Review sulle misure di neutrini ai fasci e risultati di T2K

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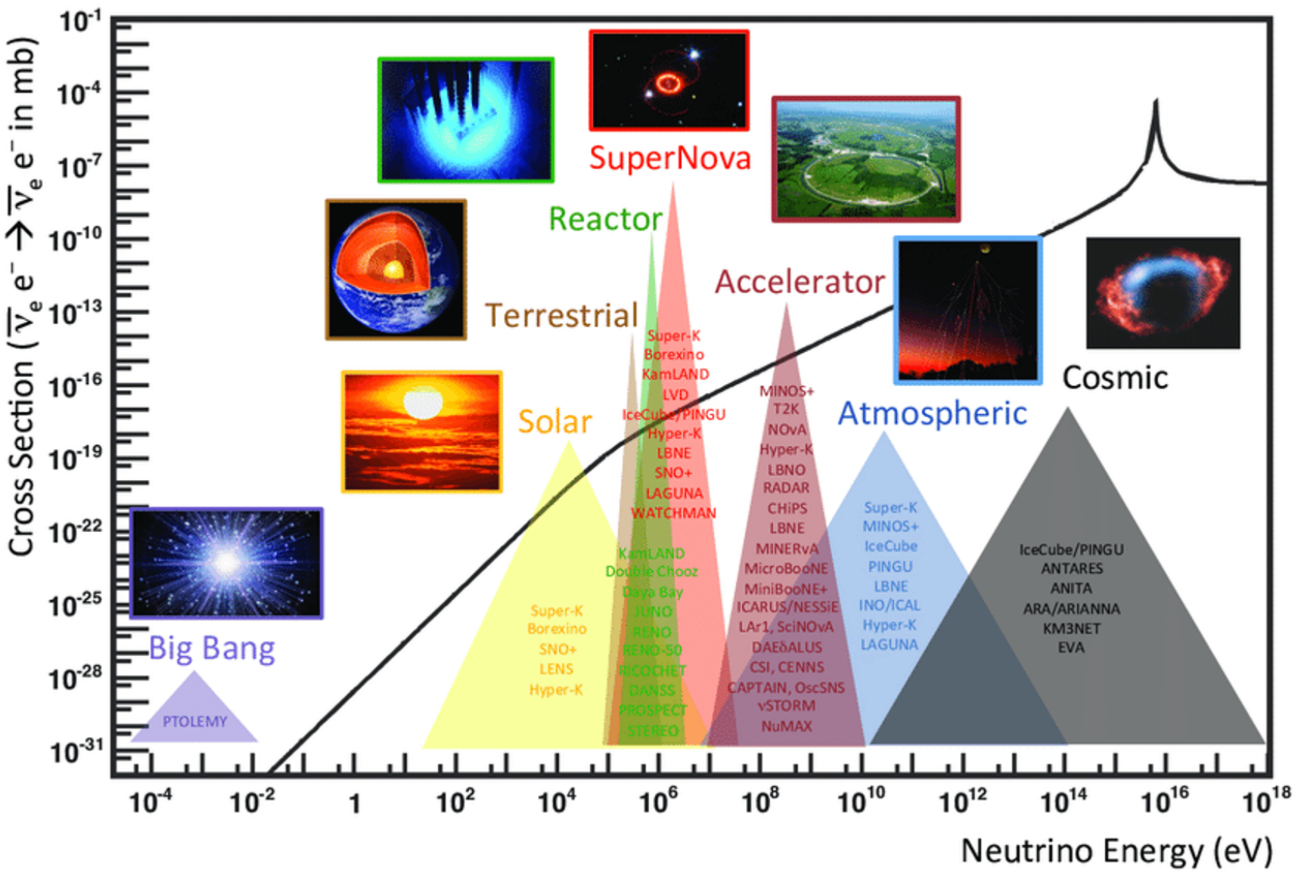
Sources of neutrinos

Neutrinos are almost everywhere:

- Particle Physics
- Astrophysics
- Cosmology
- Nuclear physics

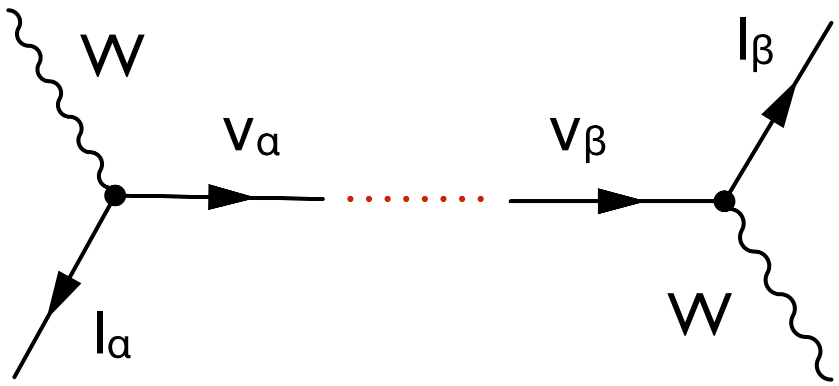


This talk will be focused on the recent results from long baseline (LBL) neutrino oscillation experiments.

In particular I will discuss the T2K neutrino oscillations results!

- Overwhelming number of sources, wide range of energies Astrophysics
- Need wide spectrum of experiments and technologies!

Mixing of three neutrinos



Neutrinos produced in weak processes (ν_α) are linear combinations of mass eigenstates (ν_i)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

where **U** is the **Pontecorvo-Maki-Nakagawa-Sakata (PMNS)** matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Super-K, K2K, MINOS, OPERA, NOνA, **T2K**

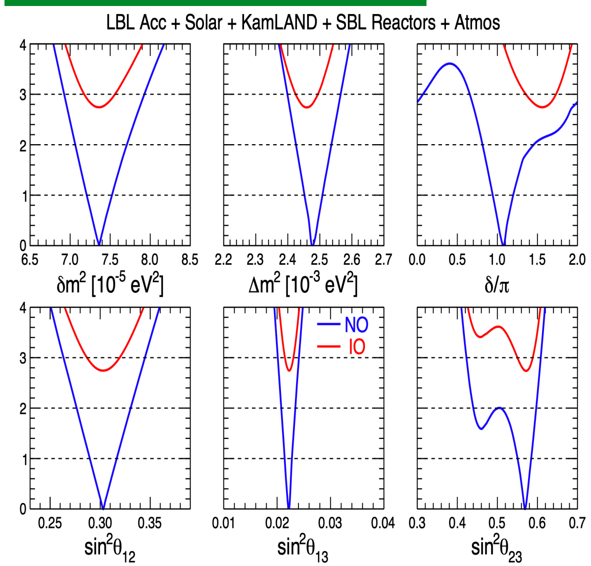
DChooz, Daya Bay, RENO MINOS, NOνA, **T2K**

Super-K, SNO, KamLAND

$c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

(PMNS Neglecting possible Majorana phases)

Global Fits
A. Marrone @ NuTel 2021



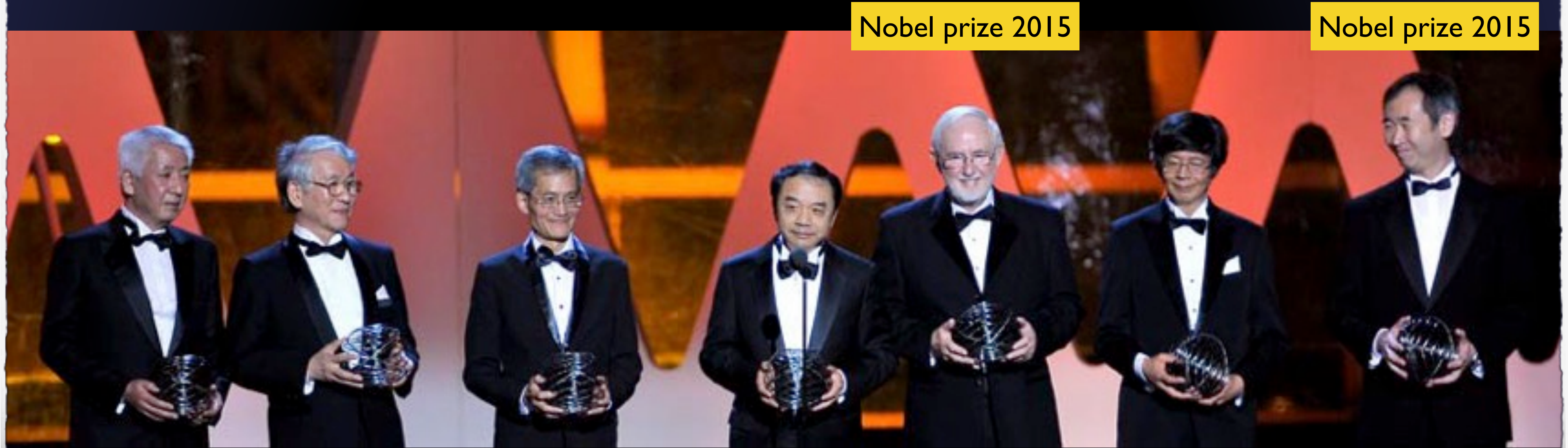
Current knowledge:

- $\theta_{12} \approx 33^\circ$
- $\theta_{23} \approx 45^\circ$
- $\theta_{13} \approx 9^\circ$
- $\Delta m^2_{21} \approx 7.4 \times 10^{-5}$ eV²
- $|\Delta m^2_{31}| \approx 2.5 \times 10^{-3}$ eV²

Open questions:

- CP violation?
- Mass hierarchy ($m_{1,2} \gtrless m_3$)?
- Is $\theta_{23} = 45^\circ$? If not is θ_{23} greater or lower than 45°?
- More PMNS symmetries?
- Majorana/Dirac?

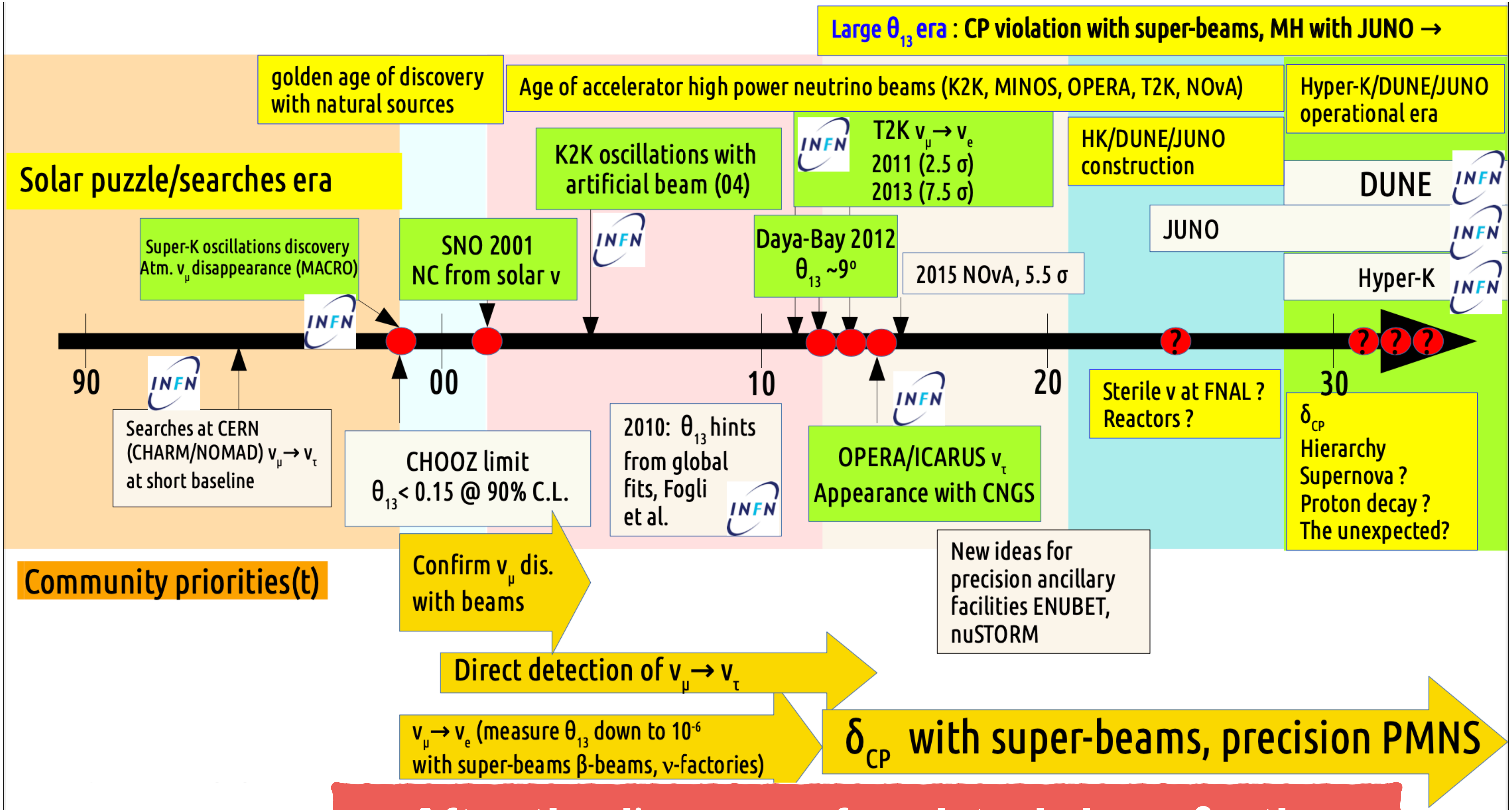
Breakthrough Prize 2016



T2K & K2K	KamLAND	Daya Bay	SNO	Super-Kamiokande
Δm^2_{32}	Δm^2_{21}	Δm^2_{31}	Δm^2_{21}	Δm^2_{32}
θ_{23} θ_{13}	θ_{12}	θ_{13}	θ_{12}	θ_{23}

…. "For the fundamental contributions to the discovery of neutrino Oscillation"

Neutrino physics development



After the discovery of a relatevly large θ_{13} the measurement of δ_{CP} becomes accessible!

From A. Longhin

Recent results from LBL neutrino oscillations experiments

Long-Baseline Facilities Across the Globe

Current:
NOvA (US)
T2K (Japan)

Future:
DUNE (US)
Hyper-K (Japan)

- New Technology, high intensity beams, large volume detectors are needed for precision
- **Next Generation Experiments: DUNE & Hyper-K**

What can be measured from ν_μ disappearance and ν_e appearance

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\Delta m^2_{31}\frac{L}{4E}$$

- Precision measurement of θ_{23} and Δm^2_{31}
- CPT test with anti-neutrino mode ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)

$$\begin{aligned}
P(\nu_\mu \to \nu_e) = \quad & 4c^2_{13}s^2_{13}s^2_{23}\sin^2\frac{\Delta m^2_{13}L}{4E_\nu} \times \left[1 \pm \frac{2a}{\Delta m^2_{13}}(1-s^2_{13})\right] \\
& +8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta_{CP} - s_{12}s_{13}s_{23})\cos\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\sin\frac{\Delta m^2_{12}L}{4E\nu} \\
& \mp 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta_{CP}\sin\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\sin\frac{\Delta m^2_{12}L}{4E_\nu} \\
& +4s^2_{12}c^2_{13}(c^2_{13}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta_{CP})\sin\frac{\Delta m^2_{12}L}{4E_\nu} \\
& \mp 8c^2_{12}s^2_{13}s^2_{23}\cos\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\frac{aL}{4E_\nu}(1-2s^2_{13})
\end{aligned}$$

θ13 driven

CP even

CP odd

Solar driven

Matter effect (CP odd)

Change sign by changing ν with $\bar{\nu}$

B. Richter, SLAC-PUB-8587

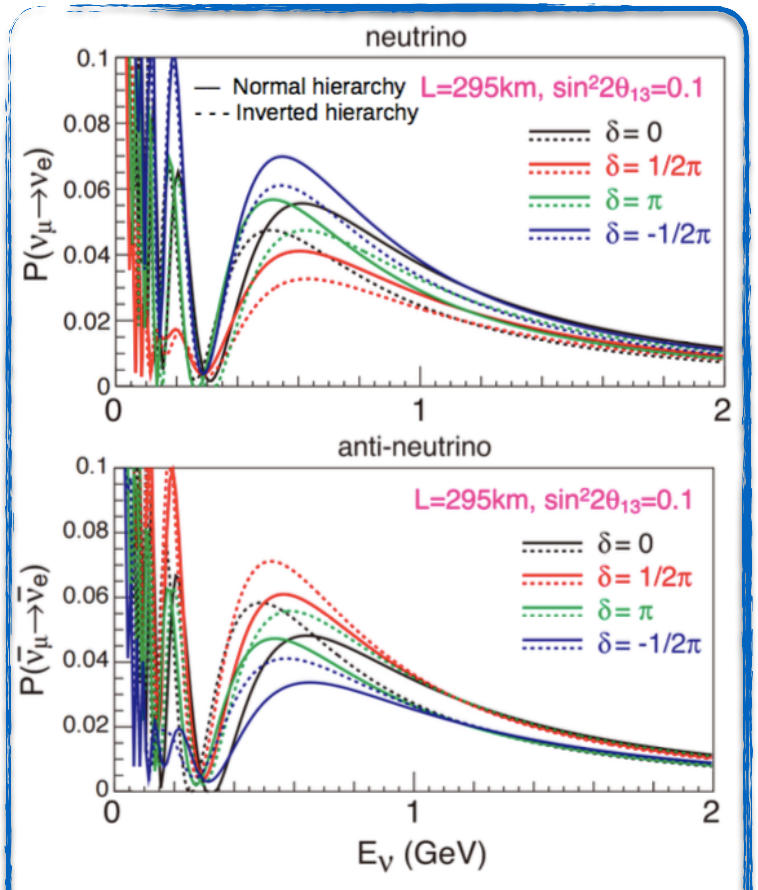
$a[\mathrm{eV}^2] = 2\sqrt{2}G_F n_e E_\nu = 7.6\times10^{-5}\rho[\mathrm{g/cm}^2]E_\nu[\mathrm{GeV}]$

- θ_{13} dependence of the leading term
- θ_{23} dependence of the leading term (θ_{23}=45° or $\theta_{23}\gtrsim$45°?)
- CP odd phase delta: asymmetry of probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if $\sin\delta \neq 0$
- Matter effect: ν_e ($\bar{\nu}_e$) appearance enhanced in normal (inverted) mass hierarchy

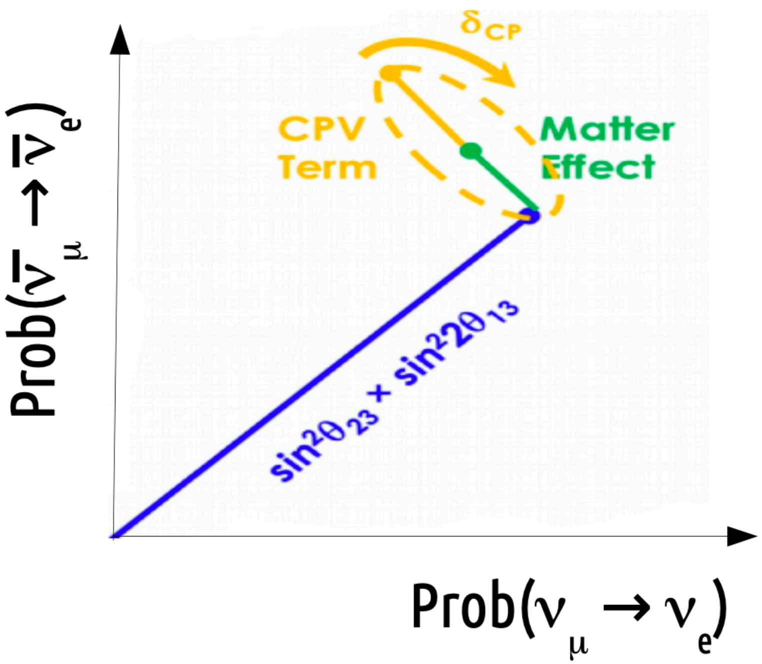
Learning from ν_e ($\bar{\nu}_e$) appearance

- $\sin^2 2\theta_{13}$ and $\sin^2\theta_{23}$
  - Enhance/suppress both ν_e and $\bar{\nu}_e$ appearance

- CP-violating phase δ_{CP}
  - **δ_{CP} = 0, π** ⇒ no CP violation: $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$ in vacuo
  - **δ_{CP} ~ -π/2**: enhance $\nu_\mu \to \nu_e$ and suppress $\bar{\nu}_\mu \to \bar{\nu}_e$
  - **δ_{CP} ~ +π/2**: suppress $\nu_\mu \to \nu_e$ and enhance $\bar{\nu}_\mu \to \bar{\nu}_e$

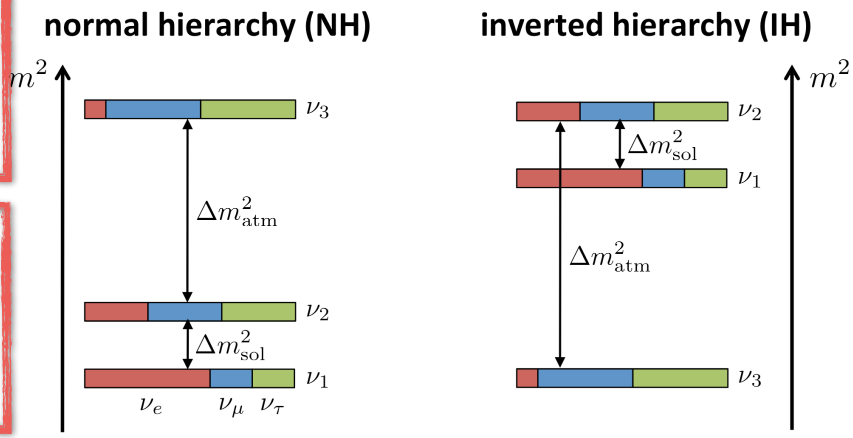


PTEP 2015 (2015) 053C02



Normal hierarchy
- Enhance $\nu_\mu \to \nu_e$
- Suppress $\bar{\nu}_\mu \to \bar{\nu}_e$

Inverted hierarchy
- Suppress $\nu_\mu \to \nu_e$
- Enhance $\bar{\nu}_\mu \to \bar{\nu}_e$

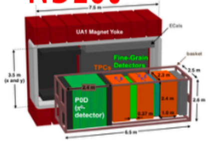


T2K vs NOνA

J-PARC Main Ring (30 GeV) ~500 kW

<E> ~ 0.6 GeV (2009)

ND280

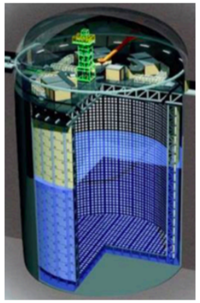


295 km

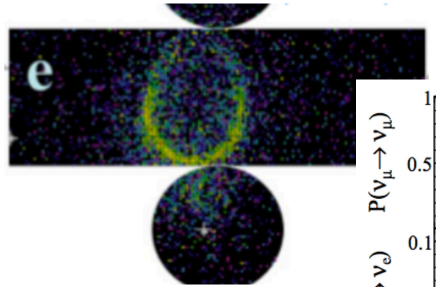
2.5° off-axis

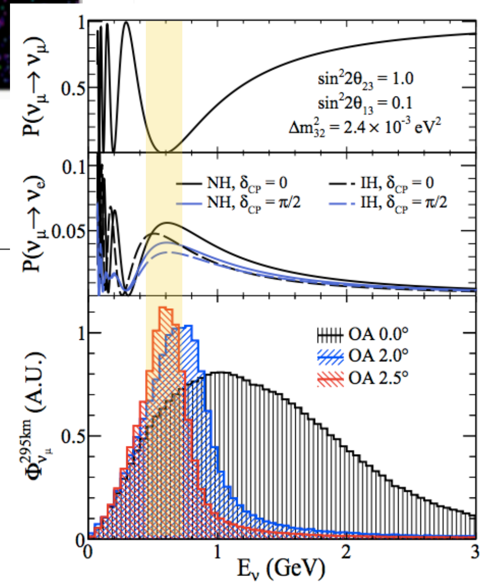
underground

Super-K 22.5 kt



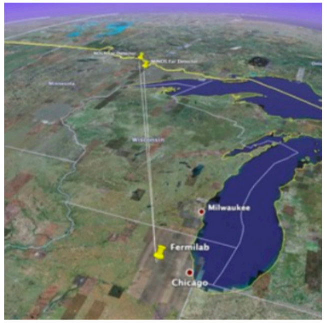
Water Cherenkov





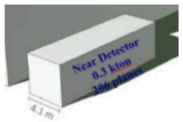
FNAL Main Injector (120 GeV) 670 kW

<E> ~ 2 GeV (2013)



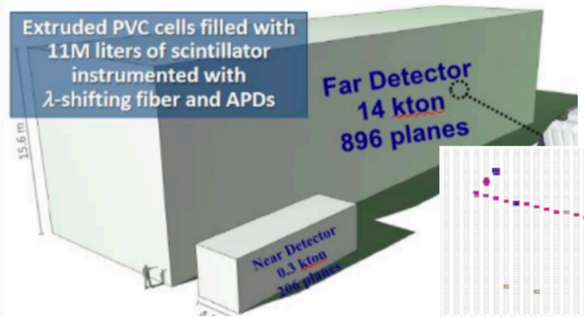
810 km

0.84° off-axis

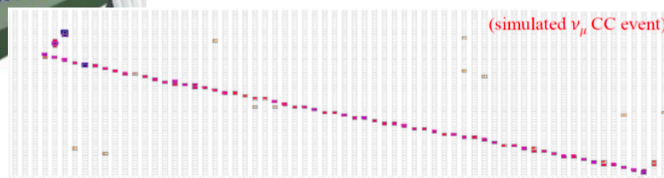


~ at surface

NOvA 14 kt



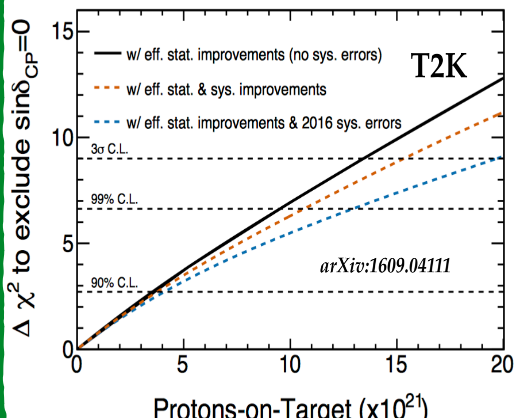
Liquid scintillator



off-axis beam

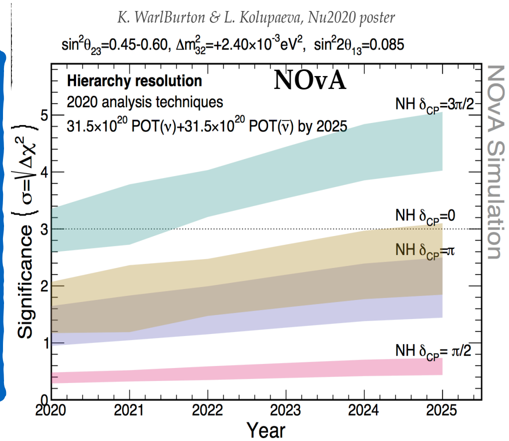
Looking ahed T2K

- Extended run of T2K (**20x10²¹ POT**) can result in 3σ for CPV 35%
- **ND280 upgrades**, WAGASCI/ BabyMIND to reduce neutrino interaction uncertainties
- **SK-Gd loading**: neutron tagging for enhanced ν/anti-ν separation

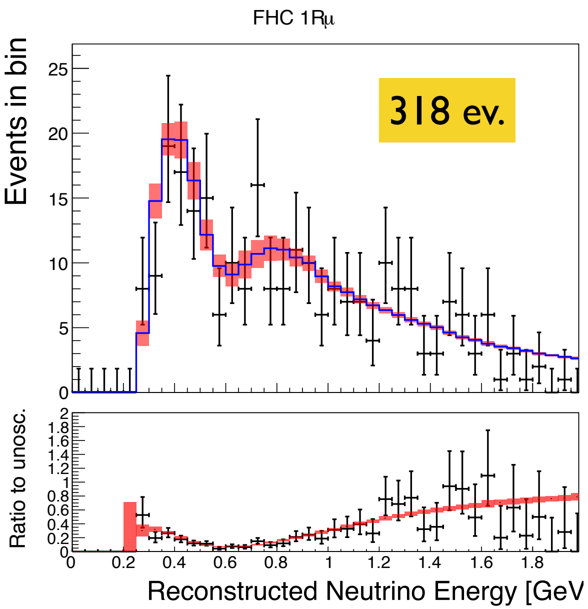


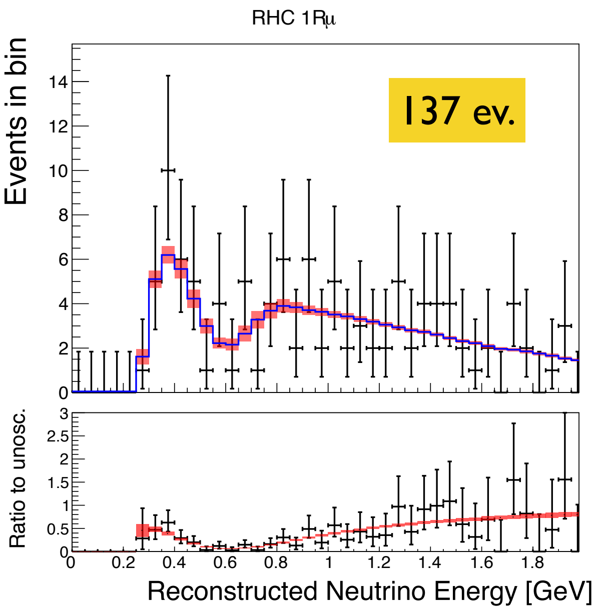
Looking ahed NOνA

- Can reach 3σ MH sensitivity for 30-50% of δ values
- **Can reach 2σ for CPV**

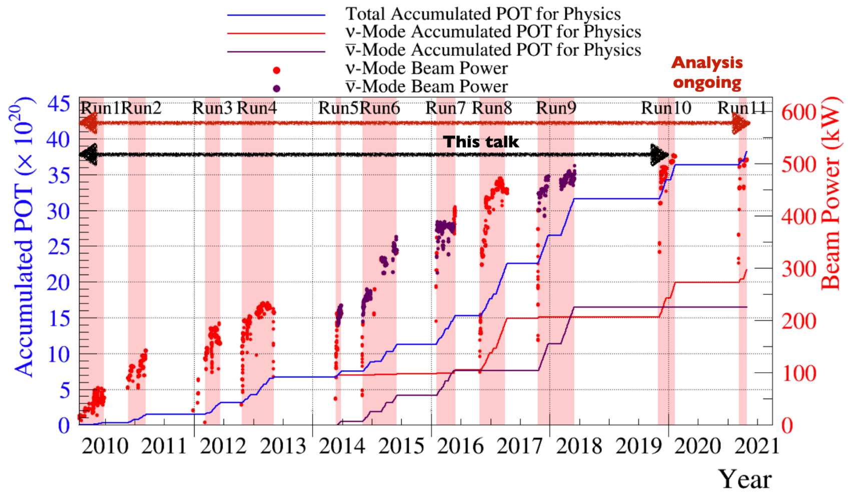


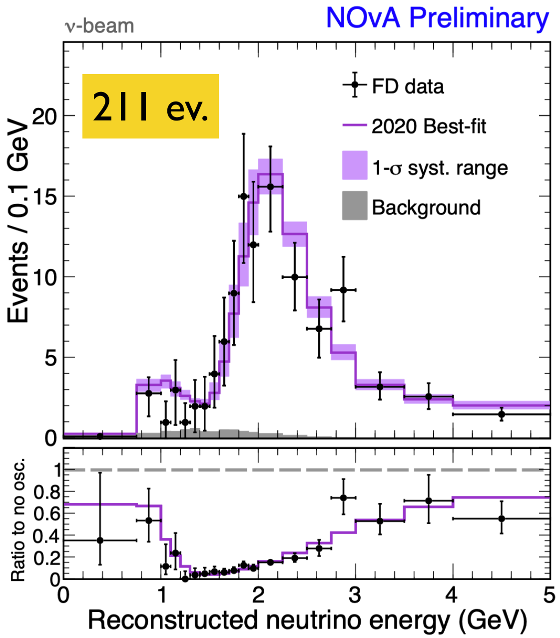
T2K-NOνA disappearance samples

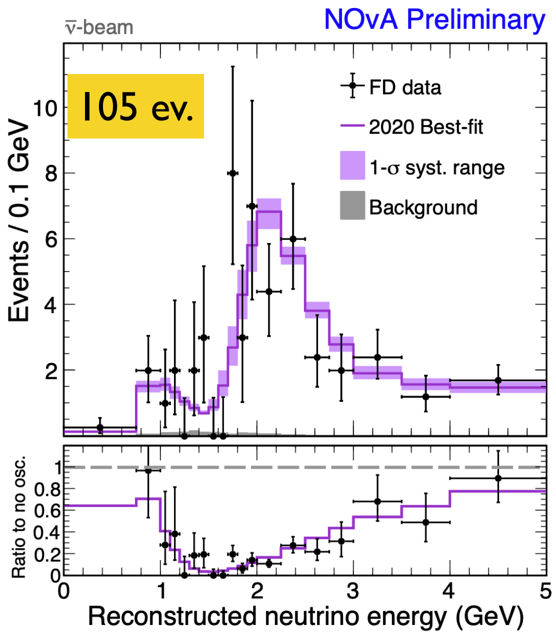




steady increase in beam power: 515 kW







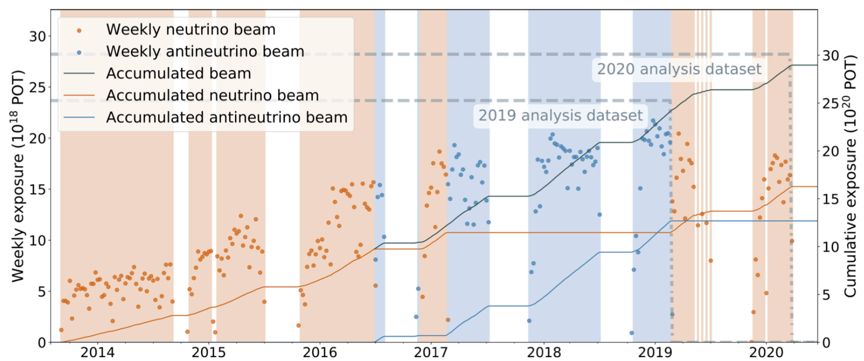
T2K 1.97×10^{21} POT in ν mode

T2K 1.63×10^{21} POT in $\bar{\nu}$ mode

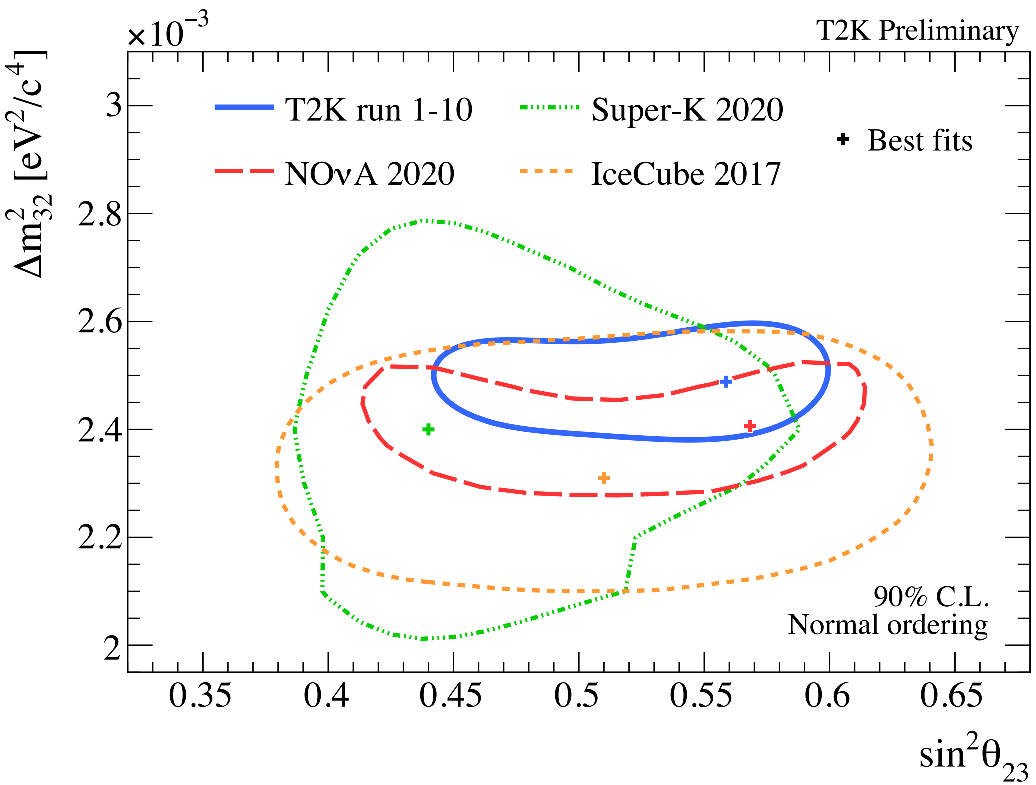
NOvA 1.36×10^{21} POT in ν mode

NOvA 1.25×10^{21} POT in $\bar{\nu}$ mode

Typical power: 670 kW



T2K-NOνA disappearance parameters

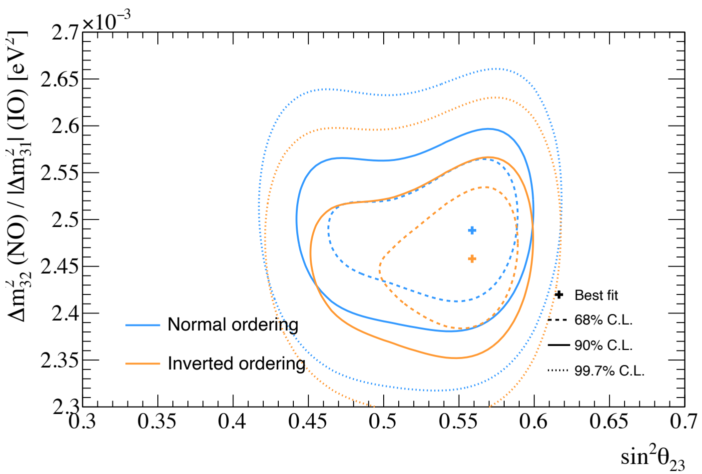


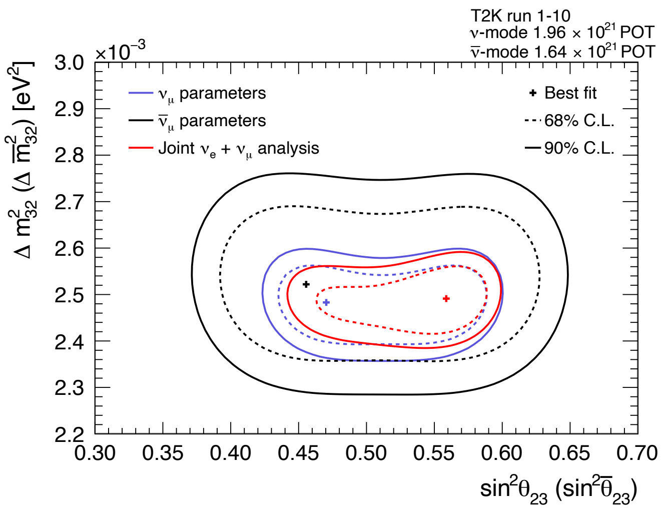
Both results have a mild preference for the **upper octant**!

T2K results shows **no violation in CPT theorem** (no significant differences between ν and $\bar{\nu}$ disappearance)

T2K has the world leading measurement $\sin^2\theta_{23}$

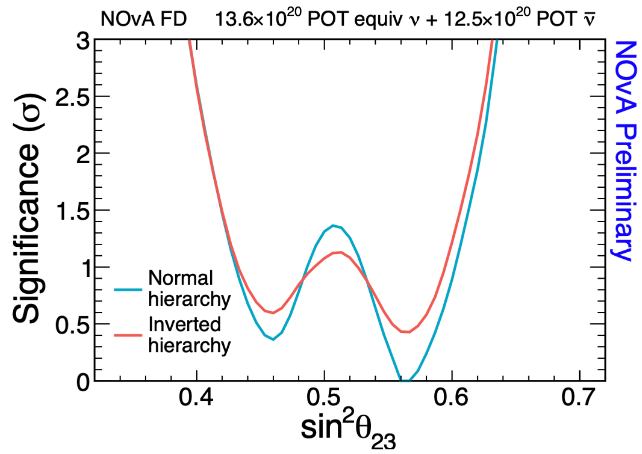
T2K





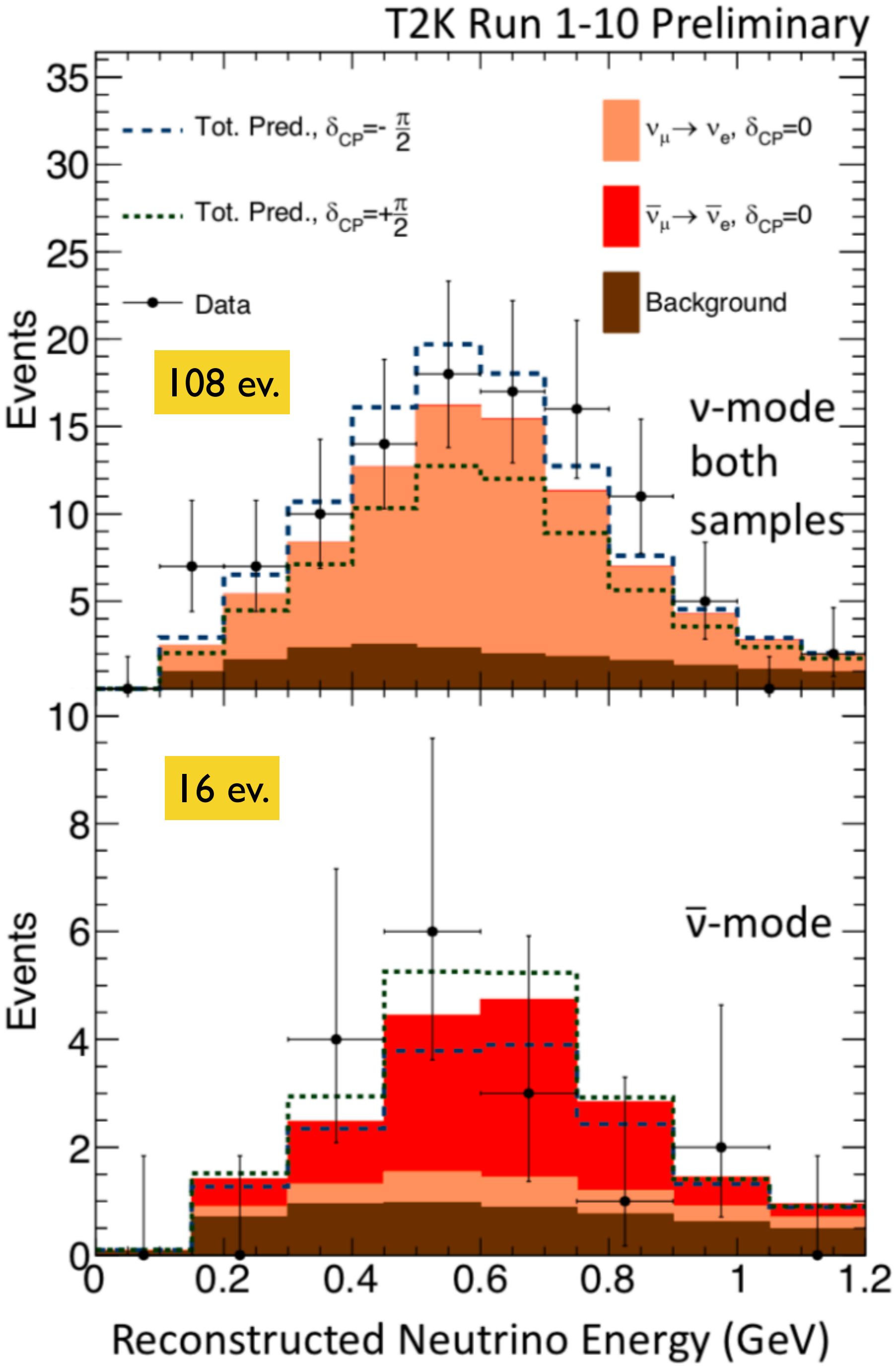
NOνA

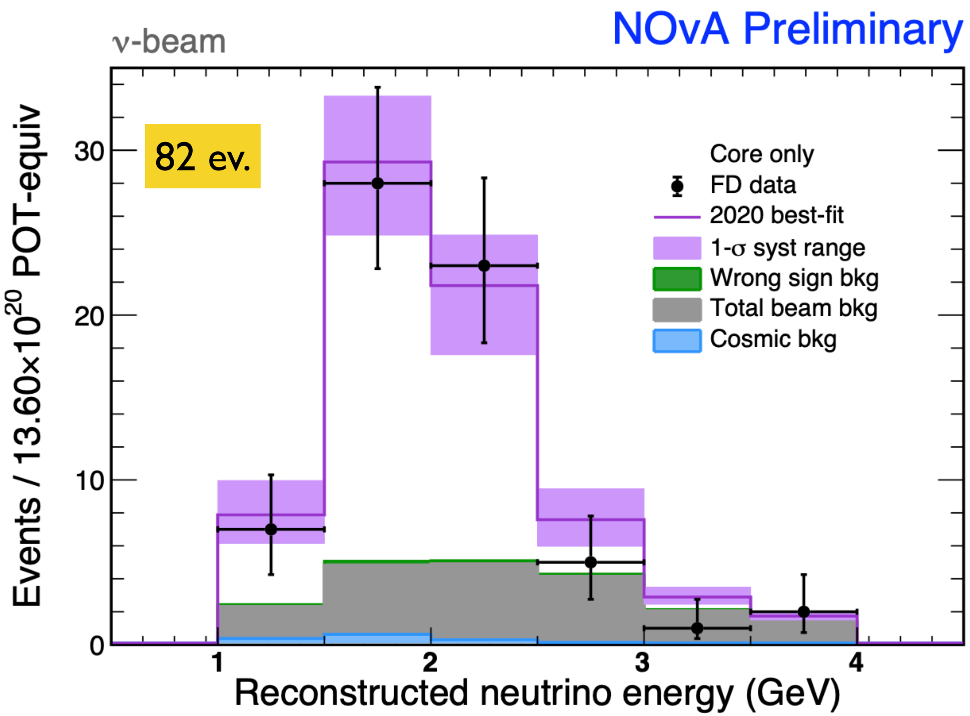
- $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\,\mathrm{eV}^2$ (normal hierarchy)

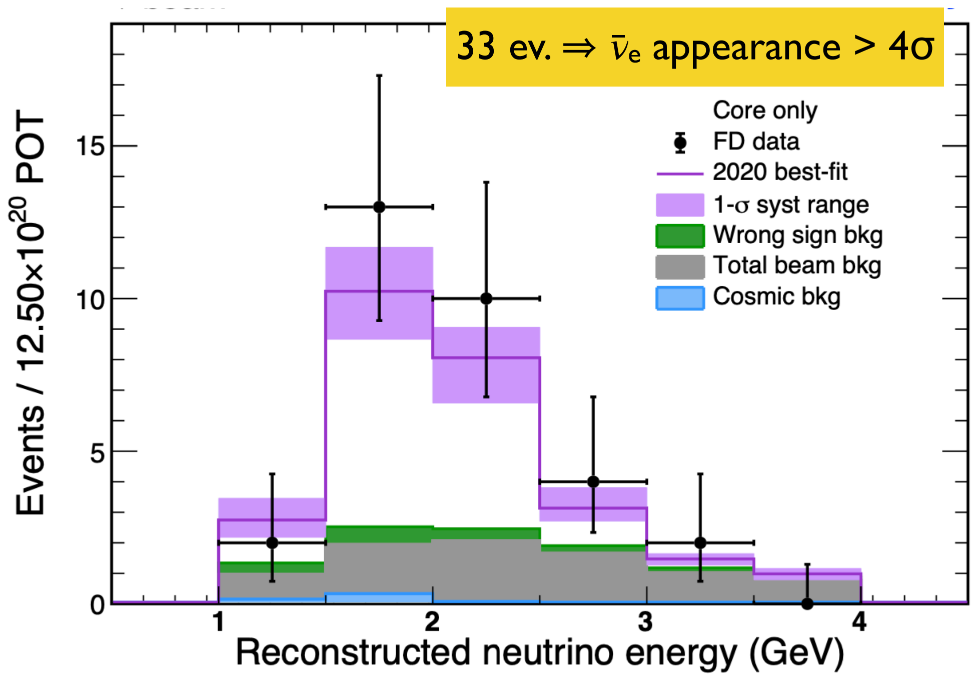


- Slight preference for upper octant, normal hierarchy
- $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

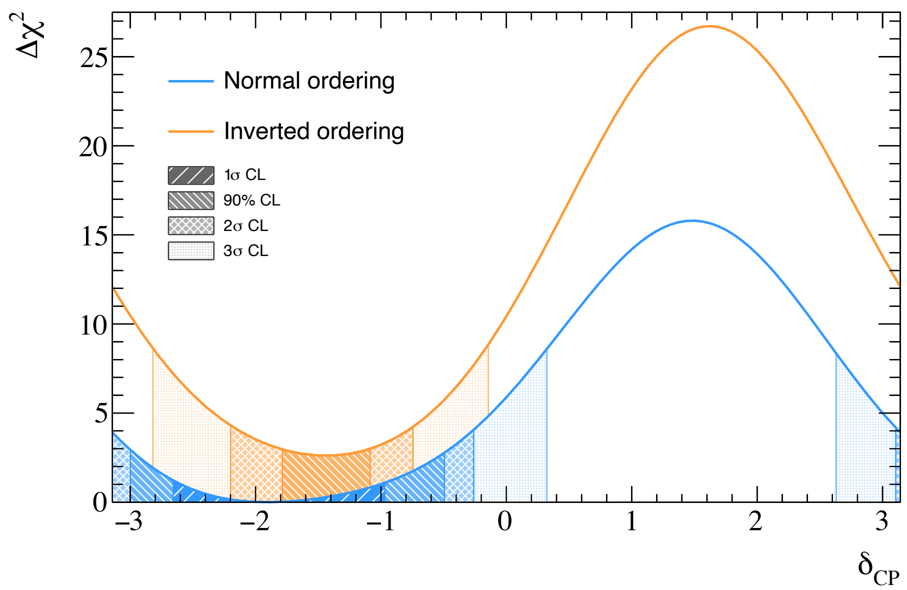
T2K-NOνA appearance samples

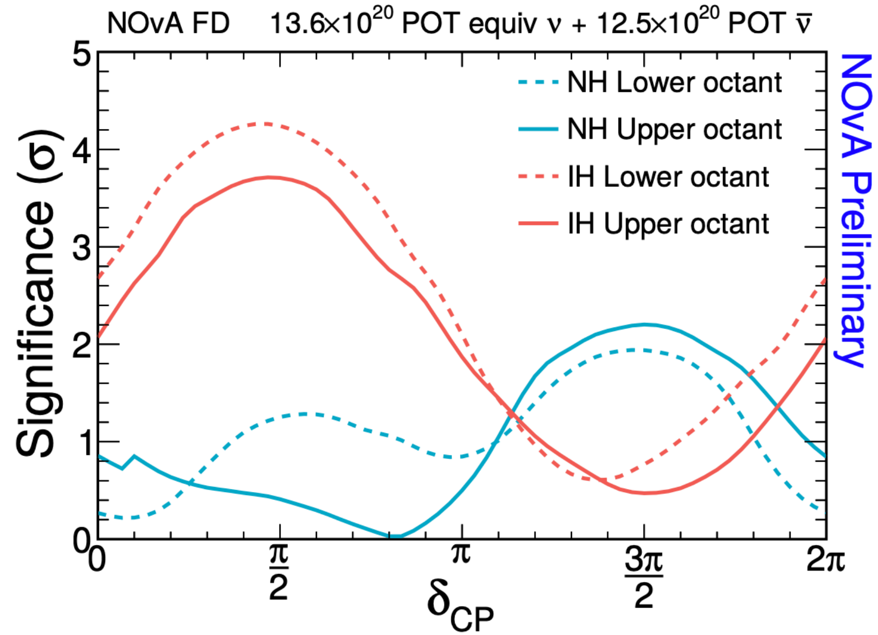






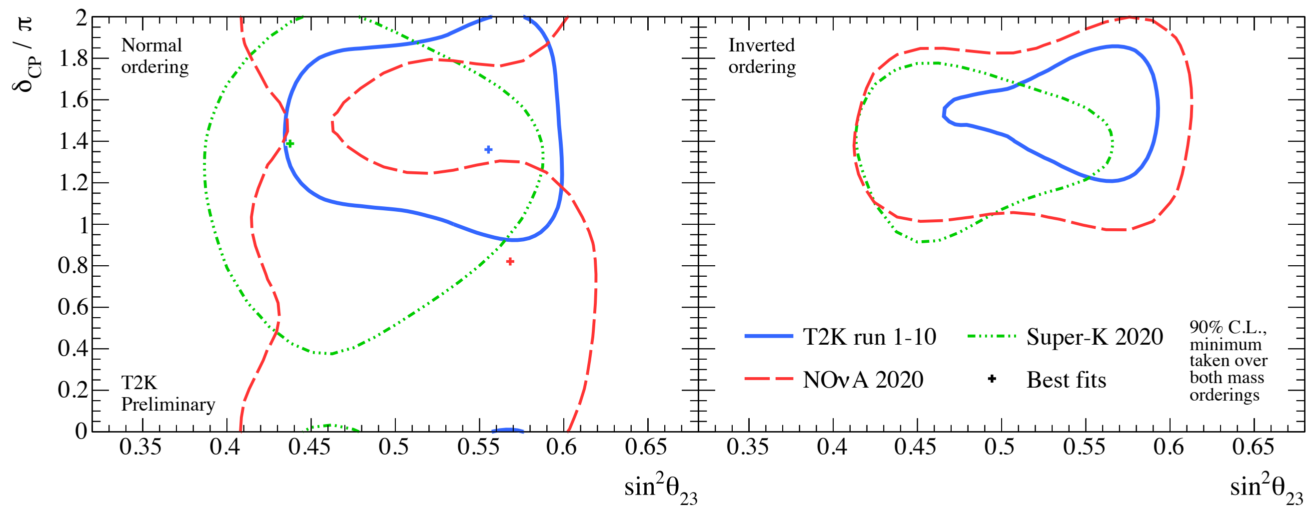
New results and comparison with other experiments



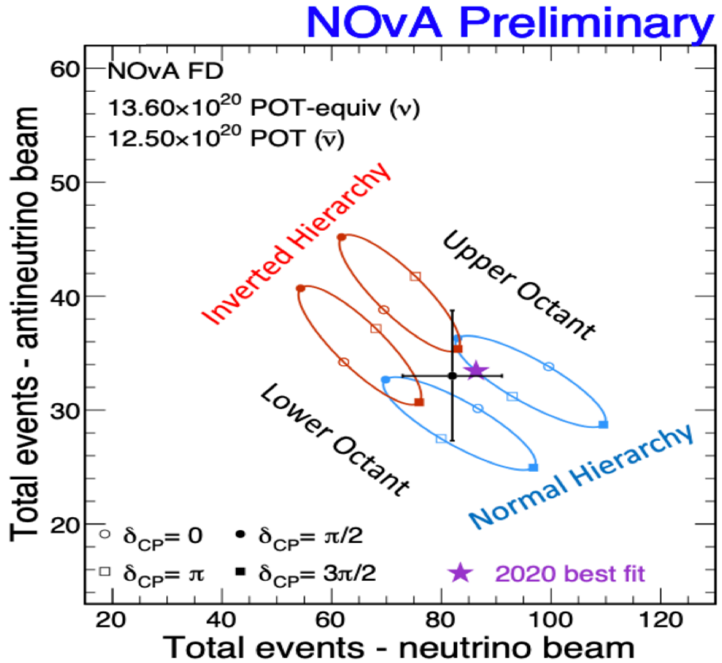


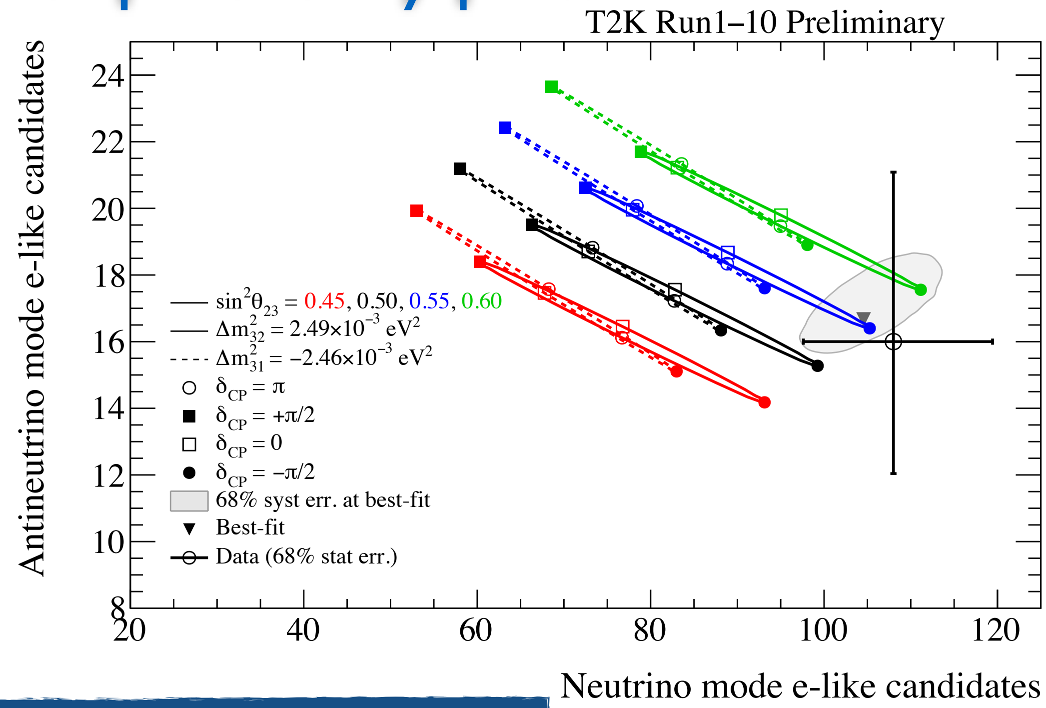
- **δ_{CP}=-π/2 favored for both NO and IO**
- 35% of values excluded at 3σ marginalised over both hierarchies
- CP conservation excluded at 90% CL.

- All values of δ_{CP} allowed at 90% CL
- Preference for normal hierarchy at 1.0σ
- Preference for upper octant at 1.2σ
- δ_{CP}=π/2 excluded at >3σ in inverted hierarchy



T2K-NOνA bi-probability plots





- Both T2K and NOνA prefer Normal Ordering ($\nu > \bar{\nu}$)
- T2K prefers the same phase irrespectively of the hierarchy while NOνA does not (opposite phases)

T2K has the world leading measurement of δ_{CP}

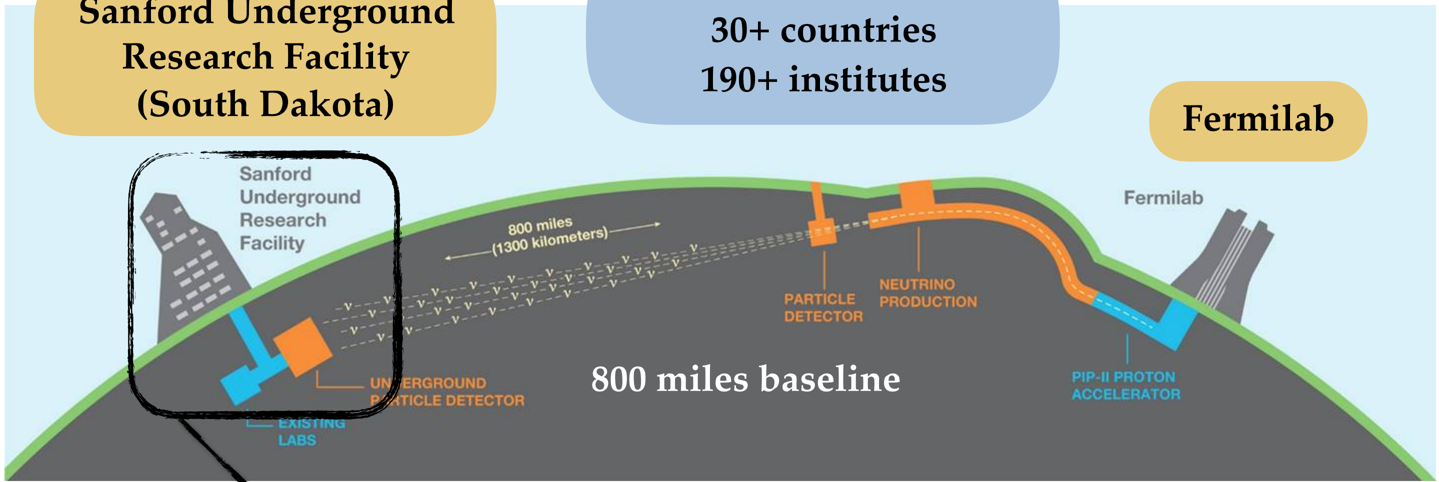
Future LBL neutrino oscillations experiments

The Deep Underground Neutrino Experiment (DUNE)

Sanford Underground Research Facility (South Dakota)

1100+ collaborators
30+ countries
190+ institutes

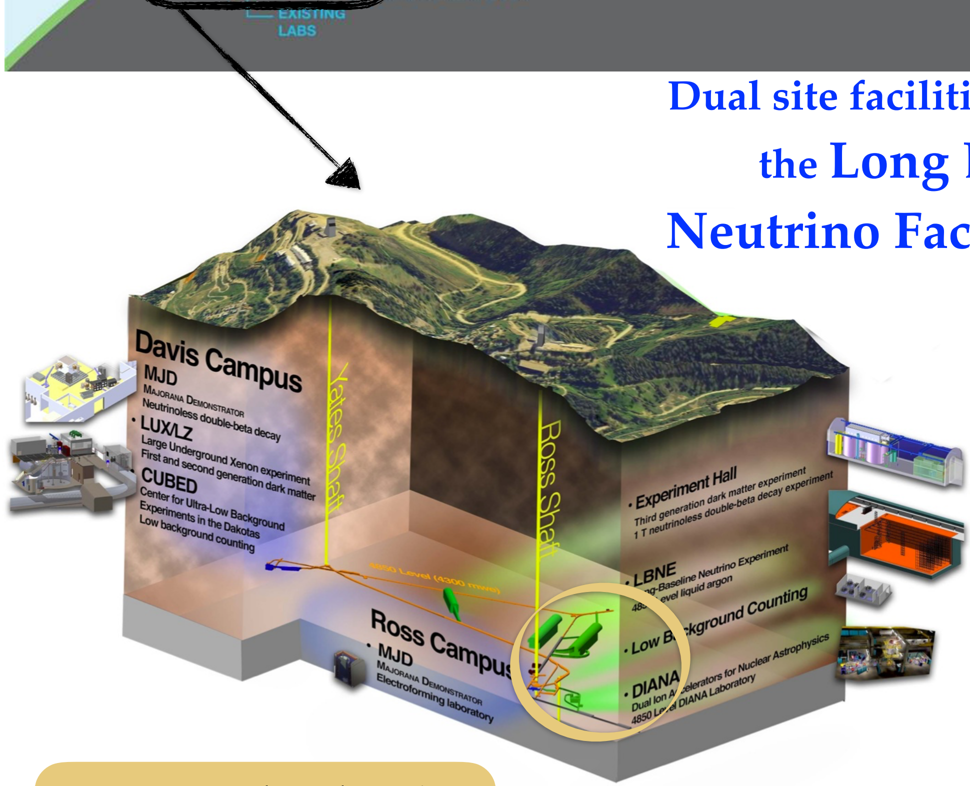
Fermilab



800 miles baseline

- Deep underground location
- 70 kton Far Detector (FD)
- Multiple technologies for the Near Detector (ND)
- MW-scale wide band neutrino beam
- FD Physics date in late 2020s
- Details of timeline will be finalized after project baselining (expected this year)

Dual site facilities provided by the **Long Baseline Neutrino Facility (LBNF)**



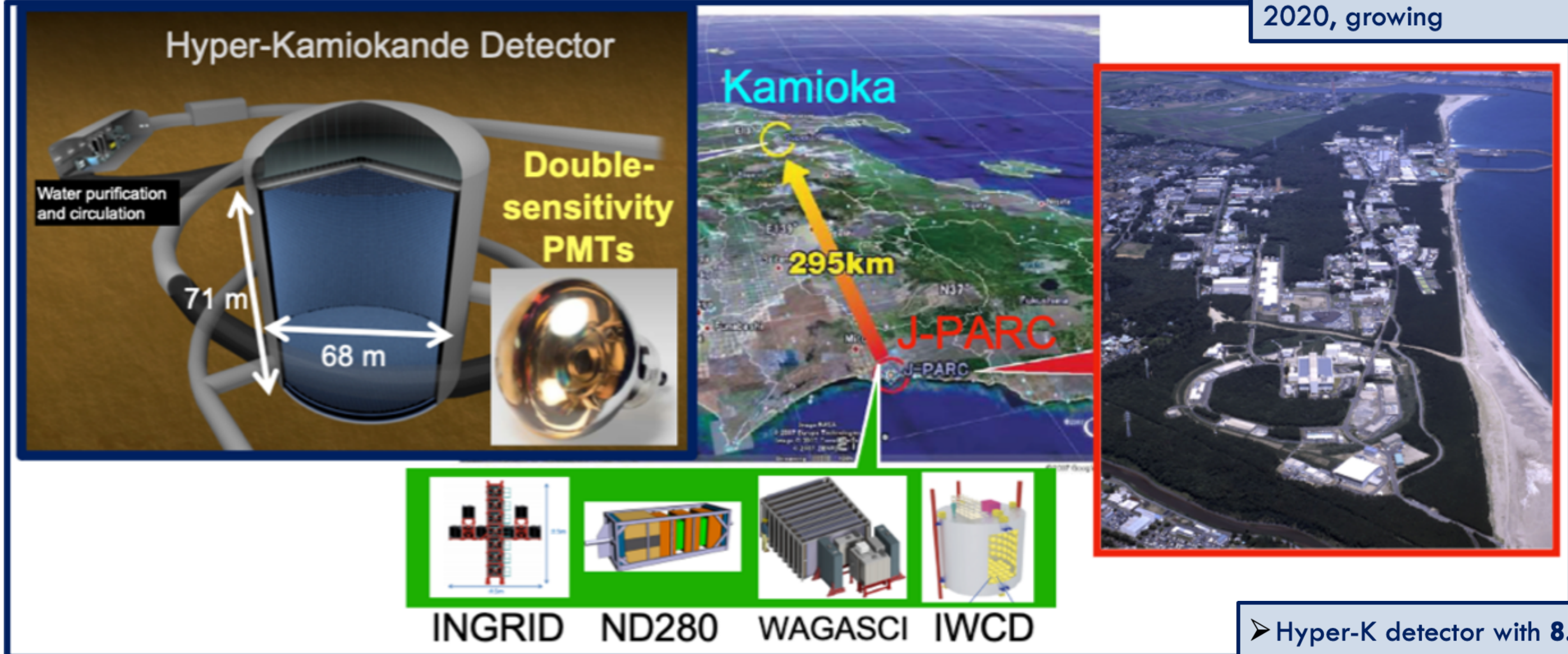
DUNE 1.5 km deep in Home Stake Mine

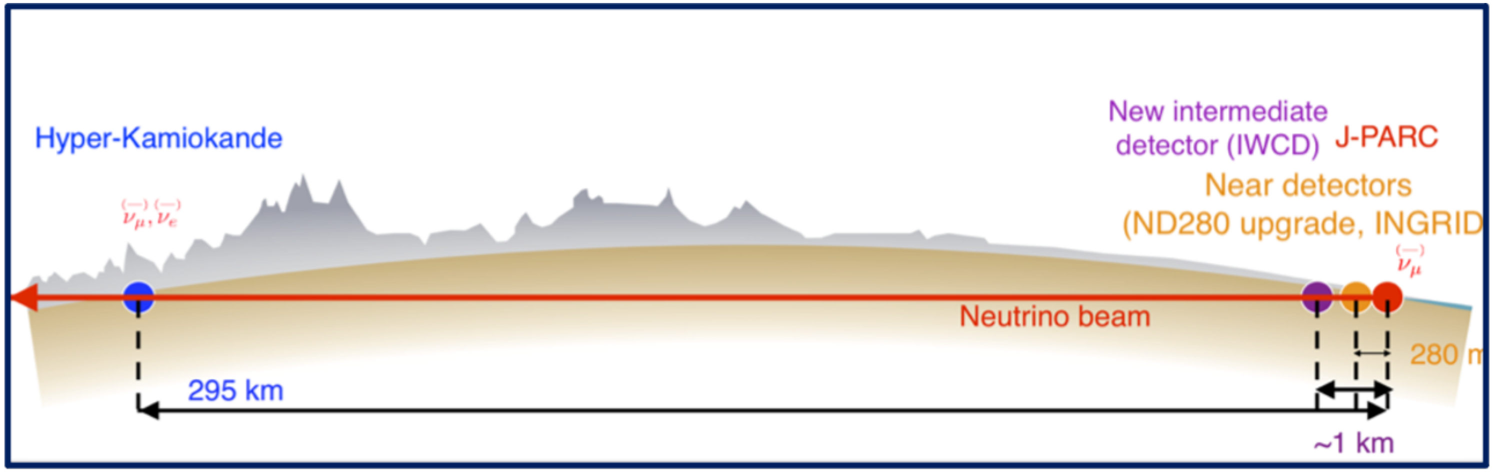
Very Rich Physics Program

- CP Violation
- Neutrino Mass Hierarchy
- Precision measurements of neutrino oscillation parameters
- Supernova & Astrophysics
- Nucleon Decay (e.g. $p \rightarrow K^{+}\nu$)
- Many BSM searches

Hyper-Kamiokande

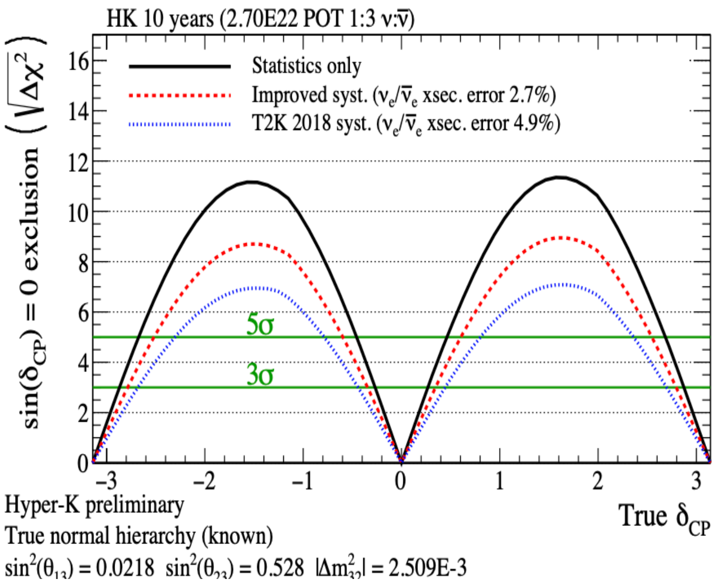
19 countries, 93 institutes, ~440 people as of November 2020, growing

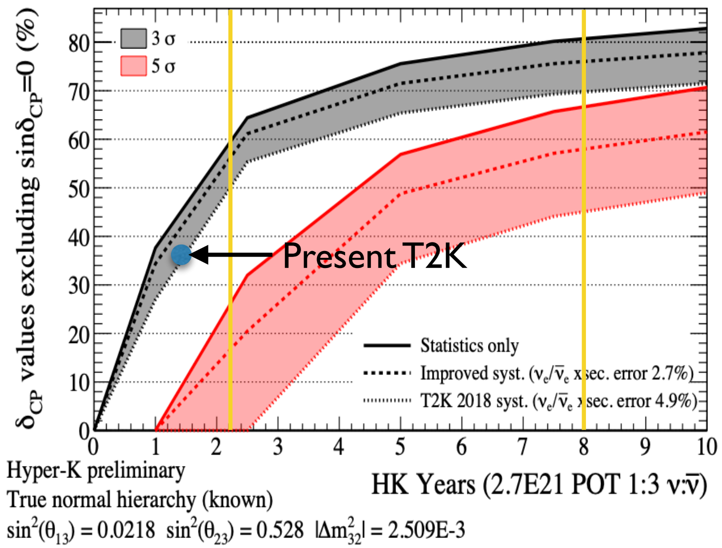




- ➢ Hyper-K detector with **8.4 times larger fiducial mass** (190 kiloton) than Super-K with **double-sensitivity PMTs**
- ➢ J-PARC neutrino beam will be upgraded from 0.5 to 1.3MW (**x2.5** higher than current T2K beam power)
- ➢ New (IWCD) and upgraded ND280) near detectors to control systematic error.

DUNE and Hyper-K sensitivities

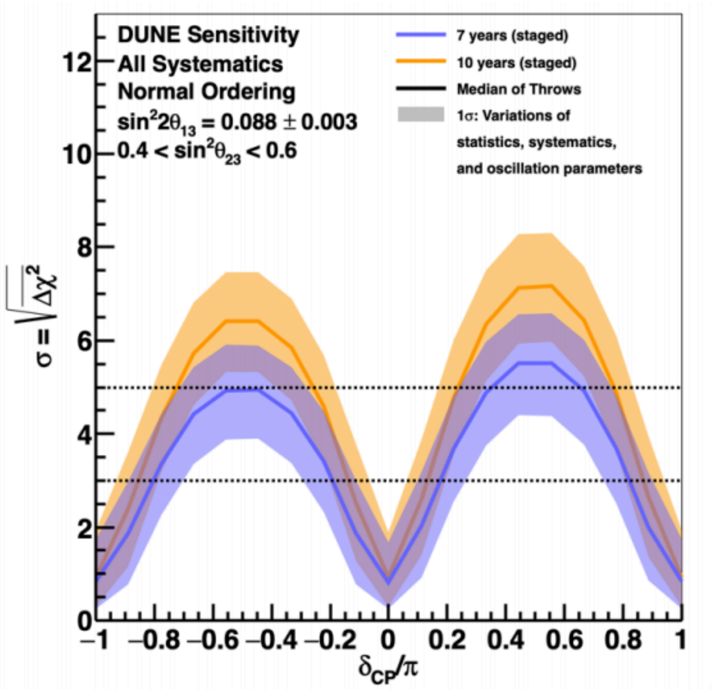


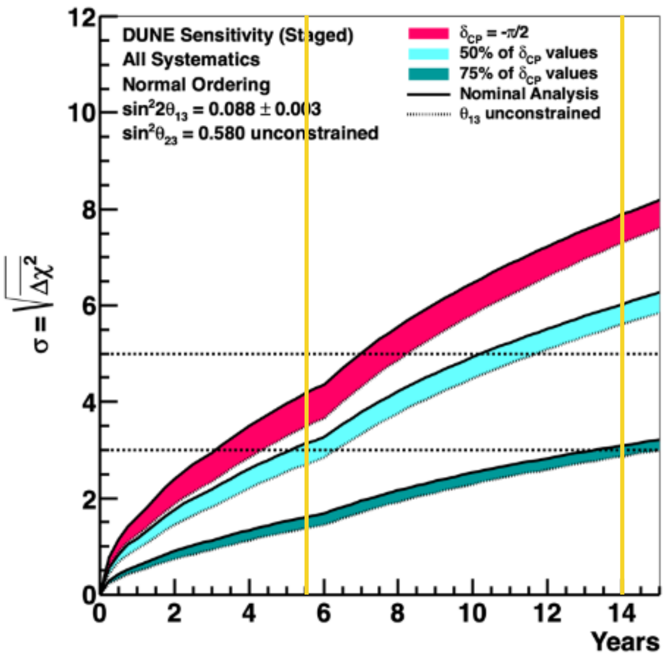


Hyper-Kamiokande

Exclusion of $\sin\delta_{cp} = 0$

- ~8 σ for $\delta_{cp}=-90°$
- More than 50% of δ_{CP} range >5σ
- 3σ for 50% of δ_{CP} values in ~2 years
- 3σ for 75% of δ_{CP} values in 8-10 years





DUNE

Staged scenario

- Assumes equal running in neutrino and antineutrino mode
- 3σ for 50% of δ_{CP} values in 5-6 years
- 3σ for 75% of δ_{CP} values in 13-14 years
- 5σ MH determination for any value of δ_{CP} in 2.5 years

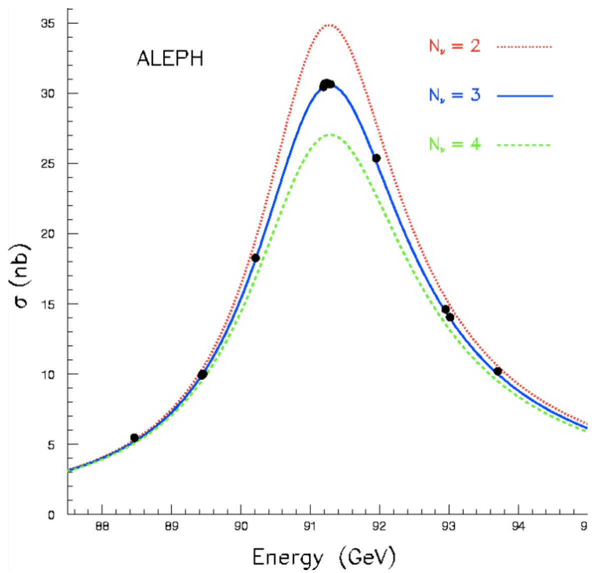
SBL neutrino program in US

Light sterile neutrinos?

Several anomalies have been found in short baseline experiments (SBL), which cannot be explained in the 3-flavor Scenario.

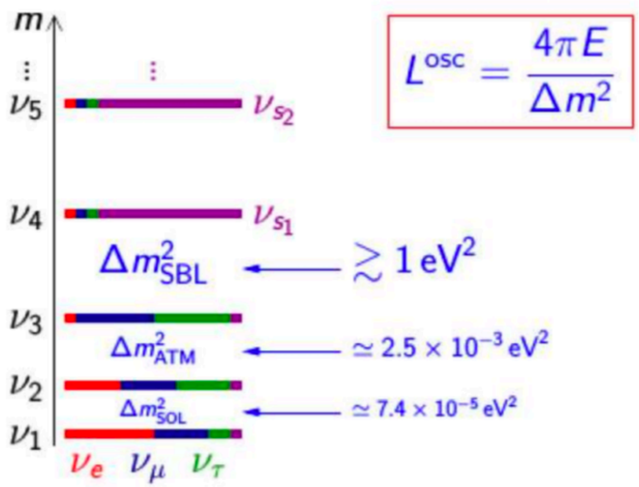
The new hypothetical eigenstate must be supposed to be sterile, i.e., **a singlet of the standard model gauge group**.

Minimal extension (3+1): assume a mass eigenstate ν_4 weakly mixed with the active neutrino flavors (ν_e , ν_μ , ν_τ) and separated from the standard mass eigenstates (ν_1 ,ν_2 ,ν_3) by a O(1eV^2)difference.



Experiment	Type	Channel	Significance
LSND	DAR accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8 σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$	4.5 σ
		$\bar{\nu}_\mu \to \bar{\nu}_e$	2.8 σ
GALLEX/SAGE	Source – e capture	ν_e disappearance	2.8 σ
Reactors	β decay	$\bar{\nu}_e$ disappearance	3.0 σ

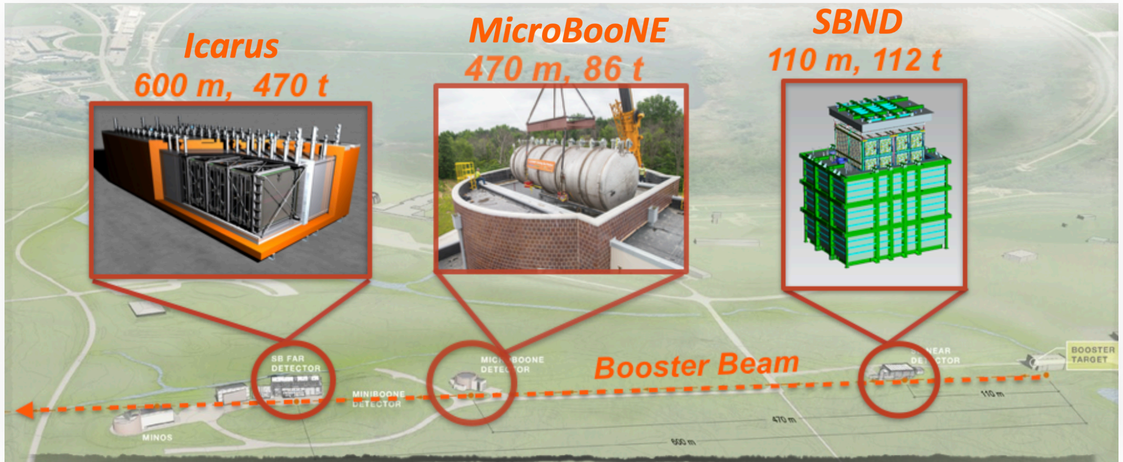
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} \end{pmatrix} \quad \vartheta_{14} \quad \vartheta_{24} \quad \vartheta_{34}$$

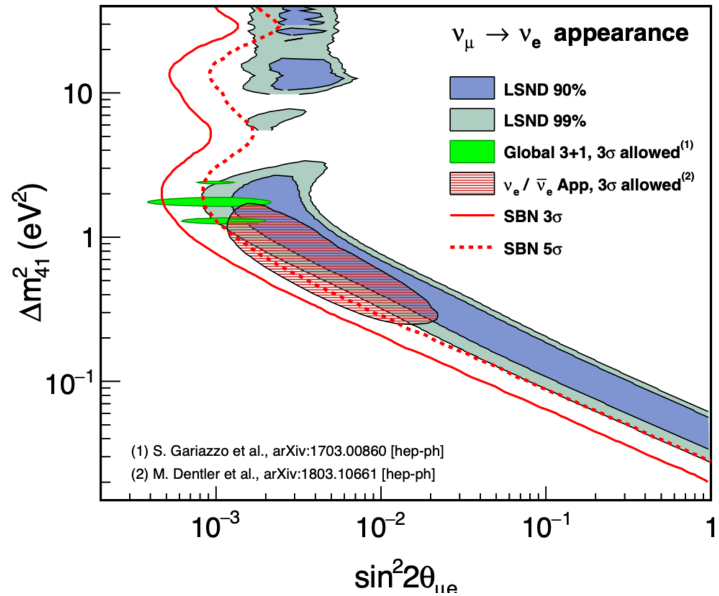


FNAL Short Baseline Neutrino (SBN) Program

Program aimed at definitely solving the "sterile neutrino puzzle" by exploiting:

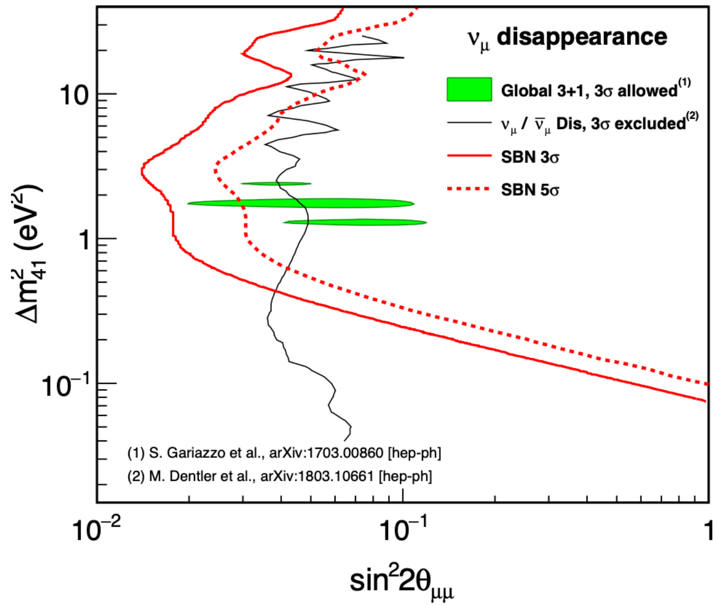
- the well characterized FNAL Booster ν beamline;
- three detectors based on the same liquid argon TPC technique.





SBN Goals

- **MicroBooNE**: Understand the nature of the MiniBooNE "low energy" excess anomaly, using the same beam.
- **SBND + ICARUS**: Search for short baseline oscillations both in appearance and disappearance channels.
- Lay the ground for future long baseline program (LAr-TPC technique and ν-Ar x-sec at energies relevant to DUNE)



Unique capability to study appearance and disappearance channels simultaneously.

More details in Falcone's talk

Conclusions

- **At the begin of the new decade, the puzzle of neutrino oscillations is getting clearer**
- **The T2K experiment has the world leading result for δ_{cp} measurement (excluded 35% of δ_{cp} values at 3σ)**
- **Both T2K and NOνA data prefer upper octant θ_{23} and Normal Ordering Masses**
- **Now we are at the beginning of the large θ_{13} era**
- **New results on δ_{cp} and mass ordering are expected from T2K (with beam and near detector upgrade) and NOνA with full statistic (T2K+ NOνA joint analysis)**
- **Expected to reject conserving values at 5σ from the new generation experiments DUNE and Hyper-Kamiokande (~2027)**
- **The SBL neutrino program at FNAL can shed a light on the mystery of sterile neutrinos**
- **Lots of exciting work and results to come in the next future!**