



# Long-Baseline Accelerator Neutrino Experiments

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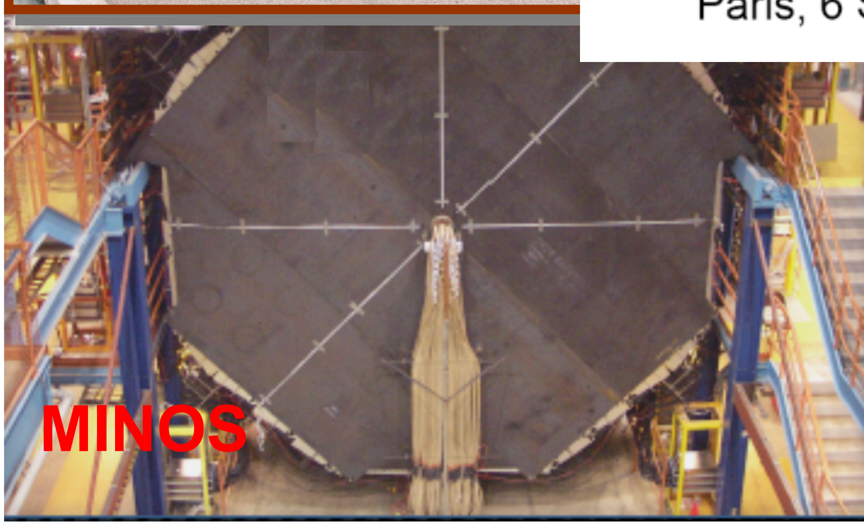
International Conference on the History of the Neutrino

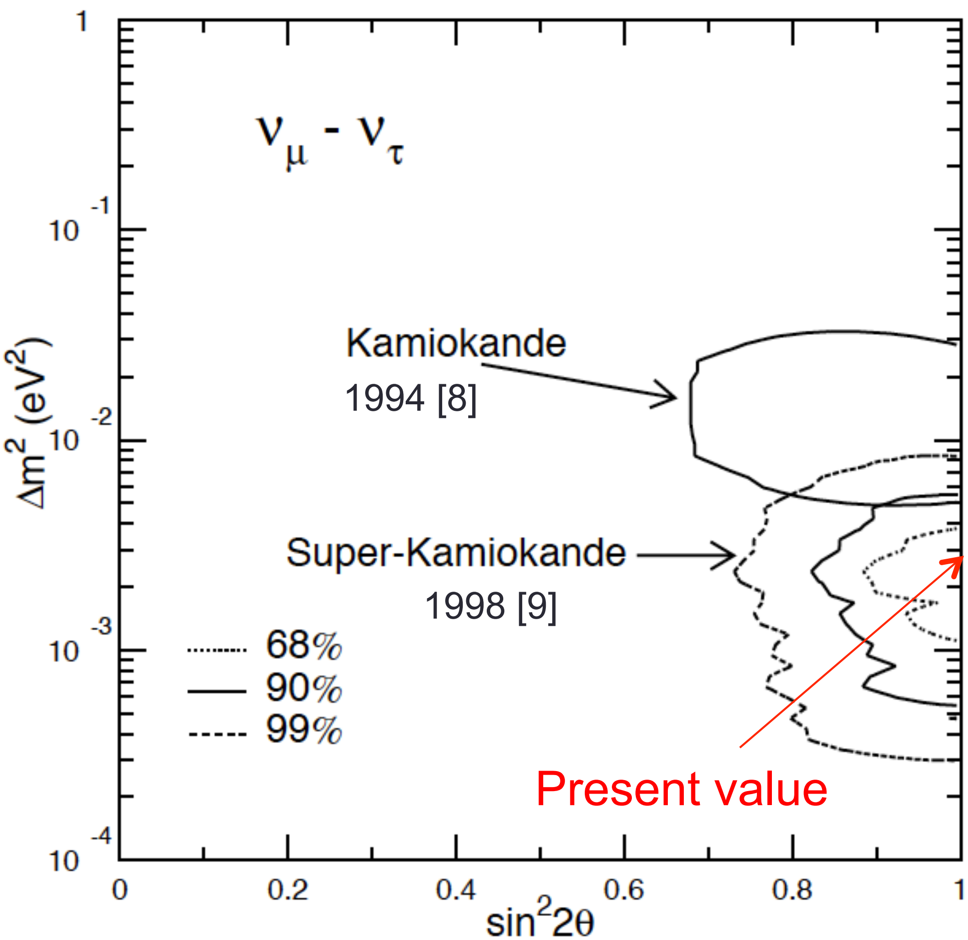
Paris, 6 September 2018


# Introduction

- There are six past and present long-baseline (>200 km) accelerator neutrino experiments:
  - 1st generation general experiments: K2K and MINOS
  - Specialized experiments: OPERA and ICARUS
  - 2nd generation general experiments: T2K and NOvA
- Since studying oscillations is the only possible reason to put your detector 100s of km from the target, I will only cover that subject although these experiments have reported on other measurements.
- Since I have only been allotted an average of 4 minutes 10 seconds per experiment, with one exception, I will not discuss sterile neutrino searches.
  - These experiments have found no evidence for sterile neutrinos. [1-7]

# Motivation for 1st Generation Experiments




[9]

The proposals for the 1st generation experiments came in 1994, motivated by the atmospheric results, particularly those from Kamiokande.

Note, however, that the Kamiokande central $\Delta m^2$ value was an order of magnitude higher than the present value, which affected planning.

# K2K: KEK to Kamioka

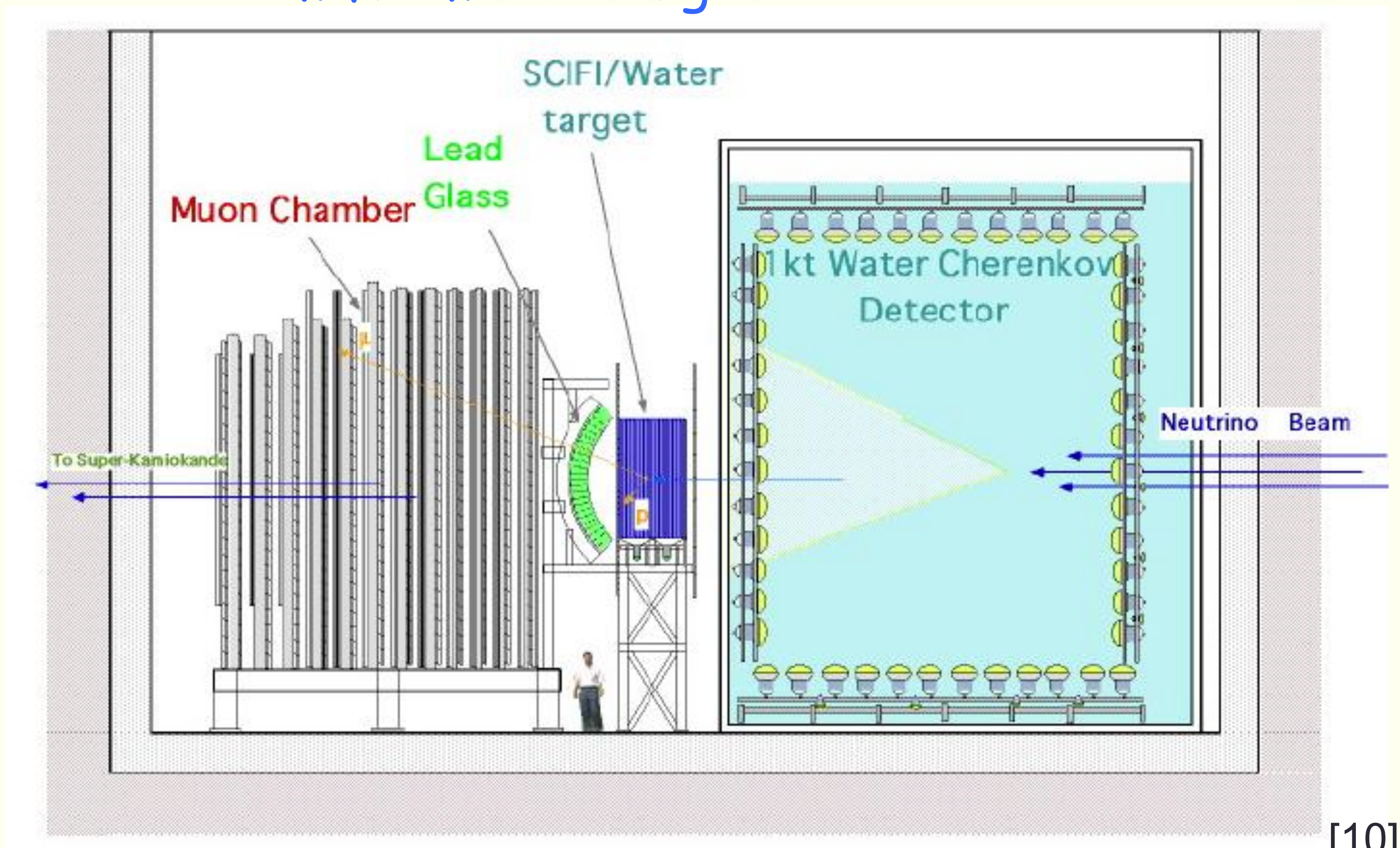
- The K2K experiment used the KEK 12 GeV synchrotron at Tsukuba, Japan to send a $\langle E \rangle \approx 1.4$ GeV neutrino beam 250 km to the 50 kt Super-Kamiokande detector [10].
- In common with all accelerator-produced neutrino beams, the K2K neutrino beam was composed of about 99% $\nu_\mu$ and 1% $\nu_e$, the latter from muon and kaon decay. Thus, the attempted oscillation measurements will be $\nu_\mu$ CC disappearance and $\nu_e$ appearance.
- In a 2-neutrino model,
  - $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{\mu\mu}) \sin^2(\Delta m^2 L / 4E)$
  - $P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta_{\mu e}) \sin^2(\Delta m^2 L / 4E)$

# Near Detectors

- All of the experiments, except for the ones at Gran Sasso, have used the comparison between a near and far detector to measure the effects of oscillations. This is an essential method of reducing systematic uncertainties, since uncertainties due flux, cross sections, and efficiencies will mostly cancel.
- The US experiments used functionally equivalent near detectors and the Japanese experiments used detectors that were functionally equivalent, fine-grained, or both.
  - The use of fine-grained near detectors for water Cherenkov far detectors are quite useful since the water Cherenkov detectors are not sensitive to the whole event.

# K2K Near Detector

300 m from the target




[10]

# K2K Objectives and Results

- K2K realized that it would not be competitive in the long run with the MINOS detector that was being proposed at the same time. However, it could be the first accelerator experiment to confirm the Kamiokande result, and, after 1998, resolve the difference in the two different $\Delta m^2$s [11].
- K2K ran from June 1999 to November 2004 and accumulated $0.9 \times 10^{20}$ POT [12].
- 1st results with a $\Delta m^2$-$\sin 2(2\theta_{\mu\mu})$ plot in 2002 [13] and final results in 2006 [12]. (next page)
- A search for $\nu_\mu \rightarrow \nu_e$ found 1 candidate with an expected background of 1.7, setting a 90% C.L. limit of $\sin^2(2\theta_{\mu e}) < 0.13$, about 3 times the current effective value. [14]

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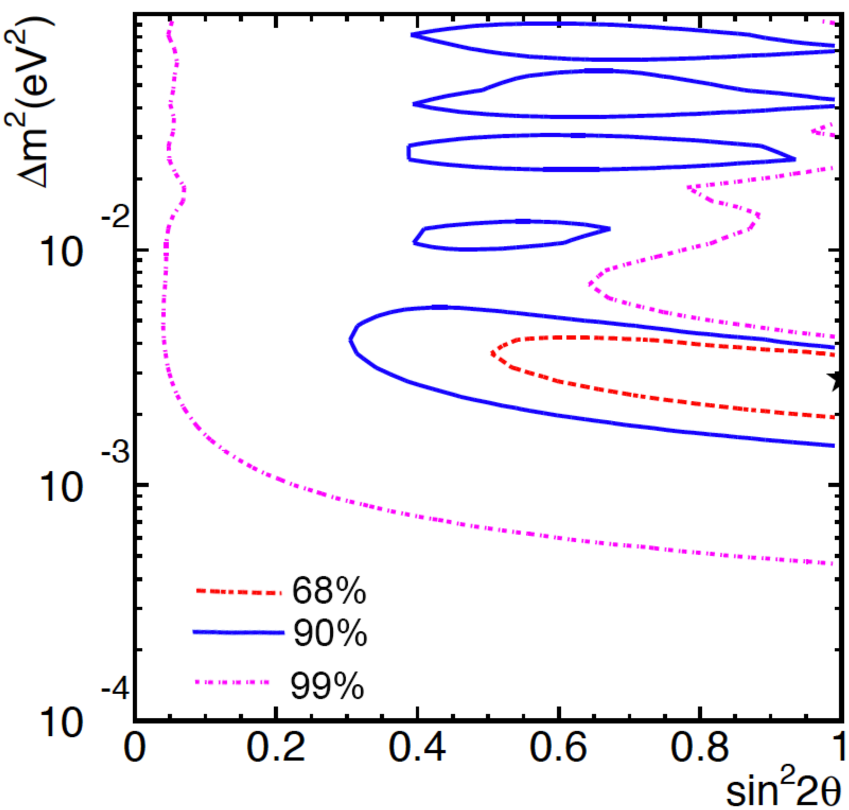
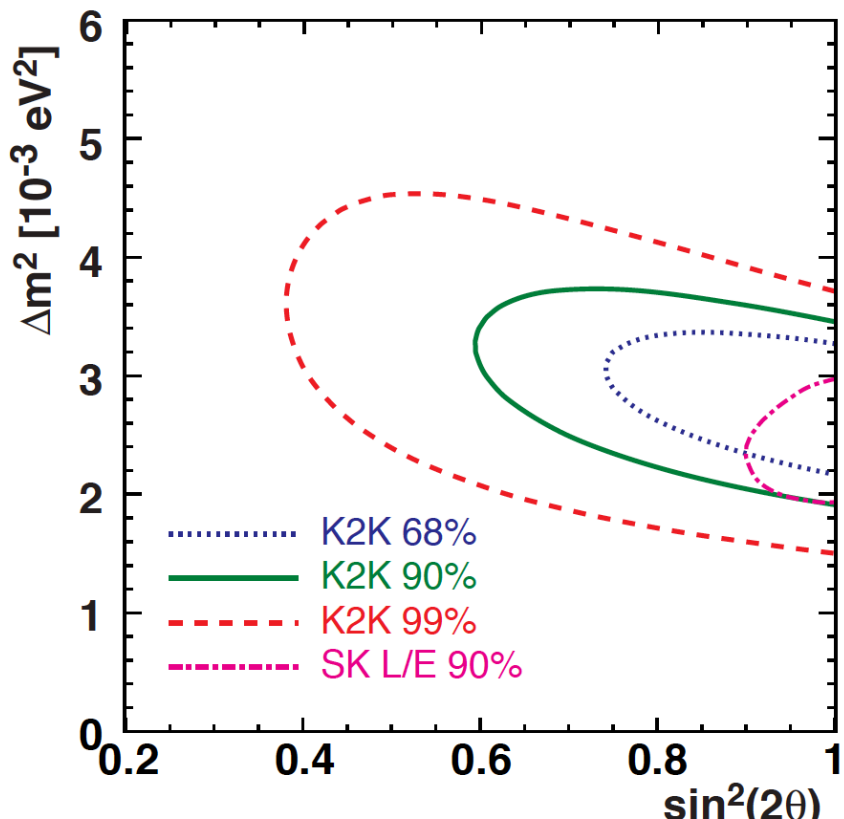
# KEK $\Delta m^2$-$\sin^2(2\theta_{\mu\mu})$ Plots

2002




[13]

2006




[12]

# MINOS: Main Injector Neutrino Oscillation Search

- The first proposal for a long baseline neutrino oscillation experiment at Fermilab came in 1991 and was updated in 1993. The Soudan collaboration proposed a beam to their 1 kt finely segmented iron calorimeter in the Soudan Mine in Northern Minnesota, which was studying atmospheric neutrino events and proton decay [15].
- The Fermilab Program Advisory Committee (PAC) felt that a 1 kt detector was too small and called for more ambitious expressions of interest (EOIs] in 1994 [16].

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# MINOS Proposal

- Three EOIs were received, one from the Soudan group, one from US groups working on the MACRO experiment, and a 1-person EOI from Stan Wojcicki [17-19]. The PAC asked the three groups to get together and submit a single proposal, which they did in 1995 [20].
  - The proposal called for a 10 kt toroidally magnetized iron-plastic limited streamer tube sandwich detector, with 4-cm thick iron plates and 1-cm tubes. What was actually built was a 5.4 kt detector with 2.54-cm thick iron plates and 4.1-cm wide plastic scintillator strips.
  - The far site was chosen to be the Soudan mine, which gave a 735 km baseline. The rationale for this choice was that the Soudan detector was there and could be used if the construction of the MINOS detector was delayed [16]. Ironically, the MINOS detector was completed two years before the NuMI (Neutrinos from the Main Injector) beam was ready.

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# Brookhaven Proposal E889

- There was also a 1994 proposal from Brookhaven (E889) for a “long” baseline experiment that had 4 identical 4.5 kt water Cherenkov detectors located at 1, 3, 24, and 68 km from the target, all at an angle of $1.5^{o}$ to the neutrino beam [21].
  - This off-axis configuration produces a narrow band beam focused (ideally) on the oscillation maximum, a scheme that would later be adopted by both the T2K and NOvA experiments.
  - However, note that this proposal was using the Kamioka measurement of $\Delta m^2$, which would have focused the beam at an L/E an order of magnitude too high.

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# Fermilab-Brookhaven Shoot Out

- In 1995, the High Energy Physics Advisory Panel (HEPAP) requested a subpanel chaired by Frank Sciulli to make recommendations on neutrino oscillation experiments.
  - In September 1995, the subpanel unanimously recommend that MINOS be supported and that E889 not be supported [22]. The three reasons the subpanel gave were:
    - MINOS had better sensitivity at low values of $\Delta m^2$.
    - MINOS had better exploration capabilities.
    - MINOS would use the same beamline as a short baseline experiment, COSMOS, which was more cost effective than having two beam lines.
      - This last reason turned out to be irrelevant since COSMOS was never funded.

# The MINOS Experiment Data

- MINOS took data from February 2006 to April 2012, accumulating 10.7 x $10^{20}$ POT in neutrino mode and 3.4 x $10^{20}$ POT in antineutrino mode.
- The first publication was in 2006 [23] and the final results were reported in 2014 [24].
  - The MINOS detector with 1.4 $X_0$ iron plates was not optimum for measuring $\nu_e$ appearance. However, MINOS was able to pull out a 1.8 σ result in neutrino mode, 152 candidate events with an expected (neutral-current dominated) background of 128 ± 5 (syst.) events [25]. In antineutrino mode, there were 20 candidates with an expected background of 17.5 ± 0.8 (syst.).
- I will show a quantitative comparison of the four general experiments at the end of the talk.

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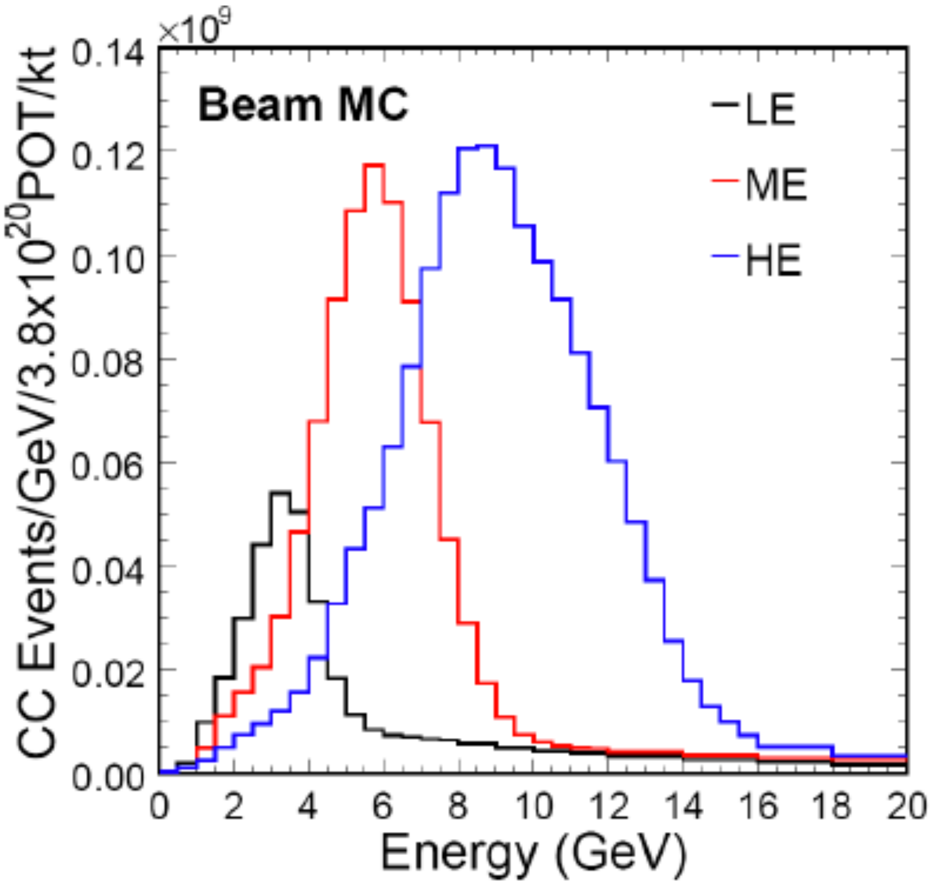
# MINOS+

- In 2013, with the start of the NOvA data taking in the medium energy beam, MINOS reorganized as MINOS+ with the main goals of searching for non-standard interactions and sterile neutrinos [1-2].
- MINOS+ ended data taking in June, 2016.



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# CNGS (CERN Neutrinos to Gran Sasso)

- In 1999, CERN committed itself to a program of $\nu_\tau$ appearance [26]. The question I want to leave for the discussion is "Why?"
- It was obvious to me at the time, and to many other people [27], that this program would not be competitive with what we would learn better from other measurements in a comparable time period.
  - The argument is simple:
    - We knew from LEP that there are only 3 active neutrino species [28-31].
    - We knew from Super-Kamiokande that $\nu_e$ appearance was small [9].
    - This left only τ-neutrinos and sterile neutrinos. And MINOS would search for sterile neutrinos with higher precision by searching for neutral current disappearance [1].

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# CNGS, Why?

- My list of possible reasons:
  1. Absence of a near detector.
     - An official CERN document claims that a near detector is not needed for an appearance measurement [32]. As a generic statement, this is not true. In this case it was, because the statistical uncertainties would be large.
     - The only possible place for a near detector was under the Geneva airport.
  2. The desire to do something different from Japan and the United States.
  3. Interest of Italian and other physicists in pursuing emulsion technology.
  4. Pressure from Italy to enhance the Gran Sasso program.
     - Italian sources were to pay for 68% of the marginal cost [26].
  5. Conviction that $\nu_\tau$ appearance is a crucial measurement.

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# OPERA (Oscillation Project with Emulsion-tRacking Apparatus)

- The OPERA detector was composed of 1.25 kt of sandwiches of 1-mm lead plates and emulsion films to identify $\nu_\tau$'s by observing kinks from their decays in the emulsion films. Scintillator trackers identified location of the events in the lead-emulsion "bricks," which could be removed for analysis [33].
- The experimental was located 730 km from the CERN SPS neutrino beam target, ran from 2008 to 2012, and accumulated 1.8 x $10^{20}$ POT.
- To optimize $\nu_\tau$ appearance, the neutrino beam was tuned to an average neutrino energy of 17 GeV. This yielded an L/E more than an order of magnitude smaller than the oscillation maximum, resulting in a more than two orders of magnitude suppression from the $\sin^2(\Delta m^2 L / 4E)$ term.

# OPERA Results

- OPERA reported its first $\nu_\tau$ event in 2010 [34] and a total of 5 events in 2015 [35].
- Recently, OPERA reported a new analysis with looser selection criteria [33]. Ten $\nu_\tau$ candidates were found with an expected background of 2.0 ± 0.4 events and an expected signal of 6.8 ± 0.8 events.

# ICARUS (Imaging Cosmic And Rare Underground Signals)

- In 1977, Carlo Rubbia proposed using liquid argon TPCs as neutrino detectors [36].
- Research started at CERN in 1985 with a 2 $m^3$ prototype and continued in 1993 in Pavia with a 10 $m^3$ prototype and finally with two 300 t modules, one of which successfully took comic data for 100 days in 2001 [37]. The 600 t detector was transported to Gran Sasso in 2004 and ran in the CNGS beam from 2010 to 2012.

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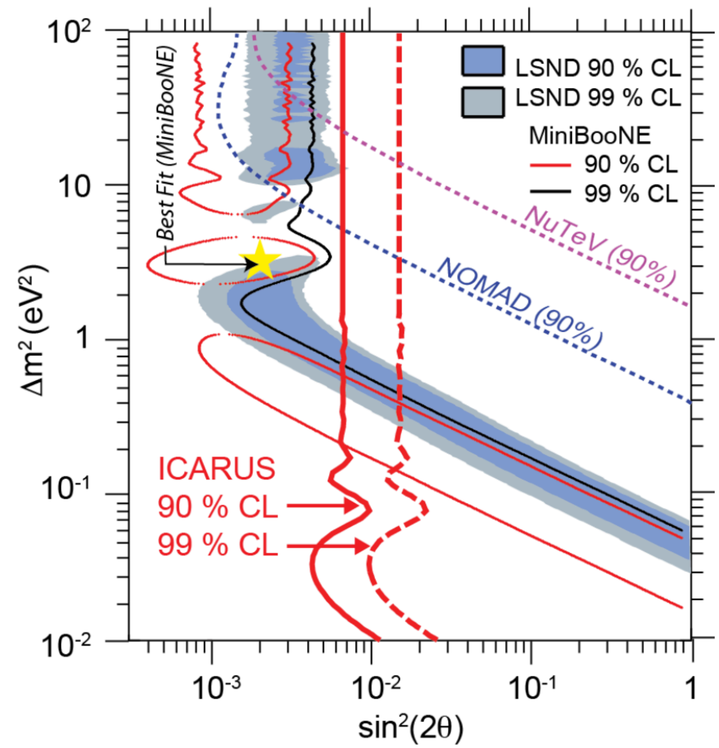
# ICARUS Results

- The ICARUS collaboration had always considered the 600 t detector as just the first part of a multi-kt detector, but additional modules were not funded. The combination of the same L/E factor of over 100 that affected OPERA and the relatively small mass of the detector prevented ICARUS from doing any oscillation physics at the atmospheric mass scale.
- The only oscillation result from ICARUS was a limit on sterile neutrinos in the $\Delta m^2 > 0.01$ eV$^2$ range [5].



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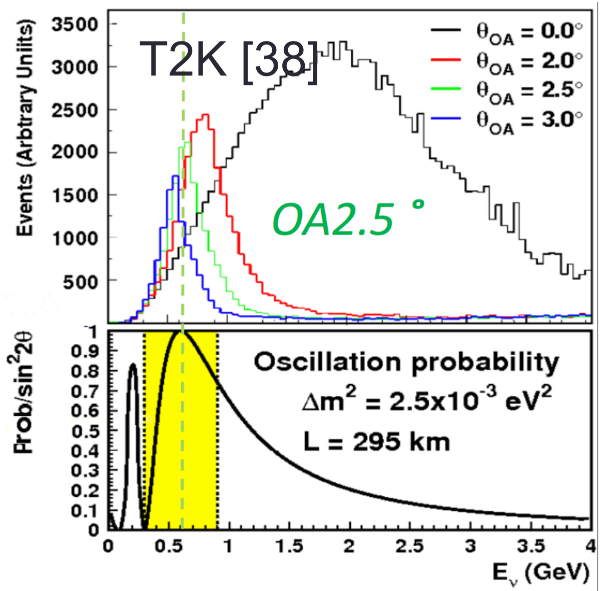
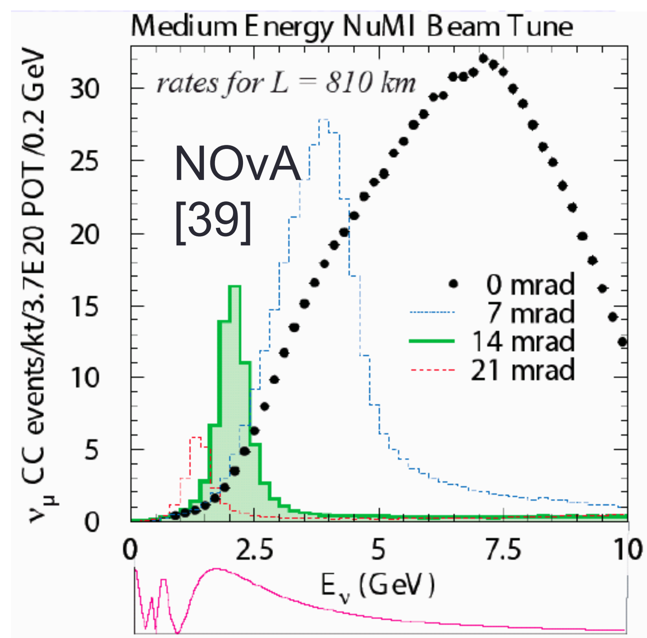
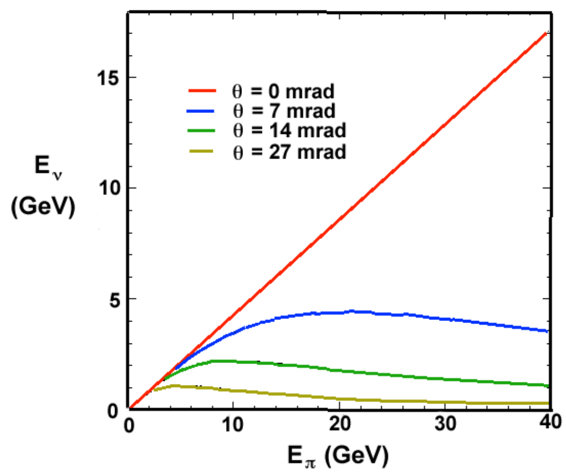
# $2^{nd}$ Generation: T2K and NOvA

- T2K and NOvA are complementary experiments with similar capabilities and interests. The major difference is the baseline.
- Both place the detectors off the beam axis to increase the neutrino flux near the oscillation maximum and reduce backgrounds from higher-energy neutral currents.



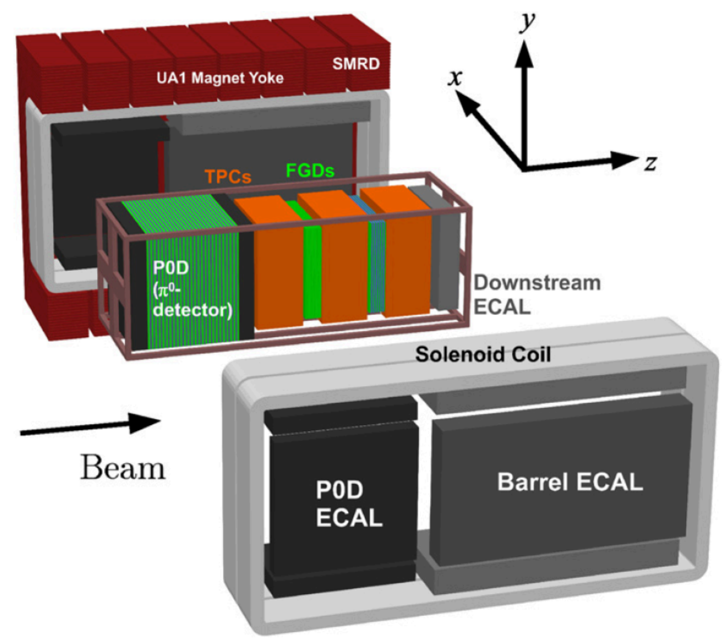



# Physics Parameters

- Both T2K and NOvA use measurements of $\Delta m^2_{21}$, $\sin^2(2\theta_{12})$, and $\sin^2(2\theta_{13})$ from other experiments [40] in combination with their measurements of $\nu_\mu$ disappearance and $\nu_e$ appearance, in both neutrino and antineutrino beams, to gain information on the other four parameters of the standard neutrino model,
  - $|\Delta m^2_{32}|$ and $\sin^2(\theta_{23})$, best measured in $\nu_\mu$ disappearance, and
  - $\delta_{CP}$ and the mass ordering, best measured in $\nu_e$ appearance.
- Note:
  - We measure $\sin^2(2\theta_{23})$, but want to know $\sin^2(\theta_{23})$
    - $P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2(\Delta m^2_{32} L/4E) + \ldots$
    - $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(\Delta m^2_{32} L/4E) + \ldots$

# T2K (Tokai to Kamioka)

- Like K2K, T2K uses Super-Kamiokande as its far detector. However, the neutrino beam is generated by the more powerful 30 GeV J-PARK proton synchrotron in Tokai, Japan for a 295 km baseline [40].
- The near detector at 280 m includes a $\pi^0$ detector consisting of sandwiches of scintillators, water bags, and either brass or lead sheets, followed by TPCs and fine-grained scintillator bars, all included in a 0.2 T magnetic field.



# T2K Timeline

- T2K submitted an LOI in 2001 [41].
- The experiment was approved in 2003 and beamline construction began in 2004.
- First run with beam was in January 2010.
- First publication on oscillations was in 2011 [42].
- Progress was hindered by laboratory closures due to the 2011 tsunami and an (unrelated) radiation incident in 2013 [43].
- Most recent report [44]:
  - $\nu$: 14.9 x $10^{20}$ POT ; $\bar{\nu}$: 11.2 x $10^{20}$ POT
  - $\Delta m^2$ precision: ±2.6%
  - $\nu_e$: signal = 75.2; bg = 14.8; FoM = 7.9
  - $\bar{\nu}_e$: signal = 4.7; bg = 4.3; FoM = 2.3

$$\mathrm{FoM} = \frac{s}{\sqrt{s+b}}$$

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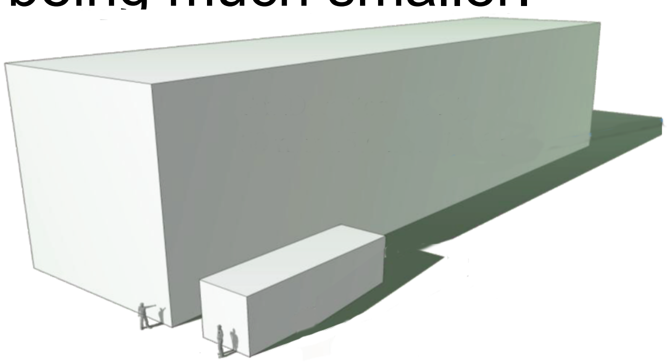
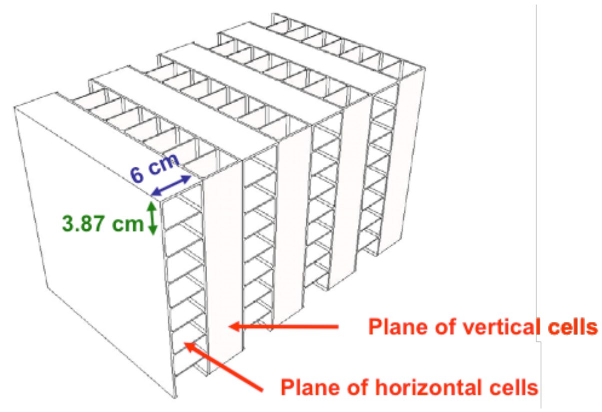
# NOvA (NuMI Off-axis $\nu_e$ Appearance Experiment)

- The NOvA far detector is located in northern Minnesota near the Canadian boarder on an 810 km baseline.
- The 14 kt detector consists of 344,064 15 m x 4 cm x 6 cm PVC cells filled with liquid scintillator, read out by a loop of wave-length shifting fiber with both ends connected to an avalanche photodiode. [46]
- The near detector is identical to the far detector, except for being much smaller.





# NOvA Timeline (1)

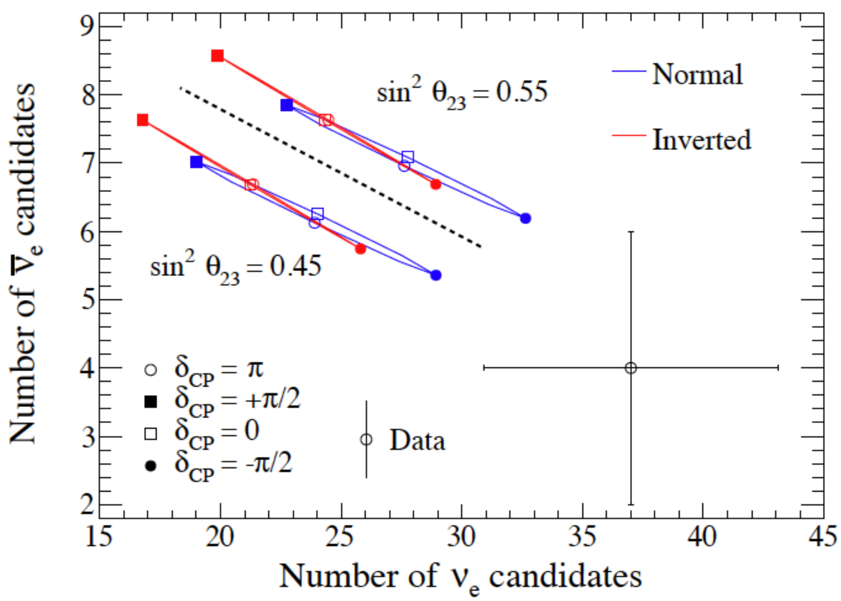
- Planning for the NOvA experiment began with workshops in 2002 leading to a proposal that was submitted to the Fermilab PAC in March 2005 and was given preliminary approval [46]. The proposal called for a 30 kt version of what was actually built. At the request of the Department of Energy (DOE), the proposed NOvA mass was downsized to 25 kt in 2006.
- June 2006: DOE High Energy Physics Advisory Panel’s P5 subpanel recommends construction of NOvA starting in 2008.
- December 2007: US Congress cut NOvA funding to zero. How this happened was never clear. Fermilab employees working on NOvA were assigned to other tasks. Funding was restored in June 2008, but it took time to rebuild the team.

# NOvA Timeline (2)

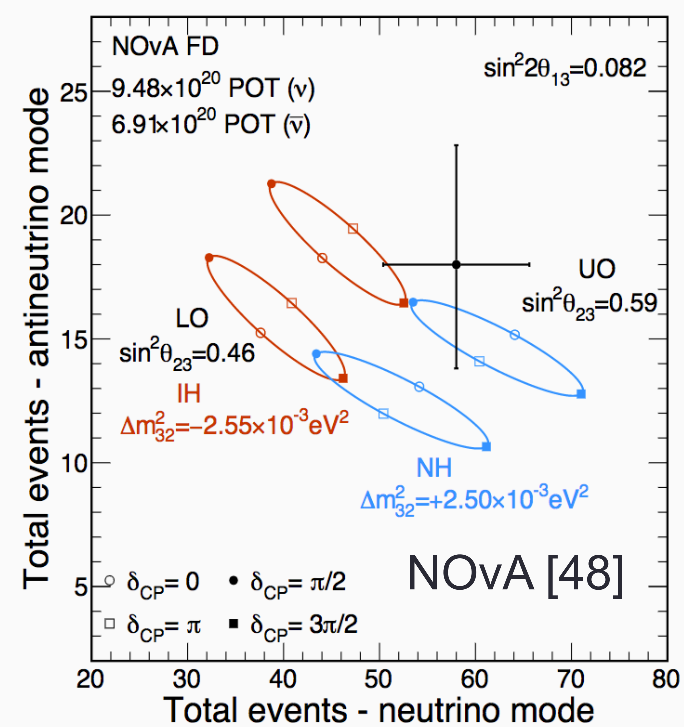
- May 2009: NOvA construction began. The cost was fixed at $278M and the DOE said to build as much possible for that amount.  The far detector pit was sized for 18 kt.
- February 2014: First data with 4 kt of the far detector; November 2014: data with the full 14 kt far detector.
- January 2016: First oscillation results published [47].
- Most recent report [48]:
  - $\nu$: 8.8 x $10^{20}$ POT ; $\bar{\nu}$: 6.9 x $10^{20}$ POT
  - $\Delta m^2$ precision: ±4.0%
  - $\nu_e$: signal = 43;    background = 15;    FoM = 5.6
  - $\bar{\nu}_e$: signal = 12.7; background =   5.3; FoM = 3.0

# $\nu_e$ vs. $\bar{\nu}_e$ Event Plots

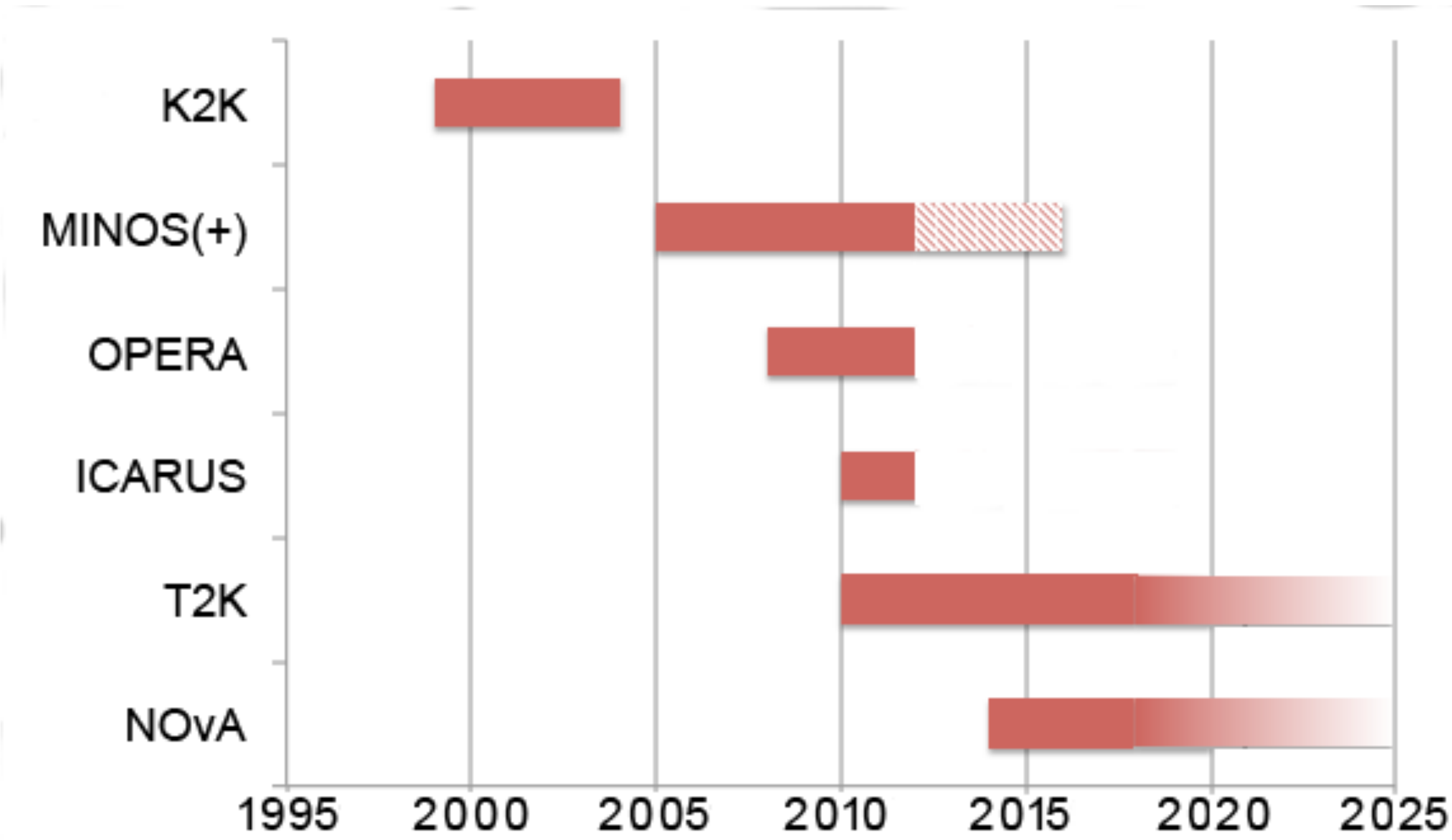
- These plots of the number of $\nu_e$ vs. $\bar{\nu}_e$ candidates are good pedagogical tools for showing the whole multivariable landscape.




T2K 2017 Data [49]



# Timeline of the Experiments Taking Data



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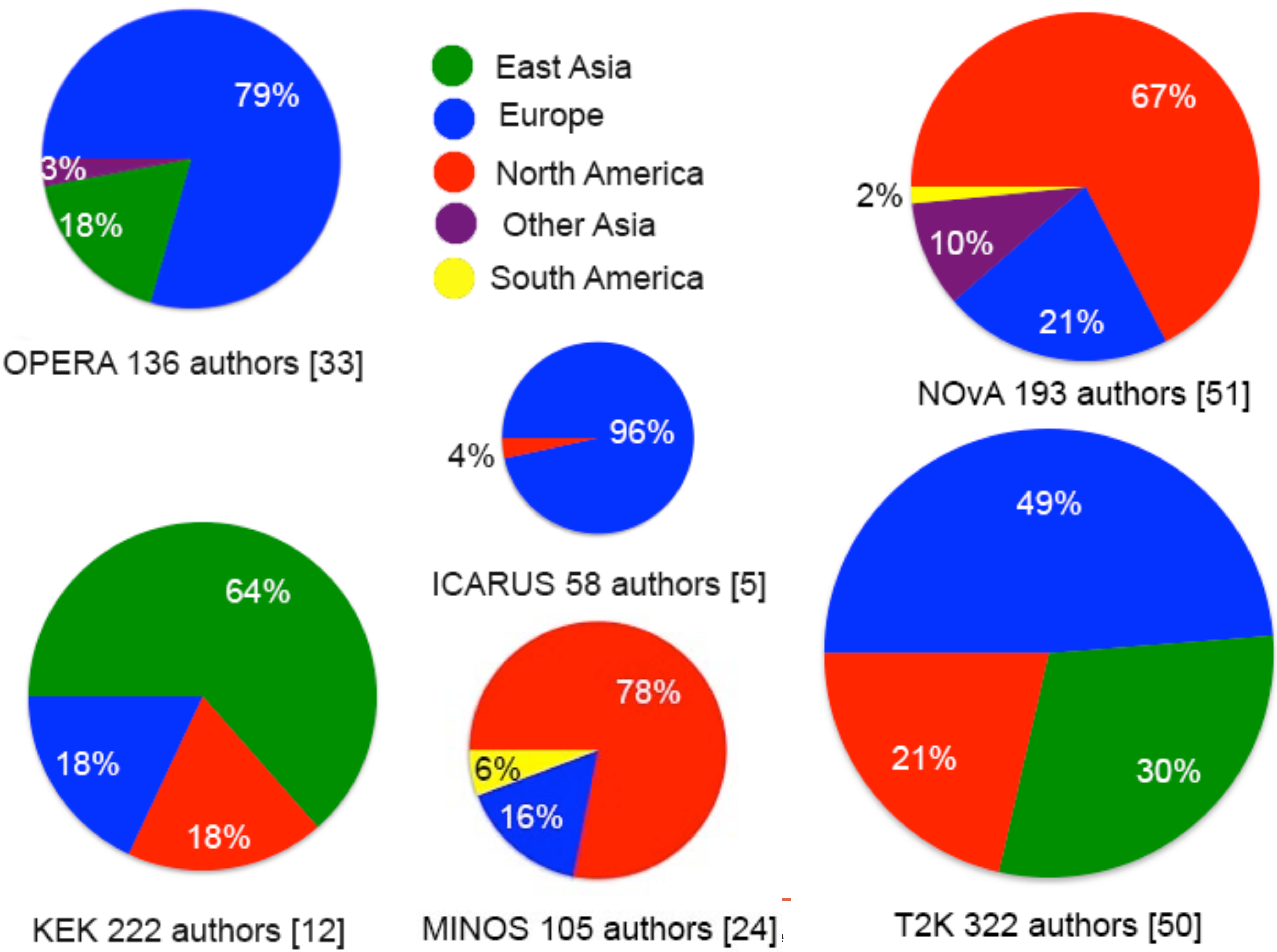
# Benchmark Measurements

| Experiment | $\text{POT} \times 10^{20}$ $\nu\ /\ \bar{\nu}$ | $\Delta m^2$ precision | $\nu_e$ FoM $\nu\ /\ \bar{\nu}$ | Reference |
|---|---|---|---|---|
| KEK | 0.9 / 0 | ±19%* | <0 / - | 12, 14 |
| MINOS | 10.7 / 3.4 | ± 4.3% | 1.9 / 0/5 | 24, 25 |
| T2K | 14.9 / 11.2 | ± 2.6% | 7.9 / 2.3 | 44 |
| NOvA | 8.8 / 6.9 | ± 4.0% | 5.6 / 3.0 | 48 |

*My estimate



East Asia
Europe
North America
Other Asia
South America
79%
3%
18%
OPERA 136 authors [33]
96%
4%
ICARUS 58 authors [5]
67%
2%
10%
21%
NOvA 193 authors [51]
64%
18%
18%
KEK 222 authors [12]
78%
6%
16%
MINOS 105 authors [24]
49%
21%
30%
T2K 322 authors [50]

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