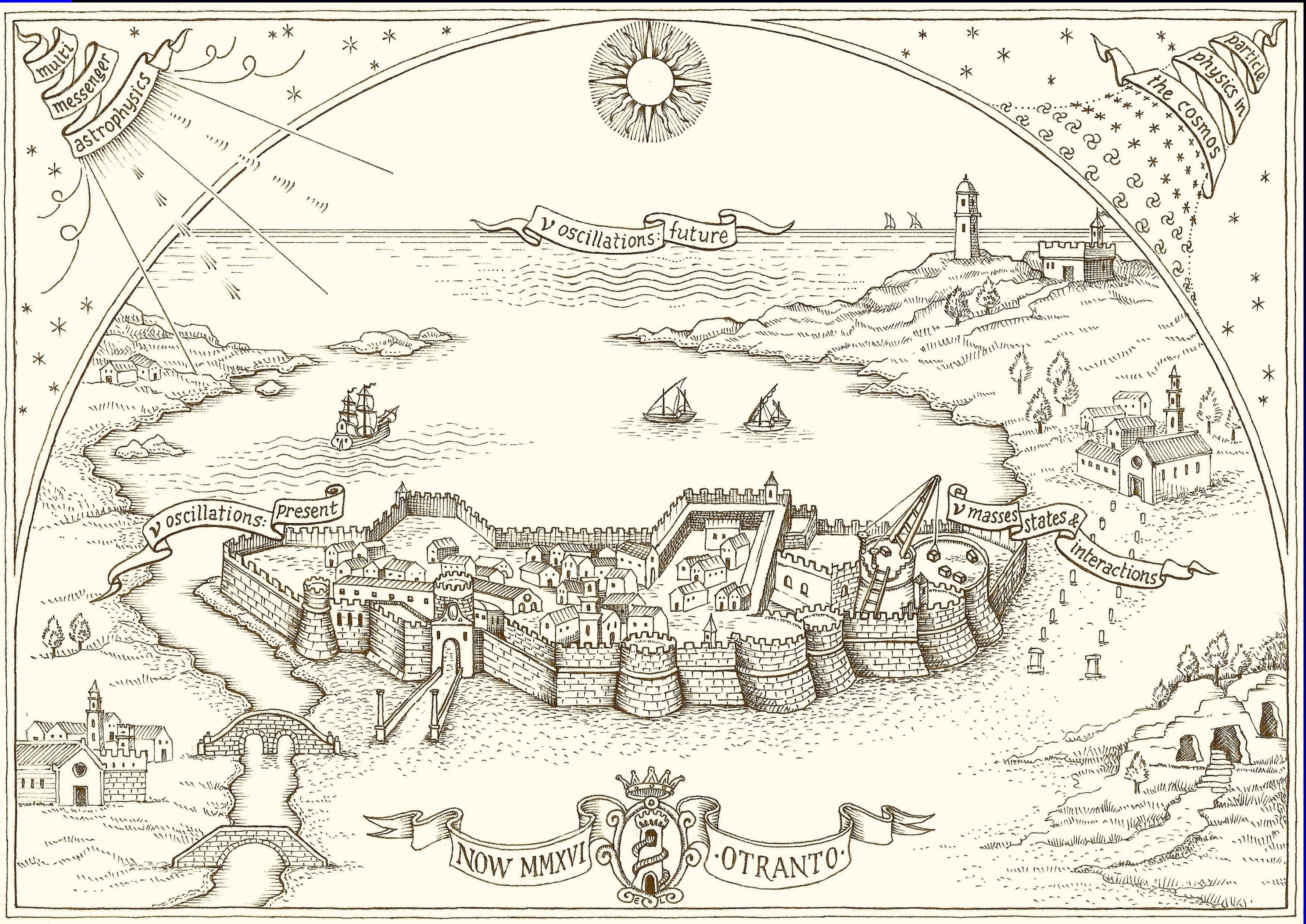


Prospects for neutrino oscillation parameters

Patrick Huber – Center for Neutrino Physics at Virginia Tech

Neutrino Oscillation Worskhop – NOW, Otranto, Italy, September 4–11, 2016

A dangerous journey

to precision neutrino physics.

What parameters?

- Mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$?
- Mass splittings: Δm^2_{21}, Δm^2_{31}?
- Sign of Δm^2_{31}?
- CP phase: δ_{CP}?
- N-th neutrino: θ_{x4}? Δm^2_{4x}?
- Non-standard interactions ϵ_{xy}?

Why do we want to measure them?

Mixing matrices

Quarks

$$|U_{CKM}| = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

Neutrinos

$$|U_\nu| = \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Neutrino masses are different

The crucial difference between neutrinos and other fermions is the possibility of a Majorana mass term

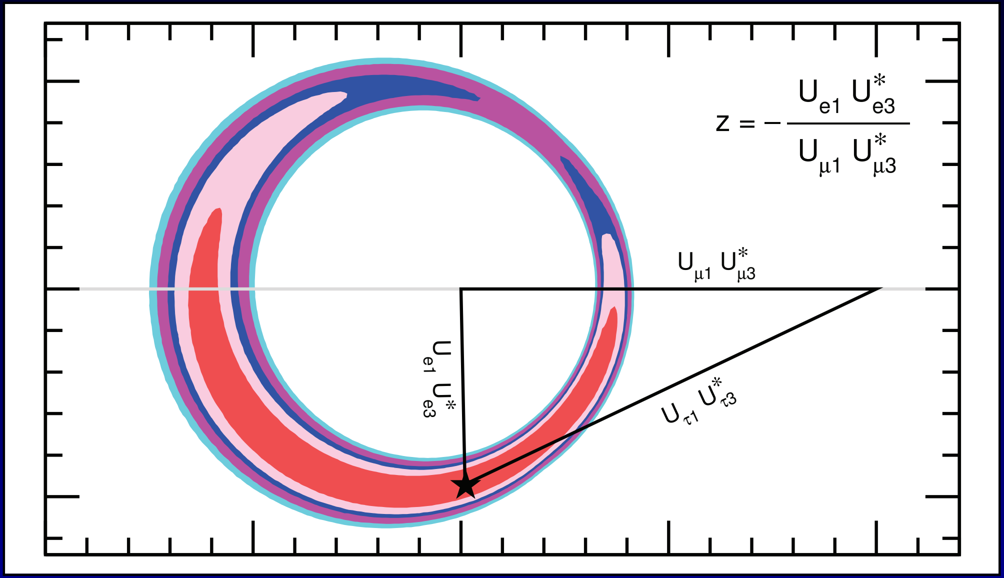
$$m_L \bar{\psi}_L \psi_R^C + m_R \bar{\psi}_R \psi_L^C$$

on top of the usual Dirac mass term

$$m_D \bar{\psi}_L \psi_R$$

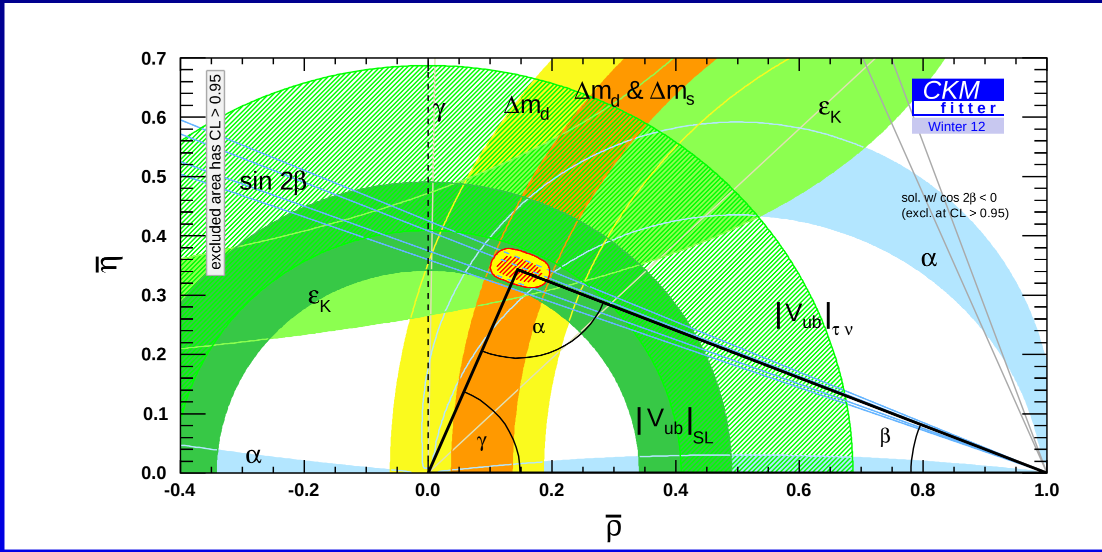
This allows for things like the seesaw mechanism (many versions) and implies that the neutrino flavor sector probes very different physics than the quark sector.

Unitarity triangles



Neutrino sector

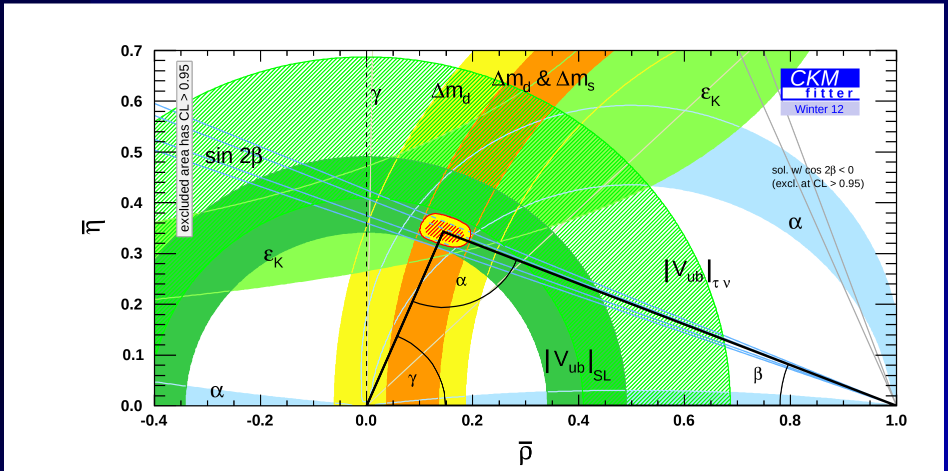
Gonzalez-Garcia, Maltoni, Schwetz, 2014



Quark sector

What did we learn from that?

Our expectations where to find BSM physics are driven by models – but we should not confuse the number of models with the likelihood for discovery.

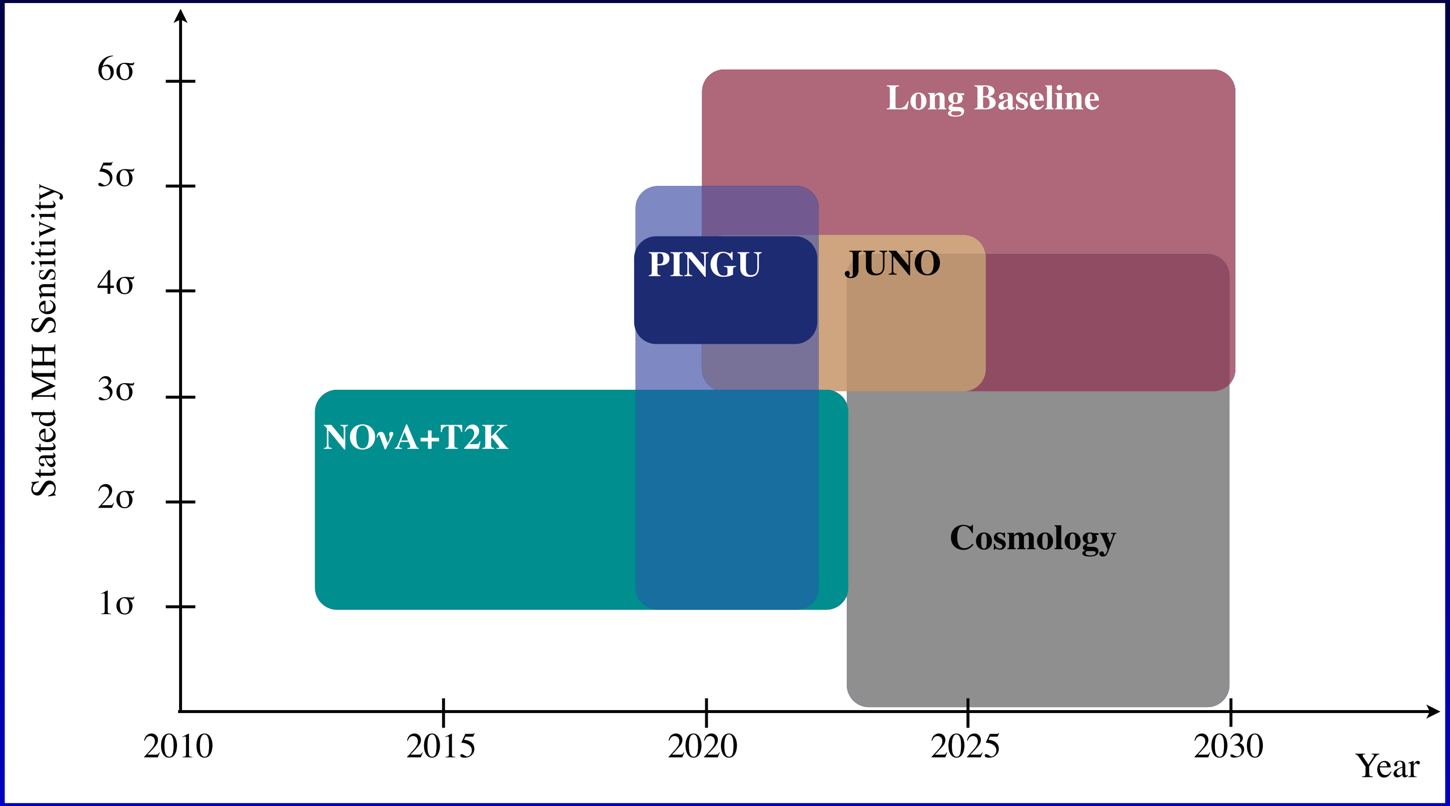


- CKM describes all flavor effects
- SM baryogenesis difficult
- New Physics at a TeV
  - does not exist or
  - has a special flavor structure

and a vast number of parameter and model space excluded.

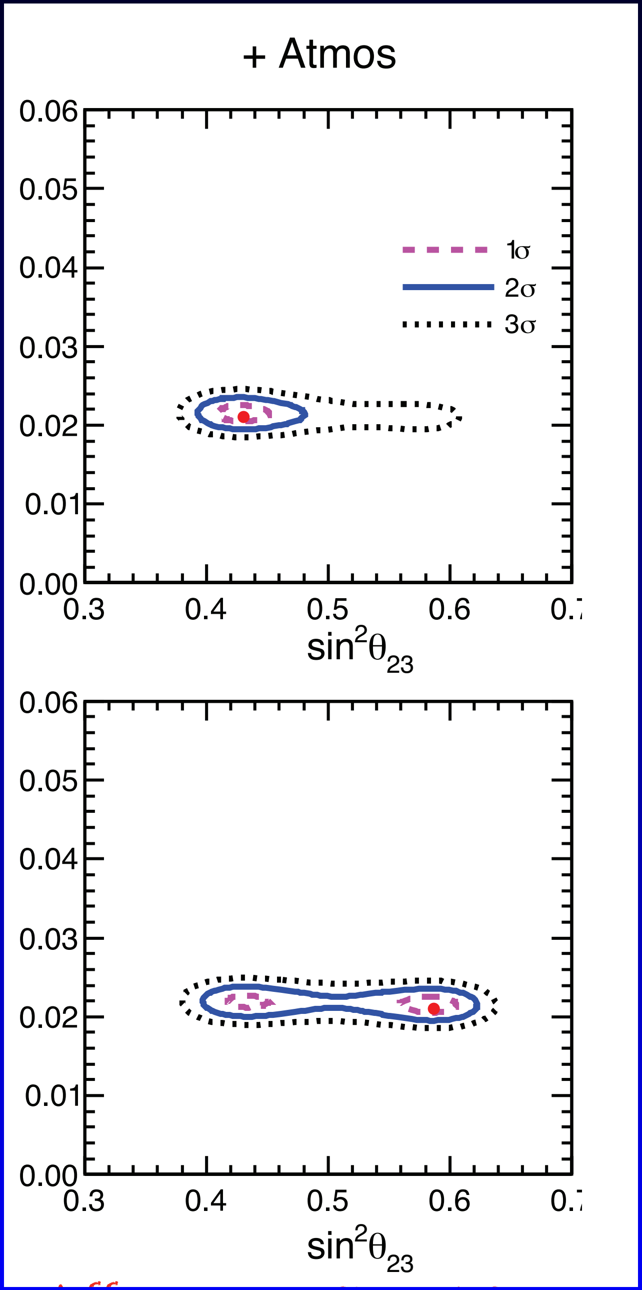
Mass hierarchy

Literature survey arXiv:1307.5487



Many experiments are expected to have a result at or above 3 σ within a decade from now. Important parameter for direct neutrino mass searches.

First hints for non-maximal θ_{23}



Marrone, Neutrino 2016

In normal hierarchy, maximal mixing is disfavored at 2σ. Important parameter for models with discrete flavor symmetries.

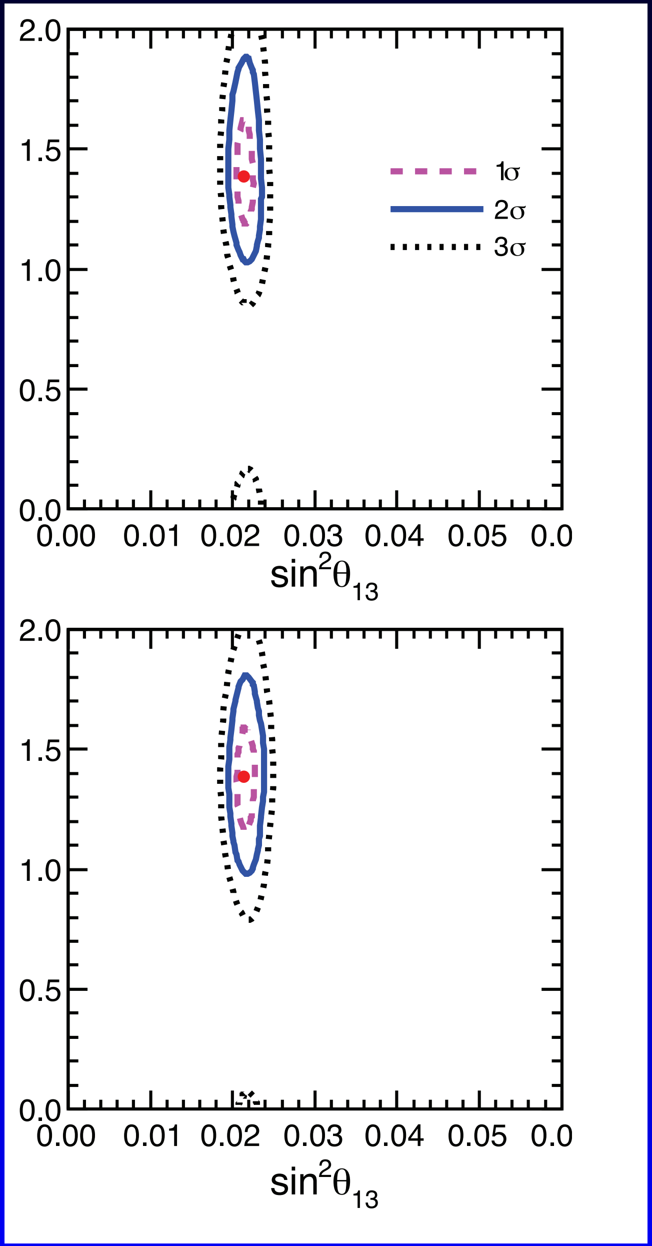
CP violation

There are only very few parameters in the νSM which can violate CP

- CKM phase – measured to be $\gamma \simeq 70^\circ$
- θ of the QCD vacuum – measured to be $< 10^{-10}$
- Dirac phase of neutrino mixing
- Possibly: 2 Majorana phases of neutrinos

At the same time we know that the CKM phase is not responsible for the Baryon Asymmetry of the Universe…

First hints for CP violation?

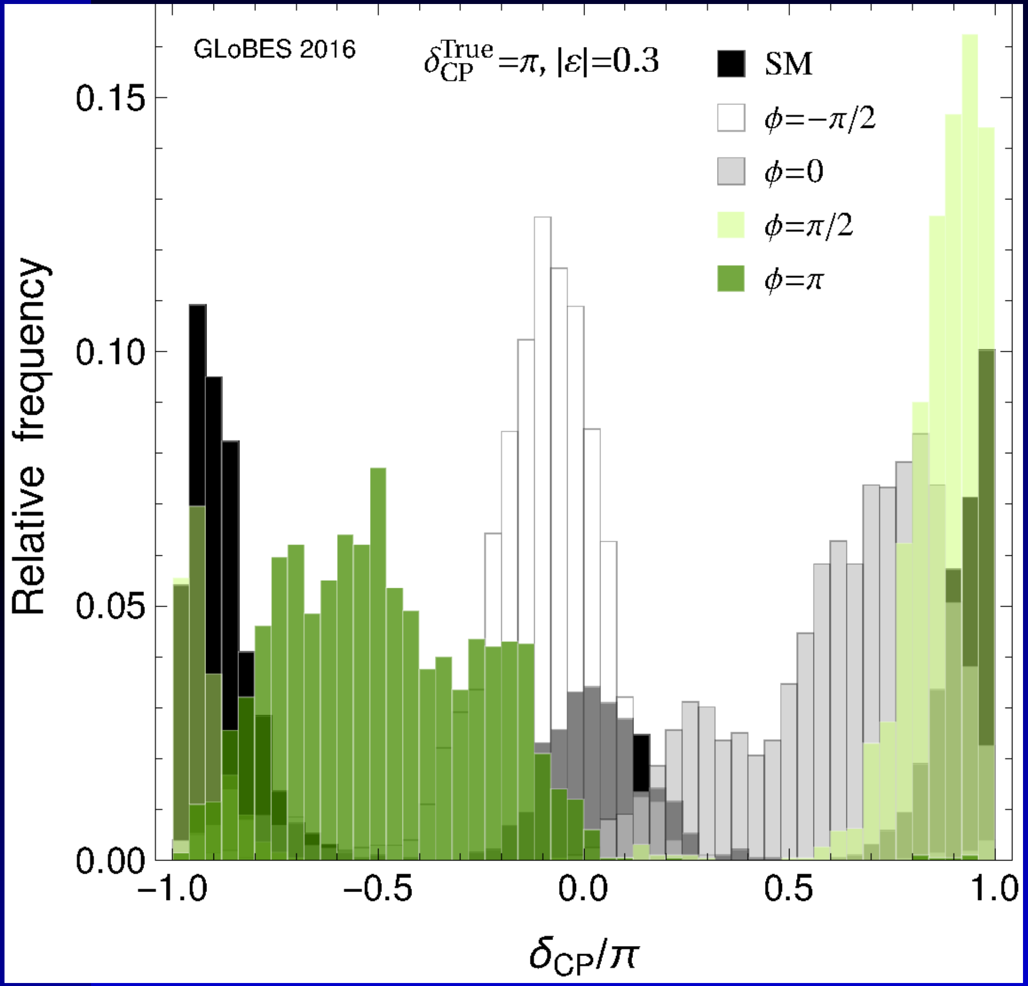


Marrone, Neutrino 2016

Latest T2K & NOvA combined with θ_{13} constraint from Daya Bay

Hint for $\delta = -\pi/2$?

Or not?



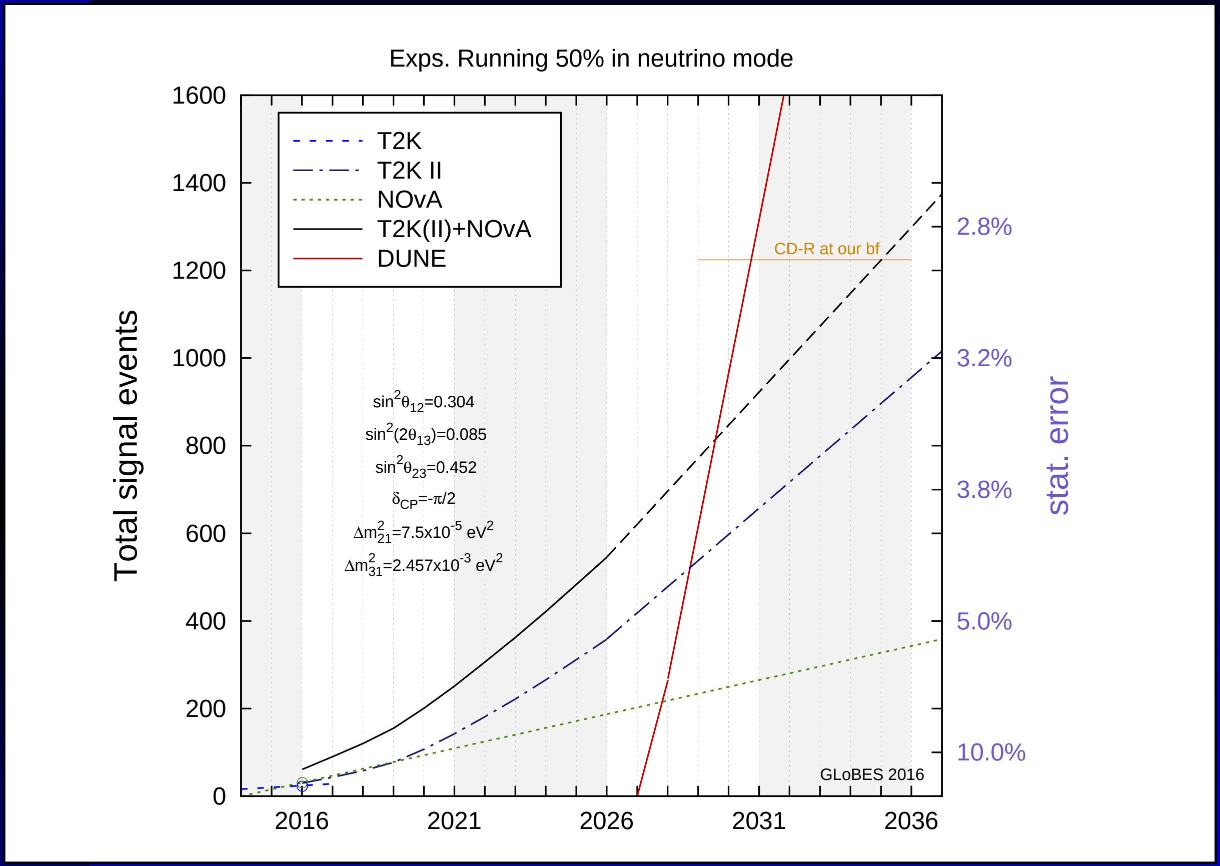
In this example, CP conserving new physics fakes CP violation in oscillation!

see, talk by D. Vangeas Forero on Wednesday

PH, D. Vanegas, 2016

It requires significant precision to distinguish this from genuine CP violation!

The way forward



Clearly, we are on the (slow) road towards 3% measurements of the event rates

Translating this into a 3% measurements of the oscillation probability is very difficult

Note, T2HK would reach 1000 ν_e signal events very quickly.

Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

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

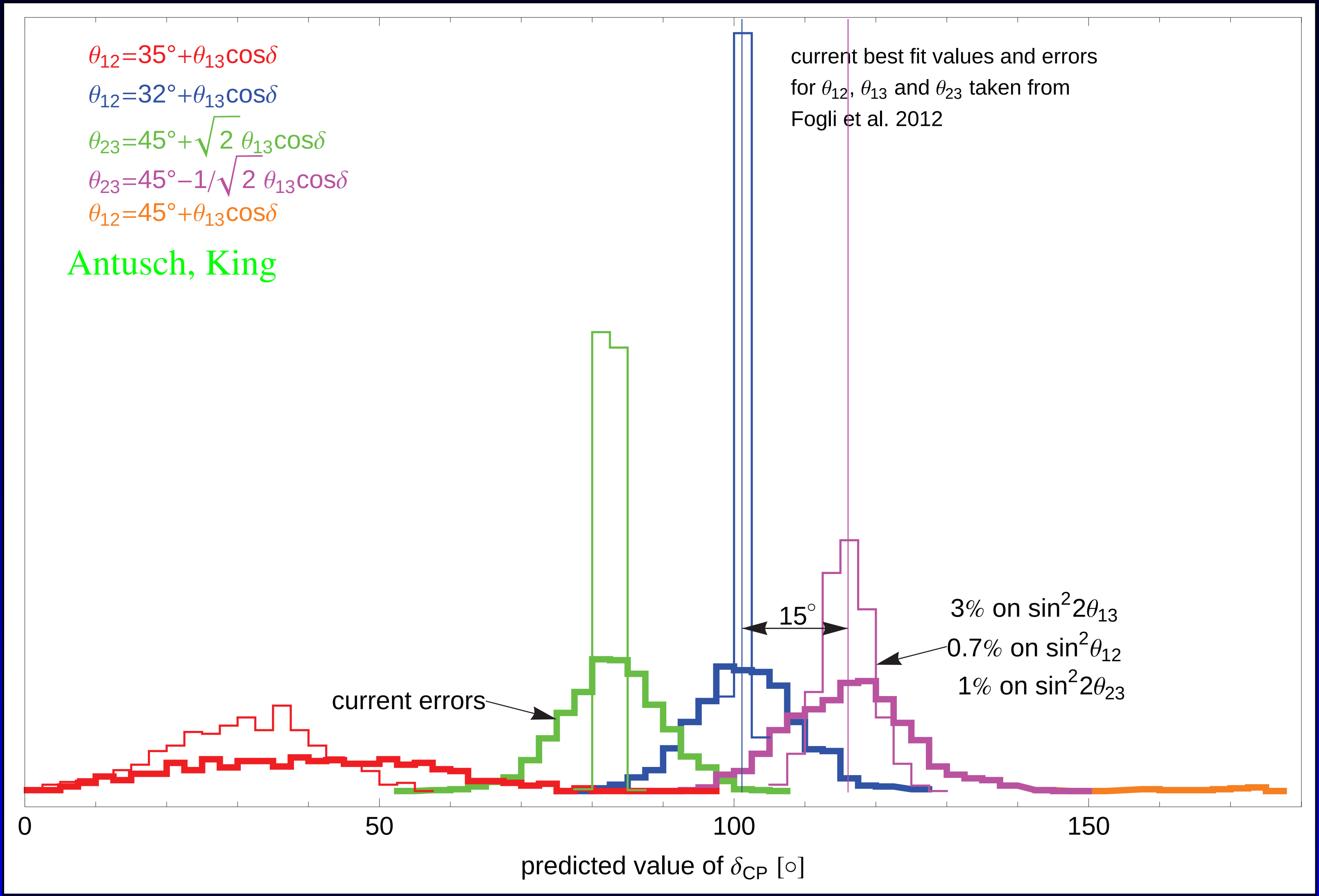
predicts flat distribution in δ_{CP}

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

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

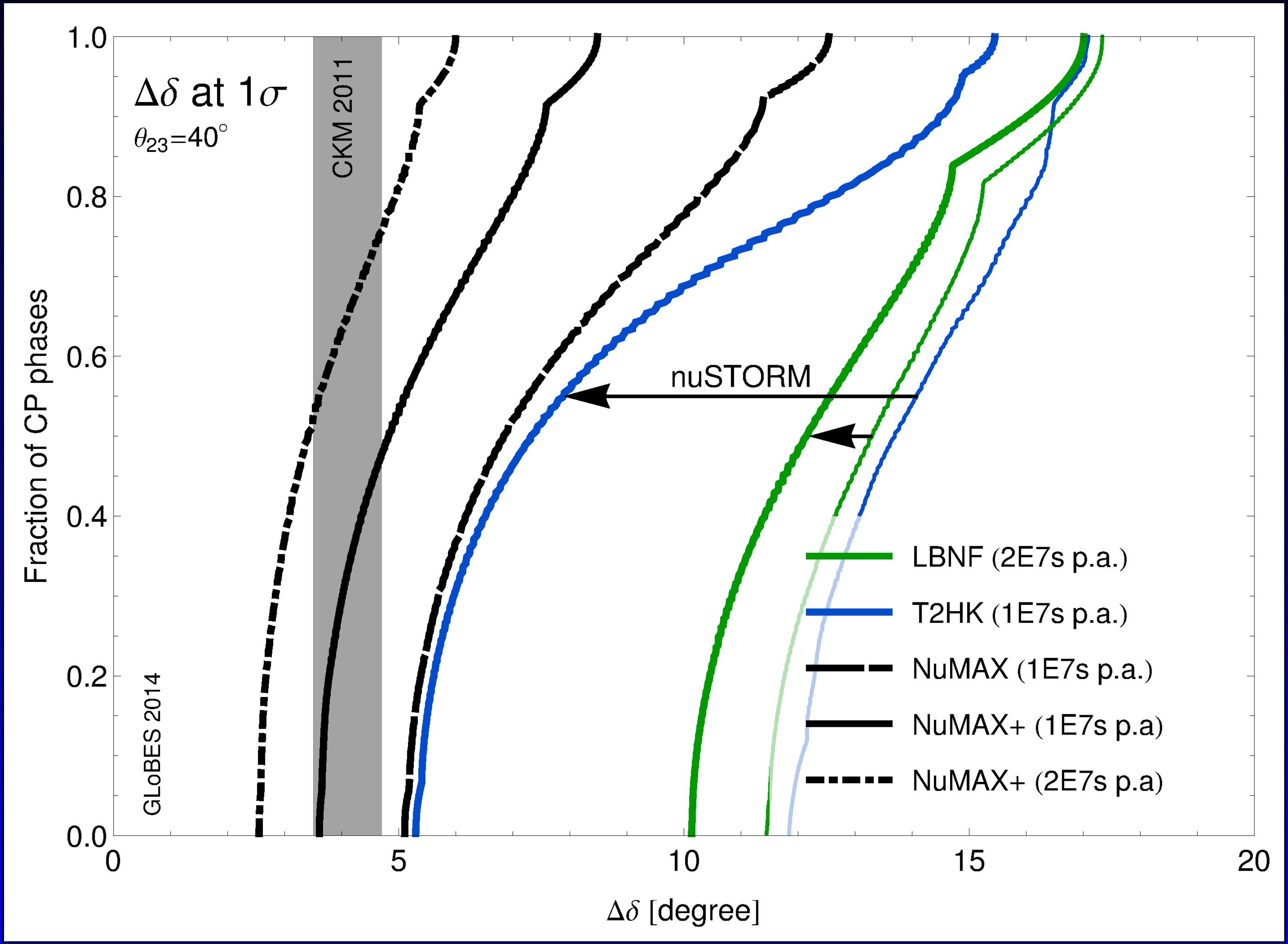
to still fit data, obviously corrections are needed – predictivity?

Sum rules



$3\,\sigma$ resolution of 15° distance requires 5° error. NB – smaller error on θ_{12} requires dedicated experiment like JUNO

How low can you go?



PH, Bross, Palmer, 2014.

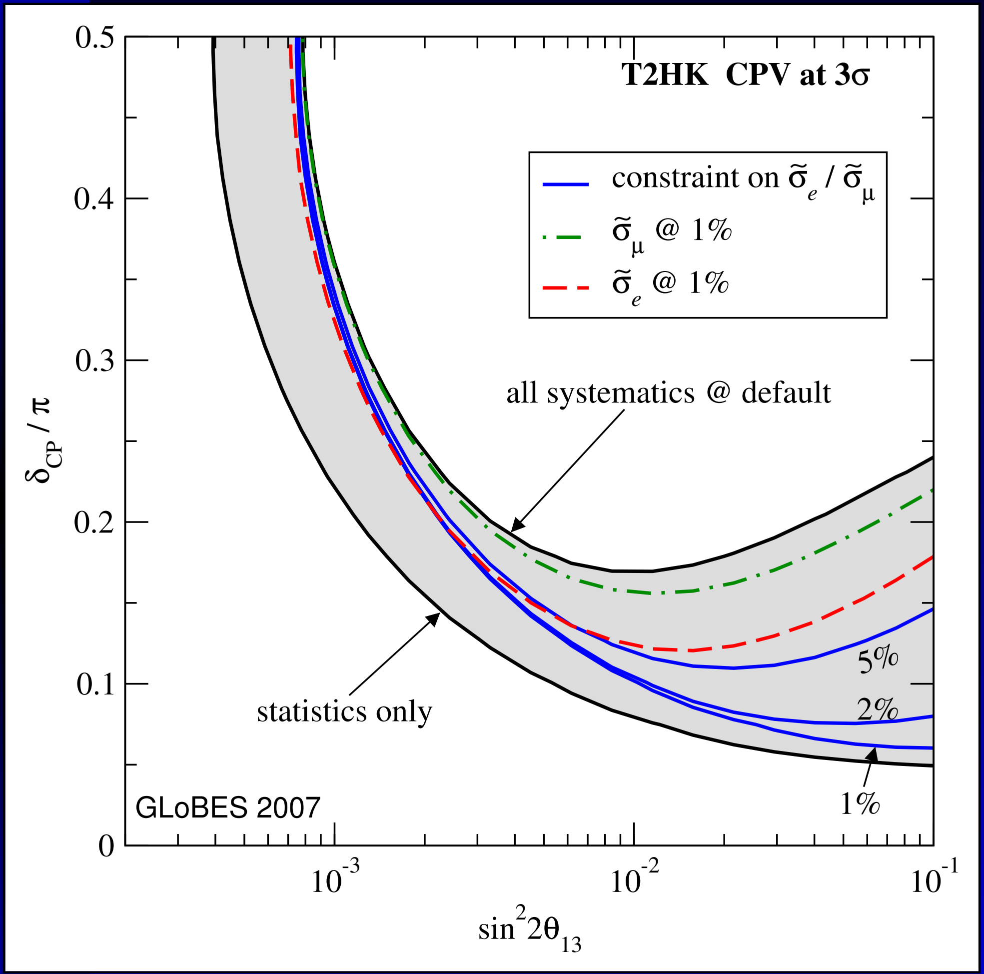
What can we learn from that?

– If we refute three flavor oscillation with significance, we have found new physics, but this requires great precision.

– If we confirm three flavor oscillation with great precision, we need the context of specific models to learn anything about BSM physics.

Corollary: Only if we do this precisely we really will learn something!

Neutrino cross sections



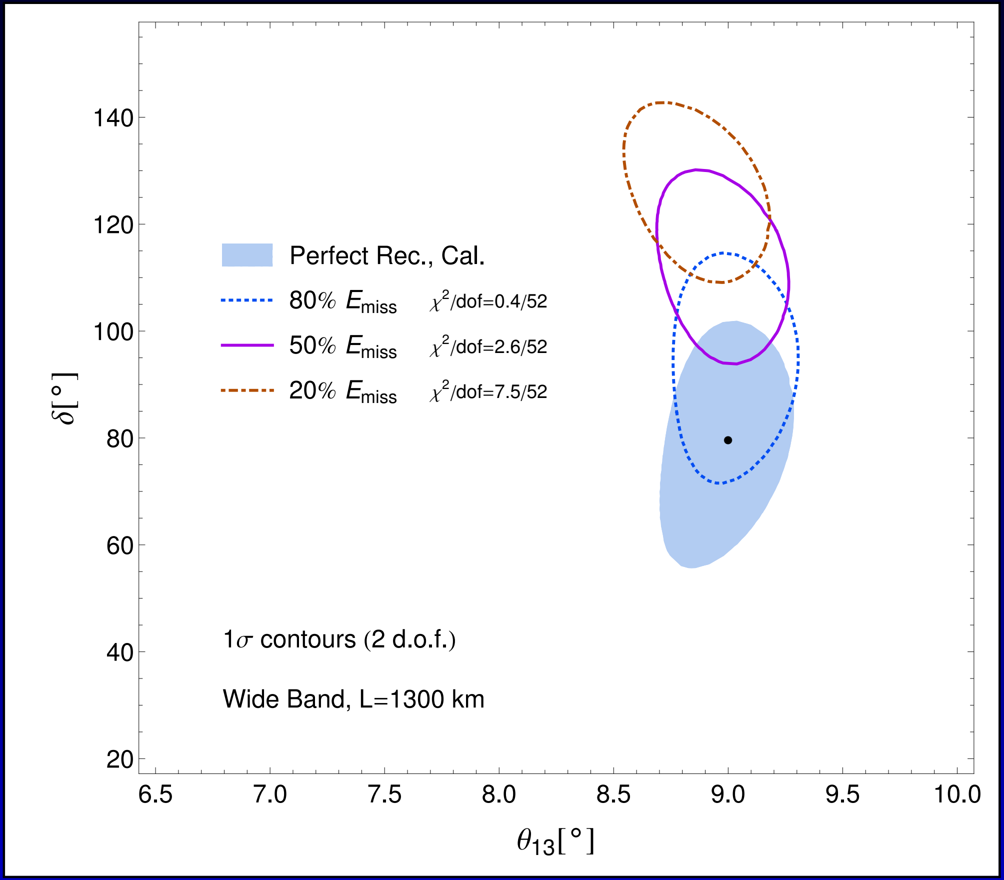
PH, Mezzetto, Schwetz, 2007

Using current cross section uncertainties and a perfect near detector.

Appearance experiments using a (nearly) flavor pure beam can not rely on a near detector to predict the signal at the far site!

Differences between ν_e and ν_μ are significant below 1 GeV, see e.g. Day, McFarland, 2012

Nuclear effects – example



In elastic scattering a certain number of neutrons is made

Neutrons will be largely invisible even in a liquid argon TPC

$\Rightarrow$ missing energy

Ankowski *et al.*, 2015

We can correct for the missing energy IF we know the mean neutron number and energy made in the event. . .

Theory and cross sections

Theory is cheap, but multi-nucleon systems and their dynamic response are a hard problem and there is not a huge number of people with expertise working on this. . .

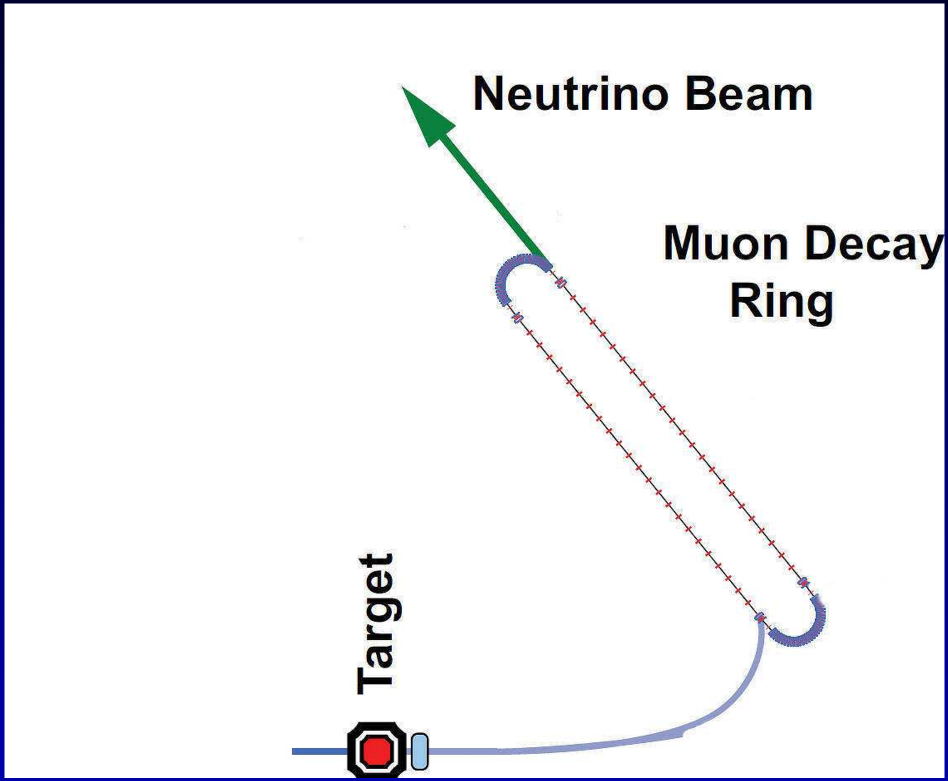
Any result will be based on assumptions and not on controlled approximation.

see talk by A. Ankowski, later today

Towards precise cross sections

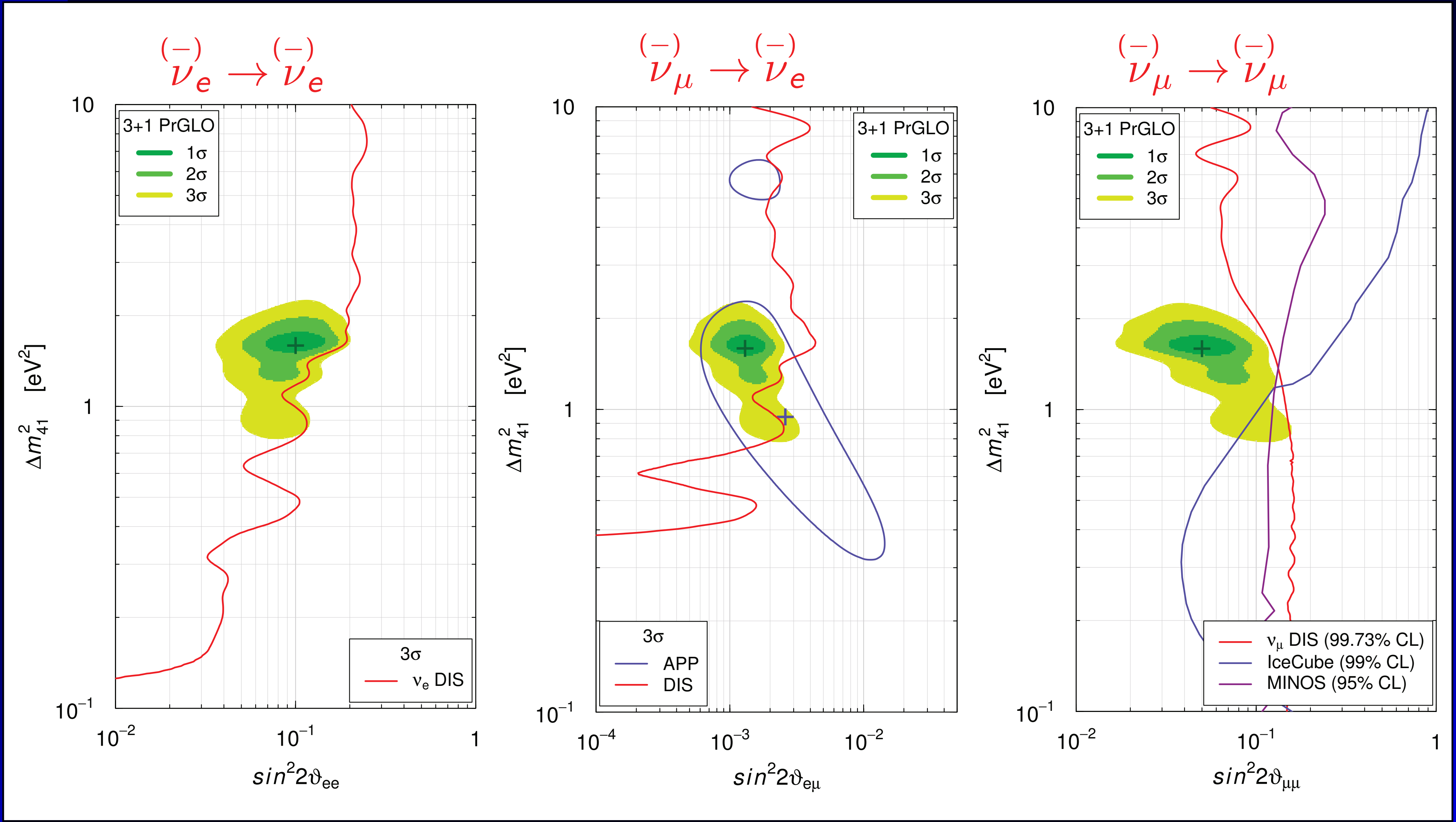
Needs better neutrino sources

- Sub-percent beam flux normalization
- Very high statistics needed to map phase space
- Neutrinos and antineutrinos
- ν_μ and ν_e



One (the only?) source which can deliver all that is a muon storage ring, aka nuSTORM.

Evidence for sterile neutrinos



Giunti, Neutrino 2016

Finding a sterile neutrino

All pieces of evidence have in common that they are less than 5 σ effects and they may be all due to the extraordinary difficulty of performing neutrino experiments or due to nuclear physics uncertainties, if not:

- N sterile neutrinos are the simplest explanation
- Tension with null results in disappearance remains

Fermilab SBN

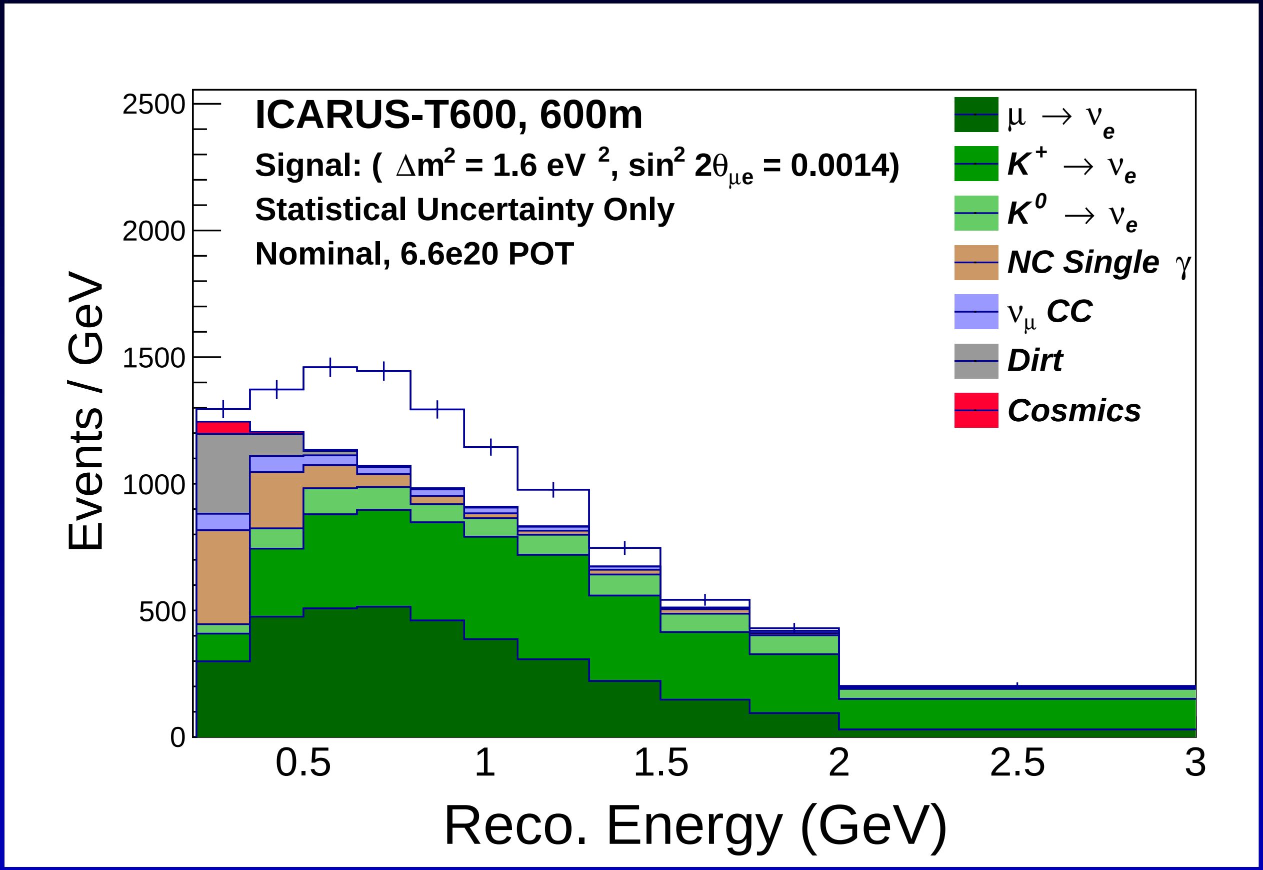
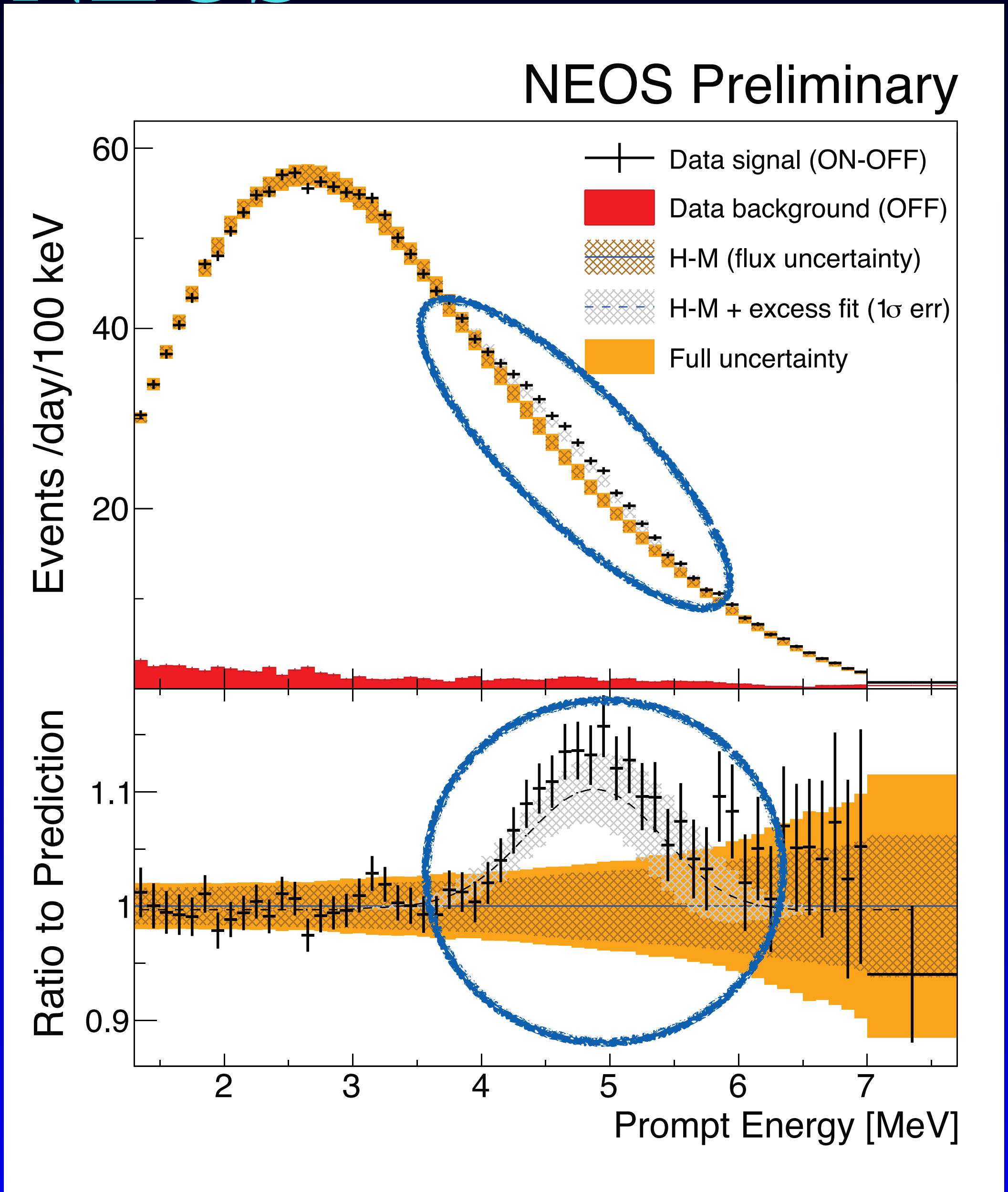


Figure courtesy D. Schmitz and C. Adams

Signal to noise not so different from LSND. . . will a near detector of completely different design help?

NEOS

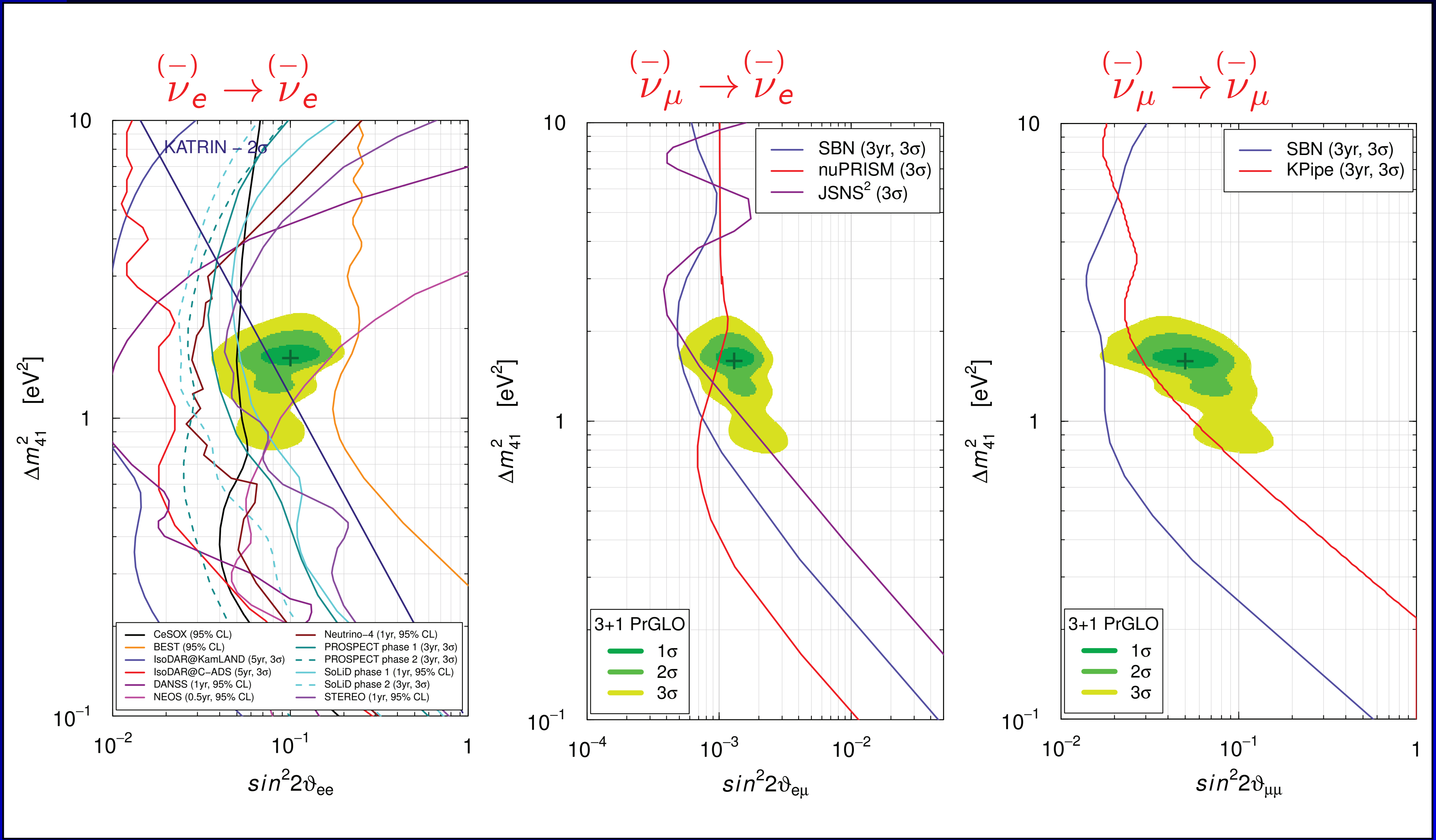


Y. Oh, ICHEP 2016

24m from a large core (power reactor), confirms bump, but unclear what it says about steriles…

appears to disfavor $\Delta m^2 < 1\,\mathrm{eV}^2$

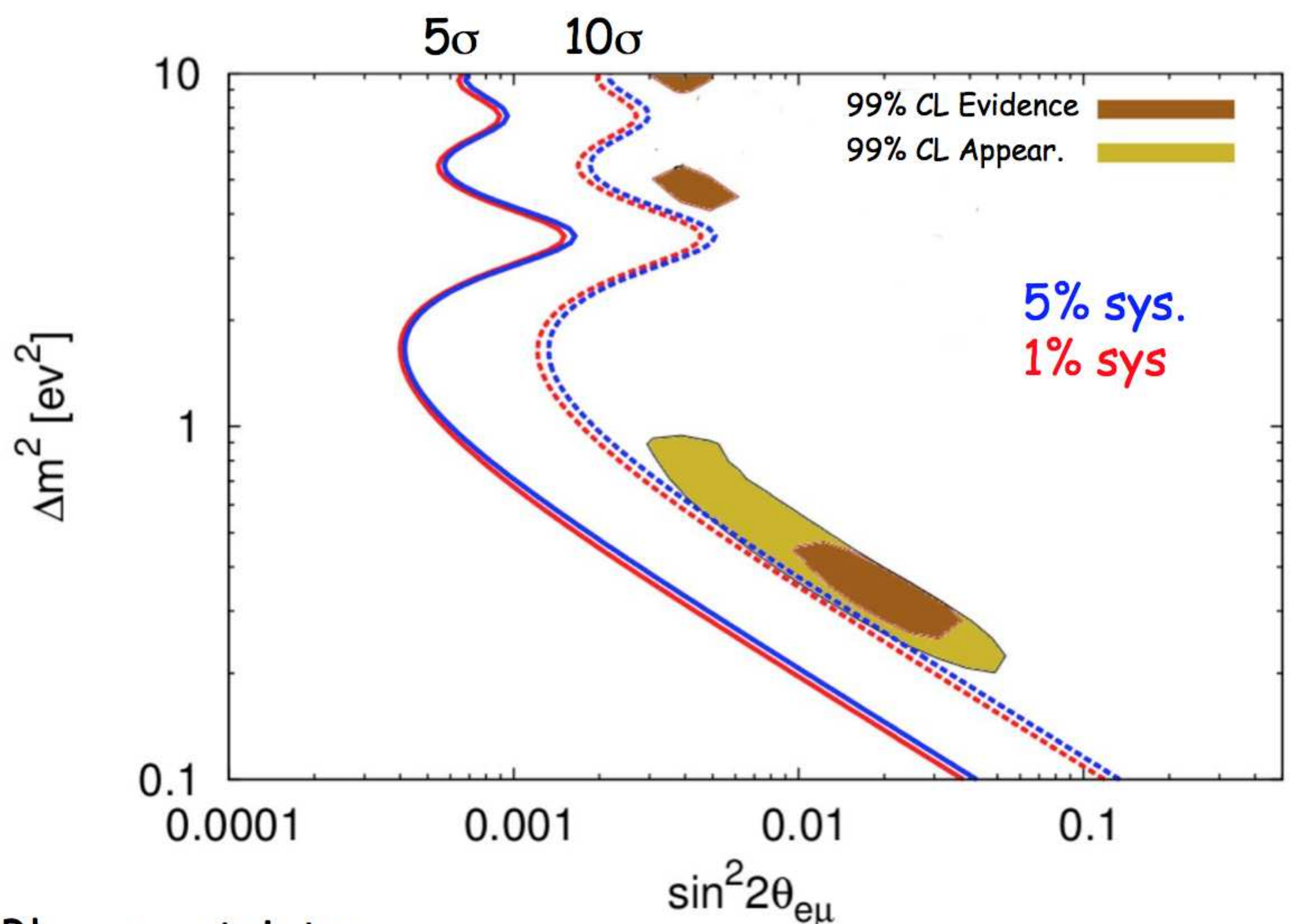
MiniBooNE reloaded?



Giunti, Neutrino 2016

. . . and that assumes all is going according to plan!

Sensitivity of nuSTORM



Bkg uncertainty:
10% → 50%

Summary

Neutrino oscillation is solid evidence for new physics

- DUNE is a factor 2 in statistics for the global program
- Can existing neutrino production techniques provide systematics to make use of better statistics?
- Current data allows large corrections to three flavor framework
- Precision measurements have the best potential to uncover even “newer” physics – either by finding discrepancies or correlations among results

Summary

Sterile neutrinos - aka anomalies

Tension in global fits

- Maybe more complicated than sterile neutrino
- and/or not all data is right
- lots of nuclear physics uncertainties

Still, best evidence we currently have for more New Physics, anywhere!

but we seem to be unable to mount a coherent program to address those anomalies

Conclusion

Neutrino oscillations have come a long way – the future is entirely dependent on getting better precision.

This will require better neutrino sources than reactors ($\sim$ 70 years old) and horn-focused beams ($\sim$ 50 years old).