Panel 1 report: 3-flavor oscillation

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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.

Yes, this is NOT: SUSY, or extra-dimensions, or a solution to the hierarchy problem, or an explanation for dark matter, or black holes at the LHC. . .

BUT at least it has been observed.

We always knew they are ...

The SM, likely, 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

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

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.

Therefore, we do not know the scale of new physics responsible for neutrino masses – anywhere from keV to the Planck scale is possible.

And of course, neutrinos could be Dirac…

Neutrino Portal

The right-handed neutrino is a gauge singlet and hence can mix with dark sector particles – fermion portal.

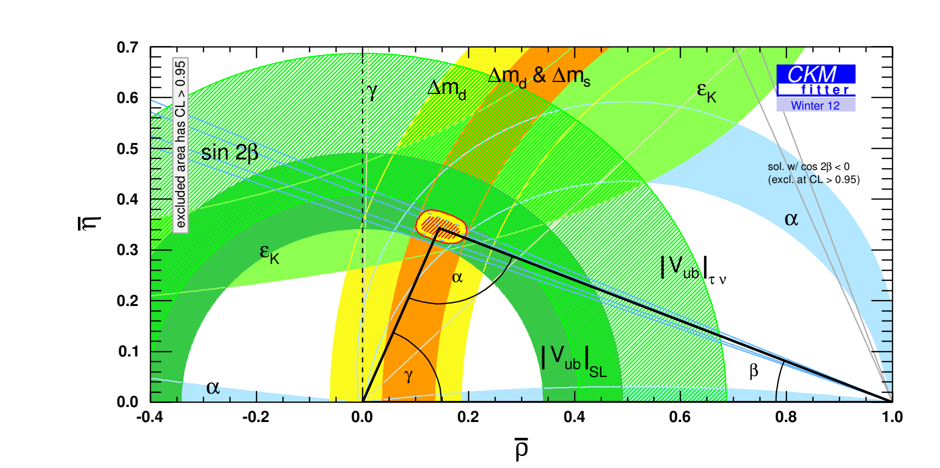
For instance, Wolfenstein, 1978:

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

Neutrino oscillation is an oscillation phenomenon and hence very sensitive to any new contribution of the phase evolution of the mass eigenstates.

What did we learn from that?

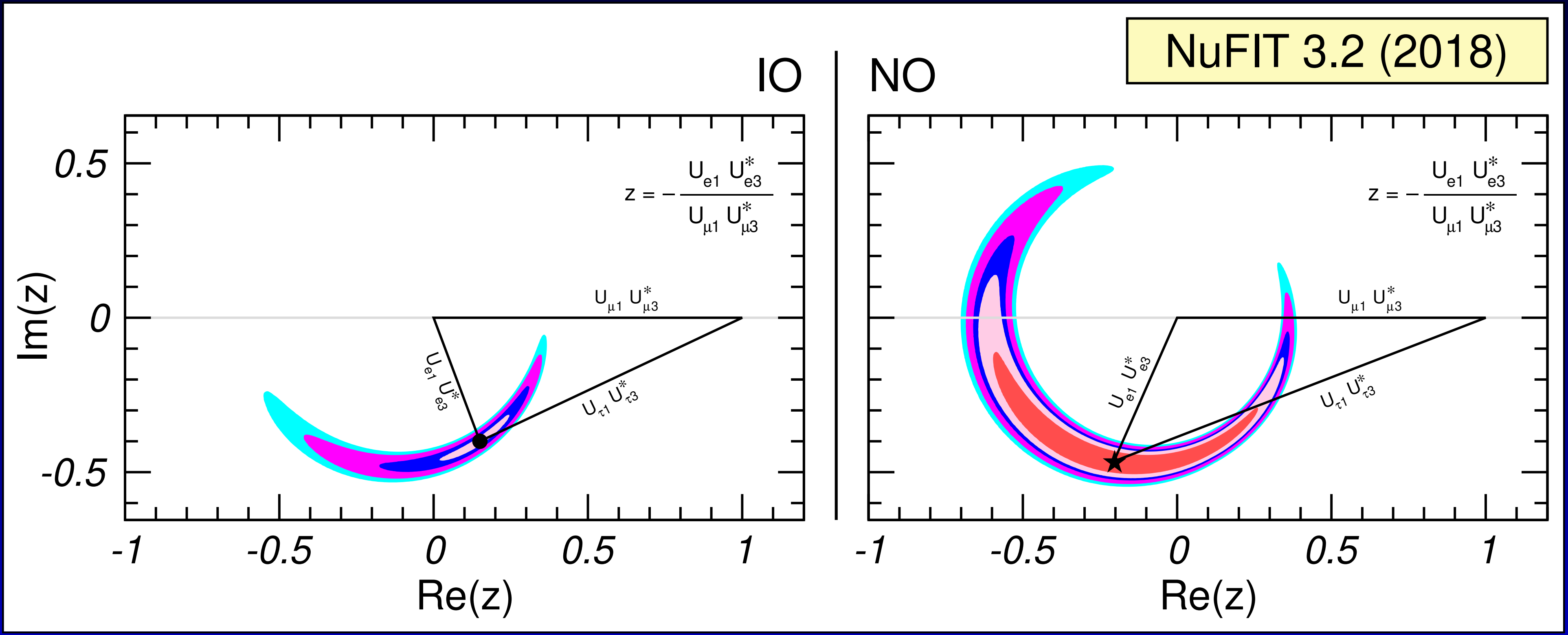
Our expectations where to find BSM physics are driven by models – but we should not confuse the number of models with the likelihood for discovery.



- 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.

Unitarity triangles



We currently have no way to directly measure any of sides containing ν_τ.

Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

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

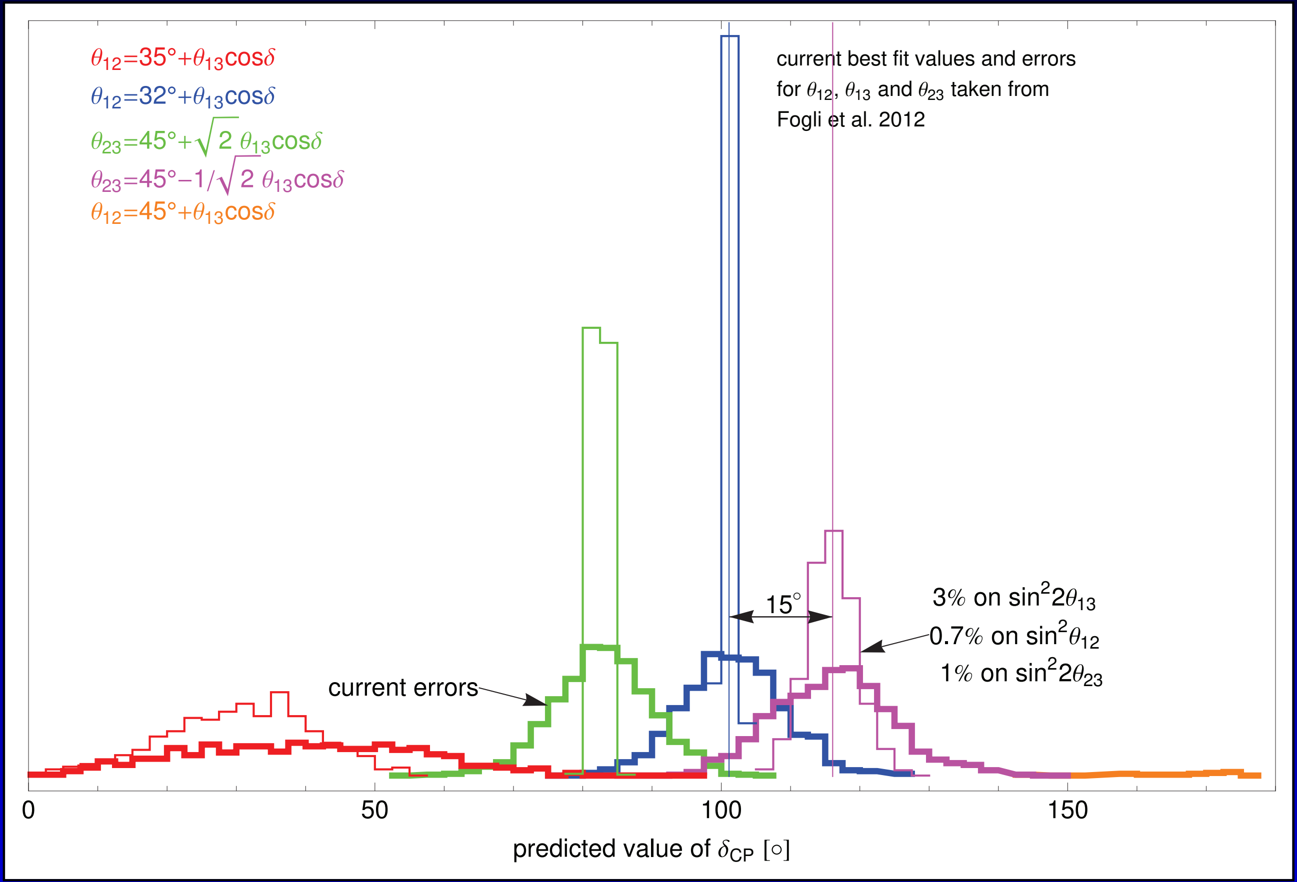
predicts flat distribution in δ_{CP}

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

All symmetry-based models require corrections to fit data, and as a result they predict correlations between mixing parameters.

Correlations – sum rules

Different symmetries yield different sum rules.



Requires high precision on all mixing parameters.

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…

From here to there

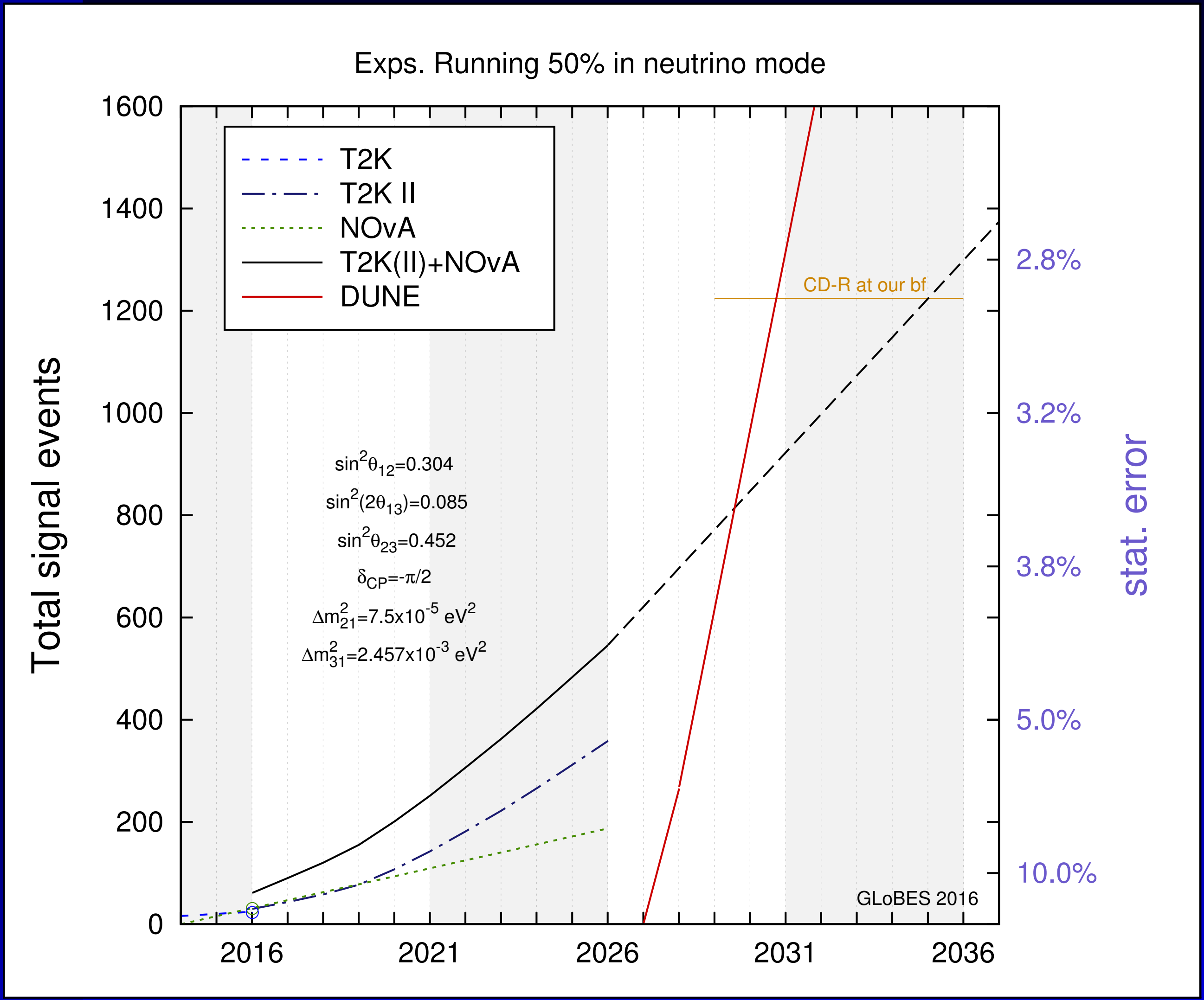
	now	JUNO	DUNE	Hyper-K
$\theta_{12}[°]$	$33.62^{+0.78}_{-0.76}$	± 0.13		
$\theta_{23}[°]$	$47.2^{+1.9}_{-3.9}$		± 0.3	± 0.5
$\theta_{13}[°]$	8.54 ± 0.15			
$\delta[°]$	$234^{+43\dagger}_{-31}$		7.5-15	7.2-23
$\Delta m^2_{32}[10^{-3}\mathrm{eV}^2]$	$2.494^{+0.033}_{0.031}$		± 0.007	± 0.014
$\Delta m^2_{21}[10^{-5}\mathrm{eV}^2]$	$7.4^{+0.21}_{0.20}$	± 0.03		
binary questions				
mass ordering [σ]	2-3†	3-4	> 5	4
octant of θ_{23} [σ]	0		>3	>3

† Exceeds predicted sensitivity.

All current values are for NO and taken from NuFit 3.2.

Systematics assumptions are critical for this.

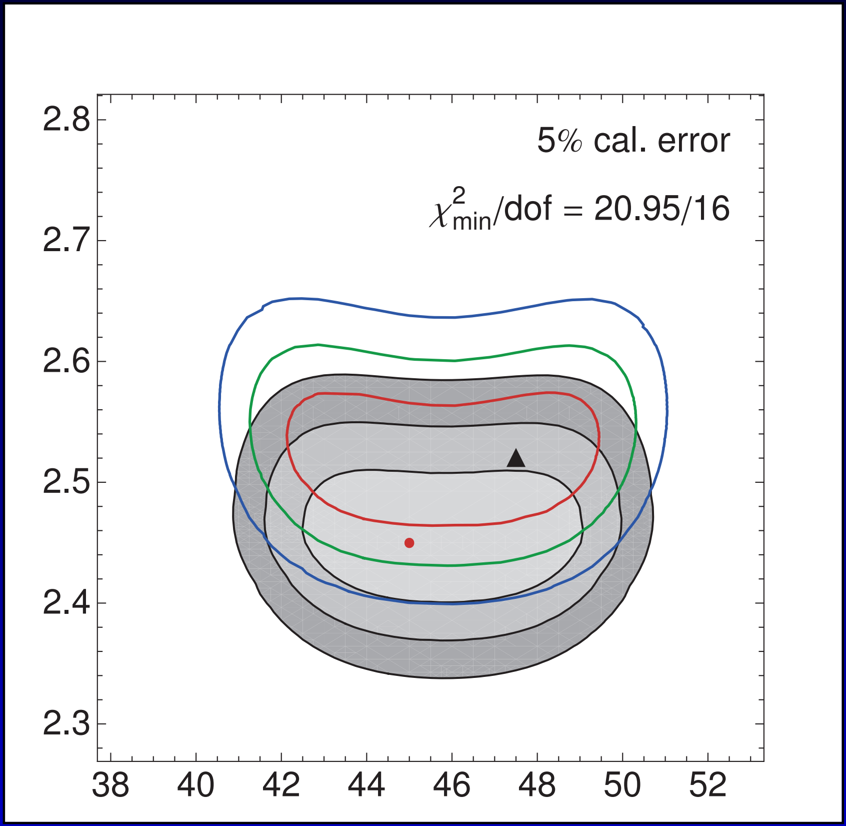
Bright future

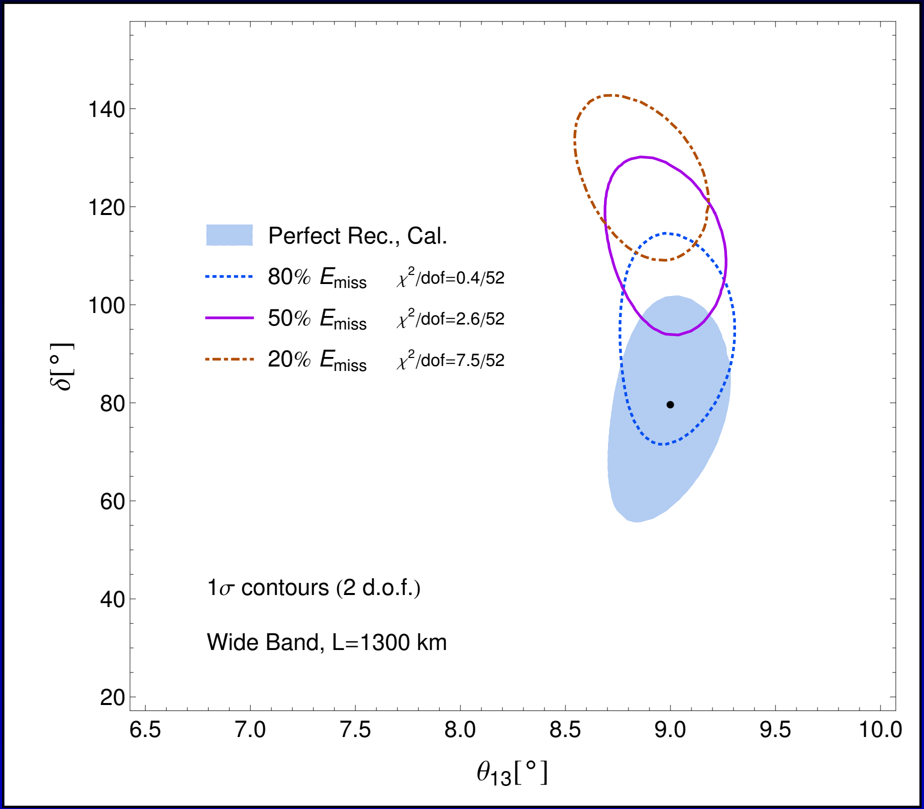


Hyper-K has similar slope as DUNE and planned start is 2027.

Statistically errors globally will reach 1-2%, can we match this in systematics?

Neutrino energy reconstruction





Coloma *et al.*, 2014

Quasi-elastic energy reconstruction in water Cerenkov

Ankowski *et al.*, 2015

Calorimetric energy reconstruction in liquid argon

True complementarity

Current long-baseline experiments have 8-12% systematics in appearance channels:

- DUNE has a argon target (A=40)
- Hyper-K has oxygen target (A=16)
- Inclusive versus exclusive energy reconstruction
- Different baselines
- Different energies

If the results from DUNE and Hyper-K agree, we would have very high confidence that systematic errors are under control at the percent level.

2nd oscillation maximum

The CP asymmetry in the 1st oscillation maximum is quite small, hence the need for percent level systematics.

The CP asymmetry in the 2nd oscillation maximum is nearly 10 times larger, but the energy is 3 times lower and hence getting statistics is difficult.

T2HKK: Second detector of same size in Korea in the Hyper-K beam

ESSνSB: 5MW beam from ESS to a large water Cerenkov detector over a 500 km baseline

Role for Europe

The next generation of large neutrino experiments are hosted in Asia and the U.S.

The European physics community is involved in all three of them at a significant level.

CERN made a significant investment into the protoDUNEs.

There is number of ideas to address the systematics challenge (ESSνSB, Enubet, nuSTORM, etc.) which all could be hosted in Europe and span a range of scales in terms of cost and effort.