CERN and European strategic plan update

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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

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

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.

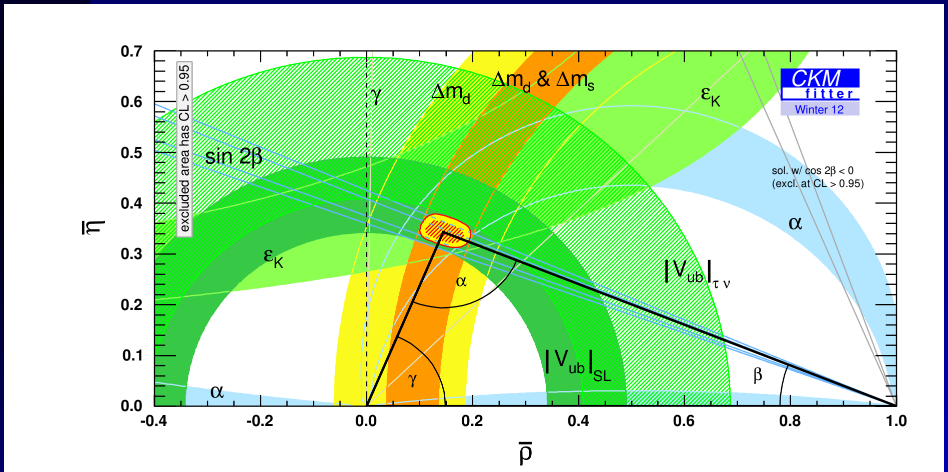
For instance, Wolfenstein, 1978:

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

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?

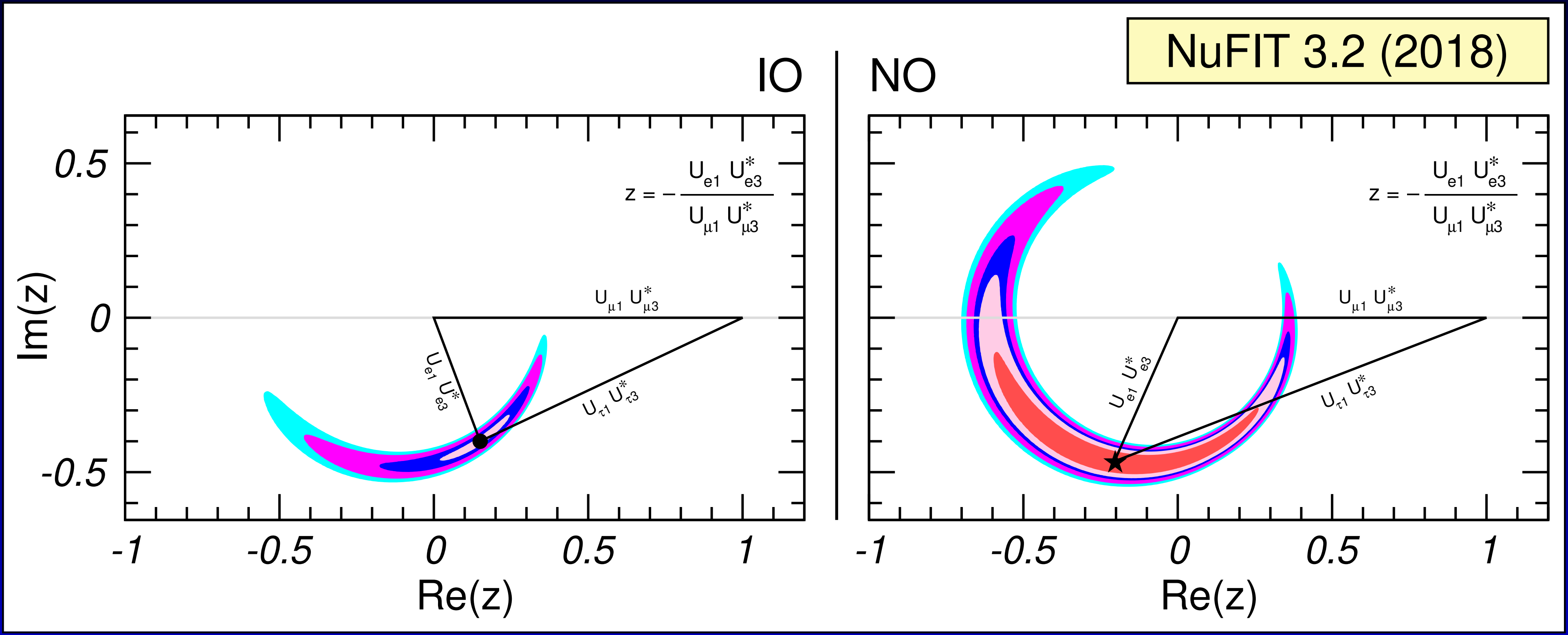
Our expectations where to find BSM physics are driven by models – but we should not confuse the number of models with the likelihood for discovery.



- 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

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

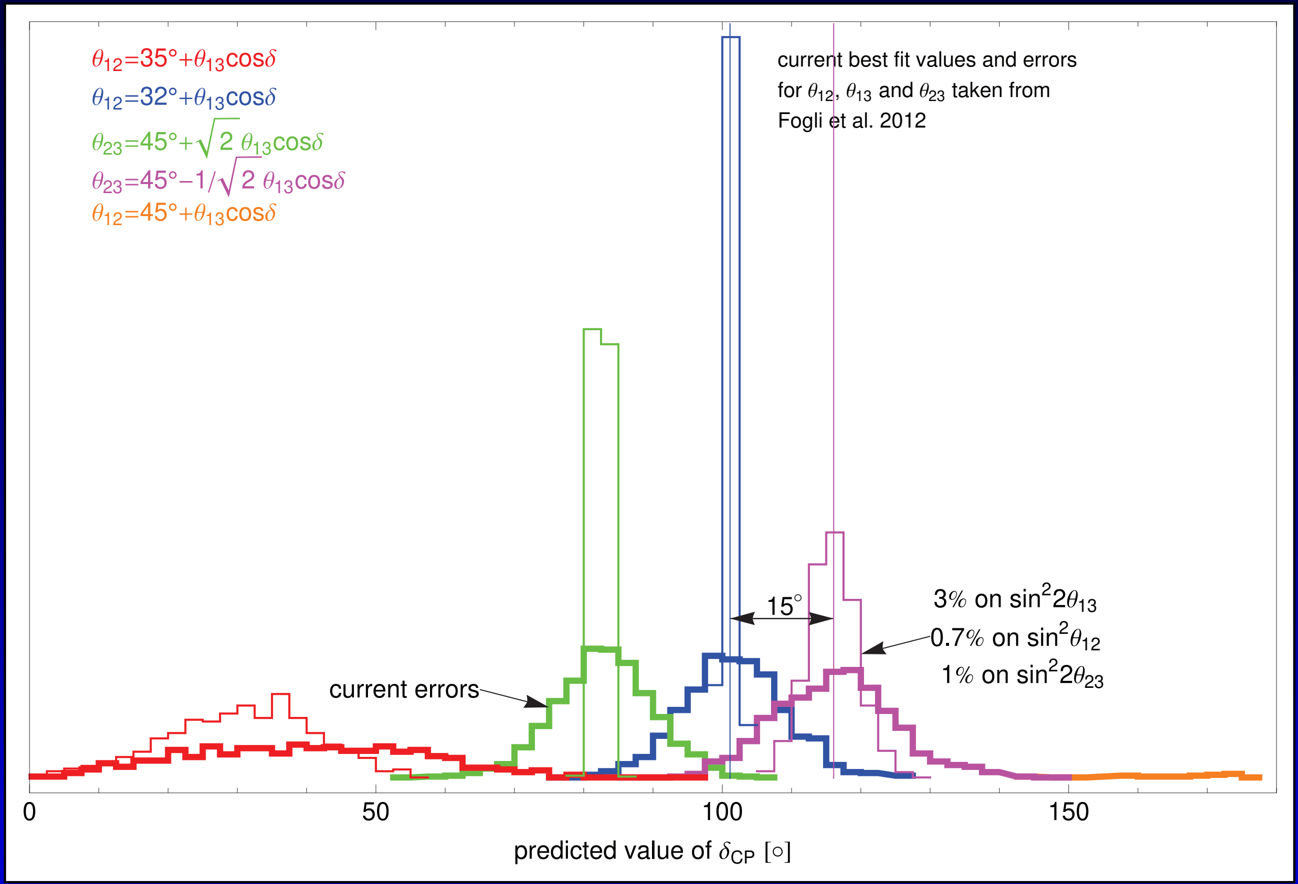
predicts flat distribution in δ_{CP}

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.

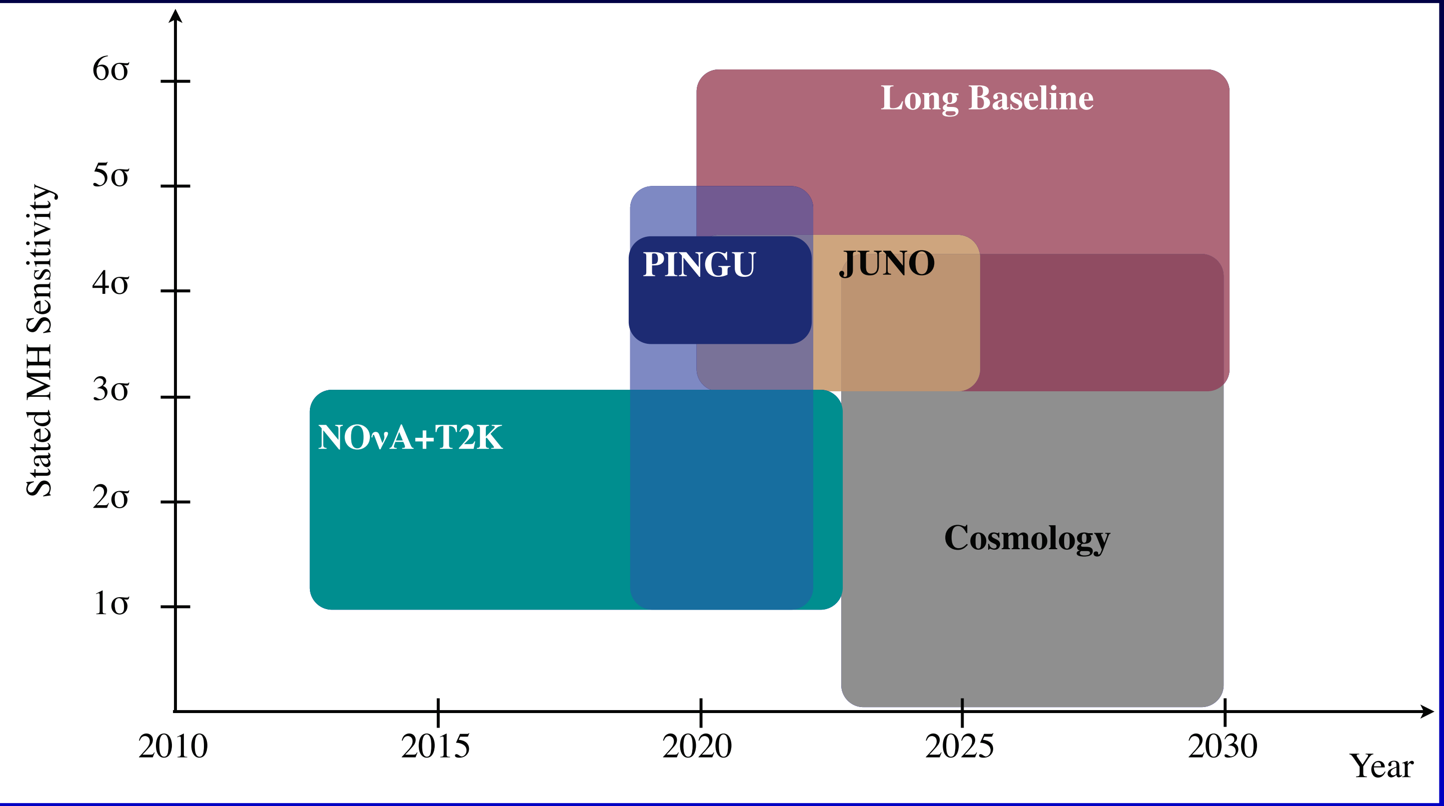
The big questions

- Are neutrinos Majorana?
- δ_{CP}
- Mass hierarchy
- $\theta_{23} = \pi/4$?
- Resolution of LSND and the other short-baseline anomalies
- New physics (on top of neutrino mass)?

The oscillation sub-panel for neutrino physics focused on the items in red.

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.

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

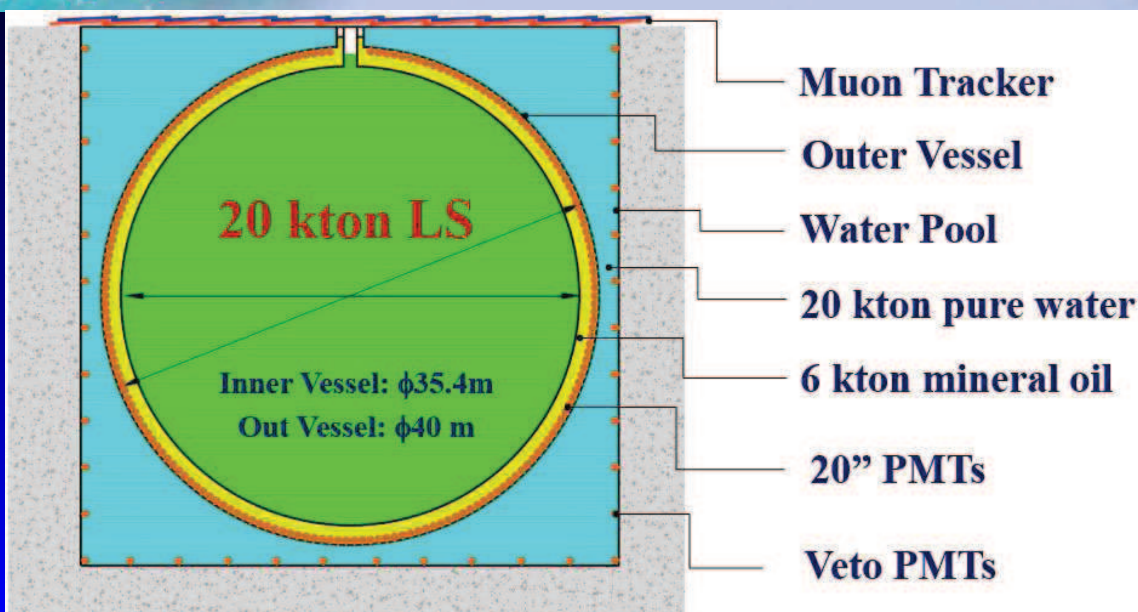
At the same time we know that the CKM phase is not responsible for the Baryon Asymmetry of the Universe…

Artificial neutrino sources

For man-made neutrino sources we have:

- Nuclear reactors – Source of $\bar{\nu}_e$ in the 1-10 MeV range, can be used to study $P(\bar{\nu}_e \to \bar{\nu}_e)$.
- Pion decay a rest – Source of $\bar{\nu}_\mu, \nu_\mu, \nu_e$ in the 5-50 MeV range, currently used for coherent neutrino nucleus scattering. Also useful to look for sterile neutrinos (JSNS^2).
- Pion decay in flight with focusing horns – Source of $\bar{\nu}_\mu, \nu_\mu$ in the GeV range, can be used to study $P(\nu_\mu \to \nu_e)$ and $P(\nu_\mu \to \nu_\mu)$ (and CP conjugates).

JUNO – China

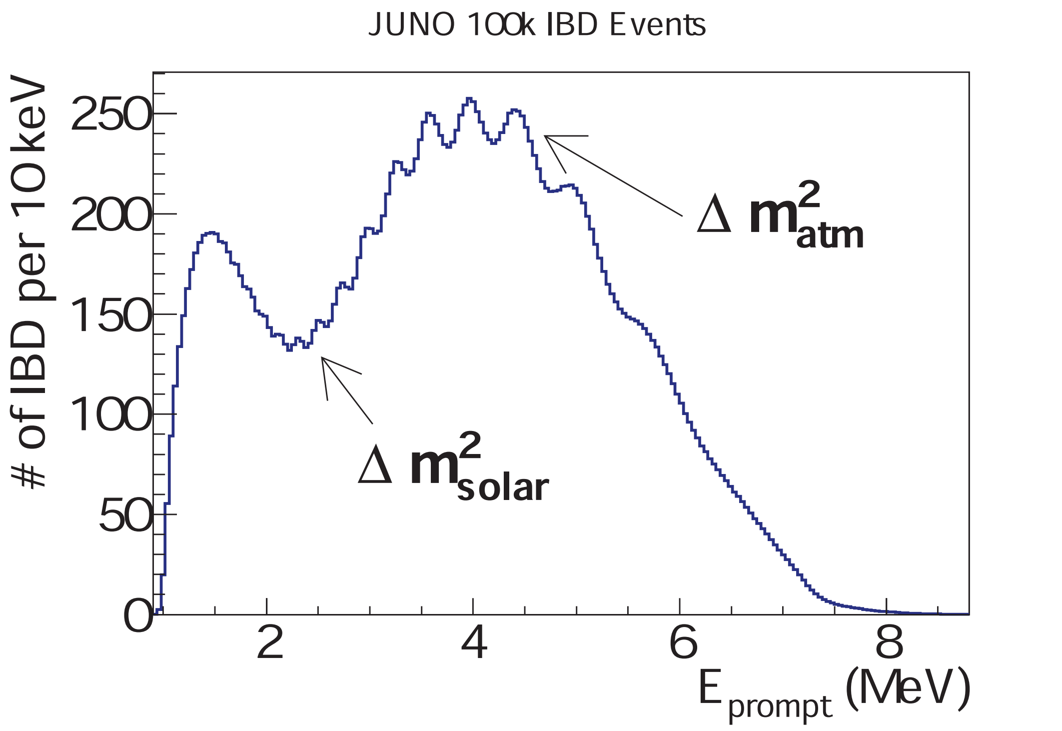


- 36 $\mathrm{GW_{th}}$ reactor power
- 20 kt liquid scintillator
- Baseline of 53 km and mean energy of 4 MeV

JUNO

JUNO's physics goals include geoneutrinos, solar neutrinos and supernova neutrinos

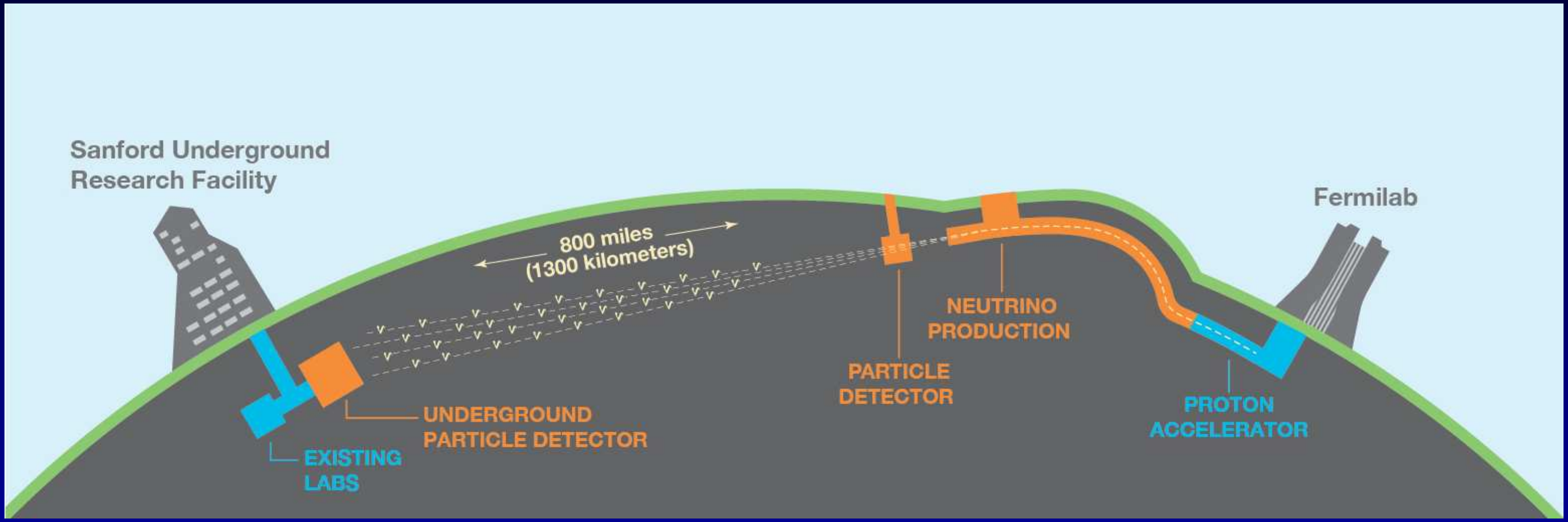
Main goal for oscillation is mass hierarchy



JUNO CDR

DUNE – U.S.A.

Deep Underground Neutrino Experiment

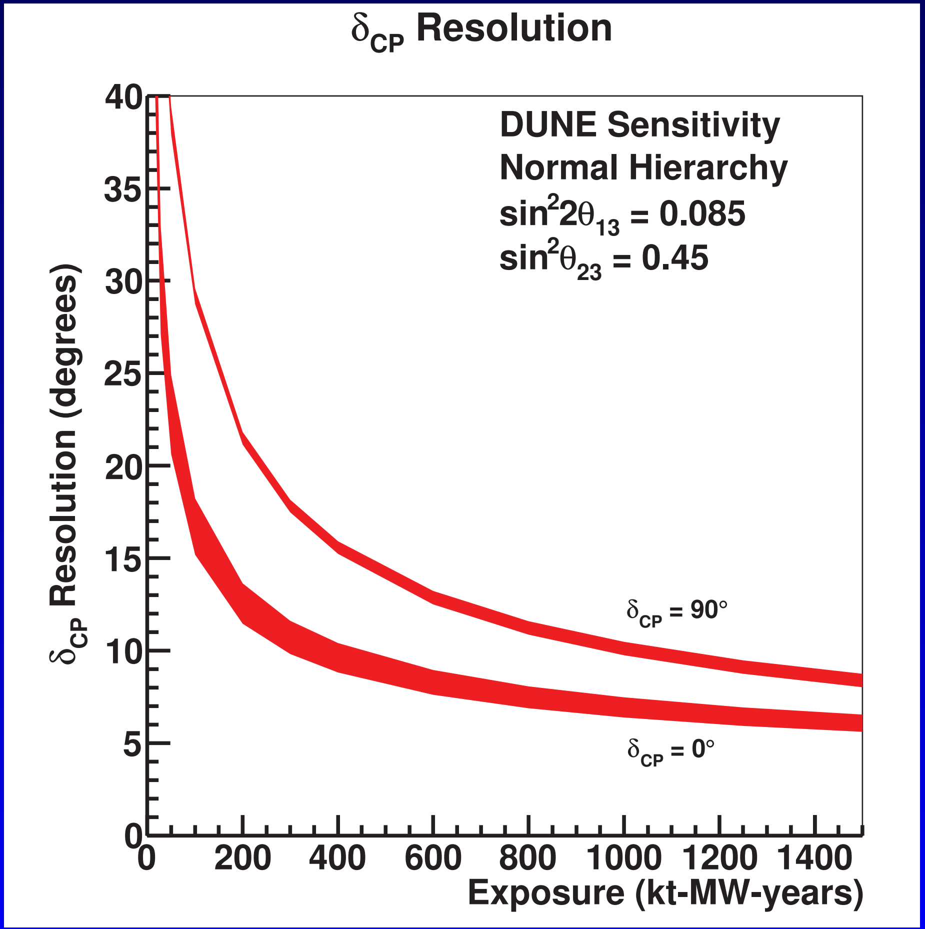


- 2.1 MW proton beam
- 4 10 kt modules of liquid argon TPC
- Baseline is 1,300 km and mean beam energy is around 2 GeV

DUNE

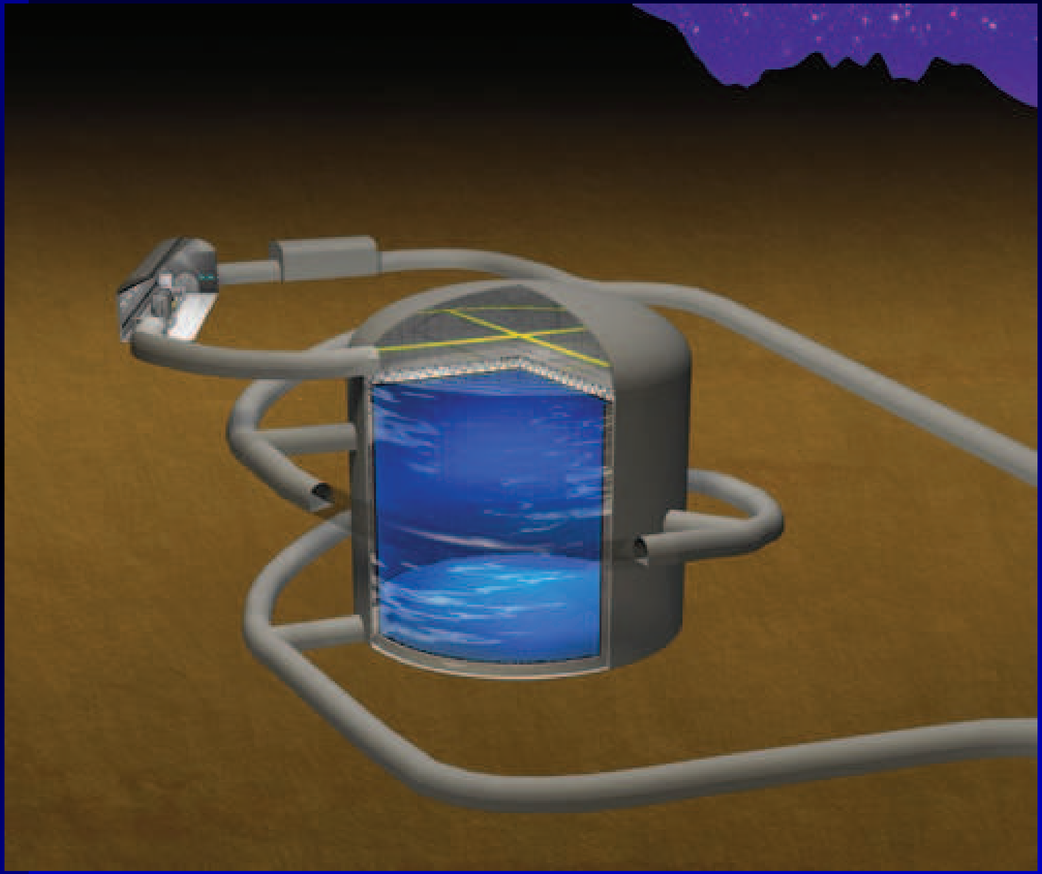
DUNE's physics goals include proton decay and supernova neutrinos and a rich program of near detector physics.

Main goal for long-baseline oscillation is CP violation



DUNE CDR

Hyper-K – Japan

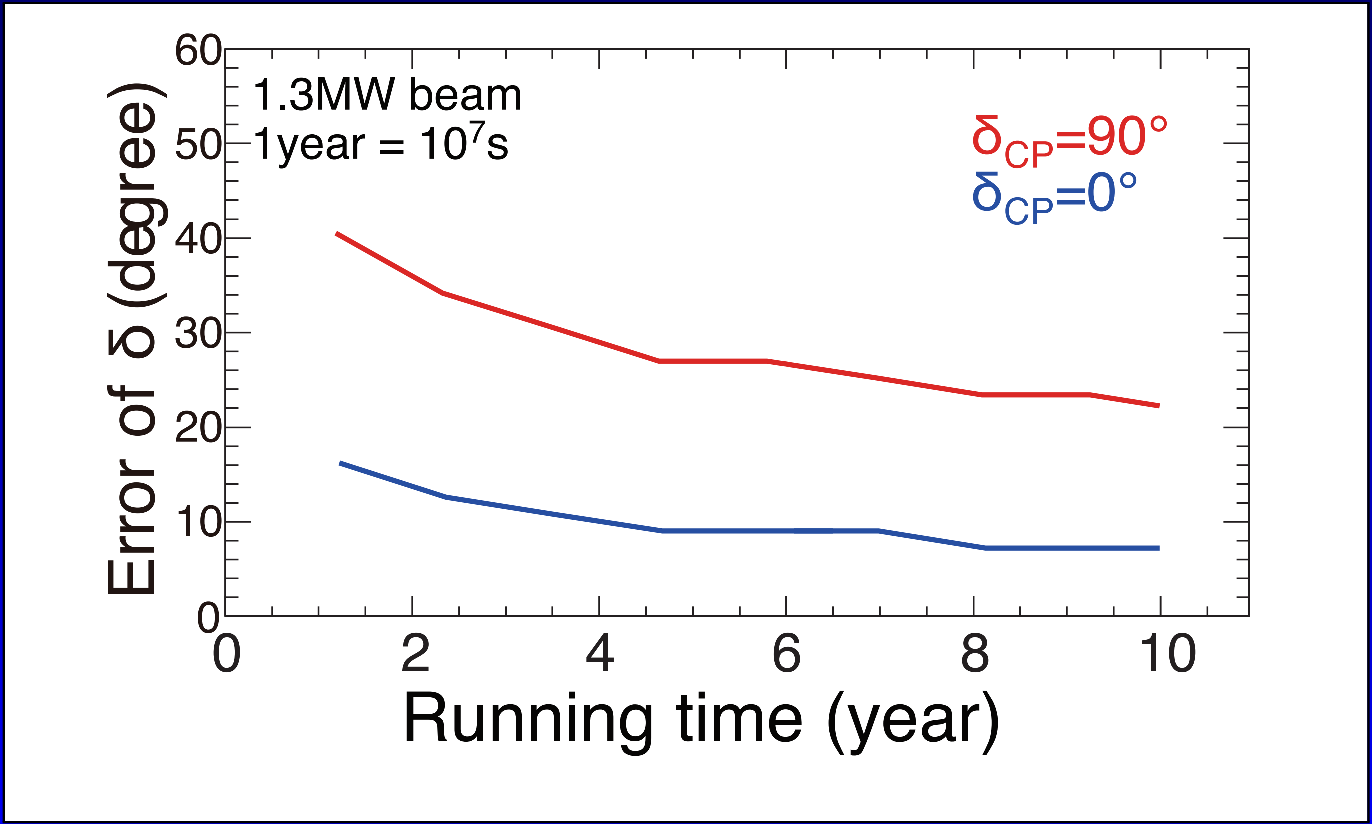


- 1.3 MW proton beam
- 187 kt water Cerenkov detector
- Baseline is 300 km and mean beam energy is around 0.7 GeV

Hyper-K

Hyper-K's physics goals include proton decay and supernova neutrinos and a rich program of near detector physics.

Main goal for long-baseline oscillation is CP violation



Hyper-K CDR

From here to there

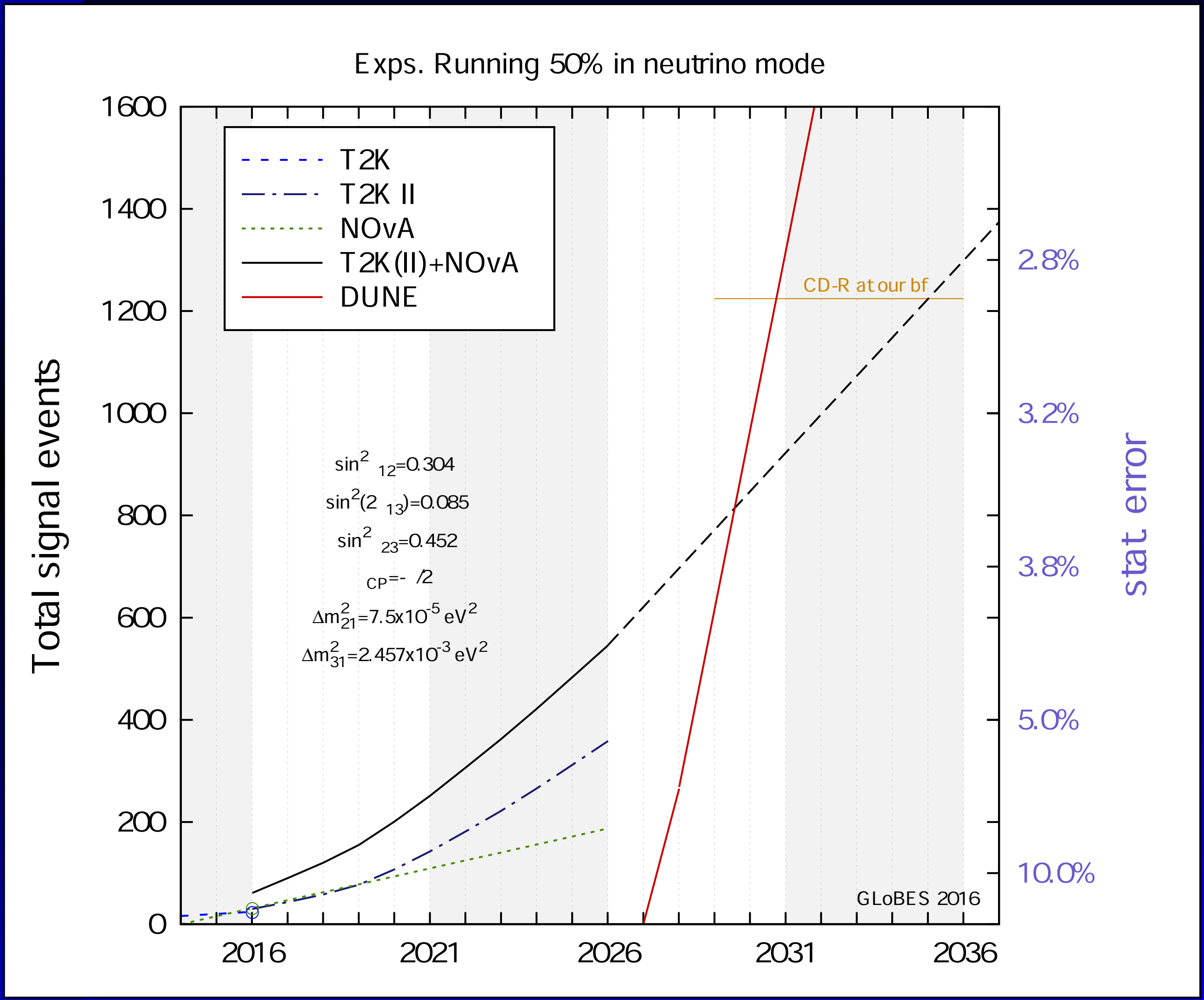
	now	JUNO	DUNE	Hyper-K
$\theta_{12}[°]$	$33.62^{+0.78}_{-0.76}$	± 0.13		
$\theta_{23}[°]$	$47.2^{+1.9}_{-3.9}$		± 0.3	± 0.5
$\theta_{13}[°]$	8.54 ± 0.15			
$\delta[°]$	$234^{+43\dagger}_{-31}$		7.5-15	7.2-23
$\Delta m^2_{32}[10^{-3}\mathrm{eV}^2]$	$2.494^{+0.033}_{0.031}$		± 0.007	± 0.014
$\Delta m^2_{21}[10^{-5}\mathrm{eV}^2]$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

† Exceeds predicted sensitivity.

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

Systematics assumptions are critical for this.

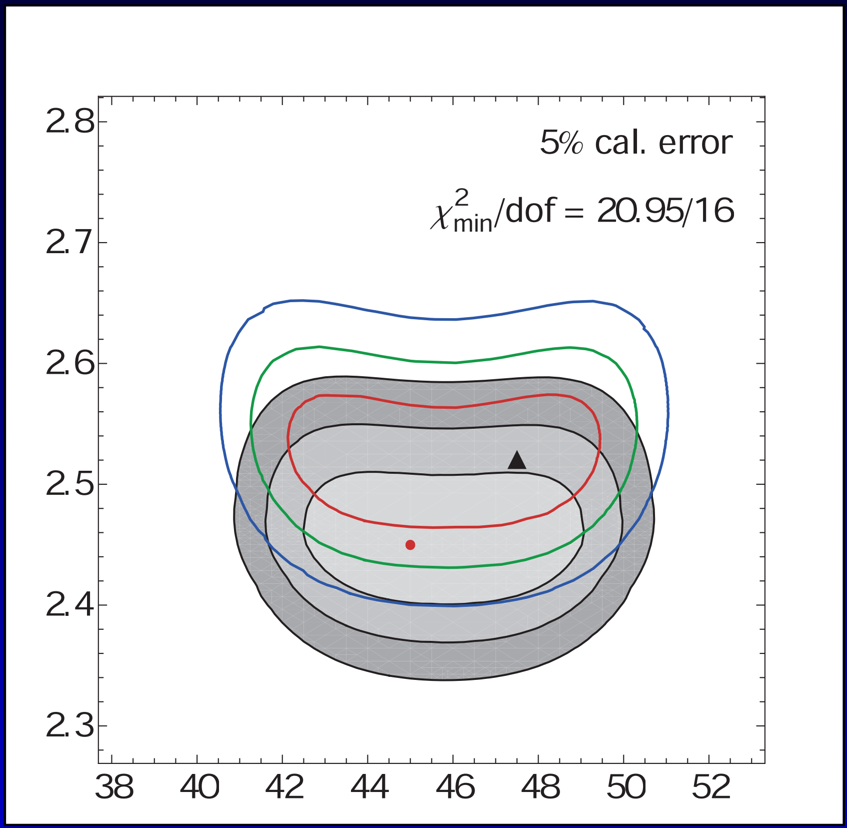
Bright future



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

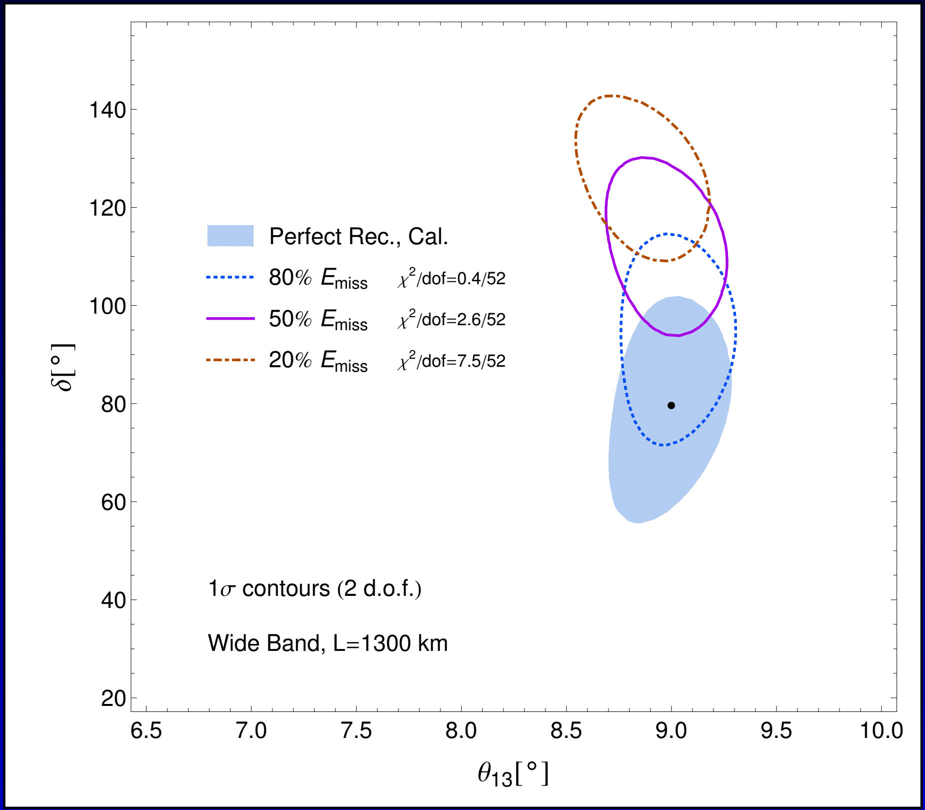
Statistically errors globally will reach 1-2%, can we match this in systematics?

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.

Summary

- It took 4 decades to experimentally establish 3-flavor neutrino oscillation.
- Neutrino oscillation only terrestrial evidence for physics beyond the Standard Model.
- The next decade will see an increase in precision by a factor of 5 in oscillation measurements.
- Room for surprises: neutrino portal, sterile neutrinos …

Europe is actively involved in all ongoing oscillation programs and has the opportunity to make critical contributions, *e.g.* NuSTORM.