MINOS/MINOS+ and NuMI

08/05/12

NuTURN Workshop

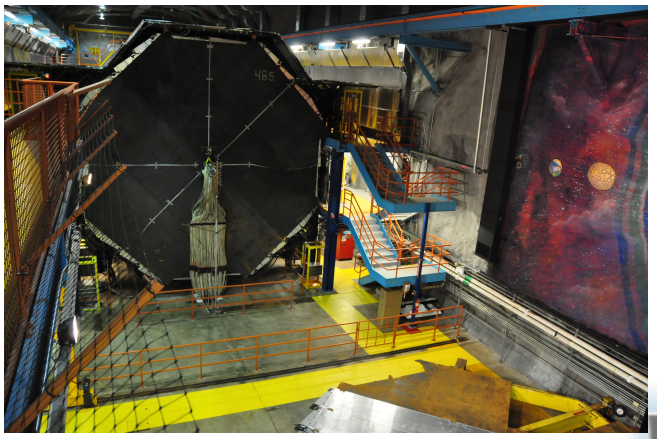
Jenny Thomas, UCL

- MINOS recap
- MINOS+ goals
- NuMI plans
- Mass Hierarchy and CP violation
- Conclusion

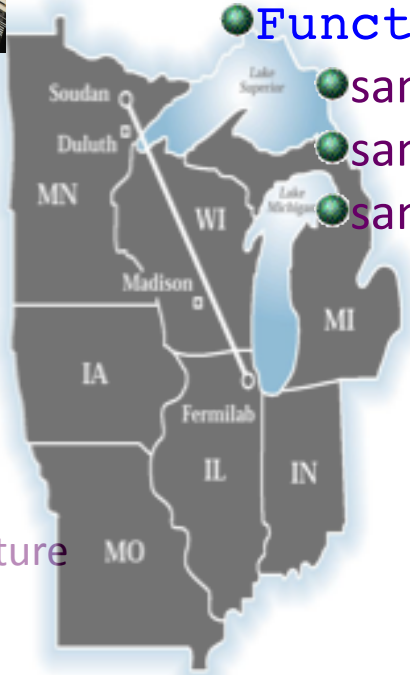
MINOS and NuMI plans

- 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)
- Full exploitation of the NuMI facility could provide opportunities for augmentation of present suite of experiments
  - Large Liquid Argon detectors

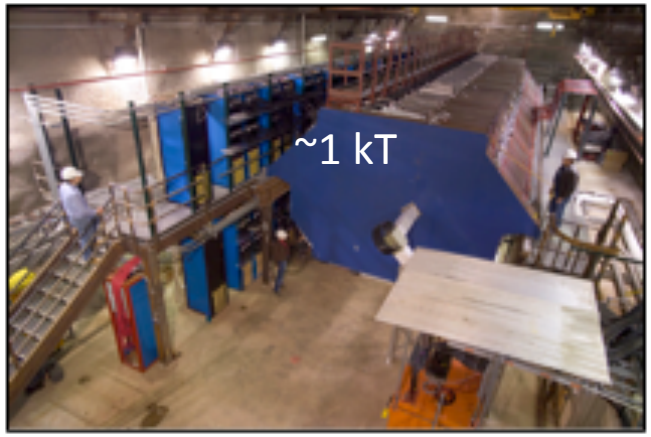
The MINOS Experiment



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

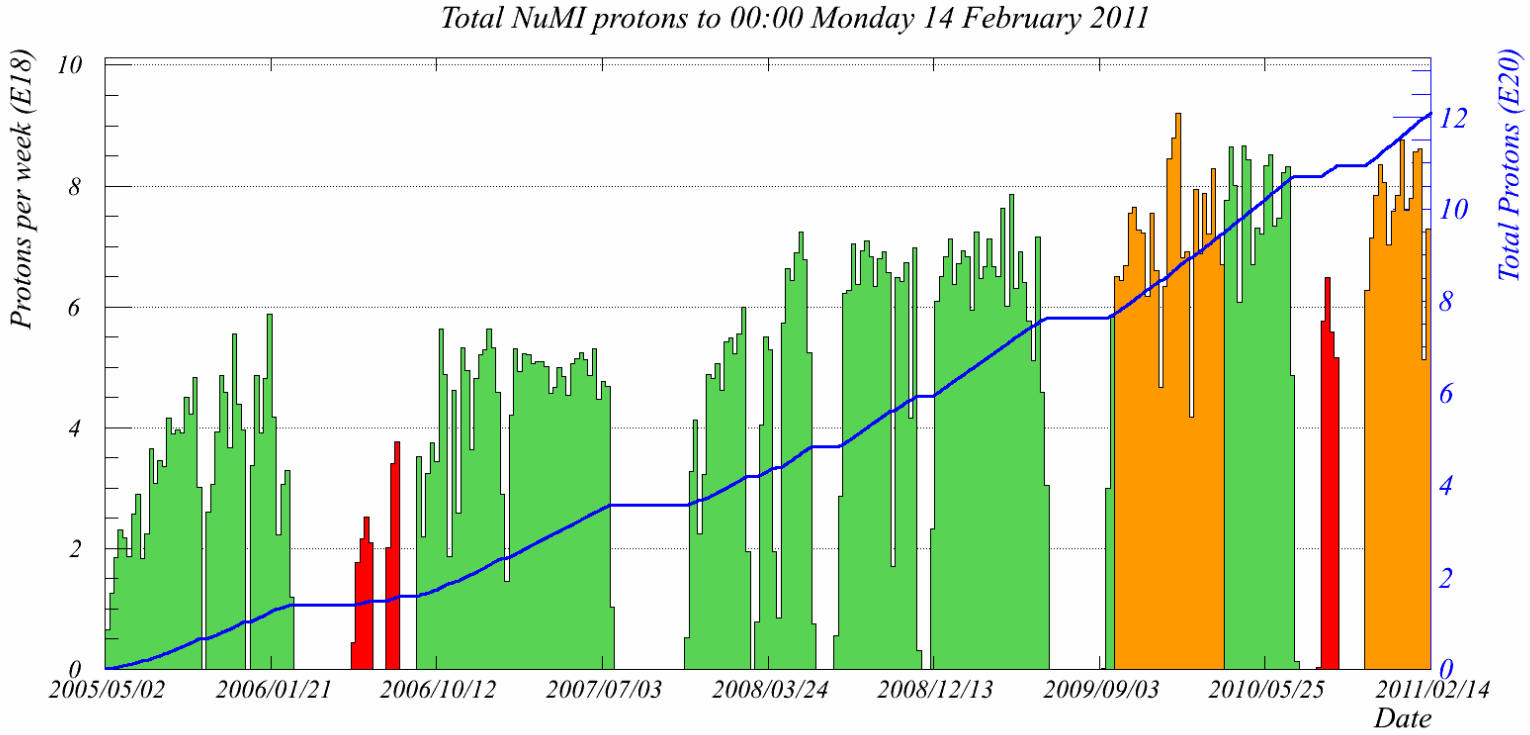


- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)



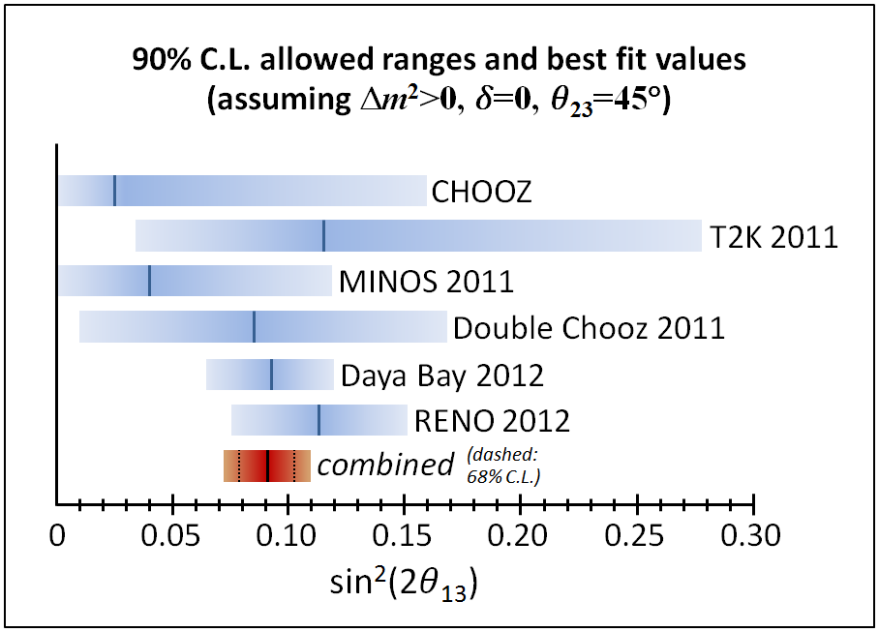
MINOS Final Results

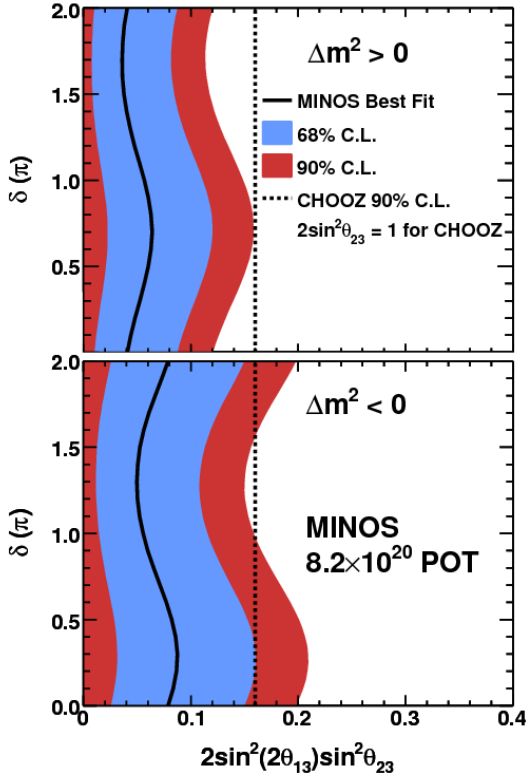
- Final MINOS results will be presented at Kyoto on
  - θ_{13}, $\overline{\theta_{13}}$, Δm^2, $\overline{\Delta m^2}$, $\sin^2 2\theta_{23}$, combined fit, and $\nu_\mu \rightarrow \nu_s$
- Total exposure is
  - 10.7×10^{20} p.o.t in FHC (neutrino mode)
  - 3.3×10^{20} p.o.t in RHC (anti-neutrino mode)
- Original proposal was for 1.6×10^{21} p.o.t. This has been achieved (when special runs are included)



MINOS θ_{13}

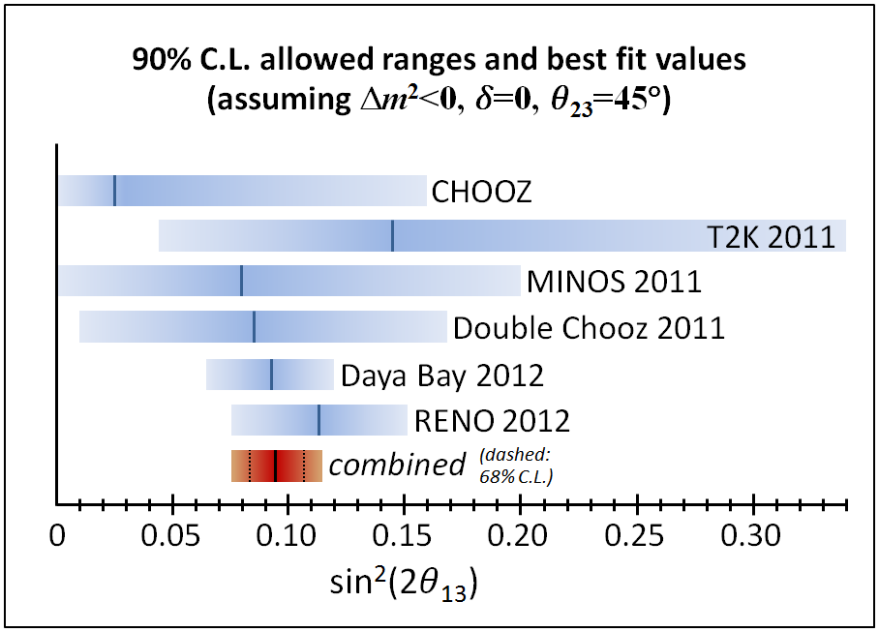
- Additional 2.4 e20 P.O.T to be added to existing 8.2e20 P.O.T
- And additional 3.3e20 RHC

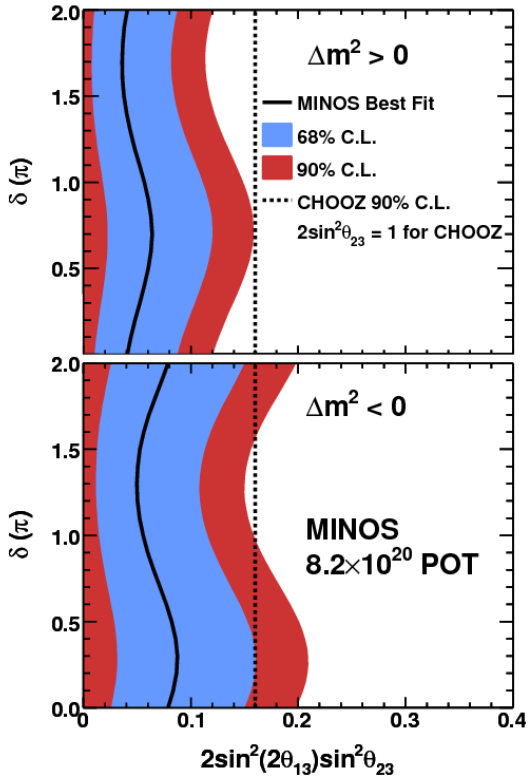




MINOS θ_{13}

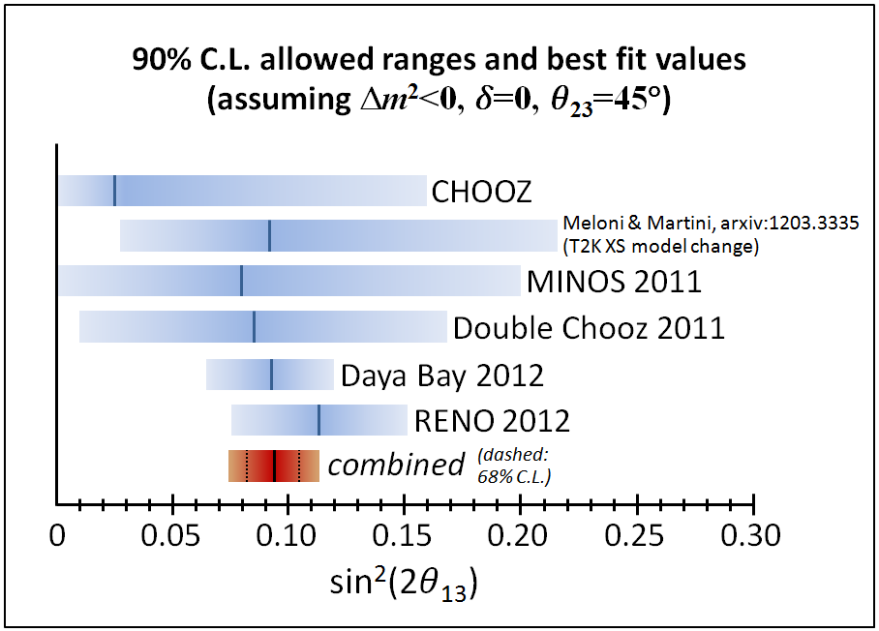
- Additional 2.4 e20 P.O.T to be added to existing 8.2e20 P.O.T
- And additional 3.3e20 RHC

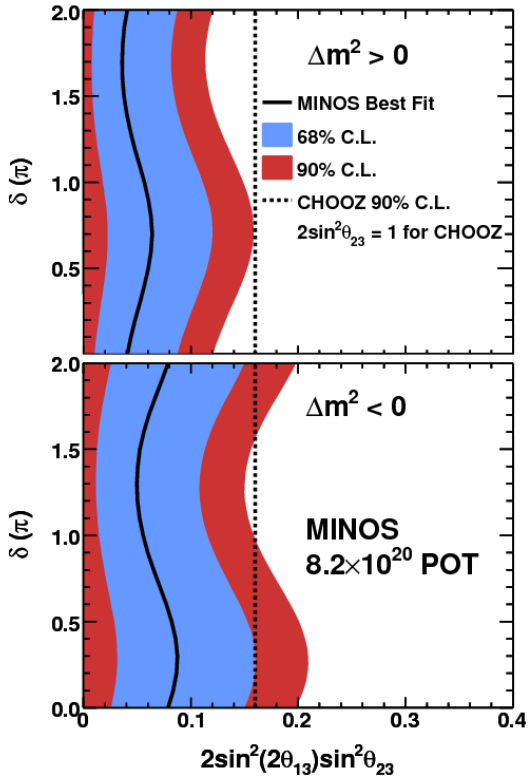




MINOS θ_{13}

- Additional 2.4 e20 P.O.T to be added to existing 8.2e20 P.O.T + addition 3.3e20 RHC
- Effective 30% more data

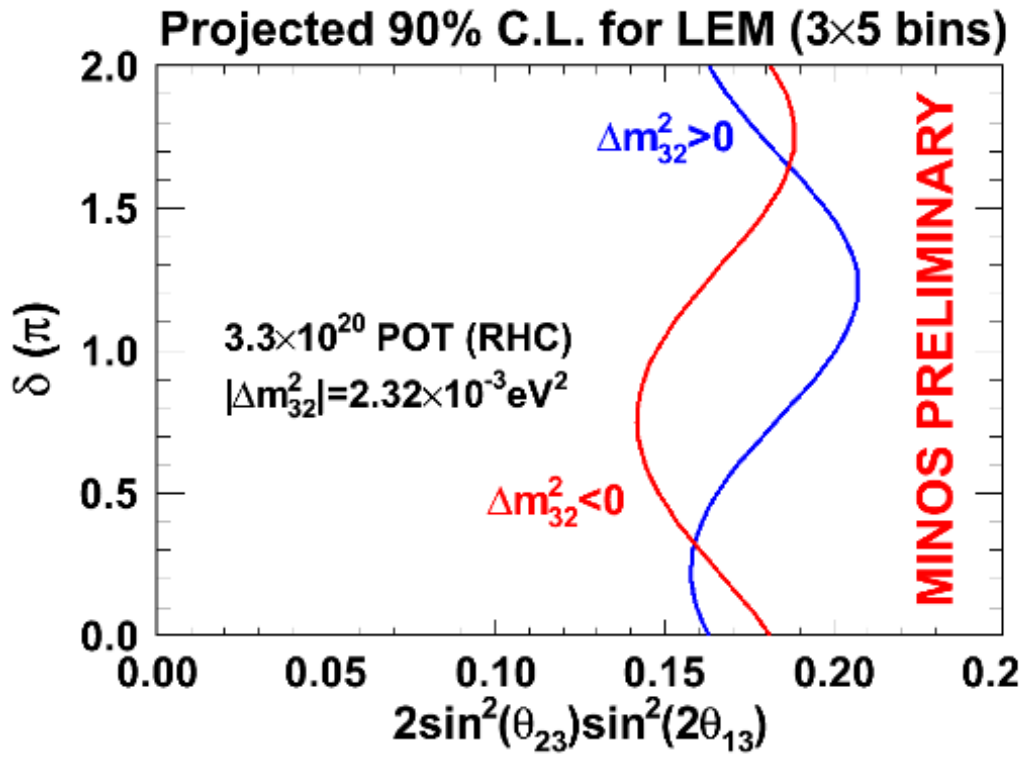




- Comparison dominated by errors on θ_{23}

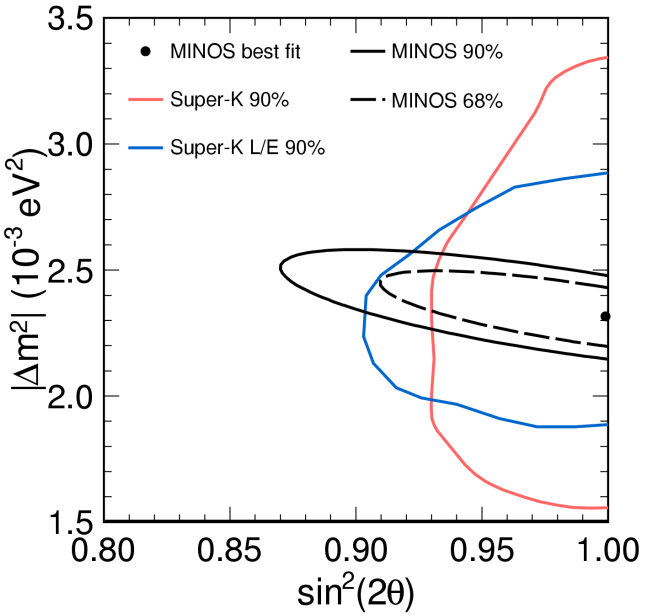
MINOS $\overline{\theta}_{13}$

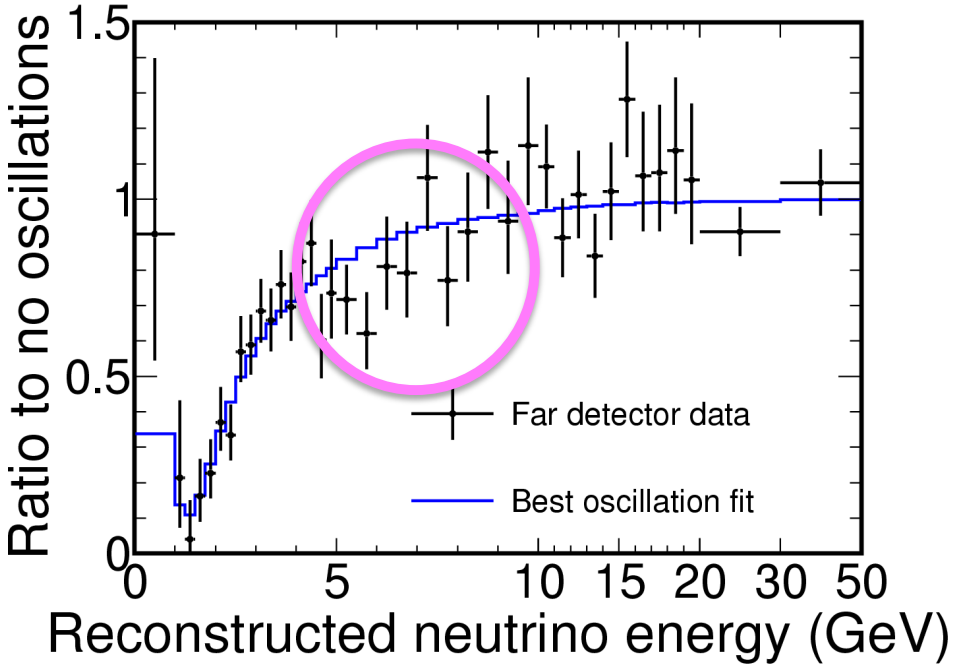
- Total 3.3 e20 P.O.T to be analyzed (RHC running)
- Expectation is for between 10.2 and 12 events on background of ~10 – unlikely to be any surprises!
- Difference of ~1 event between IH and NH ☹



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)
- Odd dip will likely have to wait for MINOS+

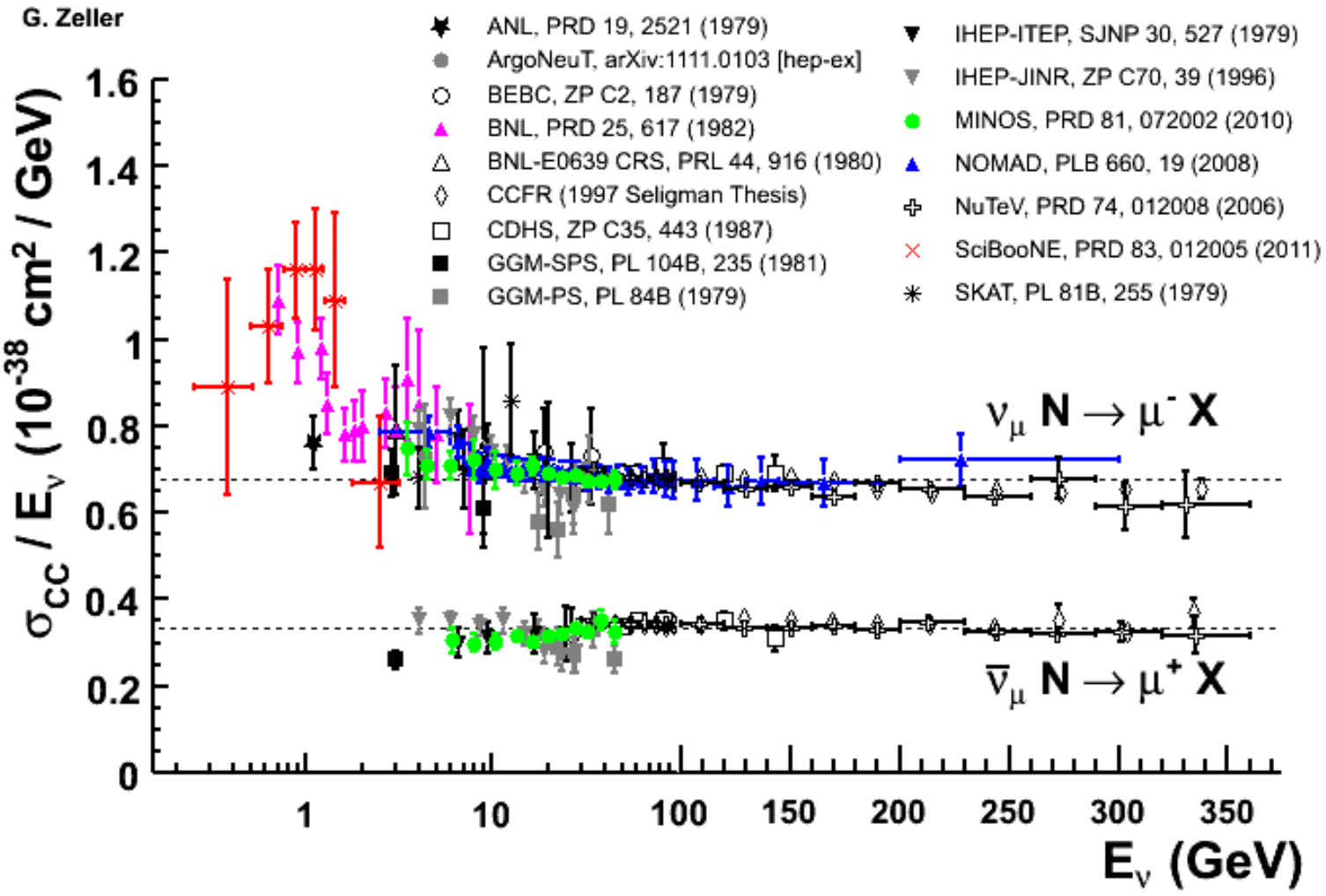




$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3}$ eV^2

$\sin^2(2\theta) > 0.90$ (90% C.L.)

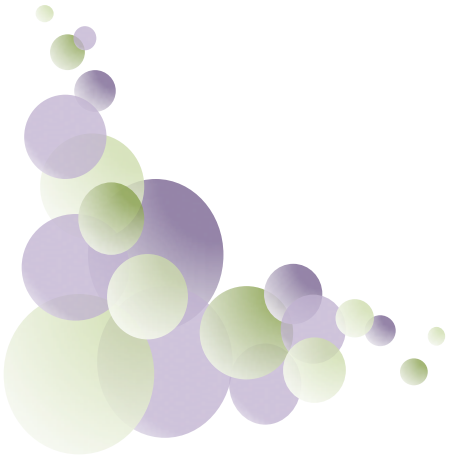
MINOS


G. Zeller
ANL, PRD 19, 2521 (1979)
ArgoNeuT, arXiv:1111.0103 [hep-ex]
BEBC, ZP C2, 187 (1979)
BNL, PRD 25, 617 (1982)
BNL-E0639 CRS, PRL 44, 916 (1980)
CCFR (1997 Seligman Thesis)
CDHS, ZP C35, 443 (1987)
GGM-SPS, PL 104B, 235 (1981)
GGM-PS, PL 84B (1979)
IHEP-ITEP, SJNP 30, 527 (1979)
IHEP-JINR, ZP C70, 39 (1996)
MINOS, PRD 81, 072002 (2010)
NOMAD, PLB 660, 19 (2008)
NuTeV, PRD 74, 012008 (2006)
SciBooNE, PRD 83, 012005 (2011)
SKAT, PL 81B, 255 (1979)
σ_{CC} / E_ν (10^{-38} cm^2 / GeV)
$\nu_\mu N \rightarrow \mu^- X$
$\bar{\nu}_\mu N \rightarrow \mu^+ X$
E_ν (GeV)

MINOS+

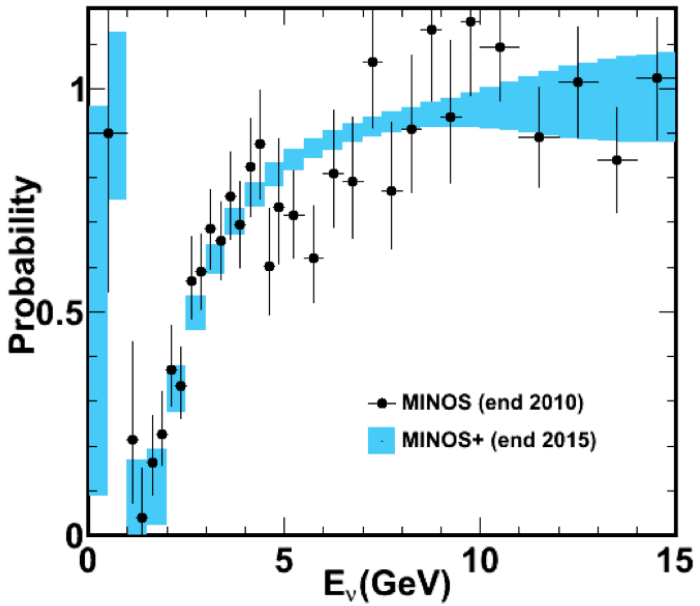
Starts April 2013 for three years

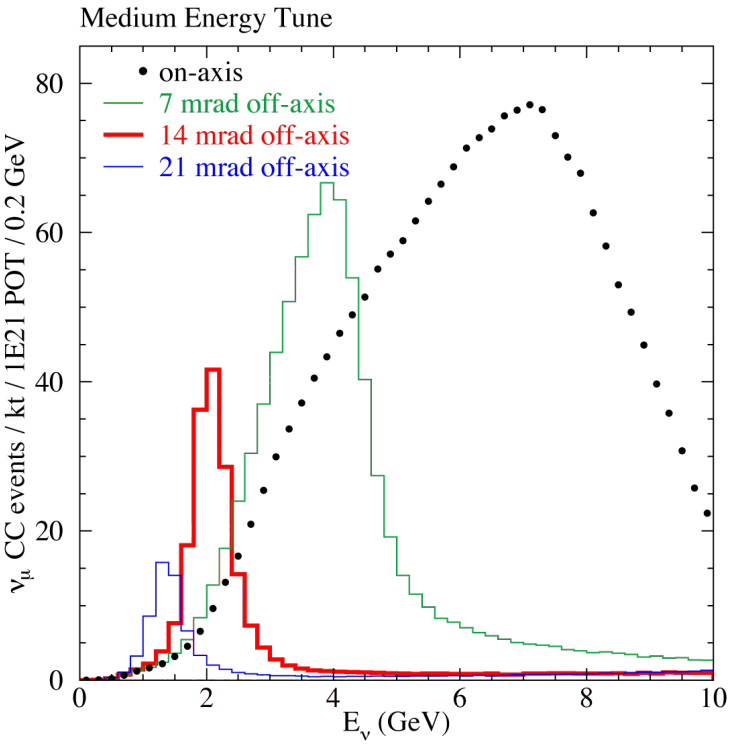
April 2013-2016



MINOS+ goals

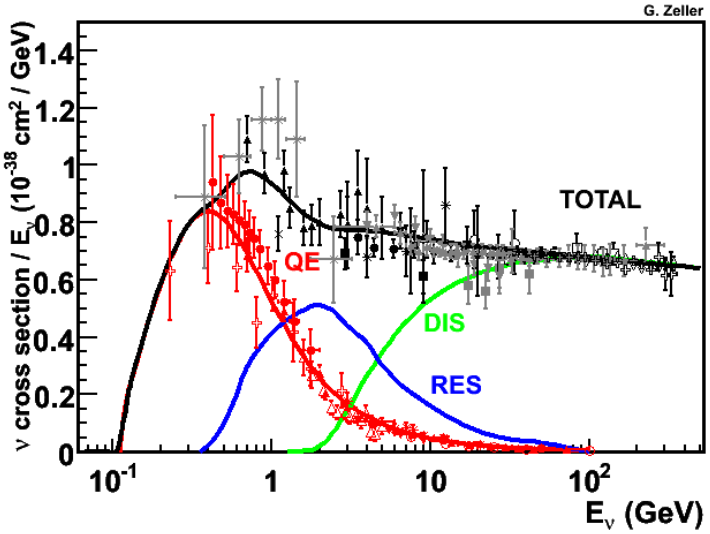
- The overarching reason to run MINOS in the NuMI-NOνA beam is to look for new physics in a previously unexplored region
- Unique high statistics experiment with charge sign measurement
  - different energy region
  - different systematics (beam, x-sec comp)
- 3000 events/year between 4-10 GeV near oscillation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

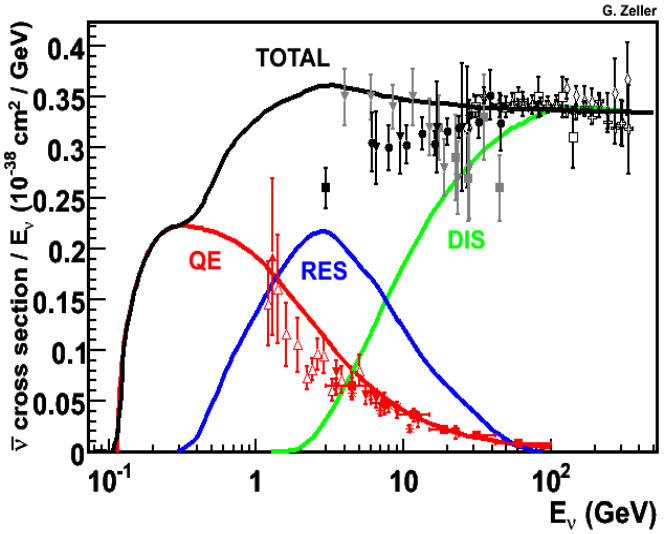




MINOS+ goals

- 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



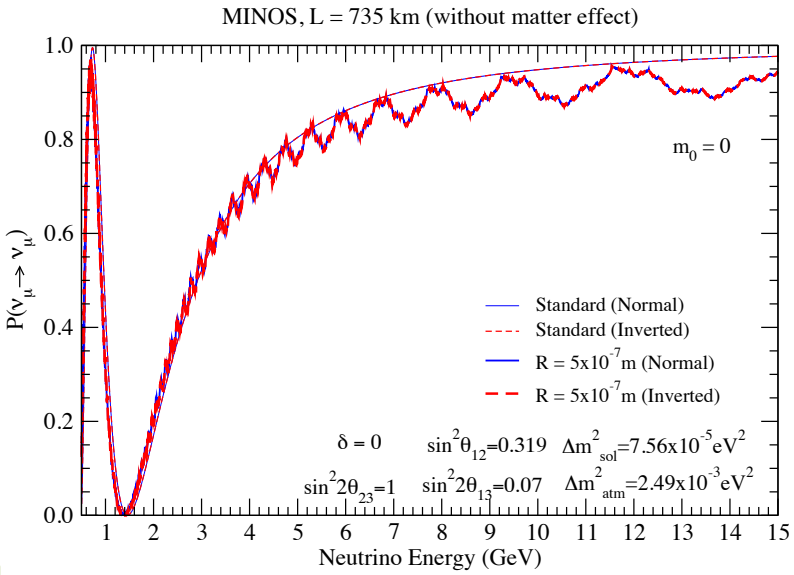


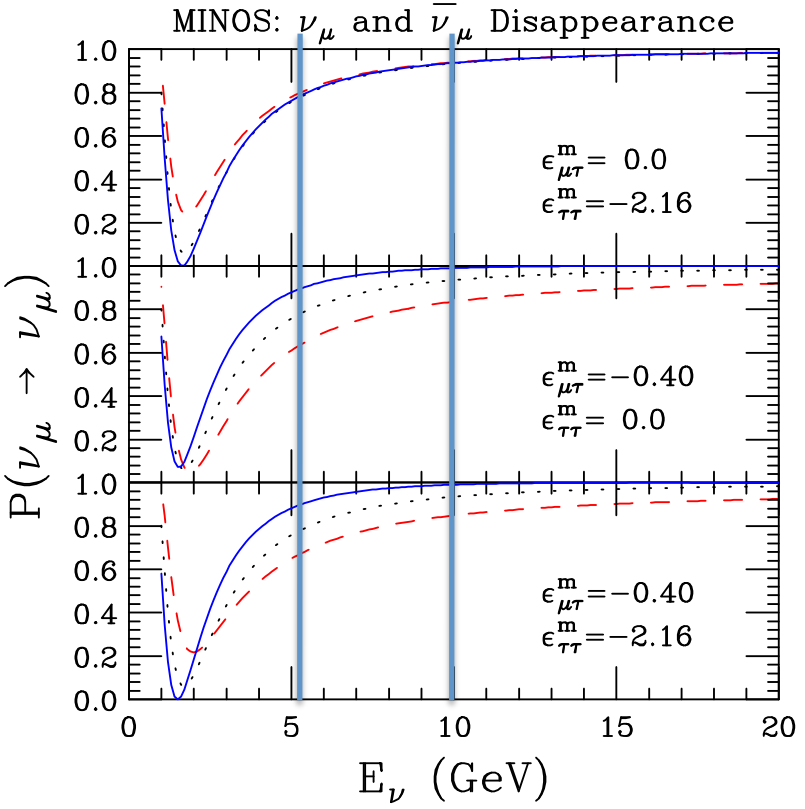
MINOS+ Goals

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).

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

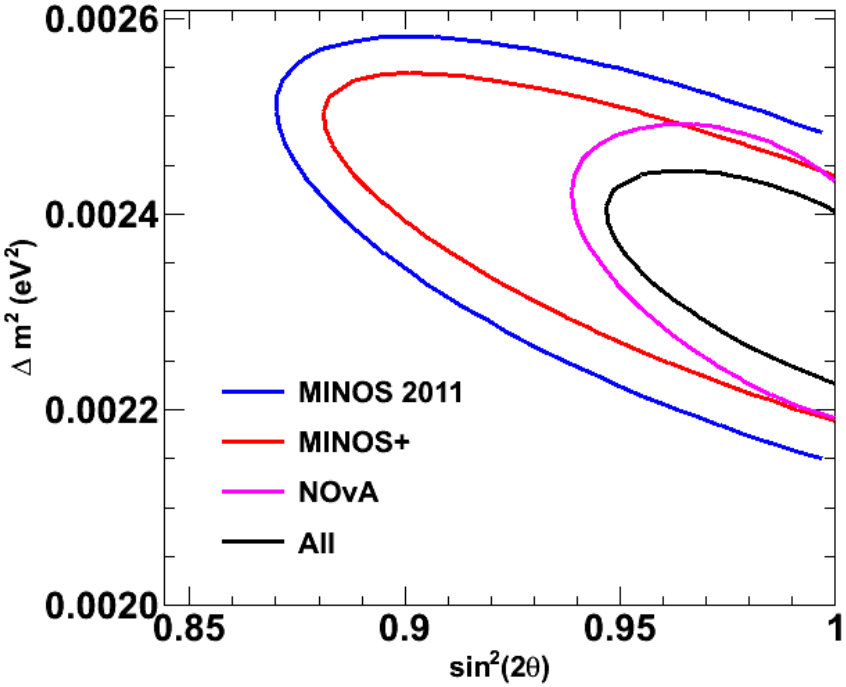


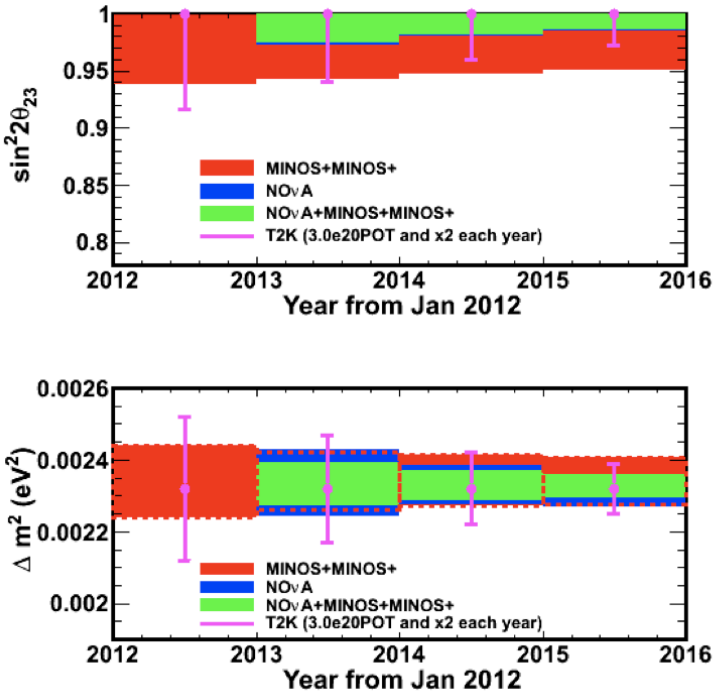


Half micron sized extra dimensions can be observed!!

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

MINOS, MINOS+ and NOνA





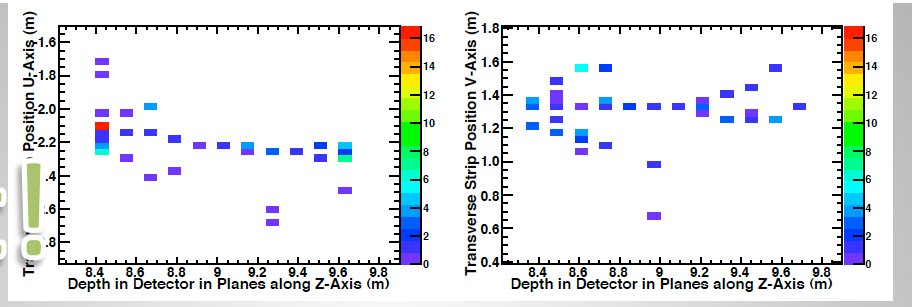
- One year of MINOS+
- MINOS continues to dominate Δm^2 measurement
- NOνA 50% complete

- Three years of MINOS+
- NOνA complete after first 18 months
- Significant improvements to parameters' accuracy over 3 years period due to MINOS+

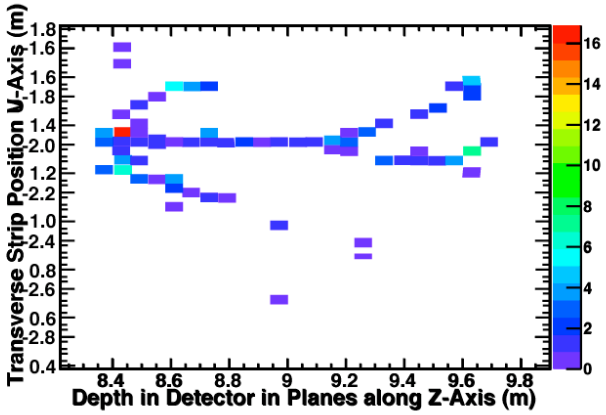
MINOS+ Goals

- 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!

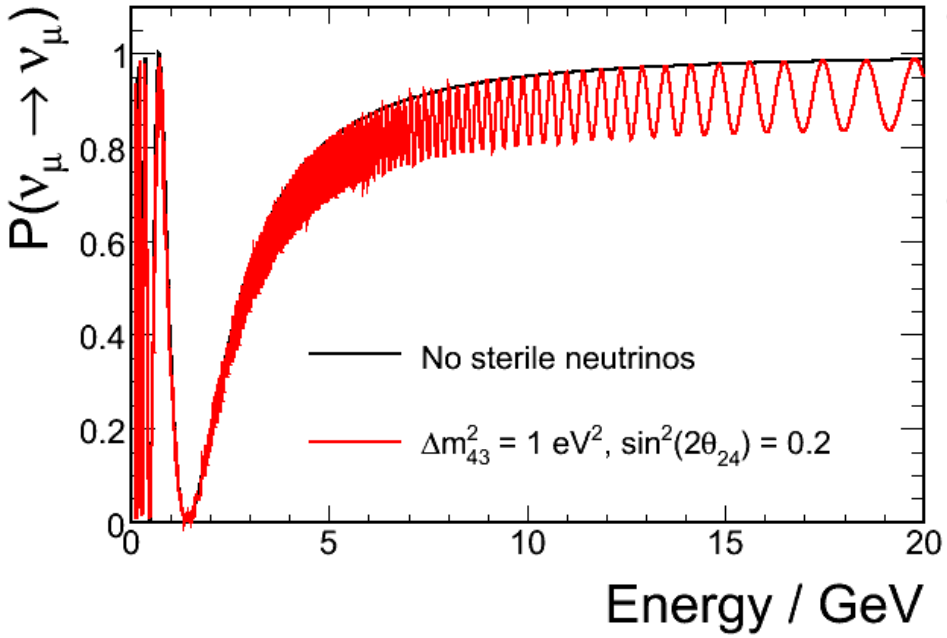


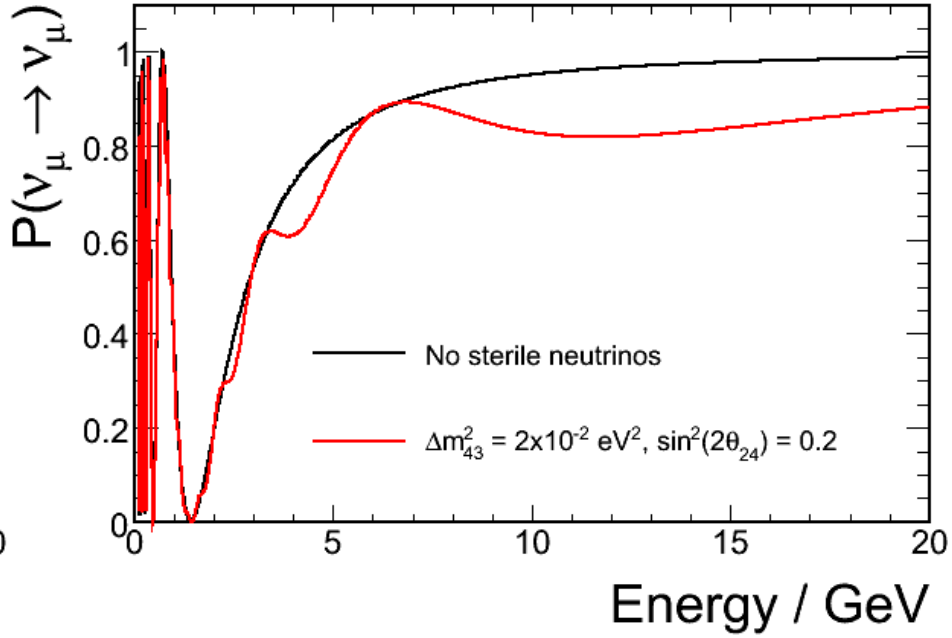
FD RUN = 46256
EVENT ID = 234466
Reco. Energy = 5.30 GeV
LEM PID = 0.13
ANN PID = 0.06



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

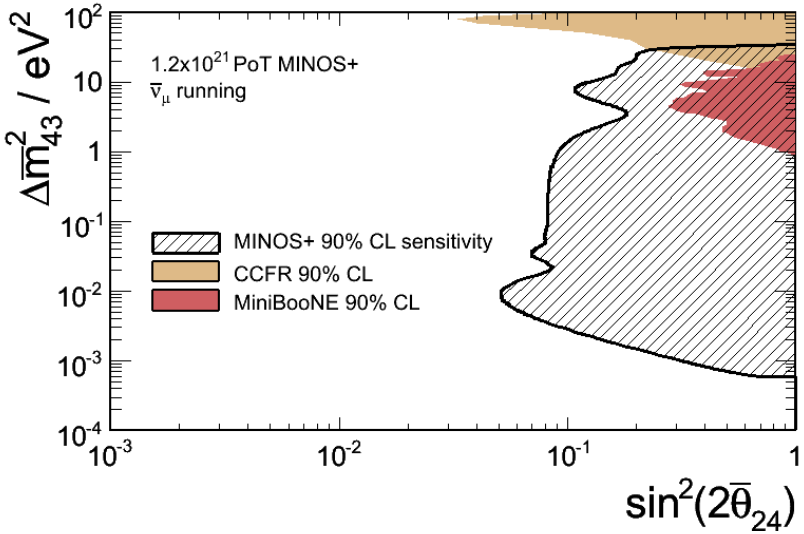
MINOS+ sterile reach

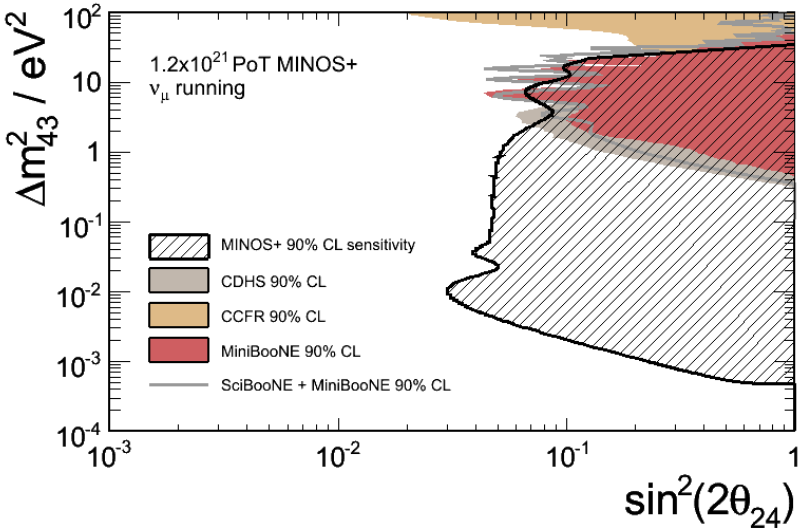
$|U_{e4}|^2 = \sin^2\theta_{14}$

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

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

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





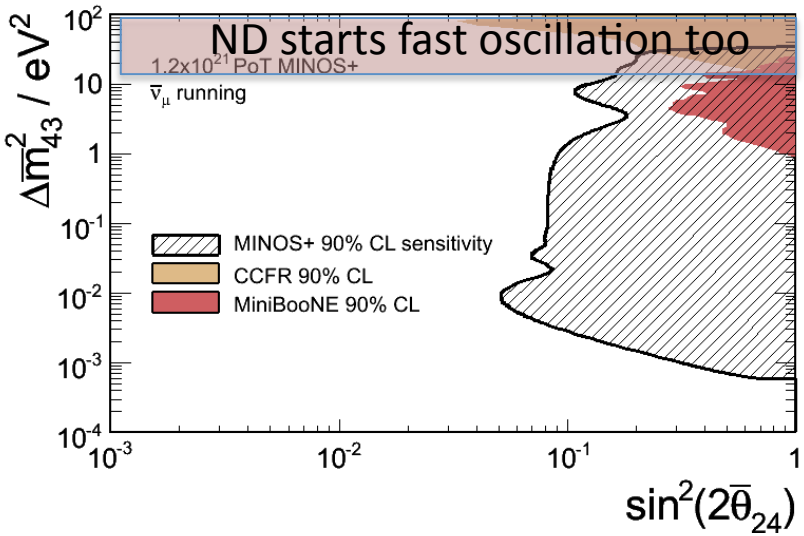
MINOS+ sterile reach

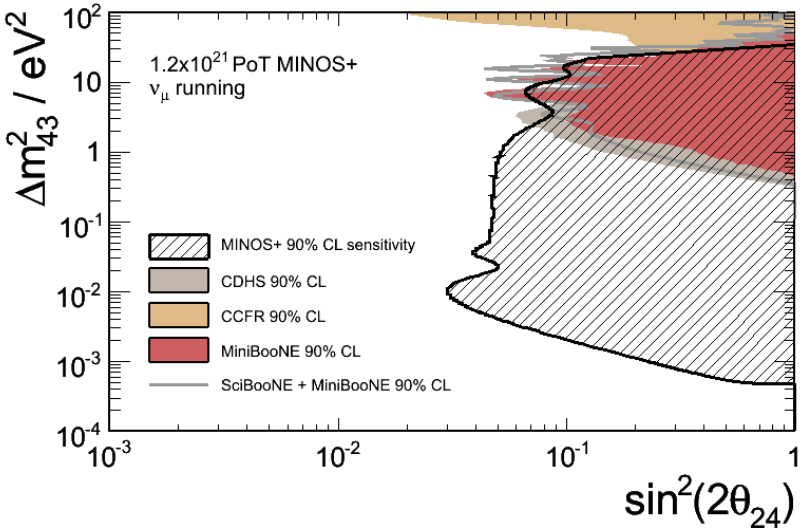
$|U_{e4}|^2 = \sin^2\theta_{14}$

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

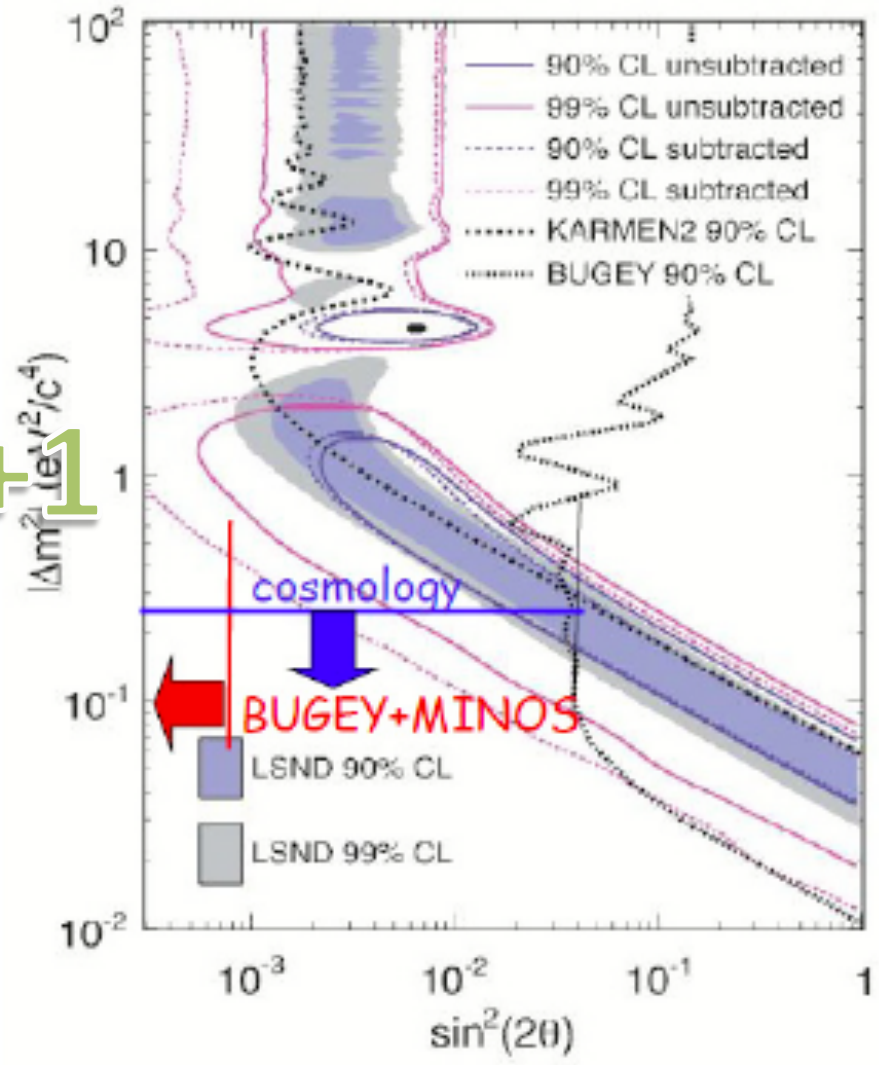
$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu 4}|^2$

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





3+1



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

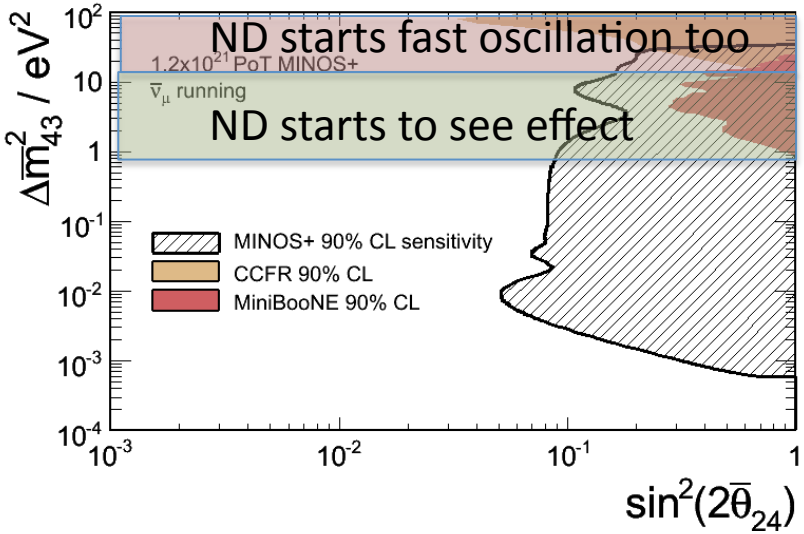
MINOS+ sterile reach

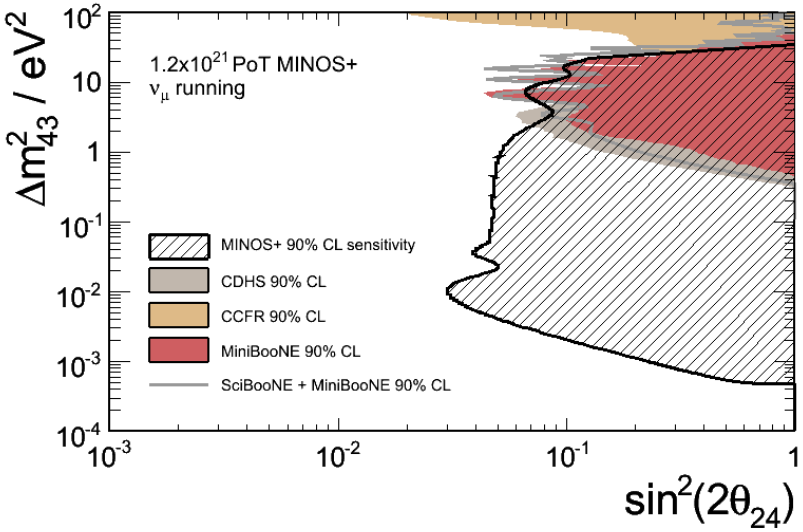
$|U_{e4}|^2 = \sin^2\theta_{14}$

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

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

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





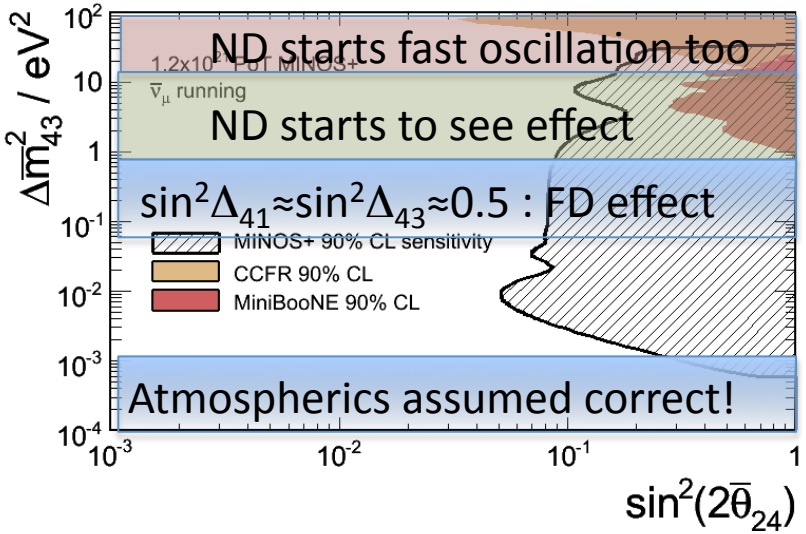
MINOS+ sterile reach

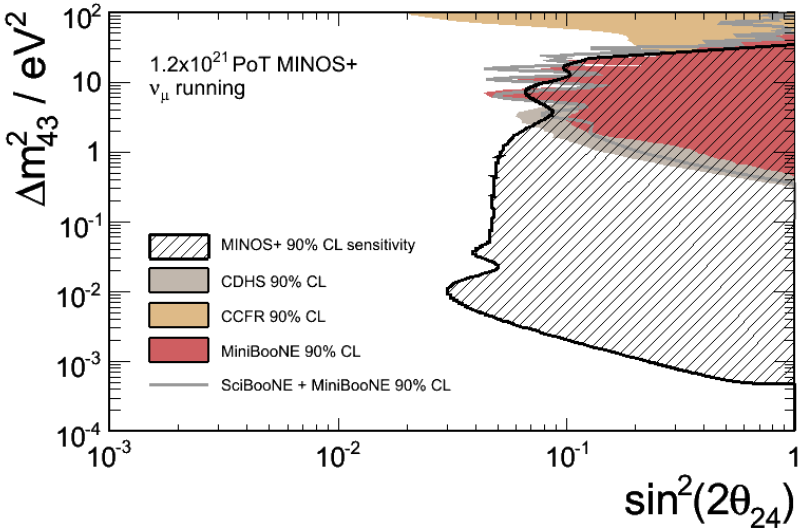
$|U_{e4}|^2 = \sin^2\theta_{14}$

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

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

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





MINOS+ sterile reach

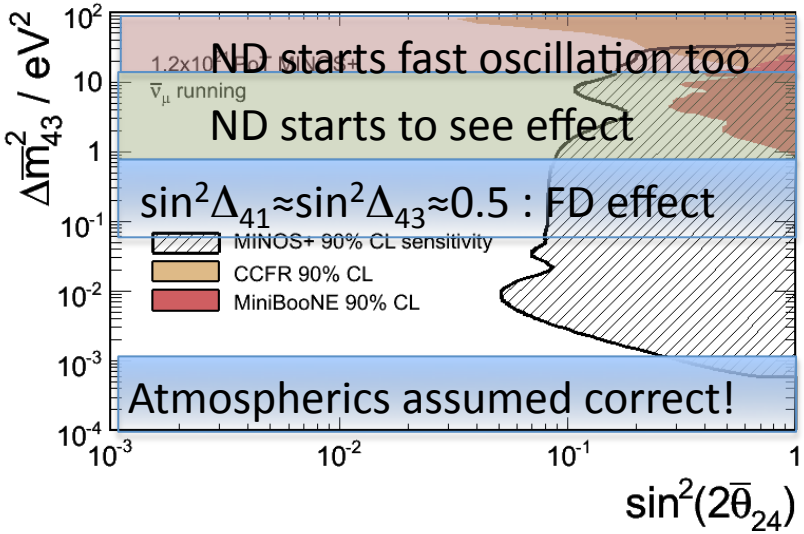
$|U_{e4}|^2 = \sin^2\theta_{14}$

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

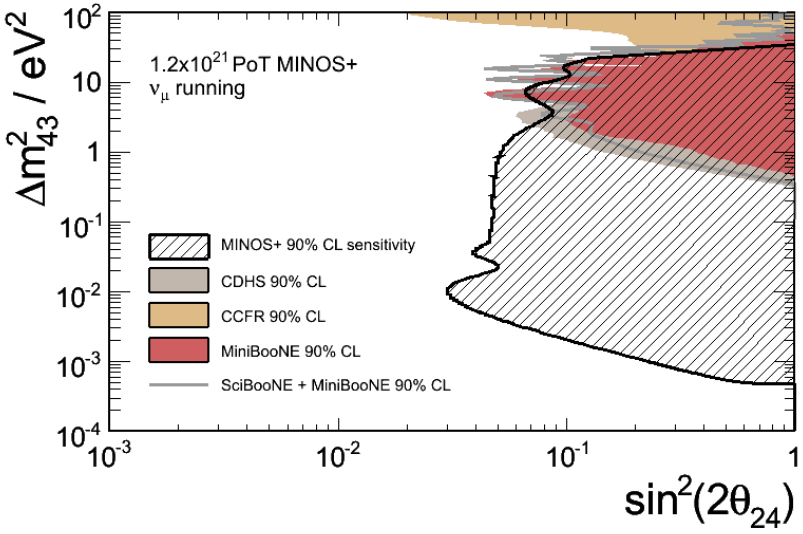
$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu 4}|^2$

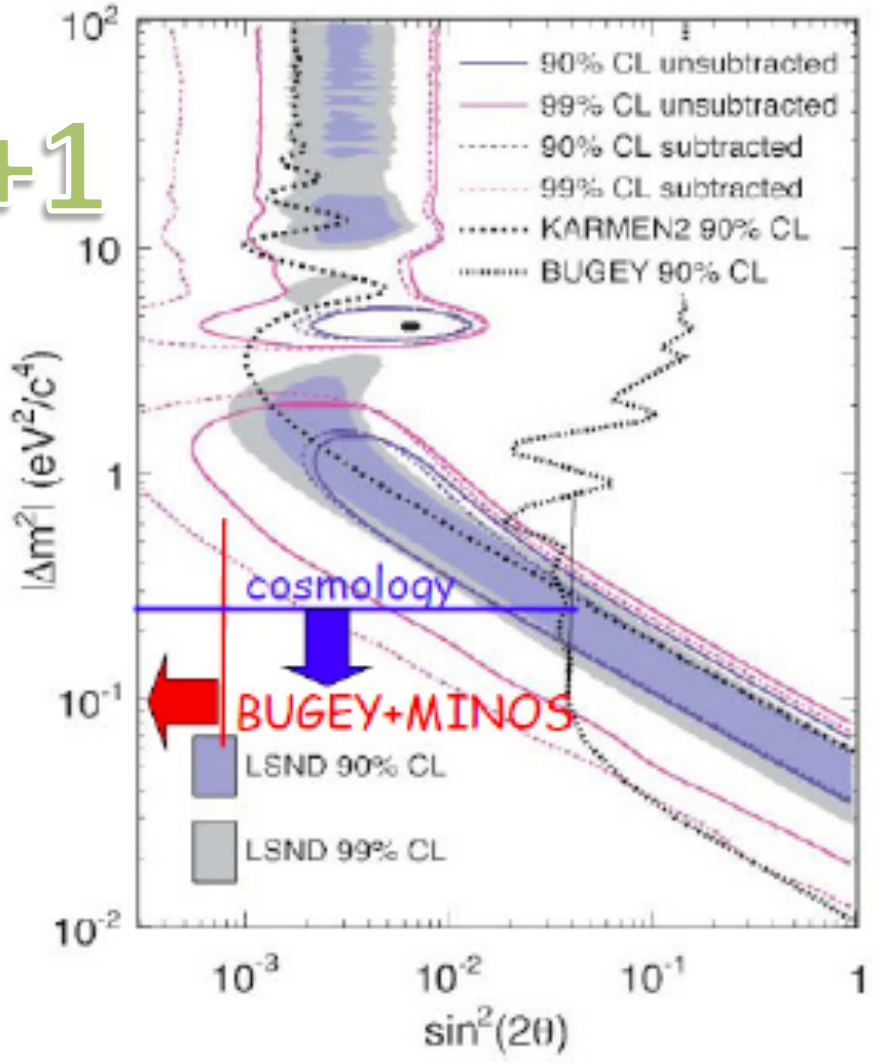
(http://lanl.arxiv.org/abs/1109.4033)

Smirnov, NuFact 2011



3+1





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

MINOS+ sterile reach

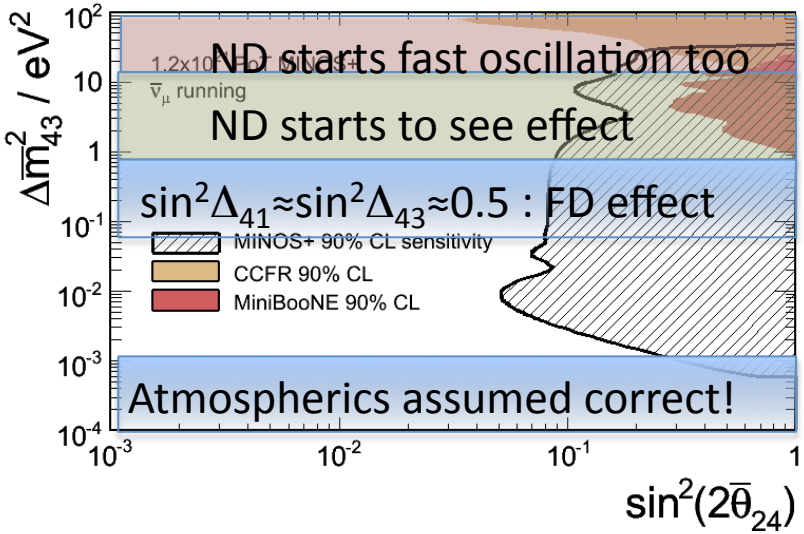
$|U_{e4}|^2 = \sin^2\theta_{14}$

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

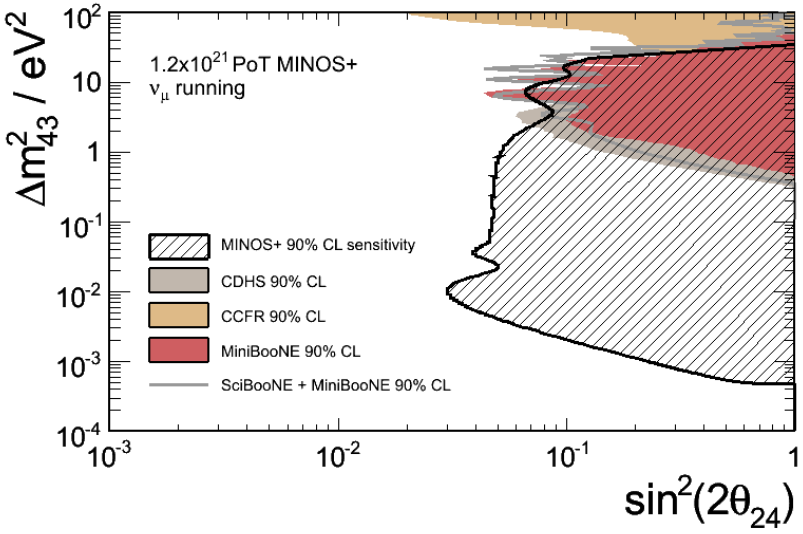
$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu 4}|^2$

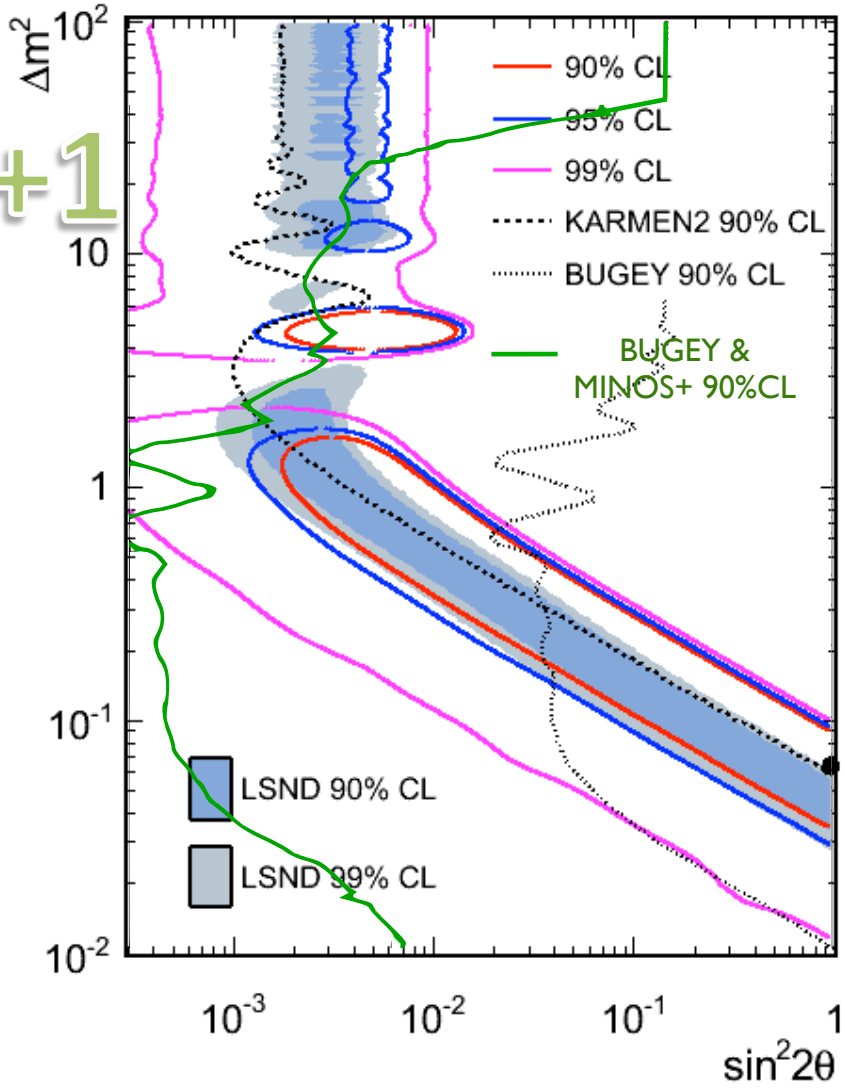
(http://lanl.arxiv.org/abs/1109.4033)

A.Sousa



3+1





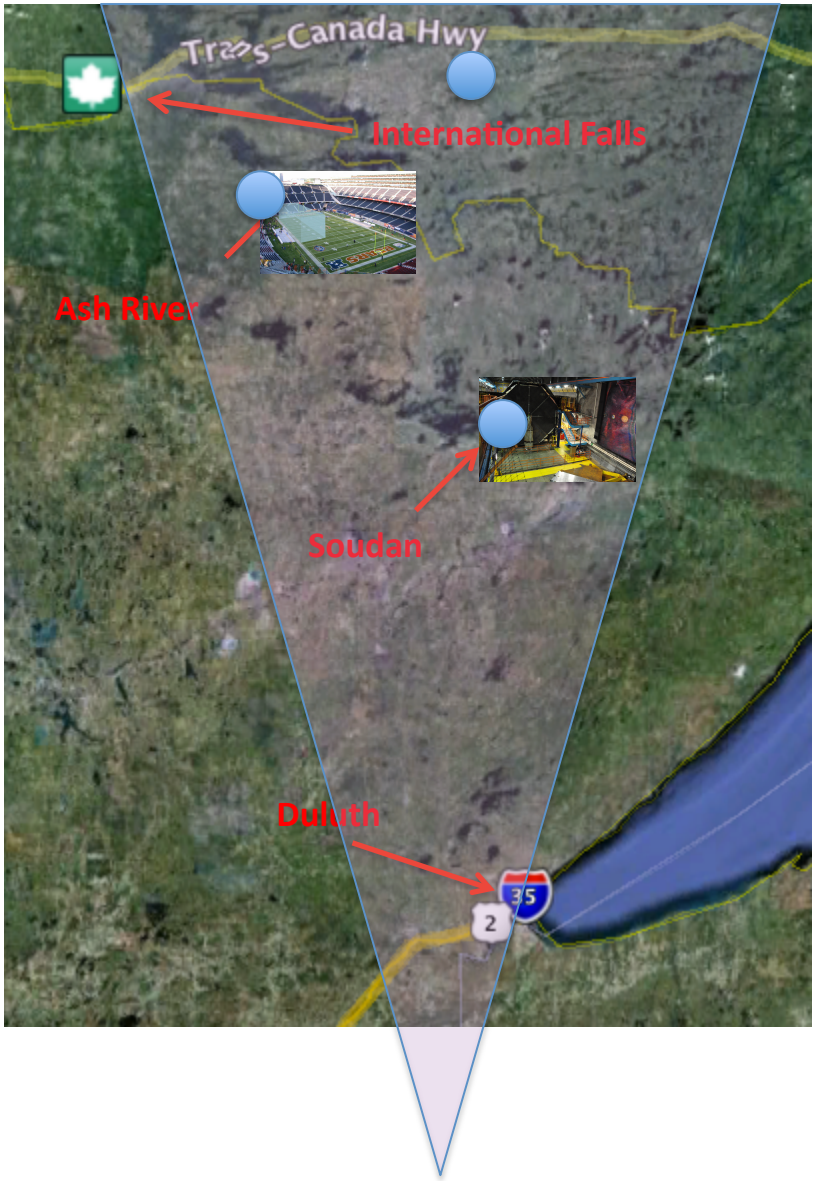
$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu 4}|^2$

NuMI Plans

- The NuMI beam will deliver 700kW proton beam over the next decade ($6x10^{20}$p.o.t/y)
- NOVA 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
  - On-axis underground at Soudan Laboratory



Exploiting NuMI

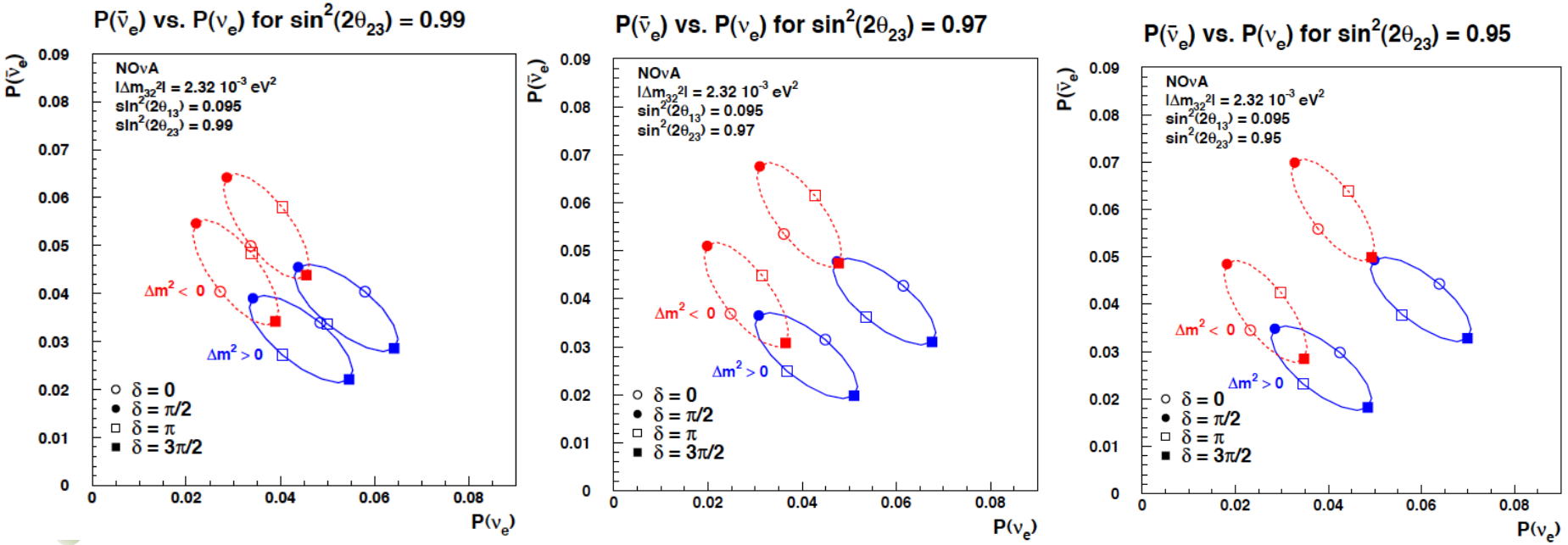
- There are two completely different strategies for *any* experiment on the NuMI beamline to resolve the mass ordering:
  - Plan A : compare neutrinos and anti-neutrinos within the same experiment
    - No NuMI experiment can ***guarantee*** that Plan A will work.
  - Plan B : compare neutrino running with an experiment on another baseline (T2K for example).

$\sin^2(\theta_{23})$ Term

$\bar{\nu}_e$ Disappearance in a reactor experiment is proportional to $\sin^2(2\theta_{13})$.

- However, $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance in an accelerator experiment is proportional to $\sin^2(\theta_{23})\ \sin^2(2\theta_{13})$, to first order.
- If $\sin^2(2\theta_{23}) \neq 1.0$, there is an ambiguity as to whether θ_{23} is larger or smaller than 45°.
  - $\theta_{23} < 45°$: ν_3 couples more strongly to ν_τ than to ν_μ.
  - $\theta_{23} > 45°$: : ν_3 couples less strongly to ν_τ than to ν_μ
- The $\sin^2(\theta_{23})$ term is unimportant when comparing accelerator experiments; however, it is crucial in comparing accelerator to reactor experiments.

Exploiting NuMI



$\sin^2(2\theta_{23}) = 0.99,\ 0.97,$ and 0.95

Plan B

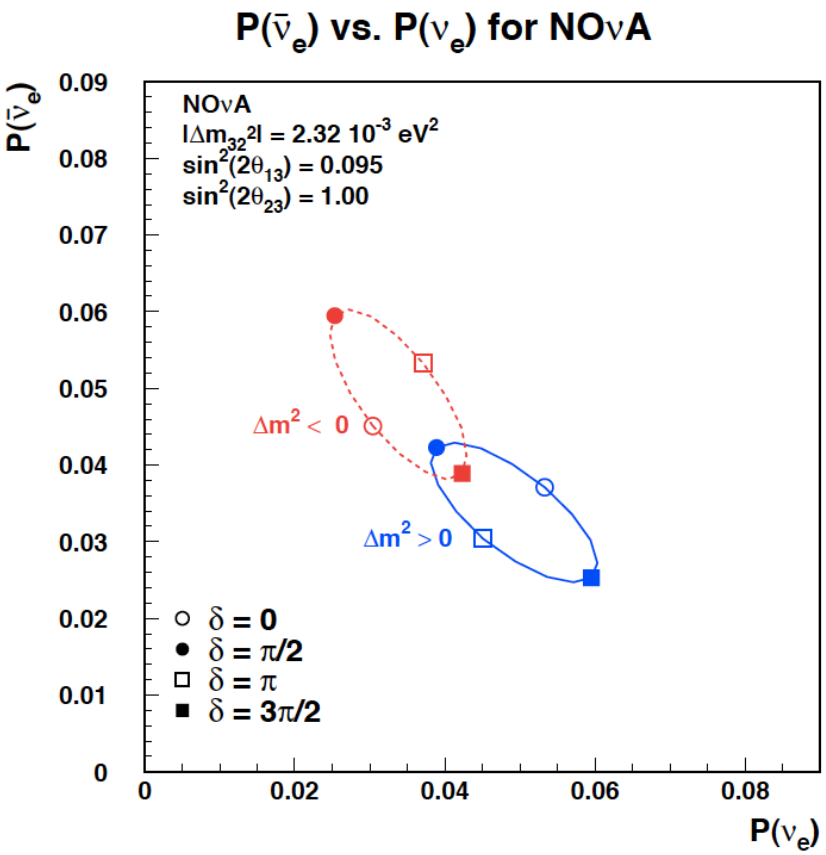
- At each point of the kinematic oscillation phase $\frac{\Delta m^2 L}{4E}$,

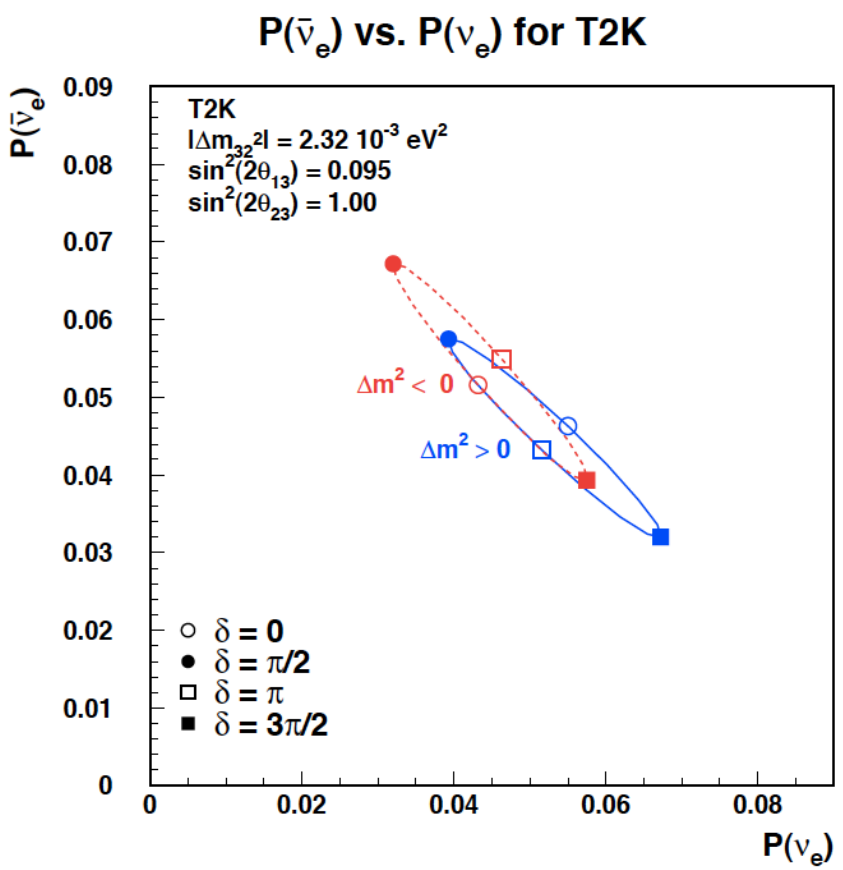
  NOνA (and another experiment on the NuMI beamline) and T2K will measure the identical oscillation probabilities, except for the matter effect, which determines the mass ordering.
- Thus, the strategy of Plan B is straightforward. Each experiment gets as much data on neutrino running as it can. If the oscillation probability is higher in NOνA, it is the normal mass ordering. Otherwise, it is the inverted.
- It is that simple (in principle, but not in practice).

GLADE

- LoI 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.

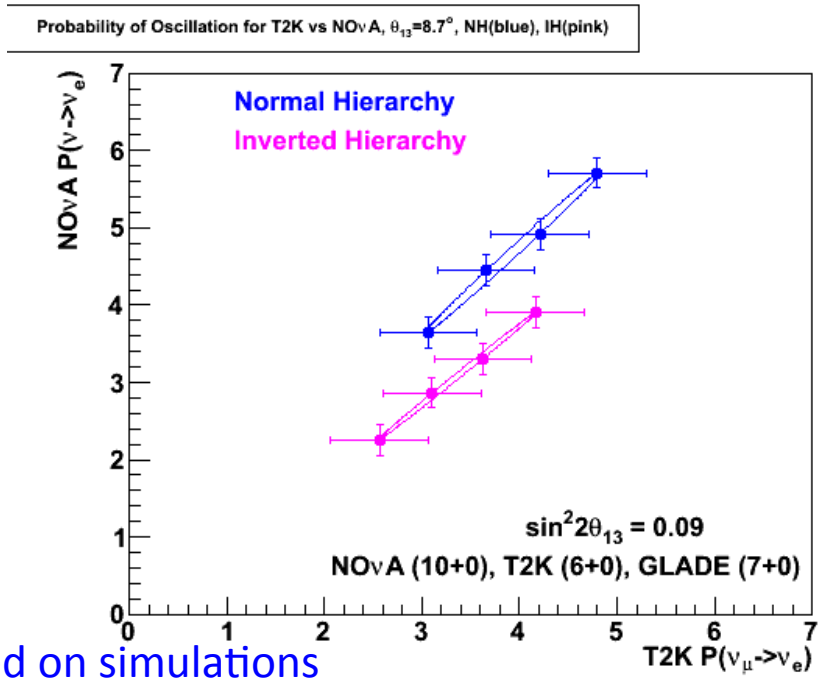
NOνA/GLADE-T2K Comparison

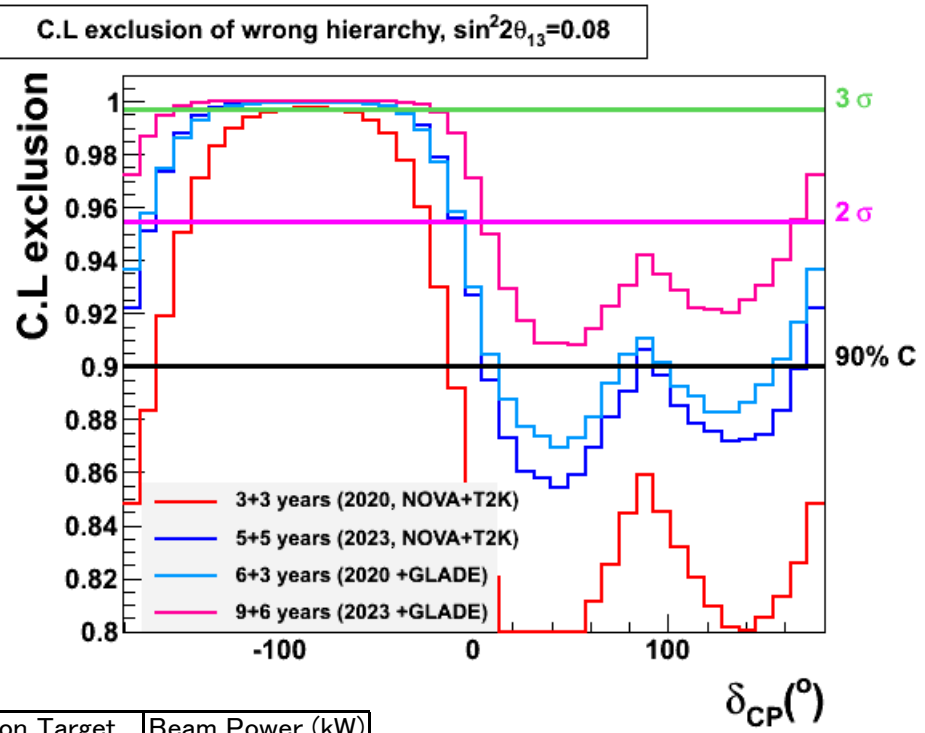




Warning: These plots are not at the same kinematic phase.

GLADE+NOVA+T2K





Based on simulations from S.Raut

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	

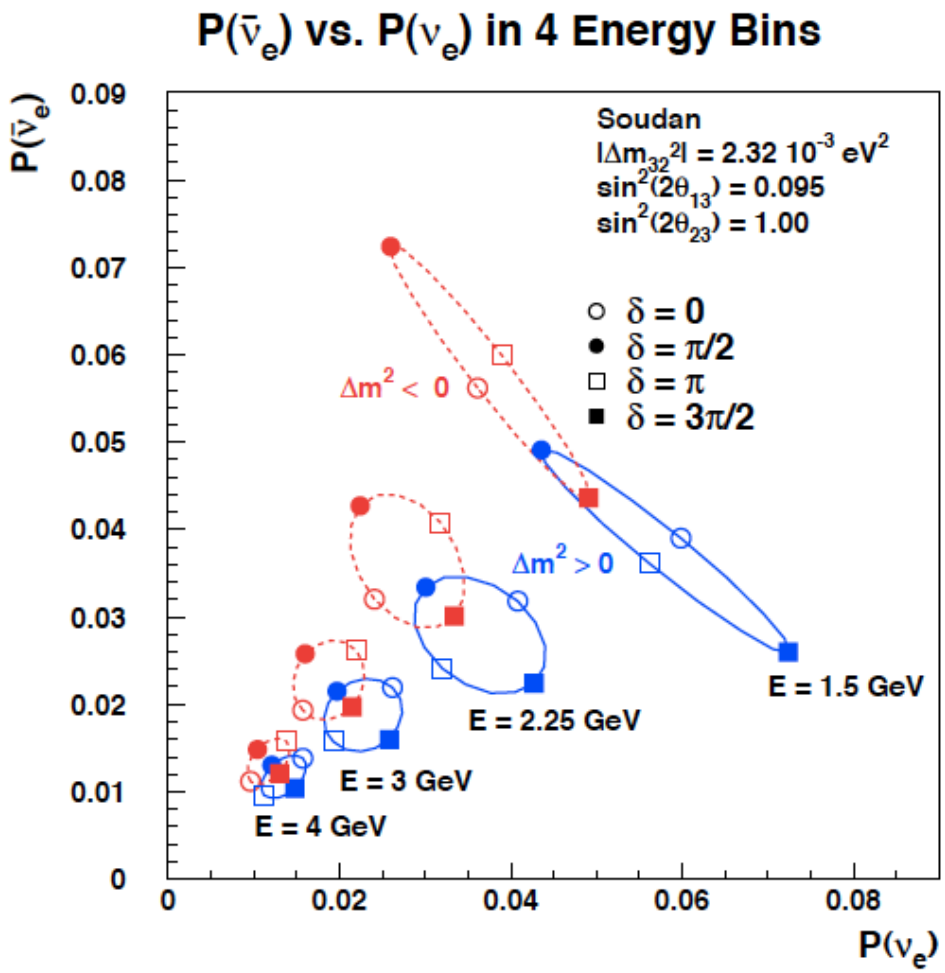
*1 Completion time of MR upgrade (assumed to be 2018) is suject to change, depending on economical situation, readiness and so on.

*2 LINAC upgrade completed

* Beam Energy 30GeV

From JPARC/KEK management

LAr on-axis in NuMI



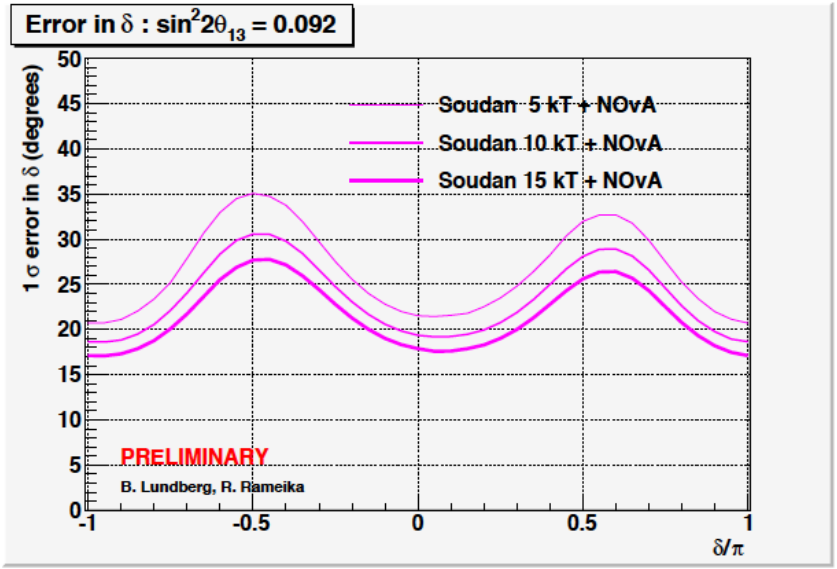
- ON-axis, LE WBB beam has spectral information
- Bi-probability plots are symmetric about the diagonal
- Invariance of oscillations to the exchange of

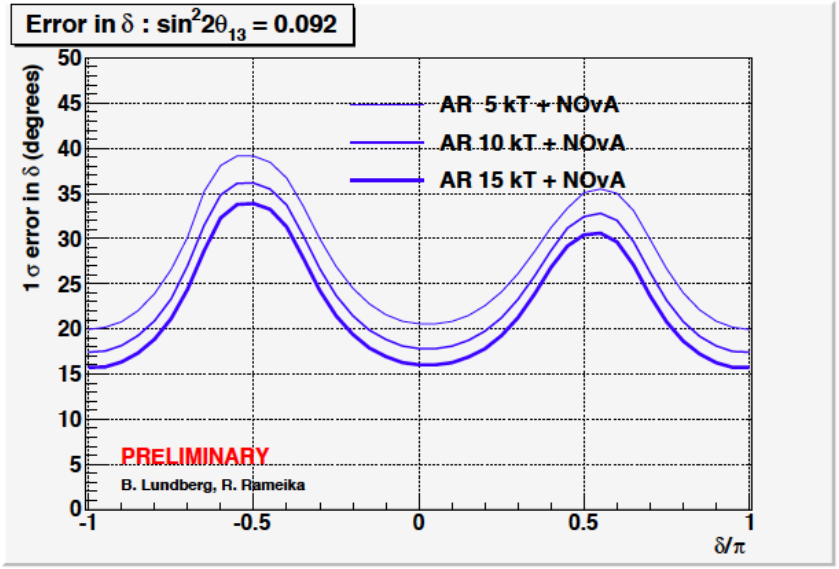
$$\nu \leftrightarrow \bar{\nu},$$

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

Error on δ_{CP} (knowing MH)

- Both Ash River and Soudan (together with NOVA) LAr detectors give similar resolution on δ_{CP}
- 5+5 years with NuMI LE beam + NOVA (3+3)





Conclusion

- MINOS has completed its program at very close to planned exposure (1.6×10^{21} P.O.T)
  - MINOS+ will pick up where it leaves off
  - Sterile neutrinos will be on the run (or not)
  - Any non-standard effects should be seen with MINOS+
- NuMI beam will be upgraded this year to deliver 700kW (6e20pot/y) for NOVA in the ME configuration
- Large Liquid Argon detector(s) on NuMI beamline are being actively considered by FNAL for short/medium term results
- Together with T2K, mass hierarchy should be known to at least 90% C.L. within the next decade (Atmospheric, T2K, NOVA, Other NuMI?)
- The NuMI beam will continue to contribute to front line knowledge for the next decade