Results on Accelerator and Reactor Neutrinos

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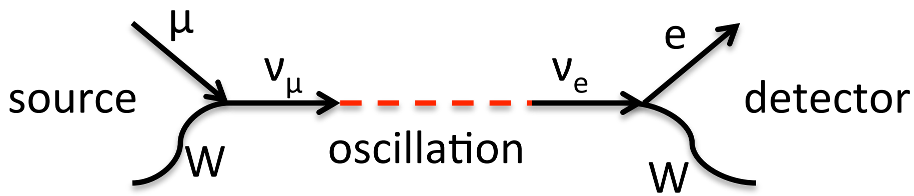
August 24, 2016

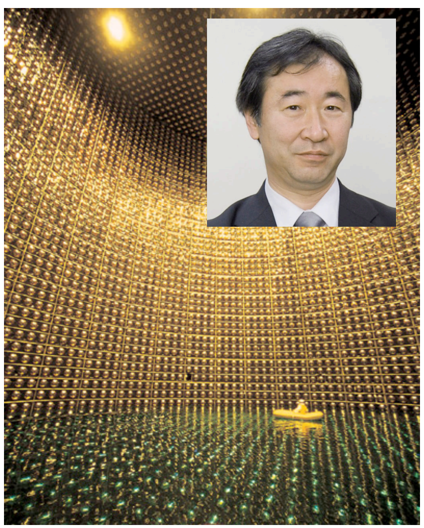
Neutrinos Have Mass

$$\left|\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix}\right\rangle = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\left|\begin{matrix}\nu_1\\ \nu_2\\ \nu_3\end{matrix}\right\rangle$$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[1.27\Delta m^2_{ij}(L/E)] + 2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin[2.54\Delta m^2_{ij}(L/E)]$$

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$





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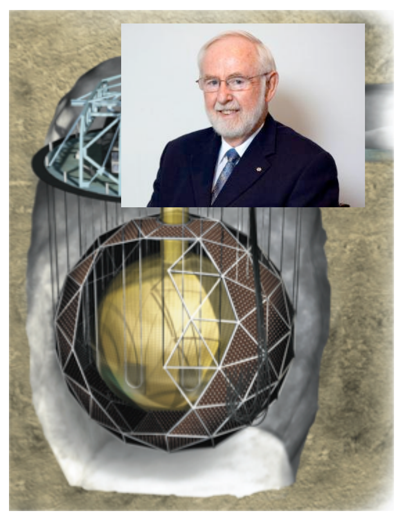

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More Than MET

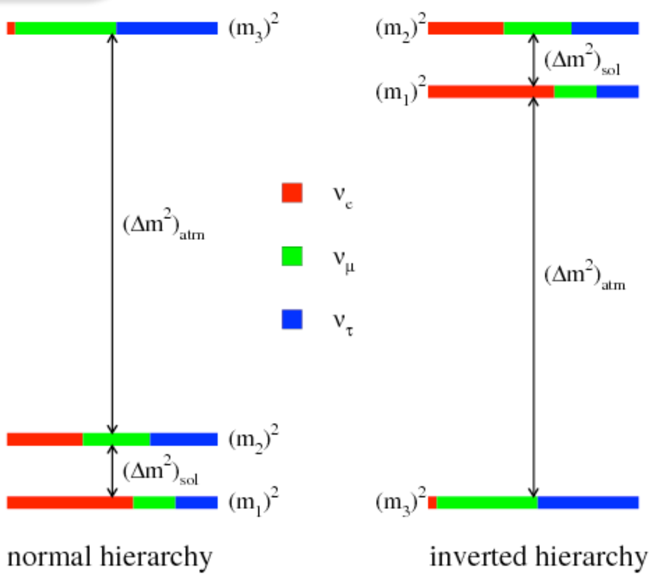
- **Four mixing matrix elements**
  - Well measured except CP-violating δ
  - θ_{23} consistent with maximal mixing

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

Phases do not affect mixing

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{pmatrix}$$

- **Three neutrino masses**
  - Sum of masses is < 0.23 eV (Planck CMB data)
  - $|\Delta m_{21}^2| << |\Delta m_{31}^2|$ (factor of ~30)
  - Sign of Δm_{31}^2 (mass hierarchy) is unknown



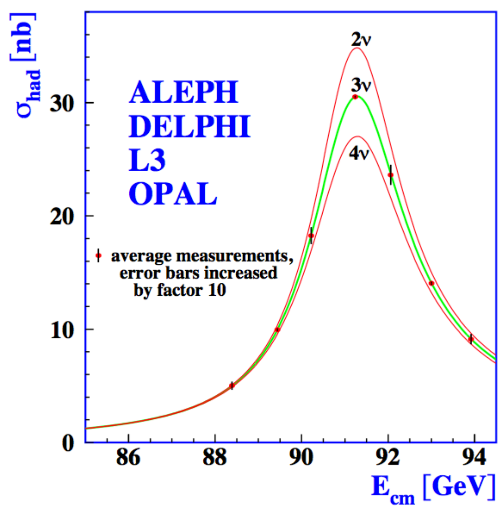
How Many Neutrinos are There?

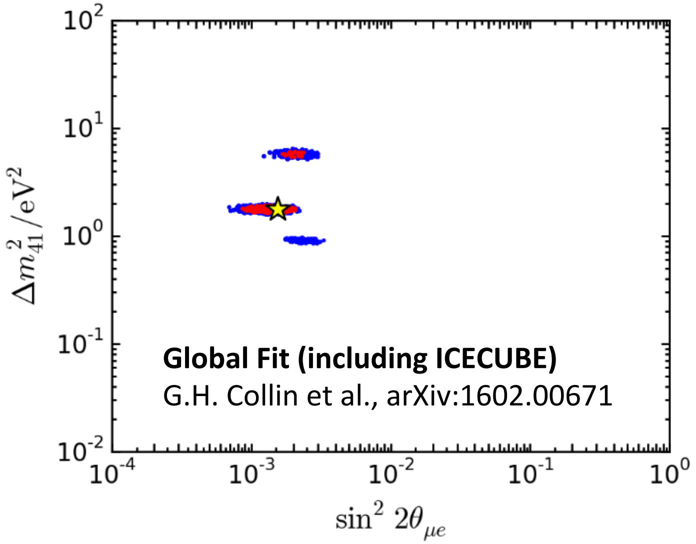
- Number of weakly-active light neutrinos is well-known to be 3 (Z decay width)

- Anomalies from accelerator, reactor, and source neutrino experiments could indicate existence of sterile neutrinos

- In a 3+1 model, data points to $\Delta m^2 \sim 1$ eV^2 (L/E ~ 1 km/GeV) and small effective mixing angle

Phys.Rept.427:257-454, 2006

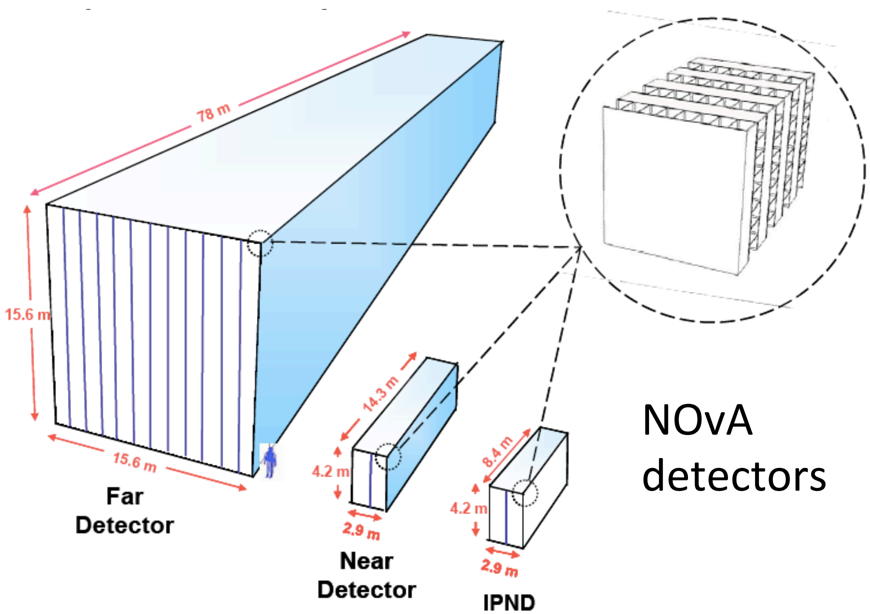




Anatomy of an Oscillation Experiment

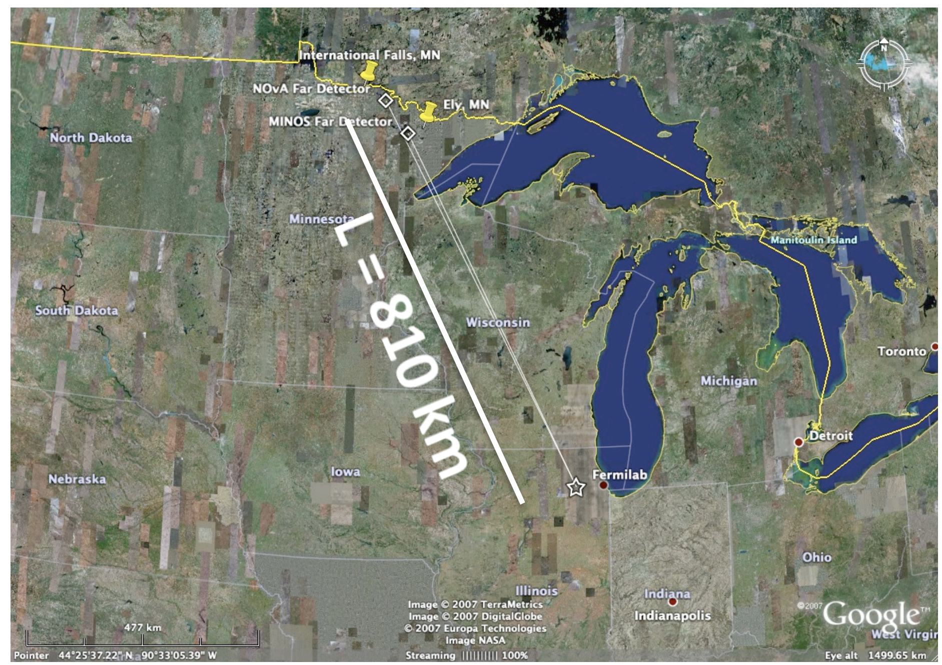
1) Intense neutrino source ($>10^5$ ν/cm^2/pulse if a beam)

2) **Massive** detector composed of heavy nuclei **FAR** away from the source



NOvA detectors

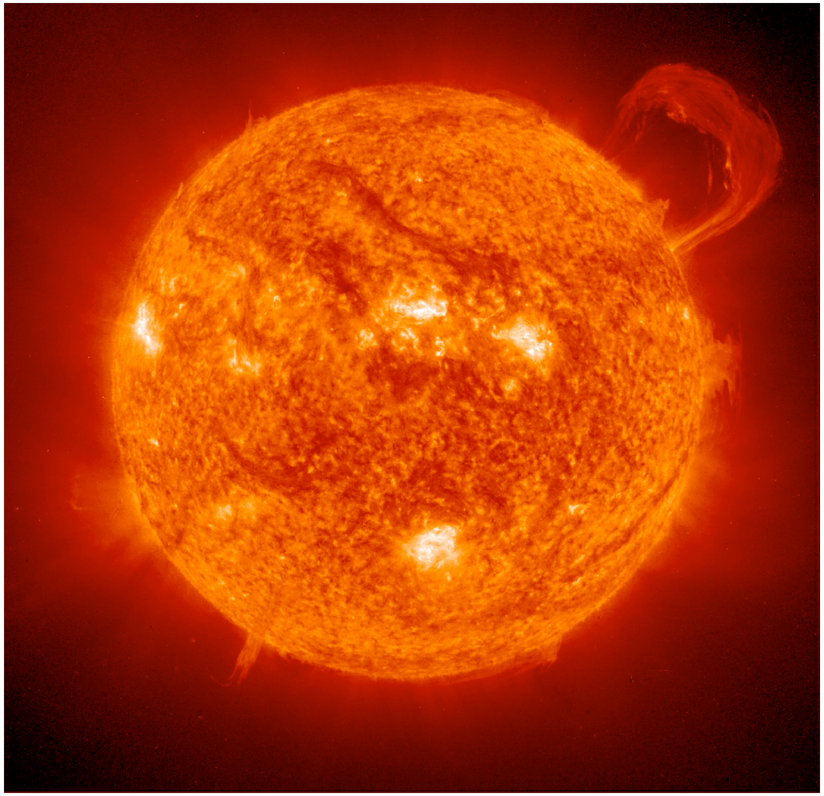
3) (Optional) near detector close to source – measure unoscillated spectrum to constrain systematics

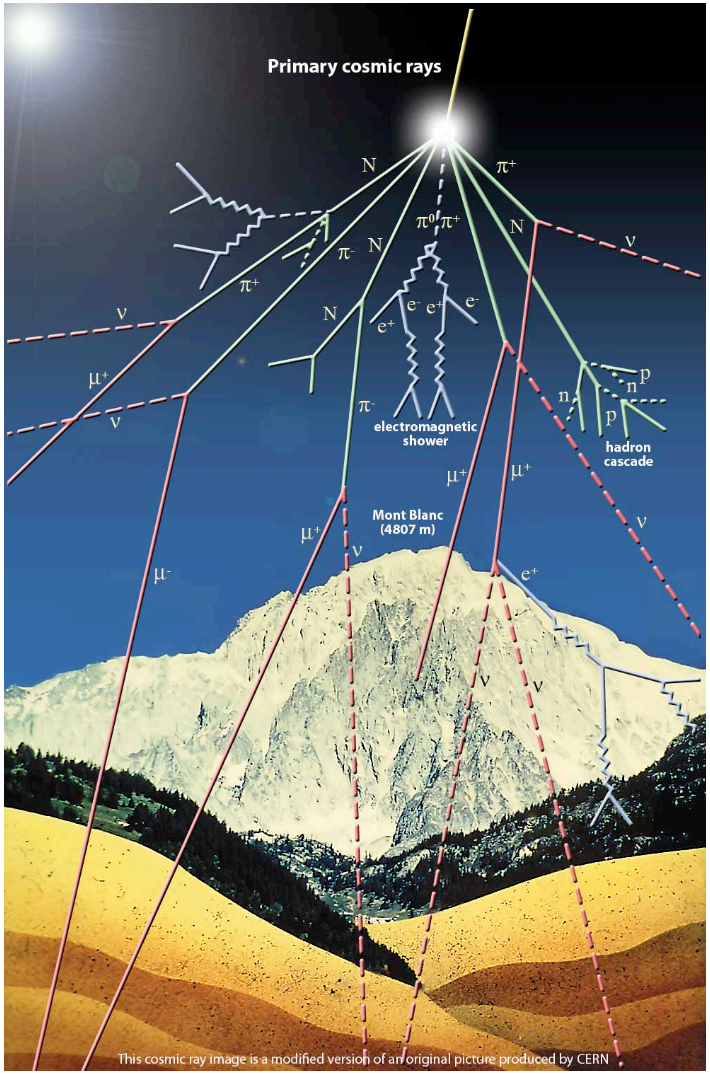


Neutrino Sources – 2015 Nobel Prize

Sun: KeV to a few MeV: ~$10^{11}/cm^2/s$ at Earth

Cosmic Rays: GeV and higher





Neutrino Sources

Relatively high amount of Potassium 40:
~ 10 neutrinos per second, few MeV

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Neutrino Sources - Reactors

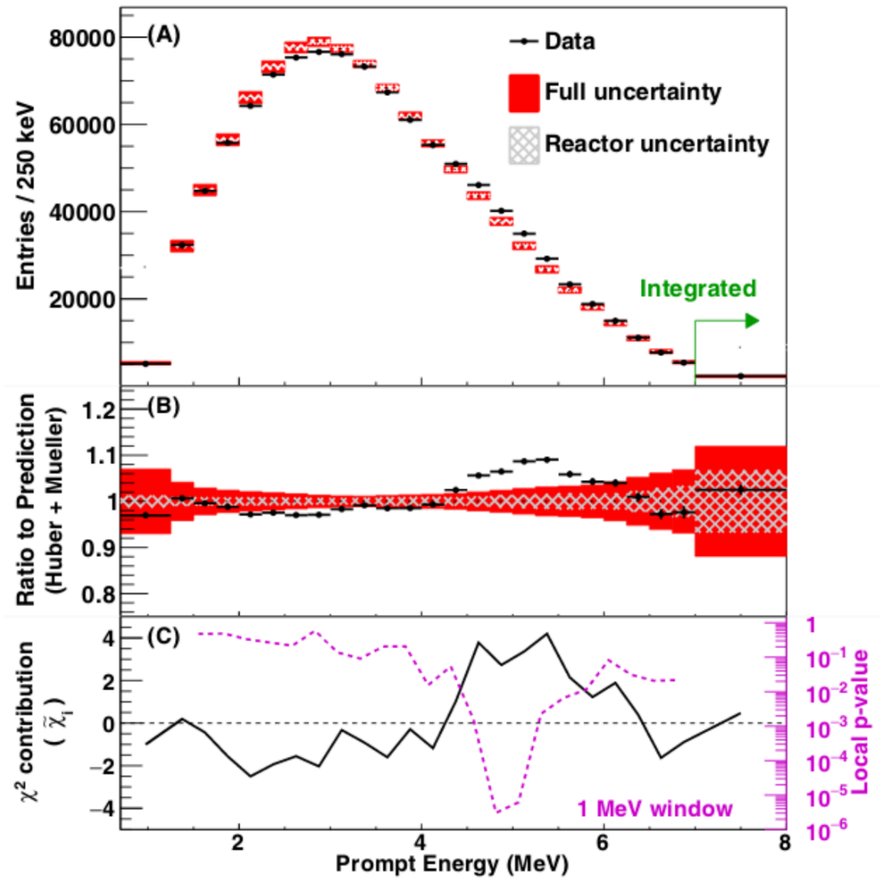
- Intense flux of few MeV anti-ν_e from beta decay of fission byproducts

- Can measure θ_{13}, Δm_{31}^2, sterile neutrinos with $\Delta m_{41}^2 < 0.1\ eV^2$ (~1 km baselines)

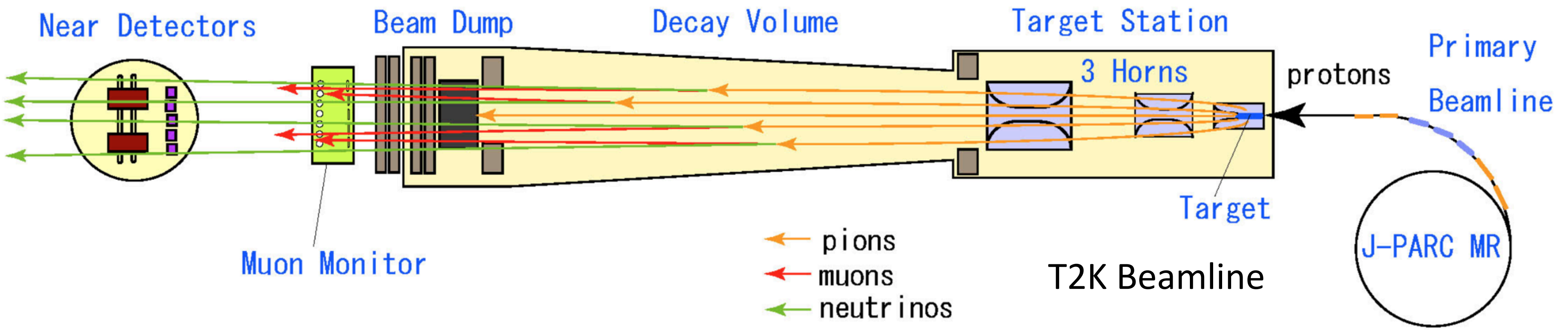
- Can measure θ_{12}, Δm_{21}^2 (~100 km baseline)

- Only anti-neutrinos: no CP violation measurement

Daya Bay prompt energy spectrum, Z. Yu, "Status of the Daya Bay Experiment", NEUTRINO 2016



Neutrino Sources - Accelerators



T2K Beamline

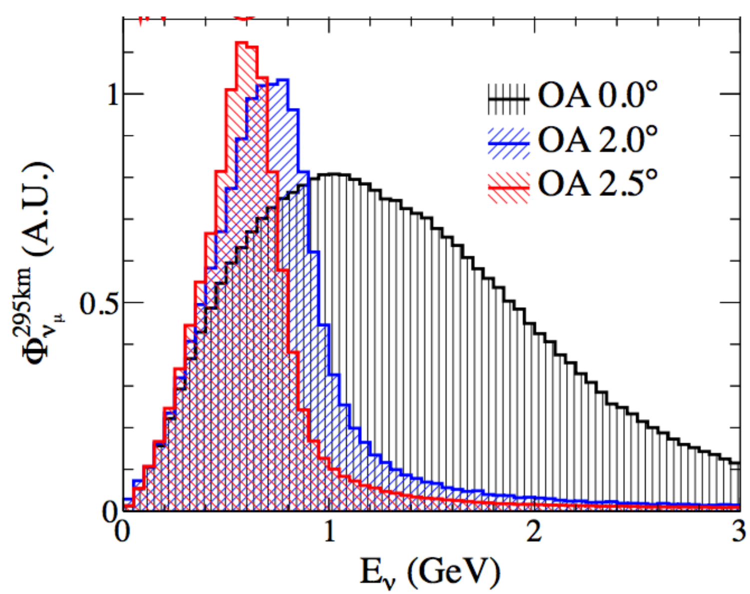
- Few 100 MeV to few GeV in energy, > 10^5 ν_μ / cm^2 / pulse

- Change focusing horn current to produce anti-neutrinos

- Measure θ_{13}, θ_{23}, Δm_{31}^2, δ (~100 – 1000 km baseline)

- Longer baselines allow for better resolution of the mass hierarchy

T2K Flux – H.A. Tanaka, "T2K: Latest Results", NEUTRINO 2016



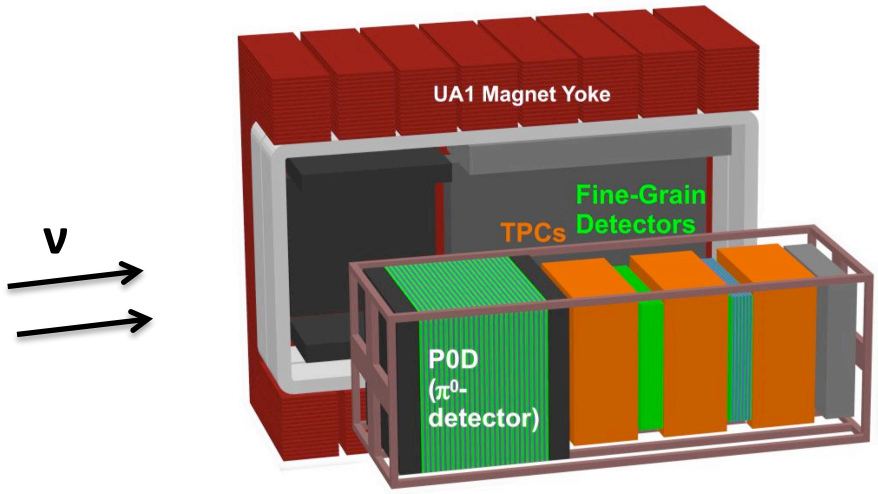
T2K Experiment

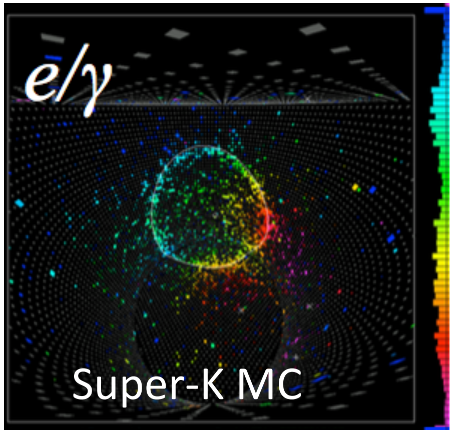
ND280:

- Off-axis near detector
- Not functionally identical to far detector, but has water targets
- Data used to tune far detector expectation

Super-Kamiokande:

- 50 kton water Cherenkov far detector (L=295 km)
- 1 km underground
- 2.5° off axis





H.A. Tanaka, "T2K: Latest Results", NEUTRINO 2016

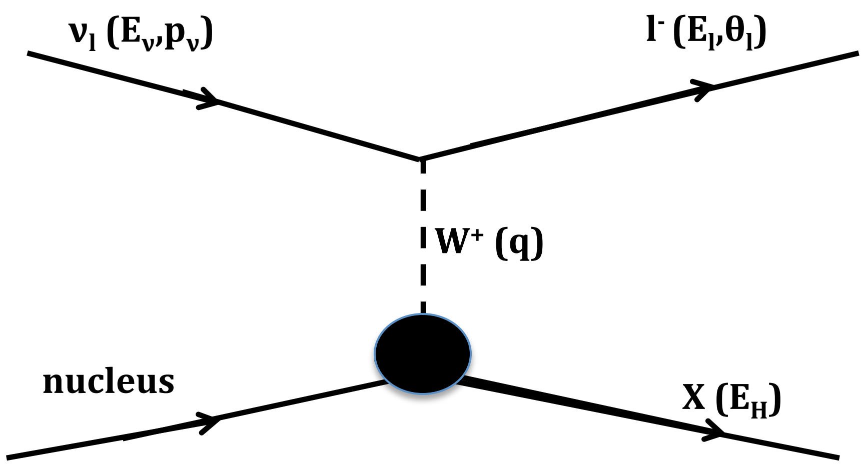
T2K Reconstruction & Analysis

(anti-)ν_μ disappearance:

- Look for (anti-)ν_μ deficit in far detector
- Measure θ_{23}, $|\Delta m_{31}^2|$

(anti-)ν_e appearance:

- Look for (anti-)ν_e excess in far detector
- Measure θ_{13}



Signal: single μ/e-like ring, X = single recoil nucleon (unobserved – below Cherenkov threshold)

Energy Reconstruction: assume 2-body kinematics, use E_l, θ_l

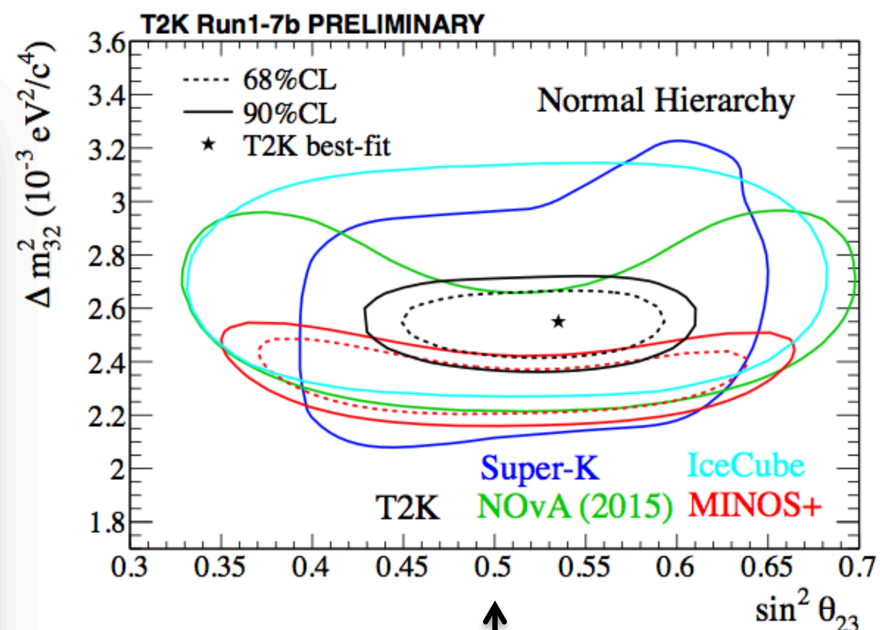
Hadronic Recoil: Reject backgrounds (pions)

T2K-Recent Results

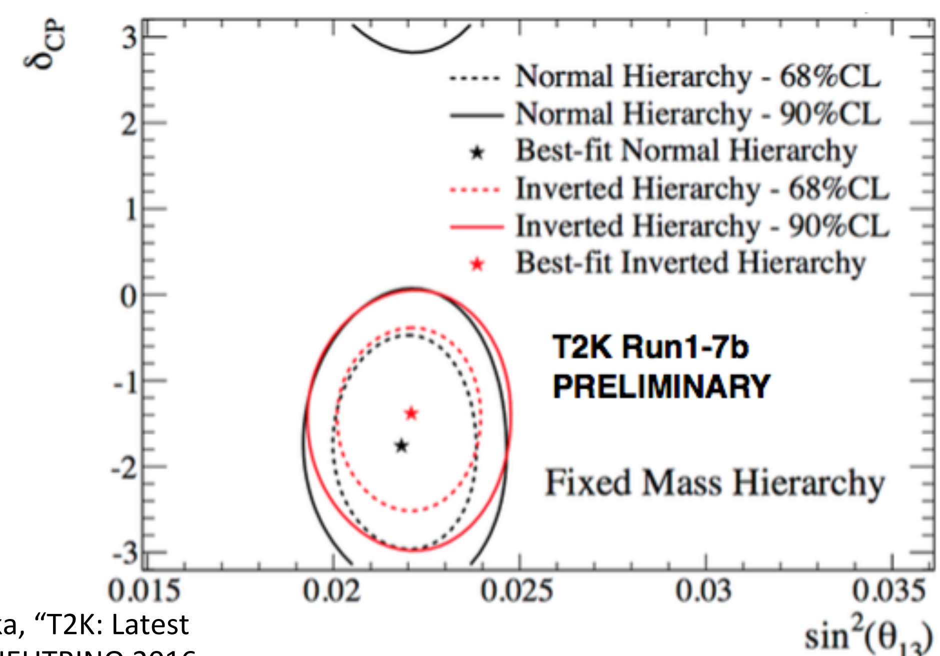
- Results from joint fit of ν_μ, anti-ν_μ disappearance; ν_e, anti-ν_e appearance

- Mild preference for Normal Hierarchy

		EXPECTED (NH, $\sin^2\Theta_{23}$=0.528)			
	OBS.	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$
ν_e	32	27.0	22.7	18.5	22.7
$\bar{\nu}_e$	4	6.0	6.9	7.7	6.8



Maximal Mixing



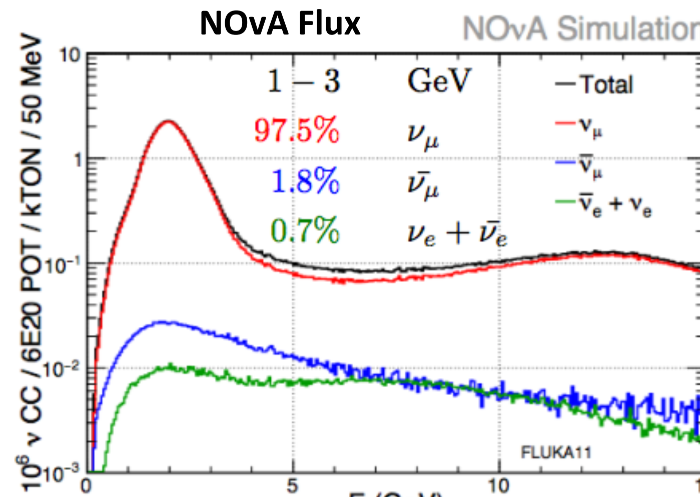
H.A. Tanaka, "T2K: Latest Results", NEUTRINO 2016

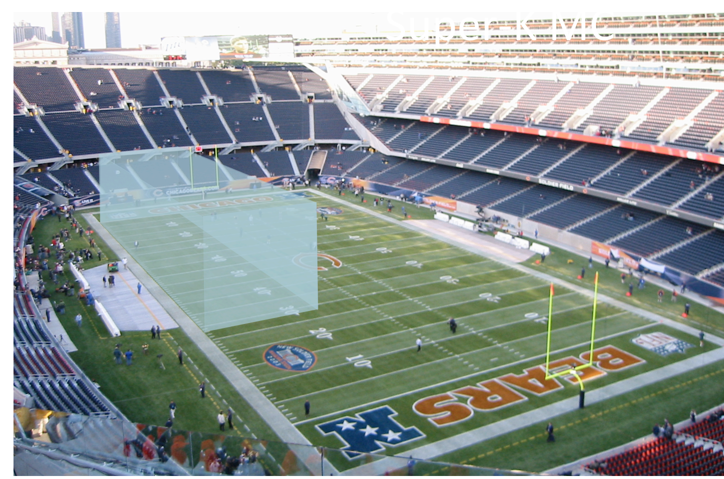
NOvA Experiment

P. Vahle, "New Results from NOvA", NEUTRINO 2016

Identical near and far detector technology

- 14 mrad off axis – 2 GeV flux peak
- 810 km baseline
- Planes of PVC strips filled with liquid scintillator, layered in orthogonal views
- 290 ton near detector underground at Fermilab – about the size of a double-decker bus
- 14 kton far detector on surface at Ash River, MN – largest free standing plastic structure in the world

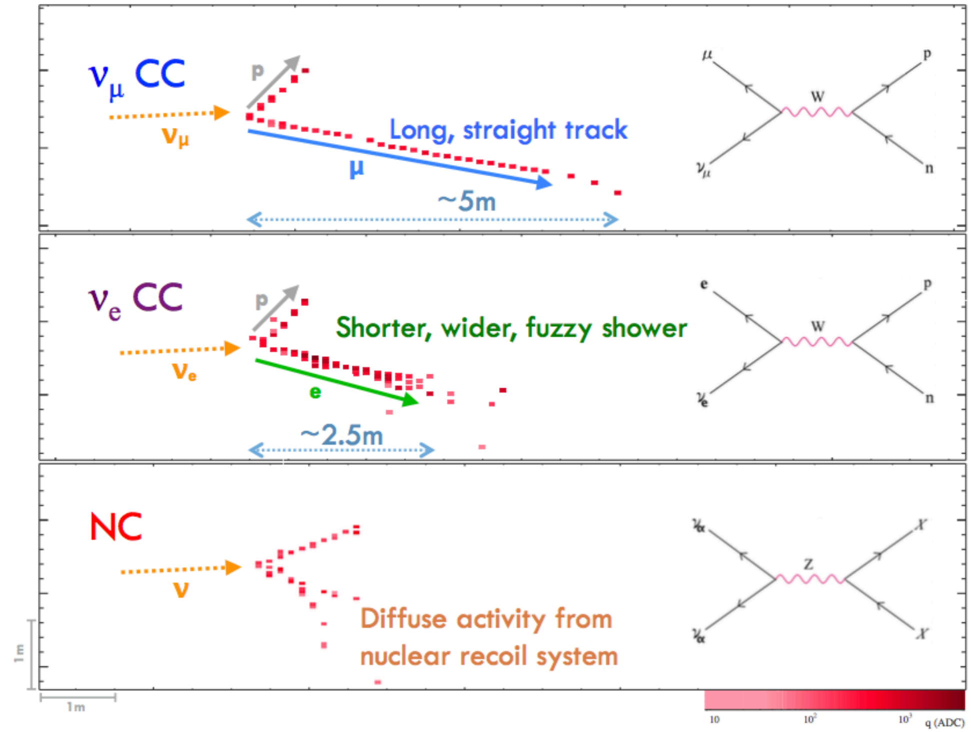




NOvA Reconstruction & Analysis

- ν_μ disappearance and ν_e appearance
- Long baseline to help resolve Mass Hierarchy
- 3-flavor NC disappearance to search for ~0.1 eV^2 Δm_{41}^2
- Uses a computer vision technique (Convolutional Visual Network) for abstract feature extraction from calibrated hit maps
- Extracted features are input to conventional neural network for event classification

P. Vahle, "New Results from NOvA", NEUTRINO 2016

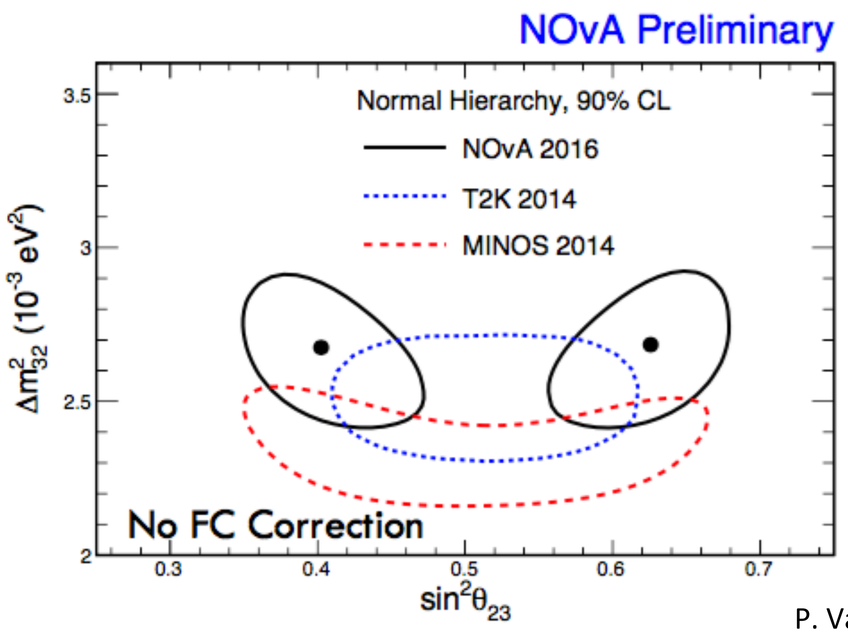


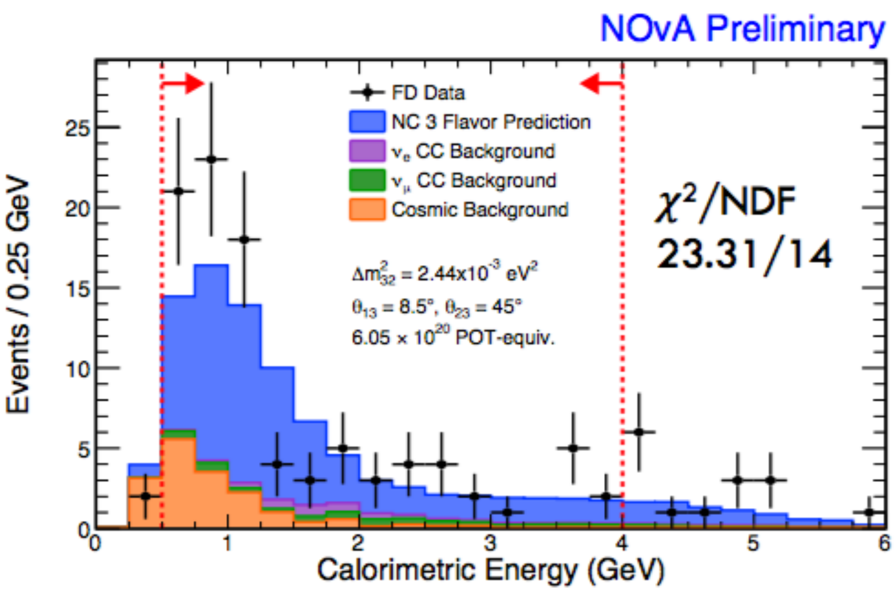
- Energy reconstructed using reconstructed lepton and hadronic recoil

NOvA – Recent Results

- **ν_μ disappearance:** 78 events observed at Far Detector
  - Expect 473 +/- 30 with no oscillations
  - Maximal mixing excluded at 2.5σ

- **NC disappearance:** 95 events observed at Far Detector
  - Expect 83.7 +/- 8.3 with no sterile oscillations

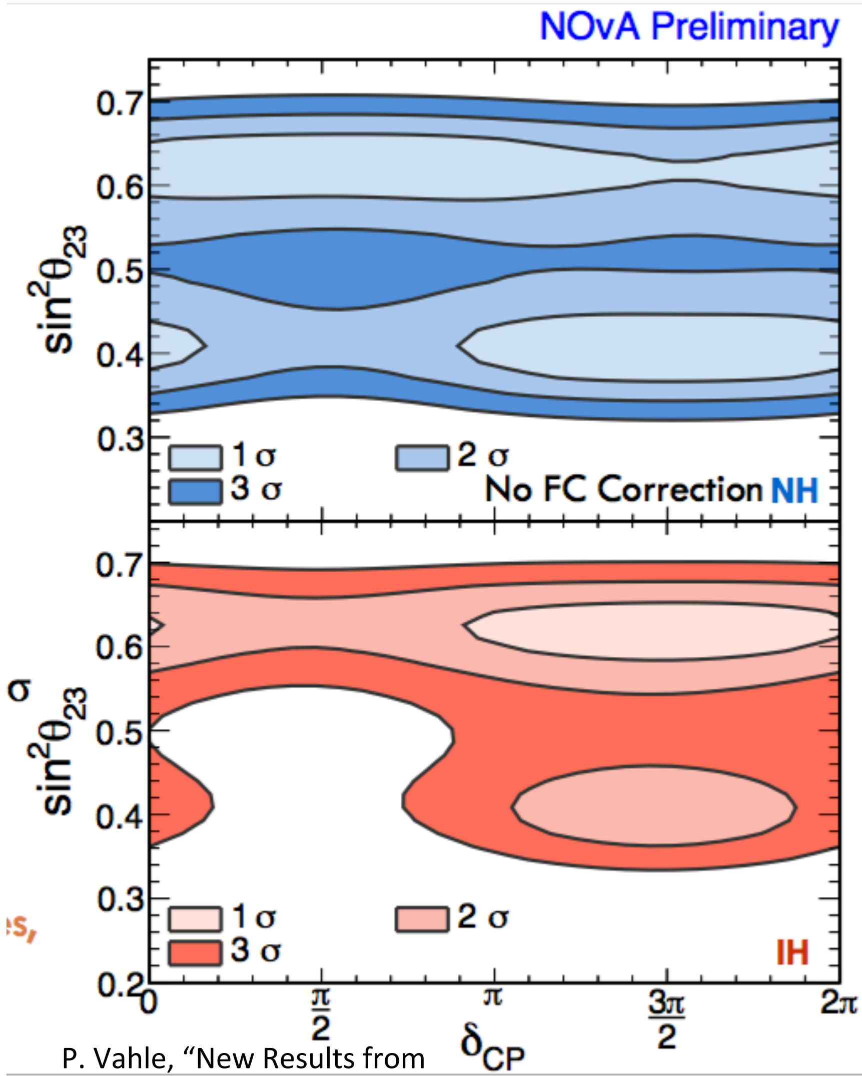




P. Vahle, "New Results from NOvA", NEUTRINO 2016

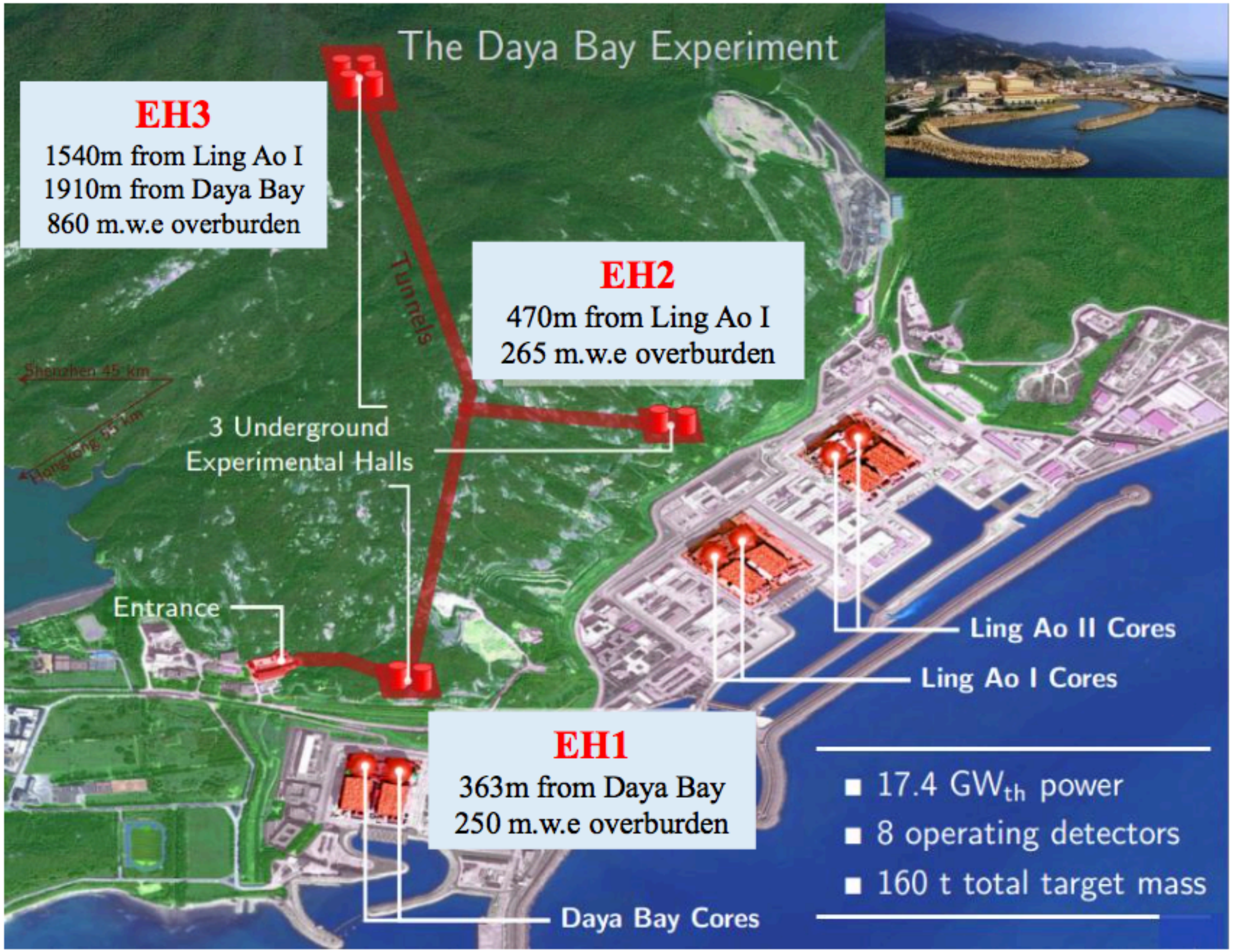
NOvA – Recent Results

- **ν_e appearance:** 33 events observed at Far Detector
  - Background expectation is 8.2 +/- 0.8
  - Fit is constrained by NOvA ν_μ disappearance, world average for θ_{13}
  - Normal Hierarchy preferred, but IH allowed at 1σ (consistent with T2K)
  - Best fit parameters
    - $\delta = 1.49\pi$ (consistent with T2K)
    - $\sin^2\theta_{23} = 0.40$



P. Vahle, "New Results from NOvA", NEUTRINO 2016

Daya Bay - Experiment



Z. Yu, “Status of the Daya Bay Experiment”, NEUTRINO 2016

Daya Bay - Experiment

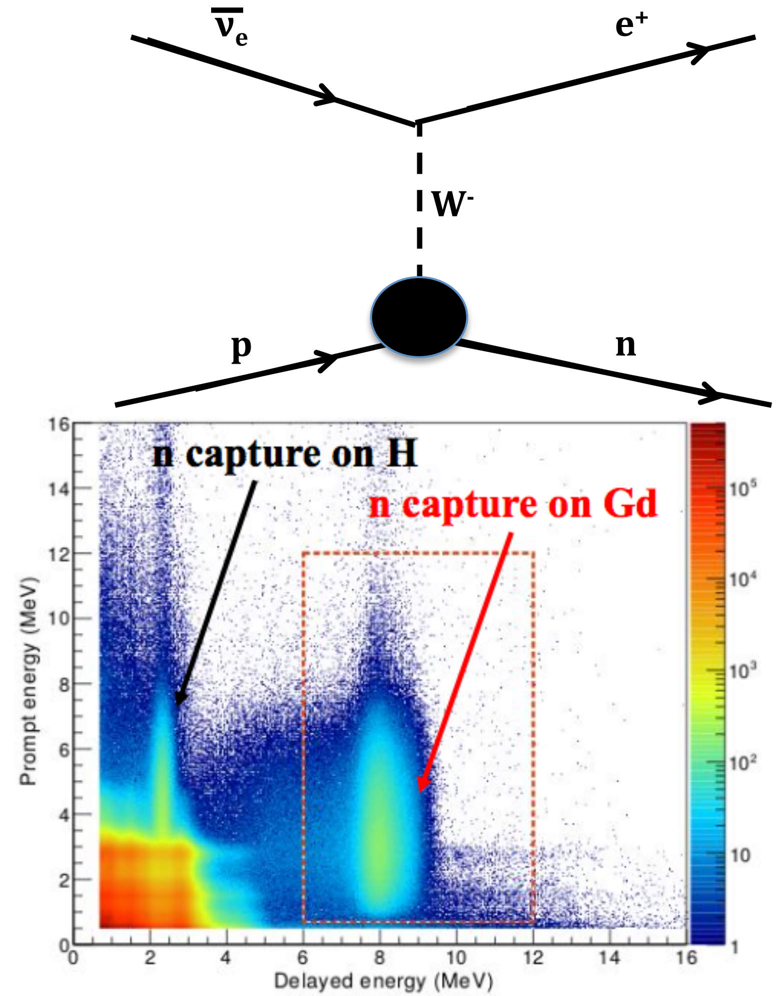
- Eight functionally-identical Gd-doped liquid scintillator detectors

- Anti-ν_e detected by inverse beta decay (IBD)
    - Prompt energy from positron shower
    - Delayed energy from n capture on Gd or H
    - 80% efficiency, ~98% purity

- Neutrino energy reconstructed using prompt and delayed energy

- First experiment to exclude θ_{13}= 0 at 5 sigma

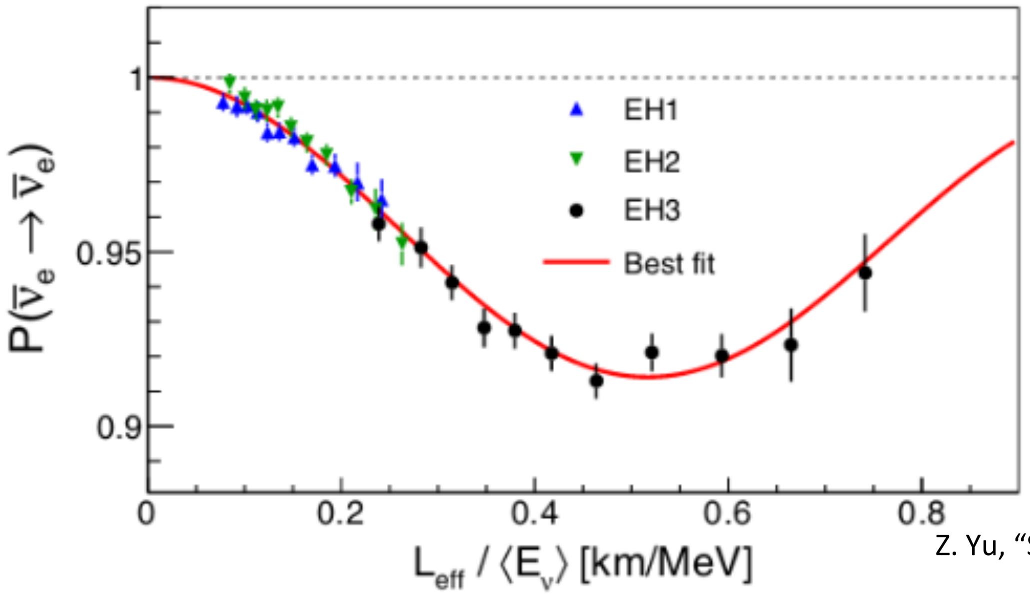
- Latest analysis has over 2.5M (300K) IBD candidates in total (at far site)
    - Doubles previous statistics



Z. Yu, "Status of the Daya Bay Experiment", NEUTRINO 2016

Daya Bay – Recent Results

Anti-neutrino disappearance



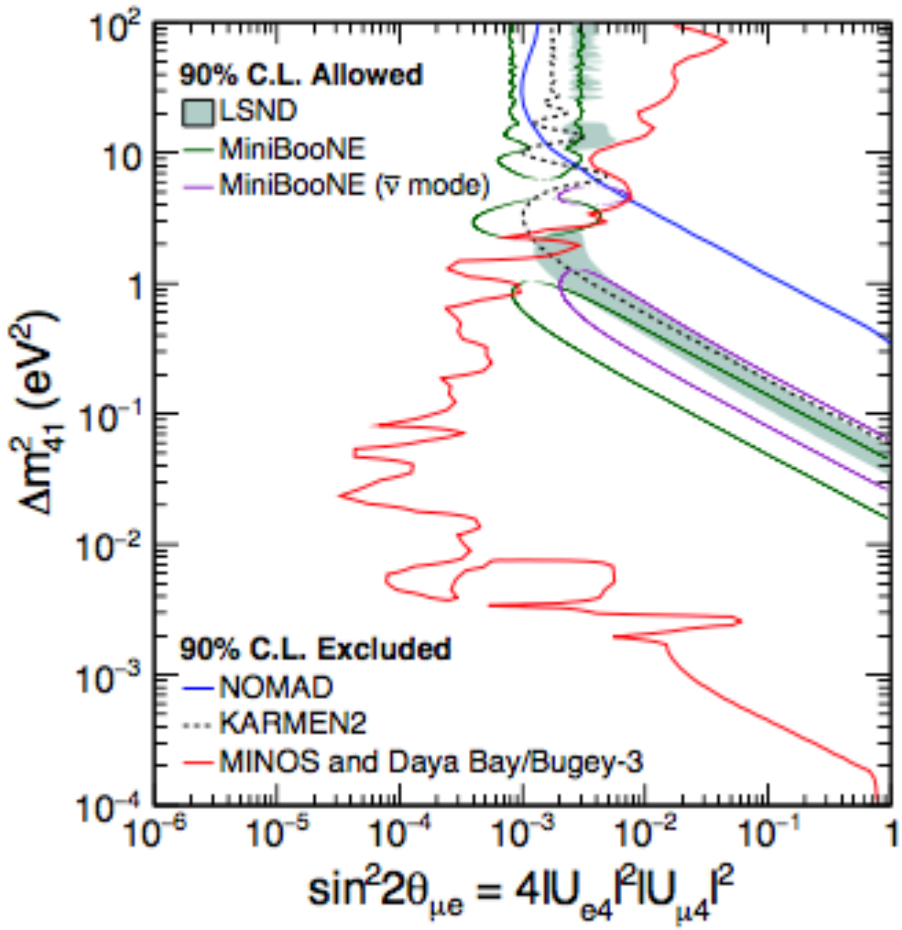
Z. Yu, "Status of the Daya Bay Experiment", NEUTRINO 2016

Best fit values (n-Gd):

- $\sin^2 2\theta_{13}$ = [8.41 +/- 0.27(stat) +/- 0.19(syst)] x 10^{-2}
- Δm^2_{32} = [2.45 (-2.55) +/- 0.08] x 10^{-3} eV^2 in NH (IH)
- Consistent with n-H results

Daya Bay and MINOS – Sterile Neutrinos

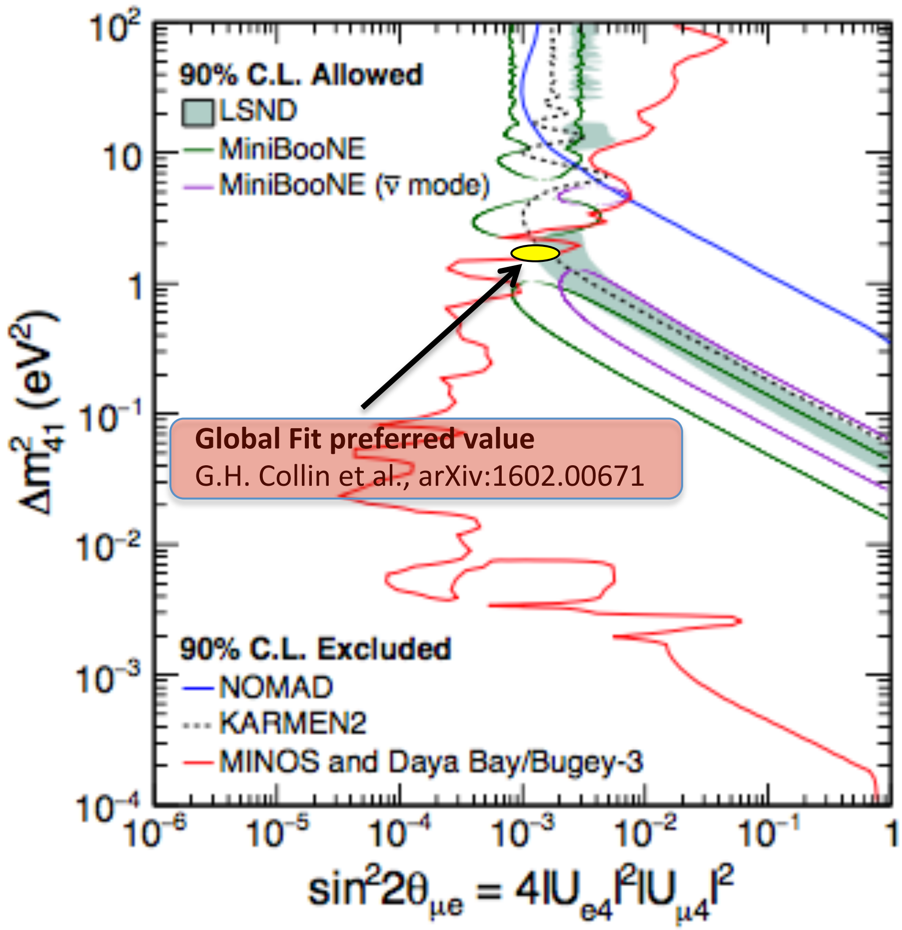
- Joint search for a light sterile neutrino (also used Bugey-3 data)



P. Adamson et al., arXiv:1607.01177

Daya Bay and MINOS – Sterile Neutrinos

- Joint search for a light sterile neutrino (also used Bugey-3 data)
- Does not appear to exclude preferred region of the joint fit showed earlier



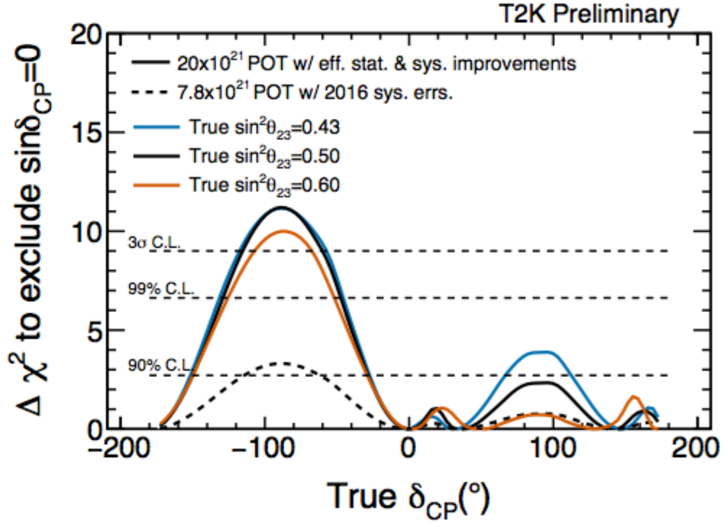
P. Adamson et al., arXiv:1607.01177

Future Prospects

- T2K proposes additional running and upgrades past 2021 – final results by ~2026
    - Excluding $\delta=0$ at 3-sigma if maximal ($-\pi/2$)
    - Measure θ_{23} to within 1.7° - possible to exclude maximal mixing to ~2-sigma

- NOvA will soon get anti-neutrino data, which will help with δ and excluding maximal mixing θ_{23}
    - First results in 2017

- Daya Bay will run until 2020, reducing uncertainties on its mixing parameter measurements to ~3%



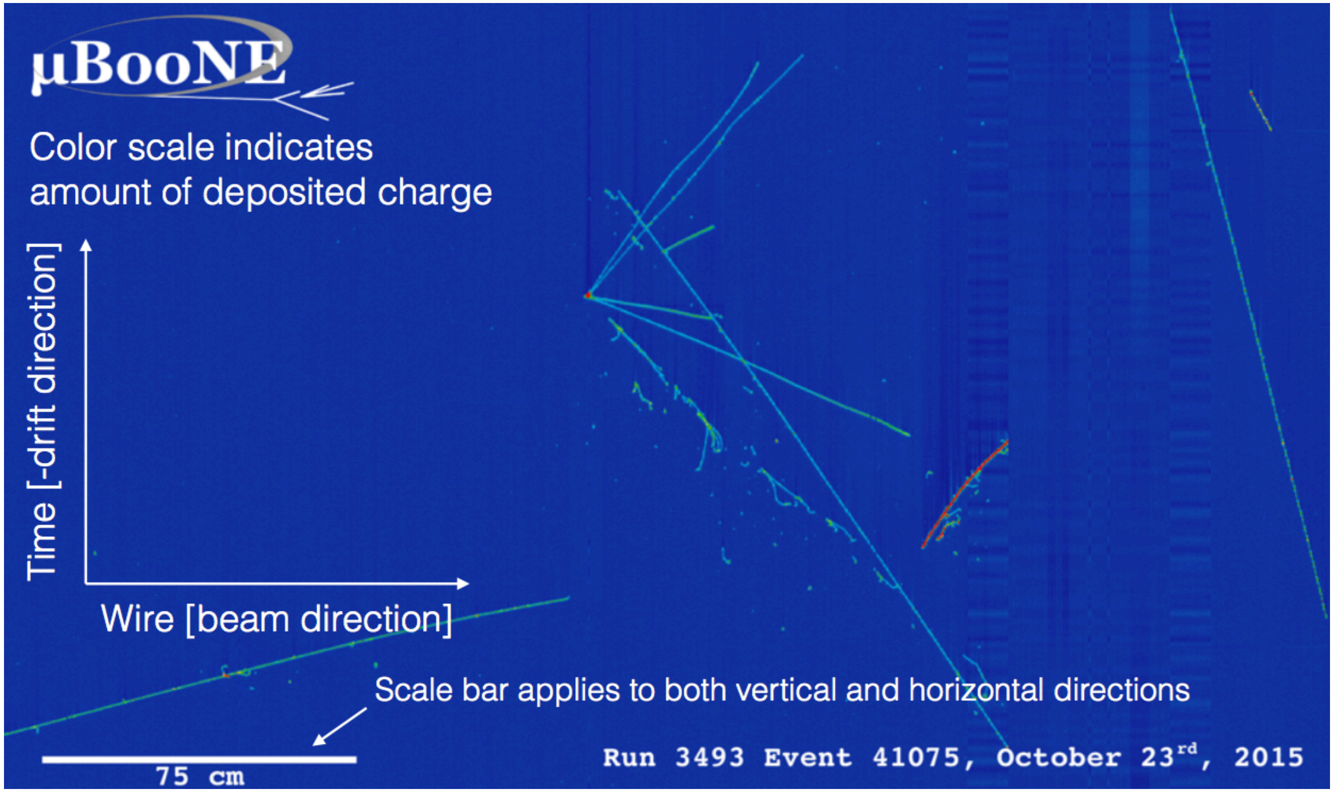
hierarchy unknown

H.A. Tanaka, "T2K: Latest Results", NEUTRINO 2016

Future Prospects - MicroBooNE

•Short baseline accelerator experiment in Fermilab booster neutrino beam, probing ~1 eV^2 sterile neutrino mixing

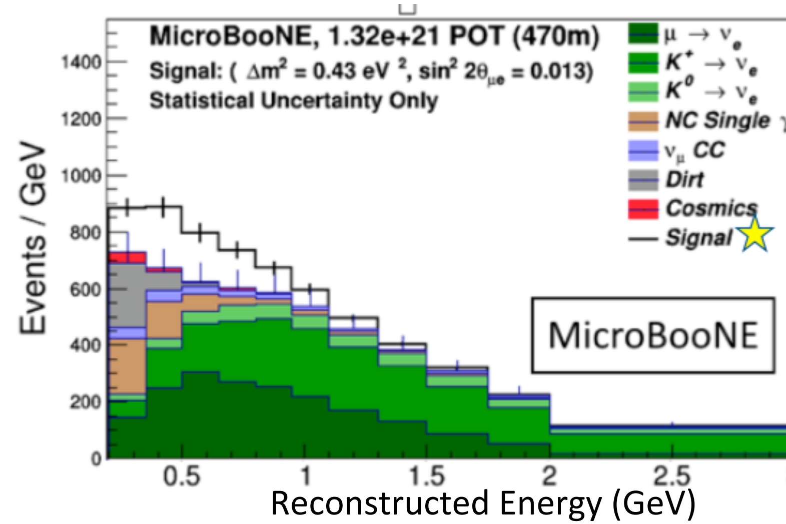
•Use “next generation” neutrino detector technology – liquid argon TPC



Future Prospects - MicroBooNE

MicroBooNE

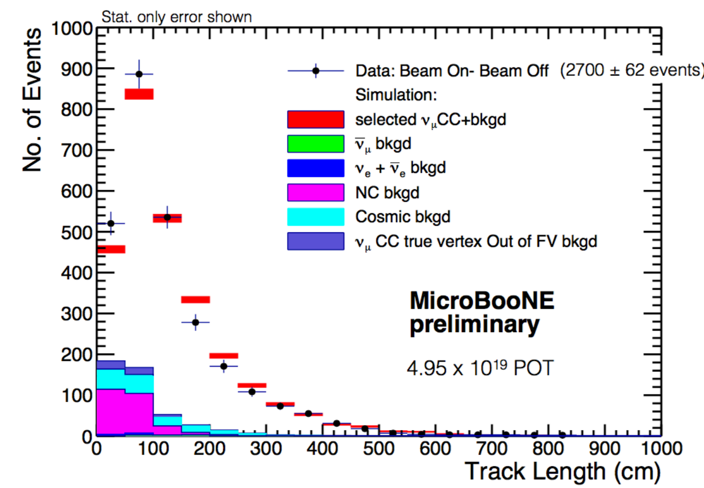
- In same beamline as MiniBooNE – probe the "MiniBooNE anomaly"
- Excellent particle ID to determine whether MiniBooNE anomaly is electron- or photon-like
- Started collecting data in October 2015, showed first results this summer!



First ν_μ CC Distributions From MicroBooNE Data

Fermilab Short Baseline Neutrino Program

- Pair MicroBooNE (470m) with a near detector (SBND – 110m) and far detector (Icarus – 600m)
- Exclude most of LSND allowed region in 3+1 sterile neutrino model by 5-sigma by ~2022



Simulation scaled to same number of events as data

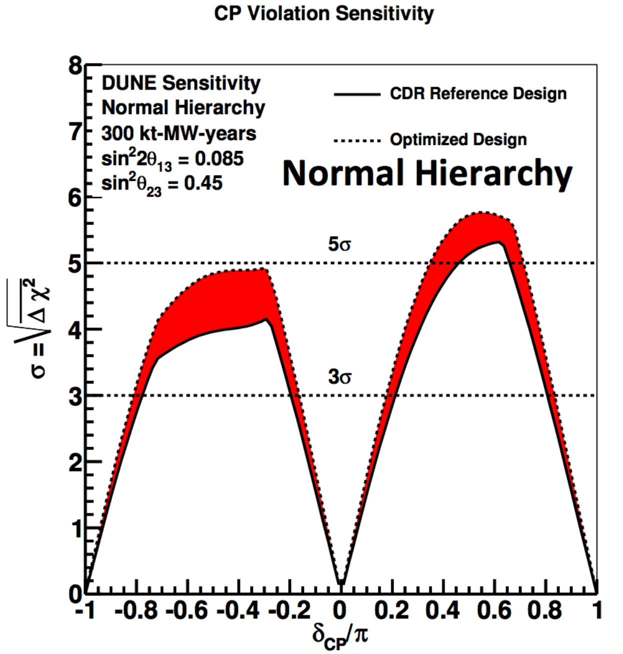
Future Prospects - DUNE

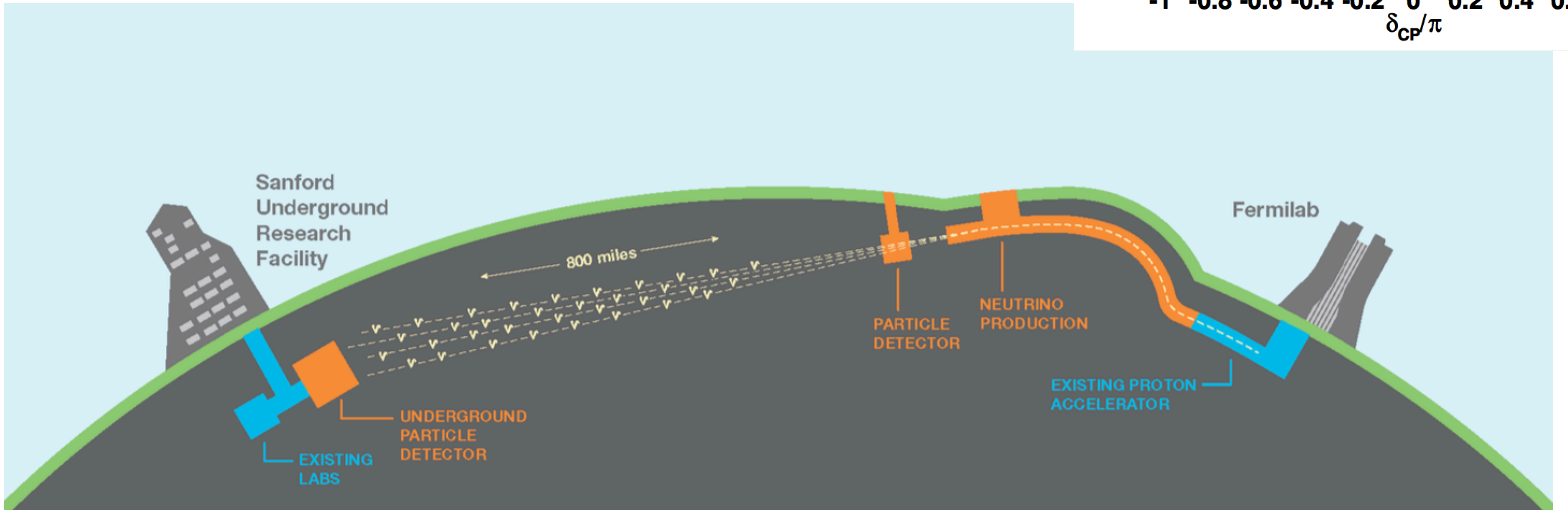
DUNE:

- 1.2 MW neutrino beam from Fermilab (upgradable to 2.4 MW). Wideband, peaking energy ~3 GeV

- Far detector is a 40 kt (fiducial) liquid argon TPC at the Sanford Underground Research Facility (1300 km baseline, on-axis)

- Greater than 3-sigma exclusion of δ=0 for ~70% of its possible values after 7 year run (ending ~2032)





Conclusions

Neutrino physics is entering an exciting era of precision

- sub-10%-level measurements of mixing parameters!

T2K and NOvA show slight preference for Normal Hierarchy, and a tantalizing glimpse of possible maximal CP violation

MicroBooNE and the Fermilab SBN program have the potential to definitively rule out sterile neutrino anomalies, or confirm them!

DUNE has fantastic CP violation discovery potential