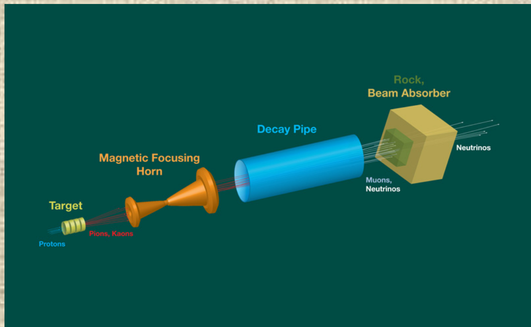
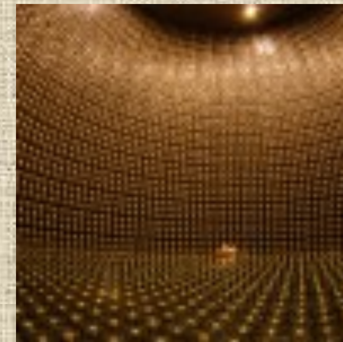
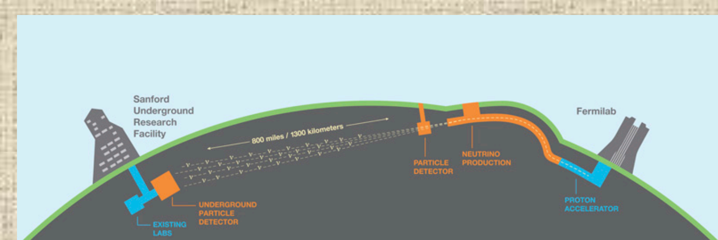




The world of accelerator neutrinos

Dr. Anna Holin
University College London
IOP HEPP 2016, 22.03.2016



Introduction

- Neutrino oscillations and mysteries left to discover
- How do we make a neutrino beam?
- Current accelerator neutrino experiments, with some atmospheric neutrinos as well
- Future accelerator neutrino experiments
- Summary

- Apologies for any experiments missed out due to limited time (e.g. ICECUBE, PINGU, ultra-high-energy neutrinos and others)!

Neutrinos

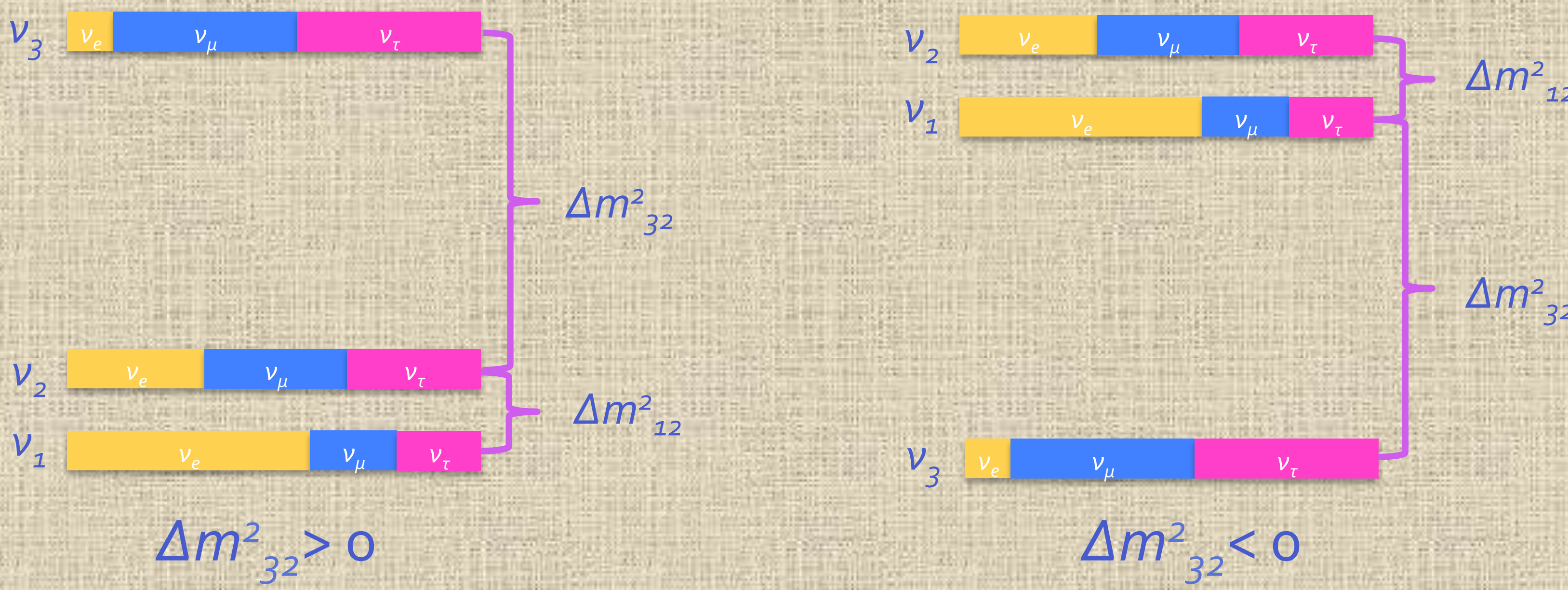
- Three active flavours of neutrino: ν_e, ν_μ, and ν_τ
- Only definite sign of physics beyond the Standard Model as they oscillate between flavours as they propagate through space and matter -> they must have mass!

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

- 3 oscillation mixing angles, 1 CP-violating phase
- 2 independent mass differences for standard oscillations

Neutrino oscillations: NOBEL PRIZE 2015!
for Takaaki Kajita from Super-K and Arthur McDonald from SNO

Neutrinos



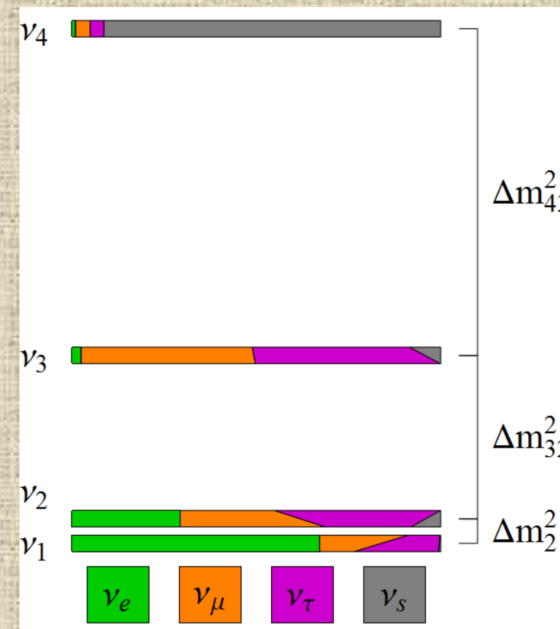
- Two possible mass hierarchies – which mass eigenstate is the heaviest?
- Affects neutrino oscillation probabilities

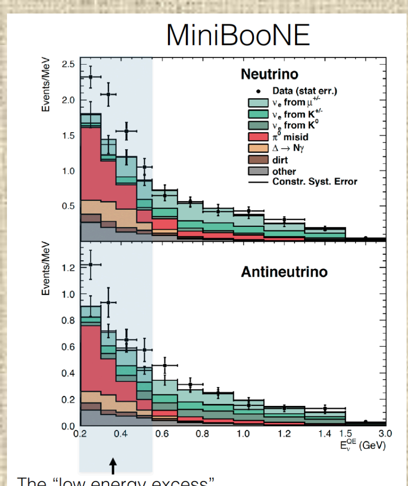
Mysteries we want to uncover

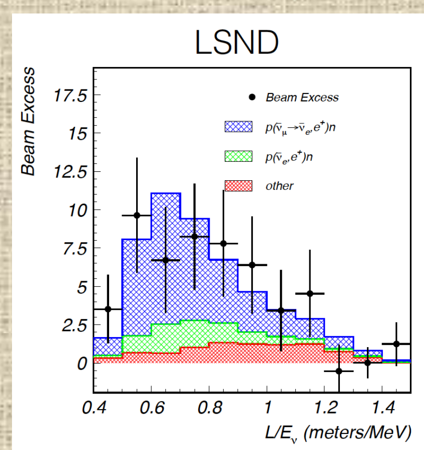
- What is the neutrino mass hierarchy? Implications for lepton generation ordering questions and also neutrinoless double-beta decay
- Is there CP-violation in the neutrino sector, i.e. $\delta_{CP} \neq 0$?
- Are there sterile neutrinos?
- What is the neutrino mass?
- Is the neutrino Dirac or Majorana?
- What is the precise value of ϑ_{23}? Is this mixing angle maximal?
- How much do neutrinos contribute to dark matter?
- Are there undiscovered neutrino behaviours/mysteries?

Sterile Neutrinos

- Are there sterile neutrinos?
- Some hints from data, e.g. LSND, MiniBooNE
- Simplest model is 3+1
- There are alternative explanations for some of the excesses seen (e.g. could MiniBooNE just have underestimated the π^0 background?)
- Experiments continue to investigate

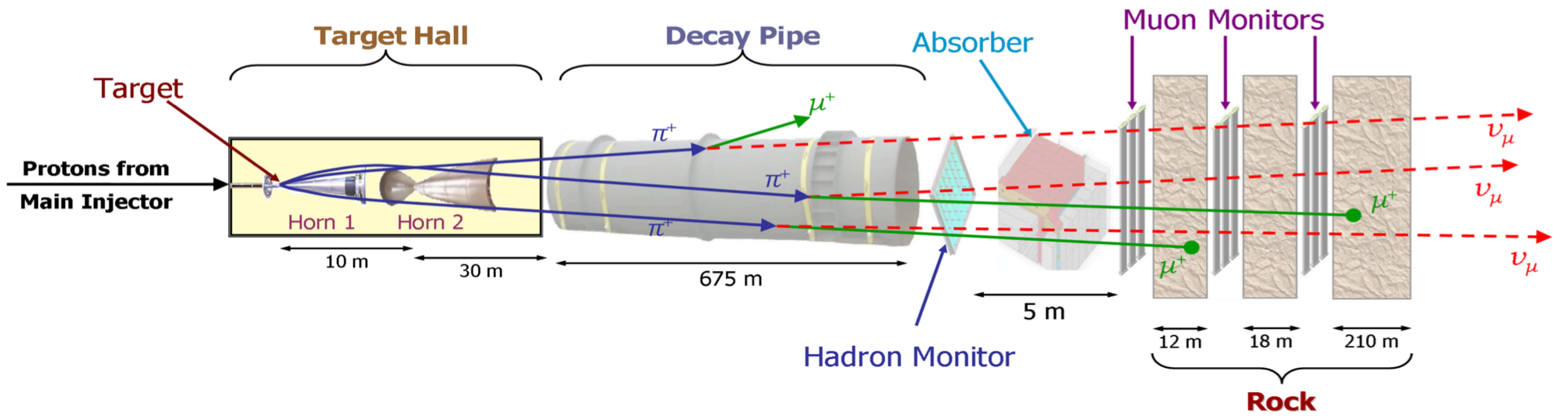






$$
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}
$$

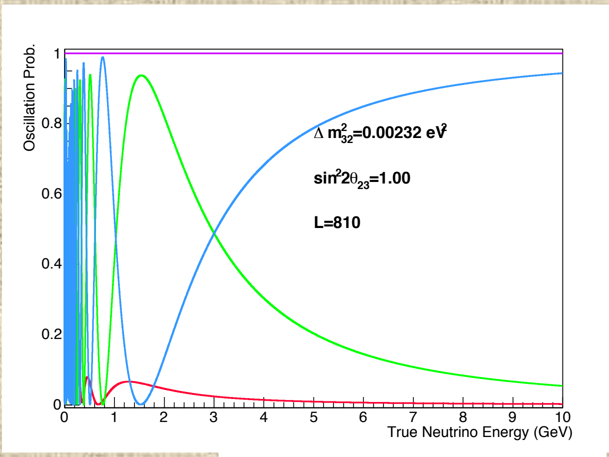
How do we make a neutrino beam

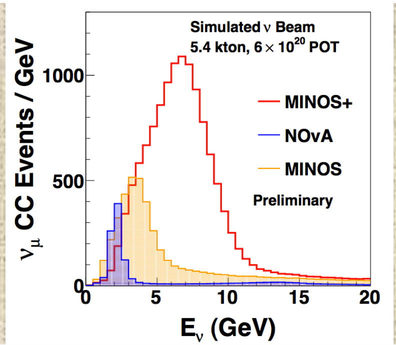


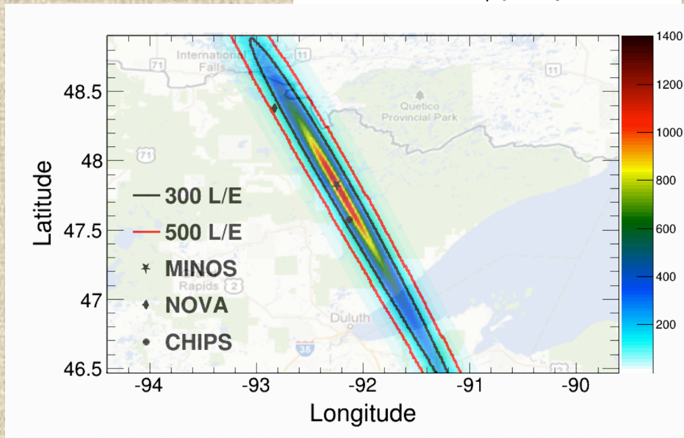
- Impact protons onto target to generate hadrons (mostly pions and kaons)
- Focus those with magnetic horns
- Hadrons then decay in a long pipe into mostly muons and neutrinos
- Those and any remaining protons absorbed by hadron absorber and rock
- Only neutrinos are left in the beam to traverse the earth and detectors

Some comments on neutrino beams

- Neutrino beams are normally dominated by ν_μ
- Those then oscillate away into ν_e and ν_τ as they traverse the earth – this depends on the real oscillation parameters
- There are several ways to adjust neutrino beams for our measurements:
  - Position of target with respect to the horns selects whether higher or lower momentum hadrons are focused and is the primary driver of the on-axis beam energy
  - We can position our detectors off-axis to sample a narrow-band lower energy neutrino spectrum
  - We can reverse the horn current to focus negatively charged hadrons instead to get an anti-neutrino dominated beam instead - but lower flux is the price



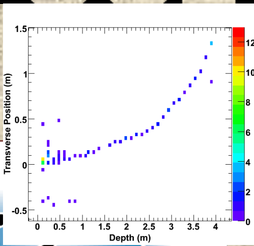


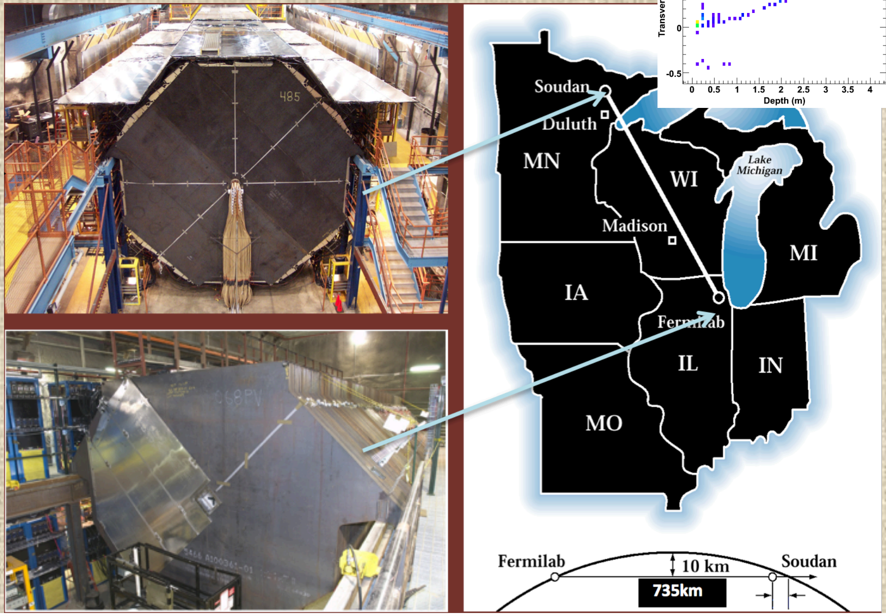


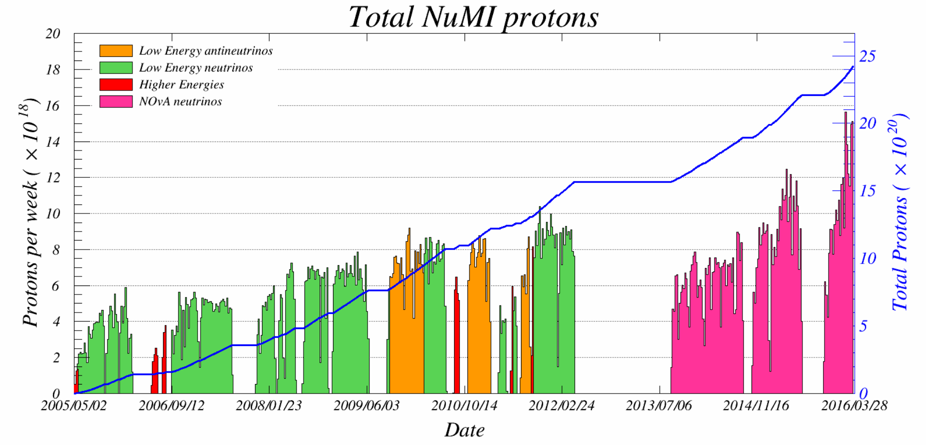
Current Experiments

MINOS/+

- Functionally identical iron scintillator calorimeters, magnetised to bend muon tracks
- A 1kT Near detector measures neutrino spectrum 1km away from the NuMI beam source at FNAL, before oscillations
- A 5.4kT Far detector measures neutrino spectrum 735km away from FNAL, in the Soudan Mine, MN, after neutrinos have traversed the Earth and oscillated
- MINOS taking beam data since mid 2005, and as MINOS+ since Sep. 2013
- MINOS/+ will finish taking data forever this coming June
- only wideband on-axis experiment
- Many measurements have come out of MINOS, some analyses still to come
- Currently NuMI beam running at highest power ever of ~520kW
- Hope to see good data before MINOS+ finish

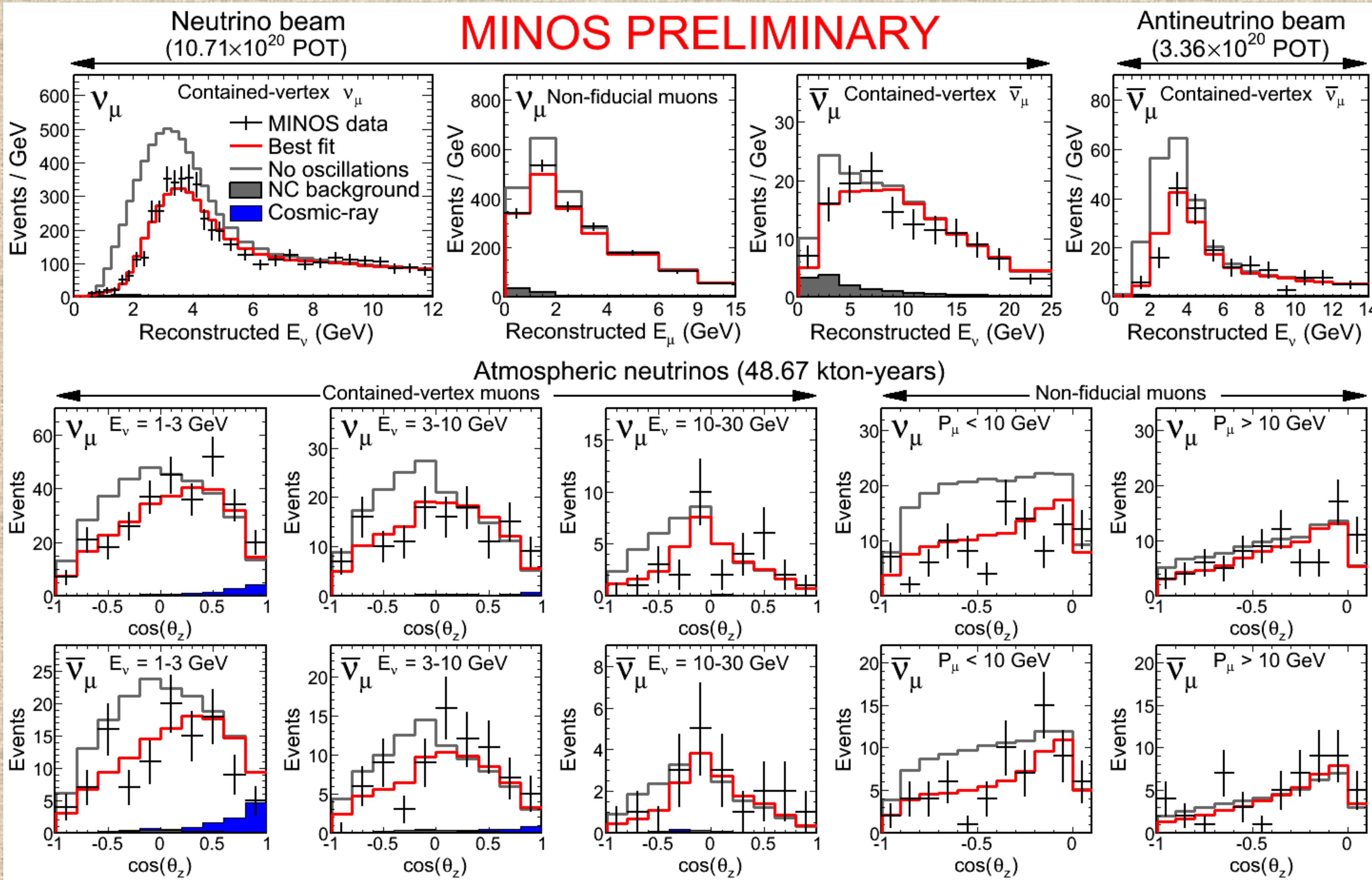






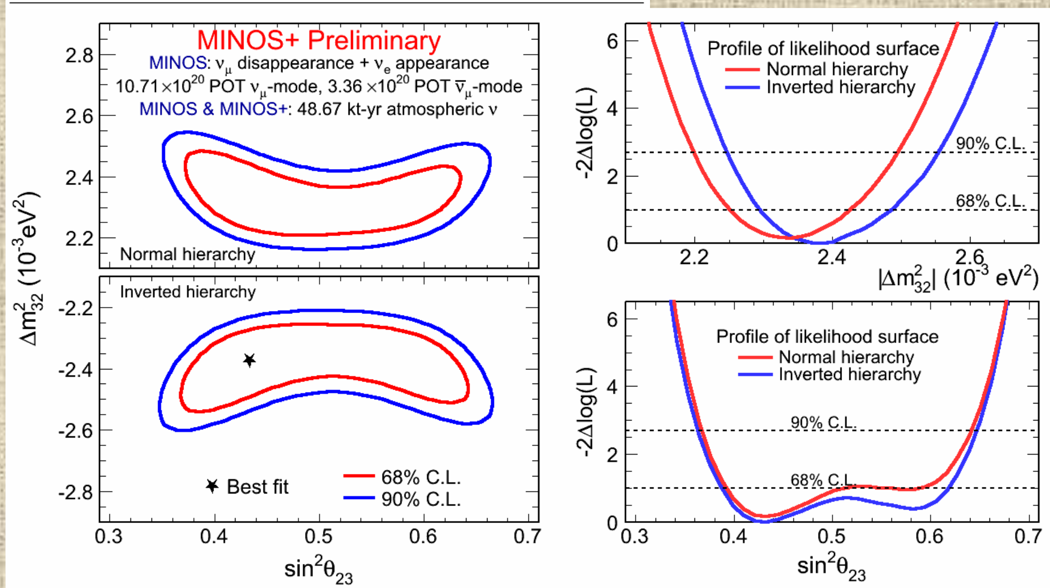
MINOS 10.71x1020 POT neutrino mode
MINOS 3.36x1020 POT in anti-neutrino mode
MINOS+ >8x1020 POT in neutrino mode so far

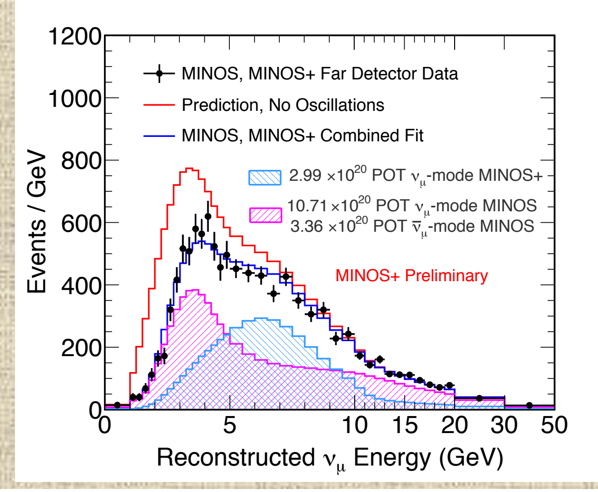
MINOS/+


Neutrino beam
(10.71×10^20 POT)
MINOS PRELIMINARY
Antineutrino beam
(3.36×10^20 POT)
Contained-vertex νμ
MINOS data
Best fit
No oscillations
NC background
Cosmic-ray
Non-fiducial muons
Events / GeV
Reconstructed Eν (GeV)
Reconstructed Eμ (GeV)
Atmospheric neutrinos (48.67 kton-years)
Contained-vertex muons
Non-fiducial muons
Eν = 1-3 GeV
Eν = 3-10 GeV
Eν = 10-30 GeV
Pμ < 10 GeV
Pμ > 10 GeV
Events
cos(θz)

MINOS/+

Data Set	Simulation No osc.	Simulation With osc.	Events Observed
ν_μ from ν_μ beam	3201	2496	2579
$\bar{\nu}_\mu$ from ν_μ beam	363	319	312
Non-fiducial ν from ν_μ beam	3197	2807	2911
Atm. contained-vertex $\nu_\mu + \bar{\nu}_\mu$	1414	1024	1134
Atm. non-fiducial $\mu^+ + \mu^-$	732	575	590
Atm. showers	932	877	899





World best measurement of Δm^2, prefers IH

Inverted Hierarchy

$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\text{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$

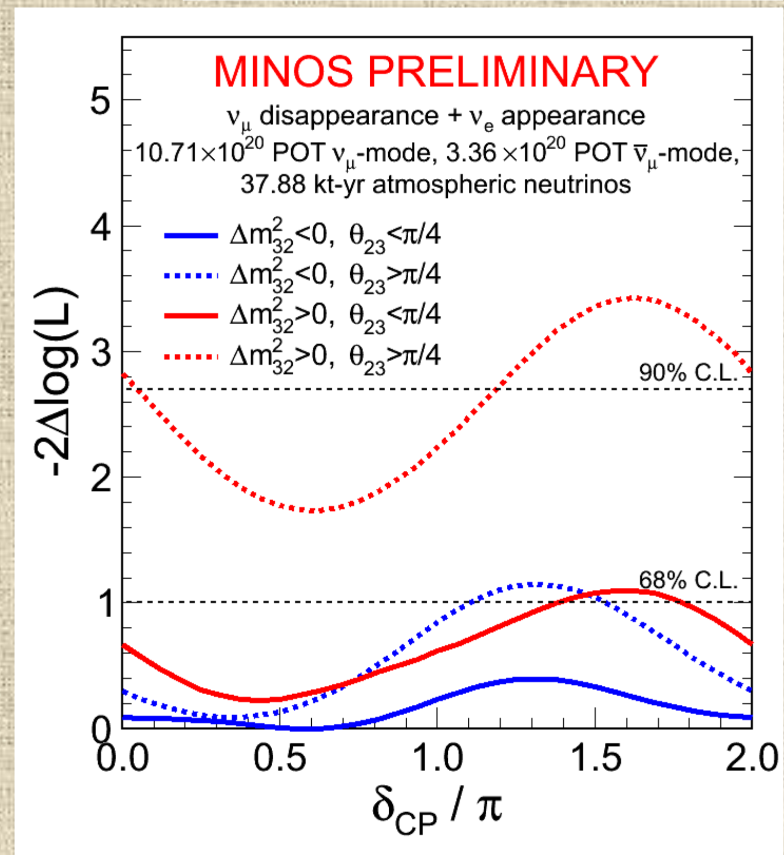
$0.36 < \sin^2\theta_{23} < 0.65$ (90% C.L.)

Normal Hierarchy

$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\text{eV}^2$

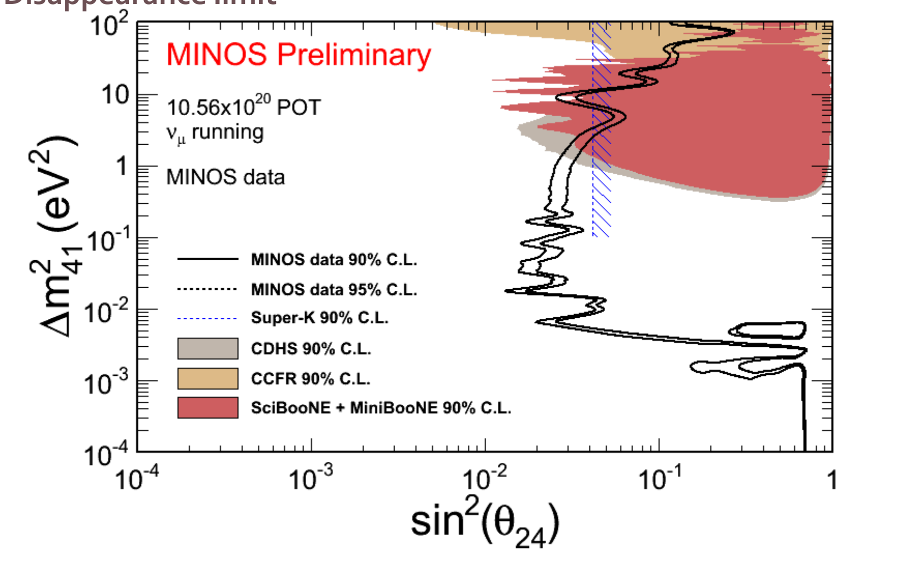
$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$

$0.37 < \sin^2\theta_{23} < 0.64$ (90% C.L.)



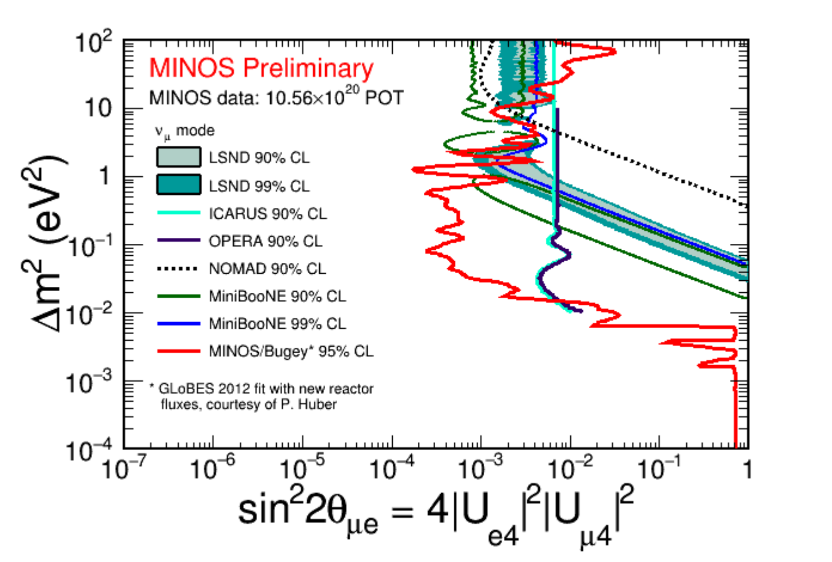
MINOS/+

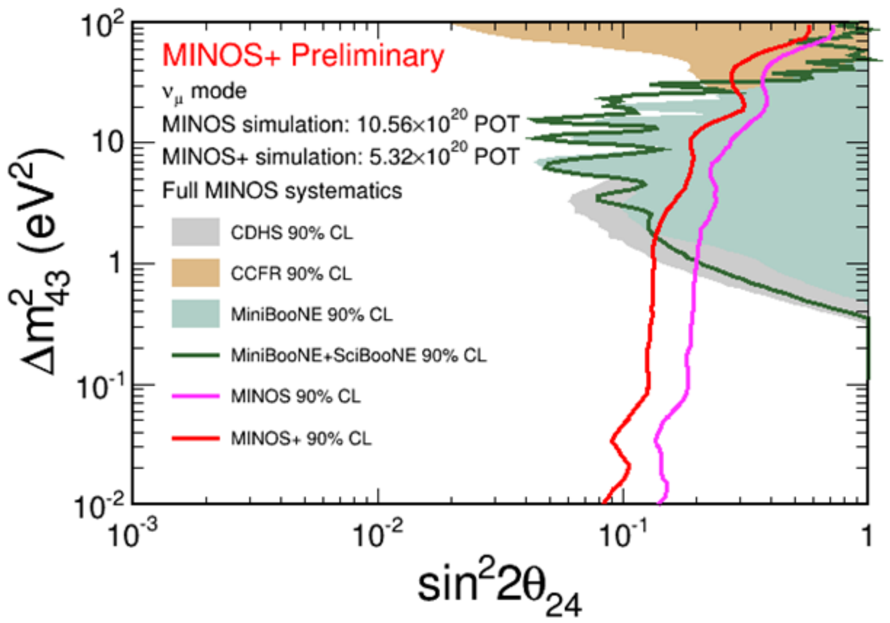
Disappearance limit



- MINOS gives strong constraint on muon neutrino to sterile neutrino oscillations for $\Delta m^2_{43} < 1\ eV^2$
- 90% exclusion over 4 orders of magnitude
- Combining with Bugey increases tension between experiment results – a lot of LSND and MiniBooNE region excluded
- Working on anti-neutrino sterile analysis and sterile neutrinos in electron neutrino appearance

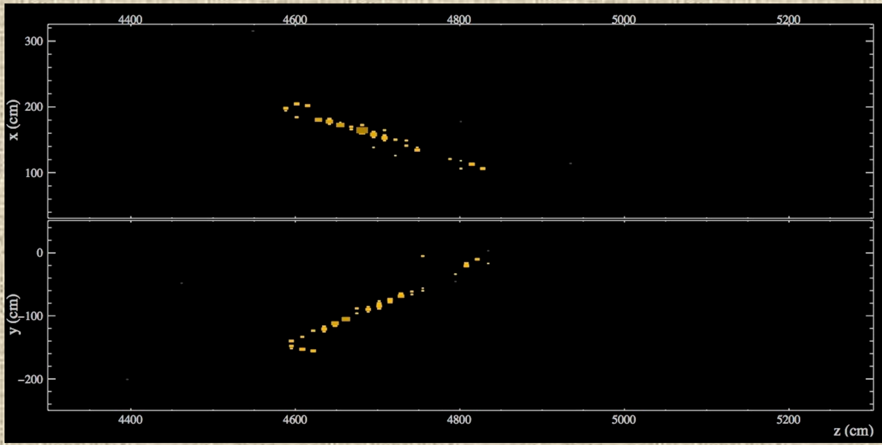
Combination with ν_e appearance from Bugey Reactor experiment





NOvA

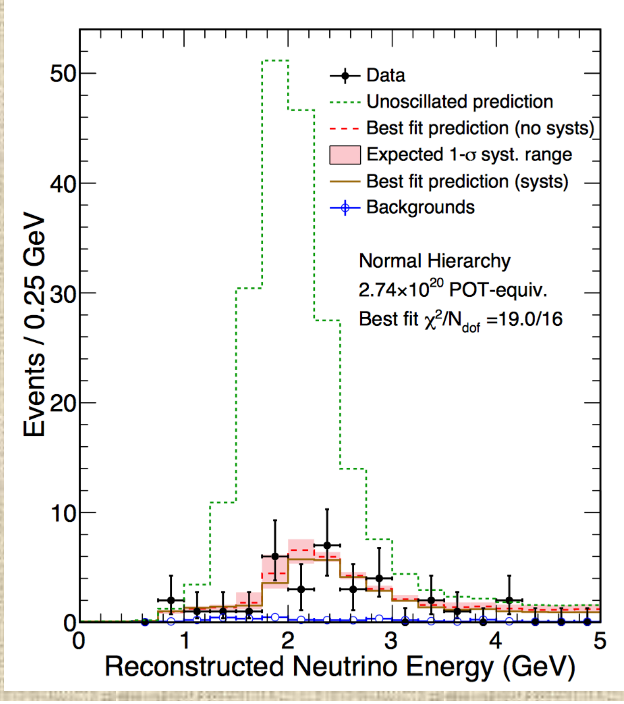
- NOvA is 14.6mrad off-axis in ME NuMI beam to hone in on the oscillations peak, also reduces muon neutrino and neutral current backgrounds
- Giant 14kT FD at Ash River, highly active, filled with liquid scintillator
- Smaller ND (300T) at FNAL 105m underground
- Signal collected by APDs from 330000 6.6cmx3.9cmx15.5m cells
- Excellent background reduction, taking data

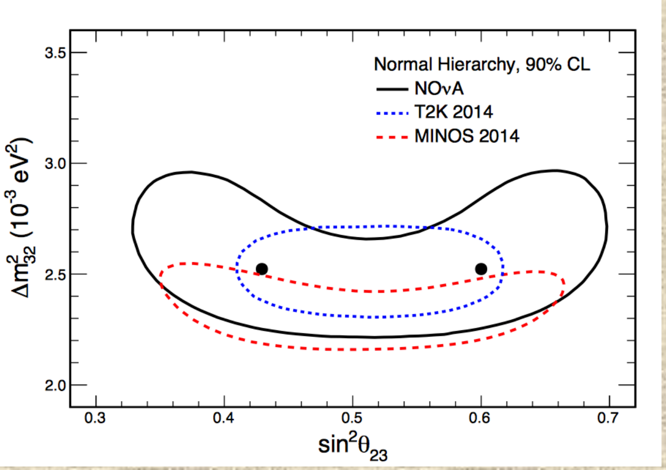


NOvA

ArXiv 1601.05037, accepted by PRD

- First disappearance and appearance analyses have been published
- Disappearance analysis observes 33 Ccnumu events when 211.8 are expected for no oscillations (with 3.4 BG). Best fit prediction is 35.4 events for both hierarchies
- 68% C.L. for $\sin^2\theta_{23}$ = [0.38,0.65] for NH, = [0.37,0.64] for the IH
- two statistically degenerate best-fit values of $\sin^2\vartheta_{23}$ of 0.43 and 0.60 for NH, and 0.44 and 0.59 for IH;
- $\Delta m^2_{23}=2.52^{+0.2}_{-0.18}\times10^{-3}eV^2$ for NH
- $\Delta m^2_{23}=(2.59\pm0.19)\times10^{-3}eV^2$ for IH

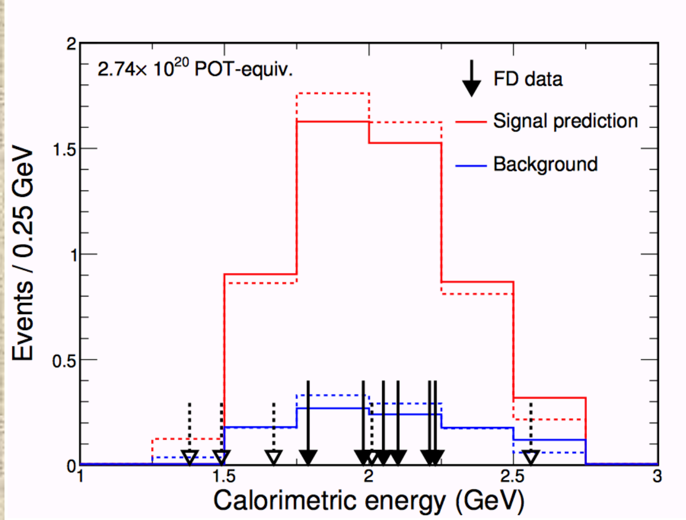


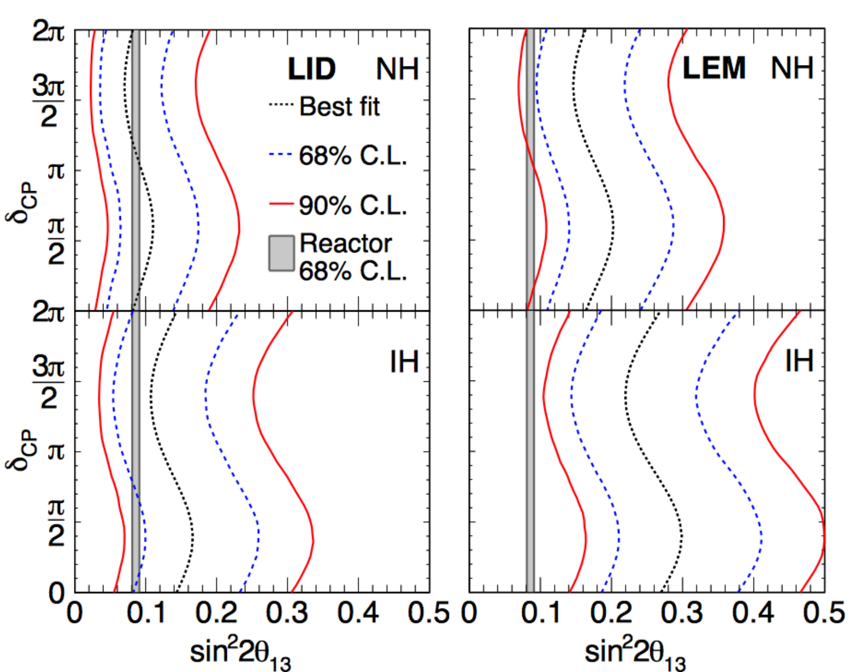


NOνA

ArXiv 1601.05022, accepted by PRL

- First appearance analysis accepted by PRL
- Predict very small background of about 1 event for each of the two PIDs
- Cut on Reco. E for primary selector (LID) to remove cosmics
- Observe 6 events (3.3σ excess) for LID
- Observe 11 events (5.3σ excess) for LEM
- Probability of observing this overlap (all LID events are selected by LEM) is 7.8%
- Data are compatible with 3-flavour mixing at the reactor value of ϑ_{13}
- For secondary analysis at least 13% of pseudo-experiments get at least as many event as data



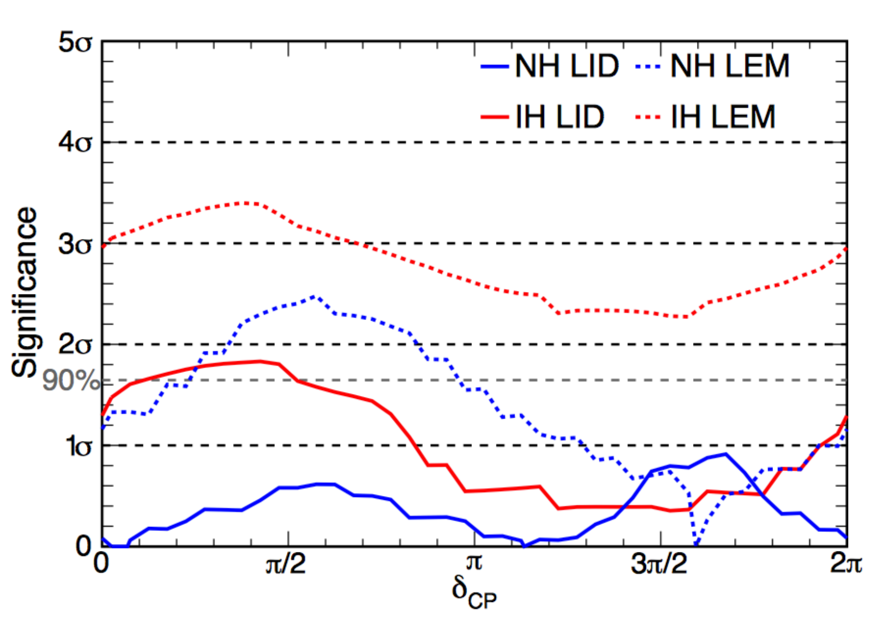


	Beam ν_e	NC	ν_μ CC	ν_τ CC	Cosmic	Total Bkg.
LID	0.50	0.37	0.05	0.02	0.06	0.99
LEM	0.50	0.43	0.07	0.02	0.06	1.07

NOvA

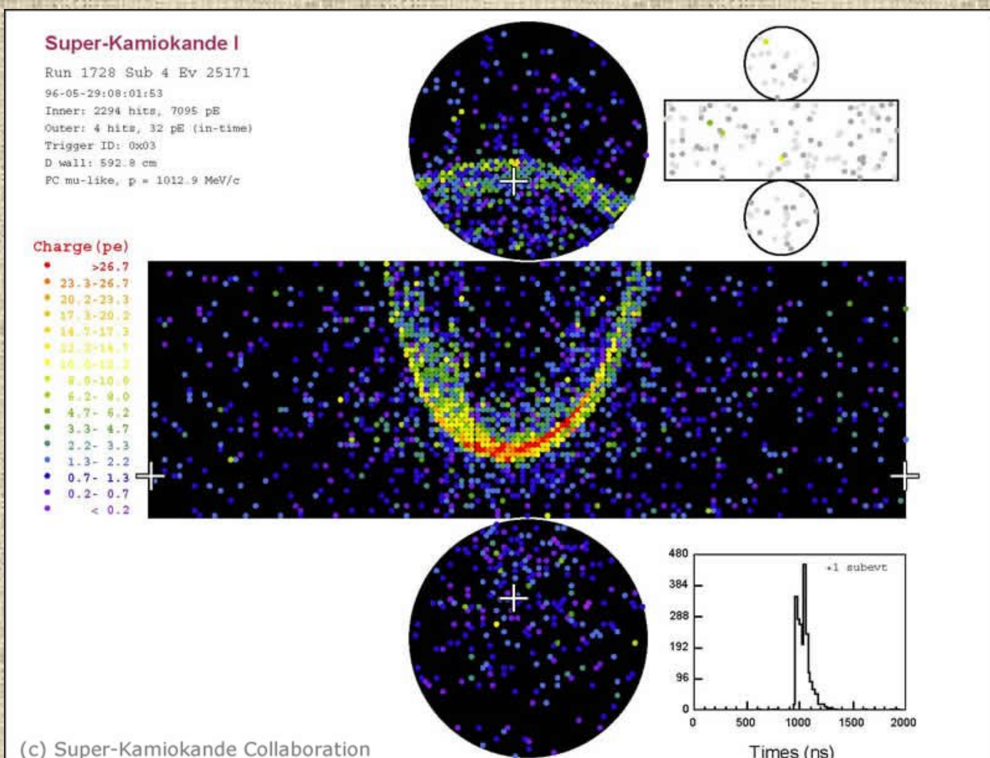
- If fixing to reactor ϑ_{13}, using the secondary selector, IH is disfavoured at >90% C.L. for all values of δ_{CP}. For NH, the range $0.25\pi<\delta_{CP}<0.95\pi$ is disfavoured at 90% C.L.
- NOvA is now working on the second analyses, with ~twice the POT
- Analysis improvements are being incorporated
- Expect to release new results in the Summer

ArXiv 1601.05022, accepted by PRL

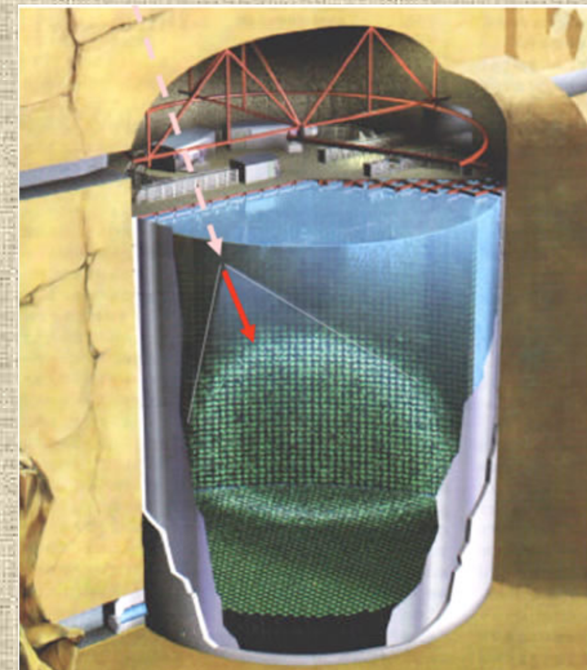


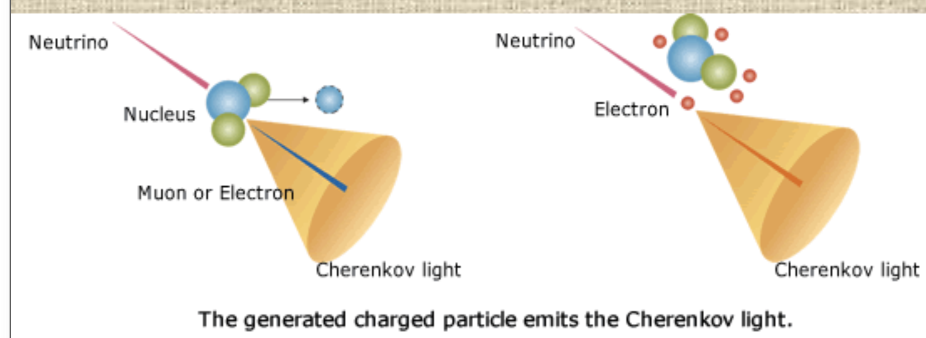
Super-K

- Giant Water Cherenkov detector
- 50kton detector volume (22.5kton fiducial)
- 11146 20" PMTs (ID) and 1885 8" PMTs (OD)



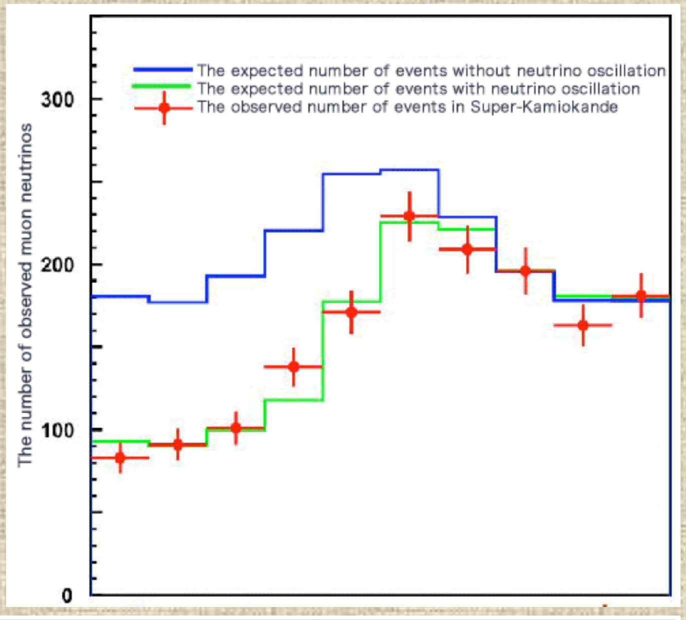
(c) Super-Kamiokande Collaboration



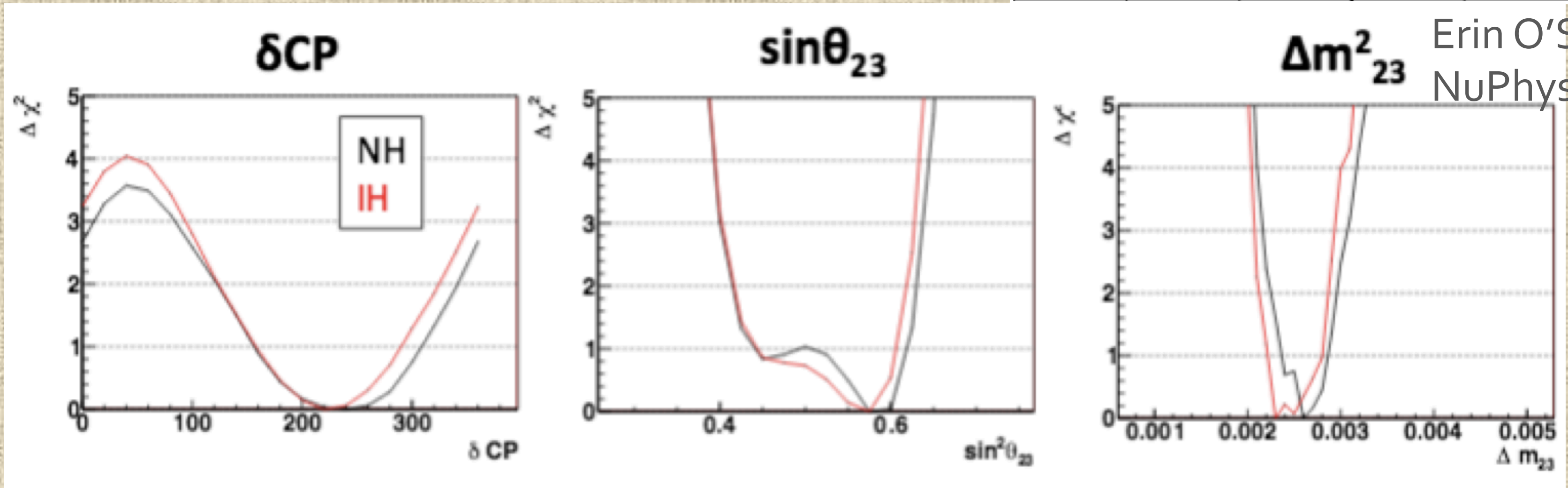


Super-K

- On its own can use atmospheric neutrinos to measure neutrino oscillations
- Also serves as the T2K FD
- For a long time had the world's best measurement of $\sin^2 2\vartheta_{23}$, now improved upon by T2K
- Best fit is non-maximal mizing
- Super-K data combined with T2K slightly favours Normal Mass Hierarchy

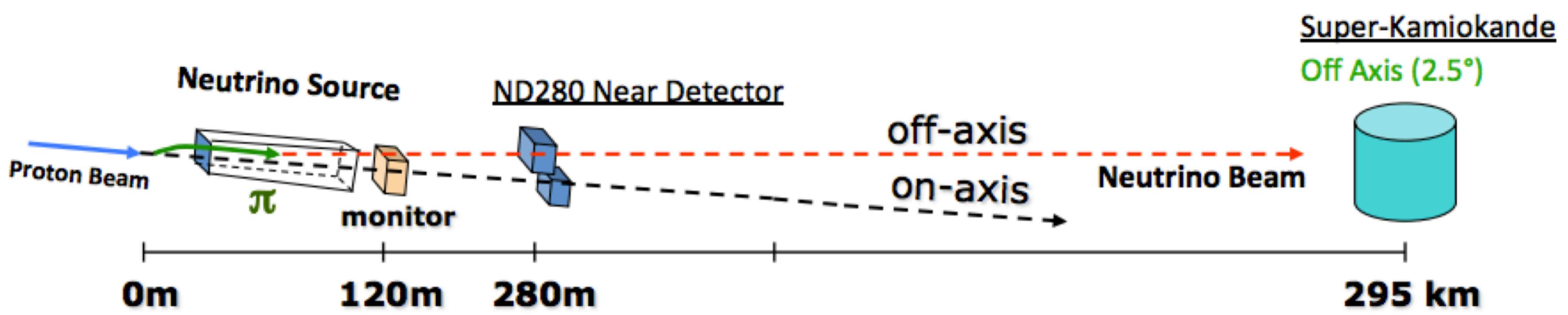


NH			IH		
δCP	$\sin^2\theta_{23}$	Δm^2_{23}	δCP	$\sin^2\theta_{23}$	Δm^2_{23}
240	0.575	0.0026	220	0.575	0.0023

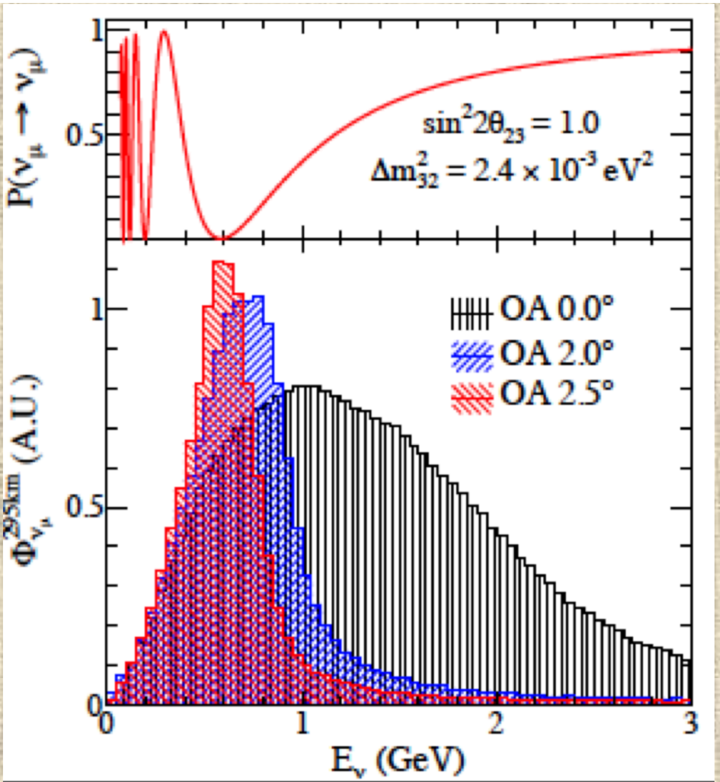


Erin O'Sullivan, NuPhys 2015

T2K

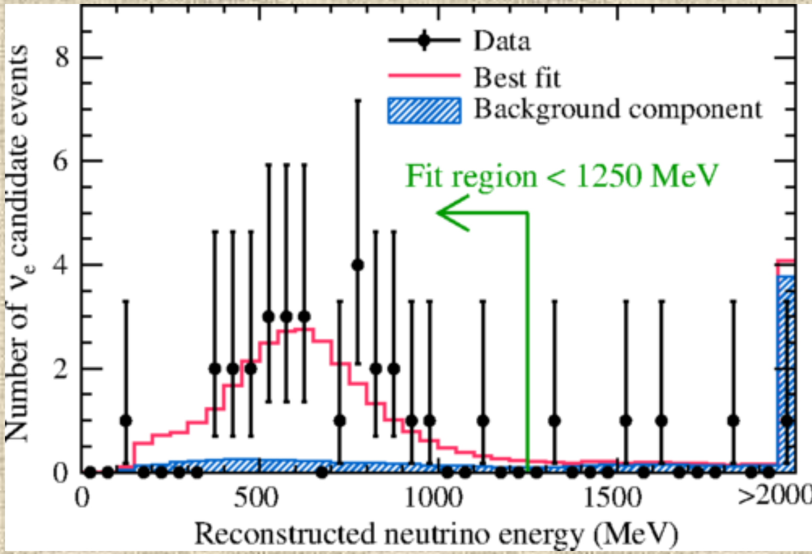


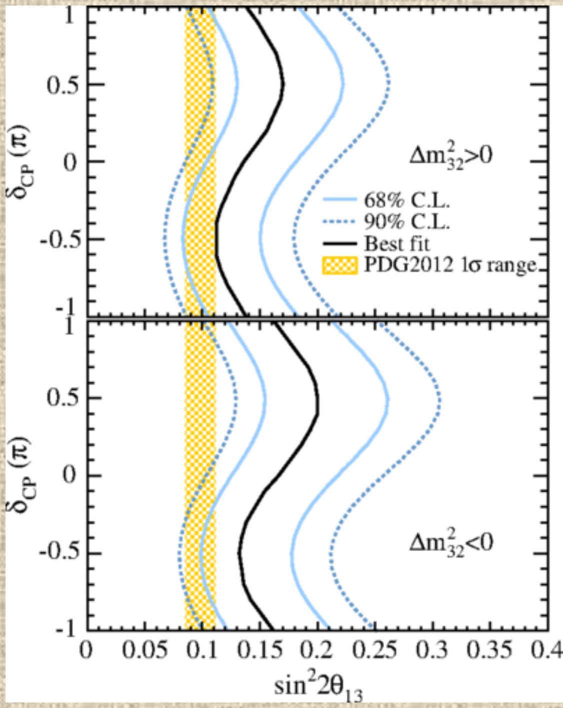
- T2K has a 295km baseline, uses Super-K as FD, off-axis
- Use their ND to determine the neutrino flux (with NA61 results), and the FD to measure neutrino oscillations
- T2K observes a narrow band beam peaked at about 0.6GeV

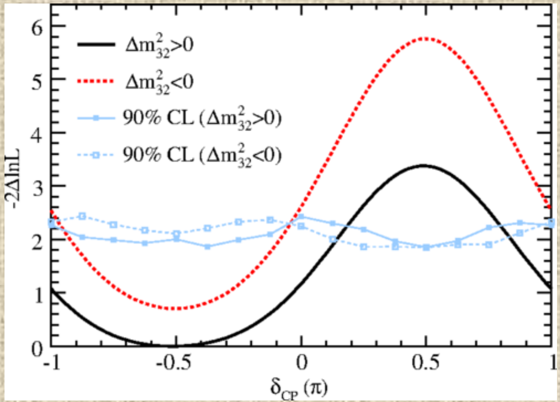


T2K

- Appearance analysis published in PhysRevLett.112.061802 (2014)
- Observed 28 electron neutrino-like events, with no oscillations expectation of 4.95± 0.55
- Assuming maximal mixing and Δm^2_{23}=2.4x10^{-3}eV^2 , T2K gets $\sin^2 2\vartheta_{13}=0.140^{+0.038}_{-0.032}$ for NH and $\sin^2 2\vartheta_{13}=0.170^{+0.045}_{-0.035}$ for IH
- 7.3σ significance over $\sin^2 2\vartheta_{13}$=0 hypothesis
- T2K prefers NH so far

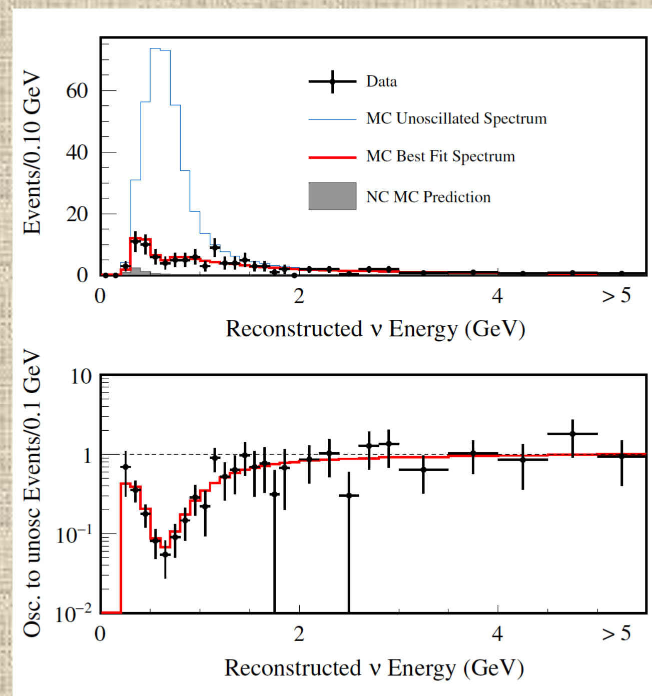


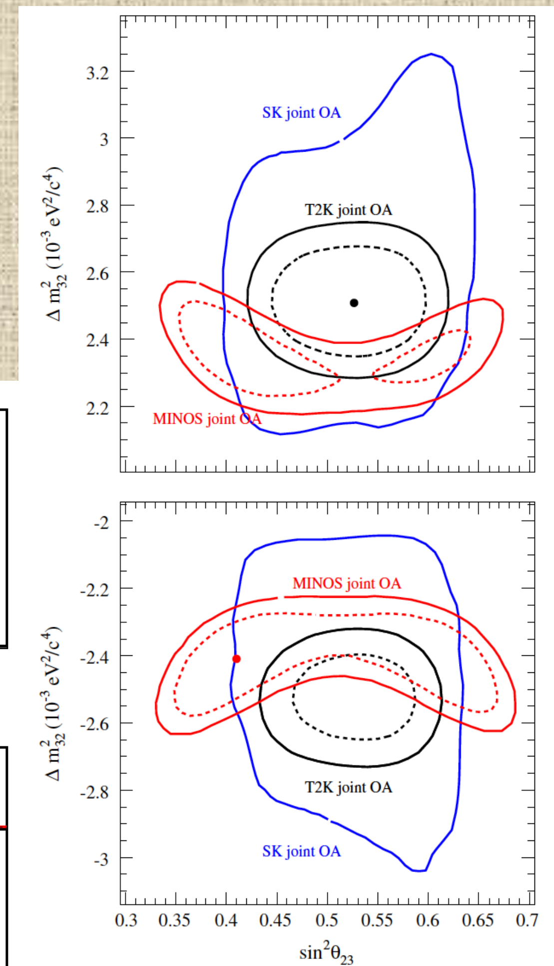




T2K

- Disappearance analysis published in PhysRevD. 91.072010 (2014)
- Observed 120 electron neutrino-like events, with no oscillations expectation of 446± 22.5
- Also did joint numu+nue analysis
- Assuming reactor constraints, get slight preference for NH
- $0.15\pi<\delta_{CP}<0.83\pi$ disfavoured at <10% probability

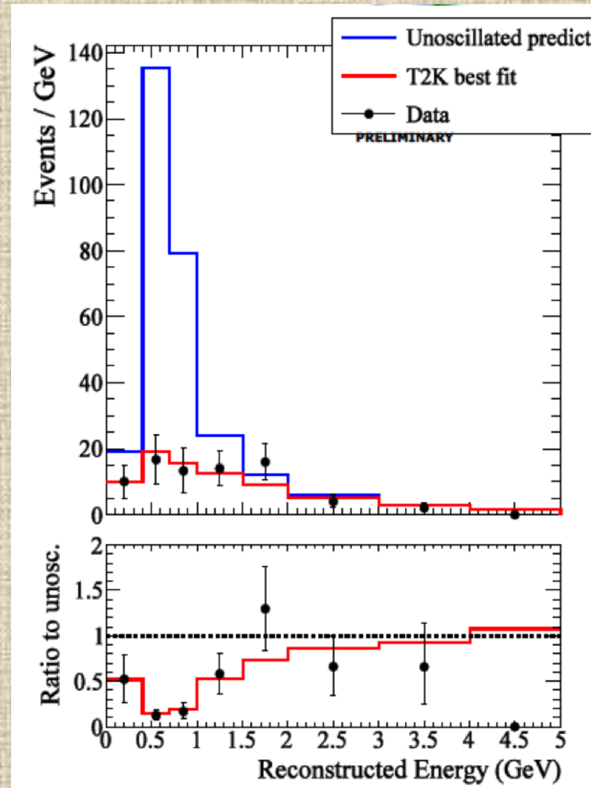


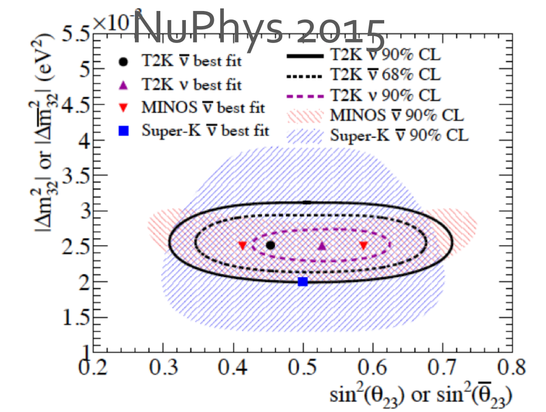


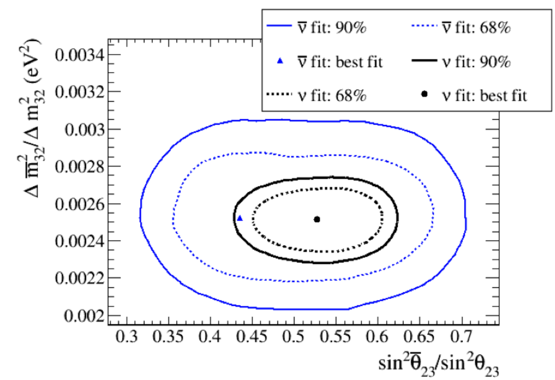
T2K

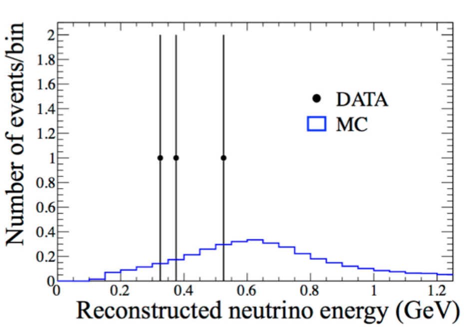
Helen O'Keeffe, NuPhys 2015

- Recently T2K have also analysed their anti-neutrino data
- Observed 34 ccnumu events with expected no oscillations of 103.6
- They have also observed electron anti-neutrinos in a ccnumubar beam for the first time
- They have many improvements underway and are constantly taking data









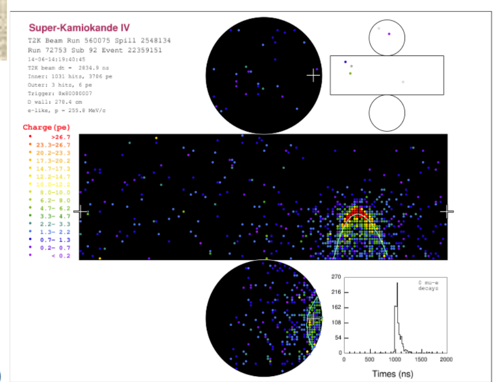


Figure 156: $\bar{\nu}_e$ candidate event #1

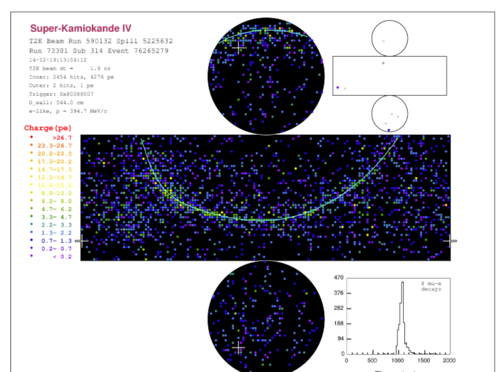


Figure 157: $\bar{\nu}_e$ candidate event #2

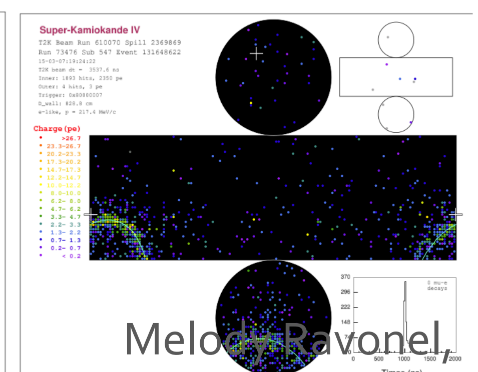
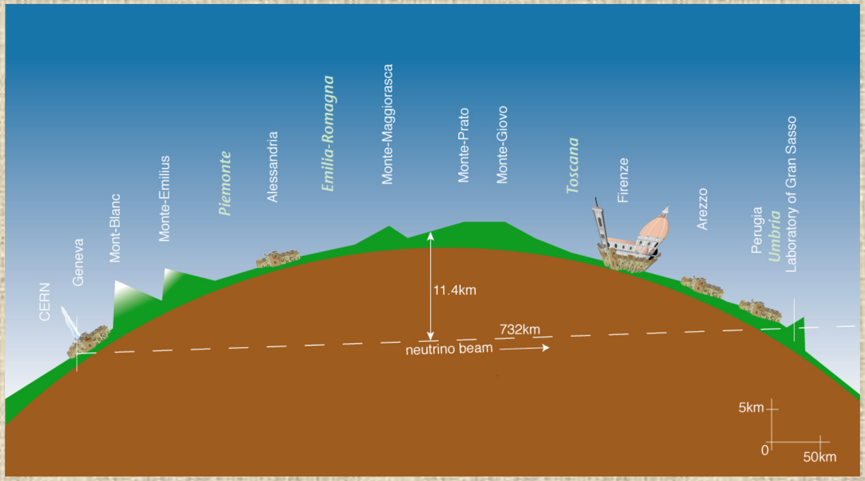


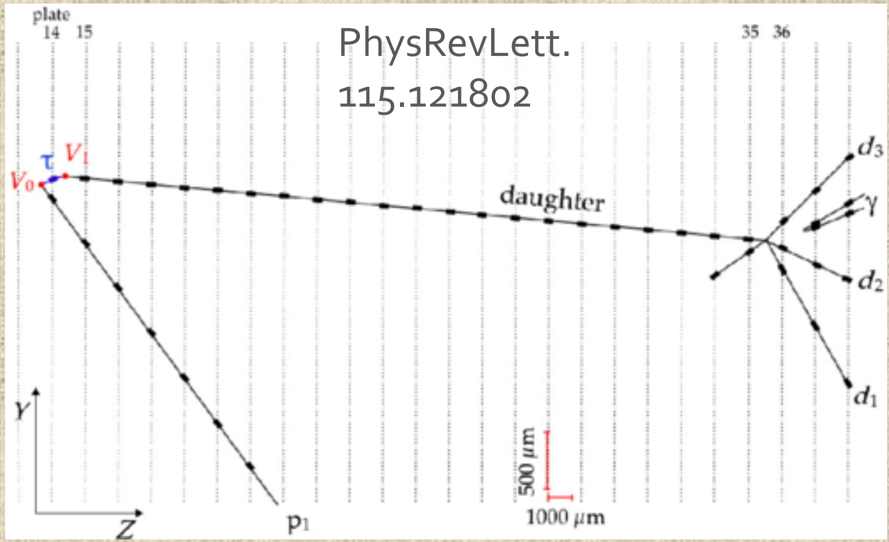
Figure 158: $\bar{\nu}_e$ candidate event #3

Melody Ravonel, EPS 2015

OPERA



- OPERA uses the CNGS beam from CERN to Gran Sasso
- Wide band beam optimized for tau neutrino appearance
- 15000 emulsion bricks as detector mass
- Have seen 5 events, 5σ tau neutrino appearance signal events, consistent with standard 3-flavour mixing



Future Experiments (including Liquid Argon)

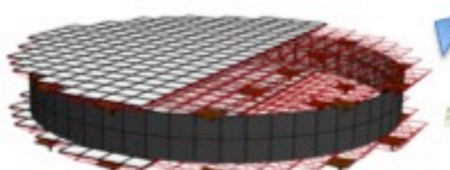
CHIPS

Courtesy of Jenny Thomas

CHIPS

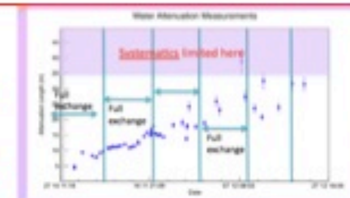
MOTIVATION
- Drastically reduce costs for a Water Cherenkov detector
  - Design only for beam neutrinos
  - Submerge in natural body of water for mechanical support
  - Reduce total number of PMTs
- Use small 3" PMTs for position and timing to maintain efficiency

PLANS
- Design of large 30m diameter detector "slice" is underway at Madison/PSL
  - 1.5kt volume for 2m height
- Idea is to build end-caps in shallow water then tow to deep water and sink
- Raise to increase wall height using floating docks in the water to increase instrumented volume over time
- Component panels will hold PMT planes
- Cost of wall : 100k/kt!
- Synergy with ICECube GEN II work including PMTs and new readout development

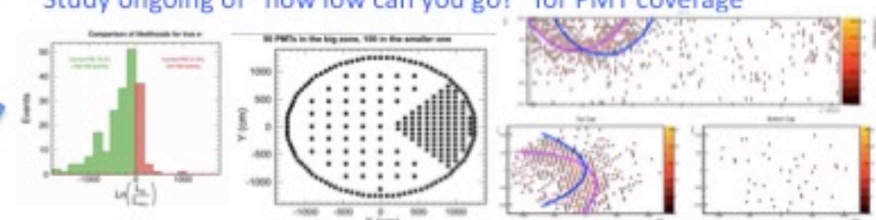


PROGRESS
- 50T CHIPS-M detector deployed at 50m depth and raised after one year
- Recirculated water via shore filter
- 2 detector planes tested in 2015 deployment:
  - one with Km3Net technology
  - One using ParisROC readout
- Read out via fibre cable
- Measured cosmic rate at pit bottom

WATER
- In test setup Wentworth water achieved > 30m attenuation length in 2 months
  - Equivalent to one full volume/10 days
- This was used in the simulations

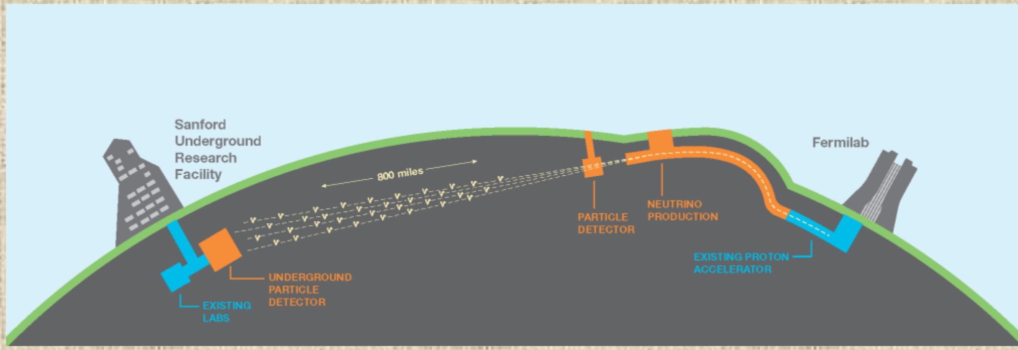


SIMULATION
- Major progress on simulation of detector (based on WCSim) and Reconstruction based on MiniBoone approach but tailored to timing and spaciel resolution of small tubes
- Study ongoing of "how low can you go?" for PMT coverage



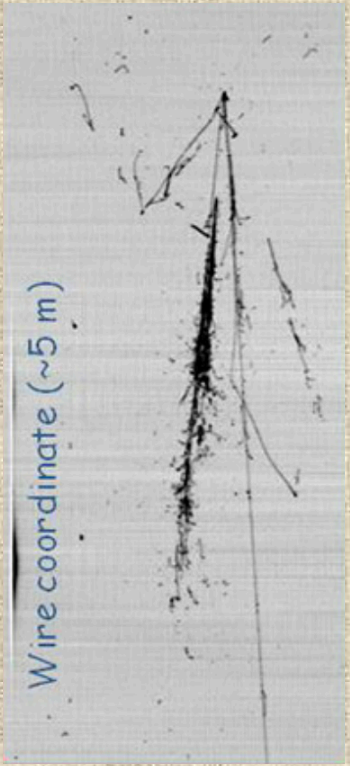
DUNE

- DUNE is the flagship neutrino experiment of the future
- Building an all new beam line from FNAL to Sanford
- On-Axis wide-band beam, long long baseline (1300km), 60-120GeV protons, 1.2MW power initially, doubled after upgrade
- Using liquid argon detector technology for exquisite event identification
- 4 10kTon modules planned
- Should have discovery sensitivity for MH and deltaCP



Immense world-wide effort ongoing, with prototypes at CERN and Fermilab

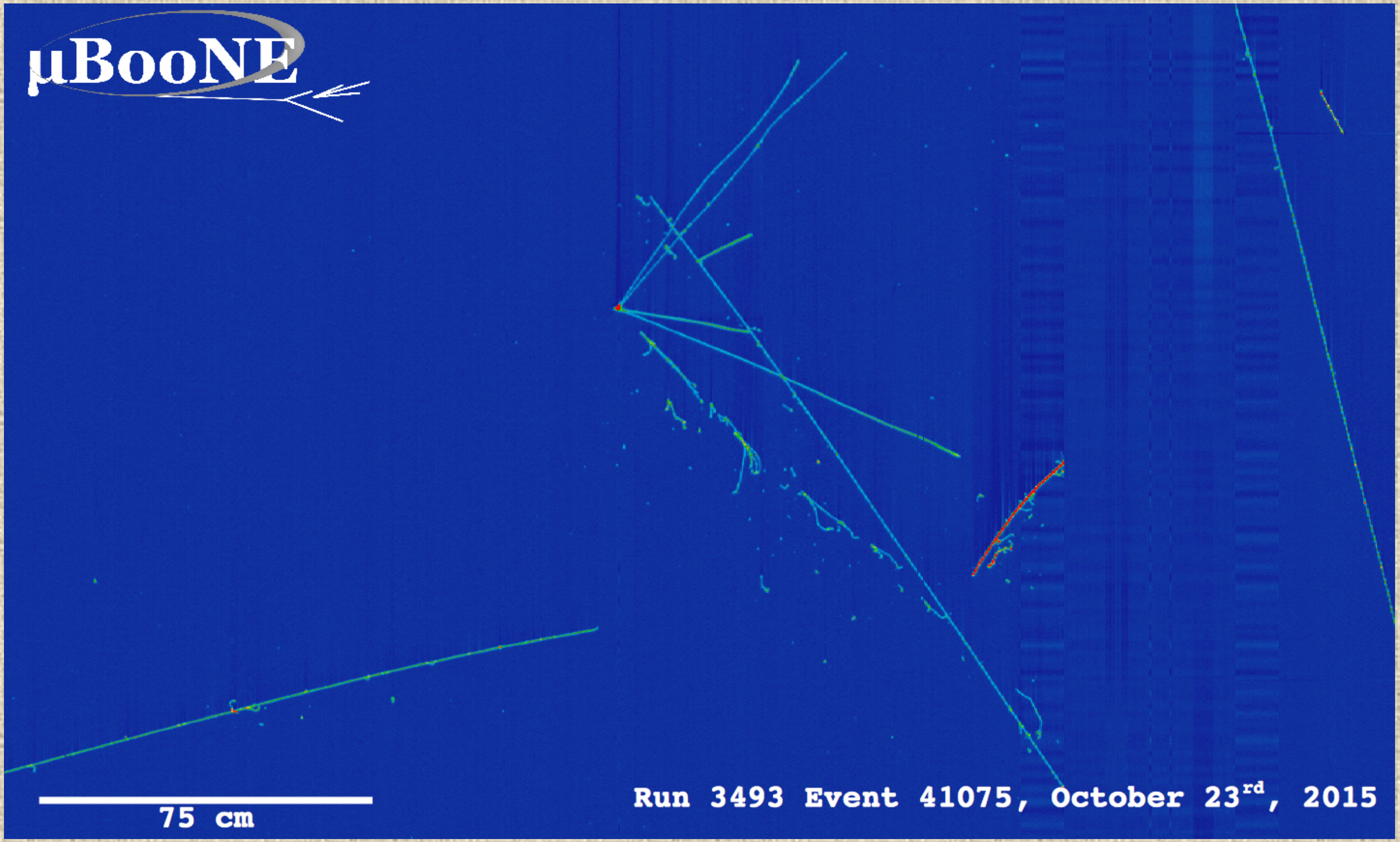
Will probably start taking data in the mid 2020s if all goes to plan



Fermilab SBN programme

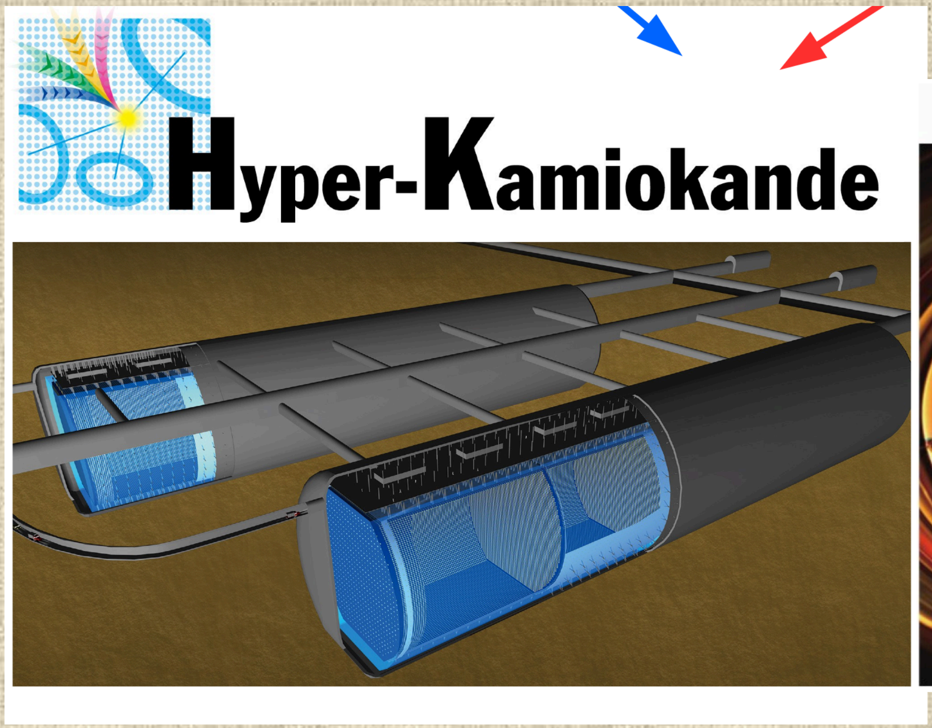
- Hunting for the sterile neutrino in short-baseline oscillations in the Booster Neutrino Beam at FNAL using three LAr detectors (SBND, MicroBooNE, ICARUS)
- Lower energy (BNB uses 8GeV protons on Beryllium target, 1 focusing horn)
- Part of an extensive LAr complex at Fermilab (others are LArIAT, 35ton,...)

Fermilab SBN programme

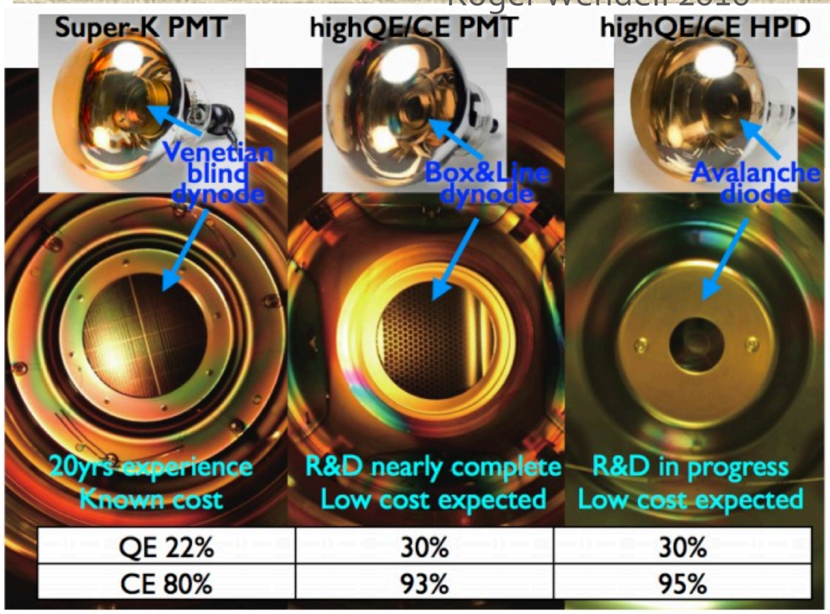


- MicroBooNE already taking data – beautiful neutrino event displays
- ICARUS being re-commissioned at FNAL
- SBND in advanced design stages, hopefully will start taking data in the next 2 years

Hyper-K



Roger Wendell 2016



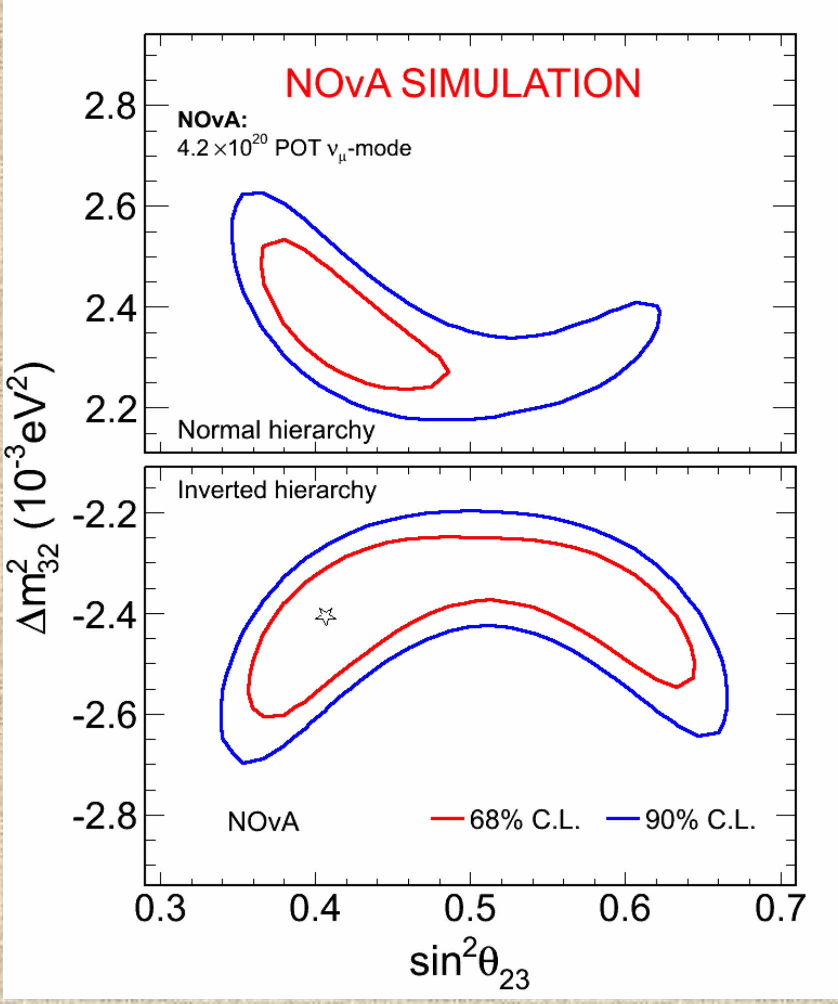
- 25 times bigger than SuperK! 560kTon water Cherenkov detector
- Using 125000 highly sensitive photodetectors!
- multipurpose goals including precision neutrino oscillations measurements
- Will be in JPARC beam – likelyhood of upgrade to >1MW power
- In planning and R&D stages, envisioned to start taking data around 2025

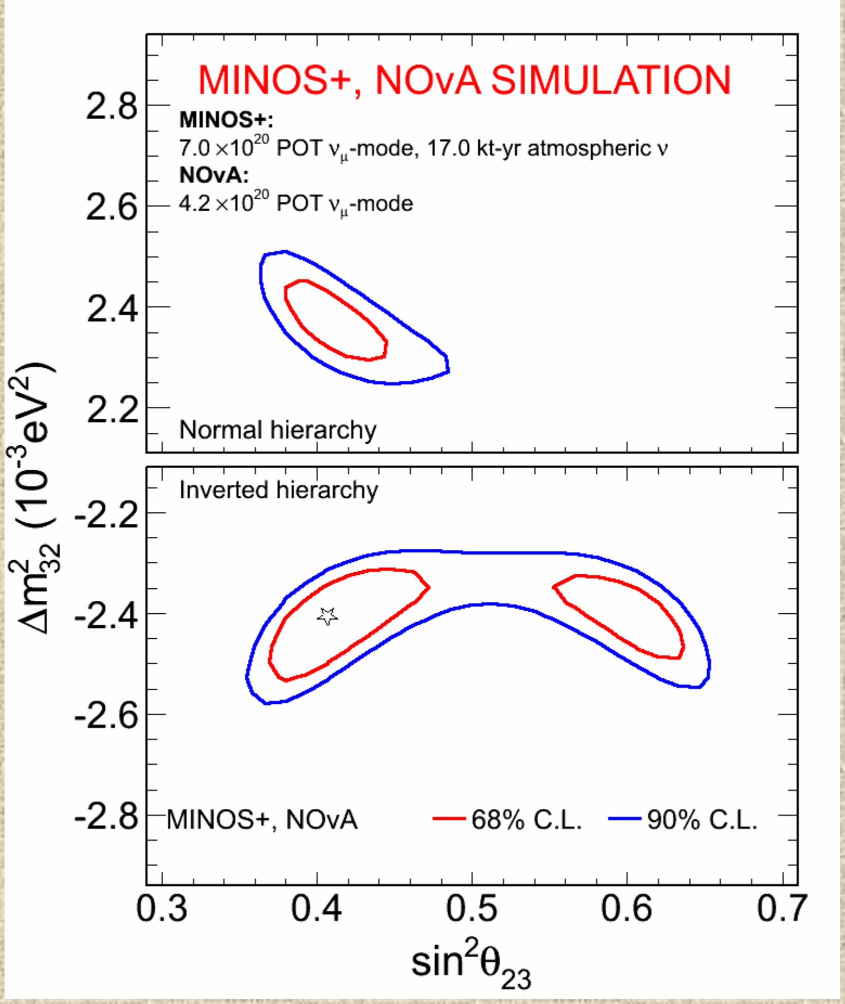
Summary

- The (accelerator) neutrino experiment community is more active than ever
- There are many on-going and future experiments trying to answer important neutrino physics questions
- The race is on to determine the mass hierarchy and, if they are there, discover CP-violation in the neutrino sector and possibly sterile neutrinos
- Neutrinos have surprised us many times, and it would be very exciting if they did so again!

Back-Up

The power of combining





- Accessing the same beam, but different oscillations phase space, means that one can combine data to yield even better results