Accelerator Neutrino Physics I: Present Decade

CHRIS WALTER, DUKE UNIVERSITY

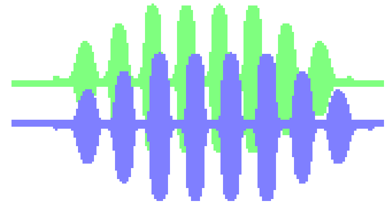
TAUP 2013
September 12th 2013

September 2013: Where do we stand?

Large Θ_{13}!

Can we measure CP violation?

- <u>The measurement of non-zero θ_{13} has changed the nature of discussions and presentations about the current experiments.</u>
- I'll go over some experimental issues related to the accelerator experiments and try to teach you how to compare the experimental results.
- Emphasis on long-baseline: T2K, MINOS, OPERA
- I'll try to explore what can we expect to know before the next generation of experiments starts.



How do νs oscillate?

"Flavor" states are mixture of mass states.

$$\nu_\mu = \nu_2 \cos\theta + \nu_3 \sin\theta$$
$$\nu_\tau = -\nu_2 \sin\theta + \nu_3 \cos\theta$$

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\nu_\mu(t)\rangle = e^{iE_2t}\,|\nu_2(0)\rangle \cos\theta + e^{iE_3t}\,|\nu_3(0)\rangle \sin\theta$$

$$P_{\mu\tau} = \sin^2 2\theta\, \sin^2 \frac{1.27\Delta m^2 L}{E}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{U} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

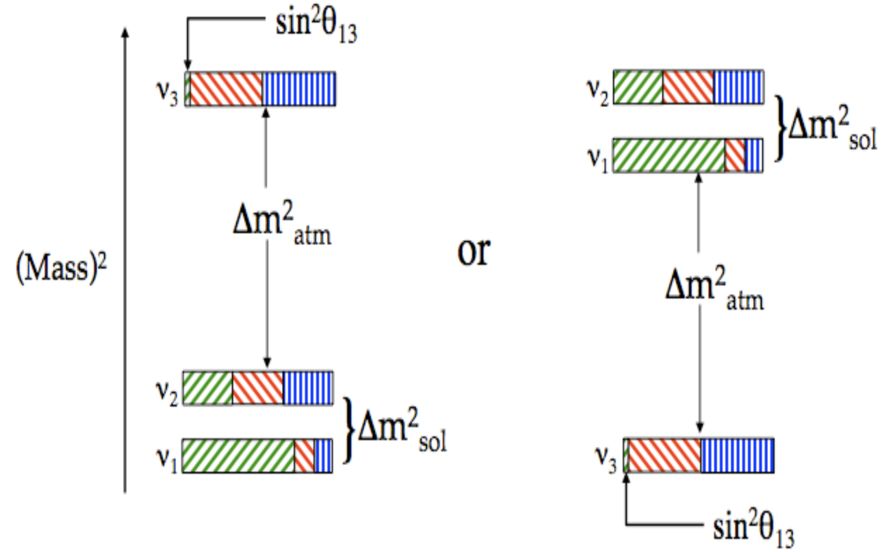
Atmos Oscillations — Reactor+ Beam (unknown: $e^{i\delta}$) — Solar Oscillations

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

$$c_{23} = \cos\theta_{23}$$
$$s_{23} = \sin\theta_{23}$$

Questions to answer

- What is the pattern of neutrino masses?
- Is there CP violation in the neutrino sector? Is it big enough to drive lepto-genesis and is it related to the quark sector?



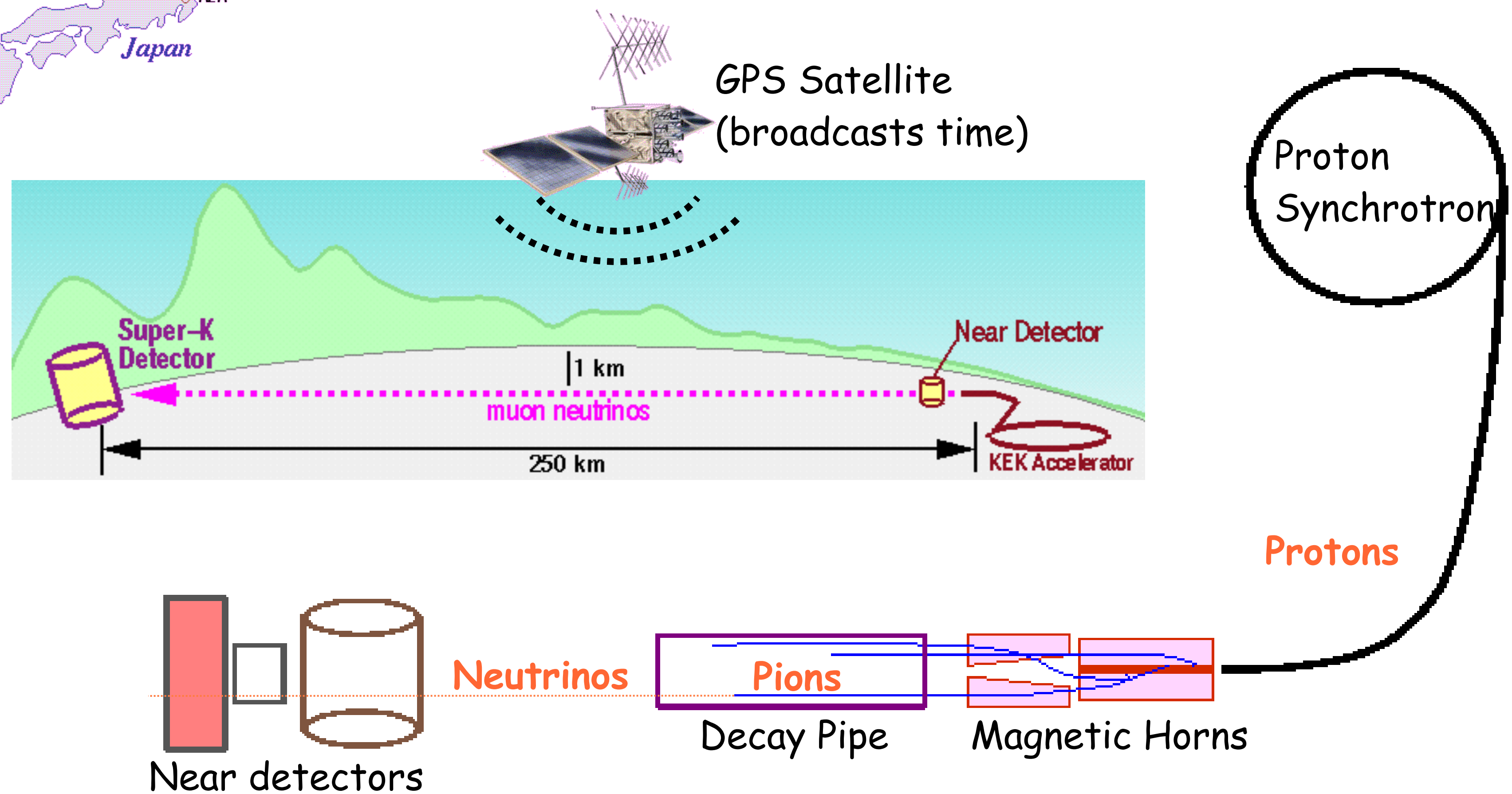
"Normal" "Inverted"

In a beam experiment, the signal for non-zero θ_{13} is ν_e appearance in a pure ν_μ beam.

There are differences in the rate of appearance between neutrinos and anti-neutrinos if there is CP violation and also for the different hierarchies in matter.

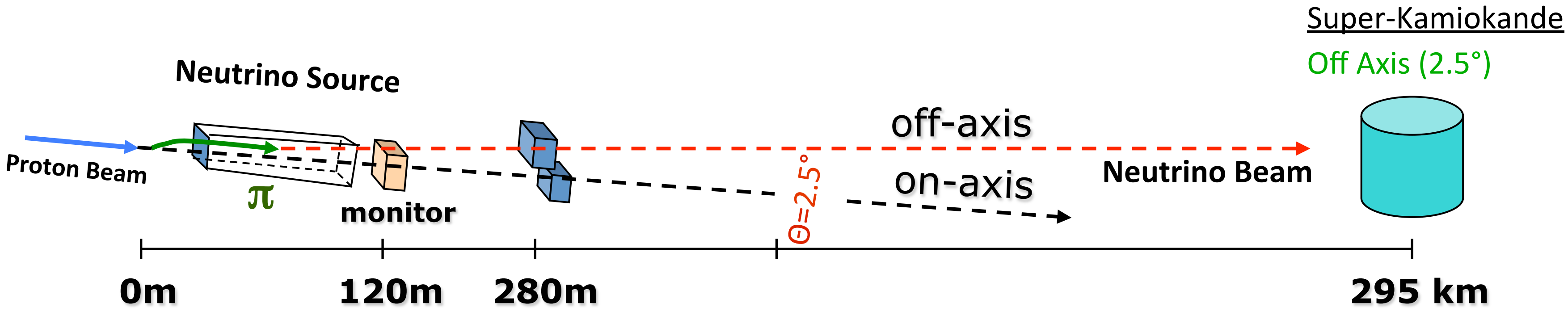
How do you build a long-baseline experiment?

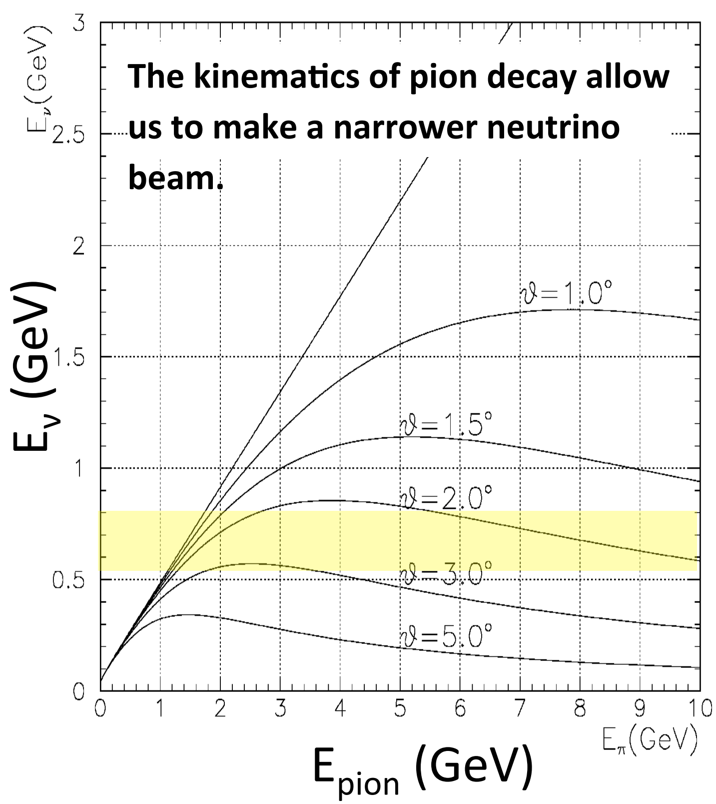
(1st example: K2K -> MINOS -> T2K -> Nova)

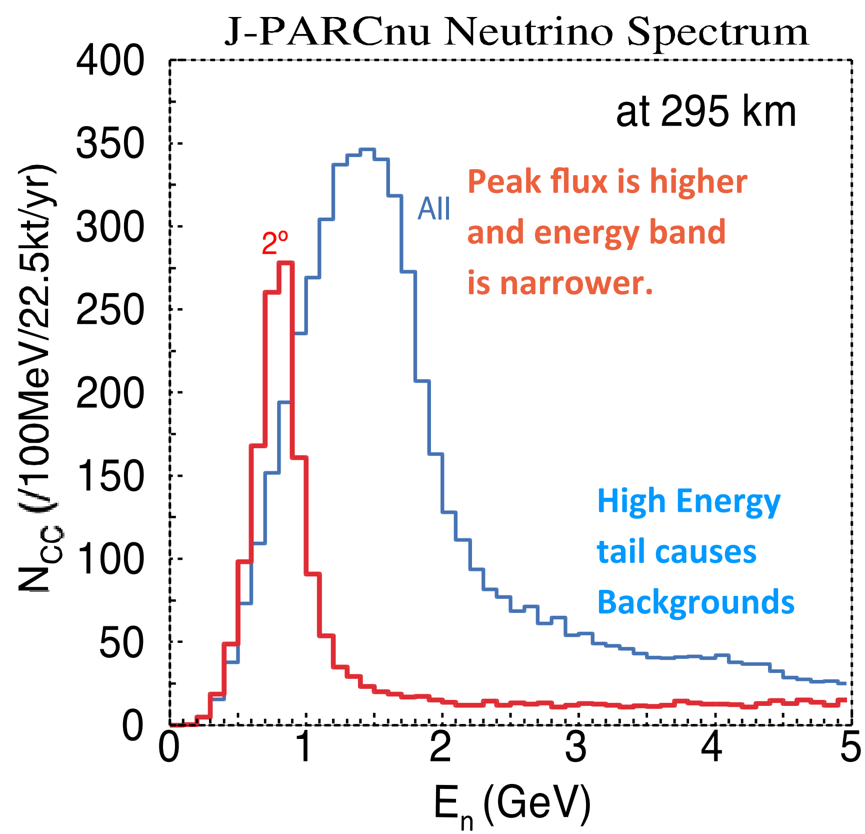


Always the same pattern:
Accelerator -> Target -> Horns -> Decay Pipe -> Near detector -> Far Detector

On and Off-Axis Beams



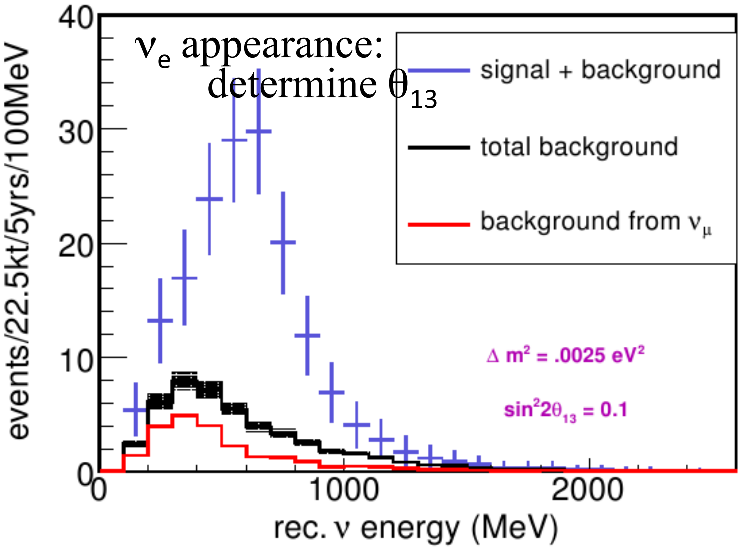




Oscillation searches at accelerators

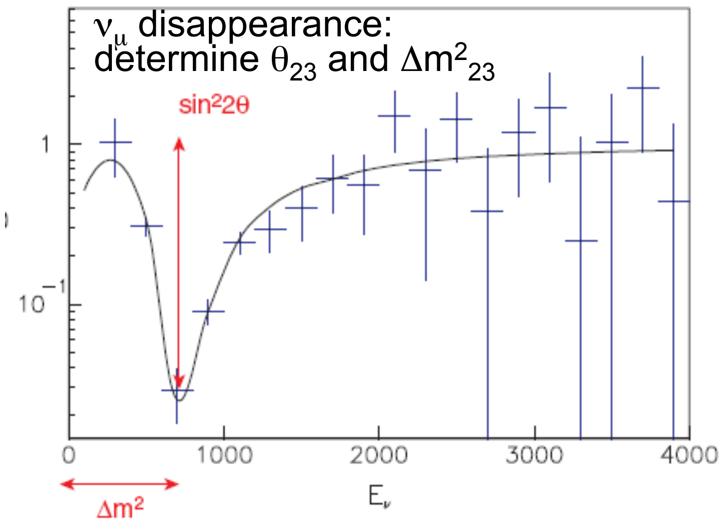
There are two types of searches:
Appearance and Disappearance

- Appearance: MiniBoone, T2K, Nova, OPERA



Enough energy to produce lepton in CC reaction.

- Disapearance: MINOS, K2K, SK

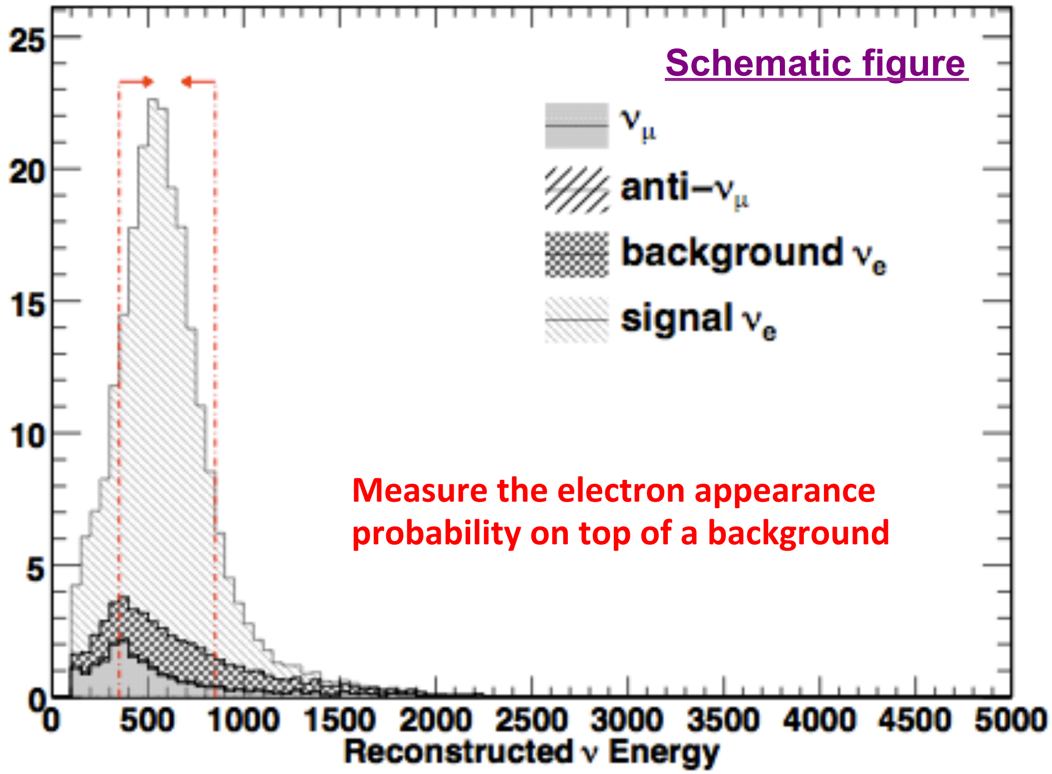


NOT enough energy to produce lepton in CC reaction.

How do we measure θ_{13}?

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E_\nu} + sub\text{-}leading\ terms$$

(sinδ is in here)



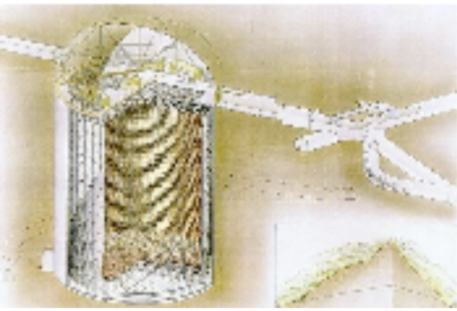
ν_e appearance is crucial for studying the MH and CPV!

For appearance three main types of background:
intrinsic ν_e, misidentified π^0, mis-identified charged μ

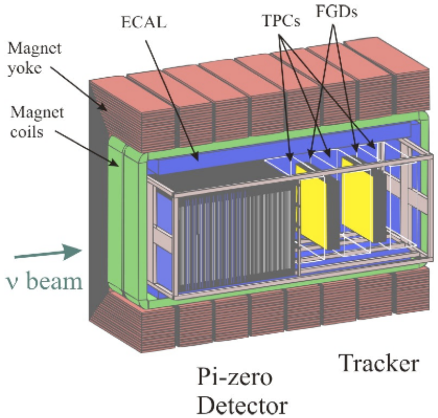
We need a very high intensity beam and a large target. Make a pure neutrino beam and look for electrons to appear.

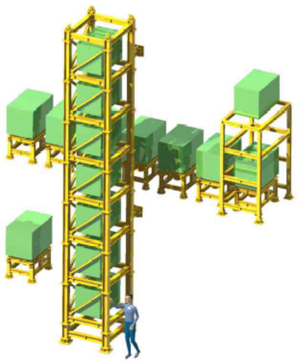
The T2K Experiment

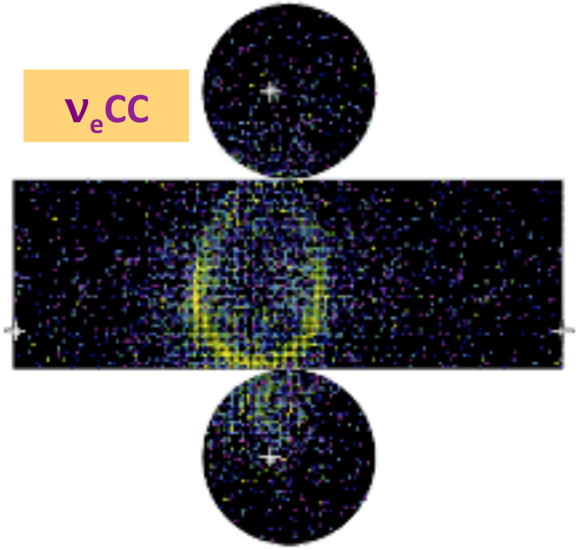
Super-K water Cherenkov Detector as far detector.
Uses the JPARC accelerator complex 295 km away

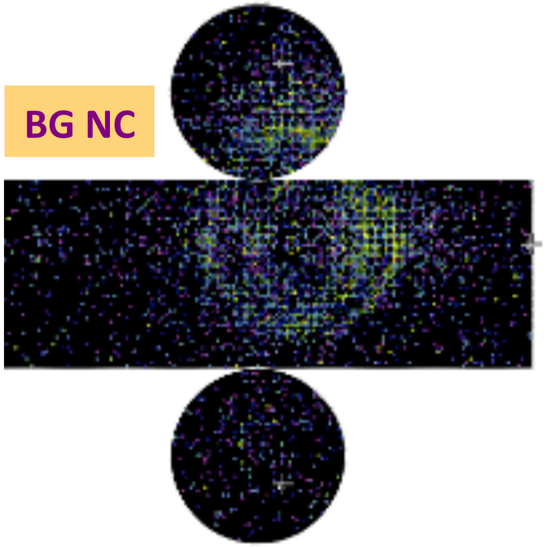


Far detector: Super-K
On and off-axis
hybrid near
detectors



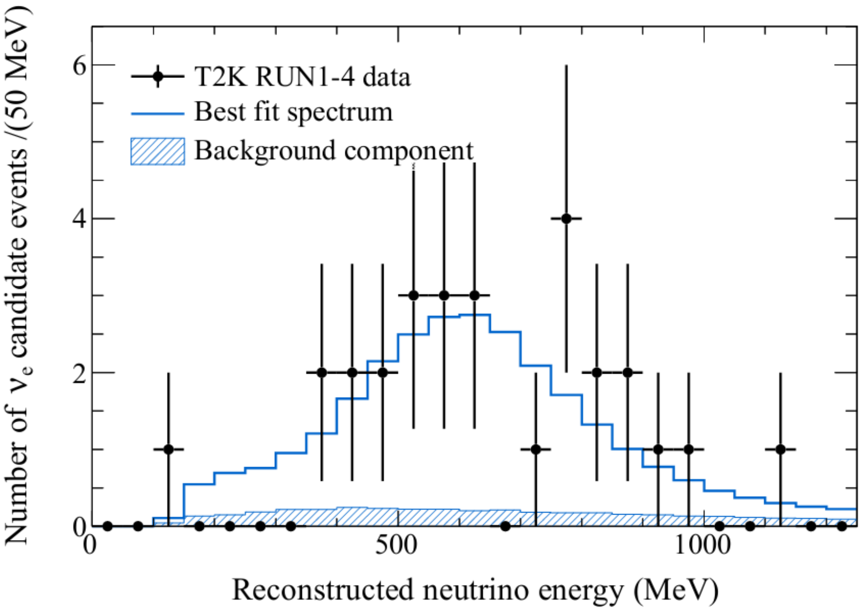


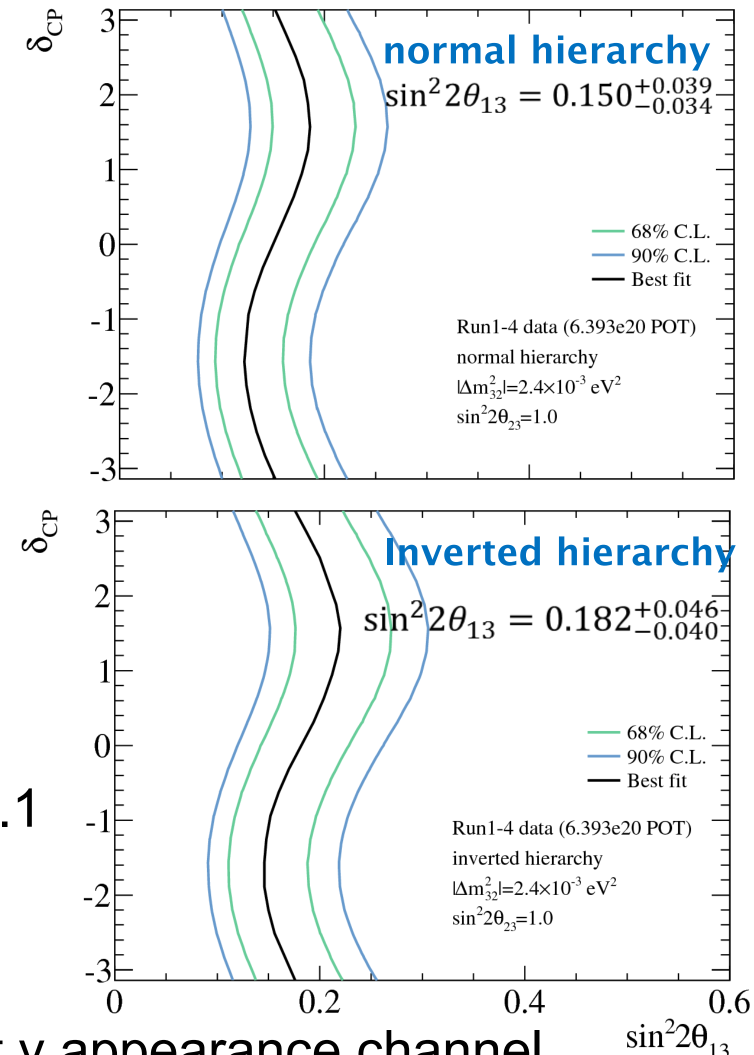




- 50 Kton Water Cherenkov Detector
- >11,000 PMTs read out by QTCs
- Image processing for reconstruction

T2K observation of ν_e Appearance





4.6 events expected background

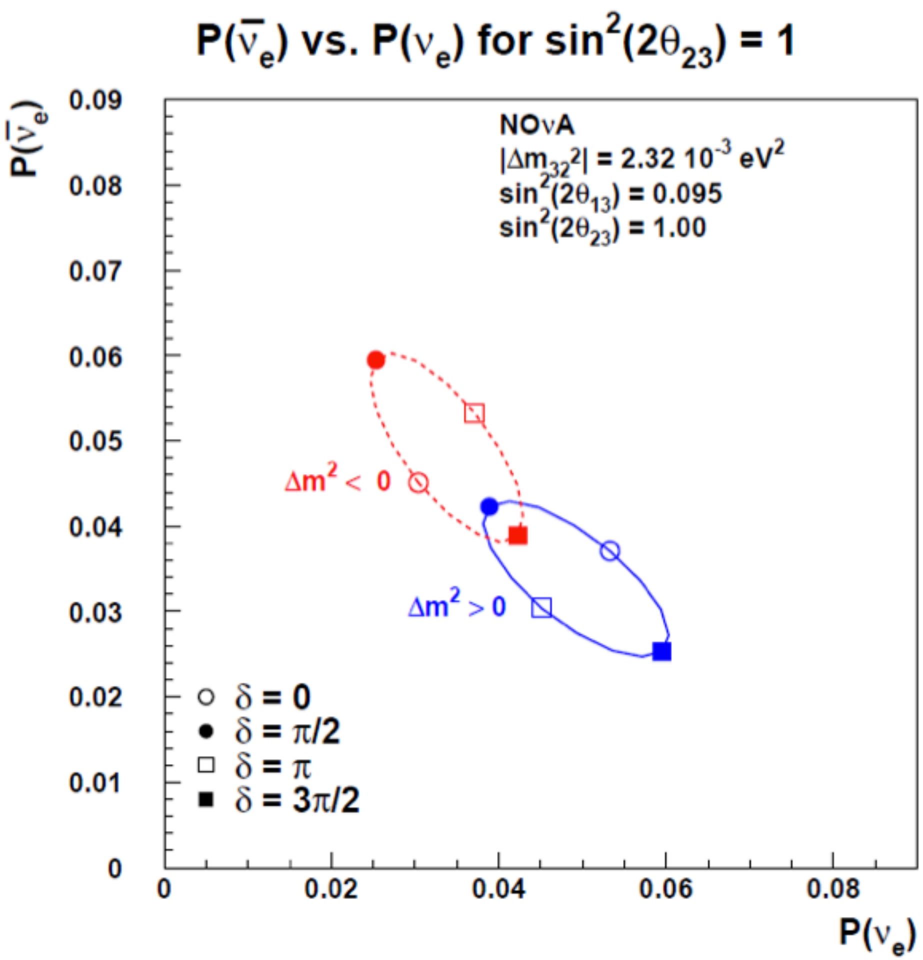
28 events observed

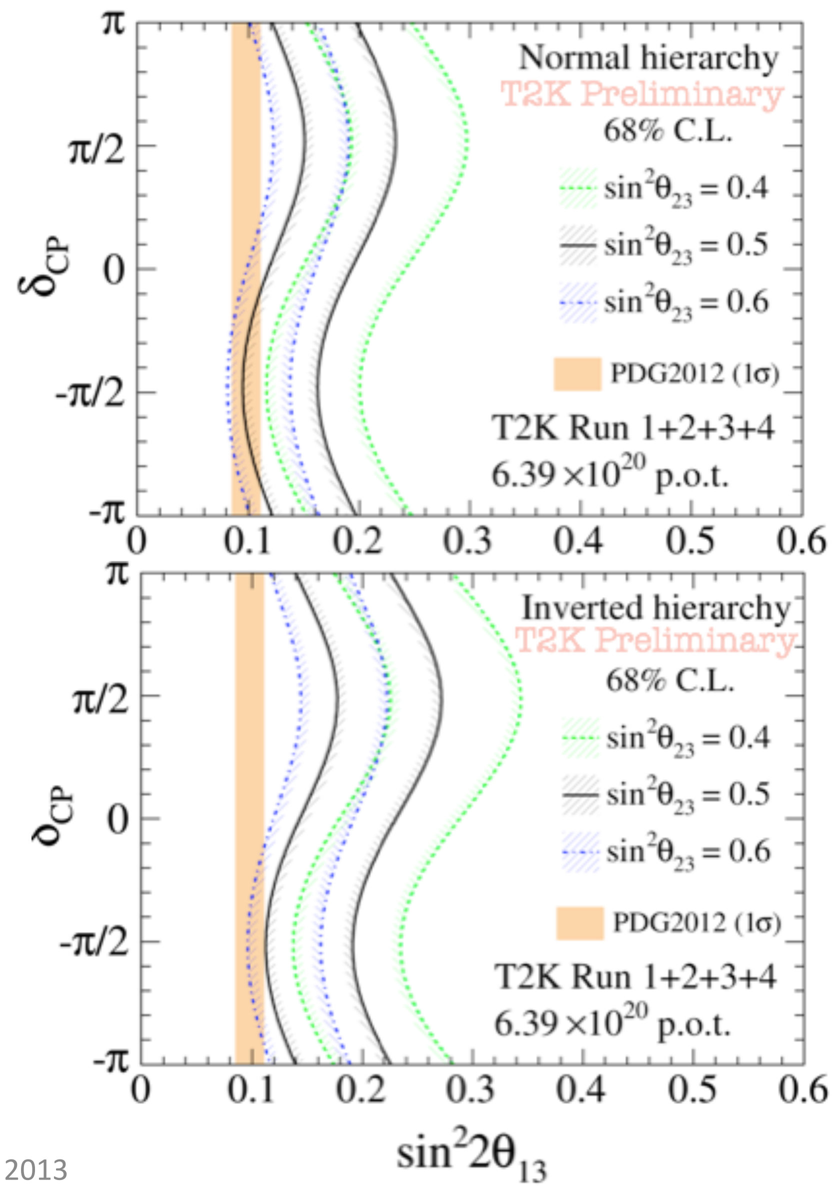
20.4 ± 0.8 events expected @ $\sin^2 2\theta = 0.1$

7.5σ significance for non-zero θ_{13}

<u>First ever observation (>5σ) of an explicit ν appearance channel</u>

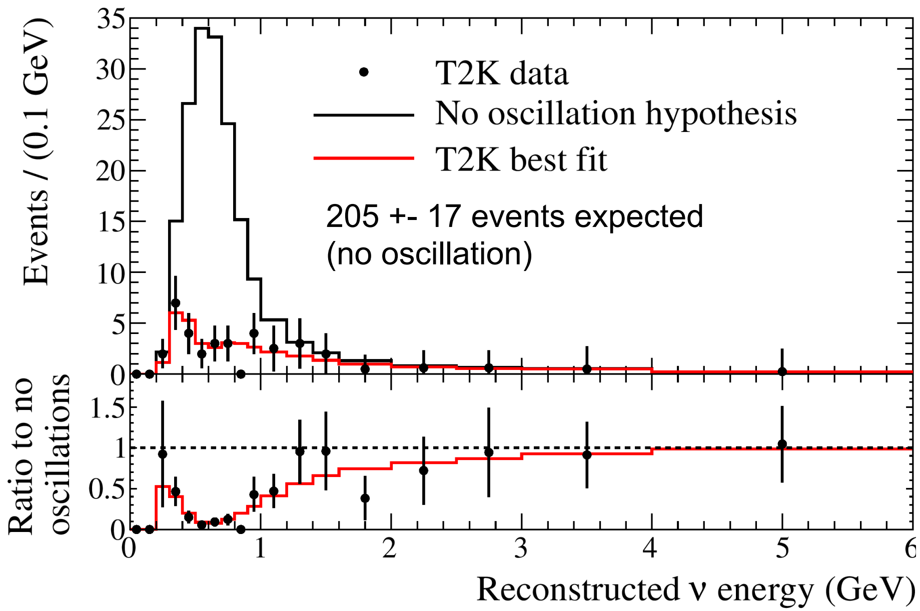
Let's think about these regions!



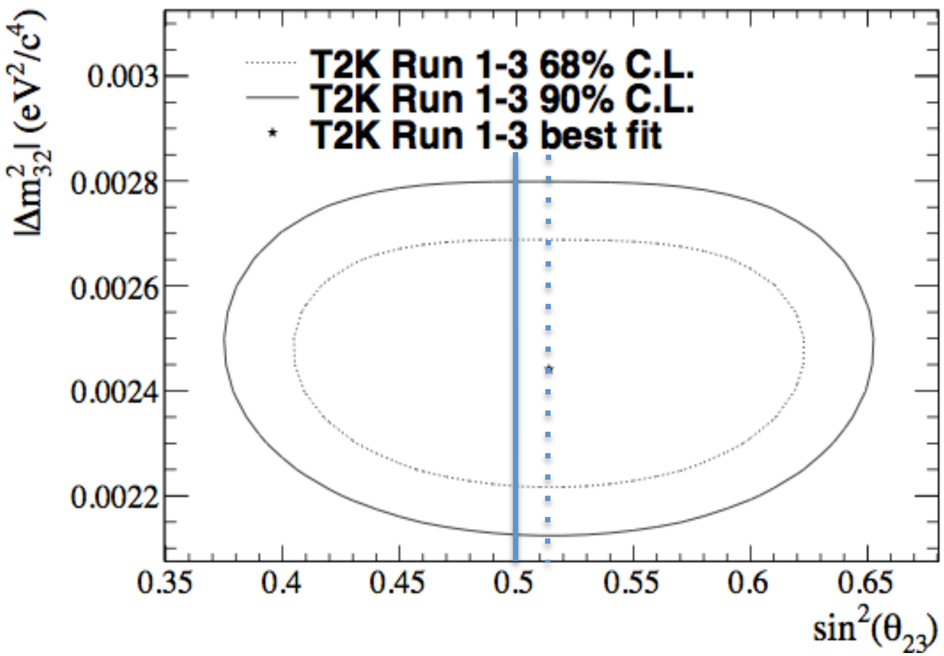


T2K ν_μ Results (Run I-III)

Shows the power of the off-axis technique!



Maximal mixing is not the same as maximum disappearance if θ_{13} is not zero!



	$\sin^2 2\theta_{23}$	Δm_{32}^2	χ^2 / ndf	N_{obs}	N_{exp}
$\theta_{23} \leq \pi/4$	1.000	2.44e-3	56.04 / 71	58	57.97
$\theta_{23} \geq \pi/4$	0.999	2.44e-3	56.03 / 71		57.92

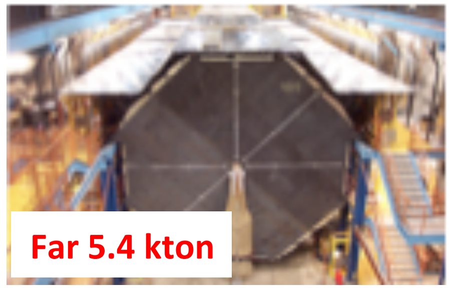
$\sin^2(\theta_{23})$ = 0.514
Δm^2_{32} = 2.44e-3 eV^2

$$P_{\mu\to\mu} \approx 1 - \sin^2(\Phi) + \sin^2(\Phi) 4\cos^4\theta_{13}\left(\sin^2\theta_{23} - \frac{1}{2\cos^2\theta_{13}}\right)^2$$

At reactor value: $\frac{1}{2\cos^2\theta_{13}} \approx 0.513$

New MINOS Results

T. VAHLE (W&M)

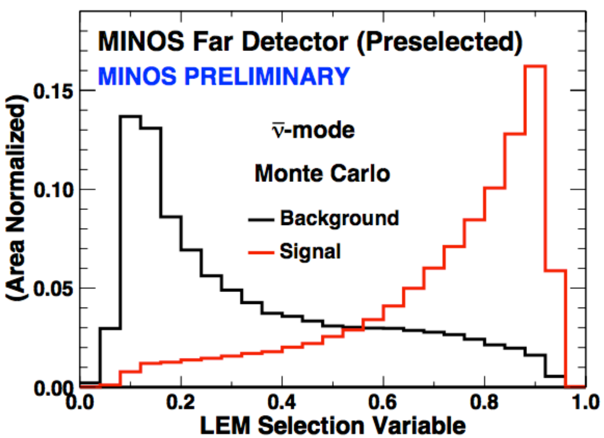


Updated results:

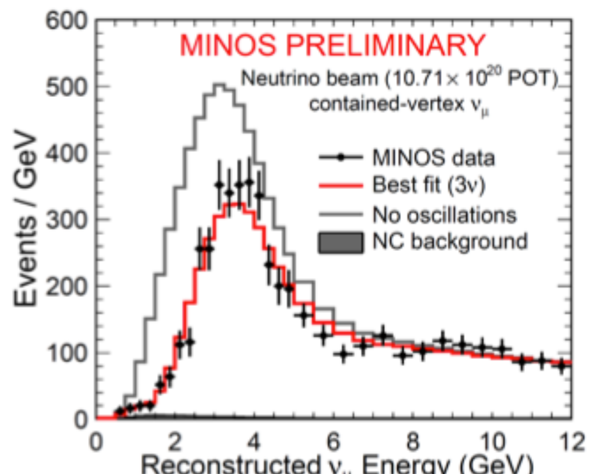
10.7 x 10^{20} pot neutrino
3.4 x 10^{20} pot anti-neutrino
37.9 kton-years atmospheric

Appearance:

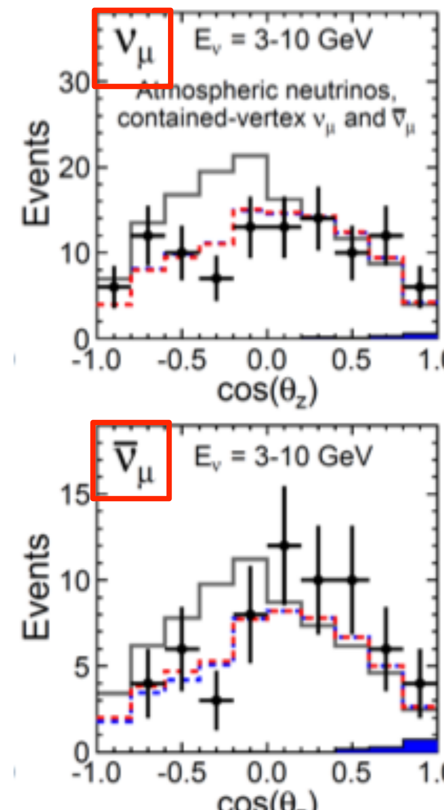
Use statistical separation based on a pattern matching library



Disappearance

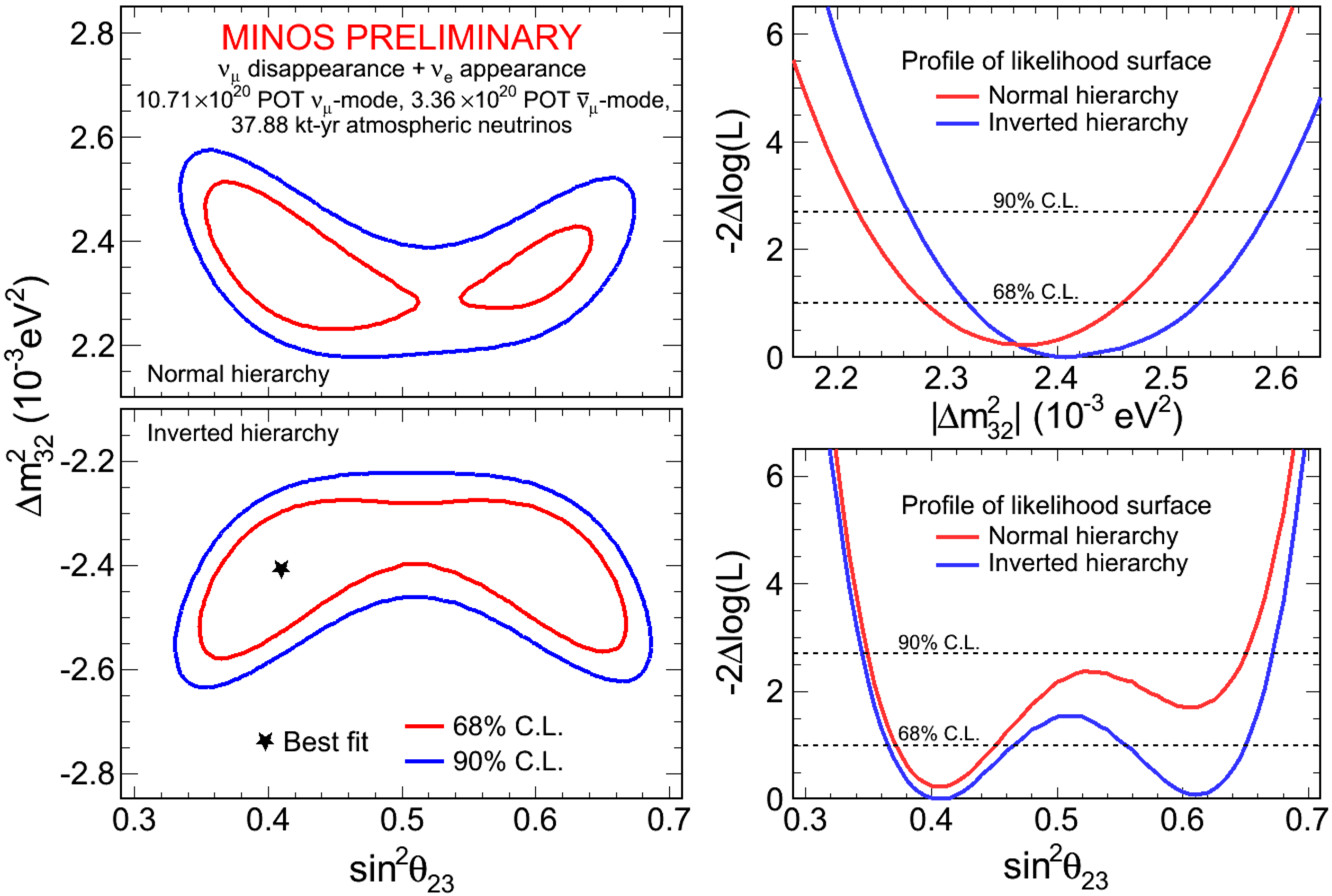


Atmospheric



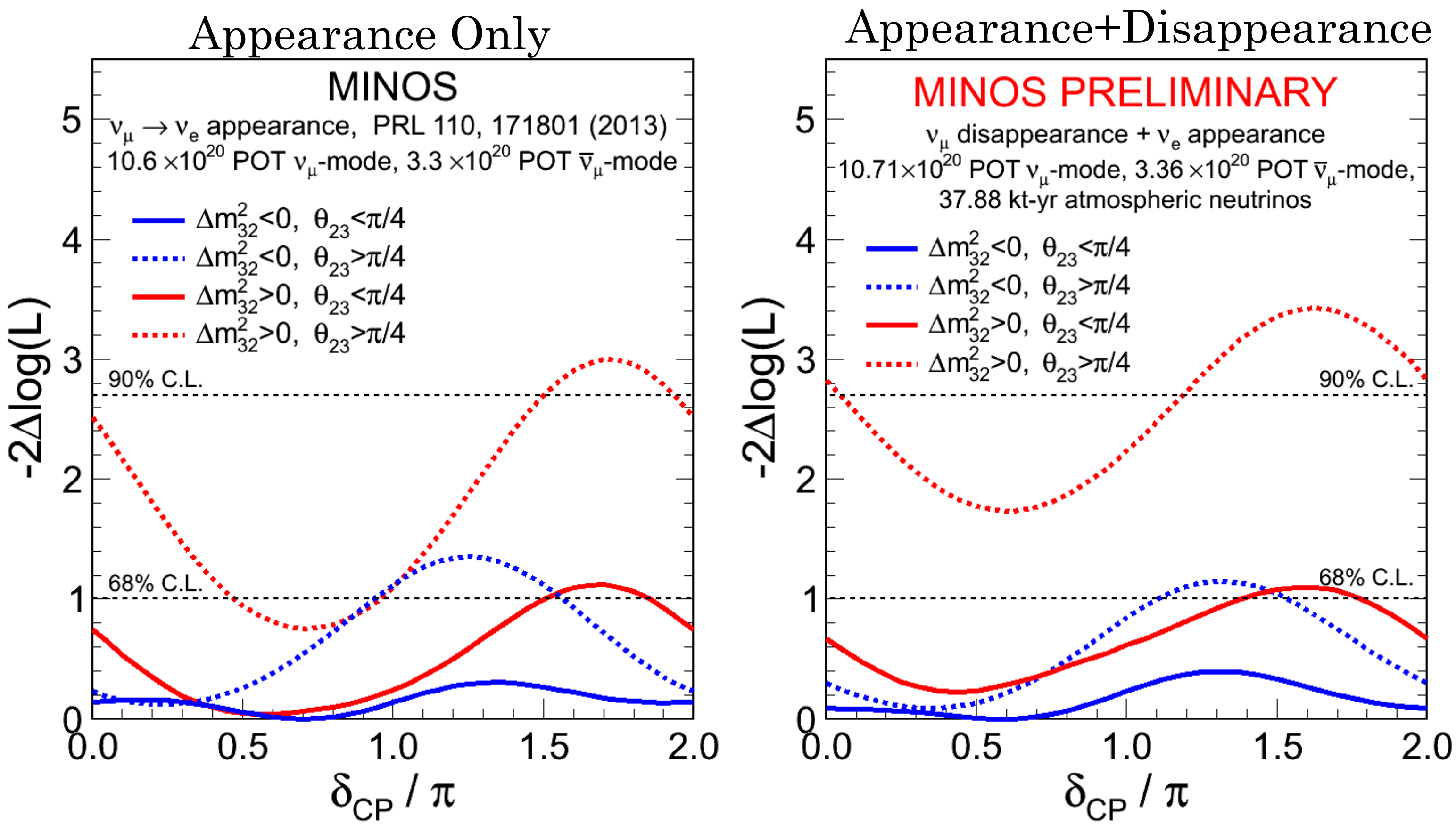
Combine Beam and Atmospheric data:

PUTTING IT ALL TOGETHER



- Solar mixing parameters fixed
- θ_{13} fit as nuisance parameter, constrained by reactor results
- δ_{CP}, θ_{23}, Δm^2 unconstrained
- major systematic uncertainties included as nuisance parameters

MINOS CPδ Dependence

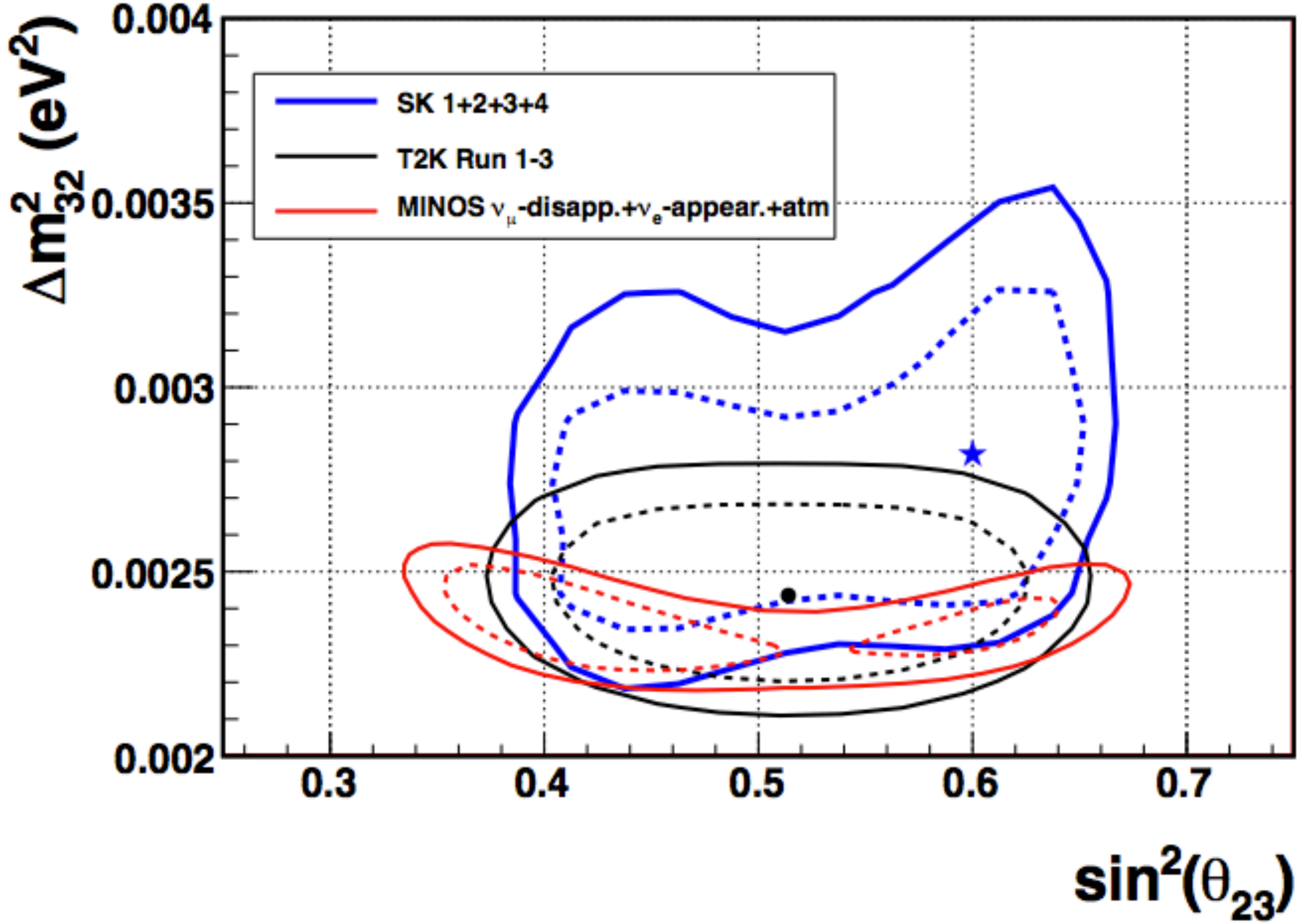


Preference for inverted hierarchy: $-2\Delta\log L = 0.23$

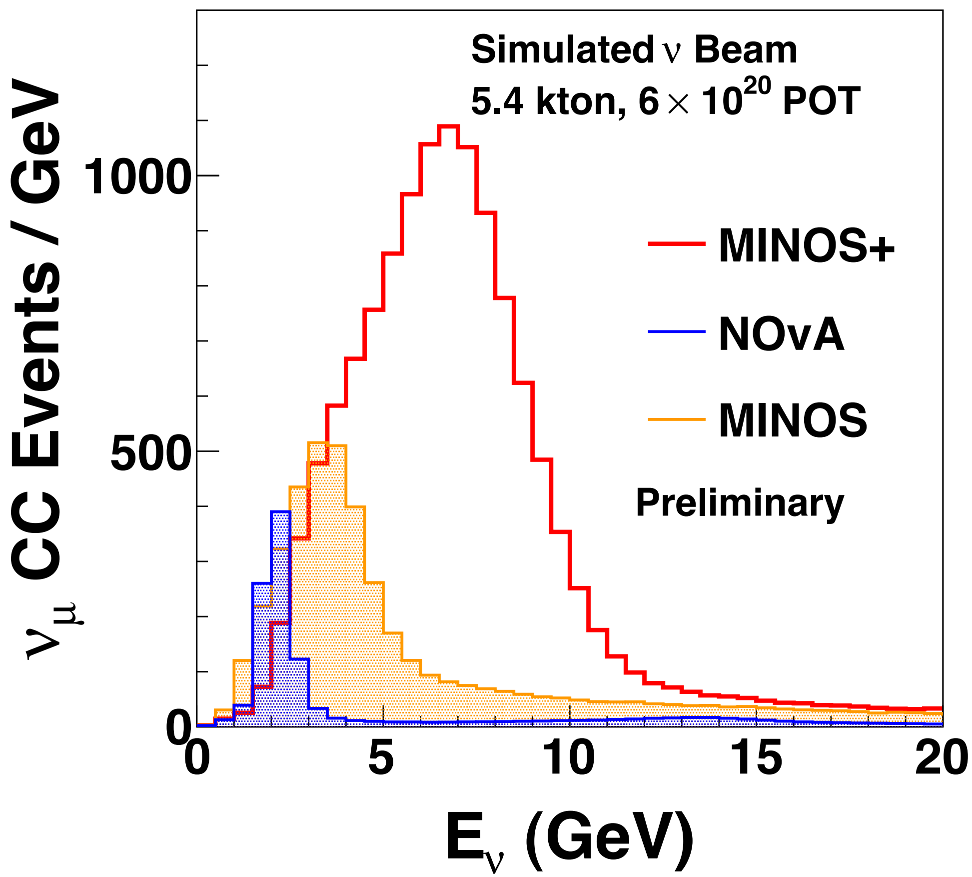
Preference for lower octant: $-2\Delta\log L = 0.09$

Preference for non-maximal mixing: $-2\Delta\log L = 1.54$ ($\Rightarrow$ 79% C.L.)

Let's compare experiments!

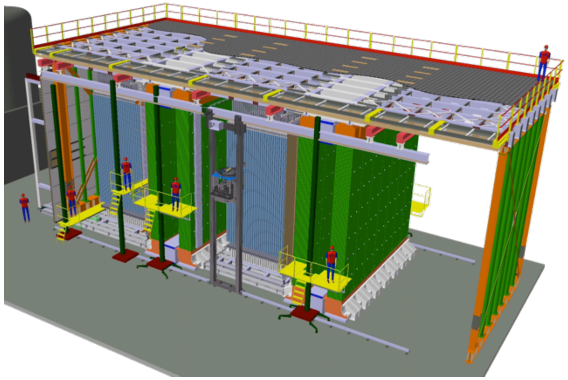


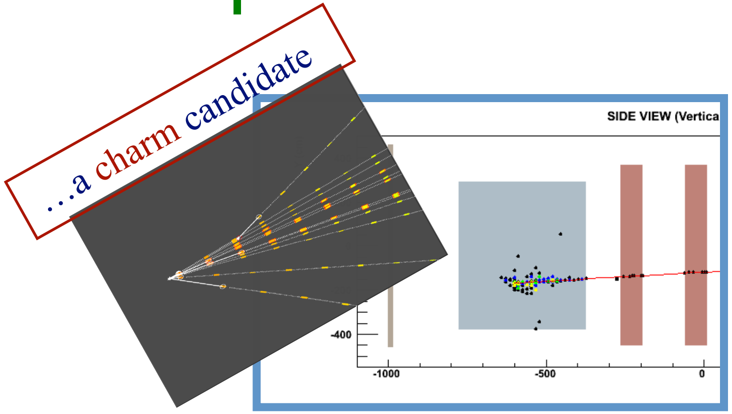
MINOS+ is coming….



- MINOS will continue to run in the NOvA era
- ME beam peaks above the oscillation dip on axis
- But they get a lot of events!
  - ~4000 muon neutrino CC events per year expected at FD
- Unique test of oscillation paradigm with sensitivity to exotic signals

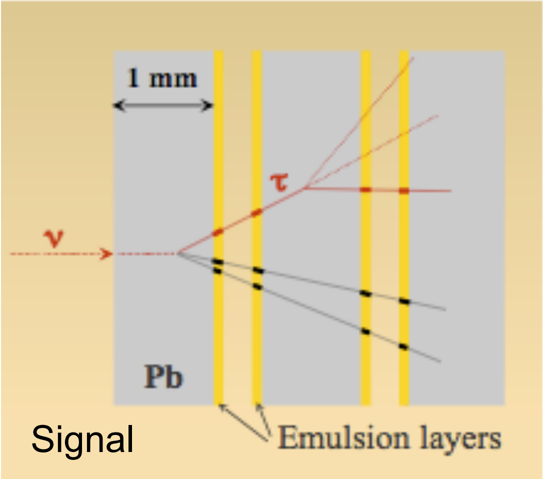
OPERA tau appearance experiment





Uses ECC (Emulsion Cloud Chamber)
With automatic scanning
+ Magnetic spectrometer.

Electronic trackers point
Back to bricks.



Ran from 2008 - 2012

3 observed events in the $\tau \rightarrow$ h, $\tau \rightarrow$ 3h and $\tau \rightarrow \mu$ channels

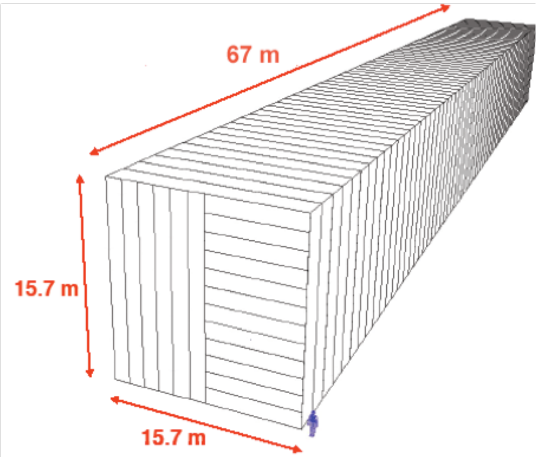
This corresponds to 3.2 σ significance of non-null observation (3.5 σ significance with a likelihood approach)

(also reported on nue search)

Nova – Low Z calorimeter

- 14 kton "totally active" **liquid** scintillator detector

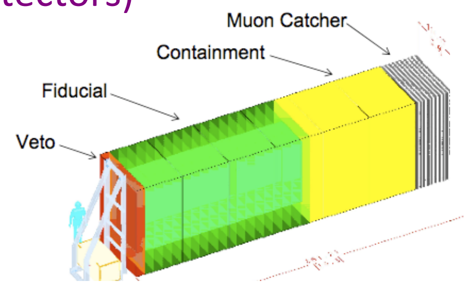
  Low Z tracking calorimeter: tracking + allow time for photons to convert and showers to develop.



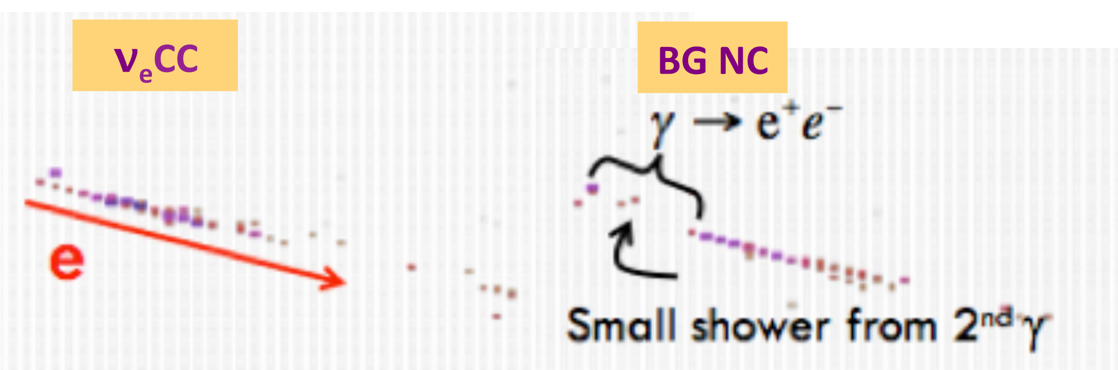
Low Z calorimeter

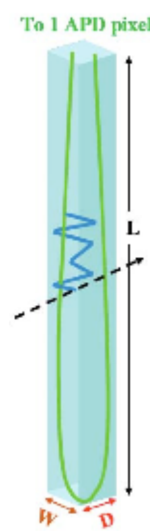
(near and far detectors)

No B field.



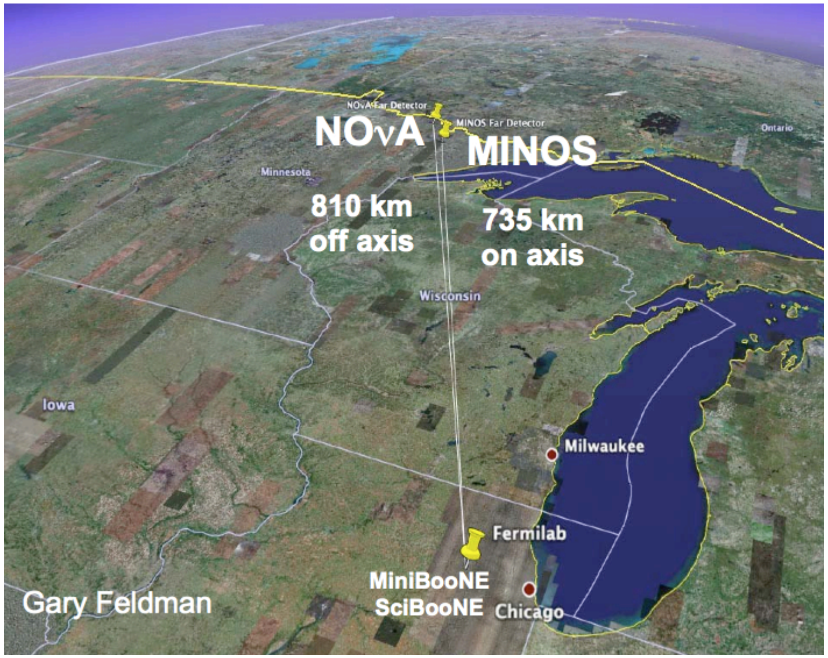
Nova is unique in current generation of experiments for addressing mass hierarchy using neutrino and anti-neutrino beams.

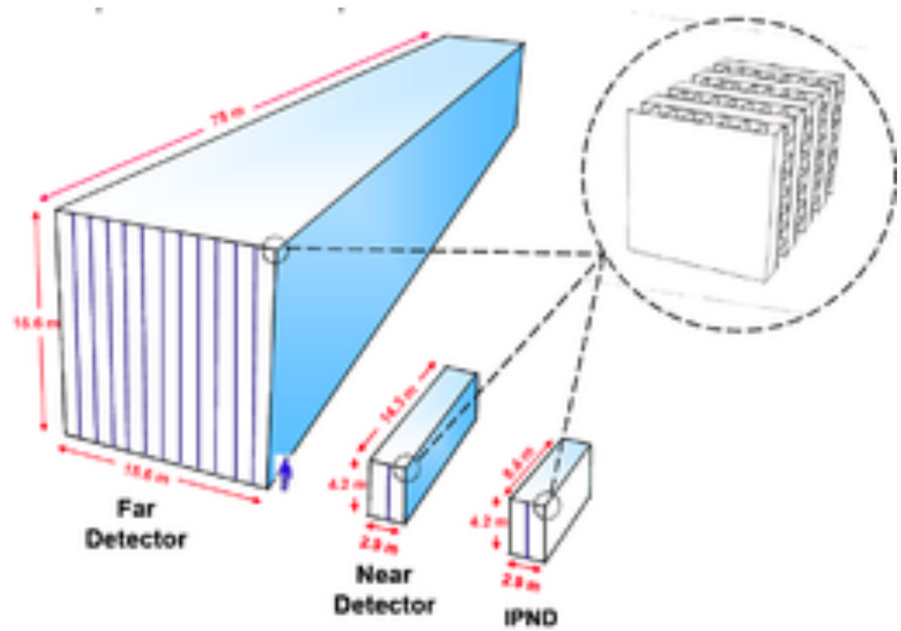


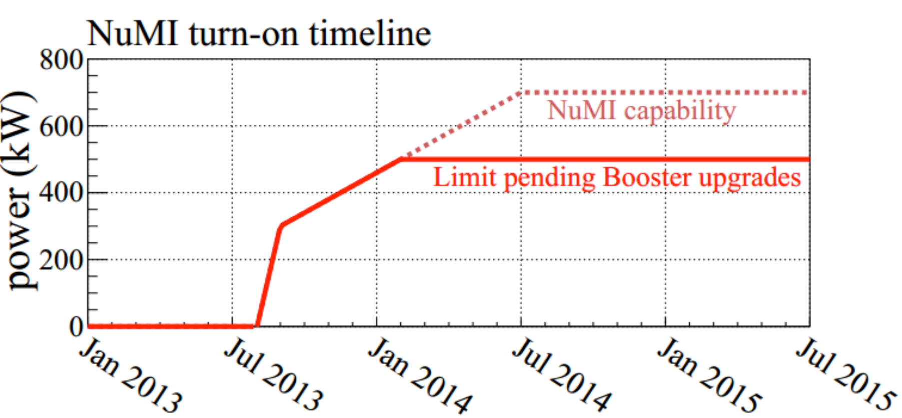


Uses an upgraded version of the current NuMi beam

The NuMi beam will be upgraded from 300 -> 700 kw.



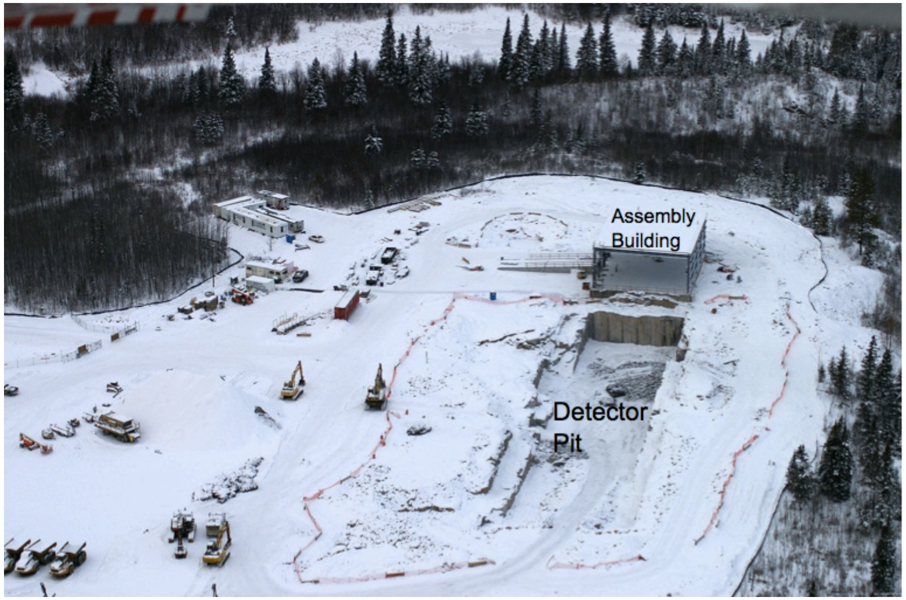


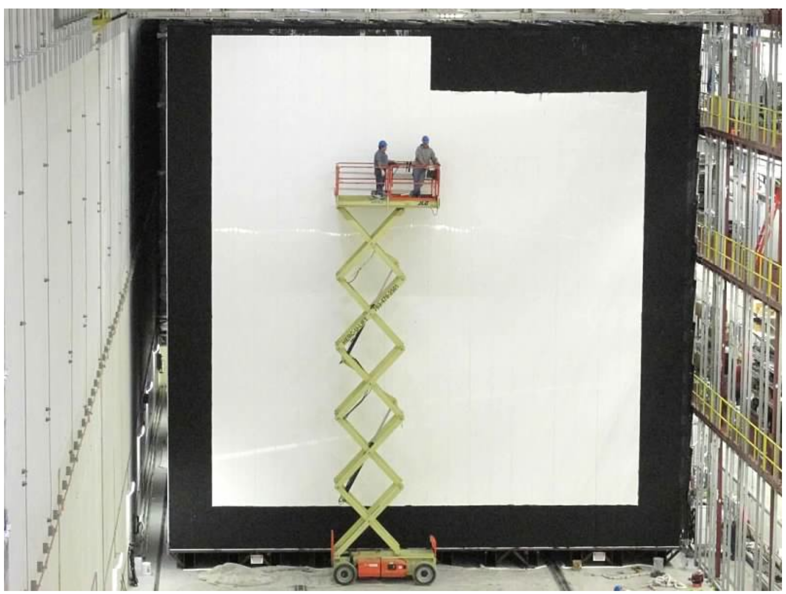


One of the largest devices ever constructed from plastic. There has been an impressive amount of R&D.

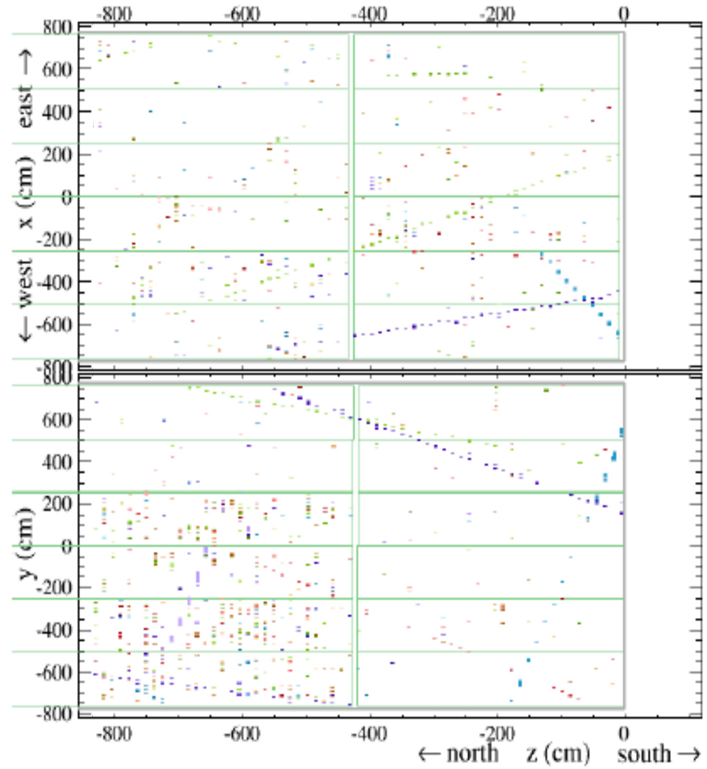
Beam turned on last week!

Detector Status





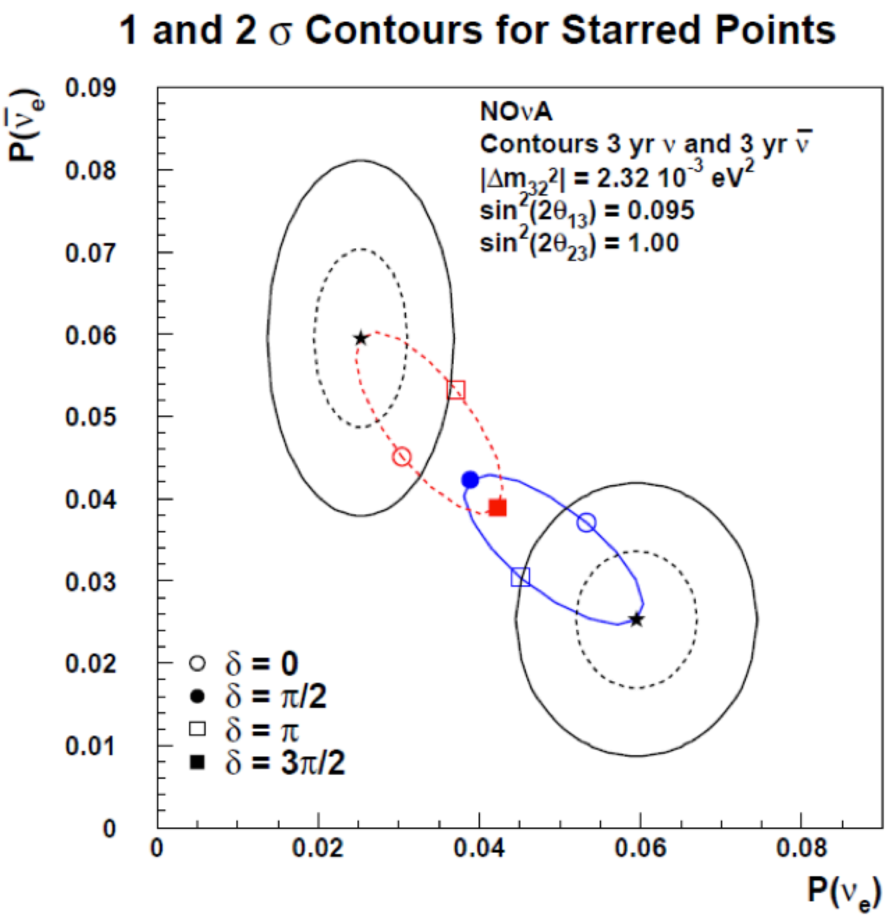
14 kilotons = 28 NOvA Blocks
20 blocks of PVC modules are assembled and installed in place
14.00 blocks are filled with liquid scintillator
4.17 blocks are outfitted with electronics

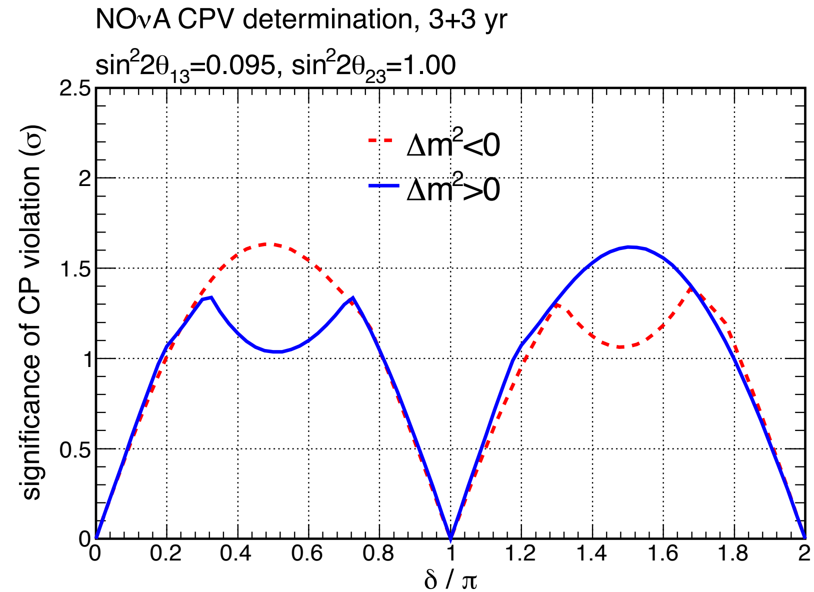


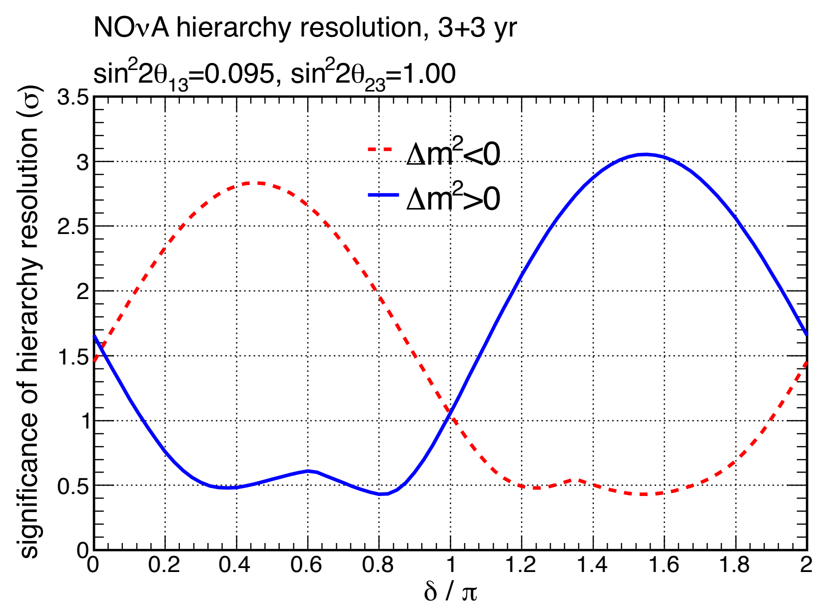
Cosmic Rays!

- Far detector completed ~May 2014
- First half near detector ready early 2014

Expected Nova Sensitivity

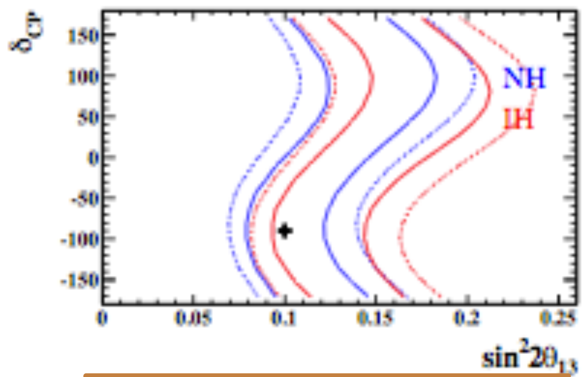




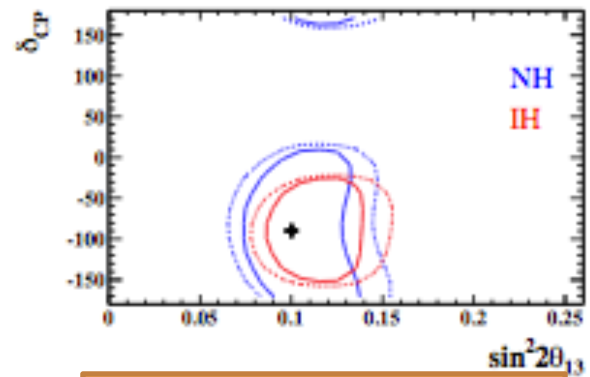


Expected T2K Allowed Regions

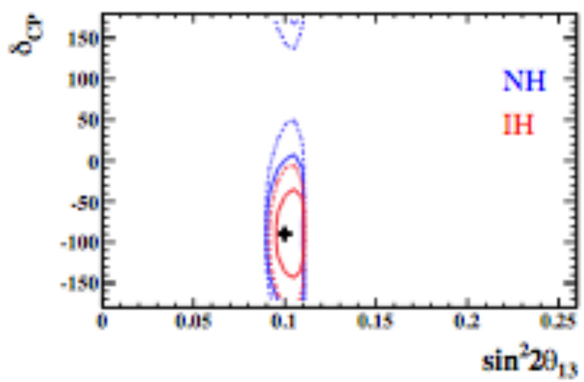
"Lucky! (δCP=-90)"



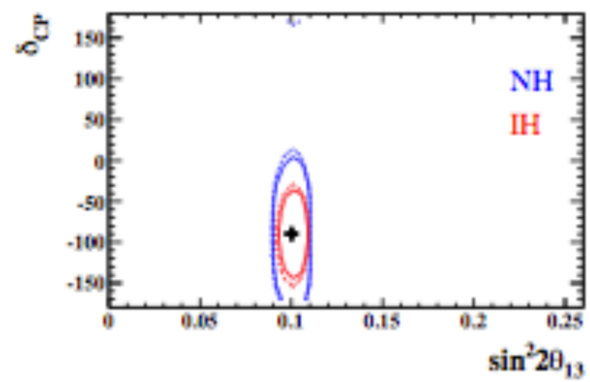
100% ν (true NH)



50% ν/50% anti-ν (true NH)



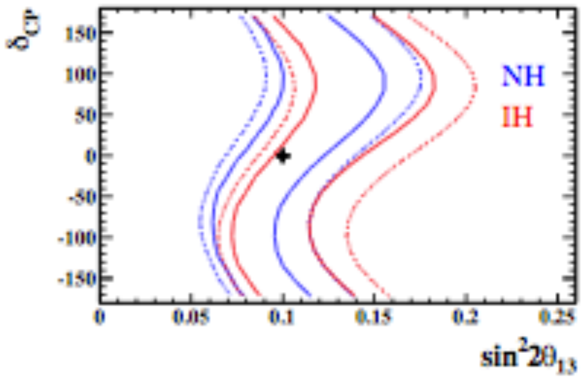
100% ν (true NH)
w/ Reactor constraint



50% ν/50% anti-ν (true NH)
w/ Reactor constraint

Expected T2K Allowed Regions

“Unlucky! (δCP=0)”



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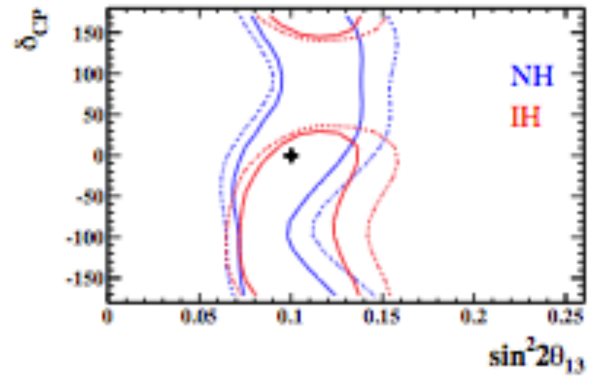
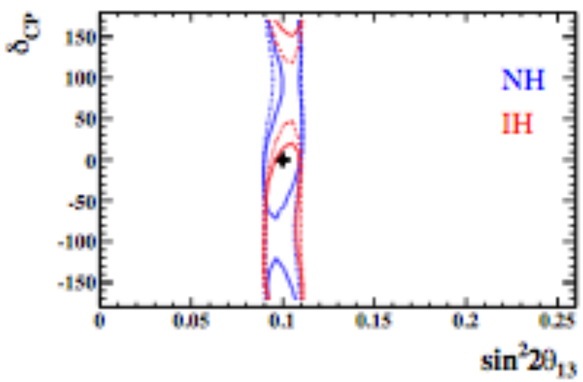


50% ν/50% anti-ν (true NH)



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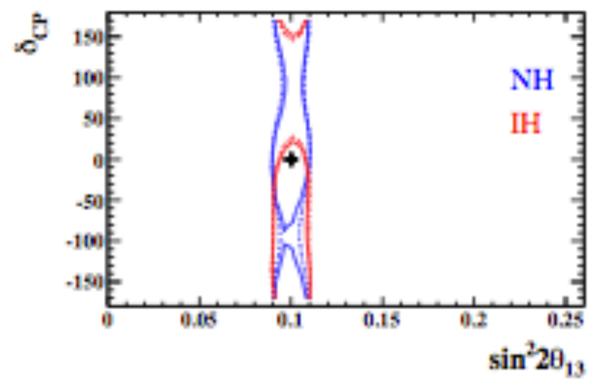
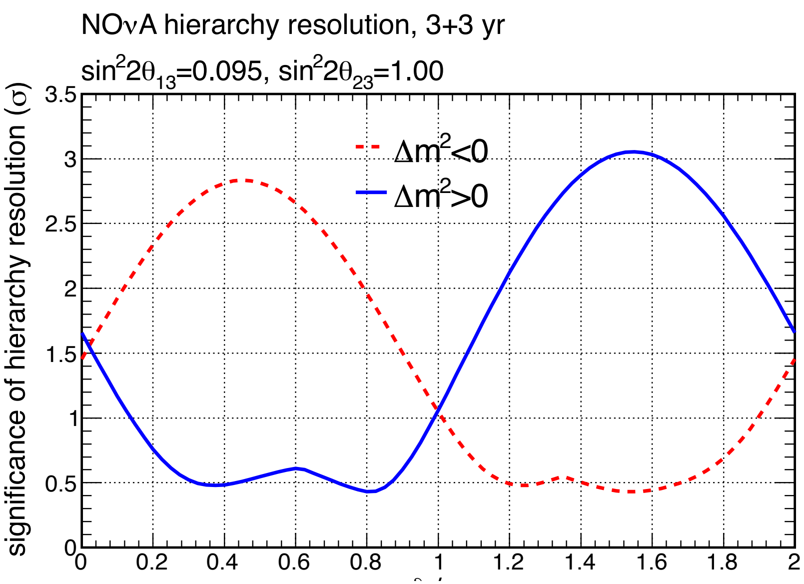
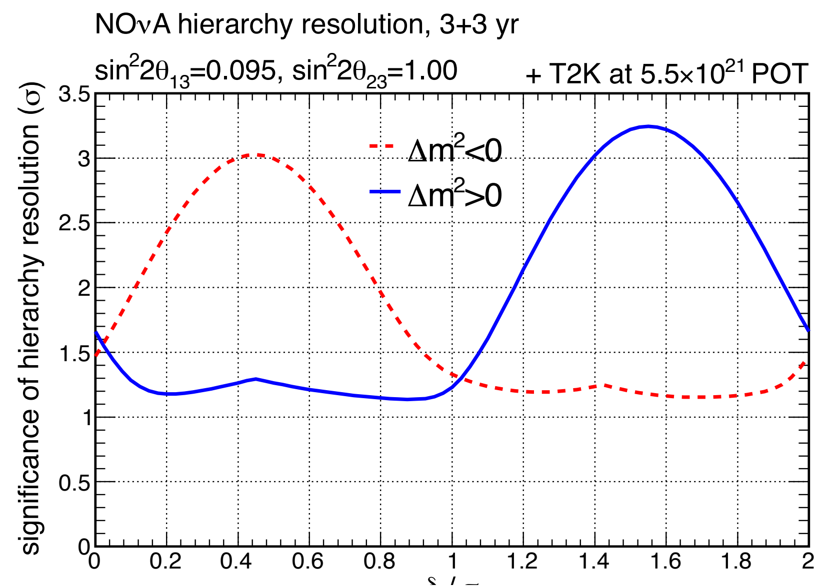
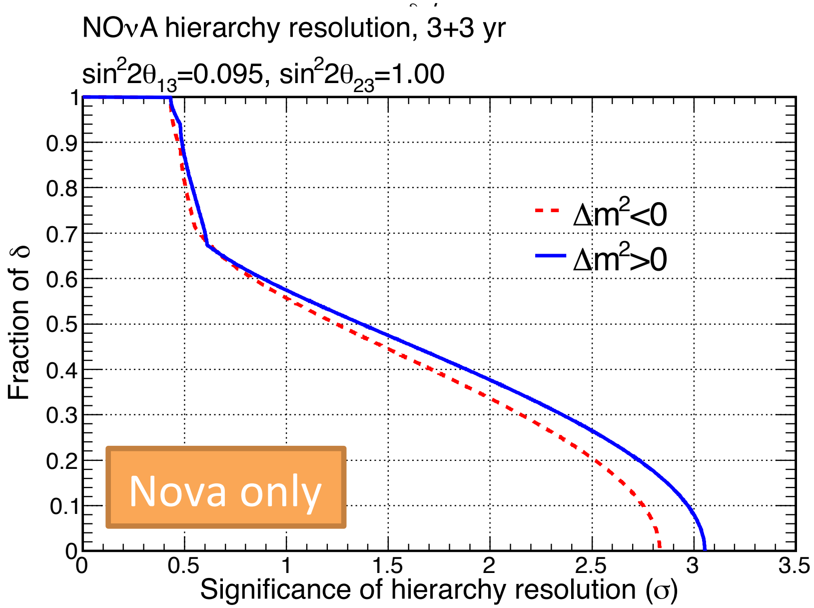


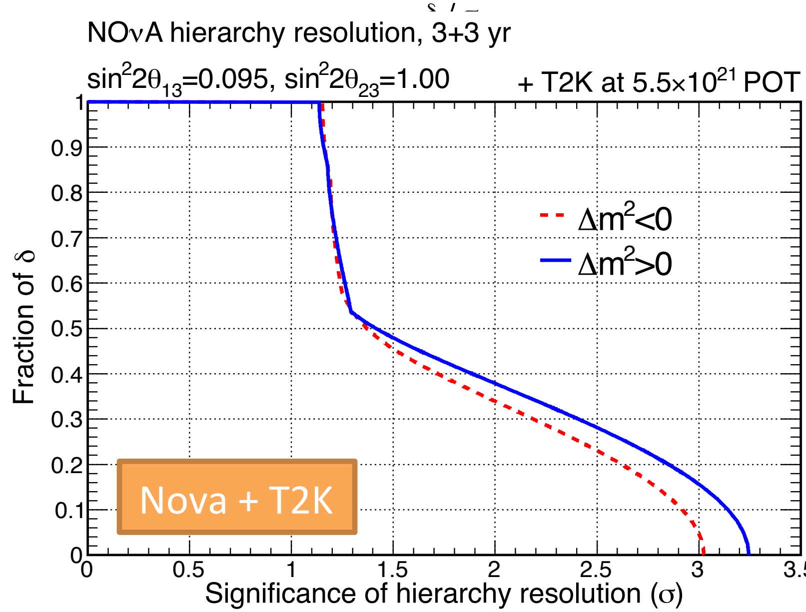
50% ν/50% anti-ν (true NH)
w/ Reactor constraint

MH using T2K and Nova



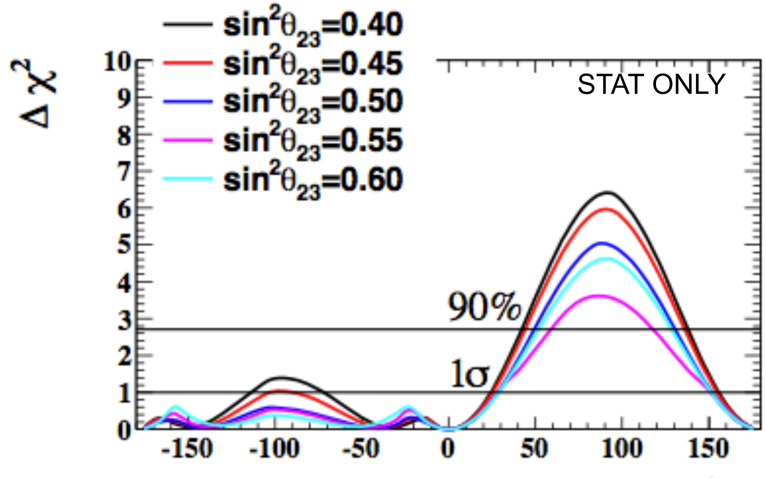


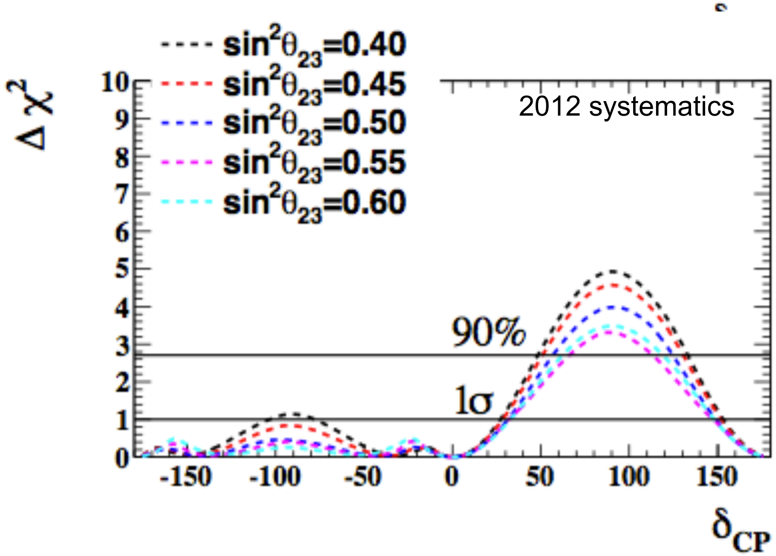


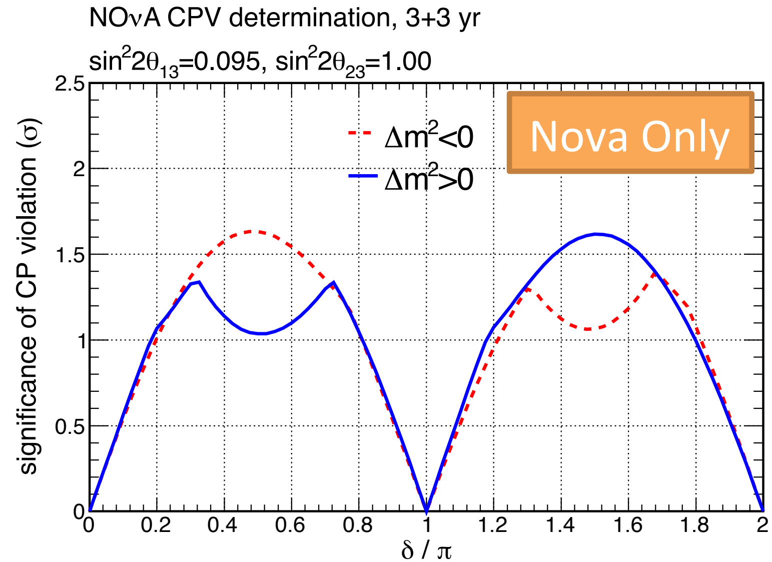


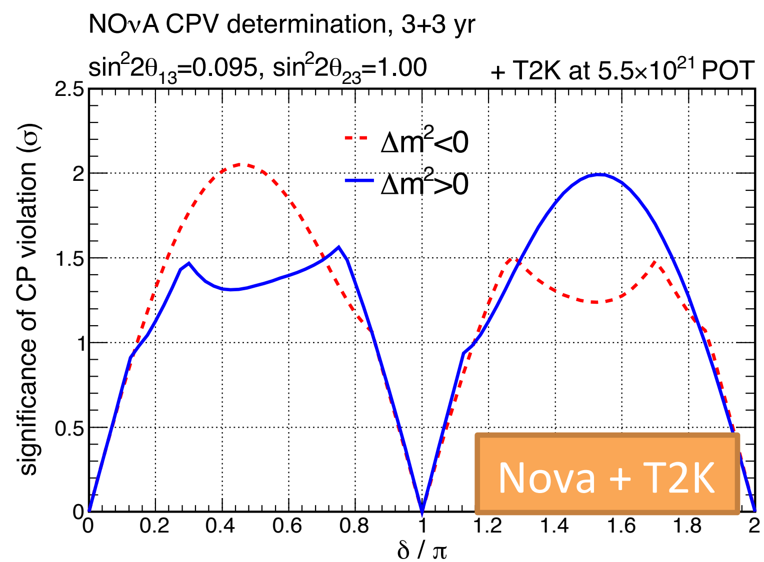
CPV using T2K and Nova

T2K only 50% ν/50% anti-ν









Accelerator Neutrino Physics II: Long-term vision

Our Strategy

Since we have measured θ_{13} we need to (with high accuracy):

- Measure the phase of δ and hopefully observe CP violation
- Determine the mass hierarchy [if not already done]
- Make precision measurements of the mixing angles.

To do this we need to both increase the intensity of our Super-beam sources, and increase the mass of our detectors.

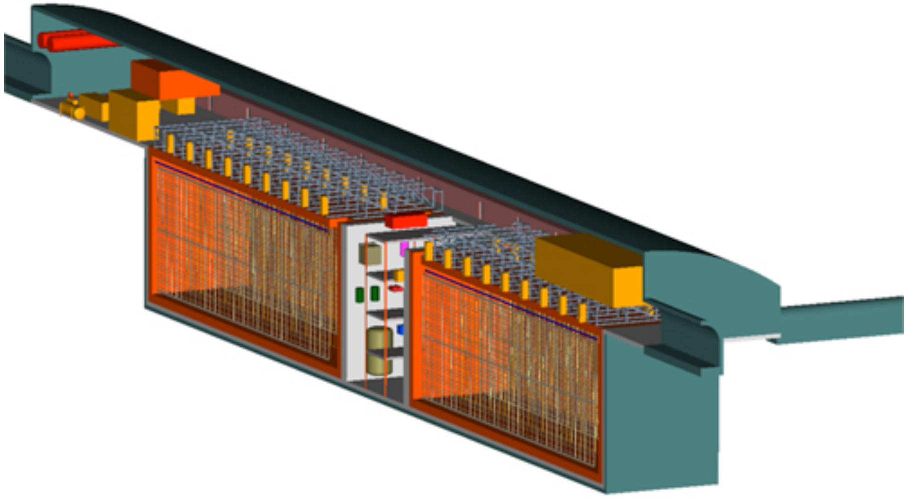
	Now or Soon	Glorious Future
J-PARC	0.75 MW (T2K)	JPARC-II to Hyper-K
FNAL (Numi)	0.70 MW (Nova)	New beam -> LBNE
	→	
Water Cherenkov	22.5 kton (SK)	560 kton
Fine Grained	14 kton (NOνA)	34 kton (LAr)

http://arxiv.org/abs/1307.7335

The LBNE Experiment

- A new neutrino beam at Fermilab
  - 700 kW, 60-120 GeV proton beam, 2.3 MW capable
- A near neutrino detector
- A 1300 km baseline: Fermilab-SURF
- A 34 kt Liquid Argon TPC with 4850' overburden

The LBNE detector and scoping



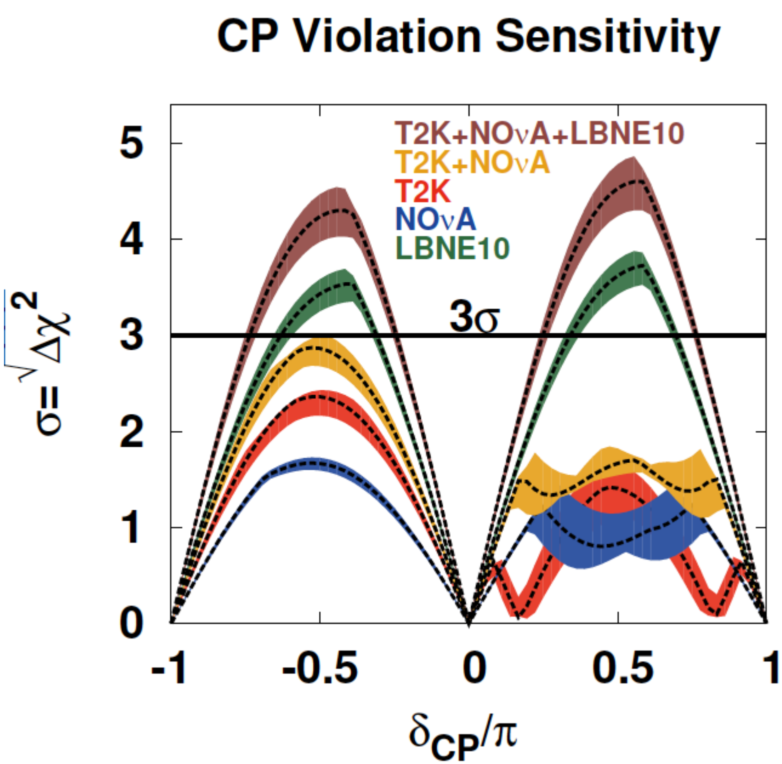
34 kton liquid Argon TPC
two 17 kton TPCs
Located underground at SURF

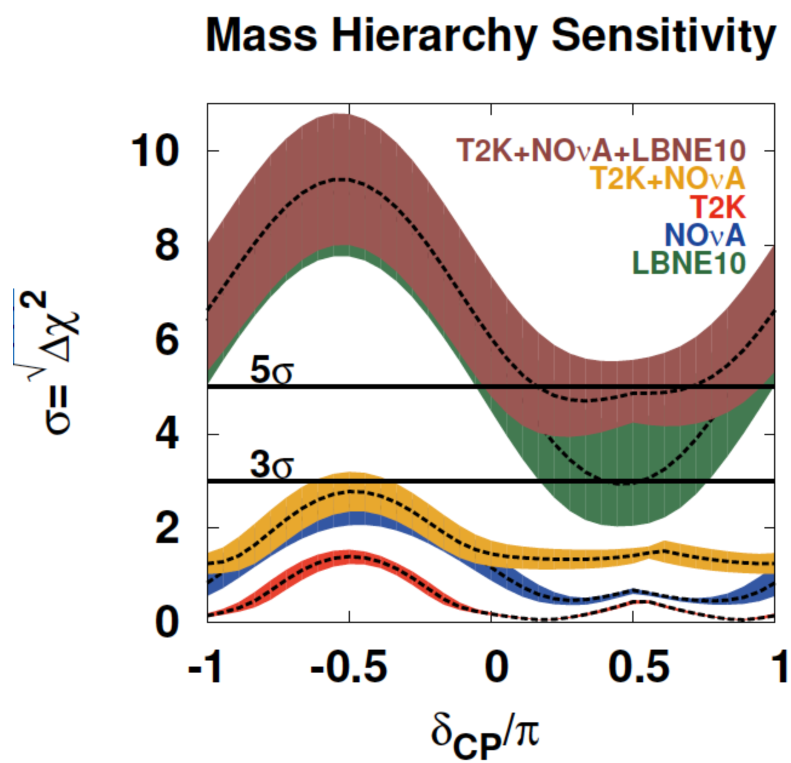
Current situation:

The experiment is funded for a 10 kton far detector on the surface.

In discussion with international partners to make the detector bigger and put it underground along with adding a near detector complex.

LBNE 10kt Sensitivity





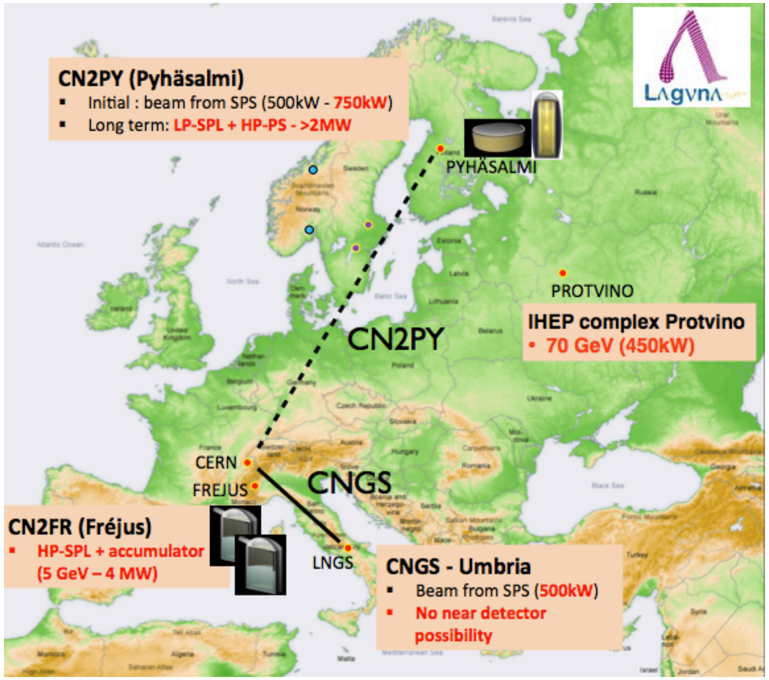
Bands: 1σ variations of θ_{13}, θ_{23}, Δm_{31}^2 (Fogli et al. arXiv:1205.5254v3)

T2K 750 kW x 5 yr ($7.8\text{x}10^{21}$pot) ν

NOνA 700 kW x (3 yr ν + 3 yr $\bar{\nu}$) (3.8 $\text{x}10^{21}$pot)

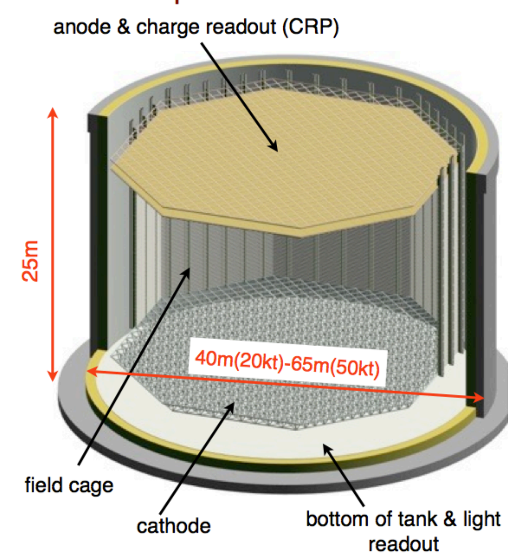
LBNE10 (80 GeV*) 700 kW x (5 yr ν + 5 yr $\bar{\nu}$) *Improved over CDR 2012 120 GeV MI proton beam

The LBNO Experiment



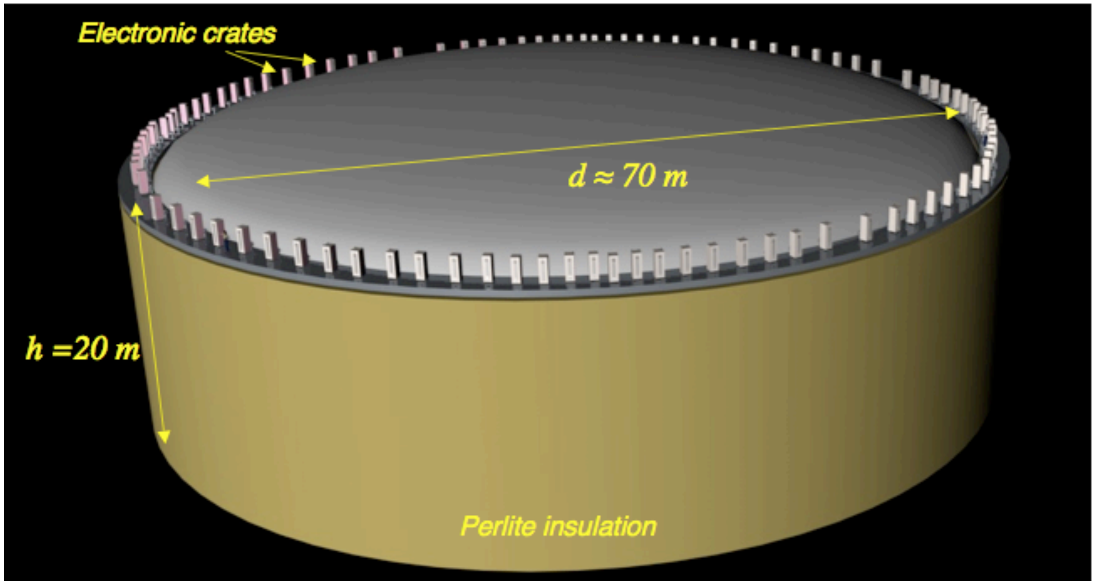
- Laguna was EU FP program to design a unification and neutrino astrophysics program in Europe.
- Several sites and detectors technologies were considered and the LBNO program was one of the products of the process.

✤Double phase LAr LEM TPC

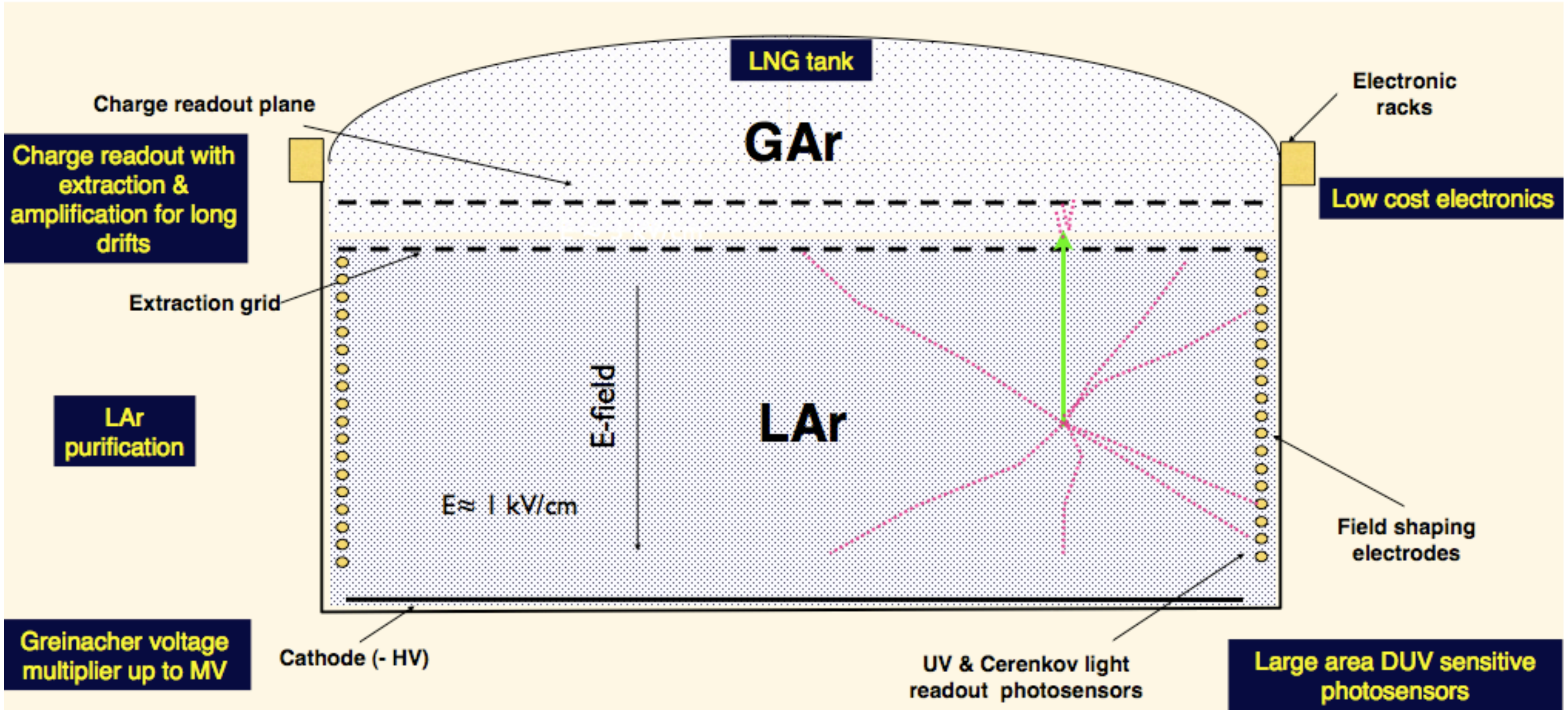


- **An incremental long-baseline program with a competitive 1st stage guaranteeing high level physics performance from the beginning.**
  - LBNO Stage 1 is based on a 20 kt fid. LAr detector (double phase) and a conventional beam from the CERN SPS of 700 kW at 2300 km.
  - If the findings from Stage 1 require, the detector and the beam will be upgraded to 70 kton mass and 2 MW proton power.
- **The costs, possible implementation schemes and physics potentials will be further studied until the end of 2014** (current preliminary estimates: ≈700M€ for underground 70kton LAr + cavern facility at Pyhäsalmi)
- **Proposed next step: Large-scale detector prototyping with CERN support, with priority emphasis on a large double-phase LAr demonstrator, using charged-particle test beams.**

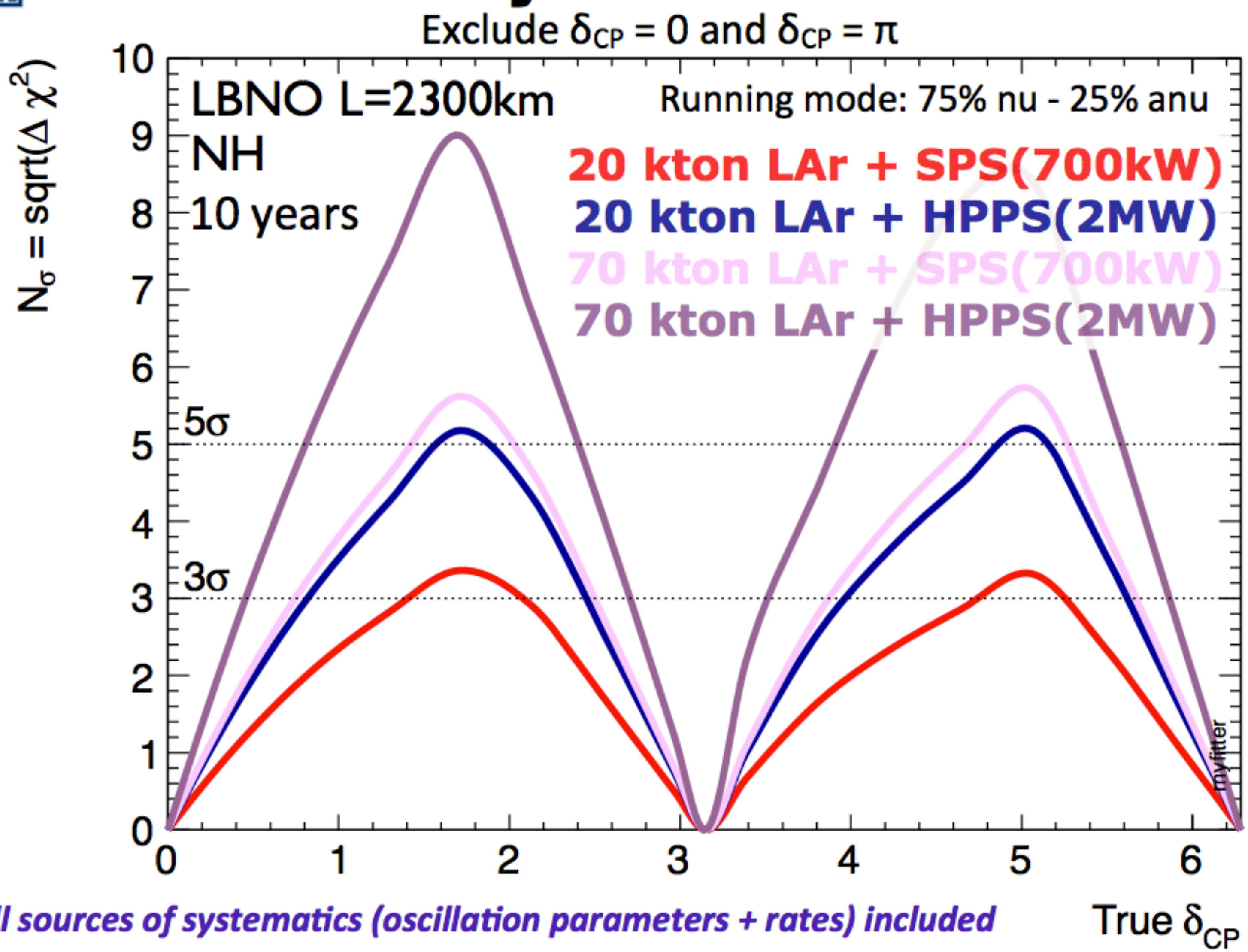
Glacier



A different approach: LNG tank based detectors.

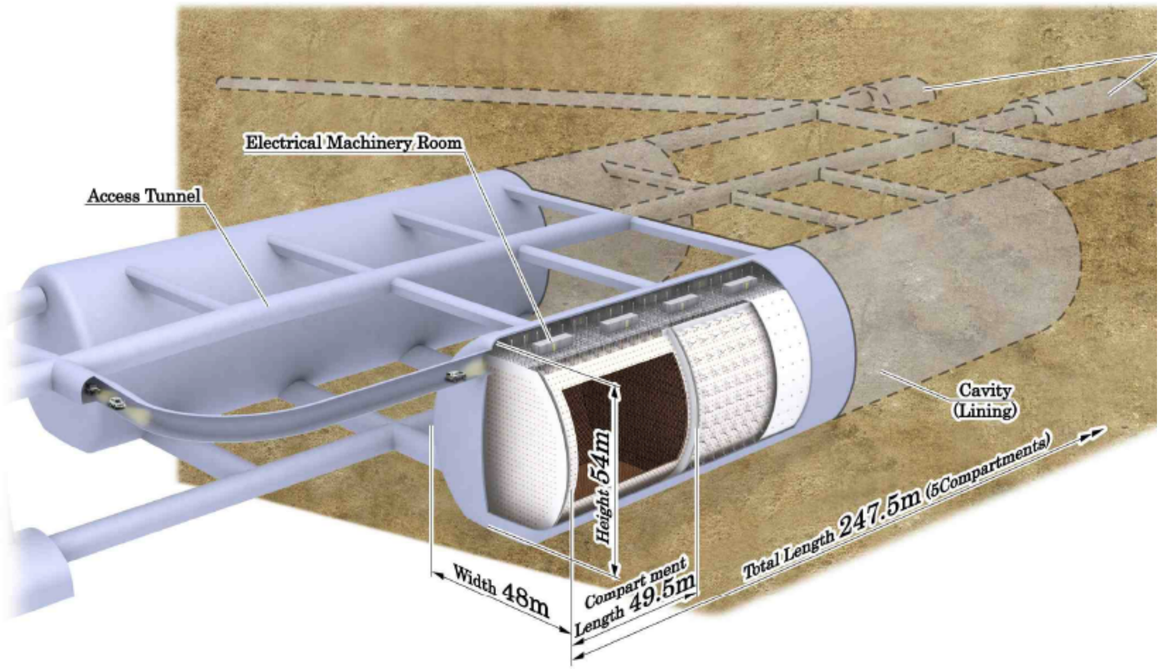


Sensitivity to CP violation



All sources of systematics (oscillation parameters + rates) included http://arxiv.org/abs/1109.3262v1

The Hyper-Kamiokande Experiment



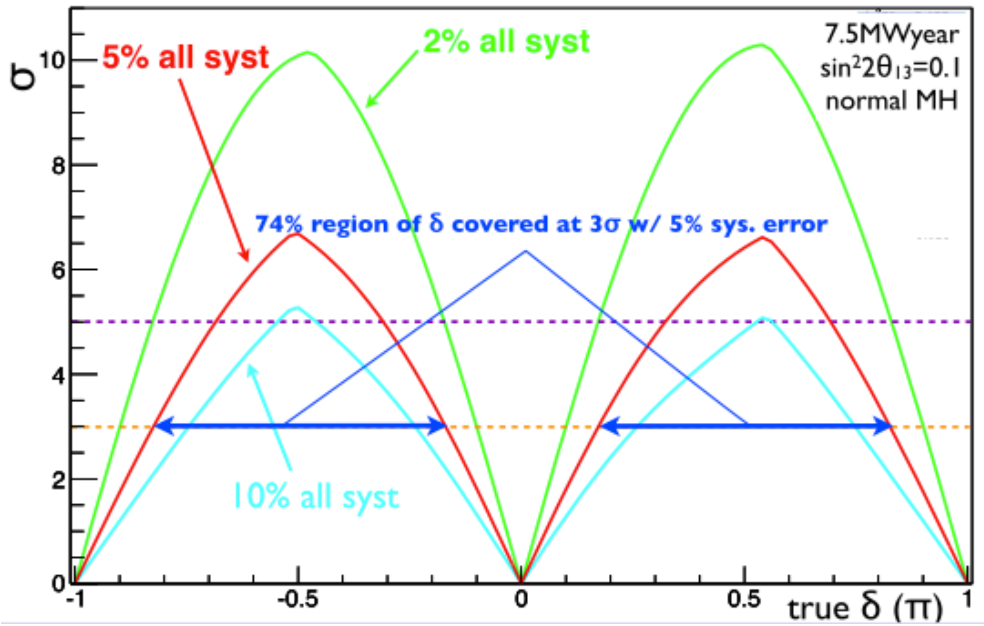
- 560 kton fiducial mass
- 99000 PMTs 20% coverage
- Outer veto detector

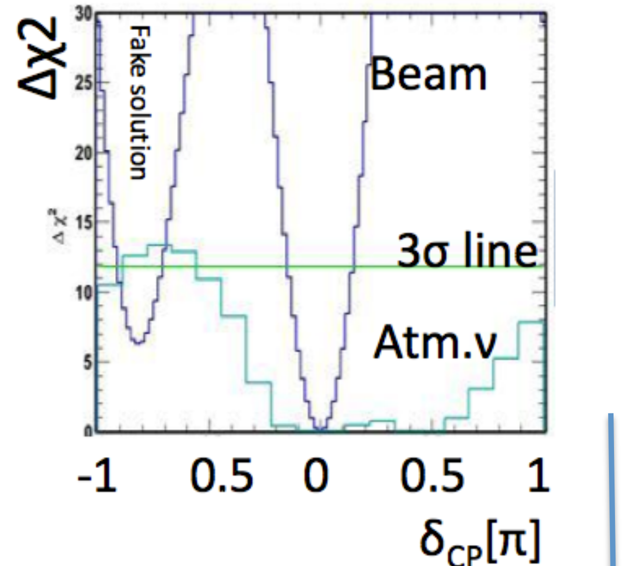
- Sensitivity studies scale SK result to large exposure, i.e. assume the same detector performance

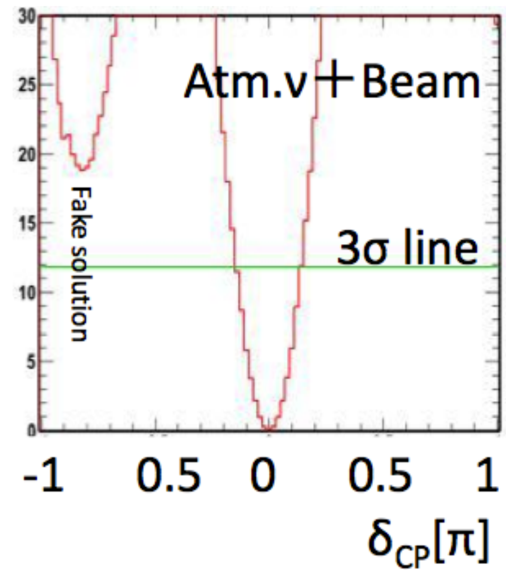
Running SK for another 10 years will get us 85% of 1 HK year.

- Uses an upgraded JPARC beam
- Sent to Hyper-K 1 Mton water Cherenkov detector in Kamioka

Hyper-Kamiokande Sensitivity



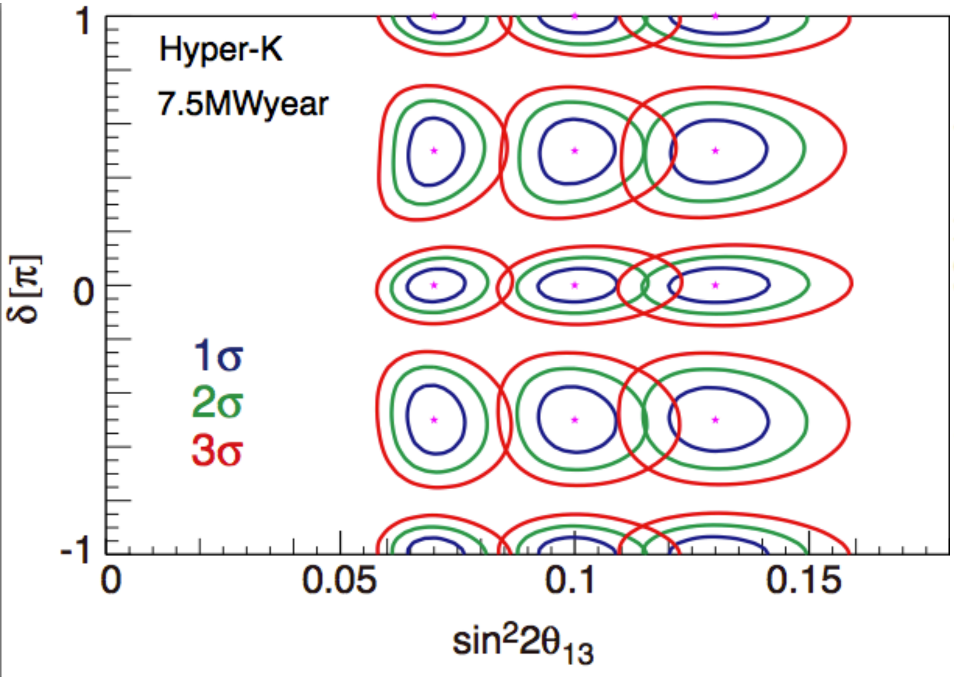




Systematics are key in these experiments!

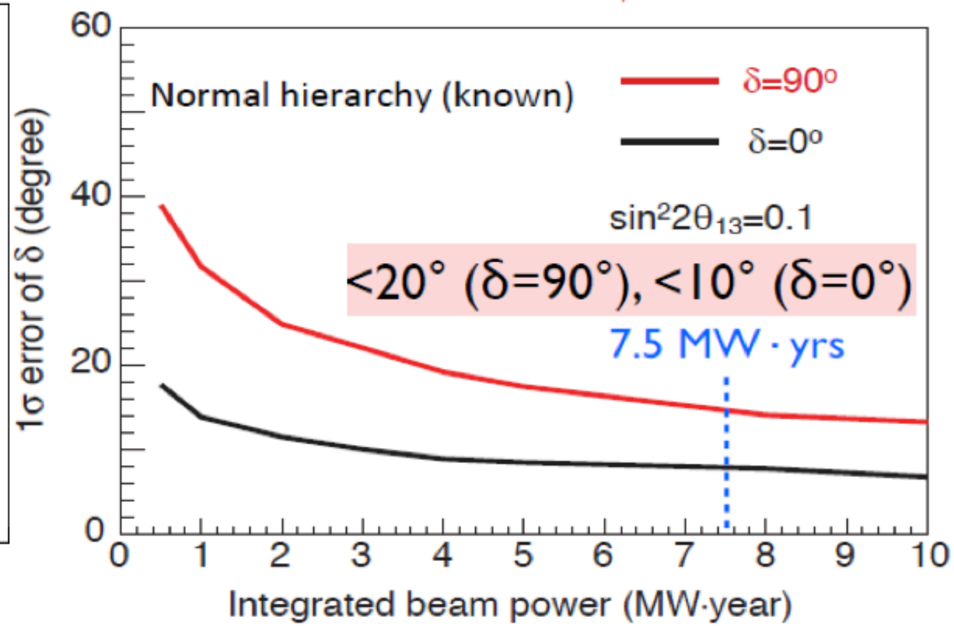
Note: In HK atmospheric neutrinos can be used to constrain MH.

Measuring zero δCP is not a failure!



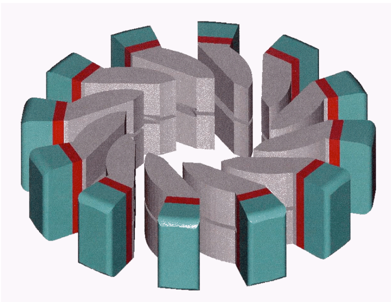
δ_{CP} resolution (1σ)

assuming 5% systematics on signal, ν_μ BG, ν_e BG, ν/anti-ν

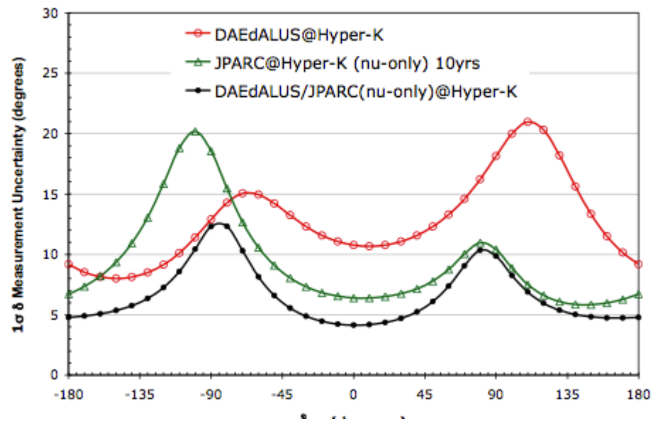


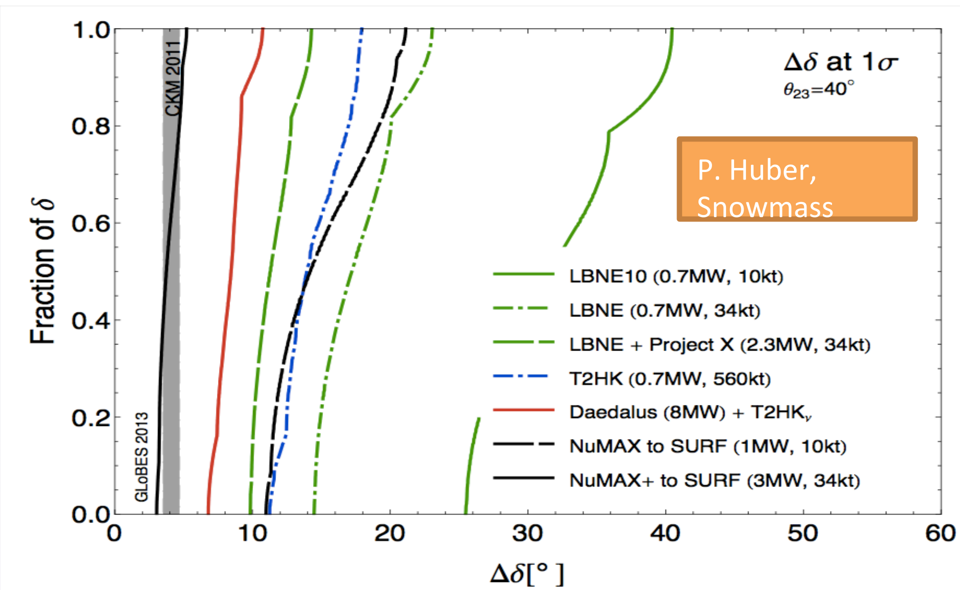
Long term reach / other options

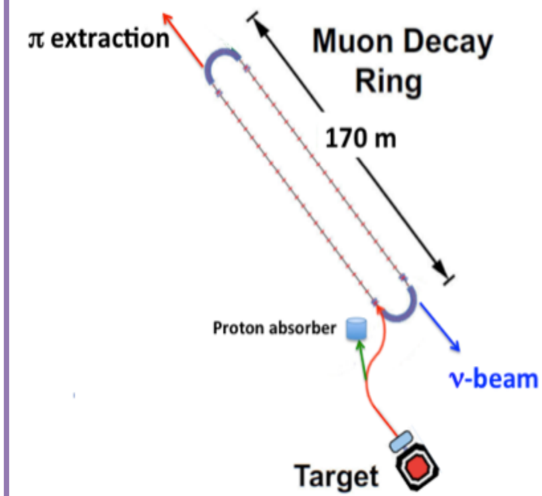
DAEδALUS



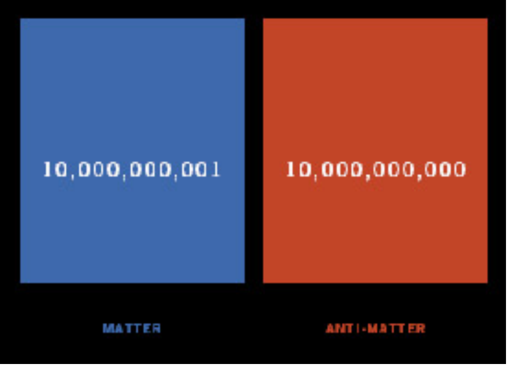
M. Toups (MIT)



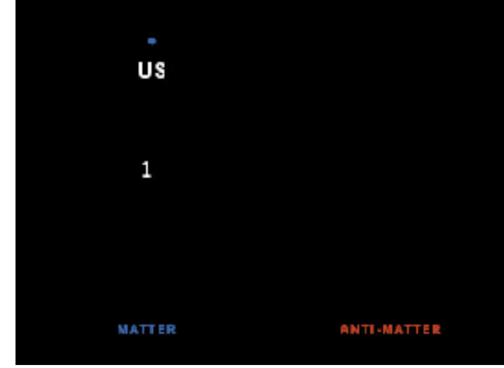




nuStorm:
Muon Storage ring experiment gets electron and muon neutrinos with a enormous flux.



Conclusion



$\sin^2 2\theta_{13}$ is now known to be non-zero! Accelerator experiments have measured an appearance signal. Values will get even more precise.

Now we can check the full consistency of our models using accelerators, atmospheric neutrinos and reactors. Let's keep working hard, and and try to measure CPV!