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# Long-Baseline neutrino experiments: a journey from discovery to precision and beyond

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The study of neutrino oscillations has evolved from the generation of anomalies, the solar and atmospheric neutrino problems, into a precision science, driven largely by long-baseline (LBL) accelerator-based experiments. We trace this evolution, beginning with the definitive evidence for neutrino mass from atmospheric and solar neutrino experiments, which motivated the need for controlled, man-made neutrino sources. We review the progression through three generations of LBL experiments, highlighting key results from K2K, MINOS and OPERA, and the currently operating T2K and NO$\nu$A experiments. A pivotal moment in the field, the discovery of the relatively large value for the mixing angle $\theta_{13}$, is discussed, as it reshaped the global strategy for addressing the remaining fundamental questions: the neutrino mass ordering, the octant of $\theta_{23}$, and the existence of leptonic CP violation. The recent results from the joint analysis of T2K and NO$\nu$A data, provide tantalizing hints but leave these questions open. Finally, we look to the future, outlining the immense scientific potential of the next-generation experiments, Hyper-Kamiokande and DUNE, which promise not only to resolve the remaining questions in the three-flavor paradigm but also to conduct sensitive searches for proton decay and provide unprecedented views of astrophysical phenomena like supernova bursts.

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## 1. The neutrino puzzles and the oscillation solution

For several decades in the late 20th century, particle physics faced two anomalies, called at that time "neutrino problems", related to the flux of neutrinos from natural sources. The first, the solar neutrino problem, arose from the observation by the Homestake experiment [1] and its successors [2, 3] that the flux of electron neutrinos ($\nu_e$) from the Sun was only about one-third of that predicted by the otherwise highly successful Standard Solar Model [4]. The second, the atmospheric neutrino problem, was the observation in water Cherenkov experiments like Kamiokande [5] and IMB [6] of a significant deficit in the ratio of muon neutrinos ($\nu_\mu$) to electron neutrinos ($\nu_e$) produced in cosmic ray showers in the Earth's atmosphere.

Both puzzles were solved by a single and elegant physics mechanism: neutrino oscillation. A quantum phenomenon where neutrinos change flavor ($\nu_e, \nu_\mu, \nu_\tau$) as they propagate. This can only occur if neutrinos possess mass and if the flavor eigenstates are a quantum mechanical mixture of the mass eigenstates ($\nu_1, \nu_2, \nu_3$).

The smoking gun evidence for atmospheric neutrino oscillations came in 1998 from the Super-Kamiokande experiment [7]. Measuring the neutrino flux as a function of the travel distance through the Earth determined by the zenith angle, the collaboration observed a distinct disappearance of upward-going $\nu_\mu$ (which travel thousands of kilometers) compared to downward-going ones (which travel only tens of kilometers), while the $\nu_e$ flux remained up/down symmetric. Two tracking calorimeter experiments, Soudan-2 and MACRO, also reported zenith angle dependent muon deficits [8, 9]. This was incontrovertible proof that $\nu_\mu$ were oscillating away over long-baselines.

The solution to the solar neutrino problem arrived in 2002 from SNO, the Sudbury Neutrino Observatory [10]. SNO's unique use of a heavy water ($D_2O$) target allowed it to measure the solar neutrino flux via three separate reactions: a charged-current (CC) reaction sensitive only to $\nu_e$, an elastic scattering (ES) reaction sensitive to all flavors but dominated by $\nu_e$, and a neutral-current (NC) reaction equally sensitive to all active neutrino flavors. The NC measurement showed that the total flux of all neutrino flavors from the Sun was in perfect agreement with the Standard Solar Model prediction. The CC measurement, however, confirmed the deficit of $\nu_e$. The conclusion was clear: electron neutrinos are produced in the Sun's core in good agreement with the flux predicted by the Standard Solar Model, but a significant fraction oscillates into other flavors during their journey to Earth.

These two landmark discoveries, recognized with the 2015 Nobel Prize, firmly established the paradigm of neutrino mass and mixing, necessitating physics beyond the Standard Model.

## 2. The framework of neutrino oscillation

The mixing between the flavor eigenstates and the mass eigenstates is described by the 3×3 unitary Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, $U$ [11–13]. This matrix is typically parameterized by three angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and one complex phase ($\delta_{CP}$), only source of charge-parity (CP) violation in the three-flavor framework. The probability of a neutrino of flavor $\alpha$ and energy $E$ oscillating to a flavor $\beta$ after traveling a distance $L$ is a function of these mixing parameters and the two independent mass-squared differences, $\Delta m^2_{21} = m^2_2 - m^2_1$ and $\Delta m^2_{32} = m^2_3 - m^2_2$.

Over the past two decades, a global program of experiments has transformed our knowledge of these parameters from rough estimates into a precision science. The "solar" parameters, $\theta_{12}$ and $\Delta m^2_{21}$, have been precisely constrained by solar and long-baseline reactor experiments (e.g., KamLAND [14]). The "atmospheric" parameters, $\theta_{23}$ and $|\Delta m^2_{32}|$, were first measured by atmospheric experiments and then refined by long-baseline (LBL) accelerator experiments. The last mixing angle $\theta_{13}$, after the first hint from long-baseline observation of $\nu_e$ appearance in a $\nu_\mu$ beam [29], was confirmed to be non-zero in 2012 by reactor experiments [15–17], opening the door to the primary goals of the current and future programs:

- **Mass Ordering:** is the mass spectrum Normal ($m_3 > m_1, m_2$) or Inverted ($m_1, m_2 > m_3$)?
- **CP violation:** is CP violated in the lepton sector ($\delta_{CP} \neq 0, \pi$)?
- **Octant:** is the mixing maximal ($\theta_{23} = 45°$) or $\theta_{23}$ lies in the lower or upper octant?

## 3. Long-Baseline experiments: a three-pillar strategy

To address these questions the LBL experimental strategy relies on three pillars:

- **Powerful Neutrino Beam**. High-intensity proton accelerators are used to create beams of pions and kaons, which are focused by magnetic horns into a decay tunnel. The in-flight decay of these mesons produces a beam composed primarily of $\nu_\mu$ (or $\bar{\nu}_\mu$).
- **Near Detector**. Located close to the target, this detector measures the un-oscillated beam's flux, energy spectrum, and flavor composition. It provides high-statistics measurements of neutrino-nucleus interaction cross-sections, which are a dominant systematic uncertainty.
- **Massive Far Detector**. Located hundreds of kilometers away, the far detector measures the oscillated neutrino flux. By comparing the event rates and energy spectra at the near and far detectors, the oscillation probabilities can be precisely extracted.

## 4. Generations of discovery and precision

The first LBL experiment was K2K in Japan (1999-2004), designed to confirm the atmospheric oscillation at a man-made neutrino source. The disappearance of $\nu_\mu$ was observed by Super-Kamiokande in a broad band beam of 1.3 GeV produced 250 km away at KEK [18]. The ratio L/E matched the first maximum in the probability $P \propto \sin^2(1.27\Delta m^2_{32}[\text{eV}^2]\,\text{L[km]} / \text{E[GeV]})$.

The second generation brought higher precision. In US MINOS (2005-2016) made the world's most precise measurements of $|\Delta m^2_{32}|$ and $\theta_{23}$ of its time, using the NuMI beam from Fermilab over a 735 km baseline [19]. A different route was taken in Europe, focusing on $\nu_\tau$ appearance at the new CERN Neutrino to Gran Sasso (CNGS) beam [20]. OPERA (2008-2012) ends a long tradition of neutrino beams at CERN, started in 1963 at with the first focused neutrino beam. [21, 22]

The global strategy for discovering CP violation hinged on the unknown value of $\theta_{13}$. Until 2011-2012, only an upper limit was known, published in 1999 by the Chooz collaboration [23]. A small value would have produced a tiny $\nu_e$ appearance signal, a measurement limited by statistic

and intrinsic background in conventional beams. The community looked at the "Neutrino Factory" [24], neutrino beams from storage rings of accelerated muons. The first NuFact workshop in 1999 [26] marked the start of an intense, decade-long global R&D and design effort [27]. Also neutrino beams from storage rings of accelerated radioactive ions, (Beta-Beam) [25]) were proposed. With few exceptions [28], much less attention was given to the scenario where a relatively large $\theta_{13}$ allows to search for CP violation at a conventional high intensity neutrino beam.

In 2011, T2K observed $\nu_e$ appearance in a $\nu_\mu$ beam [29], hinting to a relatively large $\theta_{13}$. This was confirmed in 2012 by the reactor experiments Daya Bay [15] and RENO [16], which measured $\theta_{13} \approx 9°$. This discovery was a game-changer. The main limitation became systematic, no longer statistic and the CP violation signal was accessible with conventional, high-power neutrino beams. This dramatically altered the experimental landscape, shifting the roadmap toward the super-beam experiments in preparation today.

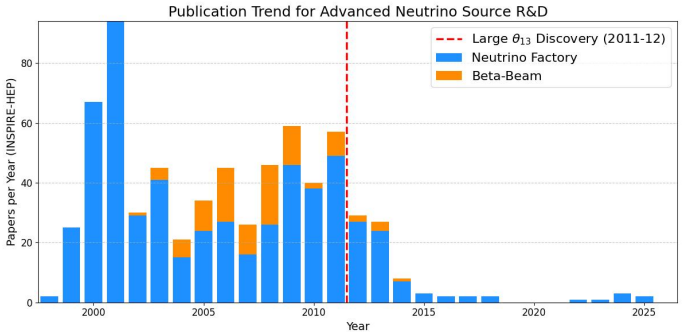


**Figure 1:** Papers on advanced neutrino beams (source: inspirehep.net)

## 5. The current generation: T2K and NO$\nu$A

Third generation of LBL experiments, T2K in Japan and NO$\nu$A in US, are poised to make precision measurements of the oscillation parameters with a chance to constrain $\delta_{CP}$.

- **T2K (Tokai to Kamioka)**. Uses for the first time a narrow-band off-axis beam, peaked at 0.6 GeV, corresponding to the first oscillation maximum for its 295 km baseline. This maximizes the oscillation probability and reduces backgrounds. T2K was the first experiment to observe $\nu_e$ appearance [29] and its latest results disfavor CP conservation, with a best fit near the maximally violating value of $\delta_{CP} = -\pi/2$ [30, 31].

- **NO$\nu$A (NuMI Off-axis $\nu_e$ Appearance)**. Uses a higher-energy (2 GeV) off-axis beam from Fermilab over a longer 810 km baseline. The longer baseline enhances matter effects, giving NO$\nu$A excellent sensitivity to the neutrino mass ordering. Its results also disfavor CP conservation [32, 33].

Due to the difference in baselines and energies at the same L/E, the comparison of these two experiments helps to partially lift the degeneracies between the oscillation parameters and between genuine CP violation and matter effects. Individually, both experiments currently show a preference

for the Normal Mass Ordering, though their best-fit points for $\delta_{CP}$ within that ordering are still compatible but clearly different. Recently a joint T2K and NO$\nu$A analysis was published [34]. The intriguing result shows a slight preference for the Inverted Ordering, though with modest statistical significance. The two collaborations are expected to increase significantly their datasets in the next two or three years and their comparison will remains a very active area of investigation.

## 6. The future: Hyper-Kamiokande and DUNE

Two next-generation observatories, Hyper-Kamiokande (Japan) [35] and DUNE (US) [36], aim to resolve the open questions:

- **Hyper-Kamiokande (Hyper-K)** [37]. The successor to Super-K in Japan, Hyper-K will be a gigantic 188-kton fiducial volume Water Cherenkov detector, exposed to the upgraded beam from the J-PARC accelerator already used by T2K over a 295 km baseline. Its primary asset is the size, which provides unparalleled statistical power. It is projected to discover CP violation at $5\sigma$ significance in a few years if $\delta_{CP}$ is maximal, as current data suggest.
- **DUNE (Deep Underground Neutrino Experiment)** [38]. Located in US, DUNE will send a high-intensity, wide-band beam from Fermilab 1300 km away, to a 40-kton fiducial mass Liquid Argon Time Projection Chamber (LArTPC) at the Sanford Underground Research Facility. This technology has unmatched particle identification and energy resolution. The very long-baseline gives high sensitivity to the mass ordering in a few years of beam operation.

Beyond accelerator neutrinos, the immense scale of these detectors makes them powerful multi-purpose observatories. Both will have world-leading sensitivity to proton decay, pushing the lifetime limits to beyond $10^{35}$ years and probing compelling Grand Unified Theories, both supersymmetric and non-supersymmetric. They will also serve as supernova sentinels, capable of detecting tens of thousands of neutrinos from a core-collapse event in our galaxy, providing a real-time movie of the explosion mechanism [39, 40]. This mirrors the past, where an incoherence emerged at the boundary of two otherwise internally consistent descriptions, the Standard Solar Model and the Standard Model of particle physics, precipitating a revolutionary leap. Similarly, the high-precision data from the next galactic supernova will provide a rigorous test at the intersection of core-collapse astrophysical models and the Standard Model, potentially revealing new inconsistencies that might foster a new, fundamental understanding.

## 7. Conclusion

The journey of long-baseline neutrino experiments is a remarkable story of scientific progress, evolving from the resolution of fundamental puzzles to an era of precision measurements. The first two generations of long-baseline experiments confirmed the oscillation paradigm and provided the first precision measurements of the atmospheric parameters. The current generation, T2K and NO$\nu$A, have provided the first crucial insights into the final unknowns of the three-flavor model. Now, the next generation, Hyper-Kamiokande and DUNE, are poised to provide answers to the neutrino mass ordering and leptonic CP violation, while simultaneously opening new windows into grand unification and astrophysics.

The next 20 years promise to be a golden age of discovery in neutrino physics.

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