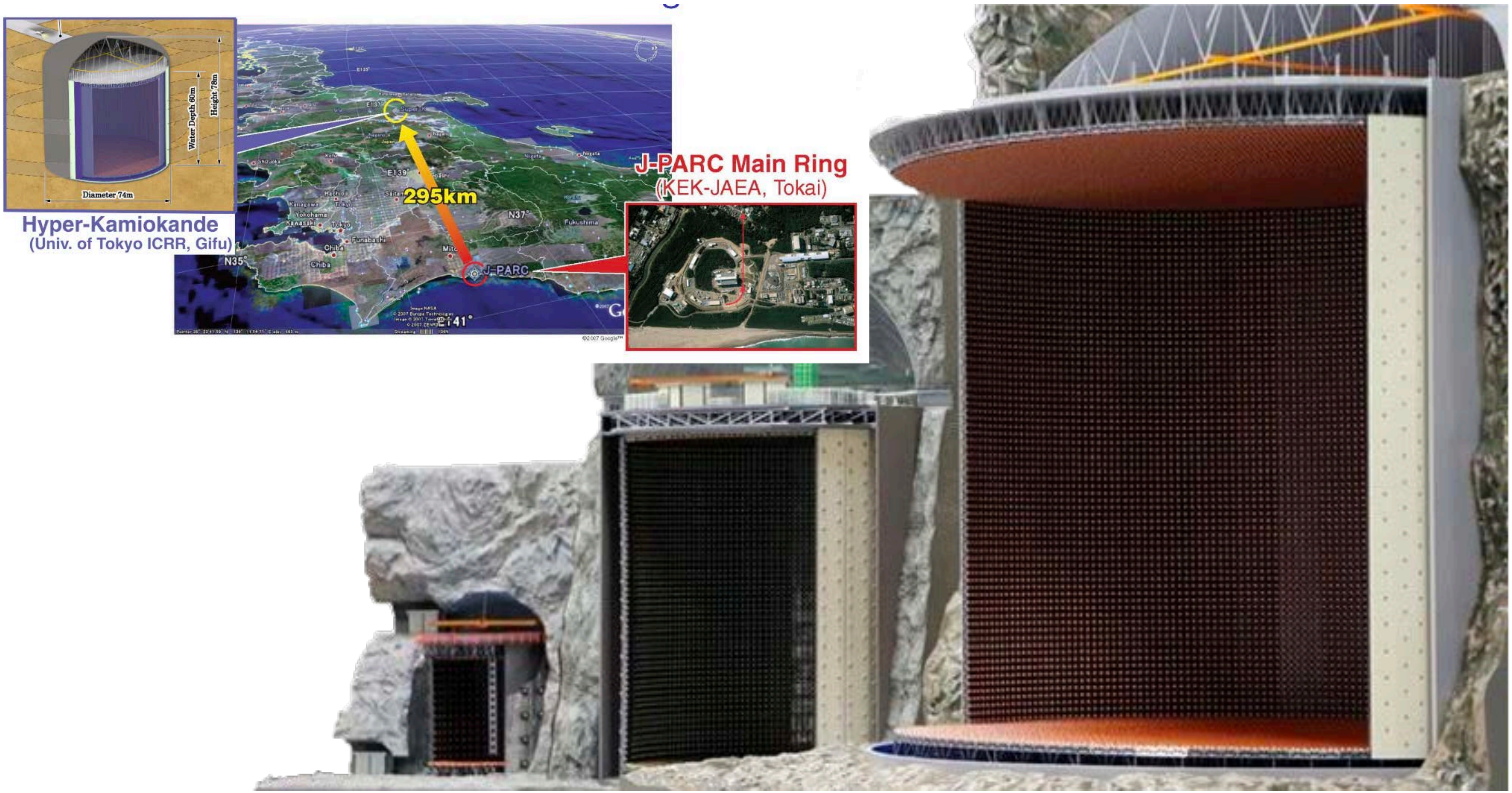


# JUNO



PDG2020 precision
JUNO 6 years
10
8
6
4
2
0
$\Delta\chi^2$
2.50
2.55
2.60
$\Delta m^2_{31}[10^{-3}\ \mathrm{eV}^2]$
7.25
7.50
7.75
$\Delta m^2_{21}[10^{-5}\ \mathrm{eV}^2]$
0.28
0.30
0.32
$\sin^2\theta_{12}$
2.0
2.5
$\sin^2\theta_{13}[10^{-2}]$

# T2 Hyper-Kamiokande



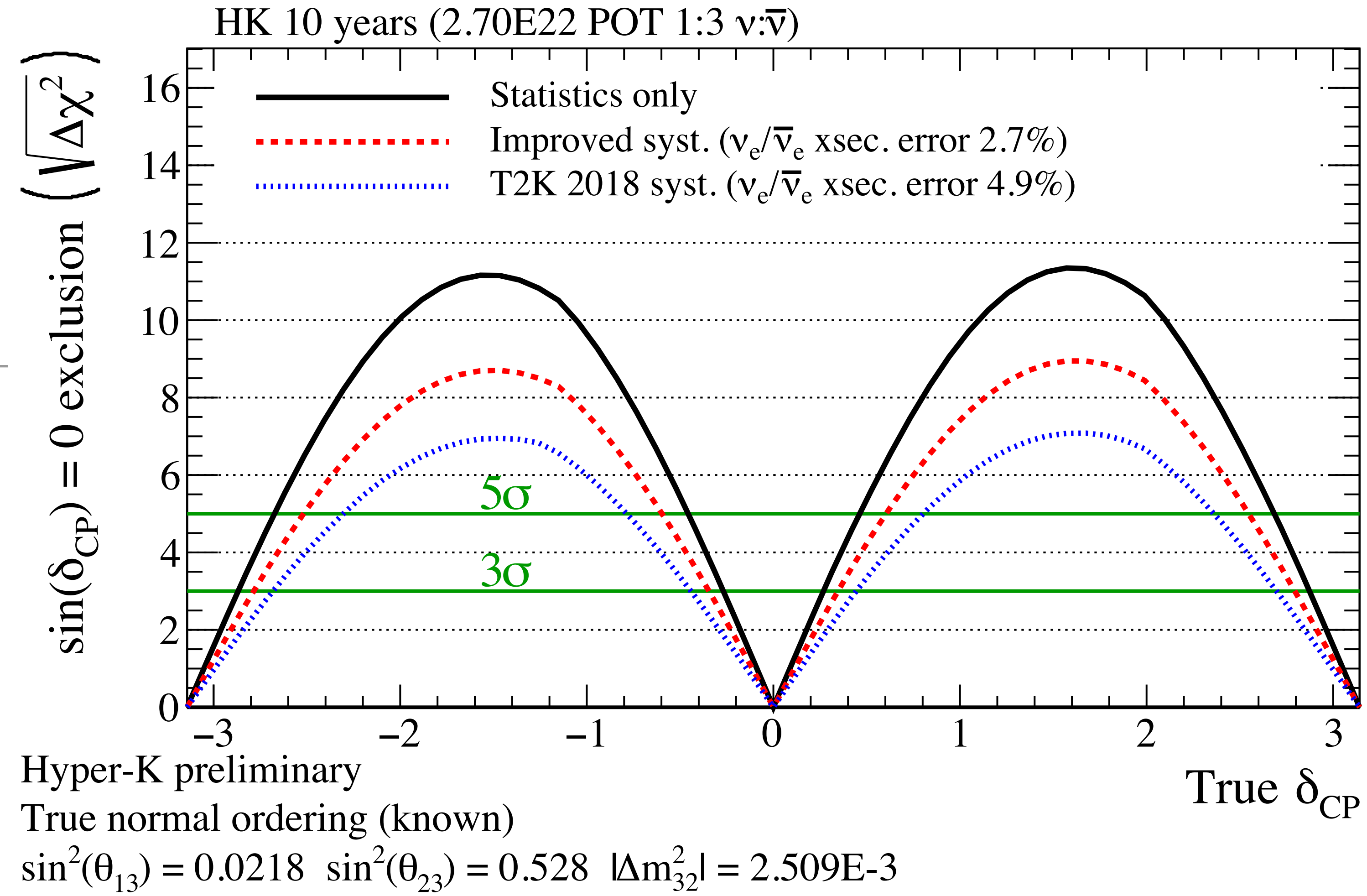

| Kamiokande | Super-Kamiokande | Hyper-Kamiokande |
| --- | --- | --- |
| 3 kton | 22.5 kton | 188 kton |

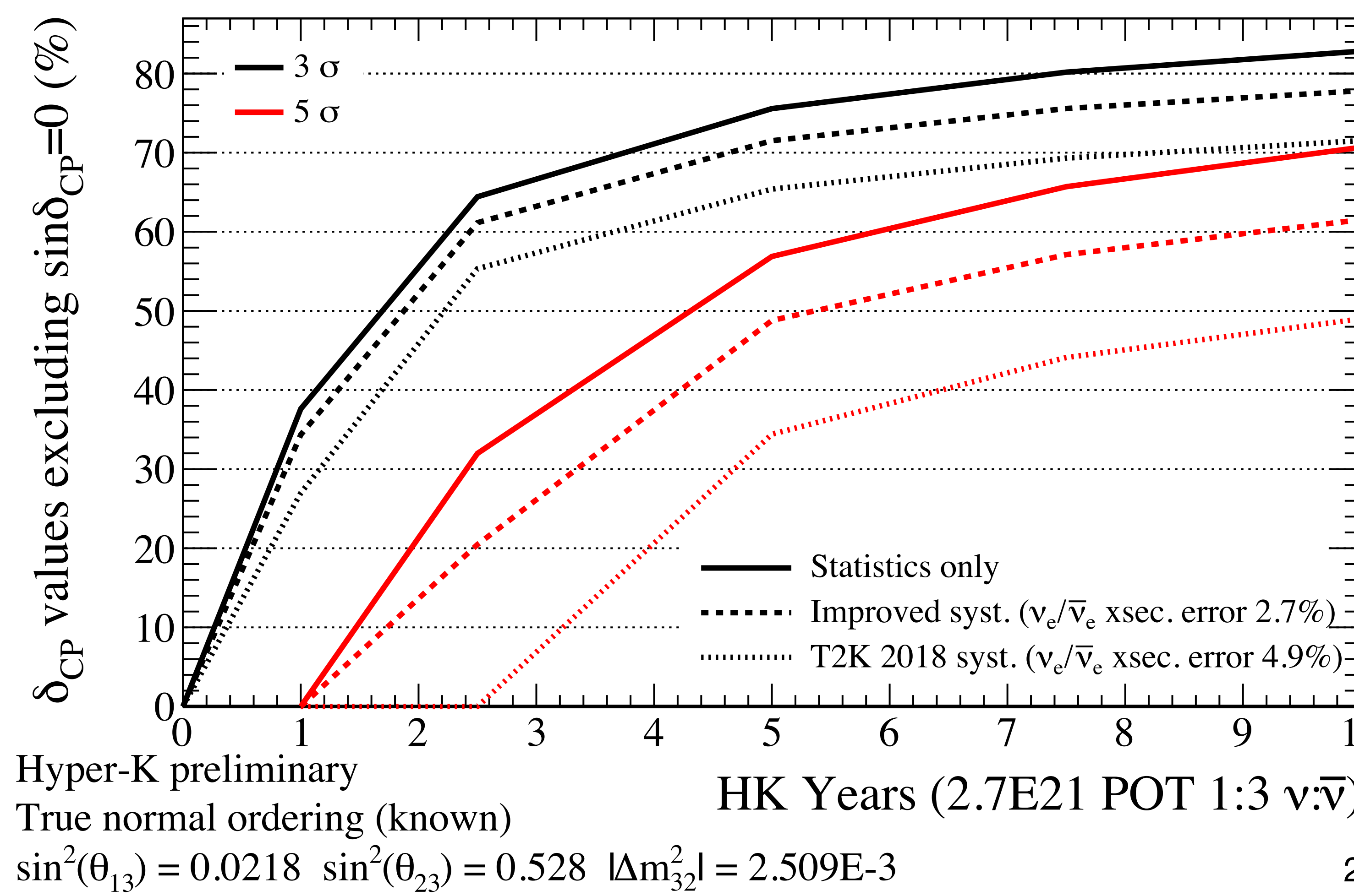
# T2HK

Data taking expected to begin in 2027

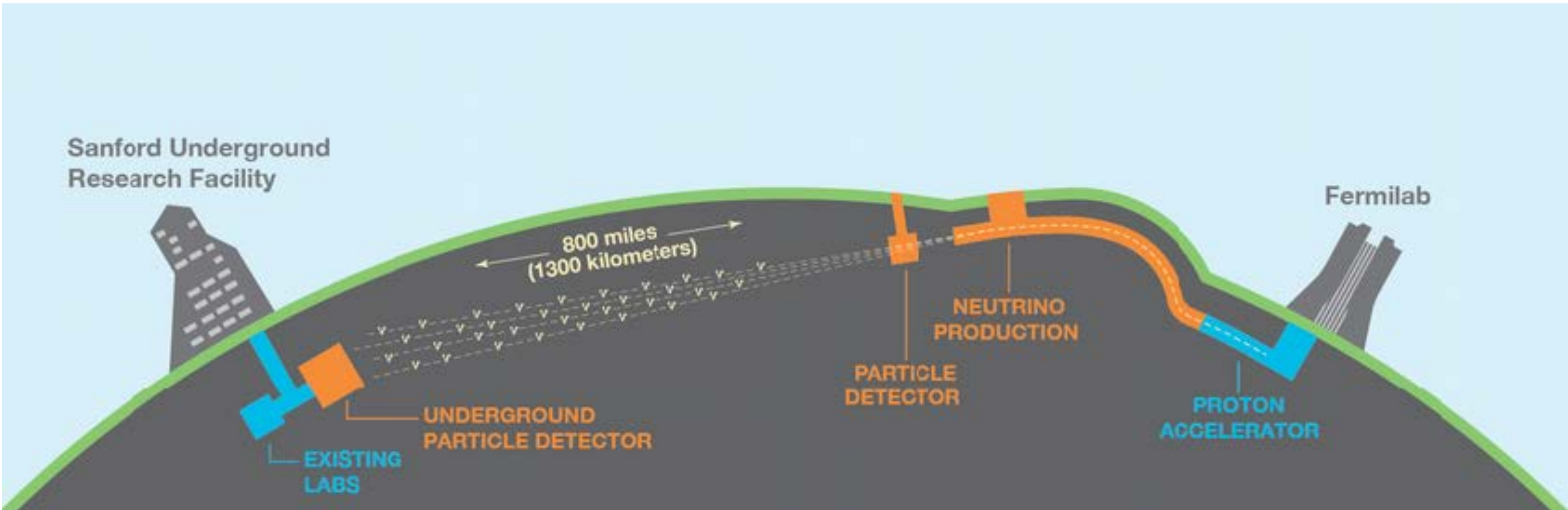
5σ discovery of CP violation in 10 years for 60% of $\delta_{CP}$ values

The search depends strongly on controlling systematic uncertainties

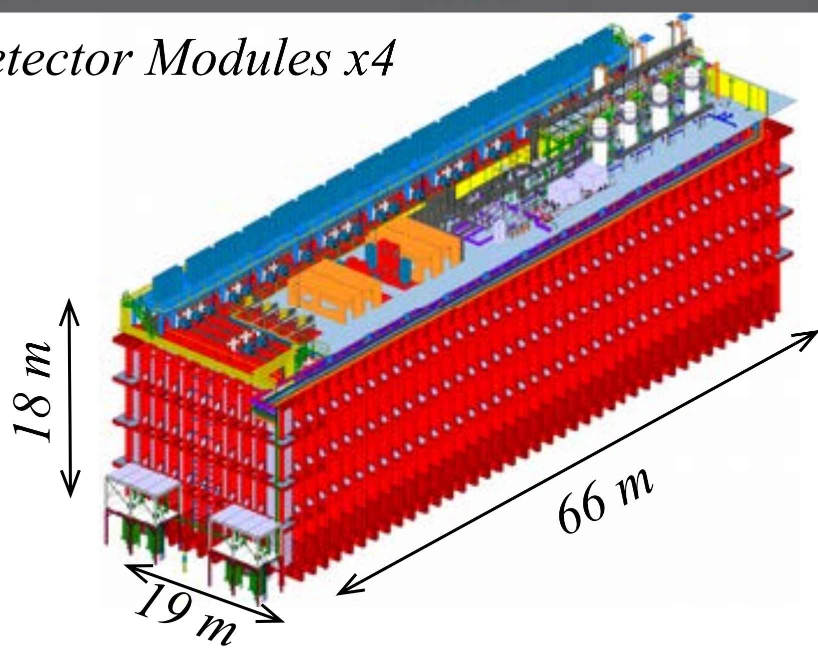


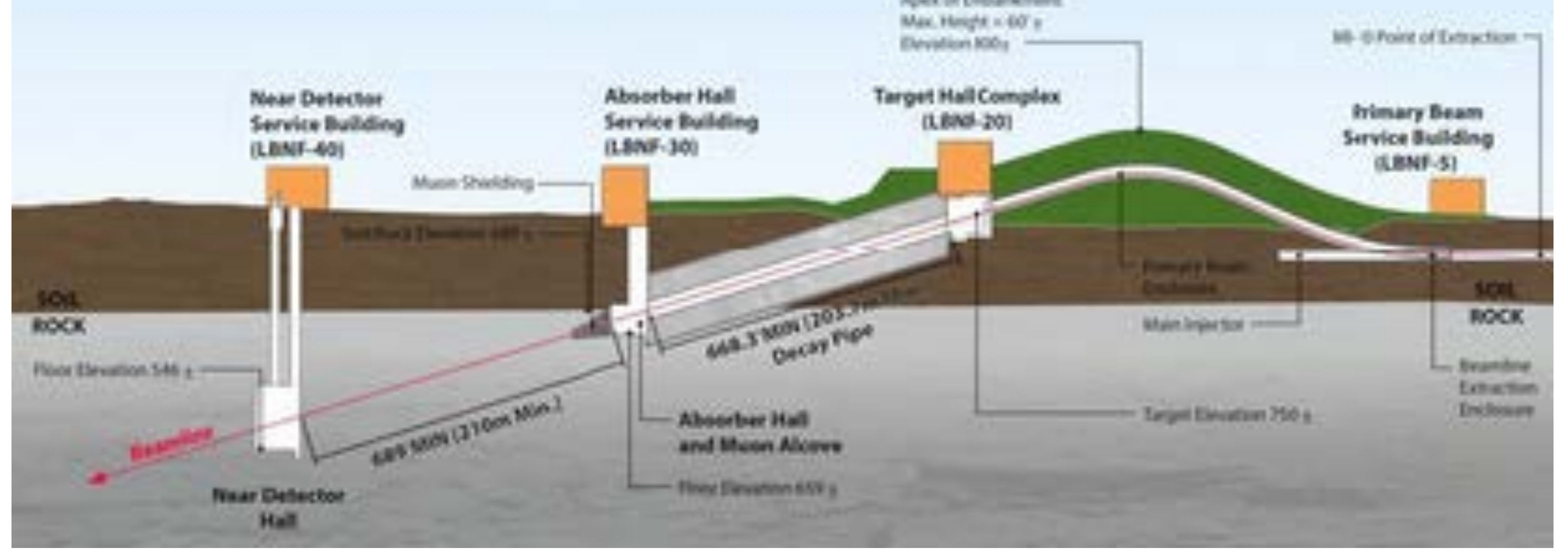
# DUNE

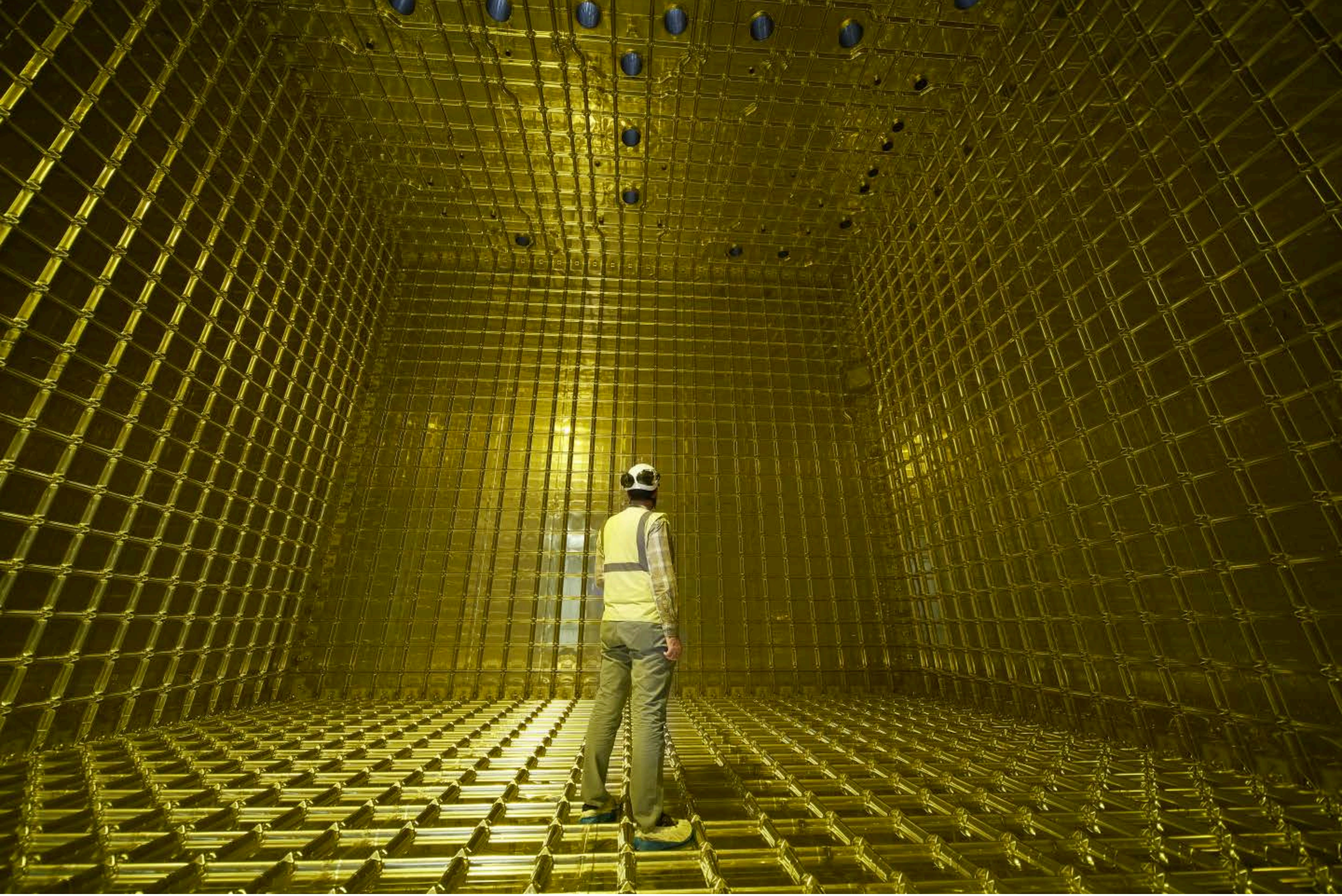



*Detector Modules x4*



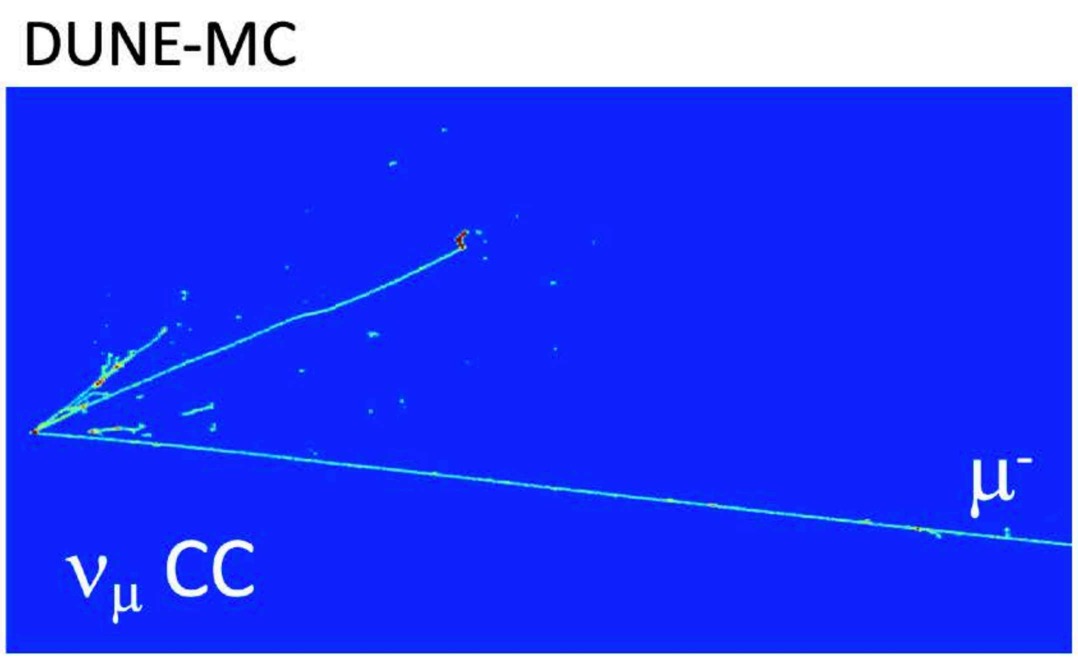

*LBNF neutrino beam and near halls*

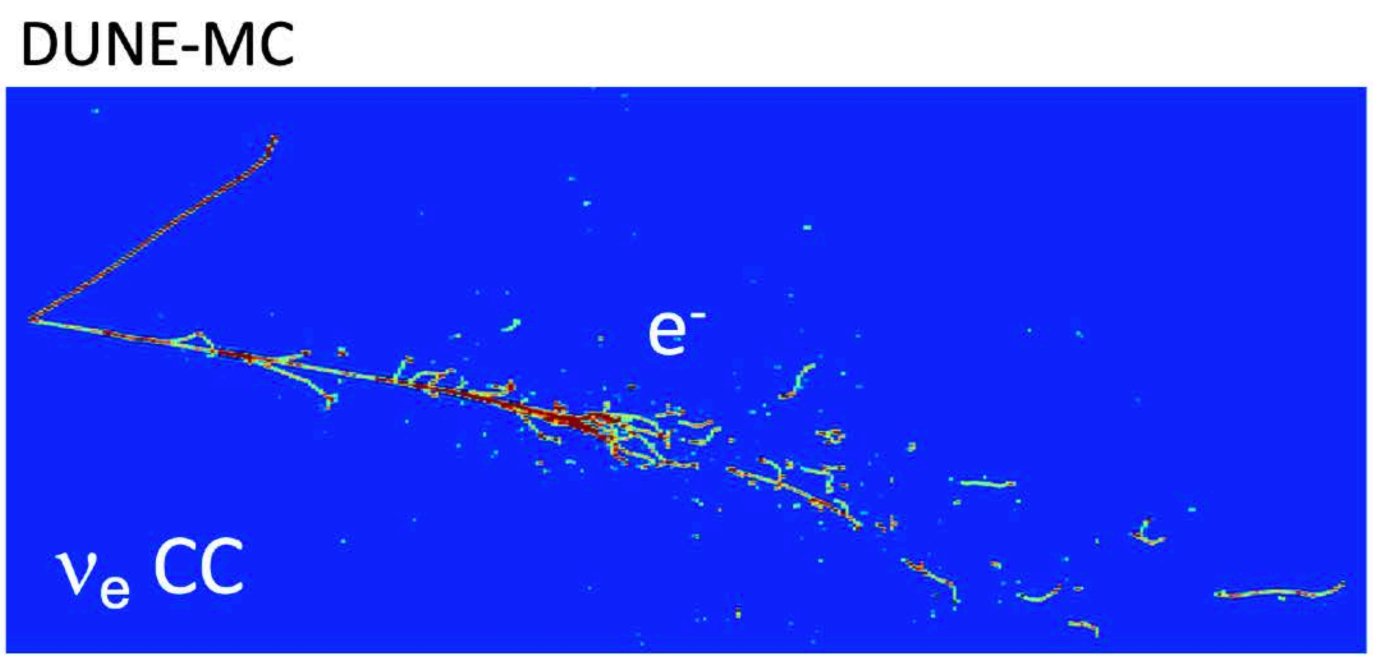




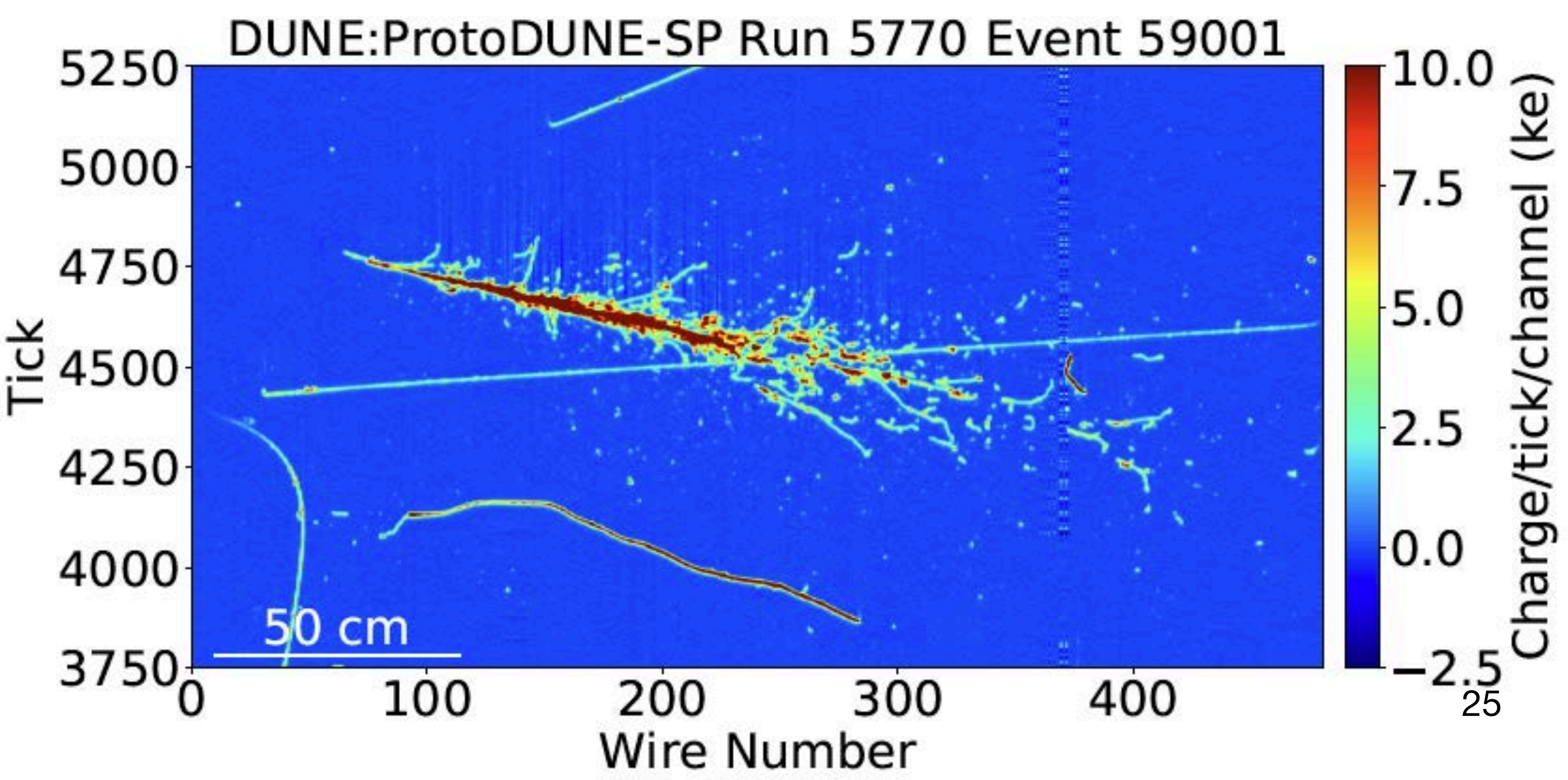
# DUNE Prototype at CERN

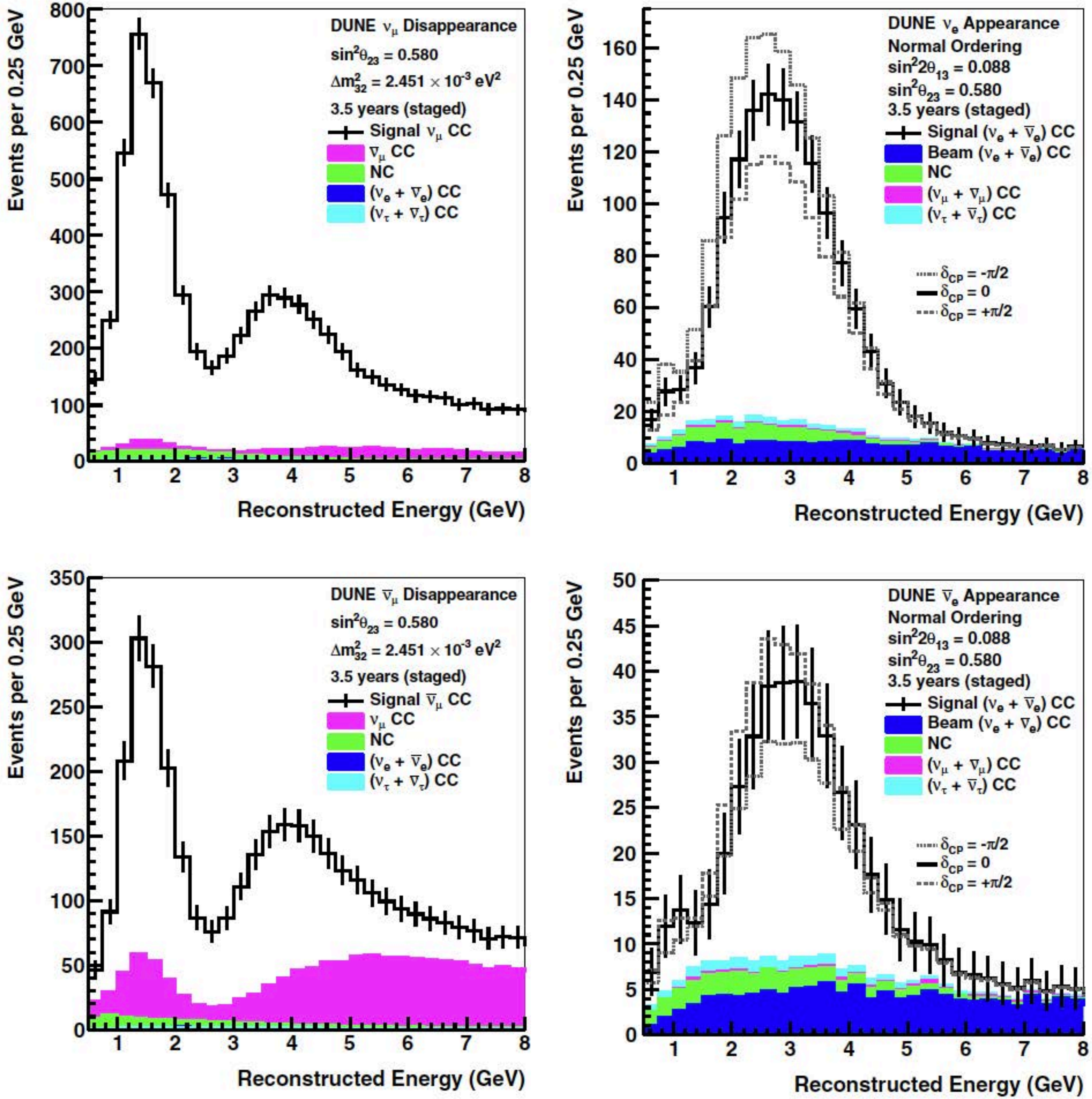
# Events in DUNE




A 6 GeV electron recorded by DUNE prototype at CERN






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 in ~2034:
5σ discovery of CP violation

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

1. Why we love neutrinos
2. Neutrino oscillations
    1. What do we know?
    2. What do we want to know?
3. The future
4. **What the future demands**
5. The payoff

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

WARNING! WAVING HANDS

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:

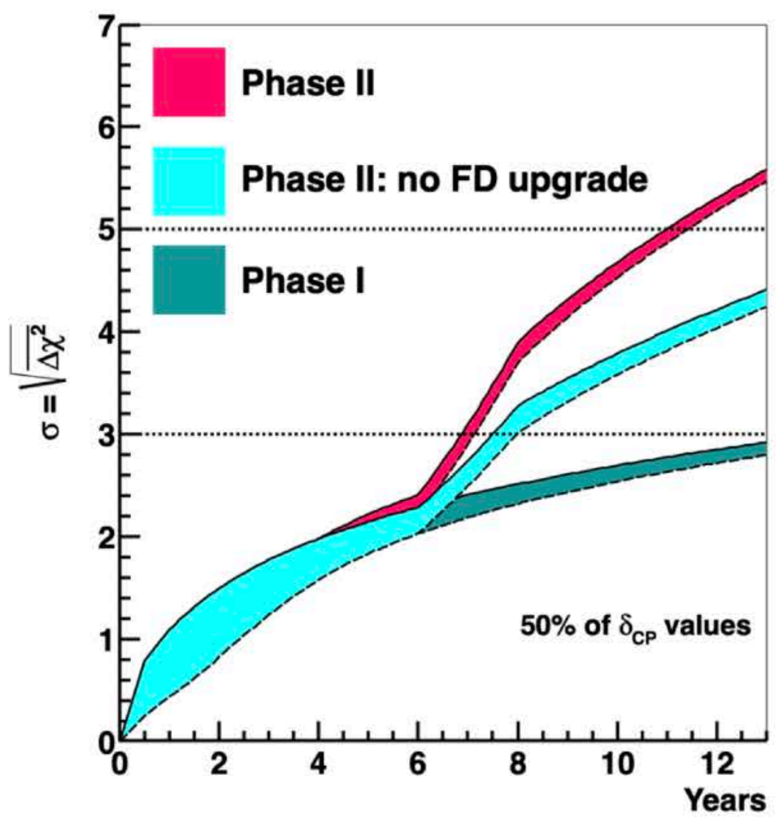
$$\frac{\mathcal{F}}{\bar{\mathcal{F}}} \cdot \frac{\sigma}{\bar{\sigma}} \cdot \frac{\epsilon}{\bar{\epsilon}} \cdot \frac{\bar{N}_e}{N_e} \stackrel{?}{=} 1$$

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

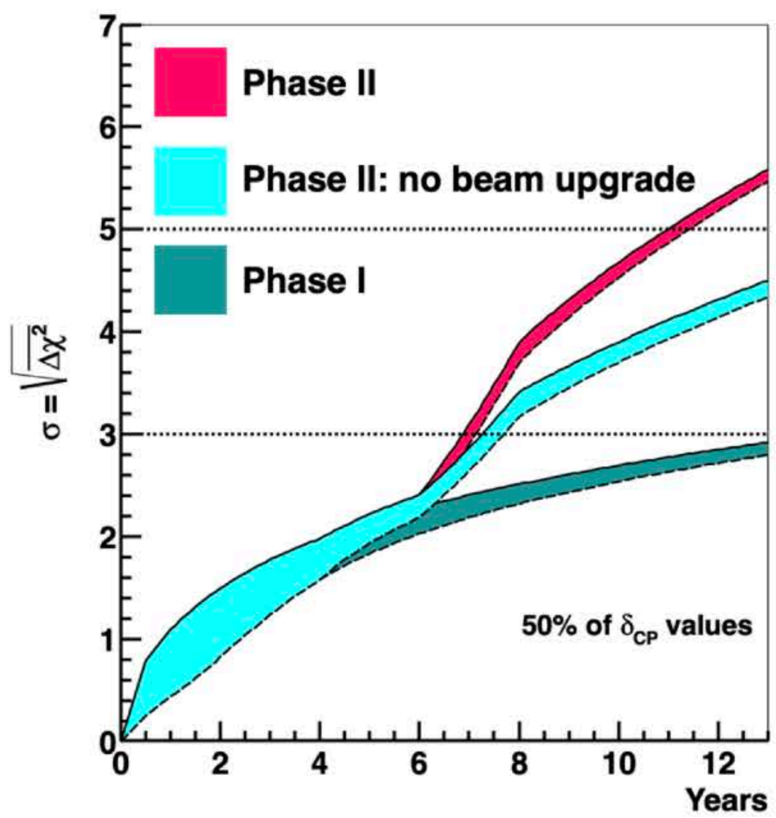
$$\frac{\mathcal{F}}{\bar{\mathcal{F}}} \cdot \frac{\sigma}{\bar{\sigma}} \cdot \frac{\epsilon}{\bar{\epsilon}} \cdot \frac{\bar{N}_e}{N_e} \stackrel{?}{=} 1$$

| 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 | Neutrino and anti-neutrino interactions produce different final states | Highly capable far detectors | Highly capable near detectors | Test Beams |
| $\mathcal{F}/\bar{\mathcal{F}}$ | Neutrino flux | 15…30% a priori differences since we produce neutrino and anti-neutrino beams | Highly capable near detectors | Dedicated measurement program | |
| $\sigma/\bar{\sigma}$ | Neutrino-nucleus cross-sections | factor of 2 to 3 depending on energy | Highly capable near detectors | Dedicated measurement and theory program | Test Beams |

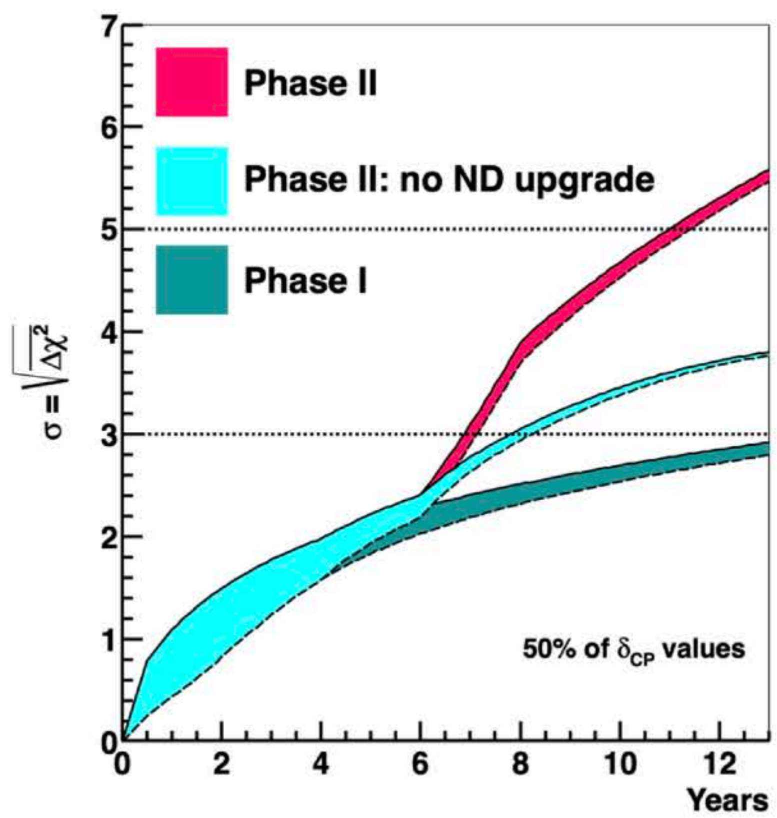
# Example:
# DUNE Discovery Potential for CP Violation




If far detector mass is 1/2 of goal




If beam intensity is 1/2 of goal




If near detector is not upgraded

1. Why we love neutrinos
2. Neutrino oscillations
    1. What do we know?
    2. What do we want to know?
3. The future
4. What the future demands
5. **The payoff**

# 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

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

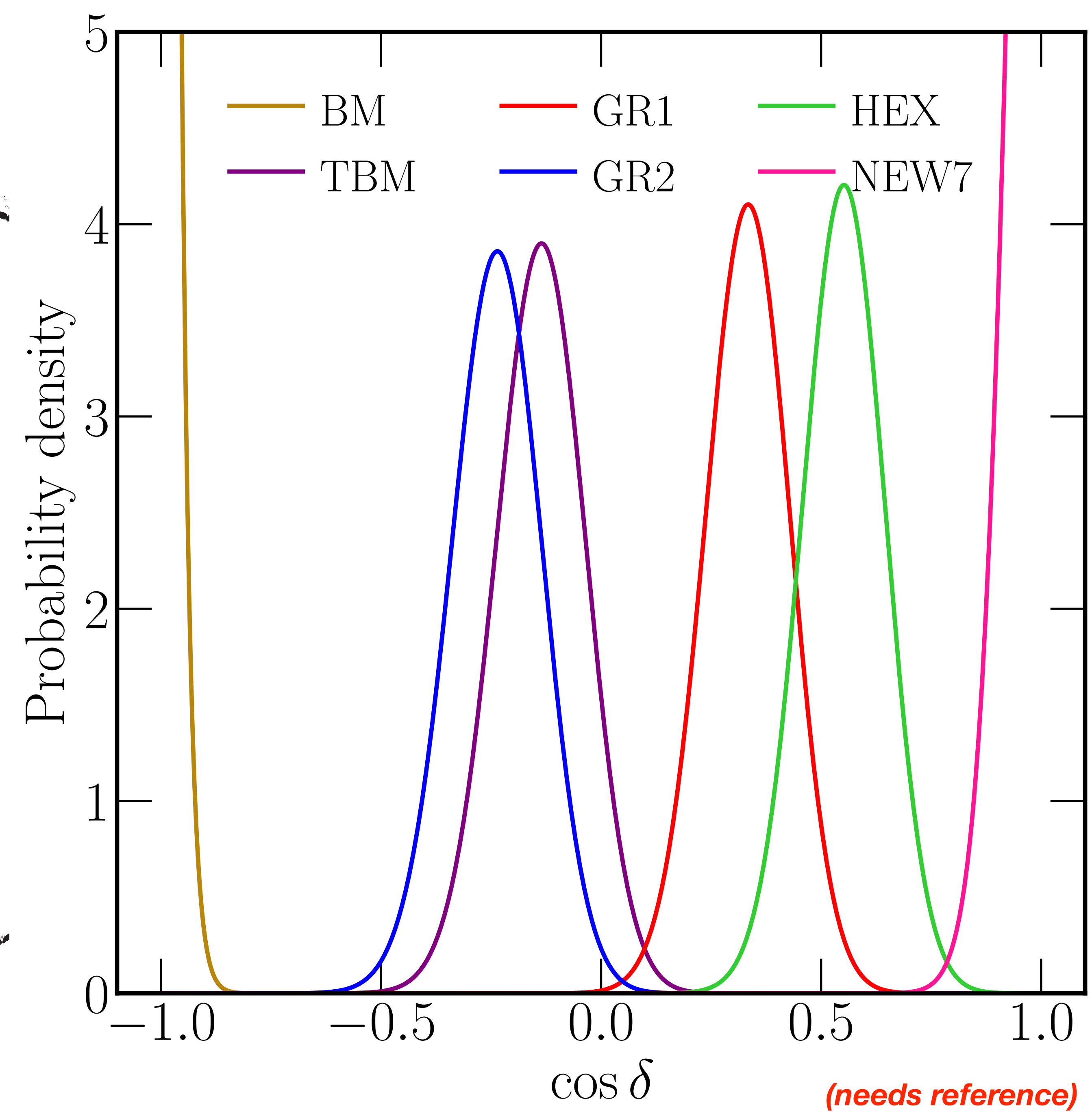
$$\sqrt{\Delta m^2_{31}}\begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

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

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

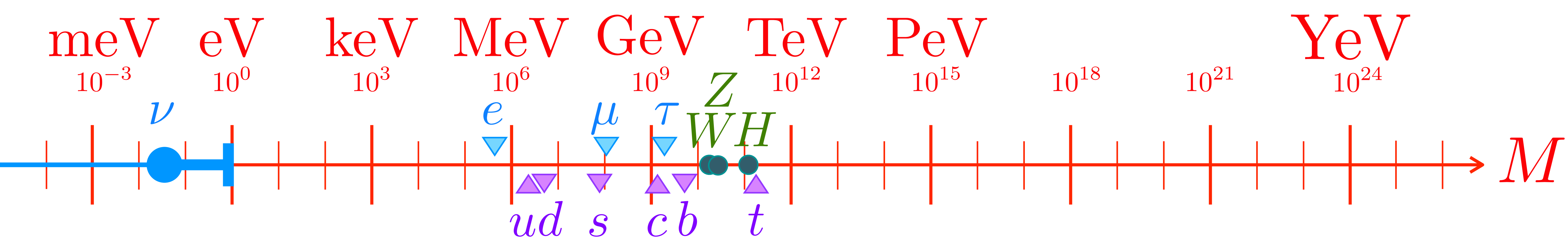
inverted mass ordering

*follows hep-ph/0510213*




***(needs reference)***

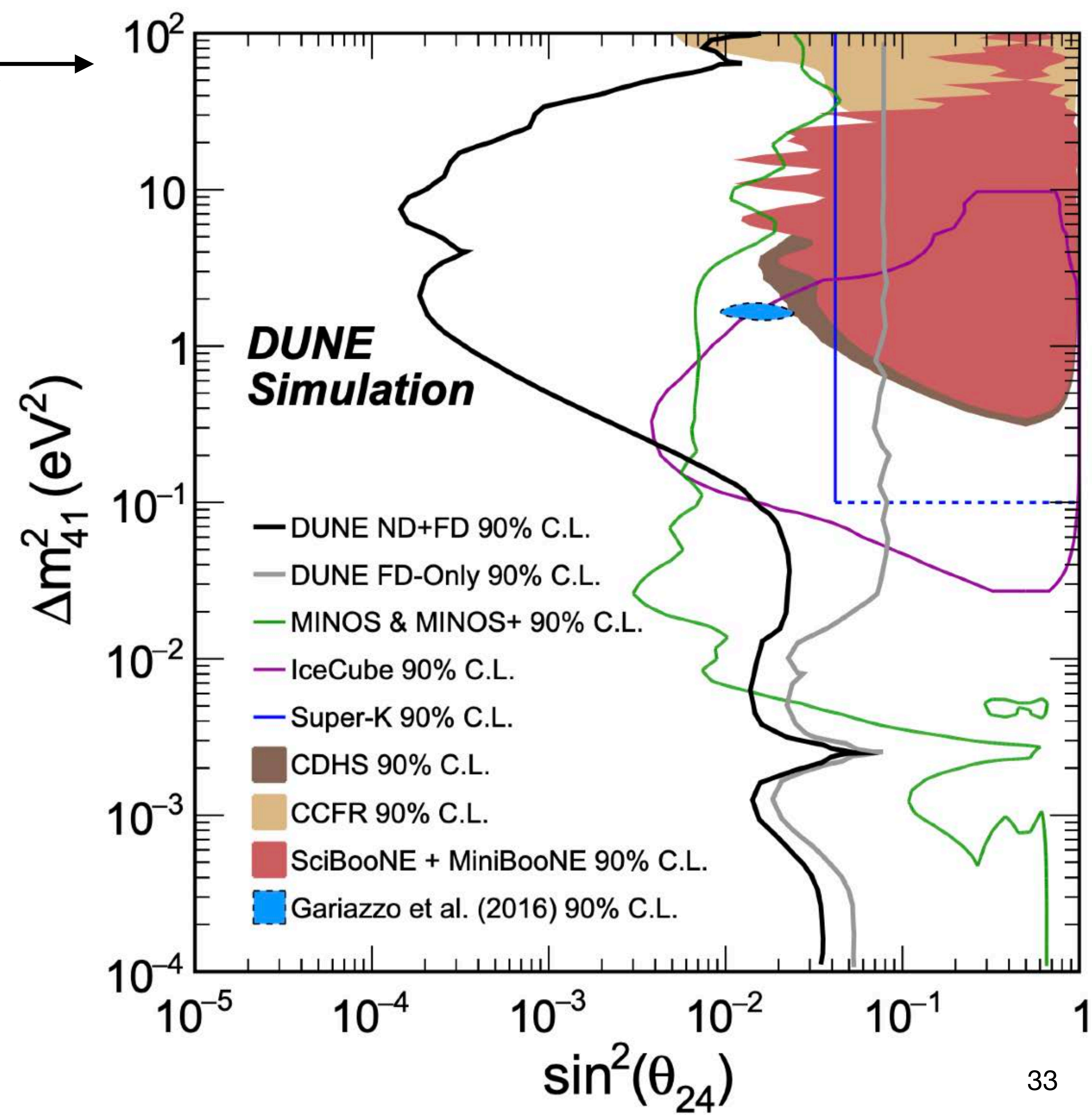
With precision, we can discern among neutrino mass models




?

*Standard Model*

***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 mass is a window on new physics at high energies
- Big questions remain: 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 US, the program will be anchored by DUNE.