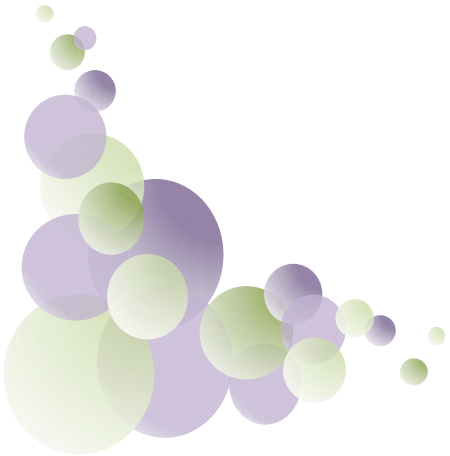
θ_{13} and the long baseline experiments

16/07/12

VIII Rencontres du Vietnam

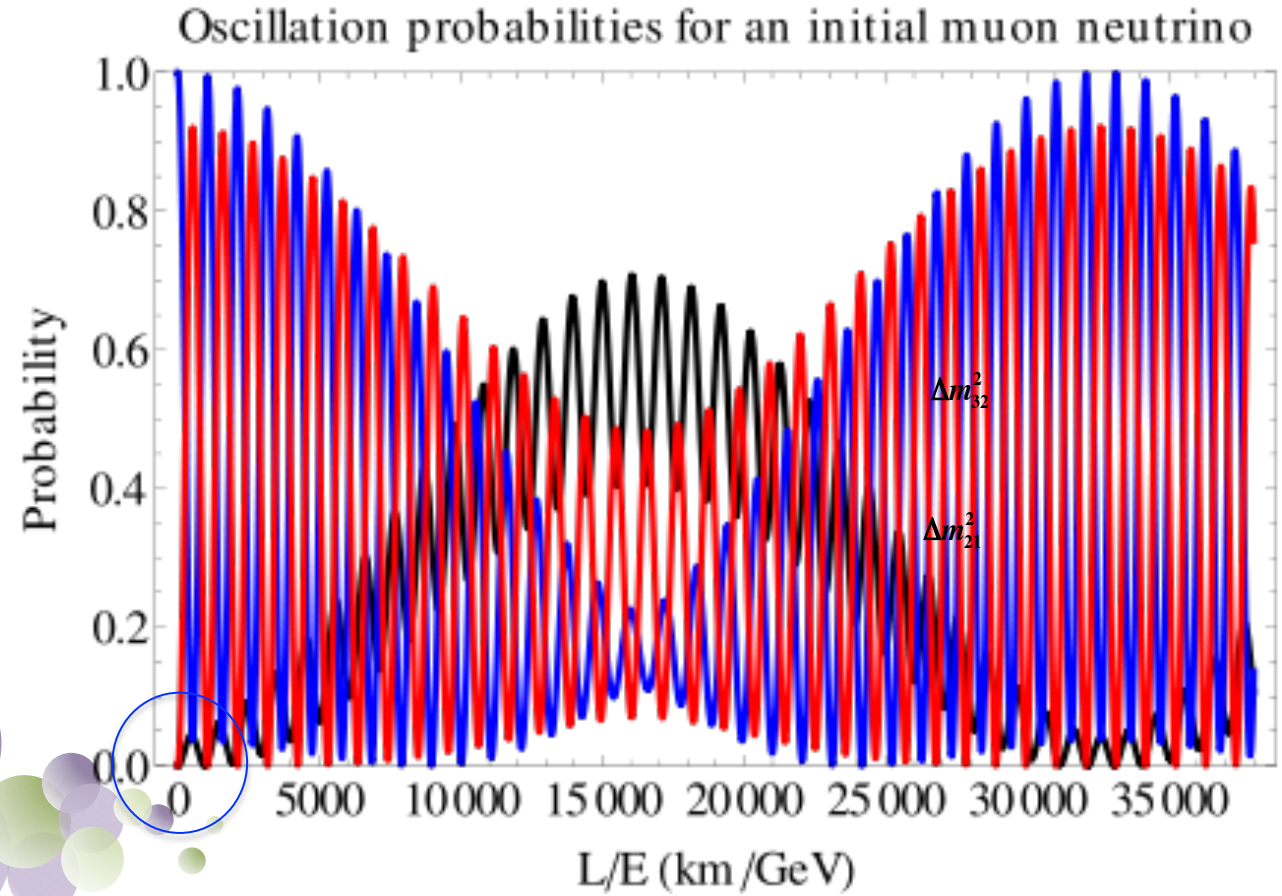
Jenny Thomas, UCL

- Introduction to the new frontier
- MINOS results
- T2K results
- NOνA goals
- MINOS+ goals
- Potential NuMI plans
- Conclusion



Introduction

- The long baseline experiments start off with ν_μ and look for disappearance of ν_μ and appearance of ν_e



Δm^2_{21}

Δm^2_{32}

Introduction

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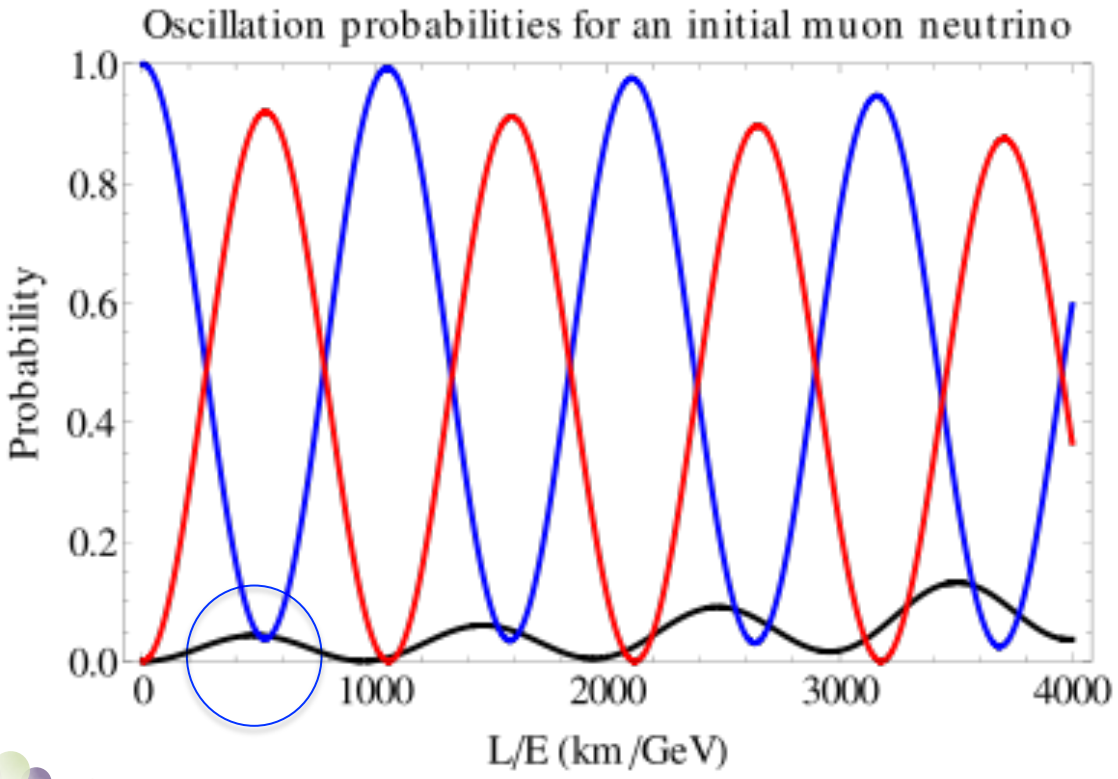
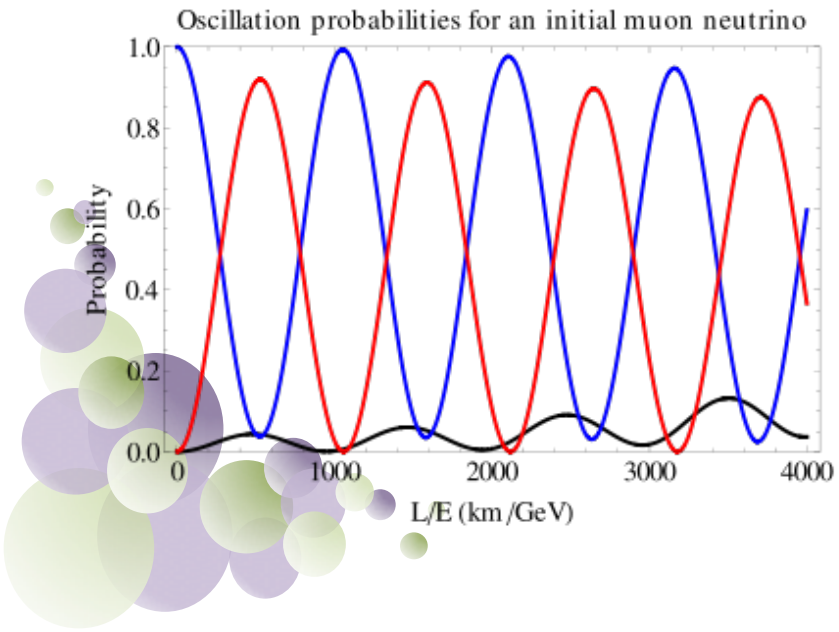
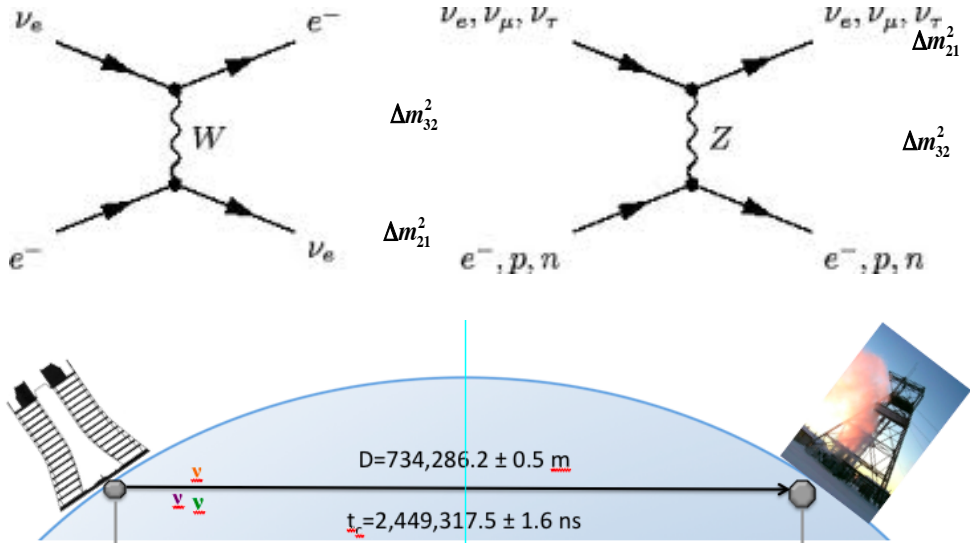


Introduction

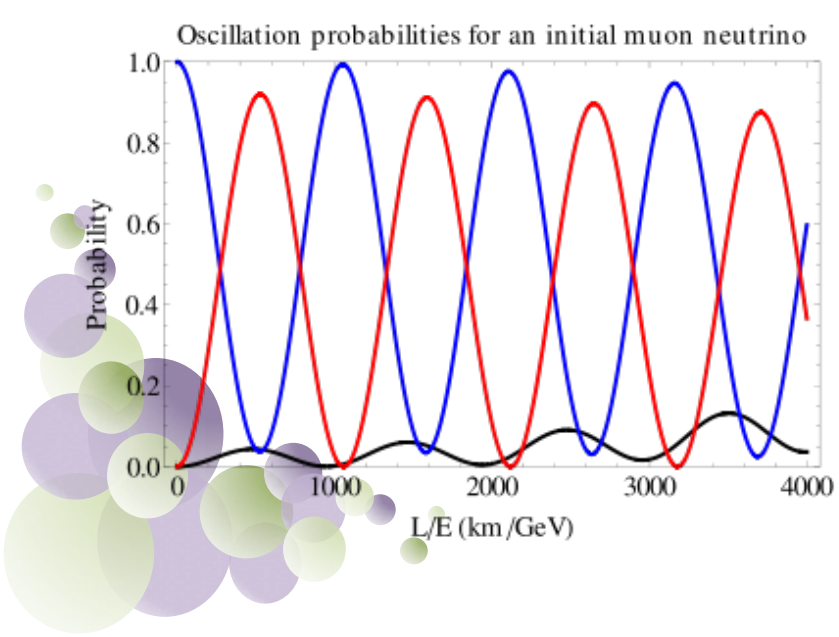
- The long baseline experiments start off with ν_μ and look for disappearance of ν_μ and appearance of ν_e
- Their beams pass through matter, and the produced ν_es interact additionally with the electrons in that matter

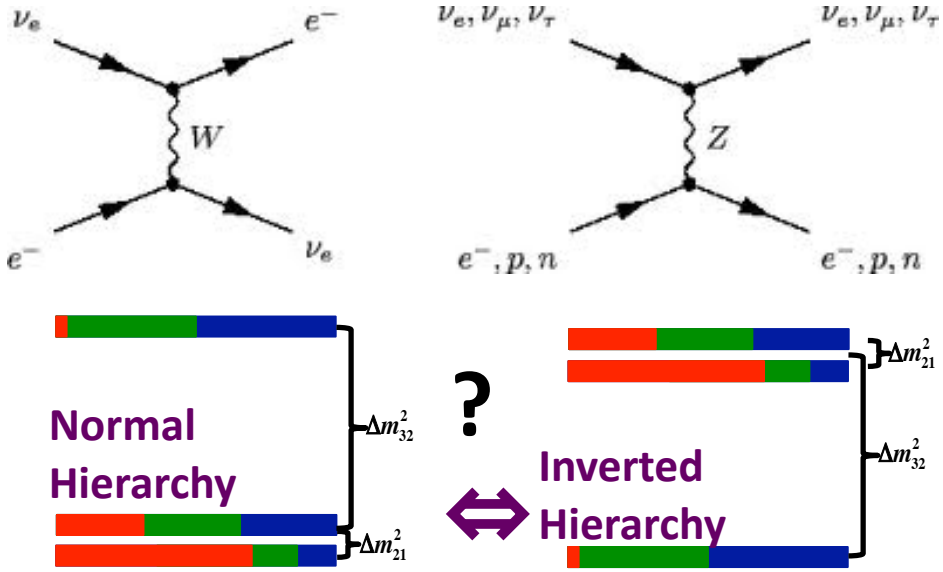




Introduction

- The long baseline experiments start off with ν_μ and look for disappearance of ν_μ and appearance of ν_e
- Their beams pass through matter, and the ν_e which are produced interact with that matter differently
- This extra interaction produces an enhancement or suppression of the oscillation probability which depends on the mass hierarchy



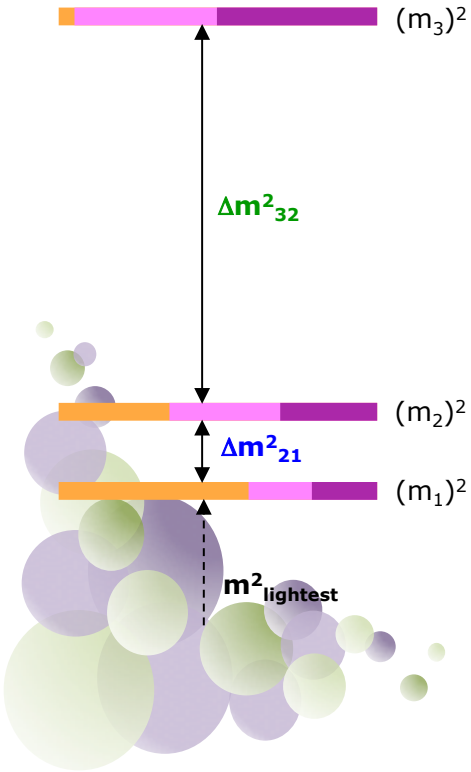


Introduction

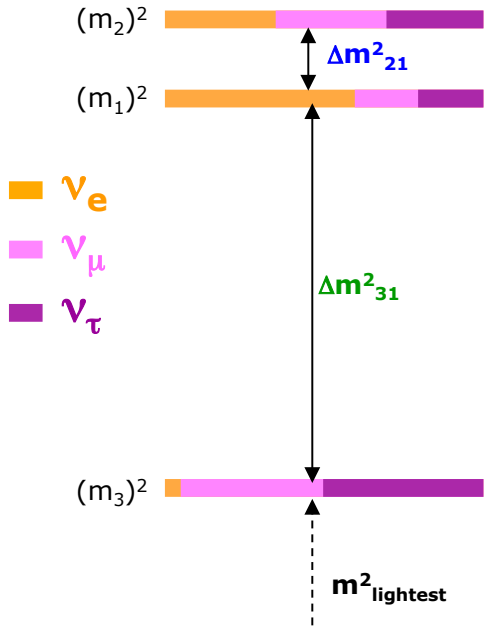
Solar&Reactor Atmospheric Reactor/LBL Double Beta

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & v0 & 0 \\ 0 & e^{i\alpha/2} & 0v \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ \nu_3 \end{pmatrix}$$

Normal hierarchy



Inverted hierarchy



3 light neutrino flavours: e, μ, τ

Δm^2_{21} : $(7.0 - 9.1) \times 10^{-5}$ eV²
$\tan^2\theta_{12}$: 0.34 – 0.62

Δm^2_{32} : $(2.32^{+0.11}_{-0.08}) \times 10^{-3}$ eV²
$\sin^2 2\theta_{23}$: 0.96 (±0.04)

$\mathrm{Sin}^2 2\theta_{13} \approx 0.09 \pm .01$
δ: unknown

Hierarchy : unknown

$m_{lightest} < 2.2$ eV
Dirac or Majorana: unknown

Introduction

- At L/E~500 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- ~5% of the missing ν_μ should change into ν_e

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

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \qquad P_{sol} \approx \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

"Atmospheric" Term
Depends on Δm^2
And θ_{13}

"Solar" Term
<1% for current accelerator experiments

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$$2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos\left(\frac{\Delta m^2_{32} L}{4E}\right) \cos\delta_{CP} \mp 2\sqrt{P_{atm}}\sqrt{P_{sol}} \sin\left(\frac{\Delta m^2_{32} L}{4E}\right) \sin\delta_{CP}$$

Interference Term

- for neutrinos

+ for antineutrinos

if $\delta_{CP} \neq 0$,

$$P\left(\nu_\mu \rightarrow \nu_e\right) \neq P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)$$

Introduction

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$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E} - aL\right) \left| \frac{\frac{\Delta m^2_{31} L}{4E}}{\left(\frac{\Delta m^2_{31} L}{4E} - aL\right)} \right|^2 \qquad P_{sol} \approx \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(aL) \left| \frac{\frac{\Delta m^2_{21} L}{4E}}{aL} \right|^2$$

$$a = \pm \frac{G_F N_e}{\sqrt{2}} \approx (4000\ \text{km})^{-1}$$

In matter, additional term in Hamiltonian from ν_e + e CC scattering modifies oscillation probability, ~30% effect at NOvA baseline

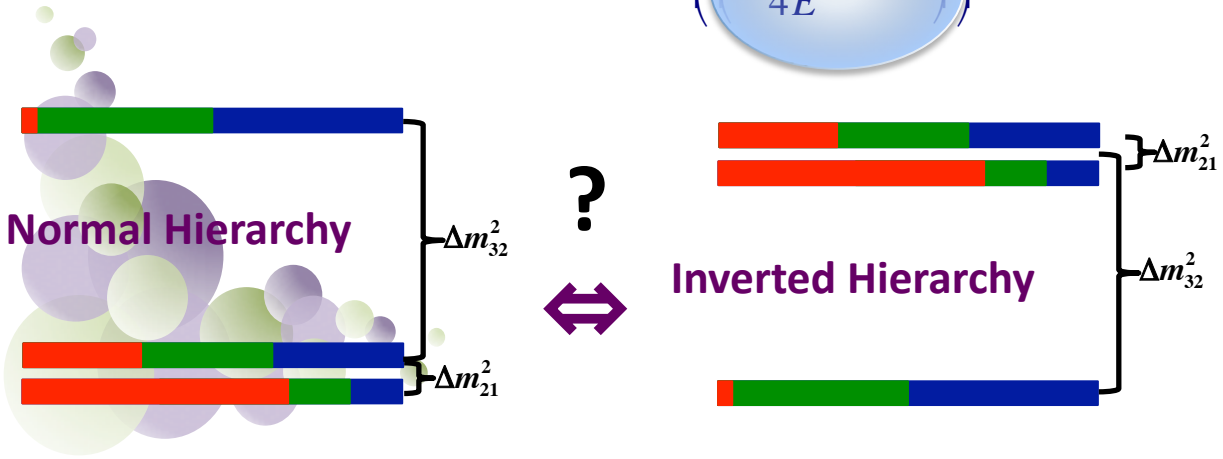
Introduction

- 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

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

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

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

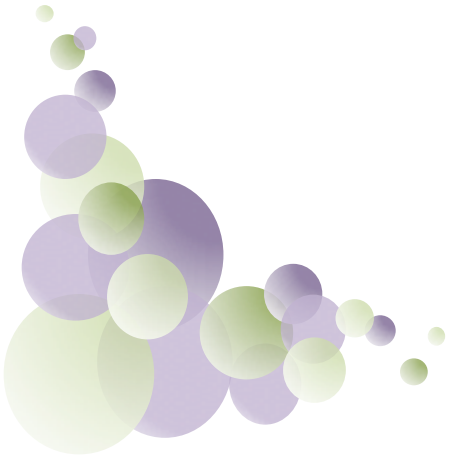


Oscillation probability depends on sign of Δm^2

NEW RESULTS THIS YEAR!

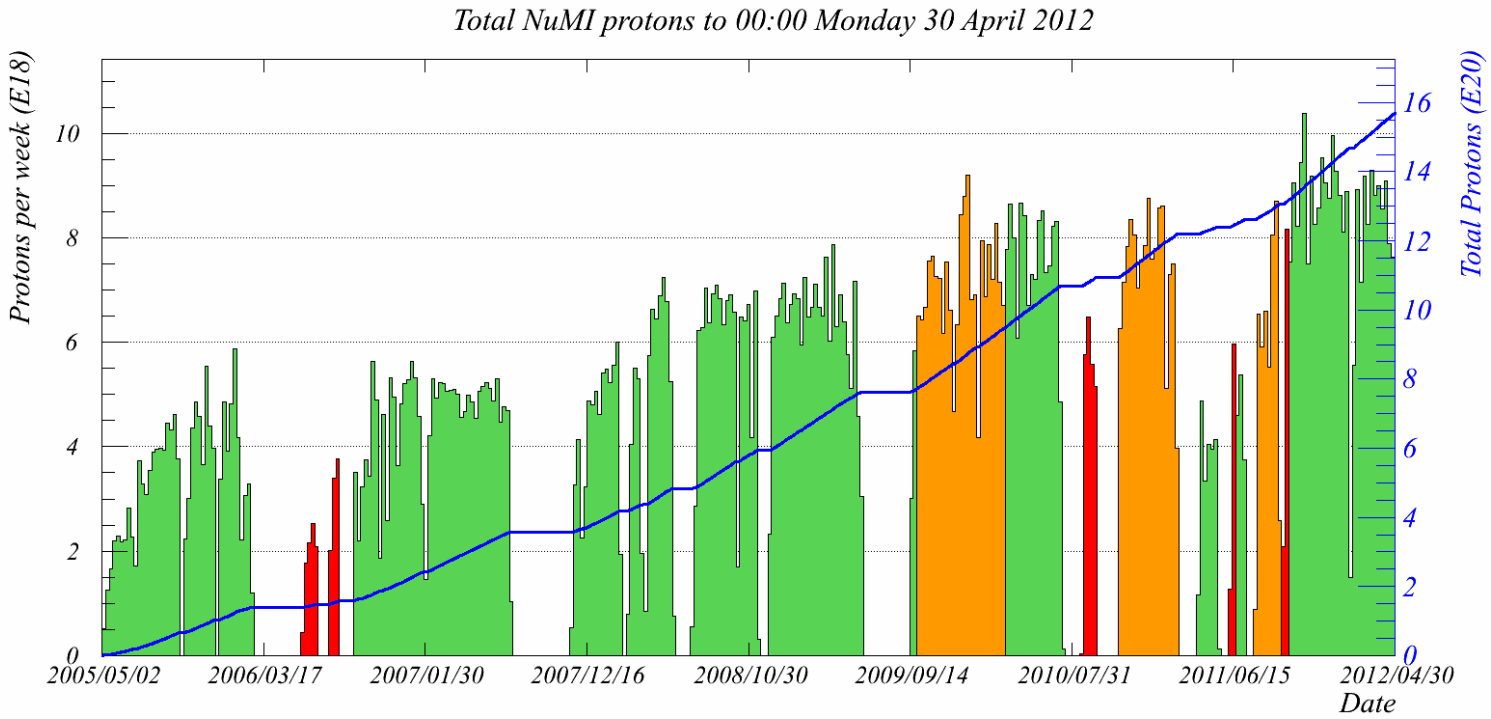
NEUTRINO CONFERENCE 2012

UPDATED T2K RESULTS

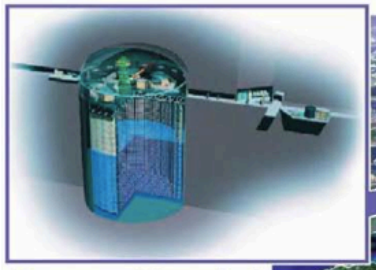


MINOS

- Final MINOS results were presented at Kyoto on
  - θ_{13}, $\overline{\theta}_{13}$, Δm^2, $\overline{\Delta m}^2$, $\sin^2 2\theta_{23}$, 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)

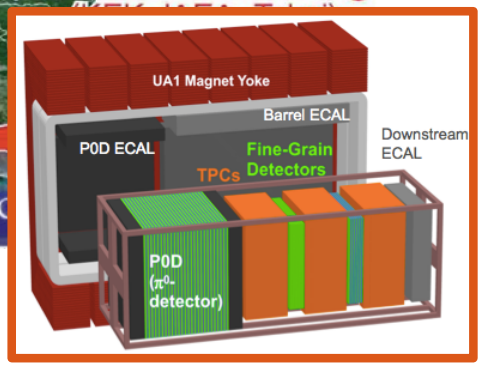


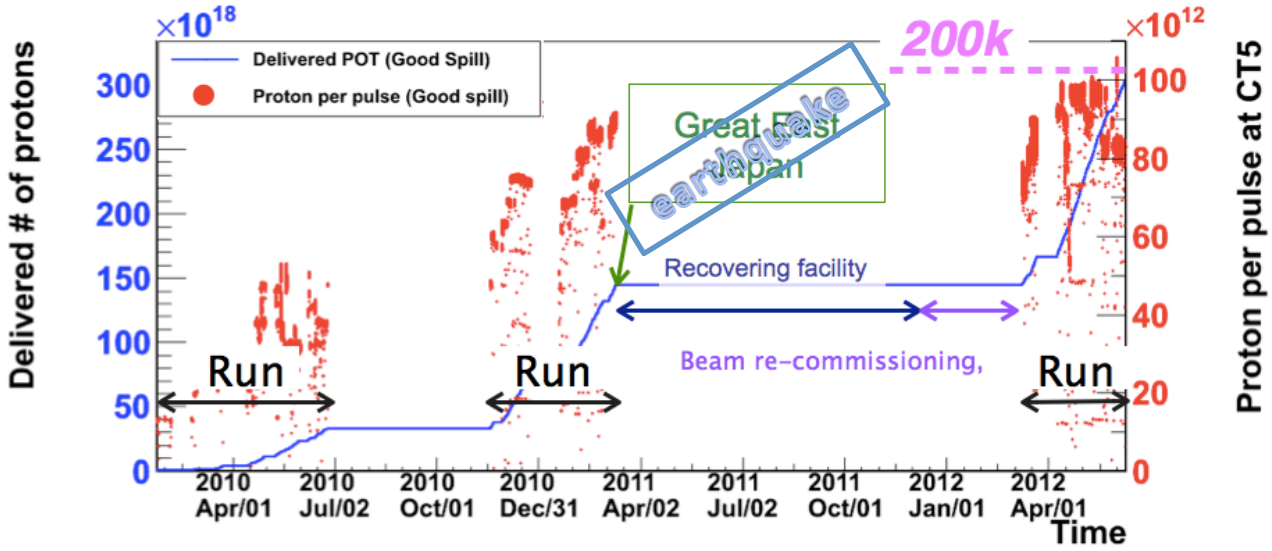
T2K



Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring





Run1 + 2 (2010-2011)
1.43 x 10^{20} p.o.t.

Run3 (2012) : 1.58 x 10^{20} p.o.t

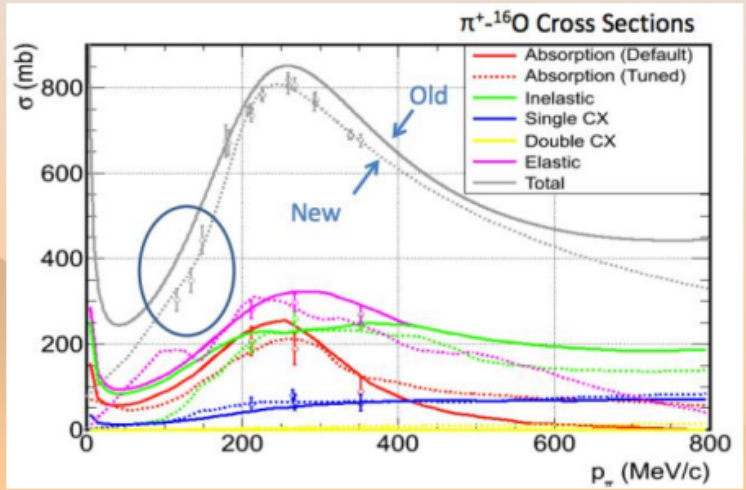
* including 0.21 x 10^{20} p.o.t. with 200kA horn current

Data now analysed 3.01 x 10^{20} p.o.t. (18% of increase over Kyoto)

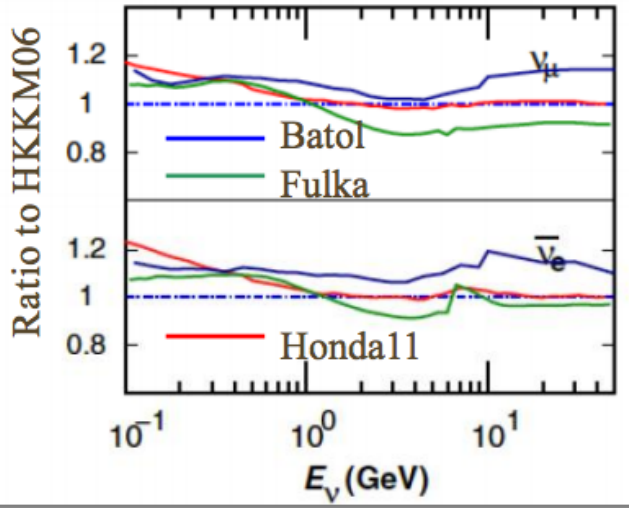
Super-K

New Super-K atmospheric neutrino data

- New 1097days of SK4 (3903days in total SK1-4)
- Reanalyzed all SK1-4 data/MC with common improved tools
- Improved neutrino interaction code (NEUT) and updated Honda11 flux

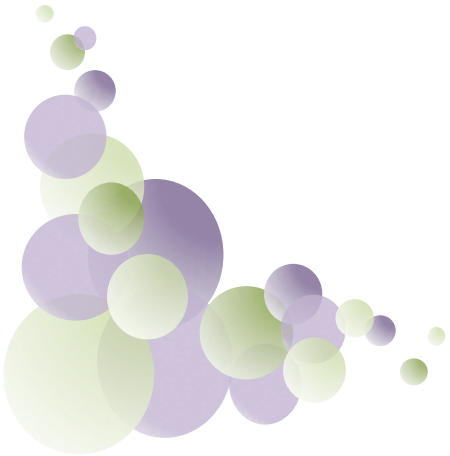


M. Honda et al.,
PHYSICAL REVIEW D 83, 123001 (2011)



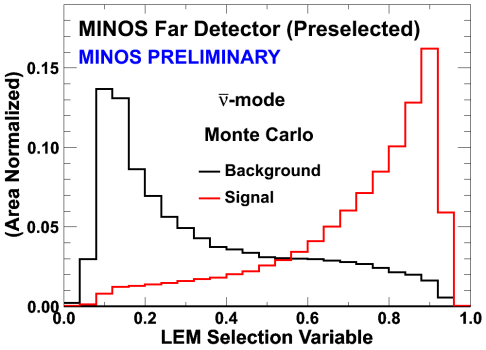
$\underline{\underline{\theta_{13}}}$

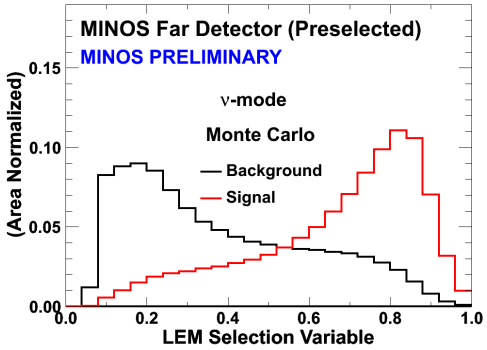
Leading to CP violation measurements and Mass Hierarchy.

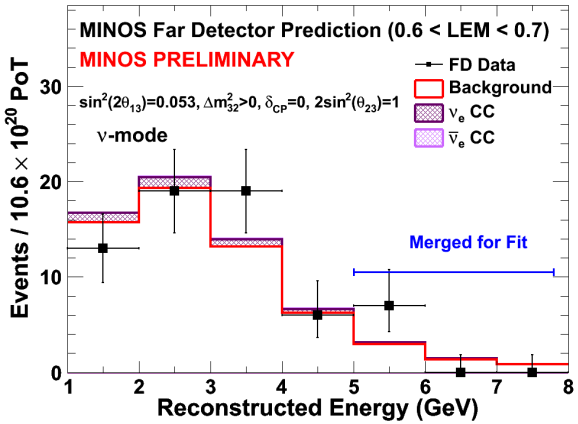


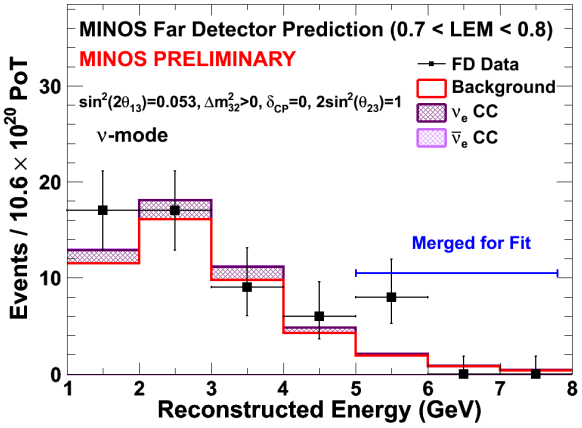
θ_{13}

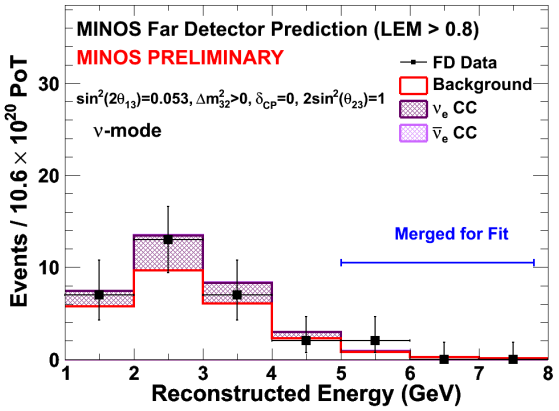
- MINOS have updated their measurement of θ_{13} using all the neutrino and anti-neutrino data of 1.4e21 p.o.t assuming same mixing parameters for ν and anti-ν
- Backgrounds measured in the ND and extrapolated separately
- Library of MC events used for event matching





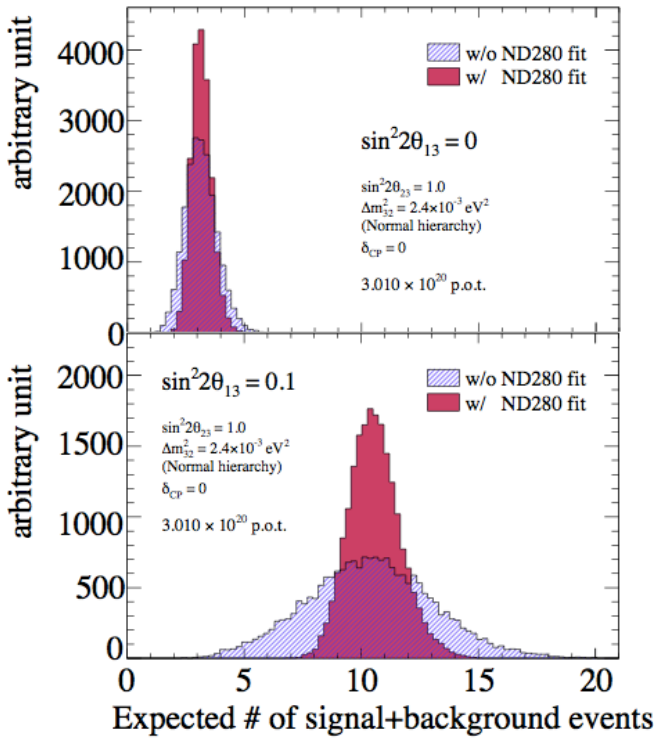






θ_{13}

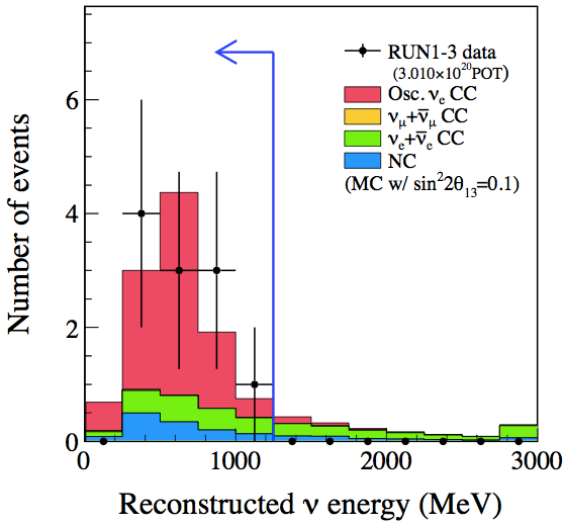
- T2K have doubled previous dataset and used ND280 to:
  - constrain backgrounds
  - constrain flux, x-sec with MC fit to ND data
  - extrapolate backgrounds
  - reduce systematic errors



The predicted # of events w/ 3.01 x 10^{20} p.o.t.

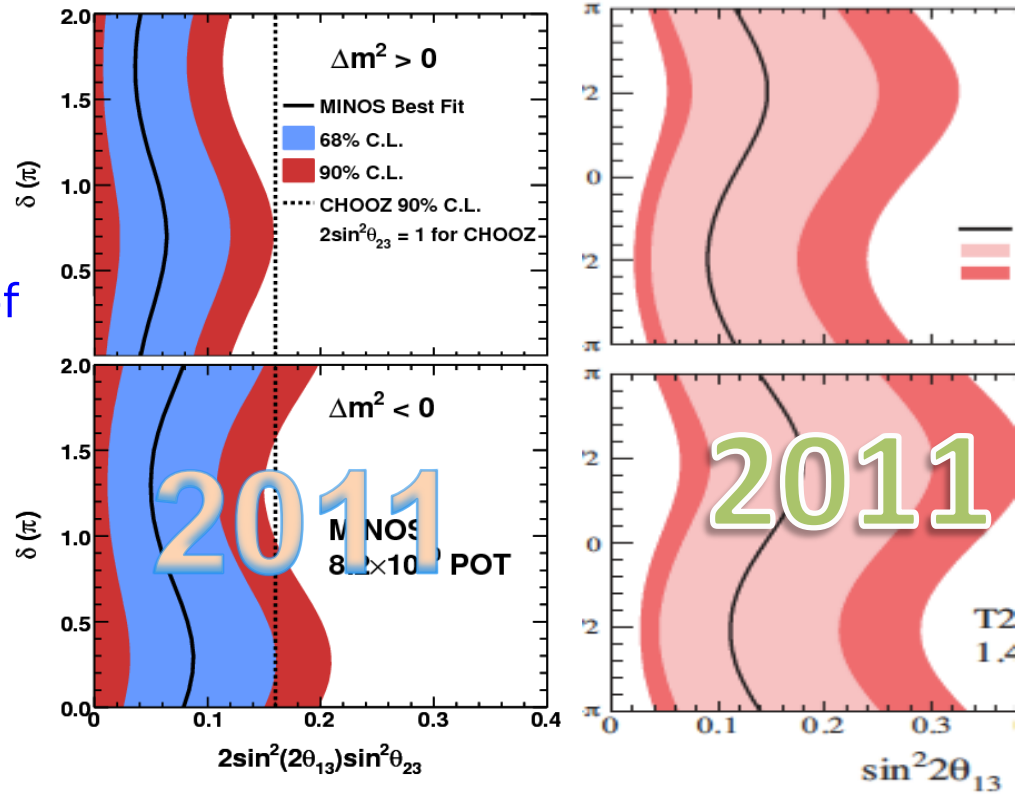
Event category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22±0.43	10.71±1.10
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background (mainly NCπ^0)	1.21	1.21
$\bar{\nu}_\mu + \bar{\nu}_e$ background	0.16	0.16

11 candidate events are observed



θ_{13}

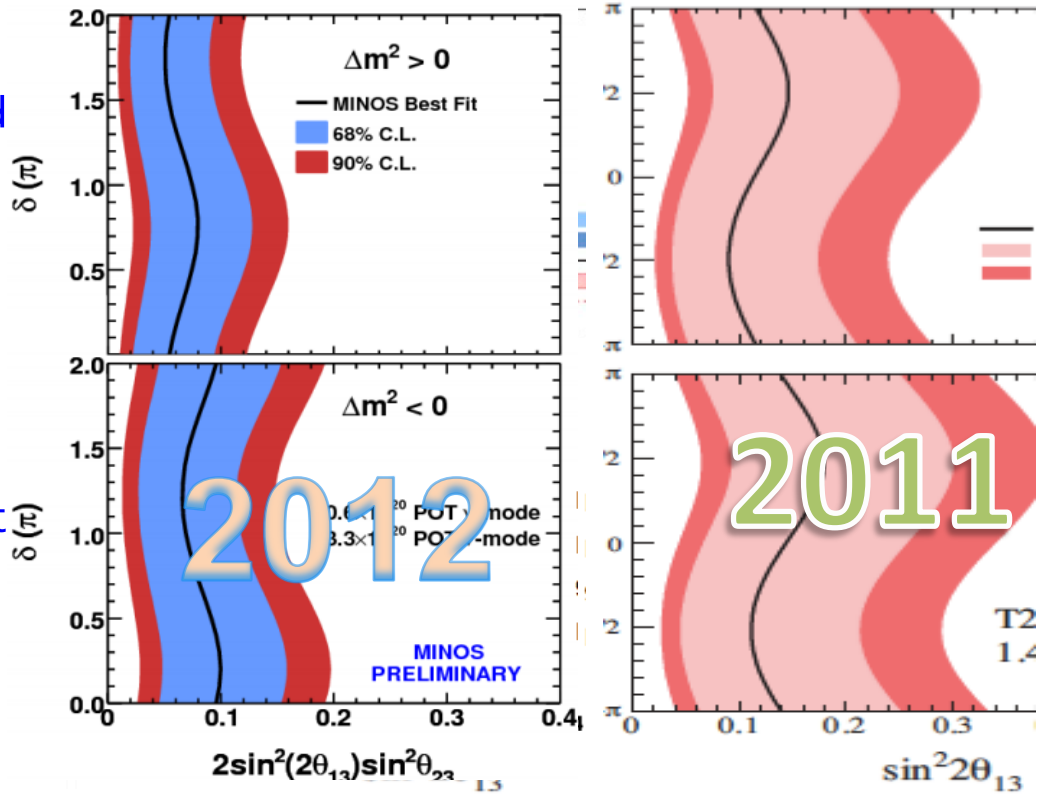
- MINOS new analysis performed with 8.2×10^{20} p.o.t
- Used a look up library of signal and background events
- Data driven measurement of the backgrounds



MINOS T2K

θ_{13}

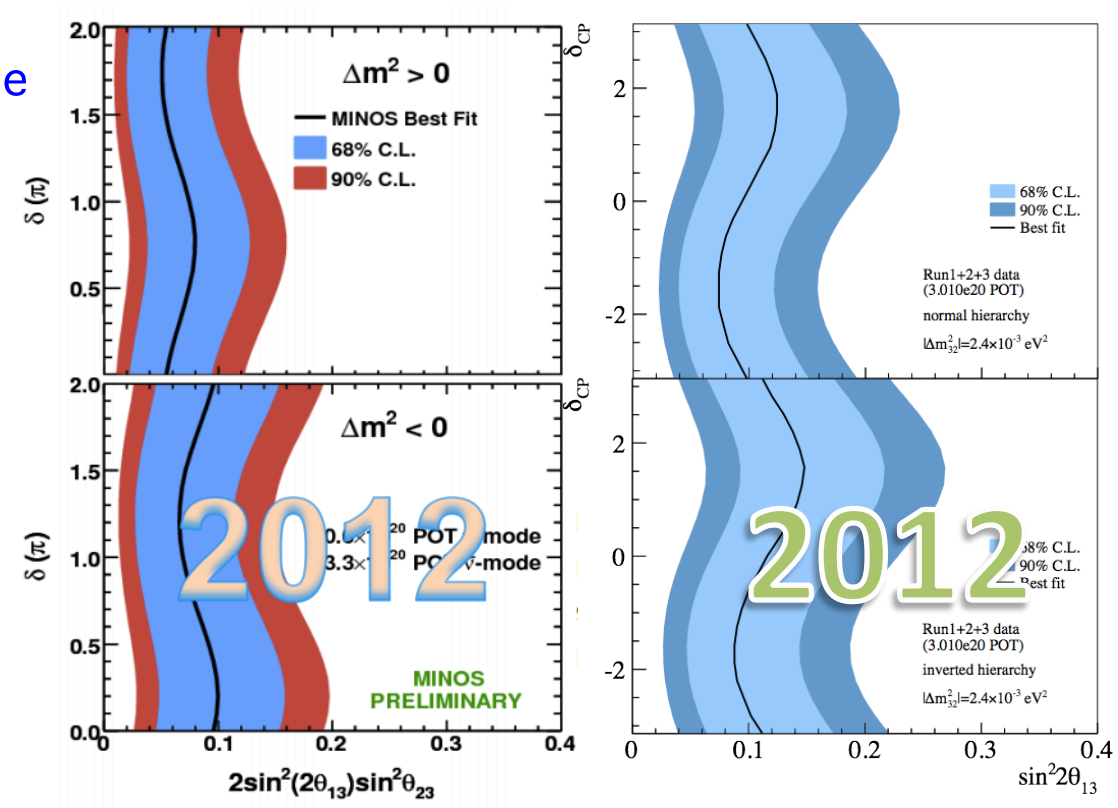
- New analysis performed with 10.71×10^{20} p.o.t and 3.36×10^{20} p.o.t of antineutrinos
- Uses a look up library of signal and background events
- Data driven measurement of the backgrounds
- Still most sensitive analysis with matter effects….



MINOS T2K

θ_{13}

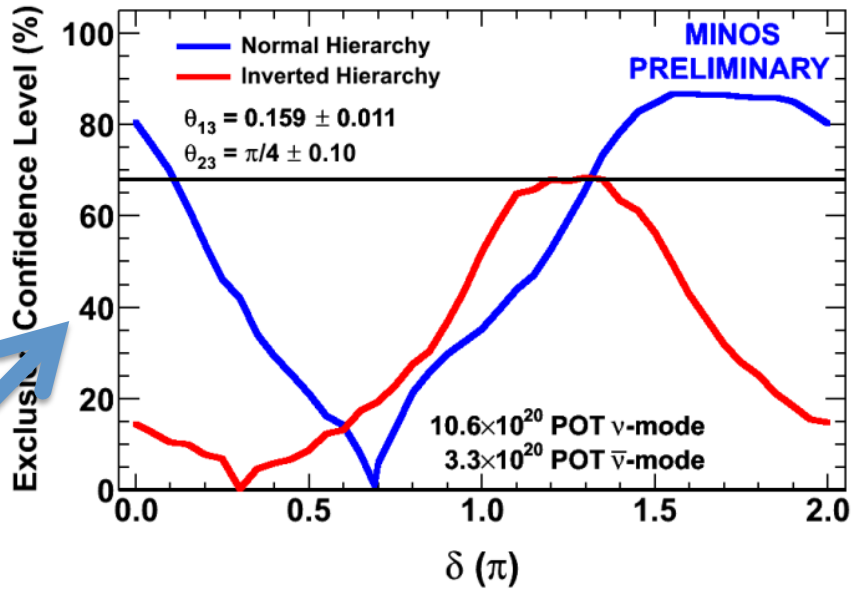
- MINOS has a respectable measurement to finish with!
- T2K now really using the power of the L/E choice, near detector etc….
- Possible tension in NH points to IH solution



MINOS T2K

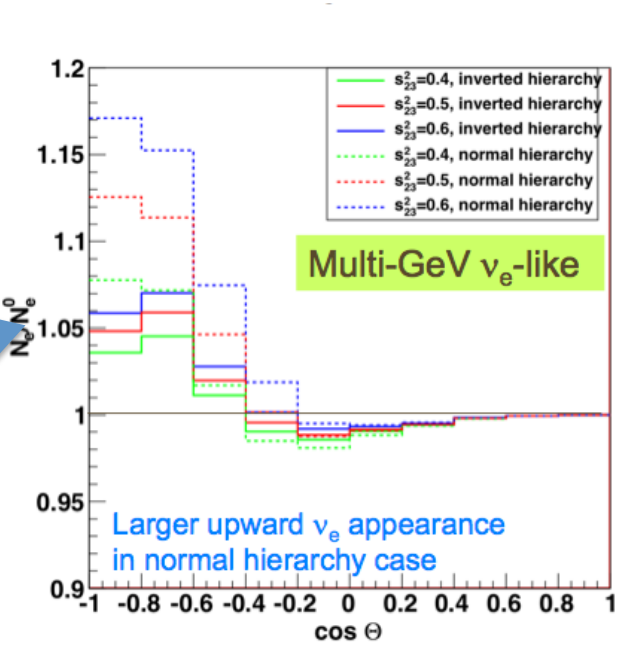
Hierarchy?

- MINOS is sensitive to matter effects from long baseline
- With non-maximal θ_{23}, this becomes four lines, two fo each octant
- Theoretical predictions fron Yanagida (Kyoto 2012):
  - Inverted Hierarchy
  - $|\delta_{CP}|=\pi/2$
  - $<m_\nu>$ =43meV !!!!



Hierarchy?

- Super-K look at low energy upward ν_e spectrum
- ~10%(NH), ~5%(IH)
- Depends also on θ_{23}: $2\sin^2\theta_{13}(r\sin^2\theta_{23}-1)$

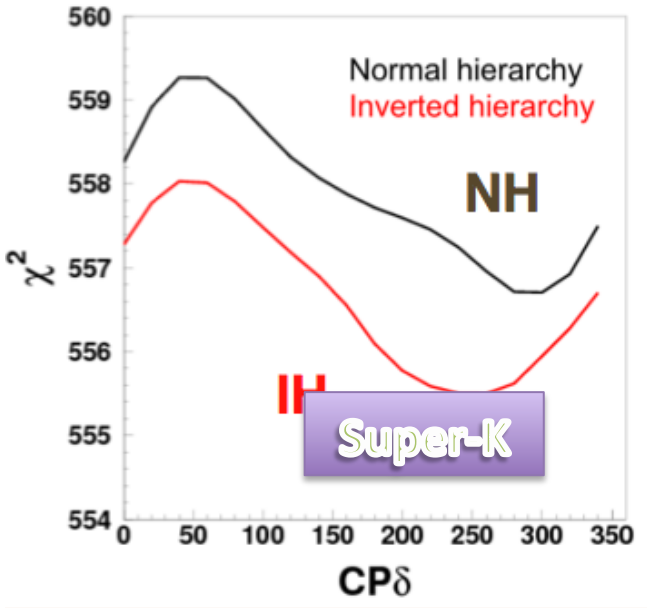


NH χ^2_{min} = 556.7 / 477 dof

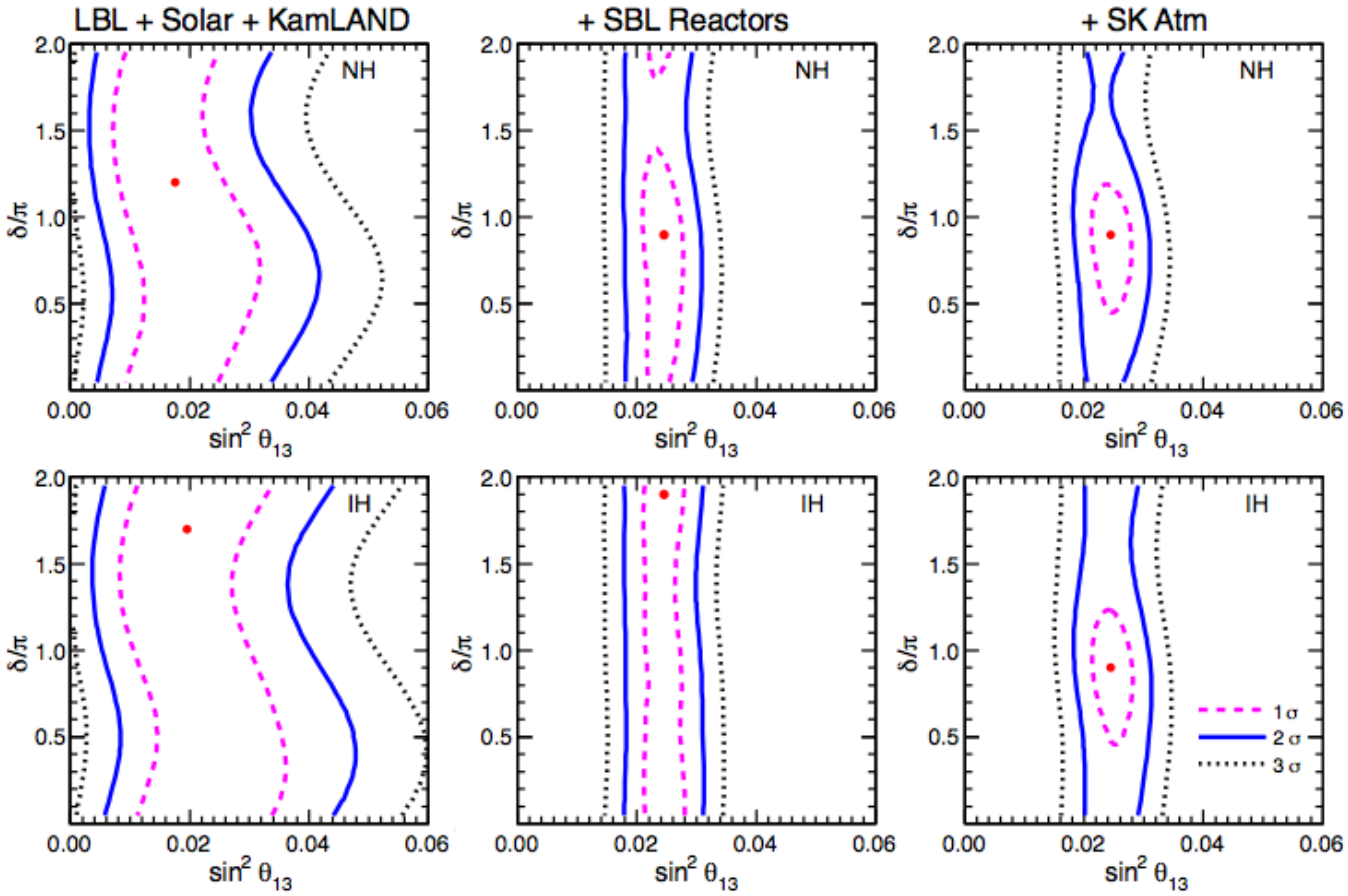
IH χ^2_{min} = 555.5 / 477 dof

$$\chi^2_{min}(NH) - \chi^2_{min}(IH) = 1.2$$

(Sensitivity for (inverted) mass hierarchy: χ^2(NH)- χ^2(IH) = 0.463

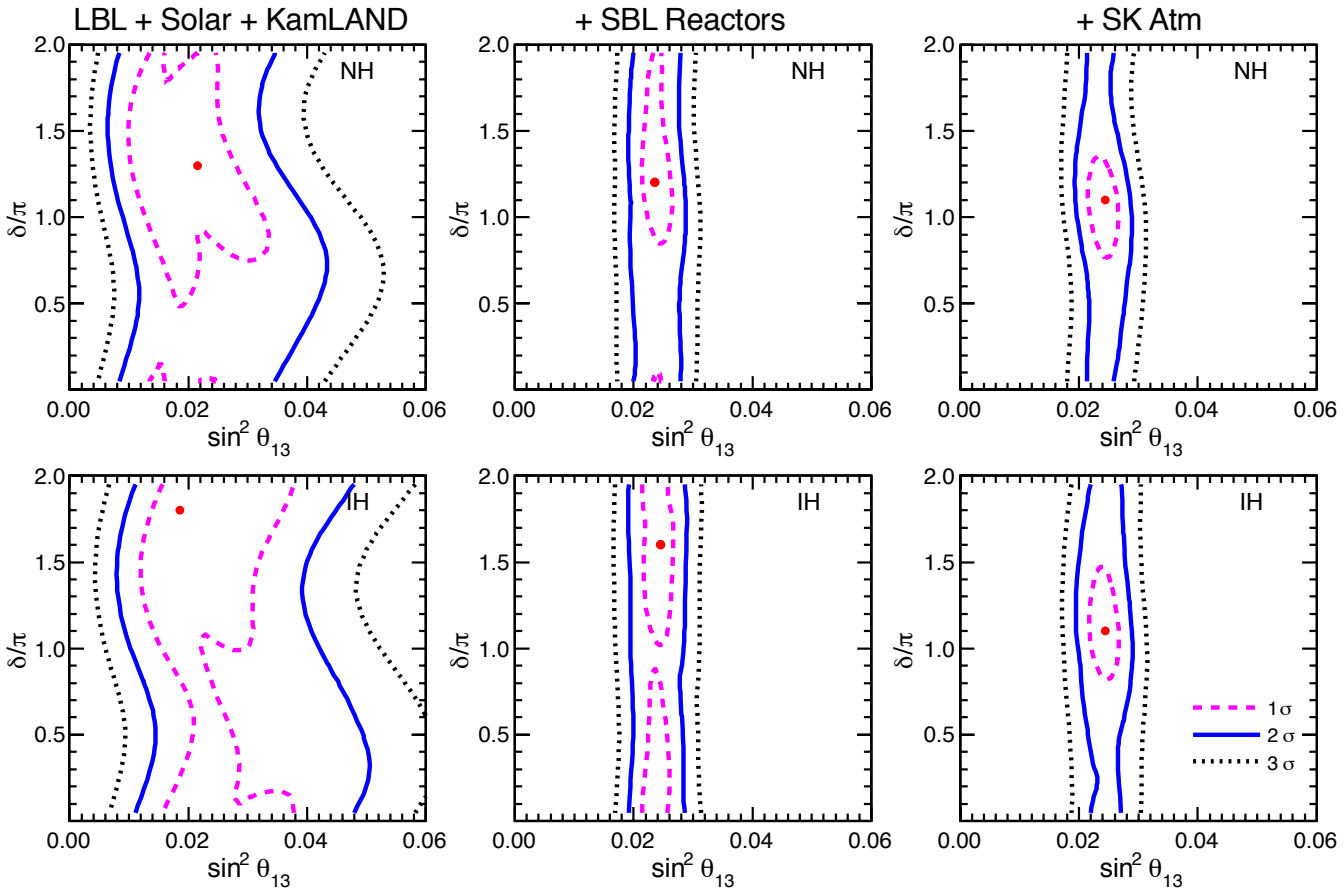


Status in June



- Pre-Kyoto results (Fogli et al. (arXiv:1205.5254v1 [hep-ph] 23 May 2012)

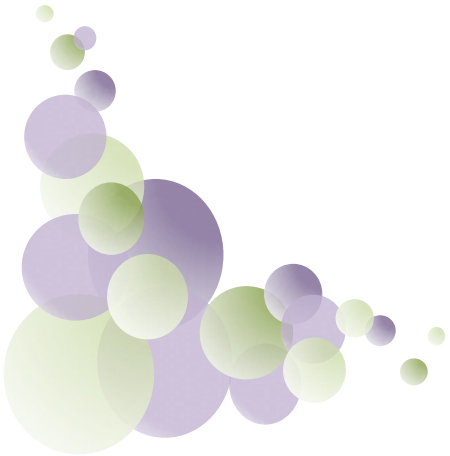
Status today



- Post-Kyoto results (Fogli et al. (arXiv:1205.5254v3 [hep-ph] 23 May 2012)
- No hierarchy preference (< 1σ) from global fit

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

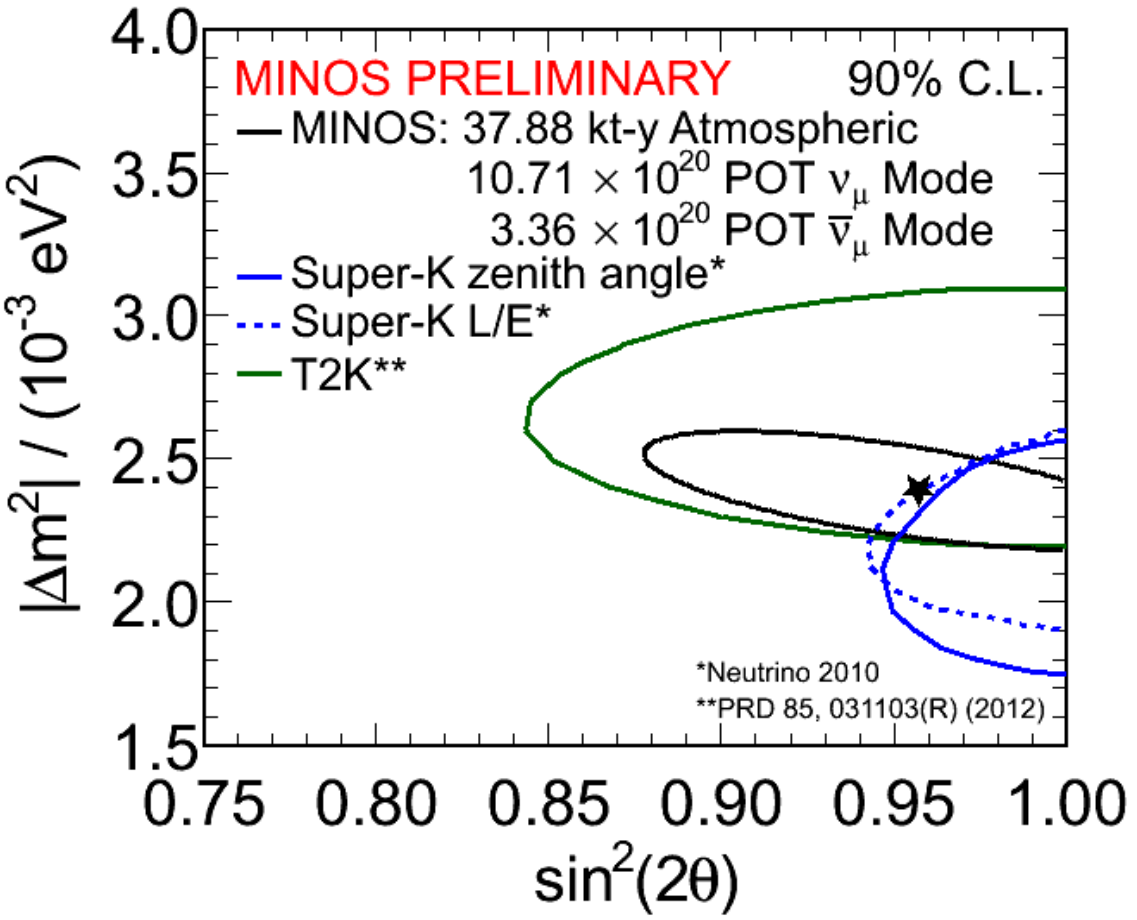
The new precision frontier!



θ_{23}

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

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



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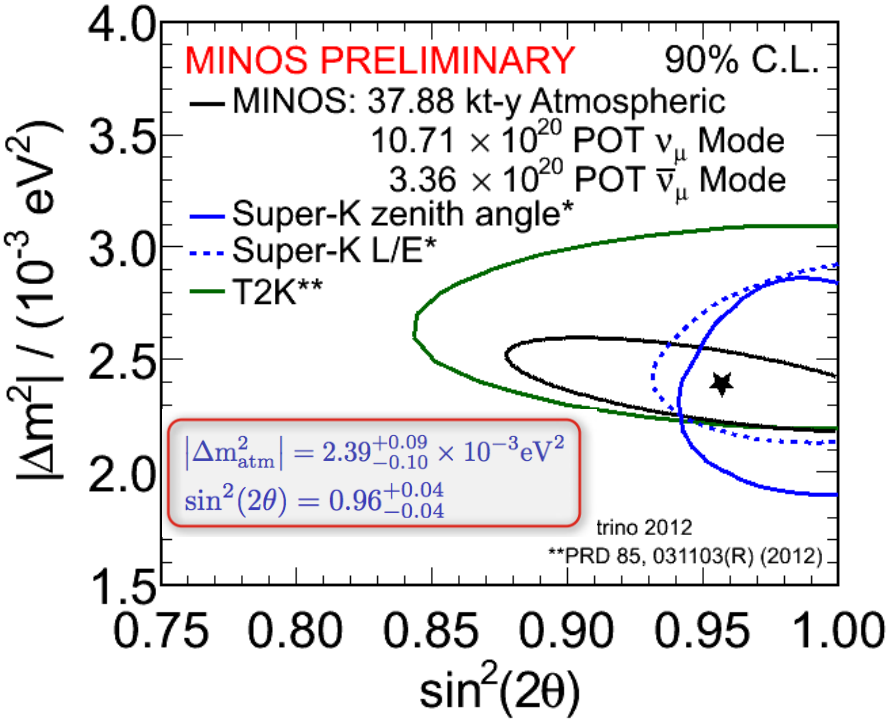
- Super-K have done full 3-flavor analysis to give $\sin^2 2\theta_{23} < 1.0$



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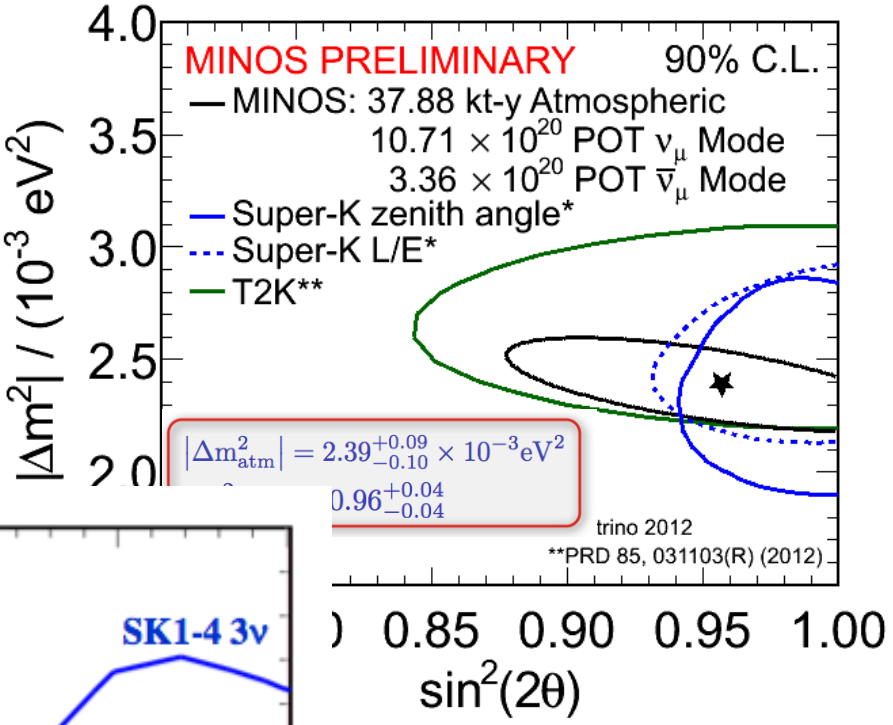

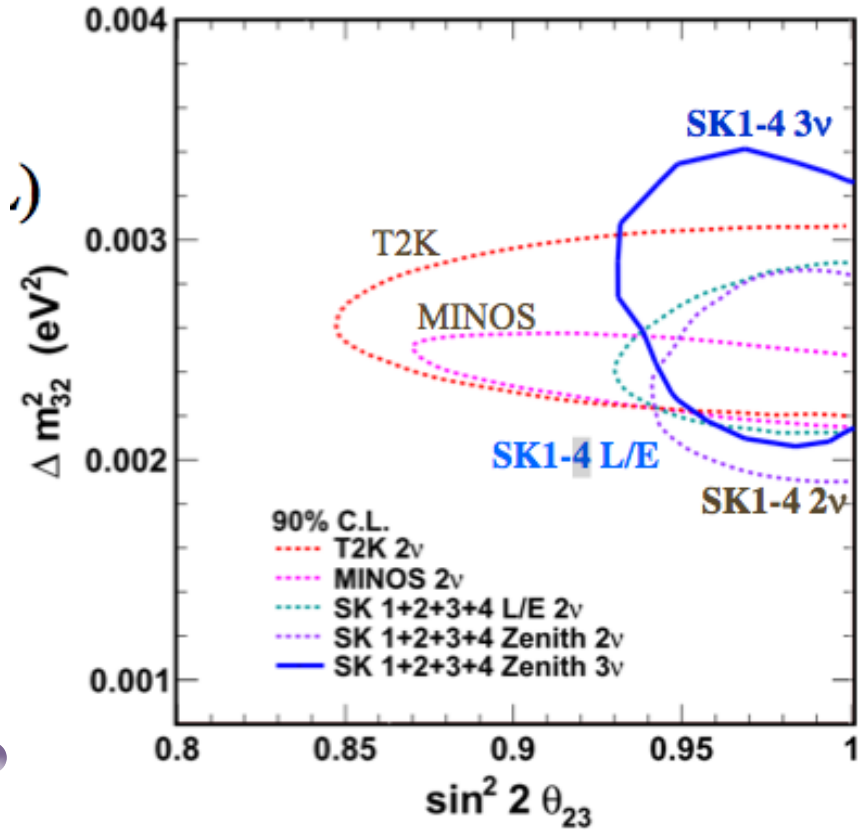

θ_{23}

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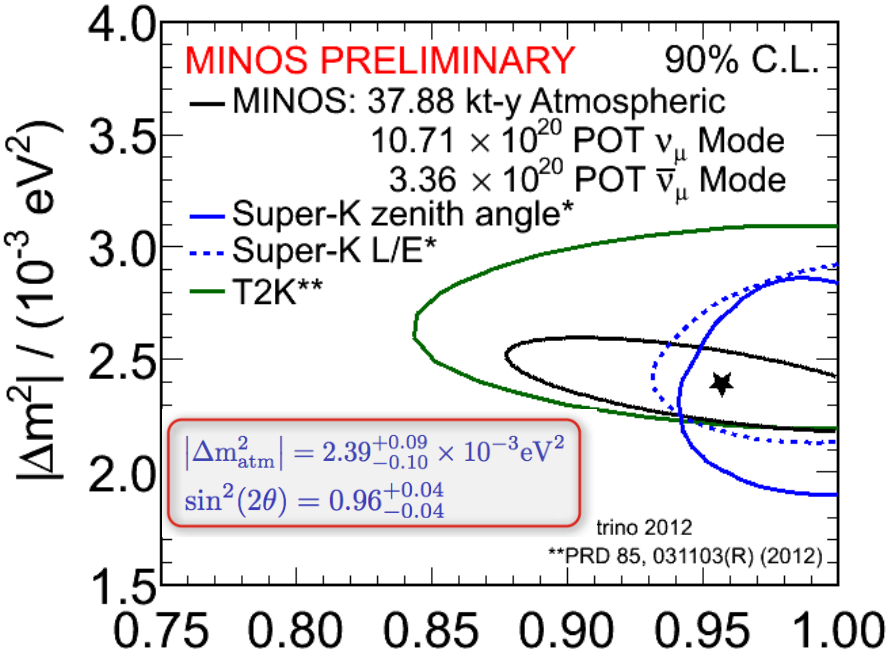
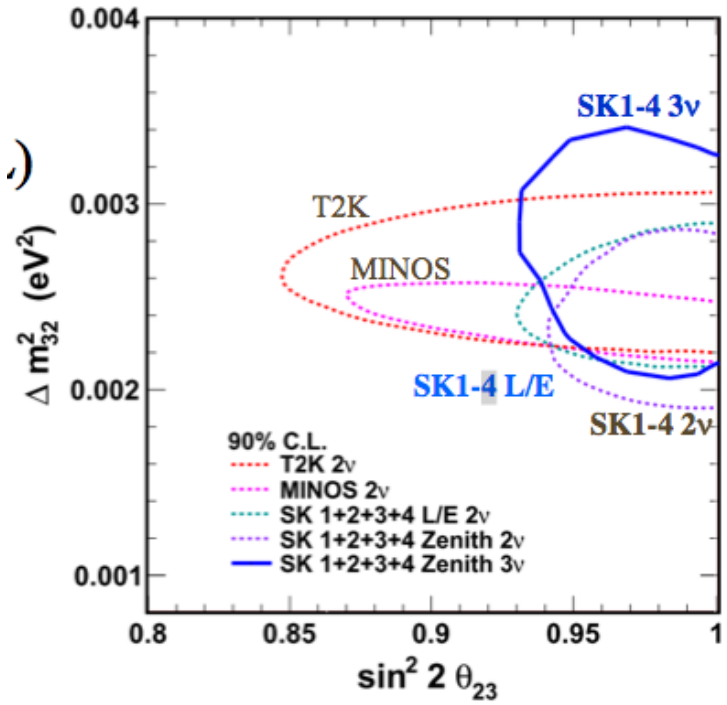
- θ_{23} is the new θ_{13} !!!
- LBL measure combination of θ_{23} and θ_{13} so precise knowledge is important





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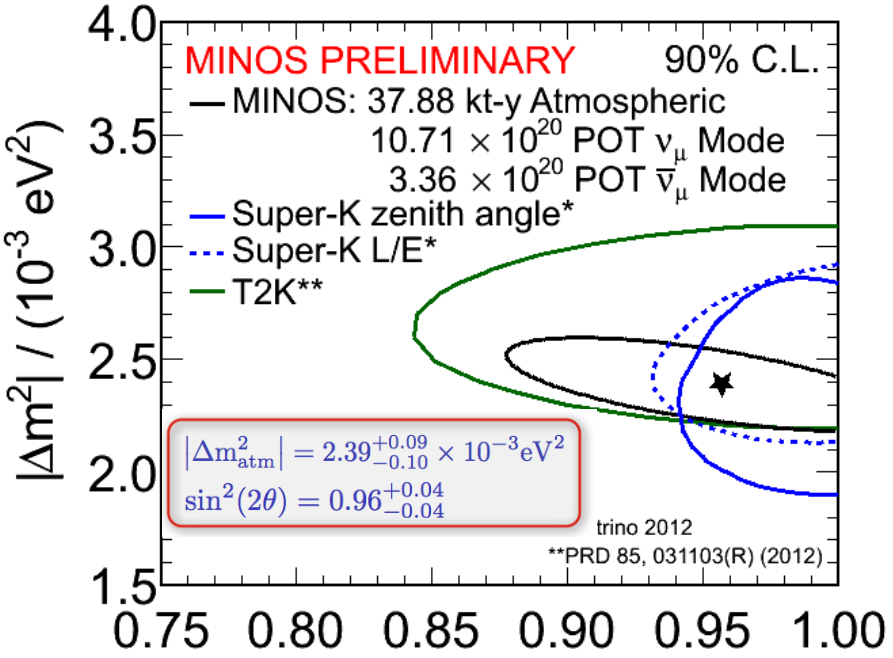
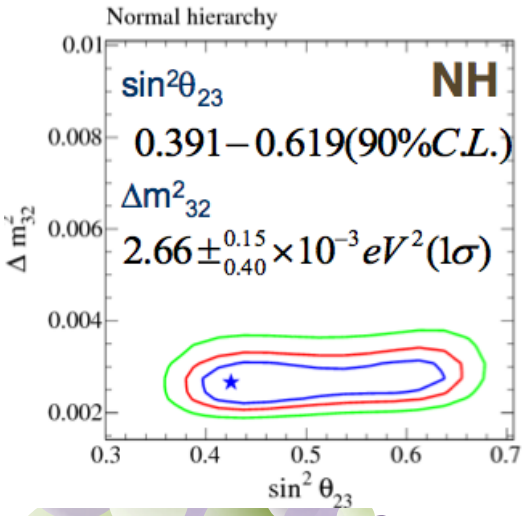
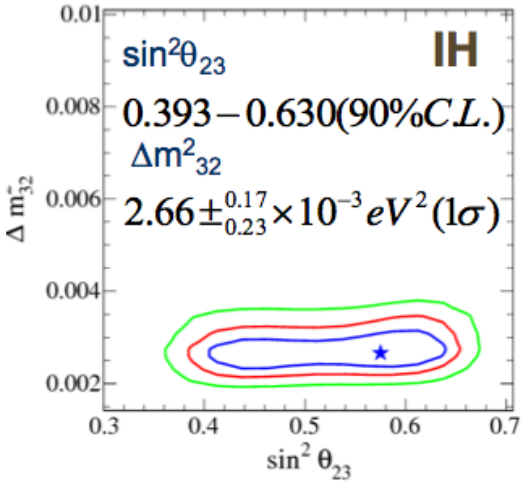
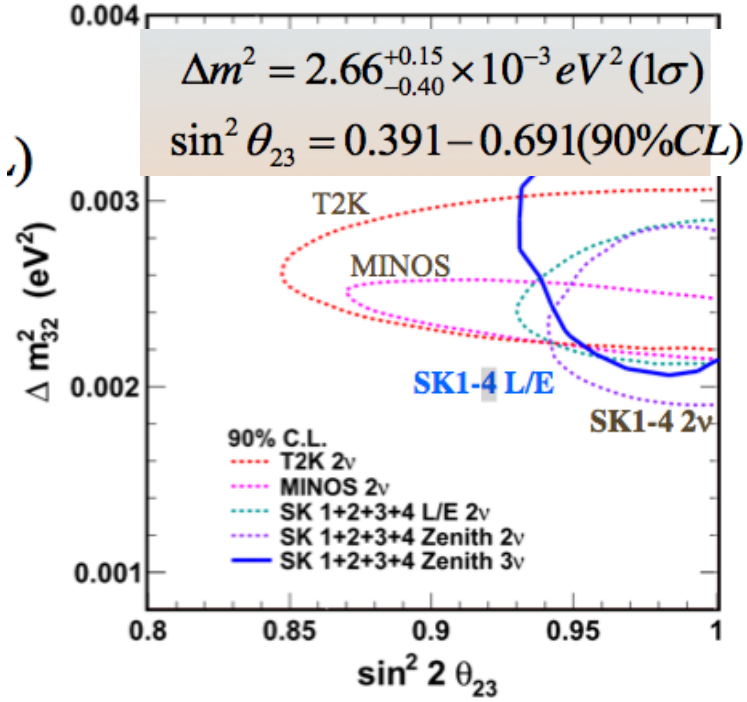






$\Delta m^2 = 2.66^{+0.15}_{-0.40} \times 10^{-3} eV^2 (1\sigma)$

$\sin^2 \theta_{23} = 0.391 - 0.691 (90\% CL)$



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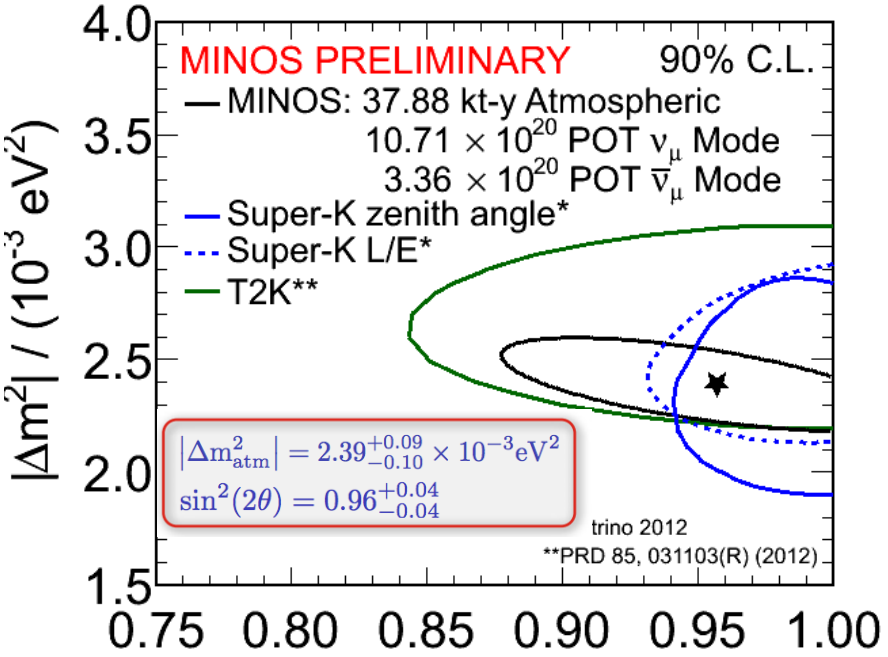
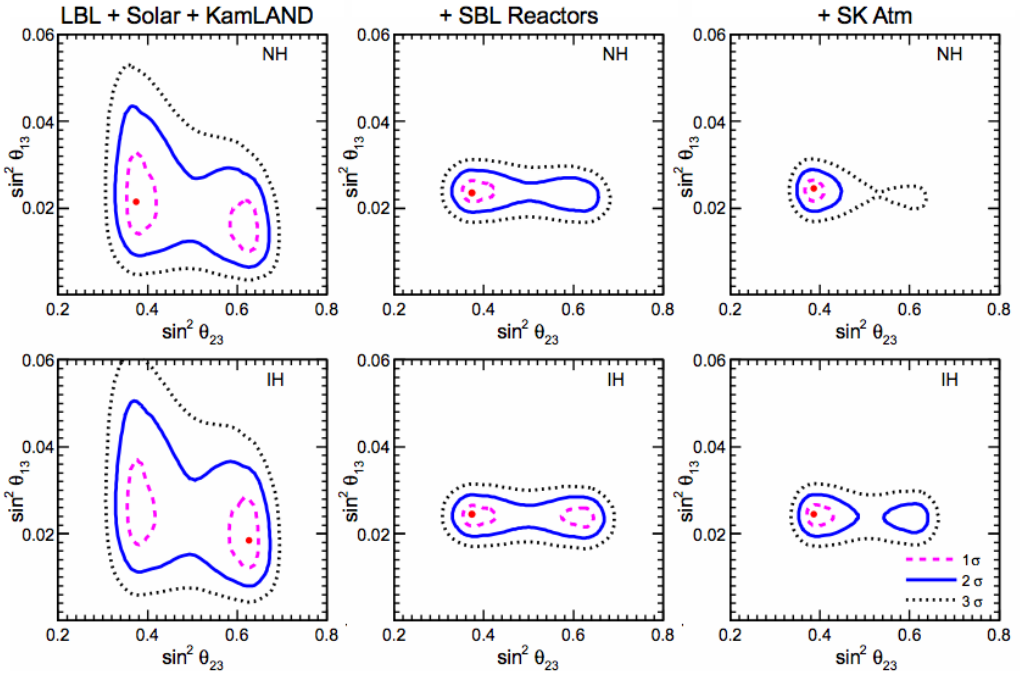
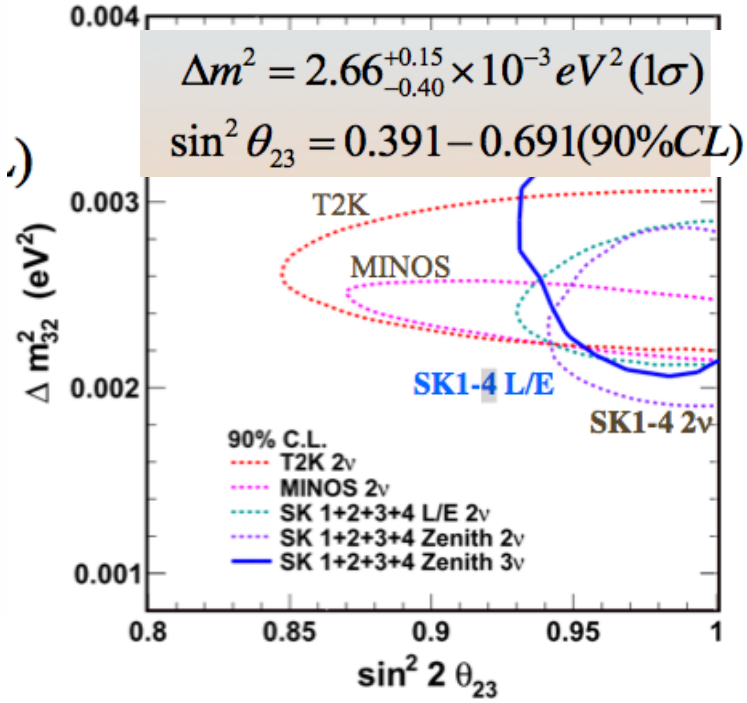
- Information about which octant θ_{23} in
- θ_{23} is the new θ_{13} !!!
- Global fit (Fogli et al.) prefers $\sin^2\theta_{23} < 0.5$

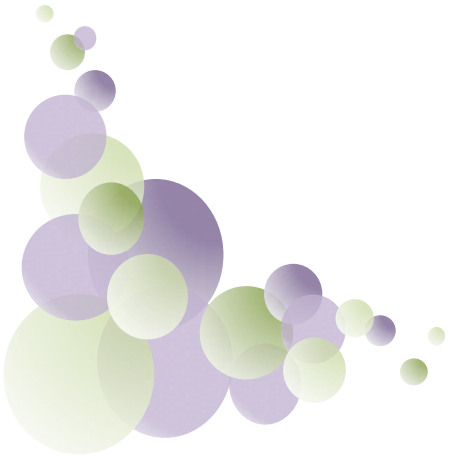






In to the (near) future

Fermilab, NuMI, MINOS+, NOνA



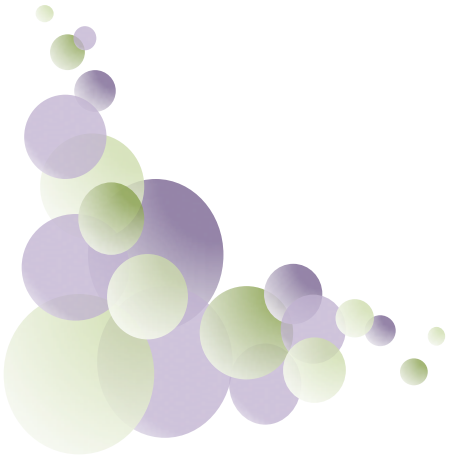
Fermilab-NuMI

- NuMI beam will be 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+

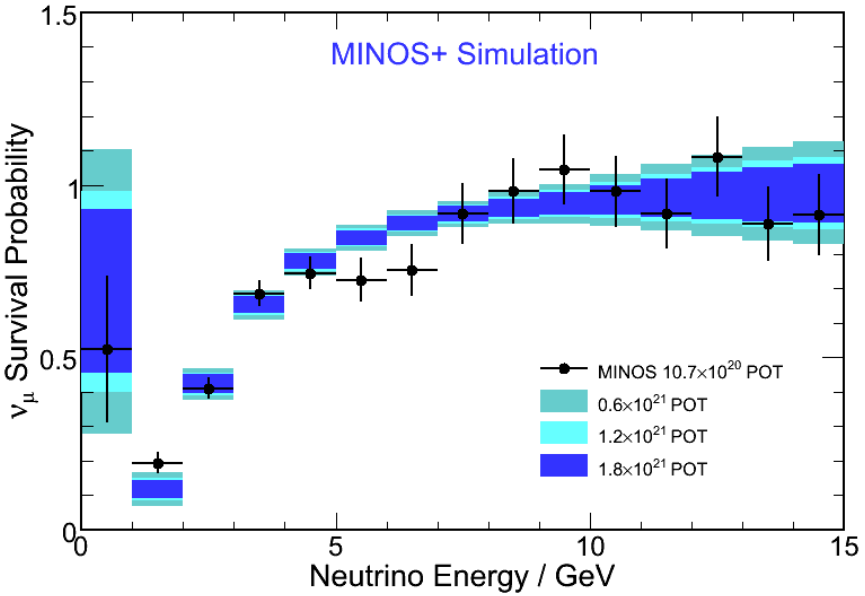
Starts April 2013 for three years

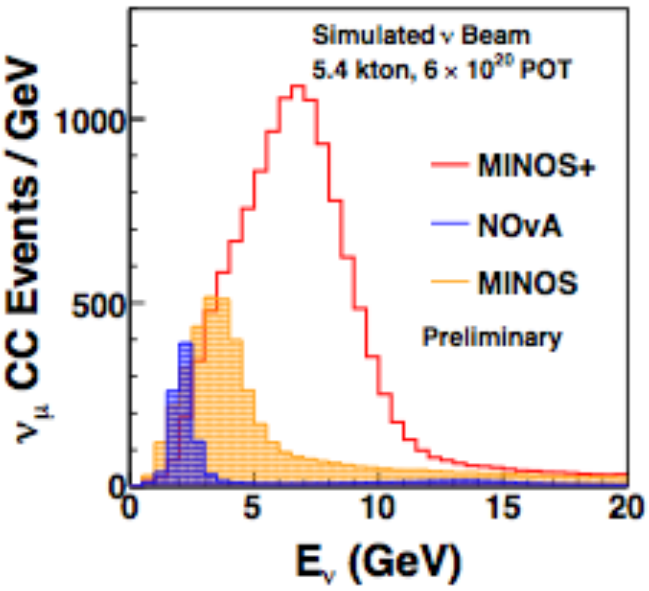
April 2013-2016



MINOS+ goals

- 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)





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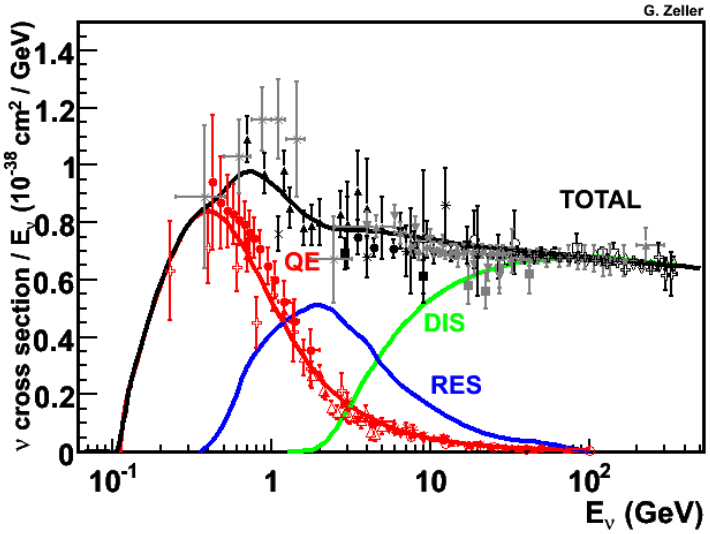
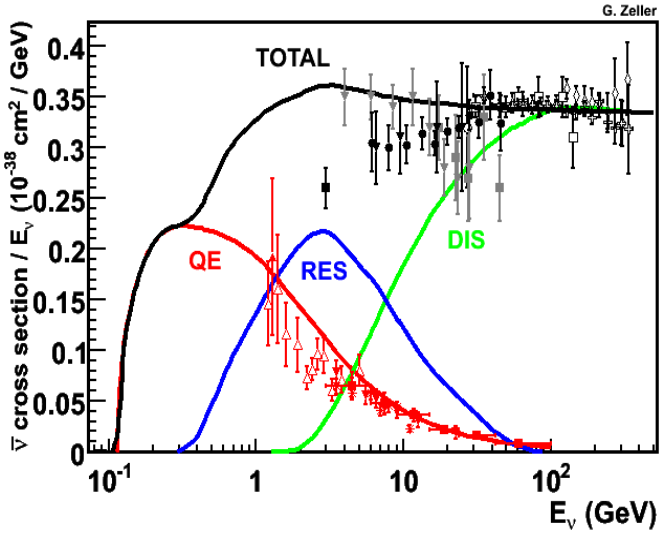
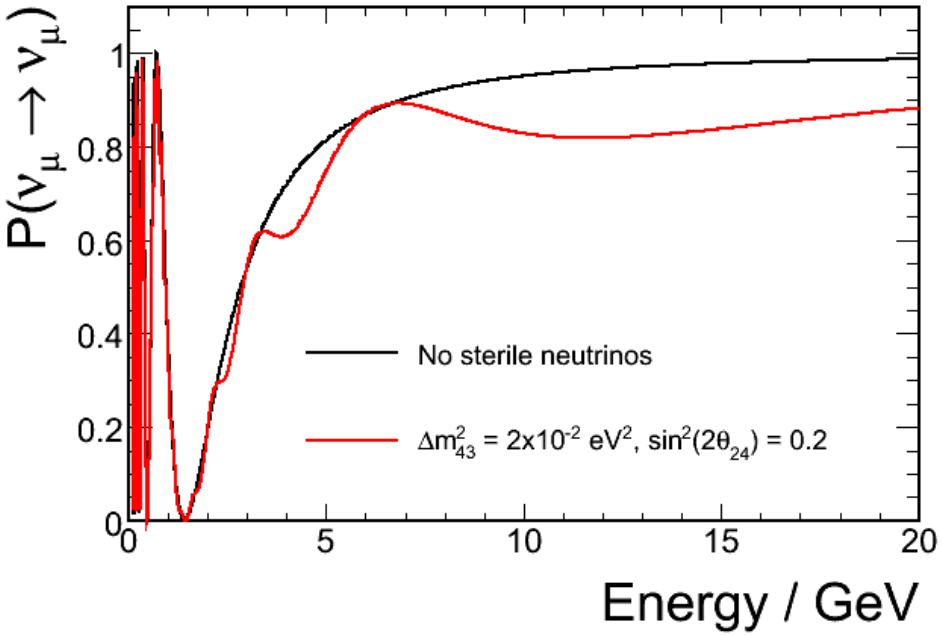
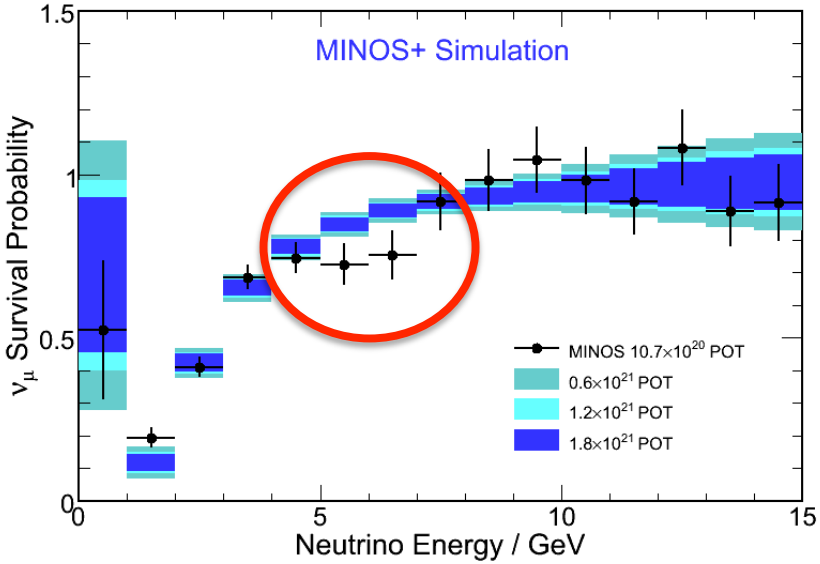




MINOS+

- 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





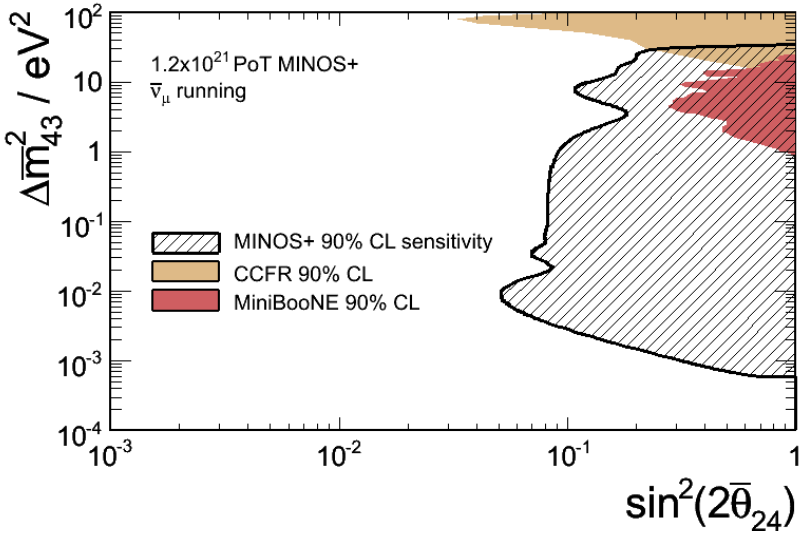
MINOS+ sterile reach

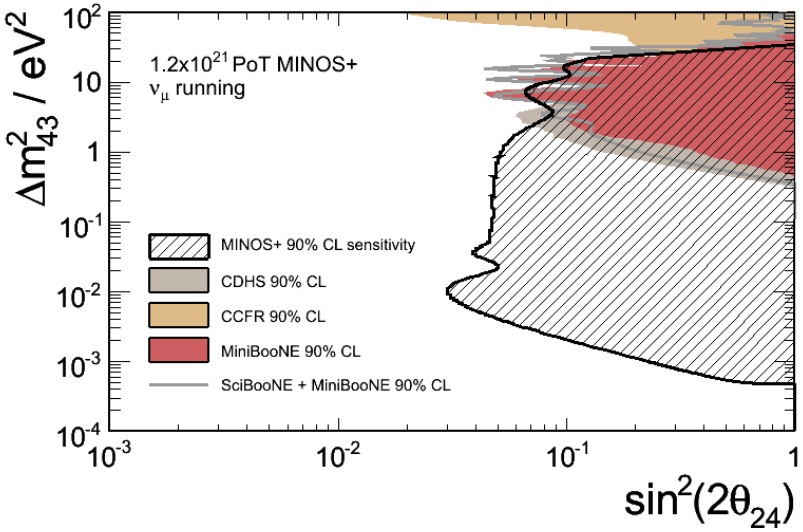
$|U_{e4}|^2 = \sin^2\theta_{14}$

$|U_{\mu 4}|^2 = \cos^2\theta_{24} * \sin^2\theta_{24}$

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

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





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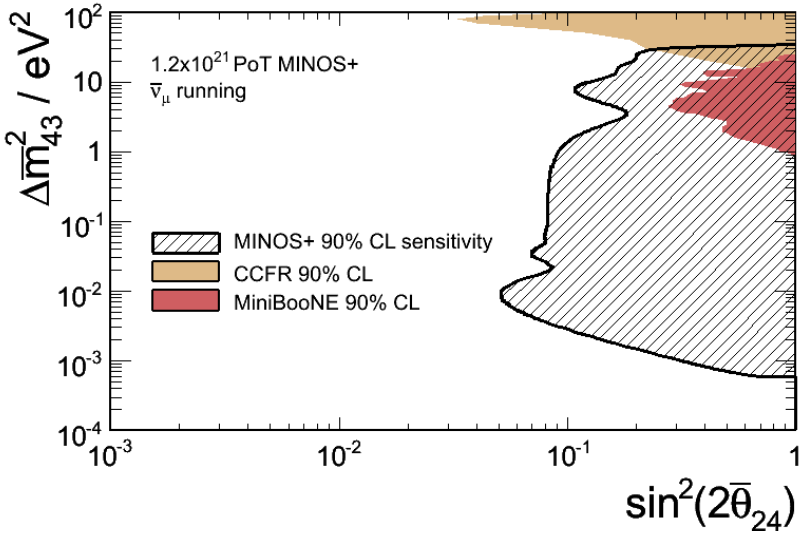
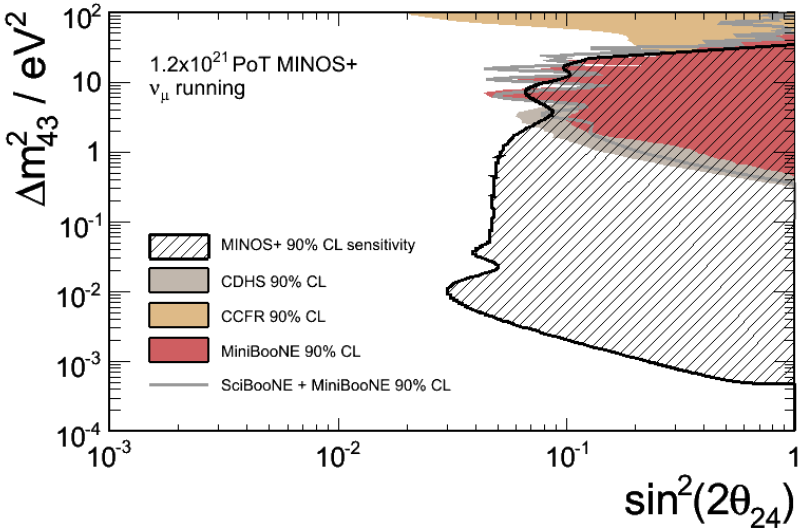
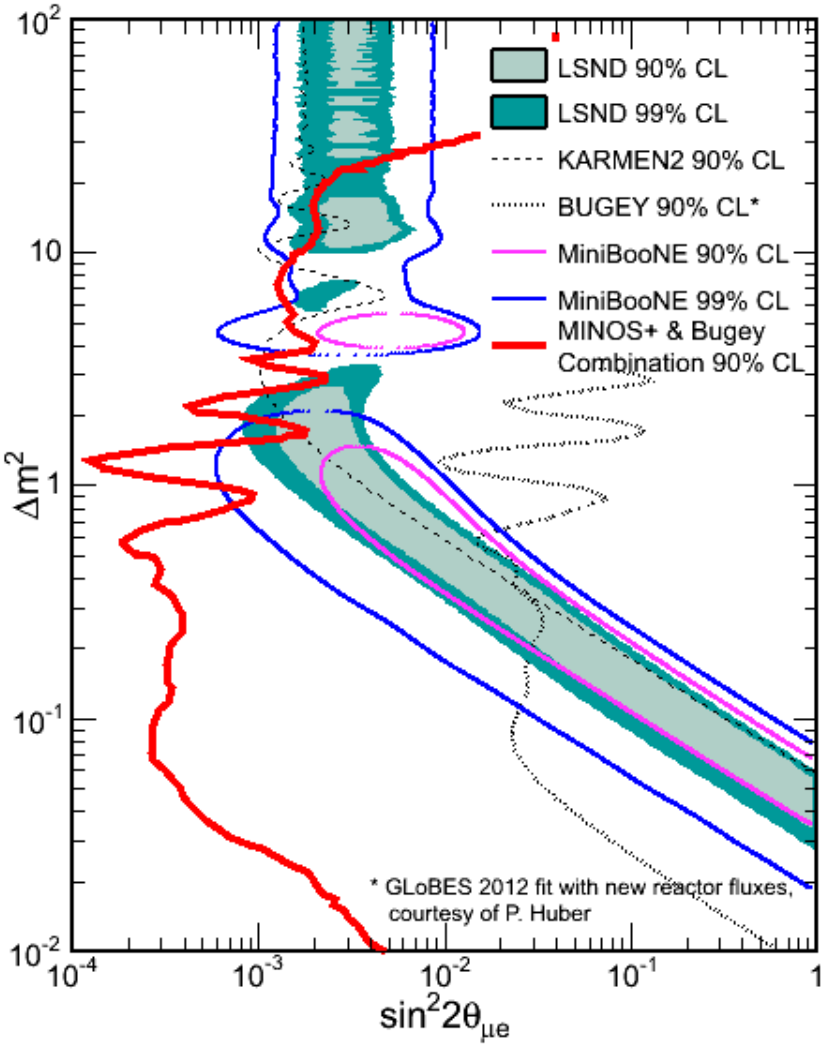
A.Sousa



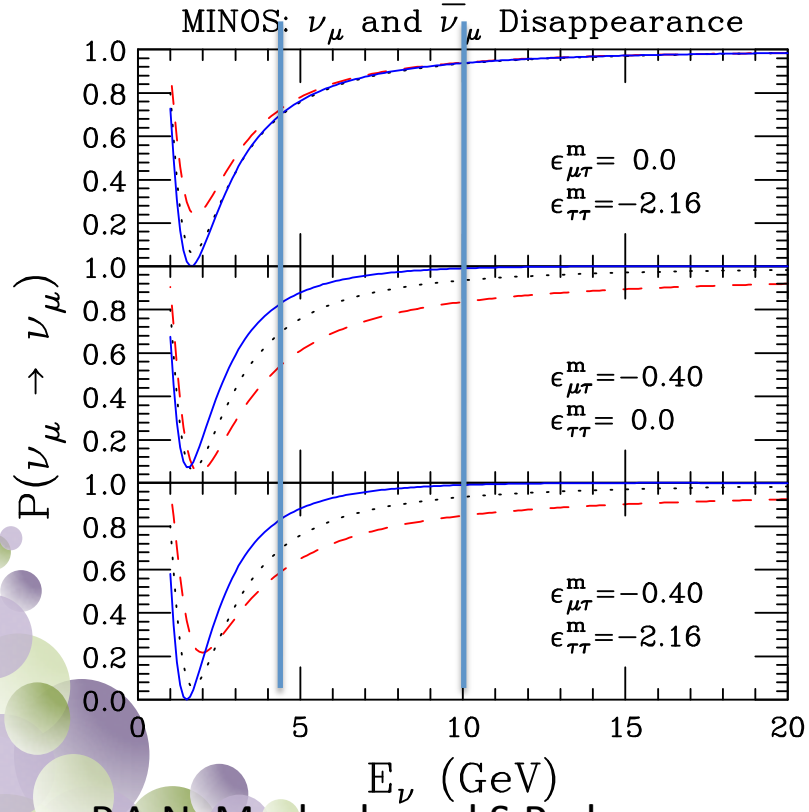




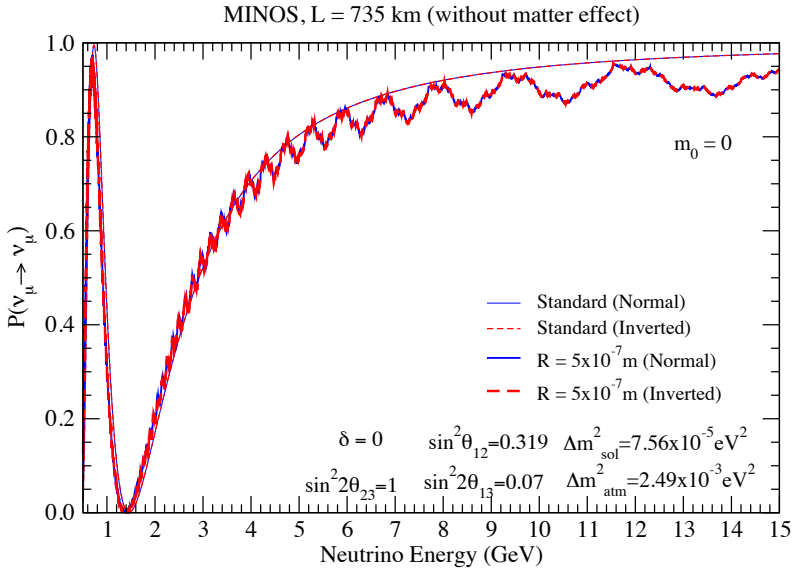
$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu 4}|^2$

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).



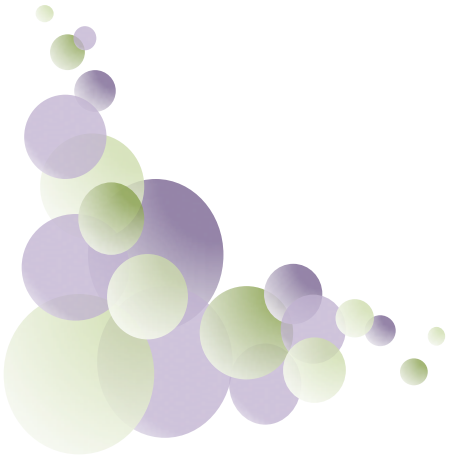
Half micron sized extra dimensions can be observed!!

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



NOνA

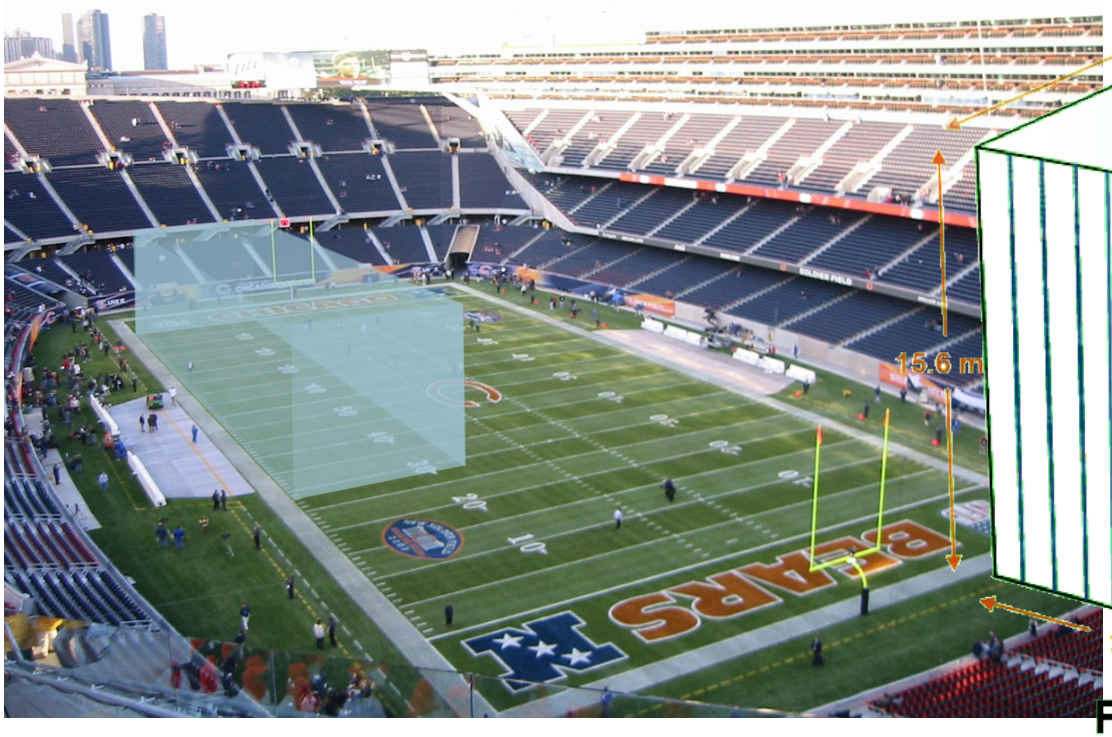
Physics Goals:

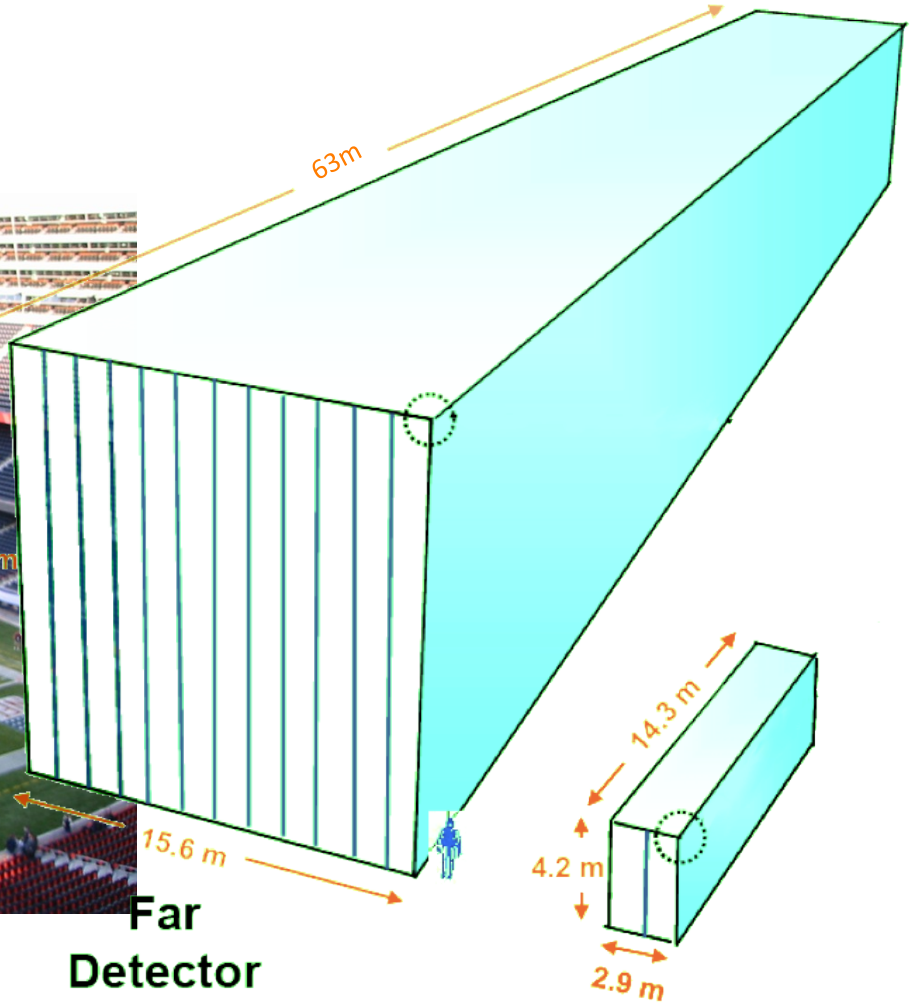
- Measure the oscillation probabilities of

  $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

  - Measure the mixing angle θ_{13}
  - Determine neutrino mass hierarchy
  - Study the phase parameter for CP Violation δ_{CP}
- Precision measurements of Δm^2_{32}, θ_{23}
- As well as:
  - ν cross sections
  - Sterile neutrinos
  - Supernova signals

NOvA



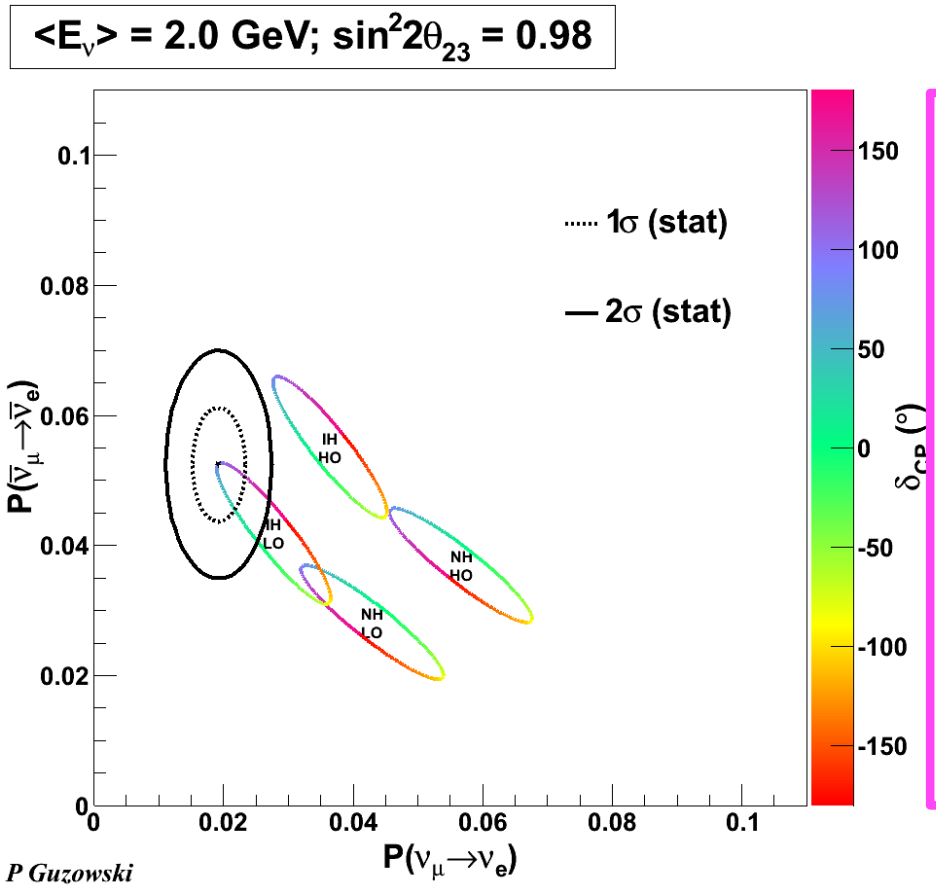


Far Detector

Near Detector

- 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

How does it work? Two ways



P Guzowski

- The different mass hierarchy and θ_{23} octants trace out different ellipses
- After 3+3 (ν + anti-ν) running NOνA would have a point on this plot
- θ_{23} uncertainty and octant is now important : Fogli prefers θ_{23}<45°
- MINOS, Super-K and T2K prefer non-maximal θ_{23}

NOνA+T2K CP violation reach

Period	Integ. No. of Proton on Target	Beam Power (kW)	
-Jun.2012	3.1E+20	170	
-Jun.2013	7.8E+20	200	
-Jun.2014	1.2E+21	250	*2
-Jun.2015	1.8E+21	250	
-Jun.2016	2.5E+21	300	
-Jun.2017	3.2E+21	300	
-Jun.2018	3.9E+21	300	
-Jun.2019	5.5E+21	700	*1
-Jun.2020	7.1E+21	700	
-Jun.2021	8.8E+21	700	

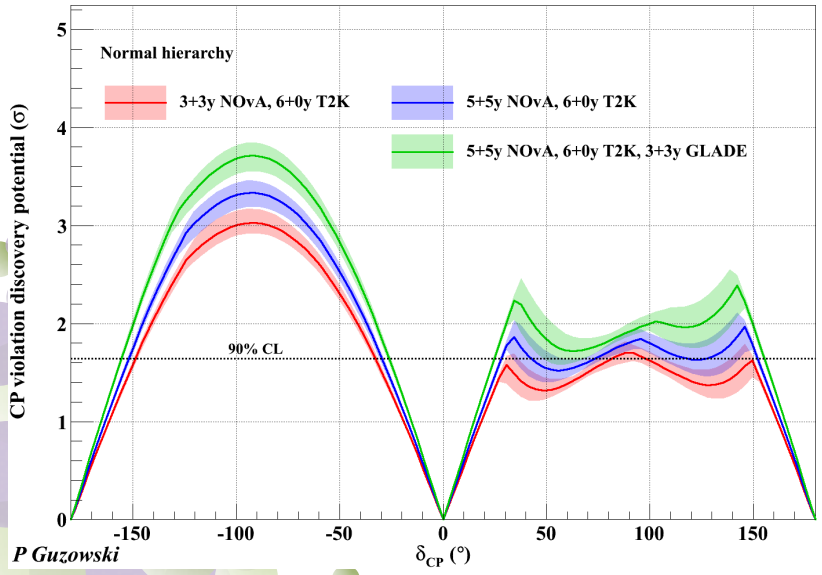
*1 Completion time of MR upgrade (assumed to be 2018) is suject to change, depending on economical situation, readiness and so on.

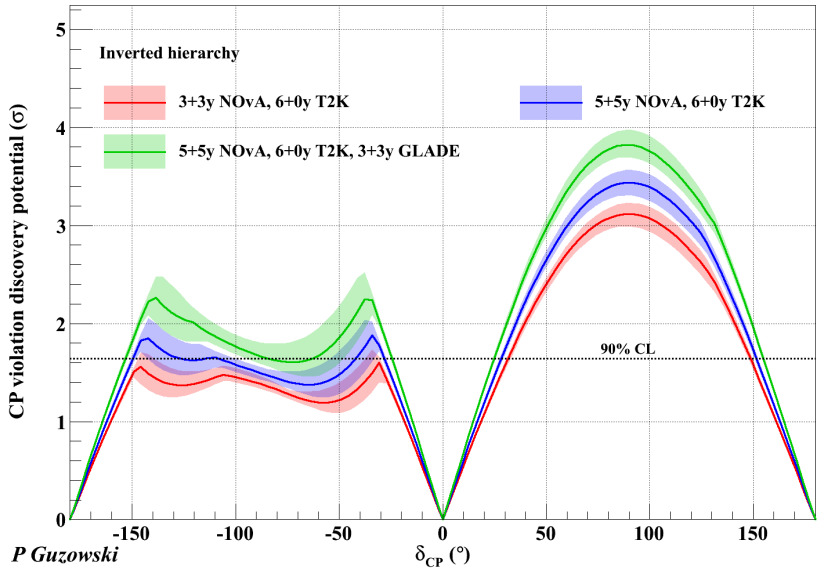
*2 LINAC upgrade completed

* Beam Energy 30GeV

- Combination with NOνA and T2K will be the quickest way to the underlying information
- Do we really need anti-neutrinos?

LATEST T2K projection is 8.8e21 by 2021





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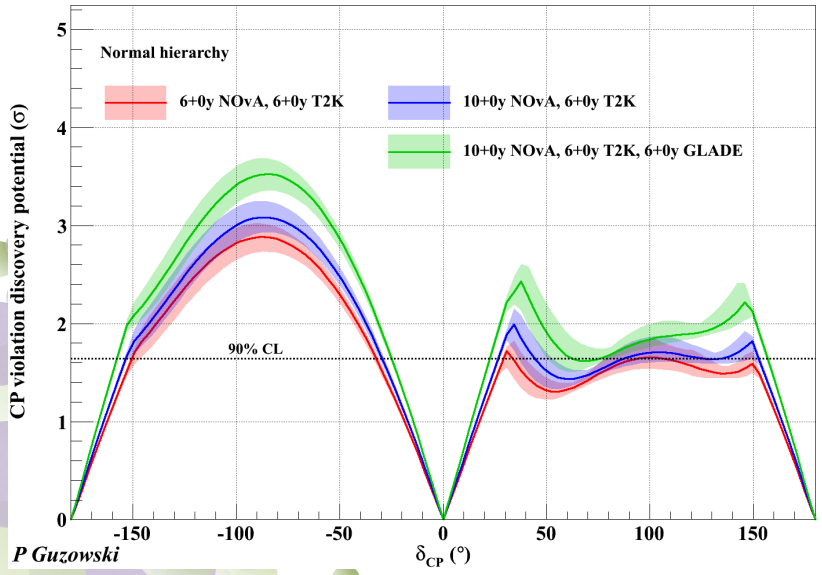
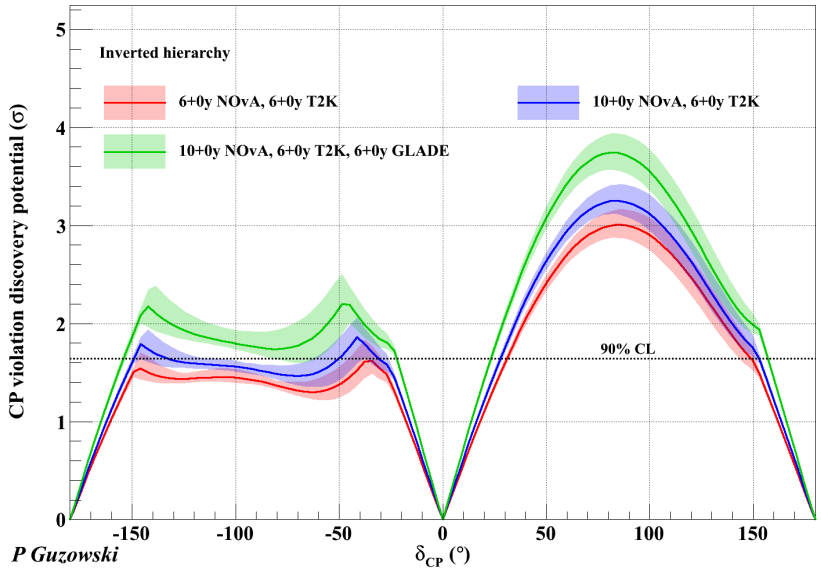
* Beam Energy 30GeV

- Combination with NOνA and T2K will be the quickest way to the underlying information
- Just running with neutrinos does the job, possibly faster

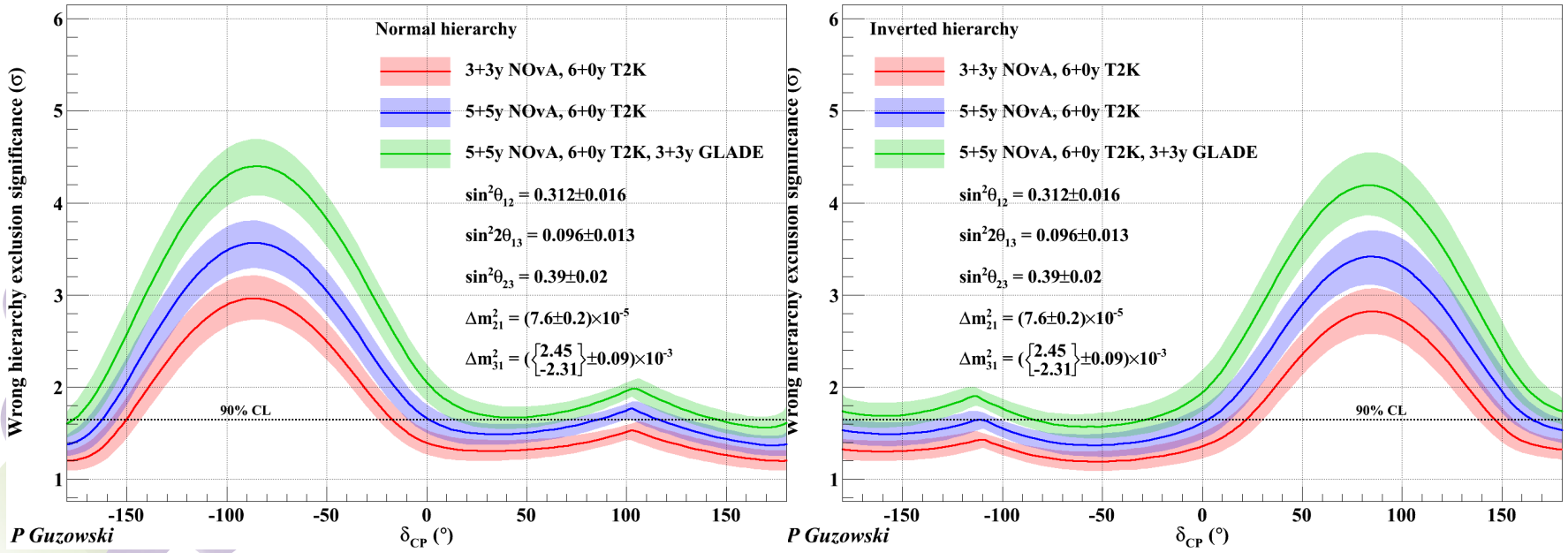
LATEST T2K projection is 8.8e21 by 2021





NOνA+T2K mass hierarchy reach

- Combination with NOνA and T2K will be the quickest way to the underlying 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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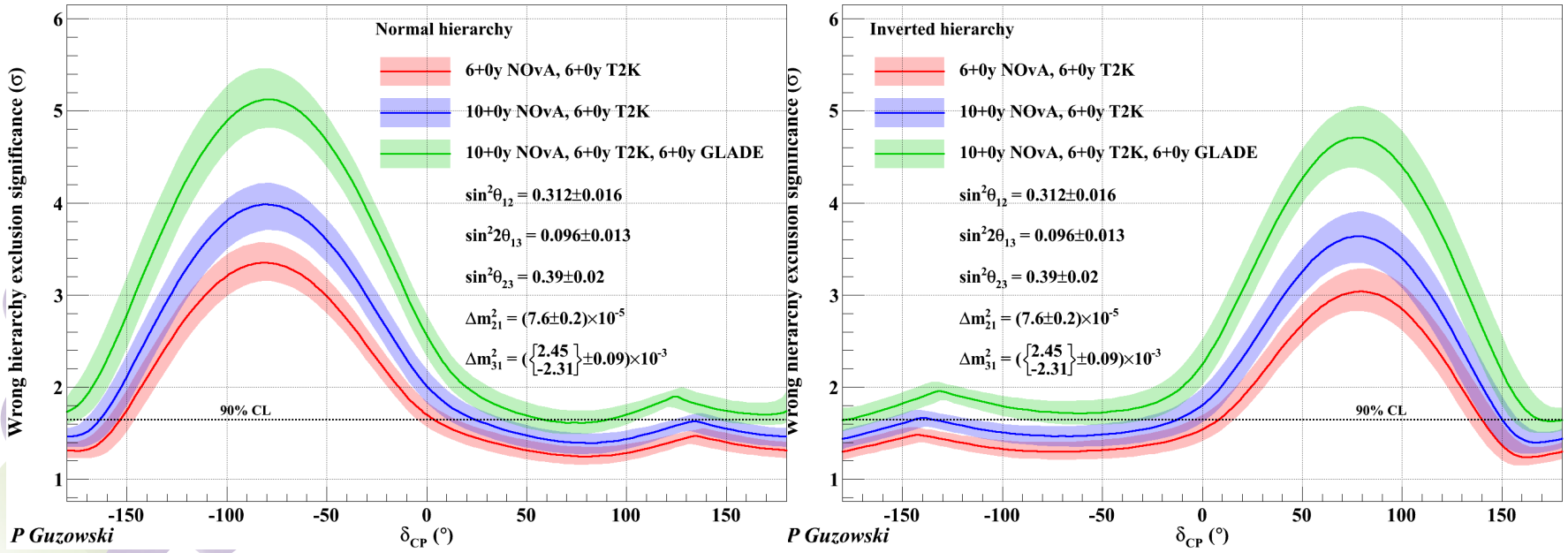


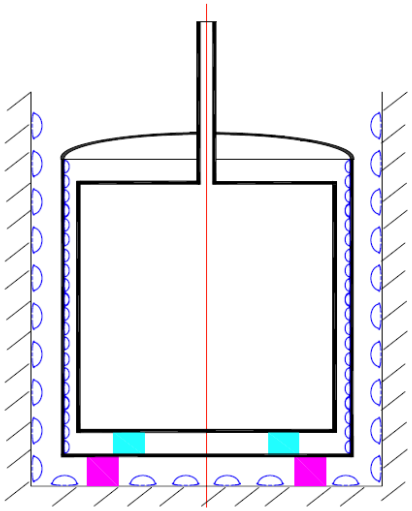
Other New Plans

Mass Hierarchy and CP violation : the sharks are circling!!!

Daya Bay
60km

>40GW

- Neutrino target: ~20kt LS, LAB based
- 30m(D)×30m(H)
- Oil buffer: 6kt
- Water buffer: 10kt
- PMT: 15000 20”



2012-2014 R&D
2015 proposal to government
2016-2020 construction
2020 start operation

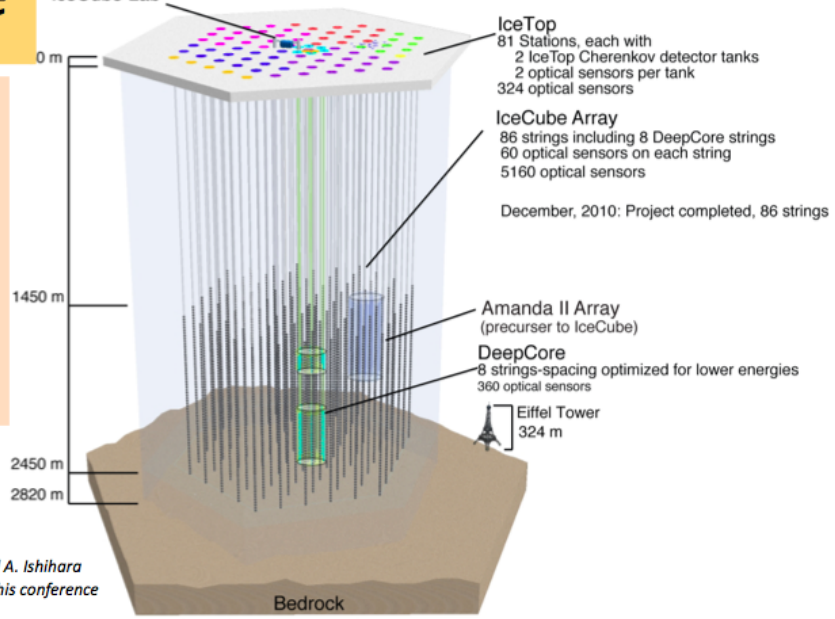
Pingu

- Deep Core has proved the method of reduction of energy threshold with higher density strings
- Pingu will push it further… and they will still have 1 MegaTon!!!
- 2 years running will measure MH to between 3-11σ

Water/ice Cherenkov detectors: IceCube

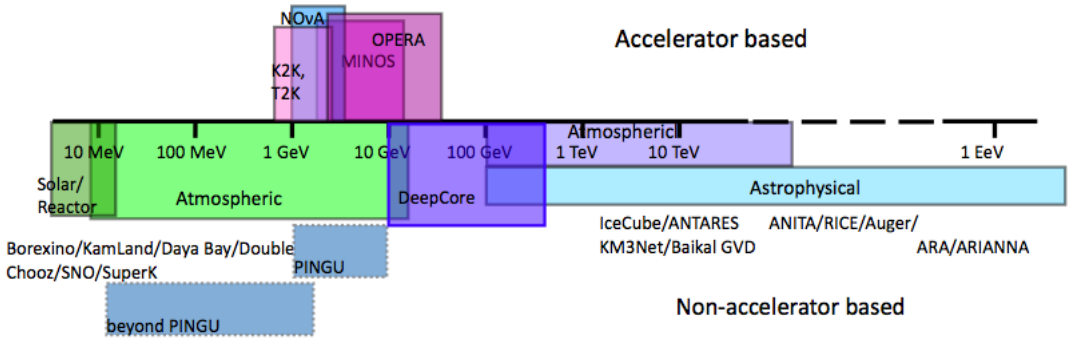
IceCube

- Total of 86 strings and 162 IceTop tanks;
- Completion with 86 strings: December 2010
- Full operation with all strings since May 2011.



For results:
see talks by G. Sullivan and A. Ishihara and numerous posters at this conference

The Neutrino Detector Spectrum



~70 active members in feasibility studies:

IceCube, KM3Net, Several neutrino experiments

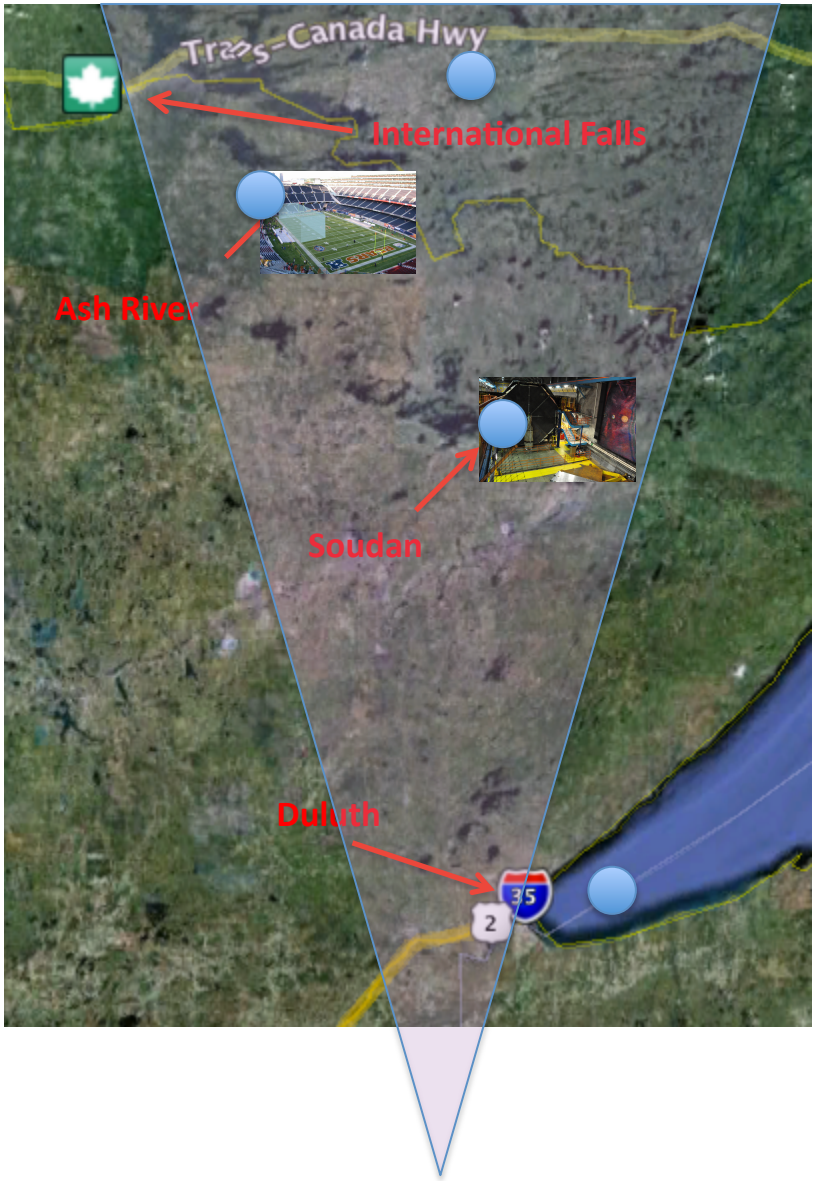
Photon detector developers

Theorists

Slide after:
Darren Grant
NNN 2011

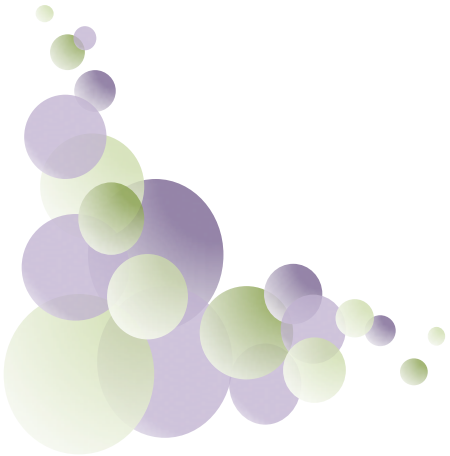
NuMI Plans

- Further exploitation of the NuMI beam could be a good idea
- FNAL considering possible experiments :
  - Off-axis at Ash River
  - On-axis on surface at Soudan or beyond
  - On-axis underground at Soudan Laboratory
  - External ideas could gain traction!



and

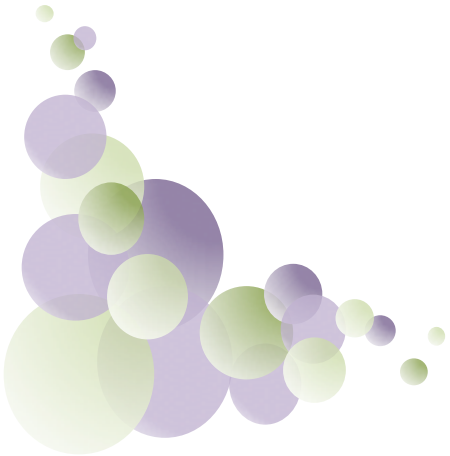
- Of course others
  - T2HK : 1Mton water Cherenkov detector in the T2K beam
  - INO : 50kt Steel/scintillator detector, India
  - …..



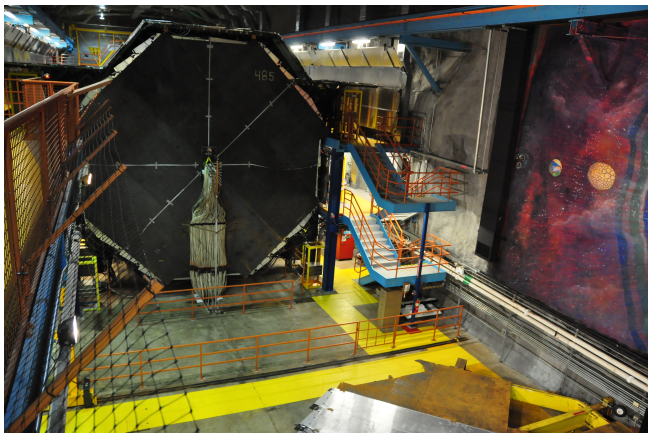
Summary

- 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+
- NOνA will start construction shortly and will start taking data with 5kt in summer 2013
- It seems likely that the mass hierarchy should be known to at least 90% C.L. within the next decade (Atmospheric, T2K, NOνA, PINGU, DB-LB, Other NuMI?)
- CP violation comes along with MH
- This is THE only place where the Standard Model is incorrect (so far..), and much is still to be discovered….

Backup information



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)