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Long-Baseline Neutrino Experiments

A Journey from Discovery to Precision and Beyond

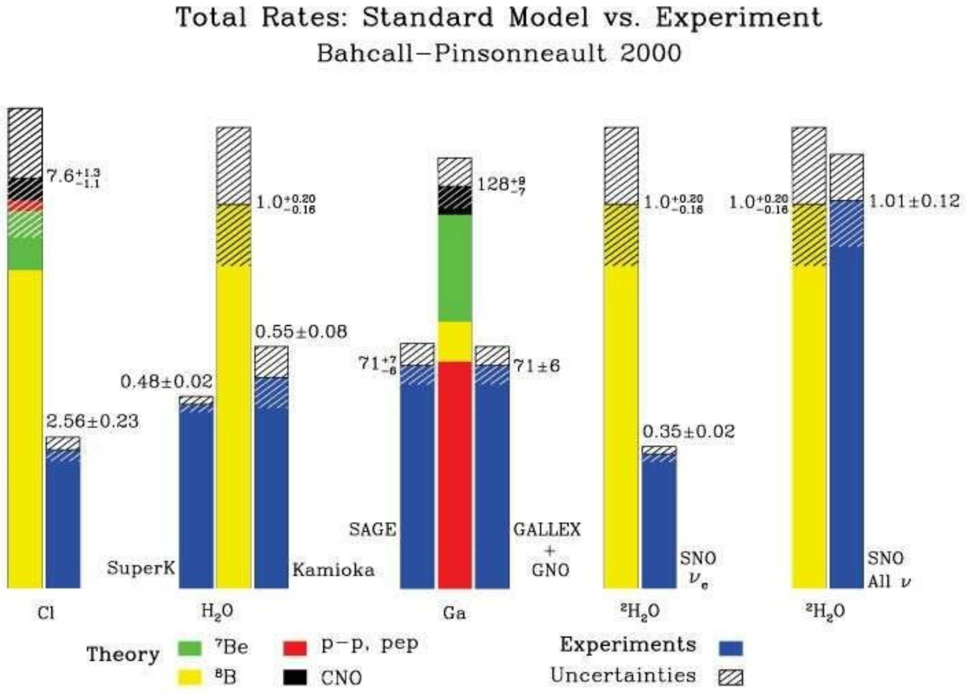
HQL 2025

17th International Conference on Heavy Quarks and Leptons

Beijing - September 18th, 2025

The neutrino problems

Decades of mystery from natural neutrino sources



- **Solar Neutrino Problem**

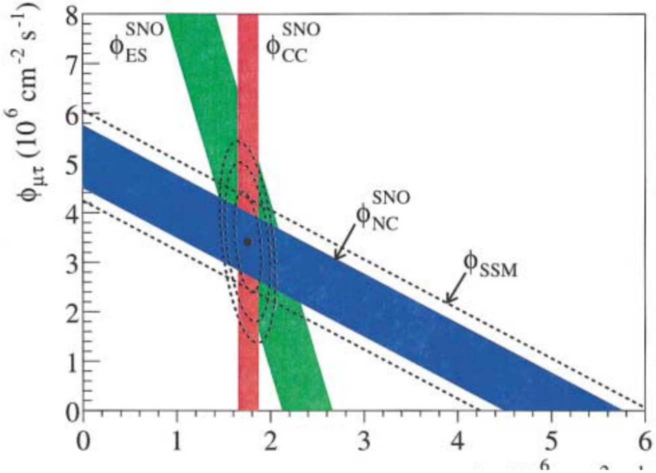
  Only 1/3 of expected electron neutrinos from the Sun were detected (Homestake, 1960s)

- **Atmospheric Neutrino Problem**

  A deficit in the flux of muon neutrinos from cosmic ray interactions (Kamiokande, IMB, 1980s)

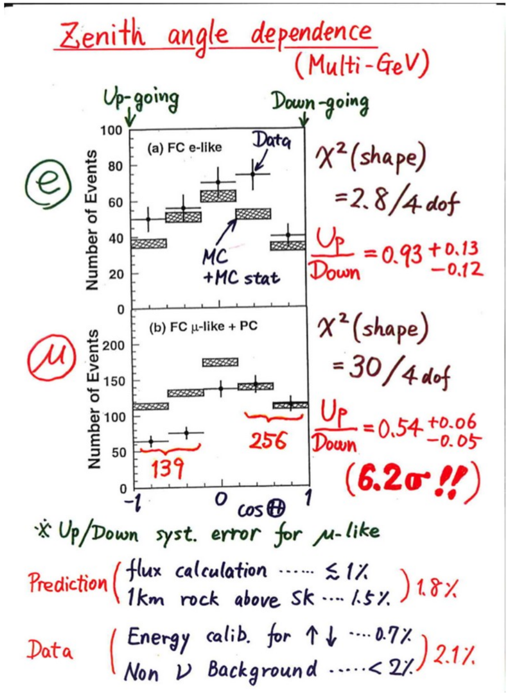
A Solution Emerges: Oscillation

Neutrinos have mass and change flavor as they travel



https://doi.org/10.1103/PhysRevLett.89.011301

- 1998: Super-Kamiokande sees up-down asymmetry in atmospheric ν_μ, conclusive evidence of oscillations
- 2002: Sudbury Neutrino Observatory (SNO) measures total solar neutrino flux, confirming flavor change



https://doi.org/10.1103/PhysRevLett.81.1562

A Nobel Winning Paradigm Shift

2002

Solar neutrinos (Homestake) and supernova neutrinos (Kamiokande), awarded with the Nobel prize to Ray Davis and Masatoshi Koshiba ***for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos***

2015

Solar neutrinos (SNO) and atmospheric neutrinos (Super-K), awarded with the Nobel prize to Arthur McDonalds and Takaaki Kajita ***for the discovery of neutrino oscillations, which shows that neutrino have mass***

The Need for Controlled Sources

Discovery confirmation & precision → needs for controlled neutrino sources

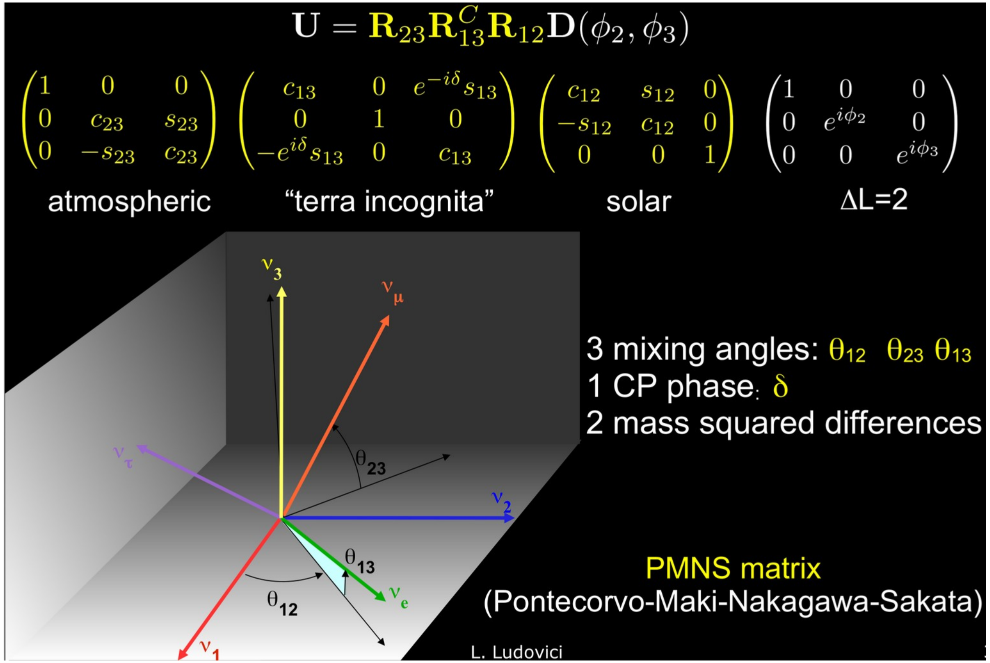
- Long-Baseline (LBL) experiments:
  - Create a beam at an accelerator and measure it hundreds of km away
- Controlled neutrino source:
  - Energy spectrum, flavor composition, and distance (baseline)

Flavor vs. Mass: The Heart of Oscillation

Flavor states (ν_e, ν_μ, ν_τ) are what we detect

Mass states (ν_1, ν_2, ν_3) are what propagate through space

Each flavor state is a quantum superposition of the three mass states



20 years ago, circa:

- θ_{12}, θ_{23}, where known to be "large"
- Little was known about θ_{13}
- Nothing about δ_{CP}

The Oscillation Probability

Phase between propagating mass states causes flavor content to change

Probability $P(\nu_\alpha \rightarrow \nu_\beta)$ depends on:

- The PMNS mixing matrix elements $U_{\alpha\beta}$
- Baseline (L) and Neutrino Energy (E)
- Mass-squared splittings (Δm^2)

$$P(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \frac{(m_i^2 - m_j^2)L}{4E_\nu}$$

$$(\pm) 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin \frac{(m_i^2 - m_j^2)L}{2E_\nu}$$

Matter-effects neglected

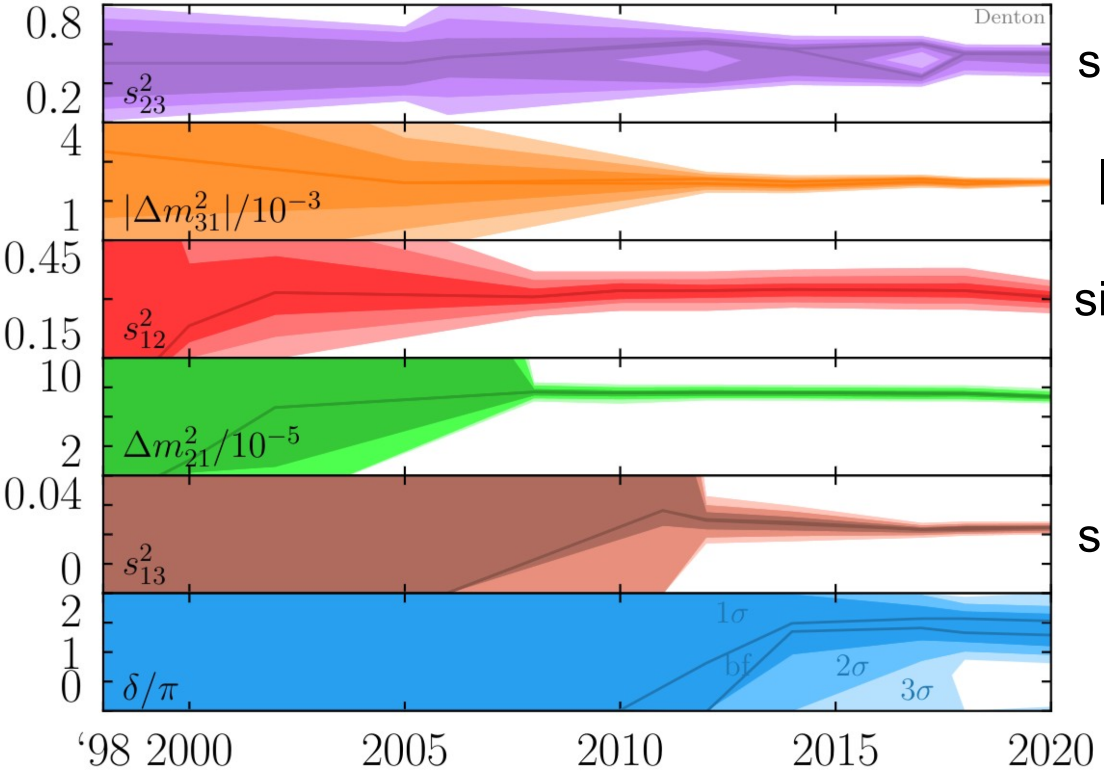
The PMNS Matrix: A Rosetta Stone for Neutrinos

- Describes the mixing between flavor and mass states
- Parameterized by 3 mixing angles (θ_{12}, θ_{23}, θ_{13}) and 1 complex phase (δ_{CP})
- δ_{CP} is the source of CP violation in the lepton sector

$$(\nu_e, \nu_\mu, \nu_\tau)^T = U_{\alpha i}^{MNS} (\nu_1, \nu_2, \nu_3)^T$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\vartheta_{12} & \sin\vartheta_{12} & 0 \\ -\sin\vartheta_{12} & \cos\vartheta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\vartheta_{13} & 0 & \sin\vartheta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\vartheta_{13} e^{i\delta} & 0 & \cos\vartheta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\vartheta_{23} & \sin\vartheta_{23} \\ 0 & -\sin\vartheta_{23} & \cos\vartheta_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Two Decades of Quest for Precision



from P.Denton

$\sin^2(\theta_{23}) = 0.534\,^{+0.015}_{-0.019}$ 3.2%

$|\Delta m^2_{32}| = 2.451 \pm 0.026 \times 10^{-3}\ \mathrm{eV}^2$ 1.1%

$\sin^2(\theta_{12}) = 0.307 \pm 0.012$ 3.9%

$\Delta m^2_{21} = (7.50 \pm 0.19) \times 10^{-5}\ \mathrm{eV}^2$ 2.5%

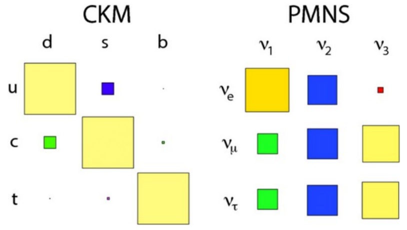
$\sin^2(\theta_{13}) = 0.0216 \pm 0.0006$ 2.8%

$\delta_{CP} = 1.21\,^{+0.19}_{-0.22}\ \pi$ rad 17%

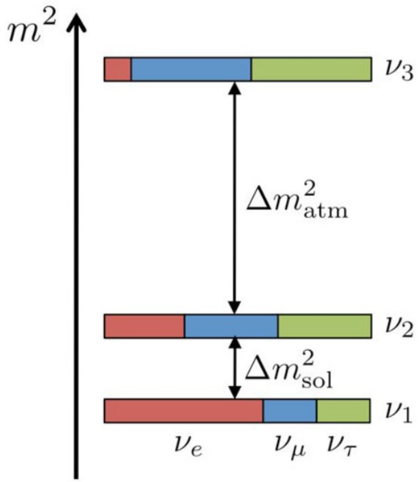
PDG 2025

The 'Known Unknowns' of Neutrino Oscillation

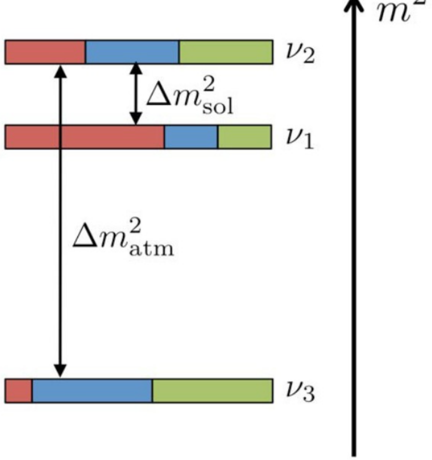
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$J_\nu = \sin\theta_{13} \cos^2\theta_{13} \sin\theta_{12} \cos\theta_{12} \sin\theta_{23} \cos\theta_{23} \sin\delta_{CP}$



Inverted Ordering



CP: is $\sin(\delta_{CP}) \neq 0$? How large is it? Jarskolg invariant J_ν might be as large as 3.2 10^{-2}

Ordering: is Δm^2_{23} positive or negative? Normal or Inverted MO?

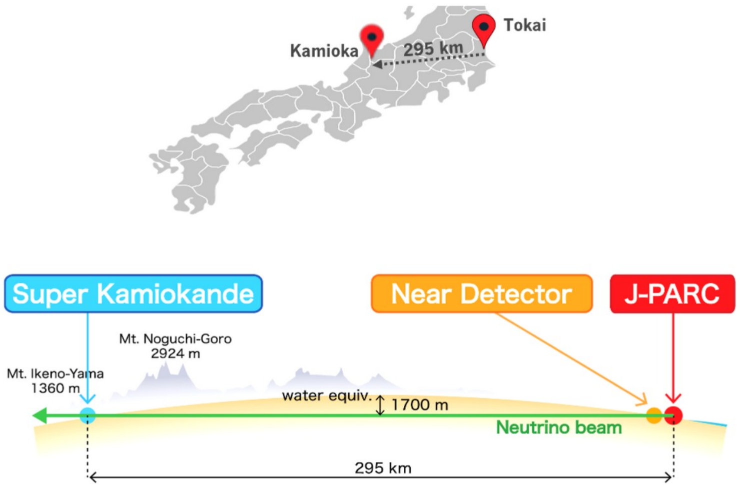
Octant: are there symmetries in the mixing matrix? e.g. $U_{\mu 3} = U_{\tau 3}$ ($\theta_{23} = 45°$) ?

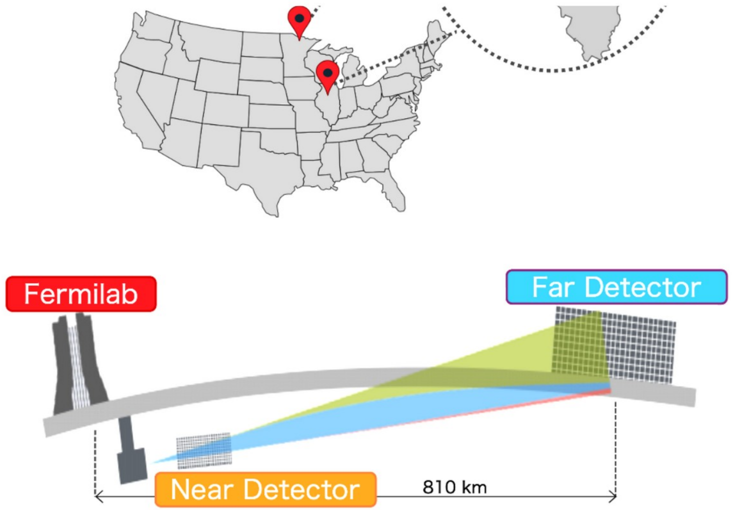
‘Unknown Unknowns’:

Is the PMNS matrix unitary? Is the three-flavour neutrino paradigm the full picture or there is new physics looming behind neutrino masses ?

The Three Pillars of a LBL Experiment

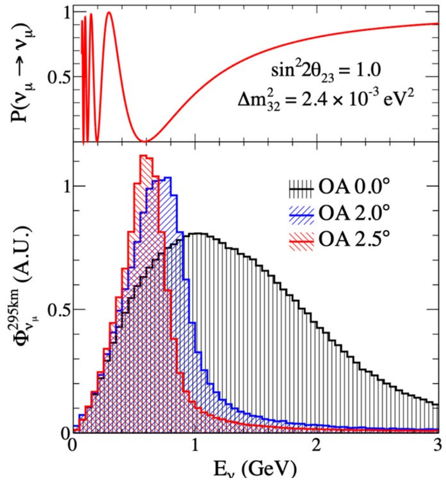
- Neutrino Beam: A powerful, well-characterized source
- Near Detector: Measure interaction rates before oscillation to constrain systematic from flux and neutrino interaction models
- Far Detector: A massive detector to measure the oscillated rates

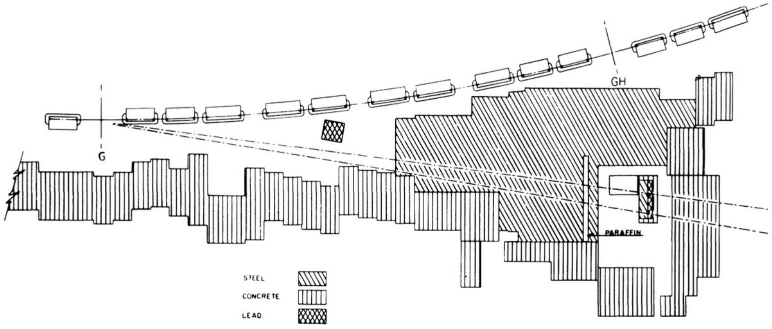




1: The Neutrino Beam

- High-energy protons strike a target, producing pions/kaons
- Magnetic horns focus these particles into a decay tunnel
- In-flight decay (e.g., $\pi^+ \rightarrow \mu^+ + \nu_\mu$) produces a ν_μ beam
- Unavoidable O(1%) ν_e from μ decay (and possibly K)
- A beam dump stops all particles except neutrinos





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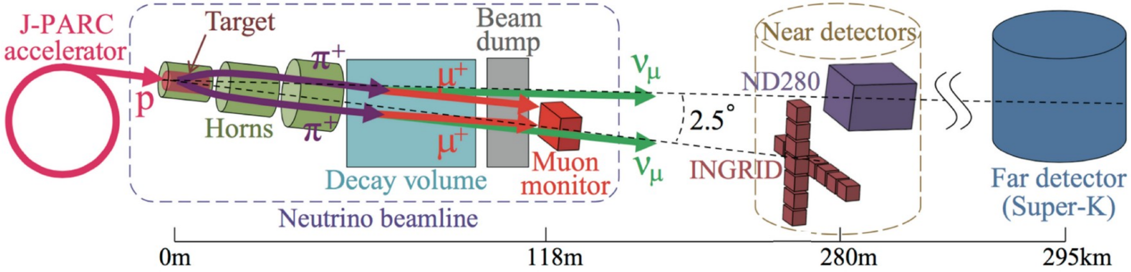
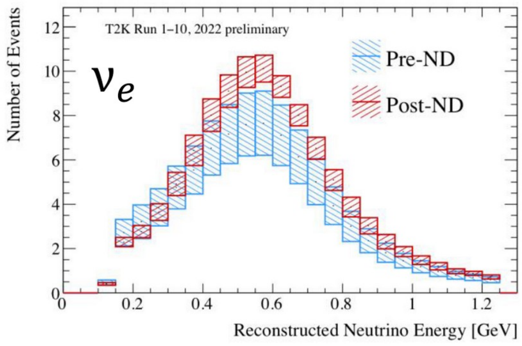
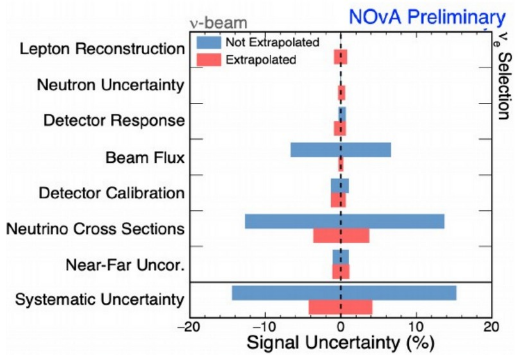
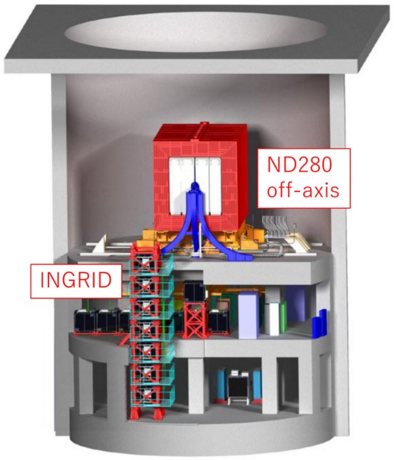


2: The Near Detector

- Measures un-oscillated beam flux, energy, and composition
- Crucially, measures neutrino interaction cross-sections
- Allows for cancellation of large systematics by comparing Near vs. Far detector rates



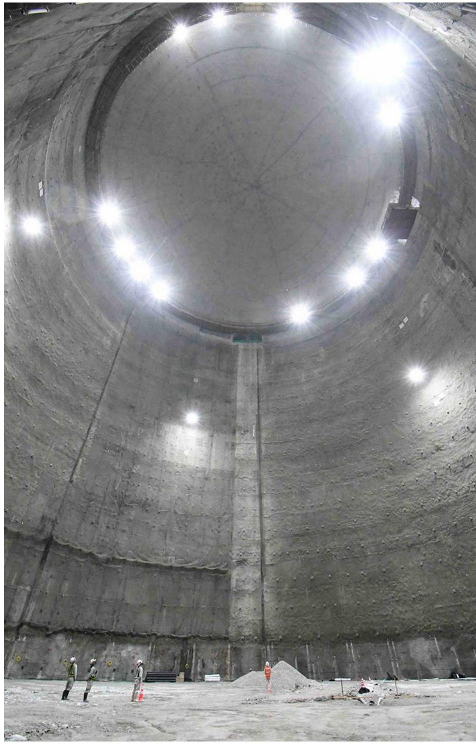




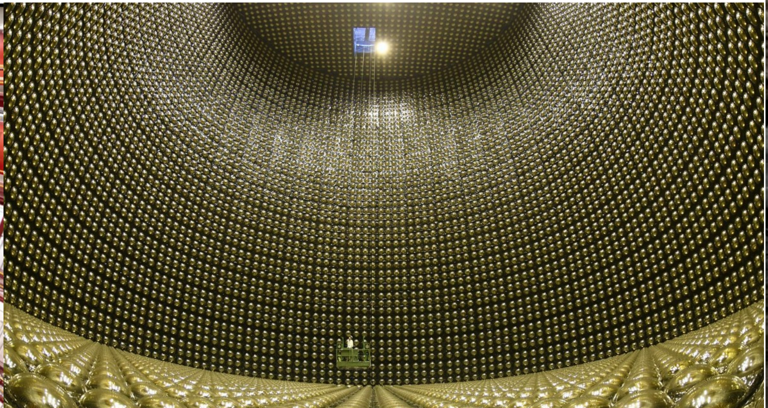
T2K

NOvA

3: The Far Detector



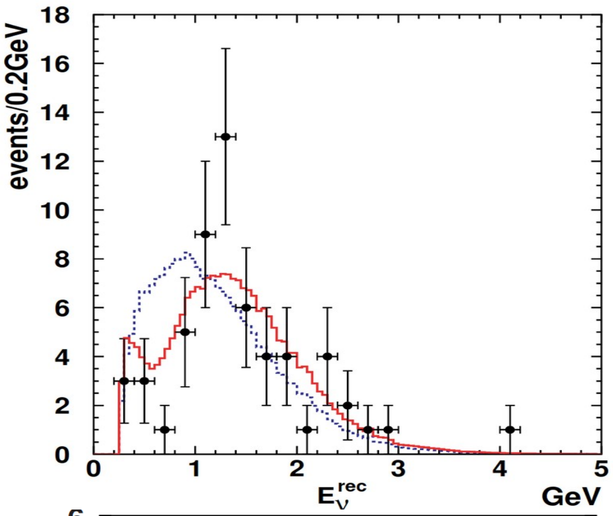
- Massive (10-1000 ktons) to achieve sufficient statistics
- Deep underground to shield from cosmic ray
- Reconstruct particles produced in neutrino interactions

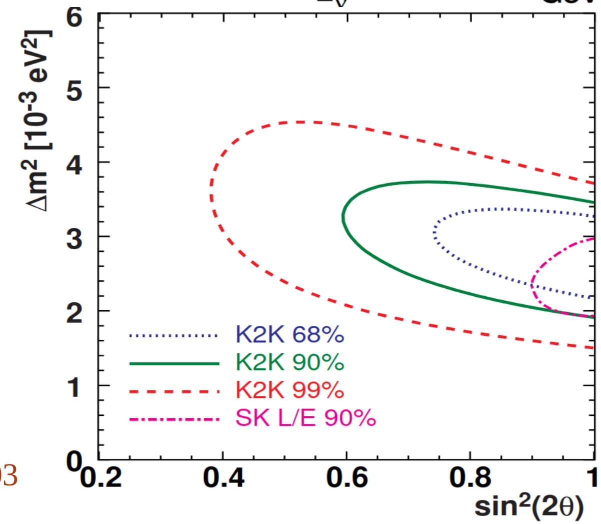




First Generation LBL: K2K

KEK to Kamioka (250 km baseline)

- Main Goal
  - Confirm atmospheric oscillation with a man-made ν_μ beam directed to Super-K
- (1999-2005)
  - Observed 112 events vs. 158 expected without oscillations
  - Confirmed ν_μ disappearance consistently with Super-K atmospheric
- Also: cross sections, ν_e appearance limit





DOI: 10.1103/PhysRevD.74.072003

The Second Generation: MINOS & OPERA

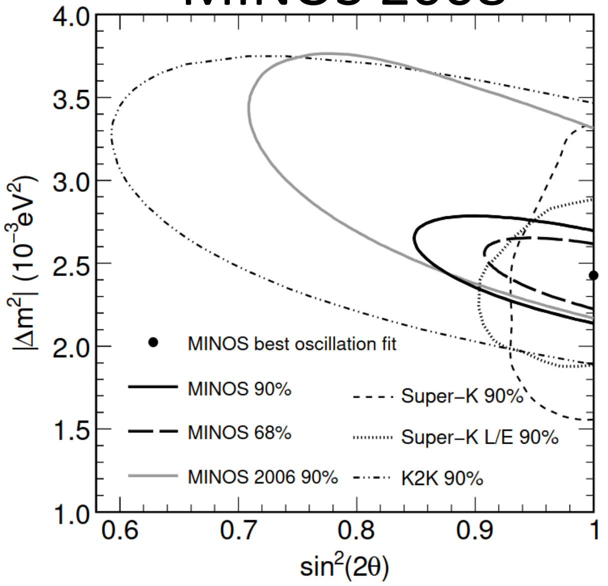
2005-2012 MINOS: NuMI at Fermilab → Soudan mine (Minnesota), 735 Km

- Precise measurements of Δm^2_{23} and θ_{23}

2008-2012 OPERA: CNGS at CERN → LNGS (Italy), 730 Km

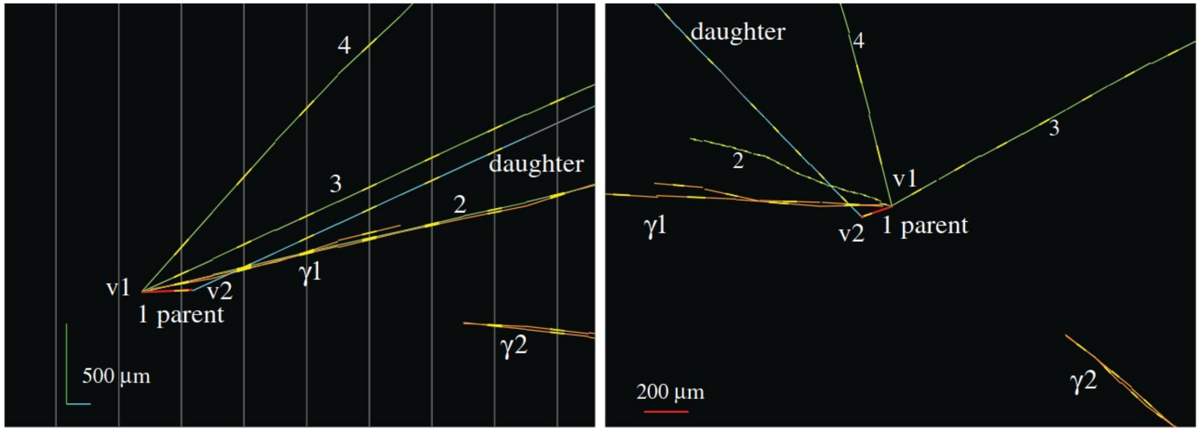
- Designed for τ appearance, observed 10 ν_τ candidates

MINOS 2008



DOI: 10.1103/PhysRevLett.101.131802

OPERA



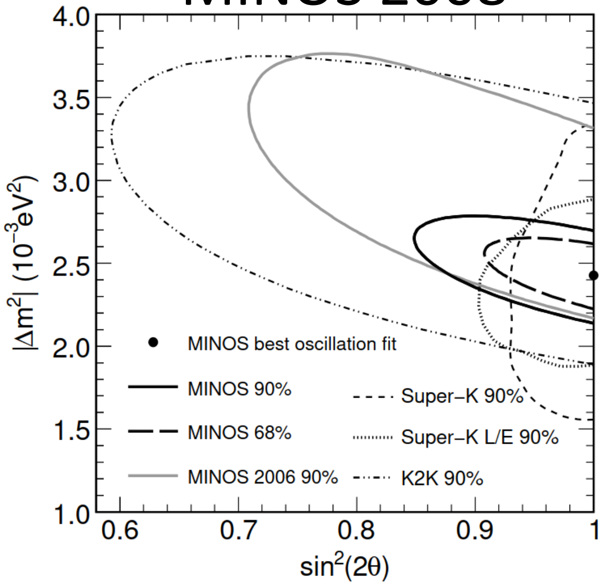
DOI: 10.1093/ptep/ptu132

The Second Generation: MINOS & MINOS+

2005-2012 MINOS: NuMI at Fermilab → Soudan mine (Minnesota), 735 Km

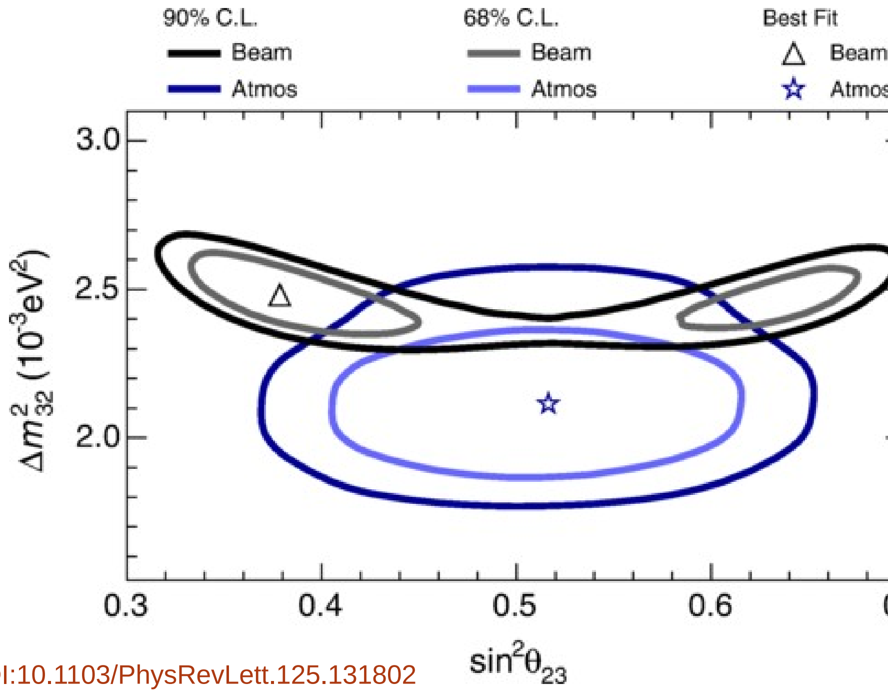
- **Precise measurements of Δm^2_{23} and θ_{23}**

MINOS 2008



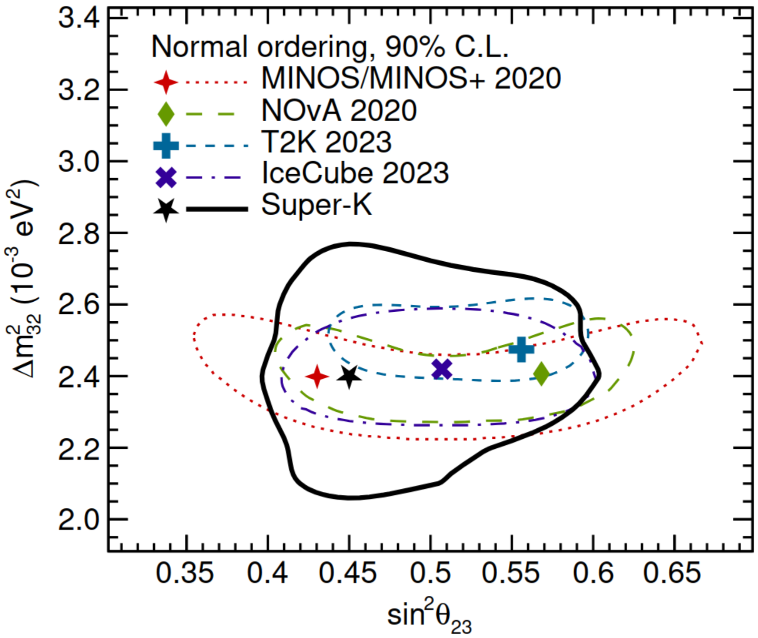
DOI: 10.1103/PhysRevLett.101.131802

MINOS & MINOS+ 2020

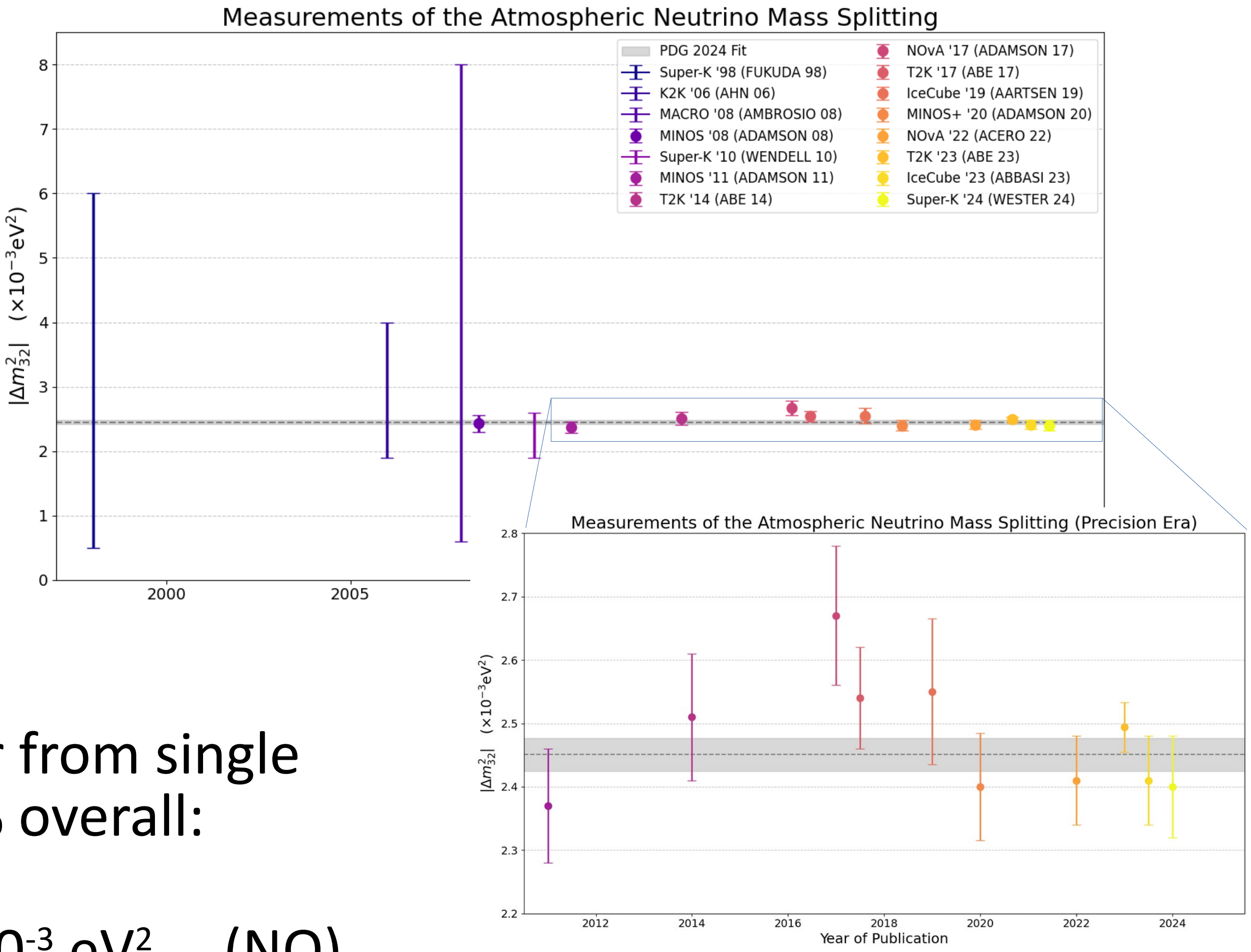


DOI:10.1103/PhysRevLett.125.131802

Δm^2_{23} (and θ_{23}) from Atmospheric and Beam



DOI: 10.1103/PhysRevD.109.072014



$\Delta m^2_{23} \rightarrow$ 1.5-2% error from single experiments, ~1% overall:

PDG Fit: $(2.451 \pm 0.026)\ 10^{-3}$ eV^2 (NO)

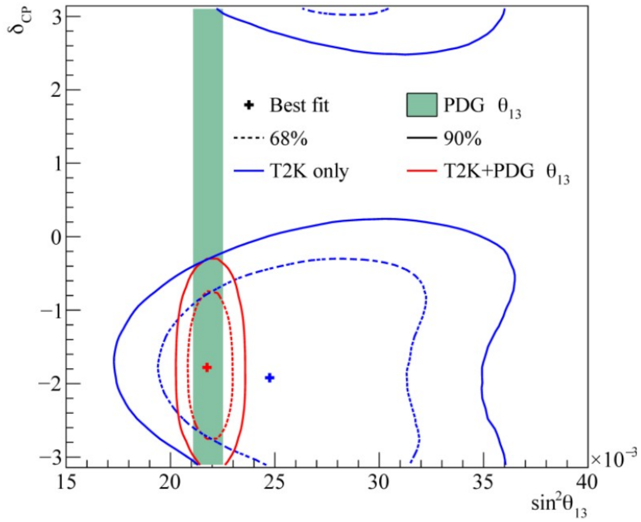
θ_{13}: Pivoting the LBL Strategy

- Until 2012, θ_{13} was the last, unknown mixing angle
  - Its size is the gateway to measuring CP violation and mass ordering
  - Appearance is proportional to θ_{13} Statistic vs Systematic

- For years, θ_{13} was expected to be very small, prompting R&D for innovative sources: neutrino factories & beta-beams

$\sin^2(\theta_{13})$ PDGID:S067P13 JSON (beta) INSPIRE

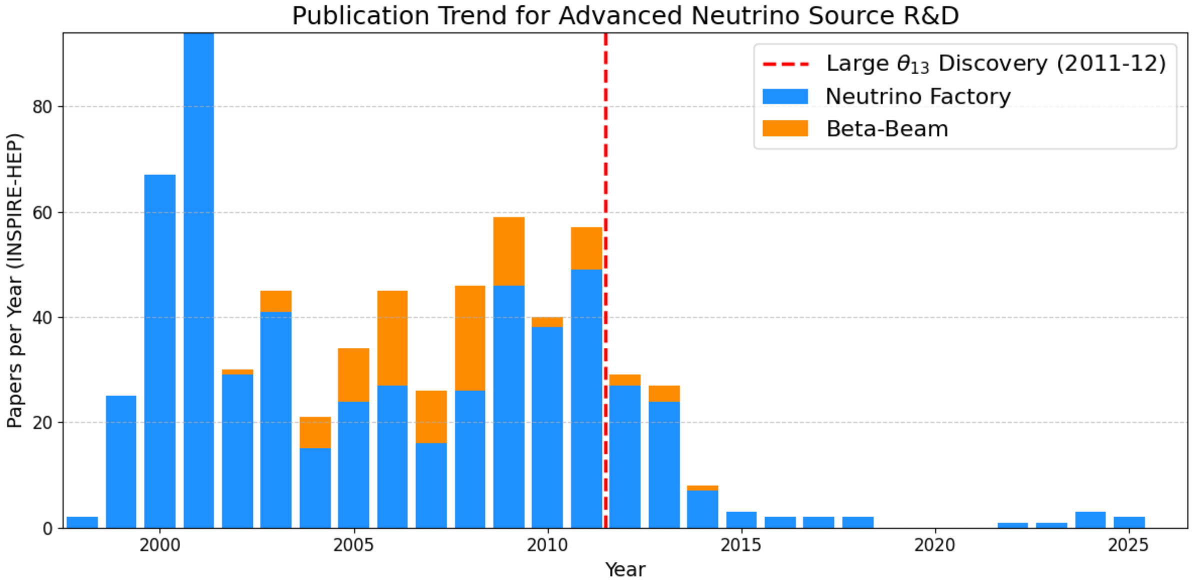
VALUE (10^{-2})	CL%	DOCUMENT ID		TECN	COMMENT
2.16 ± 0.06	OUR AVERAGE	Error includes scale factor of 1.2.			
2.2 ±0.5		[1] ACERO	2024	NOVA	Both mass orderings
2.128 ±0.057		[2] AN	2024A	DAYA	DayaBay, Ling Ao/Ao II reactors
$2.80^{+0.28}_{-0.65}$		[3] ABE	2023F	T2K	Normal mass ordering
2.70 ±0.37		[4] DE-KERRET	2020	DCHZ	Chooz reactors
2.22 ±0.21 ±0.37		[5] SHIN	2020	RENO	Yonggwang reactors
2.29 ±0.18		[6] BAK	2018	RENO	[illegible] reactors



T2K: *Eur.Phys.J.C* 83 (2023) 9, 782

θ_{13} Discovery: a New Roadmap

- 2011-2012: T2K, Daya Bay, and RENO measure a 'large' θ_{13}, just below the Chooz limit (1999)
- This was a game-changer: CP violation and Mass Ordering were accessible with conventional (super) beams



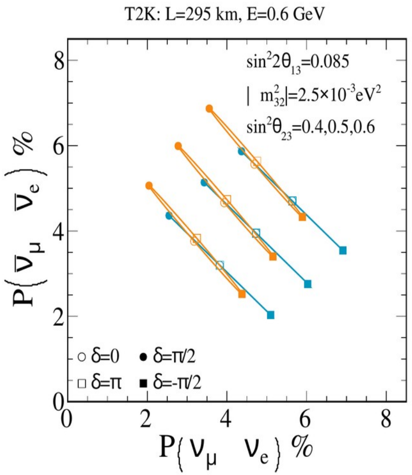
The Current Generation: T2K & NOvA

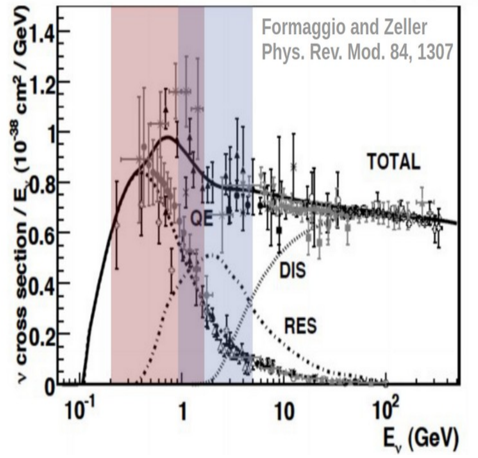
Tokai to Kamioka (295 km), off-axis beam

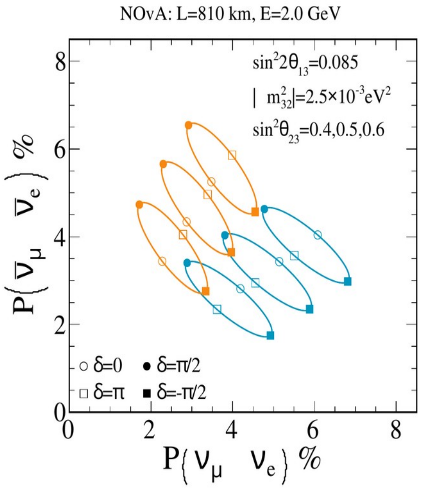
- First experiment to observe $\nu_\mu \rightarrow \nu_e$ appearance
- Show preference for maximal CP violation ($\delta_{CP} \approx -\pi/2$), degenerate values around $\delta_{CP}=0$ and π
- Higher sensitivity to δ_{CP}

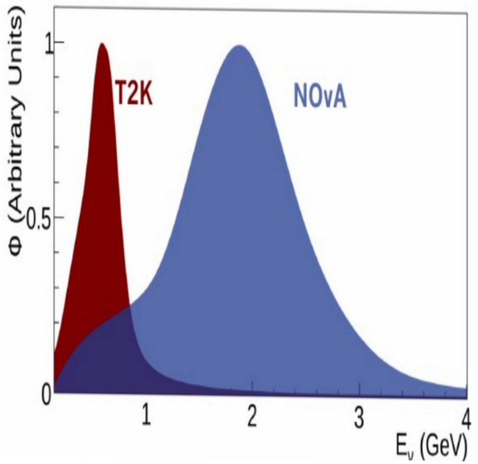
NuMI off-axis beam, (810 km), off-axis beam

- Longer baseline and higher energy: larger matter effects
- Higher sensitivity to Mass Ordering
- More δ_{CP} degeneracy around $-\pi/2$ and $\pi/2$







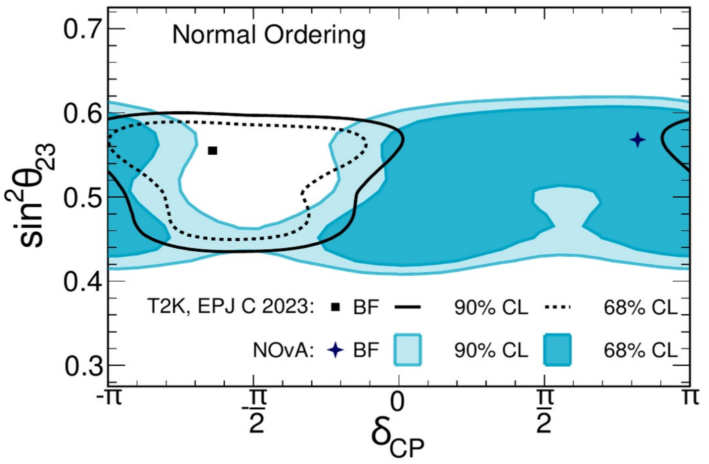


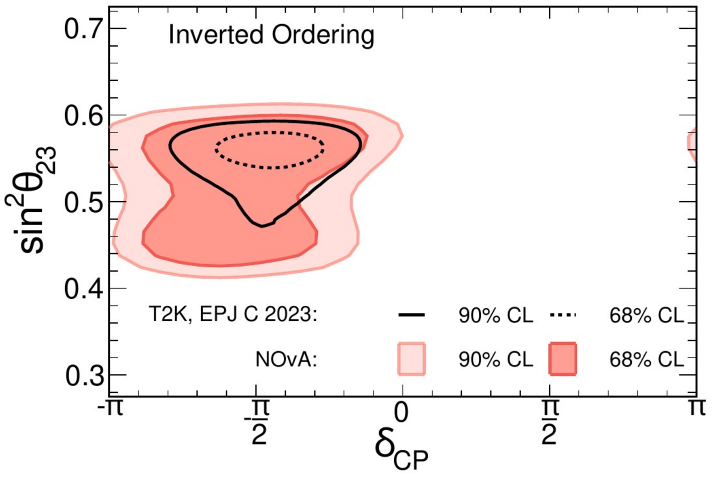
T2K & NOvA

Mild preferences for Normal MO and upper octant (both experiments)

Overlapping ($\sin^2\theta_{23}$, δ_{CP}) preferences for Inverted MO

Different regions for Normal MO (though still compatibles)





T2K & NovA & Super-K

Mild preferences for Normal MO and upper octant (both experiments)

Overlapping ($\sin^2\theta_{23}$, δ_{CP}) preferences for Inverted MO

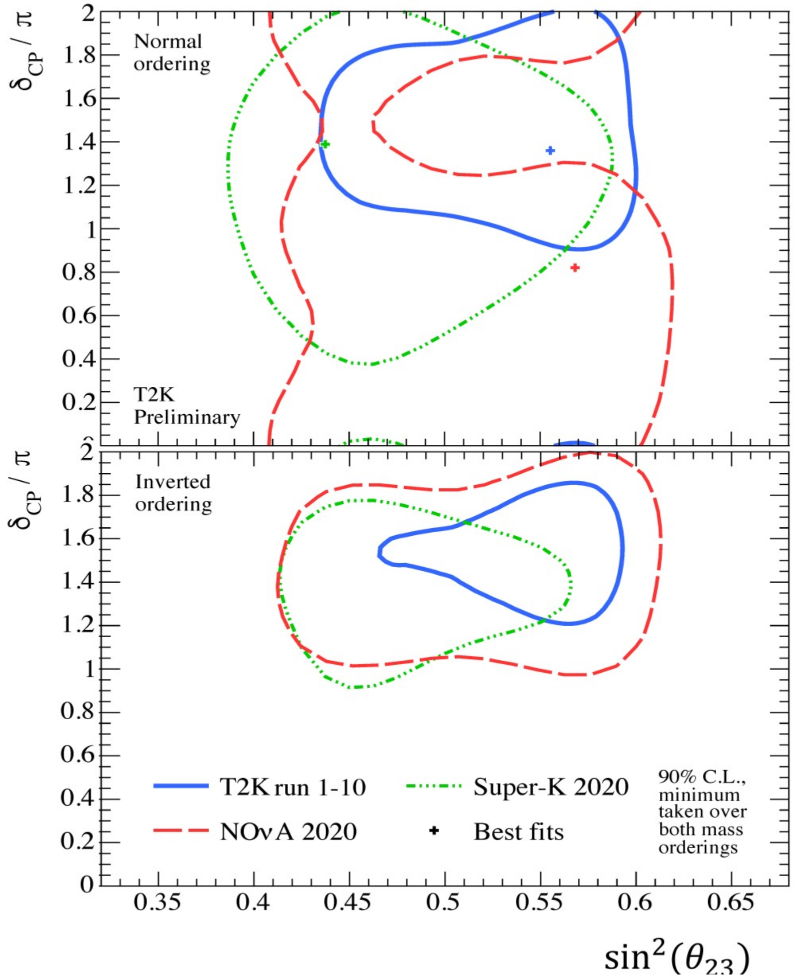
Different regions for Normal MO (though still compatibles)

Super-K has a preference for NMO and lower octant

Comparison of different baseline and energy helps to lift parameter degeneracies

T2K & NovA joint fit (to appear on Nature)

T2K & Super-K joint fit (DOI: 10.1103/PhysRevLett.134.011801)



T2K & NovA Joint Fit

Result of several years work of a T2K/NOvA joint analysis gro

Comparison of different baseline and energy helps to lift parameter degeneracies

Proper combination of full detailed likelihood with a coherent statistical inference across full phase space

Review and implementation of detectors effects, models and systematic uncertainties

Exploitation of complementary approaches in a consistent framework

Plans to continue this work as both collaboration keep taking data

T2K & NovA Joint Analysis

Leading world result on Δm^2_{32}: accuracy 1.5%

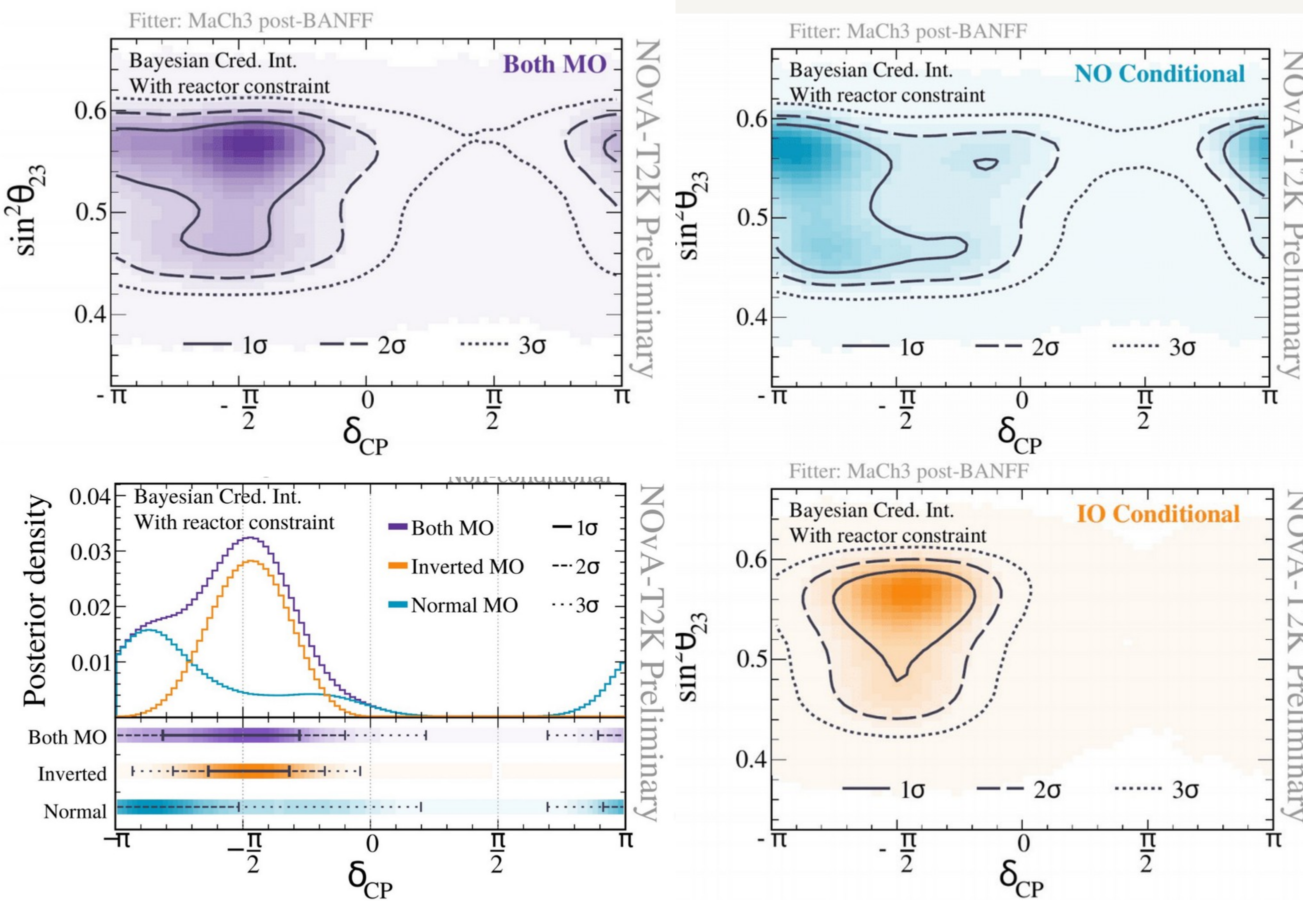
Best combined fit flips to IO, but no strong MO preference

$\delta_{CP} \sim +\pi/2$ outside 3σ interval for both orderings

For inverted ordering CPC excluded at 3σ

Wider δ_{CP} range allowed for normal ordering

Time (and data) will tell us about this tension



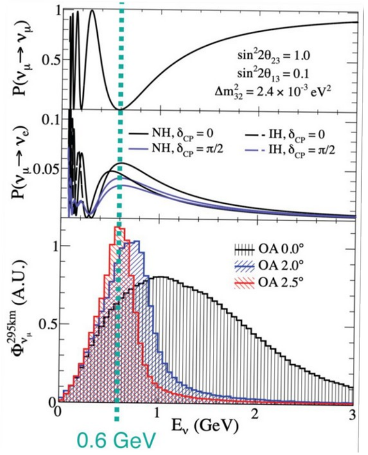
The Next Generation: A Quantum Leap

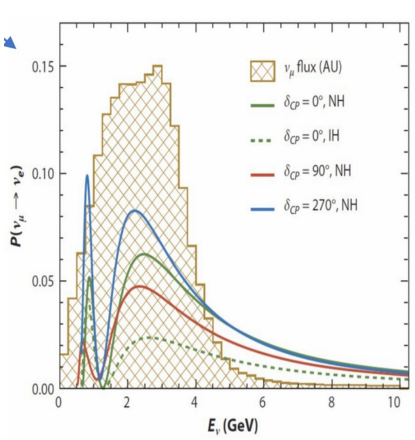
- To get definitive answers, we need more powerful experiments
  - DUNE (Deep Underground Neutrino Experiment) in US

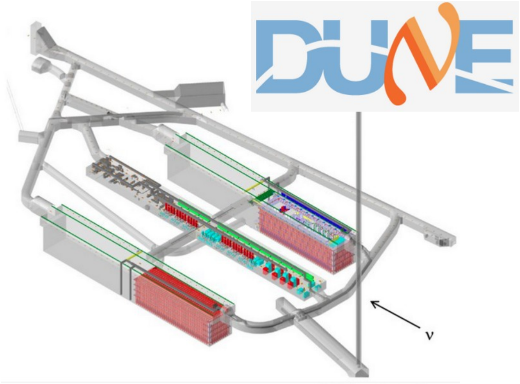
    [see talk by J. Bian]
  - Hyper-Kamiokande in Japan

    [see talk by J. Kisiel]
- Multi-purpose observatories: proton decay, supernova burst and diffuse,
- Large international collaborations

Hyper-Kamiokande vs DUNE







Multipurpose experiments. Similar goals, different and complementary strategy

Baseline/Energy choice: “tuned” on the first oscillation maximum vs first+second oscillation maxima

Energy ranges: narrow band beam (off-axis) vs wide band beam (on-axis)

Detector masses: fiducial 190 kton vs 20 (40) kton

Detection process: at 10 MeV mainly IBD (antinue) vs CC (nue)

Detector technology: water Cherenkov vs liquid Argon TPC

The Global Neutrino Program

LBL experiments are part of a wider, global effort

Great complementarity between Hyper-K, DUNE and JUNO, both in oscillation physics as well as low energy astrophysics

Higher energy astrophysics experiments, IceCube, KM3NeT, provide also crucial inputs to oscillation physics

Together, they ensure robust, definitive results

Conclusion: The Journey Continues

Neutrino physics has evolved from problem maker to discovery and precision science

After the achievement of the last 20+ years we have (at least) 20 more years of exciting neutrino physics

T2K and NOvA have provided the first crucial crack into CP conservation and a hint to the Mass Ordering, as well as some tantalizing tension

The next generation, Hyper-K and DUNE, are poised for definitive discoveries in particle physics and astrophysics

Thank You