Why neutrinos?

Patrick Huber

Center for Neutrino Physics at Virginia Tech

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Neutrinos are massive – so what?

Neutrinos in the Standard Model (SM) are strictly massless, therefore the discovery of neutrino oscillation, which implies non-zero neutrino masses requires the addition of new degrees of freedom.

We always knew they are . . .

The SM is an effective field theory, *i.e.* at some high scale Λ new degrees of freedom will appear

$$\mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

The first operators sensitive to new physics have dimension 5. It turns out there is only one dimension 5 operator

$$\mathcal{L}_5 = \frac{1}{\Lambda}(LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

Thus studying neutrino masses is, in principle, the most sensitive probe for new physics at high scales
Weinberg

Effective theories

The problem in effective theories is, that there are *a priori* unknown pre-factors for each operator

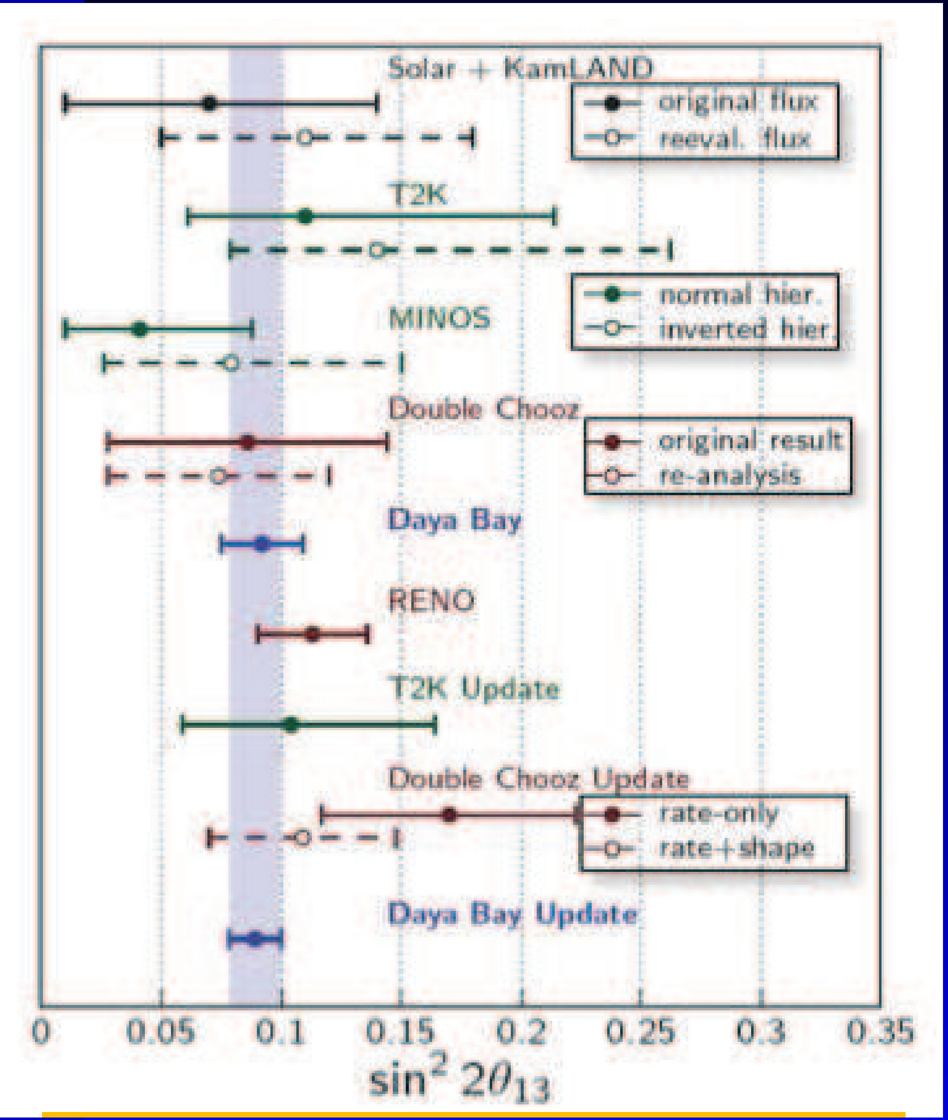
$$\mathcal{L}_{SM} + \frac{\#}{\Lambda}\mathcal{L}_5 + \frac{\#}{\Lambda^2}\mathcal{L}_6 + \ldots$$

Typically, one has $\# = \mathcal{O}(1)$, but there may be reasons for this being wrong

- lepton number may be conserved $\rightarrow$ no Majorana mass term
- lepton number may be approximately conserved $\rightarrow$ small pre-factor for $\mathcal{L}_5$

Therefore, we do not know the scale of new physics responsible for neutrino masses.

θ_{13} is large!



The Daya Bay result is

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst}),$$

which translates into a more than $5\,\sigma$ exclusion of $\theta_{13} = 0$, confirmed by RENO.

NB – a year ago we had only $2\,\sigma$ indications.

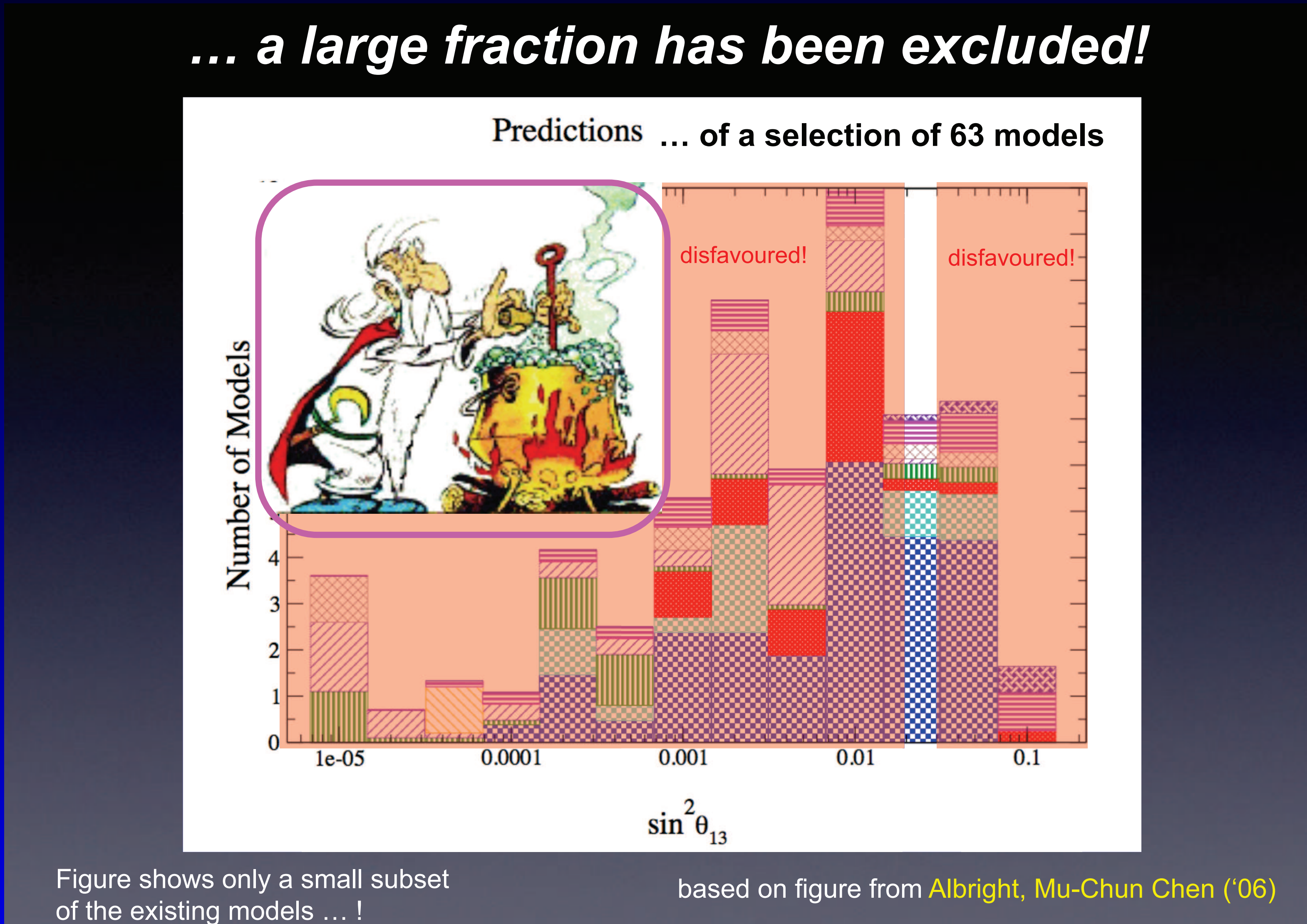
Implications

In general, this raises the following questions

- Is neutrino physics essentially done?
- Will the mass hierarchy have been determined before the next generation of long-baseline experiments?
- Are new experiments beyond NOνA and T2K necessary to discover CP violation?
- Are superbeams sufficient for precision neutrino physics?

Any of this questions is both a challenge and opportunity!

Model selection



Antusch, 2012

Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

$$dU = ds_{12}^2\, dc_{13}^4\, ds_{23}^2\, d\delta_{CP}\, d\chi_1\, d\chi_2$$

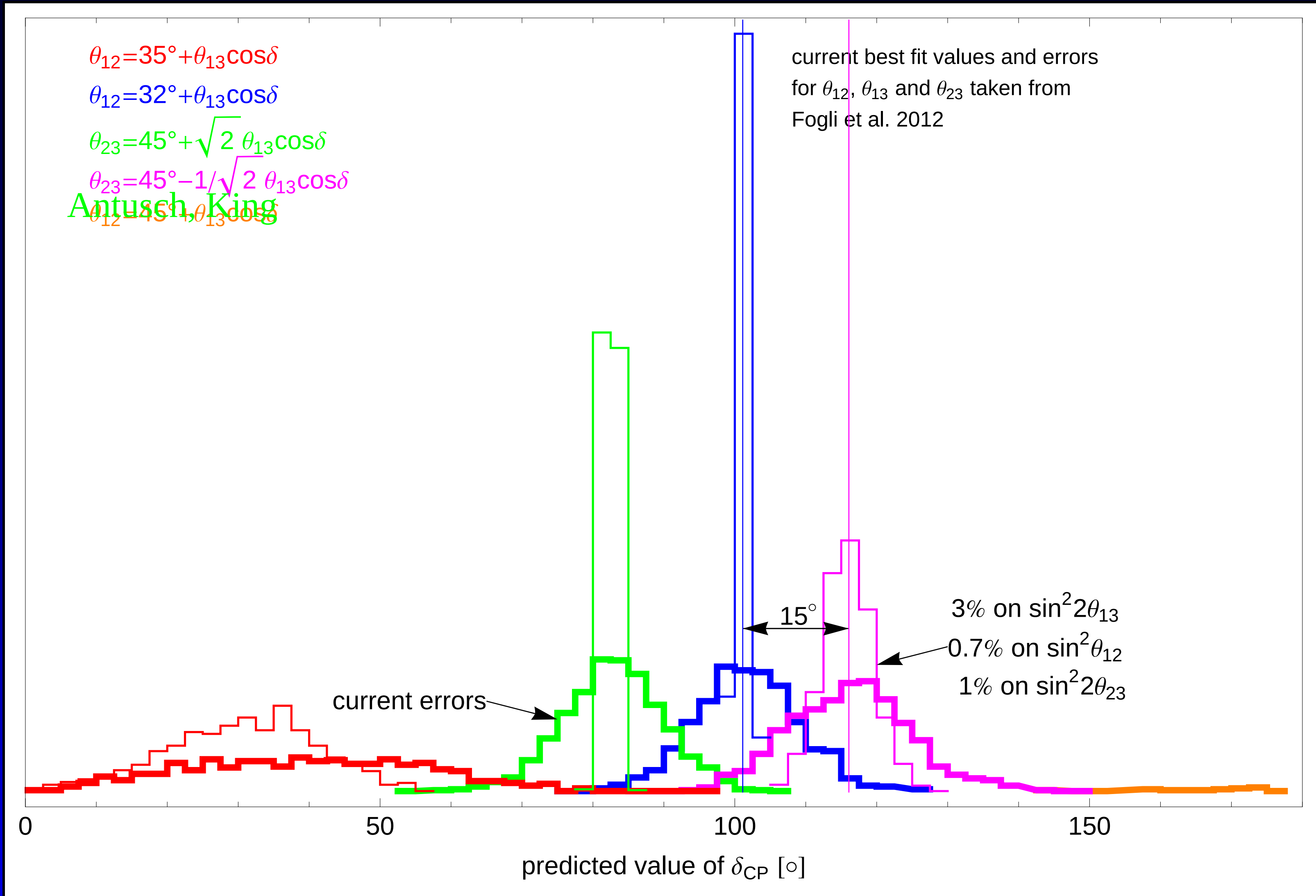
predicts flat distribution in δ_{CP}

Simplest model – Tri-bimaximal mixing Harrison, Perkins, Scott

$$\begin{pmatrix} \sqrt{\frac{1}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

to still fit data, obviously corrections are needed – predictivity?

Sum rules



$3\,\sigma$ resolution of 15° distance requires 5° error.

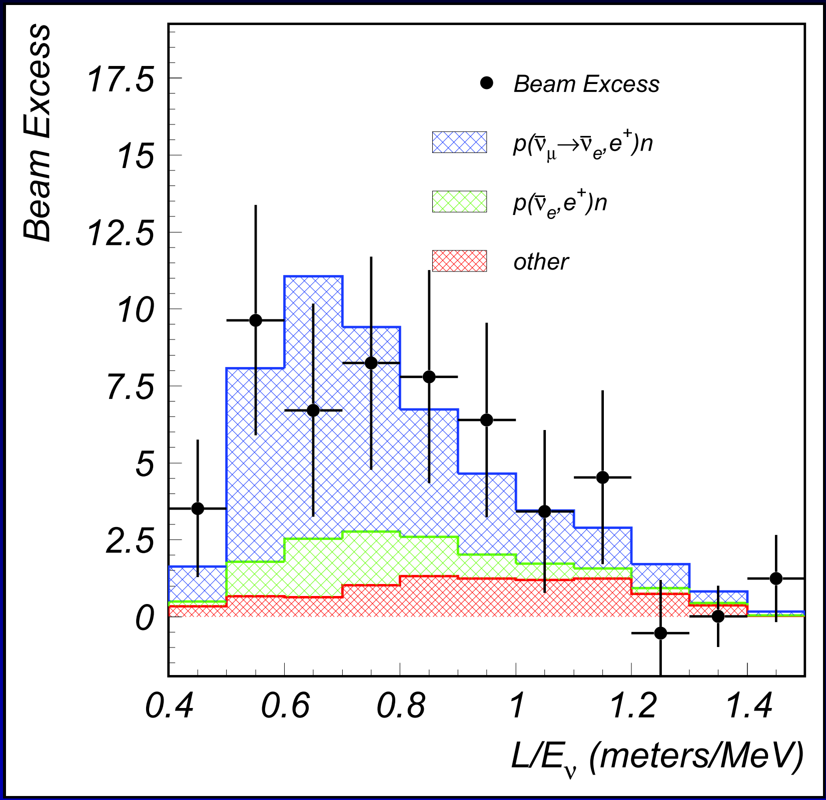
What we want to learn

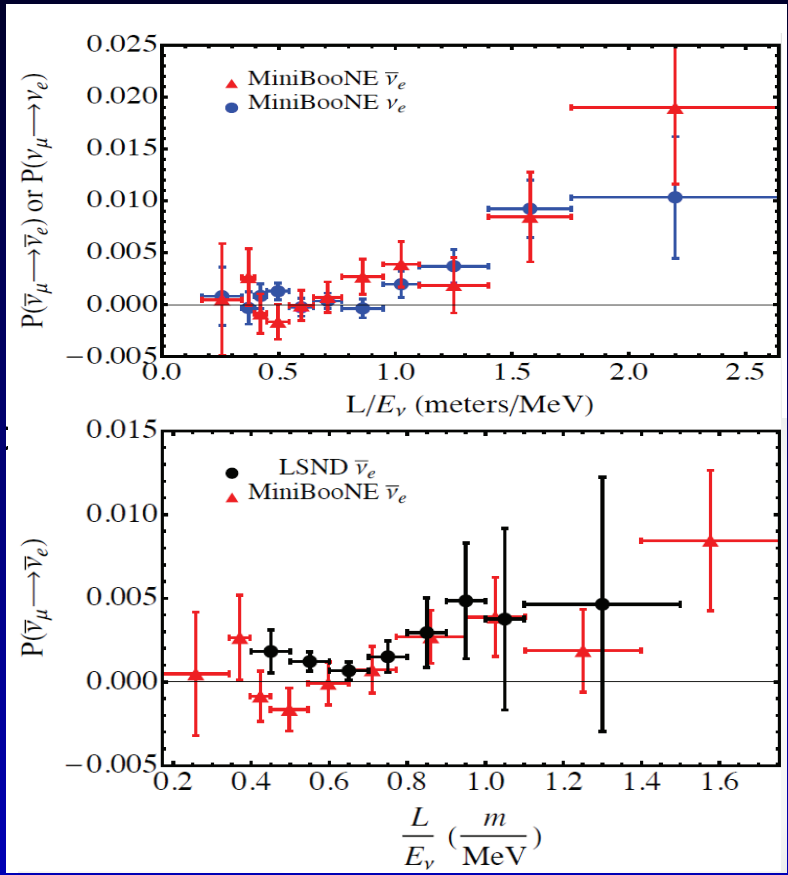
In the context of neutrino oscillation experiments

- δ_{CP}
- mass hierarchy
- $\theta_{23} = \pi/4$, $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$?
- Resolution of LSND and the other short-baseline anomalies
- New physics vs tests of the three flavor framework

Given the current state of the theory of neutrinos we can not say with confidence that any one quantity is more fundamental than any other.

LSND and MiniBooNE

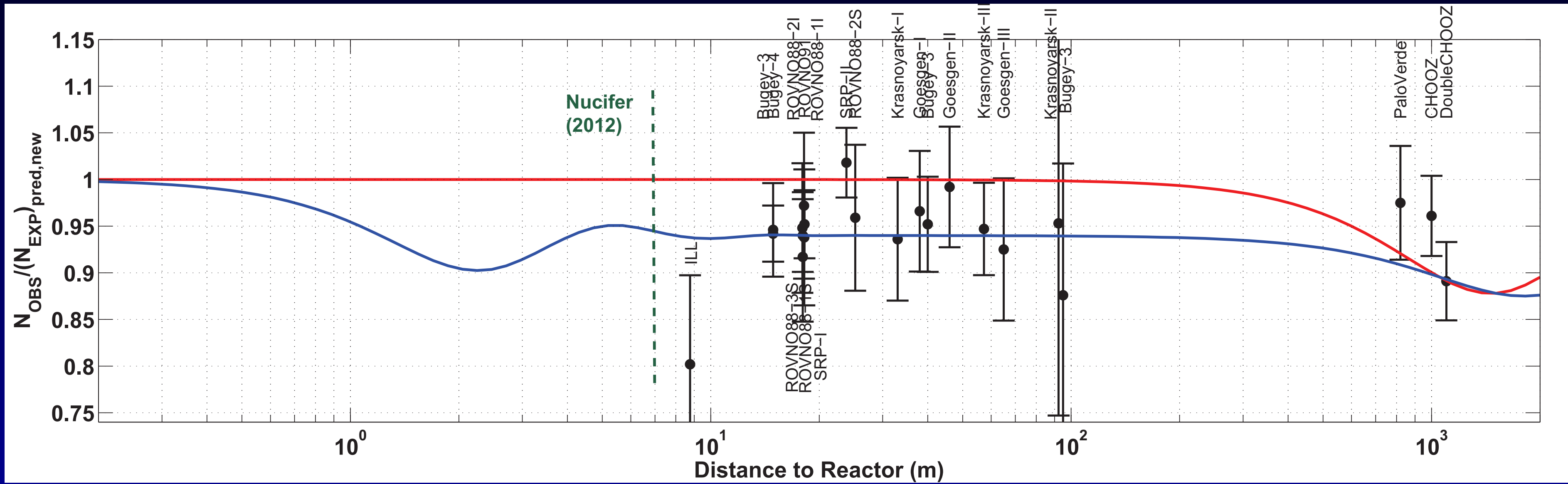




$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq 0.003$$

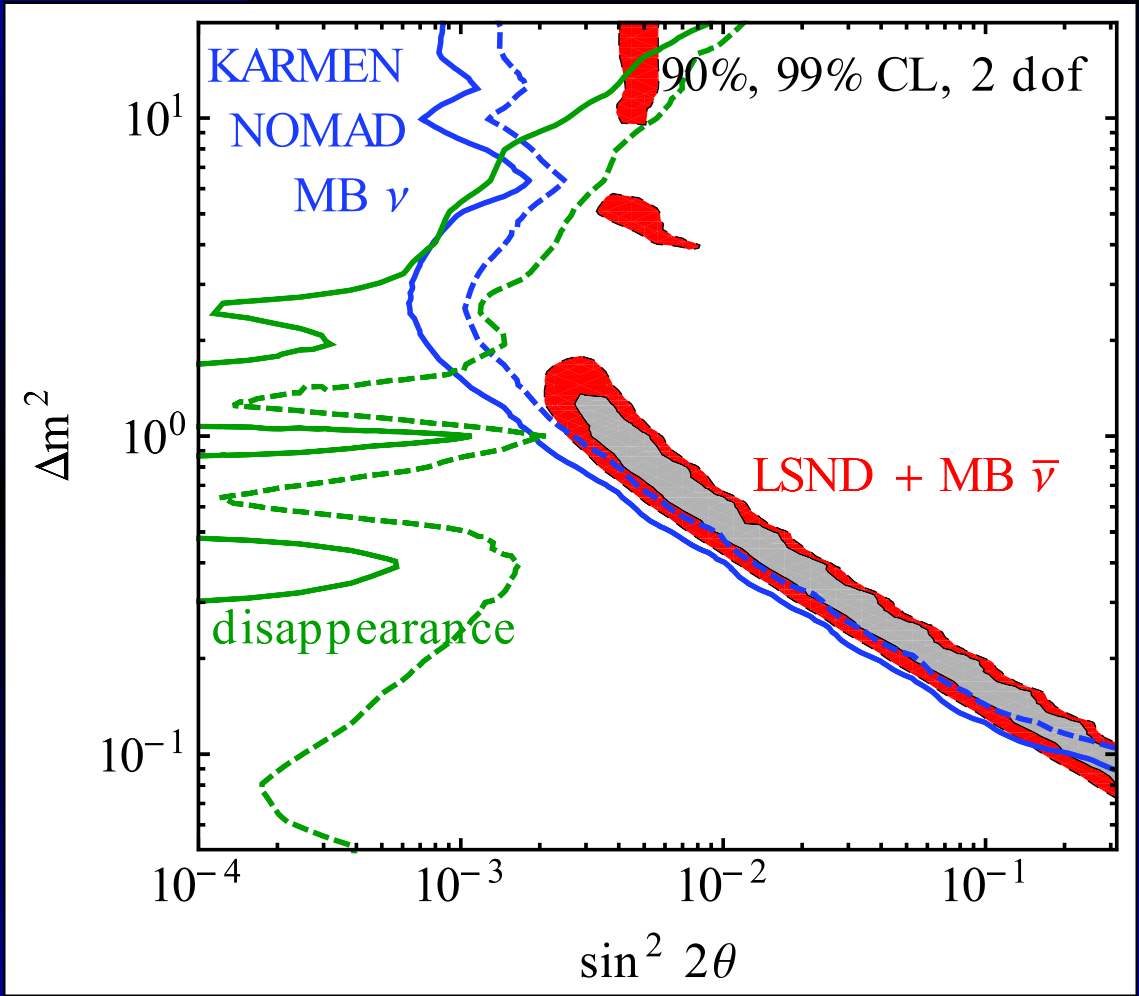
Tension between neutrino and antineutrino signals?

Reactor and Gallium anomalies



	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R_B^k	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm {}^{+0.084}_{-0.078}$
R_H^k	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm {}^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0		1.47	
source height [m]	2.7	2.38	0.72	

Disappearance constraints



Absence of effects in

- atmospheric
- Bugey
- CDHS
- MINOS
- …

data creates considerable tension in 3+N sterile neutrino models

More details can be found in the sterile neutrino white paper, arXiv:1204.5379.

Sterile oscillation

In general, in a 3+N sterile neutrino oscillation model one finds that the energy averaged probabilities obey the following inequality

$$P(\nu_\mu \to \nu_e) \leq 4P(\nu_e \to \nu_e)P(\nu_\mu \to \nu_\mu)$$

independent of CP transformations. Therefore, a stringent test of the model is to measure

- $P(\nu_\mu \to \nu_e)$ – appearance
- $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ – appearance
- $P(\nu_\mu \to \nu_\mu)$ or $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ – disappearance
- $P(\nu_e \to \nu_e)$ or $P(\bar{\nu}_e \to \bar{\nu}_e)$ – disappearance

Non-standard interactions

NSI are the workhorse of beyond the Standard Model physics in the neutrino sector. Phenomenologically the can be parametrized by terms like this

$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2}G_f \epsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\rho \nu_\beta)(\bar{f}\gamma_\rho P f)\,,$$

where f can be any fermion and P is the projection onto right and left-handed components. Wolfenstein, 1978

At higher energy, this contact term has to be replaced with a propagating exchange particle.

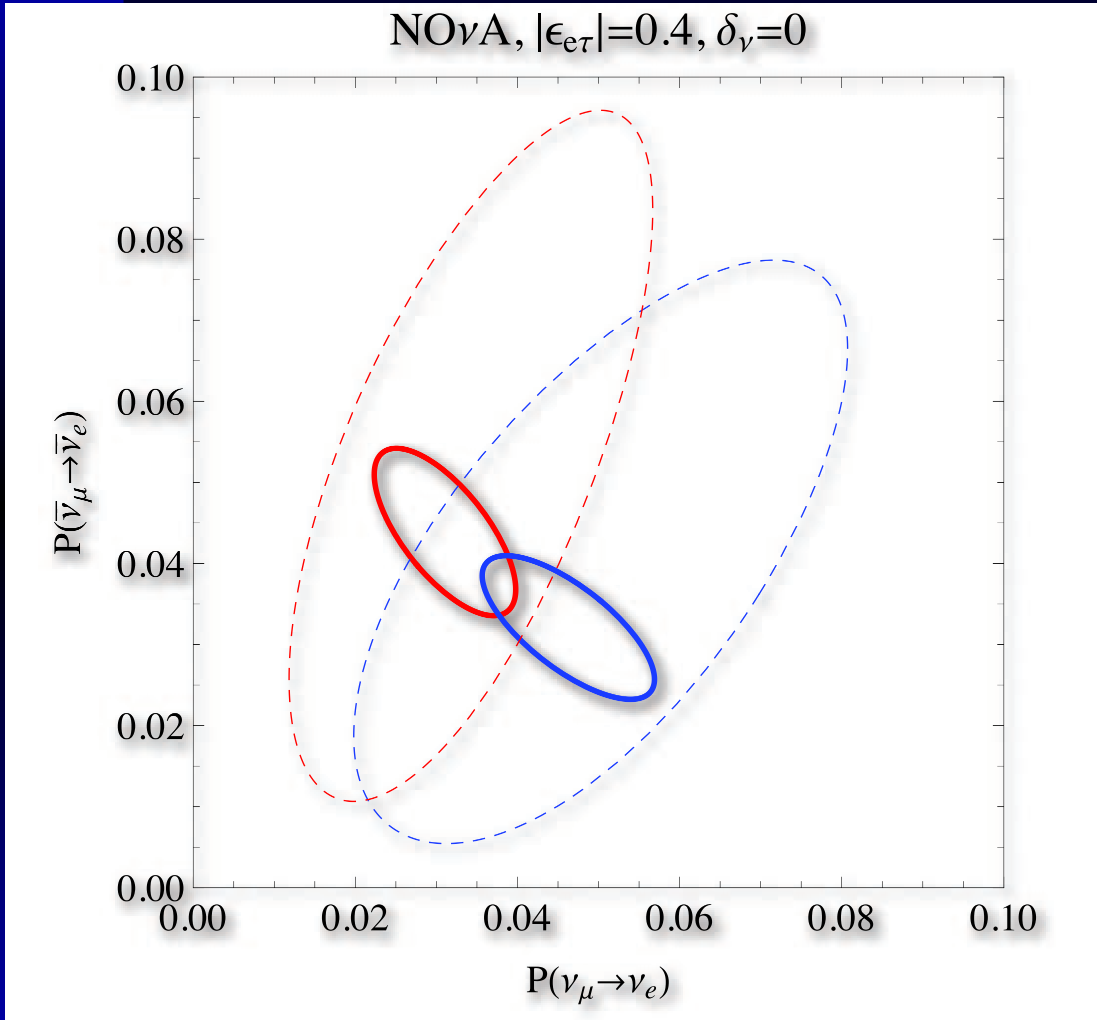
Simple example

Assume a flavor changing interaction with quarks of the type $\nu_e + q \to \nu_\tau + q$, this adds the following term to the Hamiltonian

$$H_{\mathrm{NSI}} = \sqrt{2} G_f n_e E \begin{pmatrix} 1 & 0 & |\epsilon_{e\tau}| e^{-i\delta_\nu} \\ 0 & 0 & 0 \\ |\epsilon_{e\tau}| e^{+i\delta_\nu} & 0 & 0 \end{pmatrix} .$$

Typically, $|\epsilon| \ll 1$ and thus this is a sub-dominant effect.

Impact on three flavors



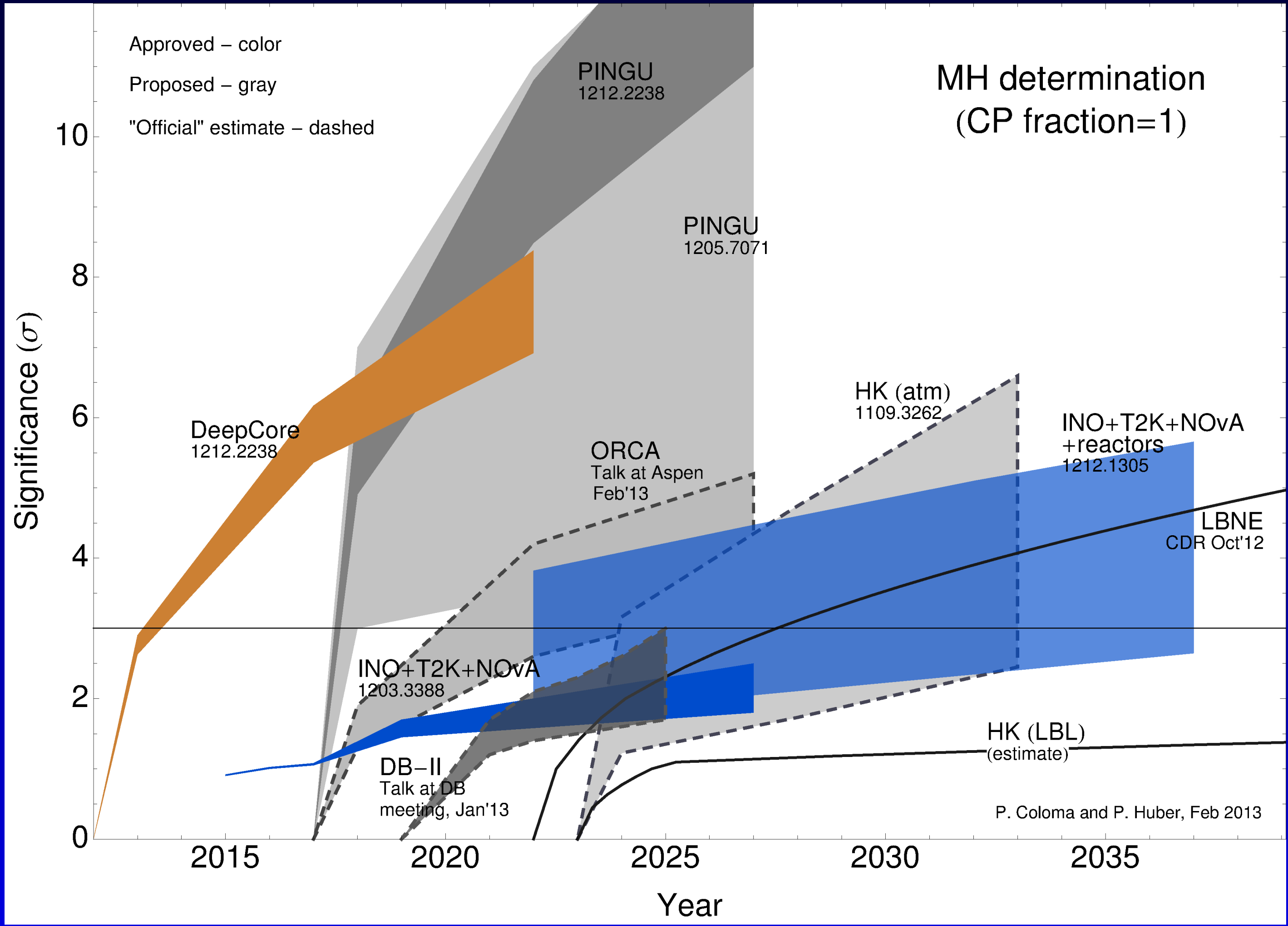
Friedland, 2012

Three flavor analysis are not safe from these effects!

Especially, global fits for the phase and mass hierarchy need to be aware of NSI.

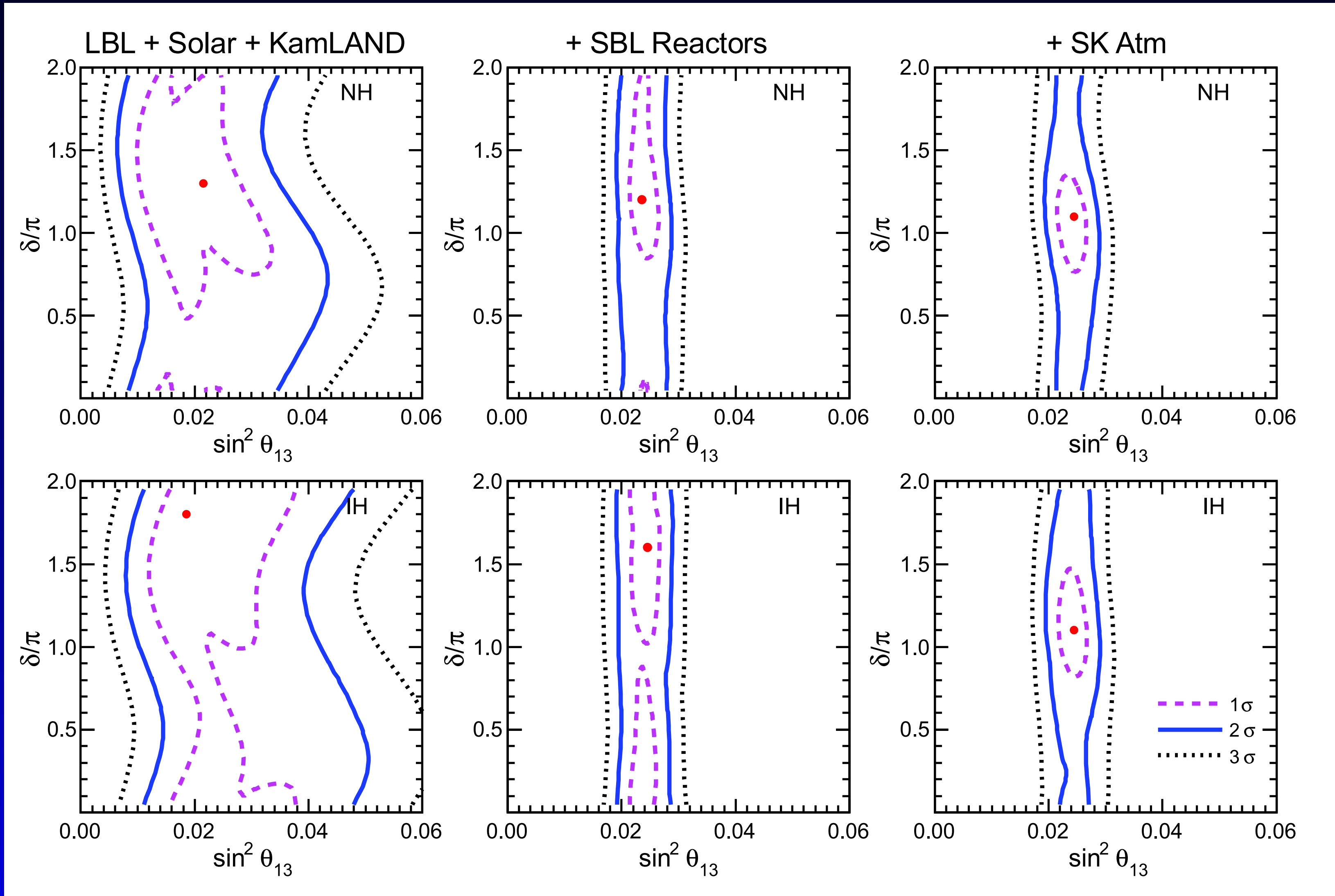
New ideas for mass hierarchy

Literature survey



The dashed ones are from collaborations – phenomenological studies are driving the field

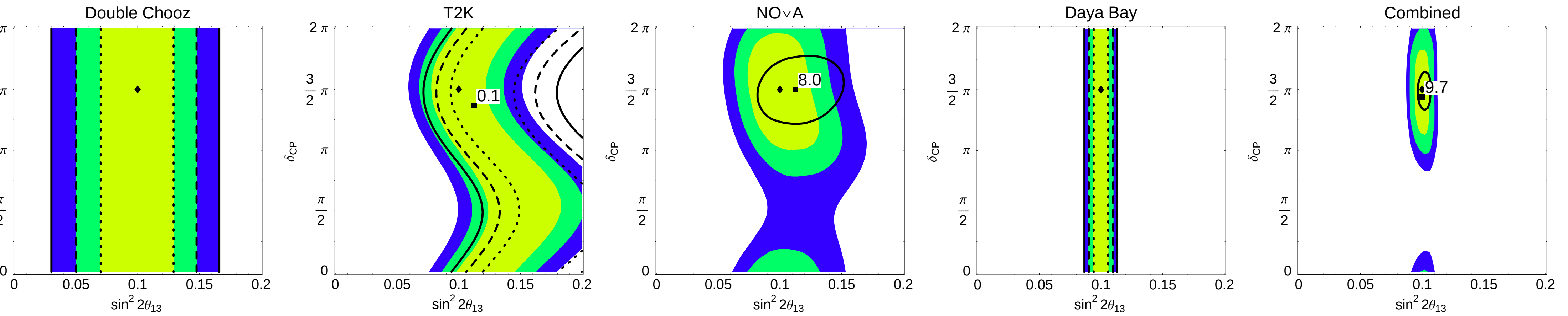
Early “hints” for CP?



Fogli, *et al.*, 2012

NB – 1 σ range for $\delta = 30 - 35^\circ$

Early hints for CP?

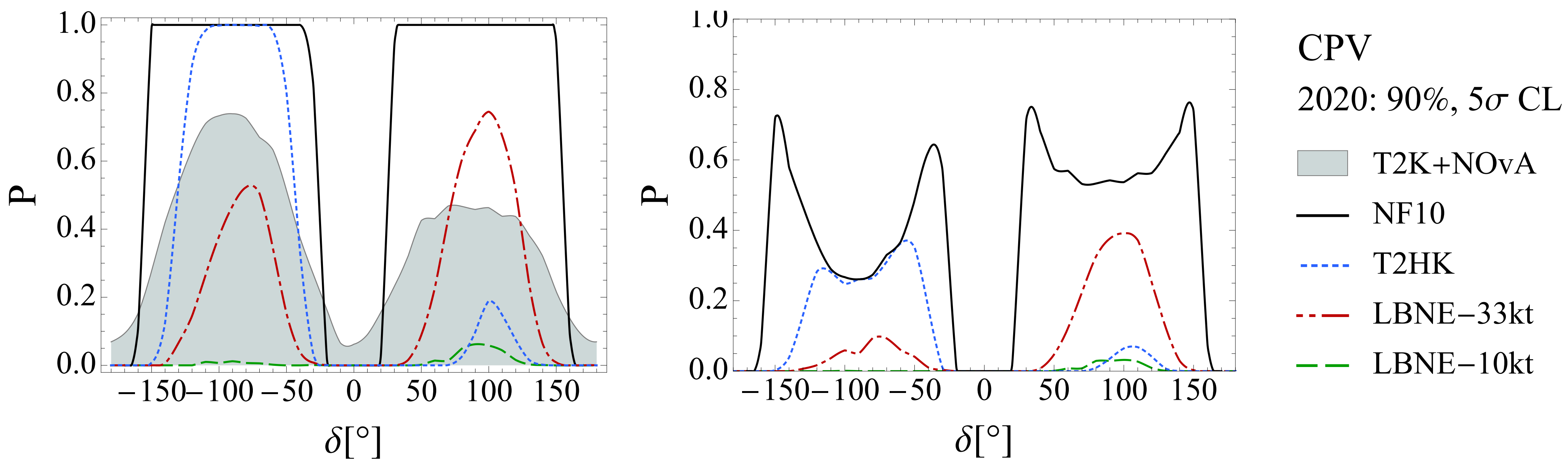


PH, *et al.*, 2009

At lower confidence levels some indications maybe obtained – impact in future program?

How much will we gain?

Assuming that the combination of T2K+NOνA has seen (or not) a hint for CP violation, what is the probability that a given facility can observe a high significance signal for CP violation?



Blennow, Coloma, Donini, Fernandez-Martnez, 2013

Summary

- Neutrino oscillation is solid evidence for new physics
- Precision measurements help to exclude a vast number of models
- Precision measurements have the best potential to uncover even “newer” physics

In combination this warrants a rich experimental program.

To be successful, this will require adequate theory support.