MINOS(+) and perspectives from US

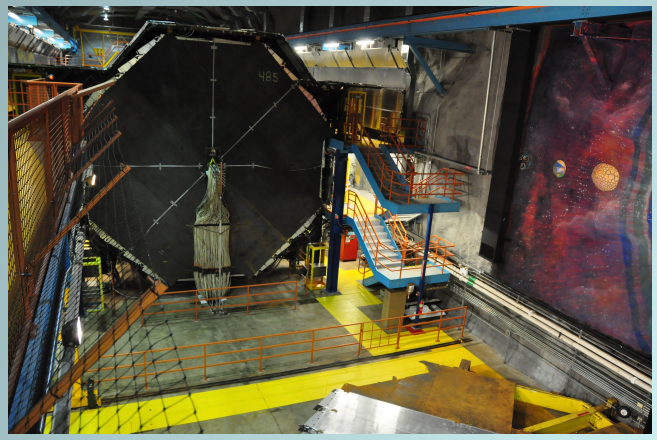
22/10/12

Lyon

Jenny Thomas, UCL

- Recent results from MINOS
- MINOS+ & NOνA
- Potential future NuMI plans
- Summary and Personal Note

The MINOS(+) Experiment



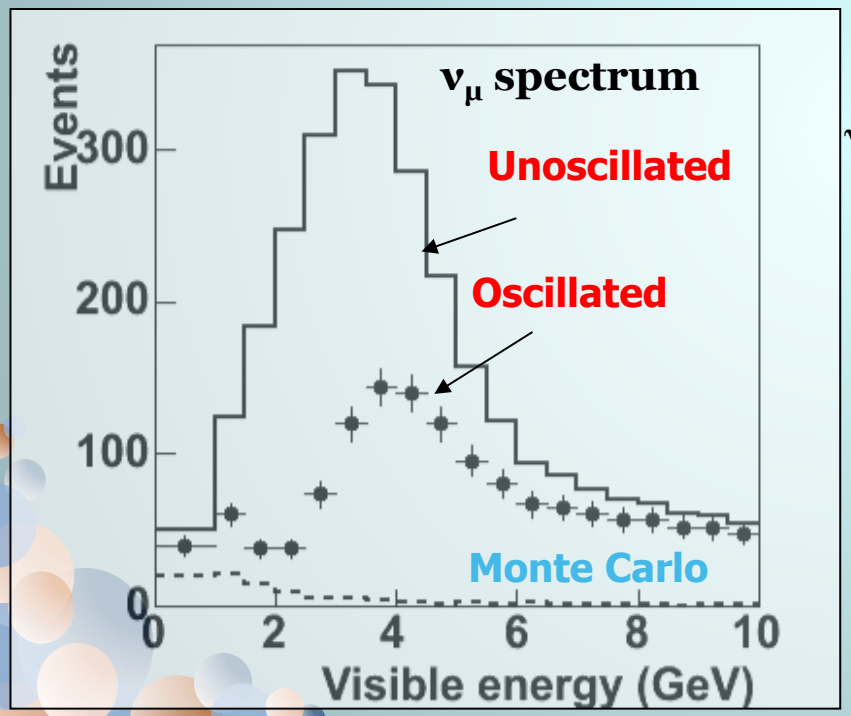
- Two detectors mitigate systematic effects
  - beam flux mis-modeling
  - Neutrino x-sec uncertainties
- L/E ~150-250 km/GeV
- Magnetized:
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-

- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
    - 1 GeV muons penetrate 28 layers
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)

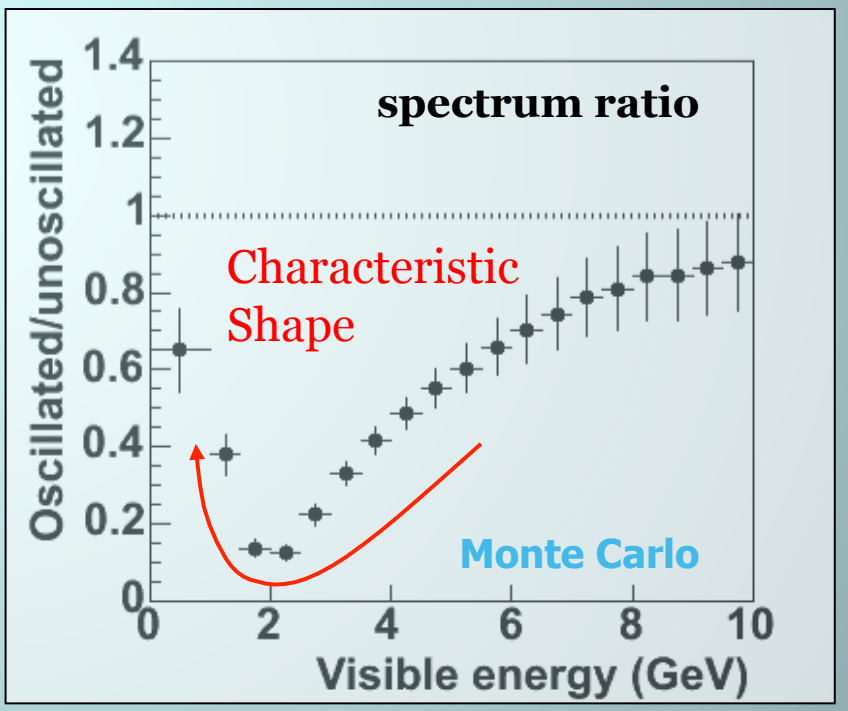
ν_μ disappearance

- Predict un-oscillated spectrum at the further detector using the nearer detector and knowledge of kinematics

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$



ν_e



(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV^2 **)**

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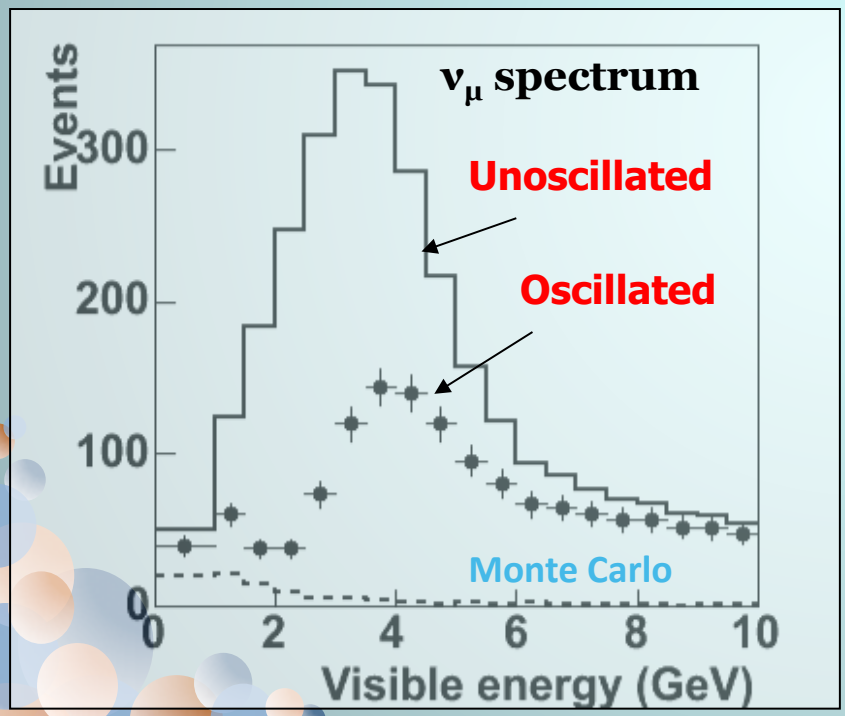

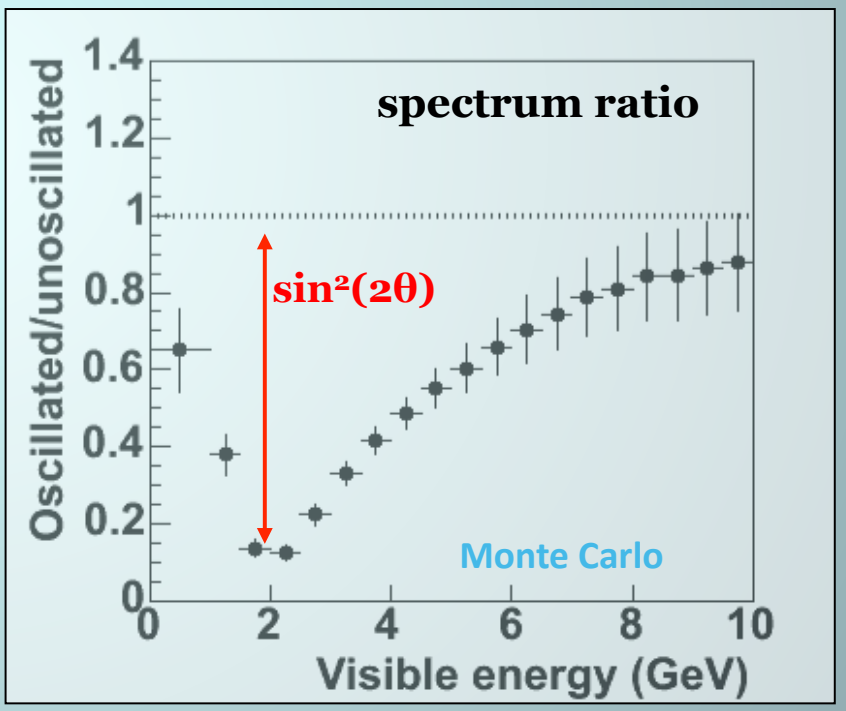

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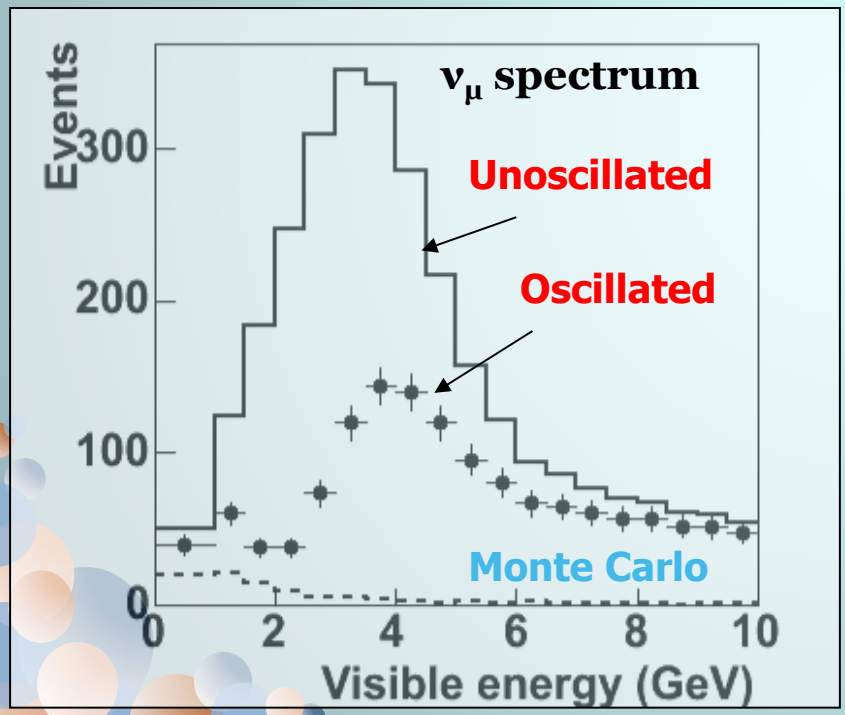

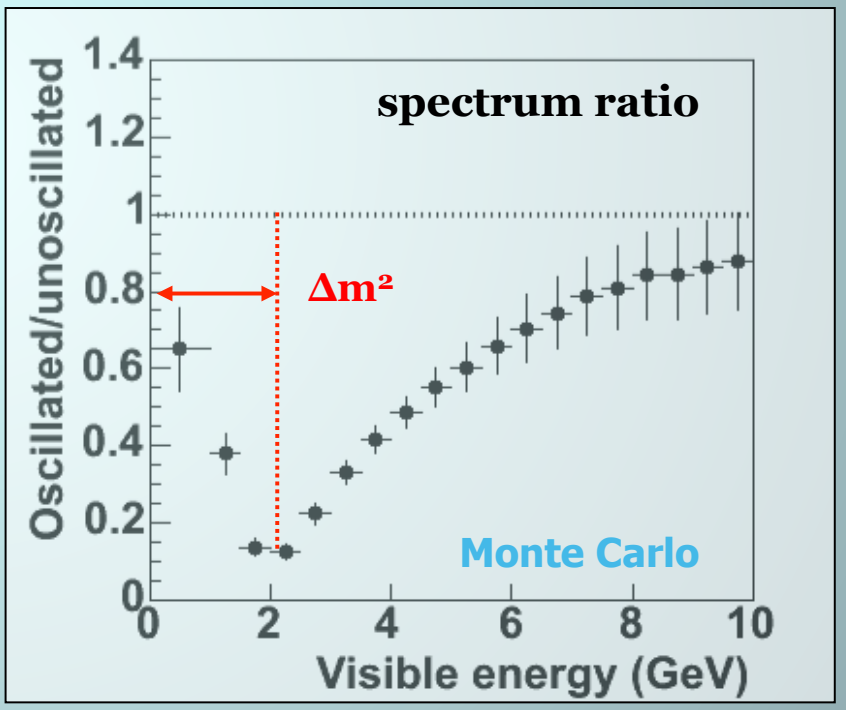

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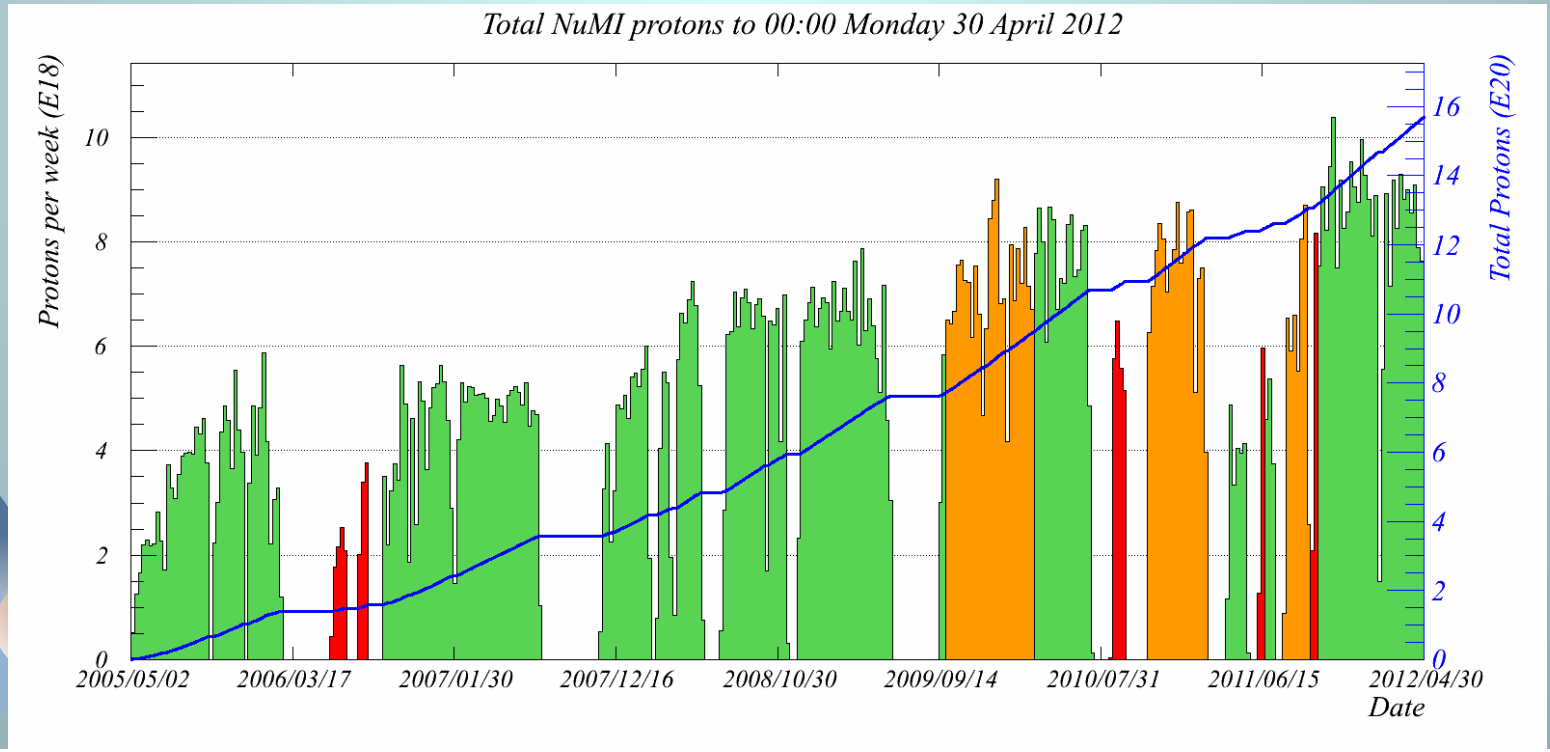
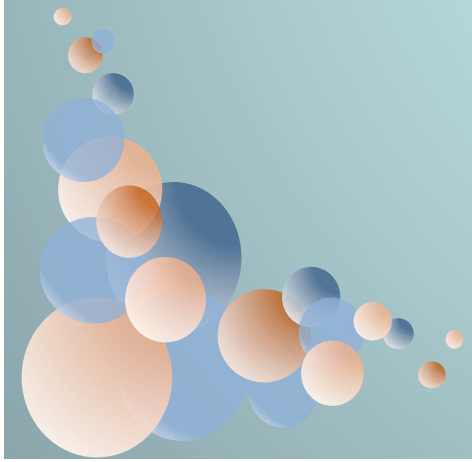
MINOS

- Final MINOS results were presented at Kyoto on
  - θ_{13}, $\theta_{13,}$ Δm^2, Δm^2, $\sin^2 2\theta_{23}$, combined fit (beam+atmospheric), and $\nu_\mu \rightarrow \nu_s$
- Total exposure is
  - 10.7×10^{20} p.o.t in FHC (neutrino mode)
  - 03.3×10^{20} p.o.t in RHC (anti-neutrino mode)
- Original proposal was for 1.6×10^{21} p.o.t. This has ≈ been achieved (when special runs are included)



$\underline{\underline{\theta_{23}}}$

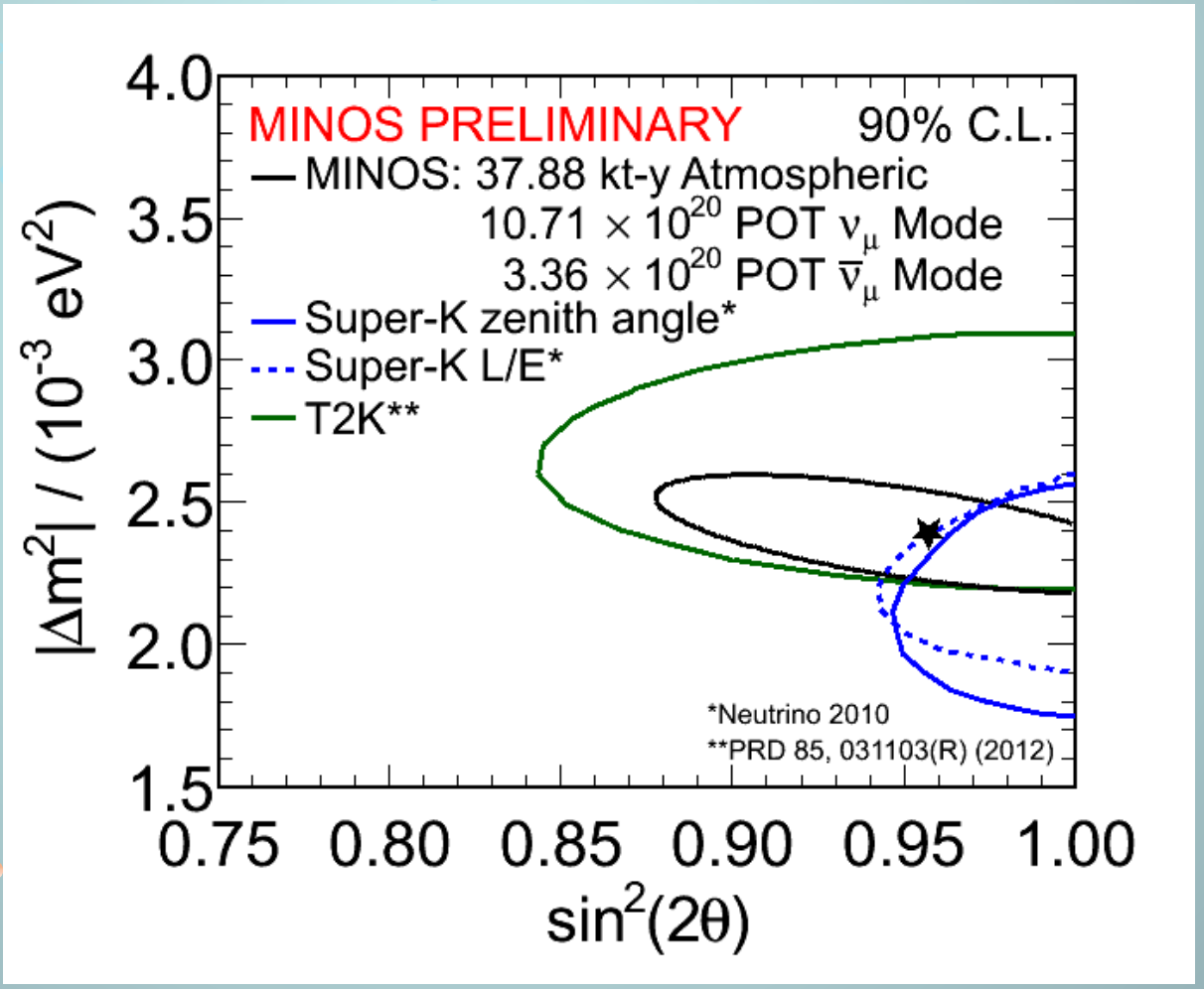
The new precision frontier!



θ_{23}

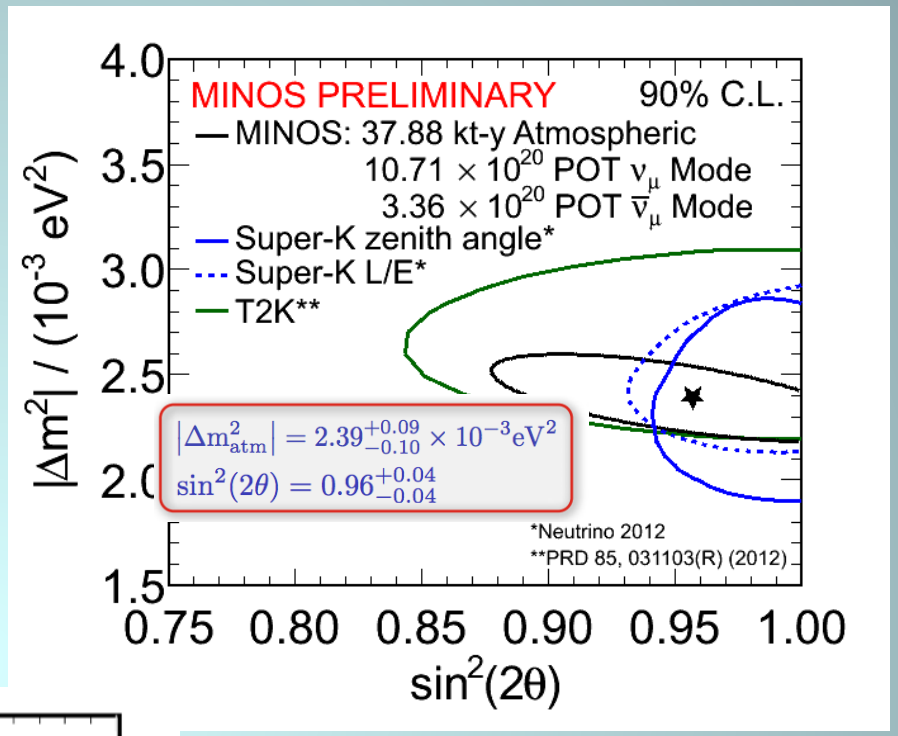
- MINOS have combined atmospheric and beam neutrinos and anti-neutrinos for most precise Δm^2 and $\sin^2 2\theta_{23} < 1.0$
- Super-K have done full 3-flavor analysis to give $\sin^2 2\theta_{23}$
- θ_{23} is the new
- LBL measure c θ_{13} so precise

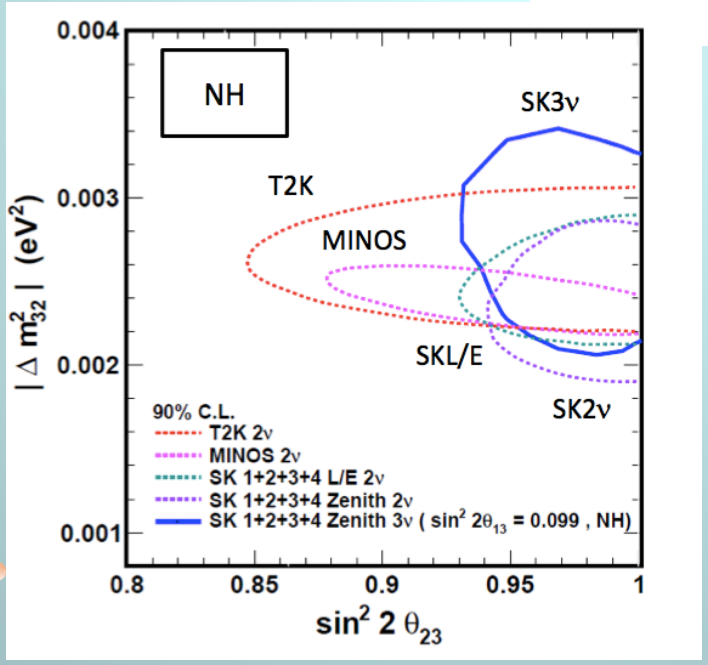
$$|\Delta m^2_{atm}| = 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$$
$$\sin^2(2\theta) = 0.96^{+0.04}_{-0.04}$$



θ_{23}

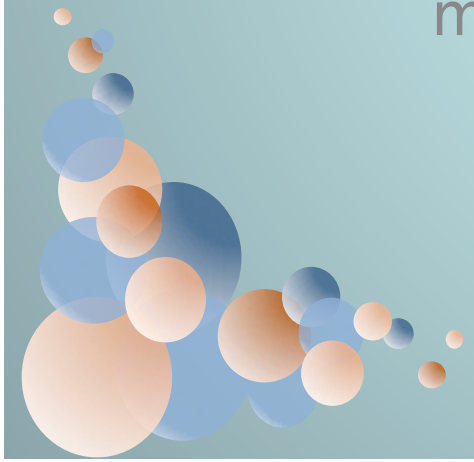
- MINOS have combined atmospheric and beam neutrinos and anti-neutrinos for most precise Δm^2 and $\sin^2 2\theta_{23} < 1.0$
- Super-K have done full 3-flavor analysis to give $\sin^2 2\theta_{23} < 1.0$
- θ_{23} is the new θ_{13} !!!
- LBL measure combination of θ_{23} and θ_{13} so precise knowledge is important





θ_{13}

Opening the door to CP violation measurements and Mass Hierarchy.



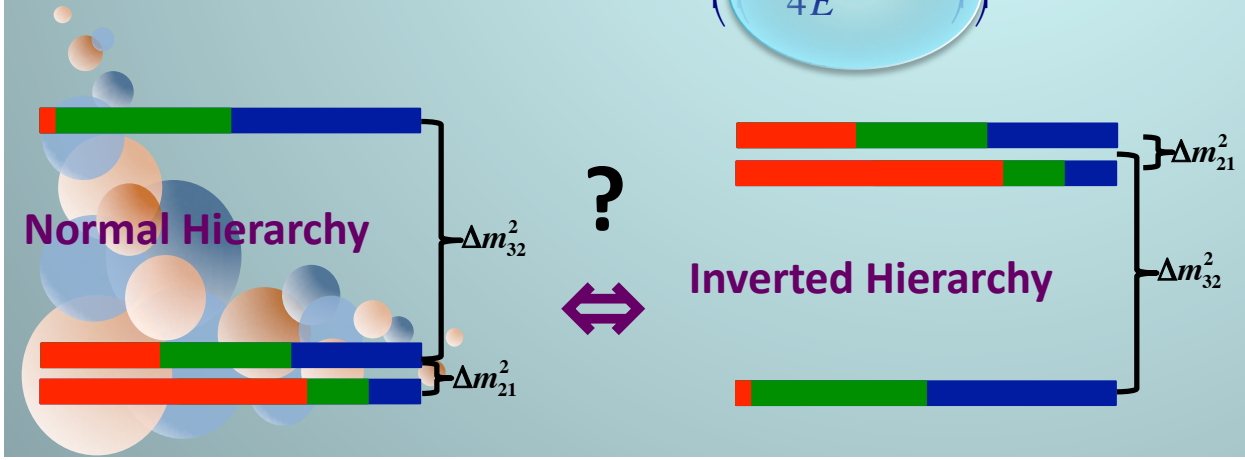
ν_e appearance : MH and δ_{CP}

- At L/E~500 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ should change into ν_e

$$P\left(\nu_\mu \rightarrow \nu_e\right) = \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E} - aL\right) \left| \frac{\frac{\Delta m^2_{31} L}{4E}}{\frac{\Delta m^2_{31} L}{4E} - aL} \right|^2$$

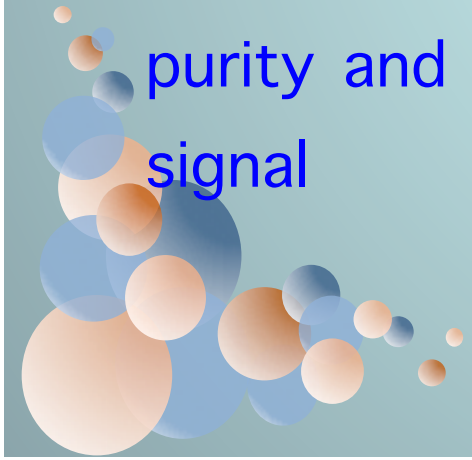
$$P_{sol} \approx \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(aL) \left| \frac{\frac{\Delta m^2_{21} L}{4E}}{aL} \right|^2$$



Oscillation probability depends on sign of Δm^2

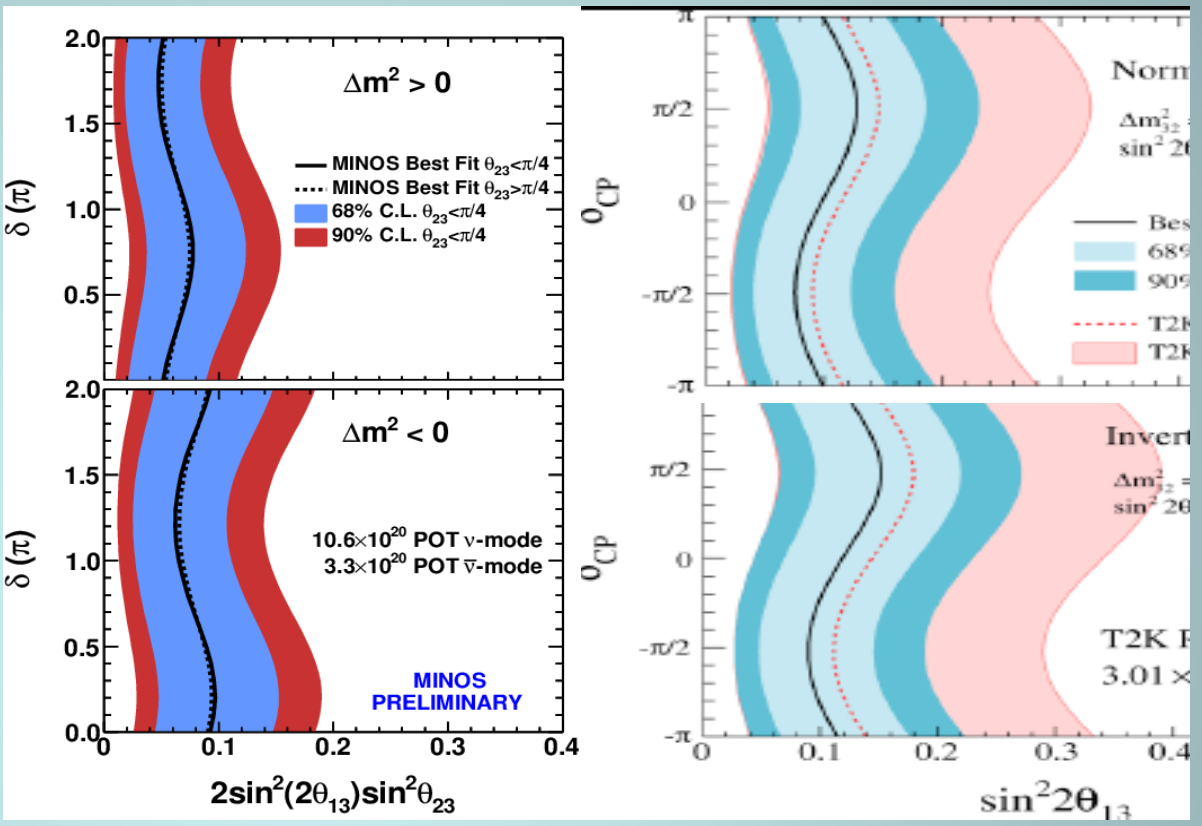
θ_{13}

- The experiments look for ν_e appearance in the ν_μ beam
- In a steel detector (MINOS), it is not easy, with low efficiency and purity
- Data driven measurement of the backgrounds using the identical near detector allow sophisticated Multi-variant analyses
- T2K use the Super-K water Cherenkov detector, good purity and reasonable efficiency make for a much cleaner signal



θ_{13}

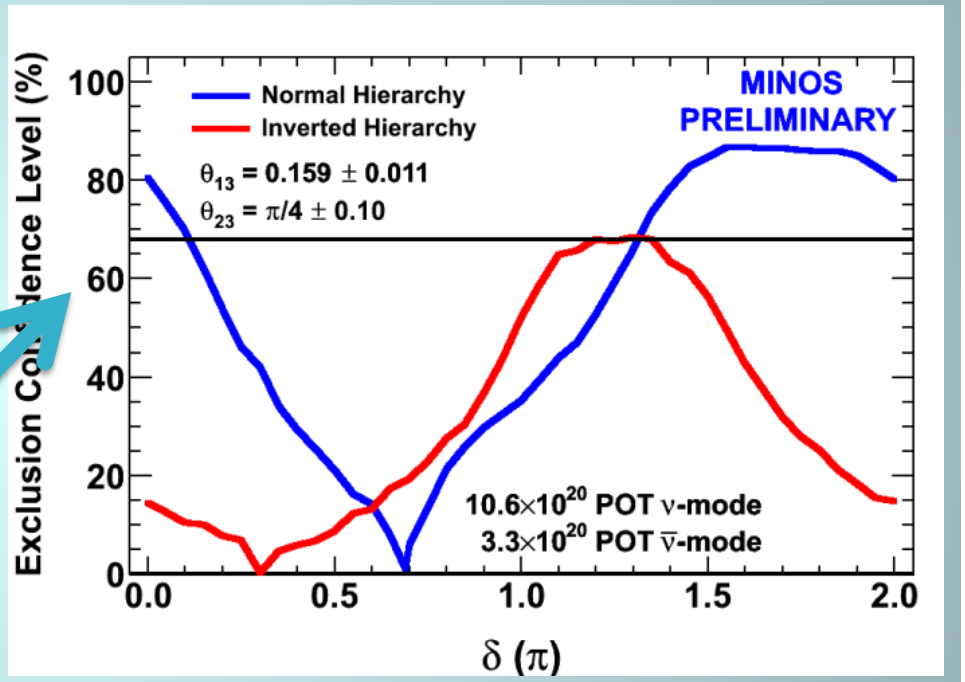
- MINOS has a respectable measurement to finish with!
- Uses 10.71×10^{20}p.o.t and 3.36×10^{20}p.o.t of antineutrinos
- T2K now really using the power of the L/E choice, near detector etc….
- Possible tension in NH could point to IH solution



MINOS T2K

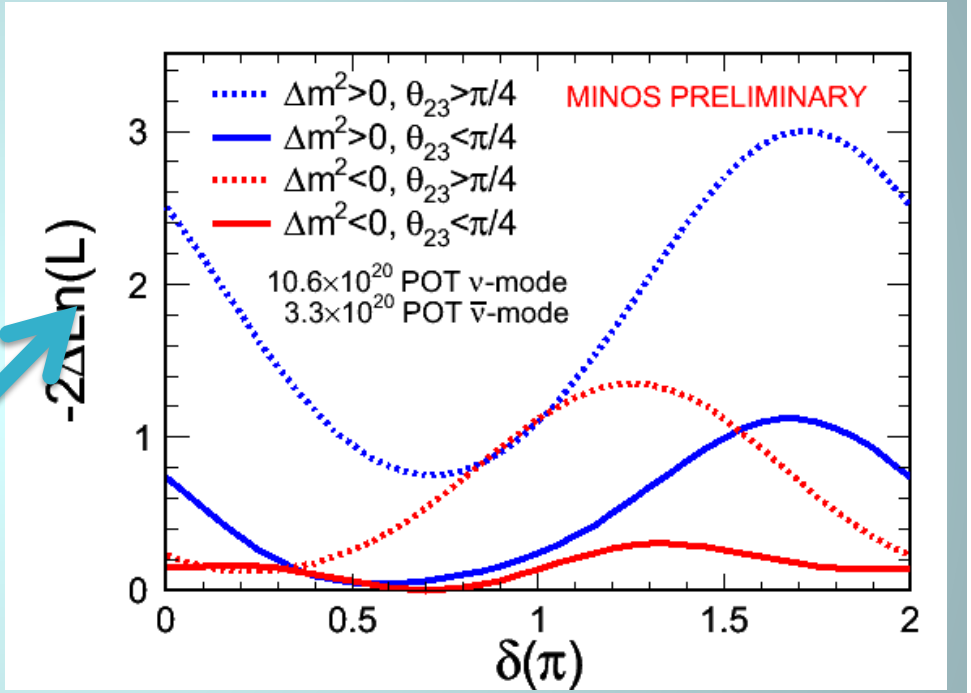
Hierarchy?

- MINOS is sensitive to matter effects from long baseline
- Using reactor value of θ_{13}, and MINOS value of $\theta_{23,}\Delta m^2$, find best fit for δ_{CP} for IH and MH
- With non-maximal θ_{23}, this becomes four lines, two for each octant



Hierarchy?

- MINOS is sensitive to matter effects from long baseline
- Using reactor value of θ_{13}, and MINOS value of $\theta_{23,}\Delta m^2$, find best fit for δ_{CP} for IH and MH
- With non-maximal θ_{23}, this becomes four lines, two for each octant
- No real significance although IH has lower ΔLL, and octant $\theta_{23}<\pi/4$ always preferred

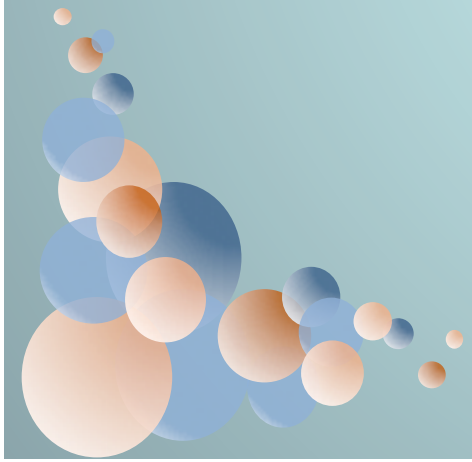


Global Fits

- The information from every neutrino needs to be used!
- Reactors use MINOS Δm^2 to get their θ_{13}: Super-K use this θ_{13} in 3-flavor fits to get another Δm^2...
- Systematic correlations between experiments are not always being handled at all
- Would be good to set up a experimental global-fit group a la LEP, to make sure no neutrino is wasted!

In to the (near) future

Fermilab, NuMI, MINOS+, NOνA



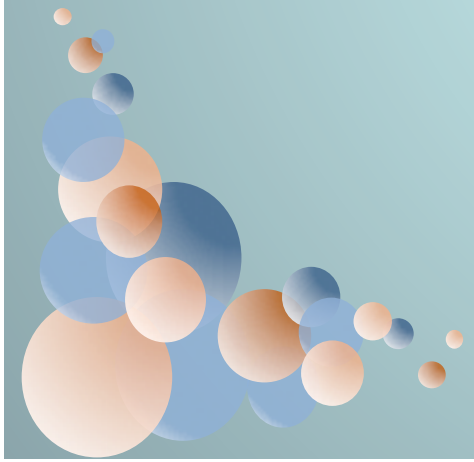
Fermilab-NuMI

- NuMI beam is being upgraded to NOVA configuration (ME) and 700kW, 6e20/y
- MINOS+ will search for any non-standard effects at high precision (10,000 events in 3 years near oscillation maximum)
- NOνA is the flagship experiment for mass hierarchy and CP violation
- Full exploitation of the NuMI facility could provide opportunities for augmentation of present suite of experiments
  - Large Liquid Argon detectors – Water Cherenkov detectors? – LSc detectors

MINOS+

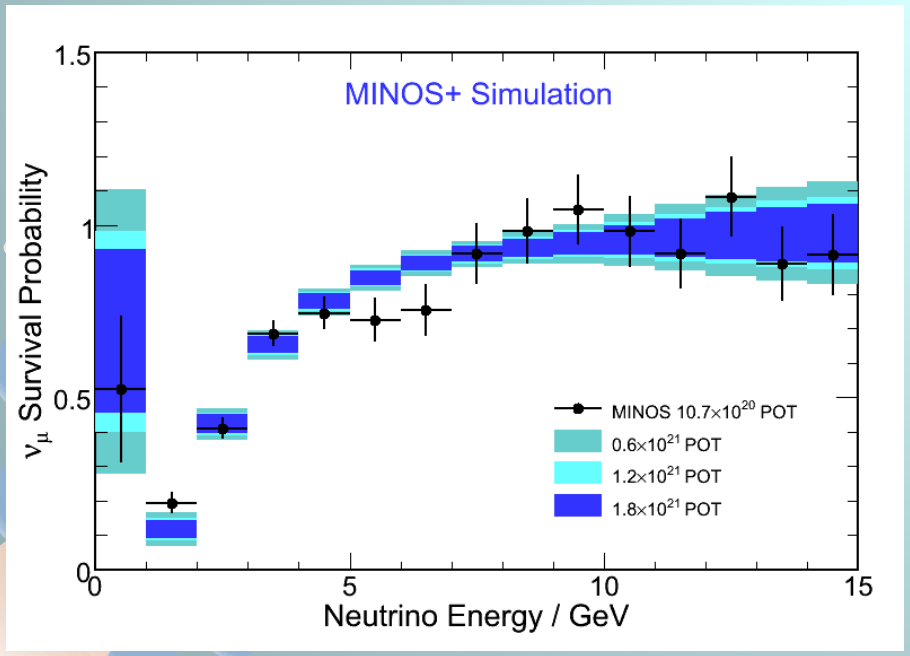
Starts April 2013 for three years

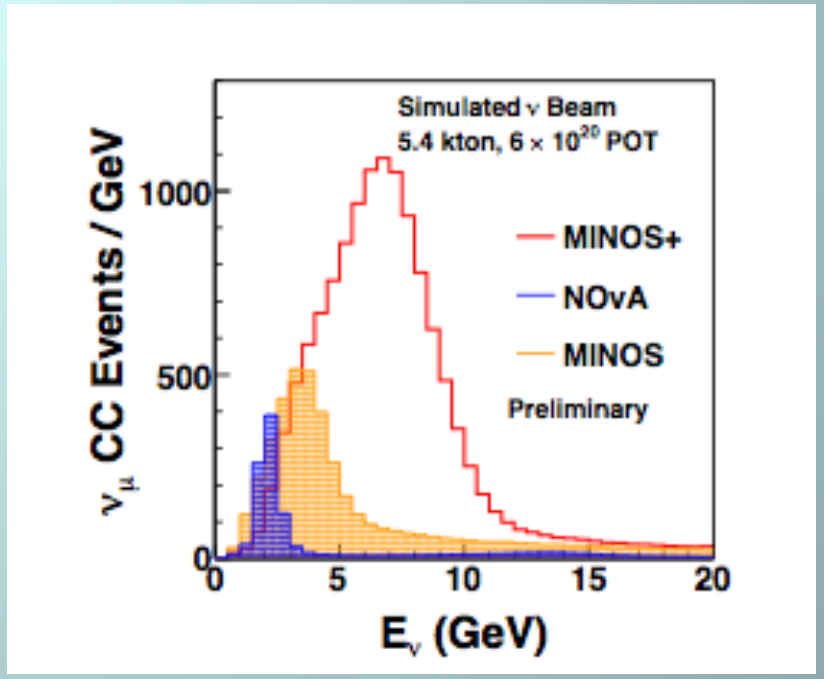
April 2013-2016



MINOS+

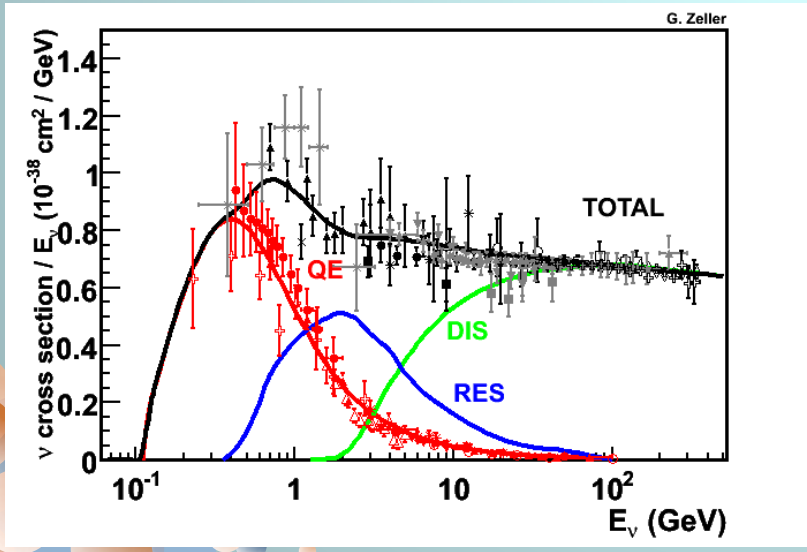
- The overarching reason to run MINOS in the NuMI-NOνA beam is to look for new physics in a previously unexplored region
- 3000 events/year between 4-10 GeV near oscillation maximum
- Precision experiment to ascertain deviations (or none) from "standard" 3x3 mixing matrix

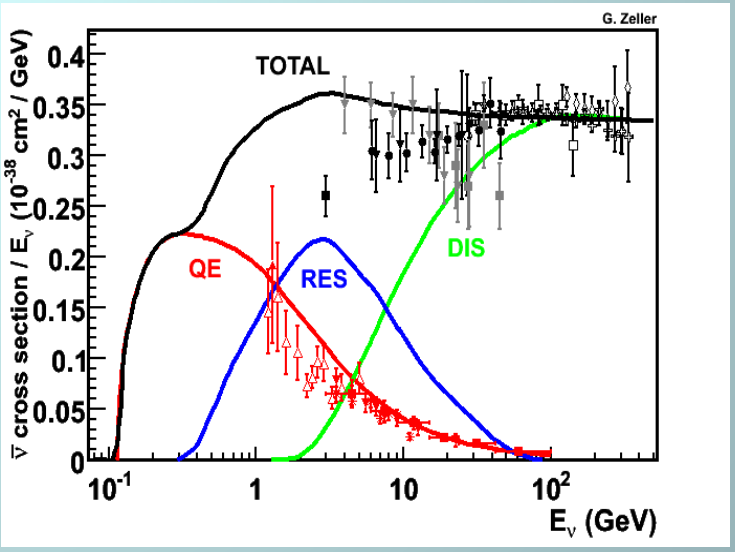




MINOS+

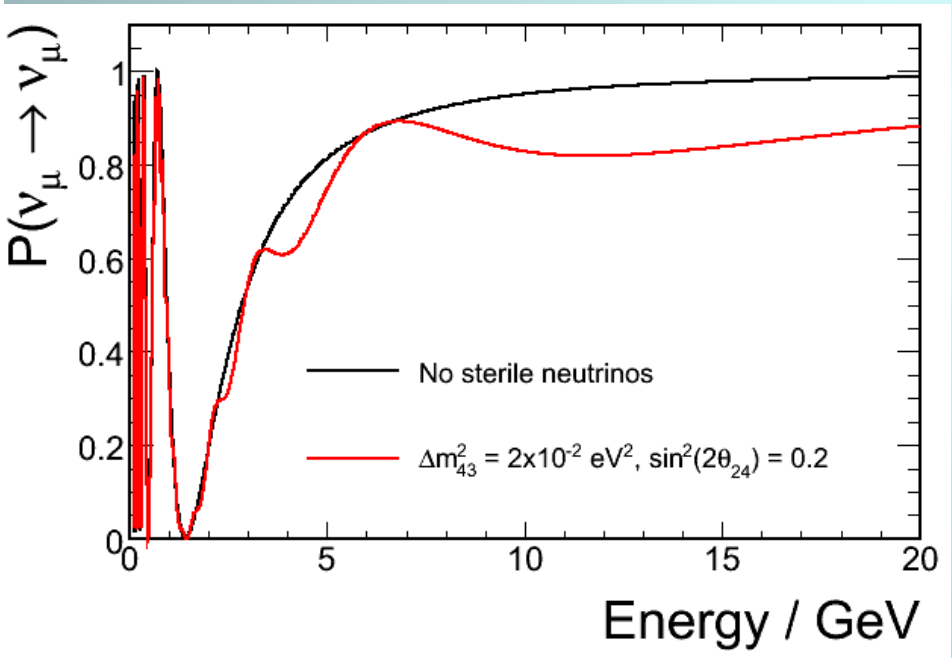
- The overarching reason to run MINOS in the NuMI-NOνA beam is to look for new physics in a previously unexplored region
- 3000 events/year between 4-10 GeV near oscillation maximum
- Unique high statistics experiment with charge sign measurement
  - different energy region
  - different systematics (beam, x-sec comp, DIS will dominate)

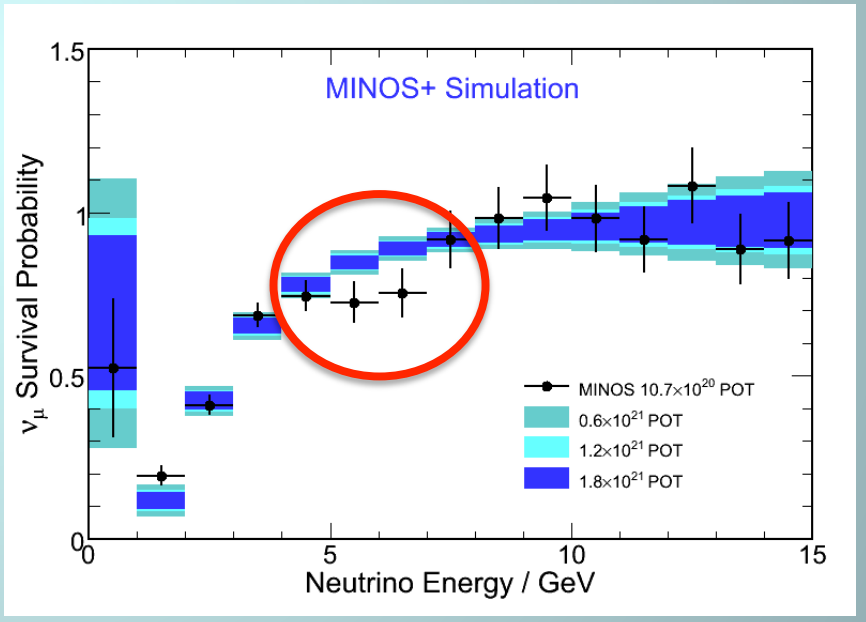




MINOS+

- Search for sterile neutrinos could be interesting
- Odd dip will have to wait for MINOS+ for more study
- Oscillation spectrum pretty insensitive to primary oscillation parameters in this region



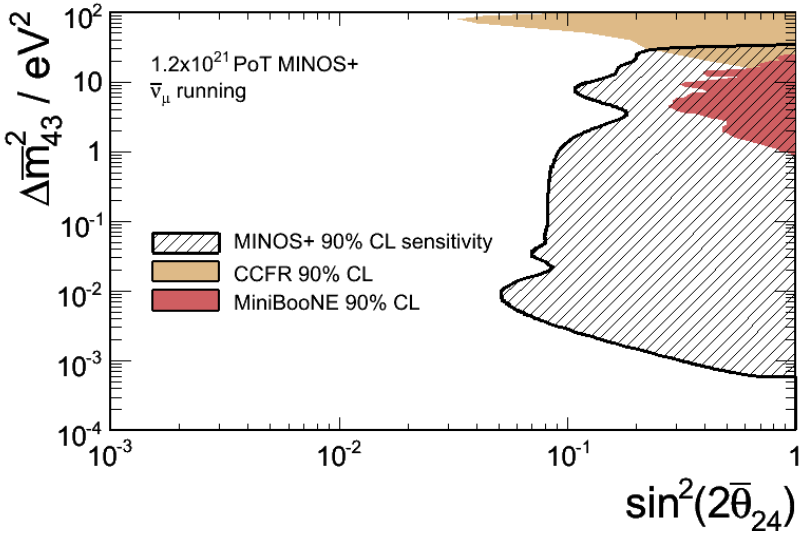


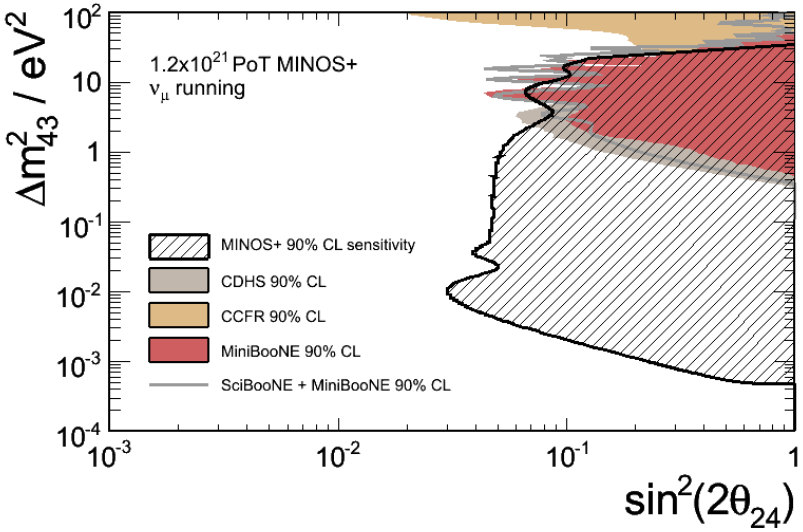
MINOS+ sterile reach

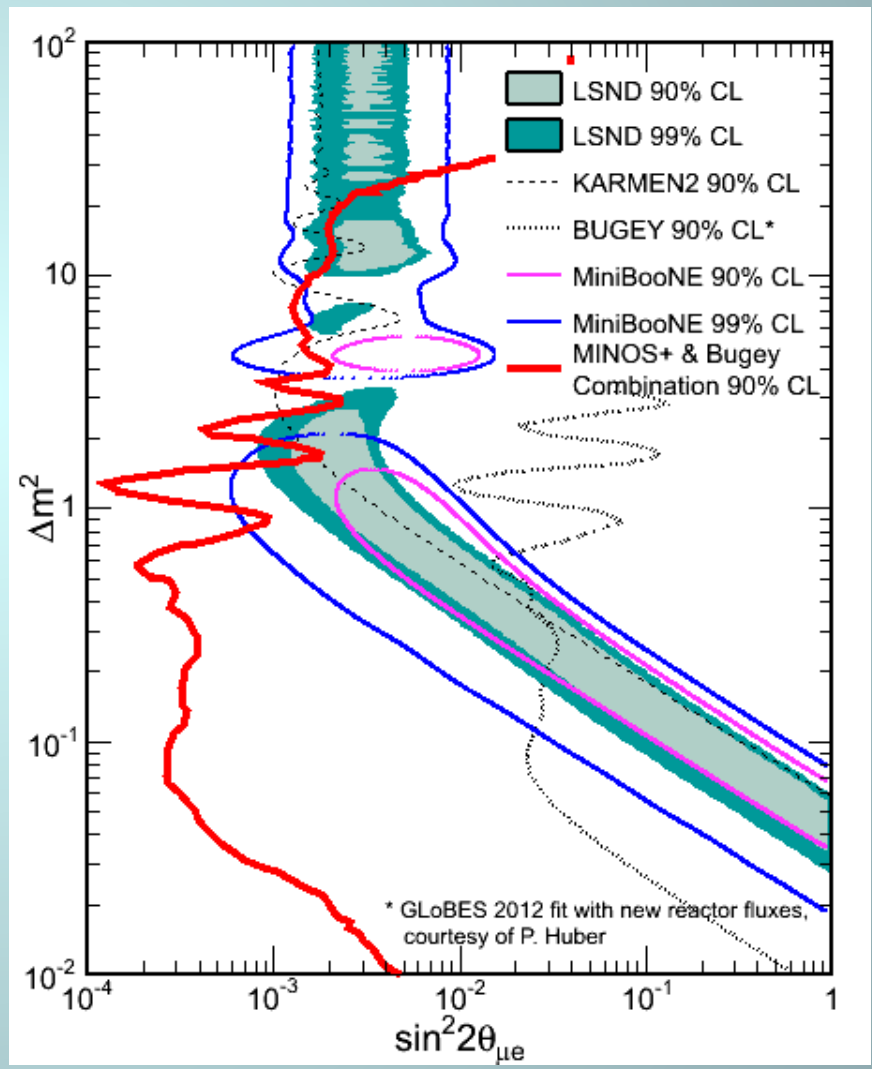
$|U_{e4}|^2 = \sin^2\theta_{14}$

$|U_{\mu 4}|^2 = \cos^2\theta_{24} * \sin^2\theta_{24}$ (http://lanl.arxiv.org/abs/1109.4033)

$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu 4}|^2$



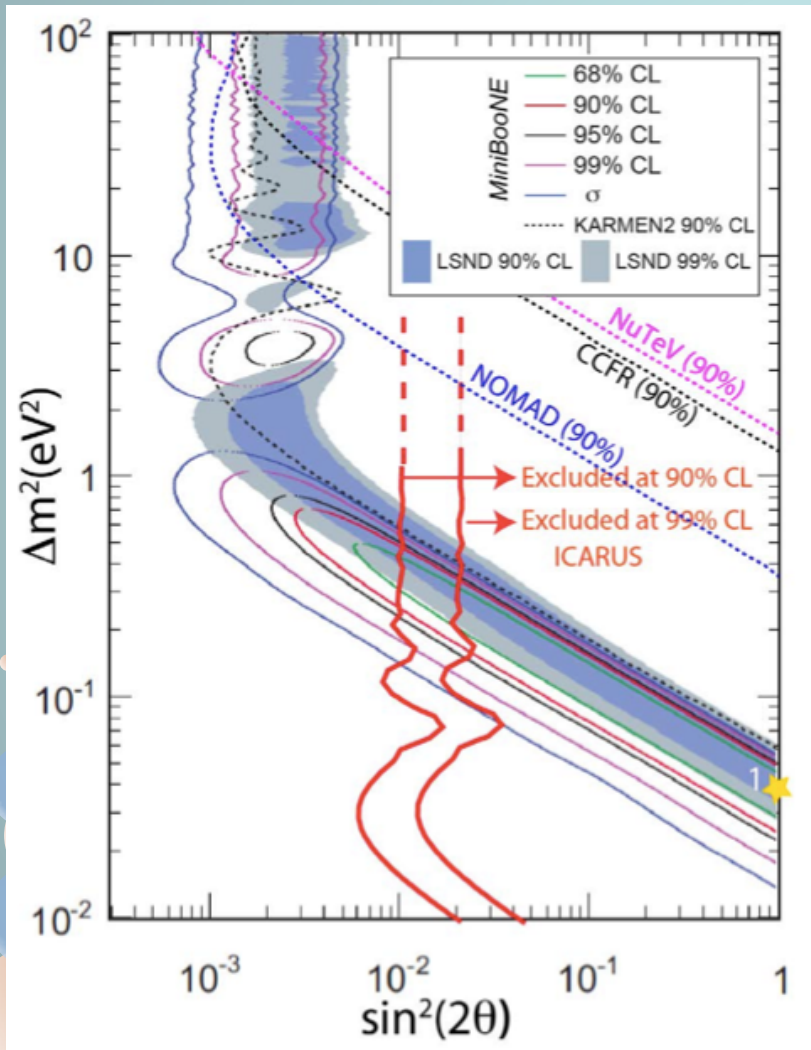




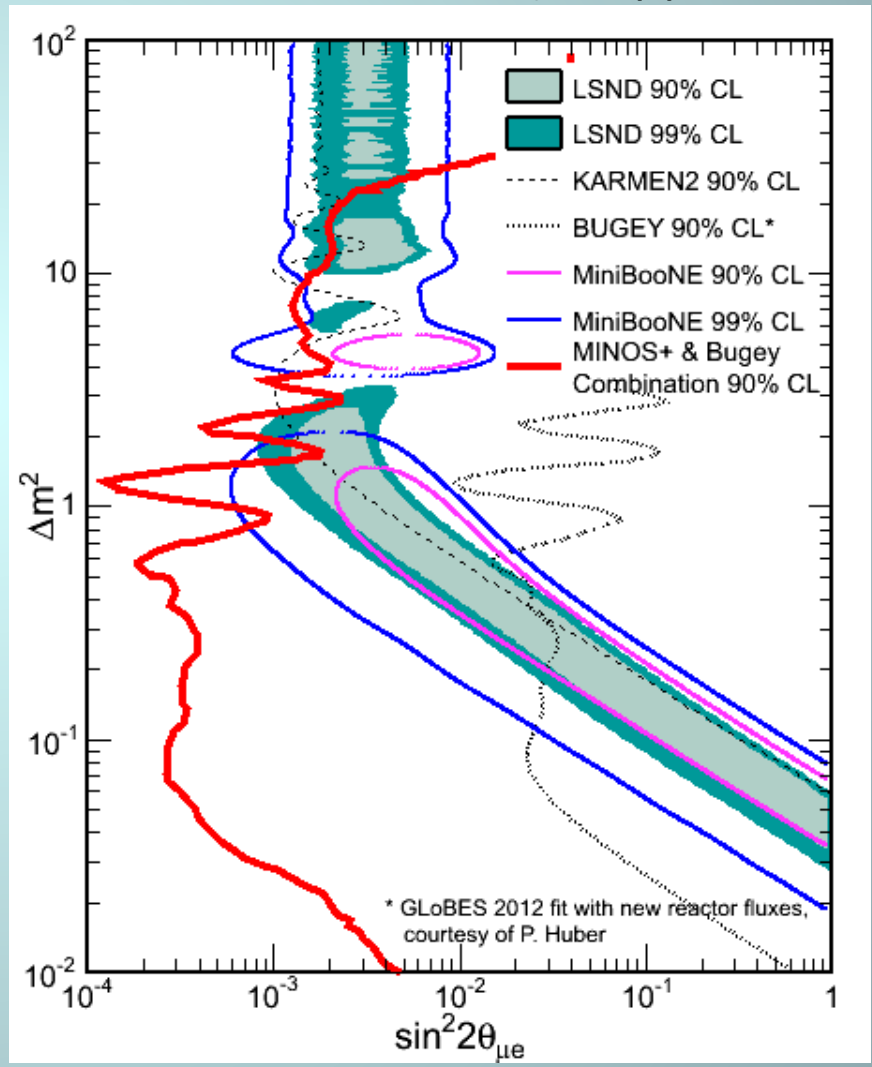
MINOS+ sterile reach

(http://lanl.arxiv.org/abs/1109.4033)

$\nu_\mu \rightarrow \nu_e$ (appearance)

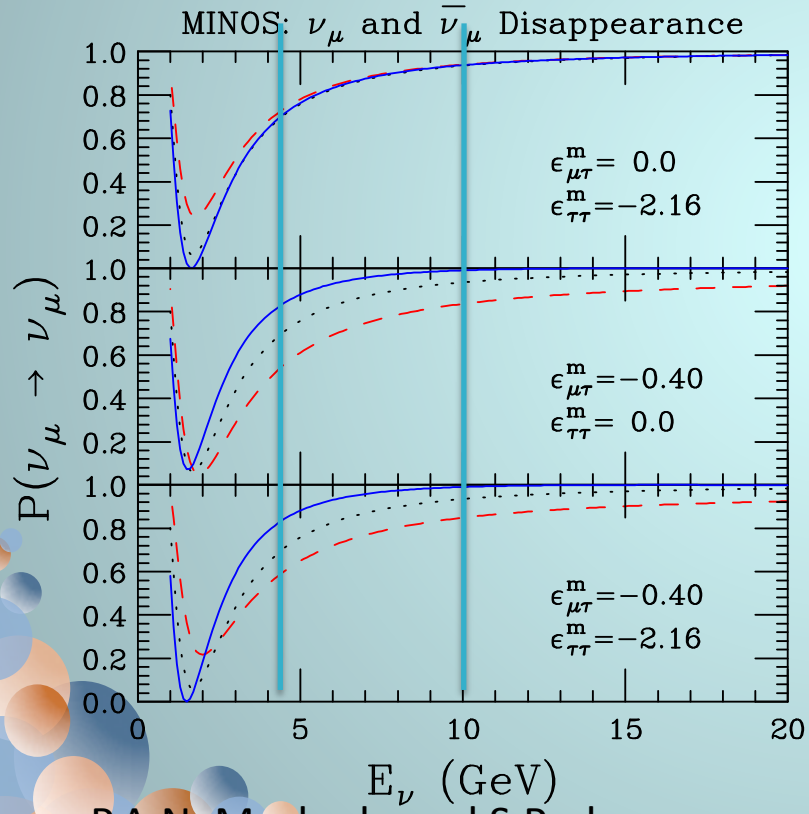


$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu 4}|^2$ (disappearance)

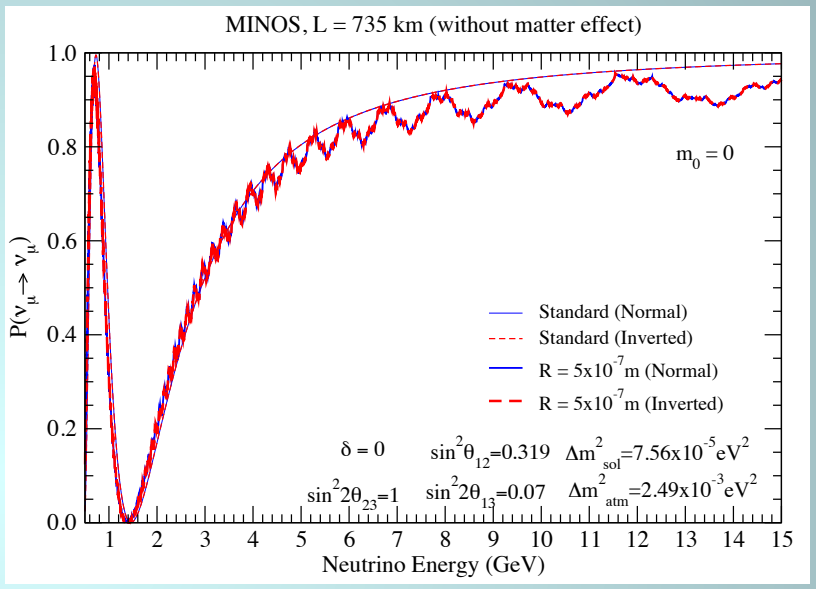


MINOS+ Goals

Dimension 5 non-standard contact interactions show up in the region of study



J. Kopp, P.A.N. Machado and S.Parke, Phys.Rev.D82:113002 (2010).



Half micron sized extra dimensions can be observed!!

P.A.N.Machado,H.Nunokawa,R.Zukanovich Funchal, hep-ph/1101.003v1

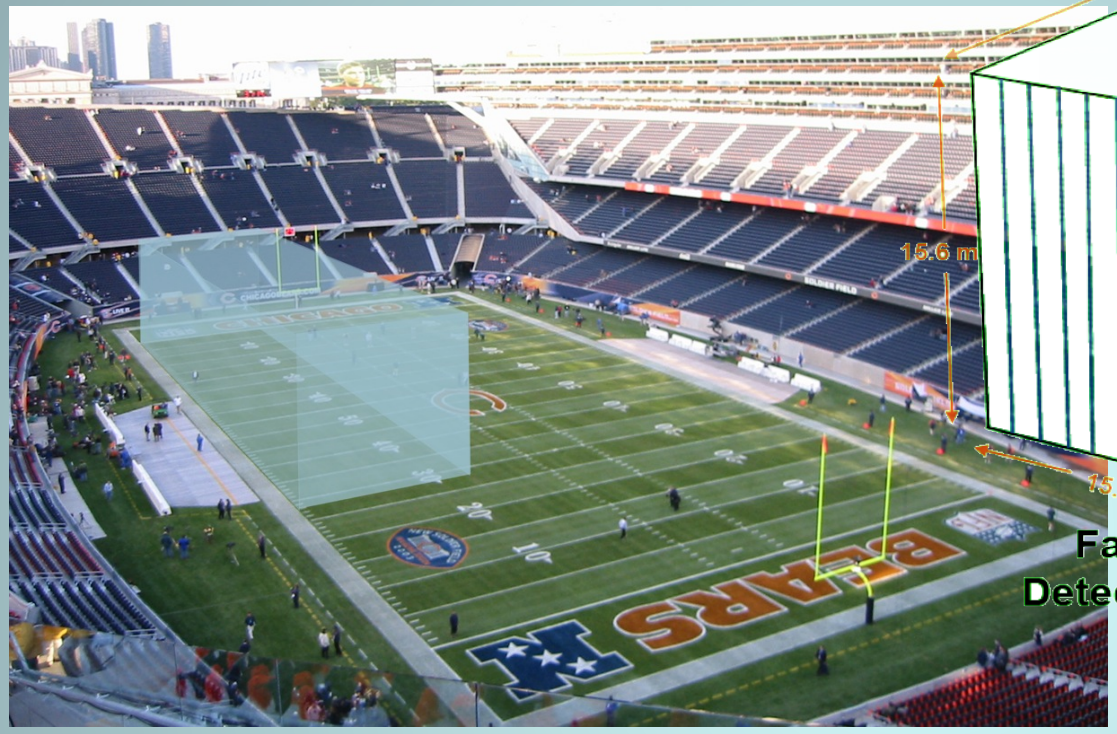
Alexander Friedland , Cecilia Lunardini, Phys.Rev.D74:033012,2006.

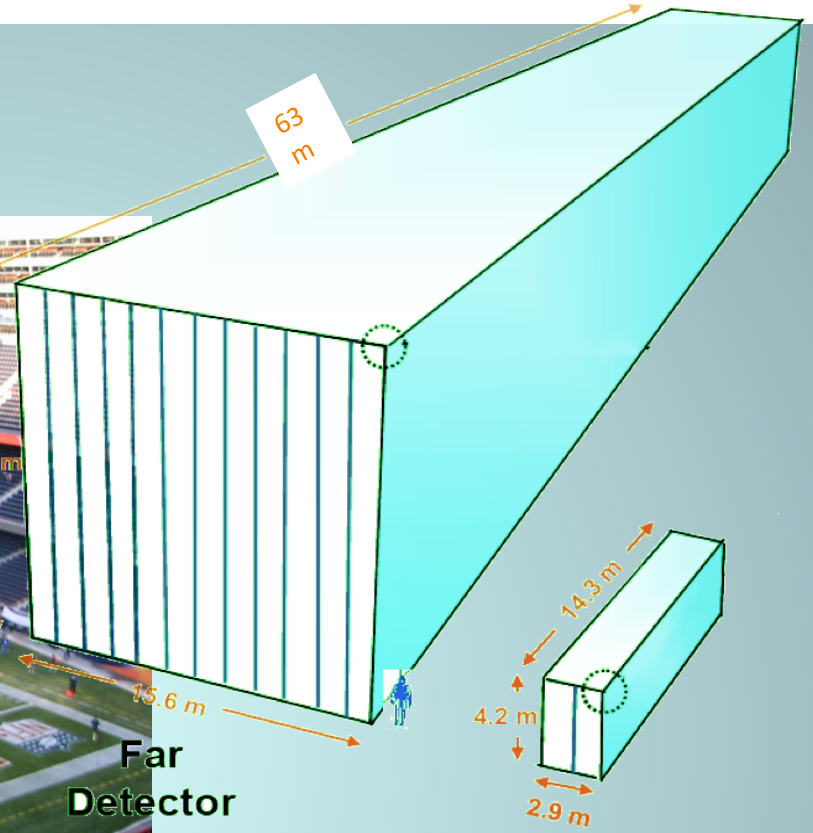
NOνA

FNAL's flagship experiment for the next decade

In (possibly) the right place at the right time!!

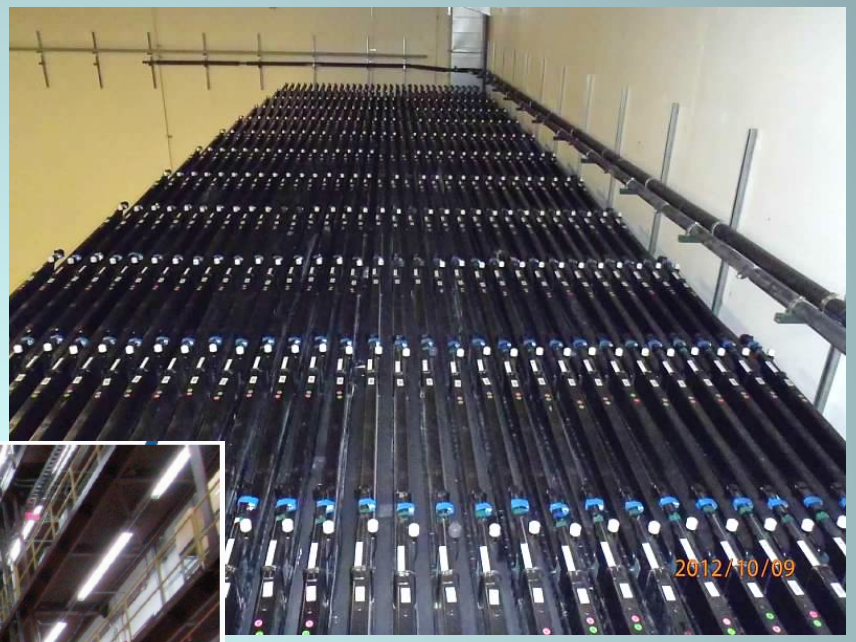
NOνA





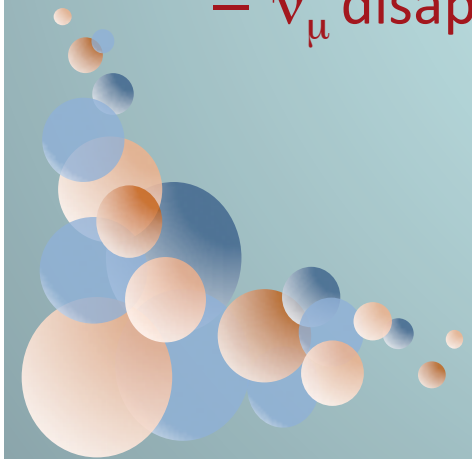
- Massive, Low-Z, 65% active Far Detector
  - 15 kton, 810 km from source
- Functionally equivalent Near Detector to mitigate systematic uncertainties
  - 220 ton Near Detector, 1 km from source

NOνA construction



The new goals

- CP violation
  - Shape measurement ideal, need energy resolution, but not long distance, neutrinos and anti-neutrinos
- Mass Hierarchy
  - Counting experiment, need big mass because of big distance :
- θ_{23} (the new θ_{13})
  - ν_μ disappearance on both sides of oscillation maximum

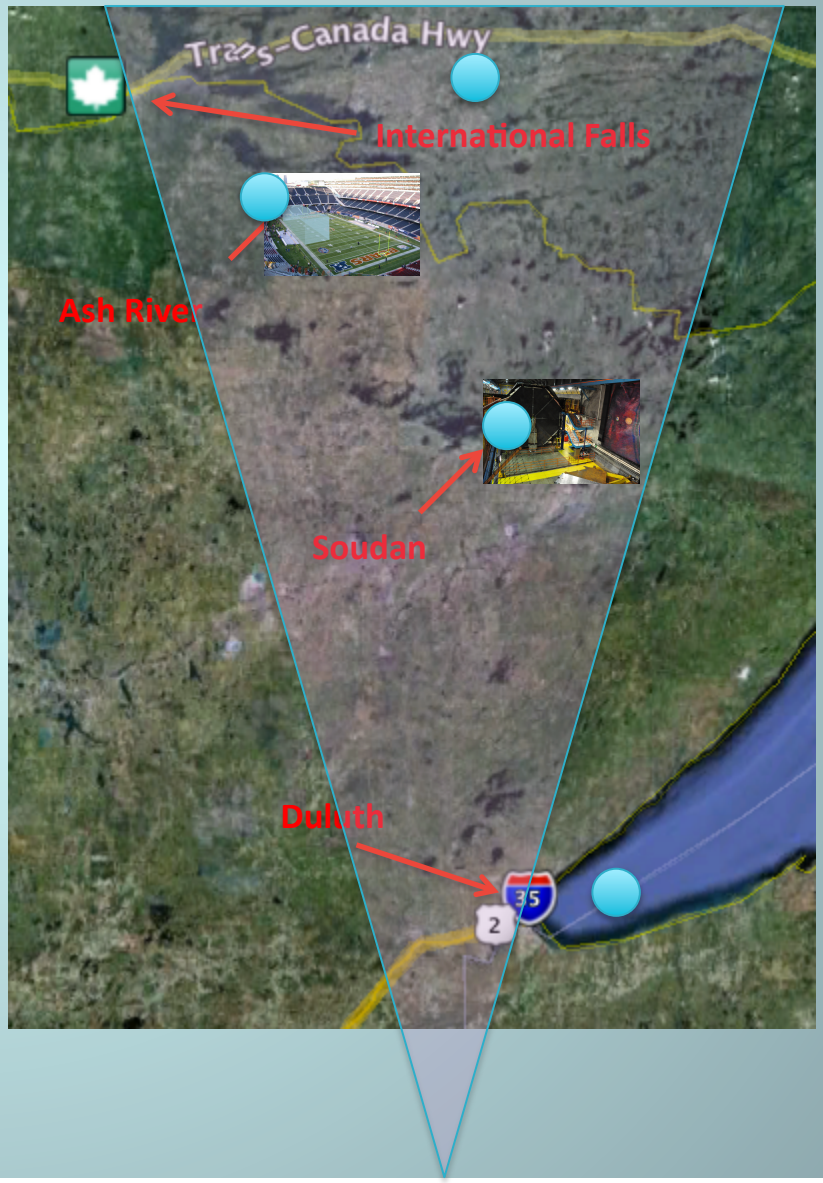


LBNE: FNAL – South Dakota

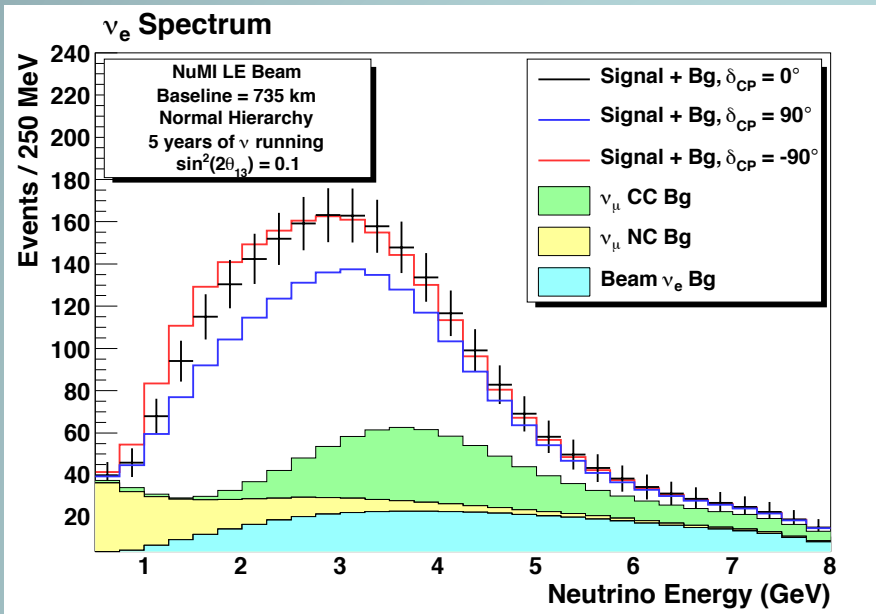
- Long-Baseline-Neutrino-Experiment
  - 1300km baseline, good for MH and δ_{CP}
  - 10kt Liquid Argon detector on the surface
    - Additional money could put this underground
    - Underground lab being developed in S.Dakota
  - NNN workshop last week pointed to more realistic timescales
    - Necessity but also the opportunity to do something in the mean time?

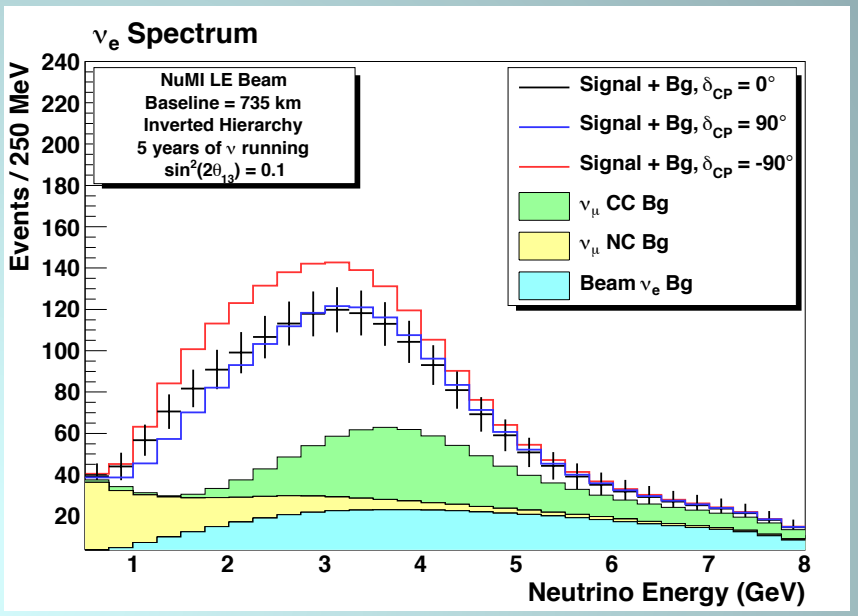
NuMI : MH,CP,θ_{23}

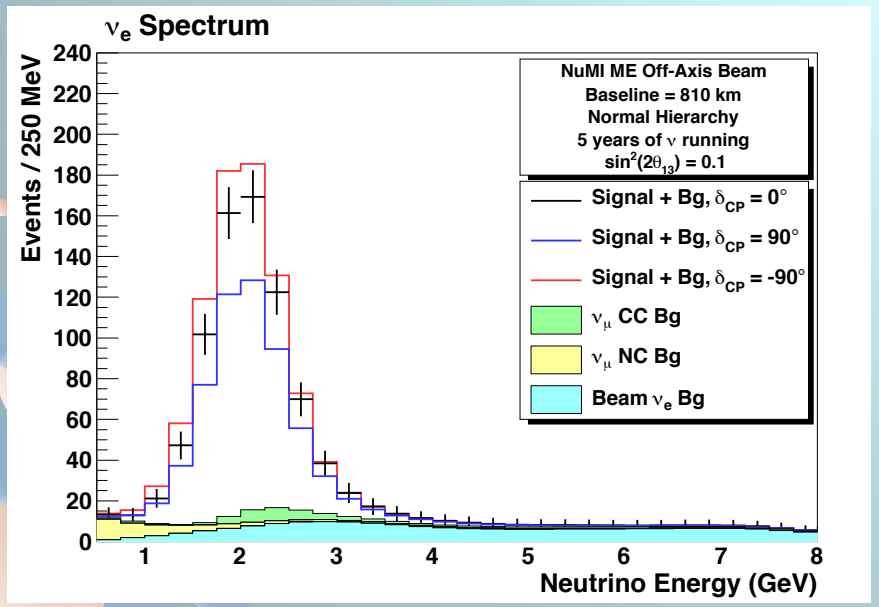
- Further exploitation of the NuMI beam seems obvious
- Beam power and detector mass are directly tradable
- Consider possible experiments:
  - Off-axis at Ash River L/E=400
  - On-axis on surface at Soudan or beyond L/E = 300
  - On-axis underground at Soudan Laboratory L/E = 300
  - Giant Water Cherenkov detector in a lake or pit L/E=400
  - External ideas could gain traction!

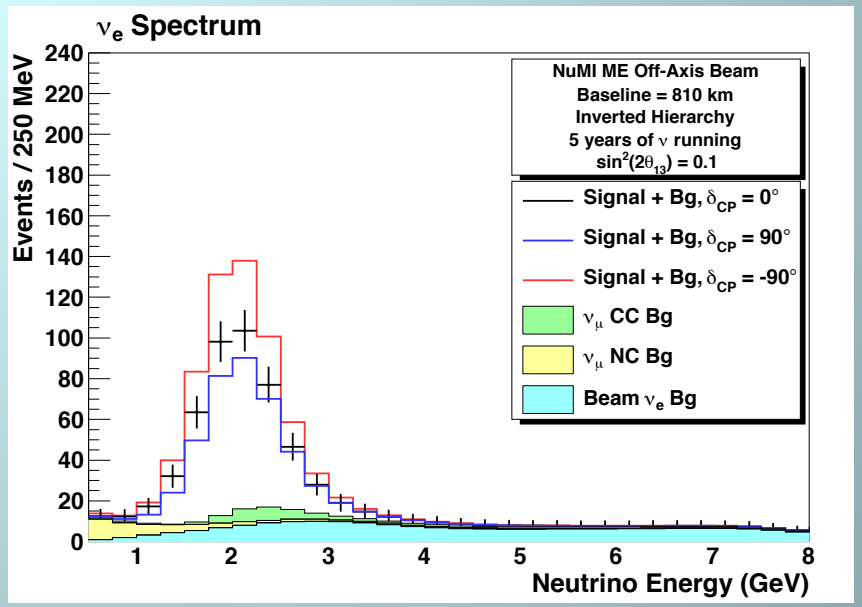


Experimental signatures

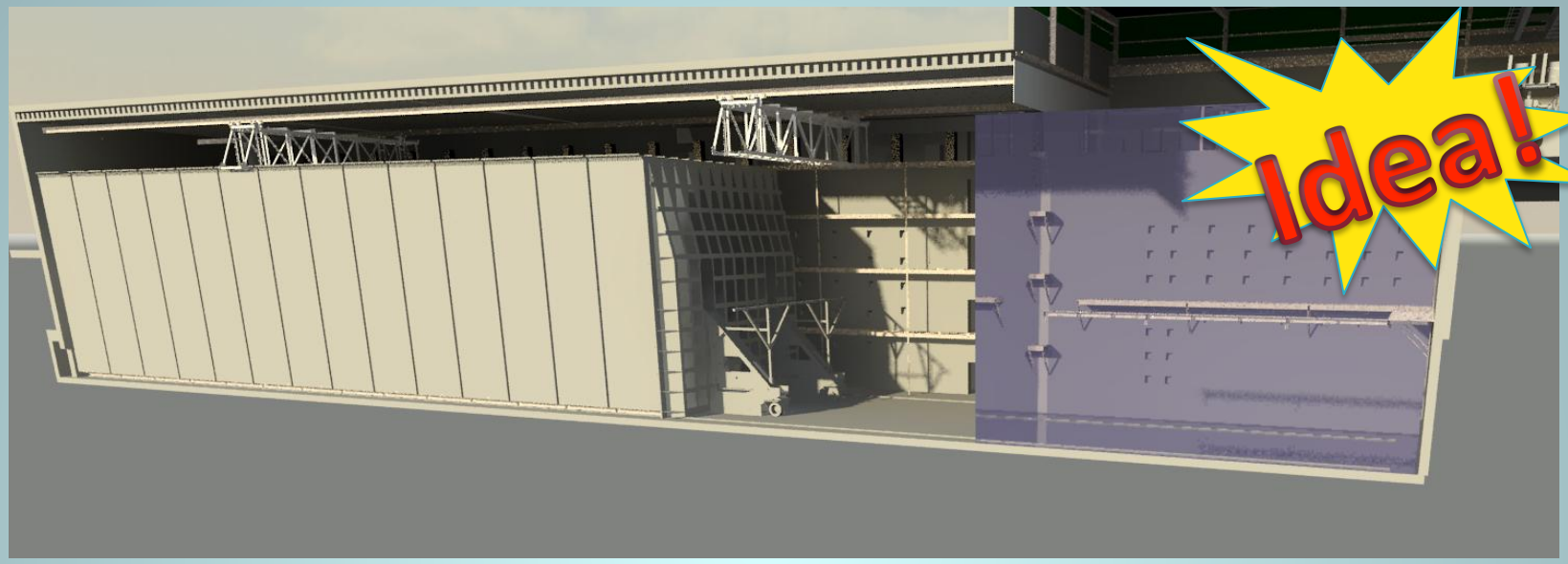








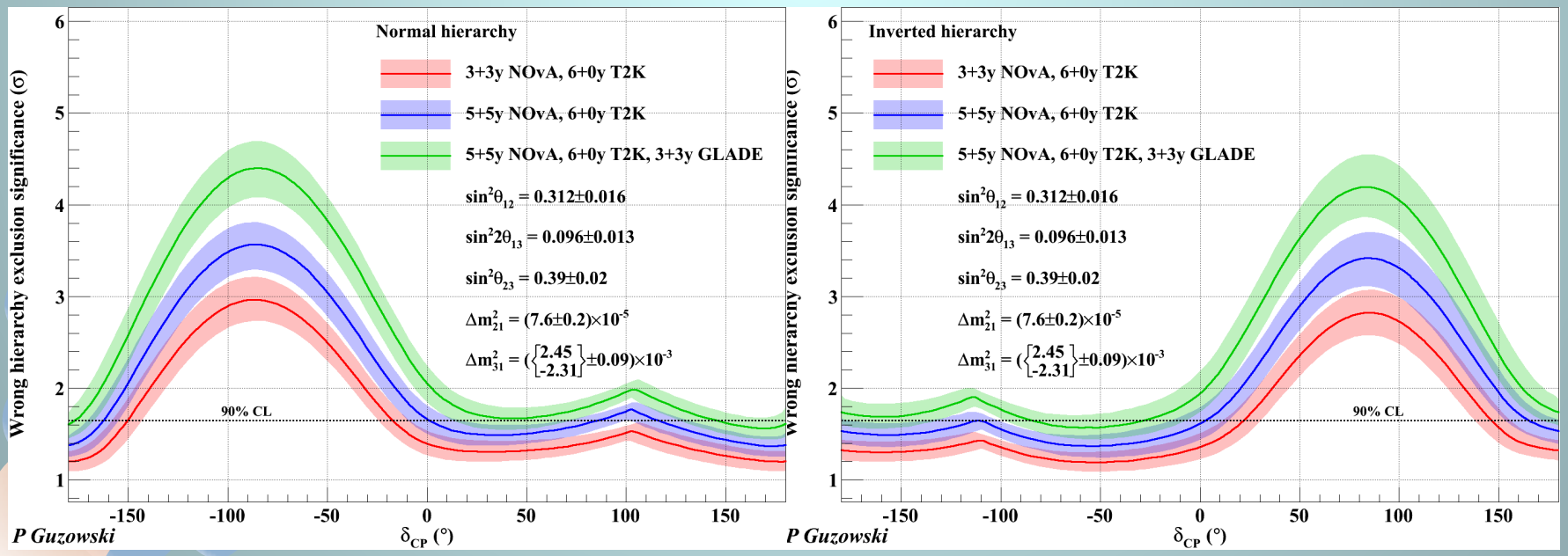
Focus on MH : GLADE



- Total volume available is 18m x 18m x 24m
- Will fit in at other end of Laboratory (pity its not at other end!)
- If dual phase used, height for drift distance will limit mass
  - 18m x 24m x 8m = ~5kT
- If "standard" wire readout used, maximum is closer to 10kT
- Space is ready: more power is needed

NOνA+T2K mass hierarchy reach

- Combination with NOνA and T2K will be the quickest way to the MH information
- Expectation is that $\sin^2 2\theta_{23}$ known to .01 by 2020 (now .04)
- θ_{23} in lower quadrant gives least sensitivity (shown)
- Allowing for all the present uncertainties
- Running neutrinos only may be fastest way



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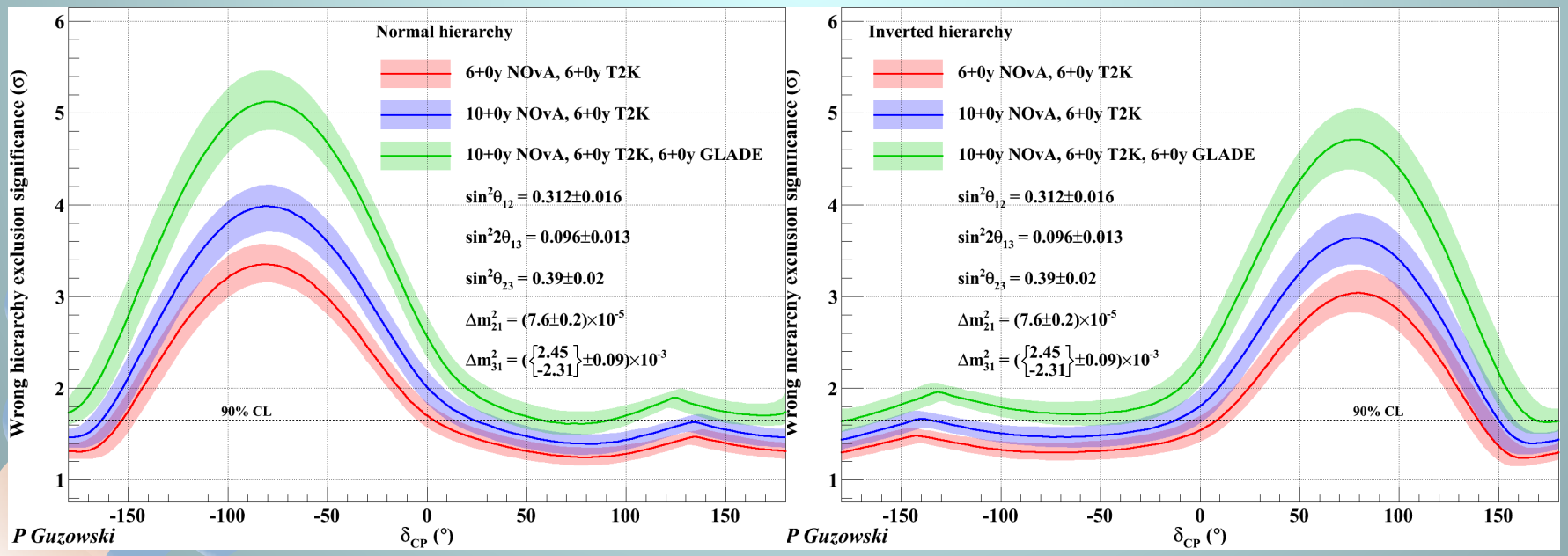
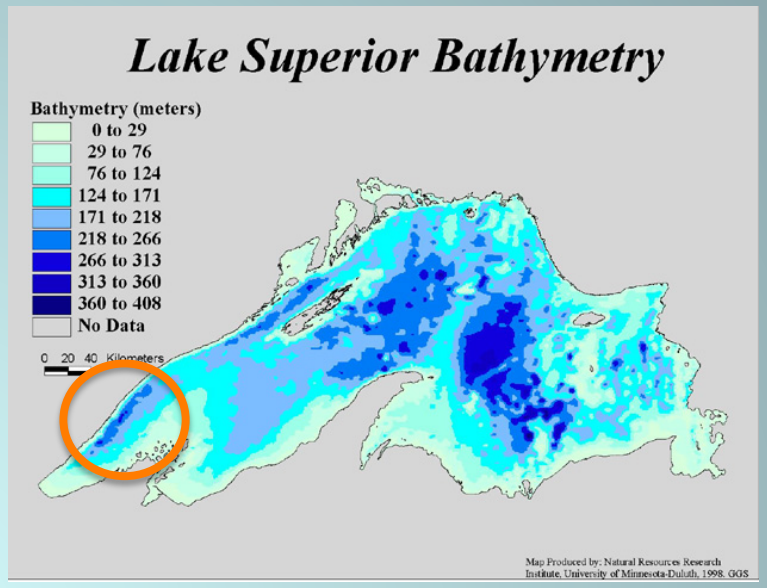


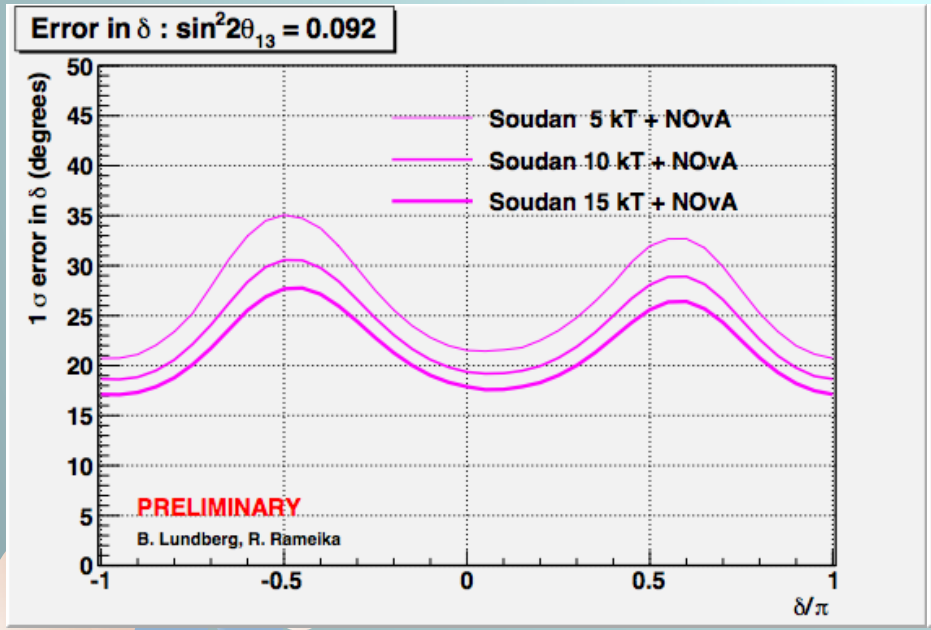
Focus on δ_{CP} : CHIPS

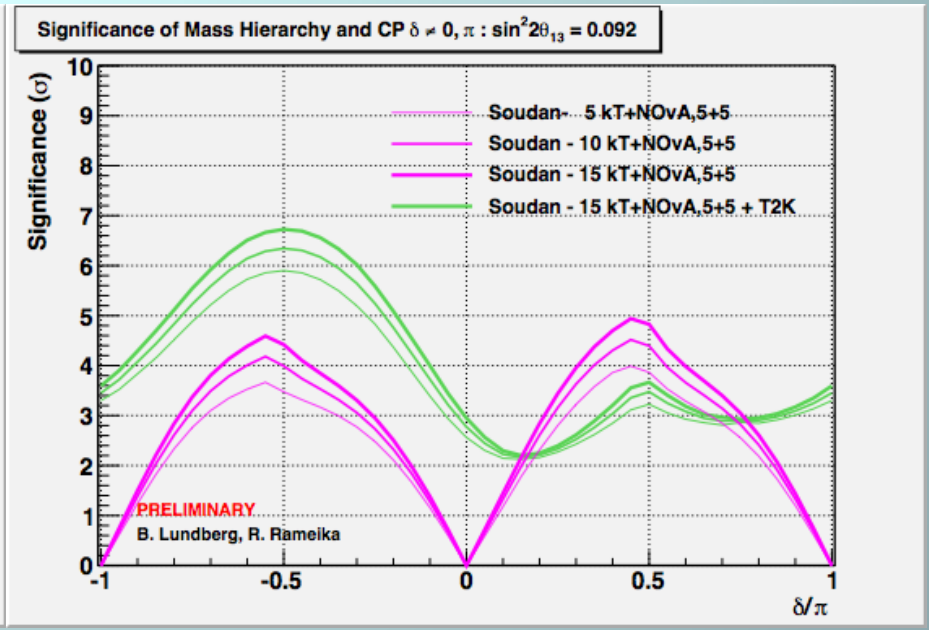
- Water Cherenkov innovations
  - Some R&D, but tested technology
  - Only way to get >100kt affordably
  - Would be underwater in Lake Superior (off –axis), or a mining pit (on-axis), below the freeze zone



Focus on δ_{CP} : CHIPS

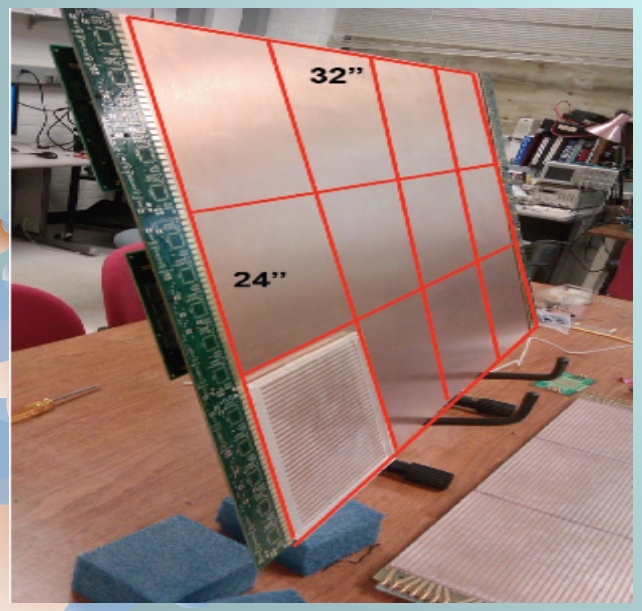
- 25kt on axis (large flux)
  - Accuracy on δ_{CP} goes goes from 15° to 35°
  - Factor 5x mass needed compared to LAr for same signal
    - 25kt of water = 5 kt of LAr



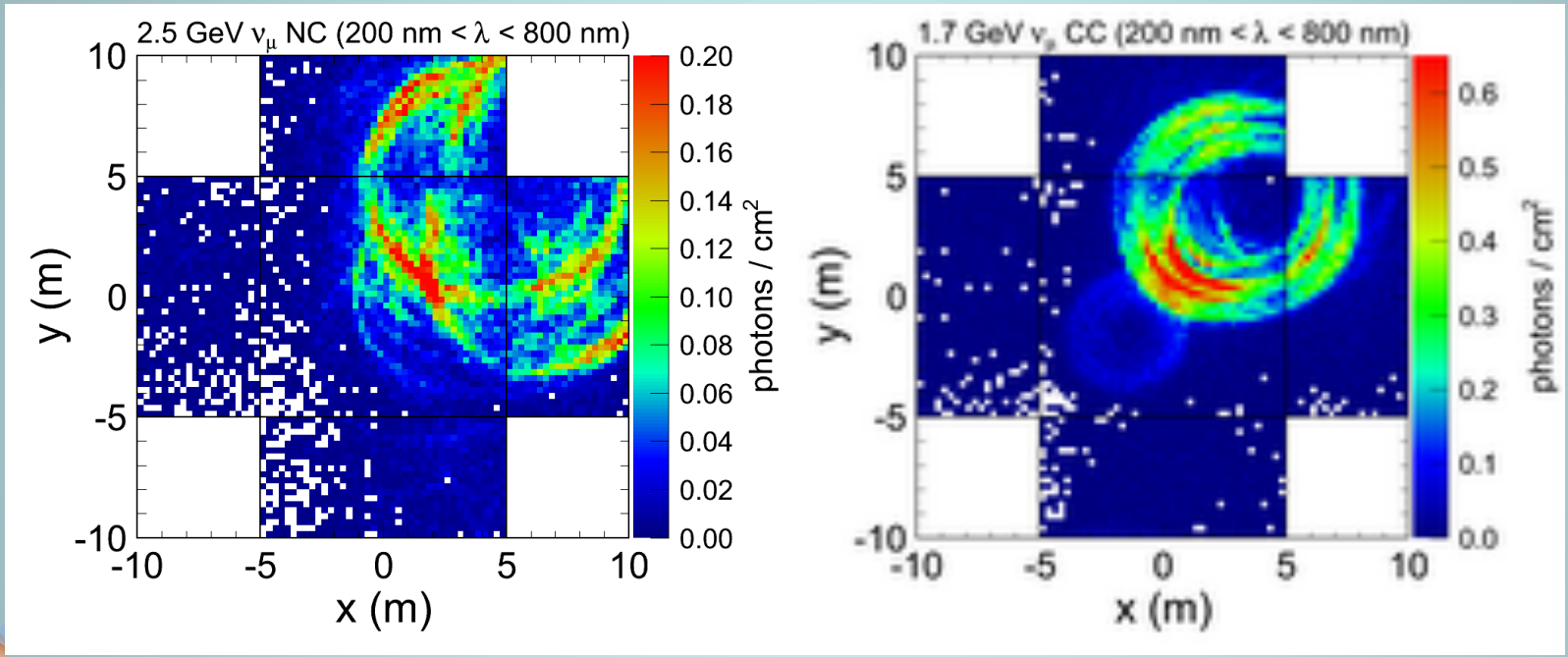


Focus on δ_{CP} : CHIPS

- Ideas for conceptual design:
  - Use large area MCPs being developed at ANL : 8100 for ~27kt for a demonstrator
  - Flat, good coverage, good QE devices, could help in having full Cherenkov coverage (Super-K is 40%)



Some pictures of events



NC

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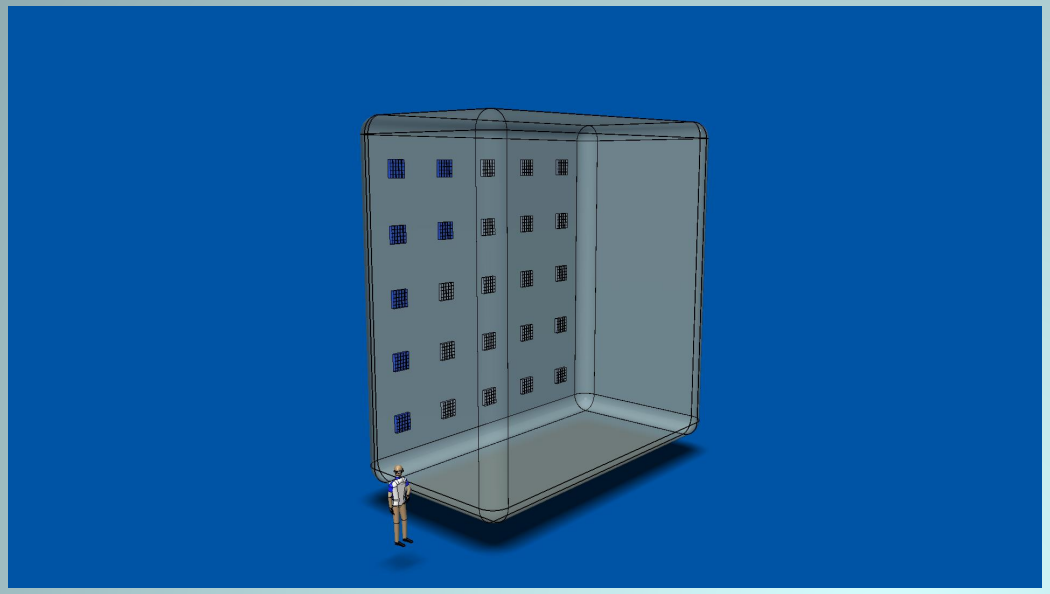
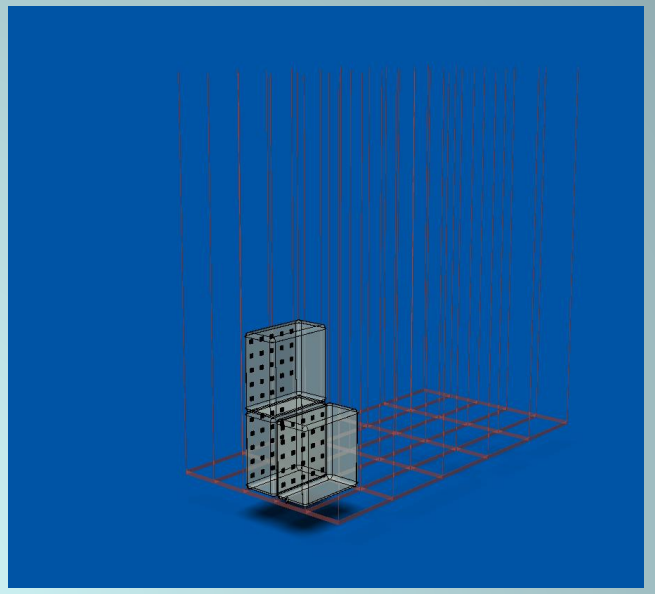
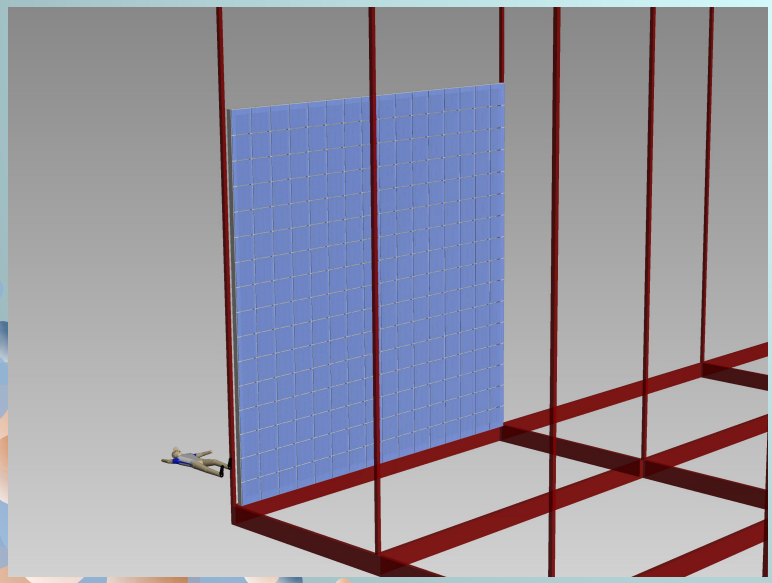
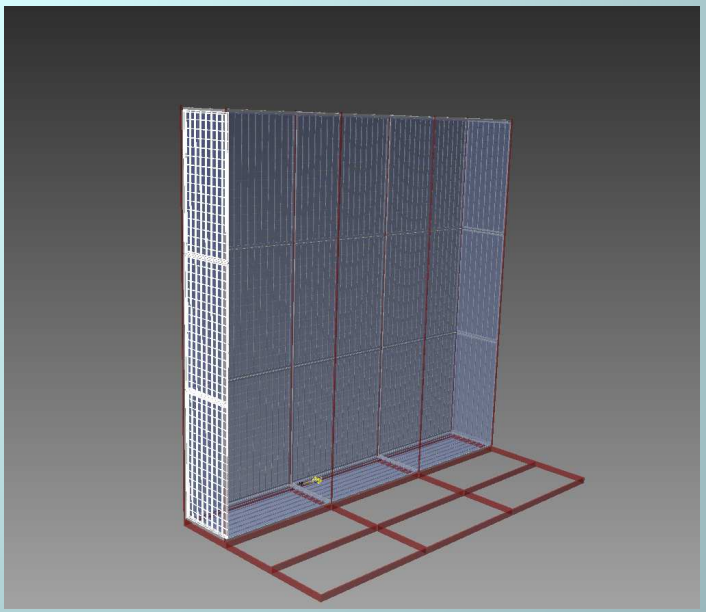
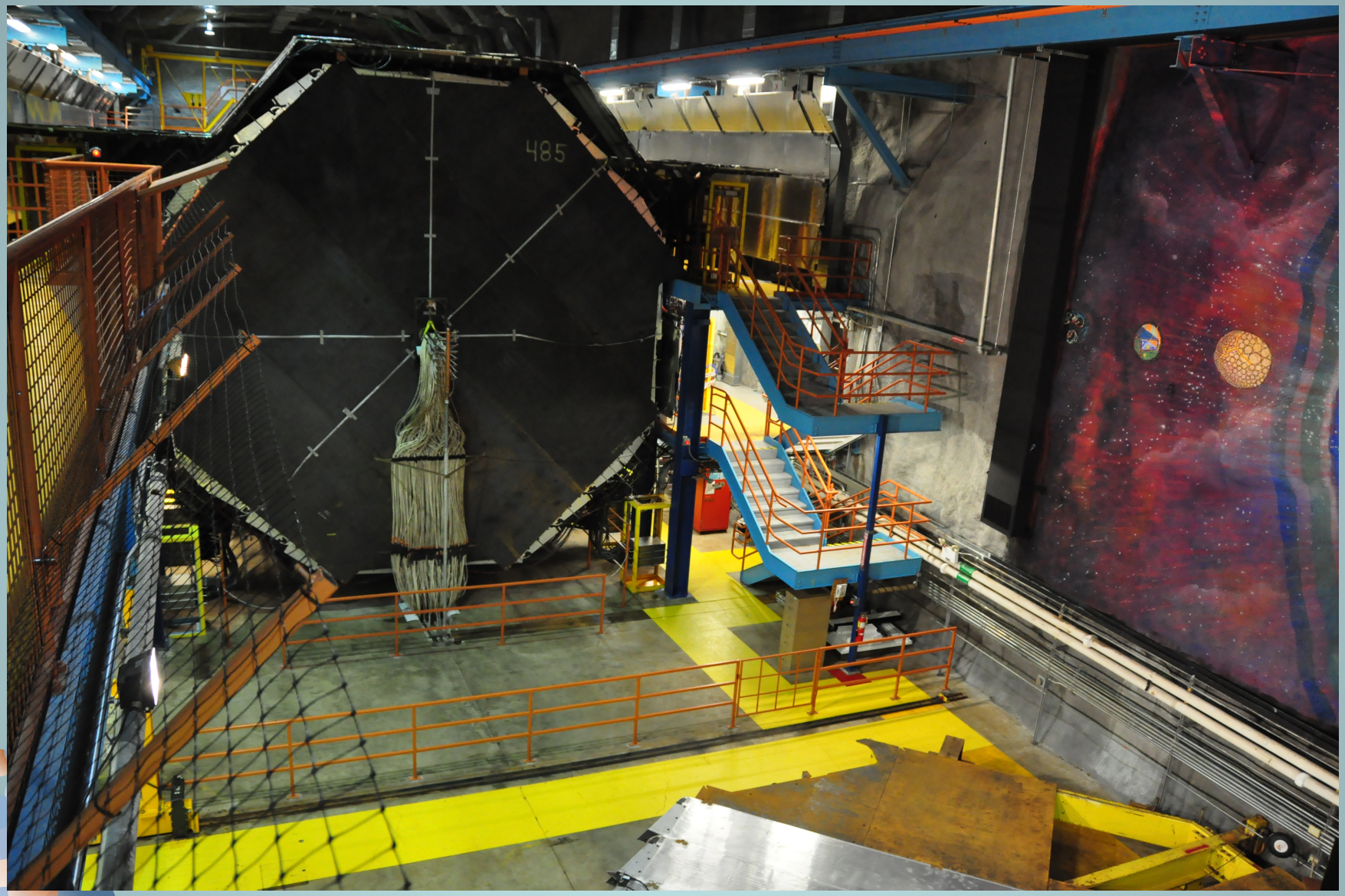


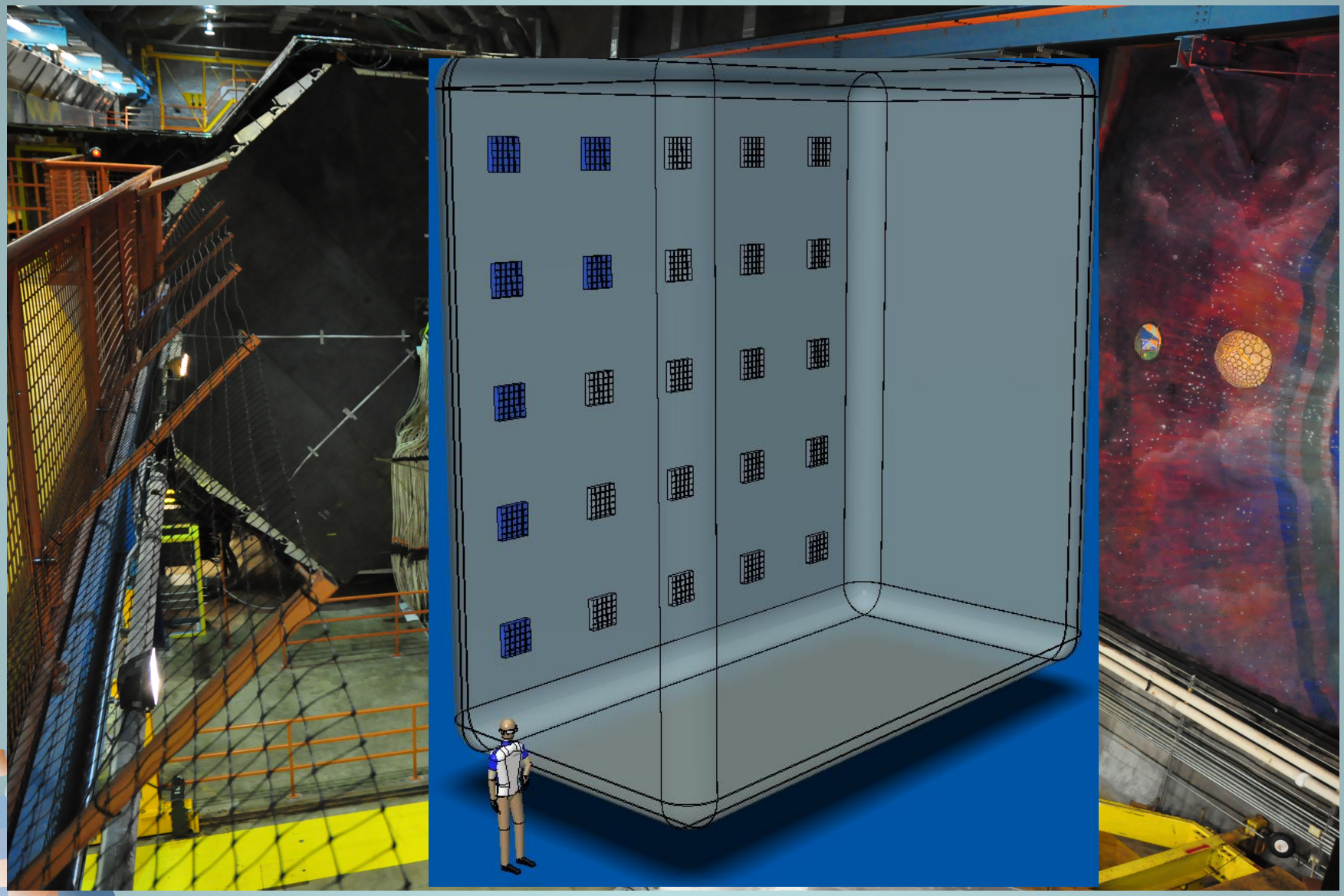






Harry Themann


485



The Point

- Both δ_{CP} and Mass Hierarchy need an appropriate L/E
- However, very long baseline NOT necessary for δ_{CP}
- Once you know MH, CP violation needs a wide band beam to investigate the spectrum
- NuMI beam might be lucky and find that δ_{CP} is in the right place to identify the MH
- More mass will be needed to get good measurement of δ_{CP} no matter what!
- Work can start on δ_{CP} with the NuMI beam.

Summary

- θ_{13} in LBL experiments offers more than just θ_{13}!
- MINOS+ will pick up where MINOS leaves off
  - Large reach in sterile search
  - Any non-standard effects should be seen with MINOS+
  - Continue high precision "standard parameter" measurements
- NOνA has started construction and will start taking data with 5kt in summer 2013
- NOνA (+ GLADE) might be lucky with MH
  - (other experiments such as DB-LB, PINGU.. Could be first)
- A new water experiment in the NuMI beam could measure δ_{CP}

Personal Note

- Contrary to popular belief, the scientific landscape in the US looks very interesting, with a number of possibilities for new ideas, which will not face the congressional approval process.
- DOE has encouraged thinking along these lines for Snowmass in July.
- European collaboration is very much encouraged in this vision of the (near) future
- Sign up to the email list:
  - listserv@fnal.gov (no subject)
  - subscribe e-numi (in the body)

Words from Jim Siegrist

Jenny, Nice to chat to you again today about challenges in neutrino physics. One of the main items we discussed was our need to try to generate a neutrino program with a steady stream of new science results coming out. There is a great deal of interest in this issue in the Washington Bureaucracy. Good ideas, especially ones that are less expensive, are always welcome in the office of science in that sense. **If members of the community have ideas, even if they don't fit in the current picture, the Office of HEP is interested in hearing about them, as I am sure your colleagues are interested in as part of the 'Snowmass' DPF planning process.** Good luck with your upcoming meeting, I hope these short comments help generate interest in the community in generating novel ideas.

The 8th Rencontres du Vietnam

Viet Nus 2012

Toward CP Violation In Neutrino Oscillations

Qui Nhon, Vietnam, Dec 17-22, 2012

Topics

- Implications of Lepton CP violation
- Experimental strategy
- Beam challenges
- Neutrino flux modeling
- Detectors

Qui Nhon is a coastal town in central Vietnam. It is about one hour flight from Ho Chi Minh City and one and a half hour from Hanoi. Qui Nhon has had a university for more than 50 years with 30 000 students with majors in science. The origins of the town stretch back to the 11th century Cham civilization, whose vestiges can be visited. The region is rich in historical remains.The present town was officially founded over 100 years ago.

Contact

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www.hep.utexas.edu/VietNus2012