MINOS/MINOS+ and NuMI

14/05/12

CERN neutrino strategy workshop

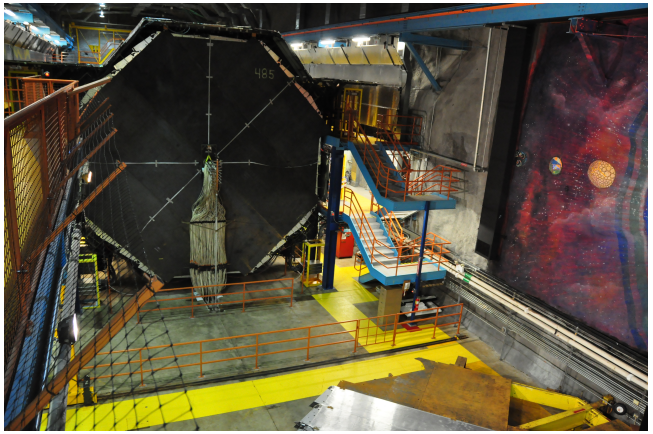
Jenny Thomas, UCL

- MINOS+ goals
- NOνA goals
- Other NuMI plans
- Conclusion

Preamble

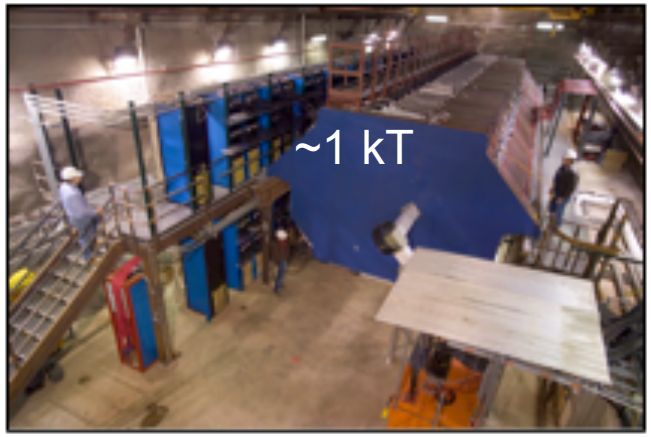
- NuMI stopped running to start upgrade on April 30th
  - Total of 1.43e21 P.O.T in physics runs to MINOS
- Beam will be upgraded to NOVA configuration and 700kW, 6e20/y
- Final MINOS (neutrino and anti-neutrino) results will be presented at Kyoto:
  - θ_{13} , Δm^2, $\sin^2 2\theta_{23}$, steriles
- MINOS+ will search for any non-standard effects at high precision (10,000 events in 3 years near oscillation maximum)
  - Sterile neutrinos
  - Non Standard Interactions (dim 5 contact interactions)
  - Large extra dimensions (to about .5 micron)
- 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

The MINOS(+) Experiment



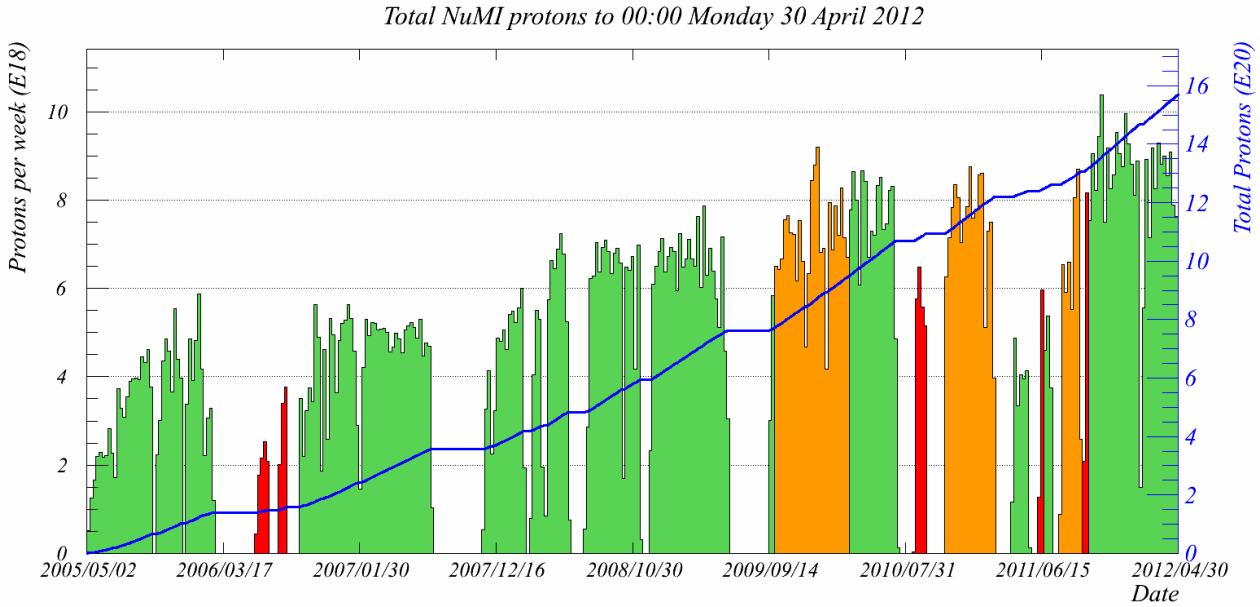
- Two detectors mitigate systematic effects
  - beam flux mis-modeling
  - Neutrino x-sec uncertainties
- L/E ~150-250 km/GeV
- Magnetized:
  - muon energy from range/ curvature
  - distinguish μ^+ from μ^-

- 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 Final Results

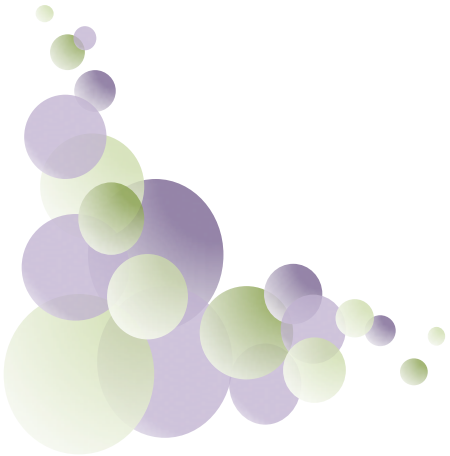
- Final MINOS results will be presented at Kyoto on
  - θ_{13}, $\overline{\theta}_{13}$, Δm^2, $\overline{\Delta m^2}$, $\sin^2 2\theta_{23}$, combined fit, and $\nu_\mu \rightarrow \nu_s$
  - +30% for Δm_2 , +40% for θ_{13}
- Total exposure is
  - 10.7×10^{20} p.o.t in FHC (neutrino mode)
  - 3.3×10^{20} 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)



MINOS+

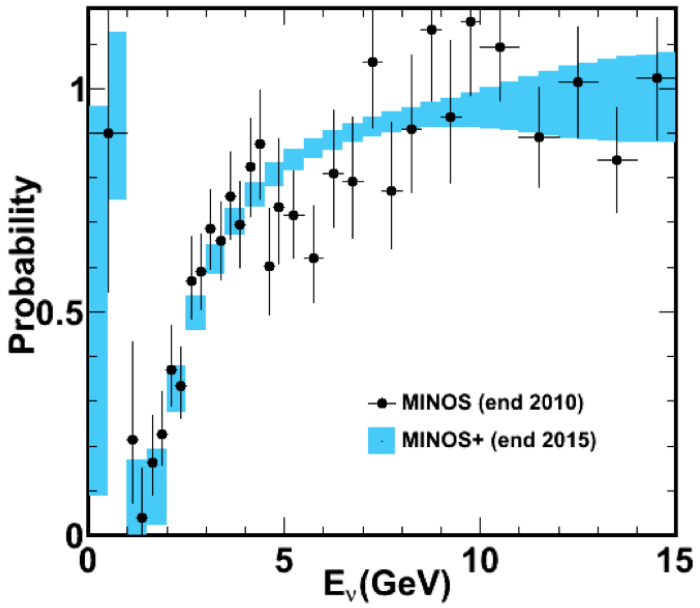
Starts April 2013 for three years

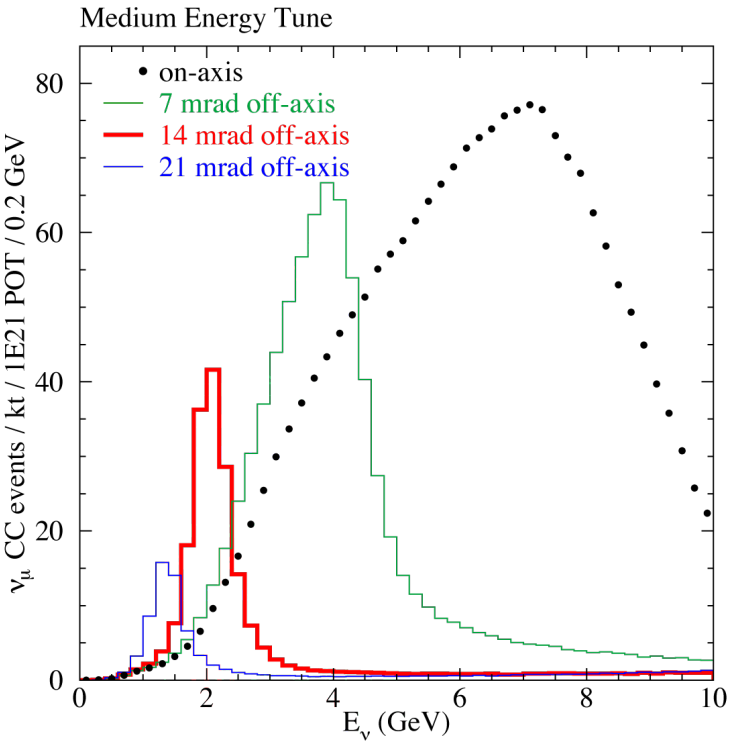
April 2013-2016



MINOS+ goals

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





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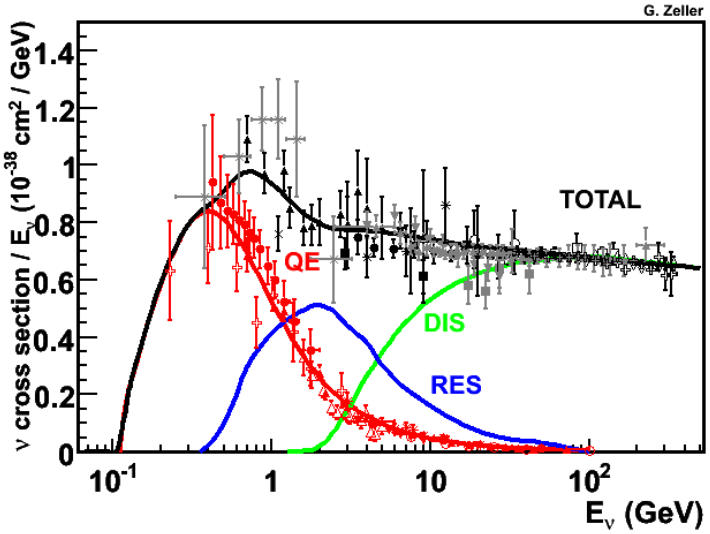
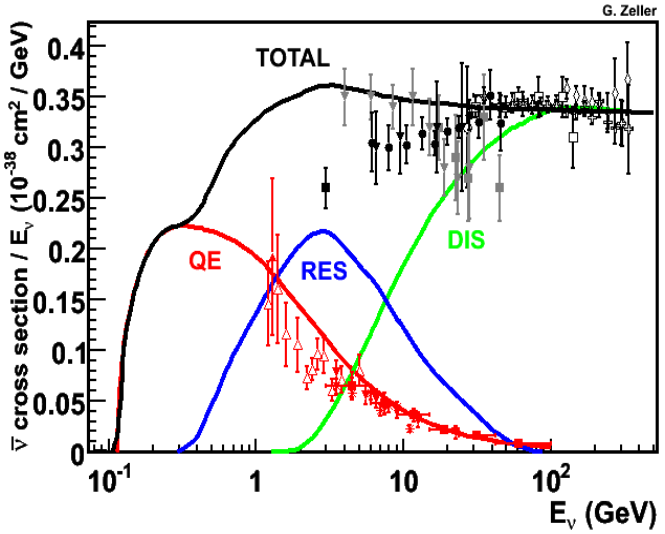
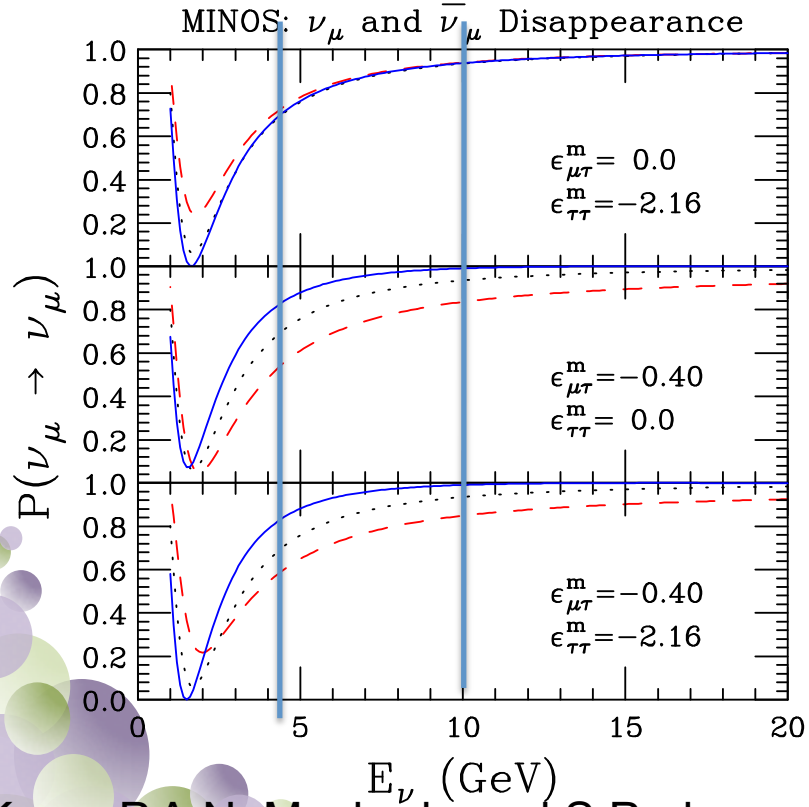


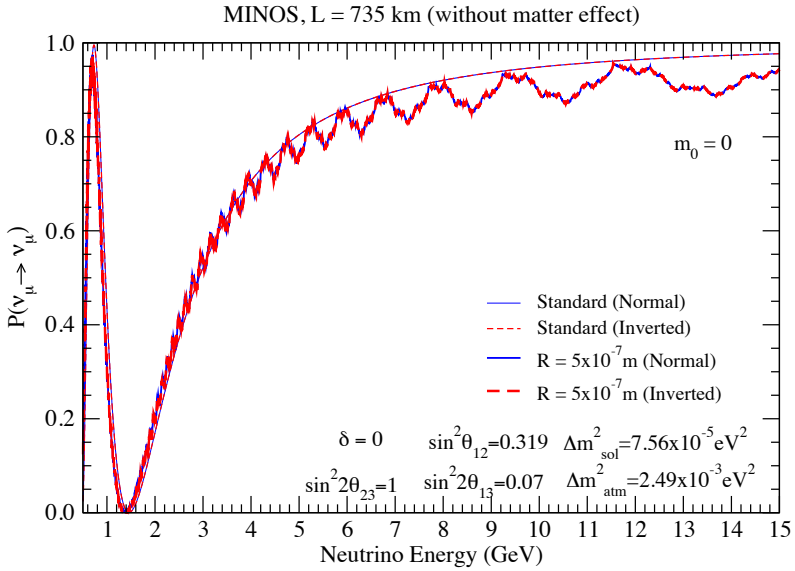


MINOS+ Goals

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!!

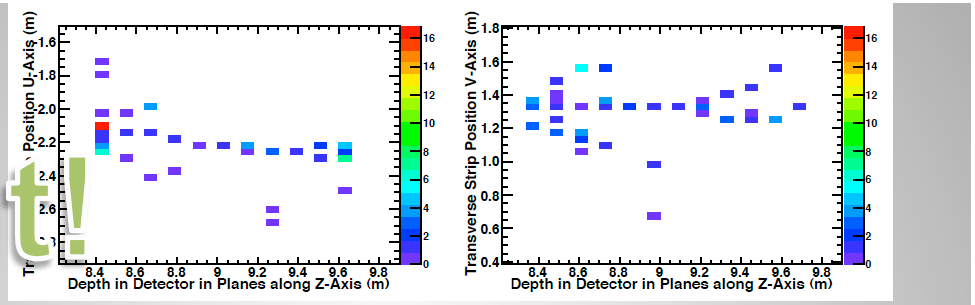
P.A.N.Machado,H.Nunokawa,R.Zukanovich Funchal, hep-ph/1101.003v1

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

MINOS+ Goals

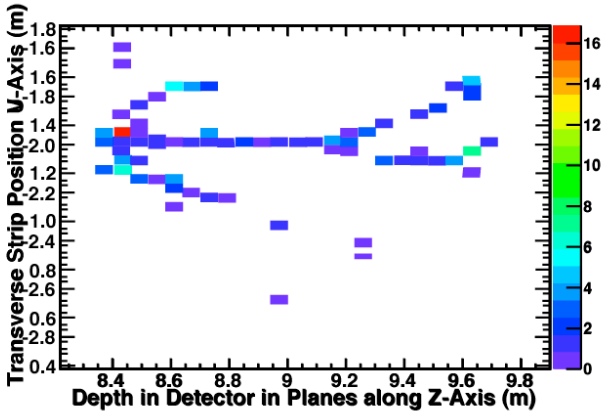
- Verification of $P(\nu_\mu \rightarrow \nu_\mu) = 1 - P(\nu_\mu \rightarrow \nu_\tau) + P(\nu_\mu \rightarrow \nu_e)$
- Quantitative evidence for tau production hoped for
  - MINOS has observed certain topologies
  - 80 tau events per year expected in MINOS+

Minos event!



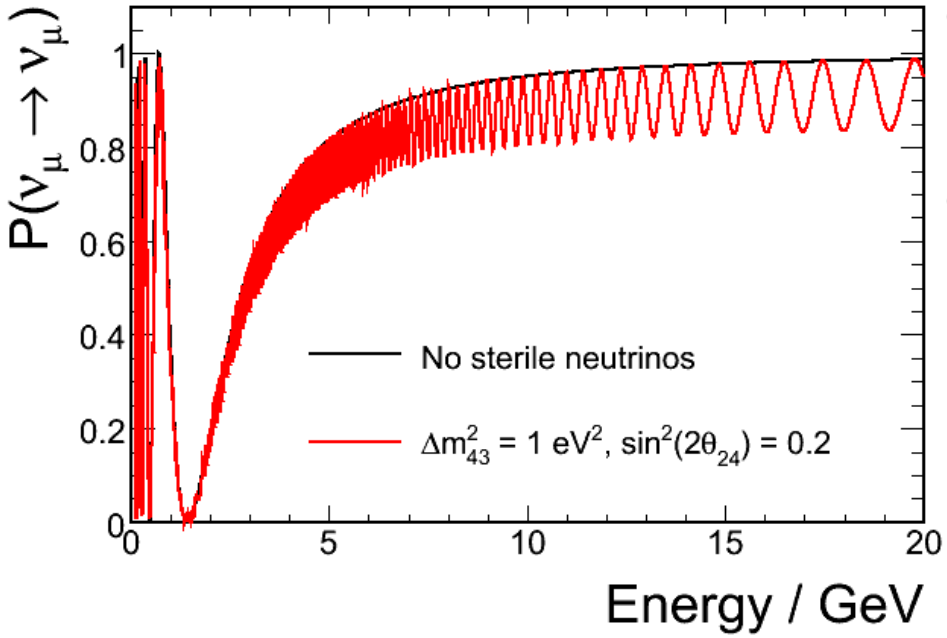
FD RUN = 46256
EVENT ID = 234466
Reco. Energy = 5.30 GeV

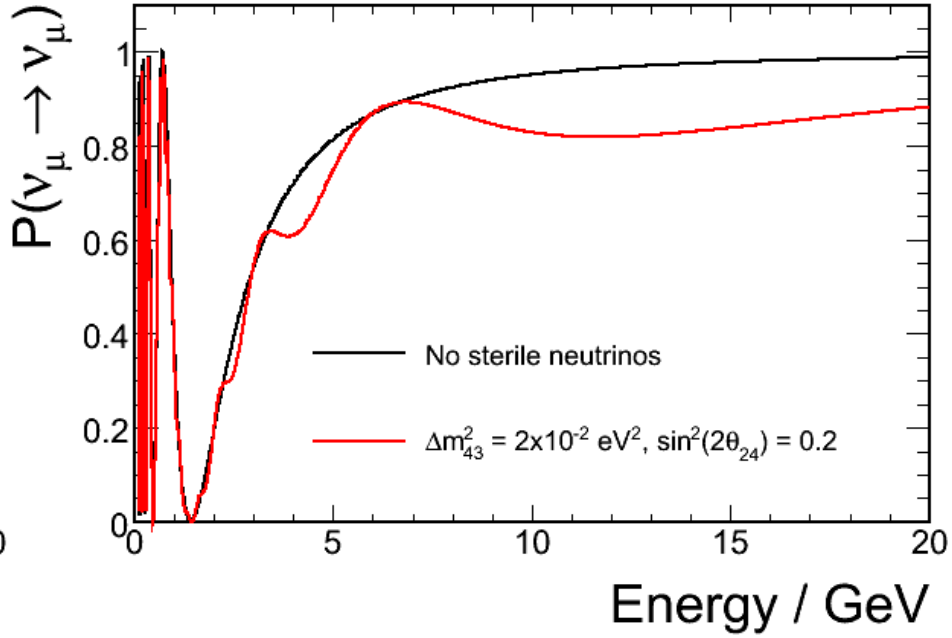
LEM PID = 0.13
ANN PID = 0.06



MINOS+ Goals

Search for Sterile Neutrinos: a couple of examples



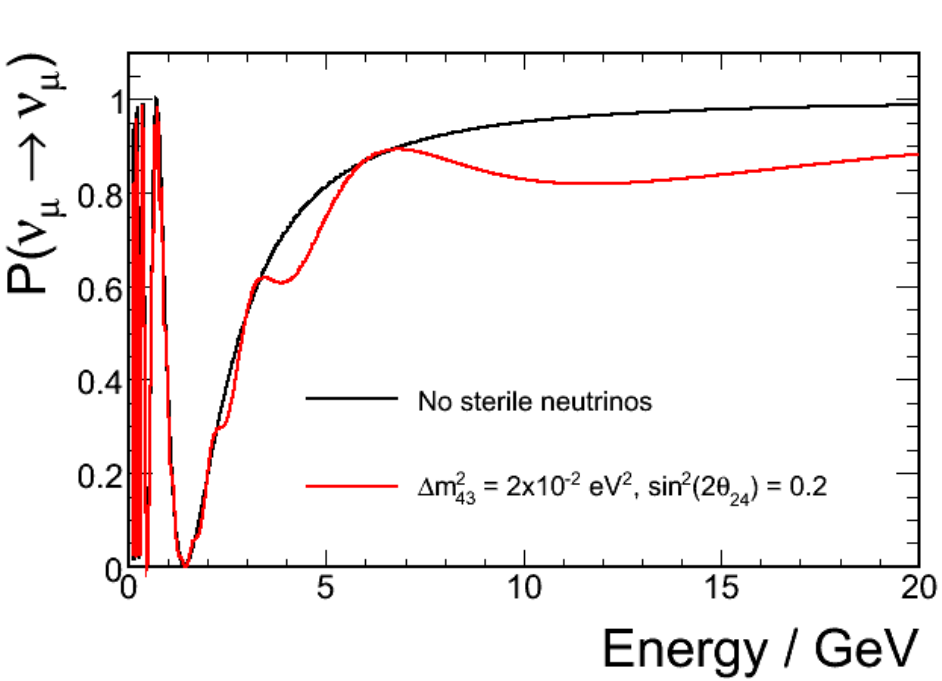


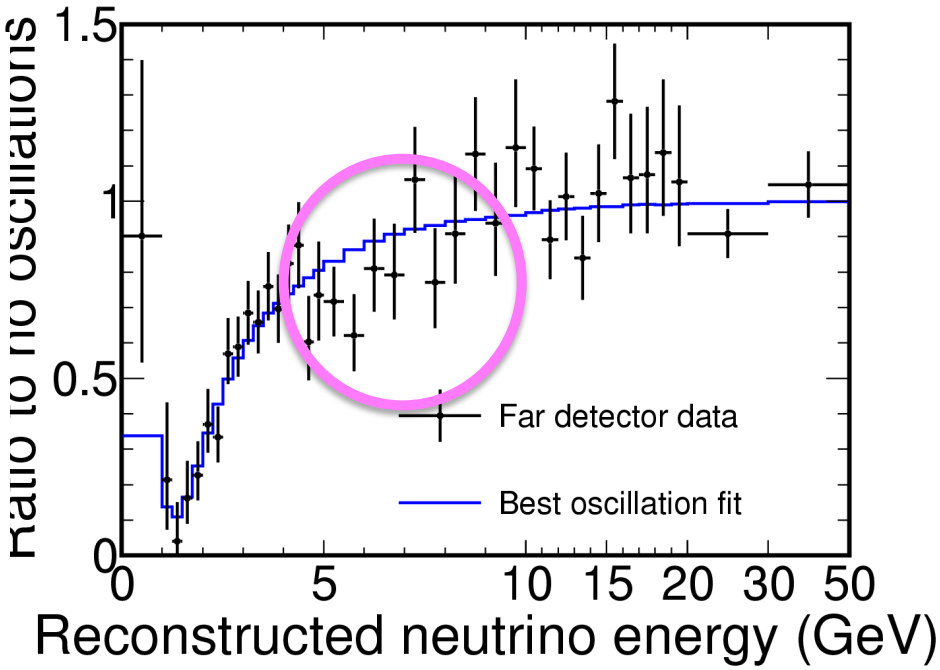
Δm^2_{43} factor averages to 0.5 at 1eV^2

Atmospheric and sterile dips apparent at Δm^2_{43}= 2x10^{-2}eV^2

MINOS+

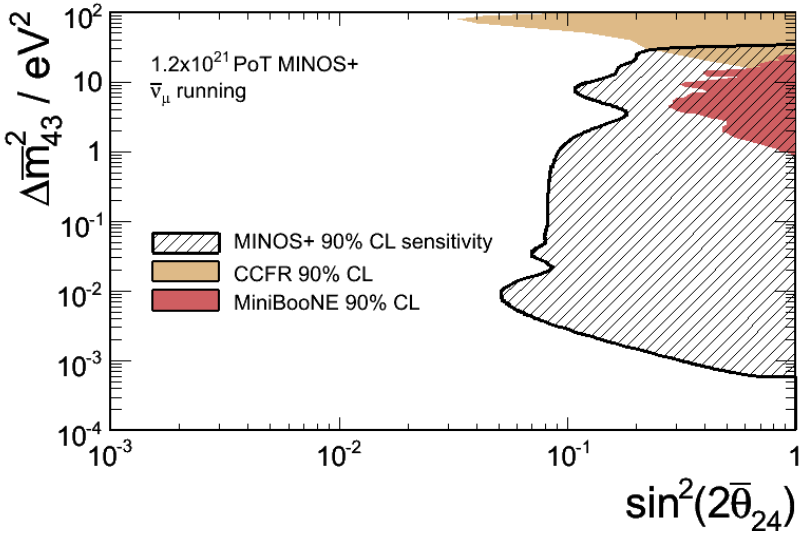
- Total 3.4 e20 P.O.T to be analyzed on top of existing 7.2e20 P.O.T. result from 2010 (almost 50% more data) for Kyoto
- Odd dip will likely have to wait for MINOS+

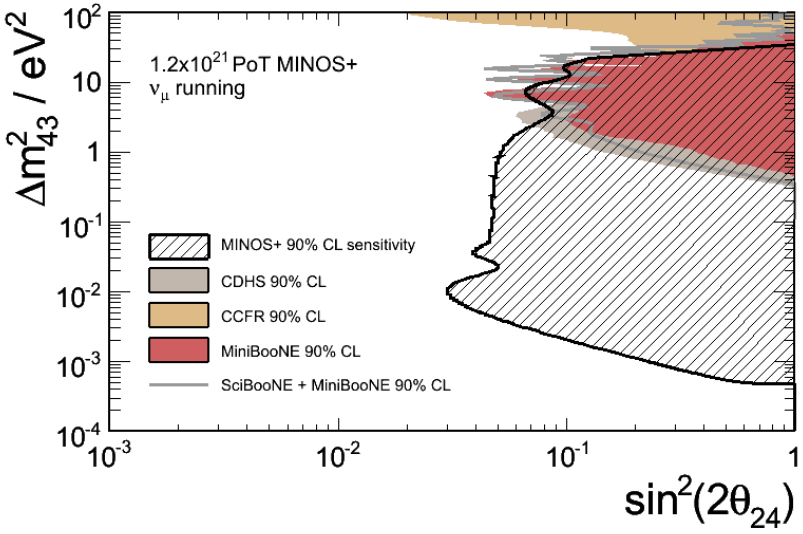




MINOS+ sterile reach

$\sin^2\theta_{24}$ is $\sin 2\theta_{\mu 4}$



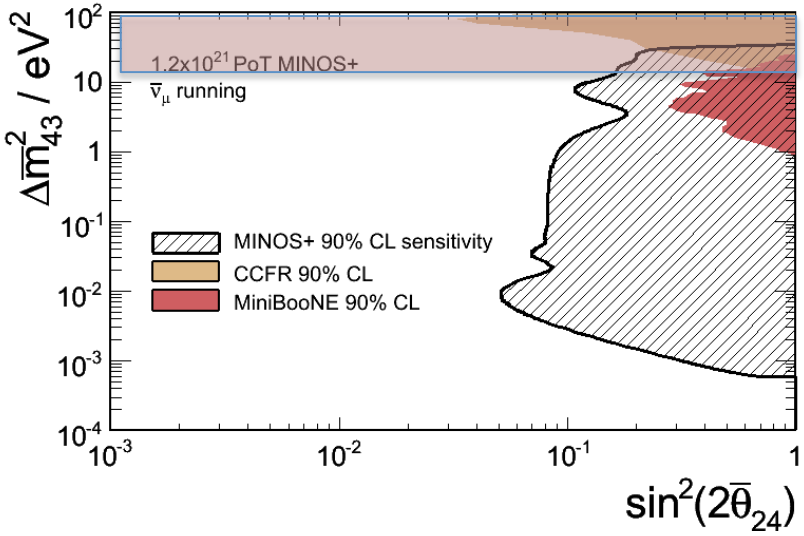


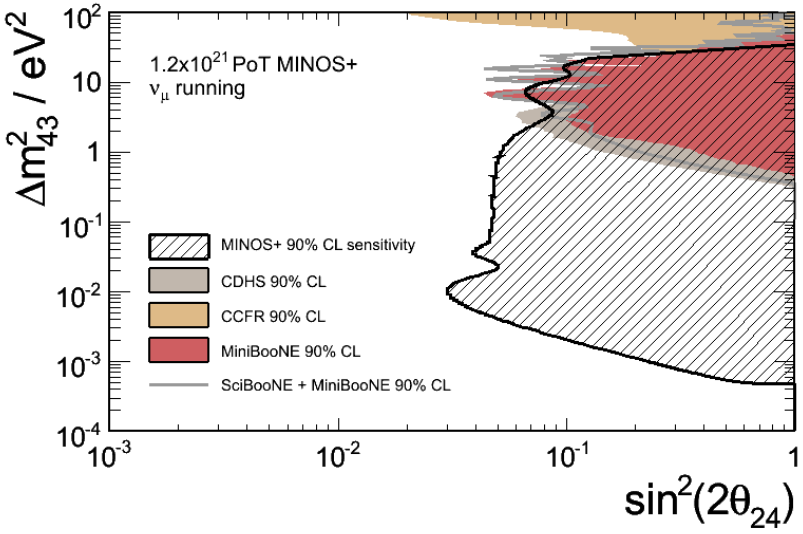
Near Detector at 1km allows short baseline and long baseline measurements

Anti-neutrino improvement is substantial over previous experiments (Bugey)

MINOS+ sterile reach

$\sin^2\theta_{24}$ is $\sin 2\theta_{\mu 4}$





Near Detector at 1km allows short baseline and long baseline measurements

At very high $\Delta m^2_{\mu 4}$, ND has fast oscillation and reach is limited

MINOS+ sterile reach

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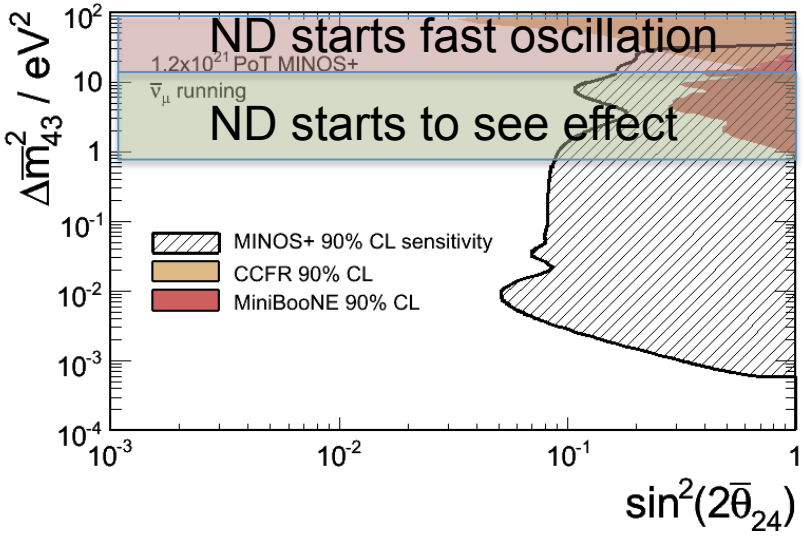
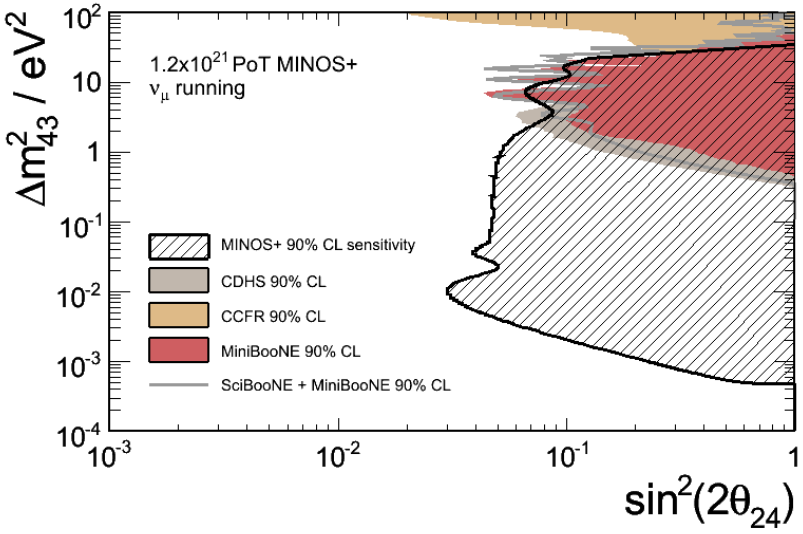


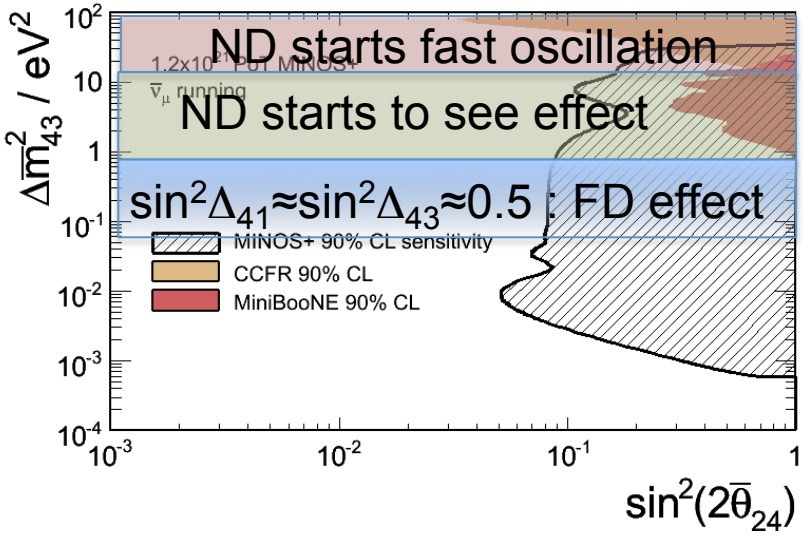


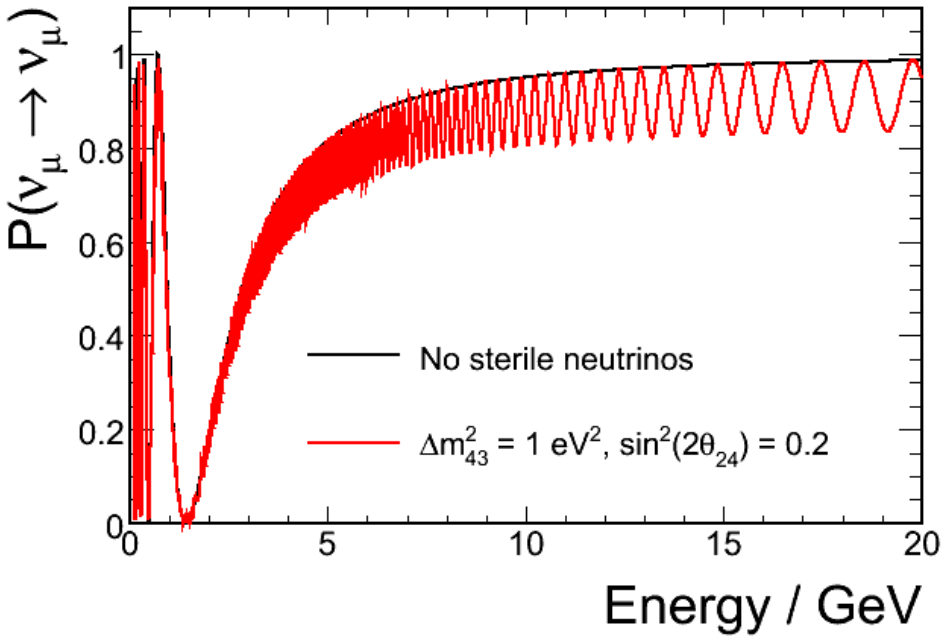
Near Detector at 1km allows short baseline and long baseline measurements

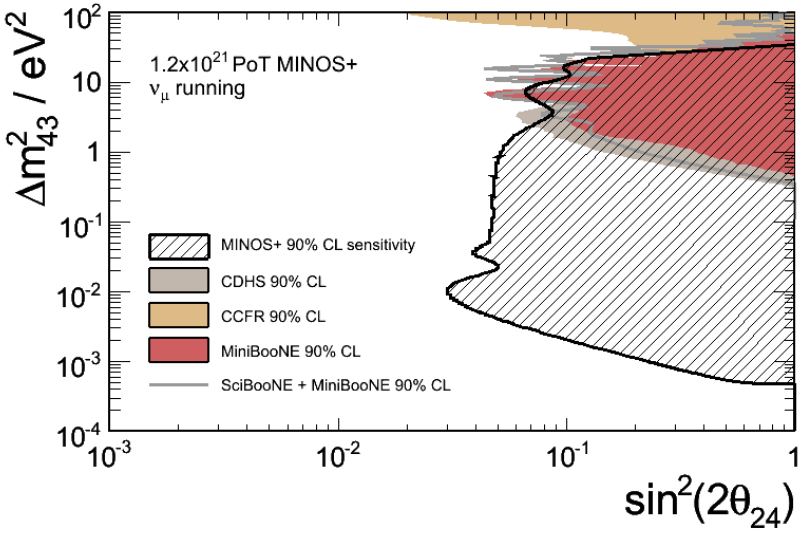
At very high $\Delta m^2_{\mu 4}$, ND has fast oscillation and reach is limited

At lower $\Delta m^2_{\mu 4}$ structure is visible in ND spectrum

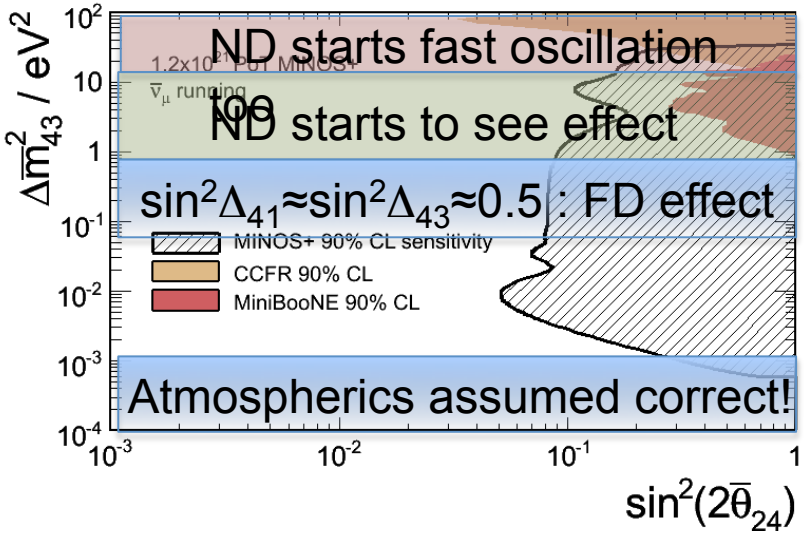
MINOS+ sterile reach

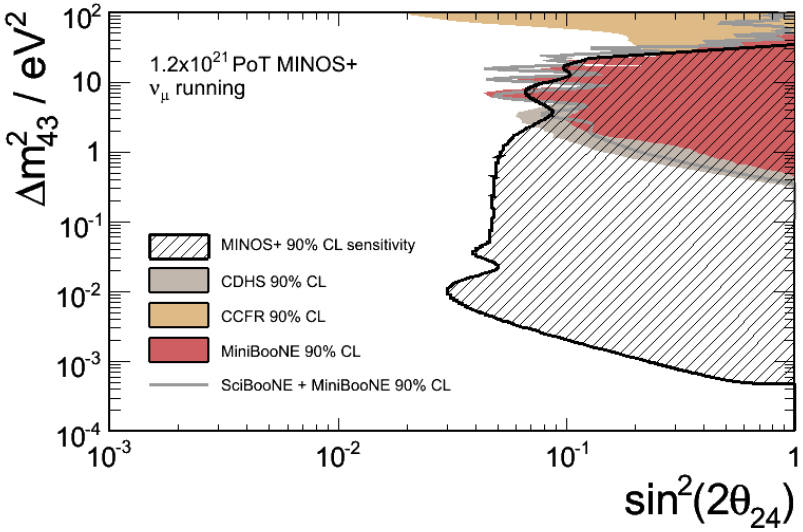


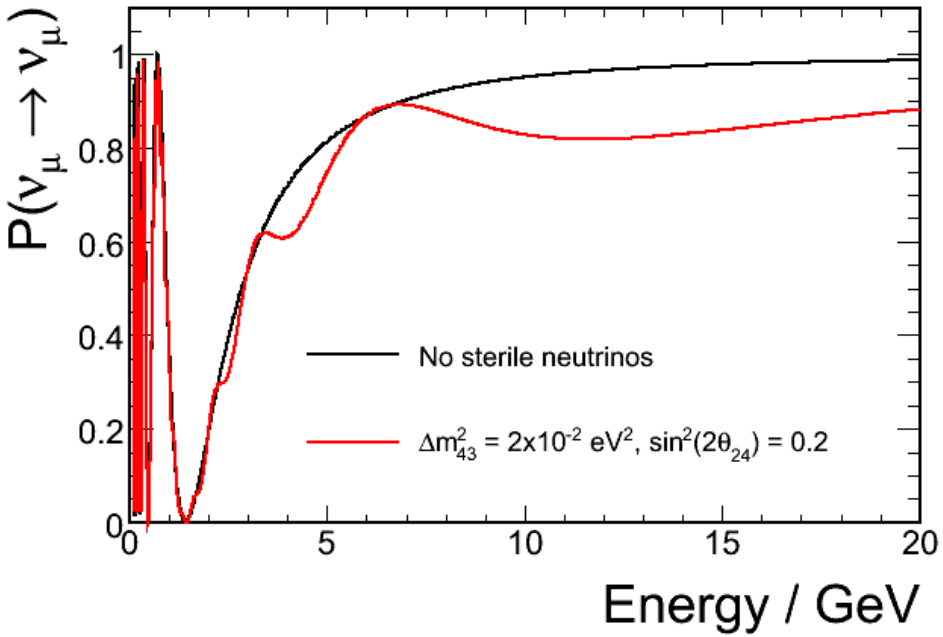




MINOS+ sterile reach







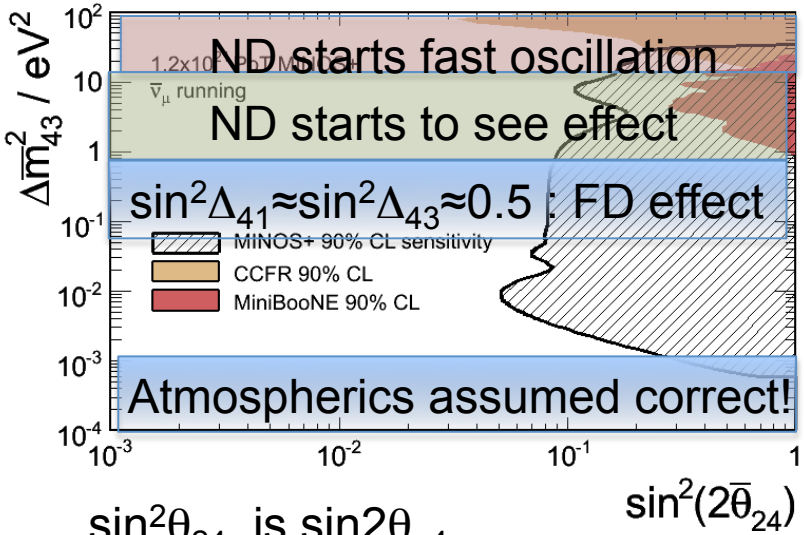
$\sin^2\theta_{24}$ is $\sin2\theta_{\mu4}$

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)

Smirnov, NuFact 2011



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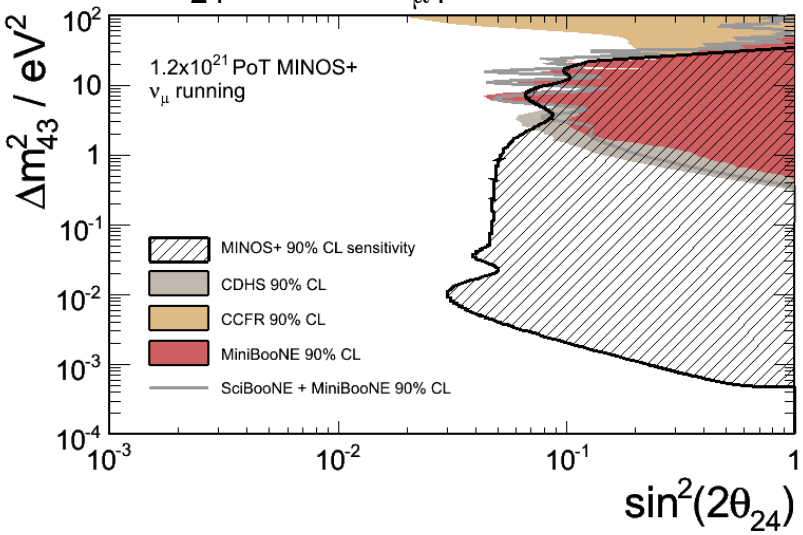

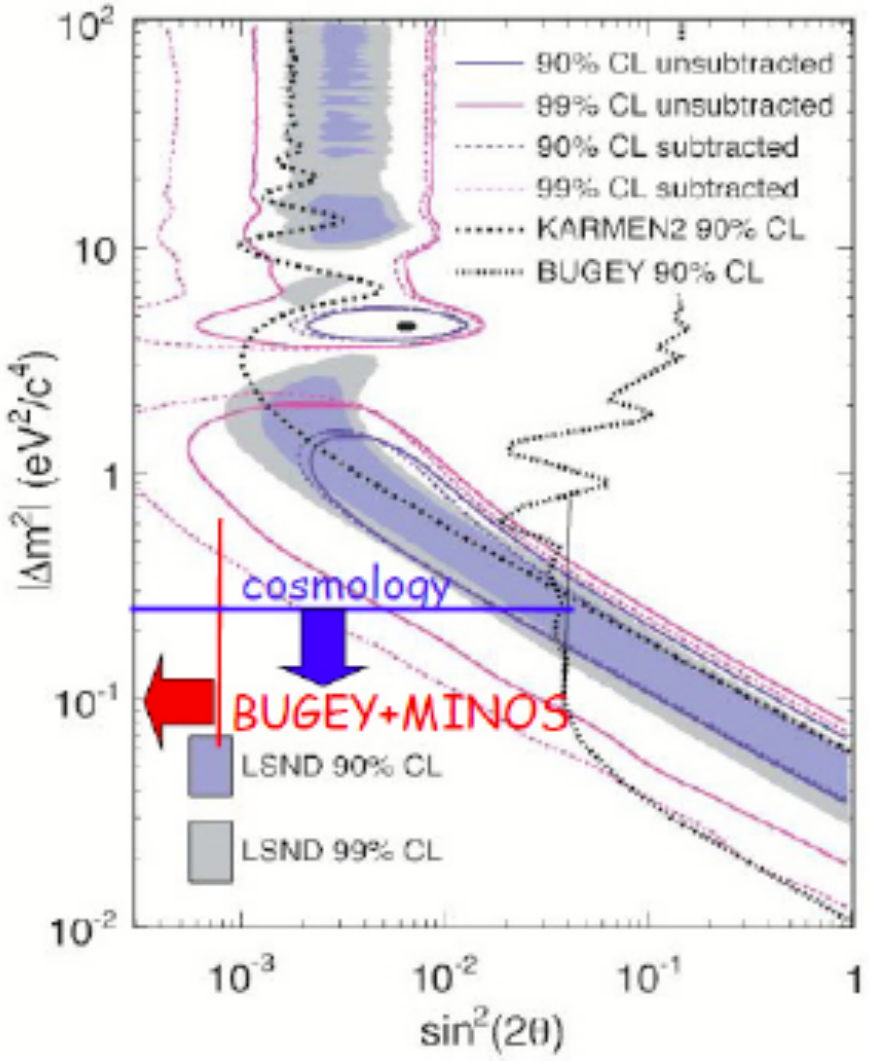

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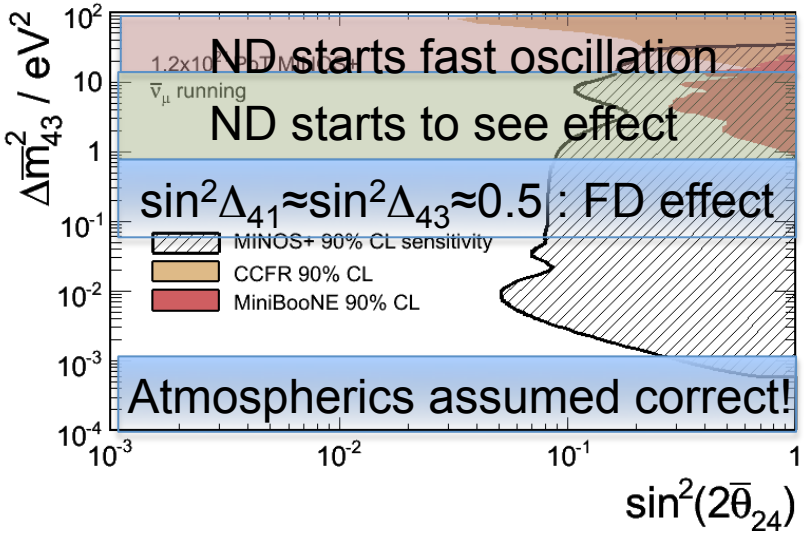
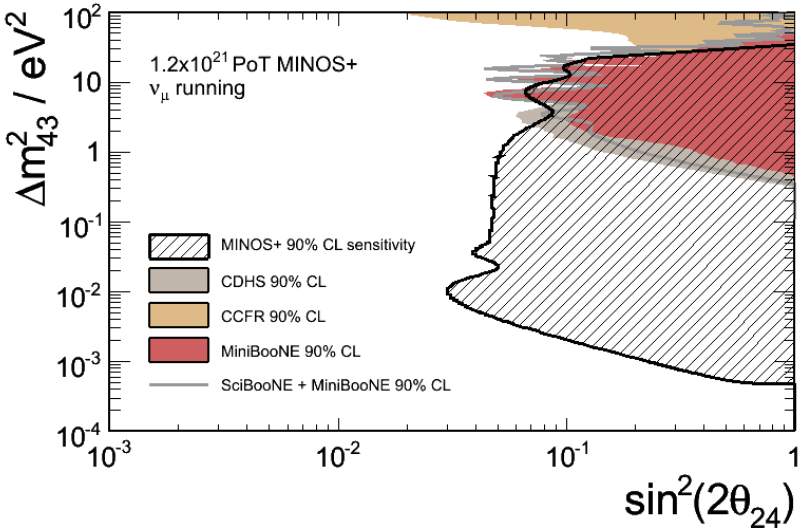
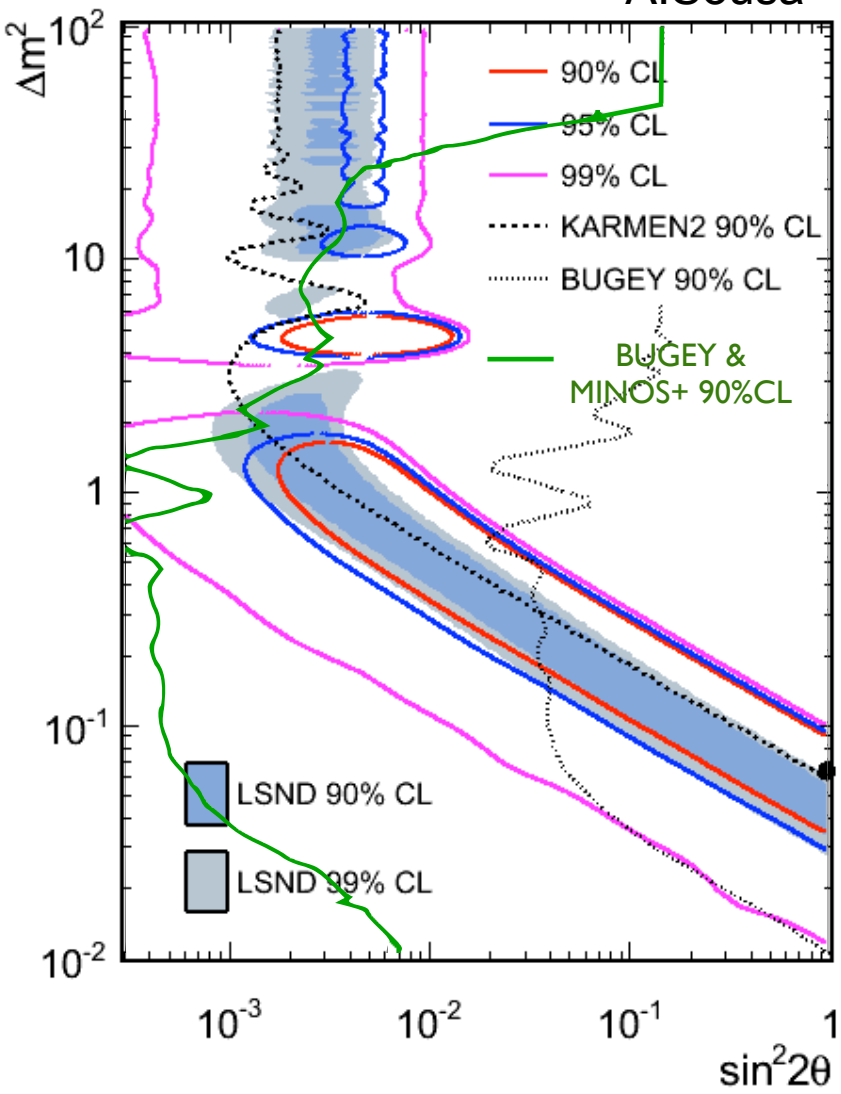
A.Sousa







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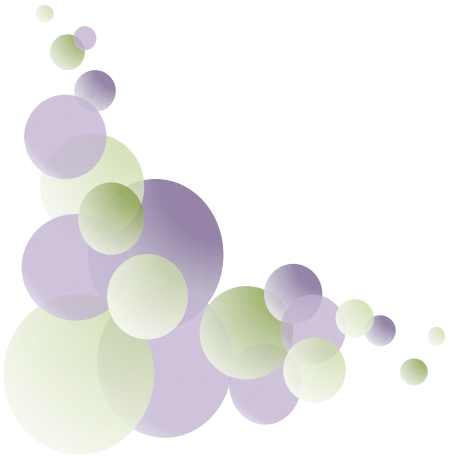
NOVA



The NOvA Experiment

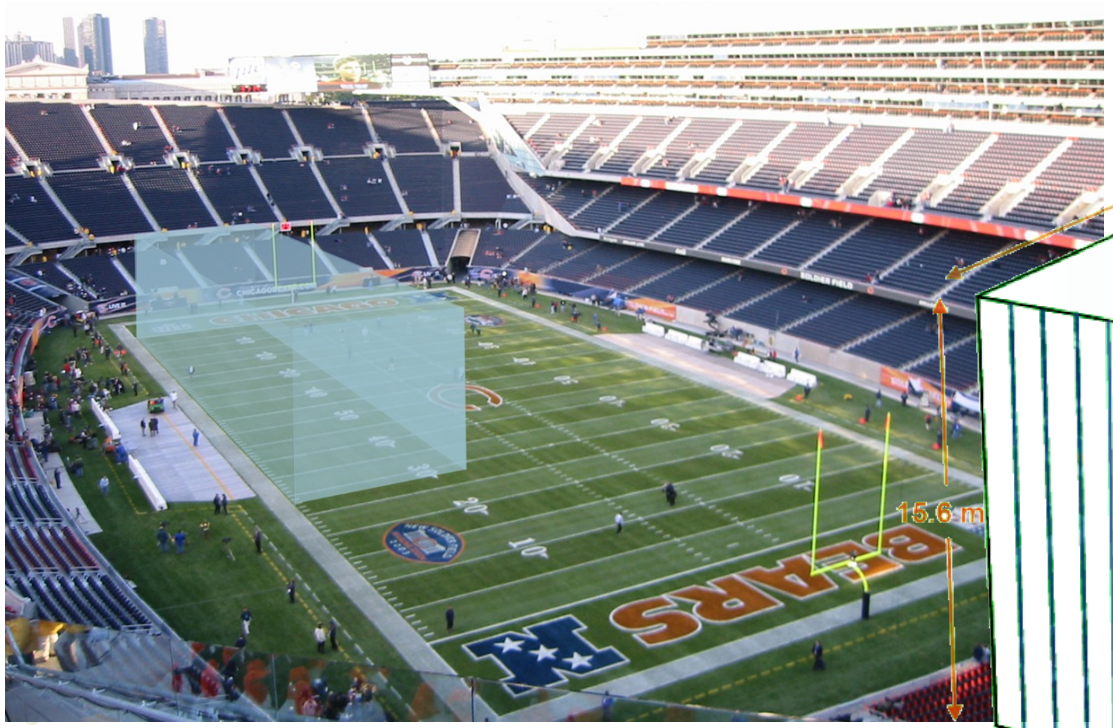
Physics Goals:

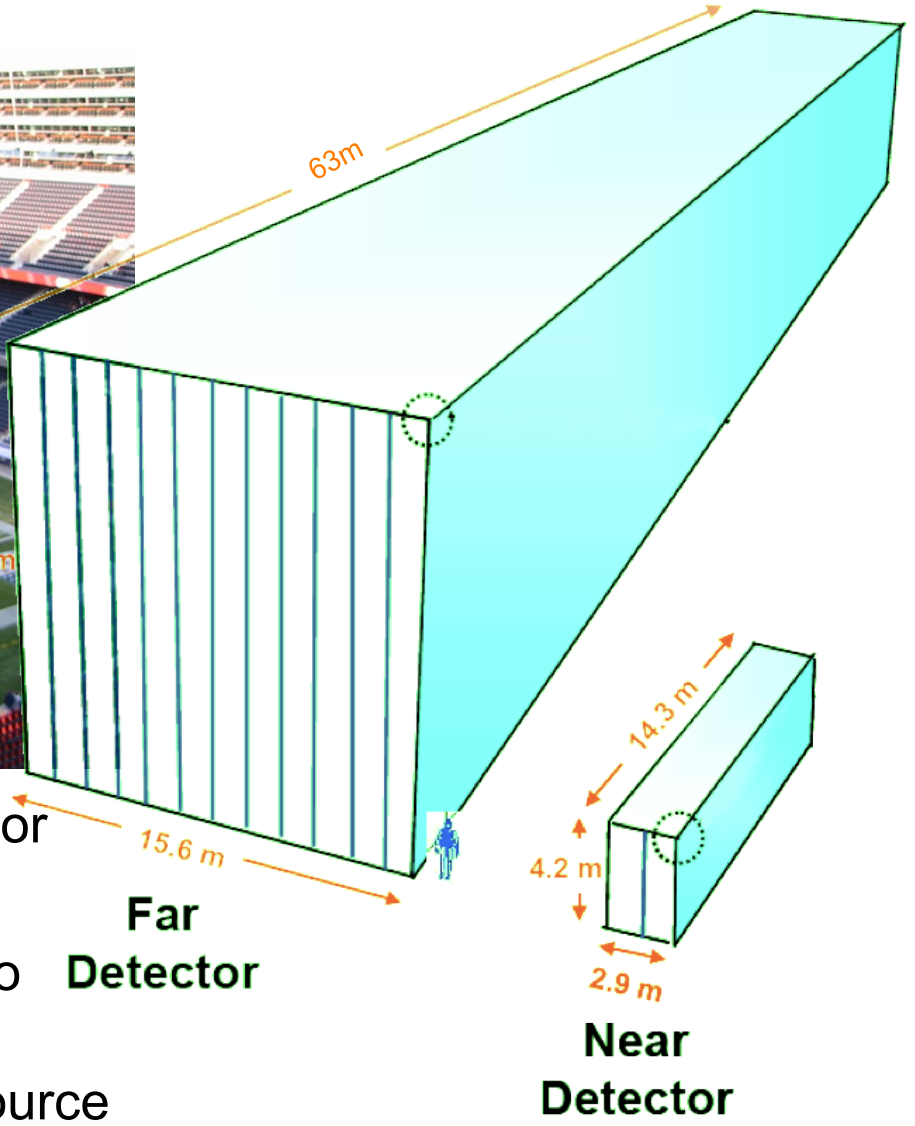
- Measure the oscillation probabilities of

  $\nu_\mu \rightarrow \nu_e$ 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:
  - v cross sections
  - Sterile neutrinos
  - Supernova signals

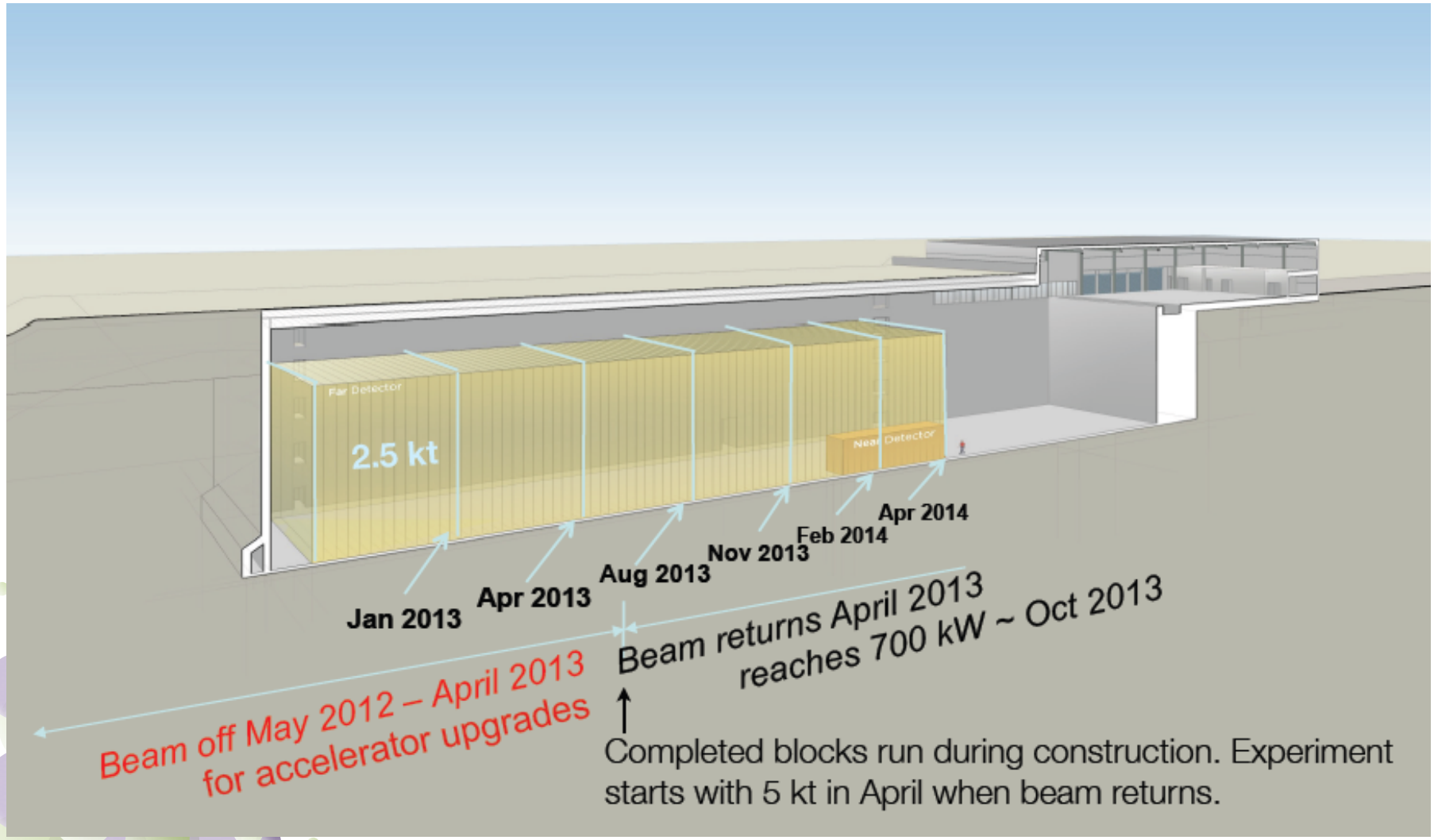
The NOvA Detectors





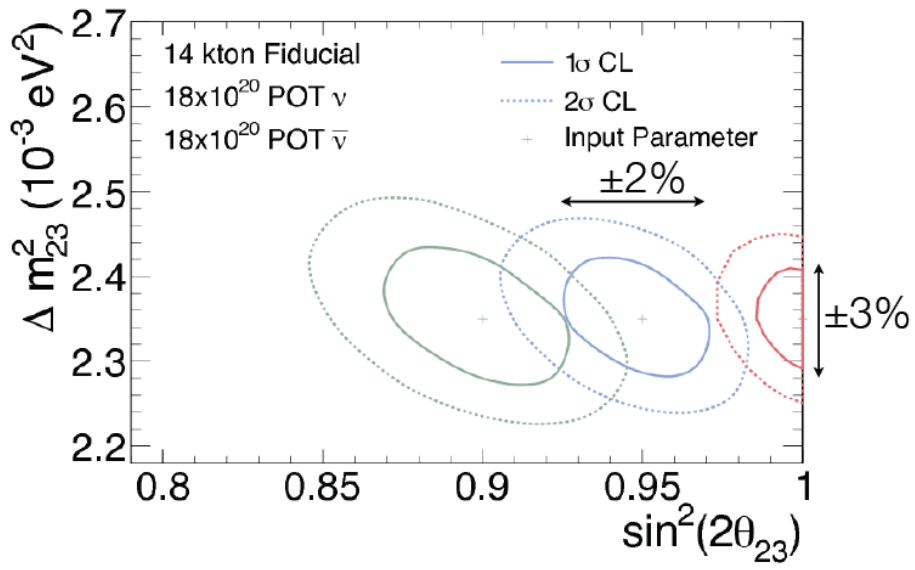
- Massive, Low-Z, 65% active Far Detector
  - 15 kton, 810 km from source
- Functionally equivalent Near Detector to mitigate systematic uncertainties
  - 220 ton Near Detector, 1 km from source

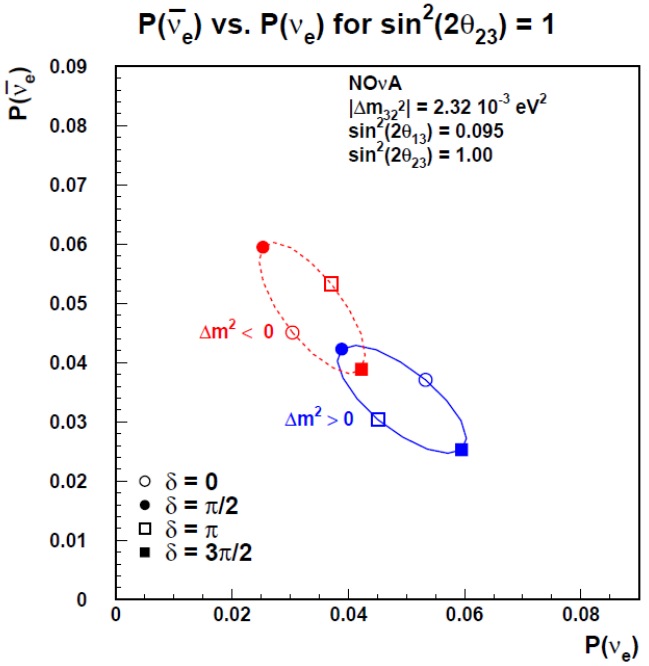
Construction Schedule



NOνA Future reach

- For the ‘standard’ neutrino parameters, NOνA is planning to tie down $\sin^2 2\theta_{23}$ to +/- 2-3%
- Major goal is dCP and mass hierarchy





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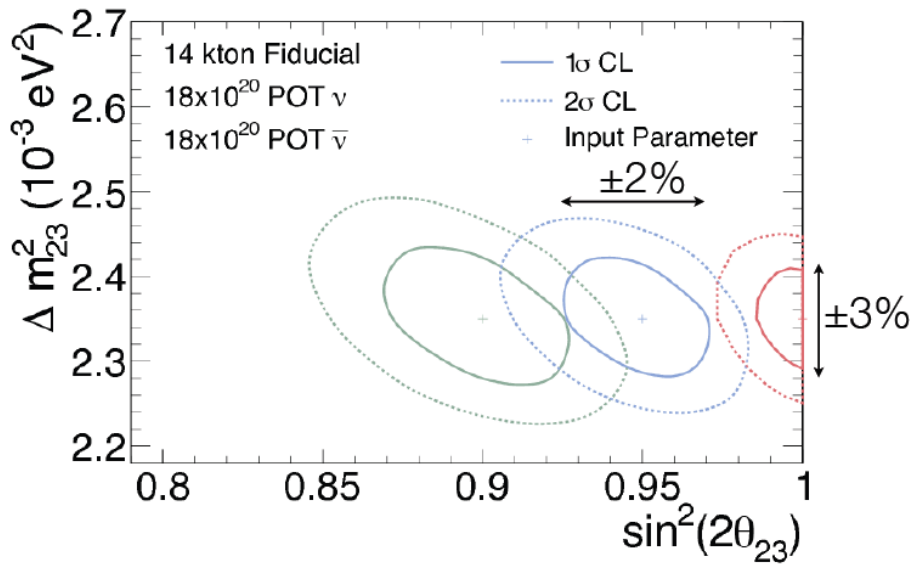
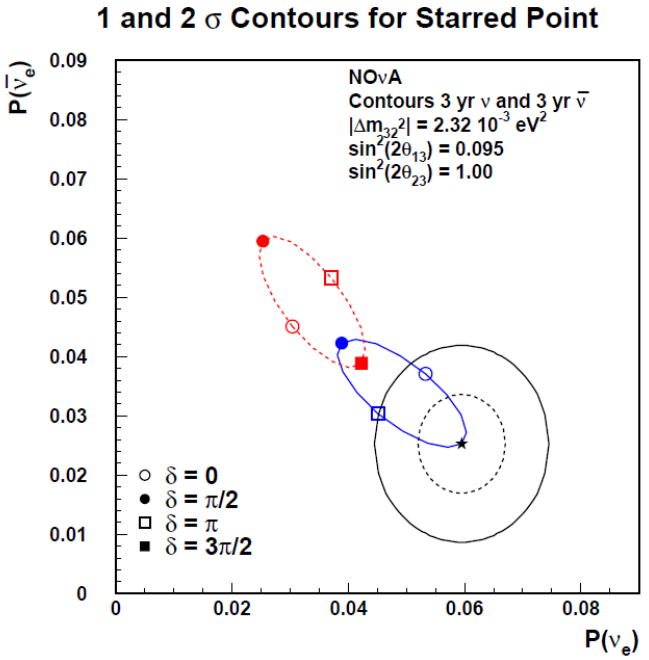
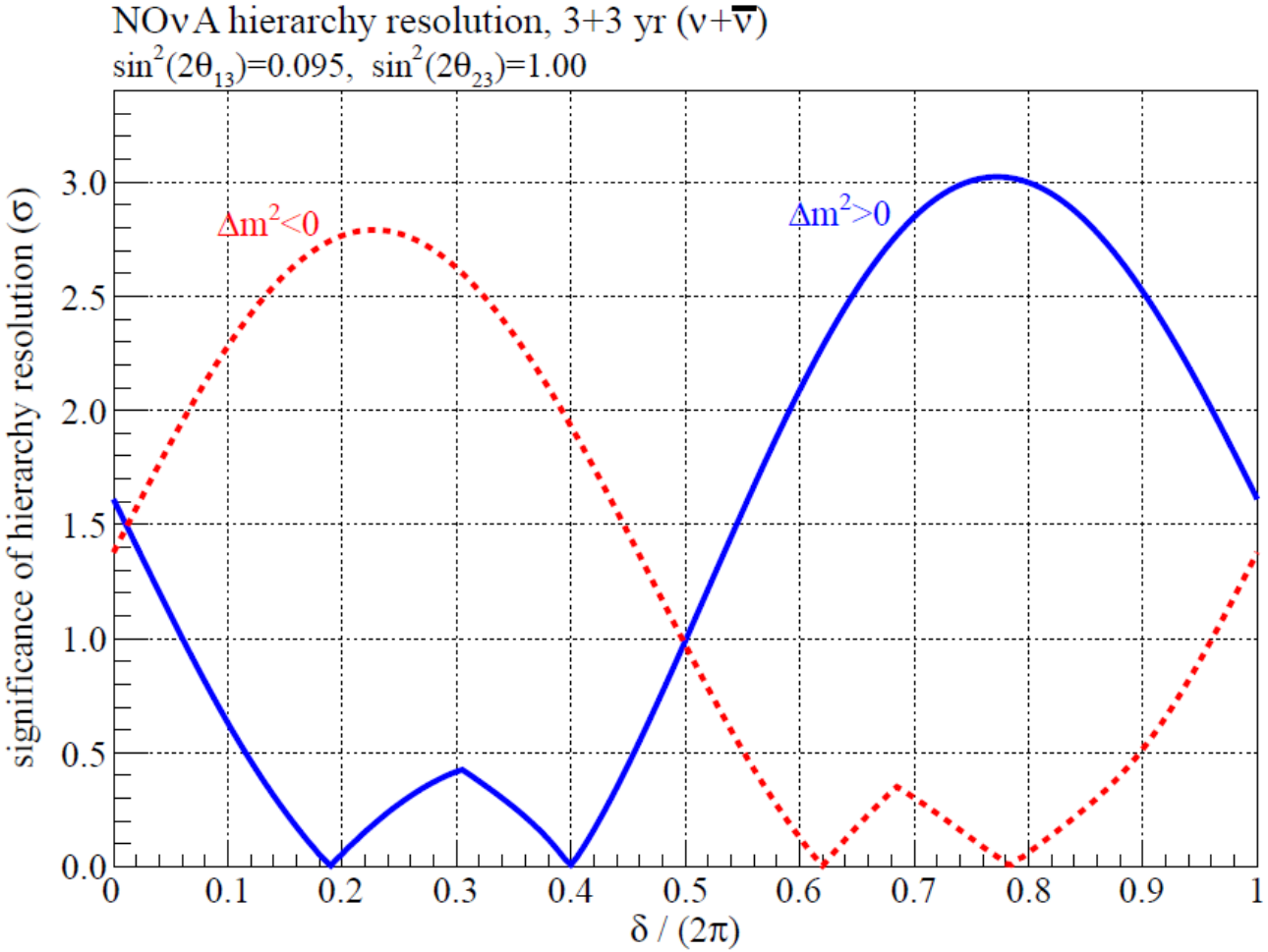




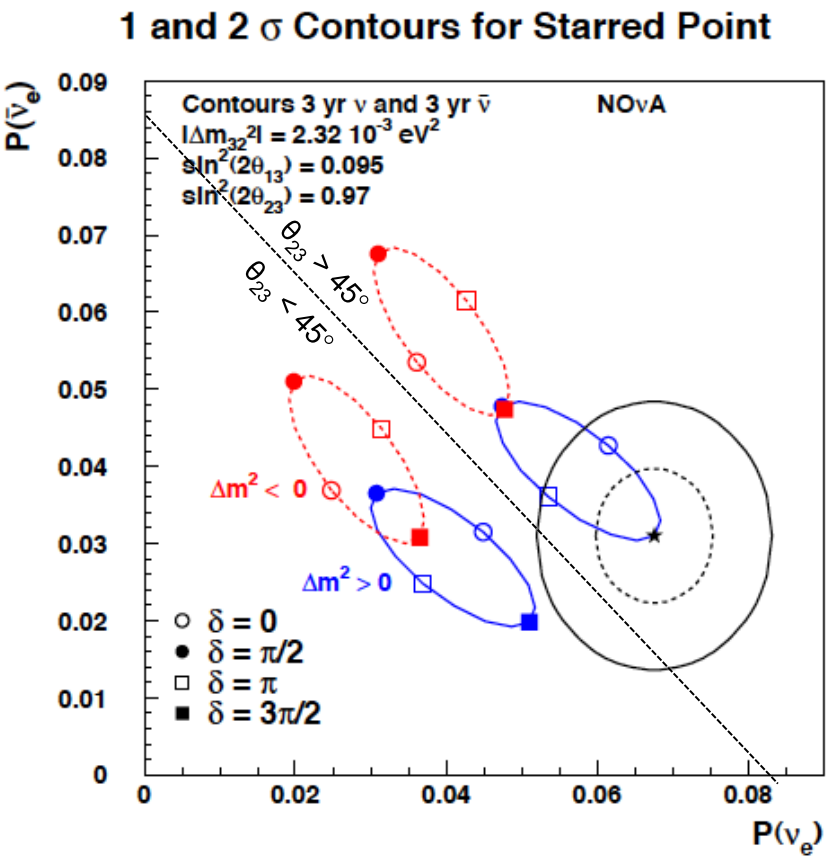
NOvA's Mass Ordering Resolution

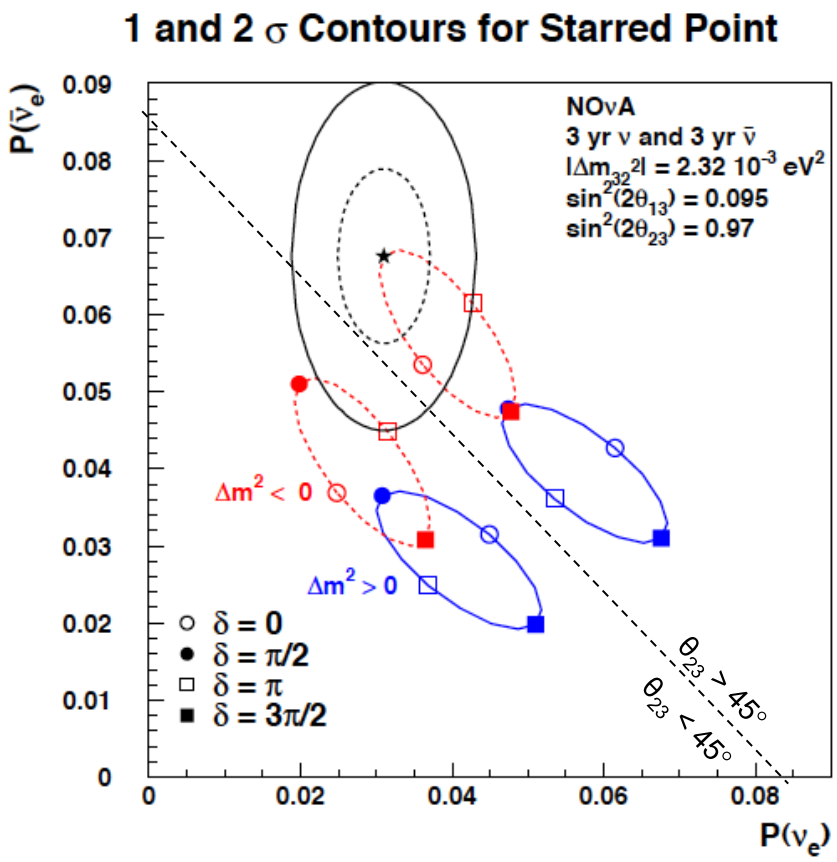
- 3+3 years example counting experiment, 10% background systematic error
- Full energy fit actively being pursued : **longer running now envisaged!**



NOvA and Non-maximal $\sin^2(2\theta_{23})$

- 3 Years each neutrino and anti-neutrino
  - information on $\sin^2(2\theta_{23})$ is available.



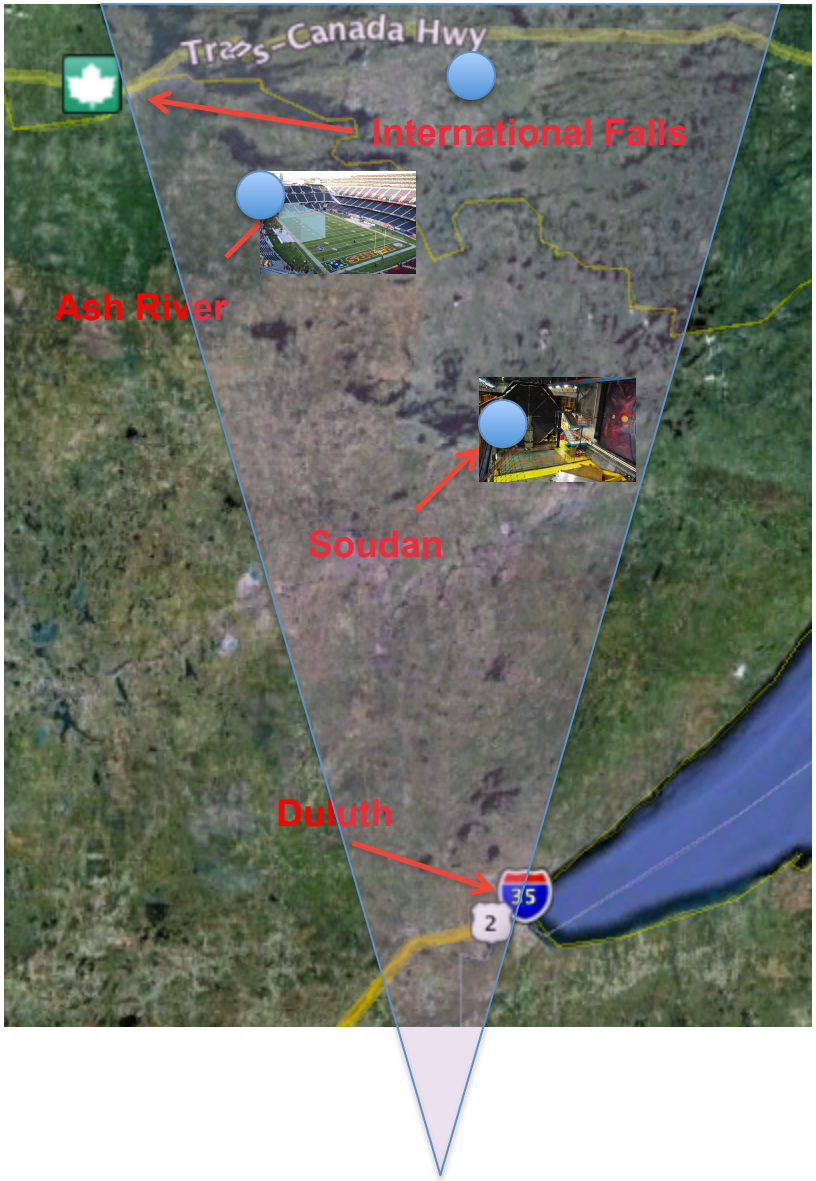


NuMI Plans

- The NuMI beam will deliver 700kW proton beam over the next decade ($6x10^{20}$p.o.t/y)
- NOνA and MINOS+ (presently) will profit from this

NuMI Plans

- Exploitation of the NuMI beam is very high priority for FNAL
- FNAL considering possible experiments :
  - Off-axis at Ash River
  - On-axis on surface at Soudan or beyond
    - 20mr off axis, 1100km Canada
  - On-axis underground at Soudan Laboratory



GLADE

- Letter of Intent for 5kt LAr detector has been submitted to FNAL Director/PAC
- Off-axis, surface detector, in remaining space at Ash River lab
- 5kt of LAr is equivalent to 15kt of NOνA
- Aids NOVA baseline reach in short/medium term (taking data before 2018) towards plan A or B.

GLADE+NOVA+T2K

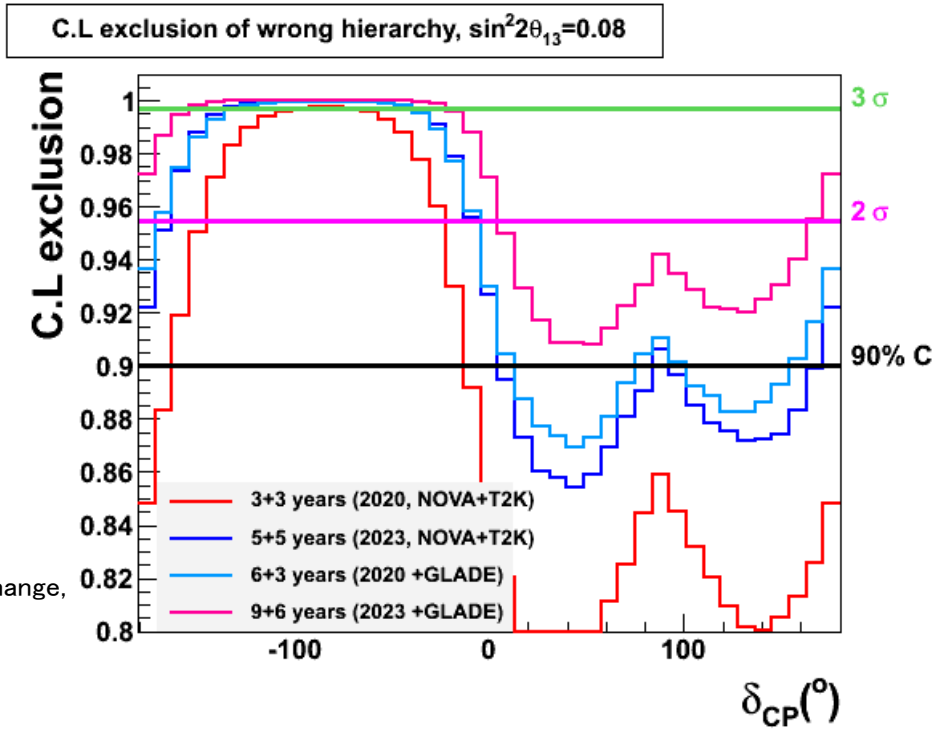
- 5kt of Liquid Argon is equivalent to NOνA

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

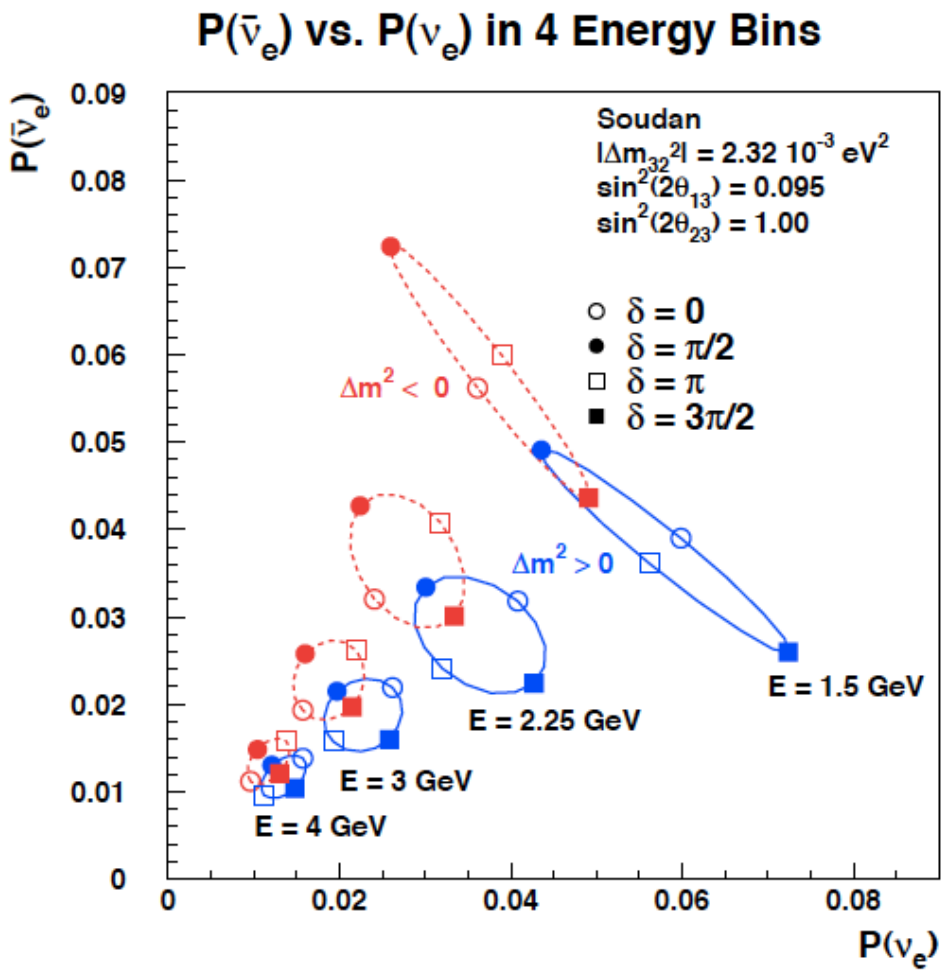
* Beam Energy 30GeV



From JPARC/KEK management

Based on simulations from S.Raut

LAr on-axis in NuMI



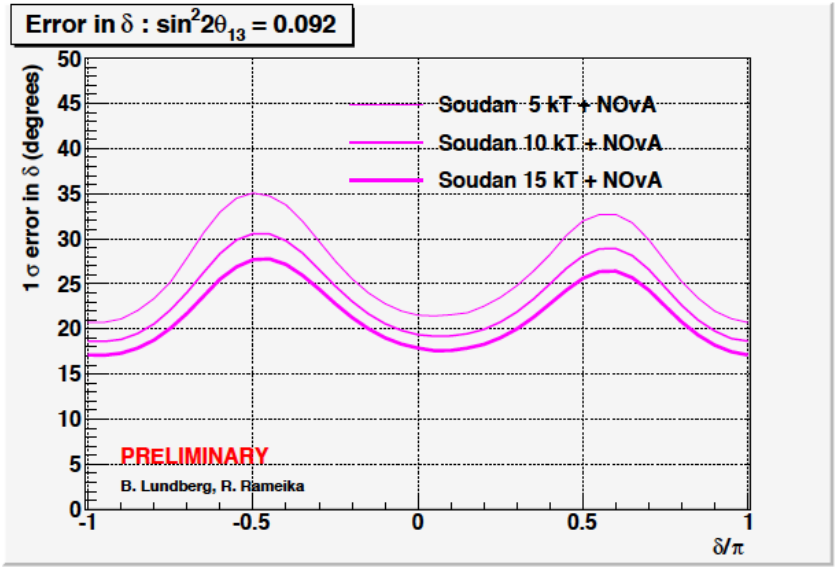
- ON-axis, LE WBB beam has spectral information
- Bi-probability plots are symmetric about the diagonal
- Invariance of oscillations to the exchange of

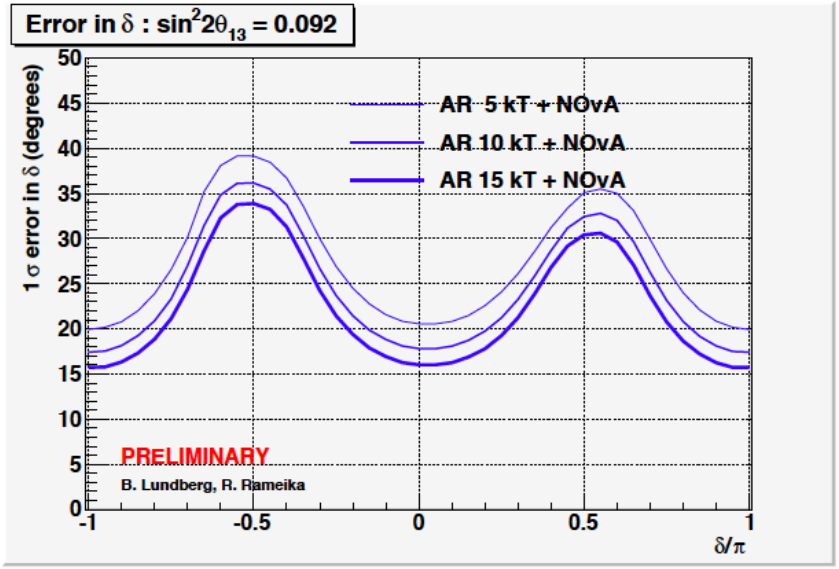
$$\nu \leftrightarrow \bar{\nu},$$

$$\Delta m^2 \leftrightarrow -\Delta m^2, \text{and } \delta \leftrightarrow \delta + \pi$$

Error on δ_{CP} (knowing MH)

- Both Ash River and Soudan Lar detectors (together with NOVA) give similar resolution on δ_{CP}
- 5+5 years with NuMI LE beam + NOVA (3+3) (by 2023?)
  - Obviously depends on when new detector gets started

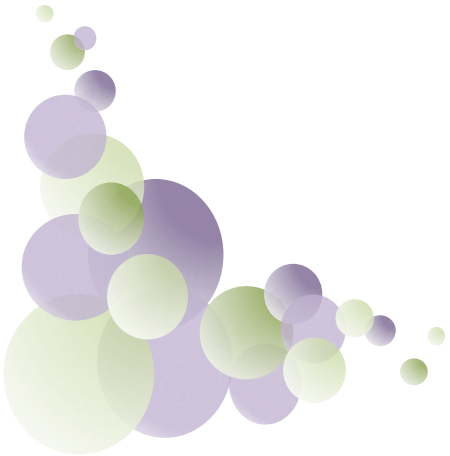




summary

- NuMI beam will be upgraded this year to deliver 700kW (6e20pot/y) for NOVA in the ME configuration
- MINOS+ will pick up where MINOS leaves off
  - Large reach in sterile search
  - A wealth of non-standard effects could be seen with MINOS+
- NOνA will start construction shortly and will start taking data with 5kt in summer 2013
- Large Liquid Argon detector(s) on NuMI beamline are being actively considered by FNAL for short/medium term results
- It seems likely that the mass hierarchy should be known to at least 90% C.L. within the next decade (Atmospheric, T2K, NOνA, Other NuMI?, Reactor LBL)
- Longer term efforts must focus on CP violation capability
- The NuMI beam will continue to contribute to front line knowledge for the forseeable future

Backup information



Exploiting NuMI

- There are two completely different strategies for *any* experiment on the NuMI beamline to resolve the mass ordering:
  - Plan A : compare neutrinos and anti-neutrinos within the same experiment
    - No NuMI experiment can ***guarantee*** that Plan A will work.
  - Plan B : compare neutrino running with an experiment on another baseline (T2K for example). Must correct for kinematic phase first
- NOνA (and another experiment on the NuMI beamline) and T2K will measure the identical oscillation probabilities, except for the matter effect, which determines the mass ordering.
  - If the oscillation probability is higher in NOνA, it is the normal mass ordering.

$$\frac{\Delta m^2 L}{4E},$$