Present status of accelerator-based neutrino oscillation measurements

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Why Accelerator Neutrinos

Create ν_μ and $\overline{\nu_\mu}$ beams with enough energy to produce elections, muons and taus (limited) in charged-current interactions

Can study least known mixing parameters by looking at:

$\nu_\mu \rightarrow \nu_e$ appearance

Δm^2_{32} (Mass Hierarchy), $\sin^2(\theta_{23})$ (octant), δ_{CP}

$\nu_\mu \rightarrow \nu_\mu$ disappearance

$|\Delta m^2_{32}|, \sin^2(2\theta_{23})$

$\nu_\mu \rightarrow \nu_\tau$ appearance (OPERA observed)

$|\Delta m^2_{32}|, \sin^2(2\theta_{23})$

Test of unitarity by probing $U_{\tau 3}$

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

$$U = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Can look for sterile neutrinos:

$\nu_\mu \rightarrow \nu_e$ appearance (at 4th Δm^2)

$\sin^2(\theta_{24})\sin^2(2\theta_{14})$

$\nu_\mu \rightarrow \nu_\mu$disappearance (at 4th Δm^2) in CC and/or NC interactions

$\sin^2(\theta_{24}), \sin^2(\theta_{34})$

Long-baseline experiments

Long-baseline experiments operating in 2016

T2K (Japan)

Currently running, data collection started in 2010

NOvA (USA)

Currently running, data collection started in 2014

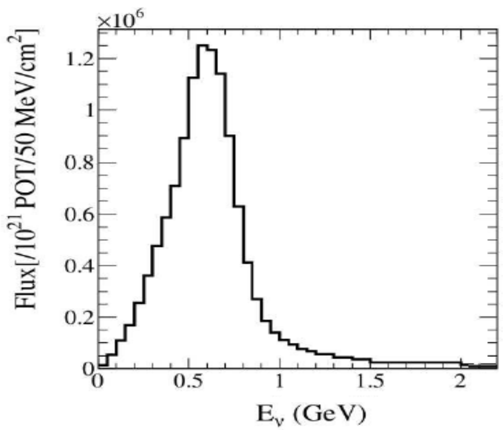
MINOS/MINOS+ (USA)

Data collection stopped in middle of 2016

T2K Experiment

295 km baseline

Beam Energy ~0.6 GeV



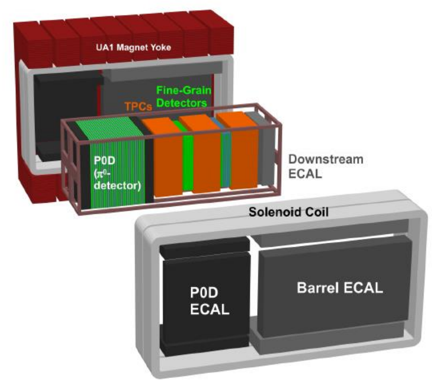
FD Water Cherenkov Detector

ND on-axis and off-axis detectors to reduce flux and cross-section uncertainties

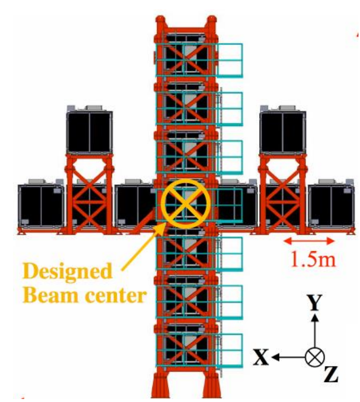
Recorded ~20% of planned data set

- **7.48e20 POT with ν beam**
- **7.47e20 POT with $\bar{\nu}$ beam**

Off-axis Detector



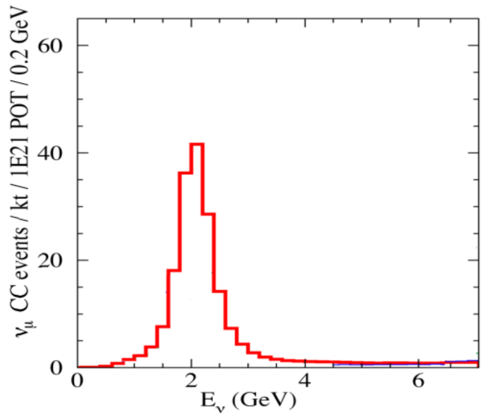
On-axis Detector



NOvA Experiment

810 km baseline

Beam Energy ~2 GeV



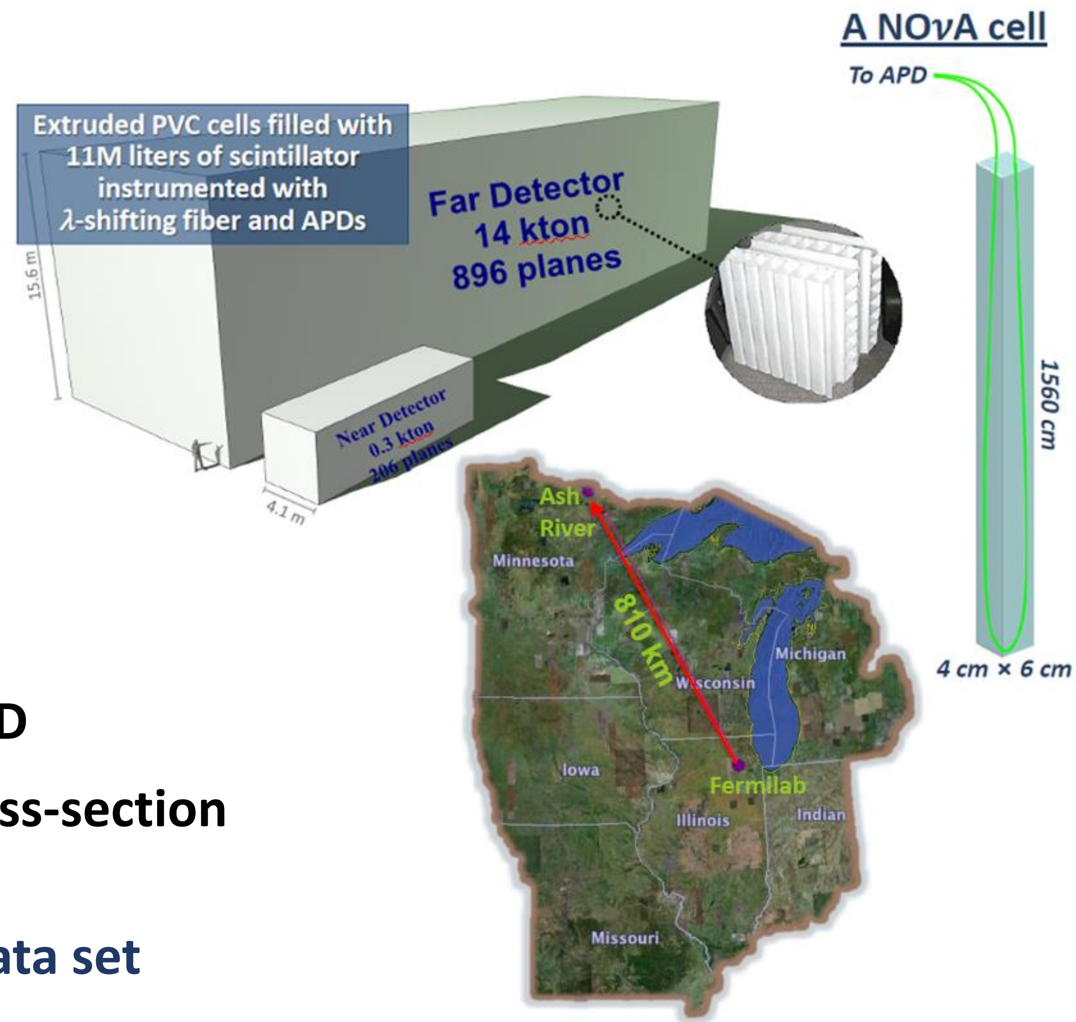
Liquid scintillator detectors

Functionally identical FD & ND

ND detector reduces flux, cross-section and selection uncertainties

Recorded ~20% of planned data set

6.05e20 POT with ν beam

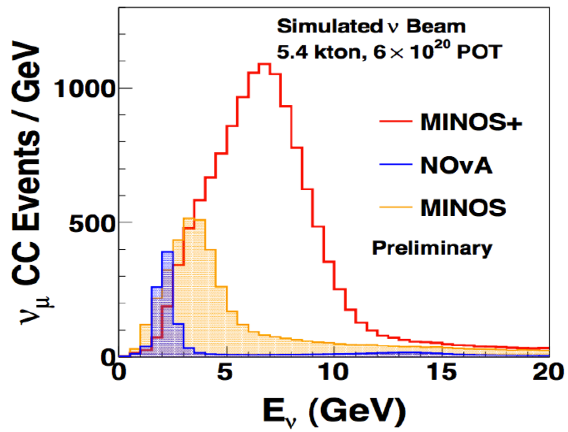


MINOS Experiment

735 km baseline

MINOS Beam Energy: ~3 GeV

MINOS+ Beam Energy: ~7 GeV



Tracking calorimeter detectors

Functionally identical FD & ND

ND detector reduces flux, cross-section and selection uncertainties

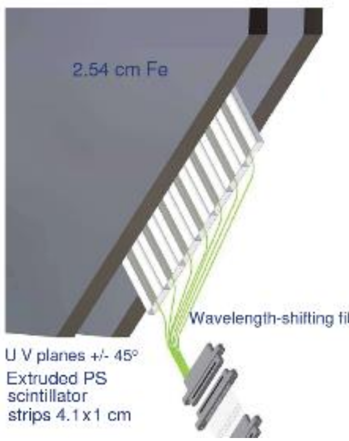
10.6e20 POT with MINOS ν beam

3.4e20 POT with MINOS $\bar{\nu}$ beam

~10e20 POT (~ $^1/_2$ analyzed) with MINOS+ ν beam

Far Detector

Near Detector



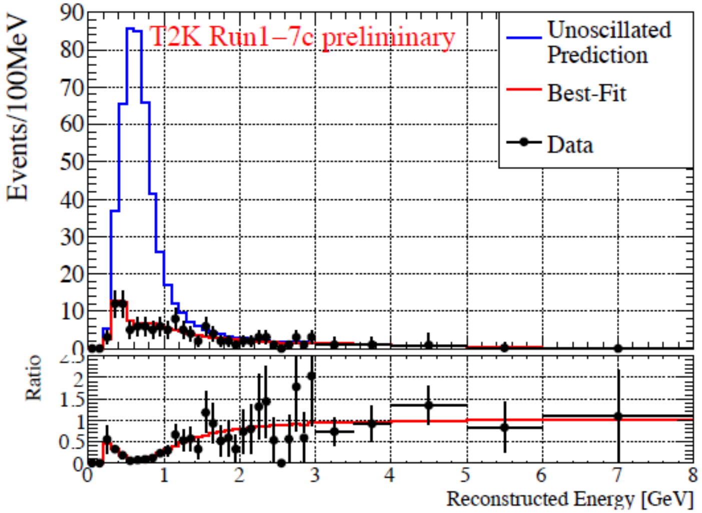
Measurements of θ_{23} and $|\Delta m^2_{32}|$

Muon Neutrino Disappearance

Measurements of θ_{23} and $|\Delta m^2_{32}|$

T2K fit to $\nu_\mu \rightarrow \nu_\mu$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_\mu}$ disappearance

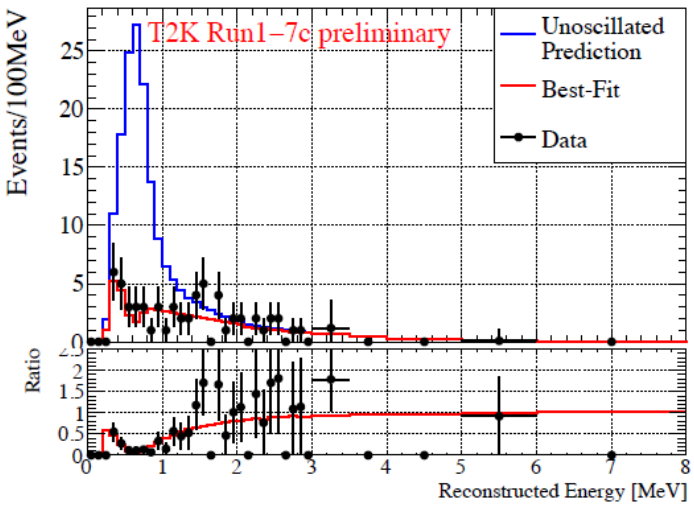
Neutrino



$$\Delta m^2_{32} = [2.34, 2.75]\times 10^{-3} eV^2 (NH) \text{ at 90\% CL}$$

$$\sin^2\theta_{23} = [0.42, 0.61](NH) \text{ at 90\% CL}$$

Antineutrino



$$\Delta \overline{m}^2_{32} = [2.16, 3.02]\times 10^{-3} eV^2 (NH) \text{ at 90\% CL}$$

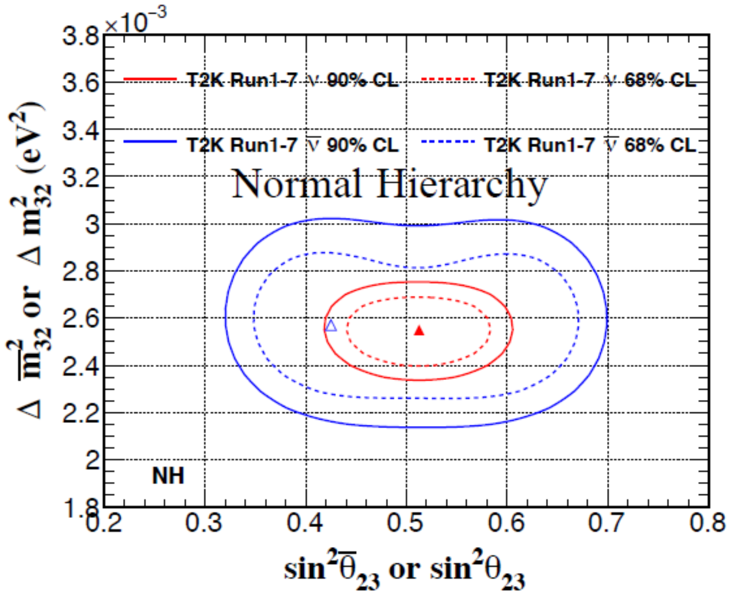
$$\sin^2\overline{\theta}_{23} = [0.32, 0.70](NH) \text{ at 90\% CL}$$

Neutrino and antineutrino parameters are consistent

No evidence of CPT violation, NSI, etc

Measurements of θ_{23} and $|\Delta m^2_{32}|$

T2K fit to $\nu_\mu \rightarrow \nu_\mu$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_\mu}$ disappearance



Neutrino sample best fit prefers maximal disappearance

Anti-neutrino best fit prefers non-maximal value

Normal Hierarchy

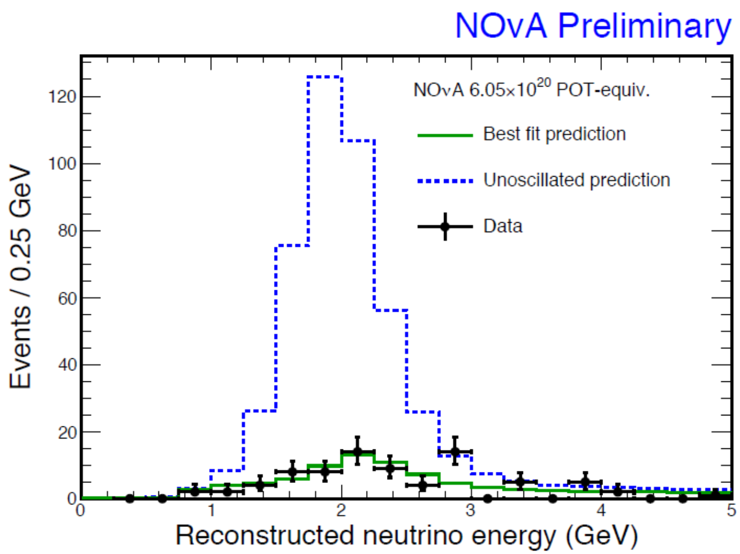
Joint Fit Results:

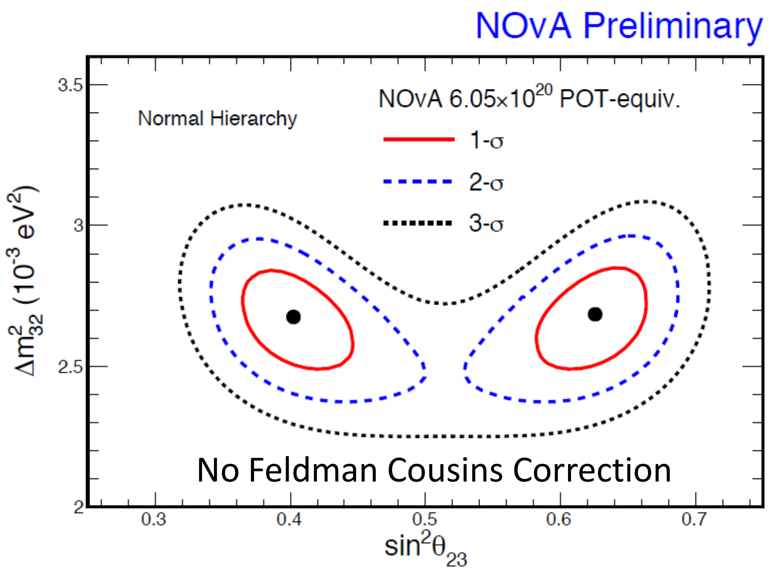
$$\sin^2\theta_{23} = 0.532^{+0.046}_{-0.068}$$

$$\Delta m^2_{32} = 2.545^{+0.081}_{-0.084} \times 10^{-3} eV^2$$

Measurements of θ_{23} and $|\Delta m^2_{32}|$

NOvA fit to $\nu_\mu \rightarrow \nu_\mu$ disappearance





NOvA excludes maximal mixing at 2.5σ (no Feldman Cousins correction)

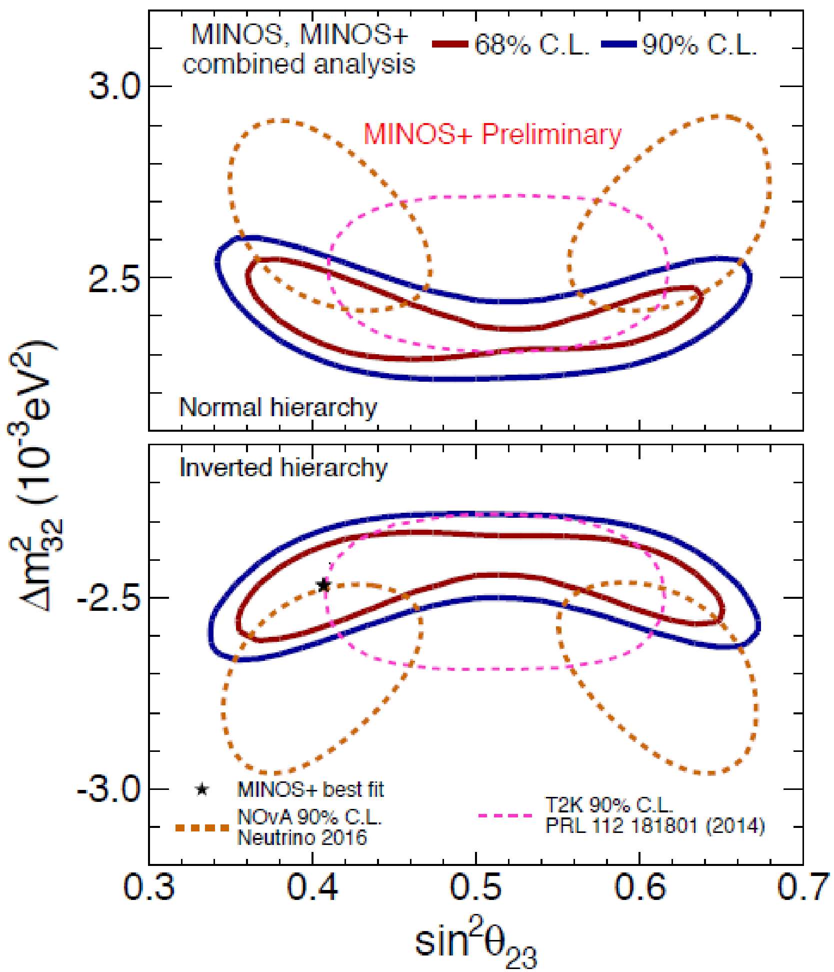
Normal Hierarchy

$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}\ (0.63^{+0.02}_{-0.03})$$

$$\Delta m^2_{32} = 2.67^{+0.12}_{-0.12}\ \times 10^{-3} eV^2$$

Measurements of θ_{23} and $|\Delta m^2_{32}|$

MINOS/MINOS+ beam and atmospheric fit to $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$



MINOS best fit value of $\sin^2(\theta_{23})$ comparable to NOvA but results also consistent with max mixing

$$\Delta m^2_{32} = \begin{cases} 2.42 \pm 0.09 \times 10^{-3}\,\mathrm{eV}^2 & \text{Normal} \\ -2.48^{+0.09}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2 & \text{Inverted} \end{cases}$$

$$\sin^2(\theta_{23}) = \begin{cases} 0.35\text{–}0.65\,(90\%\ \text{C.L.}) & \text{Normal} \\ 0.35\text{–}0.66\,(90\%\ \text{C.L.}) & \text{Inverted} \end{cases}$$

MINOS still competitive and still has ~ ½ of the MINOS+ data to analyze

Measurements of θ_{23} octant, mass hierarchy, and δ_{CP}

Electron Neutrino Appearance

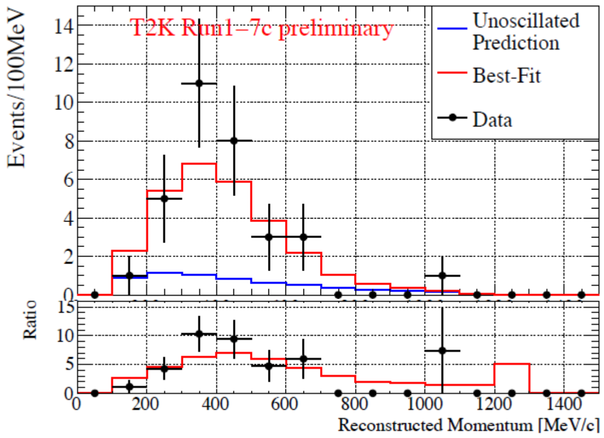
T2K fit to $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ appearance

Predictions:

ν_e: 19.6 events (NH, $\delta_{CP} = \pi/2$) to 28.7 events (NH, $\delta_{CP} = -\pi/2$)

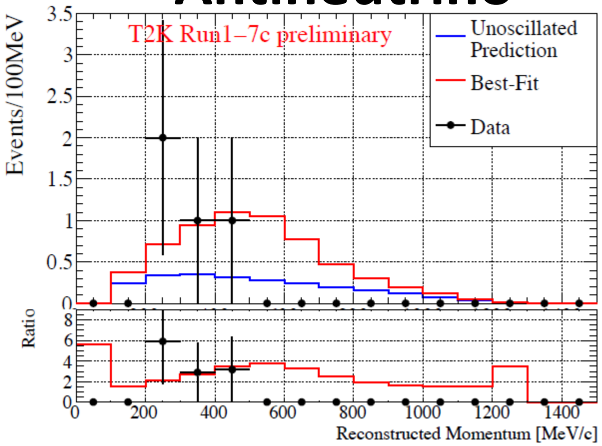
$\overline{\nu_e}$: 7.7 events (NH, $\delta_{CP} = \pi/2$) to 6.0 events (NH, $\delta_{CP} = -\pi/2$)

Neutrino



Observed 32 events

Antineutrino



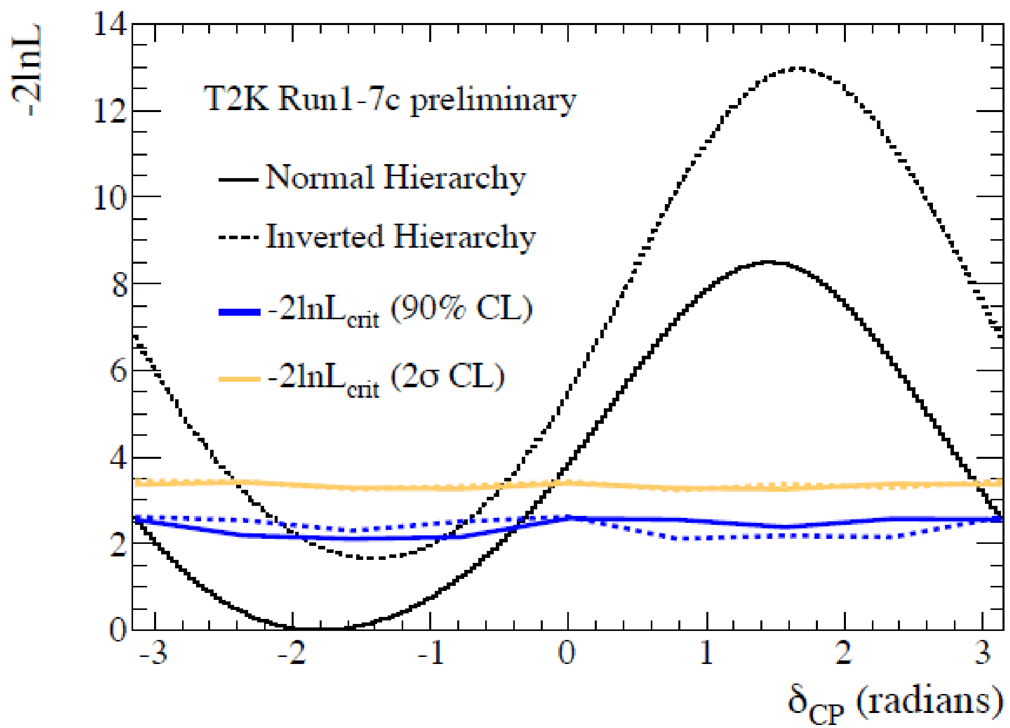
Observed 4 events

Excess of ν_e events above prediction favors NH and $\delta_{CP} = -\pi/2$ ($3\pi/2$)

Deficit of $\overline{\nu}_e$ events below prediction favors NH and $\delta_{CP} = -\pi/2$ ($3\pi/2$)

ν_e Appearance Measurements

T2K fit to $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ appearance

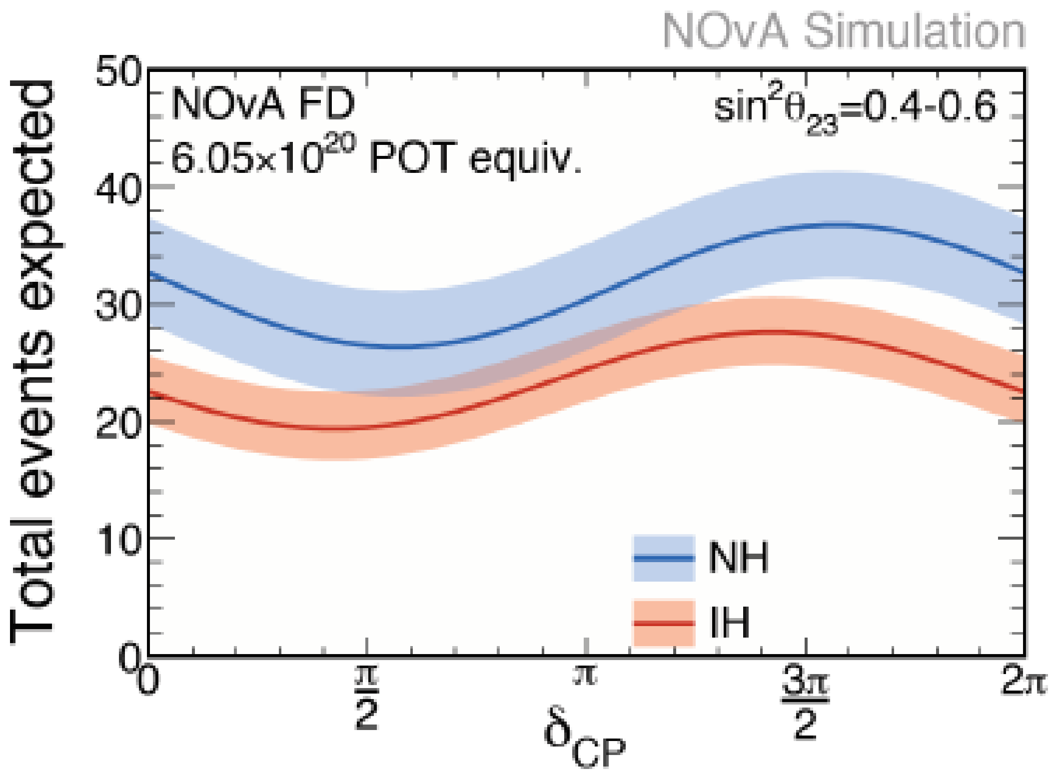


Data excludes CP conservation at 90% CL

Data favors δ_{CP} near $-\pi/2$ ($3\pi/2$) for both hierarchies

$$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH) \text{ at } 90\% \text{ CL}$$

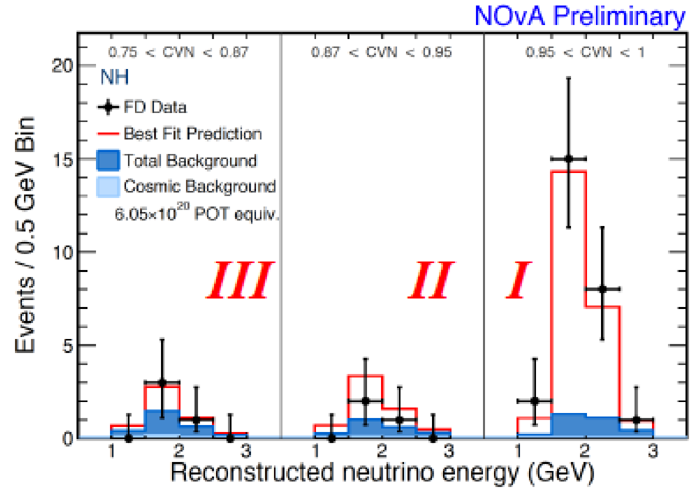
NOvA fit to $\nu_\mu \rightarrow \nu_e$ appearance

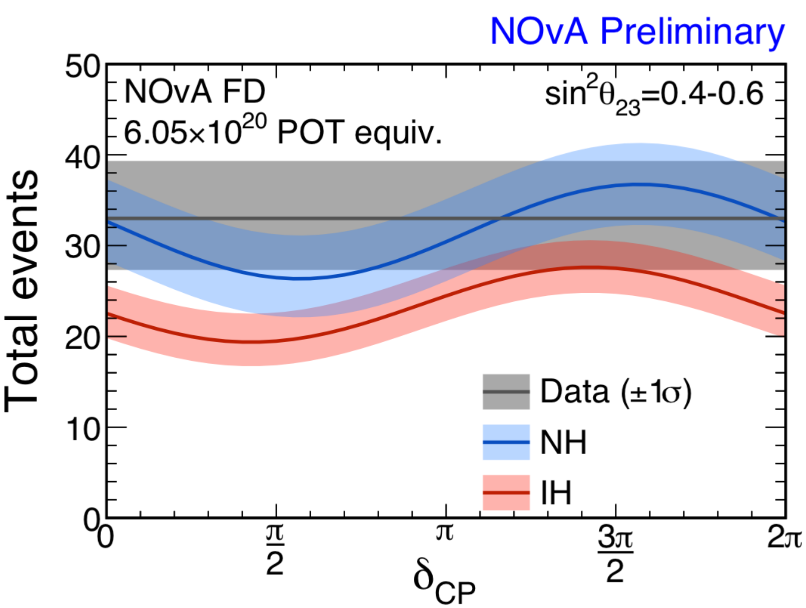


Expected event yields depend on hierarchy, octant of θ_{23}, and δ_{CP}

NOvA fit to $\nu_\mu \rightarrow \nu_e$ appearance

Observe 33 events





Data prefers NH

Similar to T2K trend

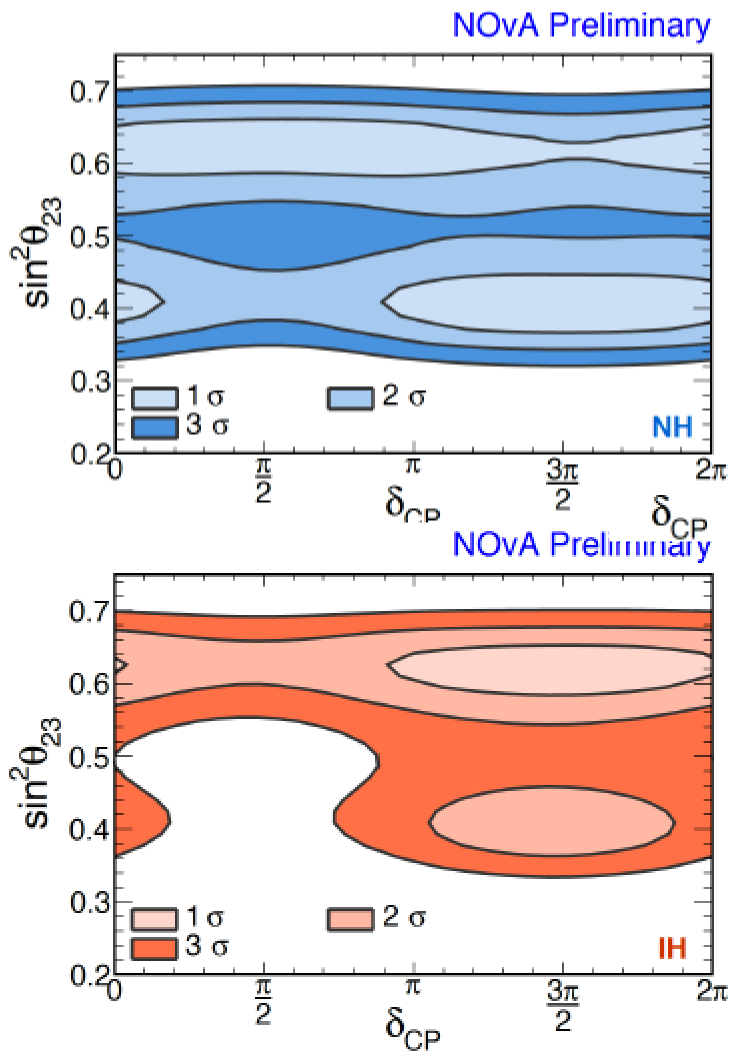
Data only likes IH for upper octant and $\delta_{CP} \approx 3\pi/2$

Similar to T2K trend

Data prefers NH lower octant for $\delta_{CP} \approx 3\pi/2$

Data prefers NH upper octant for $\delta_{CP} \approx \pi/2$

Combining NOvA $\nu_\mu \rightarrow \nu_e$ appearance and $\nu_\mu \rightarrow \nu_\mu$ disappearance



NOvA rejects δ_{CP} around $\pi/2$ for lower octant IH at 3σ

T2K similarly rejects region at 3σ

Sterile Neutrino Search

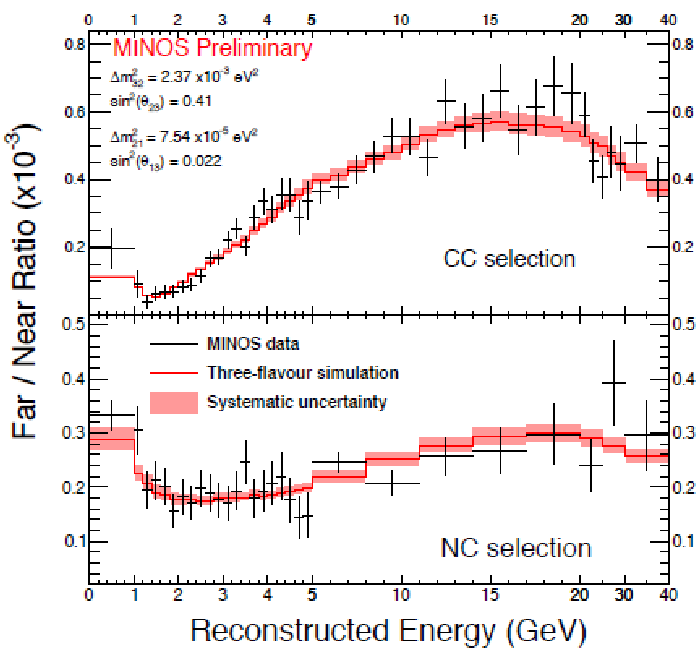
Sterile Neutrino Search

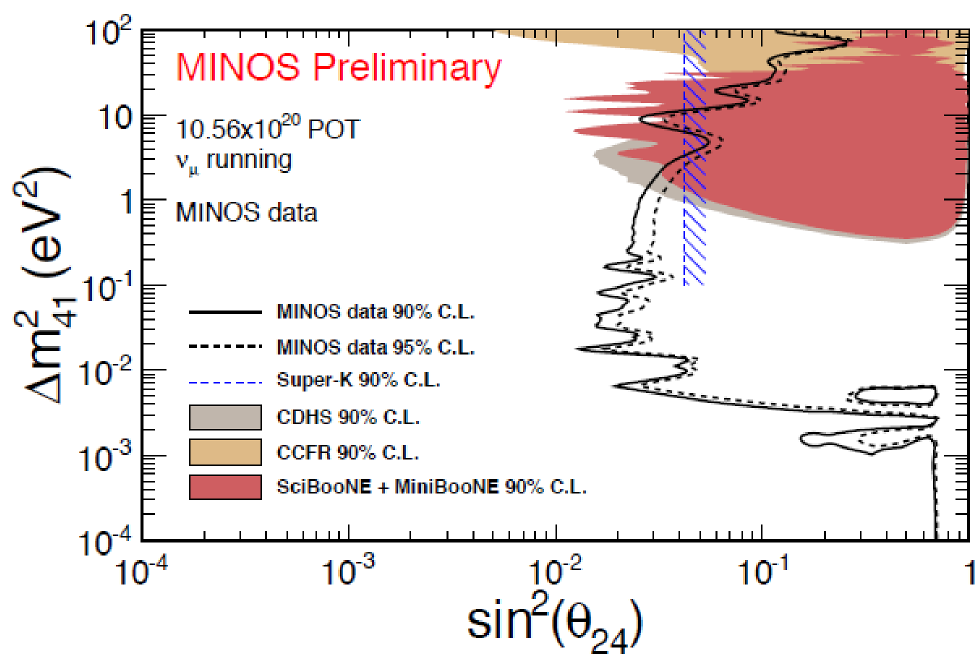
MINOS has searched for sterile mediated $\nu_\mu \rightarrow \nu_\mu$ disappearance in CC and NC events

Take into account potential oscillation in the ND and FD

Observed disappearance rate is consistent with 3-flavor model

Set limits on θ_{24}





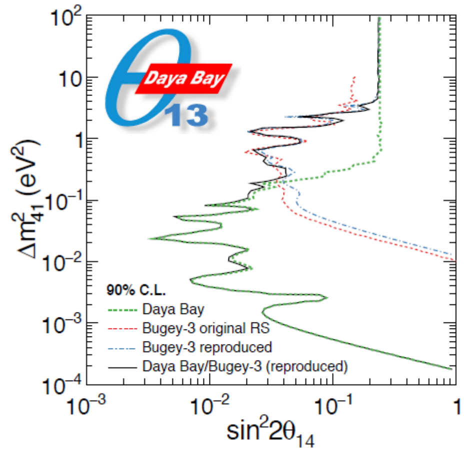
However LSND-style appearance in a 4-flavor model depends on:

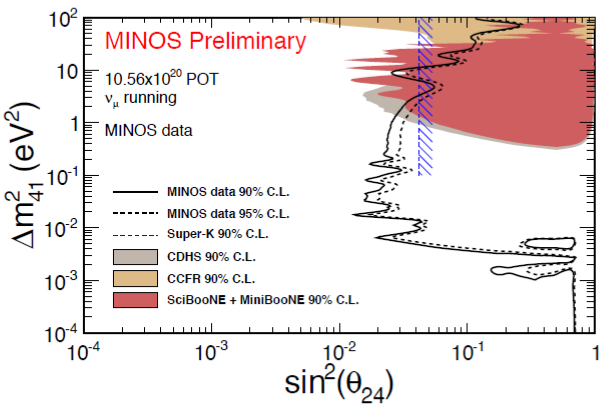
$$\sin^2\theta_{\mu e} \equiv \sin^2\theta_{24}\sin^2 2\theta_{14}$$

Need constraint on θ_{14}

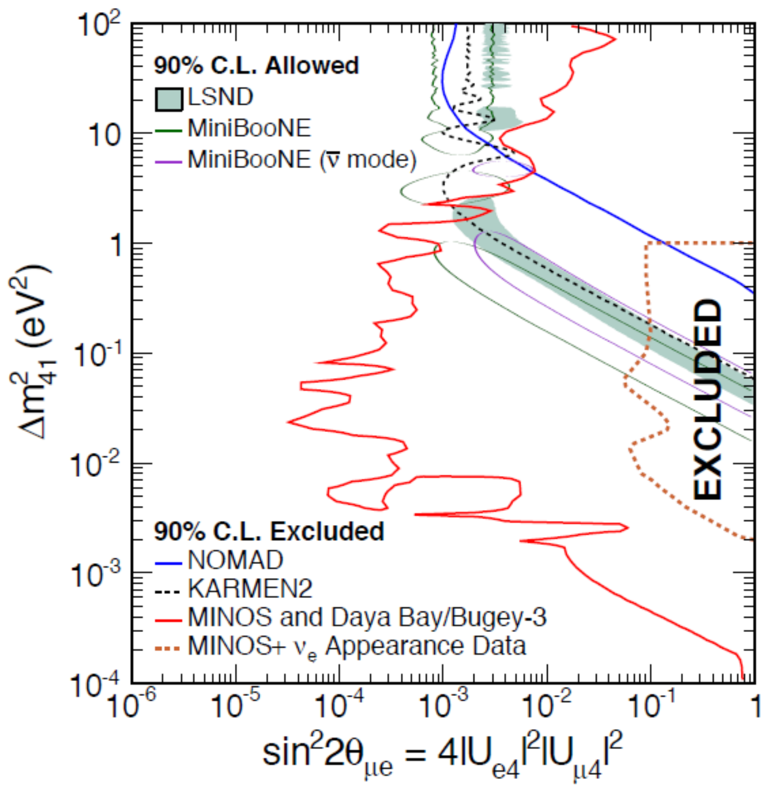
Sterile Neutrino Search

Potential sterile mediated $\overline{\nu_e} \rightarrow \overline{\nu_e}$ disappearance measured in reactor experiments are sensitive to θ_{14}





Combine
Daya Bay
&
MINOS



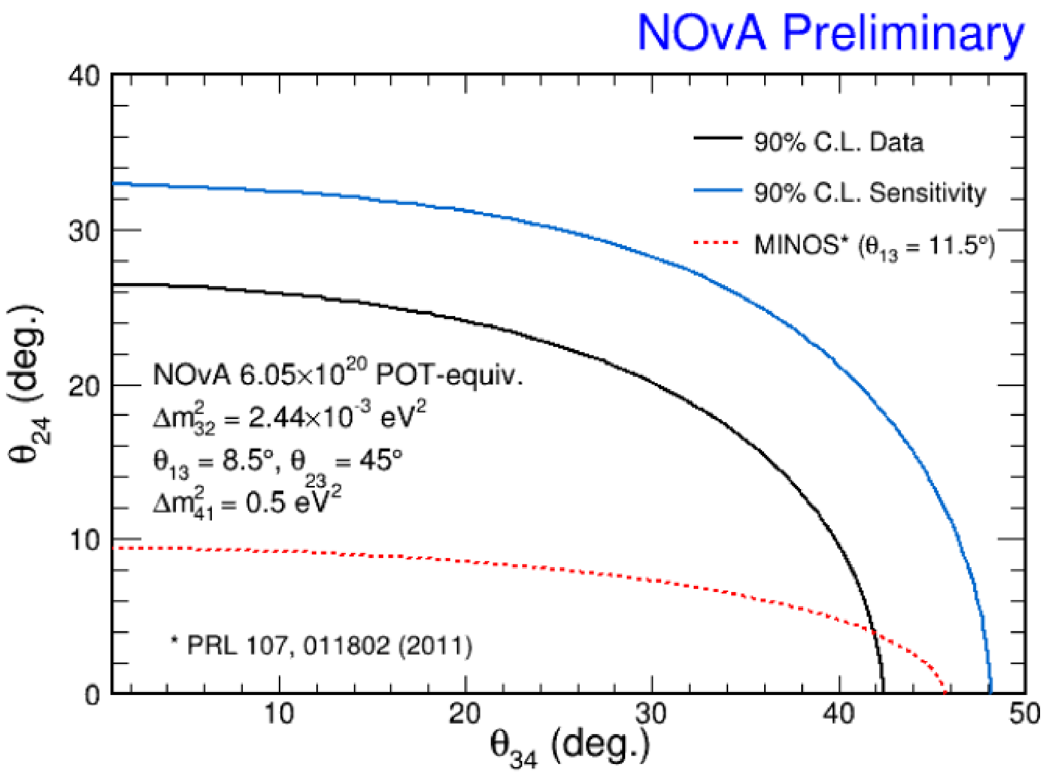
Sterile Neutrino Search

NOvA has searched for sterile mediated $\nu_\mu \rightarrow \nu_\mu$ disappearance in NC events

Observe 95 NC-like events when they expect 83.71 ± 9.15 (stat) ± 8.28 (syst)

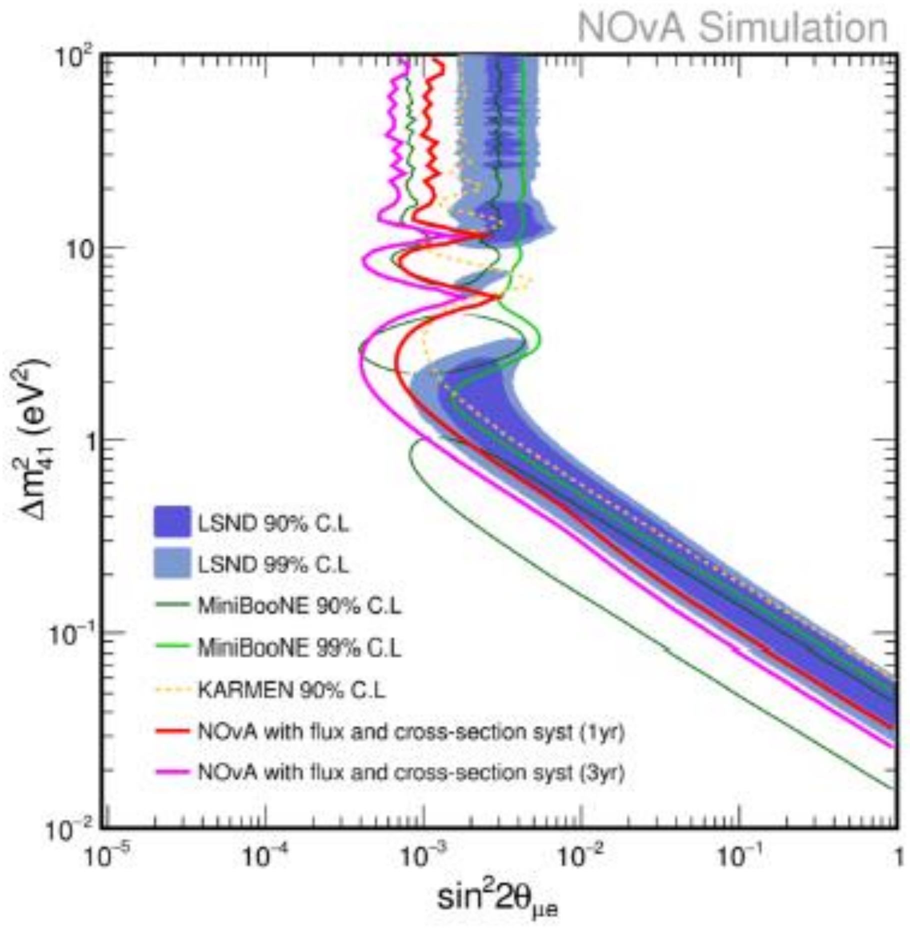
Observed disappearance rate is consistent with 3-flavor model

Set limits on θ_{24}, θ_{34}



Sterile Neutrino Search

NOvA is expected to have a future sensitivity that can probe LSND signal at 90% CL



Summary

Current long-baseline program is making interesting measurements

Indications that θ_{23} may be nonmaximal (mainly NOvA)

Indications that δ_{CP} may be around $-\pi/2$ ($3\pi/2$) (NOvA and T2K)

Indications that there might be a normal hierarchy (NOvA and T2K)

Long baseline experiments don’t see LSND-like 4-flavor mixing (mainly MINOS)

T2K and NOvA only have less than 20% of their proposed data set

Back up slides

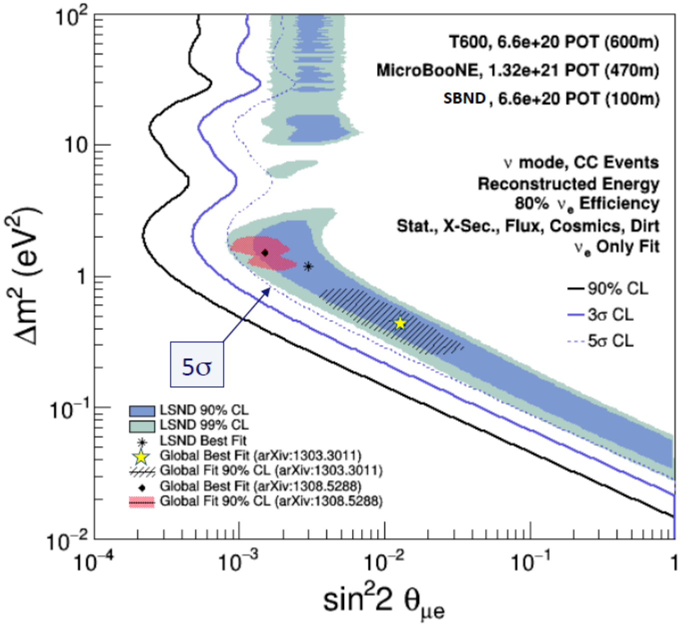
Short-baseline experiments

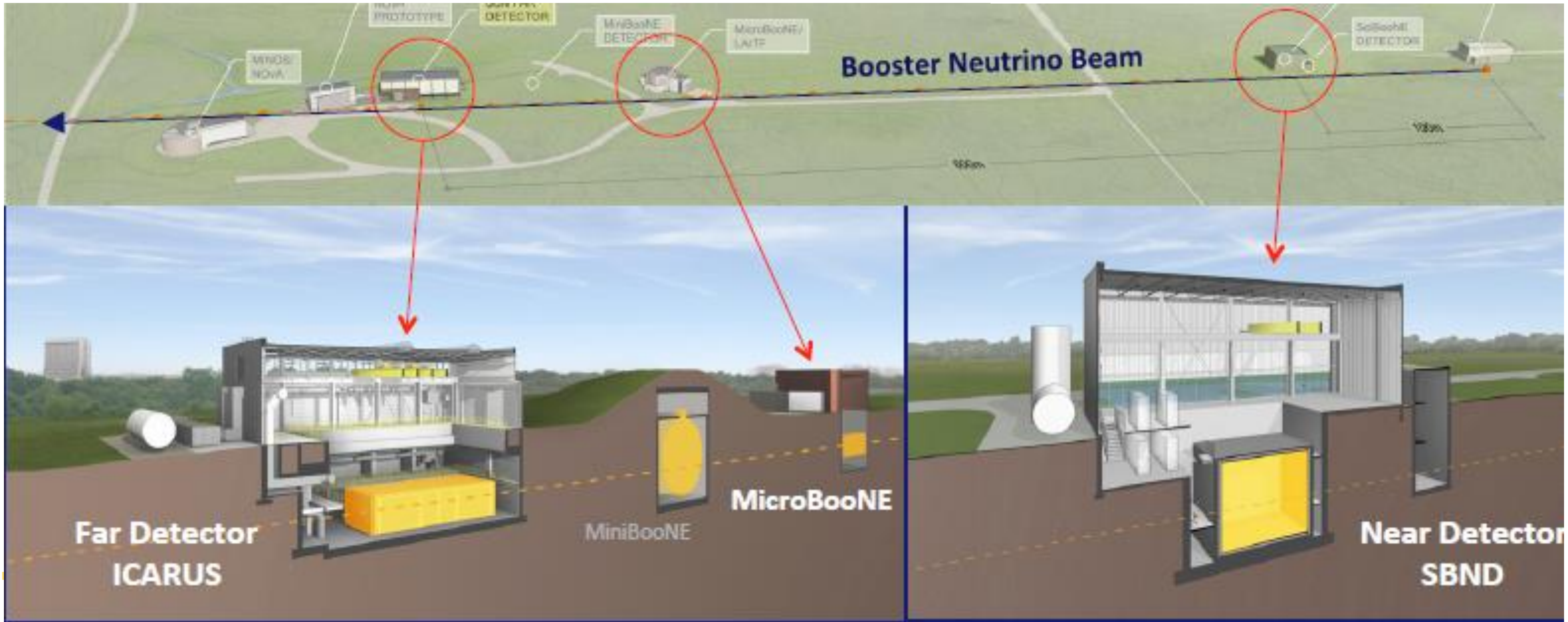
Fermilab short-baseline neutrino program

Look for sterile mediated oscillation

Liquid Argon detectors

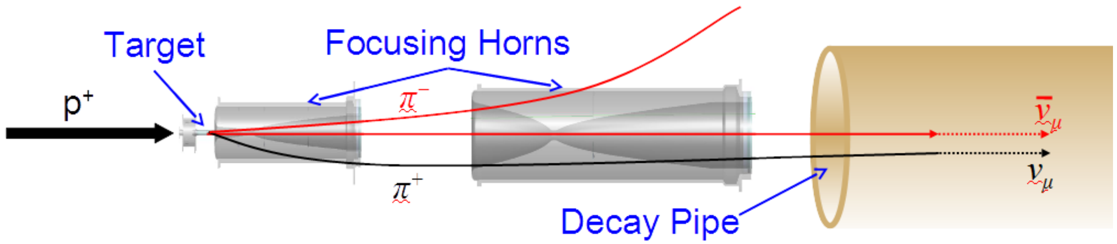
- SBND: L=110m, M=112 ton (under construction)
- MicroBooNE: L= 470m, M=87 ton (started Oct 2015)
- ICARUS: L= 600m, M=476 ton (under construction)



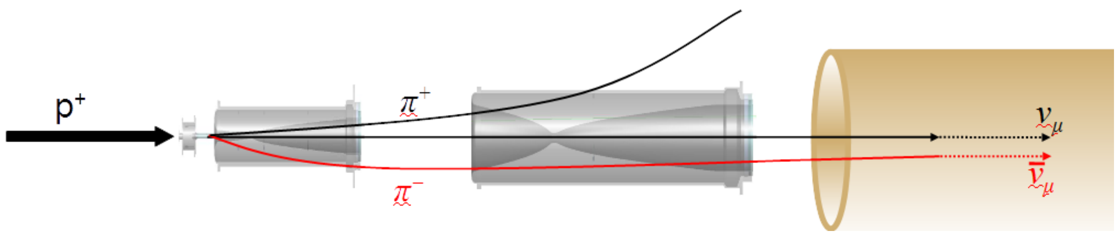


How to make a beam

Collide proton on a target, magnetically focus secondary particles into a beam, and let them decay into neutrinos



Magnet polarity determine if neutrino or antineutrino beam



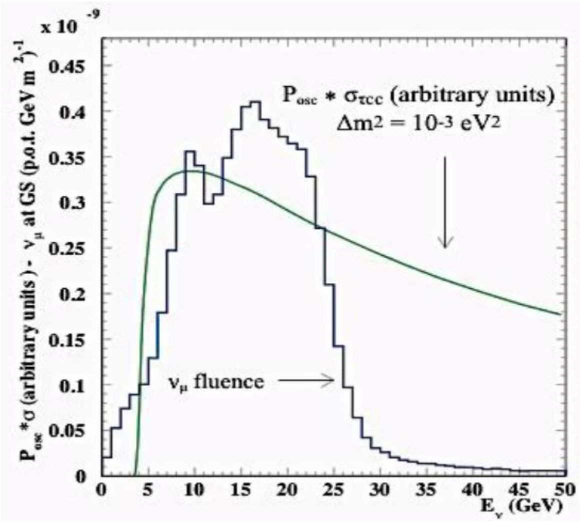
Control beam energy by magnetic focusing and angle w.r.t. axis

Current experiments use around GeV-scale beams

Opera Experiment

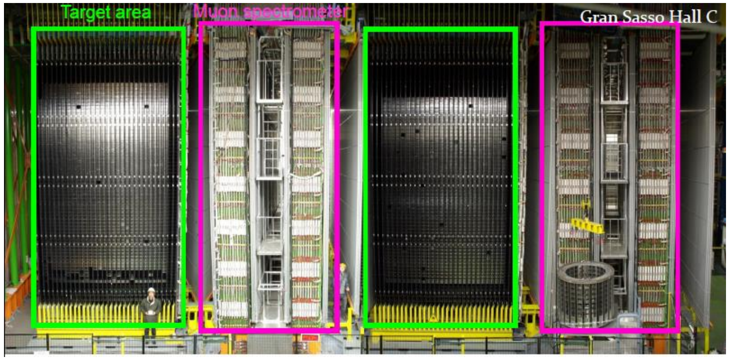
730 km baseline

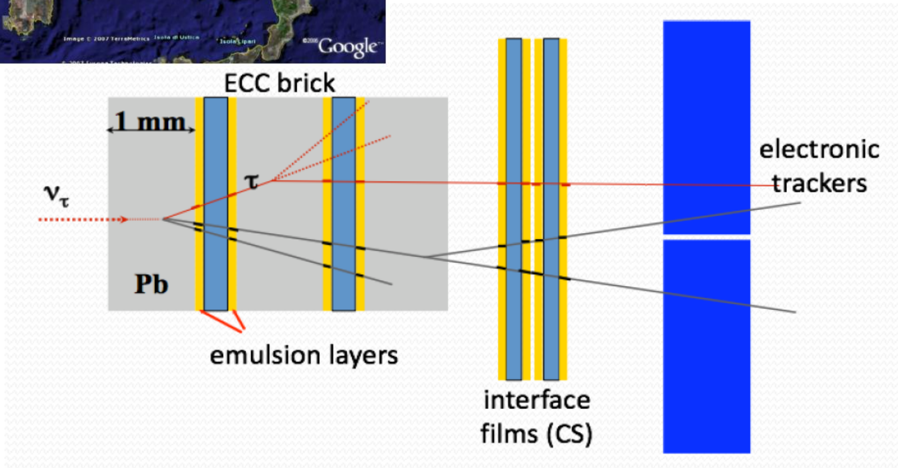
Beam Energy ~17 GeV



Emulsion cloud chamber
& electronic tracker

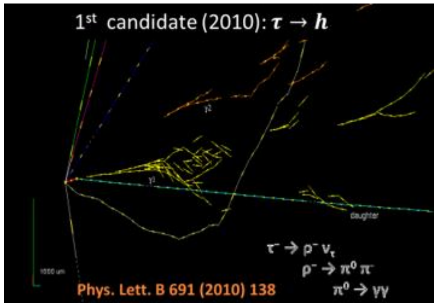
Can see $\nu_\mu \rightarrow \nu_\tau$ appearance

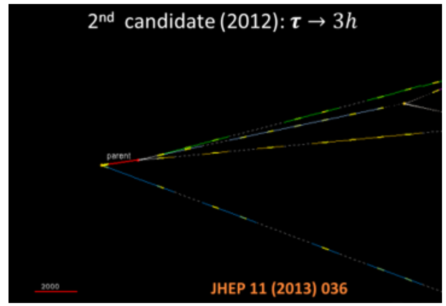


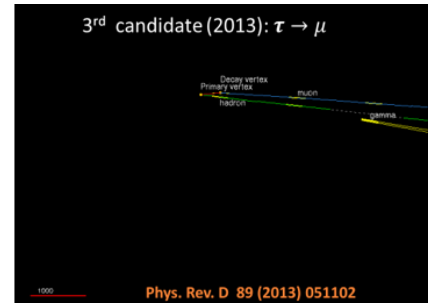


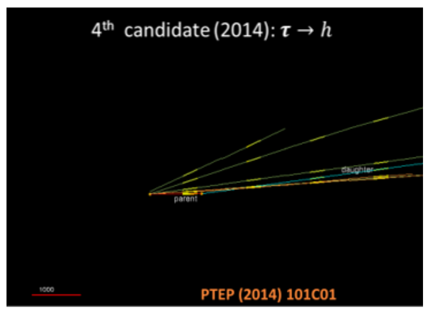
Measurement of ν_τ appearance

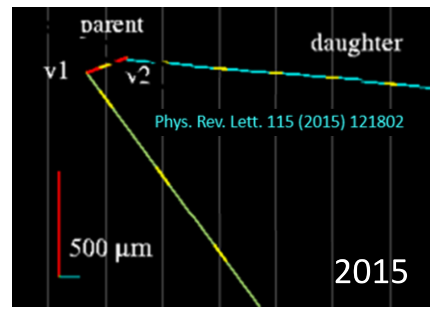
OPERA measurement of $\nu_\mu \rightarrow \nu_\tau$ appearance











OPERA sees 5 τ candidate events

with a background of 0.25 ± 0.05

5σ discovery of ν_τ appearance

Measurement of Δm^2_{32} consistent with other experiments
$2.0 \times 10^{-3}\ \text{eV}/^2 < |\Delta m^2_{32}| < 5.0 \times 10^{-3}\ \text{eV}/^2$ at 90% CL