Answers to old questions and new questions to answer

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With many thanks to all WG1 participants

NUFACT 2014

University of Glasgow, Scotland, still UK

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Neutrinos and the flavour puzzle

Question from NUFACT '13: What symmetries can we identify from the PMNS matrix element relative sizes? Which categories of models can we rule out with the current precision of mixing angle measurements

Neutrinos and the flavour puzzle

From C. Luhn talk, some simple mixing patterns easily obtained from symmetries:

$$U_{\rm PMNS} \approx U_{\rm TB} \equiv \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

"Tribimaximal"

$$\theta_{12} \approx 35.3^\circ \qquad \theta_{23} = 45^\circ \qquad \theta_{13} = 0^\circ$$

$$U_{\rm PMNS} \approx U_{\rm GR} \equiv \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\frac{\sin\theta_{12}}{\sqrt{2}} & \frac{\cos\theta_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\frac{\sin\theta_{12}}{\sqrt{2}} & \frac{\cos\theta_{12}}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

"Golden Ratio"

$$\theta_{12} \approx 31.7^\circ \qquad \theta_{23} = 45^\circ \qquad \theta_{13} = 0^\circ$$

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Already ruled out by θ_{13}

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"Golden Ratio"

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Neutrinos and the flavour puzzle

From C. Luhn talk, possible solutions:

θ_{13} generated from perturbations of the original simpler pattern

Will show up in perturbation theory. Leads to testable sum rules…

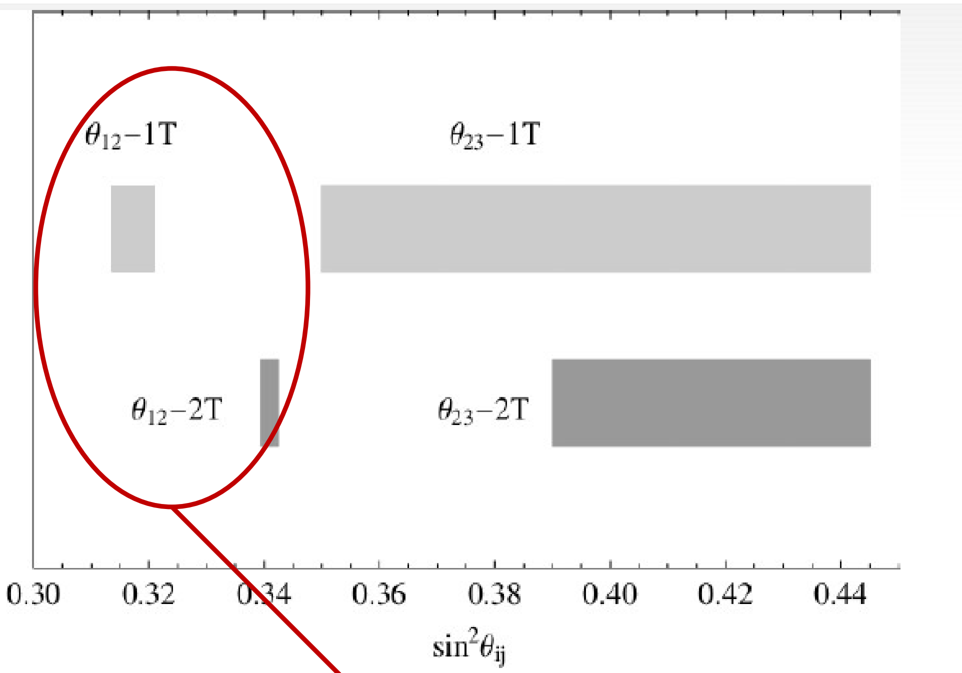
$$\theta_{12} \approx 35.3^\circ + \theta_{13} \cos\delta$$

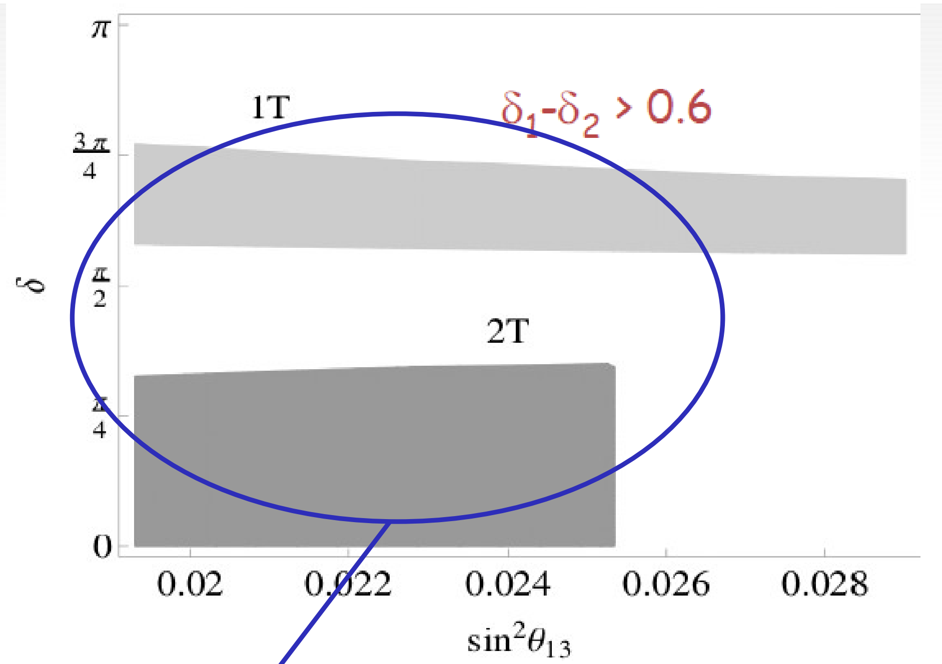
$$\theta_{23} \approx 45^\circ + \sqrt{2}\,\theta_{13} \cos\delta$$

$$\theta_{23} \approx 45^\circ - \frac{1}{\sqrt{2}}\,\theta_{13} \cos\delta$$

Neutrinos and the flavour puzzle

From D. Meloni talk, different models allow different sets of mixing parameters:





Testable at JUNO/Reno50?

Testable with T2K+NOνA CP searches?

Neutrinos and the flavour puzzle

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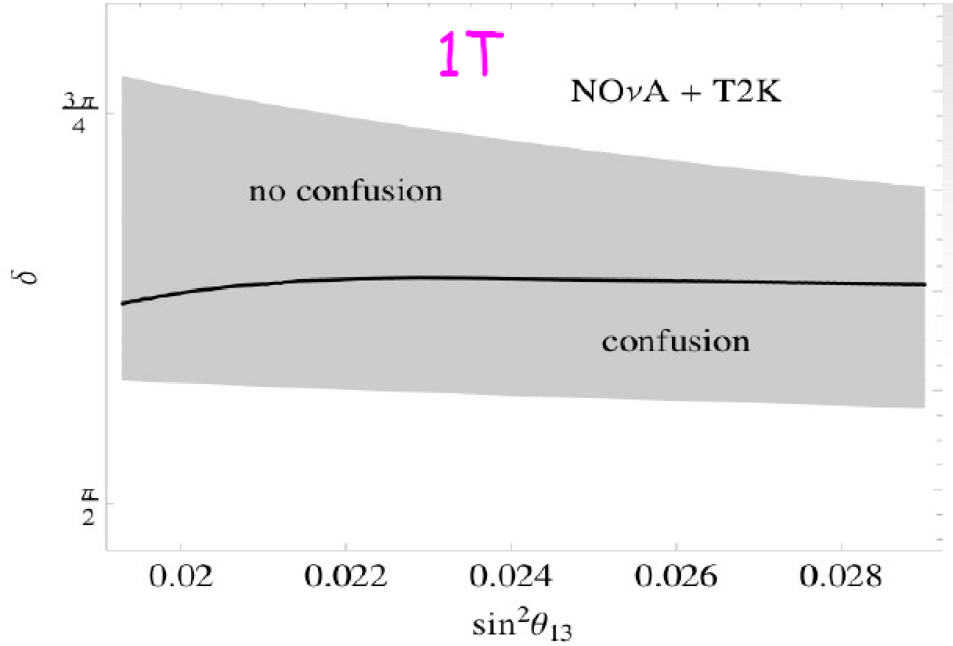

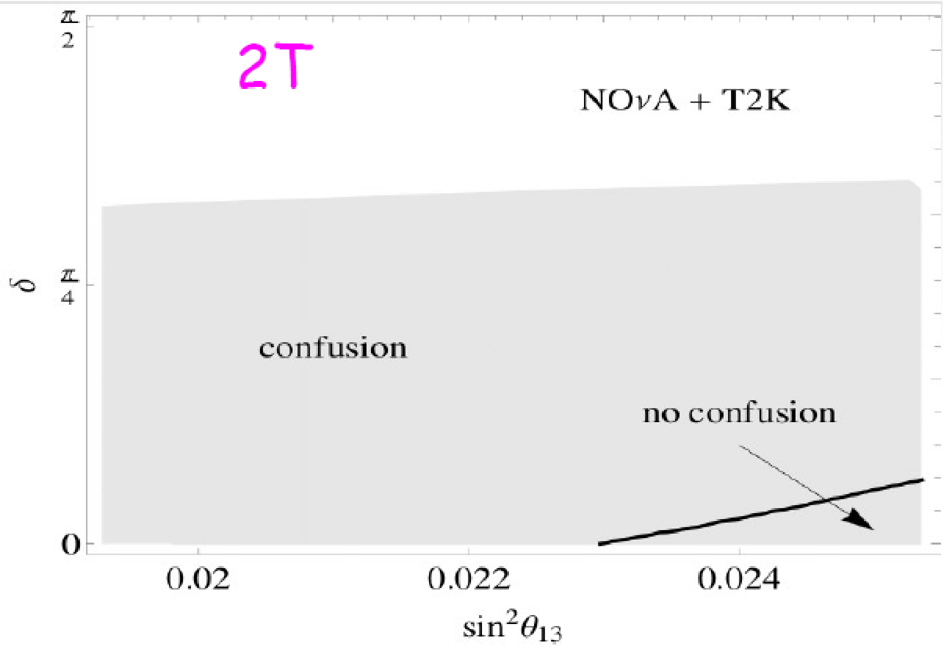

Neutrinos and the flavour puzzle

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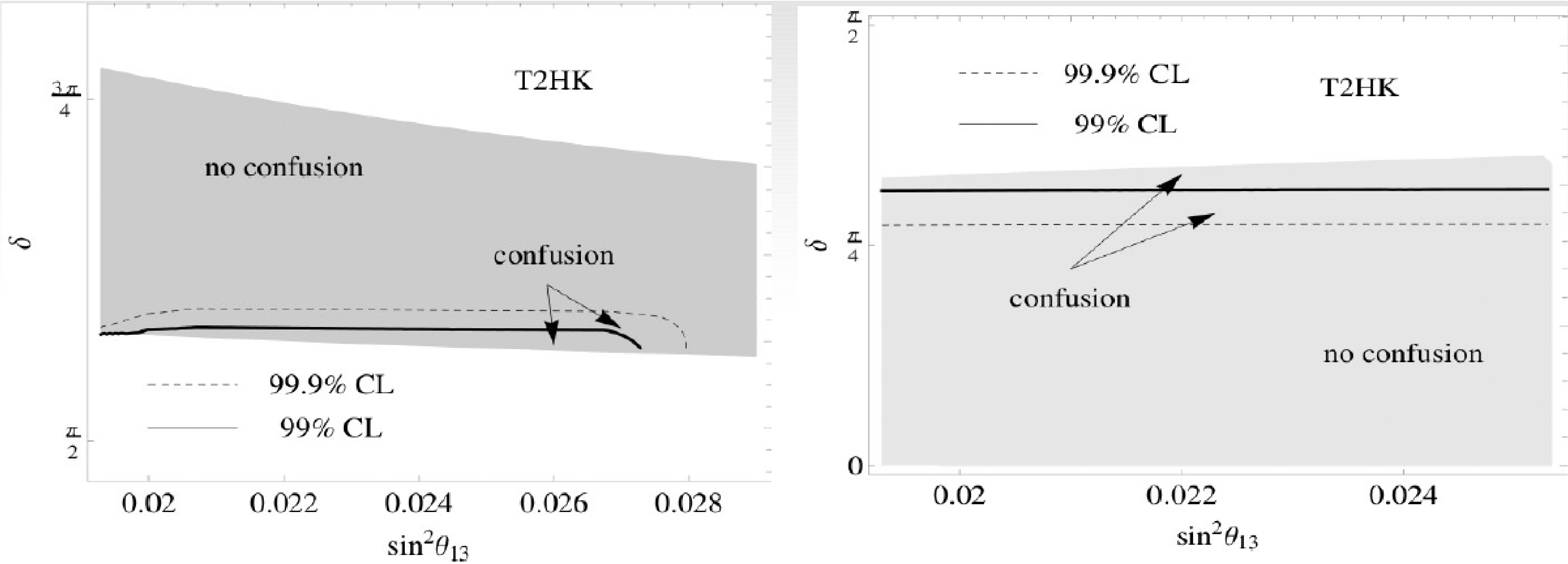


Results from current experiments

From M. Vivier talk, DCHOOZ results:

$\sin^2(2\theta_{13}) = 0.092^{+0.033}_{-0.029}$ (stat. + syst.)
$\chi^2_{min}/n_{dof} = 52.2/40$ (p-value = 9.4%)
Background rate after fit = $1.38 \pm 0.14\ d^{-1}$

From H. Seo talk, RENO results:

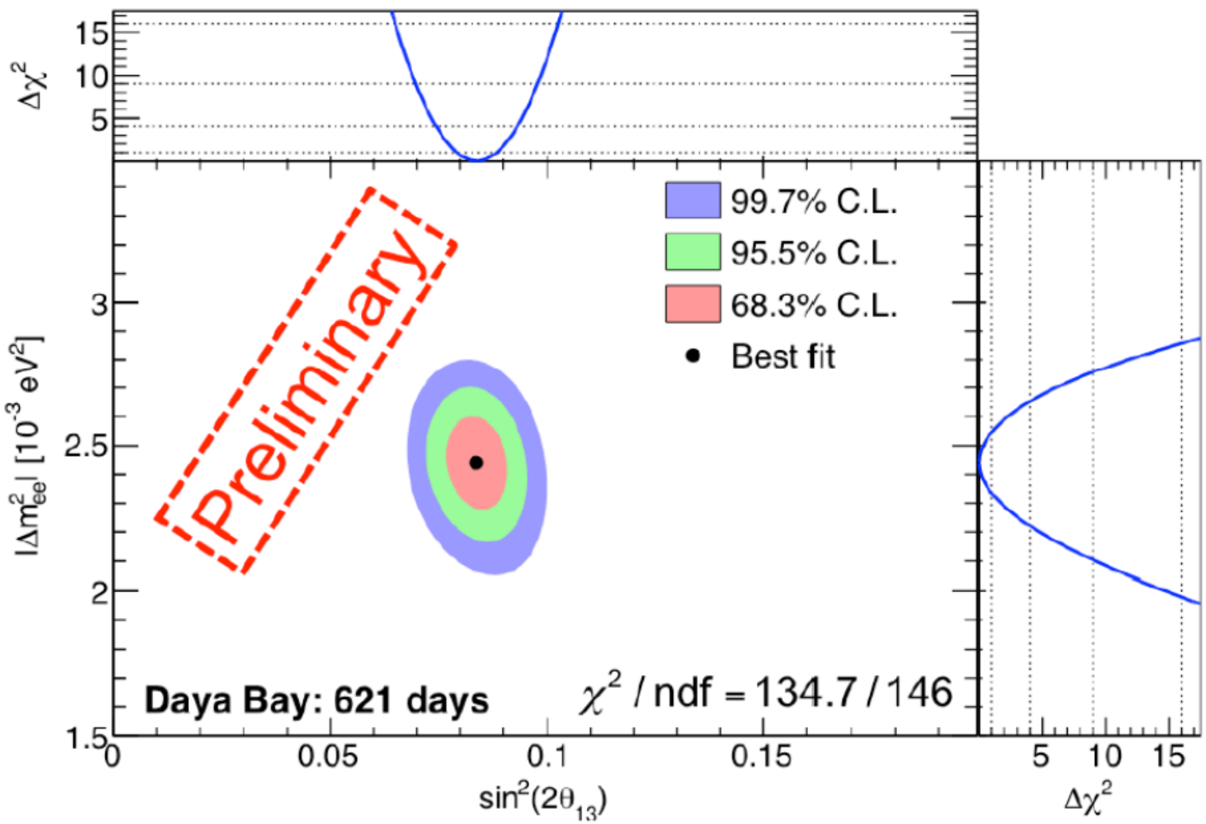
Preliminary result

C data set (~800 days)

$\sin^2(2\theta_{13}) = 0.101 \pm 0.008$ (stat.) $\pm$ 0.010 (sys.)

Results from current experiments

From J. Zhao talk, Daya Bay results:



$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

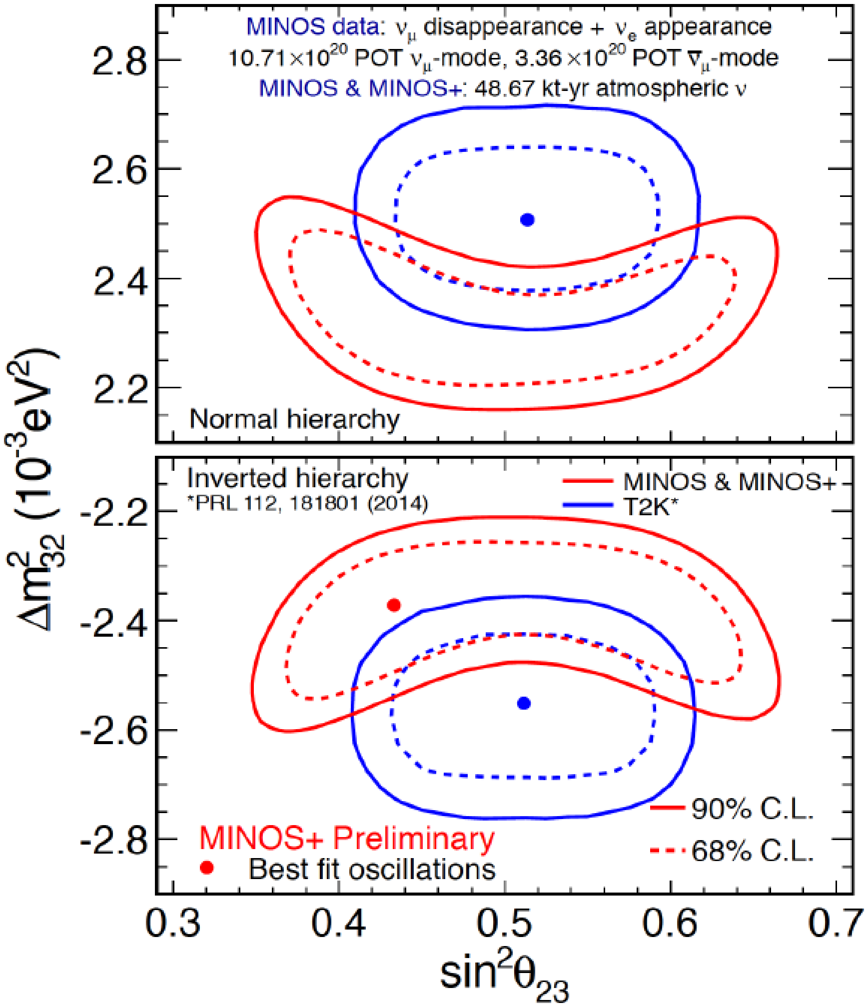
$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3} (eV^2)$$

$$\chi^2 / NDF = 134.7 / 146$$

621 days

Results from current experiments

From A. Holin talk, MINOS/MINOS+ results:



Normal Hierarchy

$$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\text{eV}^2$$

$$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$$

$$0.37 < \sin^2\theta_{23} < 0.64 \ (90\%\ \text{C.L.})$$

Inverted Hierarchy

$$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\text{eV}^2$$

$$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$$

$$0.36 < \sin^2\theta_{23} < 0.65 \ (90\%\ \text{C.L.})$$

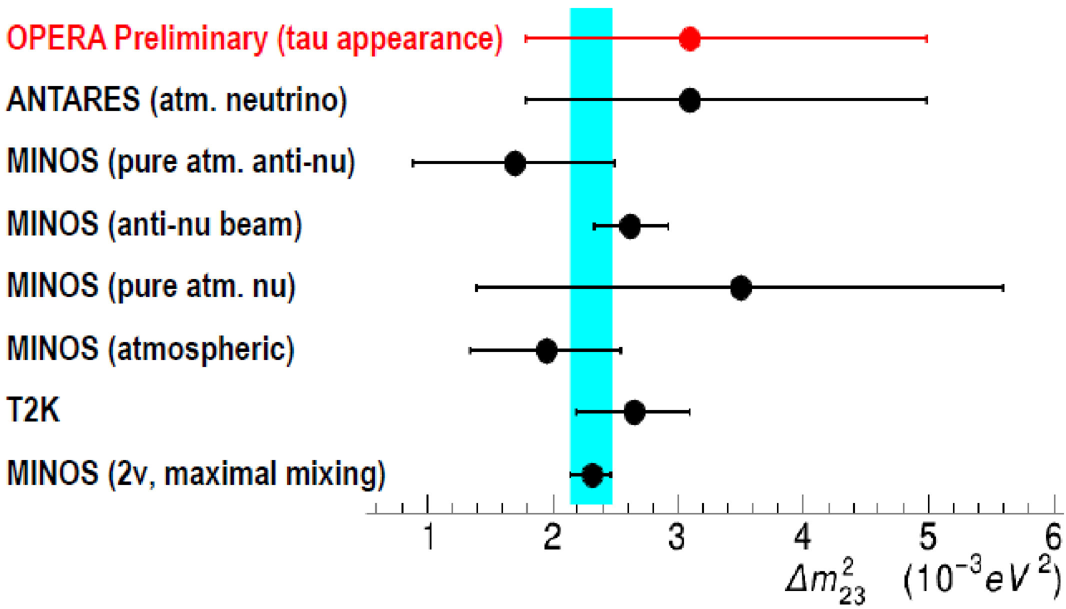
Results from current experiments

From U. Kose talk, OPERA results:

Decay channel	Expected signal $\Delta m_{23}^2 = 2.32$ meV^2	Total background	Observed
$\tau \to h$	0.41 ± 0.08	0.033 ± 0.006	2
$\tau \to 3h$	0.57 ± 0.11	0.155 ± 0.030	1
$\tau \to \mu$	0.52 ± 0.10	0.018 ± 0.007	1
$\tau \to e$	0.62 ± 0.12	0.027 ± 0.005	0
Total	2.11 ± 0.42	0.233 ± 0.041	4

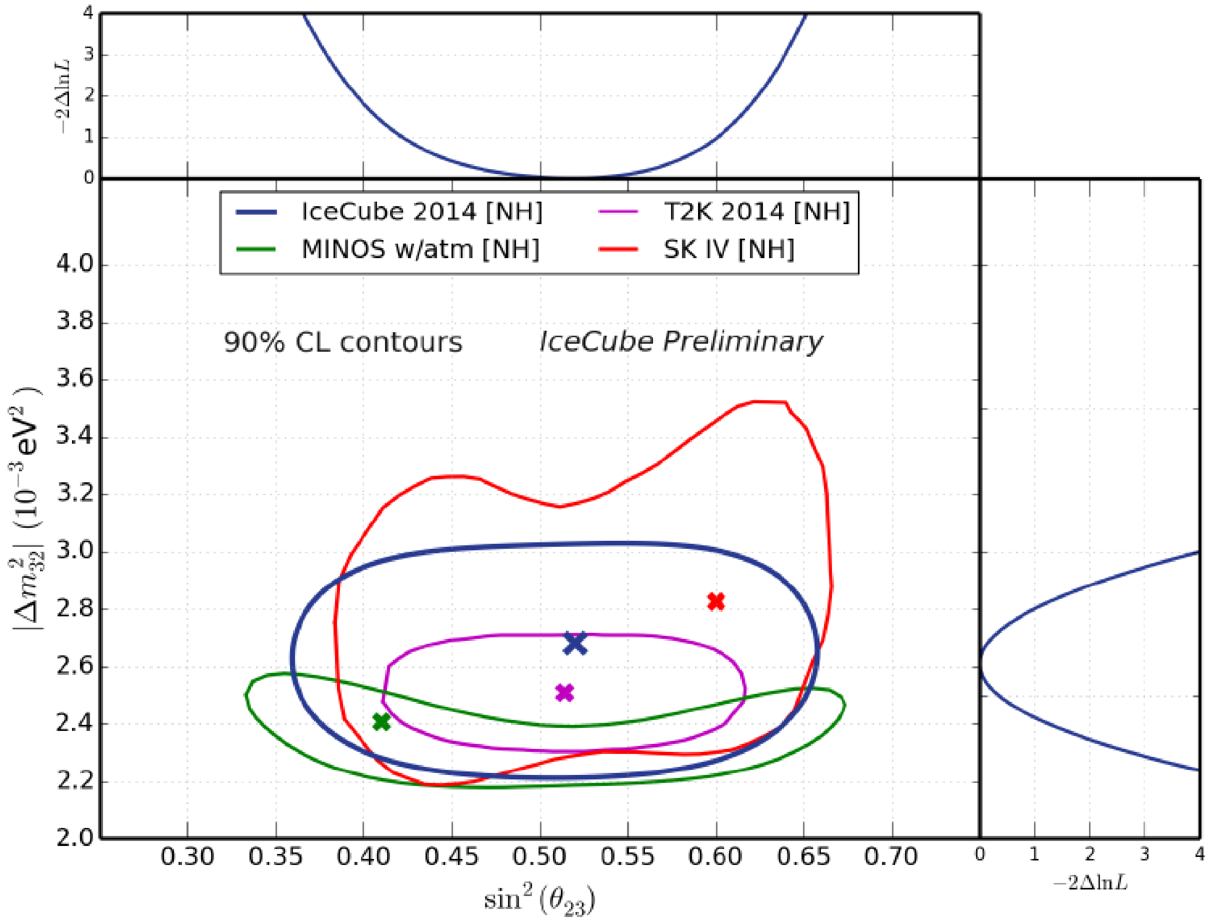
4 ν_τ candidates seen
observation of τ appearance at 4.2 σ

Determination of Δm^2_{23} in apperance



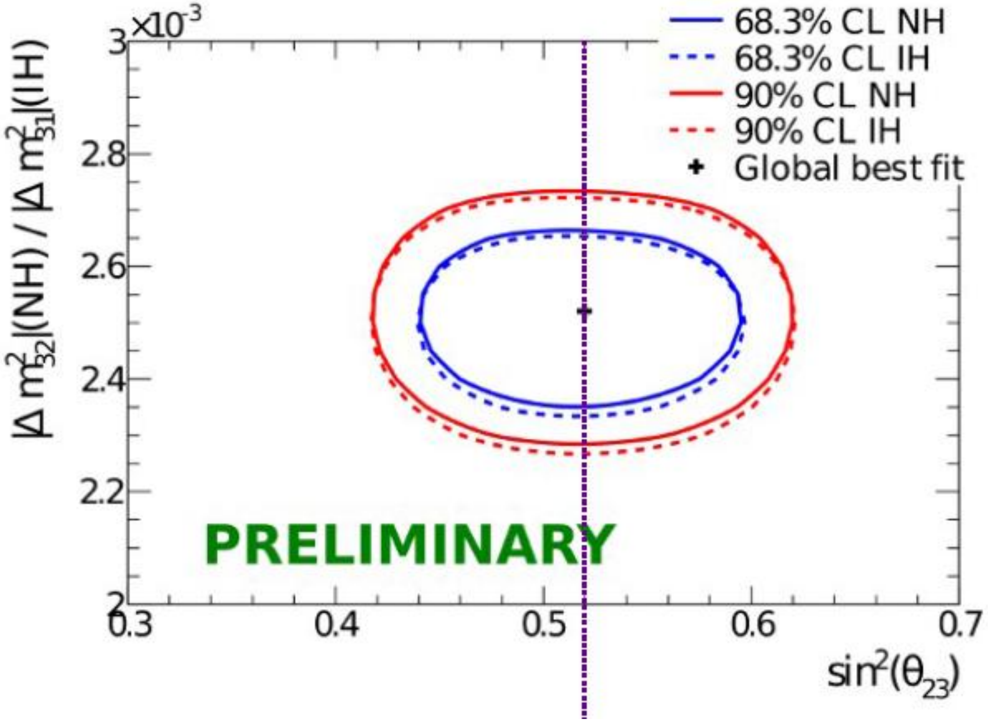
Results from current experiments

From J. P. Athayde Marcondes de André talk, IceCube results:



Results from current experiments

From C. Bronner talk, T2K results (new antinu data not included):



T2K only results favour maximal θ_{23}

Results from current experiments

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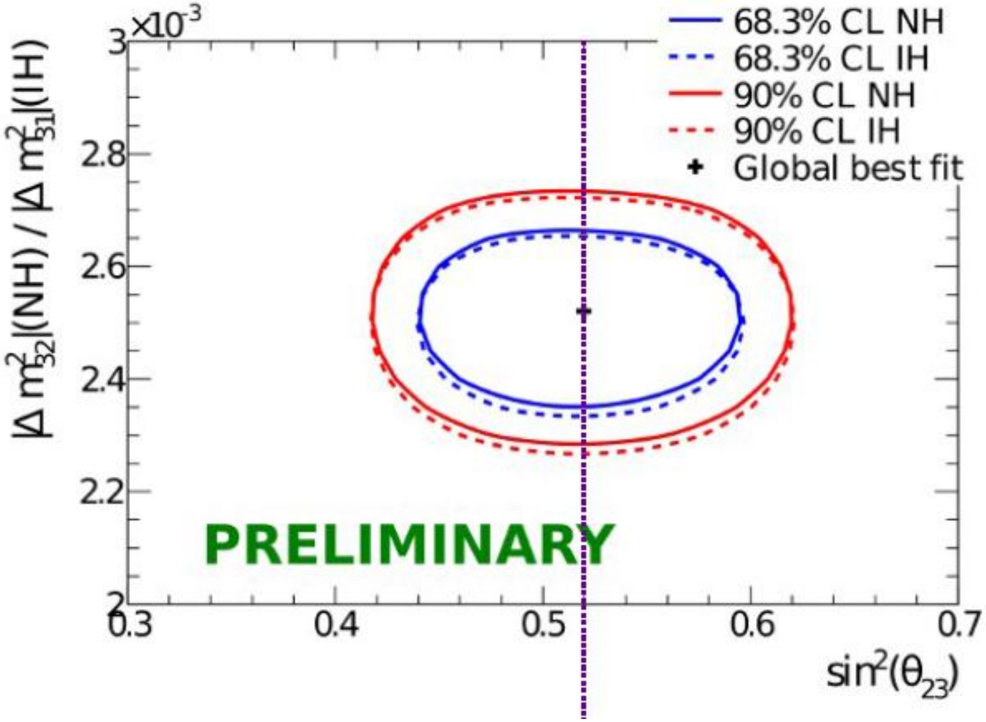
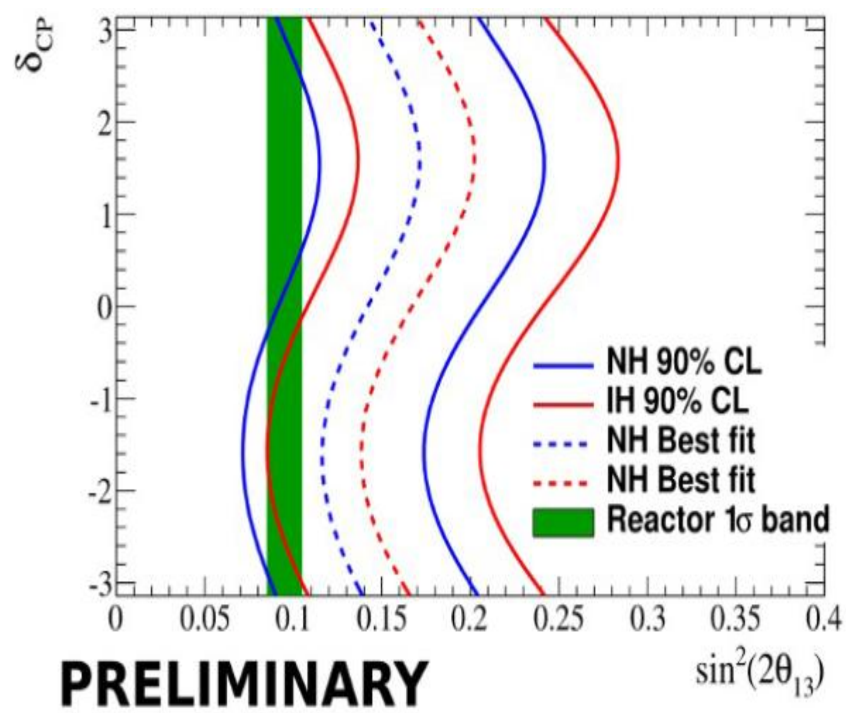


Some tension with reactor in θ_{13}



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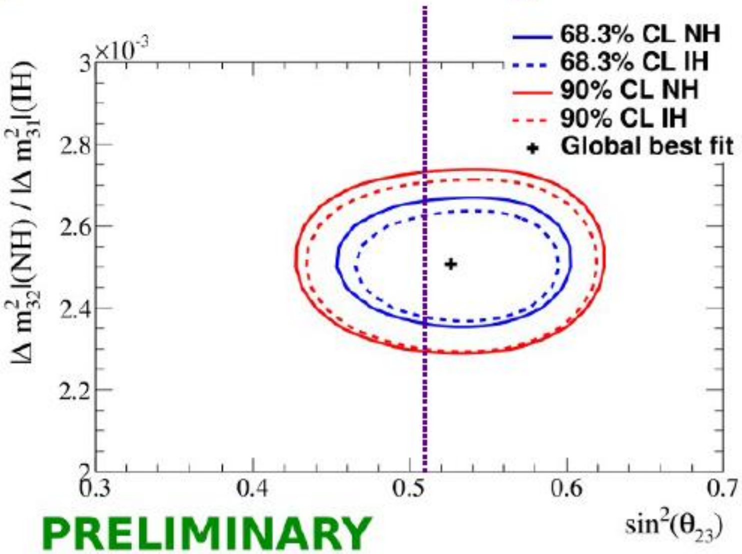
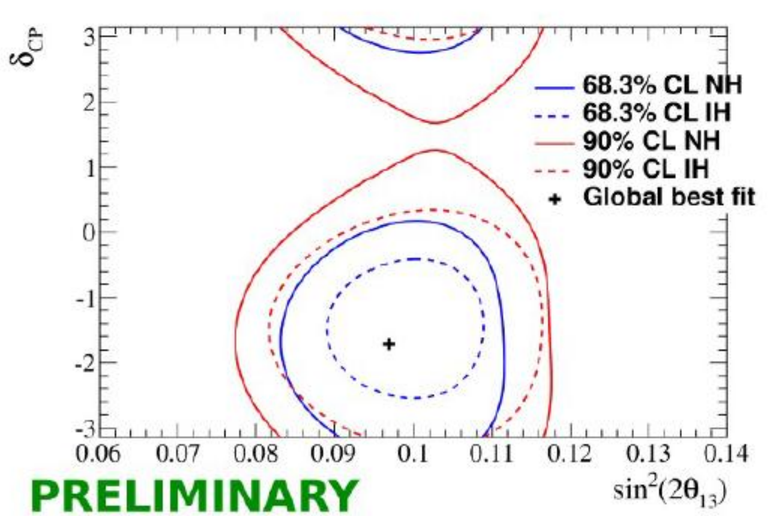
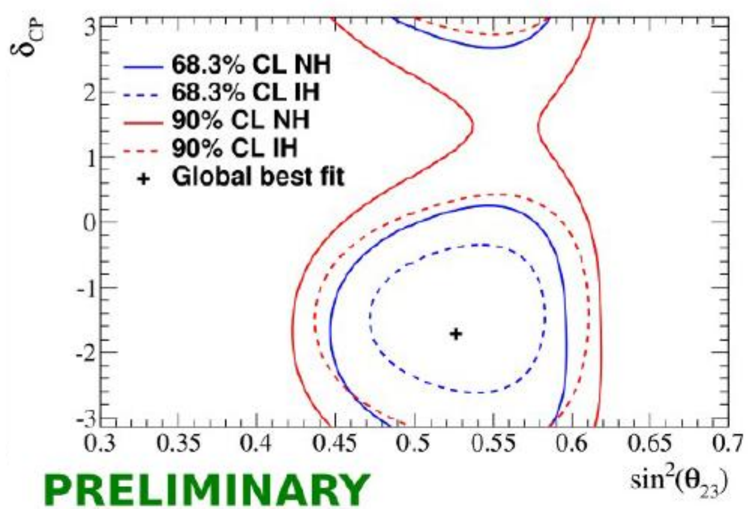




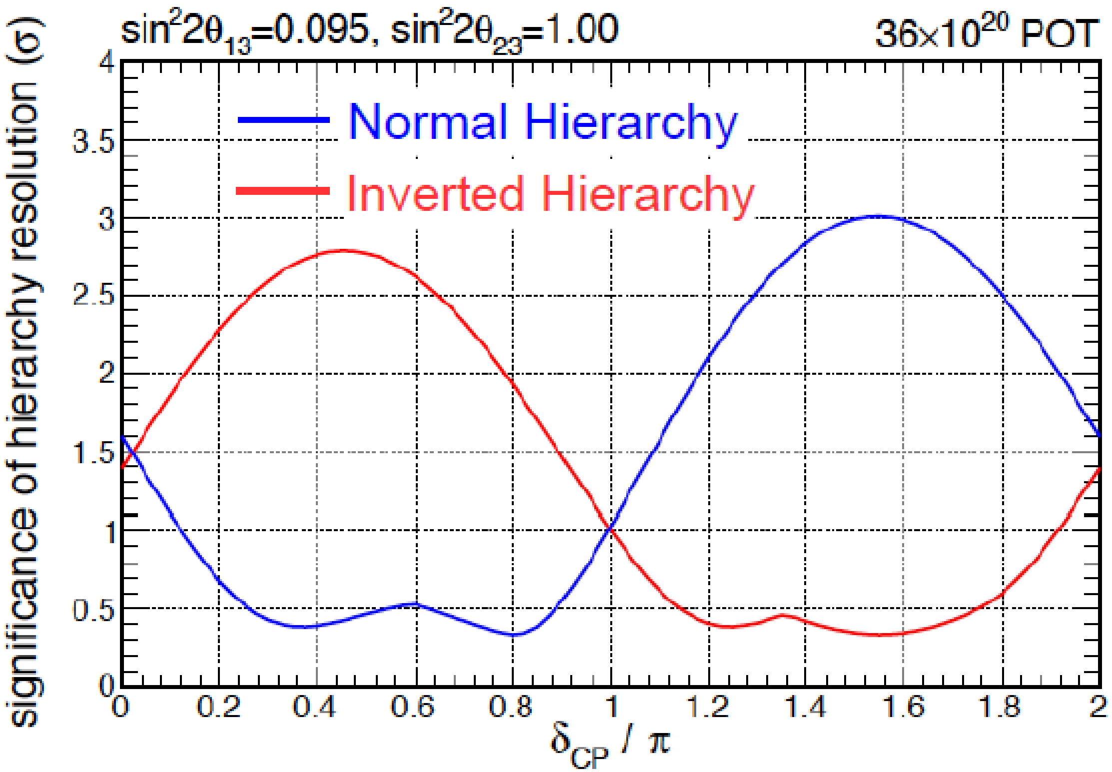
Tension translates in preference for $\theta_{23} > 45^o$ and $\delta < 0$

Normal hierarchy also slightly favoured over inverted



Prospects from current experiments

Stay tuned for future T2K and NOνA results to see how these hints for $\theta_{23} > 45^o$ and $\delta < 0$ and NH evolve



Mass hierarchy

NOνA 3+3 years from X. Bu talk

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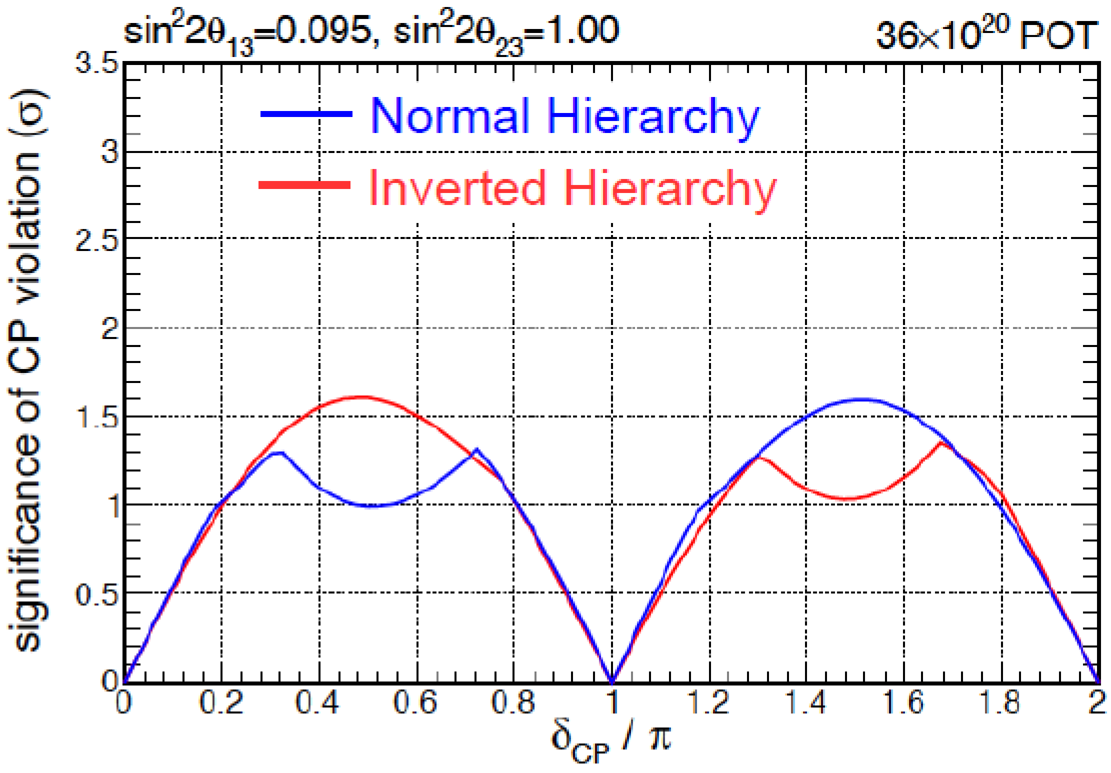

CPV

NOνA 3+3 years from X. Bu talk

Prospects from current experiments

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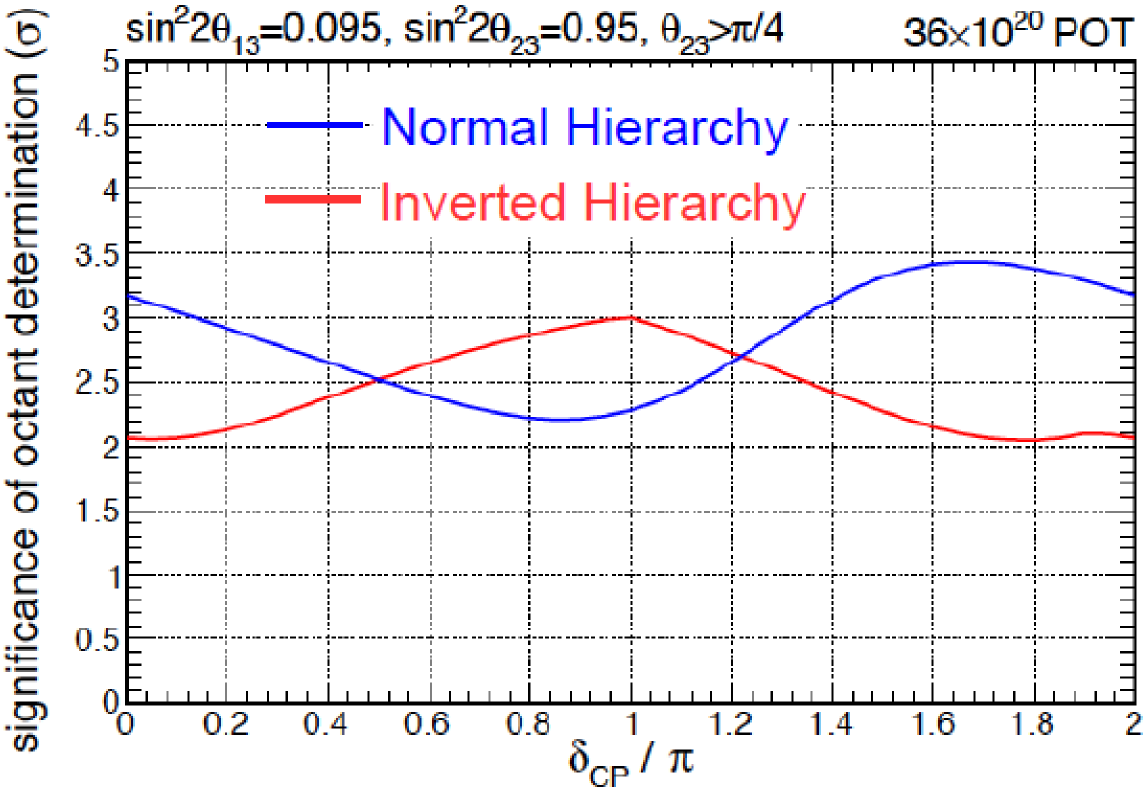
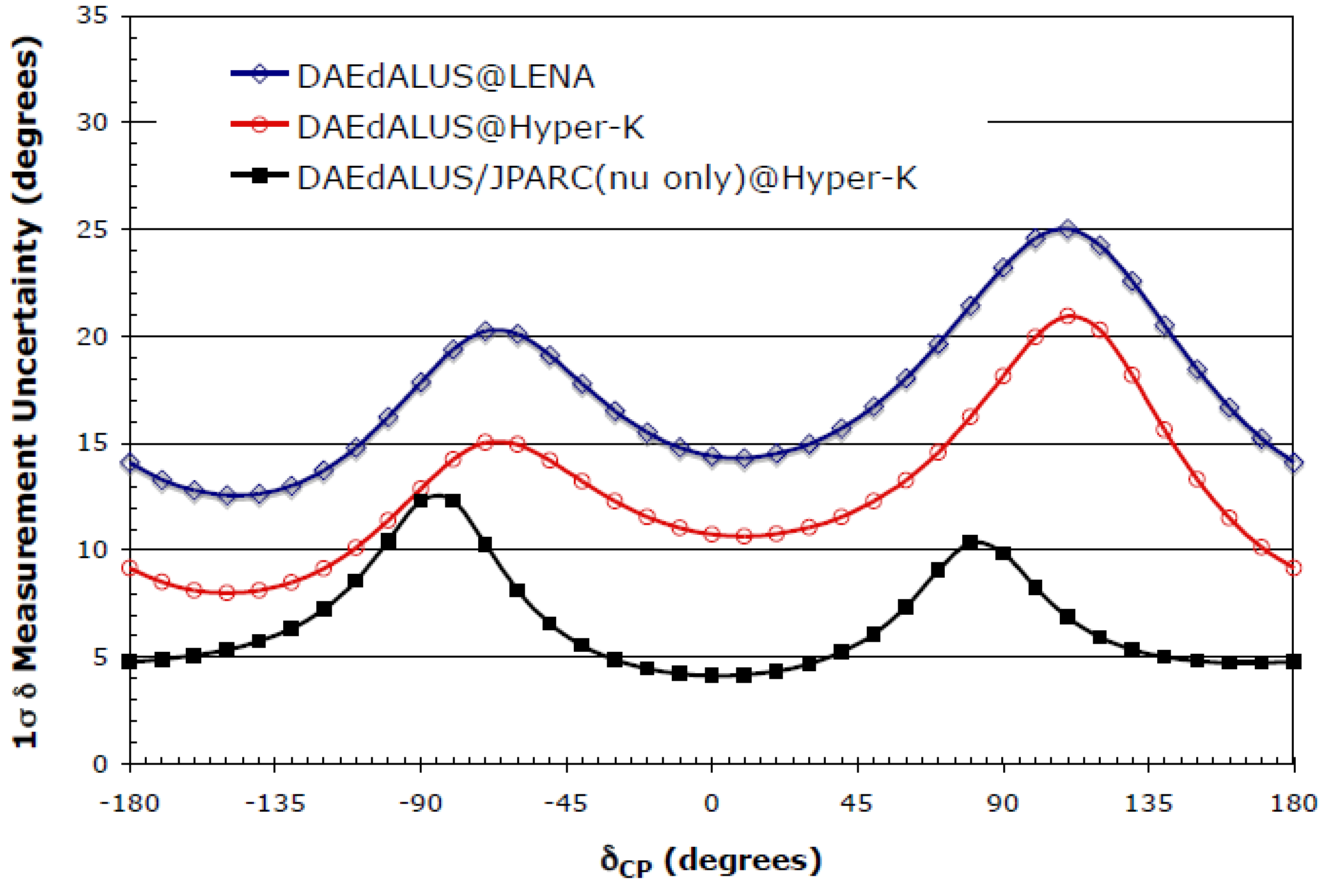


Octant

NOνA 3+3 years from X. Bu talk

Future prospects

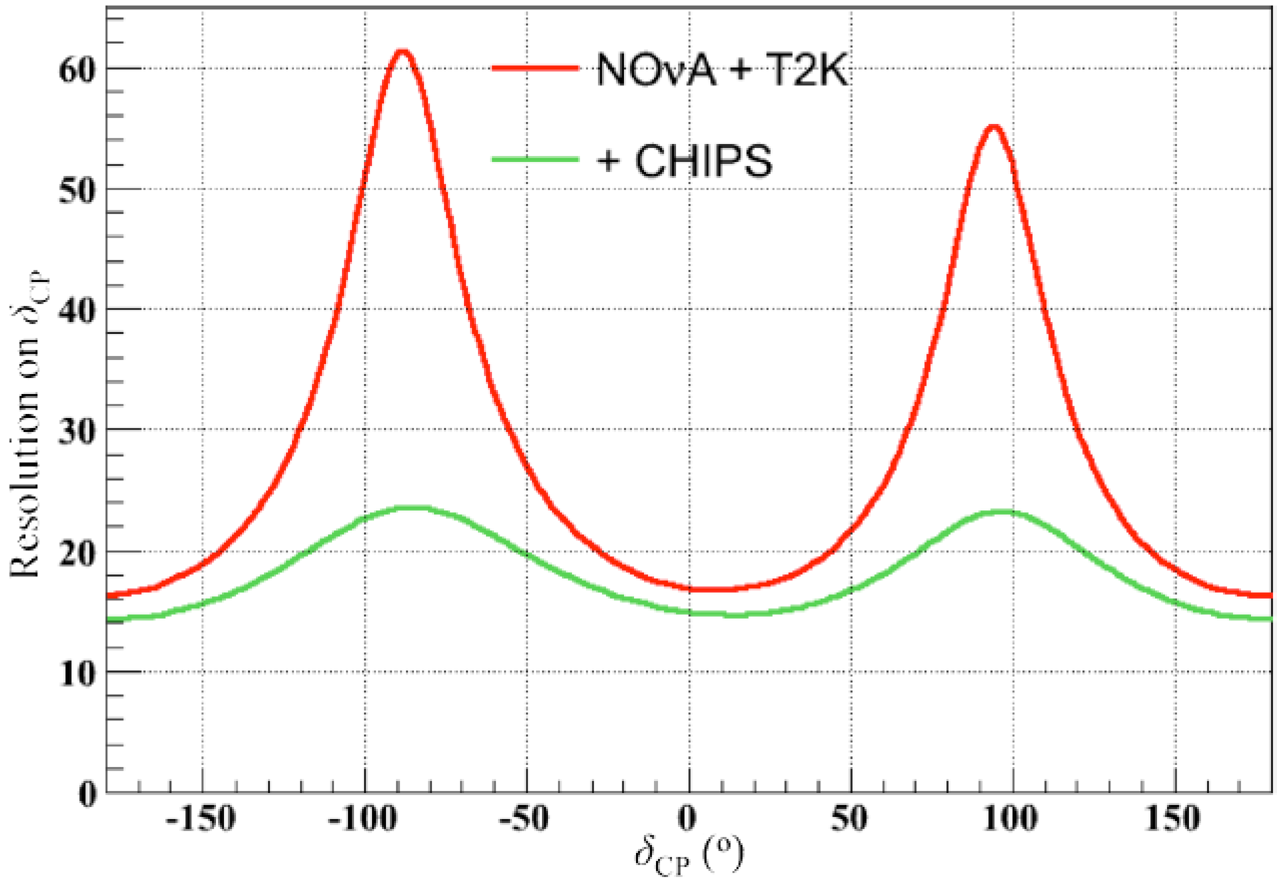
From J. Spitz talk:



DAEδALUS CP search

Future prospects

From J. Evans talk:



100 kt CHIPS
3+3 years
neutrino + antineutrino

CHIPS CP search

Future prospects

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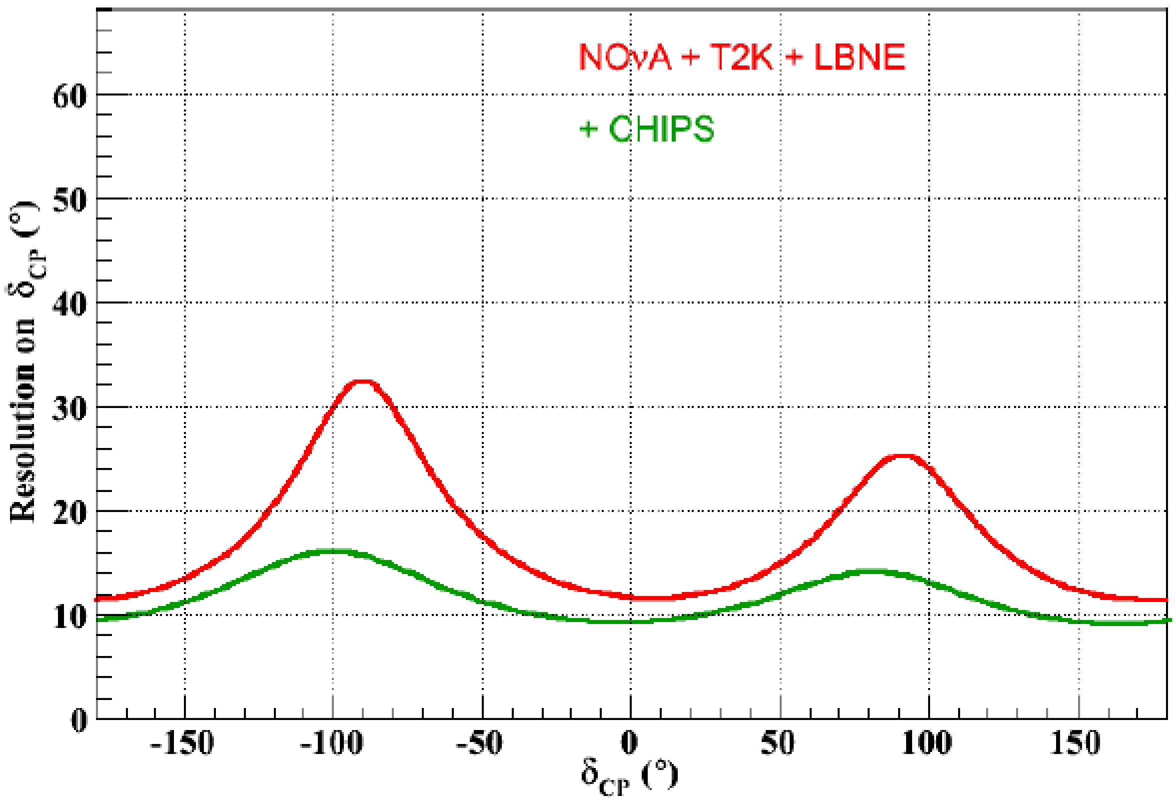
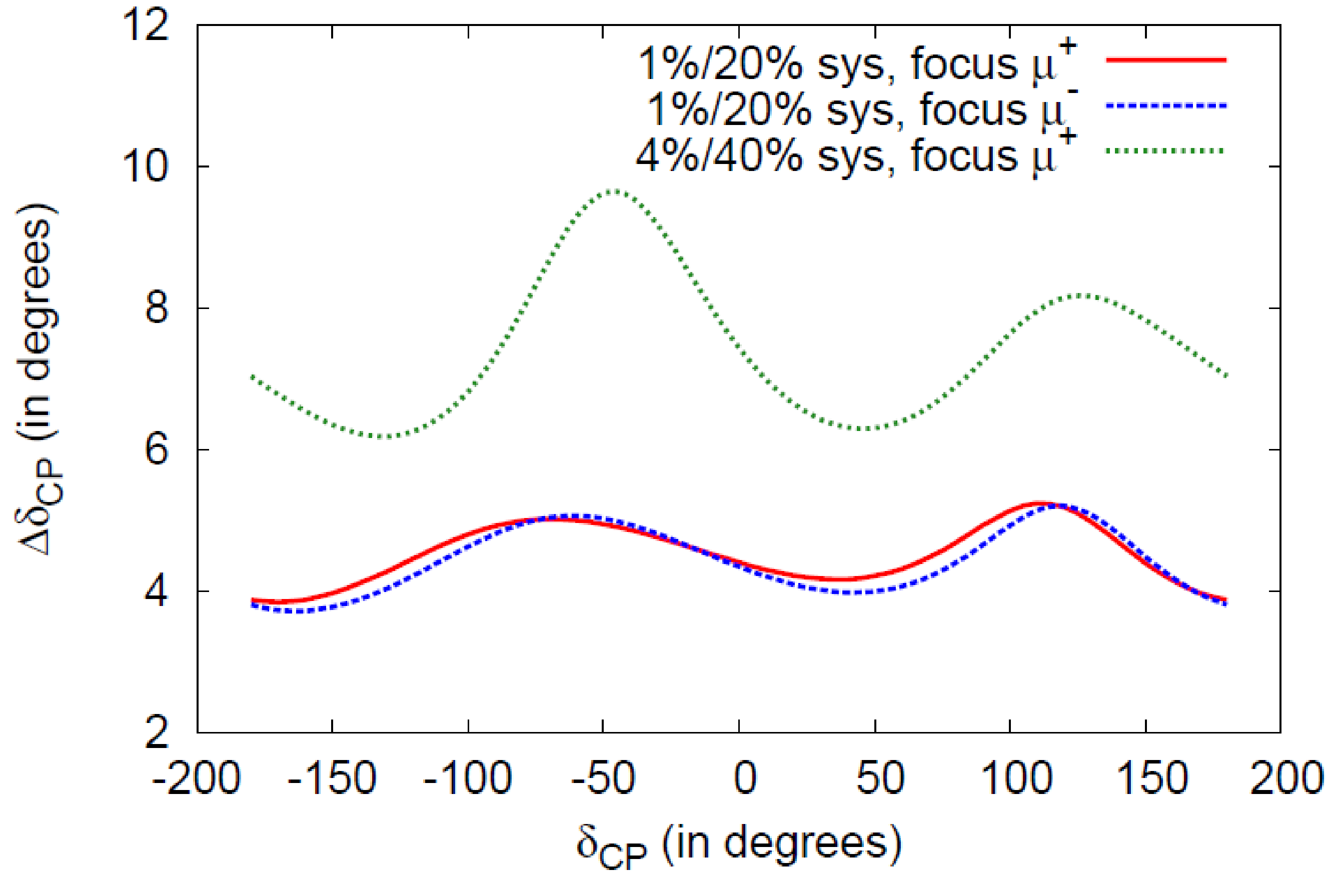


100 kt CHIPS
(Assumes 10 kt LBNE FD)

CHIPS CP search

Future prospects

From R. Bayes talk:



NF δ measurement

Results from current experiments

$$|U_{PMNS}| = \begin{pmatrix} 0.77-0.86 & 0.50-0.63 & <0.22 \\ 0.22-0.56 & 0.44-0.73 & 0.57-0.80 \\ 0.21-0.55 & 0.40-0.71 & 0.59-0.82 \end{pmatrix}$$

2007

C. Gonzalez García and M. Maltoni 0704.1800

$$|U_{PMNS}| = \begin{pmatrix} 0.79-0.85 & 0.51-0.59 & 0.13-0.18 \\ 0.21-0.54 & 0.42-0.73 & 0.58-0.81 \\ 0.22-0.55 & 0.41-0.73 & 0.57-0.80 \end{pmatrix}$$

2012

C. Gonzalez García, M. Maltoni, T. Schwetz and J. Salvado 1209.3023

$$|U_{PMNS}| = \begin{pmatrix} 0.80-0.85 & 0.51-0.58 & 0.14-0.16 \\ 0.23-0.52 & 0.44-0.70 & 0.61-0.79 \\ 0.25-0.53 & 0.46-0.71 & 0.59-0.78 \end{pmatrix}$$

nu-fit.org C. Gonzalez García, M. Maltoni, T. Schwetz and J. Salvado

Neutrinos and the flavour puzzle

> *Question from NUFACT '13: What symmetries can we identify from the PMNS matrix element relative sizes? Which categories of models can we rule out with the current precision of mixing angle measurements*

The simplest mixing patterns (Tribimaximal, Golden Ratio…) have already been ruled out by θ_{13}

This led to realize the role and importance of perturbations, which in turn lead to sum rules testable by precise measurements of θ_{12}, θ_{23} and δ.

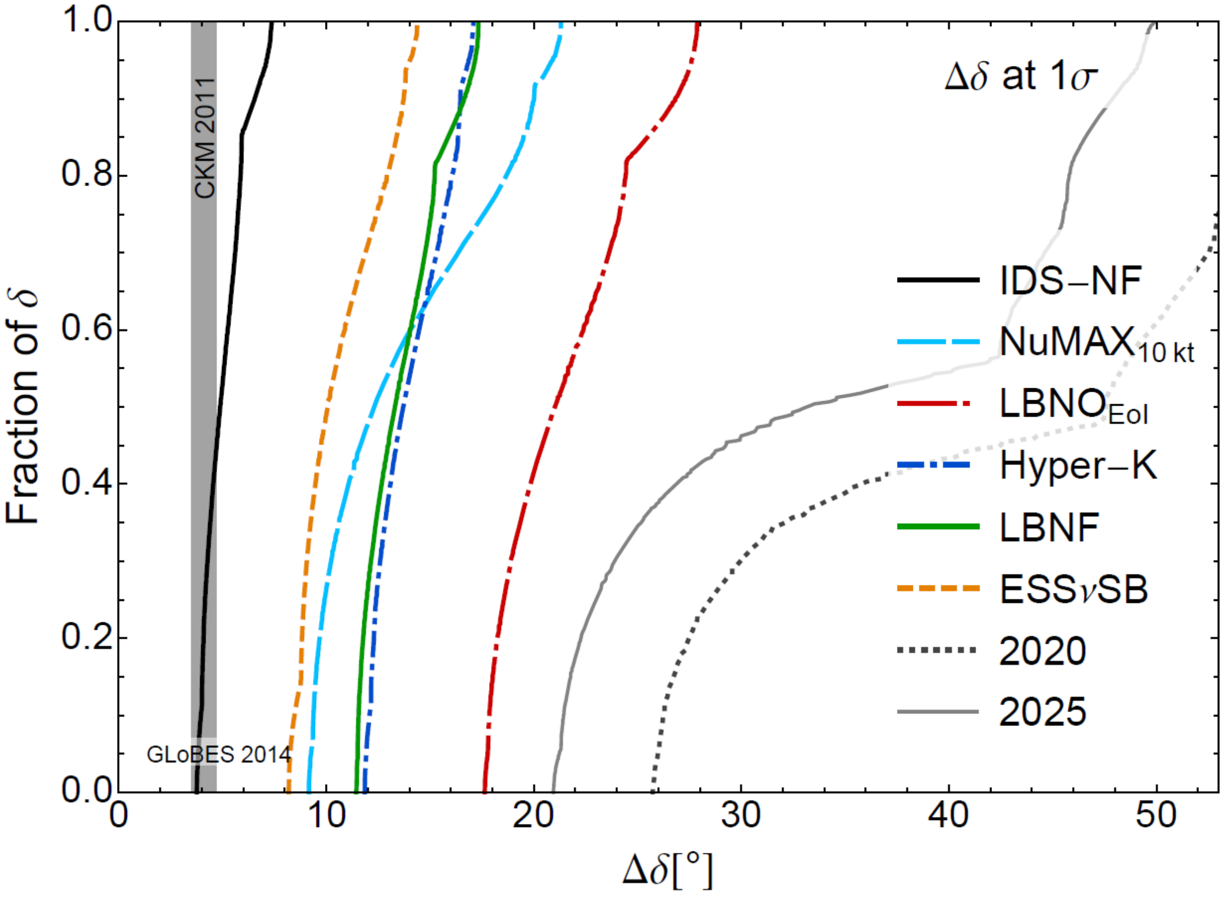
The error bars on these parameter keep improving with new data and the model parameter space reduces leading to new ideas

Importance of cross sections

Question from NUFACT '13: *Can we reach 1-2% level in systematic uncertainties for superbeam appearance experiments in order to measure leptonic CP violation? What level of optimization of the ND is required? To which level do we need to reduce the cross-section uncertainties on neutrino interactions in water, argon, carbon? Is NuStorm enough to achieve those reductions? Do we need a dedicated hadron production effort?*

Question from NUFACT '13: *How do we account for differences in neutrino interaction generators used by each experiment to model their data when we compare or combine sensitivities or results from different experiments?*

Importance of cross sections



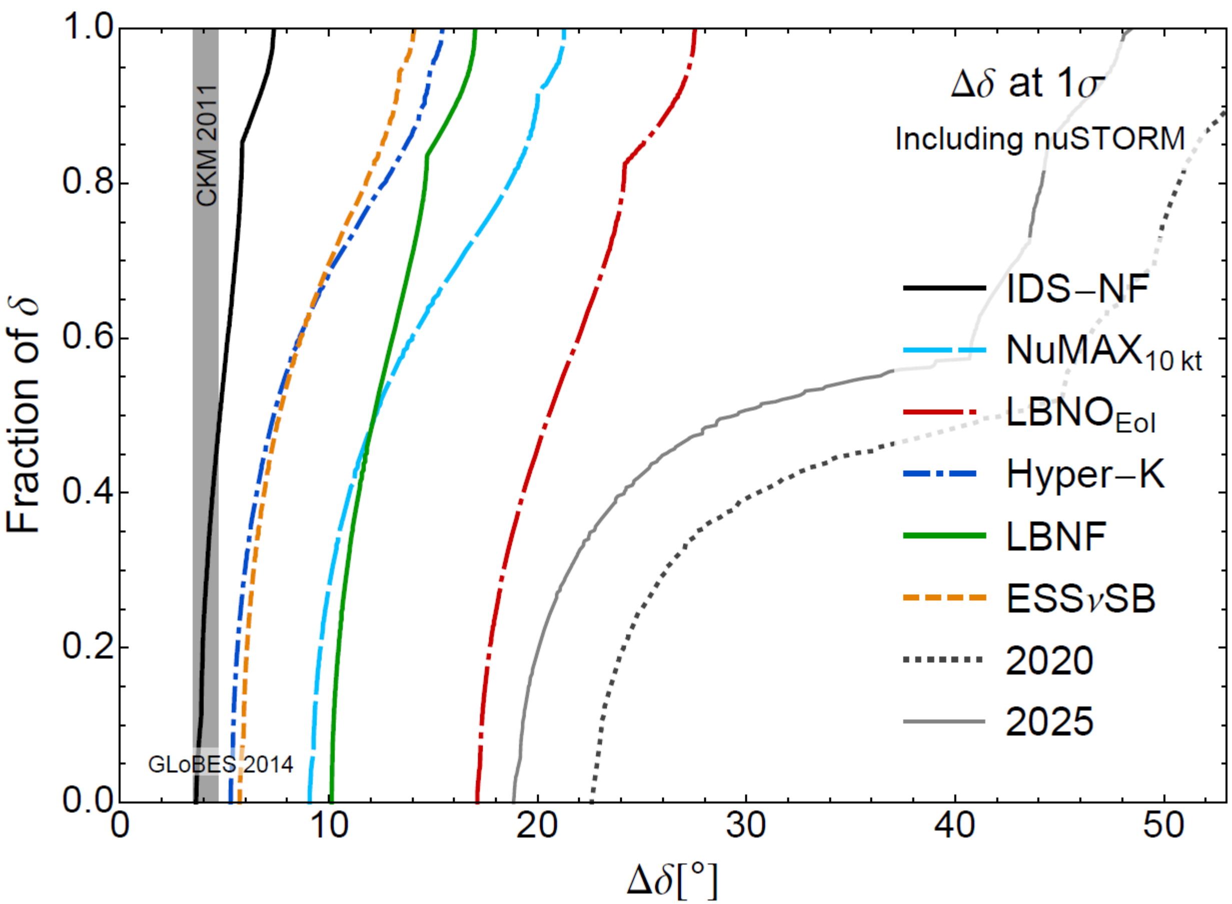
Systematics	SB Def.
Fiducial volume ND	0.5%
Fiducial volume FD (incl. near-far extrap.)	2.5%
Flux error signal ν	7.5%
Flux error background ν	15%
Flux error signal $\bar{\nu}$	15%
Flux error background $\bar{\nu}$	30%
Background uncertainty	7.5%
Cross secs × eff. QE†	15%
Cross secs × eff. RES†	15%
Cross secs × eff. DIS†	7.5%
Effec. ratio ν_e/ν_μ QE*	11%
Effec. ratio ν_e/ν_μ RES*	5.4%
Effec. ratio ν_e/ν_μ DIS*	5.1%
Matter density	2%

Courtesy of P. Coloma

P. Coloma et al 1209.5973

Importance of cross sections

+NuSTORM (1% uncorrelated errors on xsecs)



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Courtesy of P. Coloma

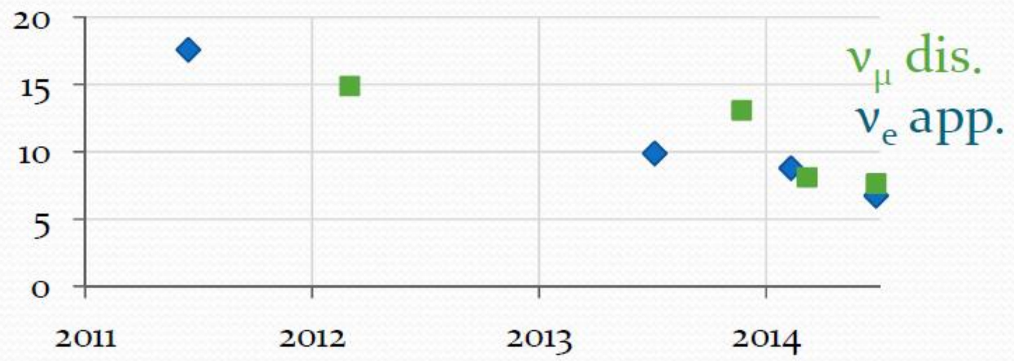
P. Coloma et al 1209.5973

Importance of cross sections

From S. Cartwright talk, T2K error budget:

- Steady improvement in systematic errors since 2011
  - better constraints from near detector
  - better inputs from external data
  - more sophisticated cross-section models
  - more sophisticated analyses

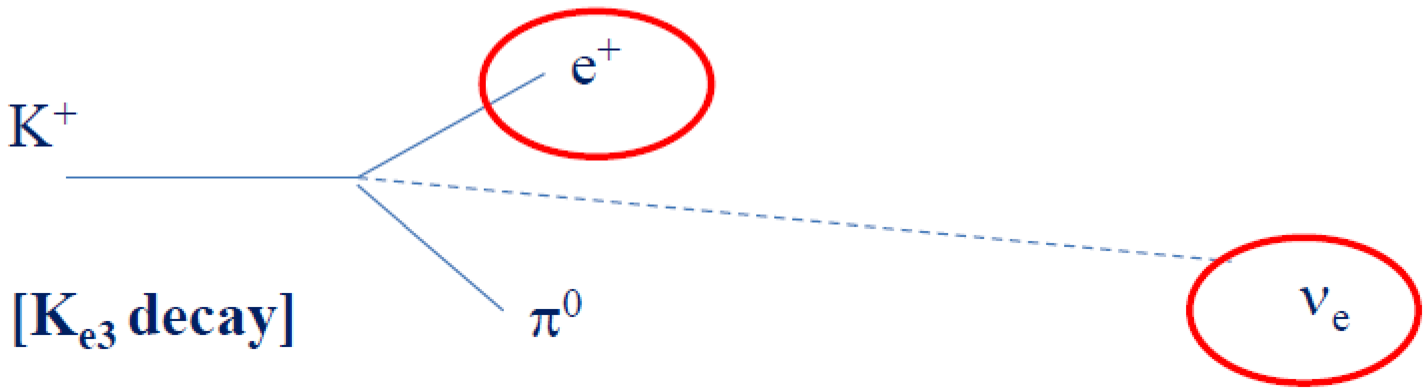
Source of uncertainty	1Rμ $\delta N_{SK}/N_{SK}$	1Re $\delta N_{SK}/N_{SK}$
SK+FSI	5.00%	3.66%
SK	4.03%	2.72%
FSI+SI(+PN)	2.98%	2.44%
Flux and correlated cross sections (prefit)	21.75%	26.04%
(postfit)	2.74%	3.15%
Independent cross sections	5.00%	4.69%
Total (prefit)	23.45%	26.80%
(postfit)	7.65%	6.75%



Importance of cross sections

From F. Terranova talk:

New ideas: try to tag the ν_e from K_{e3} decays.
This could provide a clean measurement of the ν_e cross section without flux uncertainties.



Importance of cross sections

Two joint sessions with WG2 on energy reconstruction.
Talks by N. Raddatz, S. Cartwright, C. Wilkinson, J. Wolcott, A. Ereditato and S. Boyd

Tension in cross sections at low and high E between NOMAD and MiniBooNE probed by new Minerνa data

Some tensions between Minerνa and MiniBooNE data, no single model reproduces well all observations

Most recent theoretical models still to be implemented in generators

Neut choice RFG+RPA+MEC for T2K analysis (best fit to MiniBooNE and Minerνa data)

Minerνa and ArgoNeuT data can help!

Importance of cross sections

Question from NUFACT '13: Can we reach 1-2% level in systematic uncertainties for superbeam appearance experiments in order to measure leptonic CP violation? What level of optimization of the ND is required? To which level do we need to reduce the cross-section uncertainties on neutrino interactions in water, argon, carbon? Is NuStorm enough to achieve those reductions? Do we need a dedicated hadron production effort?

Importance of NuStorm is experiment dependent.

Largest improvement for T2HK with errorbars halved in part of the param space.

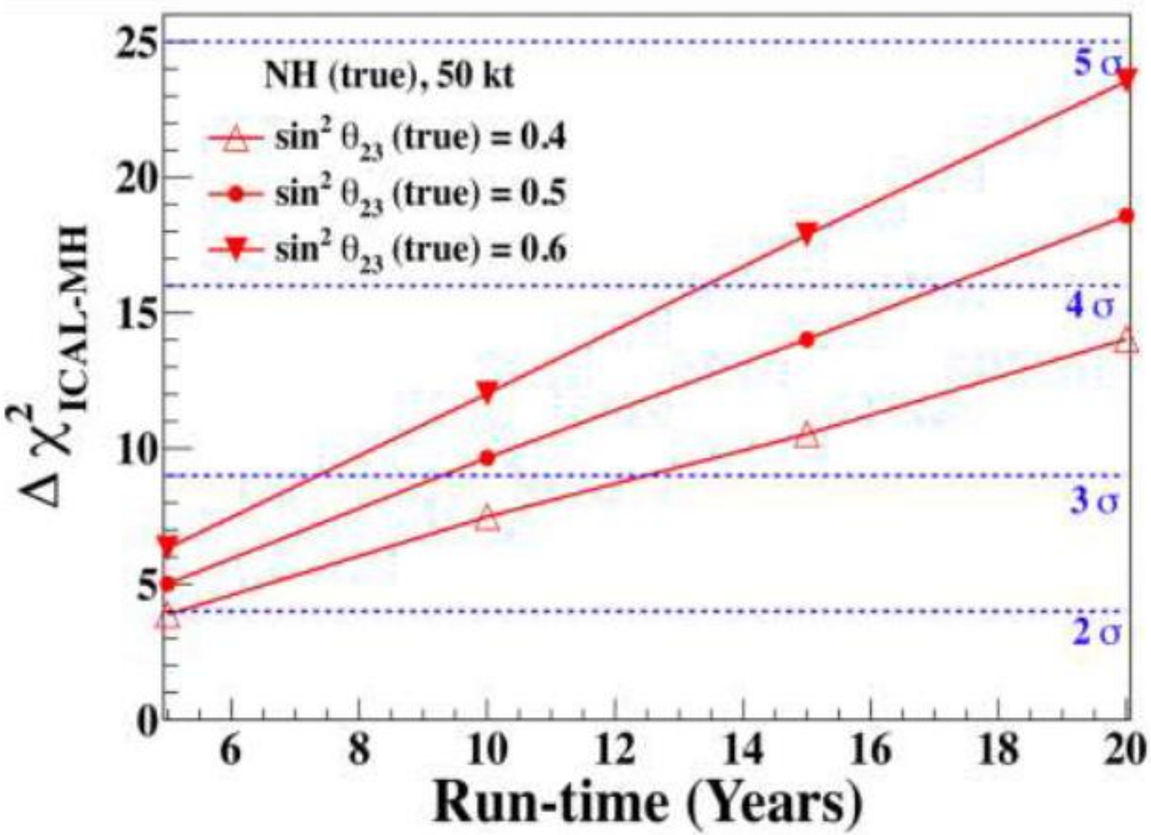
LBNF and ESSnuSB would also benefit.

Mass hierarchy

Question from NUFACT ’13: *When will the combined reach of all experiments resolve the mass hierarchy at more than 3σ for all δ? and 5σ? What impact would such measurement have on the design of future large facilities such as LBNE, T2HK, LBNO or ESS? Can we identify synergies between them?*

Mass hierarchy

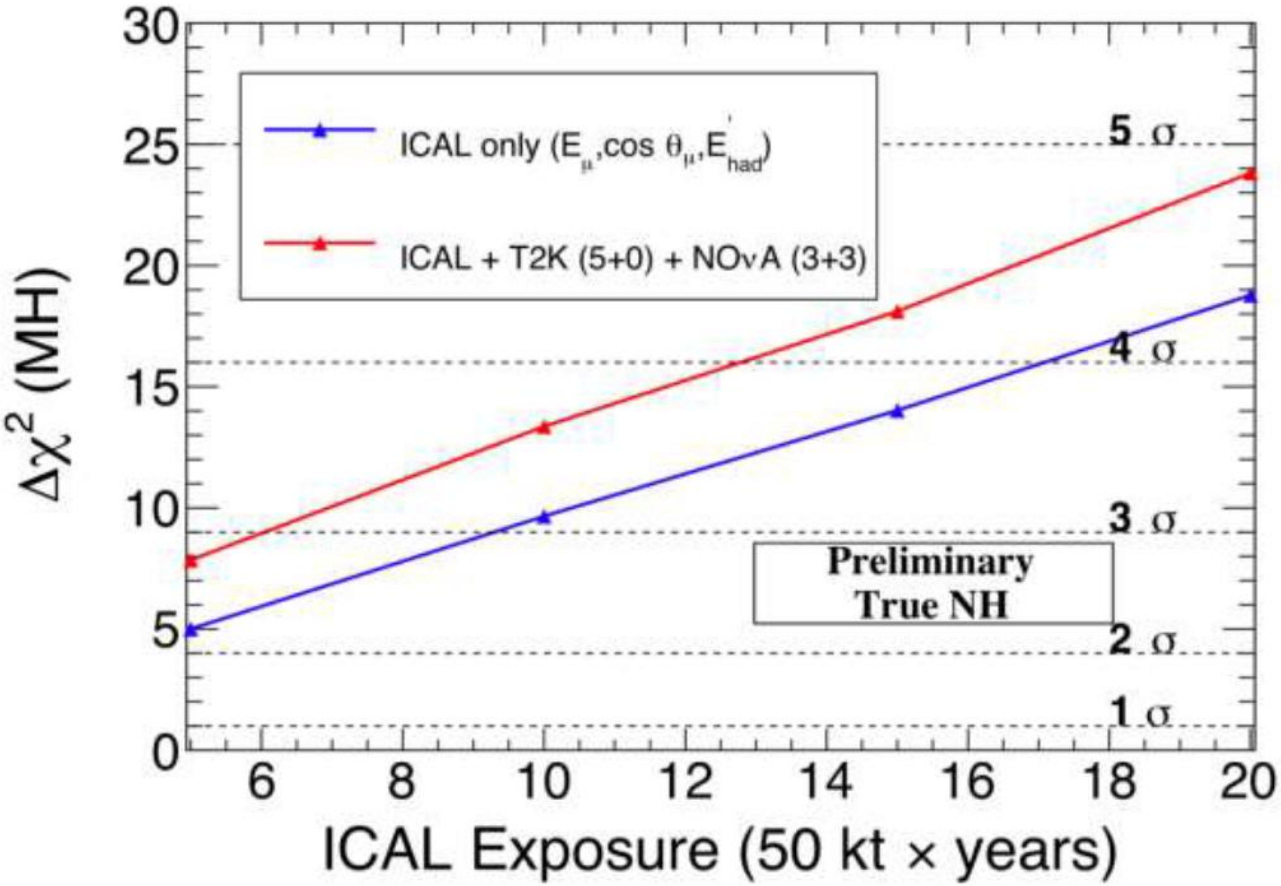
From M. M. Devi talk:



Including hadron energy information INO could reach 3 σ in 7-13y

Mass hierarchy

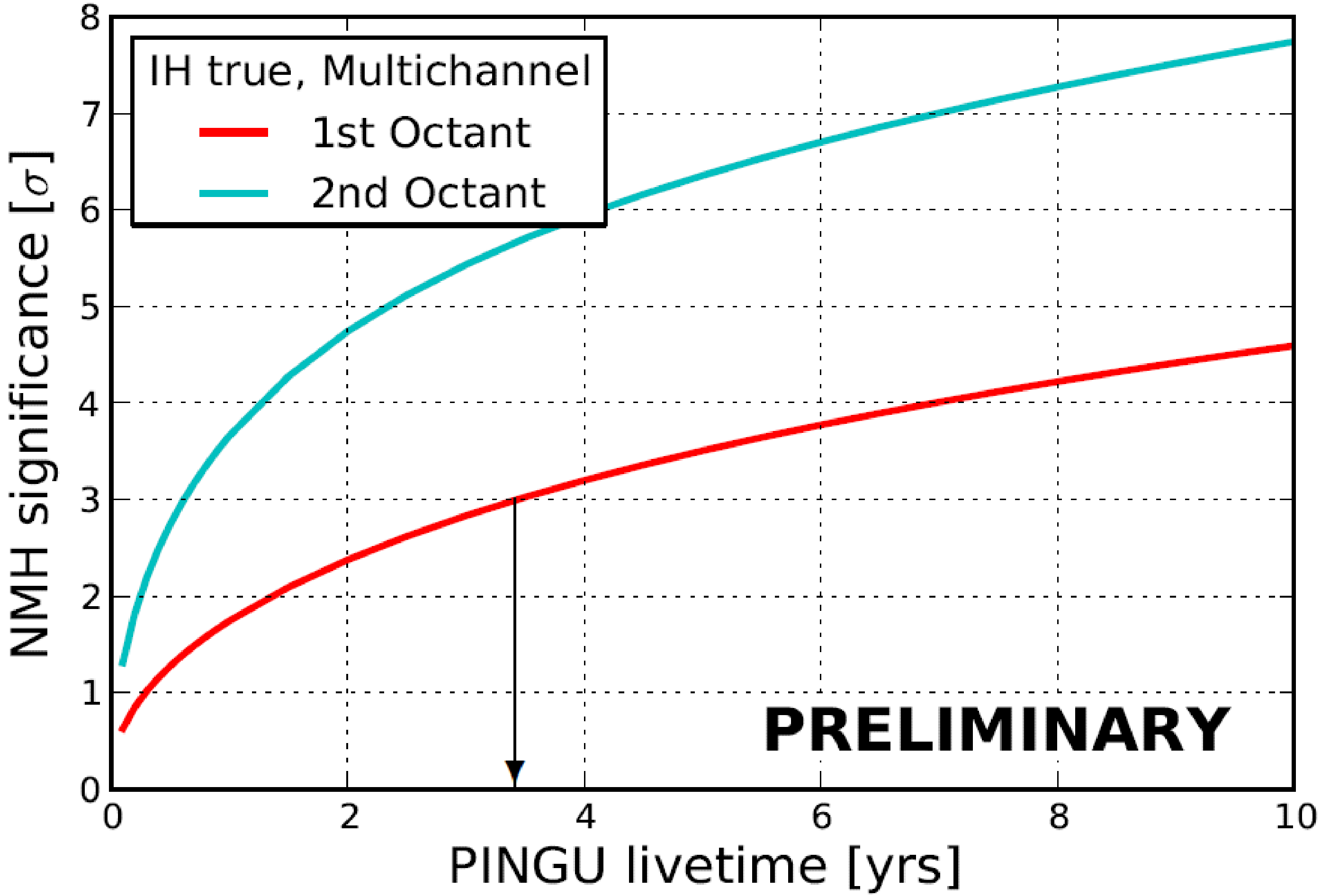
From M. M. Devi talk:



Combining data (INO+T2K+NOνA) will get you there faster!

Mass hierarchy

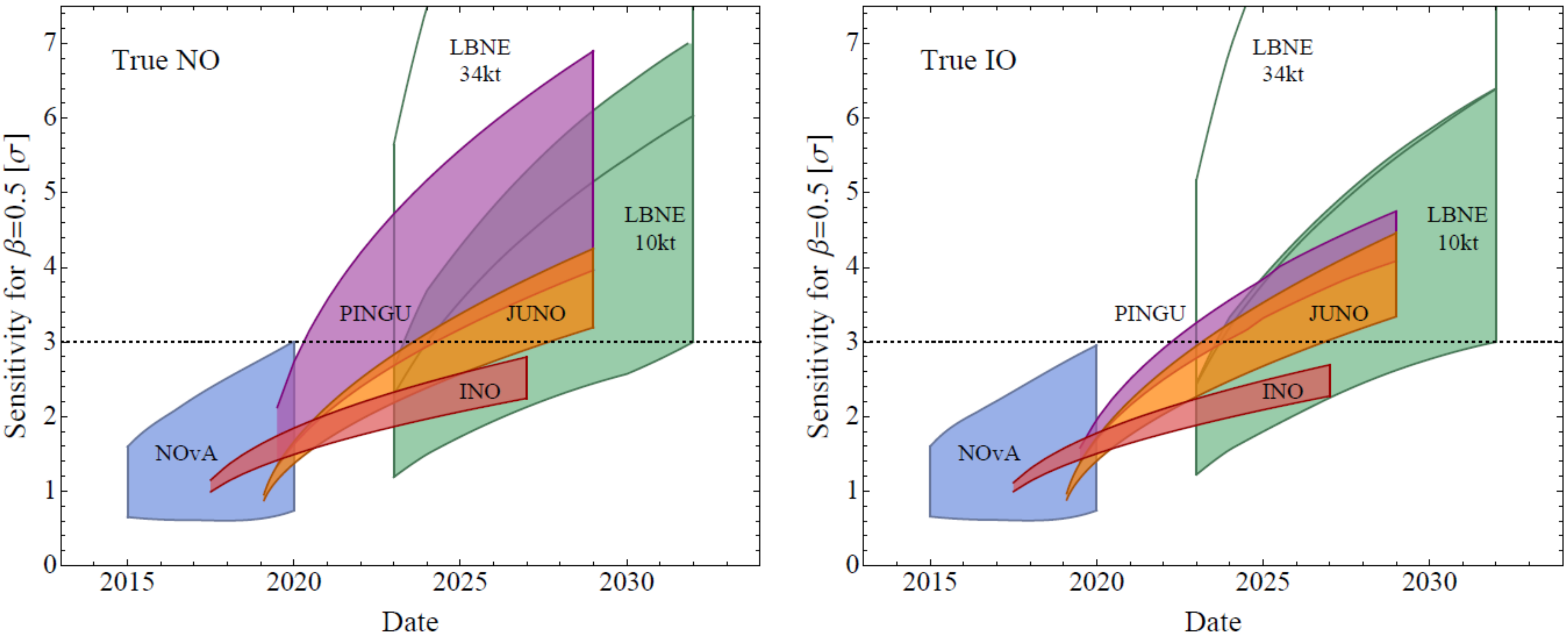
From J. P. Athayde Marcondes de André talk:



Combining tracks and cascades PINGU could reach 3 σ in 1-4y

Mass hierarchy

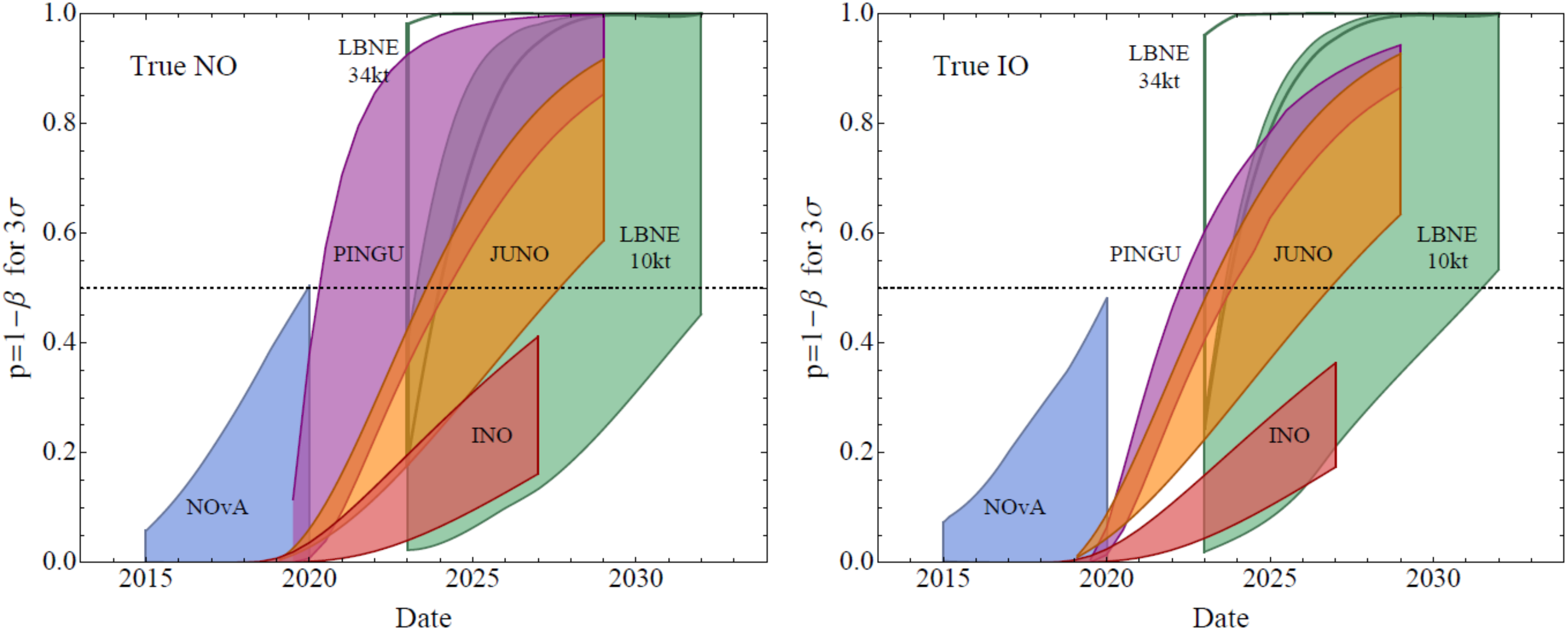
From M. Blennow talk:



Summary of future median significance for the MH

Mass hierarchy

From M. Blennow talk:

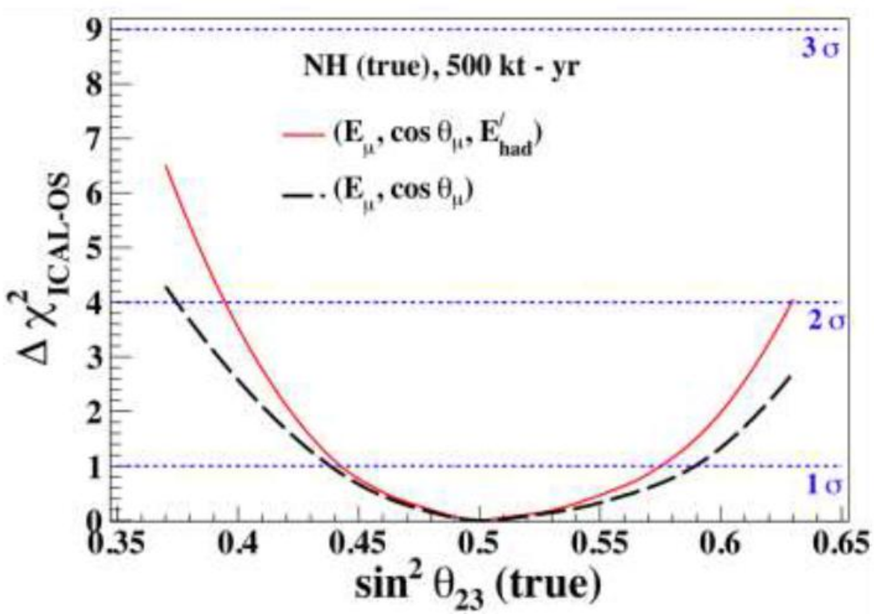


Probability to reach 3 σ level on MH

Octant

Question from NUFACT '13: What are the prospects for determining the θ_{23} octant over the next decade for current facilities? What is the sensitivity to the θ_{23} octant of medium-term atmospheric neutrino experiments such as INO, PINGU?

From M. M. Devi talk:



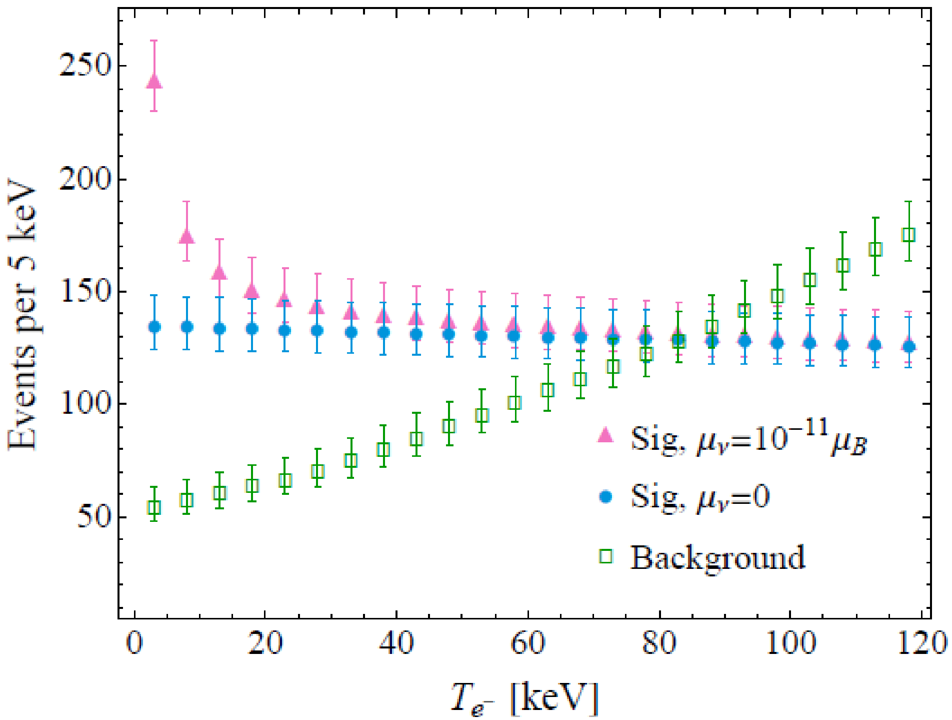
1-2 σ significance for the octant with INO. Waiting for a similar figure from PINGU and the combined sensitivity with T2K+NOνA+reactors

Neutrinos and new physics

Question from NUFACT '13: *If improved precision in oscillation parameters results in tension between measurements, which new physics beyond the 3-flavor mixing paradigm would we be probing (NSI, steriles, unitarity, CPT, etc.)? And between oscillations and other searches (neutrinoless double beta decay, CLFV, cosmology…)?*

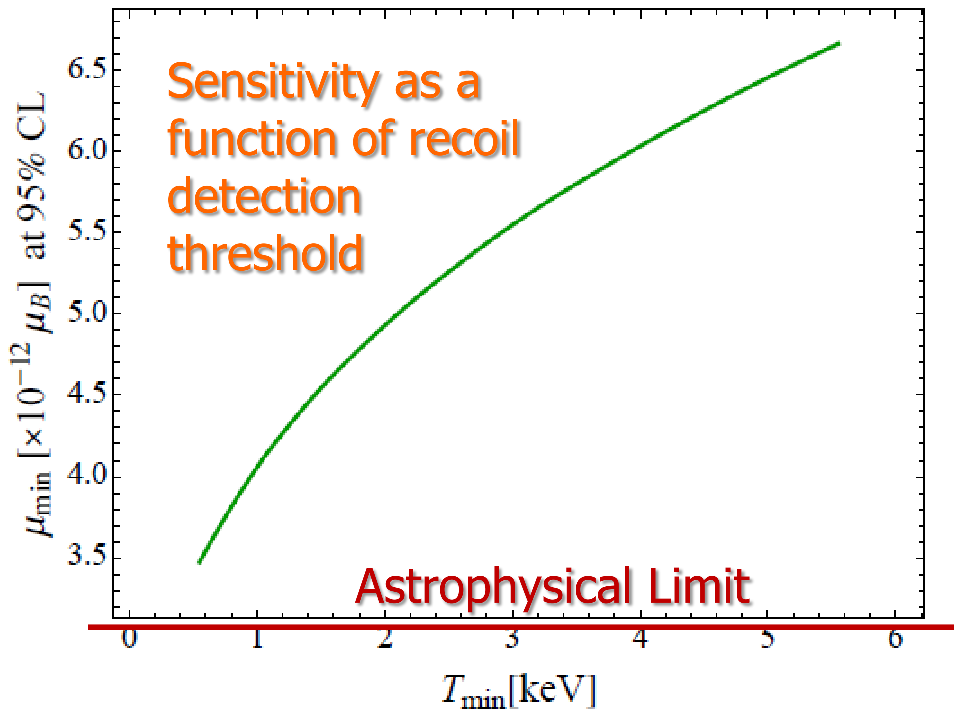
Neutrinos and new physics

From J. Link talk:



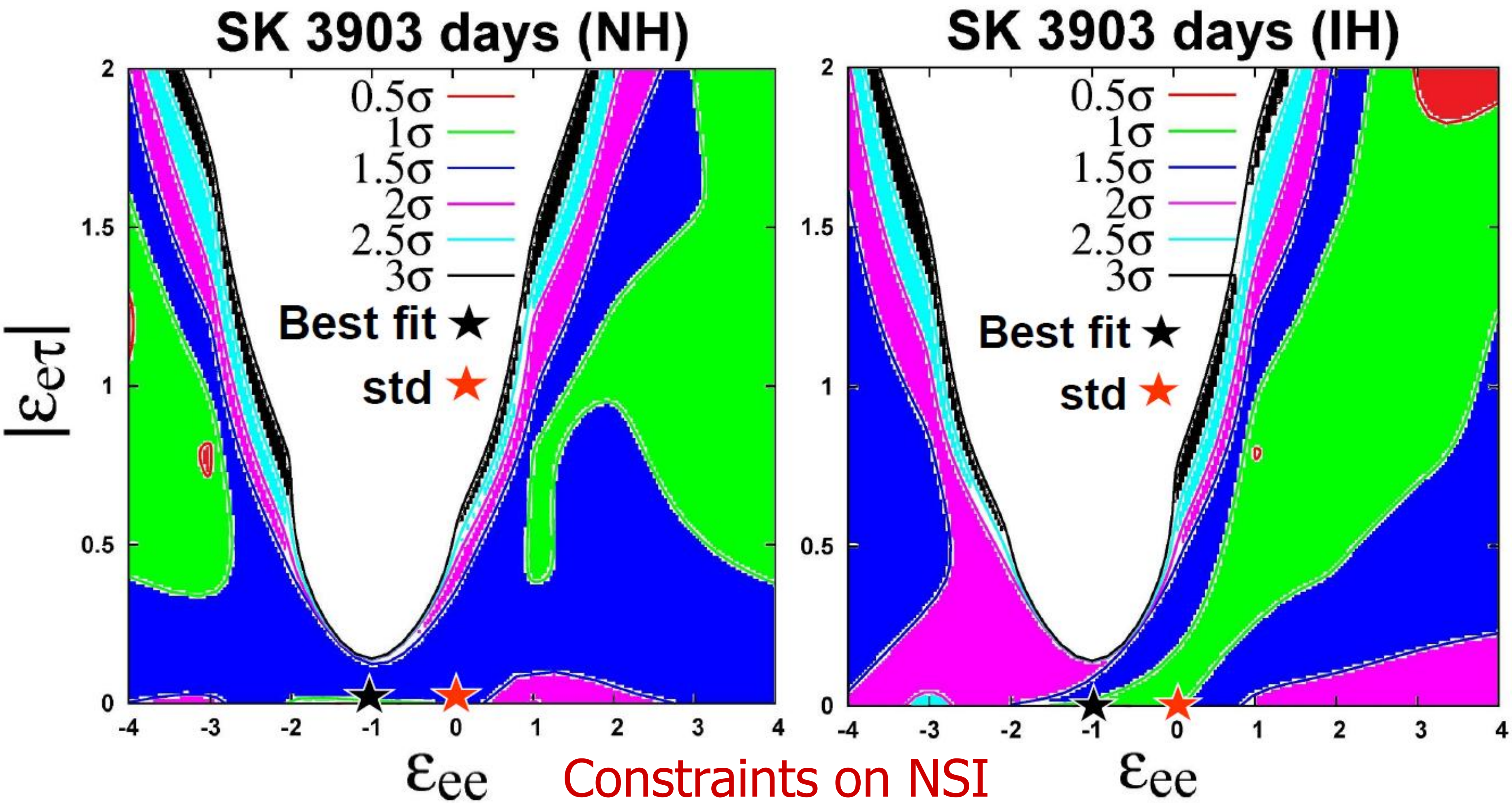
At LZ Xe DM detector. 100 days exposure to 5 MCi source. Source located 1 m from the edge of fiducial volume (a cylinder 137.2 cm high × 137.2 cm in diameter)

Evidence of a non-zero neutrino magnetic moment would appear as a dramatic increase in the scattering rate for the lowest energy recoil electrons.



Neutrinos and new physics

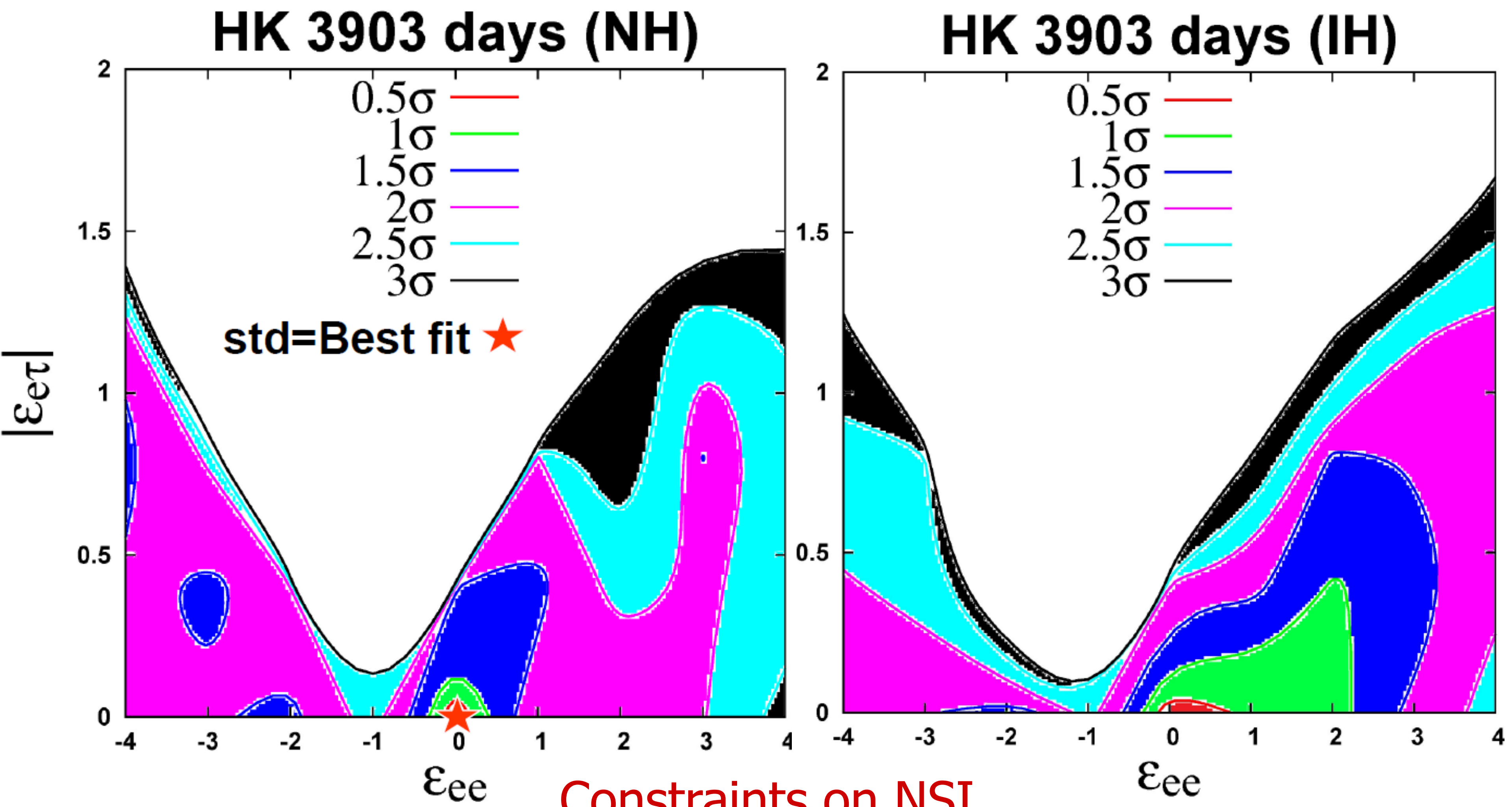
From O. Yasuda talk:



Constraints on NSI

Neutrinos and new physics

From O. Yasuda talk:



Constraints on NSI

Neutrinos and charged leptons

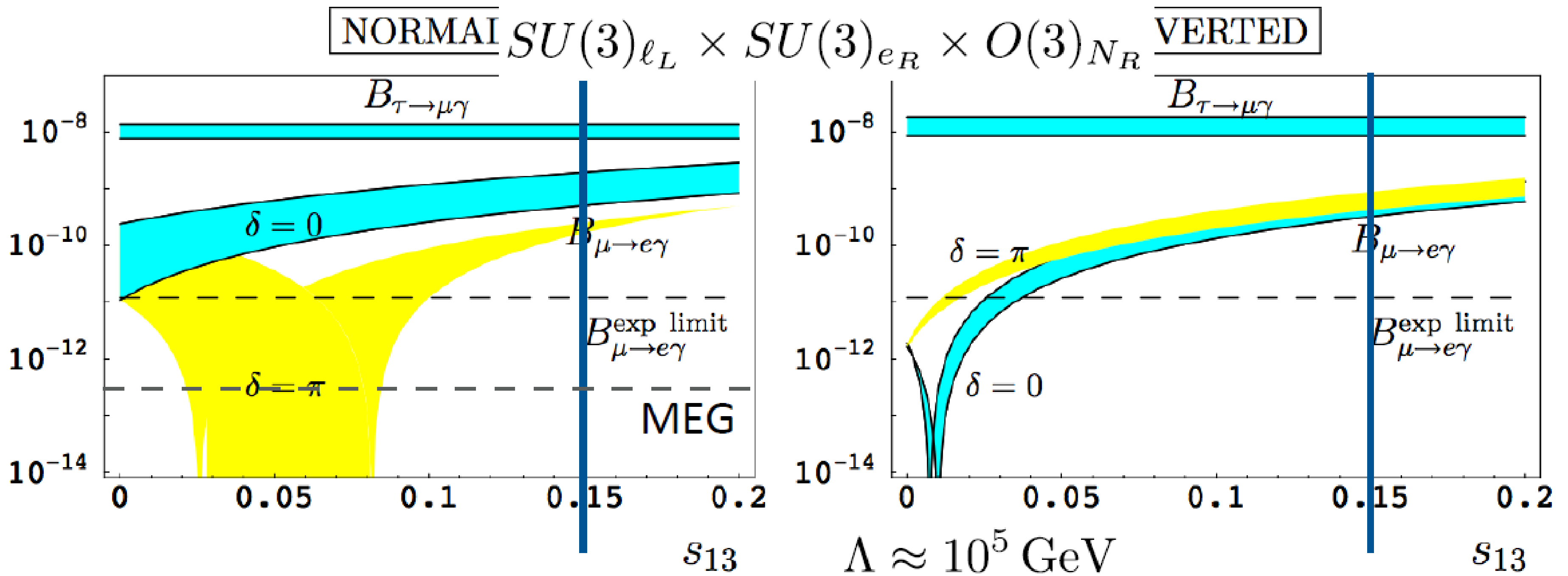
From L. Merlo talk:

Maybe the solution of the flavour puzzle comes from continous symmetries like the gauge symmetries in the SM

Can explain simultaneously quark and neutrino patterns

Can lead to signals in Charged Lepton Flavour Violation

$SU(3)_{\ell_L} \times SU(3)_{e_R} \times O(3)_{N_R}$



Neutrinos and charged leptons

From M. Passera talk, lepton g-2:

$a_\mu^{EXP} = 116592091\ (63) \times 10^{-11}$

E821 – Final Report: PRD73 (2006) 072 with latest value of $\lambda=\mu_\mu/\mu_p$ from CODATA'10

$a_\mu^{SM} \times 10^{11}$	$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}$	σ
116 591 809 (66)	$282\ (91) \times 10^{-11}$	3.1 [1]
116 591 829 (57)	$262\ (85) \times 10^{-11}$	3.1 [2]
116 591 855 (58)	$236\ (86) \times 10^{-11}$	2.8 [3]

~3 σ tension in μ g-2 between exp and th persists. Notice similar errorbars, challenge for th to keep up!

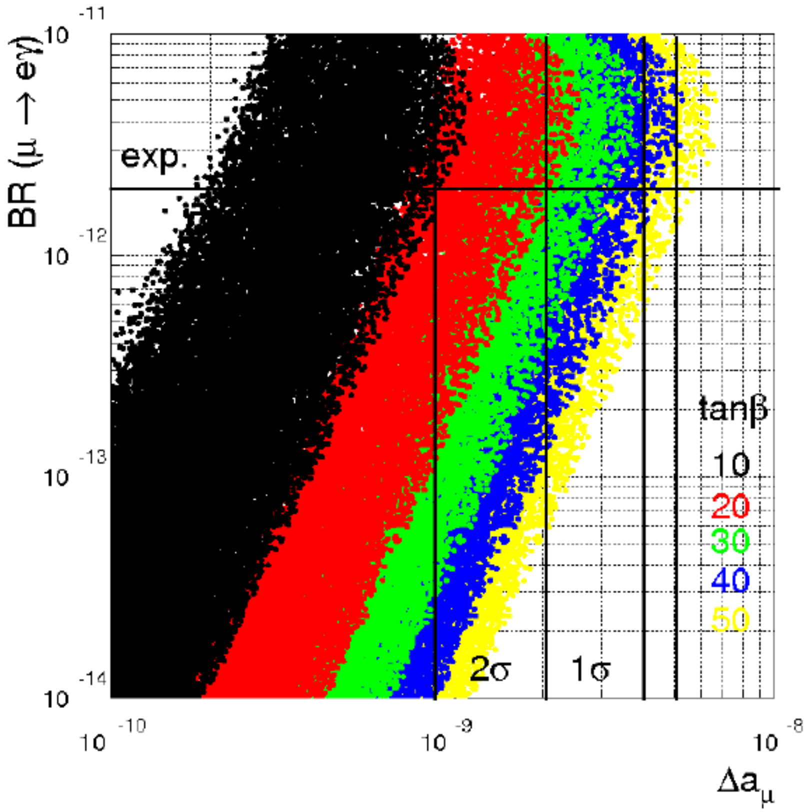
with the "conservative" $a_\mu^{HNLO}(lbl) = 116\ (39) \times 10^{-11}$ and the LO hadronic from:

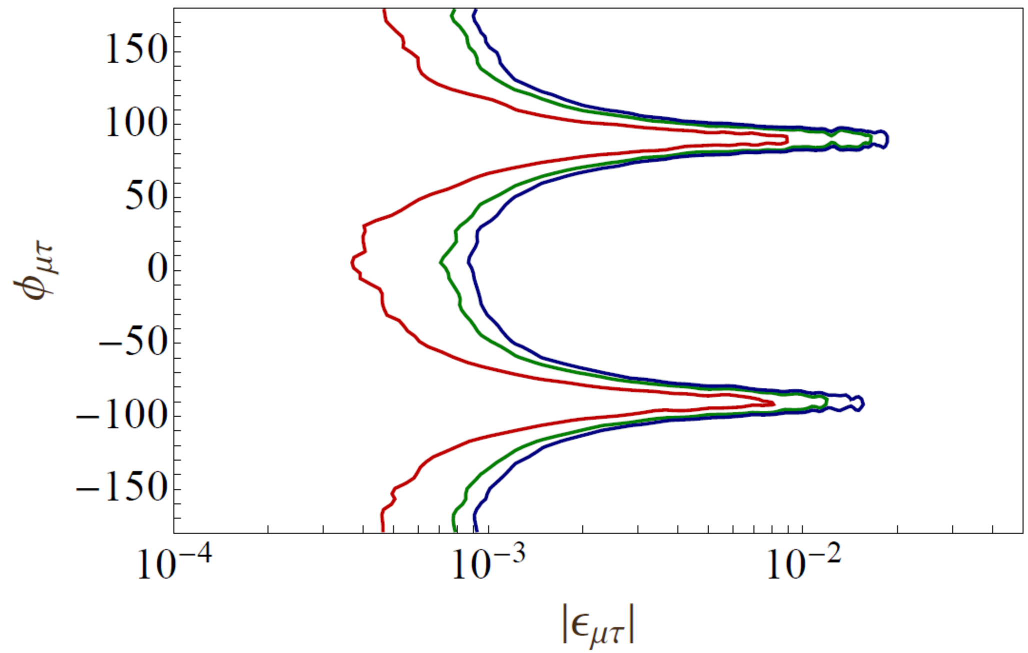
[1] Jegerlehner & Nyffeler, Phys. Rept. 477 (2009) 1
[2] Davier et al, EPJ C71 (2011) 1515 (includes BaBar & KLOE10 2π)
[3] Hagiwara et al, JPG38 (2011) 085003 (includes BaBar & KLOE10 2π)

Could be probed in the near future with e g-2. Independent determinations of α reaching comparable accuracy. Would imply a test of the QED to the 4 loop level!

Neutrinos and charged leptons

From P. Paradisi talks, lepton g-2:





arXiv:1105.5936

Also correlated with CLVF and electric dipole moments.
Can also lead to ~10^{-3} NSI in the $\mu-\tau$ sector potentially testable through precise $\nu\mu$ disappearance measurements.

Steriles?

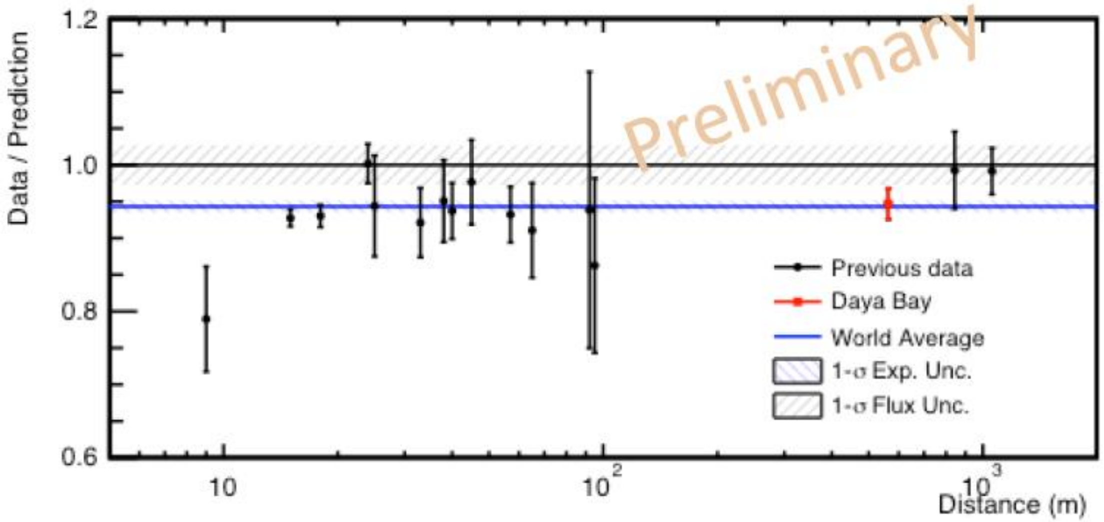
Question from NUFACT '13: *Evidence for sterile neutrinos is dominated by the LSND result. What are the prospects for rejecting or confirming LSND at more than 5σ before NuStorm is built?*

Question from NUFACT '13: *What is the effect of results from Daya Bay, RENO and Double Chooz on the reactor neutrino anomaly? Can we test the gallium anomaly with future projects?*

Question from NUFACT '13: *What constraints can we place on light sterile neutrinos using direct mass measurements?*

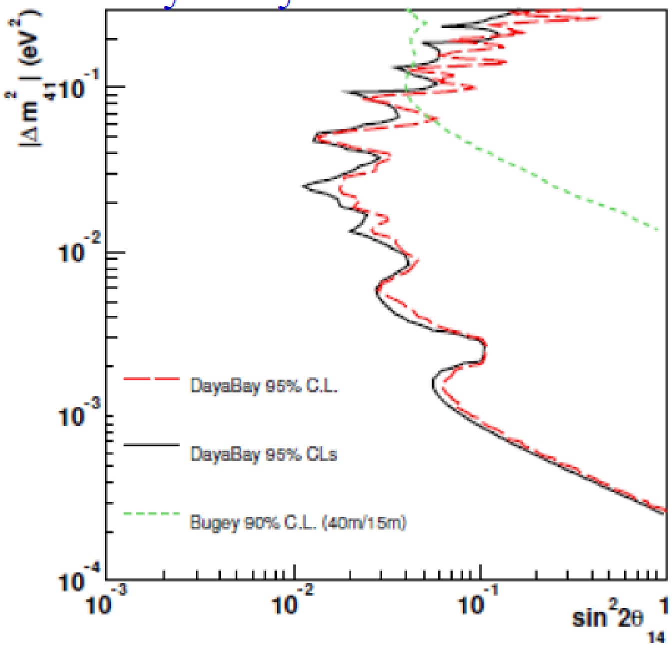
Steriles?

From F. An and Y. Wang talks, Daya Bay results:



Reactor anomaly is still there 2.4 σ

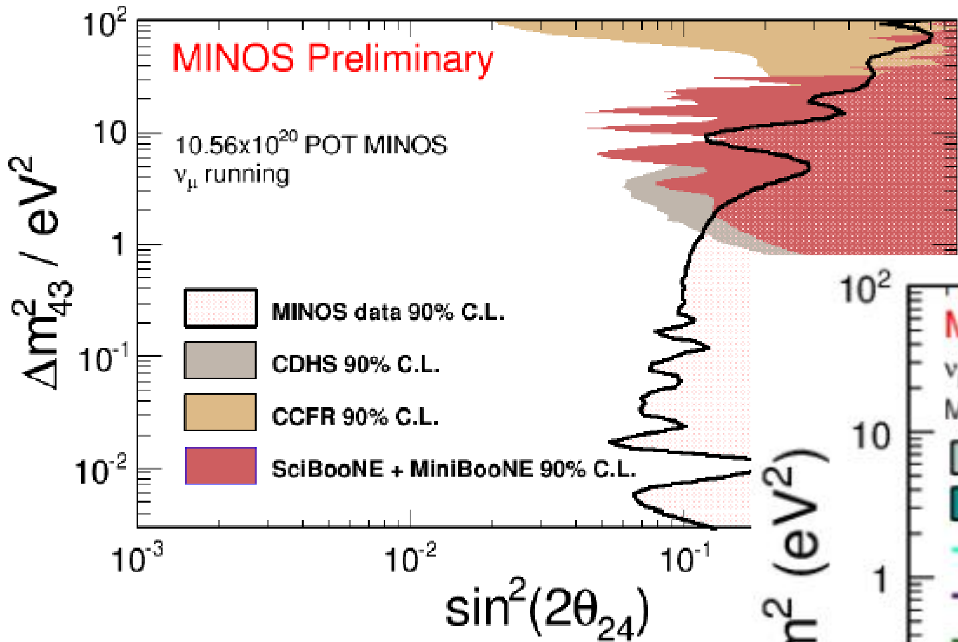
Daya Bay: arXiv:1407.7259



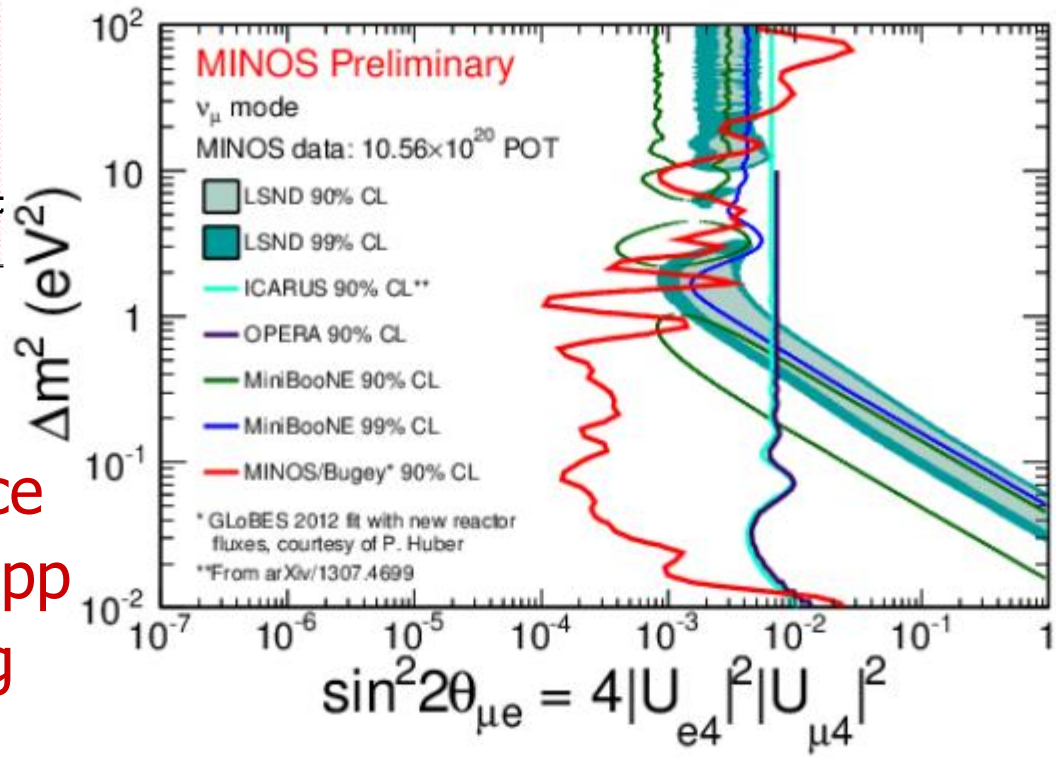
New constraints in e disappearance

Steriles?

From A. Holin talk, MINOS/MINOS+ results:



Constraints on sterile neutrinos



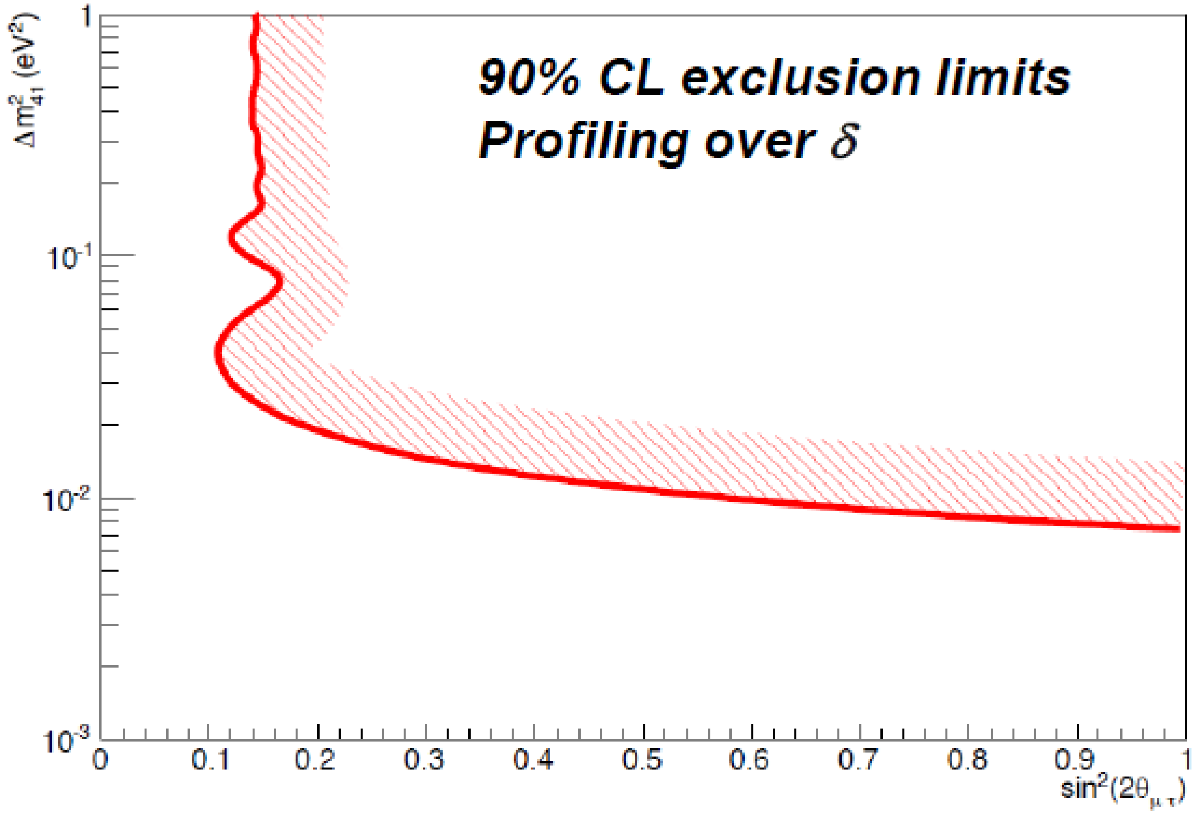
Tension between appearence channel anomalies and disapp constraints keeps increasing

Steriles?

From U. Kose talk, OPERA results:

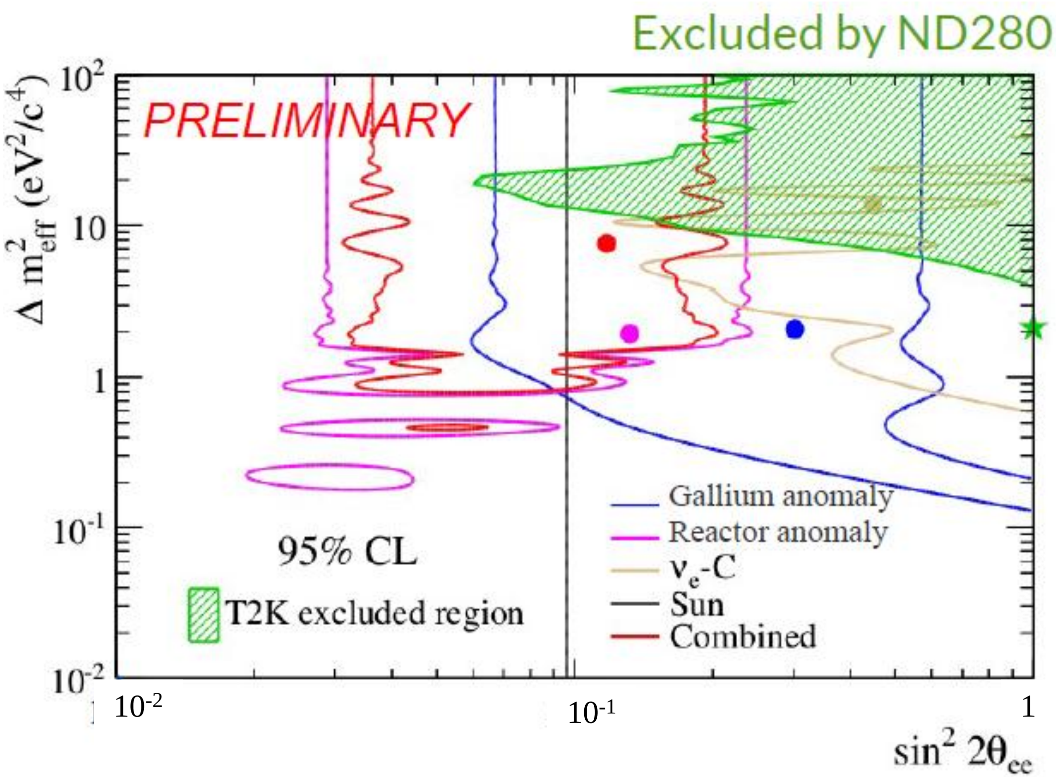
Bounds on $\mu-\tau$ mixing via steriles.

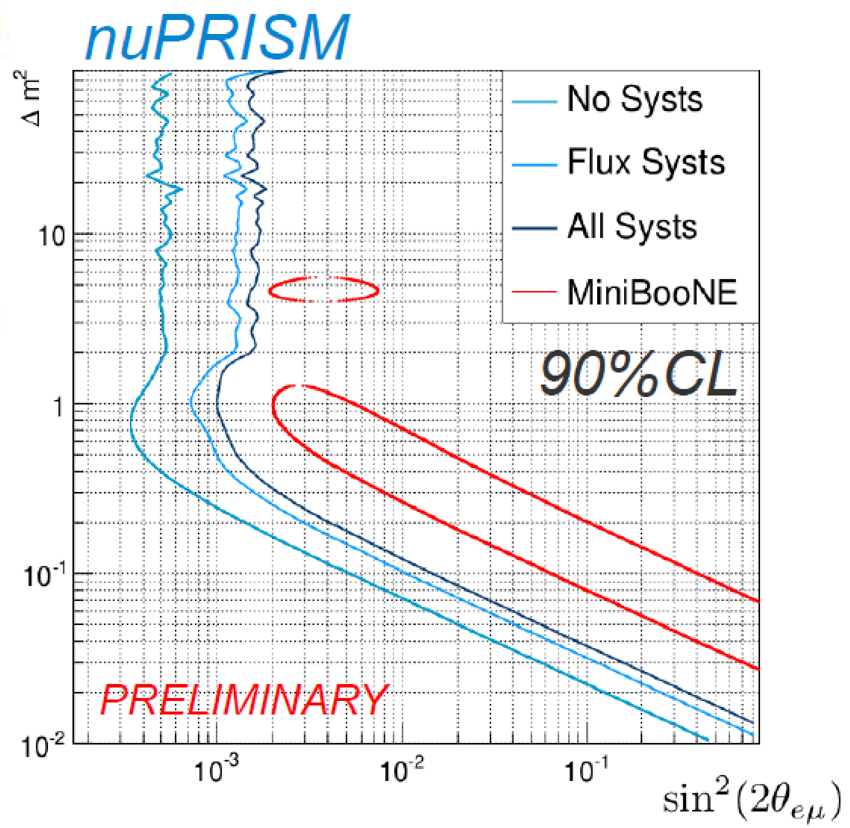
This is a very complementary channel.



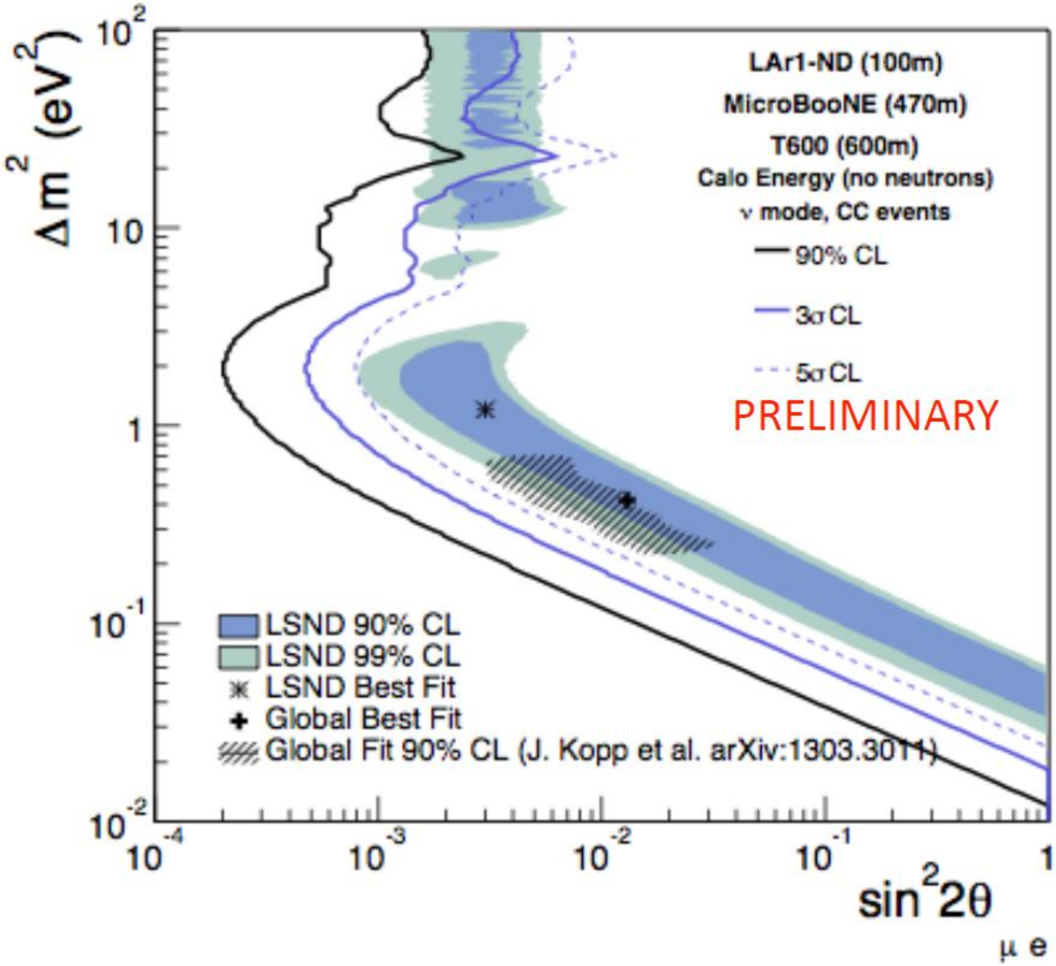
Steriles?

From J. Caravaca talk, T2K results and prospects:

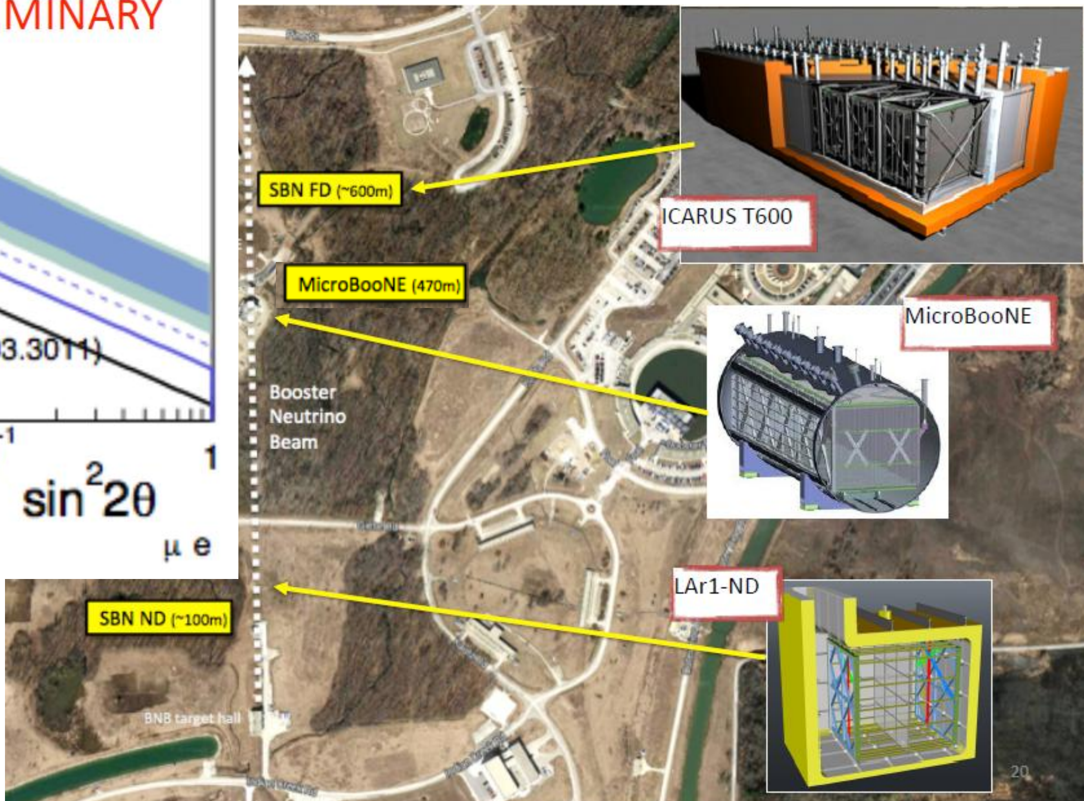




Steriles?

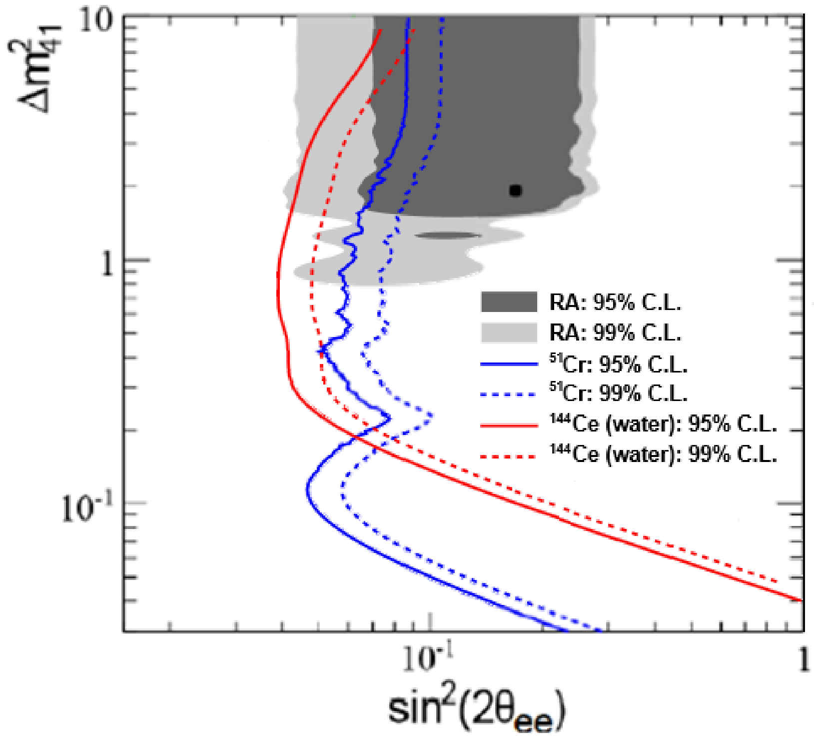


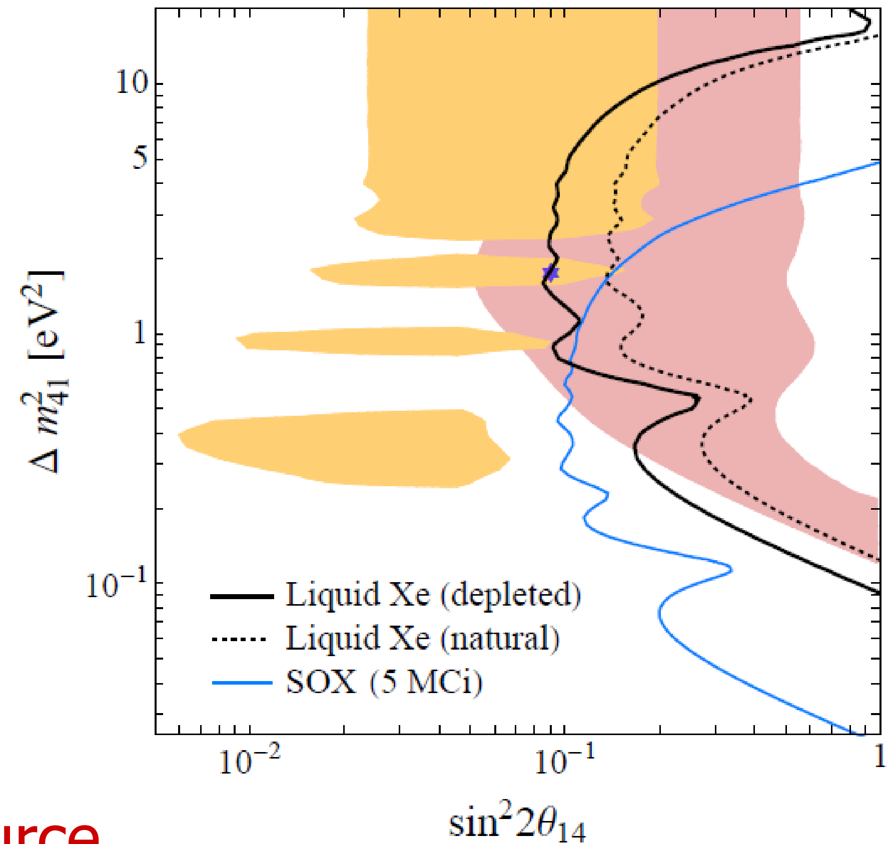
From A. Ereditato talk:



Steriles?

From J. Link talk:





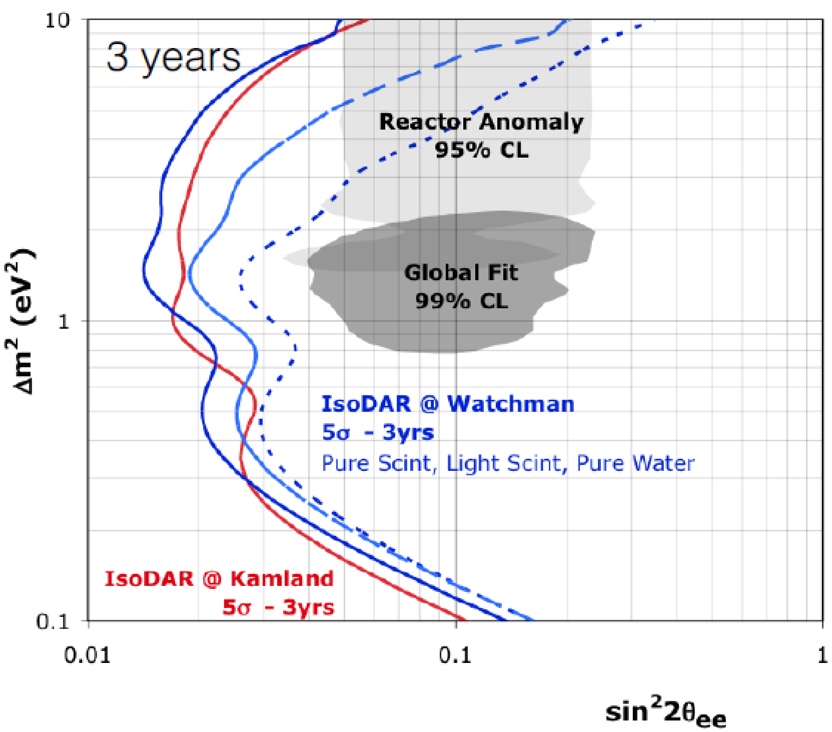
Borexino with ^{51}Cr or ^{144}Ce source

Large Xe DM detector (LZ) for 100 Days exposure to 5MCi source.

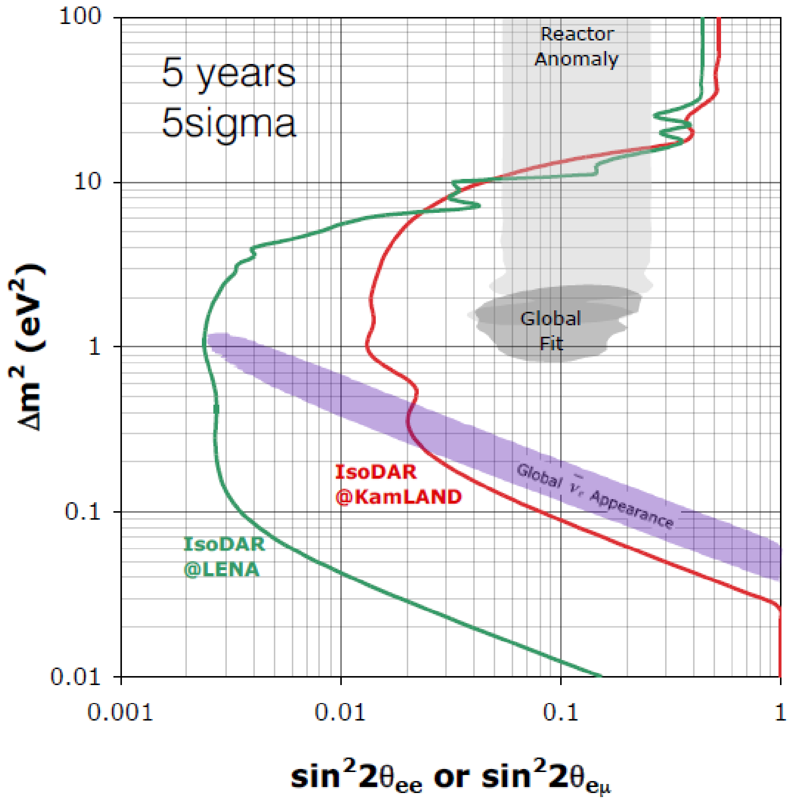
Steriles?

From J. Spitz talk:

Disappearance sensitivity with **Watchman** (1 kton Gd-doped water or scintillator)



Dis/appearance sensitivity with **LENA** (50 kton liquid scintillator)

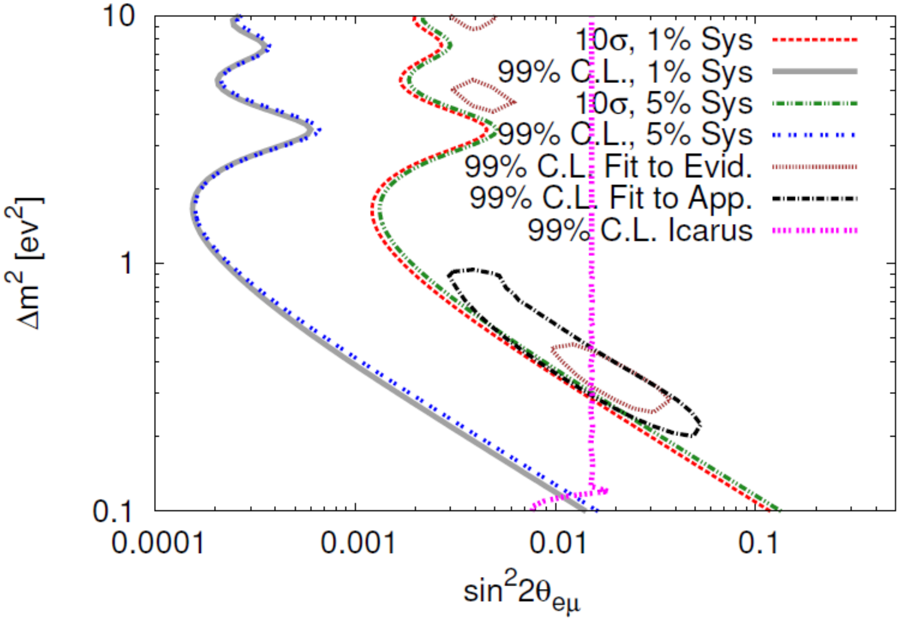


IsoDAR capabilities to probe the reactor anomaly

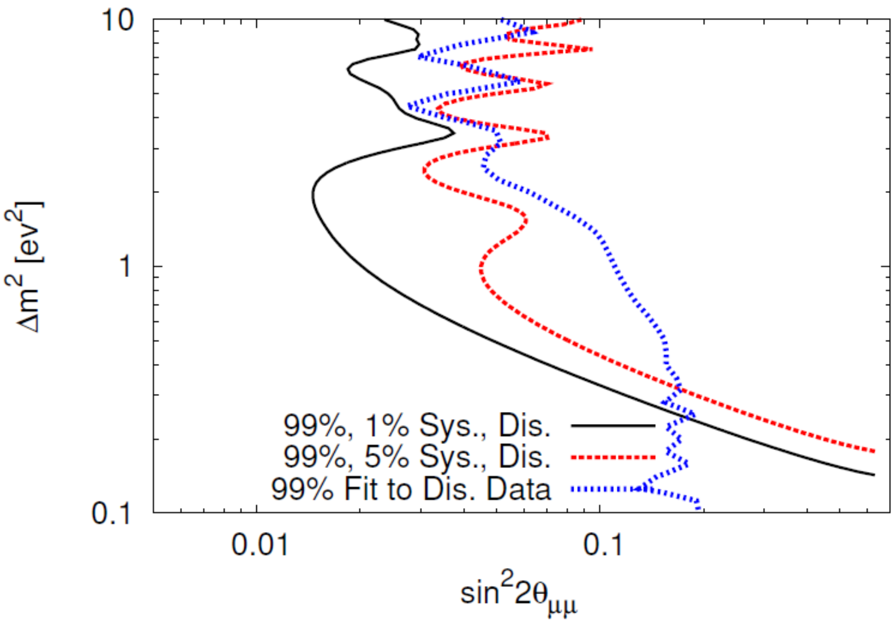
Steriles?

From R. Bayes talk:

$\nu_e \rightarrow \nu_\mu$ Appearance Search



$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ Disappearance Search



NuSTORM and steriles

New questions for Nufact 15

- What are the new developments and predictions from flavour models on neutrino oscillation parameters? What precision do we need to achieve to probe them? Which parameters (or combinations of them) are more powerful to test them?

- Do the current bounds on new physics in the neutrino sector (NSI, non-unitarity, steriles…) allow for effects large enough to interfere with CPV searches? Which experimental setups can improve these bounds?

- Explore the synergy between neutrino oscillations and other experiments (absolute mass searches, cosmological constraints, CLFV) to constrain new physics.

New questions for Nufact 15

- Are atmospheric neutrino measurements competitive with next generation long baseline facilities in the determination of the mass hierarchy? And the octant of θ_{23}? How much complementarity is there between them?

- What is the target for the systematic error budget of next generation facilities? What do we need to reach this level? How much improvement in constraining flux uncertainties can we expect from nuPRISM and dedicated hadron production efforts?

- What is the best strategy to fully probe the LSND anomaly? And the reactor/gallium anomaly?

- What can we say about the new Majorana mass scale implied by neutrino masses? What are the current bounds and how much will they improve over the next decade?