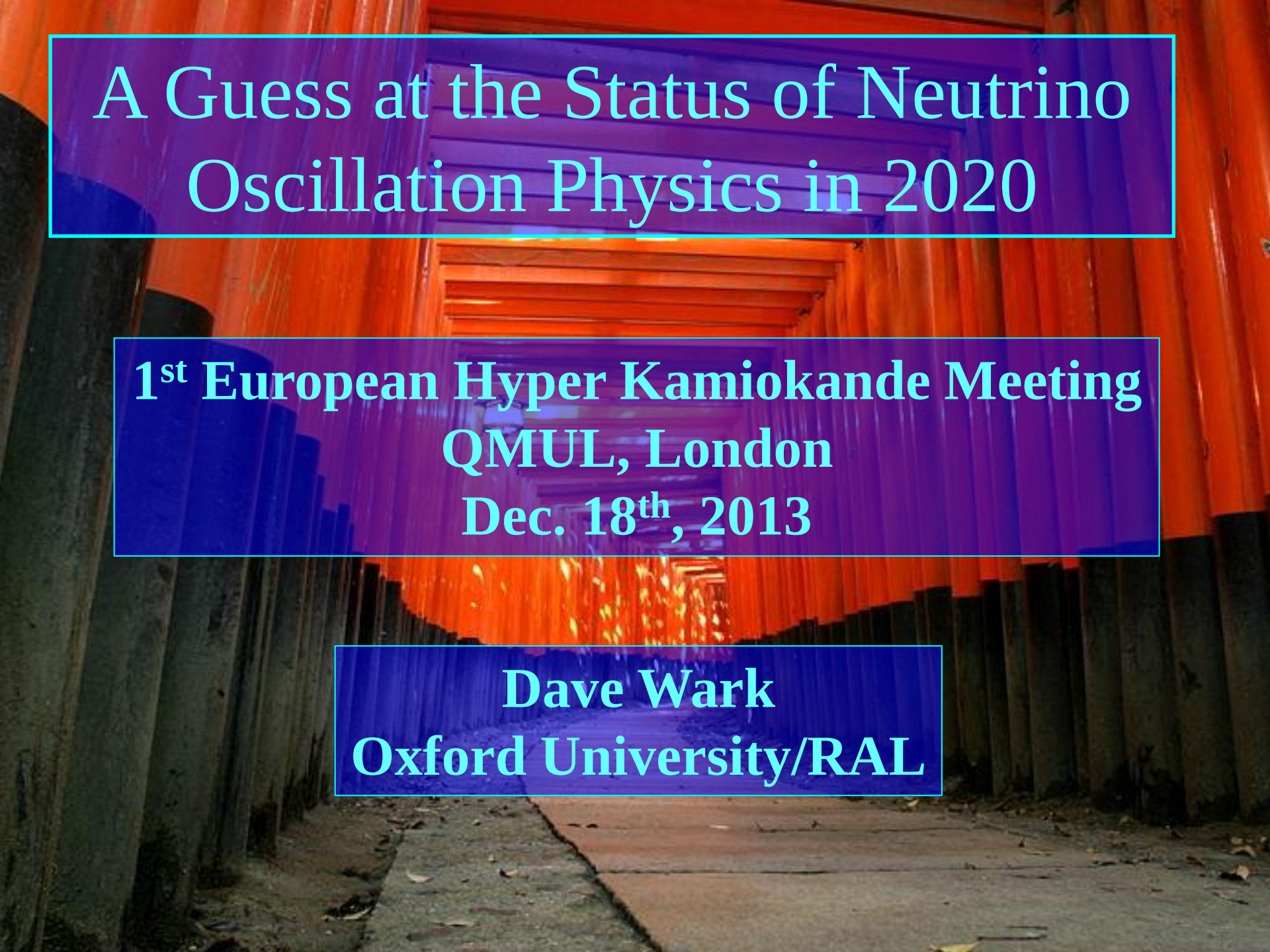
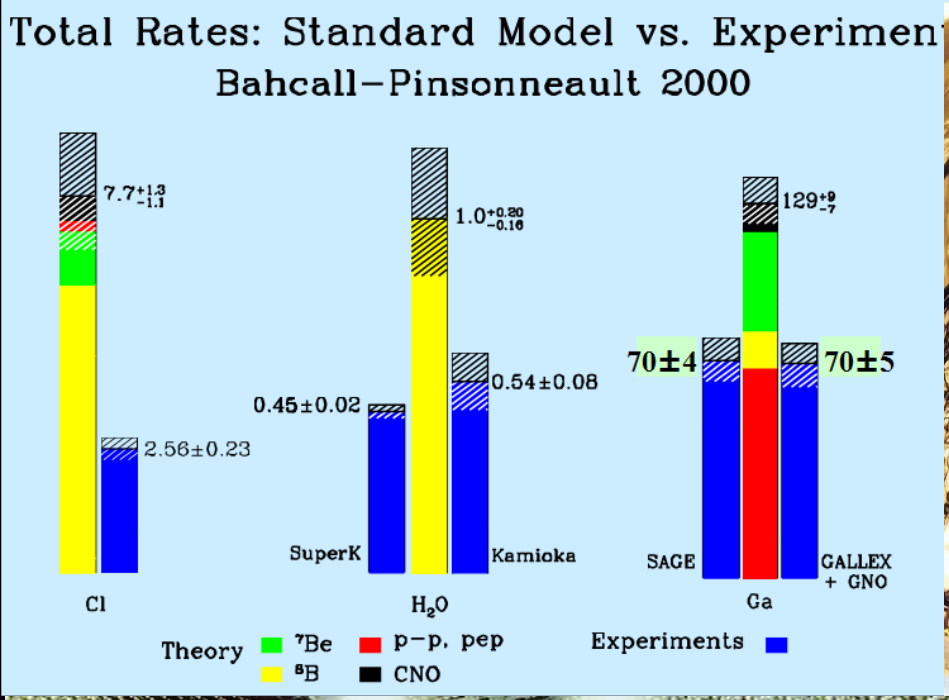
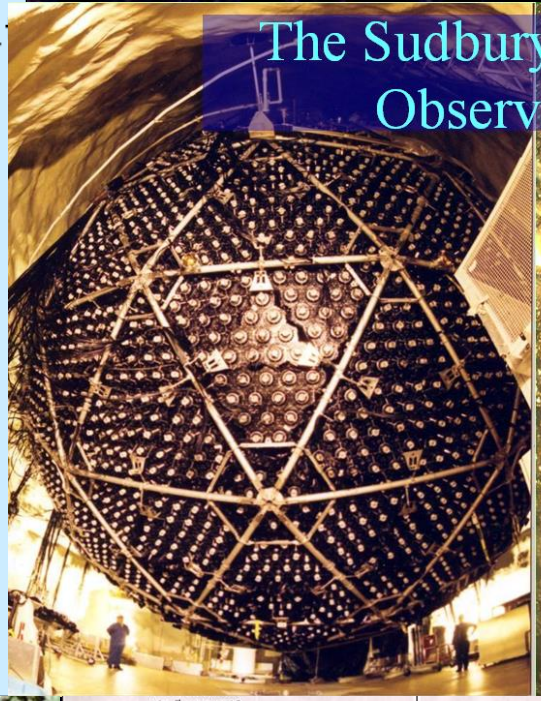


A Guess at the Status of Neutrino Oscillation Physics in 2020

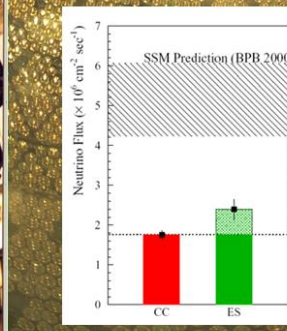
1st European Hyper Kamiokande Meeting
QMUL, London
Dec. 18th, 2013

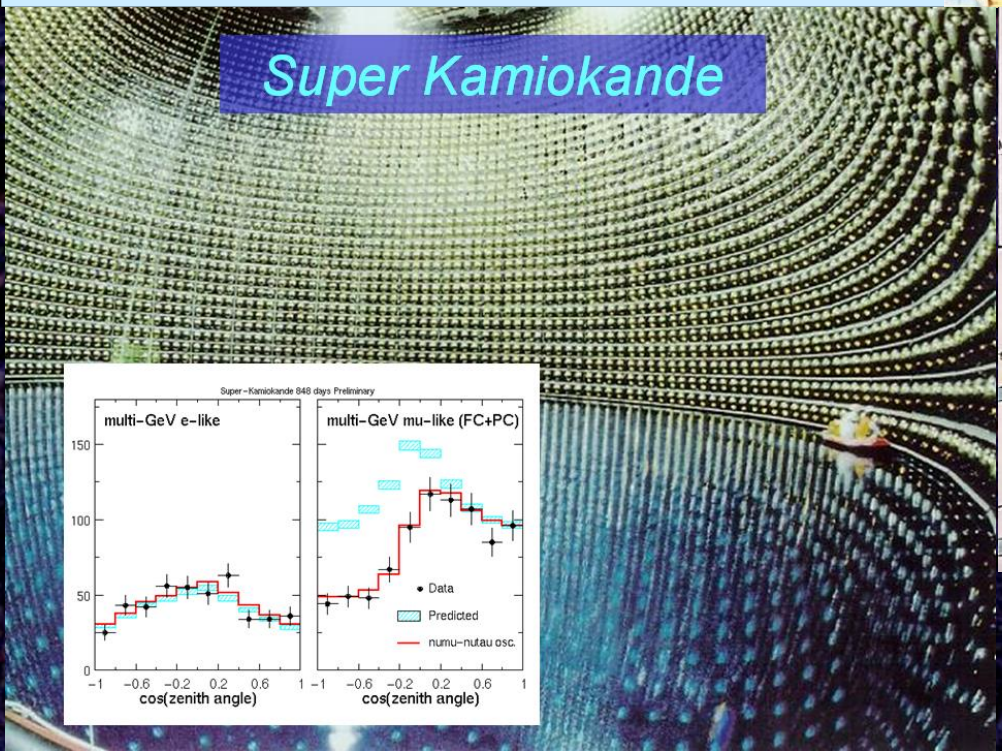
Dave Wark
Oxford University/RAL



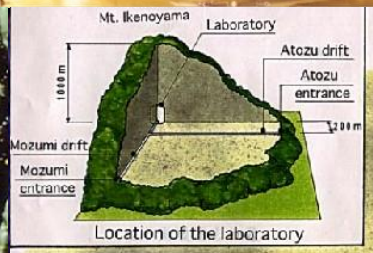


The Sudbury Neutrino Observatory

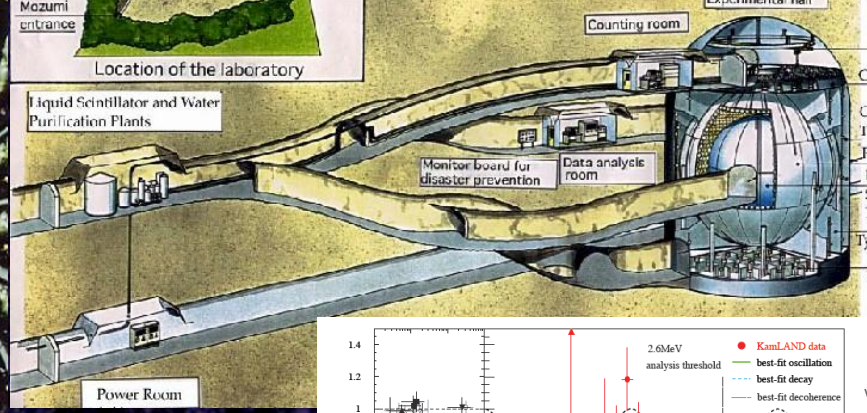


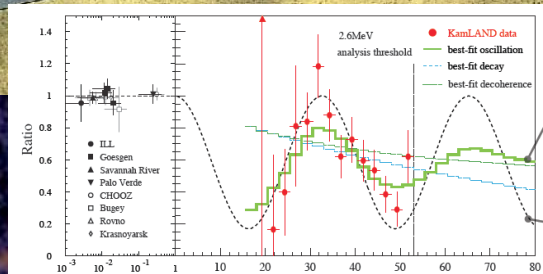


Super Kamiokande



KamLAND





Three neutrino mixing.

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$

CP sensitivity mainly because this term flips sign for ν and anti-ν

Complicated equation means covariances and degeneracies!

$$\frac{\Delta m^2_{31} L}{4E} \times \left(1 + \frac{2a}{\Delta m^2_{31}} \left(1 - 2S^2_{13}\right)\right)$$

$$+8C^2_{13}S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cos\frac{\Delta m^2_{32}L}{4E} \sin\frac{\Delta m^2_{31}L}{4E} \sin\frac{\Delta m^2_{21}L}{4E}$$

$$-8C^2_{13}C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta \sin\frac{\Delta m^2_{32}L}{4E} \sin\frac{\Delta m^2_{31}L}{4E} \sin\frac{\Delta m^2_{21}L}{4E}$$

$$+4S^2_{12}C^2_{13}\left\{C^2_{12}C^2_{23} + S^2_{12}S^2_{23}S^2_{13} - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\right\} \sin^2\frac{\Delta m^2_{21}L}{4E}$$

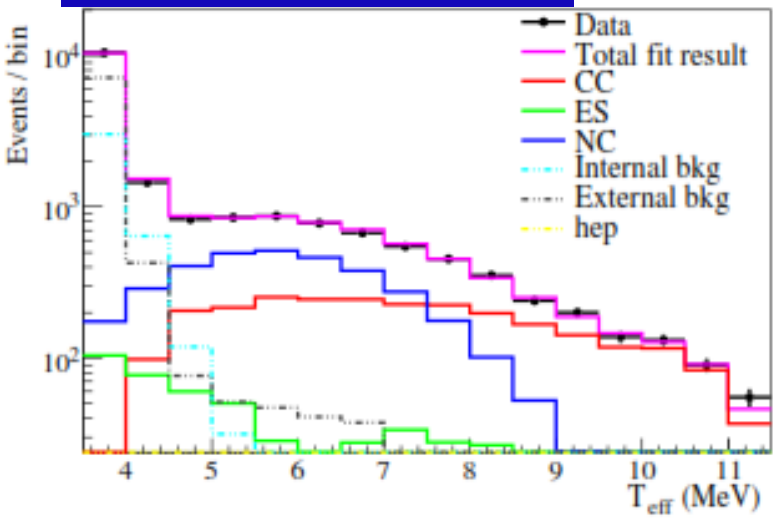
$$-8C^2_{13}S^2_{13}S^2_{23}\cos\frac{\Delta m^2_{32}L}{4E} \sin\frac{\Delta m^2_{31}L}{4E} \frac{aL}{4E} \left(1 - 2S^2_{13}\right)$$

Need Matter effects to get the signs of Δm^2_{ij}

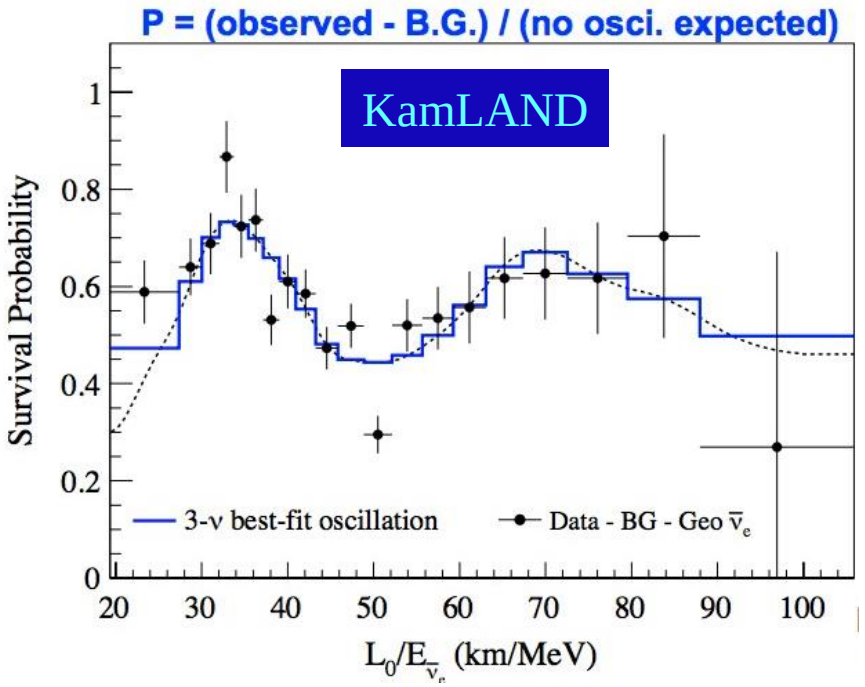
How do we know θ_{12}, Δm_{12}?

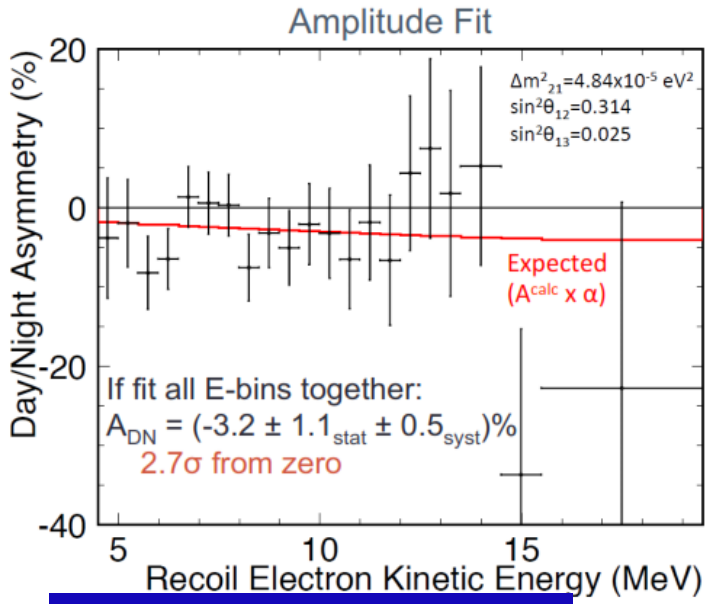
Raaf, this conference. arXiv:0910.2984v2 [nucl-ex] 9 Jun 2010

SNO LETA and 3-Phase

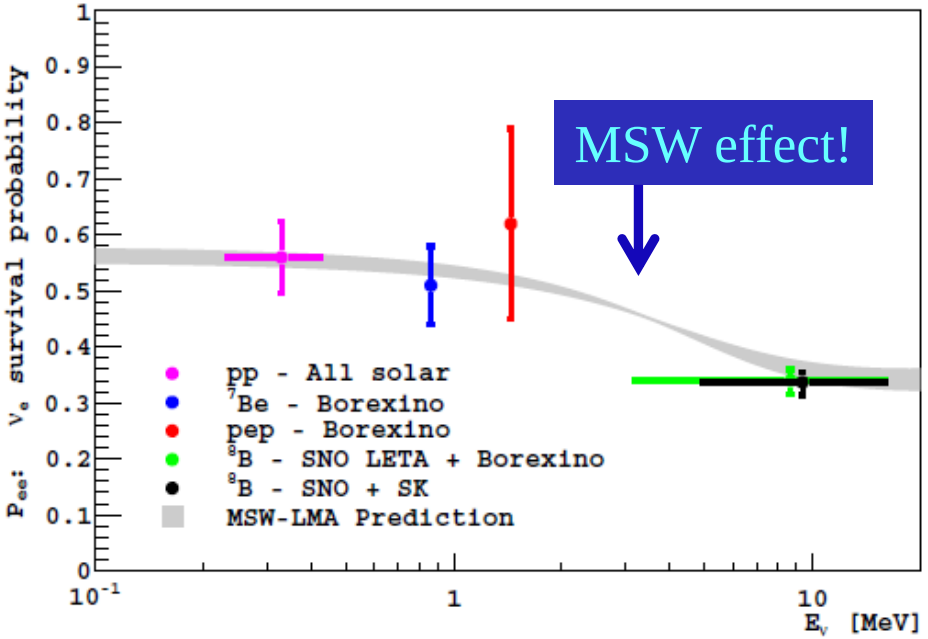


KamLAND





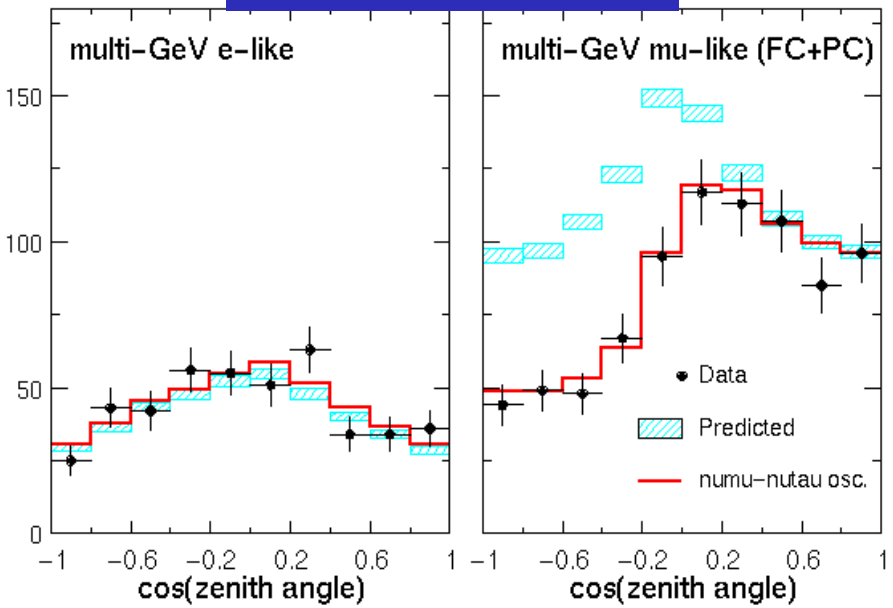
Super Kamiokande D/N!



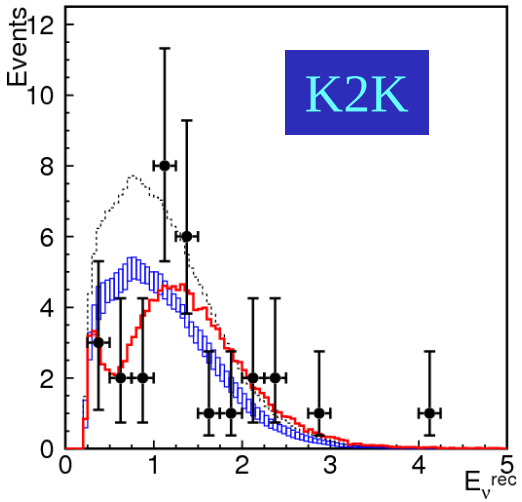
arXiv:1110.3230v1 [hep-ex] Ishidoshiro, this conference.

How do we know θ_{23}, Δm_{23}?

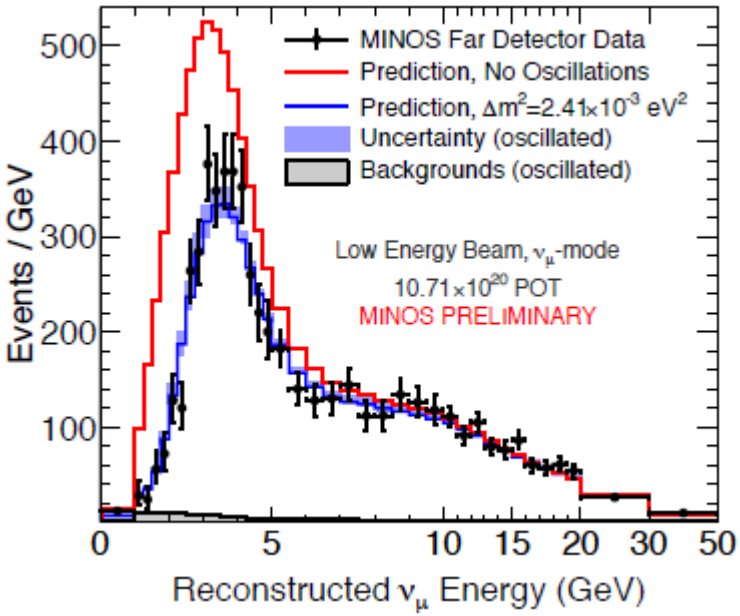
Super Kamiokande



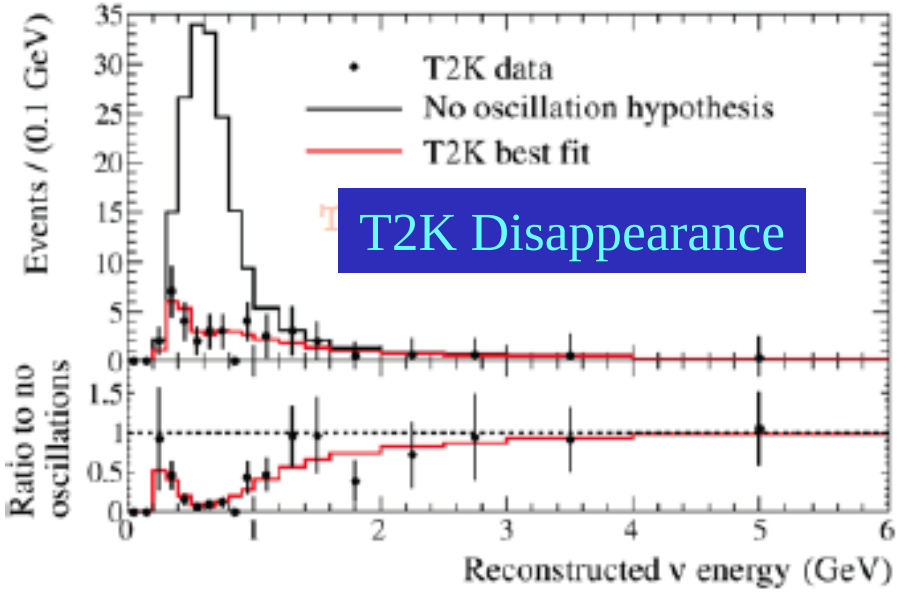
K2K



MINOS Beam and Atm.

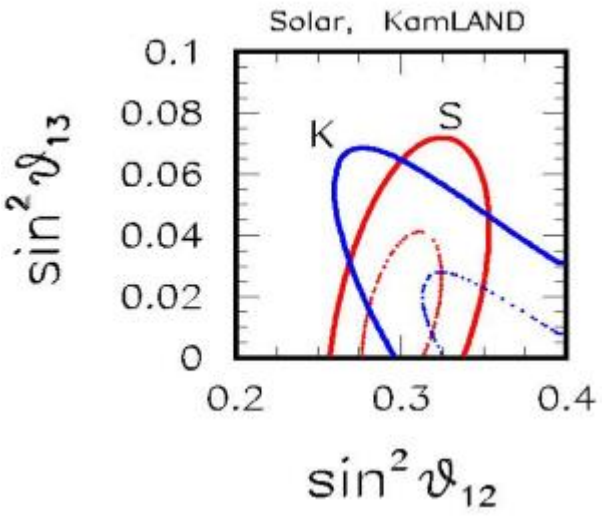


T2K Disappearance

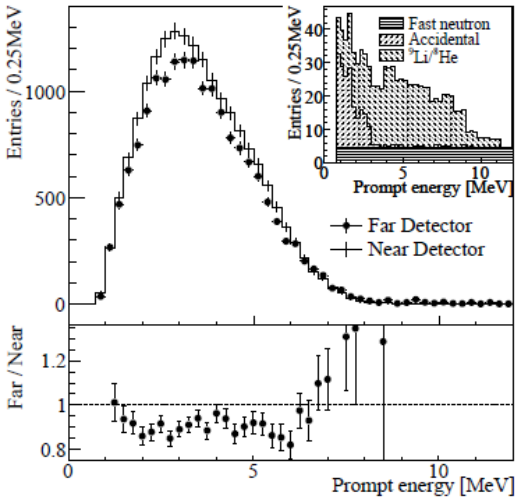


How do we know θ_{13}, Δm_{13}?

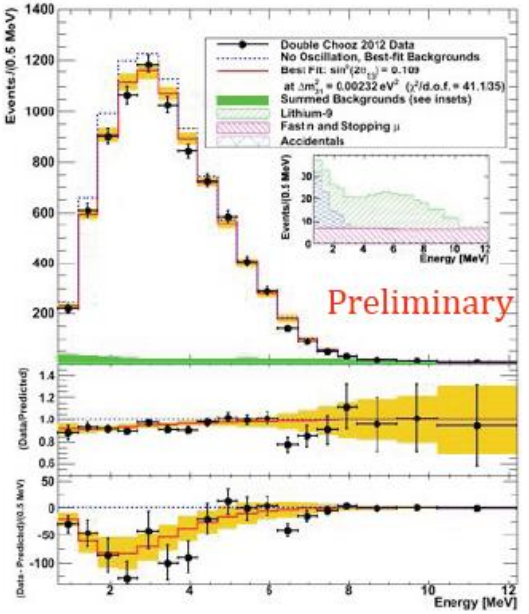
hep-ph/0806.2649

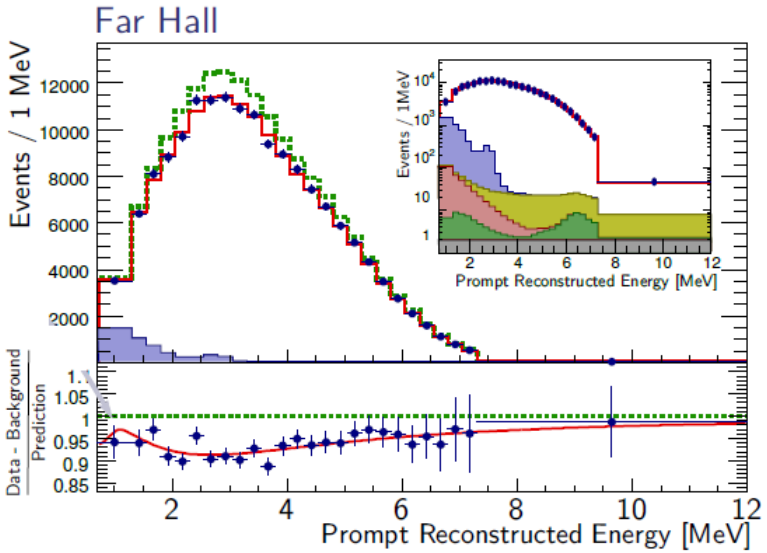


RENO

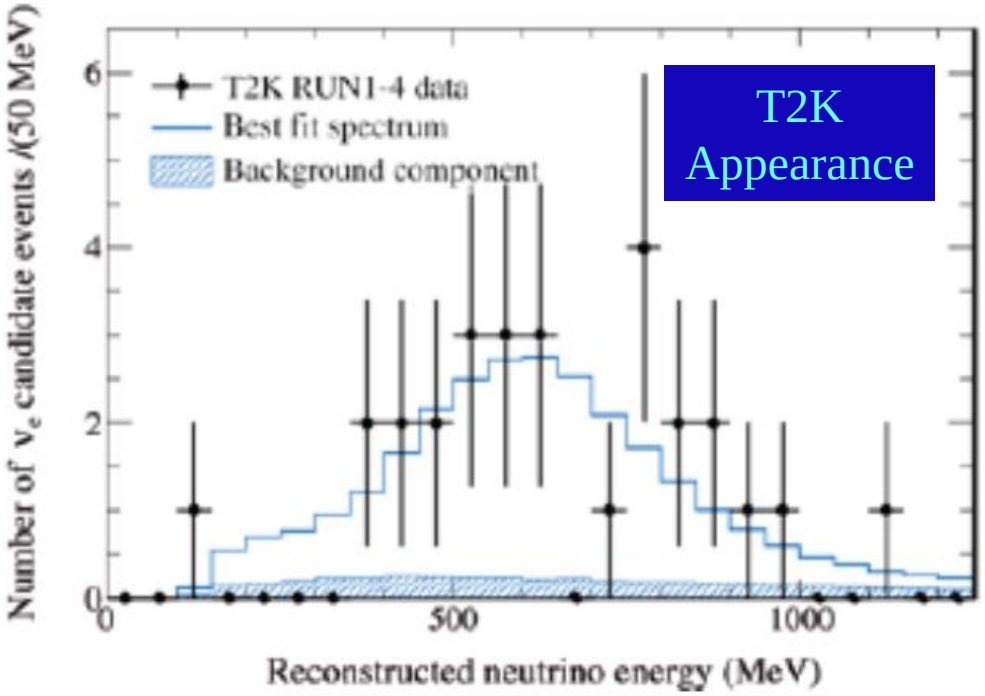


Double Chooz



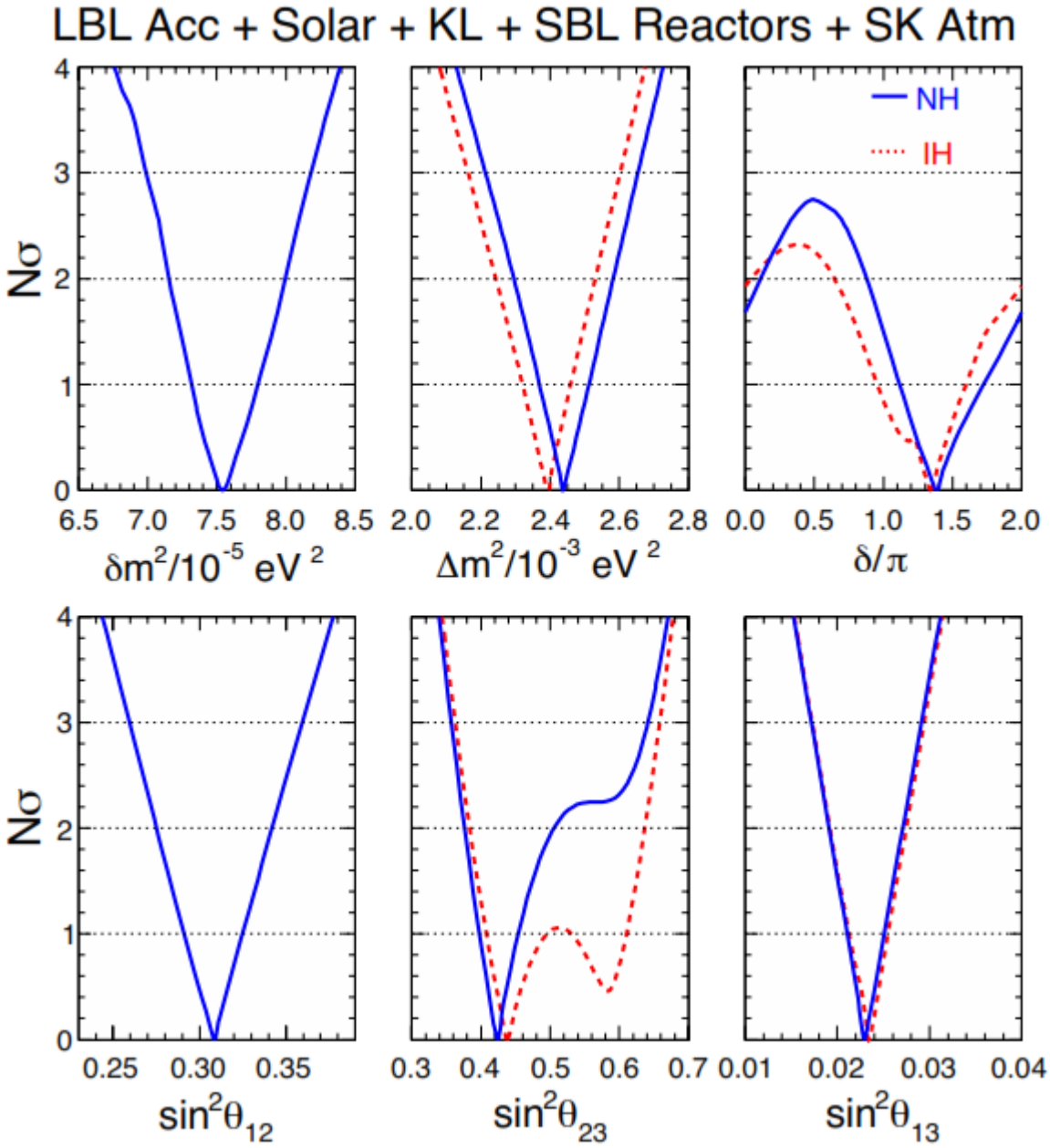


Daya Bay rate plus shape

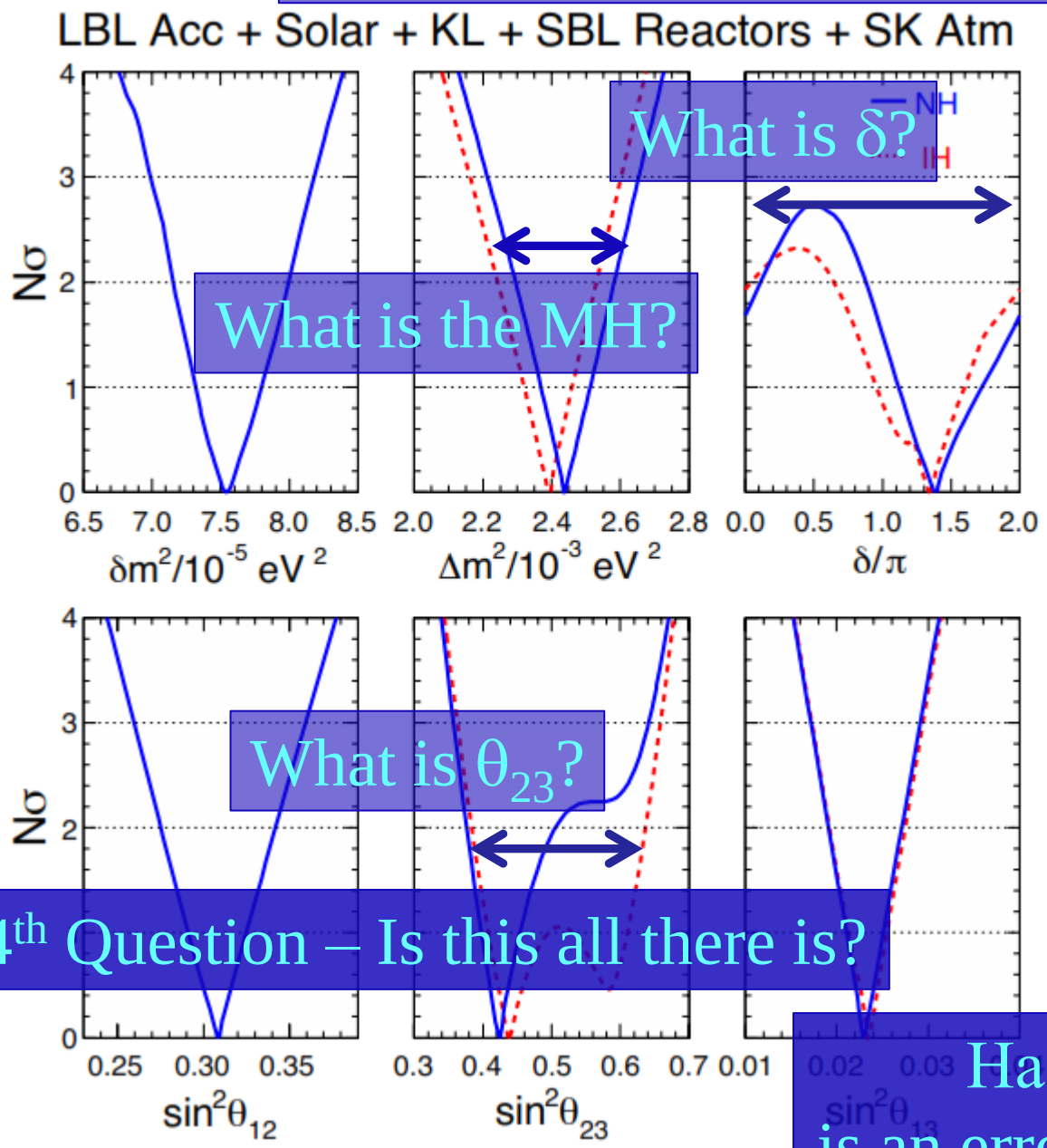


T2K Appearance

Latest Global Fit, shown tomorrow by Lisi



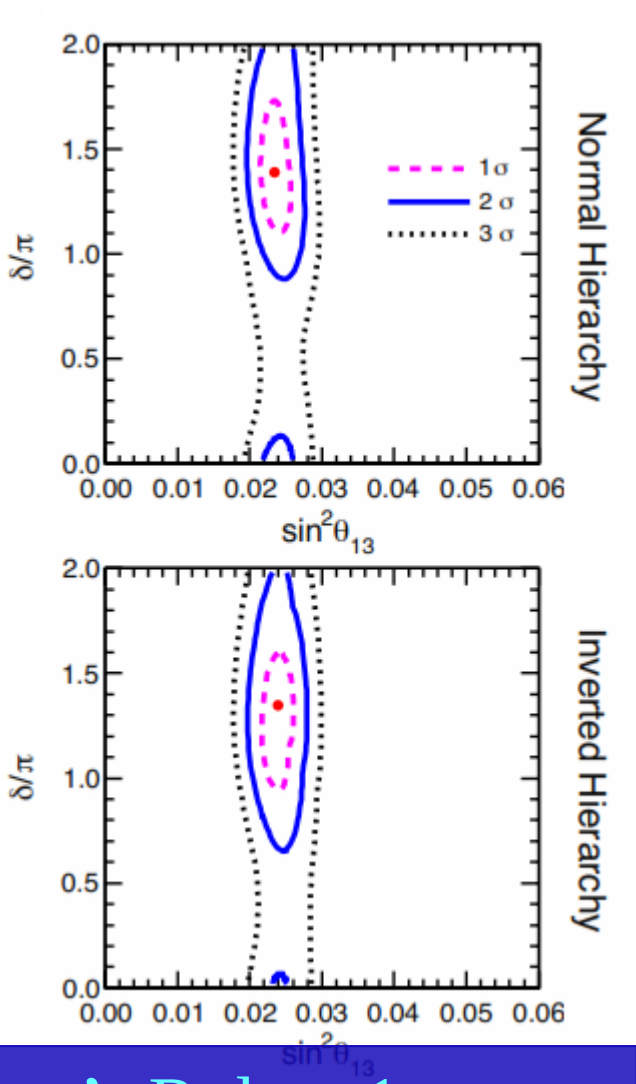
We are left with 4 questions for 3ν…



What is δ?

What is the MH?

What is θ_{23}?



4th Question – Is this all there is?

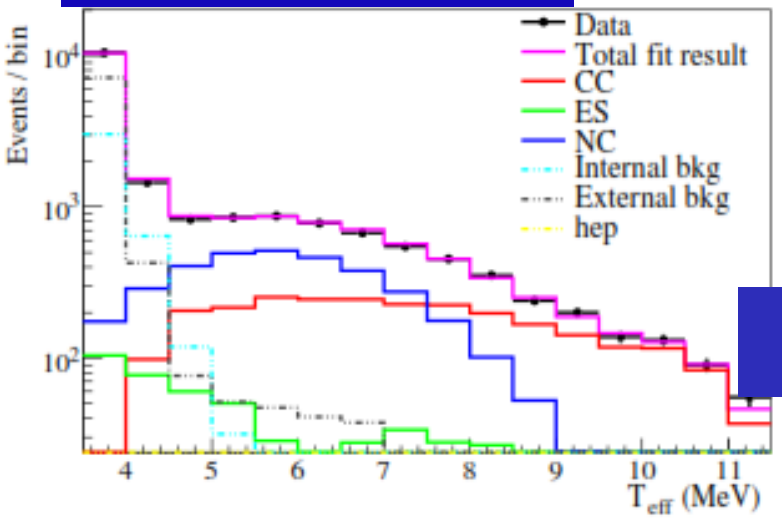
Halzen's Rule – 1σ
is an error bar, not a discovery

Why do we need 5σ?

- There is no calculation that you do which tells you that what you need to discriminate against wrong results is to find 5σ.
- The editors of PRL just got tired of arguing with authors who wanted to title their articles "Discovery of X" on the basis of a 2.2σ excess, so they decreed 3σ is evidence, 5σ is a discovery.
- We don't have to agree.
- The fact remains that the history of our field is littered with wrong results – my first exposure to ν physics was Reines et al. "discovering" neutrino oscillations, as did Bugey, and about a dozen other experiments, and there was Lubimov's ν mass and the 17 keV neutrino and at least a dozen others – superluminal neutrinos come from a proud tradition of ν anomalies.
- ν experiments are hard – so why do we believe the current crop?

How do we know θ_{12}, Δm_{12}?

SNO LETA and 3-Phase



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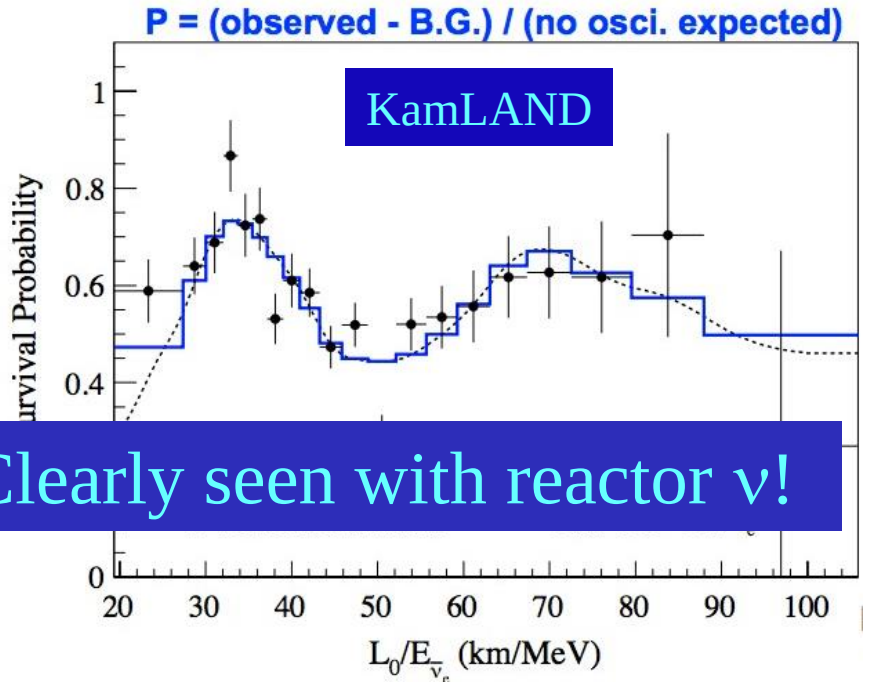
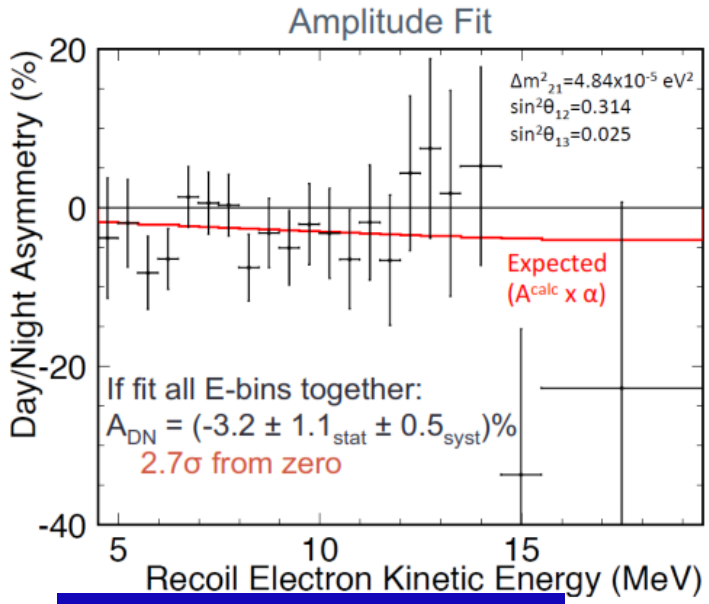
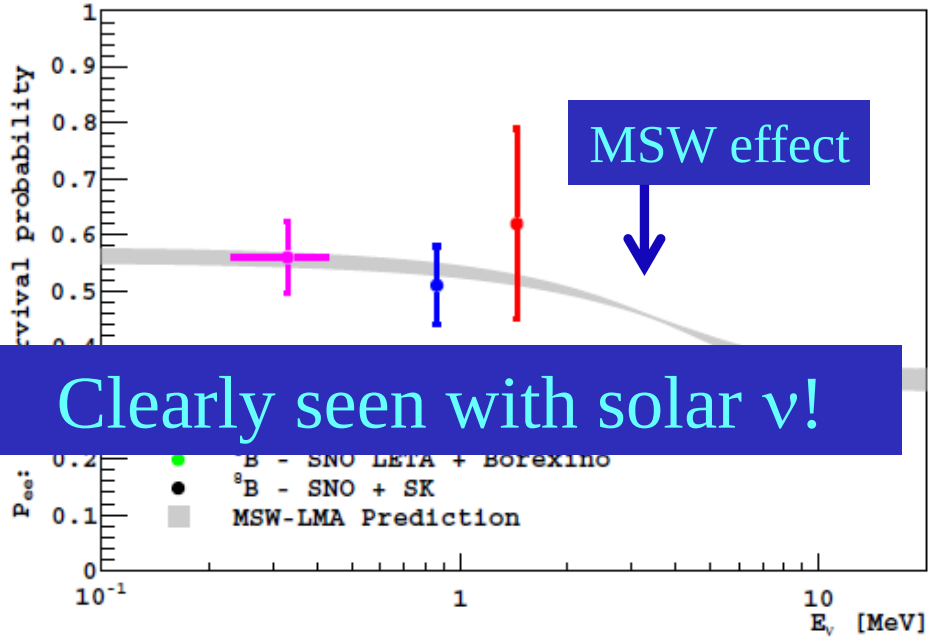


Clearly seen with reactor ν!



Super Kamiokande D/N



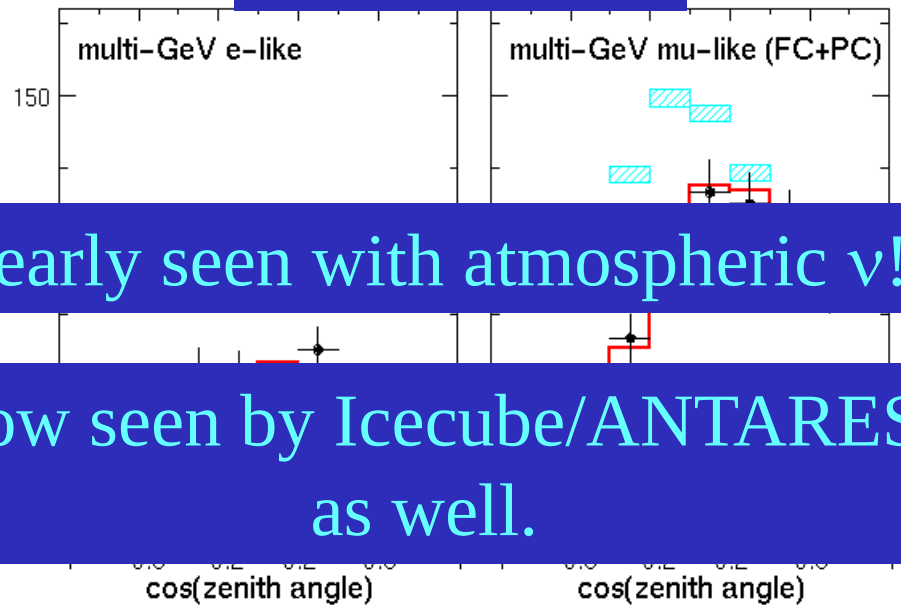
Clearly seen with solar ν!

Raaf, this conference. arXiv:0910.2984v2 [nucl-ex] 9 Jun 2010

Ishidoshiro, this conference. arXiv:1110.3230v1 [hep-ex]

How do we know θ_{23}, Δm_{23}?

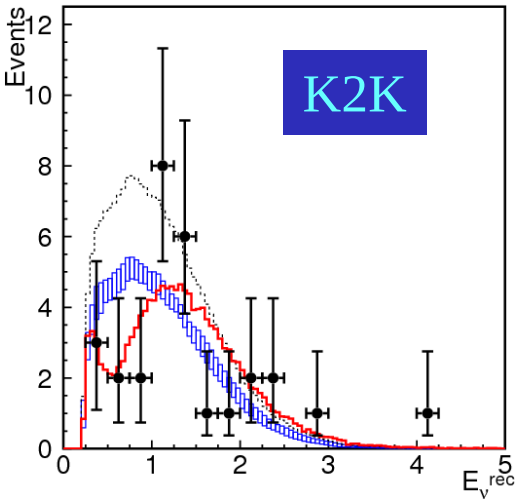
Super Kamiokande



Clearly seen with atmospheric ν!

Now seen by Icecube/ANTARES as well.

K2K



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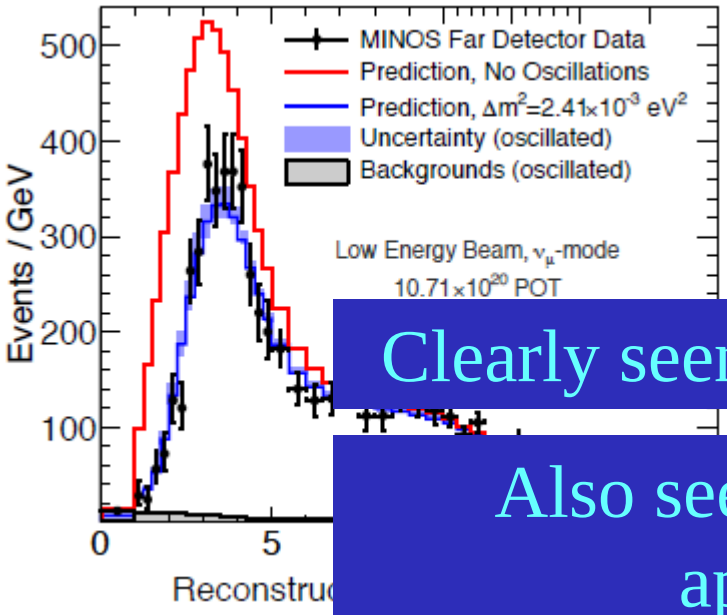
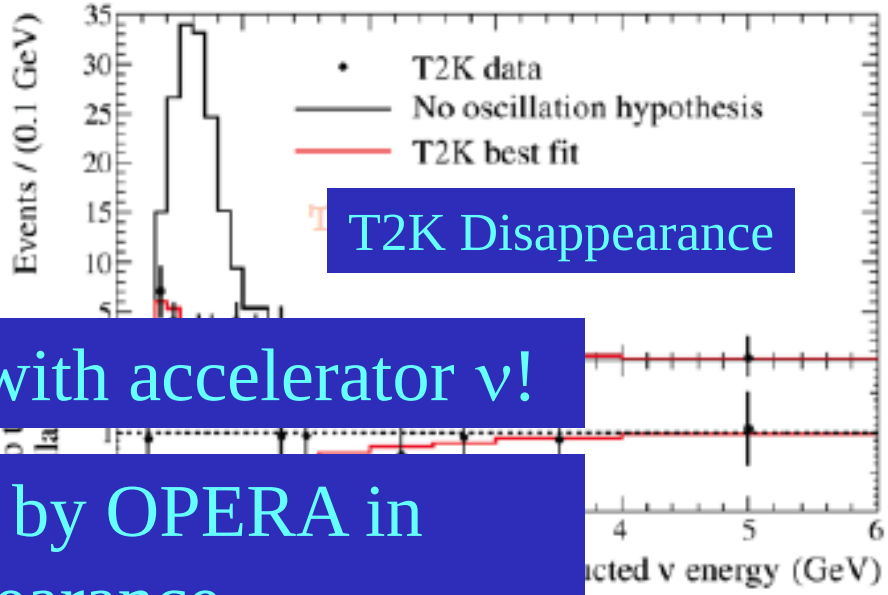




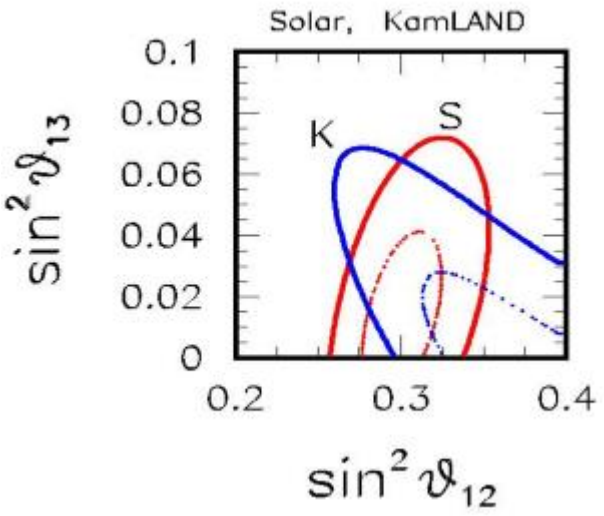
T2K Disappearance

Clearly seen with accelerator ν!

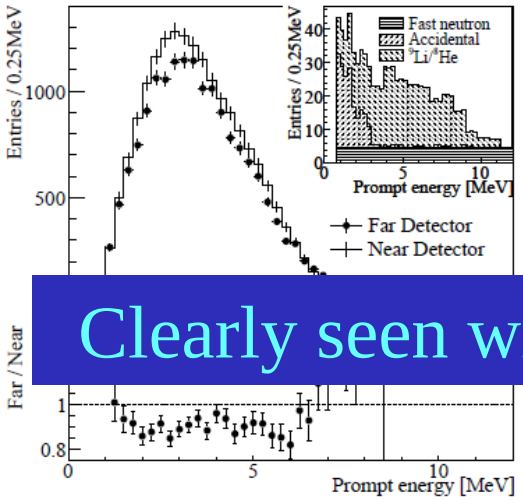
Also seen by OPERA in appearance.

How do we know θ_{13}, Δm_{13}?

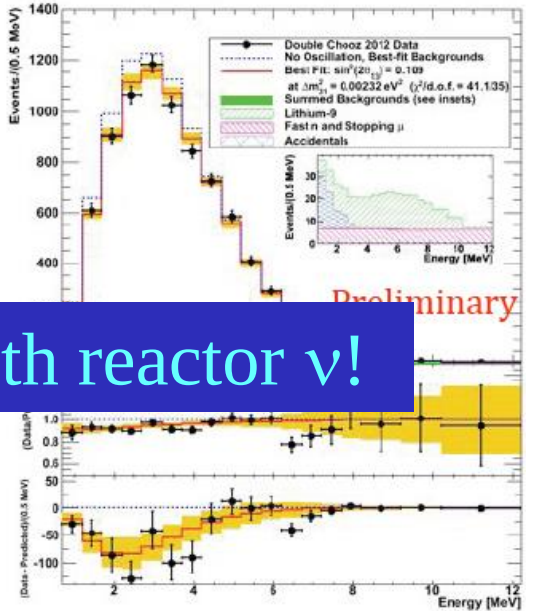
hep-ph/0806.2649



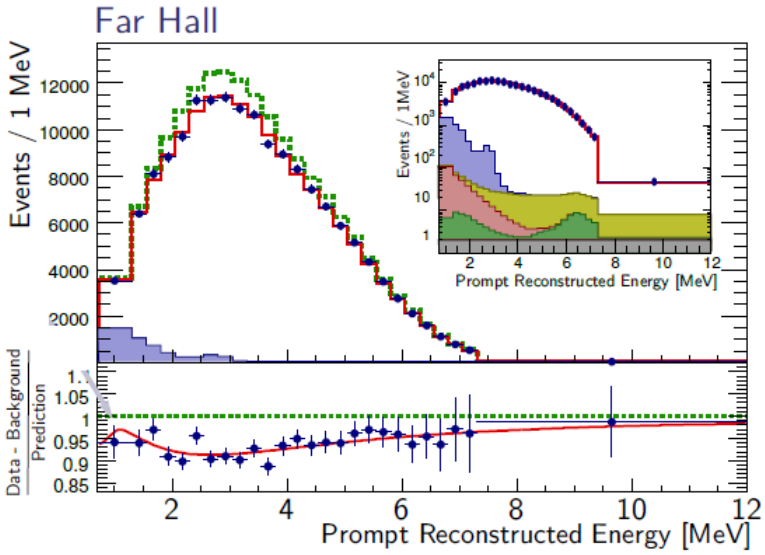
RENO



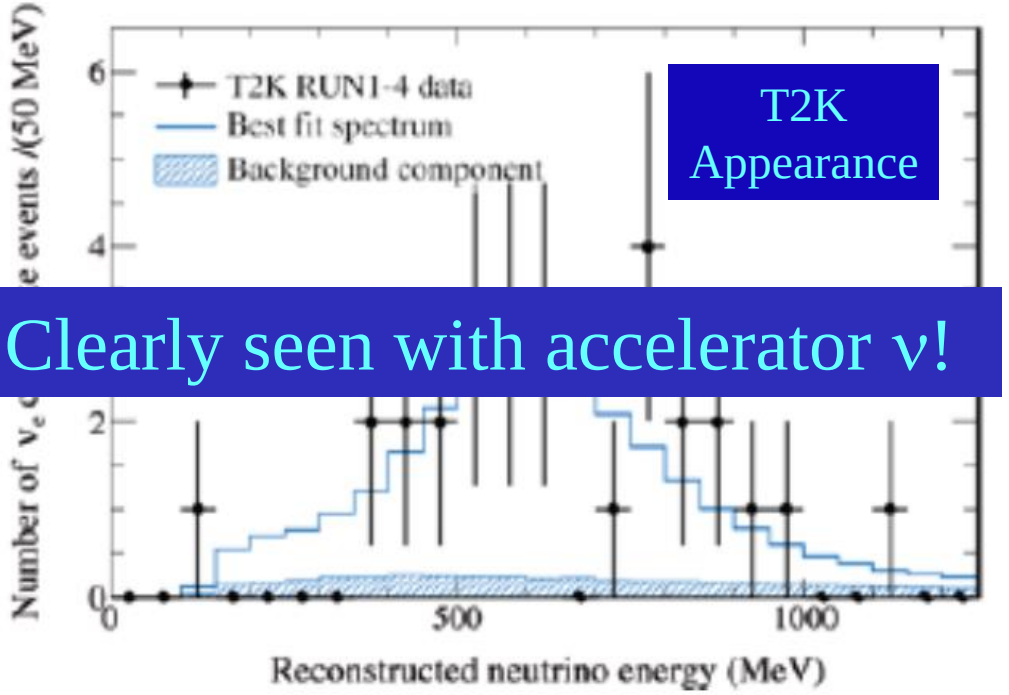
Double Chooz



Clearly seen with reactor ν!



Daya Bay rate plus shape

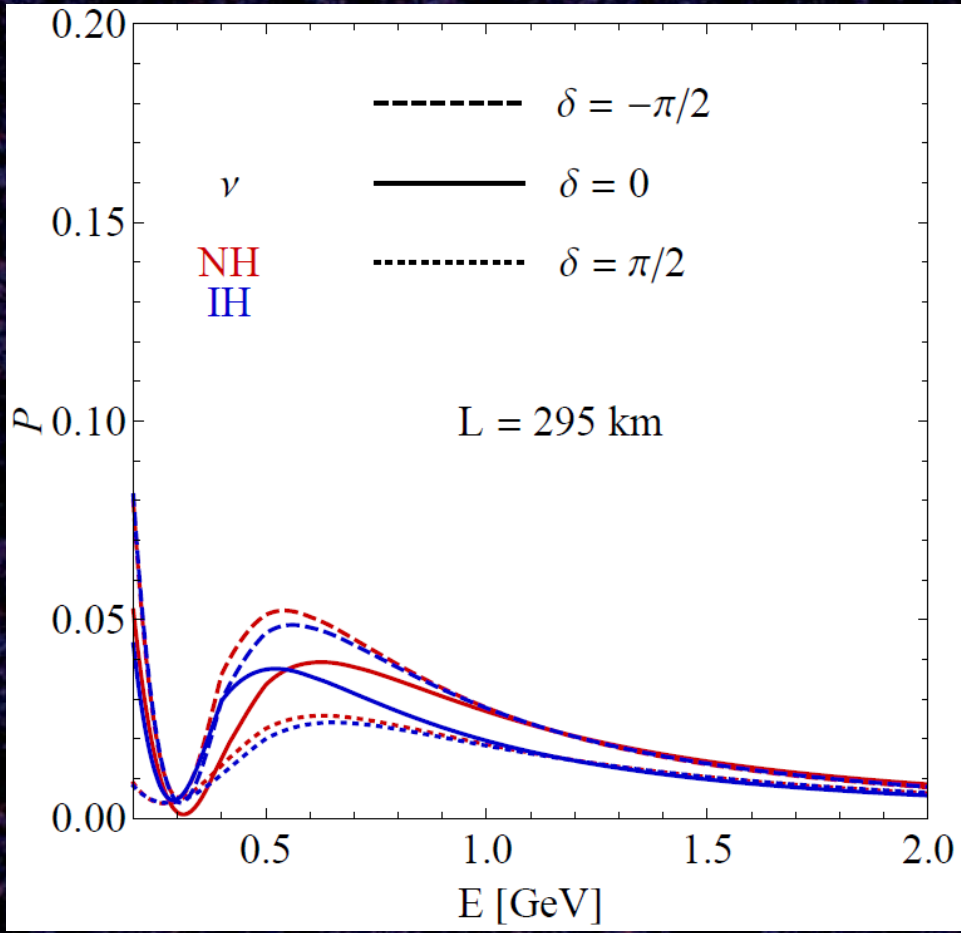


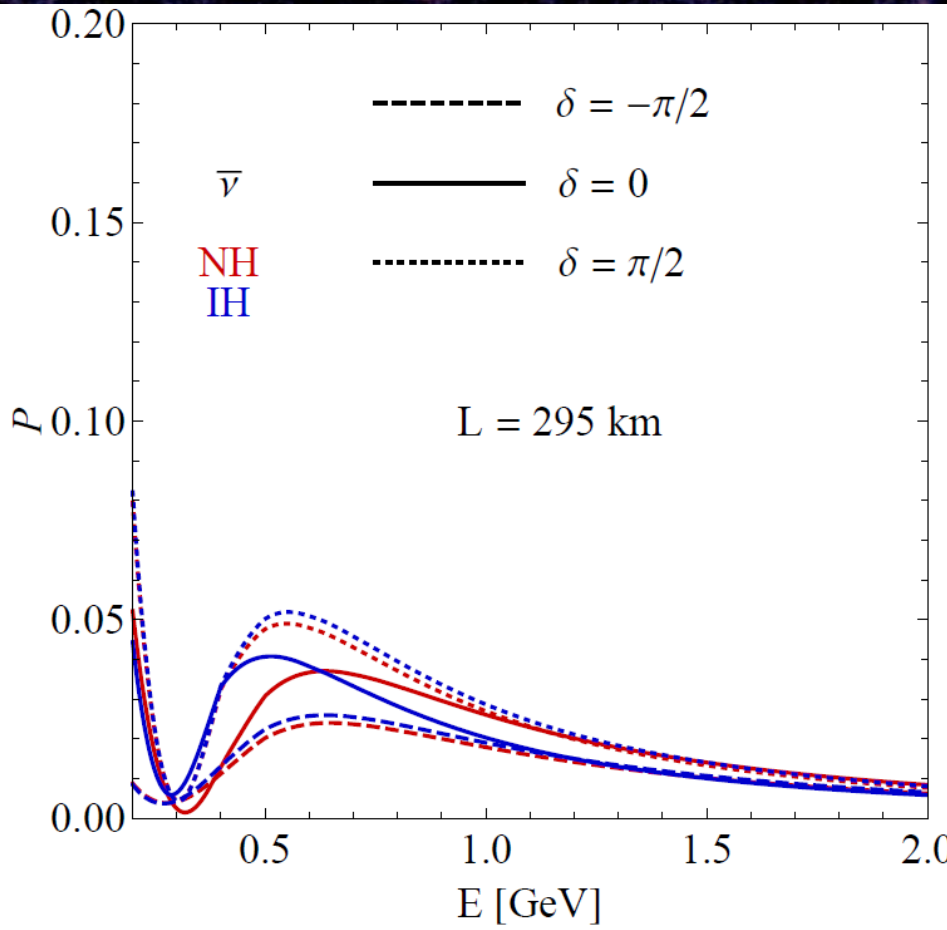
T2K Appearance

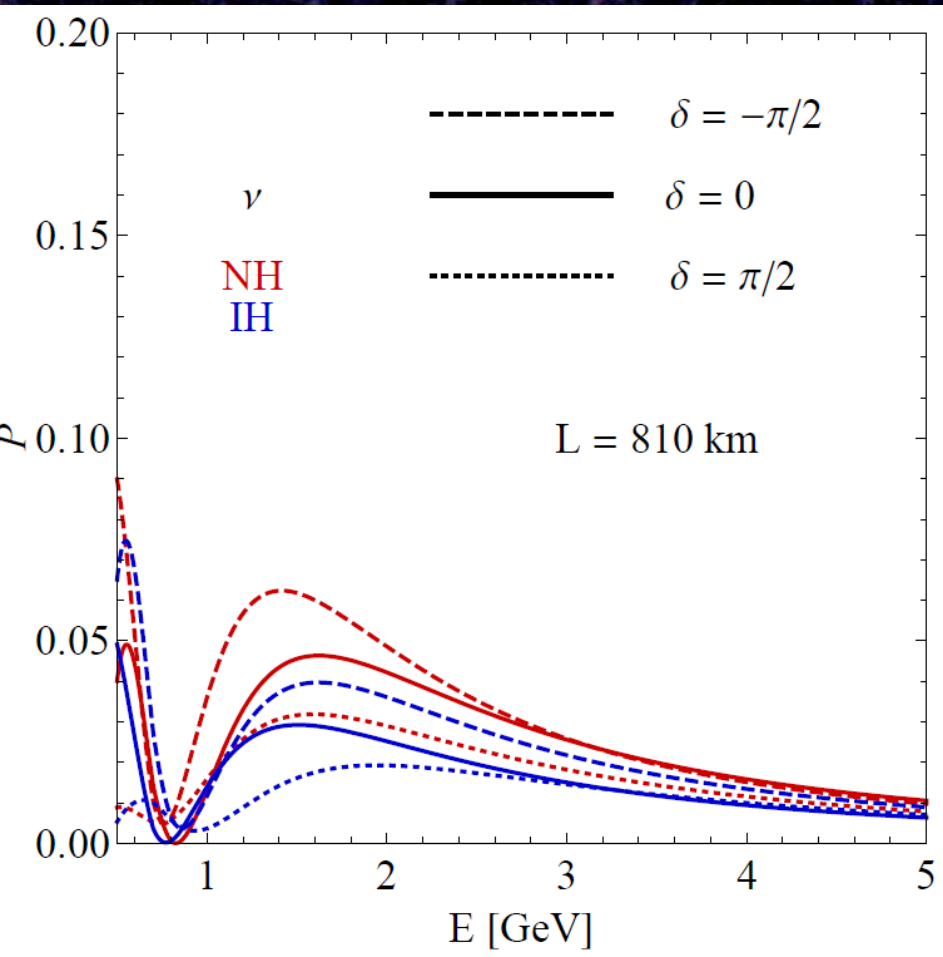
Clearly seen with accelerator ν!

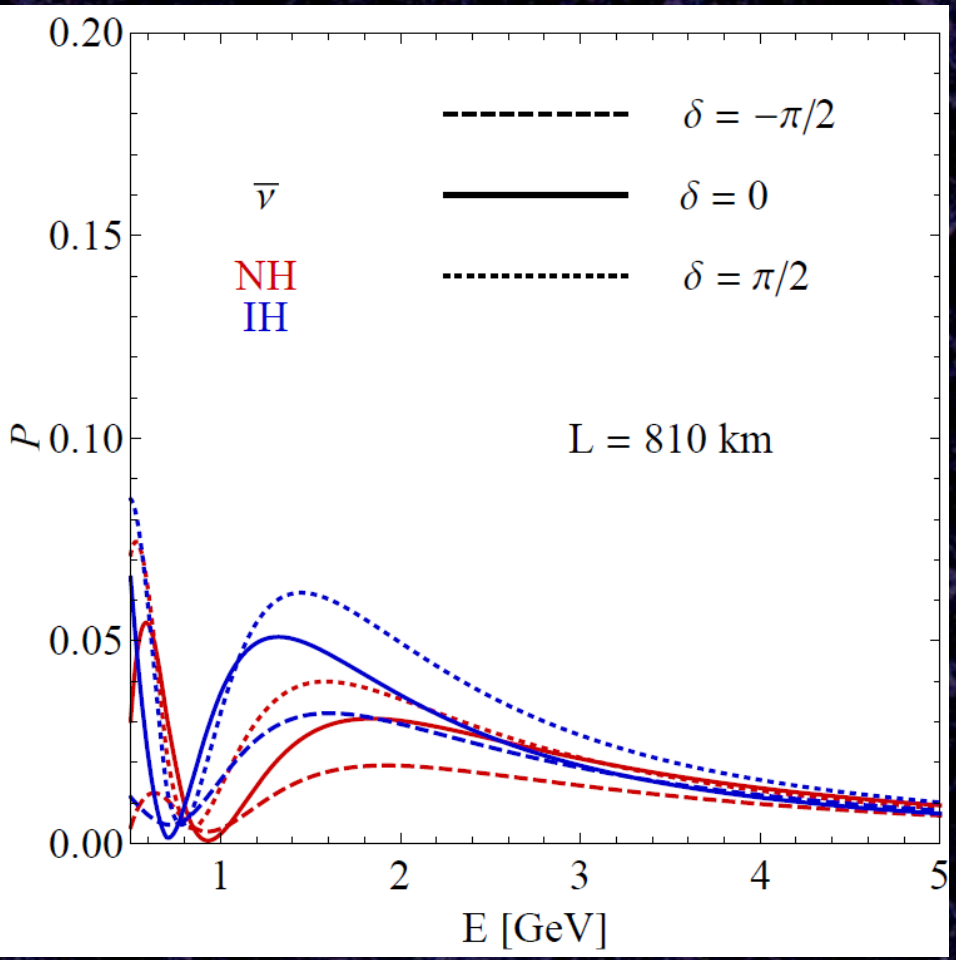
Which experiment should we do?

- I think that is the wrong question.
- The right question is: How many, and which experiments do we need to do to have complementary confirmations for the answers to all the big questions.
- Another thing to emphasize is multiple observables or techniques within each of the experiments (if possible).
- The SNO experiment was never going to be repeated, so we measured the critical NC signal three different ways within the same experiment.
- So what new experiments will help us answer these questions?

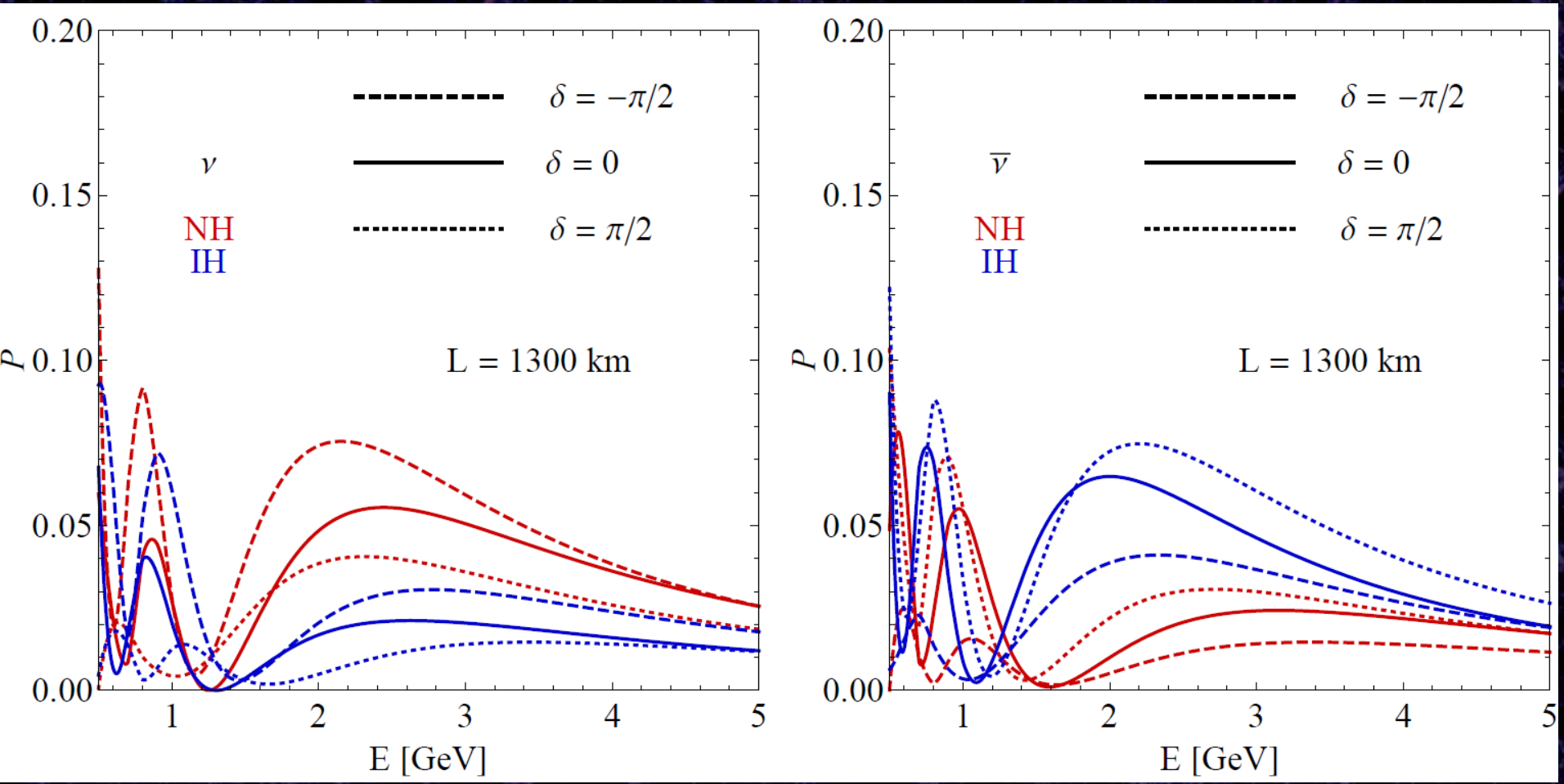

0.20
0.15
0.10
0.05
0.00
P
0.5
1.0
1.5
2.0
E [GeV]
$\delta = -\pi/2$
$\delta = 0$
$\delta = \pi/2$
ν
NH
IH
L = 295 km

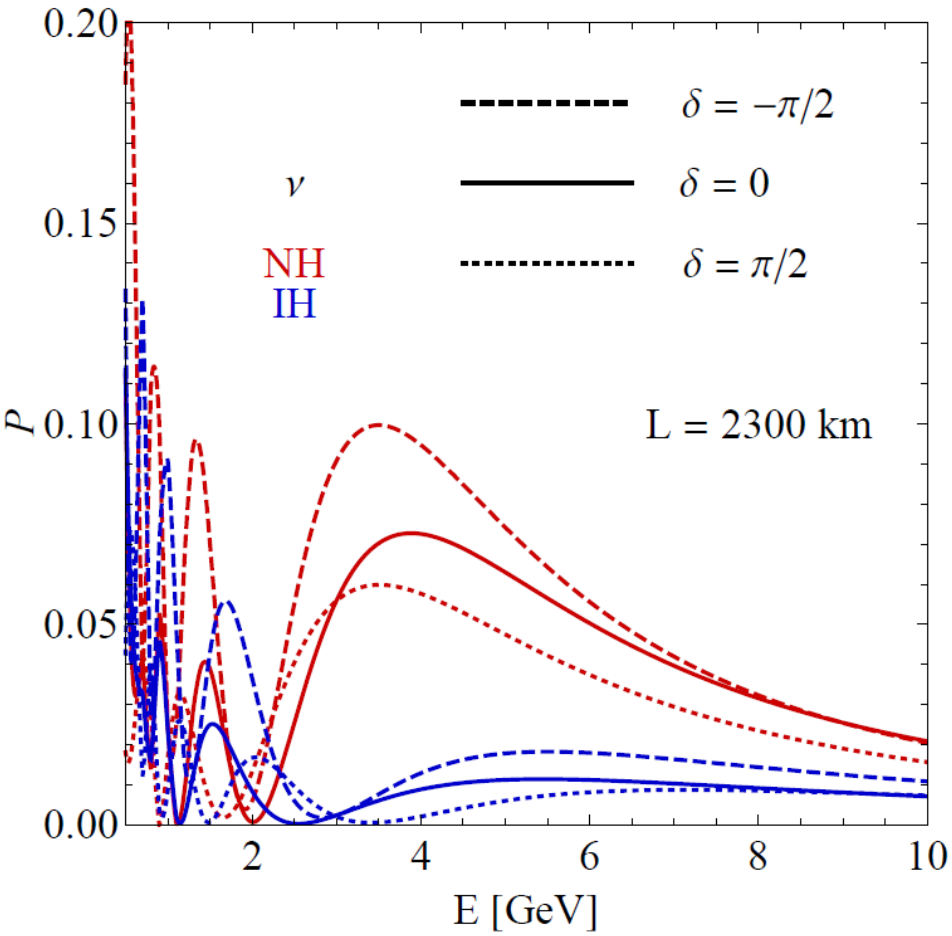

0.20
0.15
0.10
0.05
0.00
P
0.5
1.0
1.5
2.0
E [GeV]
$\delta = -\pi/2$
$\delta = 0$
$\delta = \pi/2$
$\overline{\nu}$
NH
IH
L = 295 km

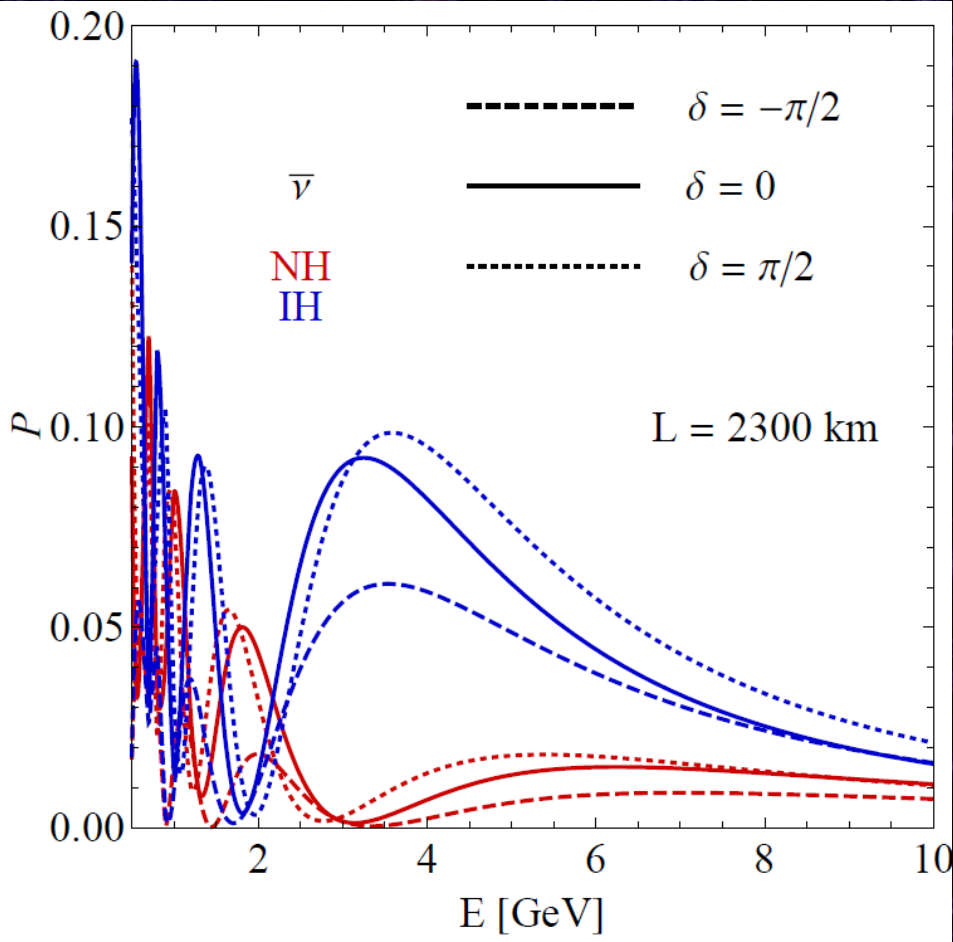




Dave Wark
Oxford U./RAL


0.20
0.15
0.10
0.05
0.00
P
1
2
3
4
5
E [GeV]
ν
NH
IH
$\delta = -\pi/2$
$\delta = 0$
$\delta = \pi/2$
L = 1300 km
$\overline{\nu}$

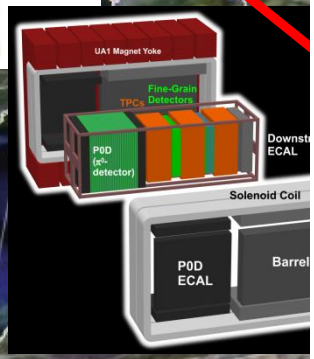


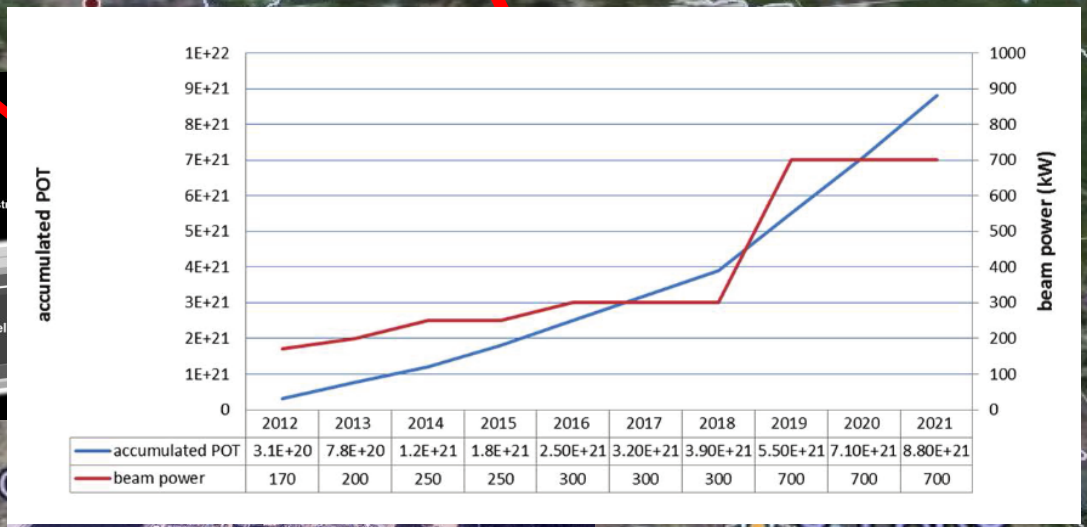


MH effect increases with baseline,
CP effect is ~roughly constant.

Note size of CP effect in second maximum…

Dave Wark
Oxford U./RAL



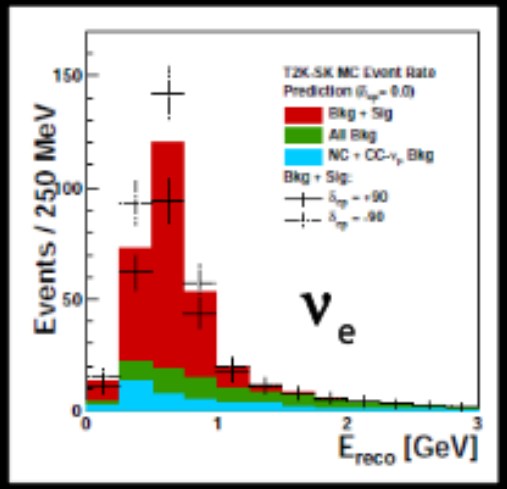


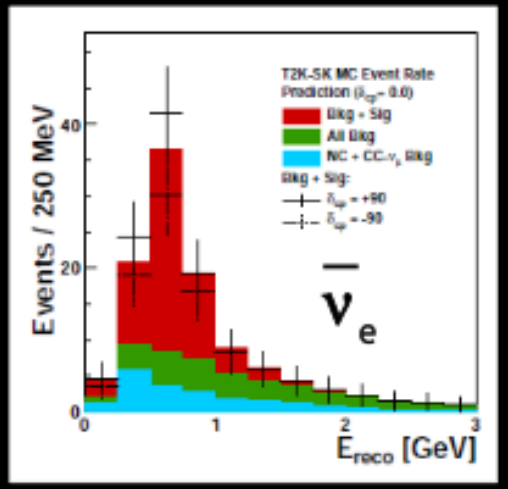
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
accumulated POT	3.1E+20	7.8E+20	1.2E+21	1.8E+21	2.50E+21	3.20E+21	3.90E+21	5.50E+21	7.10E+21	8.80E+21
beam power	170	200	250	250	300	300	300	700	700	700

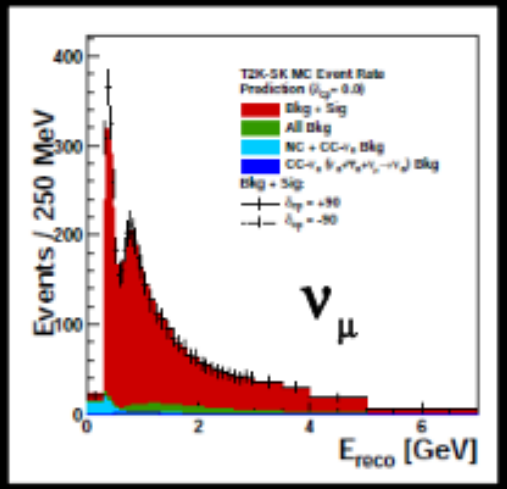
Assume we will get ~7.8 x 10^{21} p.o.t. by 2020

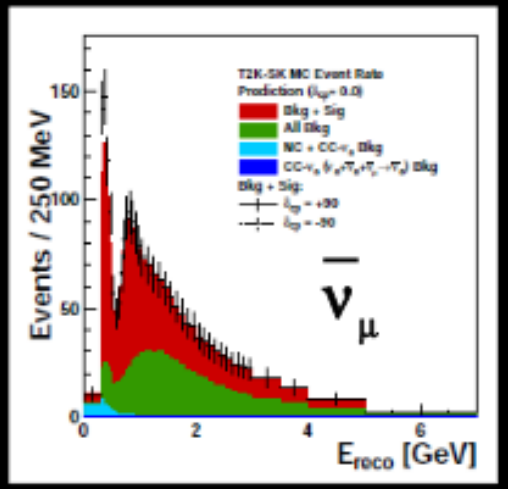
T2K Spectra at SK for 7.8×10^{21} POT

- Calculated FD spectra for full T2K statistics
  - Project SK MC to higher exposure
  - Estimate $\bar{\nu}$ beam MC from flux ratios
- Simultaneous fit of ν_μ, ν_e, $\bar{\nu}_\mu$, and $\bar{\nu}_e$ samples
- Oscillation parameter uncertainties
  - Fix solar terms
  - Allow atmospheric terms to float within current uncertainties
  - Project θ_{13} uncertainties to Daya Bay systematic uncertainty:
    ($\sin^2(2\theta_{13}) = 0.1 \pm 0.005$)
  - MH and δ_{cp} are unconstrained
- Assume various true values for:
  θ_{13}, θ_{23}, δ_{cp}, and MH

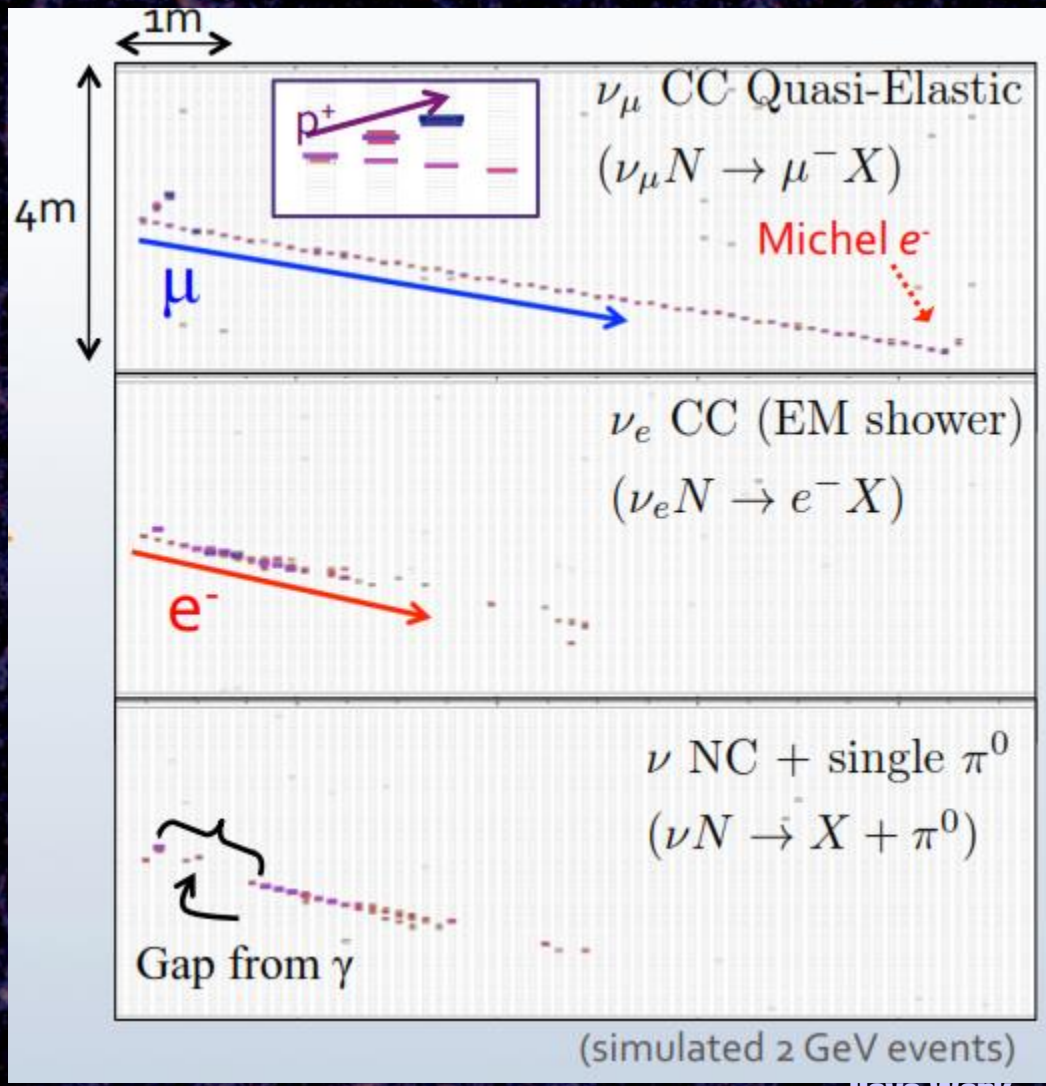






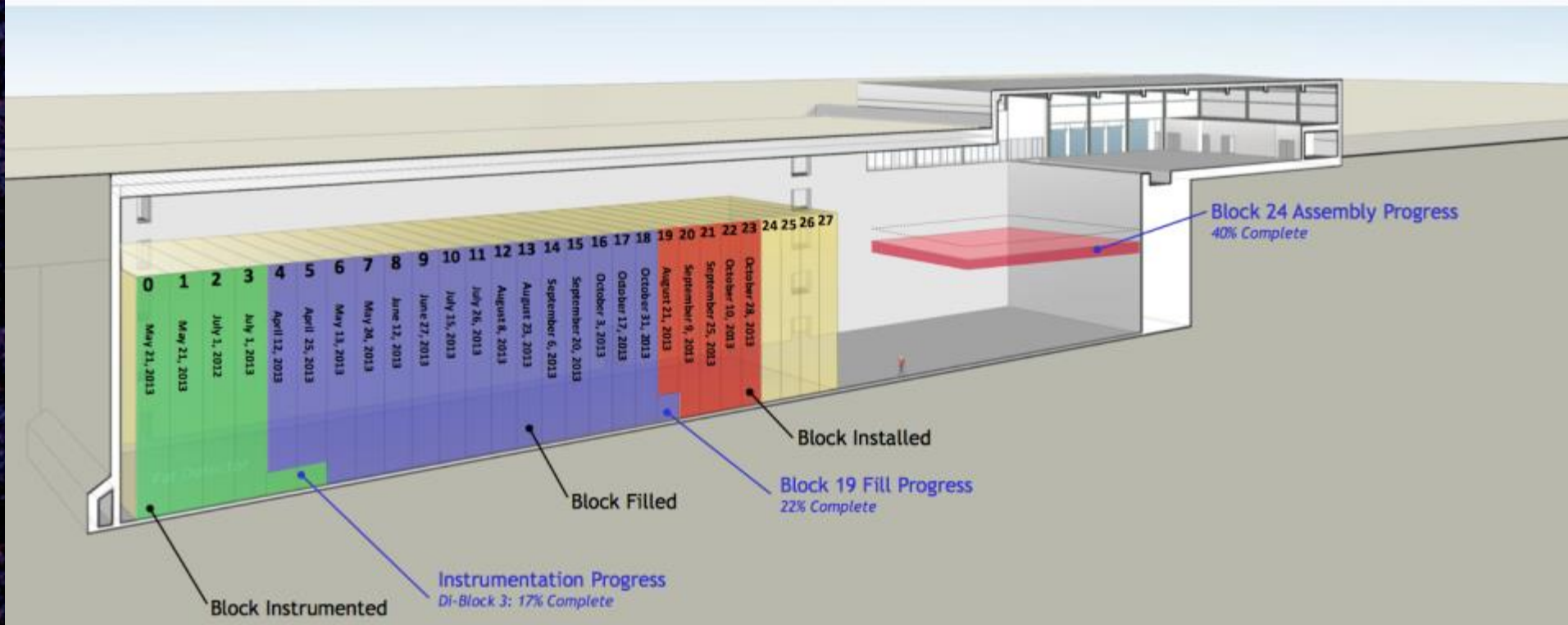


The NOvA Experiment



Dave Wark
Oxford U./RAL

Far Detector Status



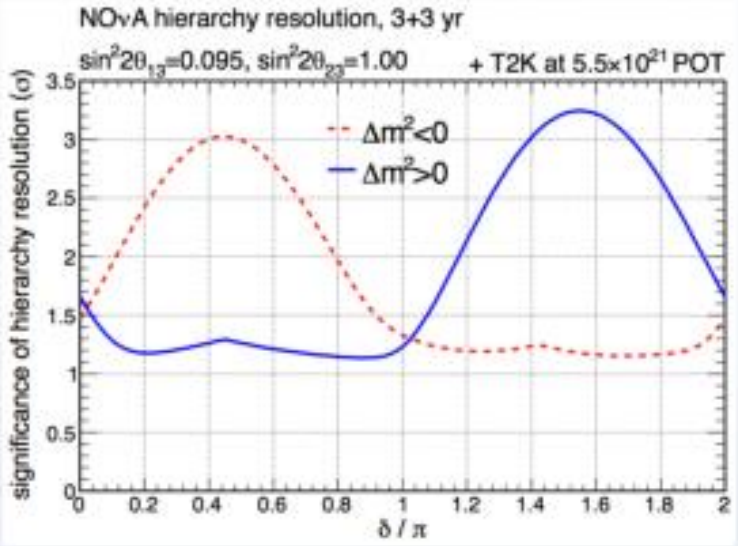
14 kilotons = 28 NOvA Blocks

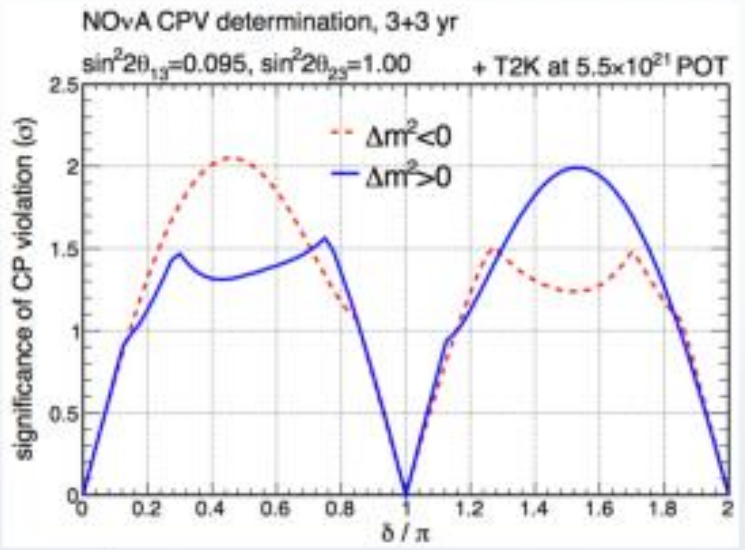
24 blocks of PVC modules are assembled and installed in place

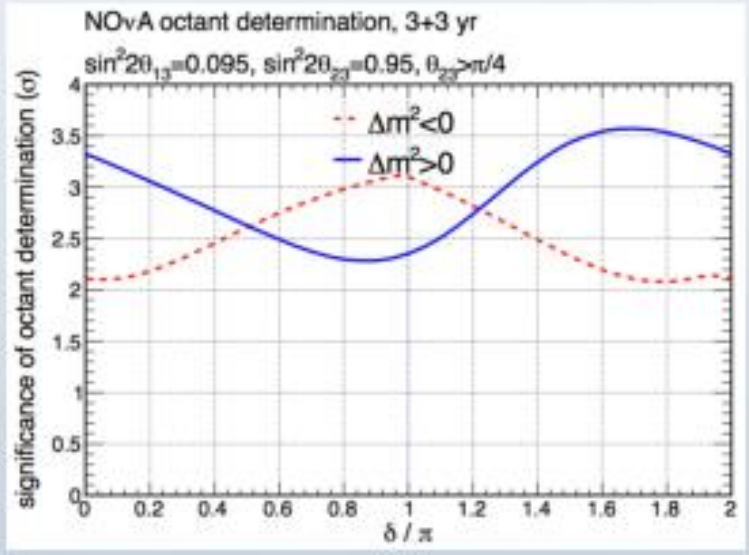
19.22 blocks are filled with liquid scintillator

4.34 blocks are outfitted with electronics

Physics Reach

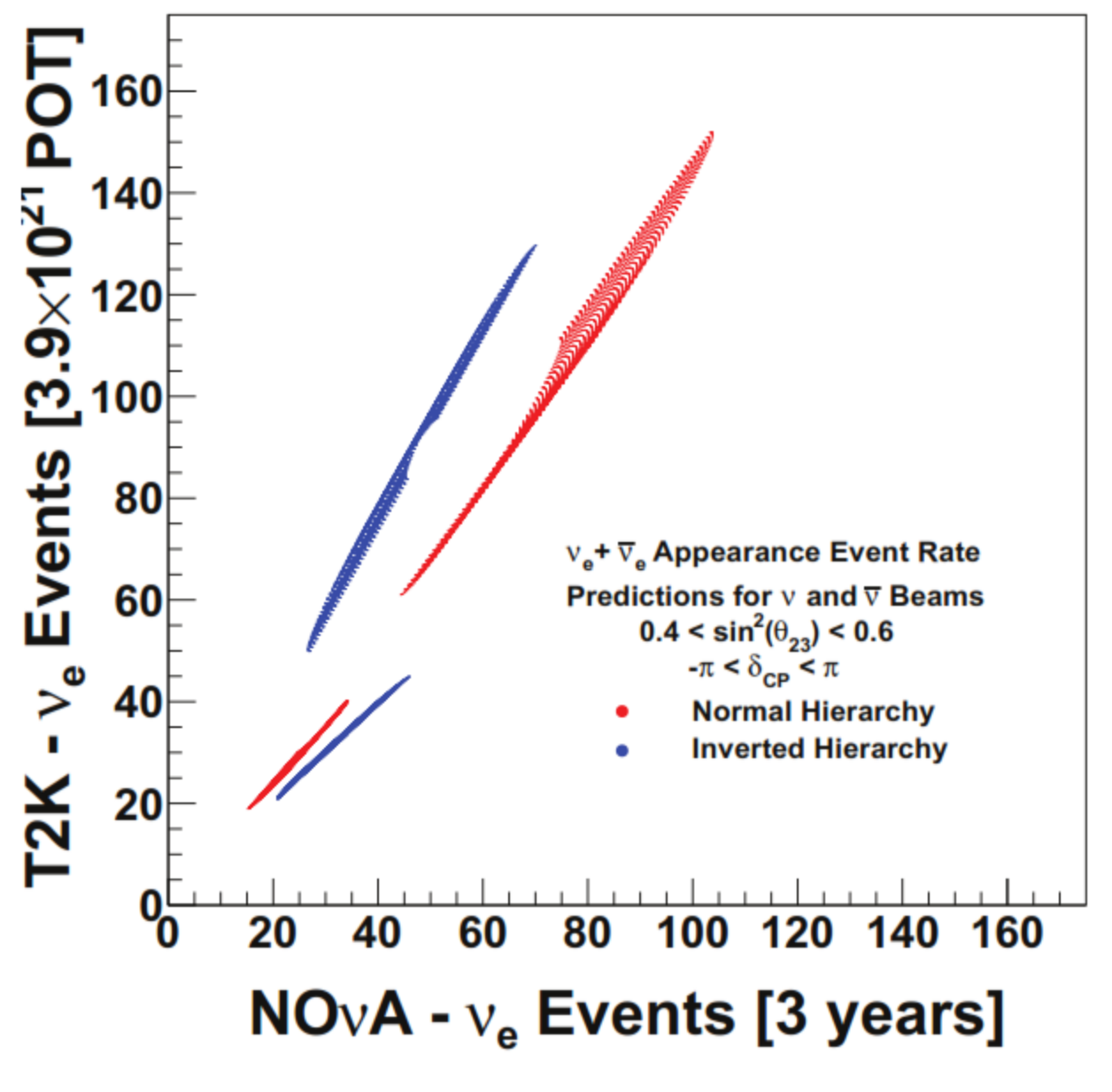






Sensitivities assume

- $\sin^2 2\theta_{13}$=0.095
- 3 years neutrino + 3 years anti-neutrinos running
- Optimization for ~4% oscillation probability
- 10% uncertainty on backgrounds



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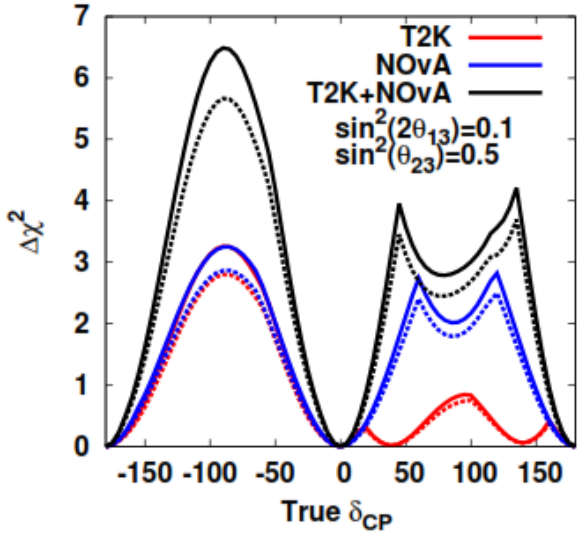
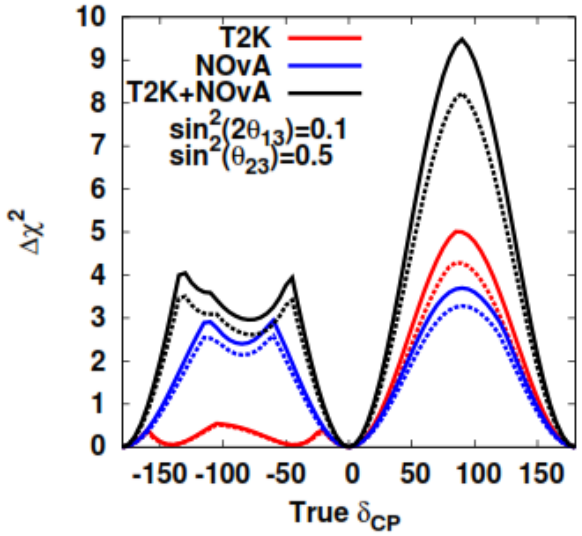
Oxford U./RAL

δ_{CP} Sensitivity

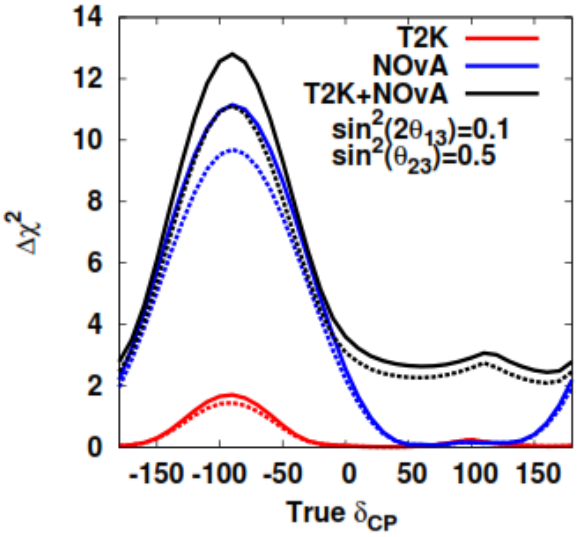


(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH

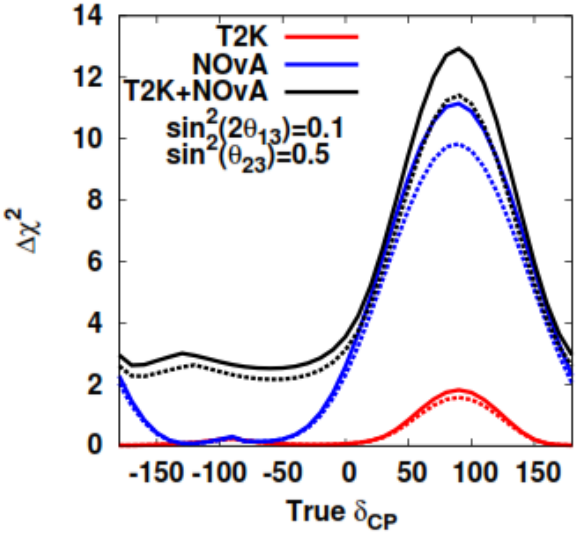


(d) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, IH

MH Sensitivity



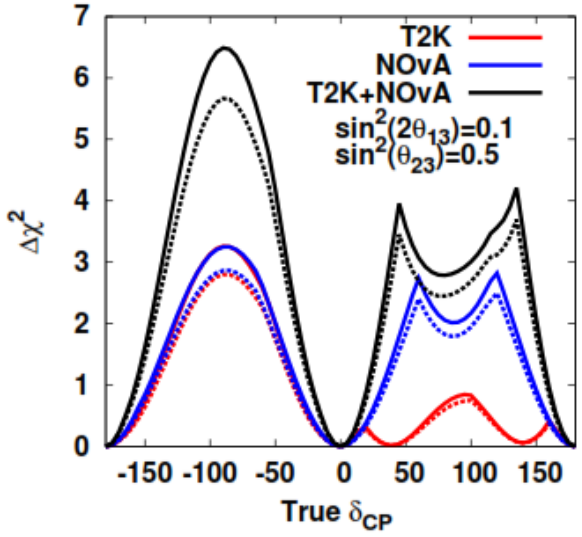
(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH



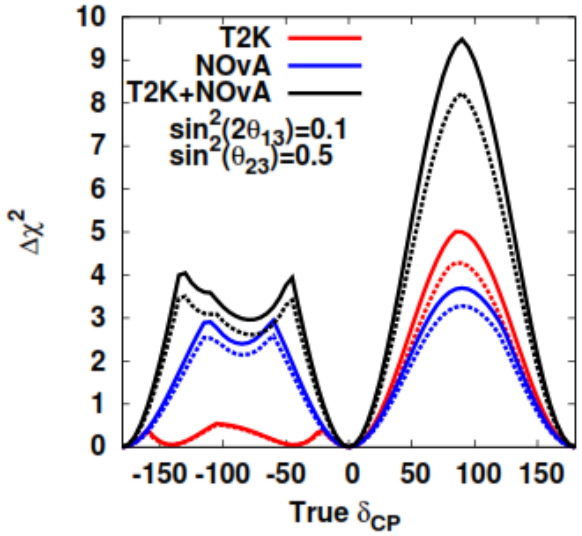
(d) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, IH

T2K + NOvA + Reactor Constraints.

δ_{CP} Sensitivity

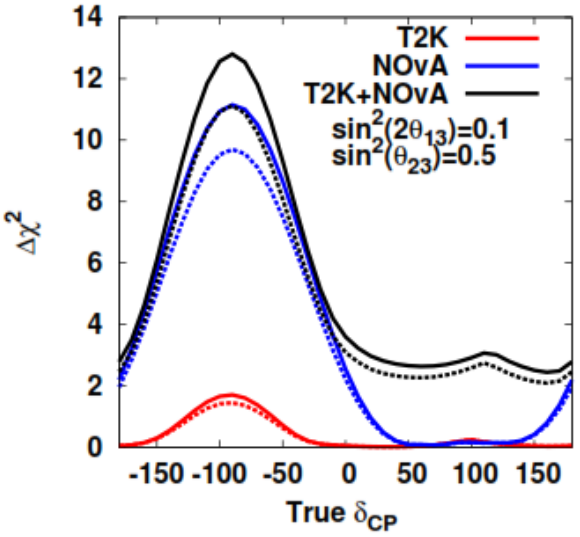


(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH

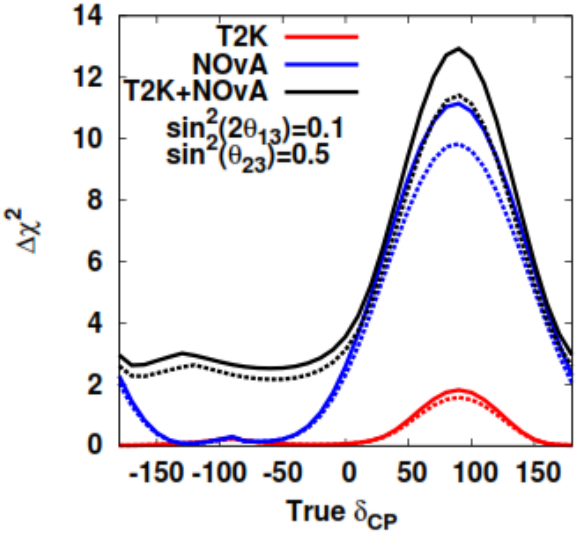


(d) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, IH

MH Sensitivity

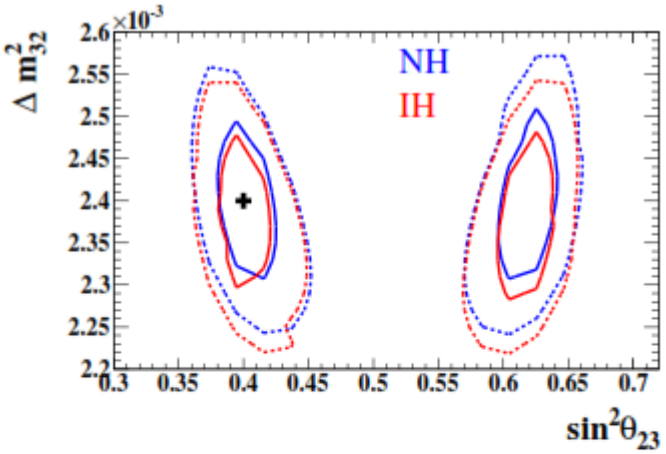


(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH

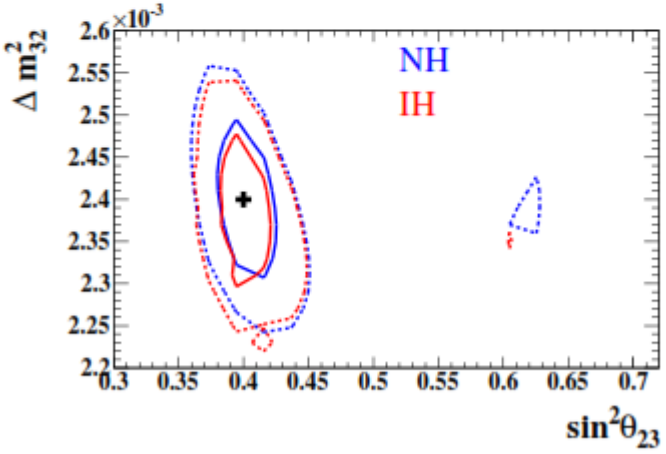


(d) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, IH

ν_μ Disappearance



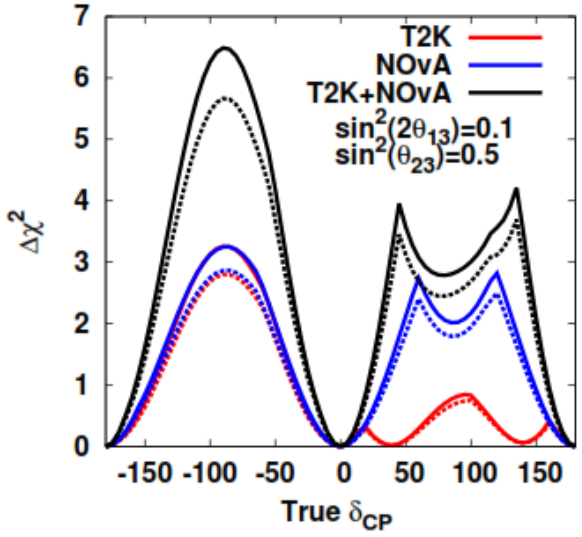
(b) 50% ν-, 50% $\bar{\nu}$-running, true NH.



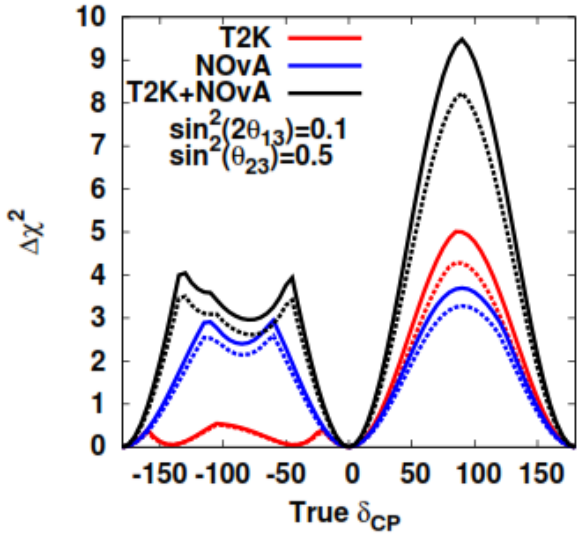
(d) 50% ν-, 50% $\bar{\nu}$-running, with ultimate reactor error, true NH.

Only T2K, but full T2K Statistics

δ_{CP} Sensitivity

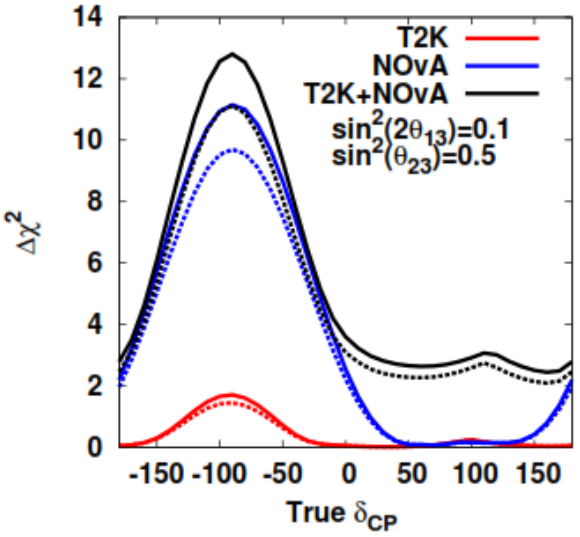


(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH

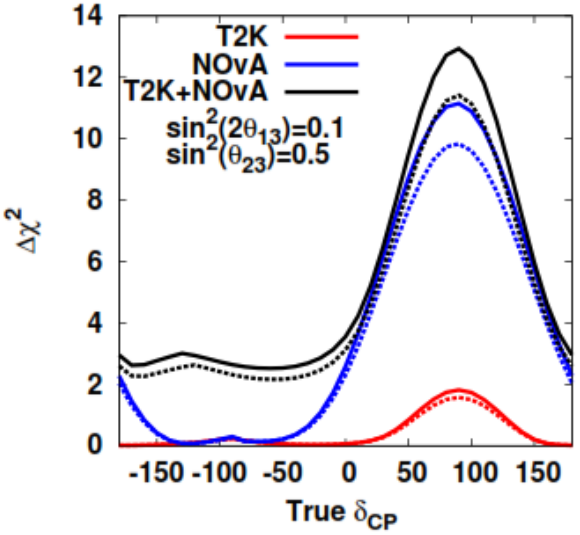


(d) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, IH

MH Sensitivity

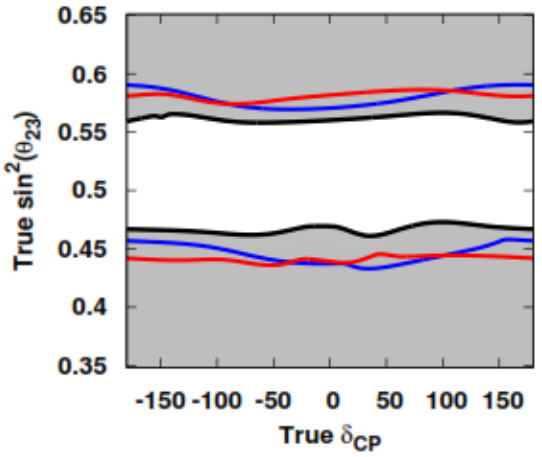


(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH

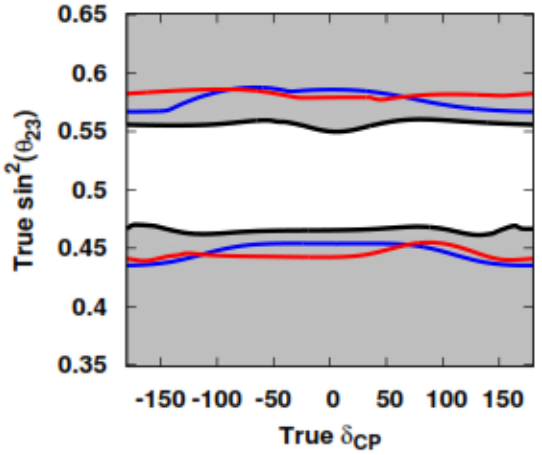


(d) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, IH

Octant Sensitivity

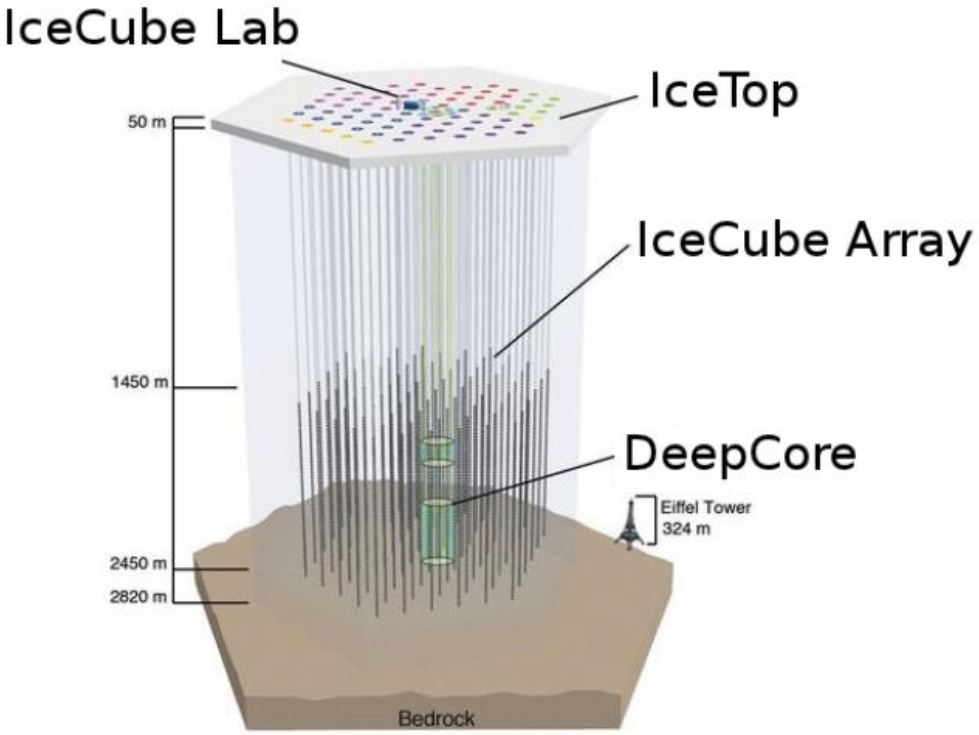


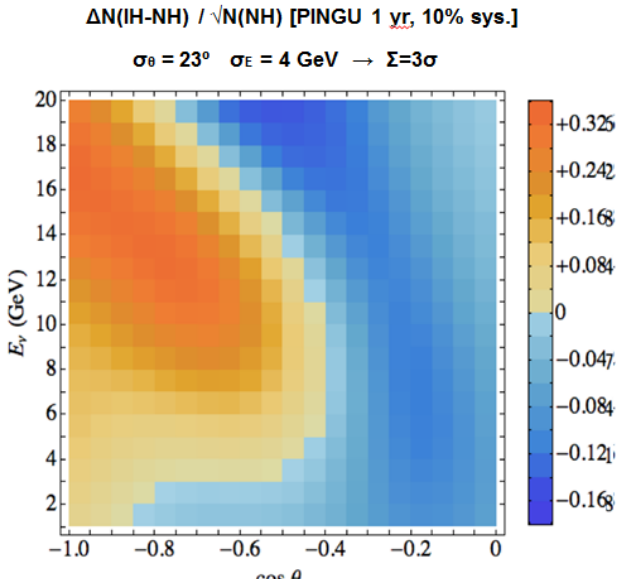
(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH, Simple systematics

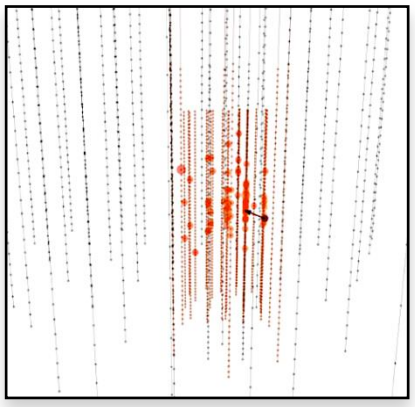


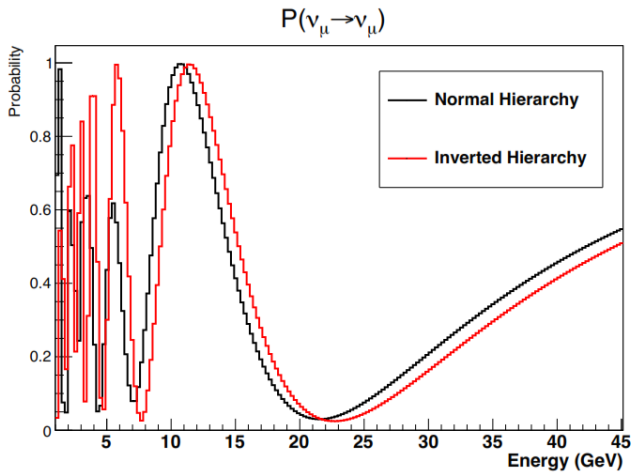
T2K + NOvA + Reactor Constraints.

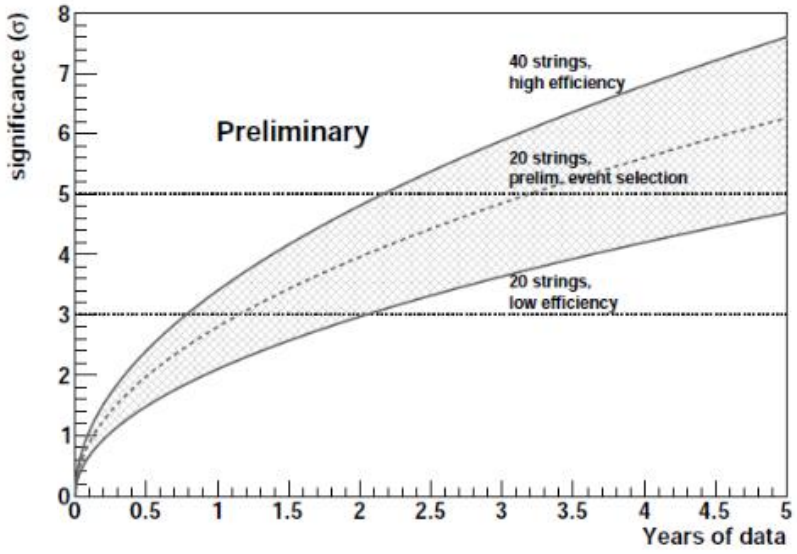
Many are called to measure the MH: PINGU





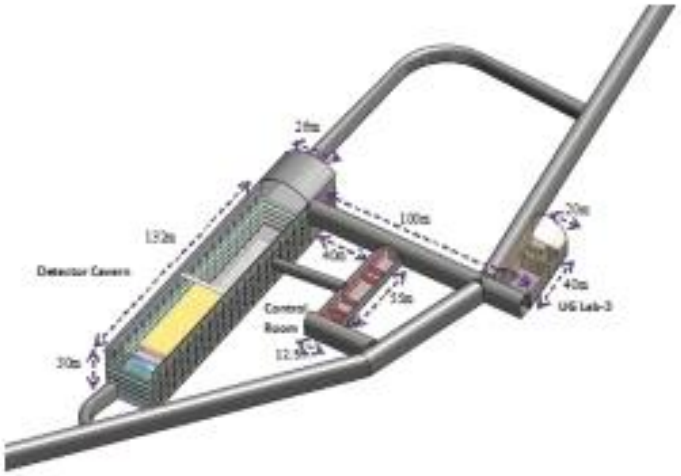


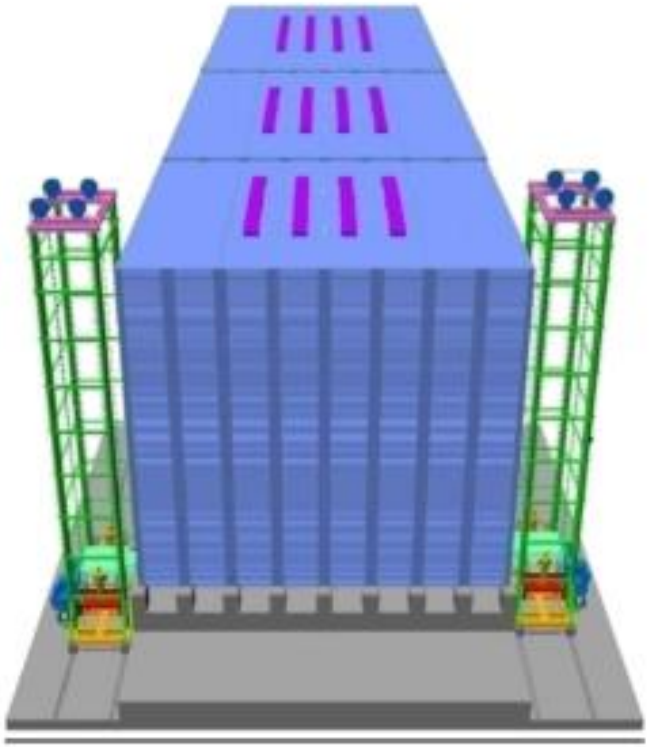


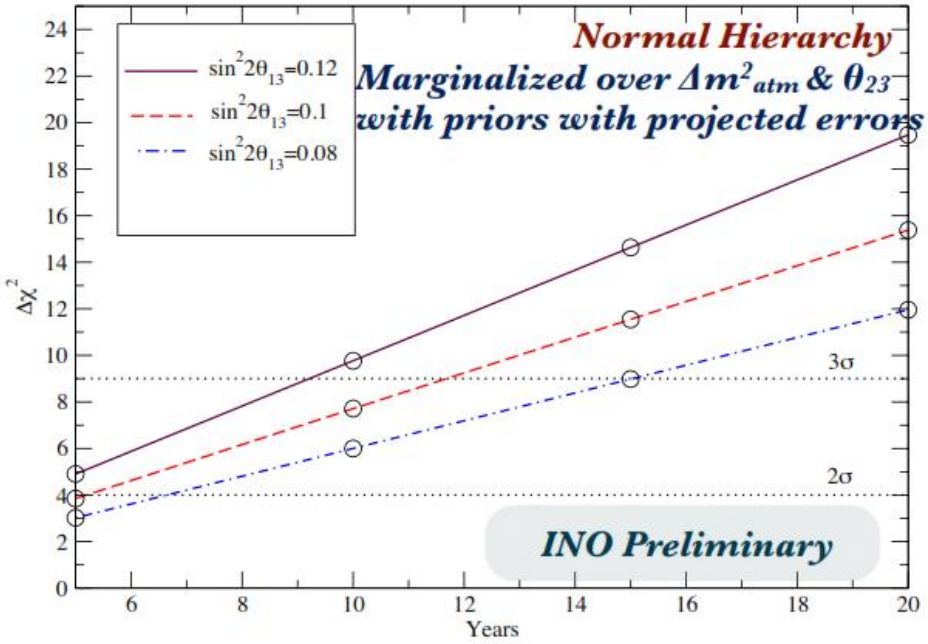


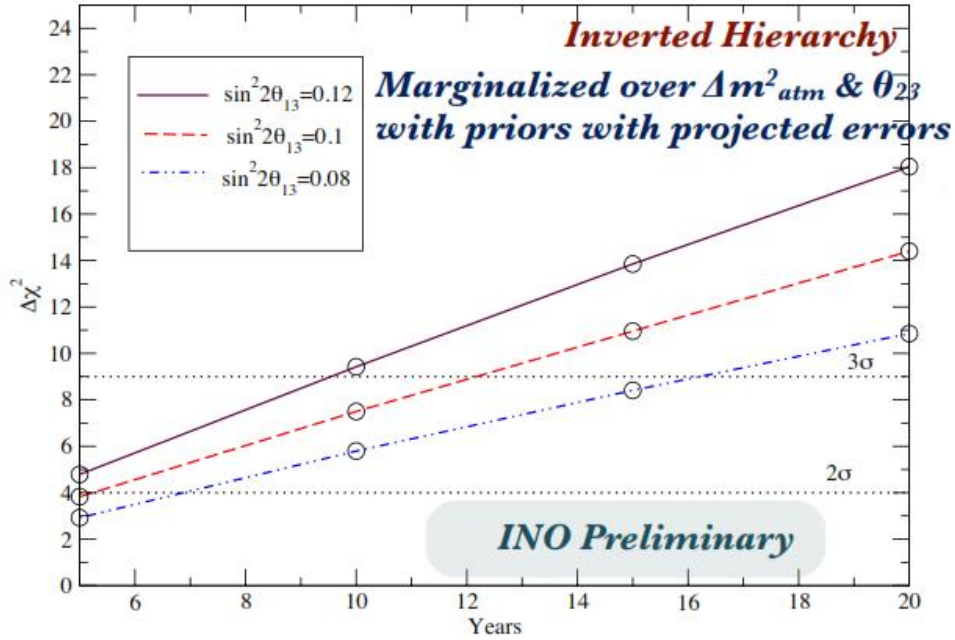
Many are called to measure the MH: INO

Choubey@neutrino'12



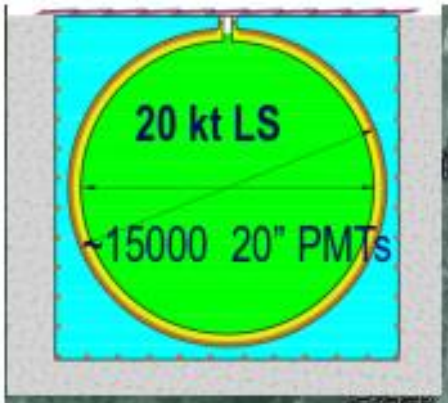


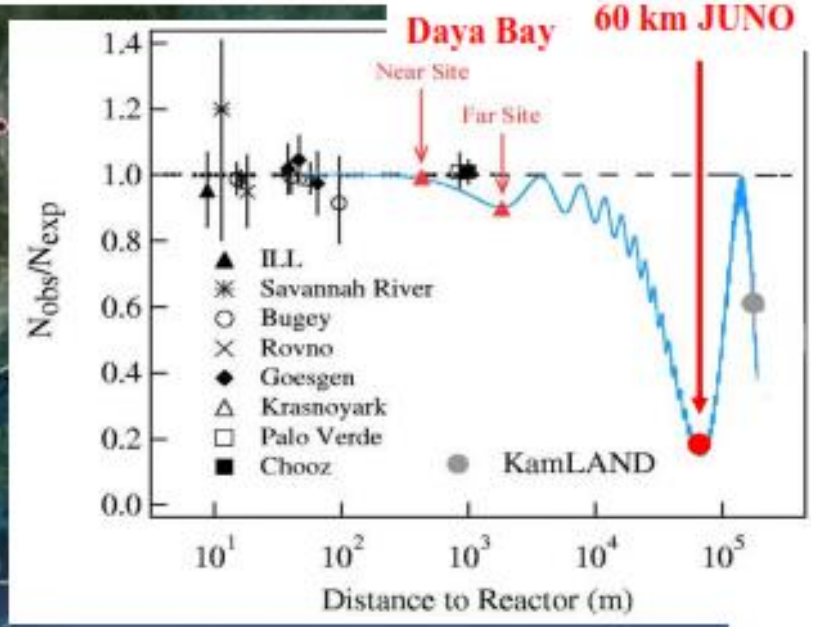




Many are called to measure the MH: JUNO

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	running	planned	approved	Construction	construction
power/GW	17.4	17.4	17.4	17.4	18.4

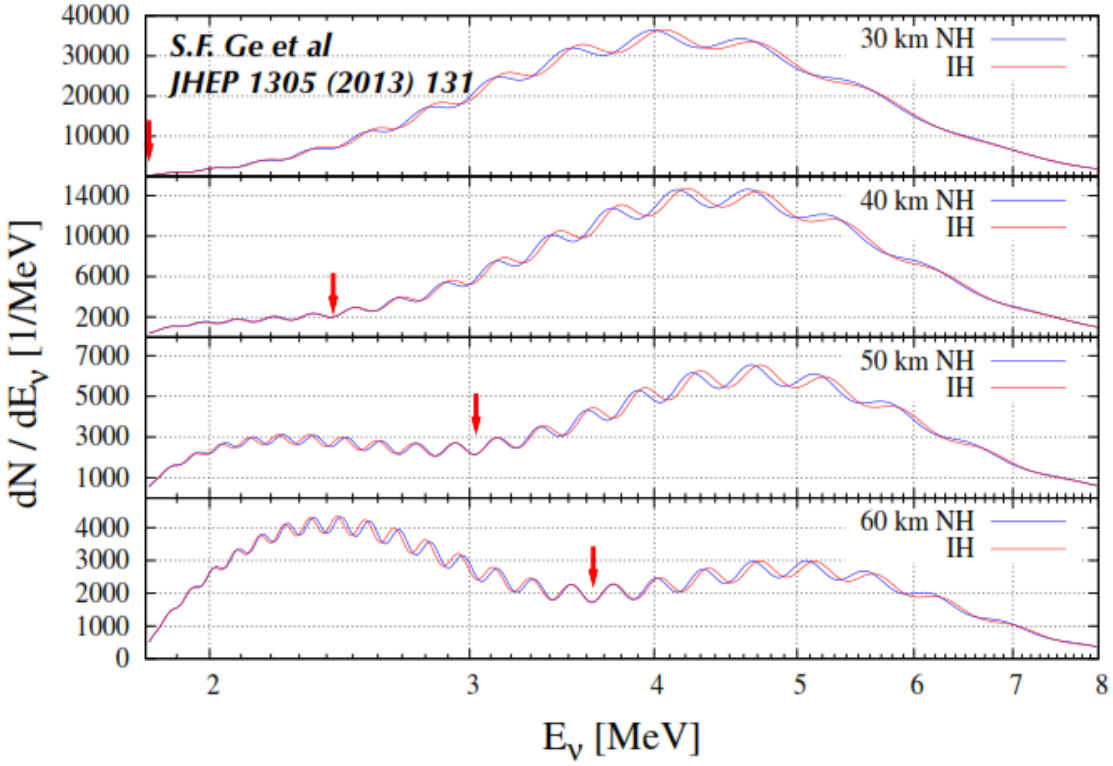


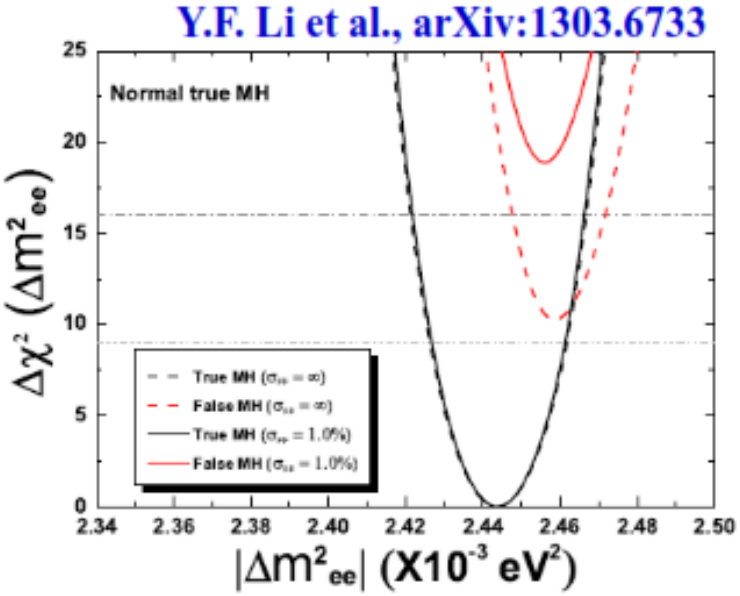


Talk by YFW at ICFA seminar 2008, Neutel 2011; by J. Cao at NuTurn 2012 ;

Paper by L. Zhan, YFW, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

Many are called to measure the MH: JUNO

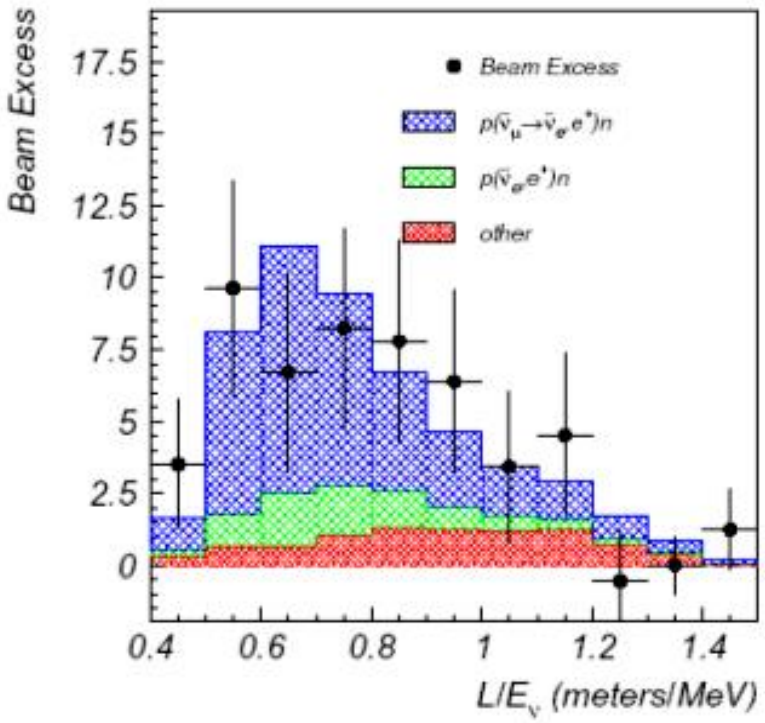




For 6 years, mass hierarchy cab be determined at 4σ level, if $\Delta m^2_{\mu\mu}$ can be determined at 1% level

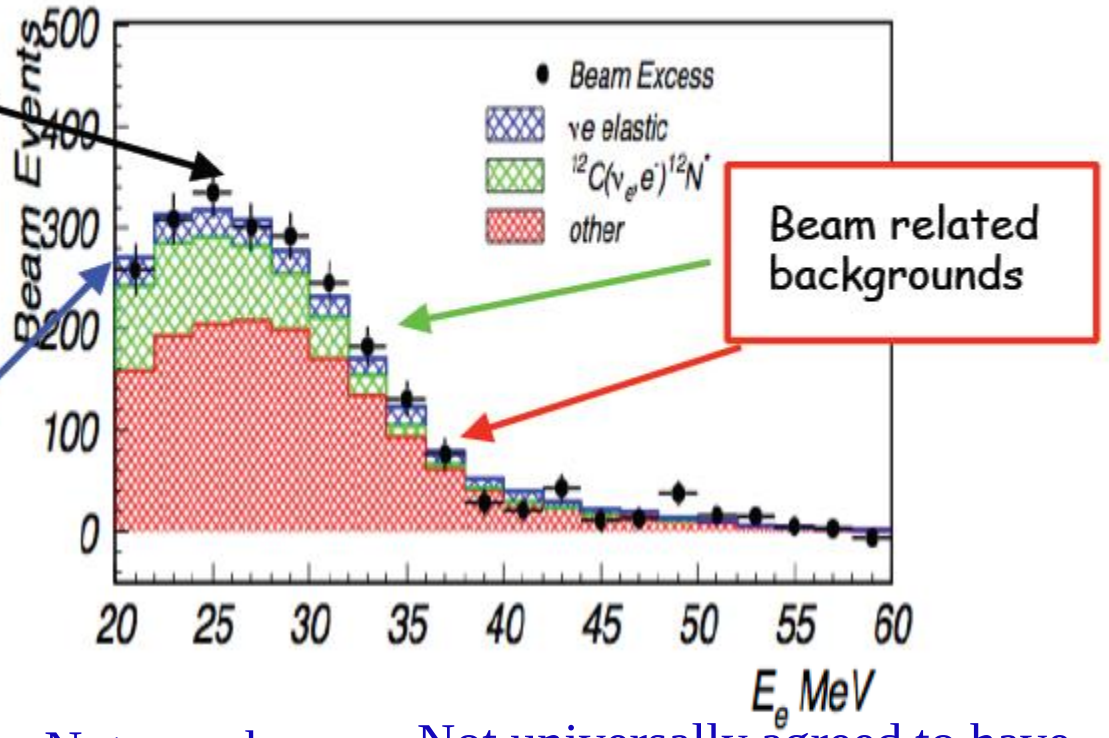
We also have an anomaly from LSND...

- Backgrounds in green,red
- Fit to oscillation hypothesis in blue



We also have an anomaly from LSND...

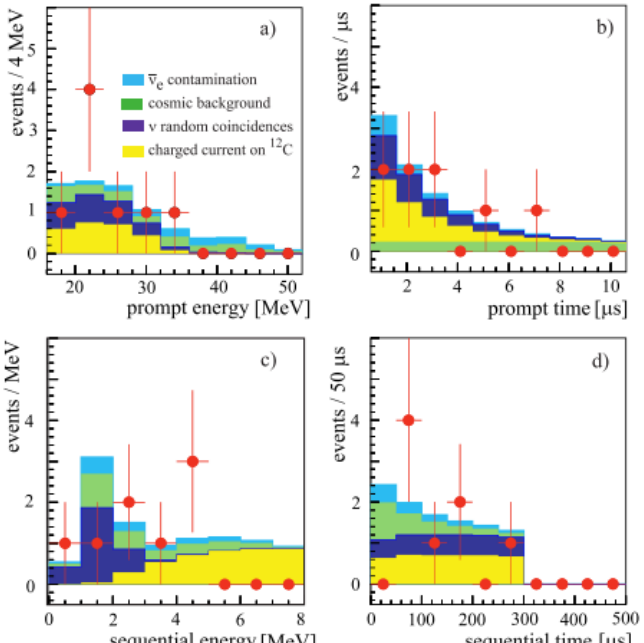
Excess of events: 87.9 ± 22.4 ± 6.0



Data points before background subtraction

Beam related backgrounds

Expectation for oscillations



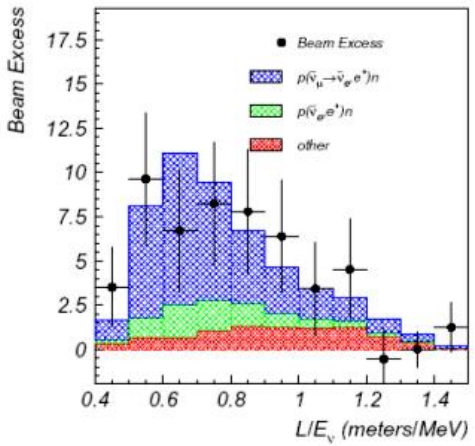
Not seen by KARMEN…

Not universally agreed to have been seen by LSND

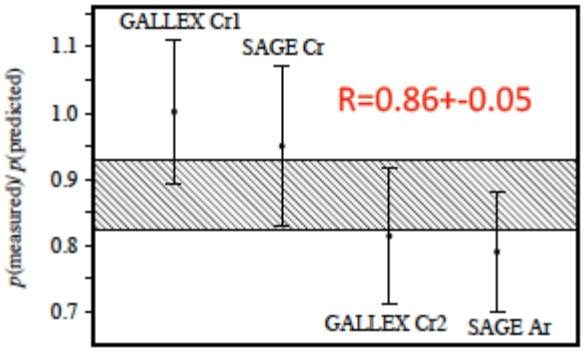
Luckily the MiniBooNE experiment at Fermilab was built to provide a clear resolution…

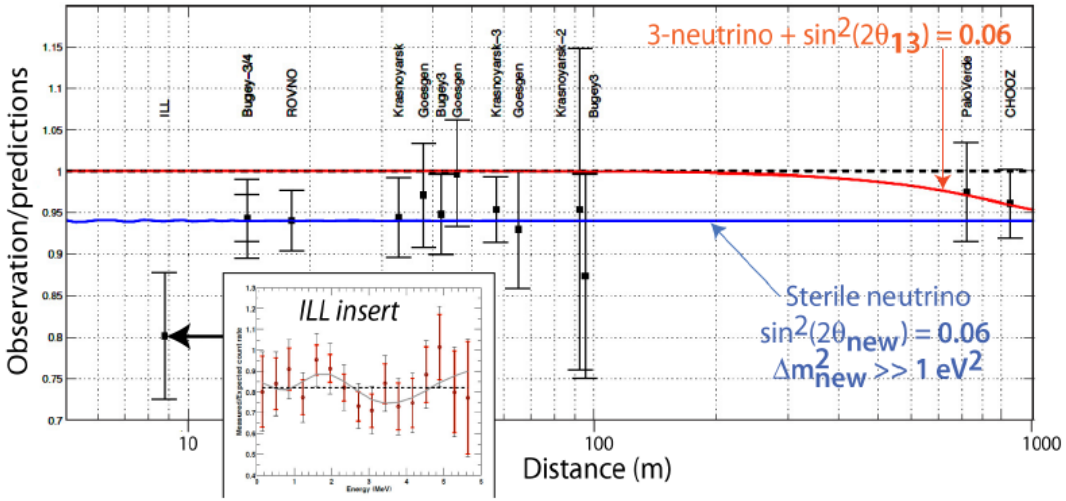
.....ooohhh.

Sterile Indications…

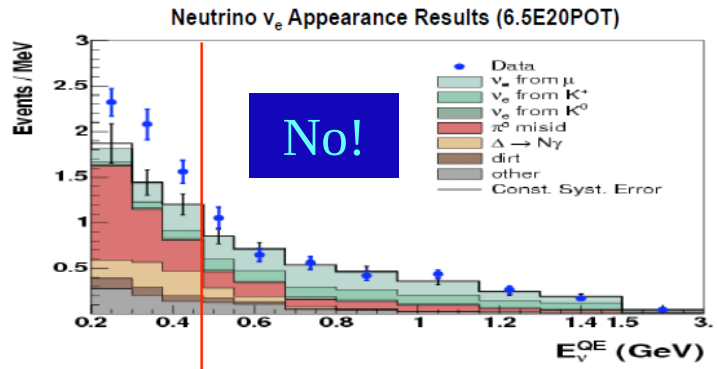


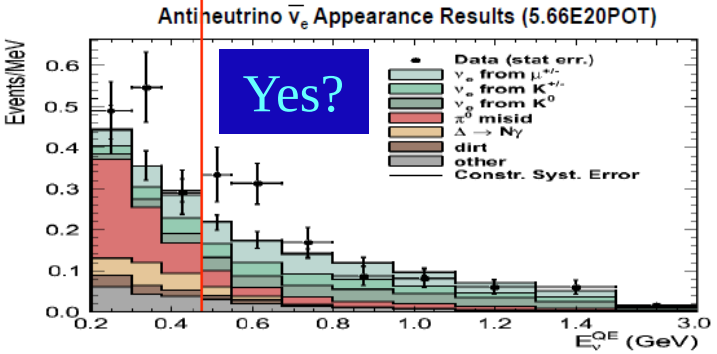
Short baselines (L/E ~ 1) and Sterile ν.



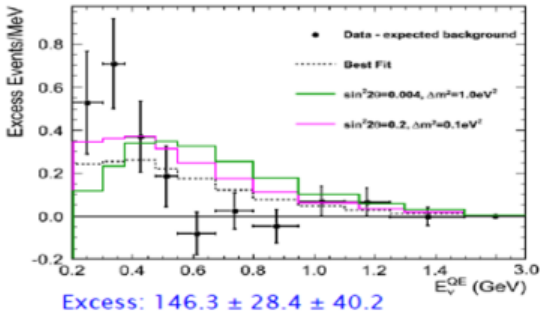


MiniBooNE says....

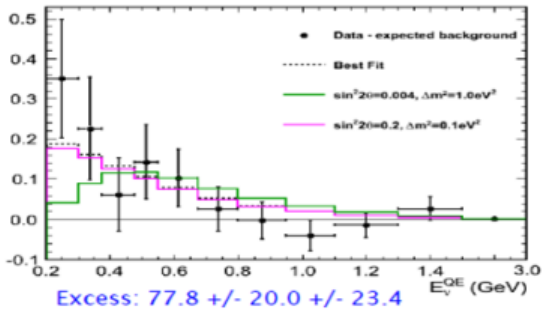




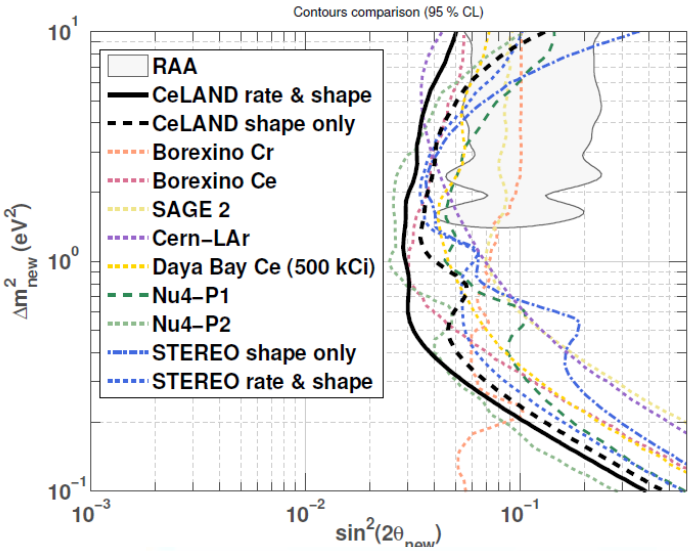
Latest…

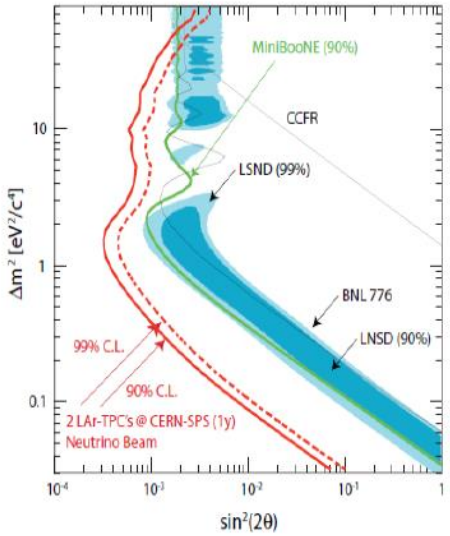


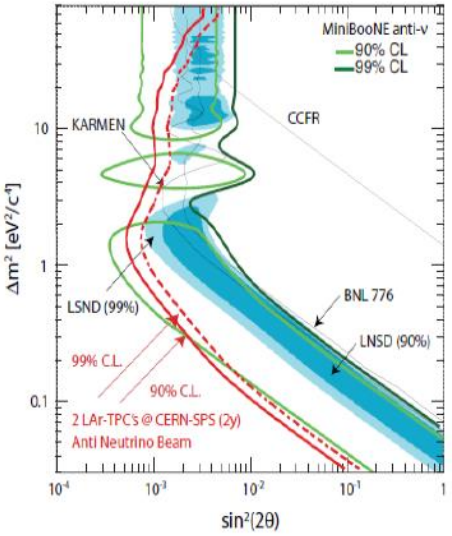
Excess: 146.3 ± 28.4 ± 40.2



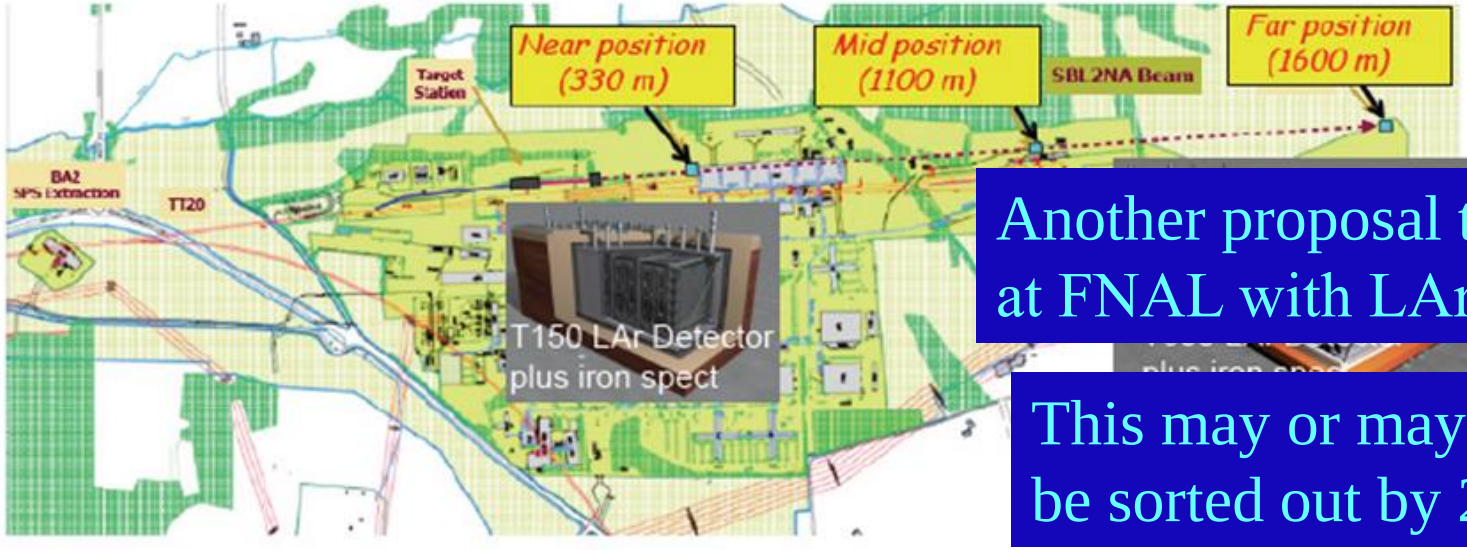
Excess: 77.8 +/- 20.0 +/- 23.4







New Neutrino Facility in the CERN North Area



Another proposal to test at FNAL with LAr1…

This may or may not be sorted out by 2020.

100 GeV primary beam fast extracted from SPS; target station next to TCC2; decay pipe l =100m, ø = 3m; beam dump: 15m of Fe with graphite core, followed by μ stations.

Conclusions

- Existing experiments have proven that neutrino oscillate and measured all the angles and mass differences (although more precision is needed).
- We are left targeting the MH, the octant, and especially CP violation (and looking for deviations, of course!).
- Over the next ~10 years we will almost certainly get much new data from T2K and NOvA and the reactor experiments Daya Bay, RENO, and Double Chooz.
- We may also get new data from some combination of PINGU, INO, JUNO, and various sterile neutrino experiments.
- We may have a much better idea of the MH and the octant by then, however we won't have any more than hints (at best) on CP violation.
- We will therefore need a large experiment targeted on CP violation!

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