Progress on experiments with existing facilities: *Neutrinos*

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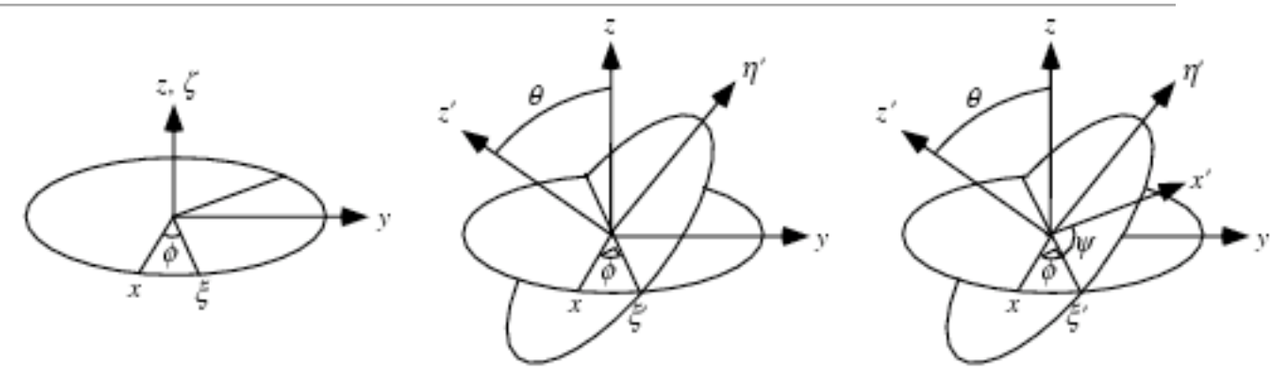
Indiana University

4th Project-X Workshop
November 9th, 2009
Fermilab

Neutrino oscillations

- Neutrinos of definite flavor do not have definite mass.
- The flavor eigenbasis is rotated wrt the mass eigenbasis

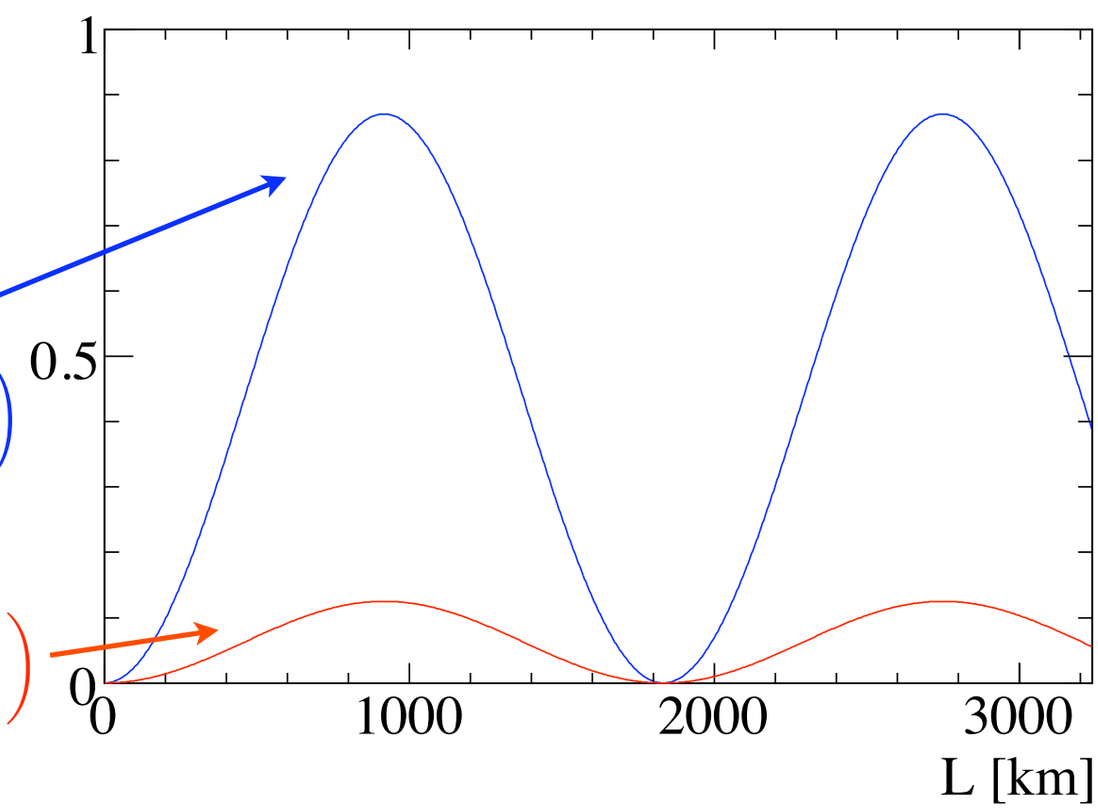


$$\left|\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix}\right\rangle = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & s_{13}e^{-i\delta}\\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\left|\begin{matrix}\nu_1\\ \nu_2\\ \nu_3\end{matrix}\right\rangle$$

- Interference between mass states means a neutrino produced as a ν_μ can be detected later as a ν_τ or ν_e

$$P_{\nu_\mu\to\nu_\tau} = \sin^2 2\theta_{23}\cos^4\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{23}[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

$$P_{\nu_\mu\to\nu_e} = \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{23}[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$



SNO/SK/Radiochemical/KamLAND

What are the solar neutrino oscillation parameters?

SK solar neutrino flux:

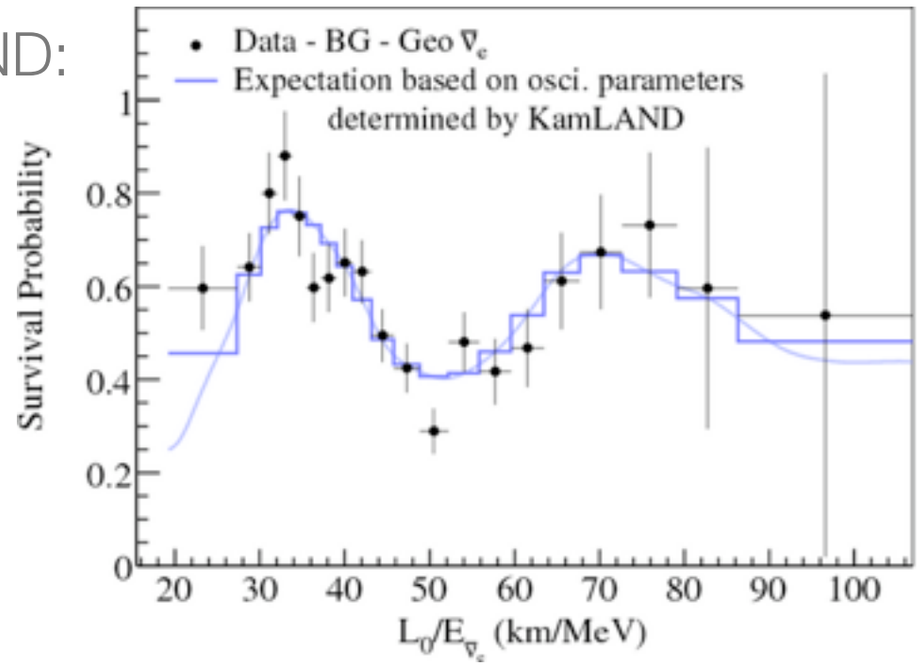
$$(2.38 \pm 0.05(\text{stat.})^{+0.16}_{-0.15}(\text{sys.})) \times 10^6 \ \text{cm}^{-2}\text{sec}^{-1}$$

SNO solar neutrino fluxes:

$$\Phi_{^8\text{B}} = 5.046\,^{+0.159}_{-0.152}(\text{stat})\,^{+0.107}_{-0.123}(\text{syst})$$

$$\Phi_{\text{NC}} = 5.140\,^{+0.160}_{-0.158}(\text{stat})\,^{+0.132}_{-0.117}(\text{syst})$$

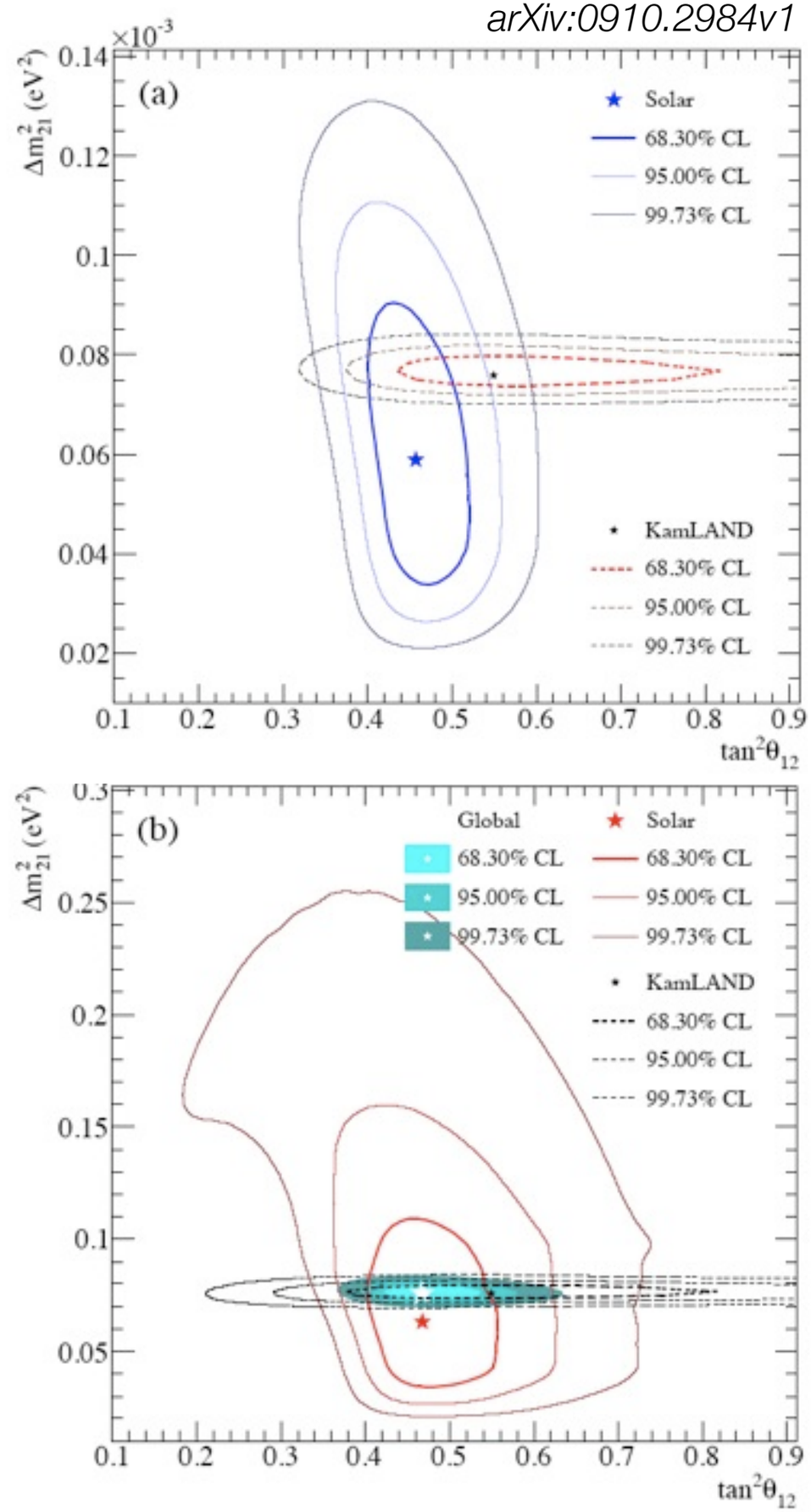
KamLAND:



$$\theta_{12} = 34.06\,^{+1.16}_{-0.84} \text{ degrees}$$

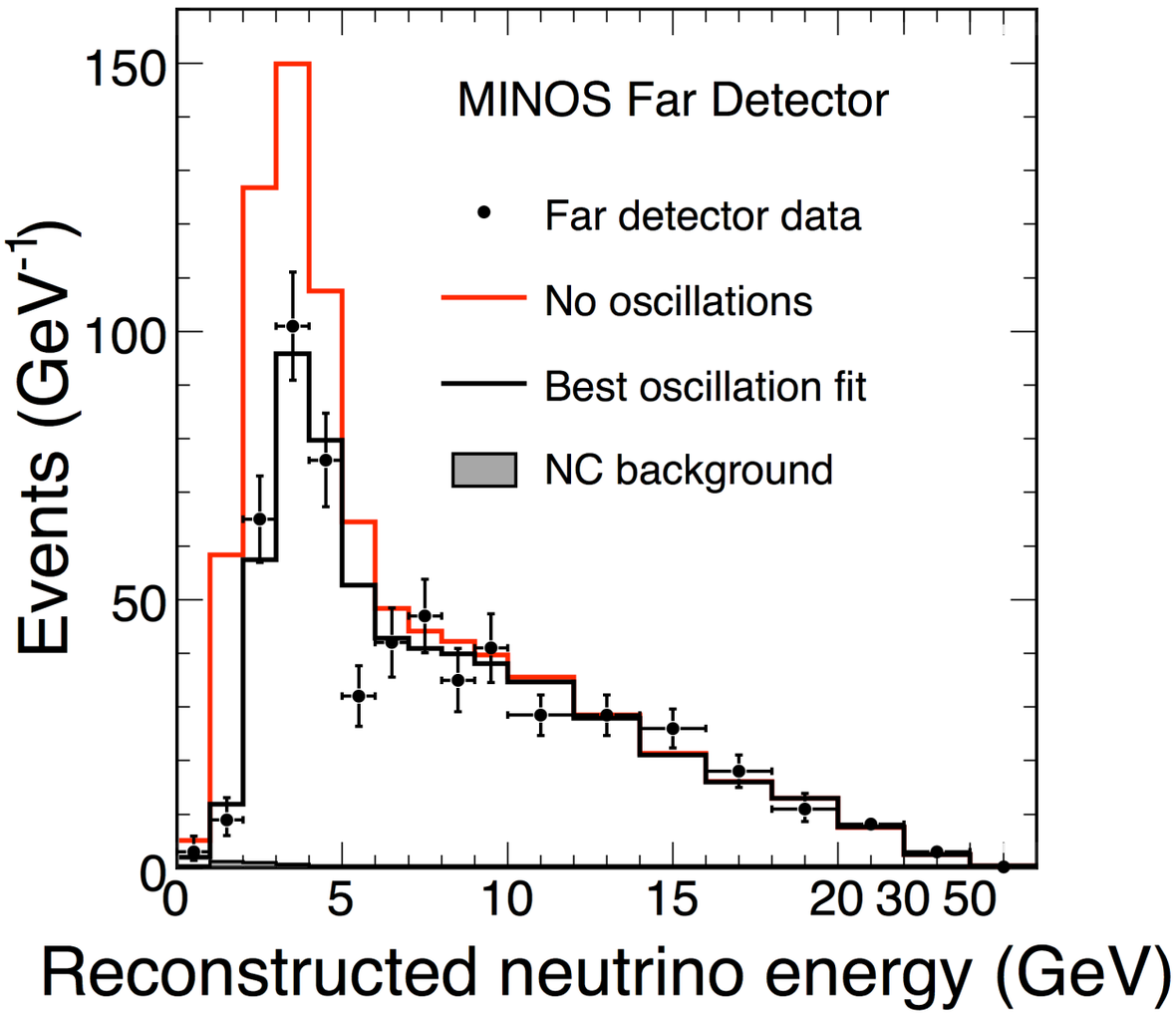
$$\Delta m^2_{21} = 7.59\,^{+0.20}_{-0.21} \times 10^{-5} \text{ eV}^2$$

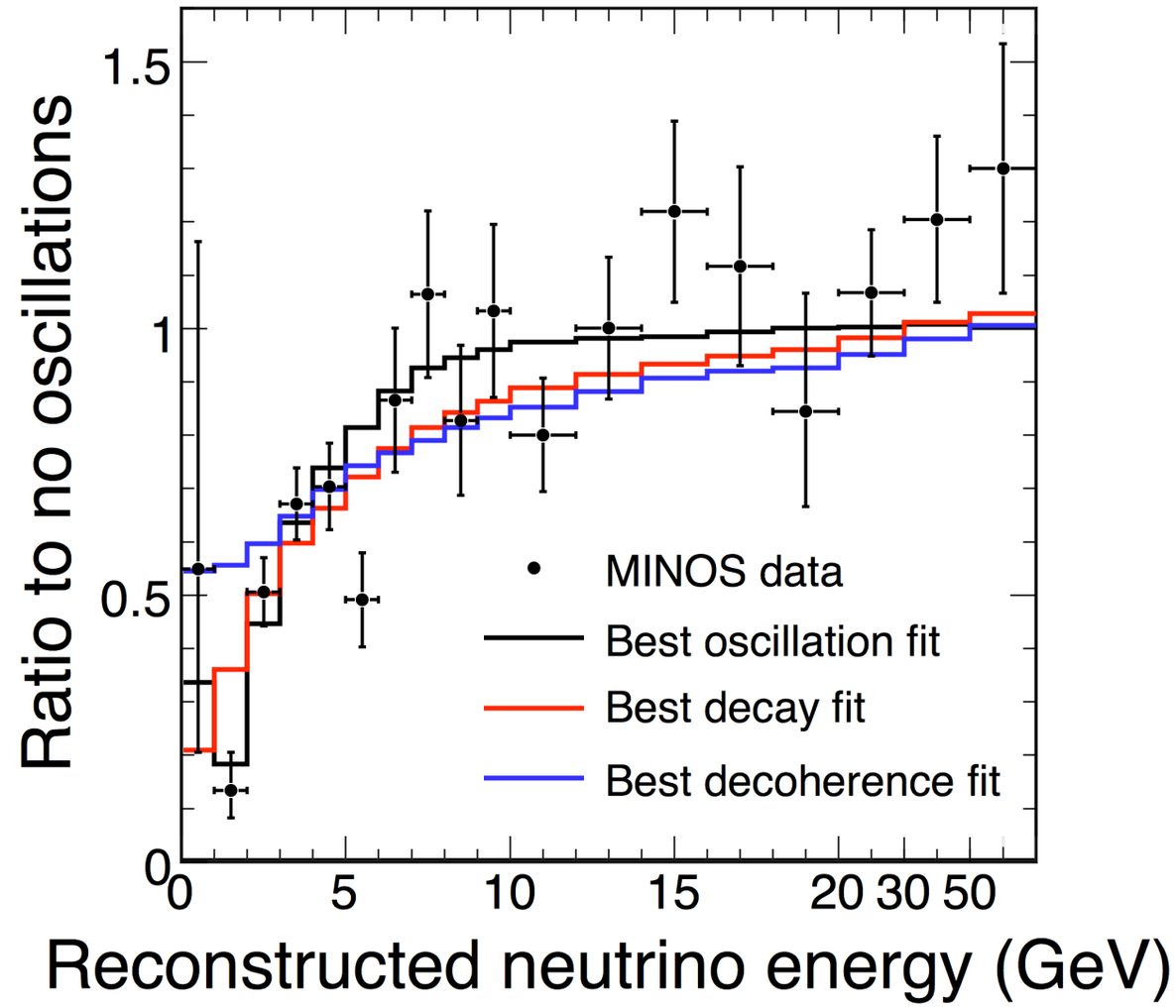
arXiv:0910.2984v1



MINOS

What are the parameters of muon neutrino oscillation?





848 events observed / 1065 expected

$|\Delta m^2| = 2.43 \pm 0.13$ meV^2 (5% measurement)

$\sin^2 2\theta > 0.90$ (90% CL)

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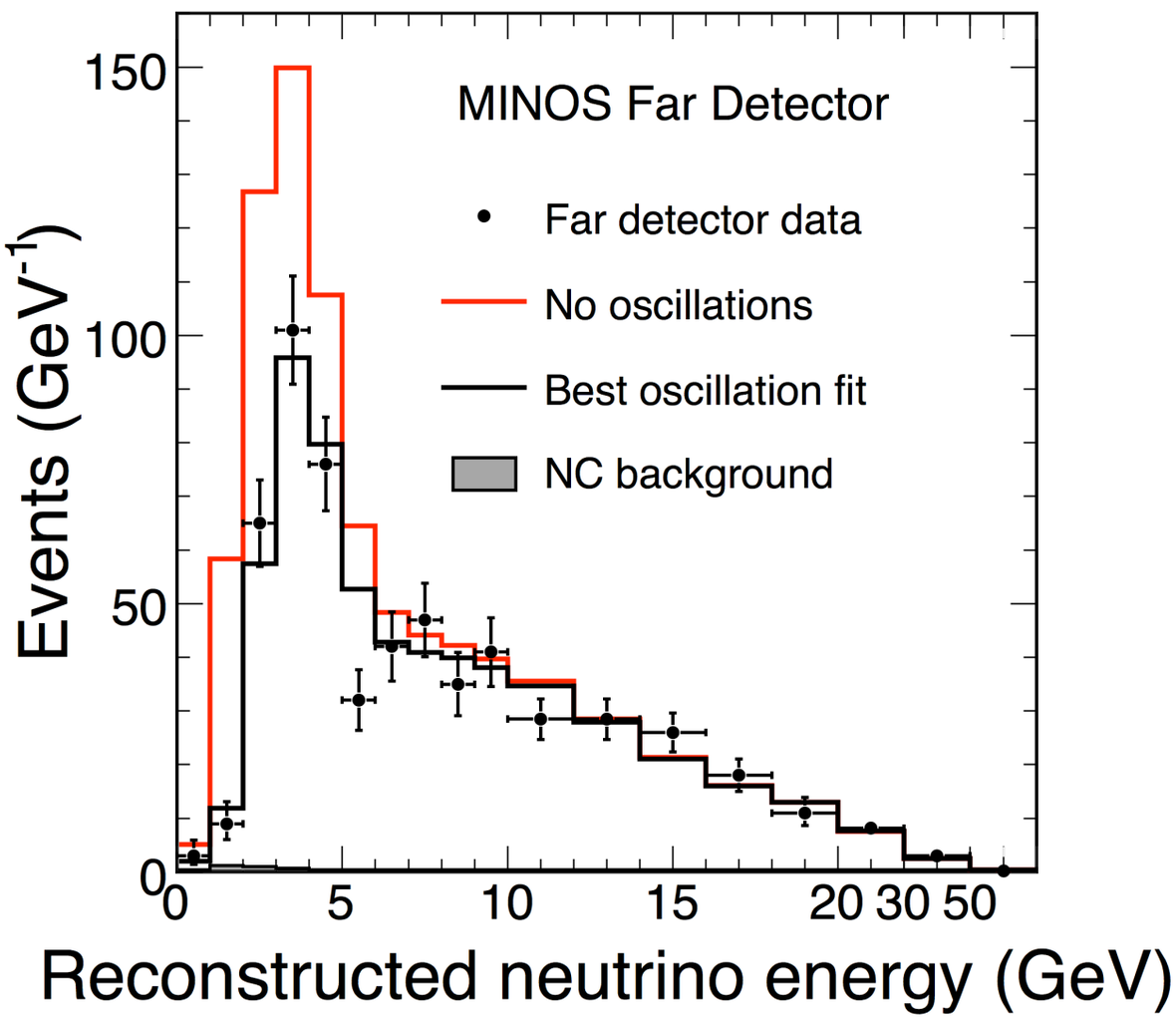

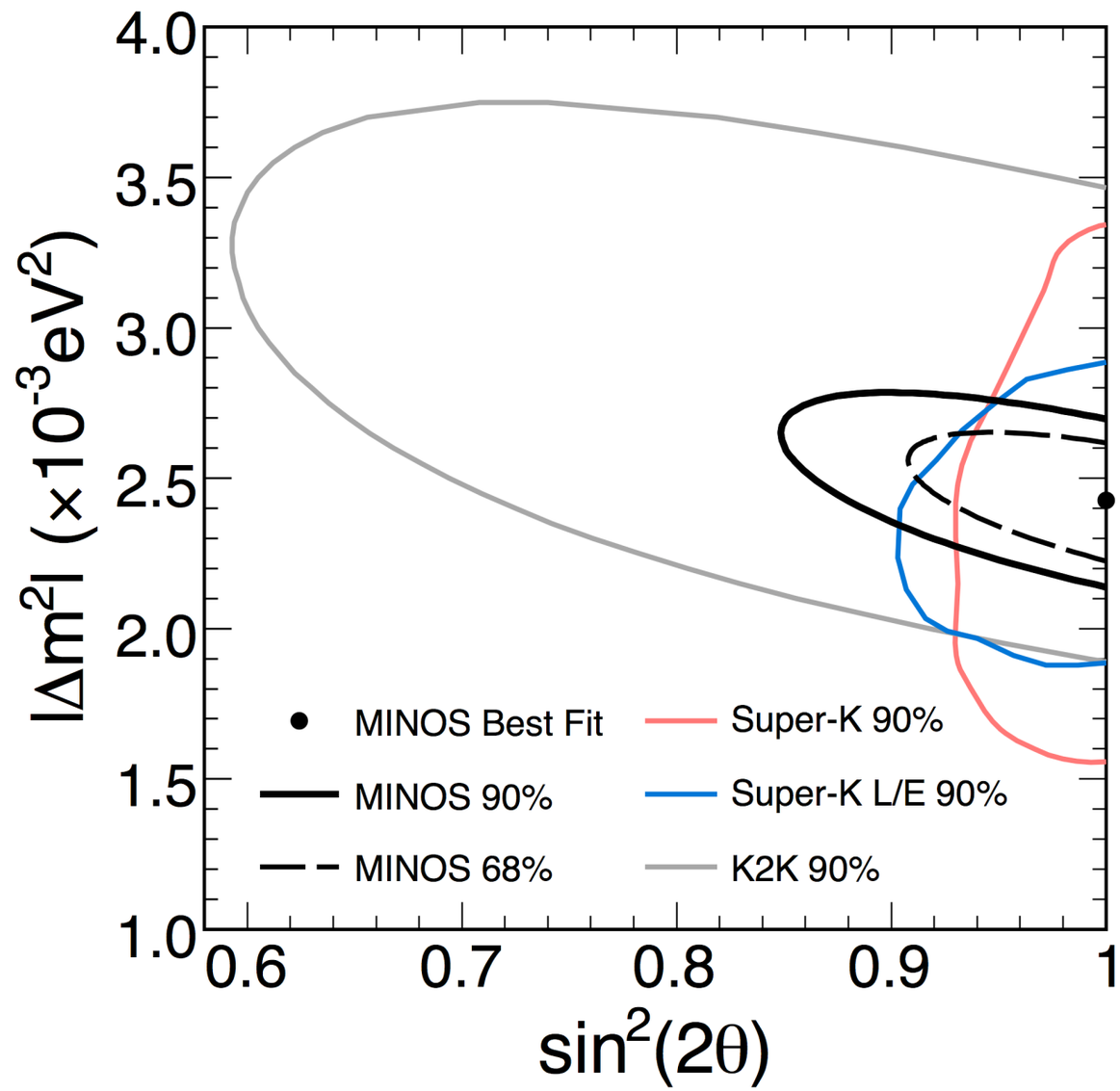

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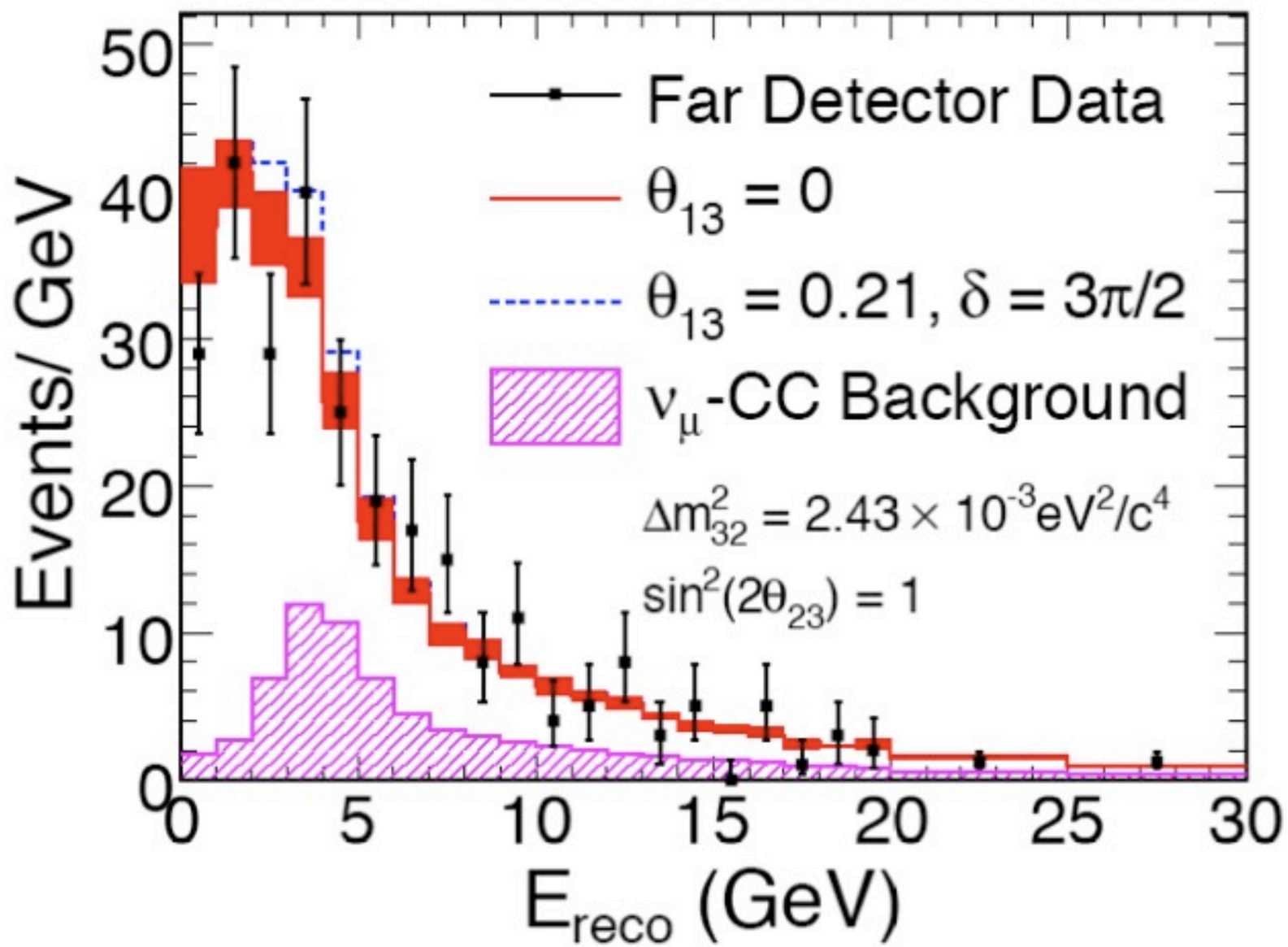
Is the total active neutrino flux conserved?



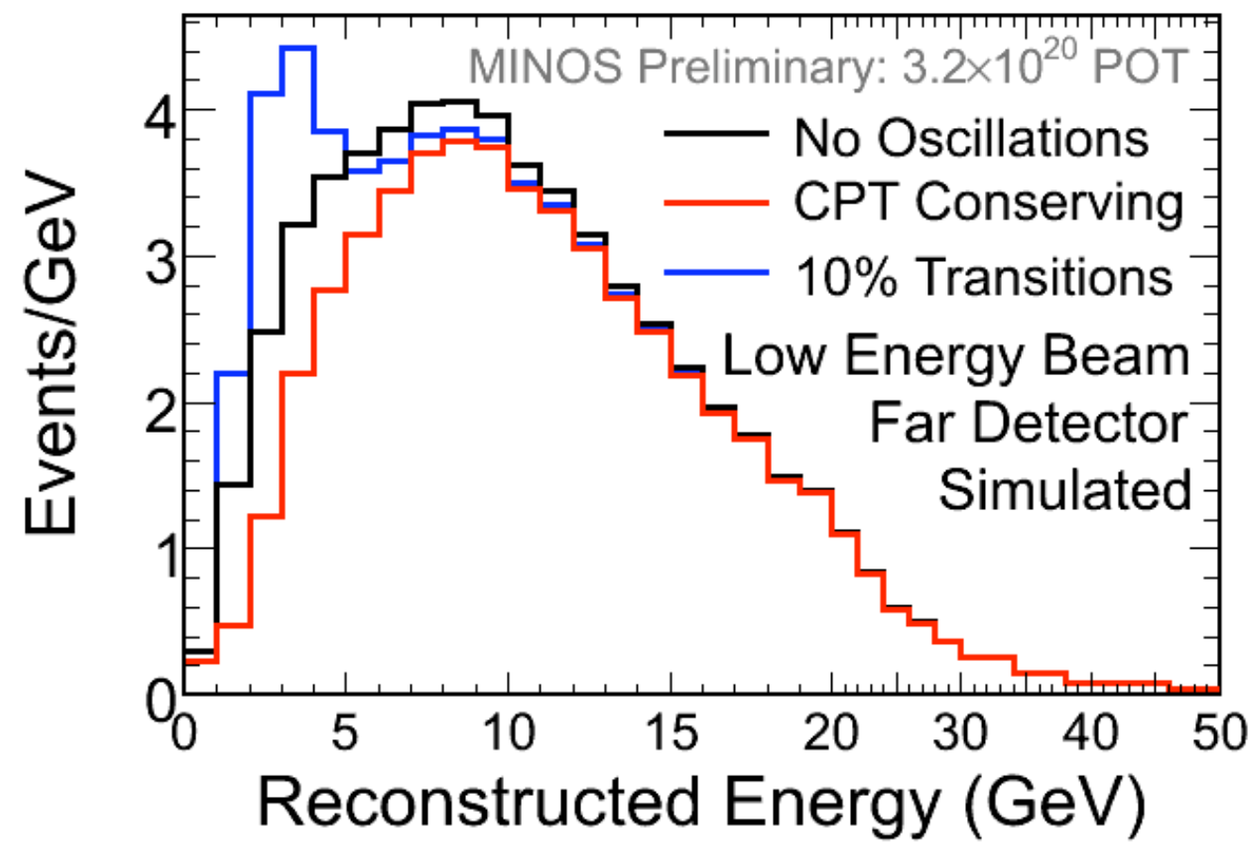
100 events observed / 115 expected (0-3 GeV)

Limits fraction of muon neutrinos converting to sterile neutrinos to less than 68% at 90% CL.

MINOS
Do neutrinos convert to anti-neutrinos? $\nu_\mu \rightarrow \bar{\nu}_\mu$?

The NuMI neutrino beam used by MINOS is a nearly pure muon neutrino beam 91.7% ν_μ, 7% $\bar{\nu}_\mu$, 1.3% ν_e+$\bar{\nu}_e$.

Since MINOS is a magnetized detector it can measure ν_μ and ν_μ separately and ask if any of the neutrinos we produced convert to anti-neutrinos.



<u>Observe:</u> 42 ν_μ events
<u>Expect:</u>
64.6 ± 8.0 (stat.) ± 3.9 (syst.)
w/o oscillations
57.3 ± 7.6 (stat.) ± 3.6 (syst.)
w/ oscillations same as neutrinos

No excess: **$P(\nu_\mu \rightarrow \bar{\nu}_\mu) < 2.6\%$ [90% C.L]**

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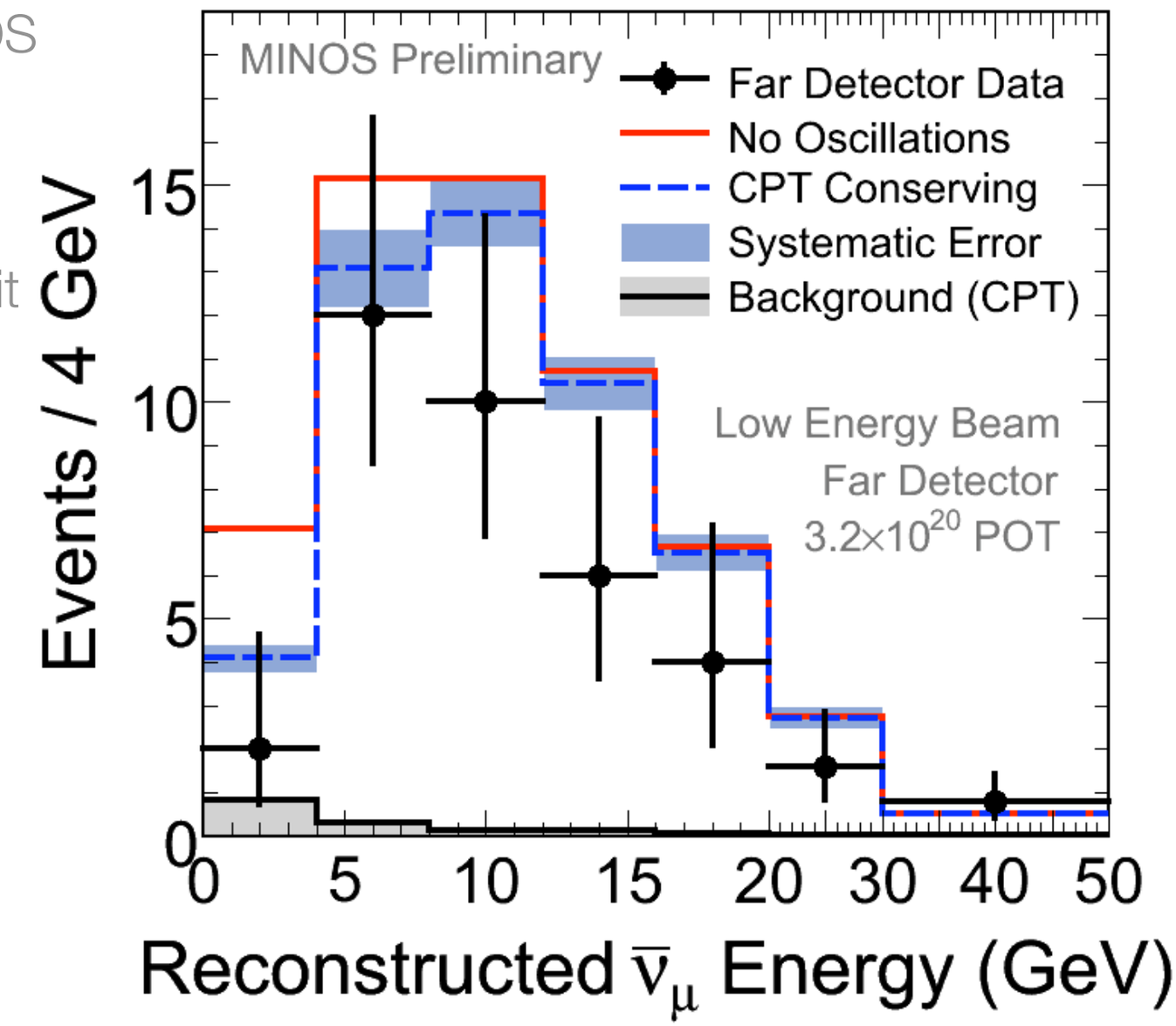
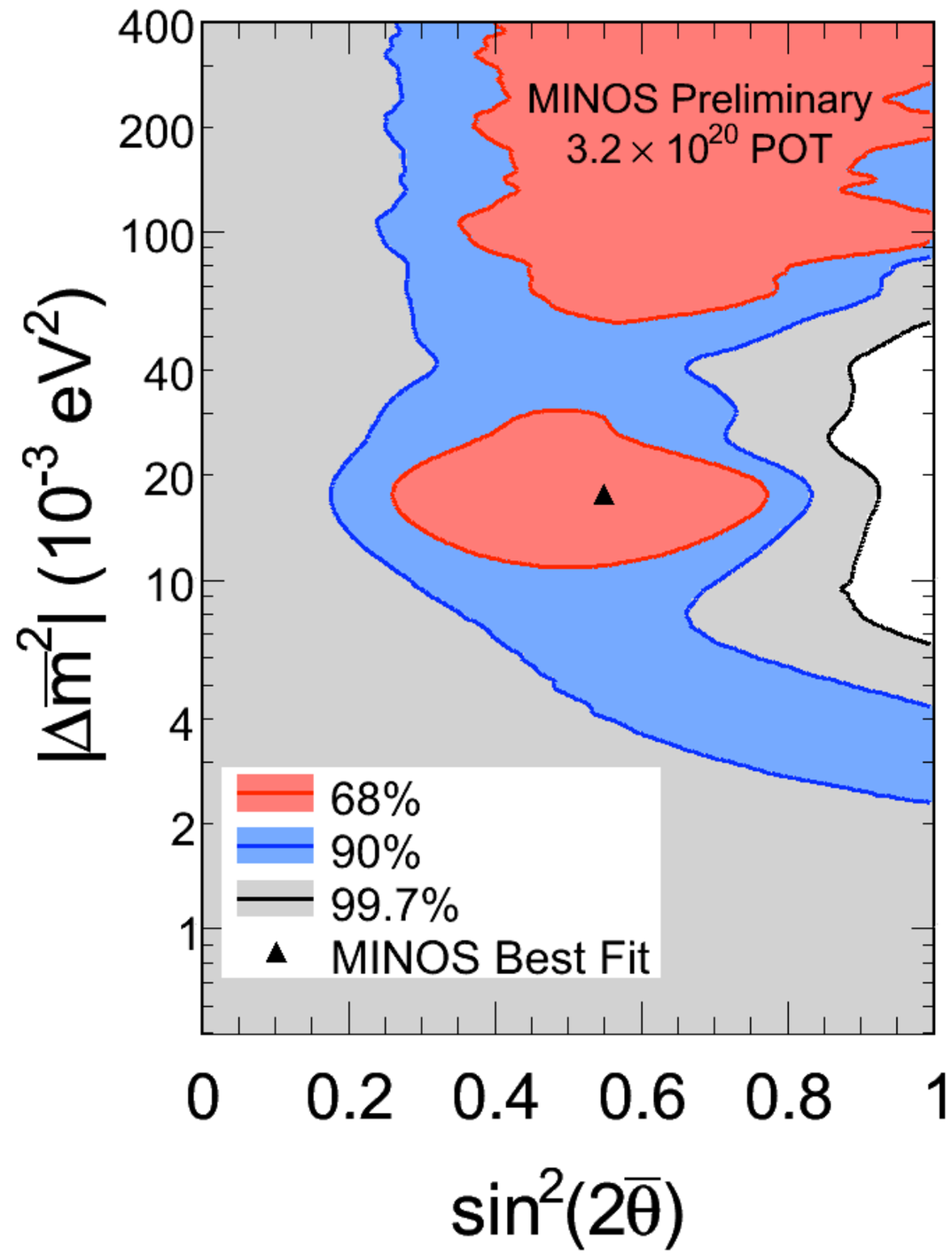


MINOS

Do anti-neutrinos oscillate in the same way as neutrinos?

$$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = P(\nu_\mu \to \nu_\mu)?$$

- As best we can tell, yes [90% CL].
- This is not the optimal setup for measuring anti-neutrino oscillations. Optimal setup is to reverse the horn focus and run with anti-neutrinos as the majority species. That measurement is currently underway with MINOS and will continue until March 2010.



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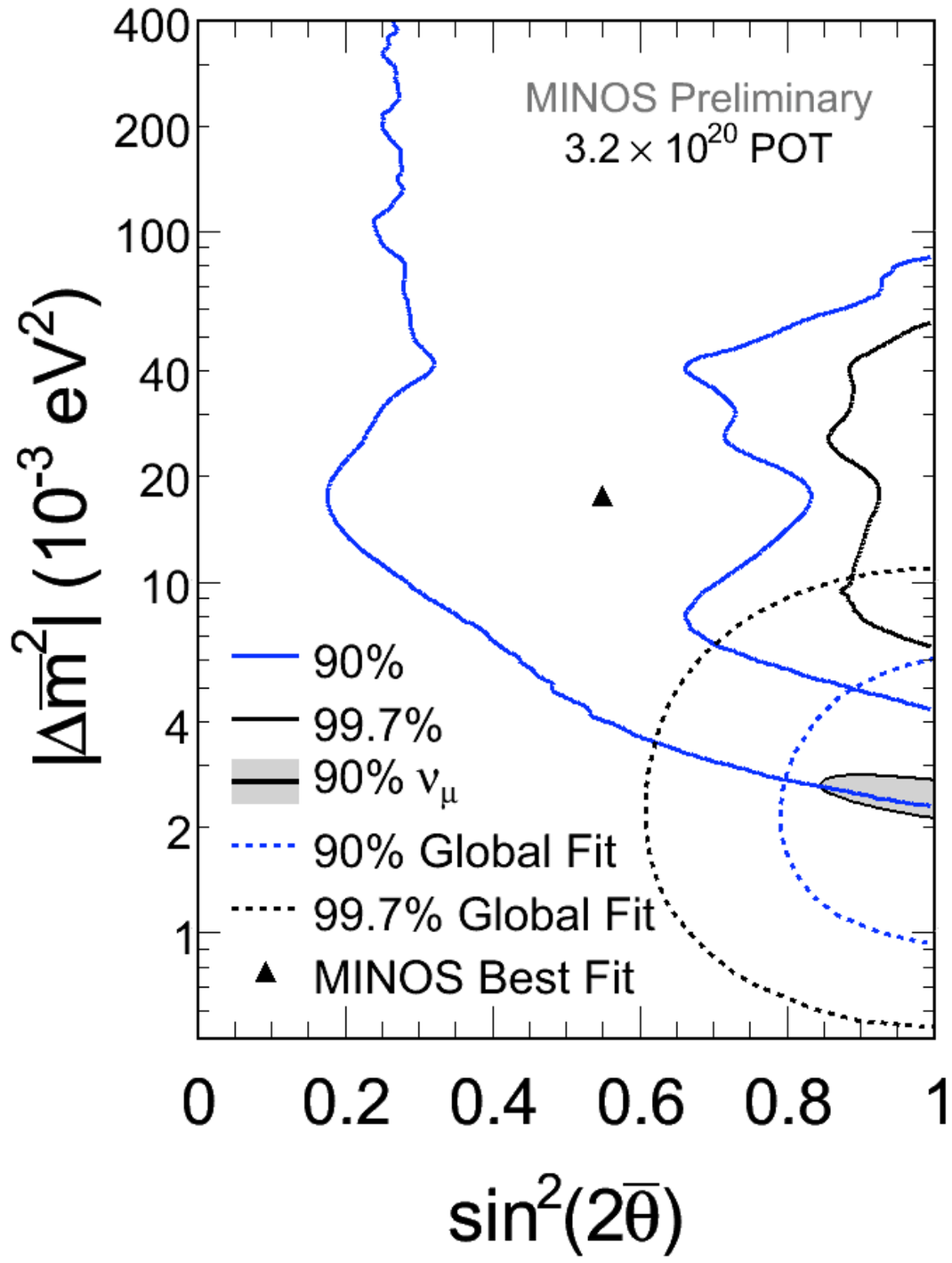

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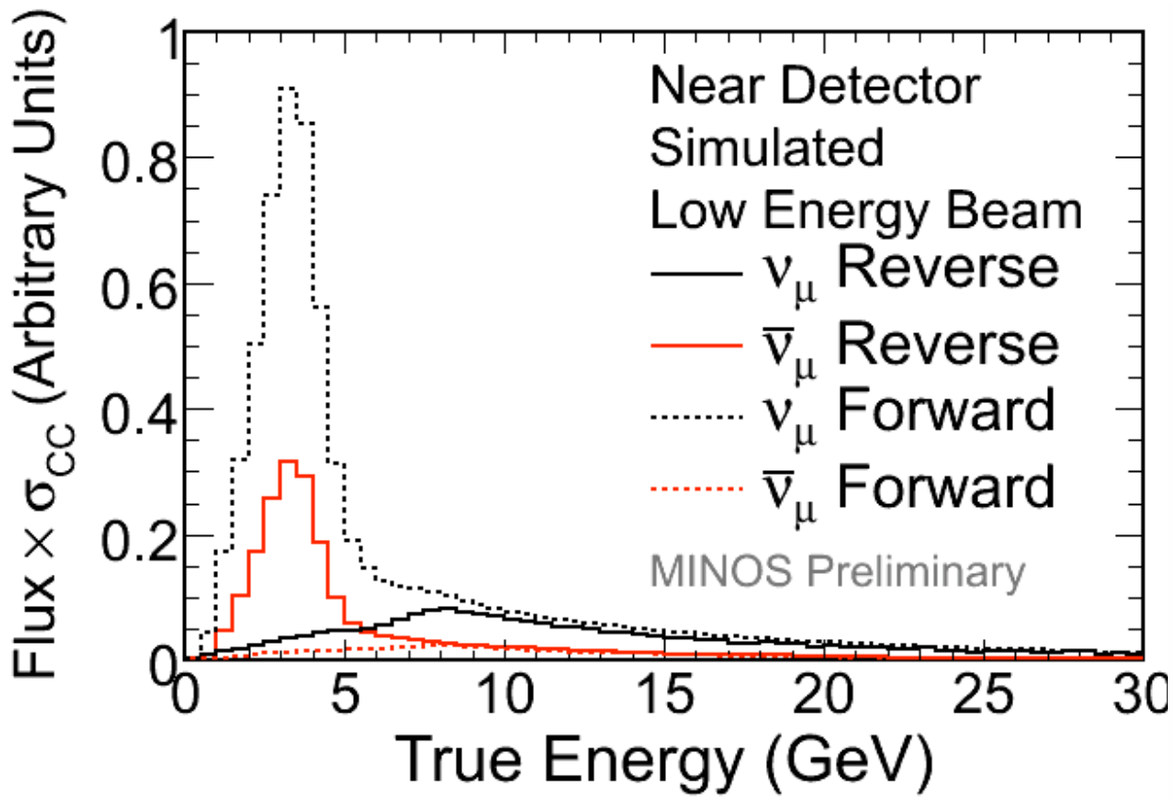
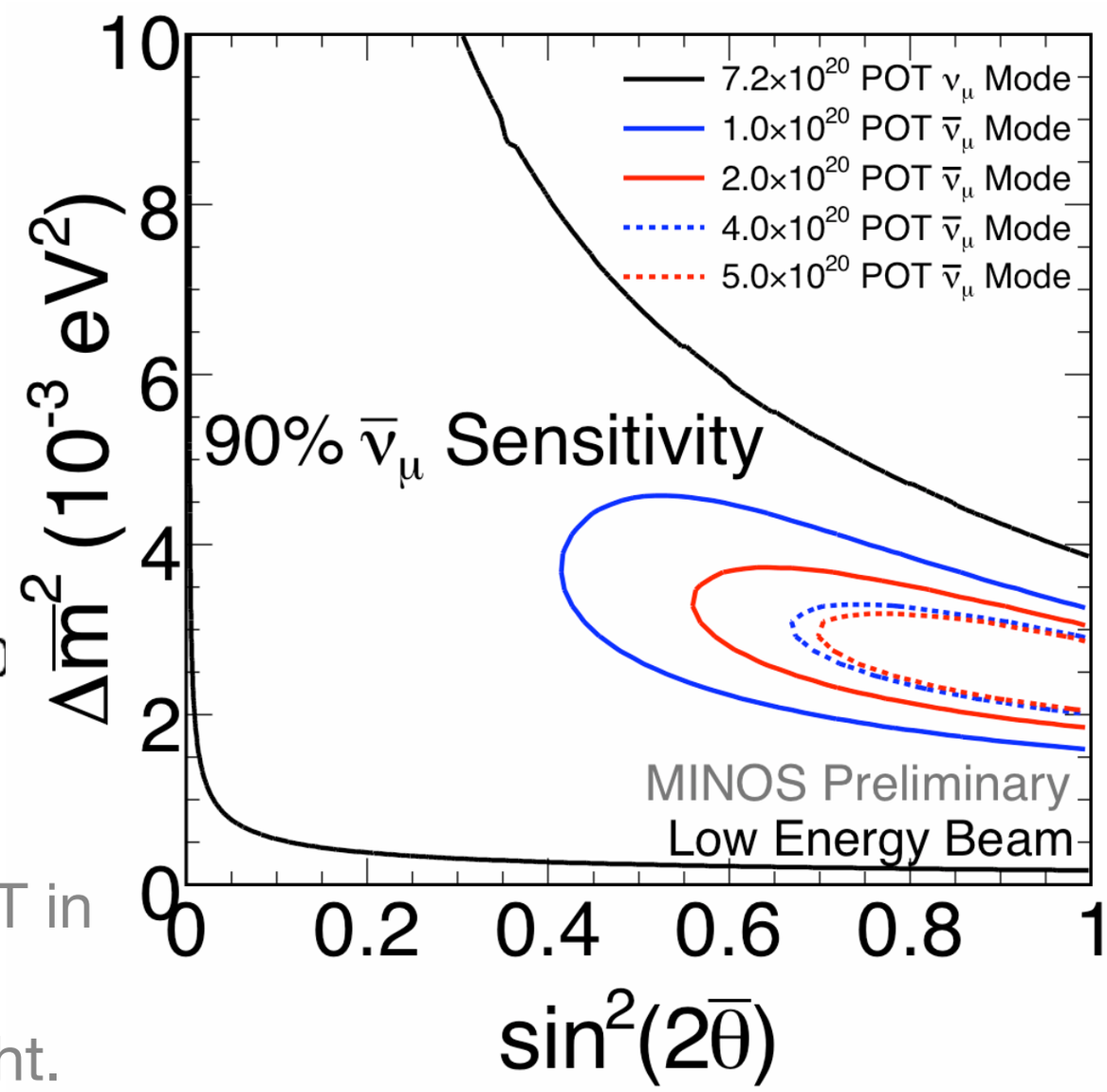
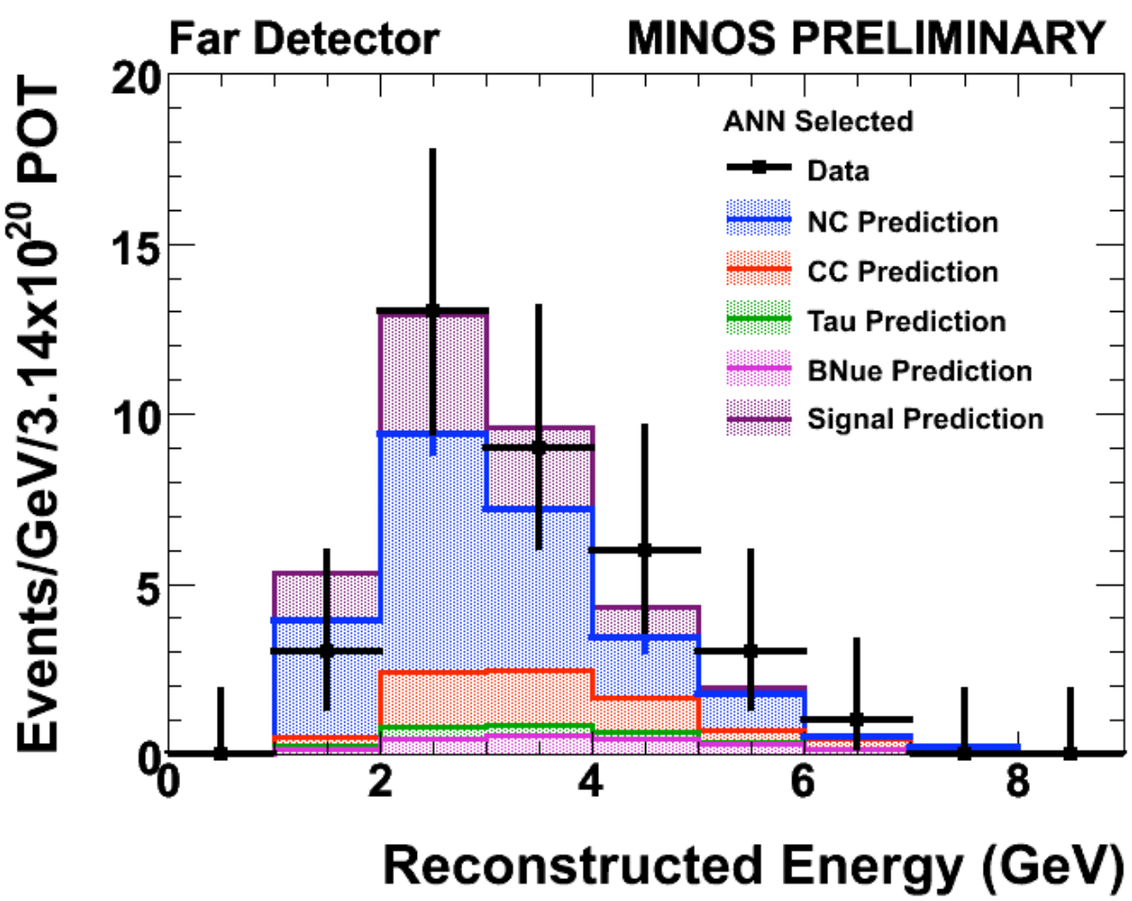
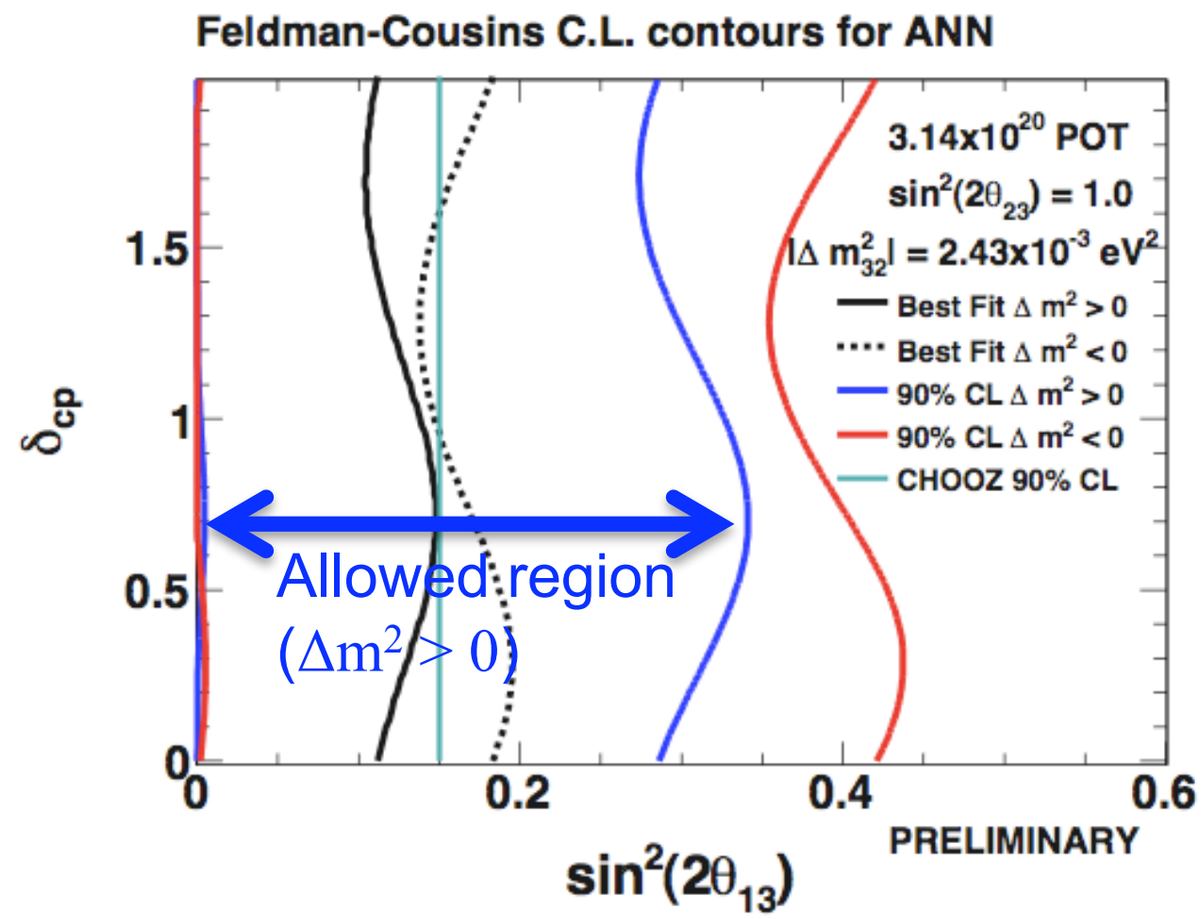




- In 2009 run (September - March) MINOS will accumulate ~1.5E20 POT in anti-neutrino beam. Somewhere between blue and red in figure at right.
- Enables ~30% measurement of $\Delta\bar{m}^2$

MINOS
Do muon neutrinos convert to electron neutrinos?





3.2E20 POT exposure
35 events measured / 27 ± 2 (syst.) expected
1.5 sigma excess
$\sin^2 2\theta_{13} < 0.29$ (0.49) normal (inverted) hierarchy @ 90% CL
7E20 POT in the can. Sensitivity will exceed CHOOZ or provide >90% CL signal

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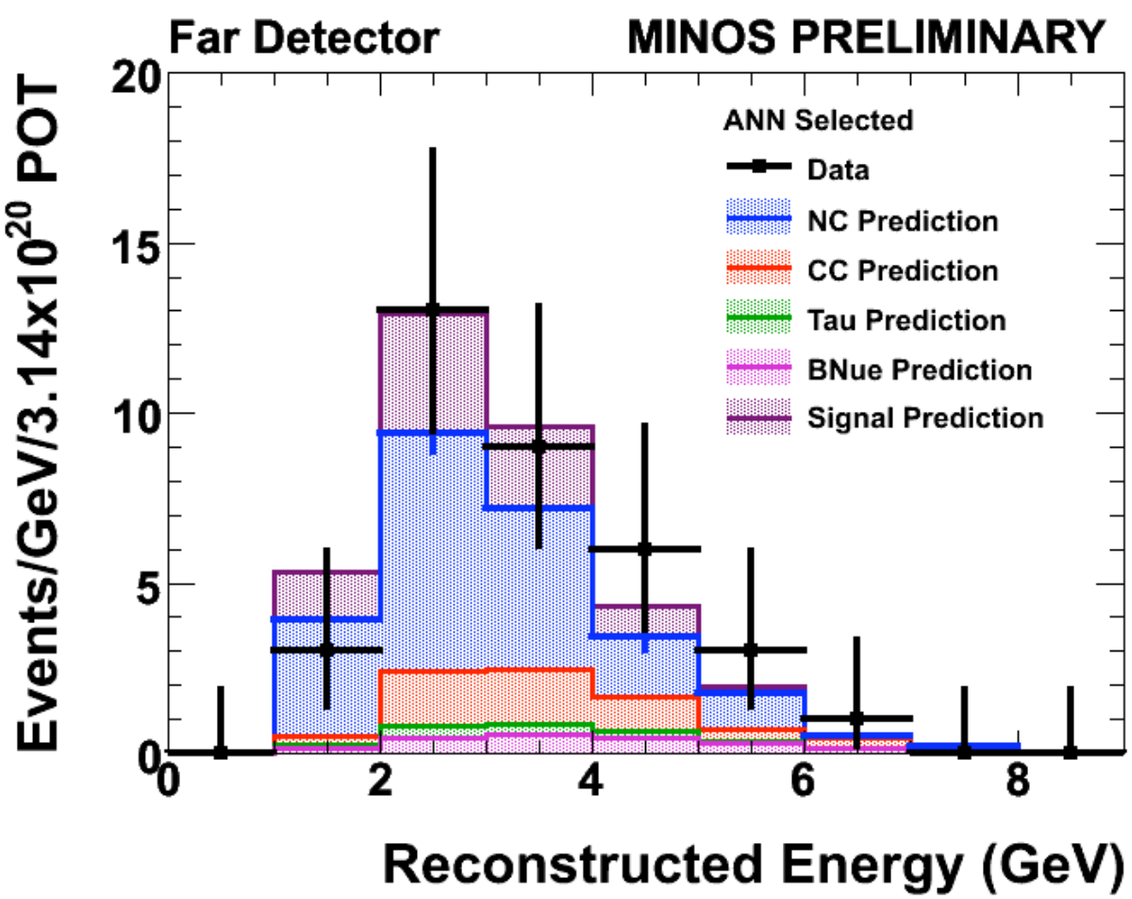

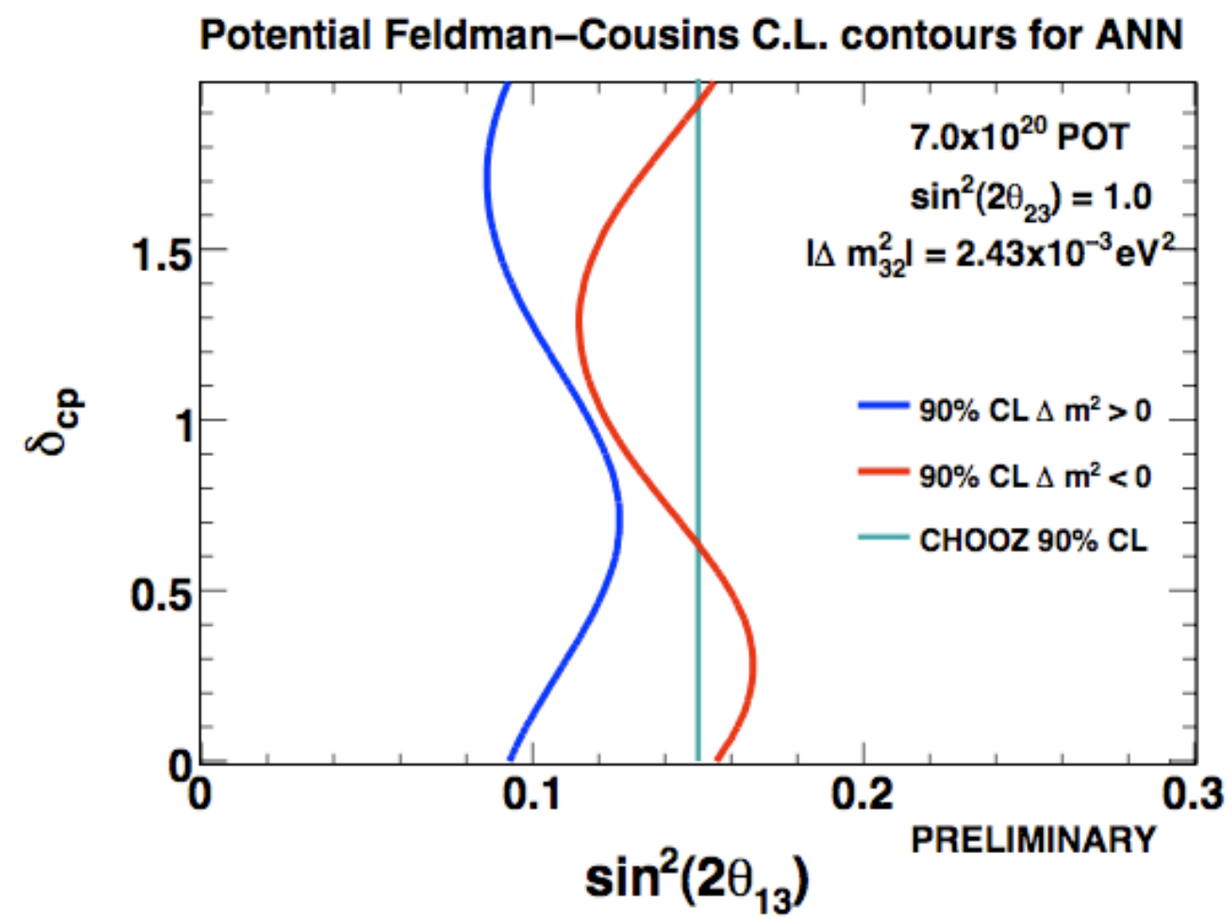

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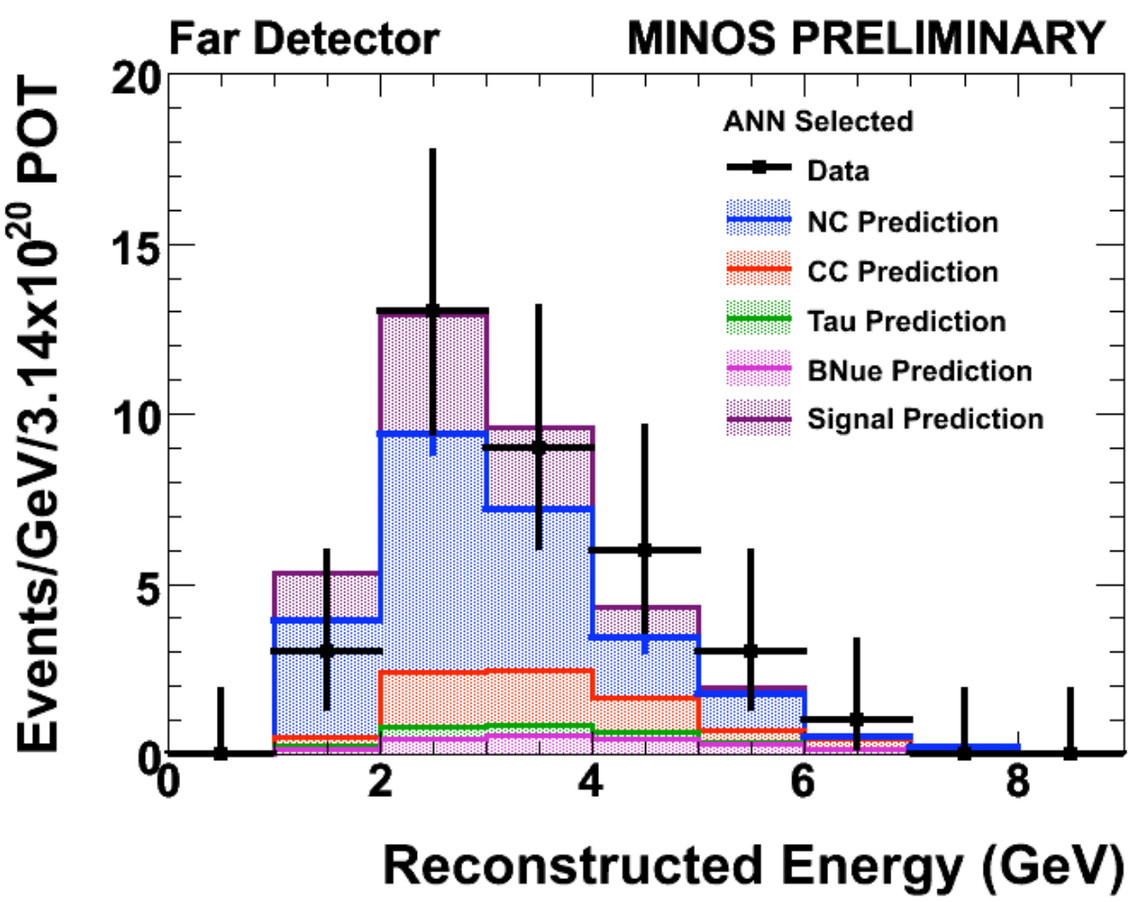

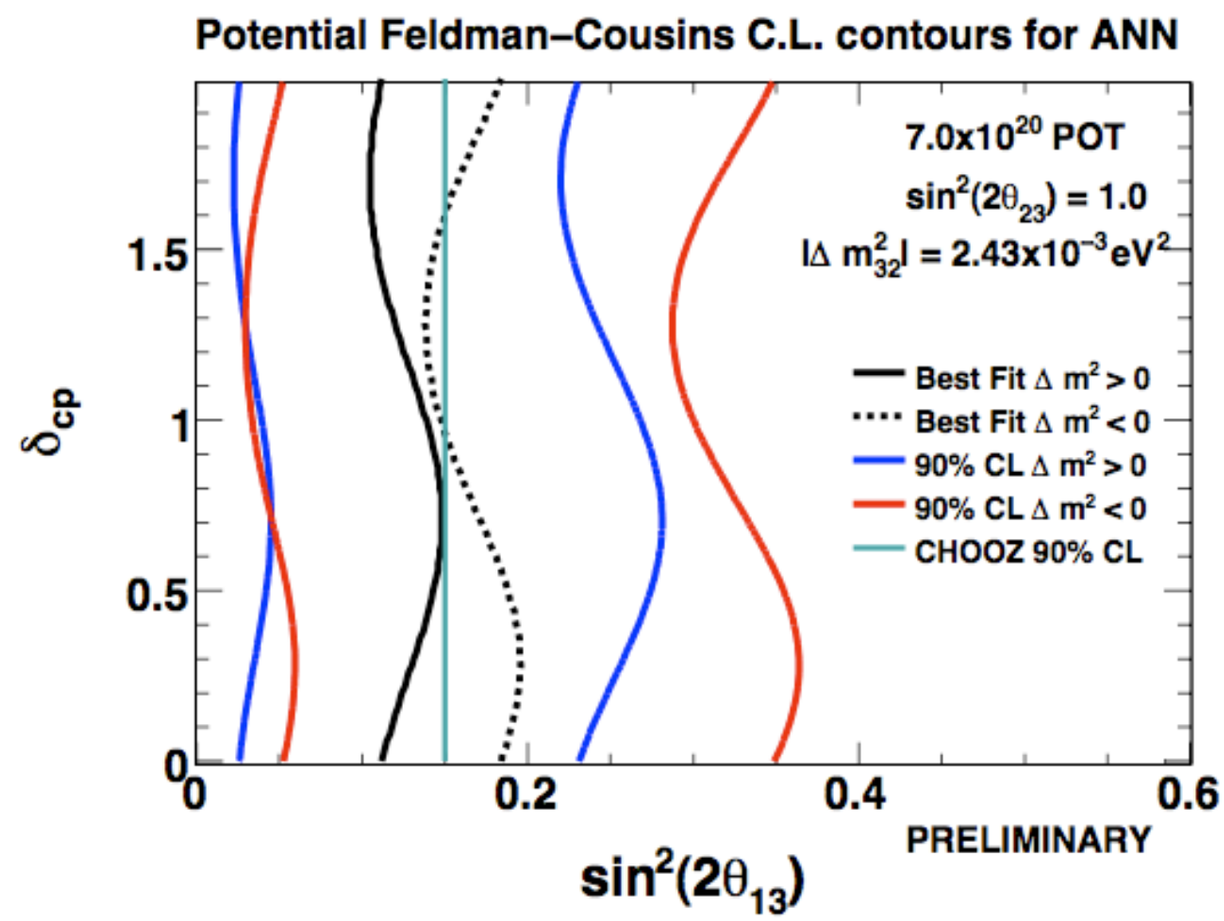

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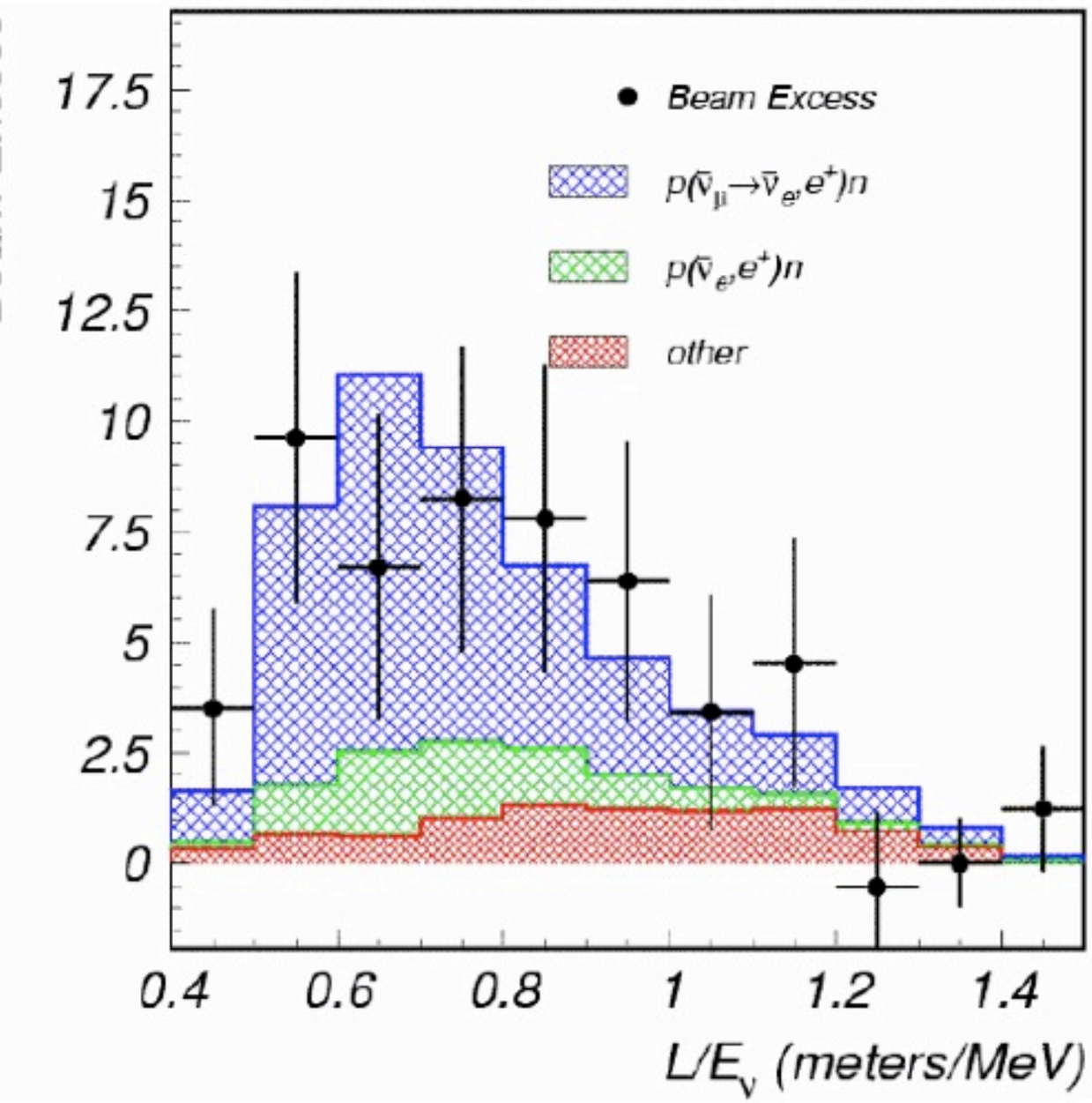
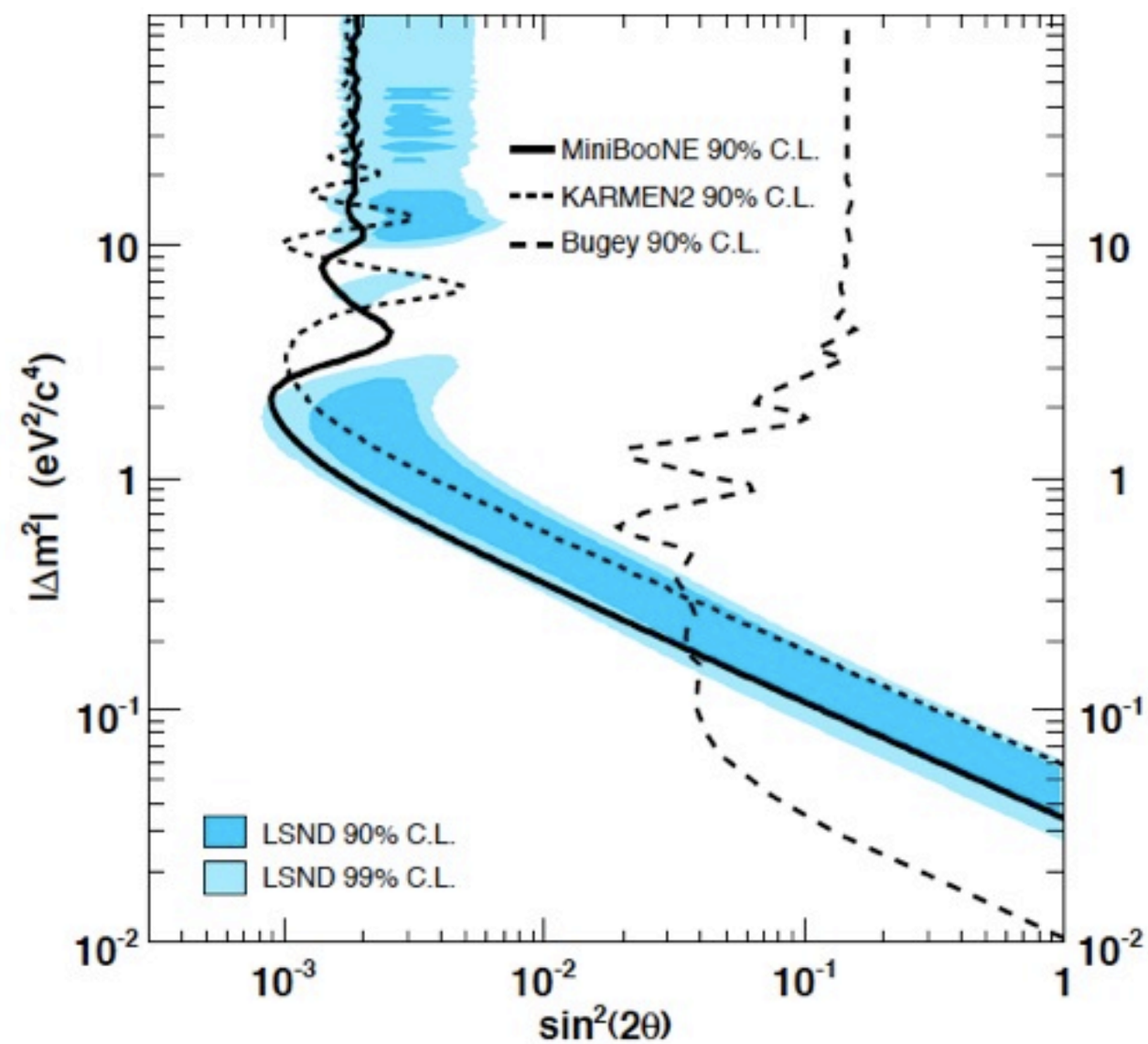
MiniBooNE
What produced the excess seen by LSND?





- Not conventional neutrino oscillations (98% CL)
- Low energy excess remains unexplained

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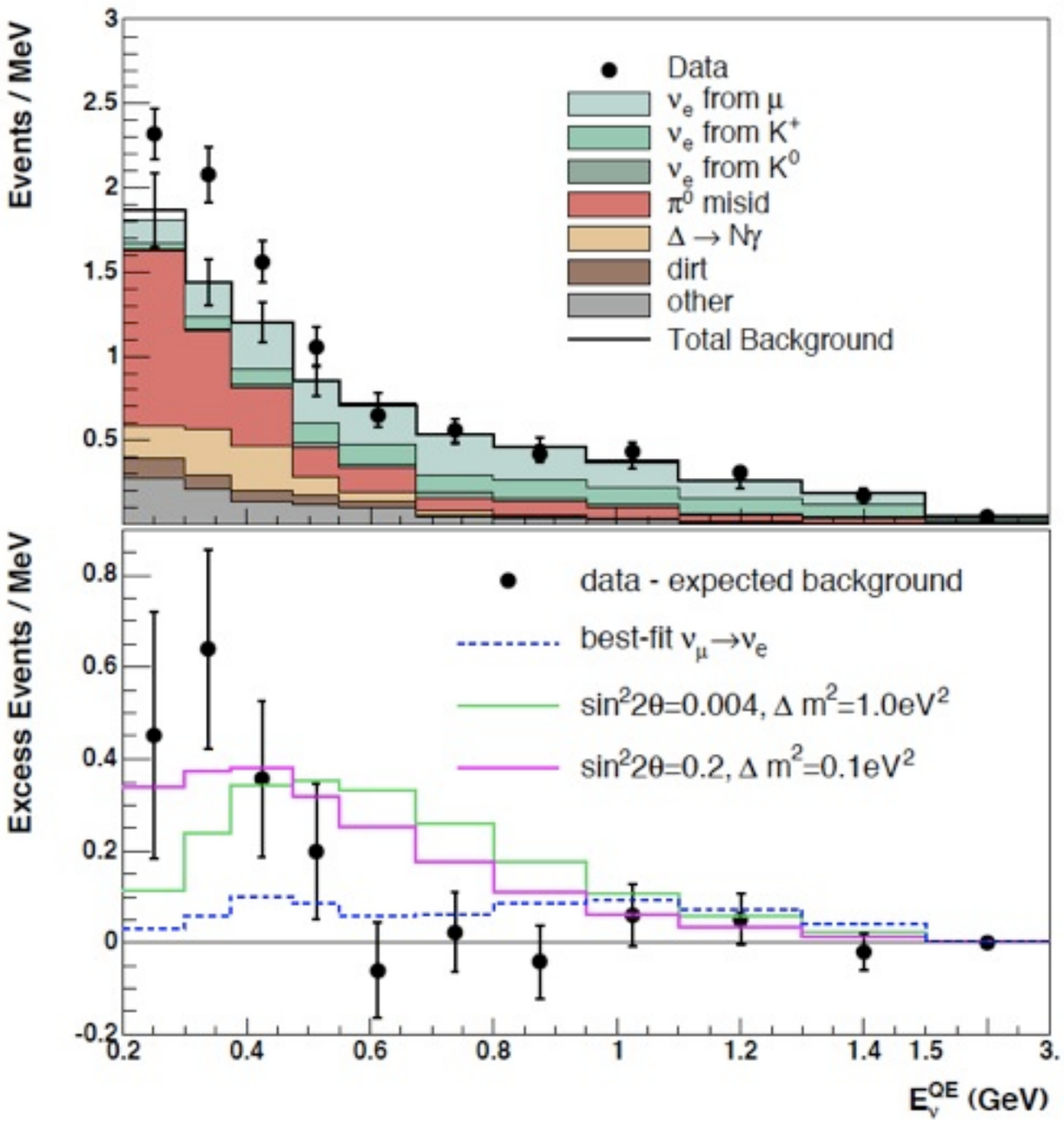

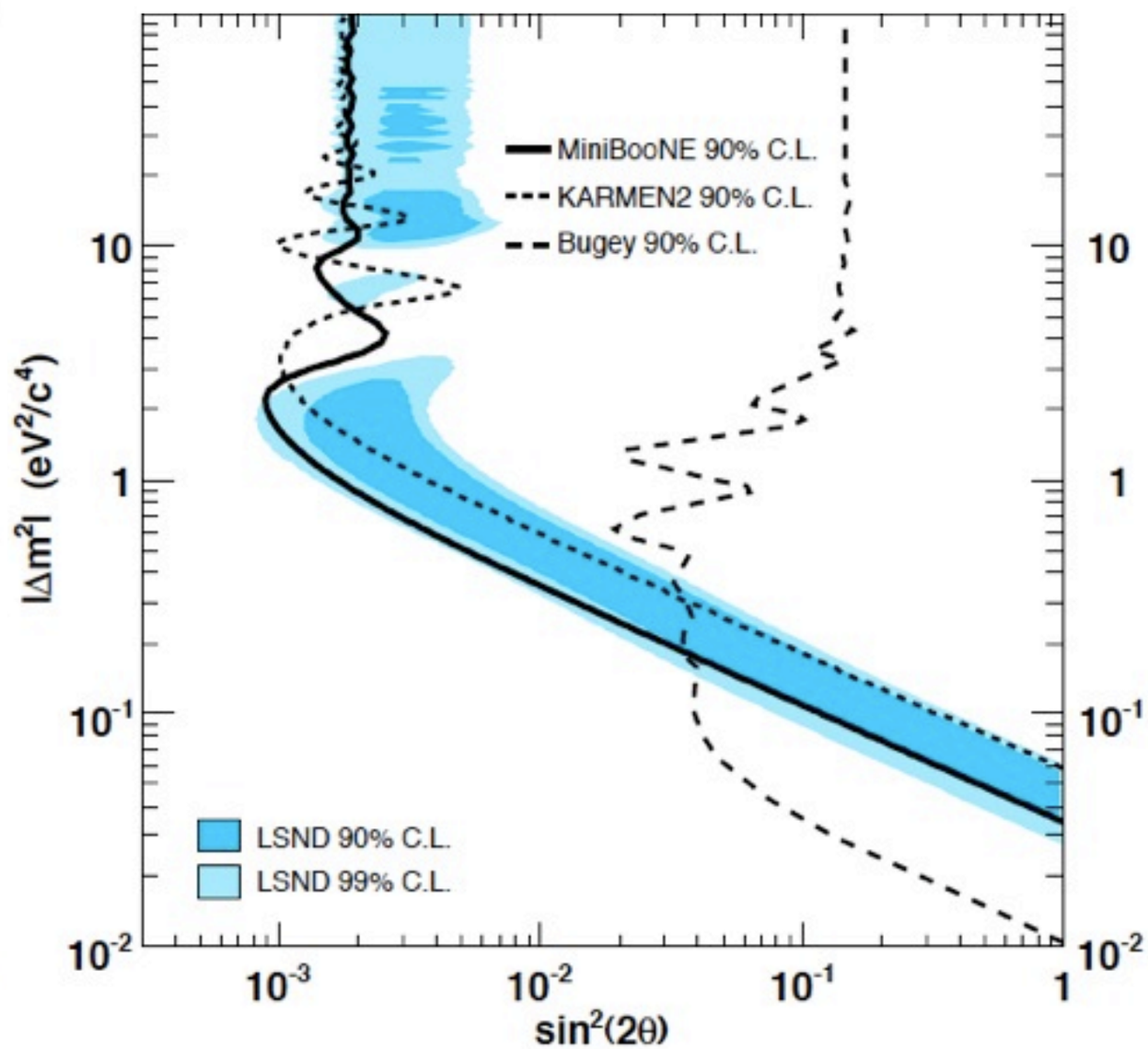

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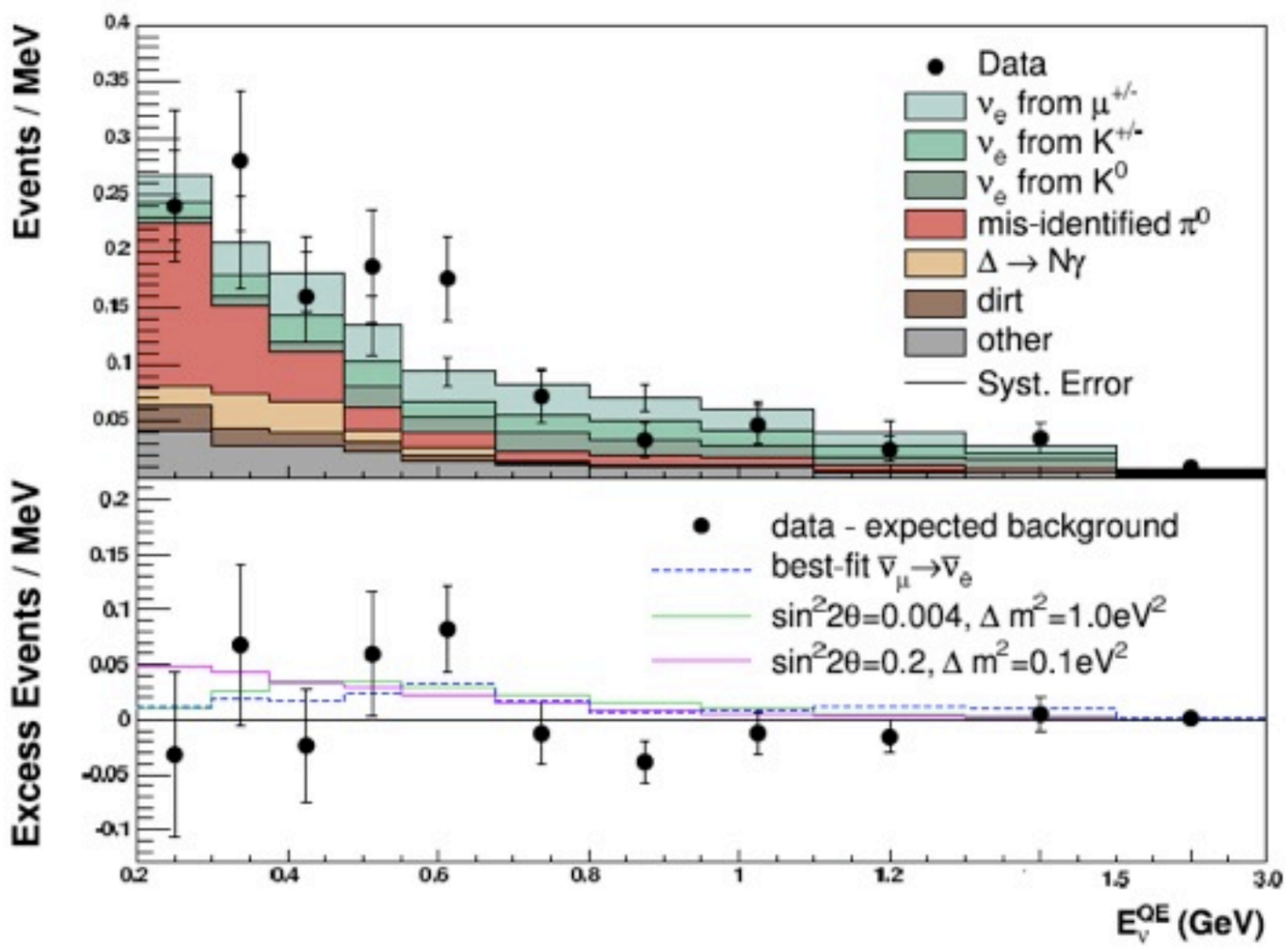
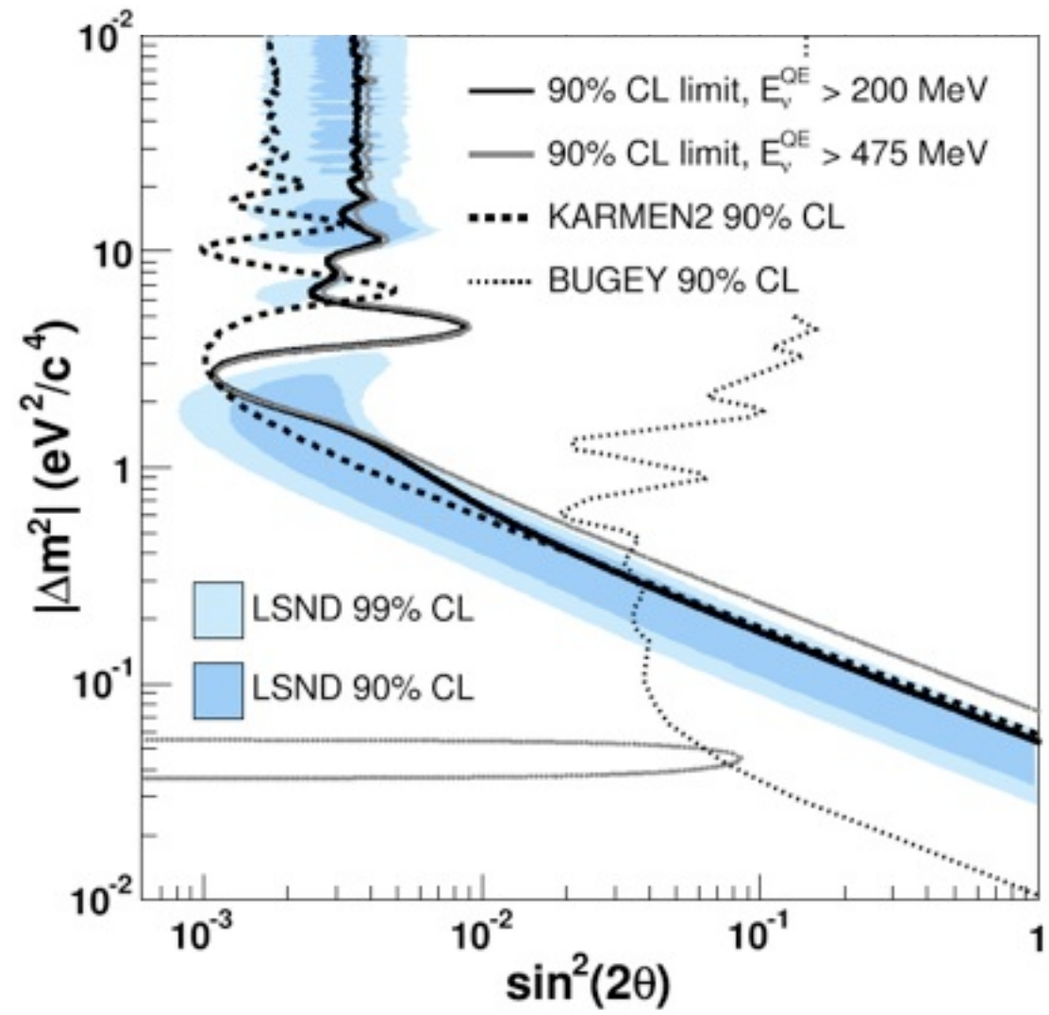
MiniBooNE
Could LSND signal be only in anti-neutrinos?

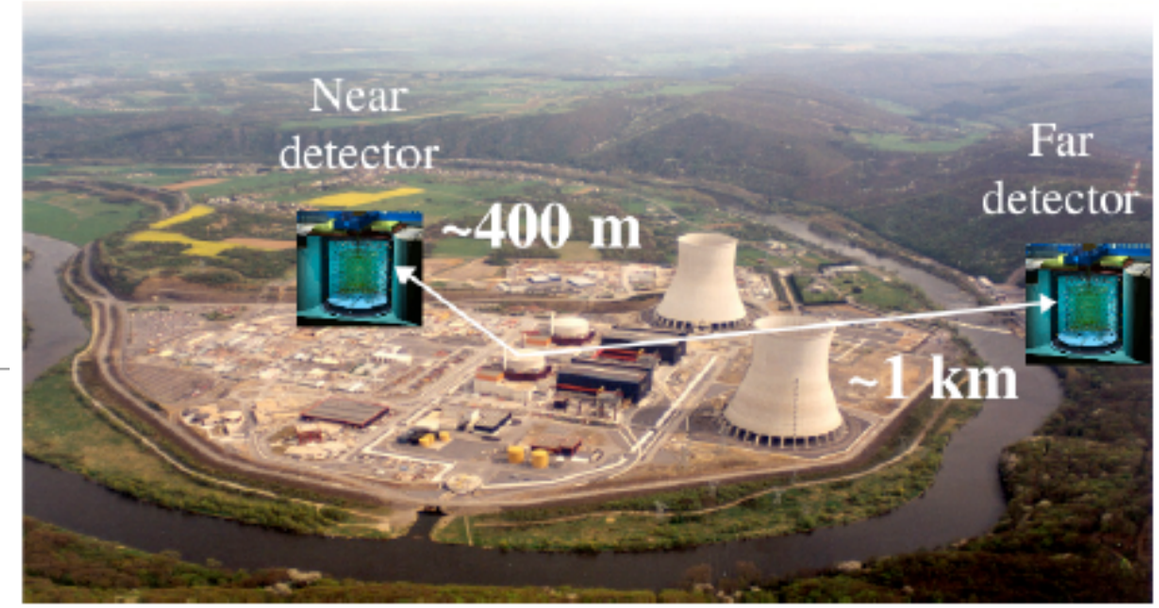




- Excess seen in neutrinos seems not to be reproduced in anti-neutrinos
- No conclusion possible with present statistics
- Situation may be further clarified by SciBooNE and microBooNE data

Double CHOOZ / Daya Bay / Reno

Is $\theta_{13}>0$?



Double Chooz

- Installation of far detector nearing completion by April 2010
- Construction of near lab begins in 2010
- $\sin^2 2\theta_{13} = 0.06$ (90%CL) by 2011
- $\sin^2 2\theta_{13} = 0.03$ by 2014

RENO

- Civil construction completed.
- Finish installation in 2010
- $\sin^2 2\theta_{13} = 0.02$ by 2014

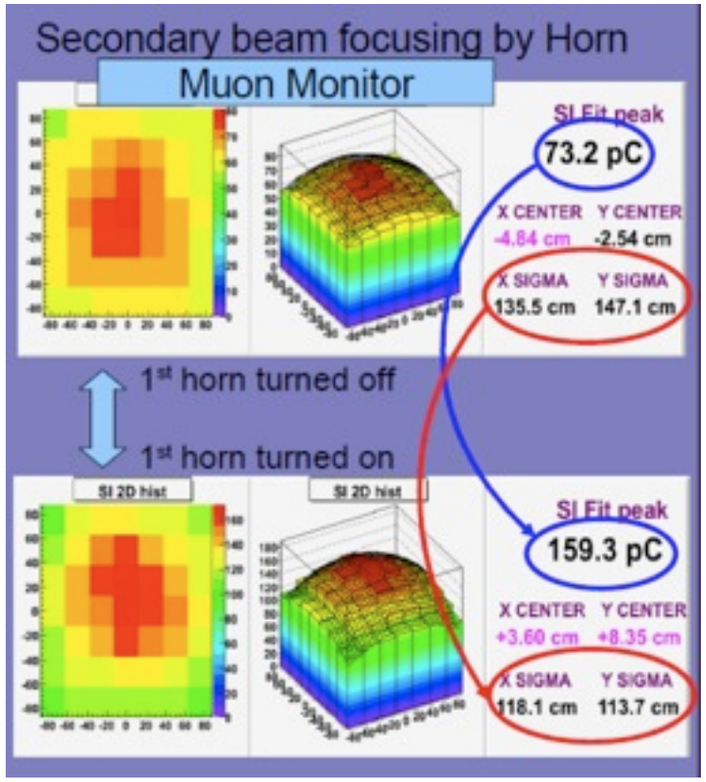
Daya Bay

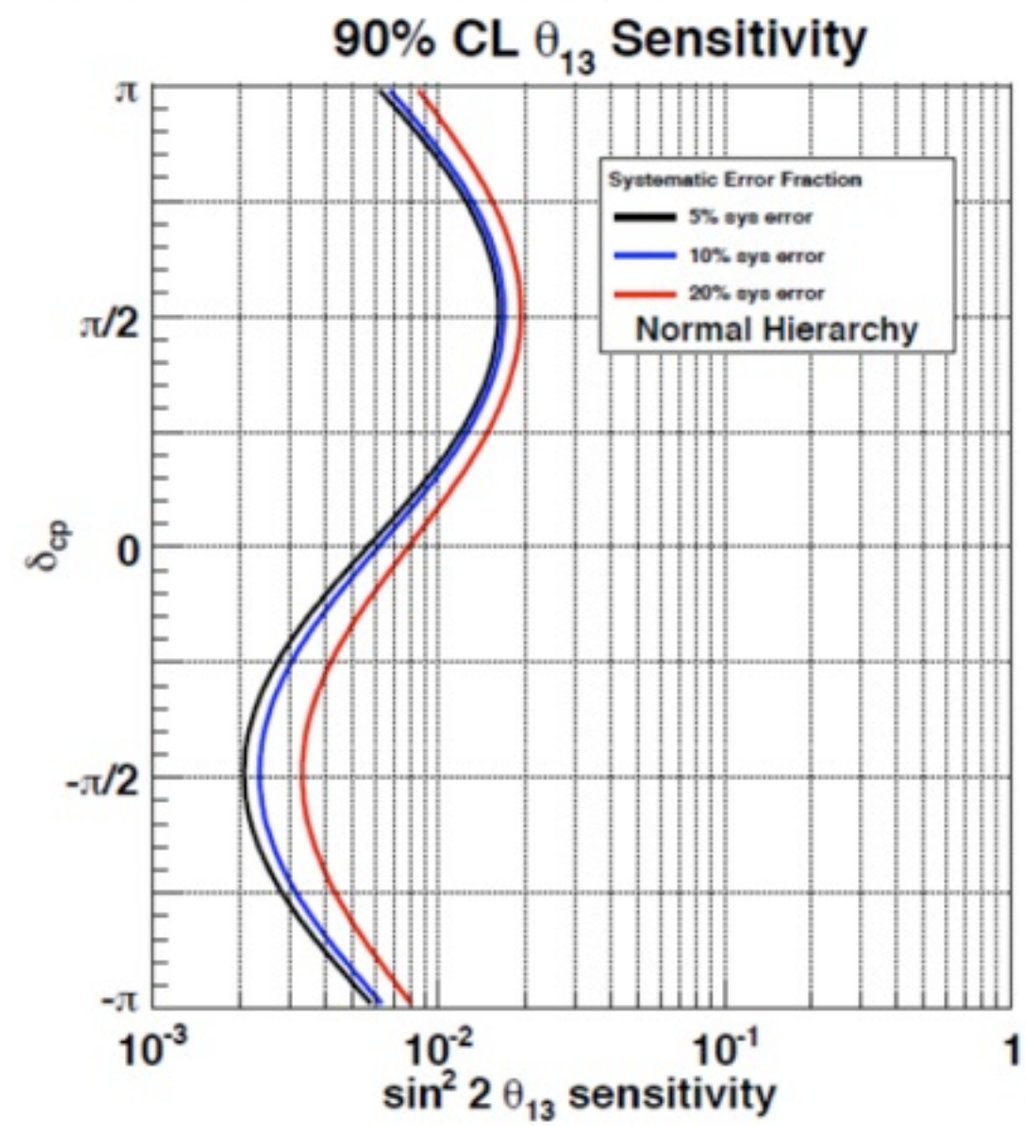
- Excavation ~70% complete
- Halls ready for data taking in summer '11
- $\sin^2 2\theta_{13} = 0.01$ by 2014

T2K
Is $\theta_{13}>0$?

New off-axis neutrino beam directed at 50 kton Super-Kamiokande detector

First beam to T2K target in April 2009
Near detector installation nearing completion
Beam line re-commissioning starting now. 120 kW in RCS and 40 kW to T2K





First run through 2010: $\sin^2 2\theta_{13} = 0.06$ (90% CL)
Ultimate sensitivity $\sin^2 2\theta_{13} = 0.006$

T2K
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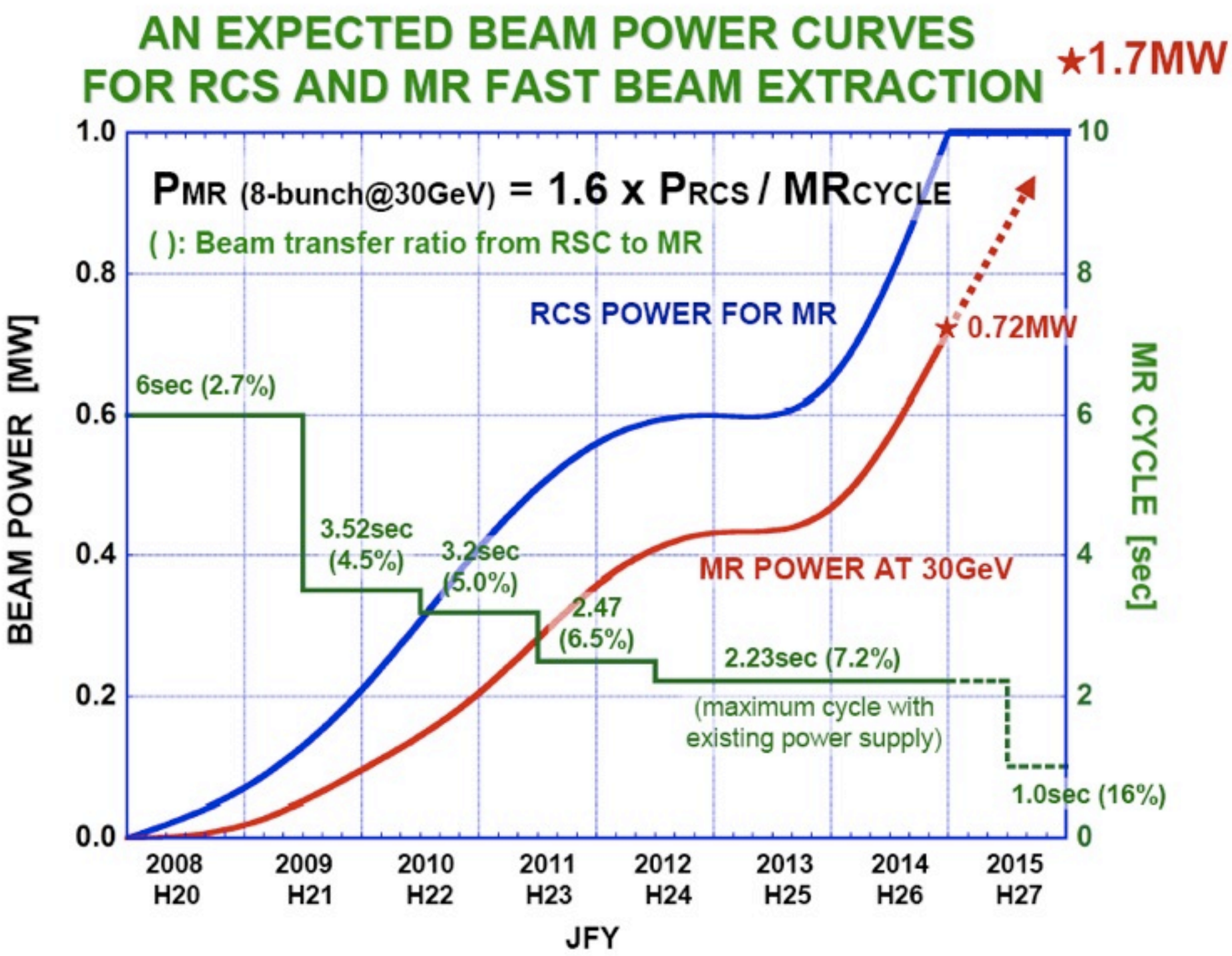
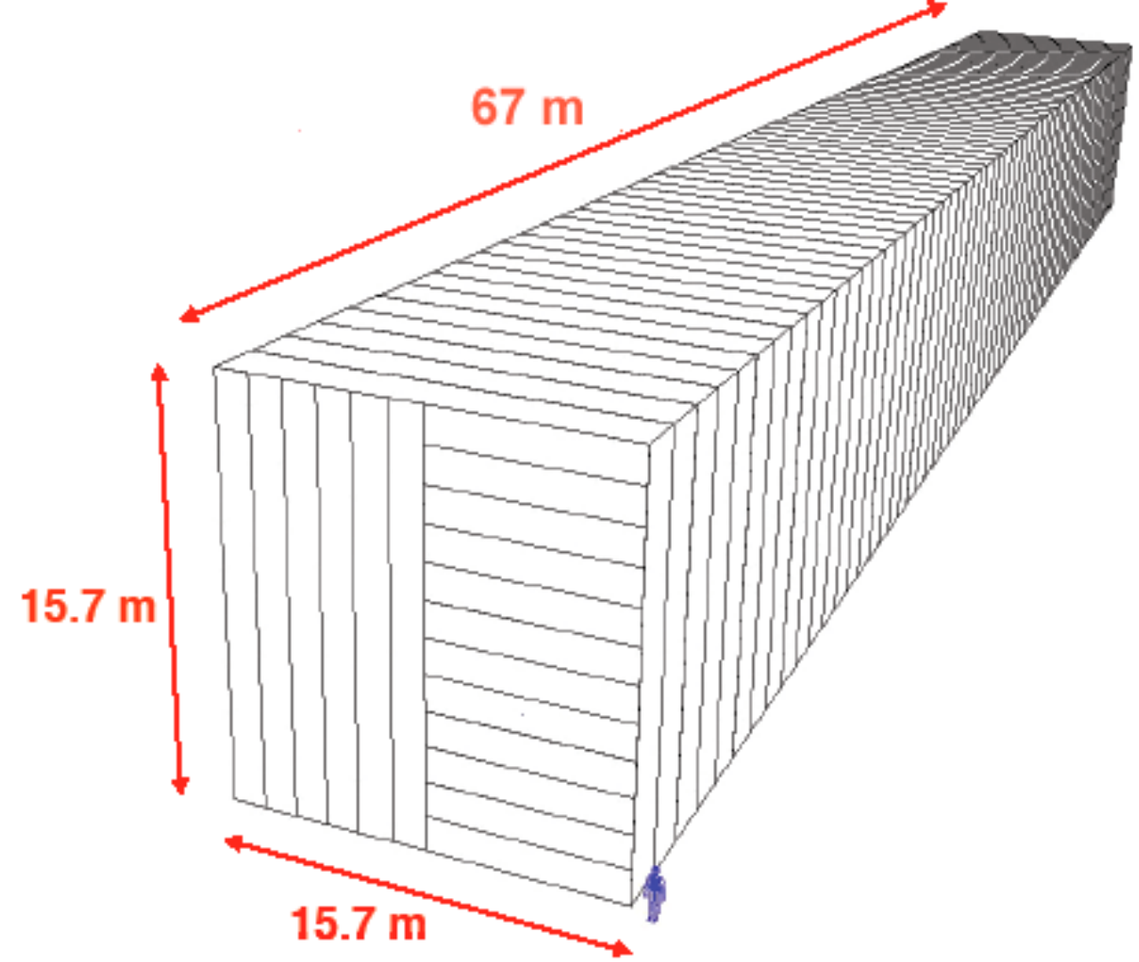
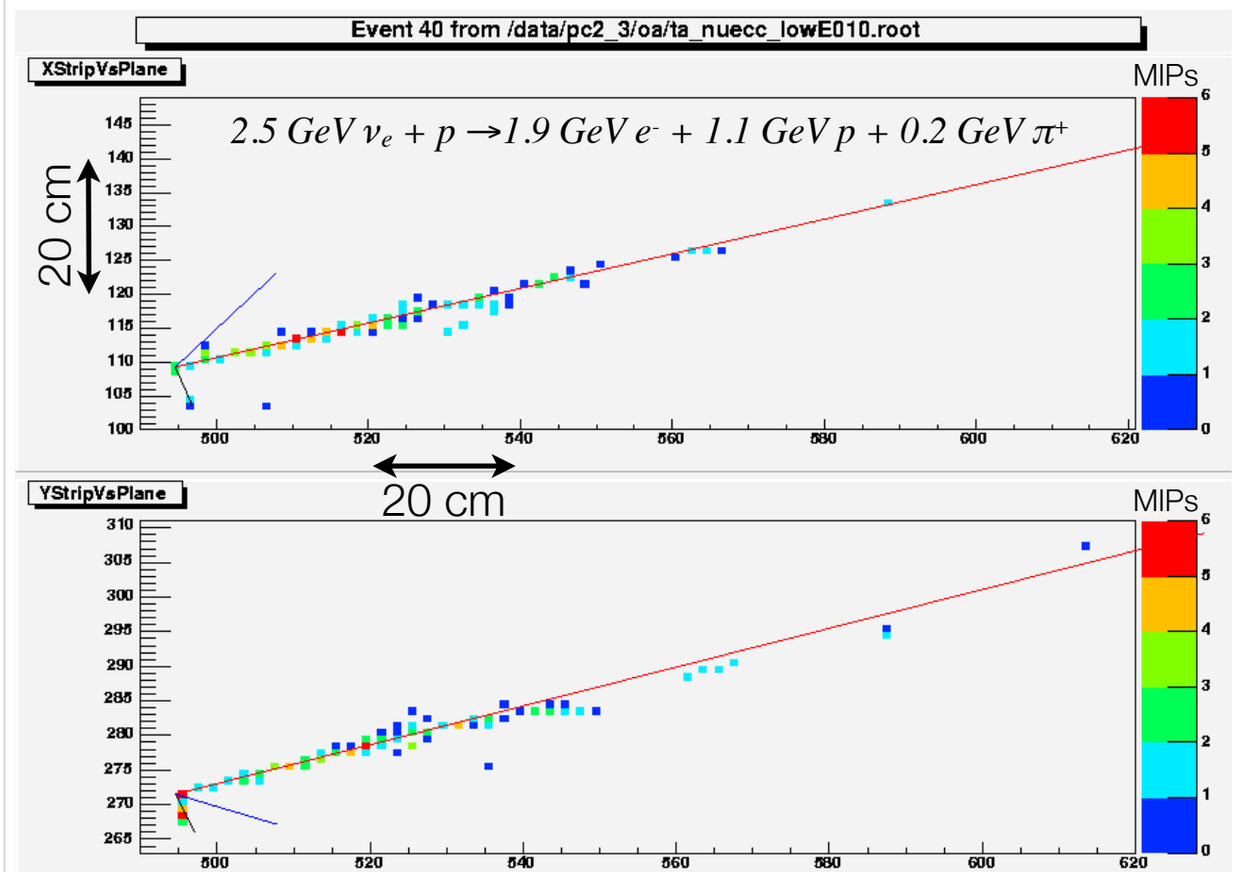


NOvA

What is the mass hierarchy?
What can we learn about δ_{CP}?

- NOvA is a second generation experiment on the NuMI beamline which is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
- NOvA is:
  - An upgrade of the NuMI beam intensity from 400 kW to 700 kW
  - A 15 kt "totally active" tracking liquid scintillator calorimeter sited 14 mrad off the NuMI beam axis at a distance of 810 km
  - A 220 ton near detector identical to the far detector sited 14 mrad off the NuMI beam axis at a distance of 1 km





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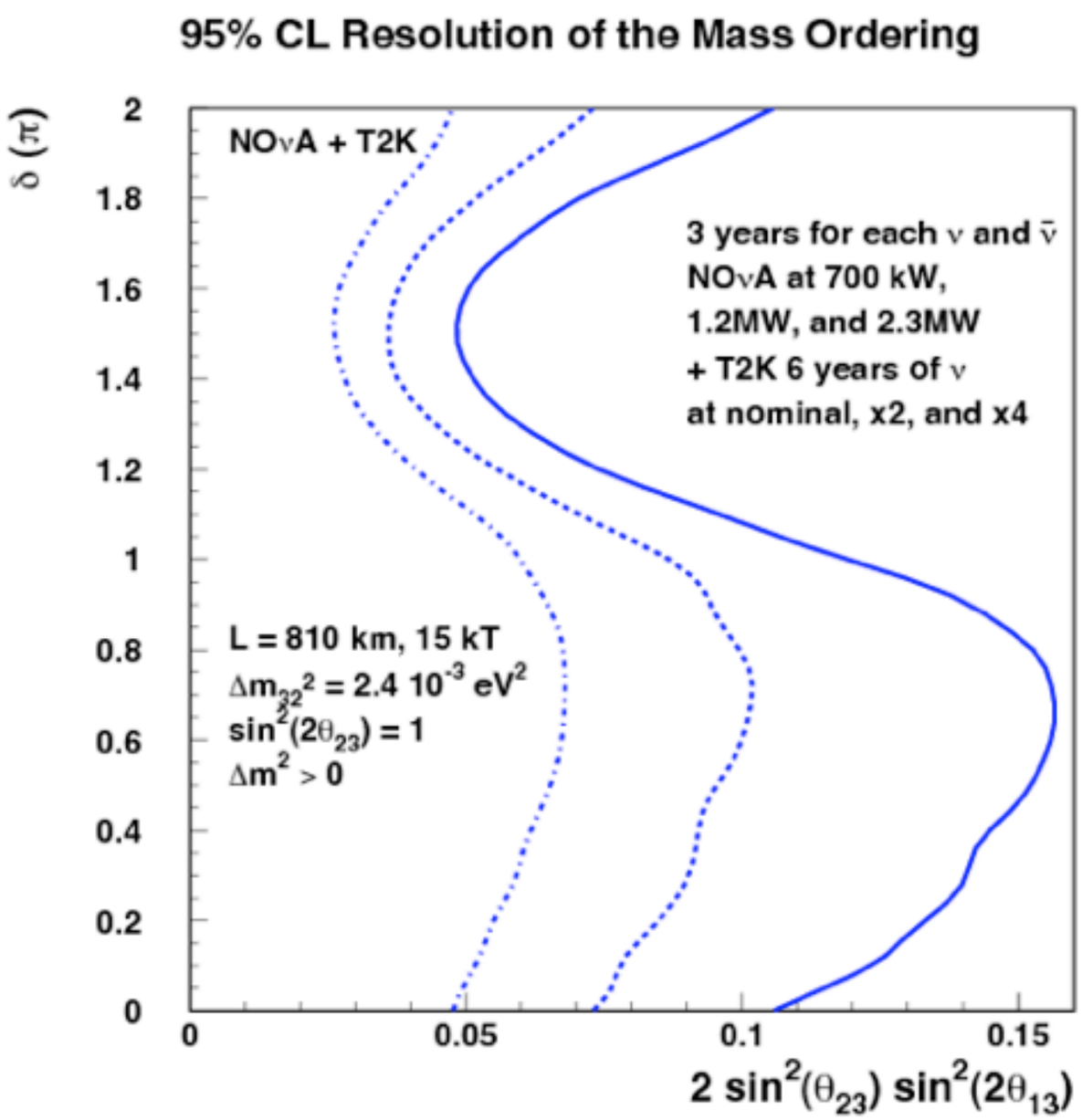

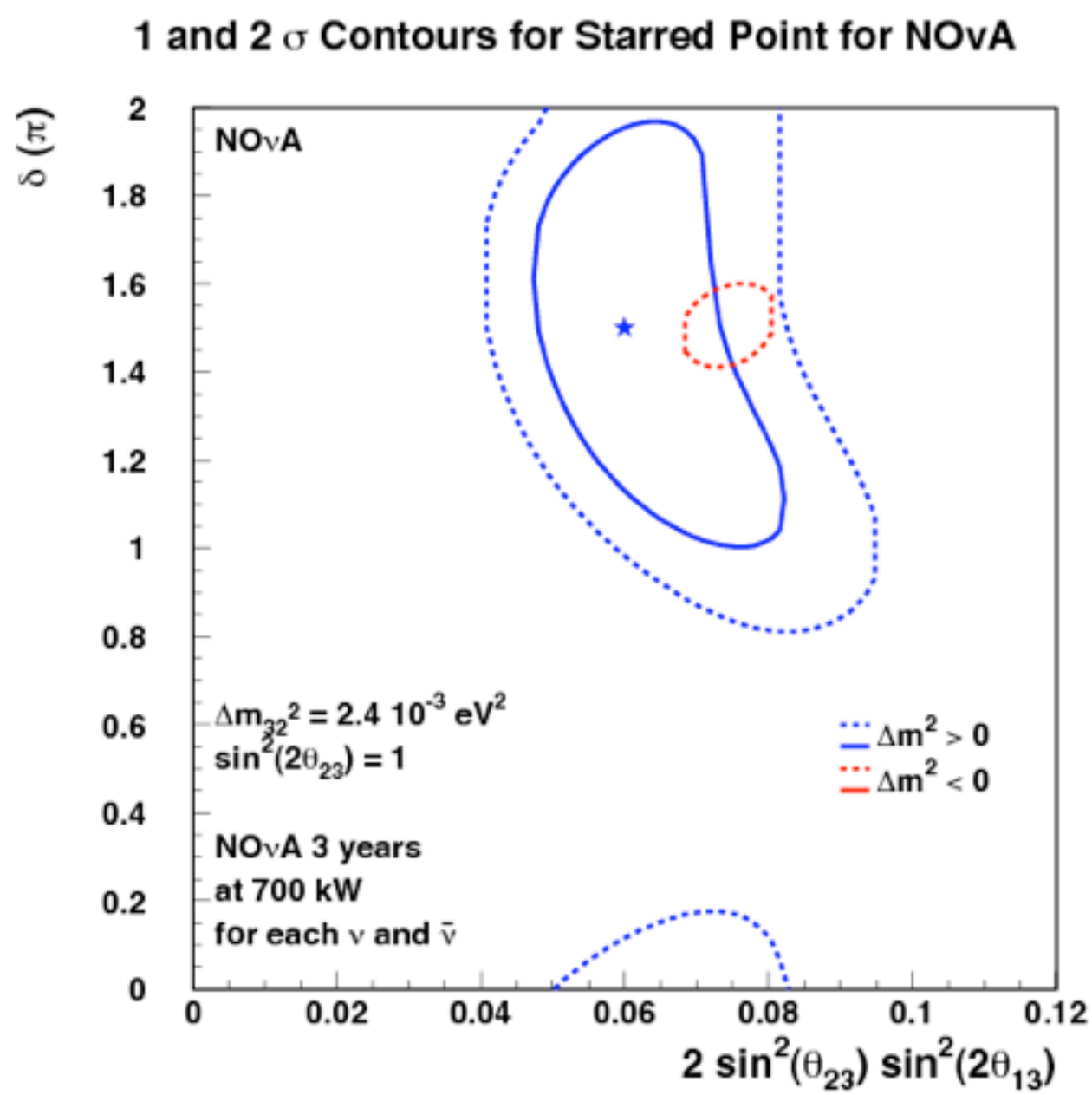

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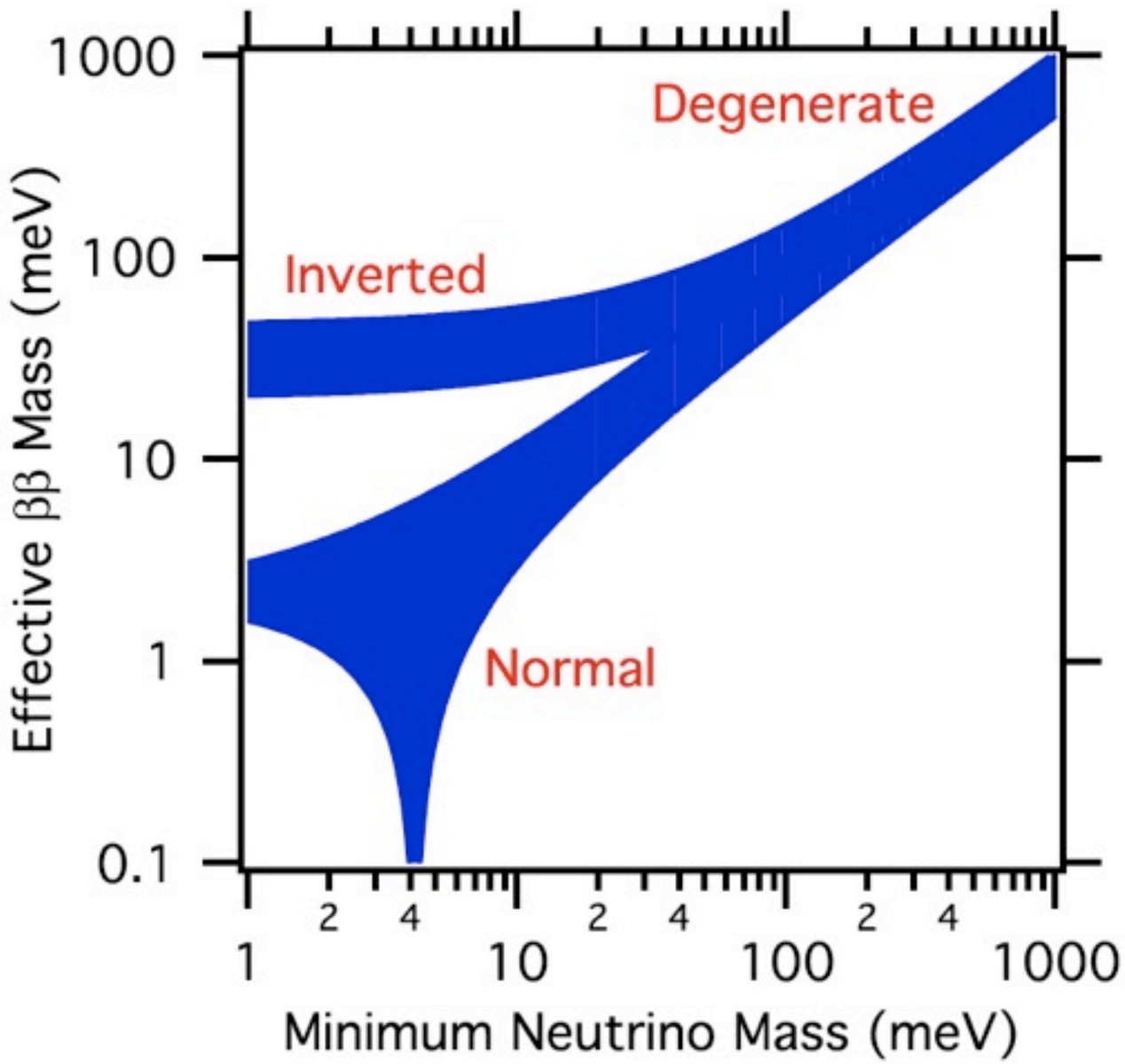

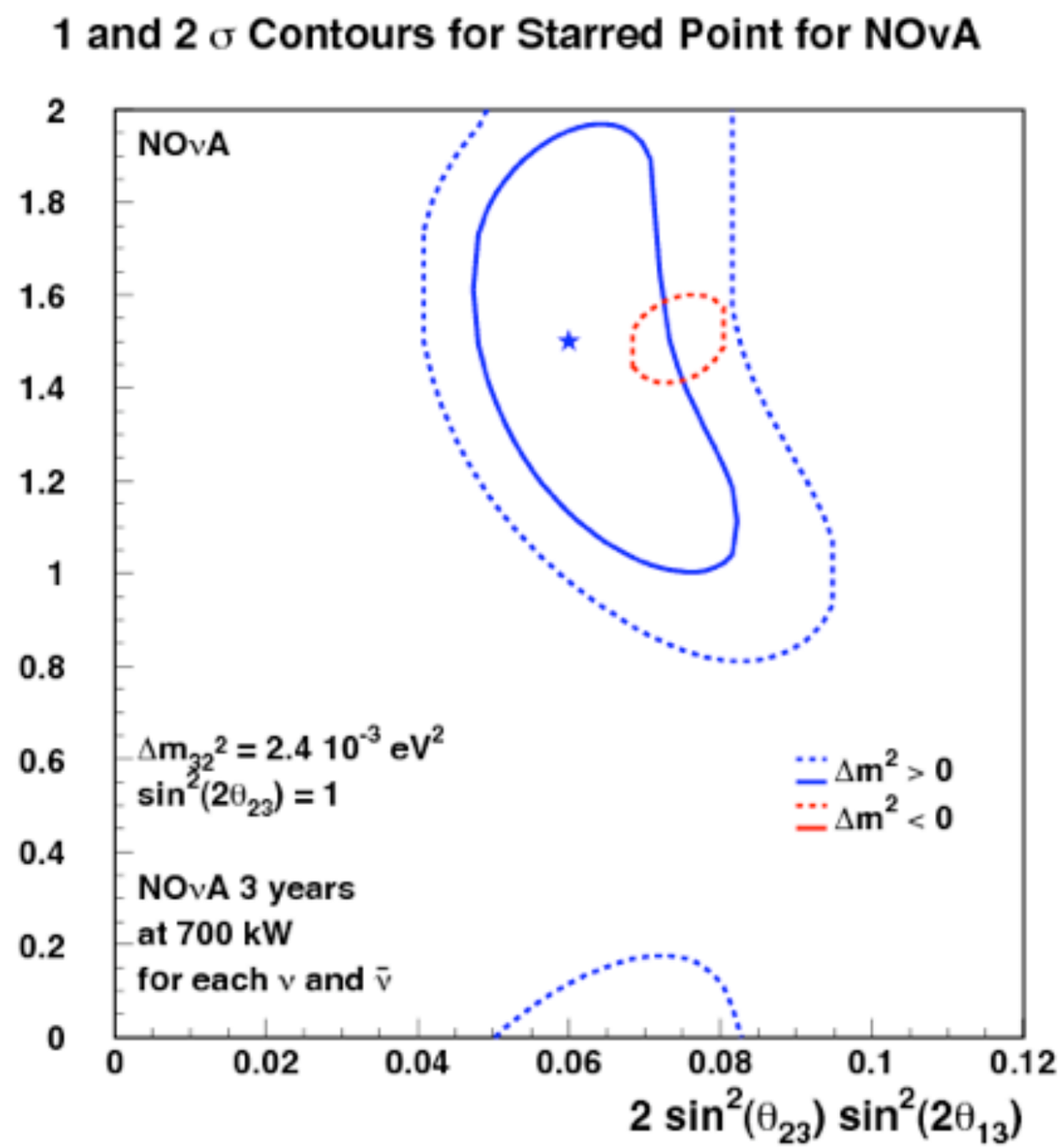

Far detector laboratory construction
2 November 2009

NOvA construction

CD3b signed 29 October 2009

NOvA

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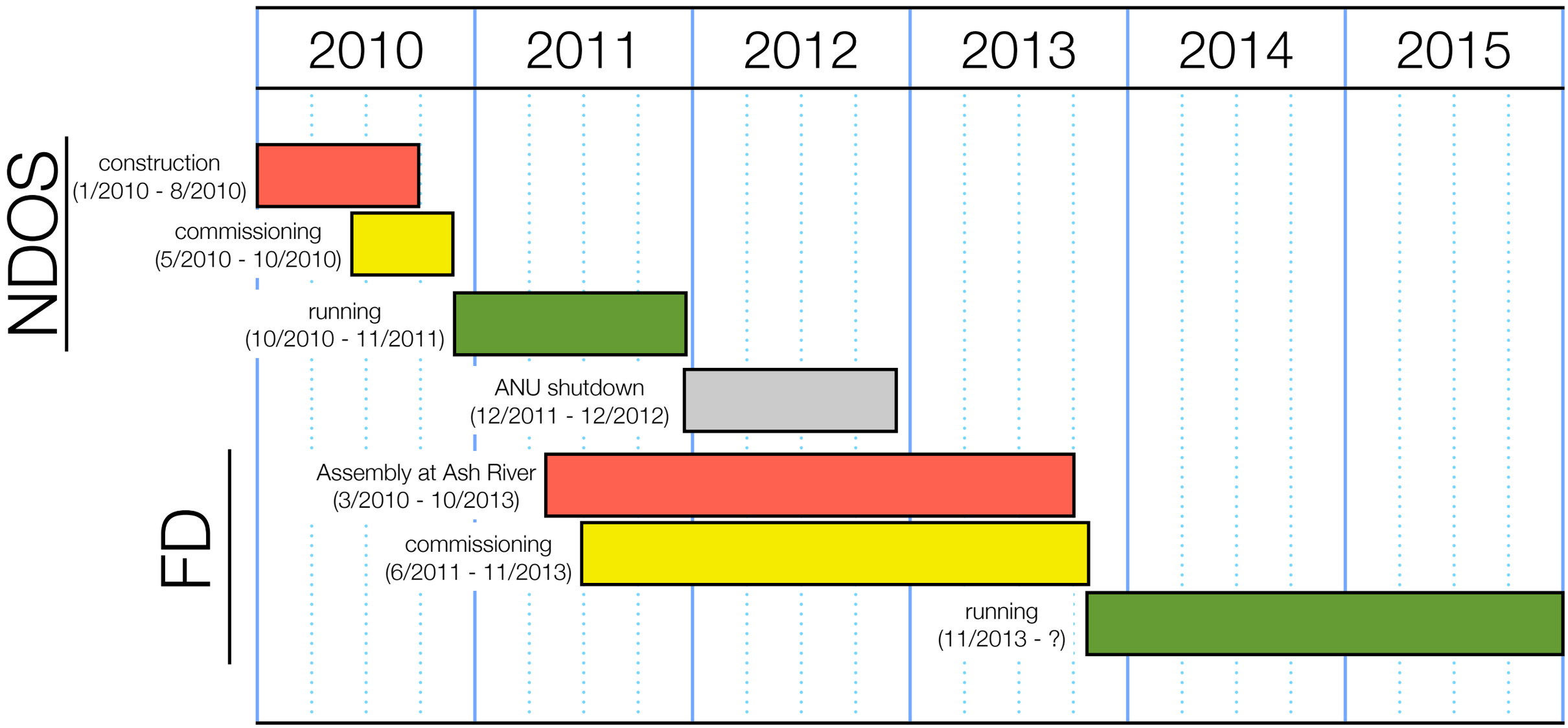

NDOS = near detector on the surface
FD = far detector at Ash River