Precision Neutrino Experiments

MINOS+ and other options

24/05/13

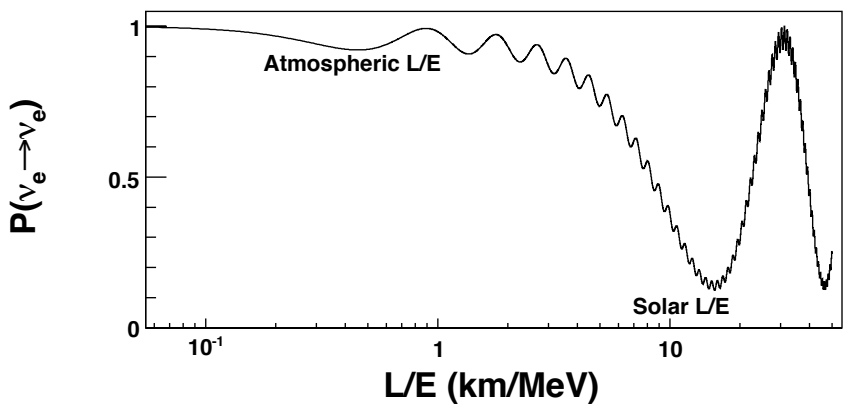
Prague

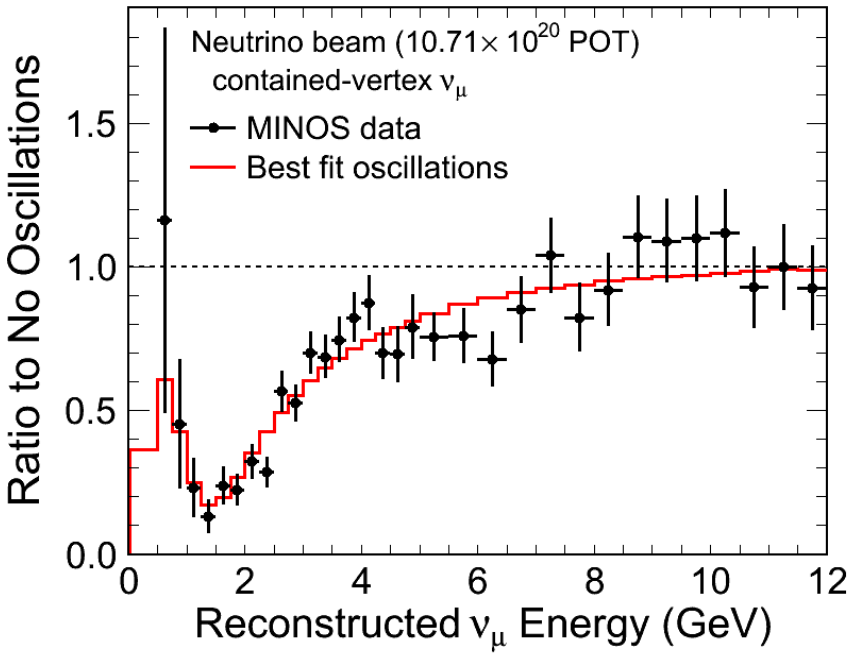
Jenny Thomas, UCL

- The need for precision ν oscillation measurements
- MINOS+
- The precision future
  - CHIPS@LBNE, but first CHIPS@NuMI
  - LAr detector in MINOS ND Hall
- Summary

The Precision World

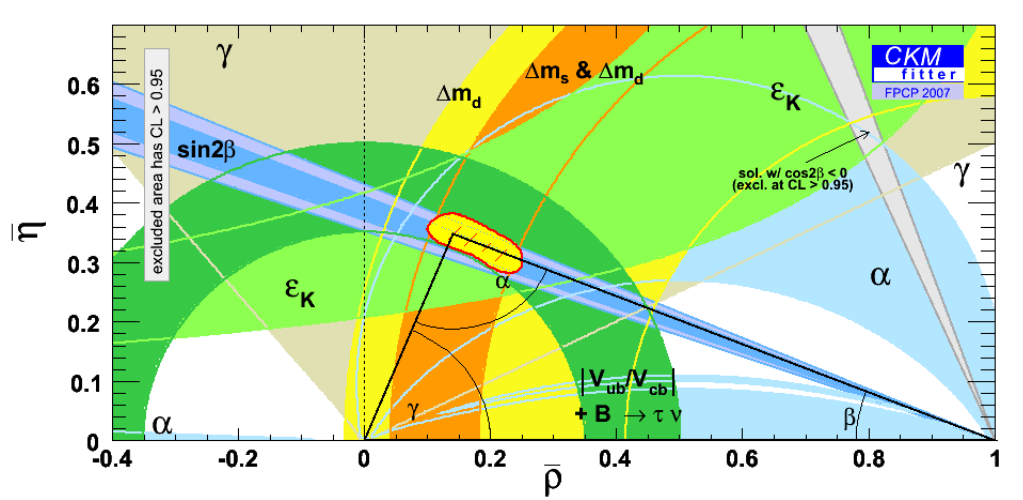
- Neutrino mass is the only evidence that Standard Model is incomplete
- Oscillation is now incontrovertible but:
  - Do we know its 3x3?
  - Our 4% measurements of mixing "parameters" are just fits to a 2x2 (& 3x3) model
  - Additional activity could be hidden in the poor statistics





The Precision World

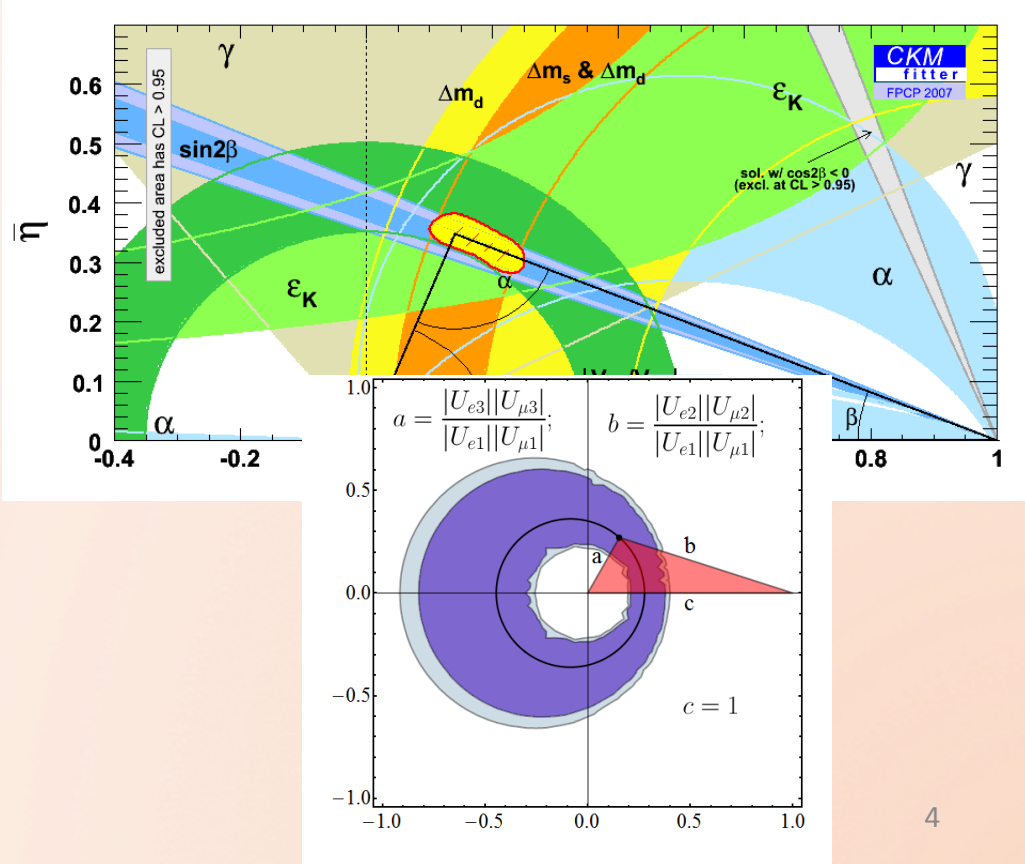
- Neutrino mass is the only evidence that Standard Model is incomplete
- Oscillation is now incontrovertible but:
  - Do we know its 3x3?
  - Our 4% measurements of mixing "parameters" are just fits to a 2x2 (& 3x3) model
  - Additional activity could be hidden in the poor statistics
- This talk is about trying to move into the precision era….
  - CP violating phase ≠ 0?



The Precision World

- Neutrino mass is the only evidence that Standard Model is incomplete
- Oscillation is now incontrovertible but:
  - Do we know its 3x3?
  - Our 4% measurements of mixing "parameters" are just fits to a 2x2 (or 3x3) model
  - Additional activity could be hidden in the poor statistics

- This talk is about trying to move into the precision era….
  - CP violating phase ≠ 0?



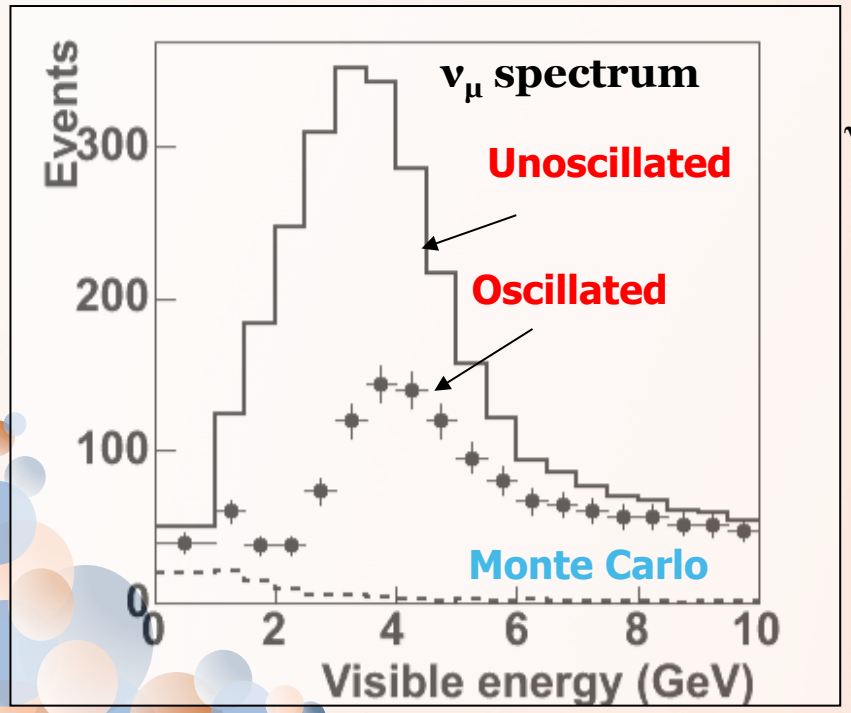
DISAPPEARANCE

Two Detector Gold Standard

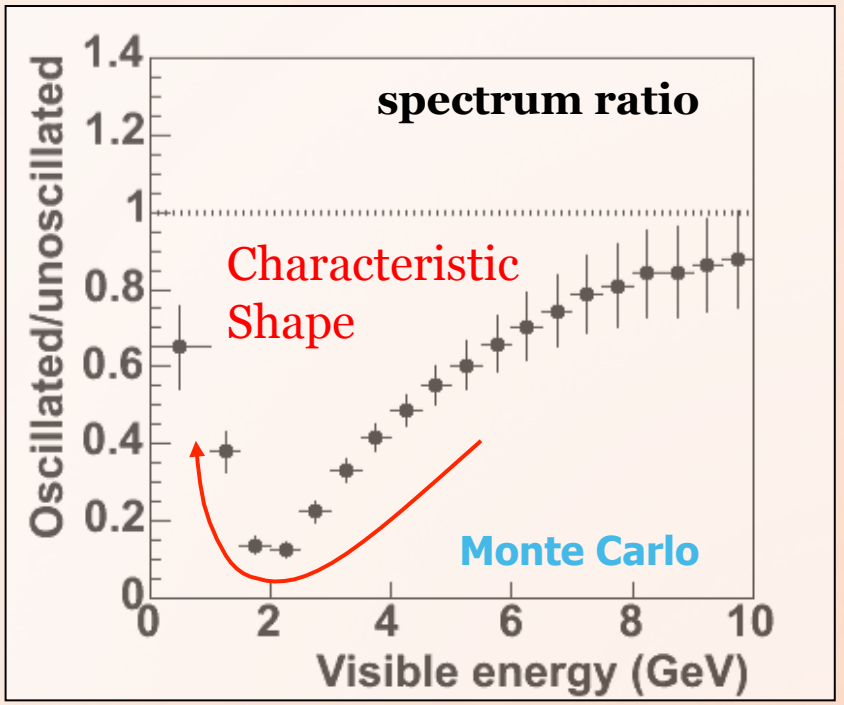
ν_μ disappearance : the 2 detector gold standard

- Predict un-oscillated spectrum at the further detector using the nearer detector and knowledge of kinematics
- No CP *violating* effects in disappearance

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



ν_e

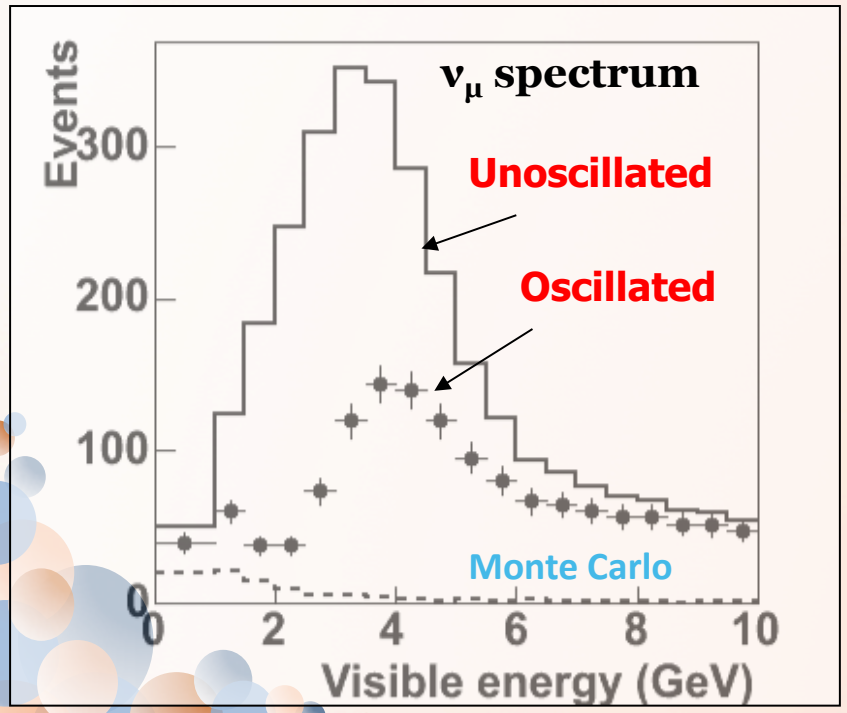


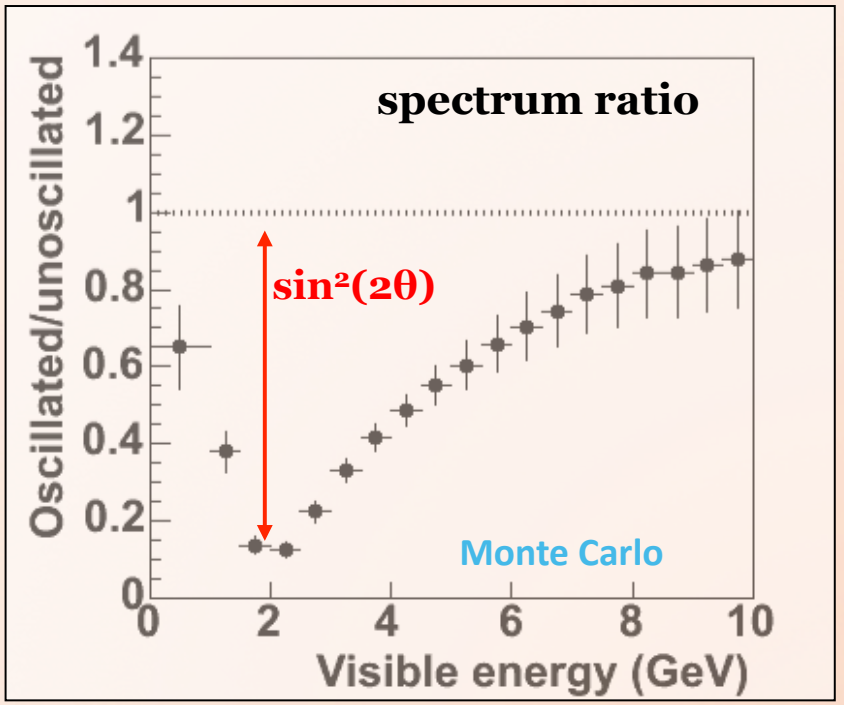
(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV^2 **)**

ν_μ disappearance : the 2 detector gold standard

- Predict un-oscillated spectrum at the further detector using the nearer detector and knowledge of kinematics
- No CP *violating* effects in disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.267 \Delta m_{32}^2 L/E)$$

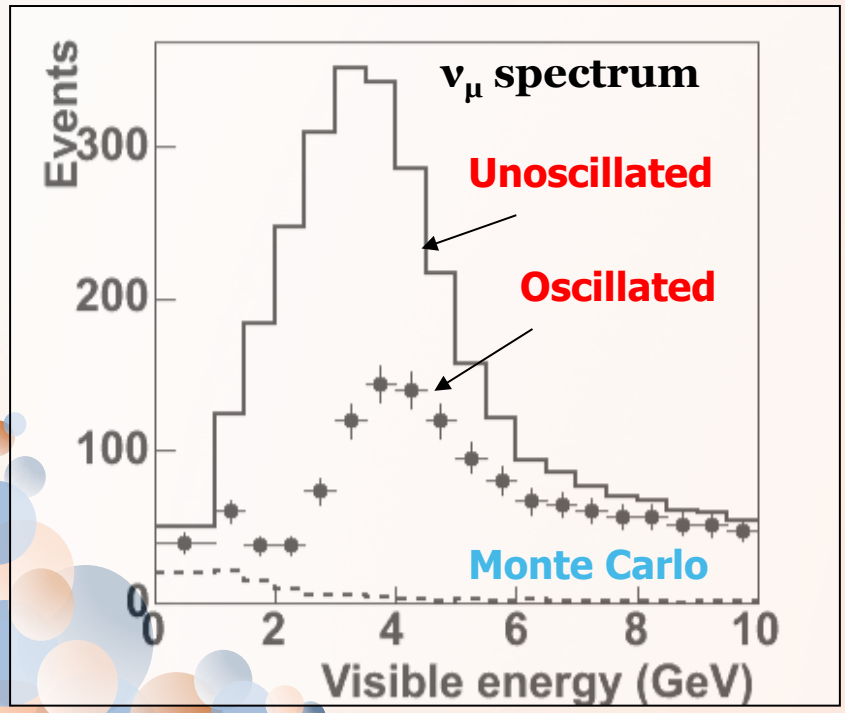


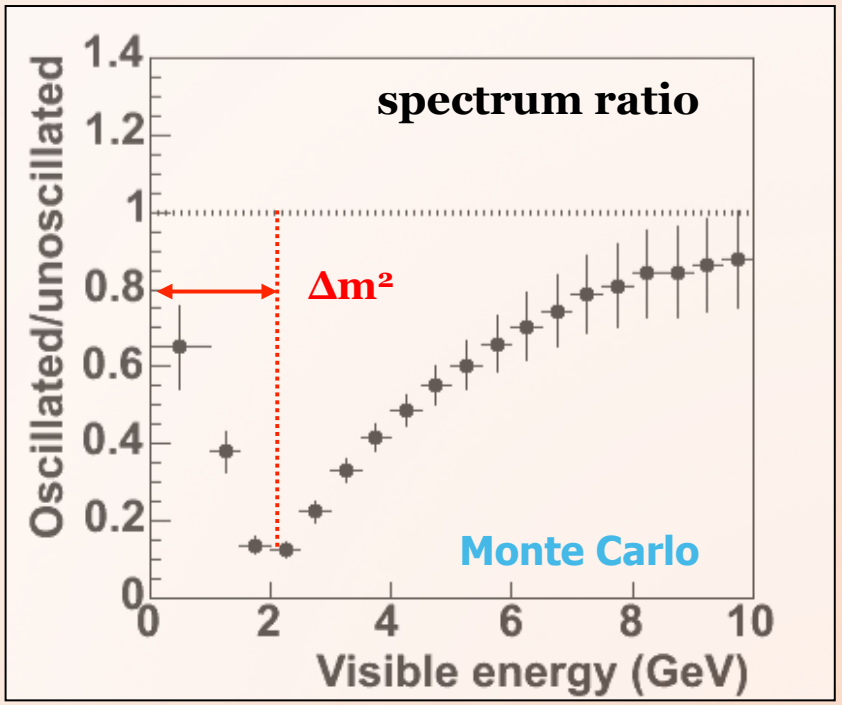


(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV^2 **)**

ν_μ disappearance : the 2 detector gold standard

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.267 \Delta m_{32}^2 L/E)$$



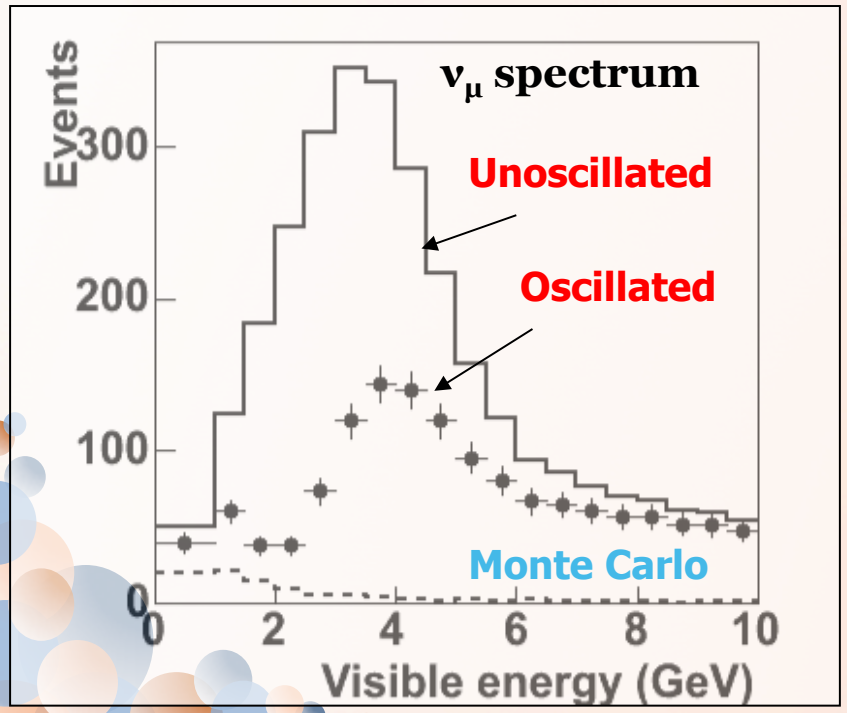


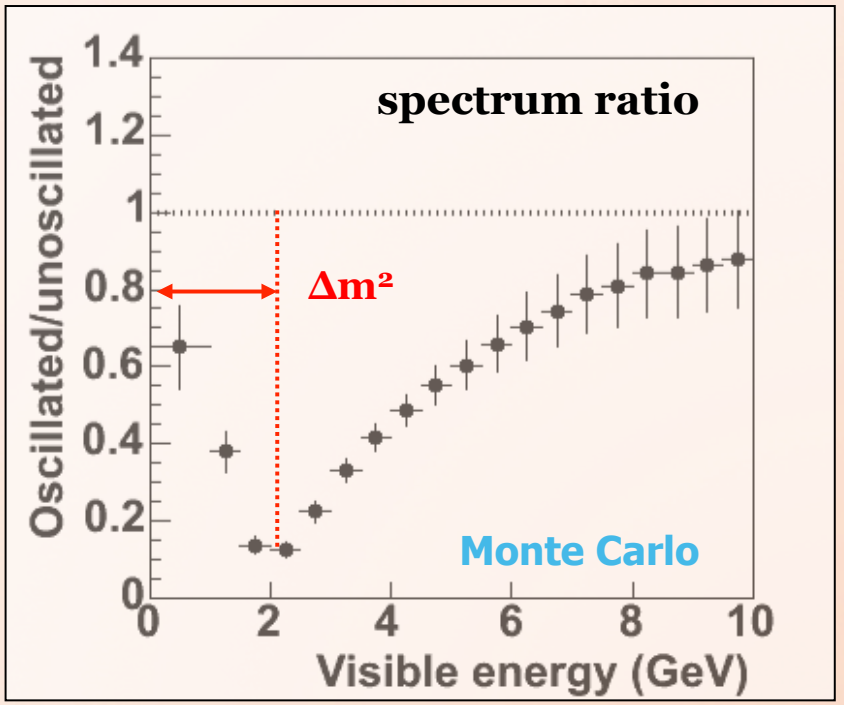
(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV² **)**

ν_e disappearance : the 2 detector gold standard

- Exactly the same idea as for the reactor measurement of θ_{13} (and later Δm^2_{31})
- No CP *violating* effects in disappearance

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m_{31}^2 L/E)$$





(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV² **)**

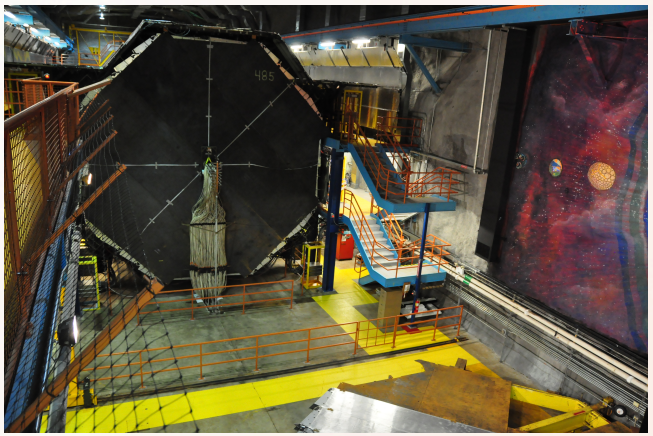
MINOS+

Starts June 2013 for three years

June 2013-2016

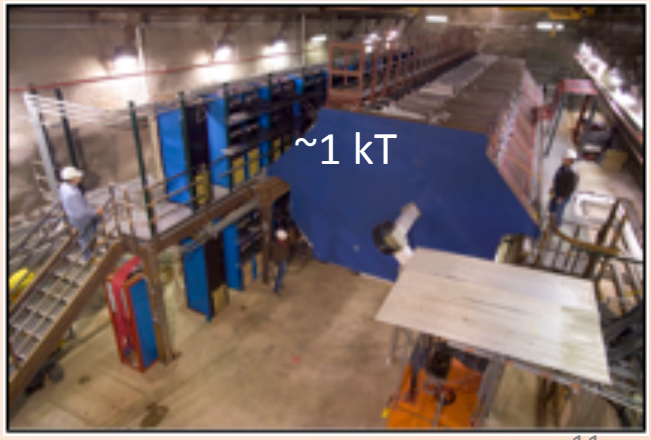
Unique physics reach

The MINOS(+) Experiment



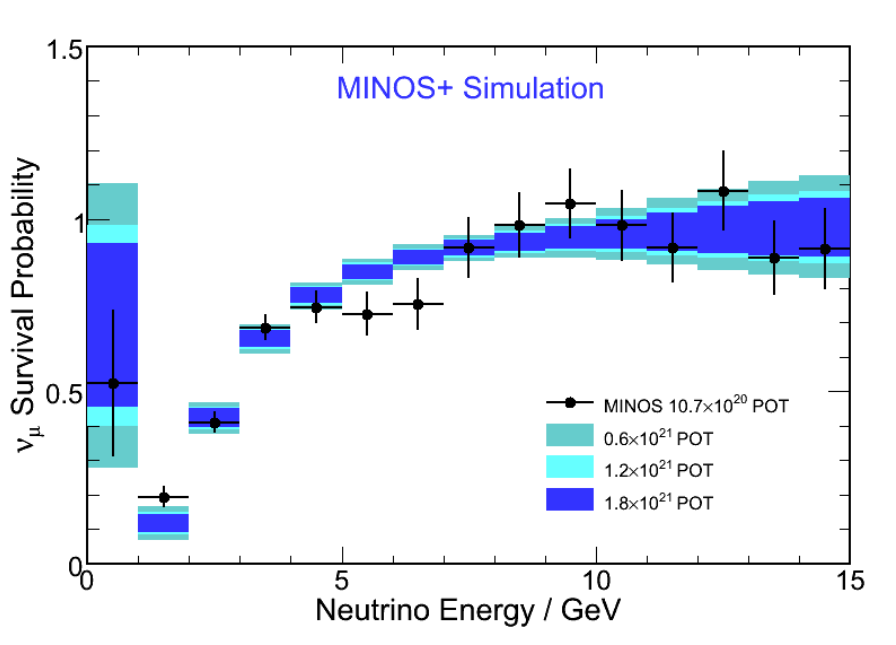
- Two detectors mitigate systematic effects
  - beam flux mis-modeling
  - Neutrino x-sec uncertainties
- L/E ~150-250 km/GeV
- Magnetized:
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-

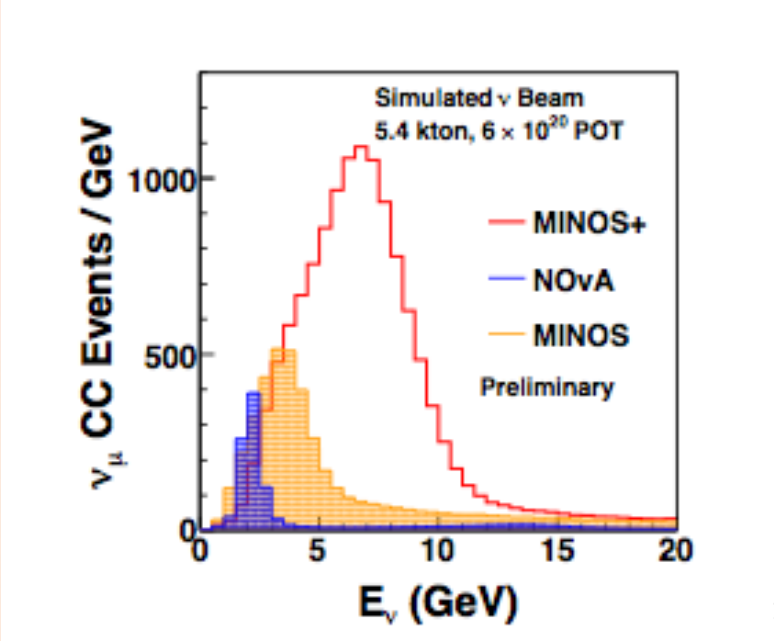
- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)



MINOS+

- The overarching reason to run MINOS in the NuMI-NOνA beam is to look for "non-standard" physics in a previously "unexplored" region :
  - Precision will be significantly increased (factor 60 in statistics in 3 years)
  - Where else would you look for evidence of non-3x3 effects?
    - Not at the oscillation maximum, main oscillation dominates
- 3000 events/year between 4-10 GeV near oscillation maximum



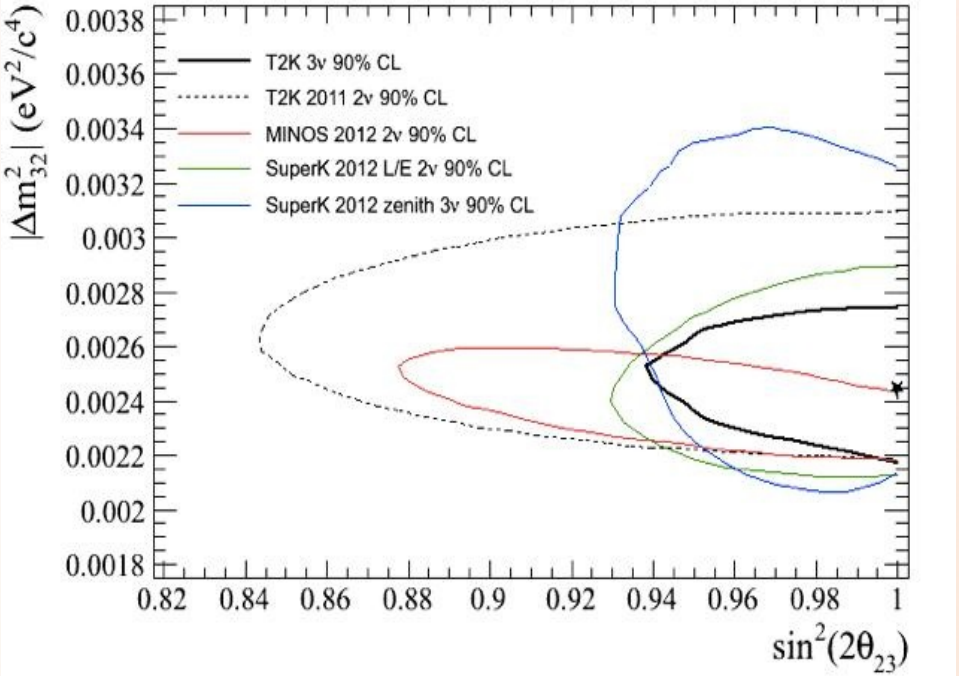


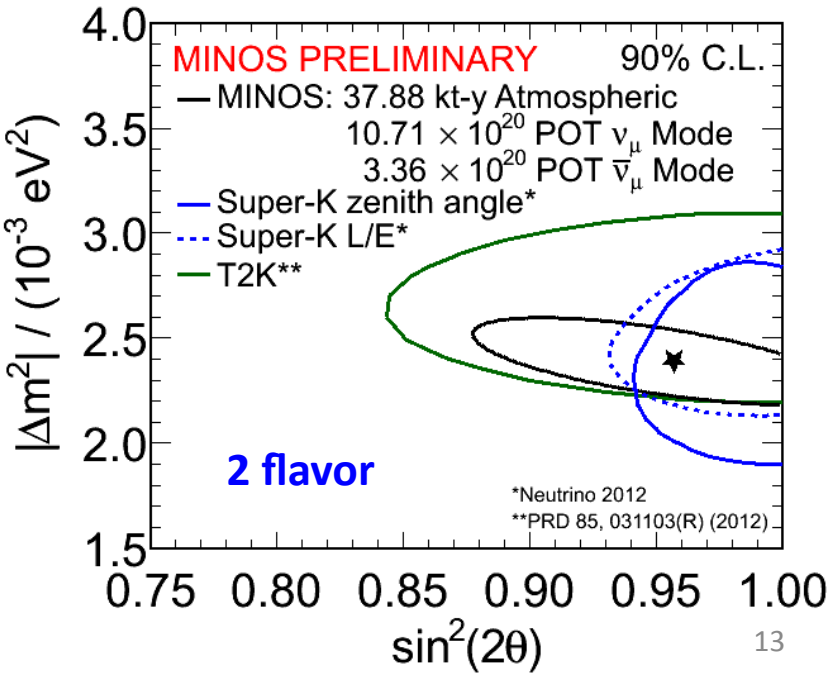
Δm^2 and $\sin^2 2\theta_{23}$

- MINOS has combined atmospheric and beam neutrinos and anti-neutrinos for most precise Δm^2 and $\sin^2 2\theta_{23} < 1.0$

- T2K BFV $\sin^2 2\theta_{23} = 1.00$ (2013)
- MINOS BFV $\sin^2 2\theta_{23} = 0.95$
- Super-K BFV $\sin^2 2\theta_{23} = 0.96$

θ_{23} NON MAXIMAL??





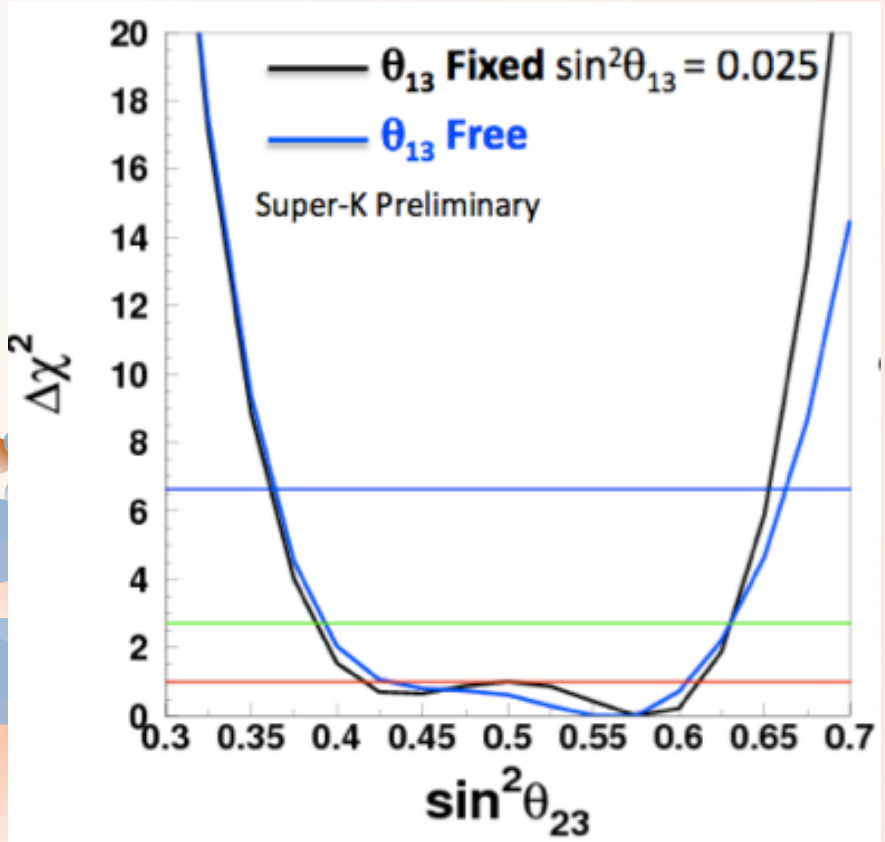
$\sin^2\theta_{23}$

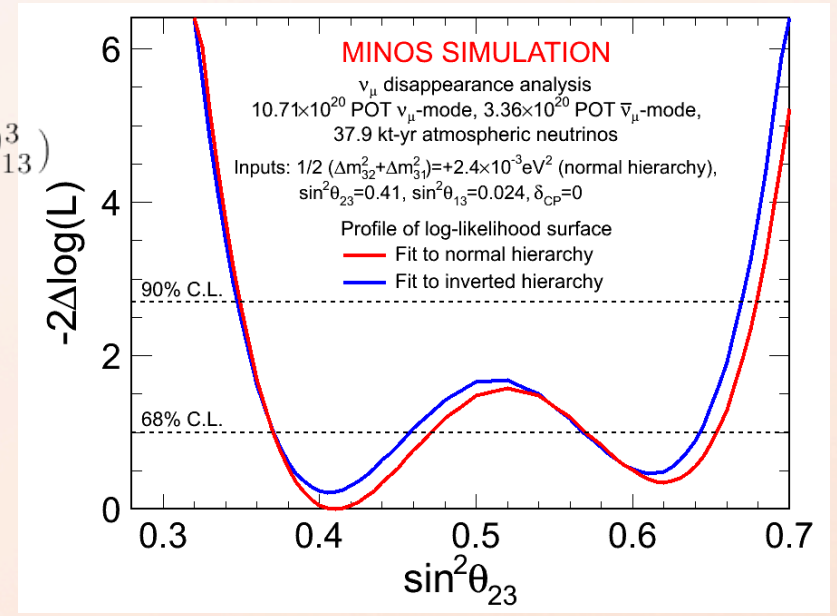
(Comes JUST from disappearance)

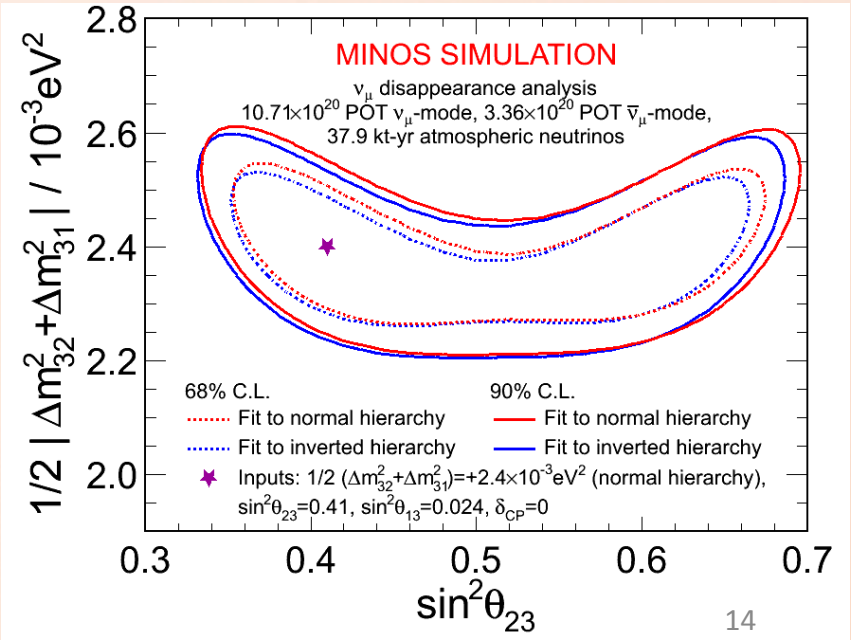
$$\mathcal{P}(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{eff}) \sin^2\left(\frac{\Delta m^2_{eff} L}{4E}\right) + \mathcal{O}(\theta^3_{13})$$

$$\sin^2(\theta_{eff}) = |U_{\mu 3}|^2 = \sin^2\theta_{23} \cos^2\theta_{13}$$

$$(\sin^2 2\theta_{eff} \approx \sin^2 2\theta_{23} : \theta_{13} \approx 0)$$







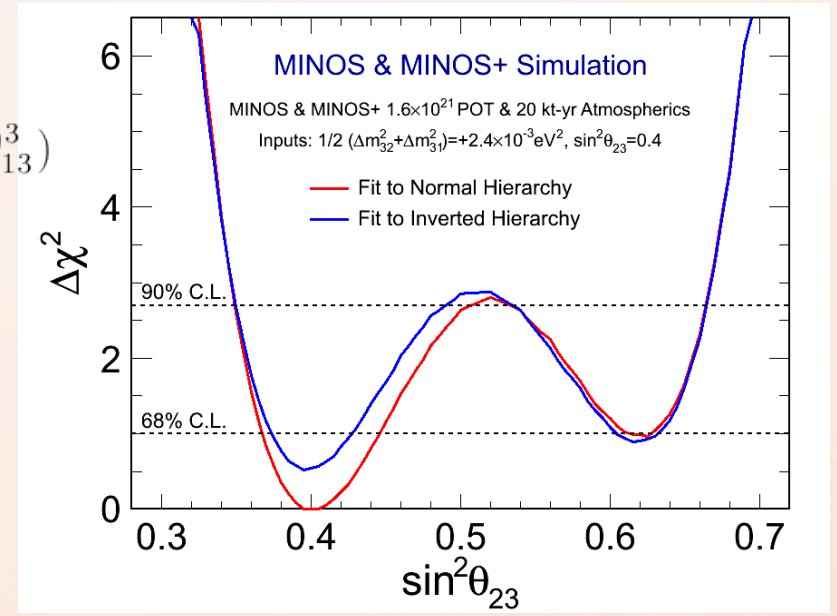
$\sin^2\theta_{23}$

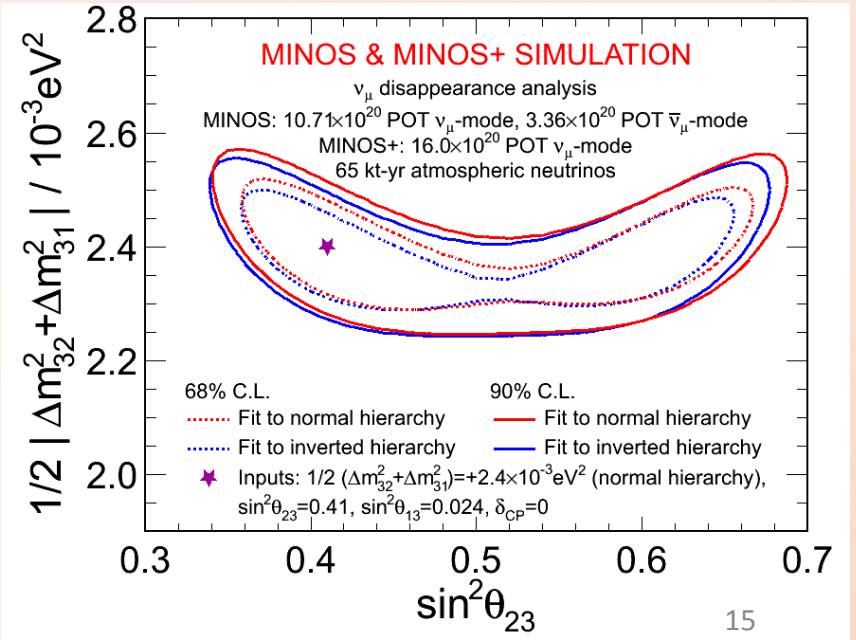
(Comes JUST from disappearance)

$$\mathcal{P}(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{eff}) \sin^2\left(\frac{\Delta m^2_{eff} L}{4E}\right) + \mathcal{O}(\theta^3_{13})$$

$$\sin^2(\theta_{eff}) = |U_{\mu 3}|^2 = \sin^2\theta_{23} \cos^2\theta_{13}$$

$$(\sin^2 2\theta_{eff} \approx \sin^2 2\theta_{23} : \theta_{13} \approx 0)$$





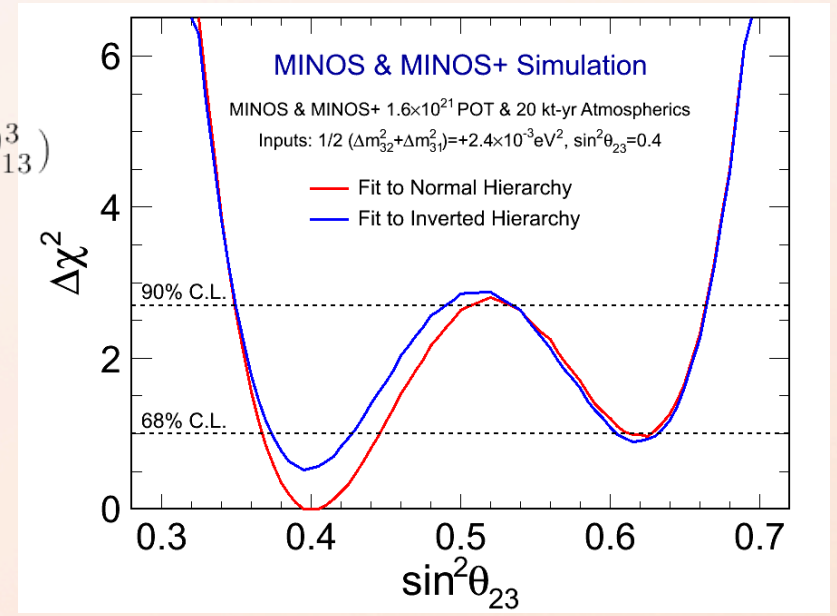
$\sin^2\theta_{23}$

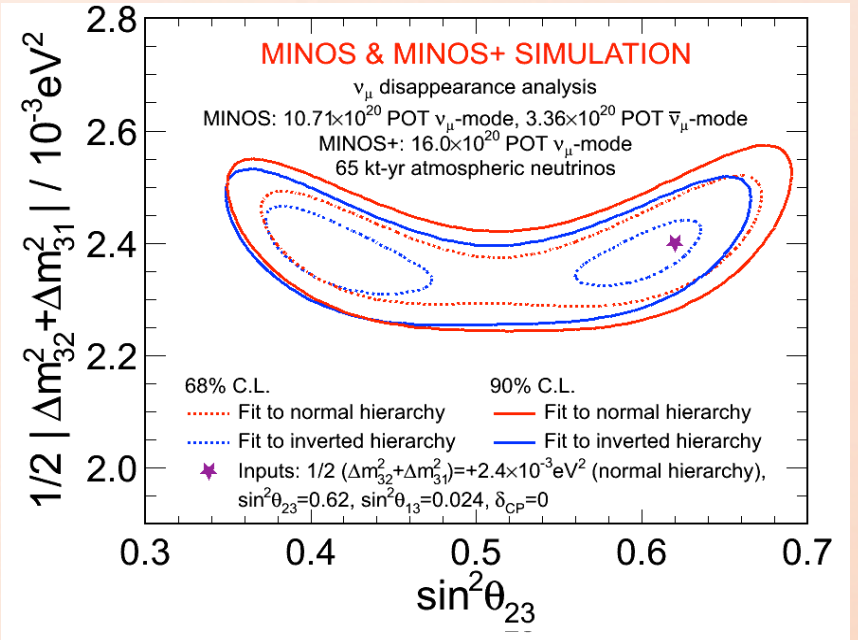
(Comes JUST from disappearance)

$$\mathcal{P}(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{eff}) \sin^2\left(\frac{\Delta m^2_{eff} L}{4E}\right) + \mathcal{O}(\theta^3_{13})$$

$$\sin^2(\theta_{eff}) = |U_{\mu 3}|^2 = \sin^2\theta_{23} \cos^2\theta_{13}$$

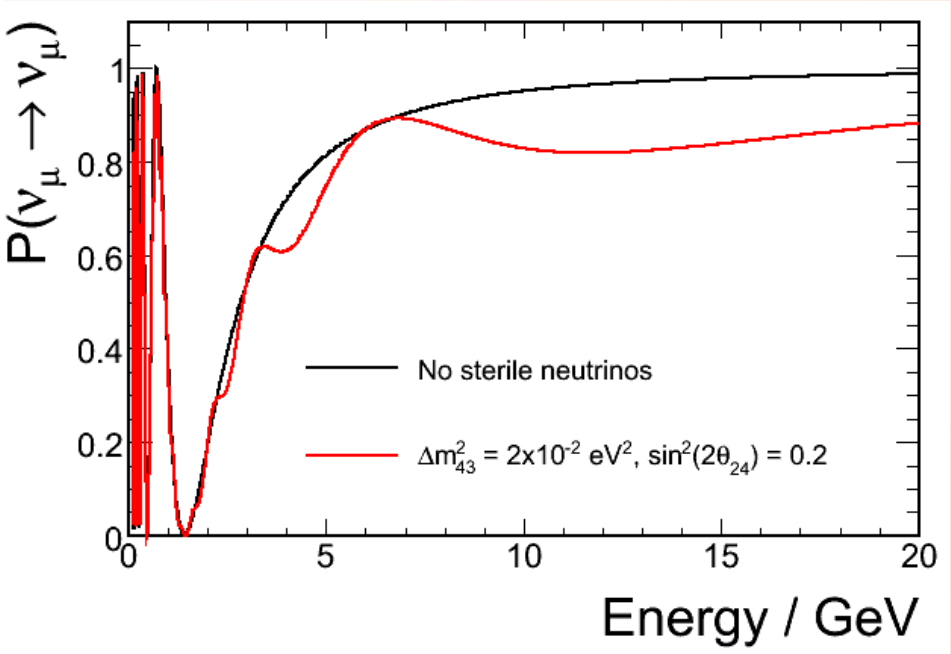
$$(\sin^2 2\theta_{eff} \approx \sin^2 2\theta_{23} : \theta_{13} \approx 0)$$

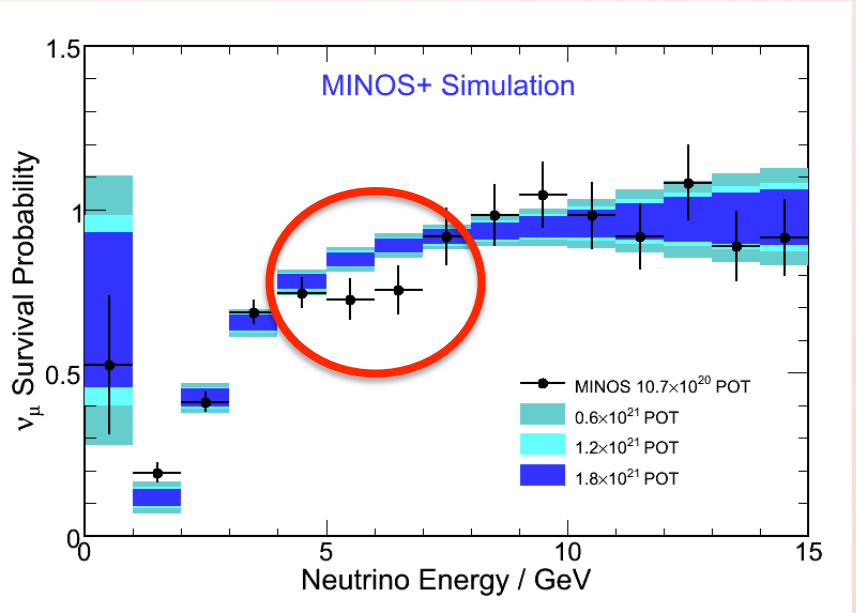




MINOS+

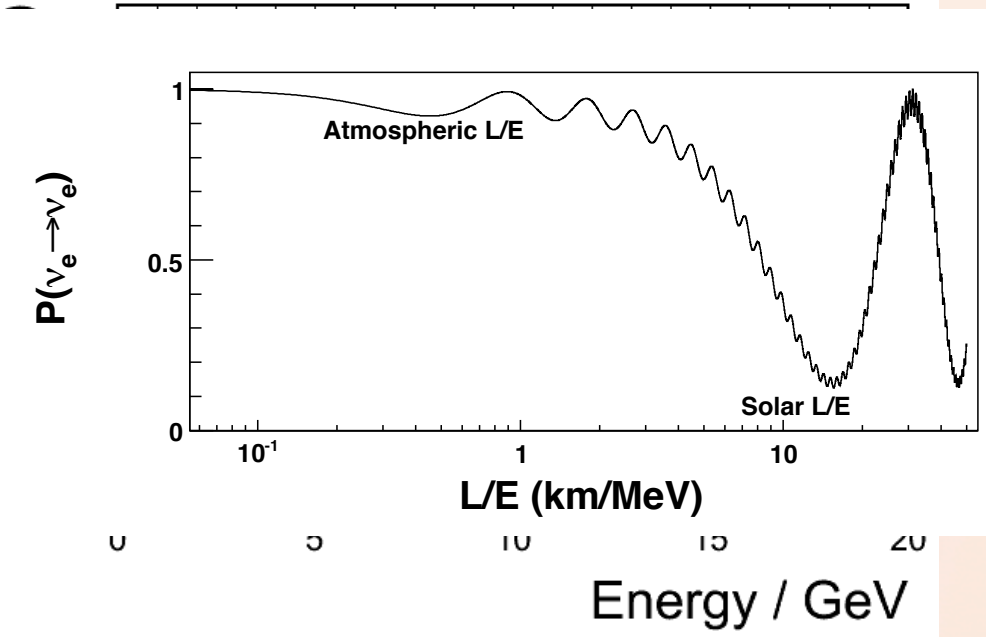
- Search for sterile neutrinos could be interesting
- Odd dip will have to wait for MINOS+ for more study
- Oscillation spectrum pretty insensitive to primary oscillation parameters in this region

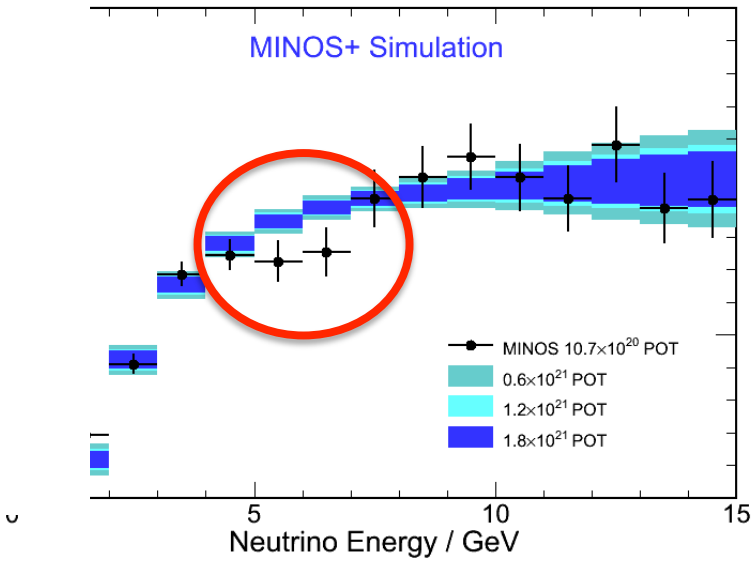




MINOS+

- 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

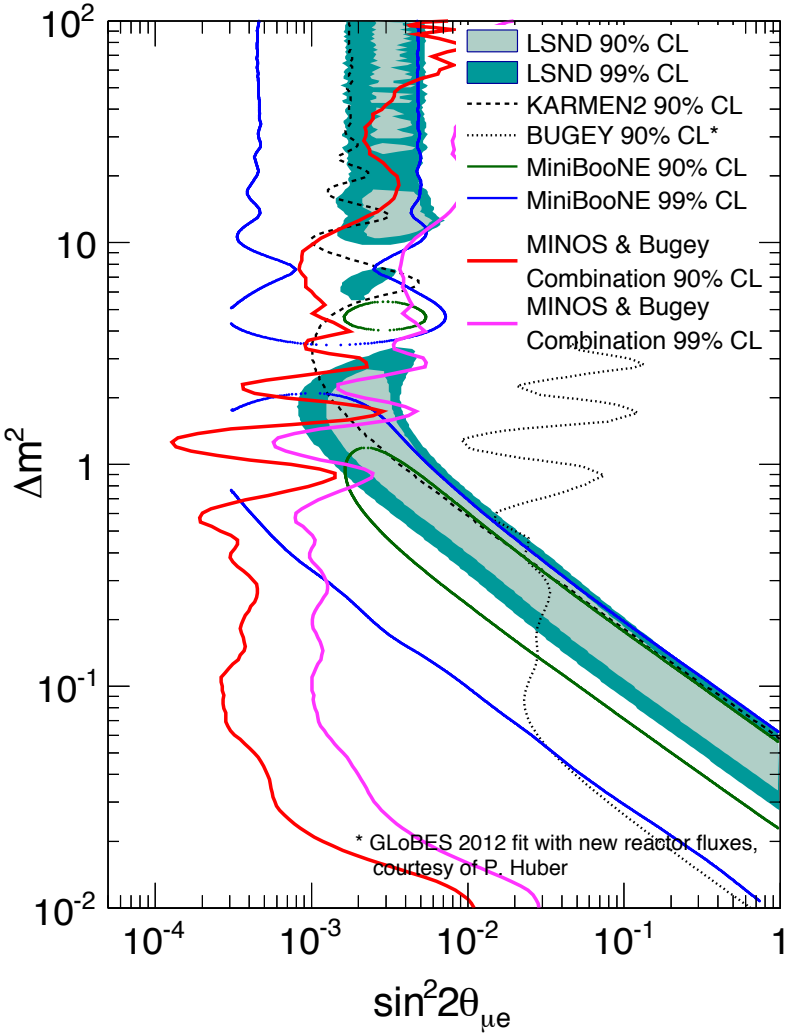




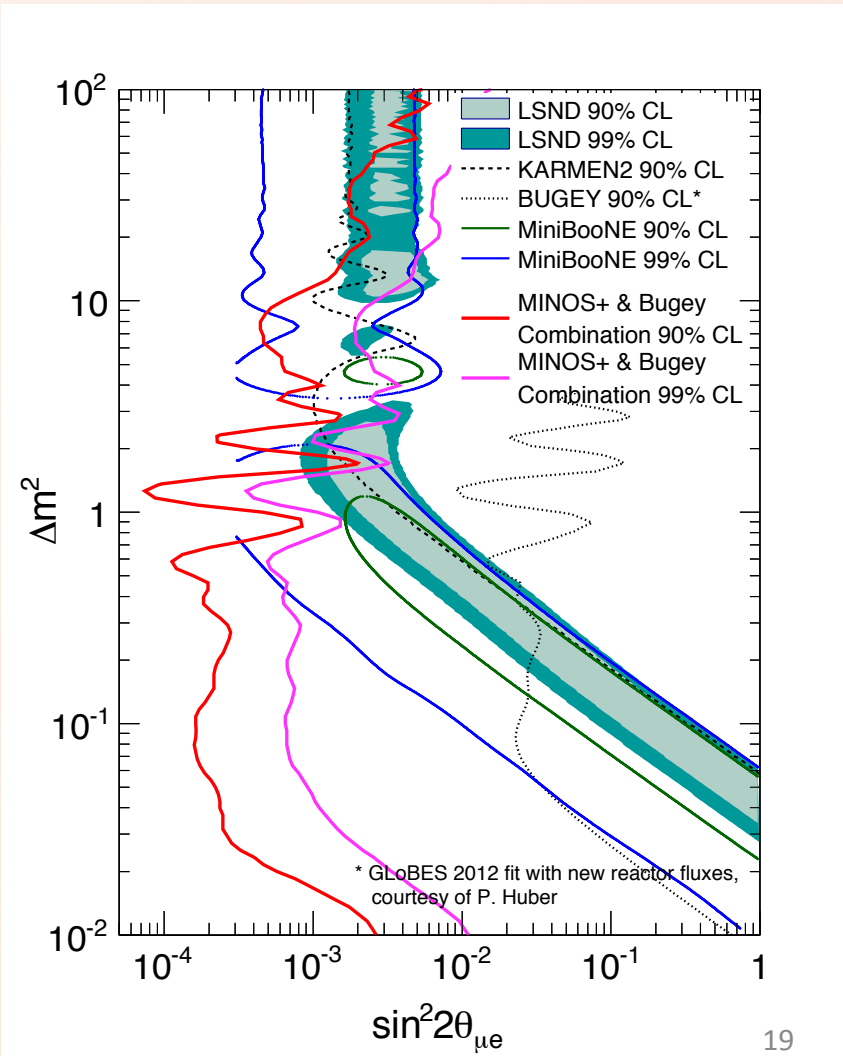
MINOS and MINOS+ sterile reach

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

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



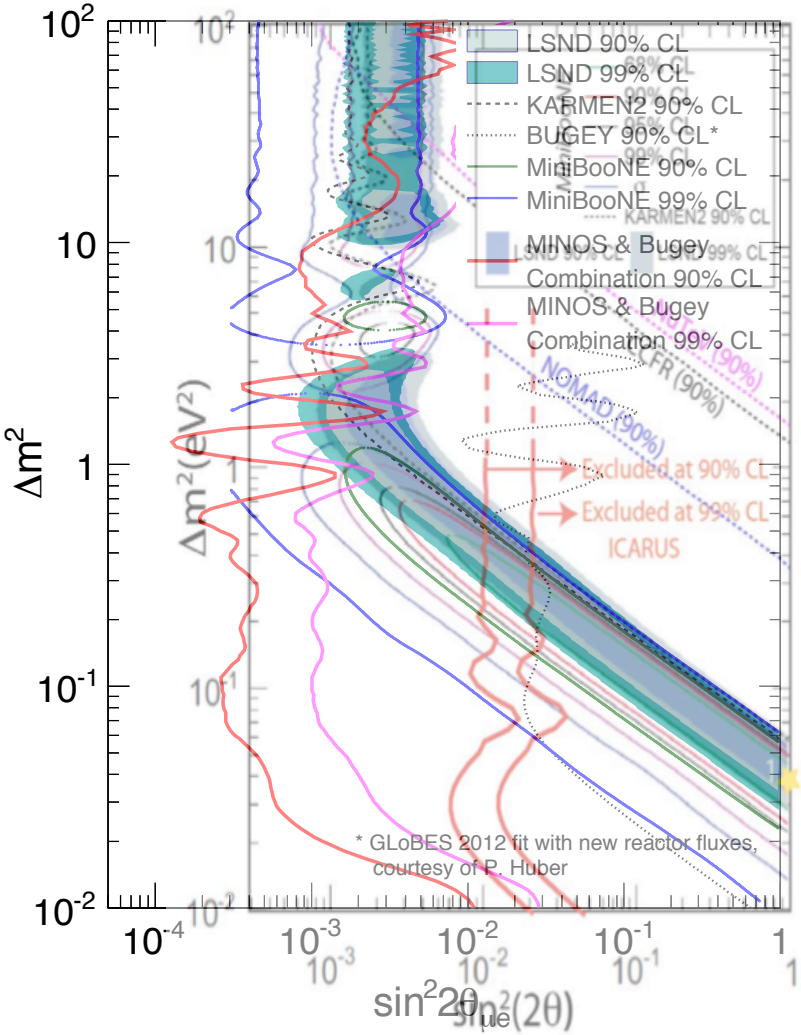
$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu 4}|^2$ (disappearance)



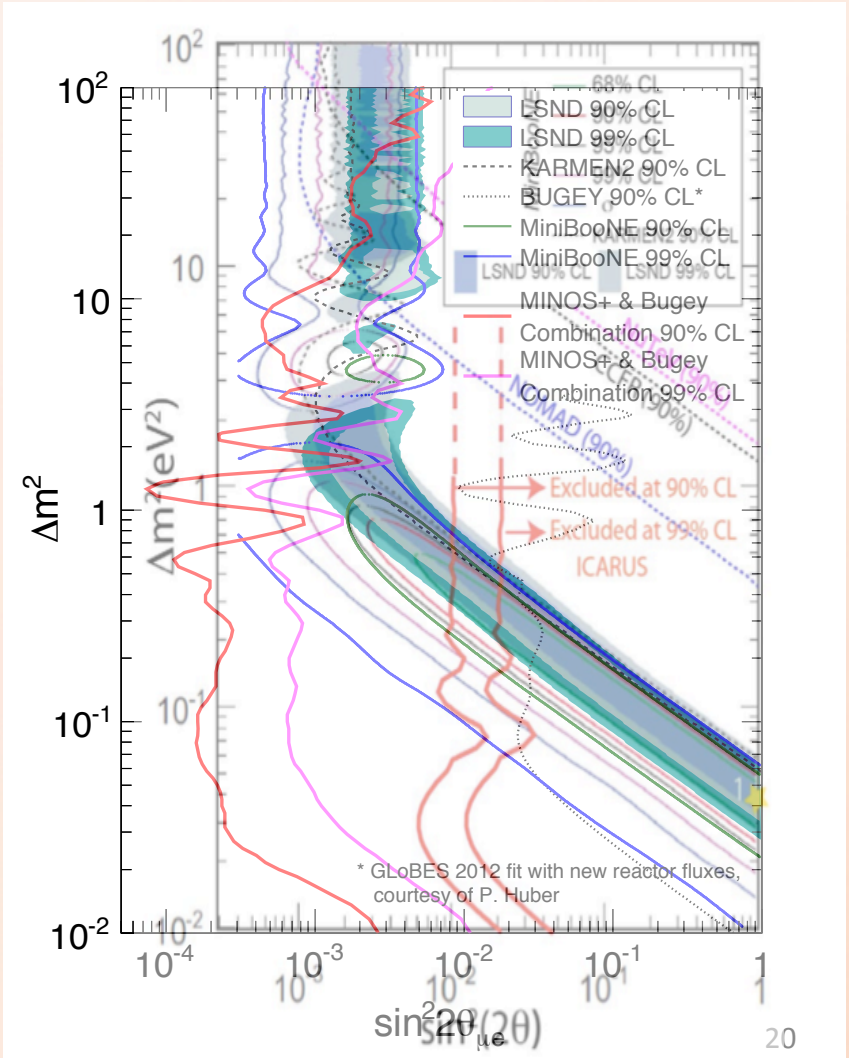
MINOS+ sterile reach

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

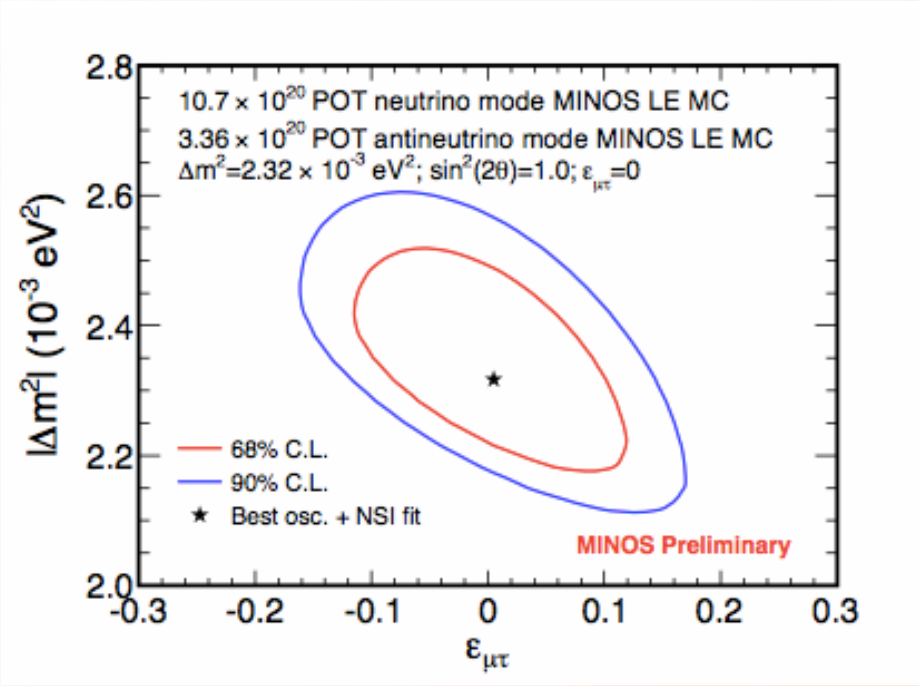
$\nu_\mu \rightarrow \nu_e$ (appearance)

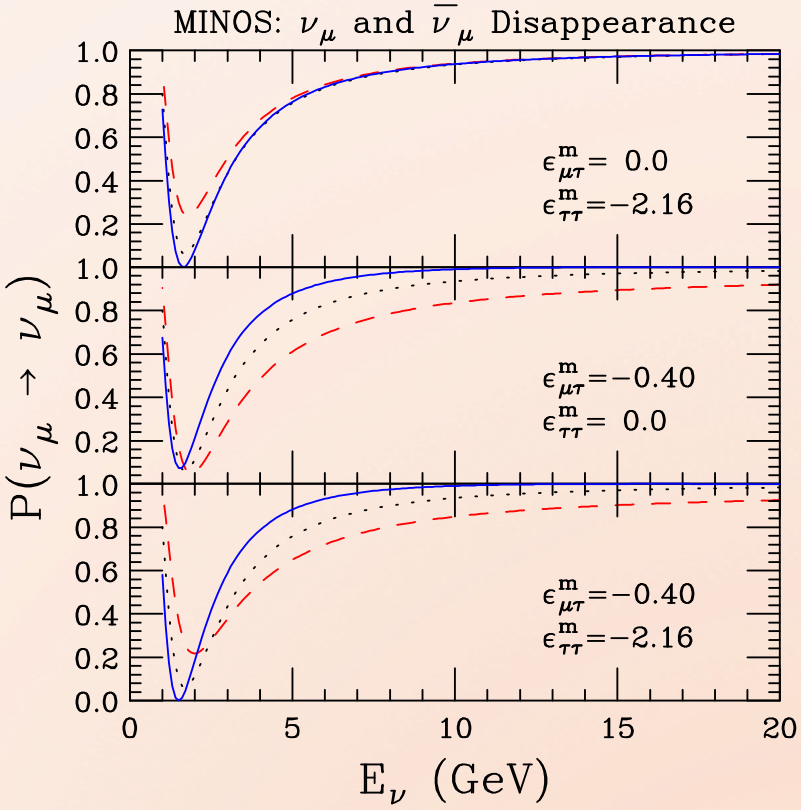


$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu 4}|^2$ (disappearance)



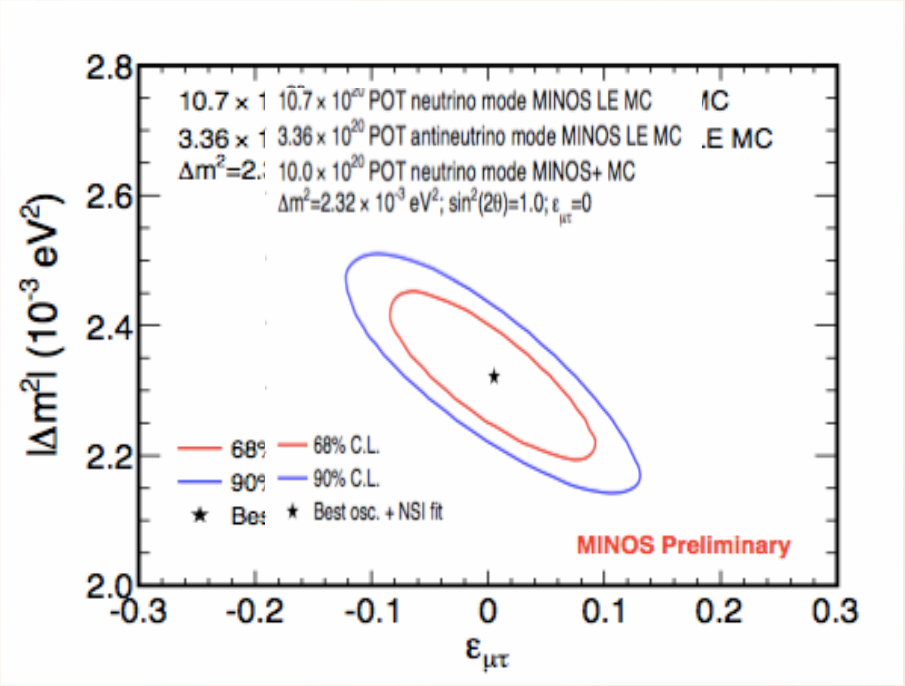
- At dim. 5, neutrino mass $m_\nu \rightarrow \frac{y_\nu^2}{\Lambda}(LH)(LH)$

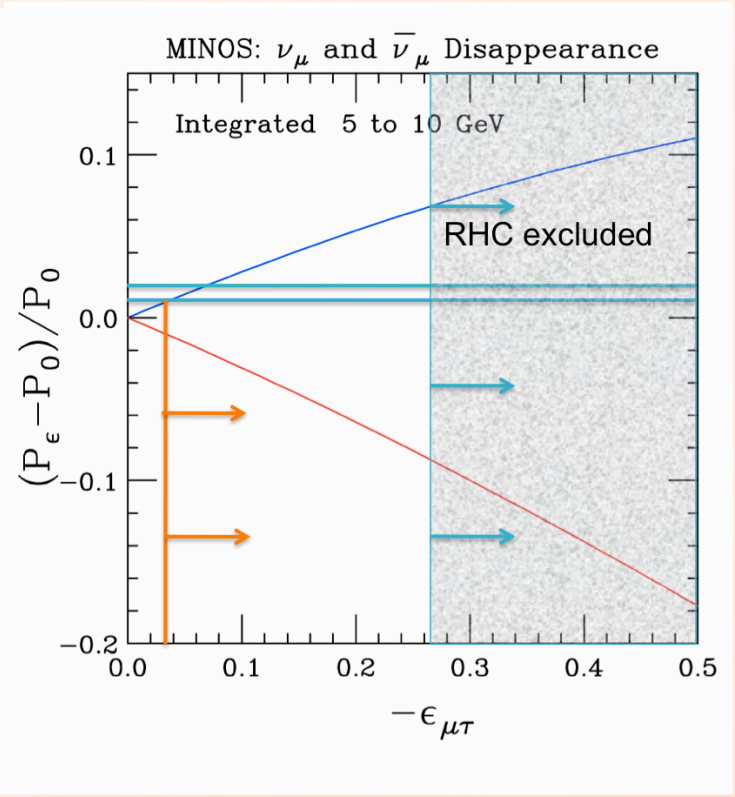




- Dimension 5 interactions are natural for Majorana (Lepton number violating) neutrinos
- Does not need a new force (like Dark Energy or Super Symmetry)
- Somehow a new force is more interesting, but surely less likely!!!
- Alexander Friedland , Cecilia Lunardini, Phys.Rev.D74:033012,2006.
- Oscillation spectrum pretty insensitive to primary oscillation parameters in this region

- At dim. 5, neutrino mass $m_\nu \rightarrow \frac{y_\nu^2}{\Lambda}(LH)(LH)$

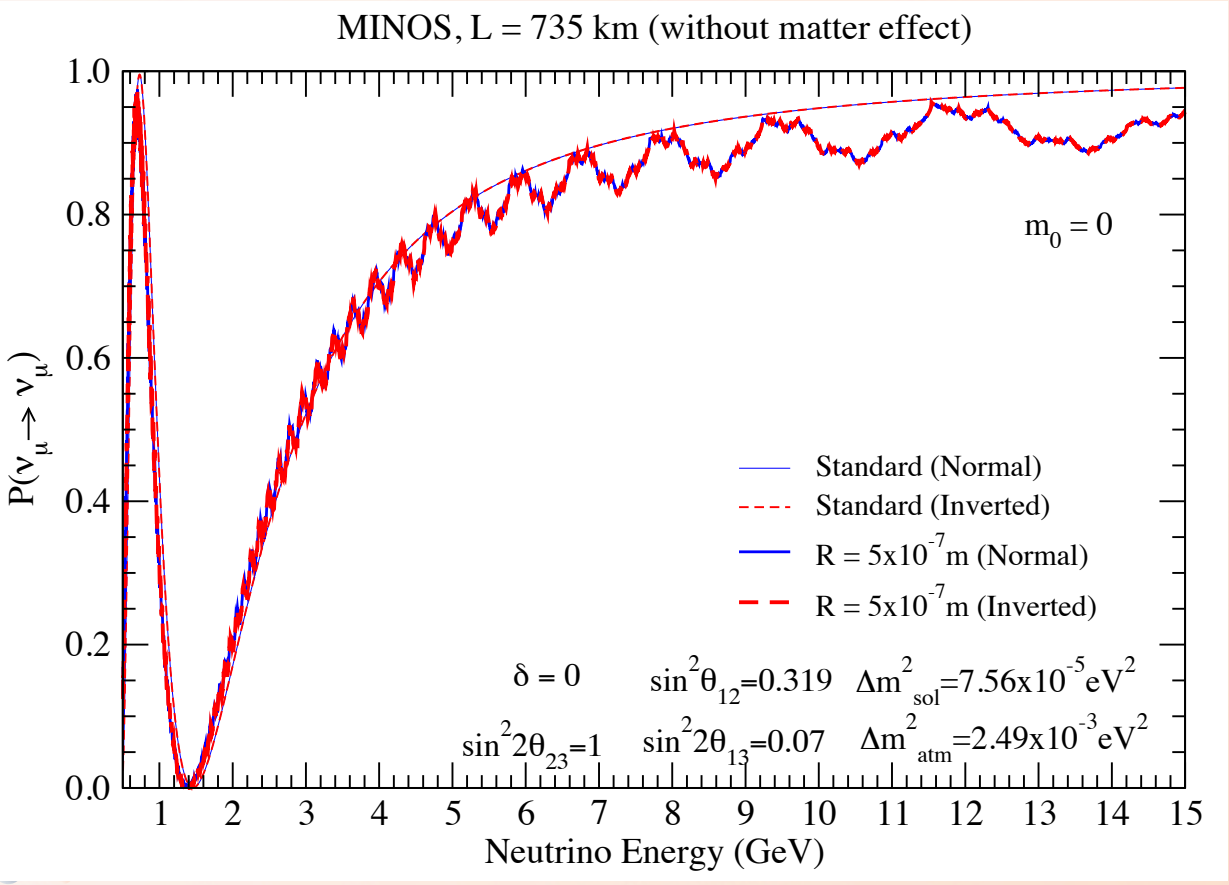




- Dimension 5 interactions are natural for Majorana (Lepton number violating) neutrinos
- Does not need a new force (like Dark Energy or Super Symmetry)
- Somehow a new force is more interesting? But surely less likely!!!
- J. Kopp, P.A.N. Machado and S.Parke, Phys.Rev.D82:113002 (2010).
- Oscillation spectrum pretty insensitive to primary oscillation parameters in this region

Large extra dimensions with MINOS+

Half micron sized extra dimensions can be observed!!



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

$\sin^2 2\theta_{13}$ and $\sin^2 \theta_{23}$
($\sin^2 2\theta_{e3}$ and $\sin^2 \theta_{\mu 3}$)

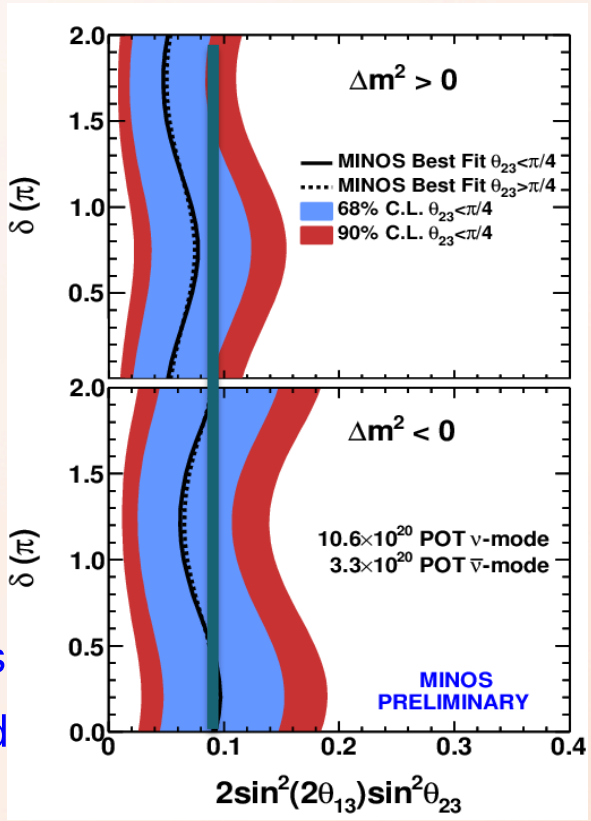
The "new" parameters

Opening the door to CP violation, θ_{23} octant determination and Mass Hierarchy.

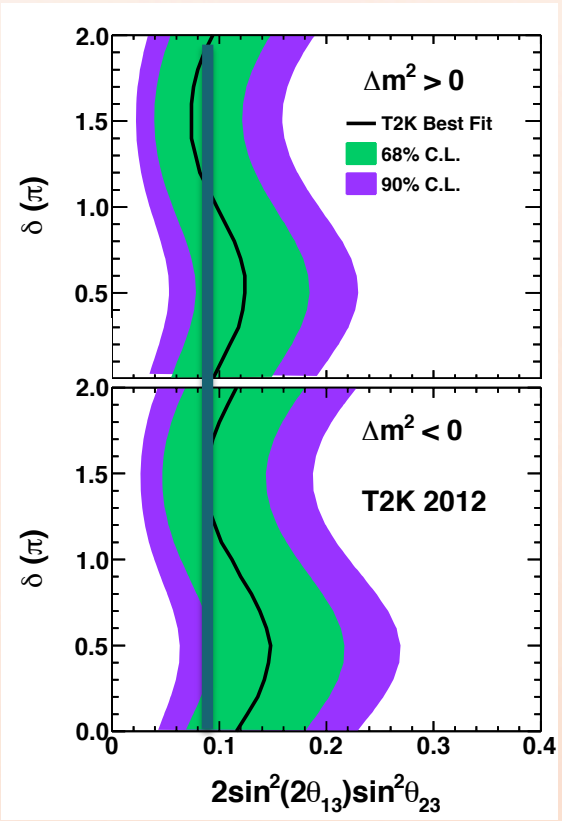
$2\theta_{13}$

- MINOS has completed θ_{13} study
- Used 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?
- MINOS used ND for background measurements
- Combination of MINOS and T2K could give more insight

(NH,δ_{CP}=0) $0.051^{+0.038}_{-0.030}$



$0.094^{+0.053}_{-0.040}$



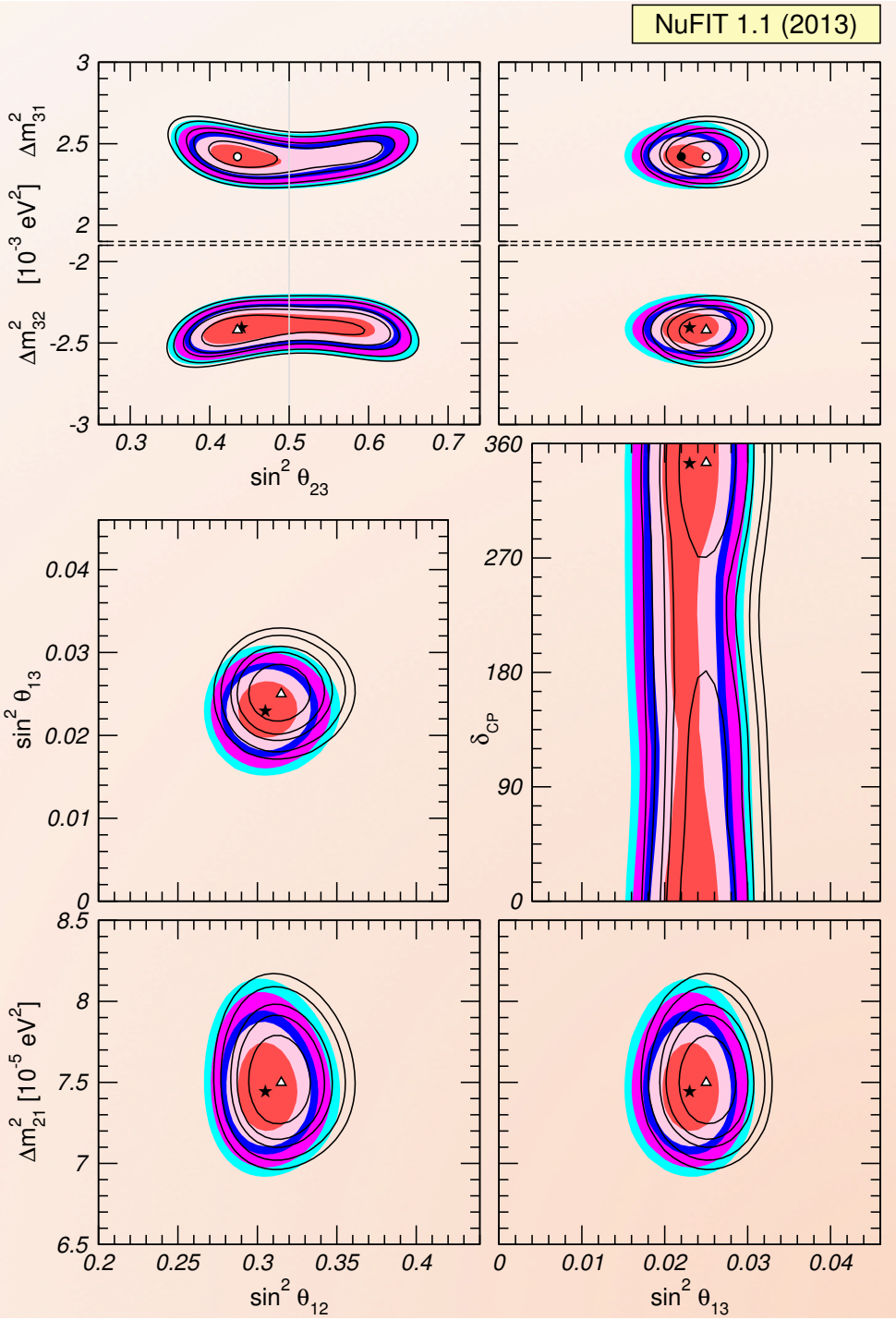
(IH,δ_{CP}=0) $0.093^{+0.054}_{-0.049}$

$0.116^{+0.063}_{-0.049}$

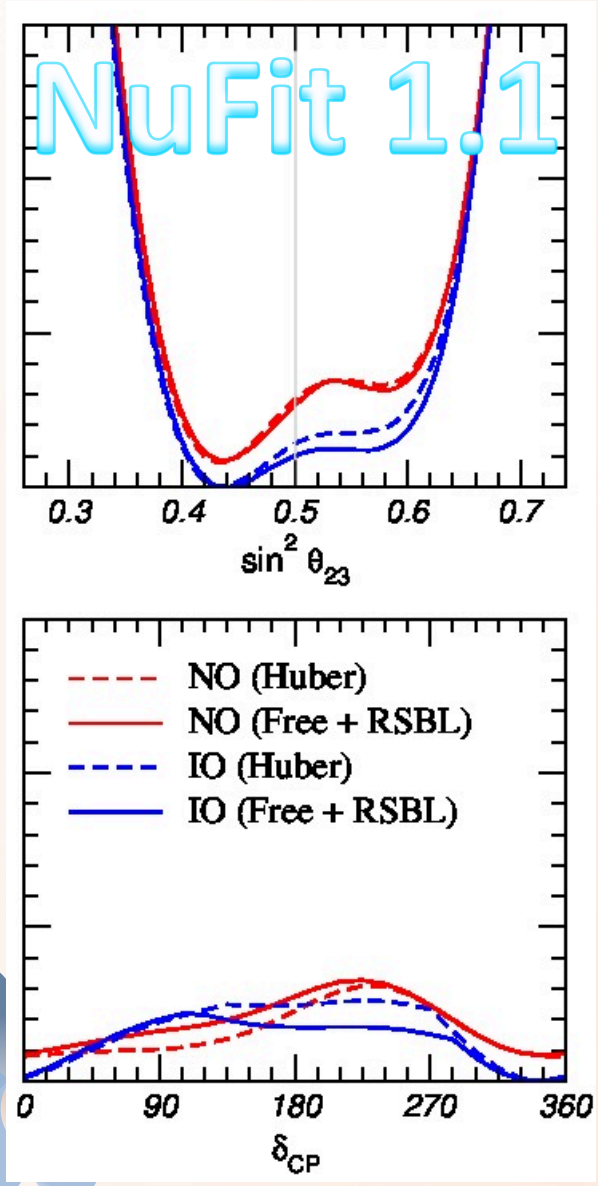
Daya Bay : $\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})$

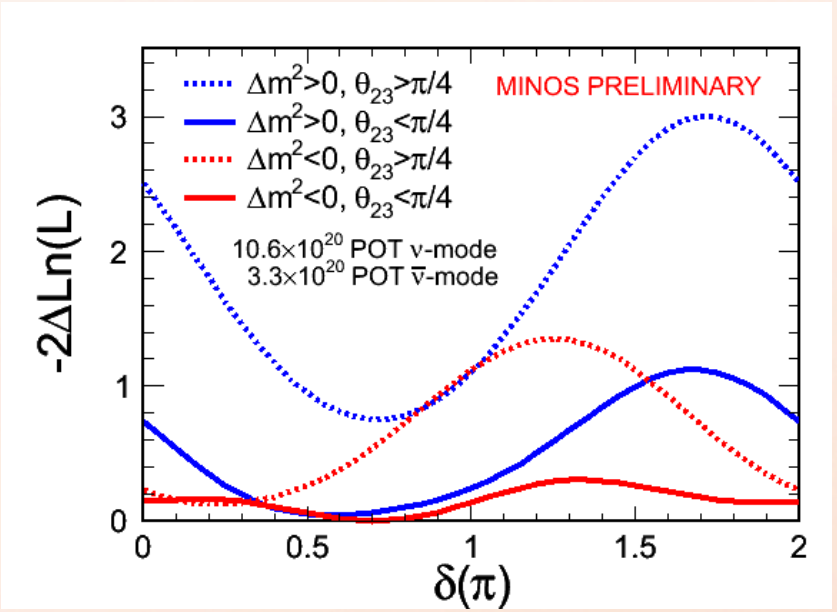
δ_{CP} and octant

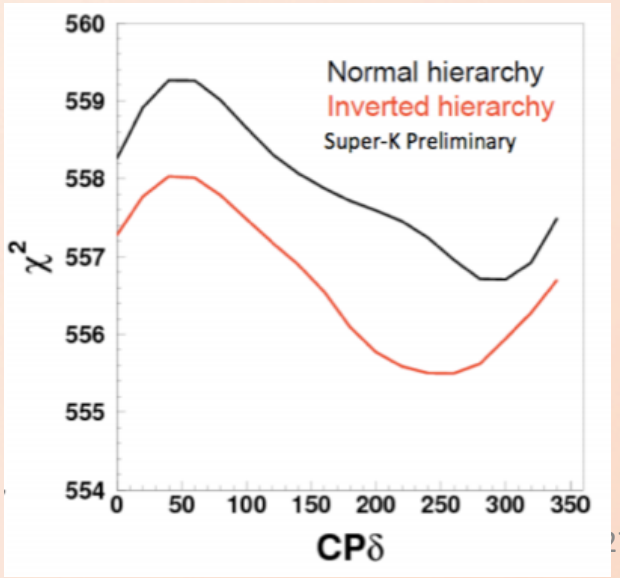
- NuFit 1.1 (2013) prefers δ_{CP} at close to 2π and hints at lower octant
  - M. C. Gonzalez-Garcia, Michele Maltoni, Jordi Salvado, Thomas Schwetz
  - JHEP 12 (2012) 123, arXiv:1209.2023 and NuFit



δ_{CP}


NuFit 1.1
0.3
0.4
0.5
0.6
0.7
sin² θ23
NO (Huber)
NO (Free + RSBL)
IO (Huber)
IO (Free + RSBL)
0
90
180
270
360
δCP


Δm²>0, θ23>π/4
Δm²>0, θ23<π/4
Δm²<0, θ23>π/4
Δm²<0, θ23<π/4
MINOS PRELIMINARY
10.6×10²⁰ POT ν-mode
3.3×10²⁰ POT ν̄-mode
-2ΔLn(L)
δ(π)


Normal hierarchy
Inverted hierarchy
Super-K Preliminary
χ²
CPδ

In to the future

At Fermilab

NOνA, ……., LBNE

In to the future @NuMI then LBNE

At Fermilab

NOνA, ……., LBNE

The Bright Shining Physics Future

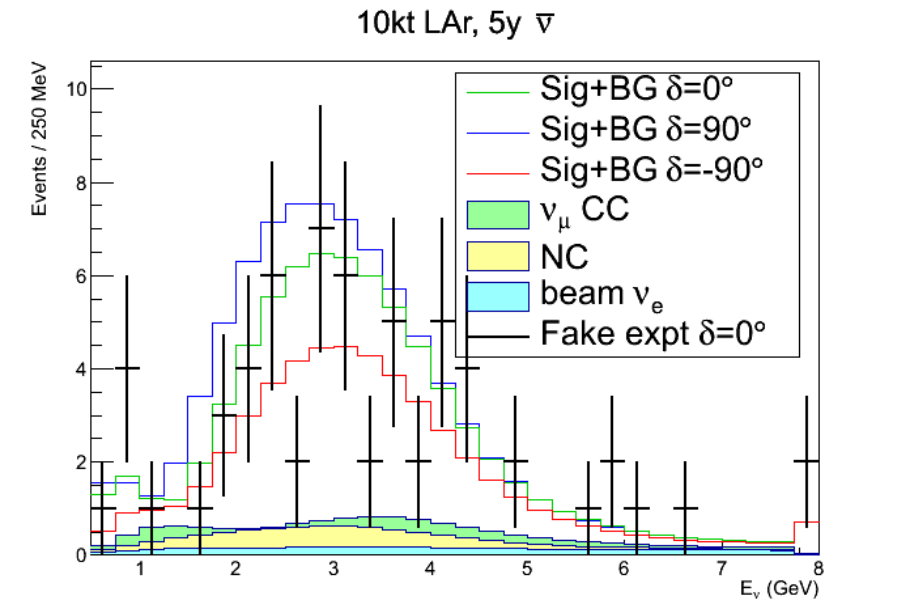
- Neutrinos hold their own against Higgs
  - Are they Majorana?
  - Are there more than 3?
  - Which is the heaviest?
  - Do they explain the matter anti-matter asymmetry?
- A new window of opportunity has opened to search for δ_{CP} MUCH SOONER than anyone had hoped!
- FNAL will have an ideal baseline for MH
- The US (FNAL) will have the best beam for neutrino oscillation measurements for the next 30 years
- WE NEED BIGGER DETECTORS to fully exploit the investment

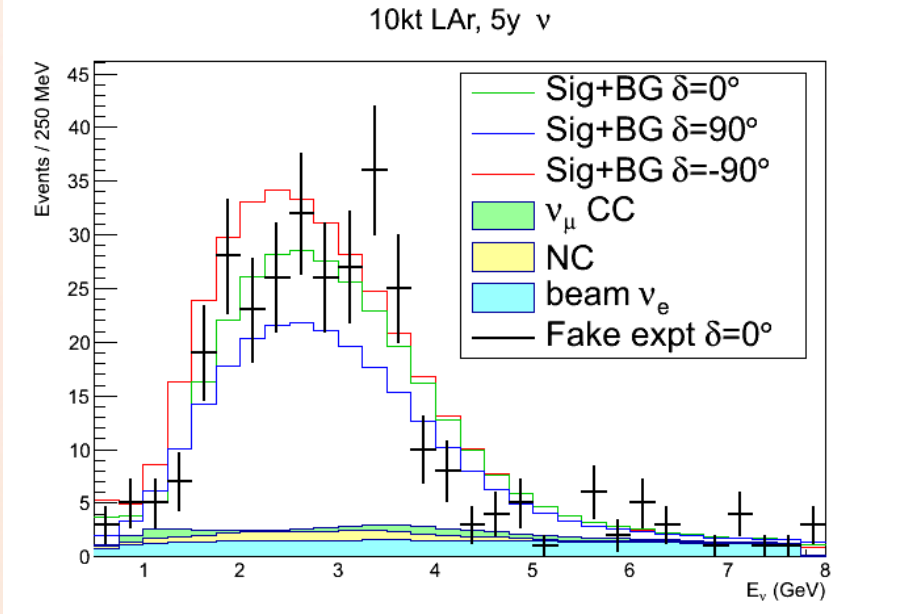
E(xploitation of)-NuMI

- 80-strong group formed to look at the options
- A bigger vision has emerged
  - We need huge detectors to move the field into the precision arena
    - Beam improvements can only get factor 2, maybe 3
  - Searching for minute θ_{13} was more heavily reliant on superb background identification
    - Now the goal-posts have moved we need additional thinking
- The main idea is to join up NuMI and LBNE into an opportunity for seamless access to the best neutrino beam in the world for oscillation studies
  - Intermediate physics opportunities
  - Development of Mt detectors for LBNE (CHIPS)
  - MC Benchmarking and x-section studies (LAriat, SciNova)

LBNE: The new (precision?) frontier

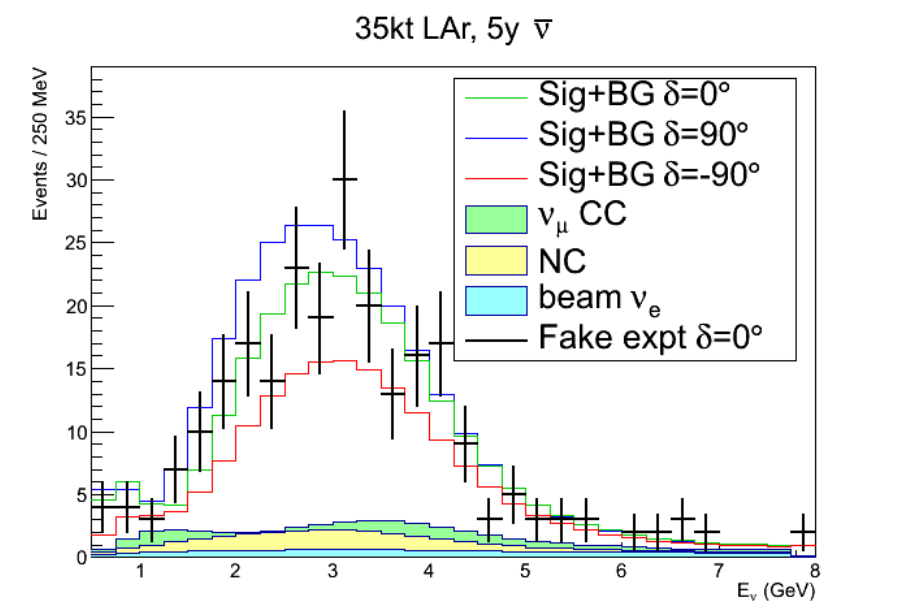
- What does that mean?
  - We presently have planned a precision DETECTOR (10 or 35 kt of LAr)
  - We do NOT have a precision experiment
    - 1000 events max in 10 years or even 3500 events in 10 years will not give us real precision (remember MINOS plots? ~3000 events)
    - With this new facility, we have to think about real precision neutrino experiments, where precision means <1%, not 10% (or 4%)
    - All neutrino events add…no matter which machine they are taken at!

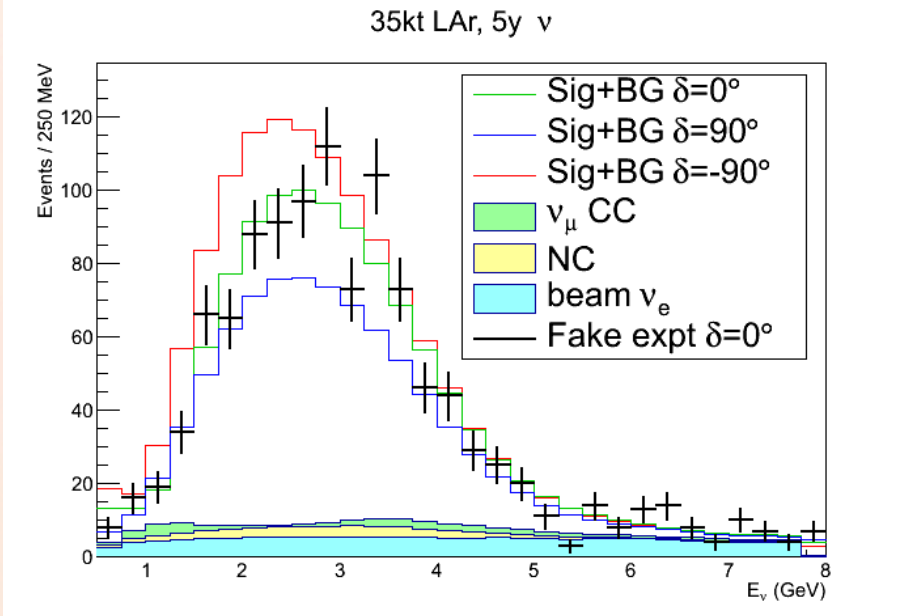




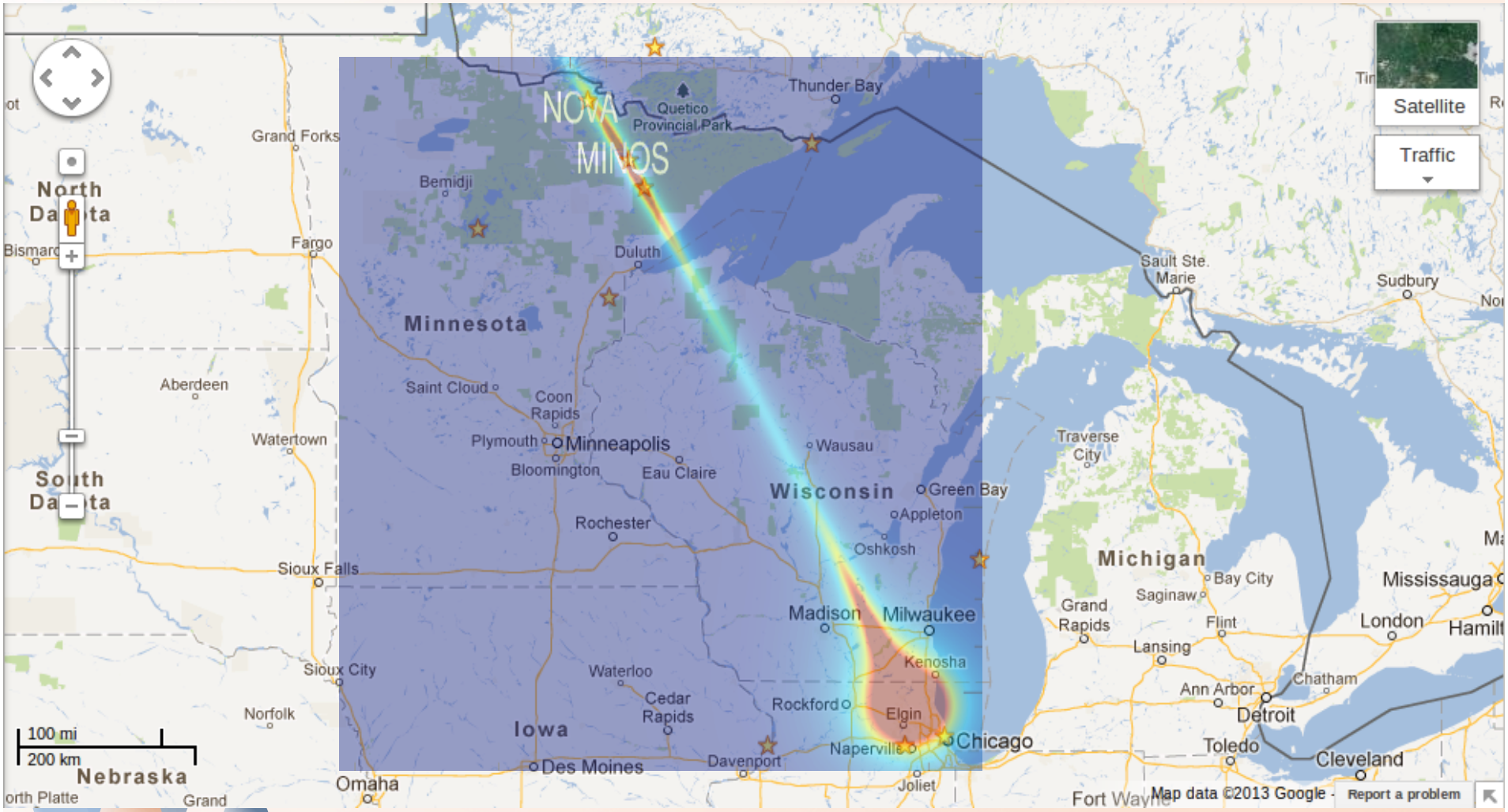
LBNE: The new (precision?) frontier

- What does that mean?
  - We presently have planned a precision DETECTOR (10 or 35 kt of LAr)
  - We do NOT have a precision experiment
    - 1000 events max in 10 years or even 3500 events in 10 years will not give us real precision (remember MINOS plots? ~3000 events)
    - With this new facility, we have to think about real precision neutrino experiments, where precision means <1%, not 10% (or 4%)
    - All neutrino events add…no matter which machine they are taken at!

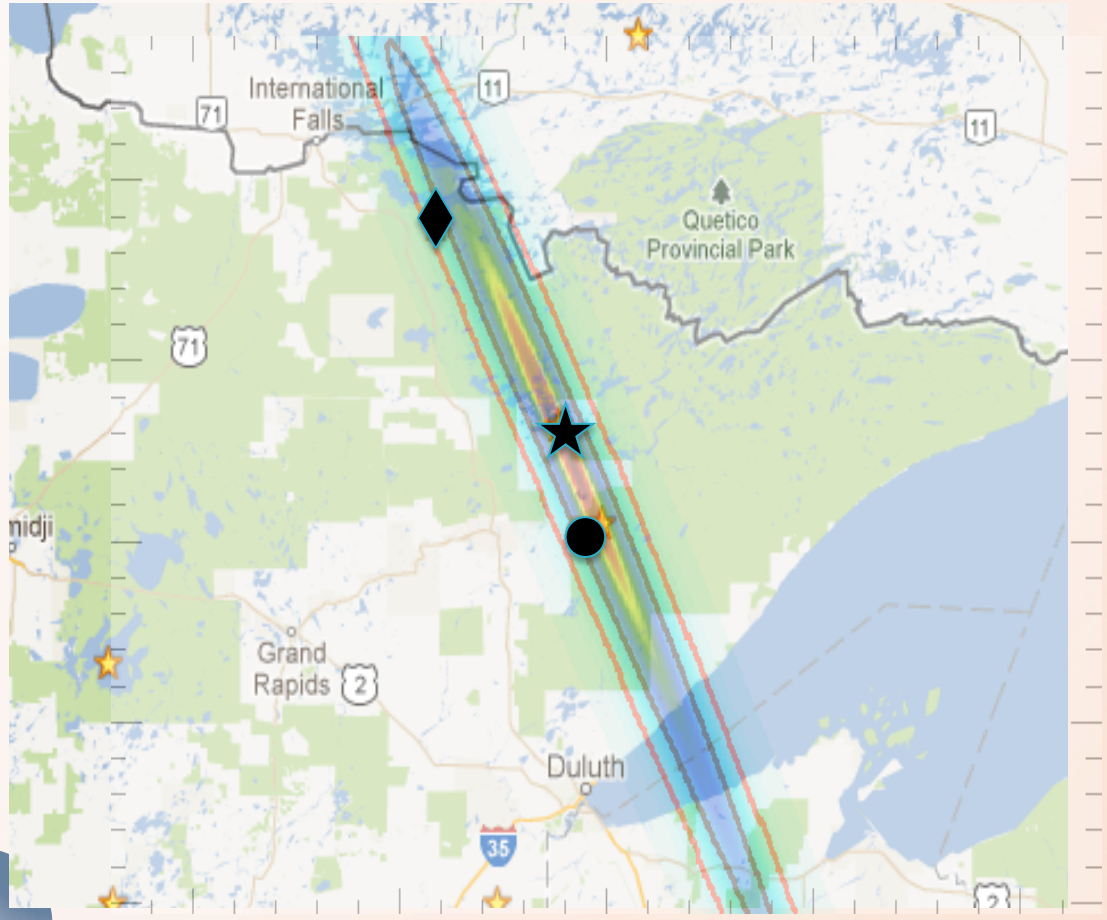


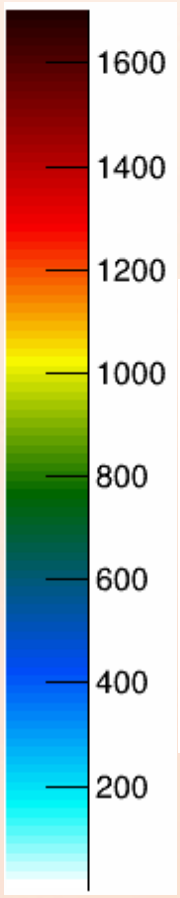


Looking At the NuMI Beam : Flux



Looking at the NuMI Beam : Events





300 L/E

500 L/E

MINOS

NOVA

CHIPS

CHIPS : δ_{CP}
Water Cherenkov Detector

This is not a new idea, IMB, GRANDE, (Koshiba in JAPAN), but there is a bit of new thinking: Beam Only, Fishing Industry, CHEAP! “Cheap as Chips!”

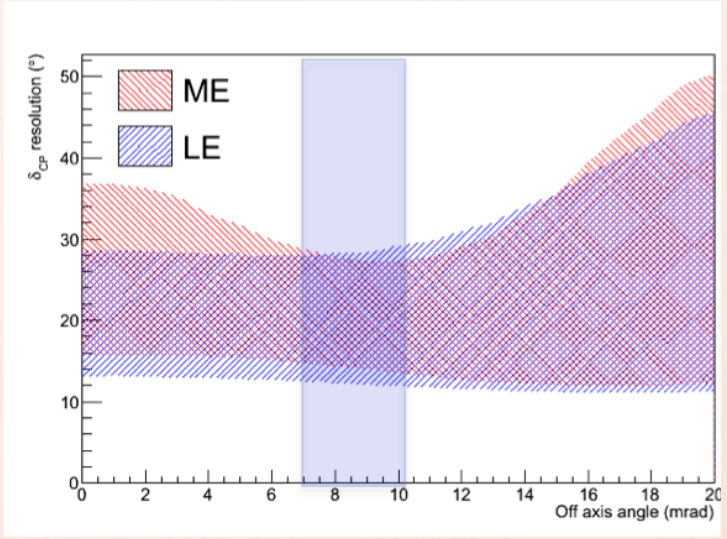
CHIPS

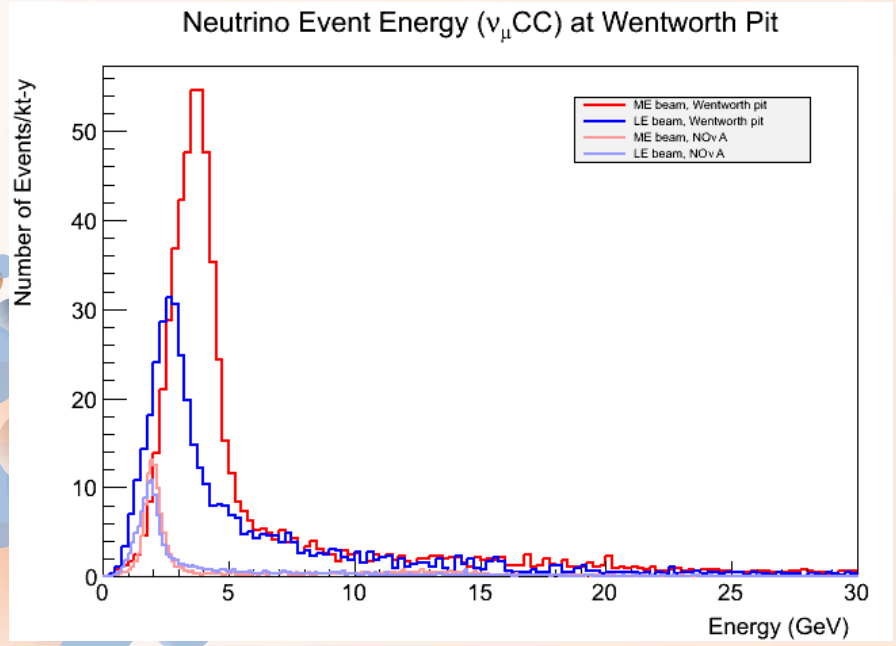
- If you want Mt, you need CHEAP!
  - NOVA:$8M/kt, MINOS:$10M/kt, LAr: $20M/kt
- If you want CHEAP, you have to consider water
  - CHIPS:$1-2M/kt
- If you want Mt and CHEAP you need a naturally occurring water mass that's reasonably deep
  - CHIPS goal : $100k/kt, or a 100bucks a ton
- If you want to be in the right L/E range you need to be in Minnesota for NuMI (and South Dakota for LBNE…later)
- Minnesota is the Land O' Lakes…….

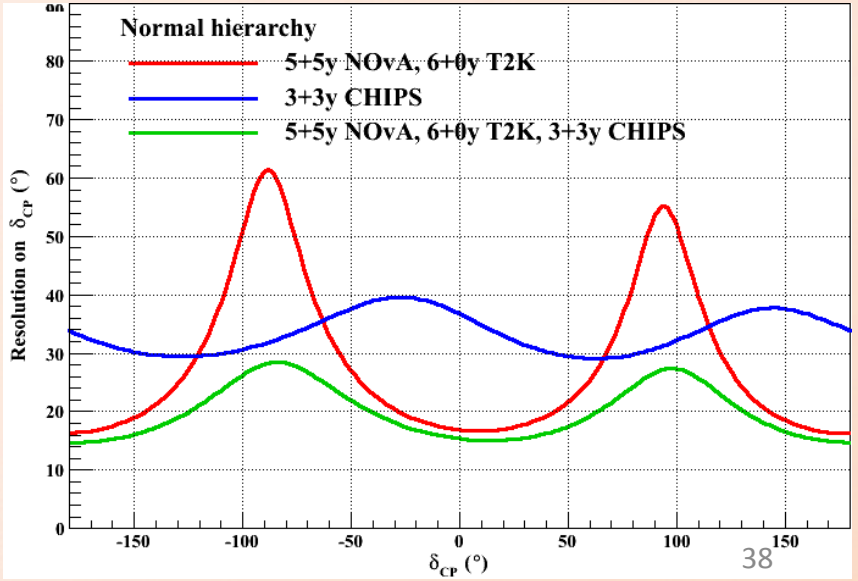
CHOOSE YOUR PIT!

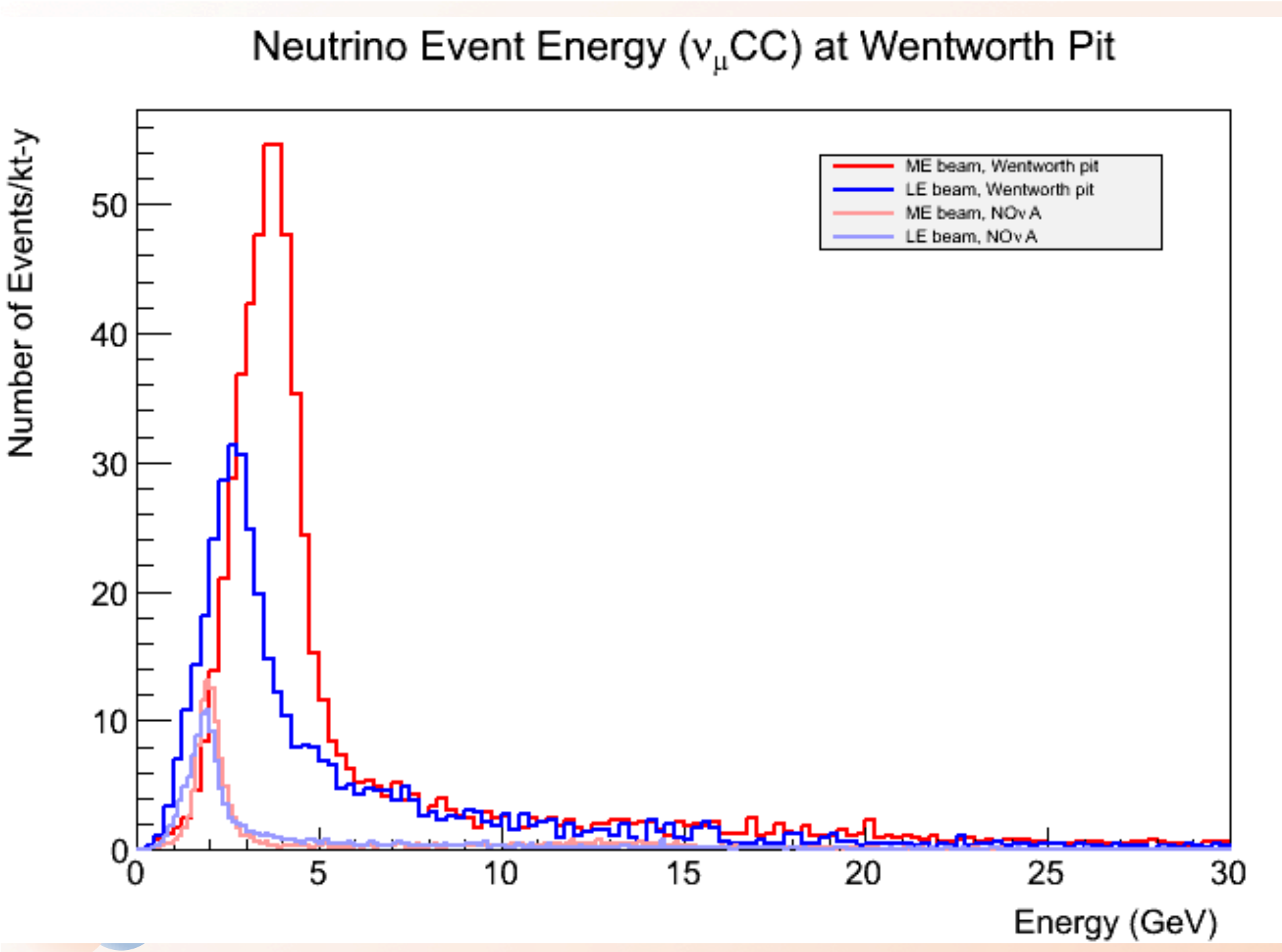
Physics Reach

- Off-axis between 7-10mr gives best reach in δ_{cp}
  - More on-axis increases background, more off-axis reduces rate
- Study 100kt reach, but grow to that slowly
- Ability to run in both ME and LE beam
- Make use of > 50% QE and resonance ν events between 1-3 GeV



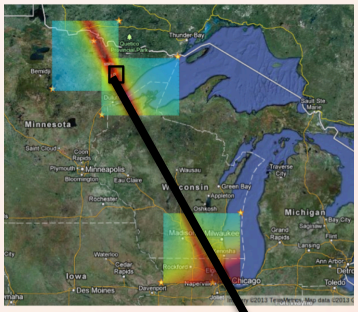


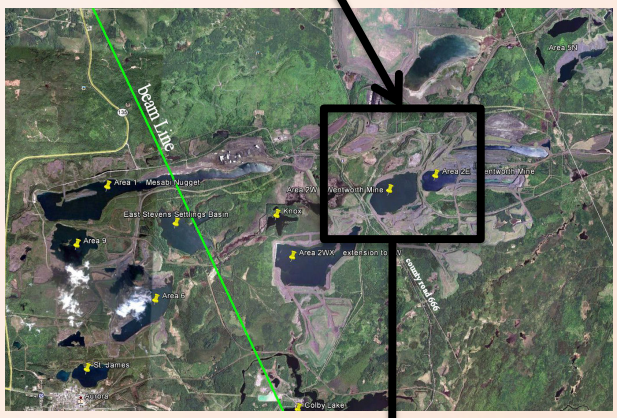


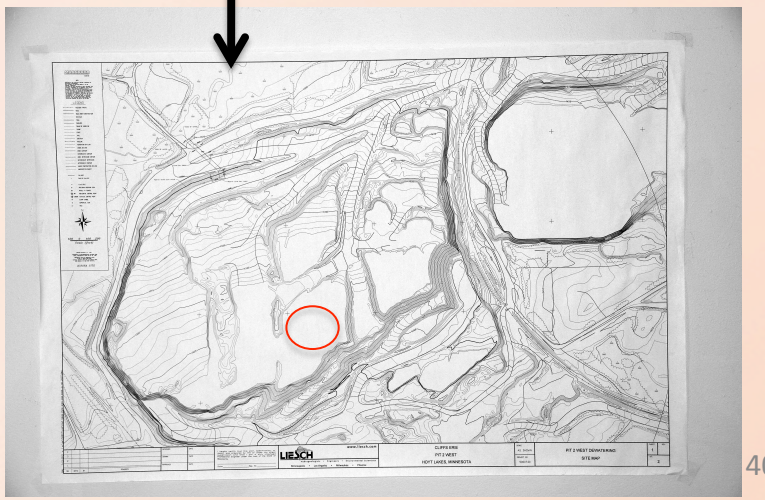

Neutrino Event Energy (ν_μCC) at Wentworth Pit
Number of Events/kt-y
Energy (GeV)
ME beam, Wentworth pit
LE beam, Wentworth pit
ME beam, NOvA
LE beam, NOvA
0
10
20
30
40
50
0
5
10
15
20
25
30

CHIPS : Wentworth Pit

- The water CHerenkov detector In mine PitS
- The Wentworth mine pit is 7mr off axis of the NuMI beam and > 60m deep
  - Deeper region shown
- Veto region needed, 1-100kHz background leads to about <=5% dead-time
- Leasing arrangement already under discussion

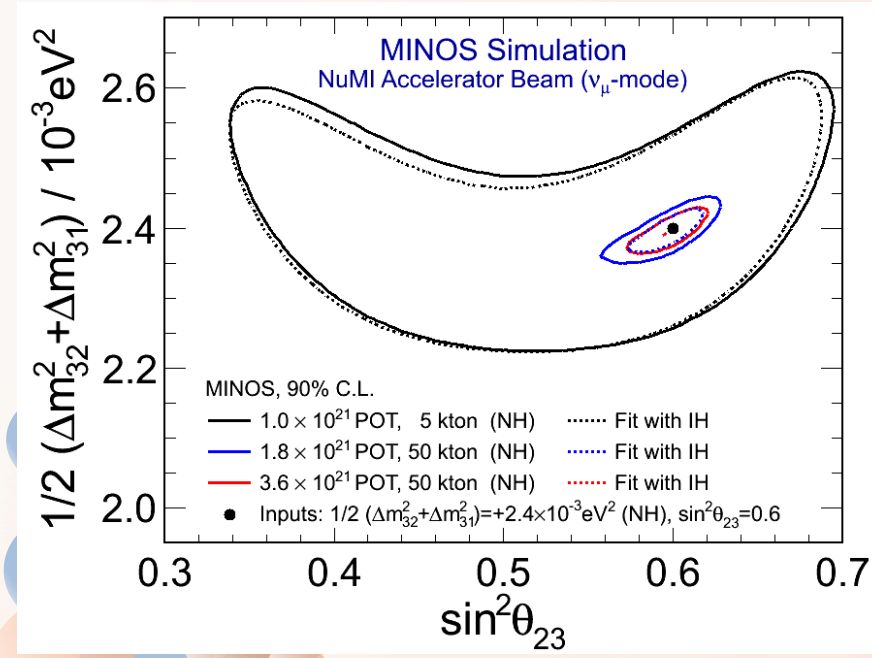


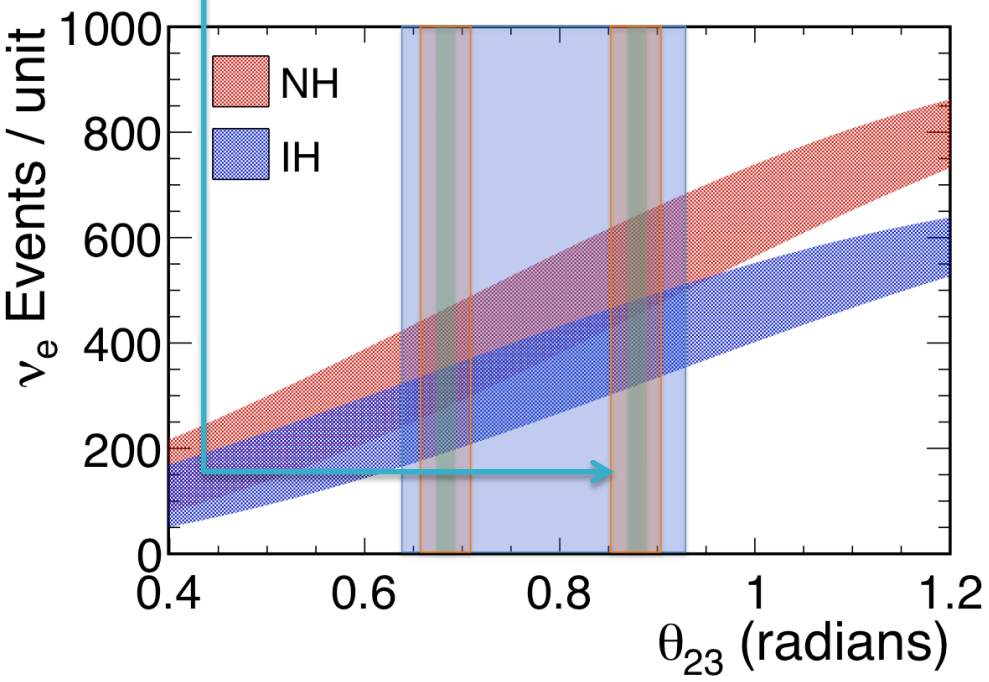




Other physics : $\sin^2\theta_{23}$, MH?

- Very conservative estimate of $\sin^2\theta_{23}$ using MINOS efficiencies
- If θ_{23} not maximal, and in upper octant, reach is enhanced, and MH could be ascertained
- Red and Blue bands reflect totally unknown δ_{CP}





How?

This has been thought about before

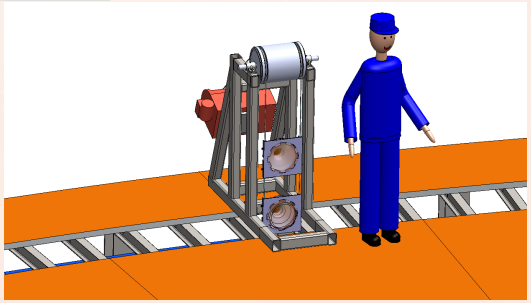
IMB,GRANDE,LBNE……

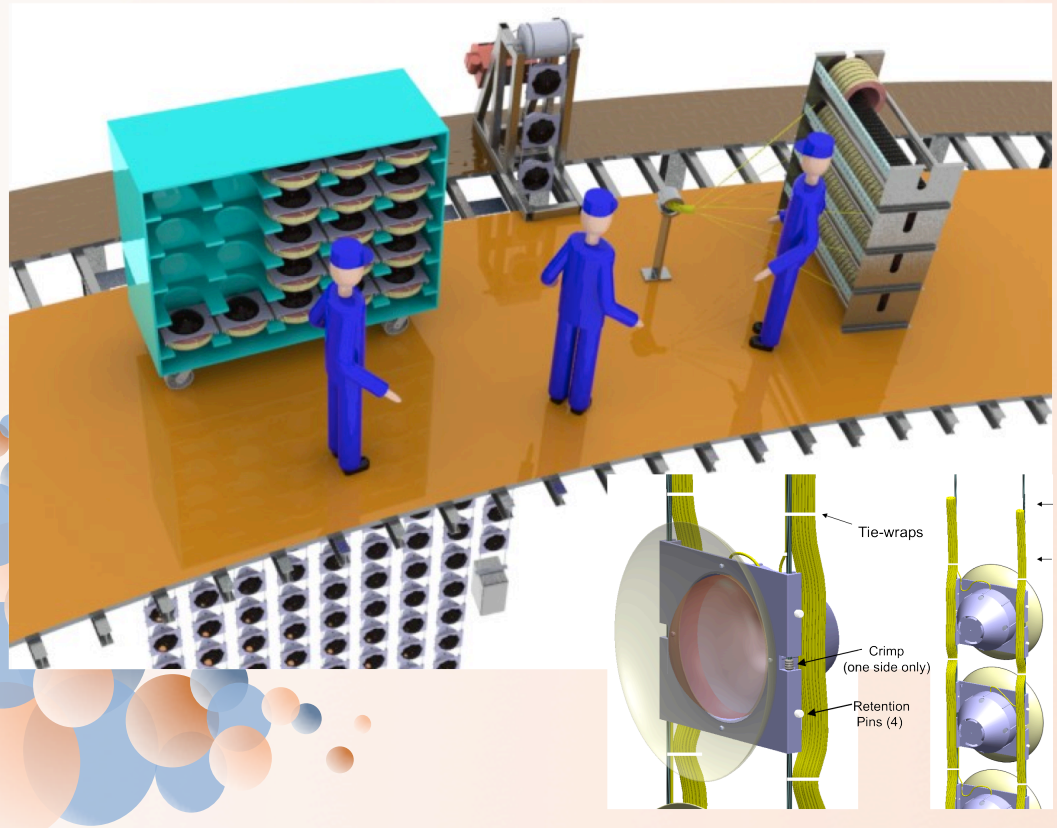
δ_{CP} : CHIPS concept

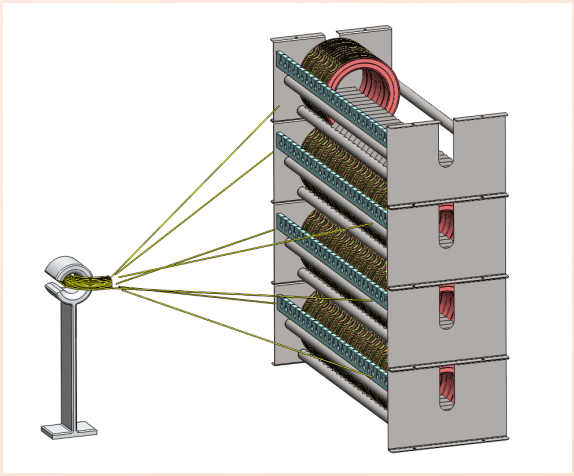
- Deploy from floating platform using industrial products from the fisheries industry
- Replace nets with PVC + KEE roofing membranes rated for continuous underwater use including aggressive oil spill environments, low permeability and light tight
- Fill with cleaned water for neutrino target
- Pit water acts as mechanical support
- Ice build up easily prevented by water circulation pumps
- Deployment Idea developed by Madison/PSL groups for LBNE but has similarities with IMB and the GRANDE proposal

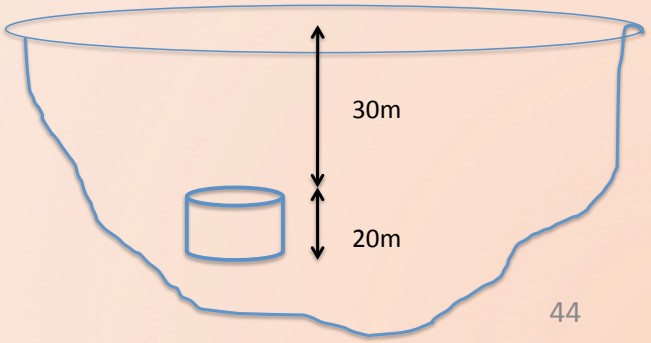
CHIPS design: Madison,PSL

- Focus on recyclability, what goes down must come up
- Concept for floating deployment developed for LBNE WC
- Use technology based on Ice Cube design
  - 10% HQE PMT coverage, PMTS encased in pressure spheres and deployed on wires
- Suspended at ~40-60m under water level







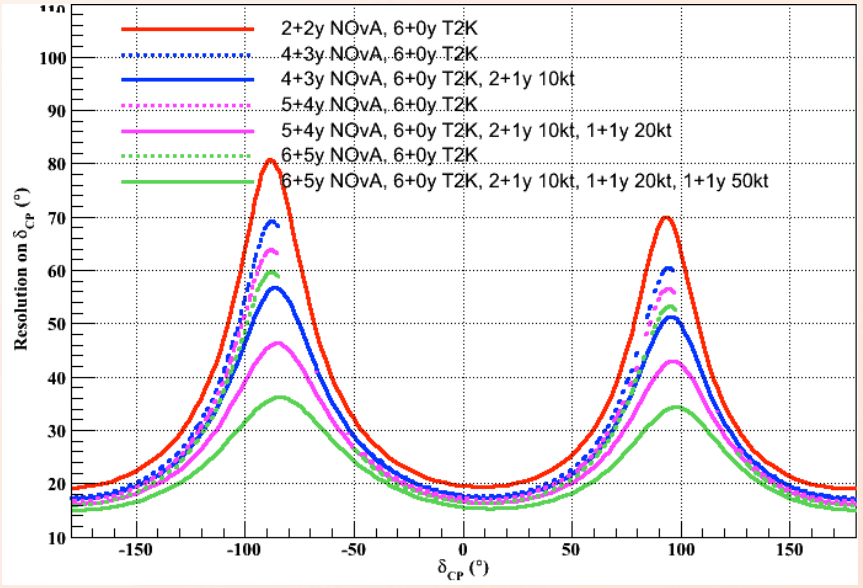


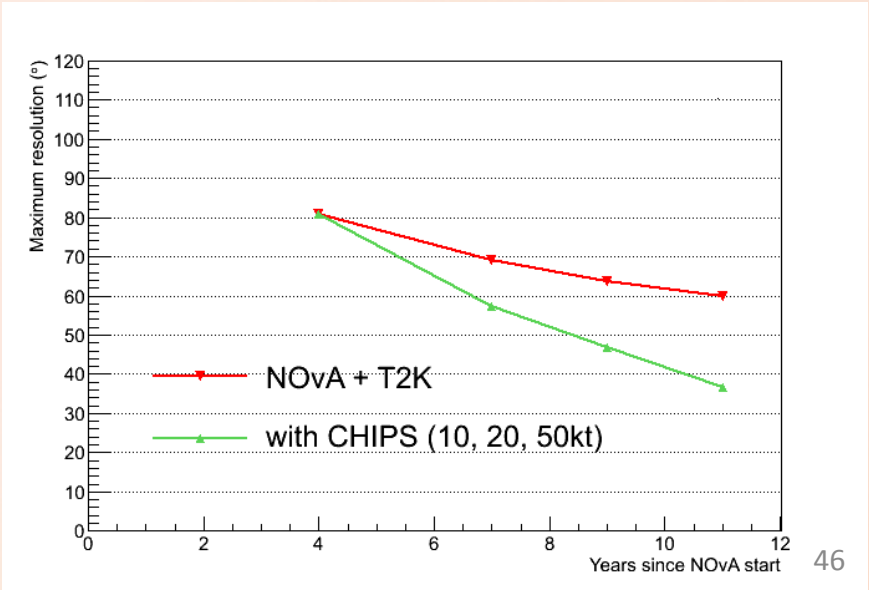
When

Soon, and staged, and then later

Getting started fast

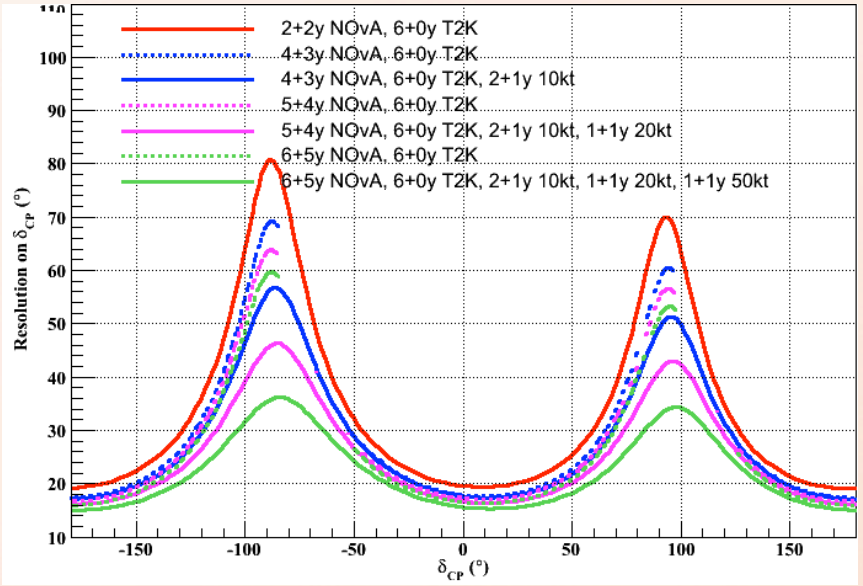
- Starting small can still yield important results
- Imagine starting with 10kt after 4 years of NOVA running
  - 3 years with 10kt then 2 years with 20kt, finally 2 years at 50kt
  - 10kt is about $10M over next three years
- Push over next decade on PMT development
  - Cost presently dominated by PMT cost
  - APD-PMT, MCP-PMT, Chinese vs Japenese….

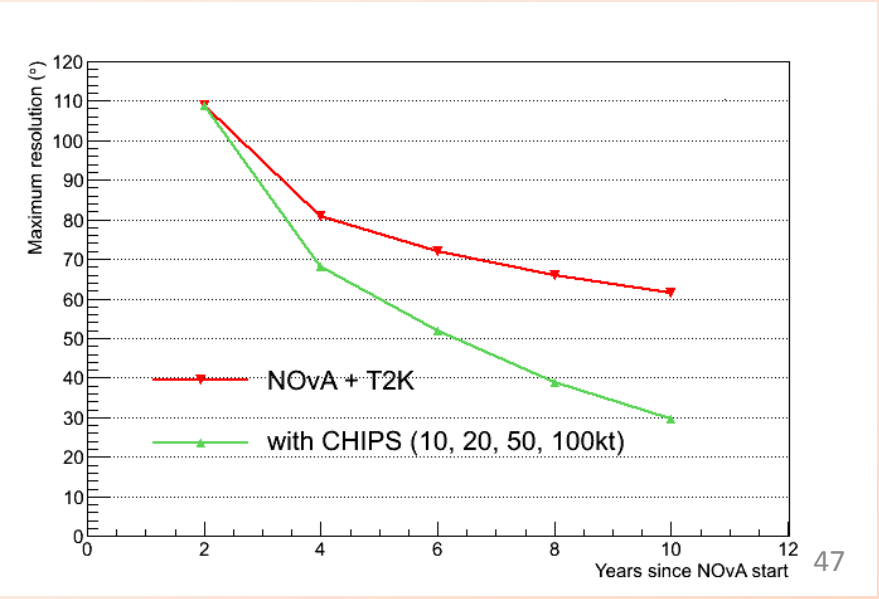




Getting started fast

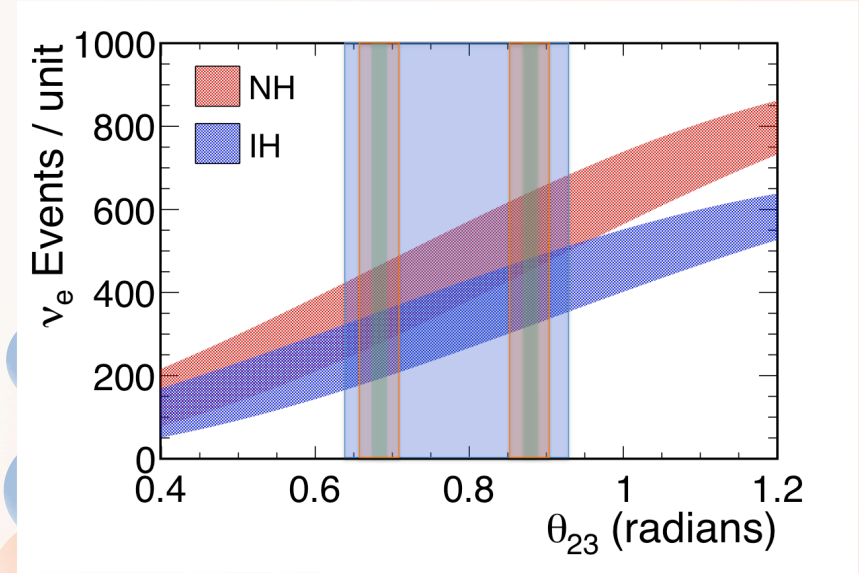
- A faster schedule would be to start with 10kt after 2 years of NOVA running
  - 2 years with 10kt then 2 years with 20kt, 2 years at 50kt then 2 at 100kt
- Has advantage of understanding real costs and schedules : no crazy contingencies
- Slow but continuous detector growth could be possible allowing low and constant funding level ($5-10M/yr)
- Real costs and processes can be fully understood avoiding huge contingencies
- LOI to DoE/FNAL this fall

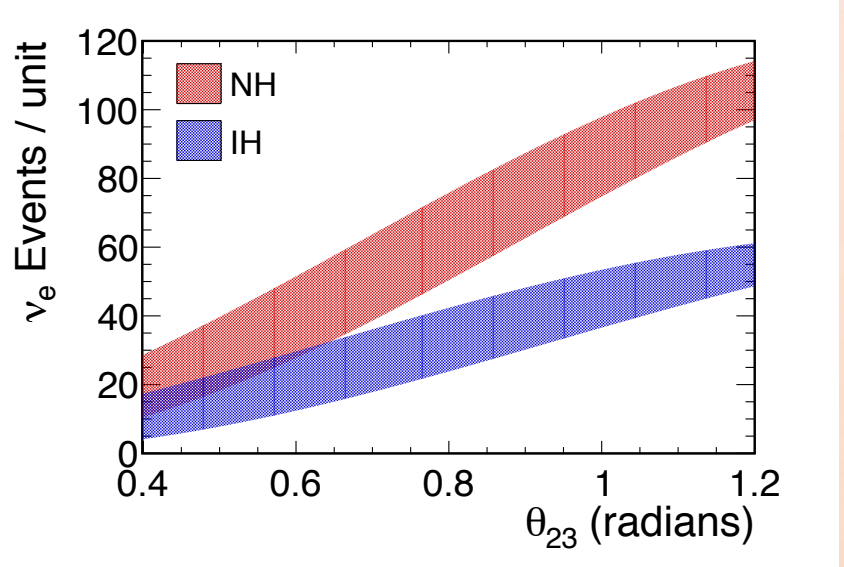




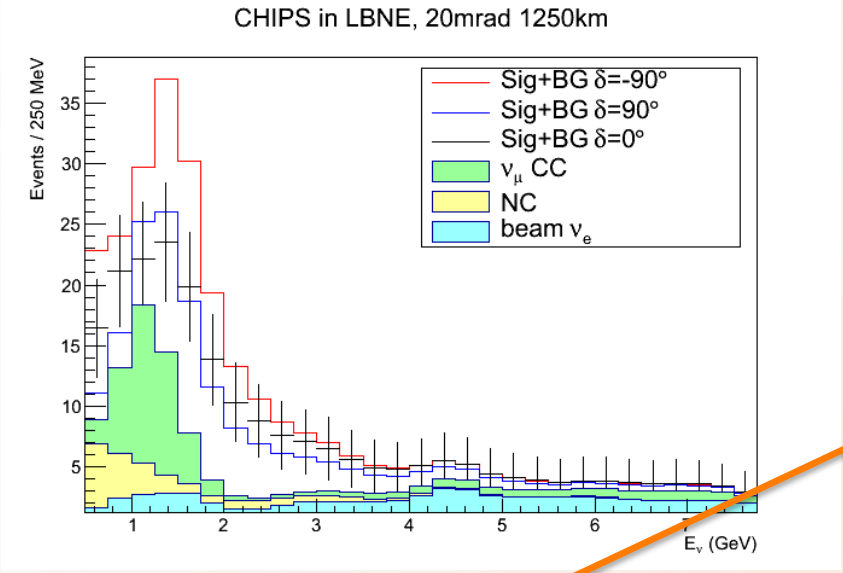
NuMI to LBNE : θ_{23}

- LBNE has better choice of L/E and will take over the heavy lifting at some point in the future
- Redeploy the CHIPS detector somewhere close to the LBNE beam
  - Off axis for low energy and again, complementarity
- A 100kt CHIPS in LBNE beam would provide results (together with LAr-10) much faster than 5+5 years of 10kt presently foreseen





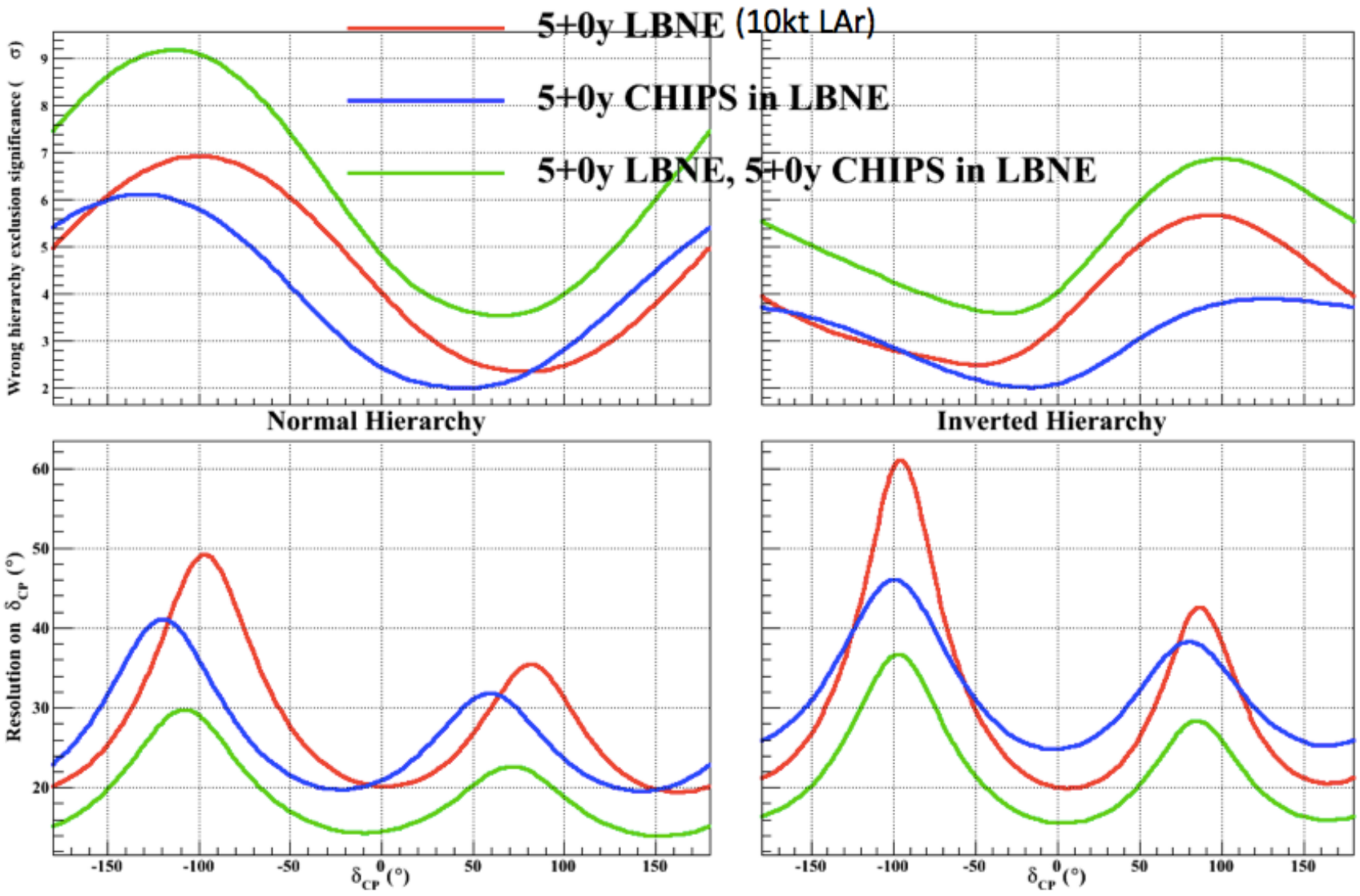
CHIPS@LBNE



Pactola Resevoir, SD

- There is (at least) one (40m) reservoir in the beam line
- Proof of principle for Mt scale detectors at a cost of ~ $0.5M/kt?
- If proof of principle works, it's a necessary upgrade/ augmentation path for LBNE

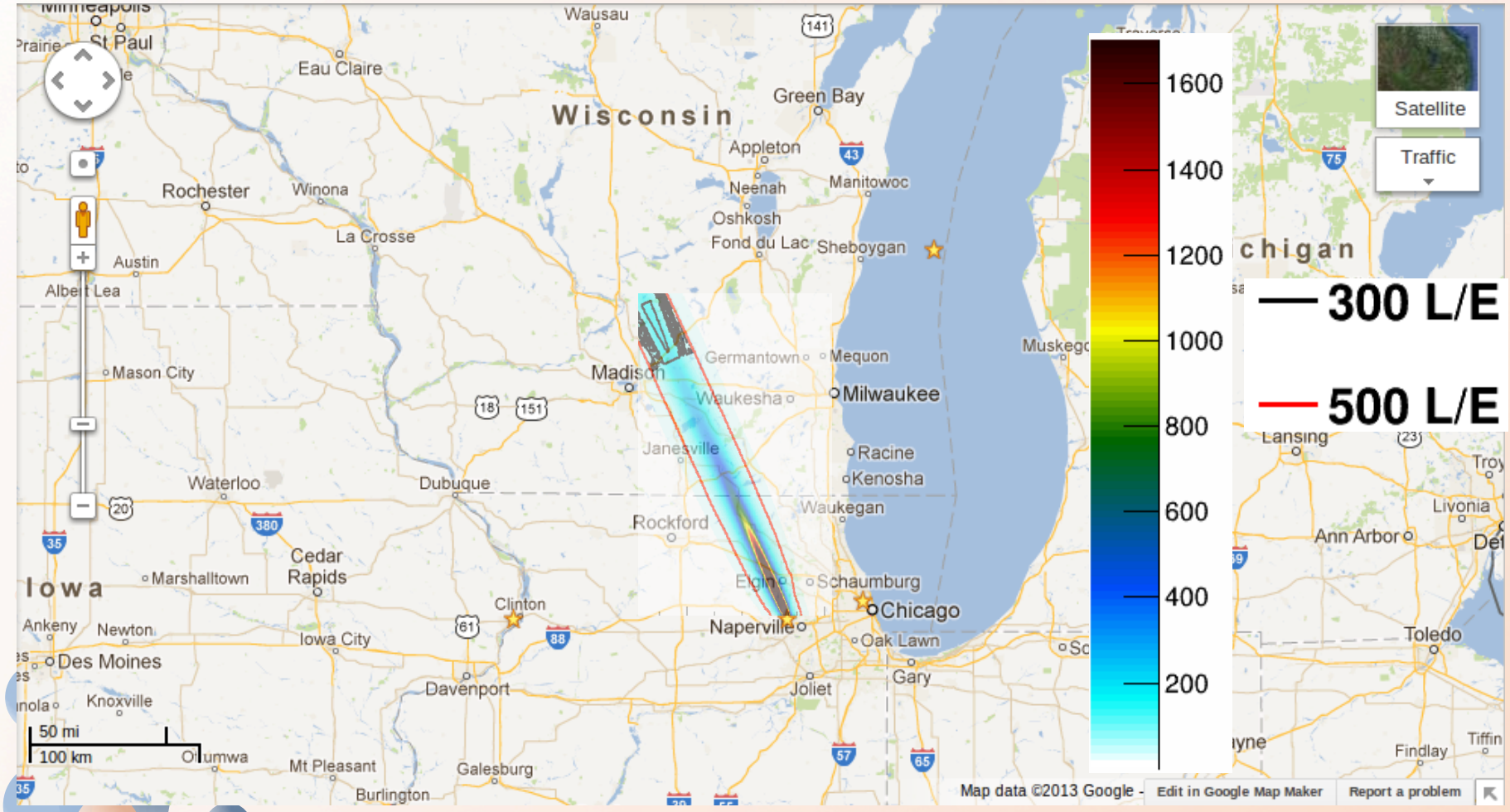
Comparison of CHIPS with LBNE



Liquid Argon Detector Studies

Liquid Argon Development can lead to important physics

Looking At the Short Baselines (Events)



Google Map image with Short Baseline area event rate shown.

LARIAT or MicroBOONE in the MINOS ND Hall

- Why do we need Liquid Argon?
  - It has exquisite resolution
  - It will improve our understanding/modelling of neutrino events for MC benchmarking
  - It has very good background rejection because of resolution
- We must benchmark the MC : not just charged particle beams
  - small detector in the NuMI Beam
  - Same energy region as LBNE
  - Only 30t needed (50 events / spill !!)
  - This is not only interesting, but NECESSARY for LBNE
  - Modeling improvements of neutrino interactions possible
  - Without a fully functioning MC, no neutrino experiment is possible
- After LARIAT in the charged particle beam, move to NuMI for MC benchmarking campaign
  - Several years of leading physics results would be the outcome
  - Preparation for LBNE-10 data taking

Summary

- The scientific landscape in the US is exciting, with the best neutrino beam in the world for the forseeable future in the only arena in PP where there is new physics.
- Key vision is to join up the NuMI and LBNE programs to provide seamless access to the worlds highest intensity neutrino beam
- We have to plan for success, and plan for the precision frontier future:
  - Combination of Mt detectors and precision detectors
  - On axis and off axis
- There are a number of possibilities for new ideas providing cutting edge results over a long time period
- Intermediate (NuMI) work is an insurance against temporary cancellation for European groups and is THE advantage the US has over the Japanese and CERN competition
  - Each neutrino detected at NuMI will contribute to the LBNE measurement for δ_{CP}

A vision of LBNE