The quest for leptonic CP violation

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Invisibles 15 – Invisibles meet visibles

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Status quo

A common framework for all the neutrino data is oscillation of three active neutrinos

- $\Delta m^2_{21} \sim 8 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m^2_{31} \sim 2 \cdot 10^{-3}\,\mathrm{eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \sim 0.16$

This implies a lower bound on the mass of the heaviest neutrino

$$\sqrt{2 \cdot 10^{-3}\,\mathrm{eV}^2} \sim 0.04\,\mathrm{eV}$$

but we currently do not know which neutrino is the heaviest.

Mixing matrices

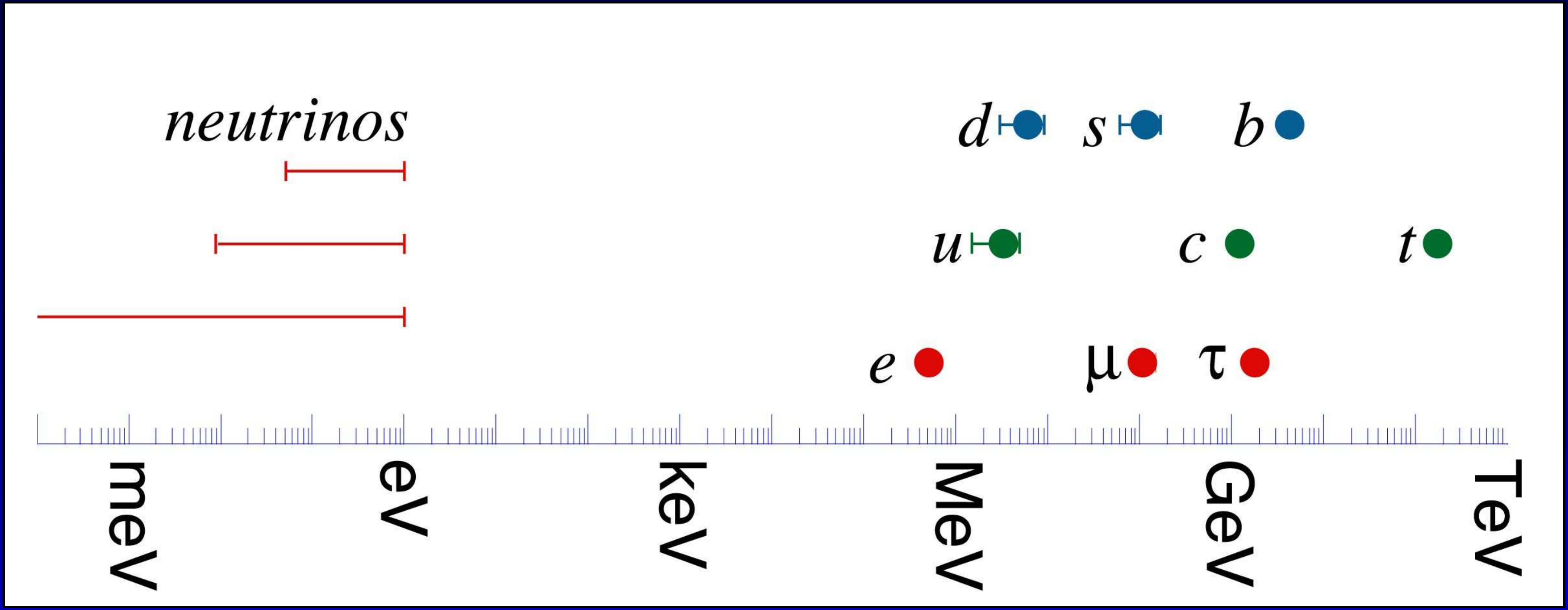
Quarks

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

Neutrinos

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

Fermion masses



θ_{13} is large!

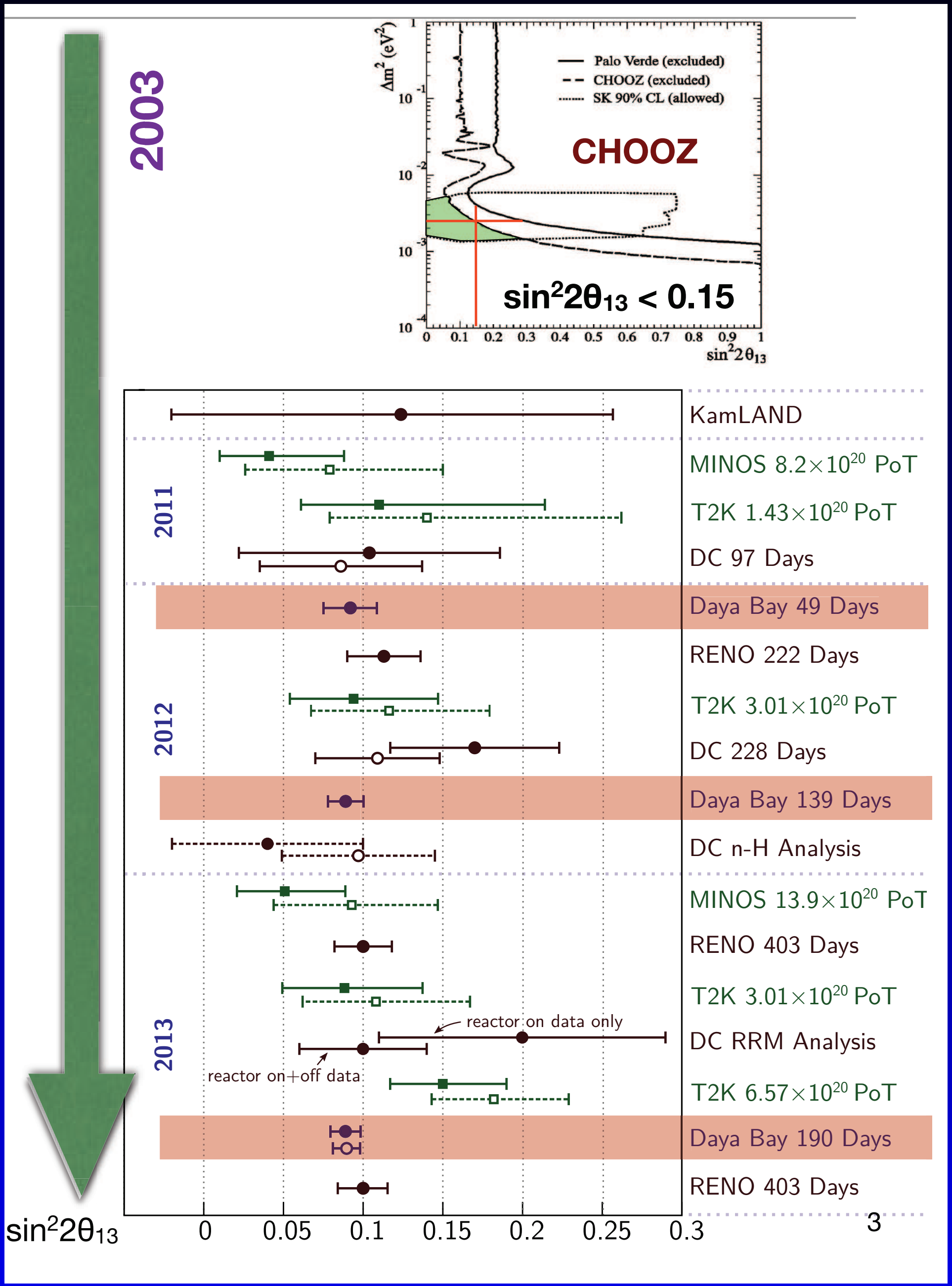
Many results from reactor and beam experiments

Some single results exceed 5 σ significance

All results agree well

Current Daya Bay result

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$



Zhang, Neutrino 2014

Model selection

… a large fraction has been excluded!

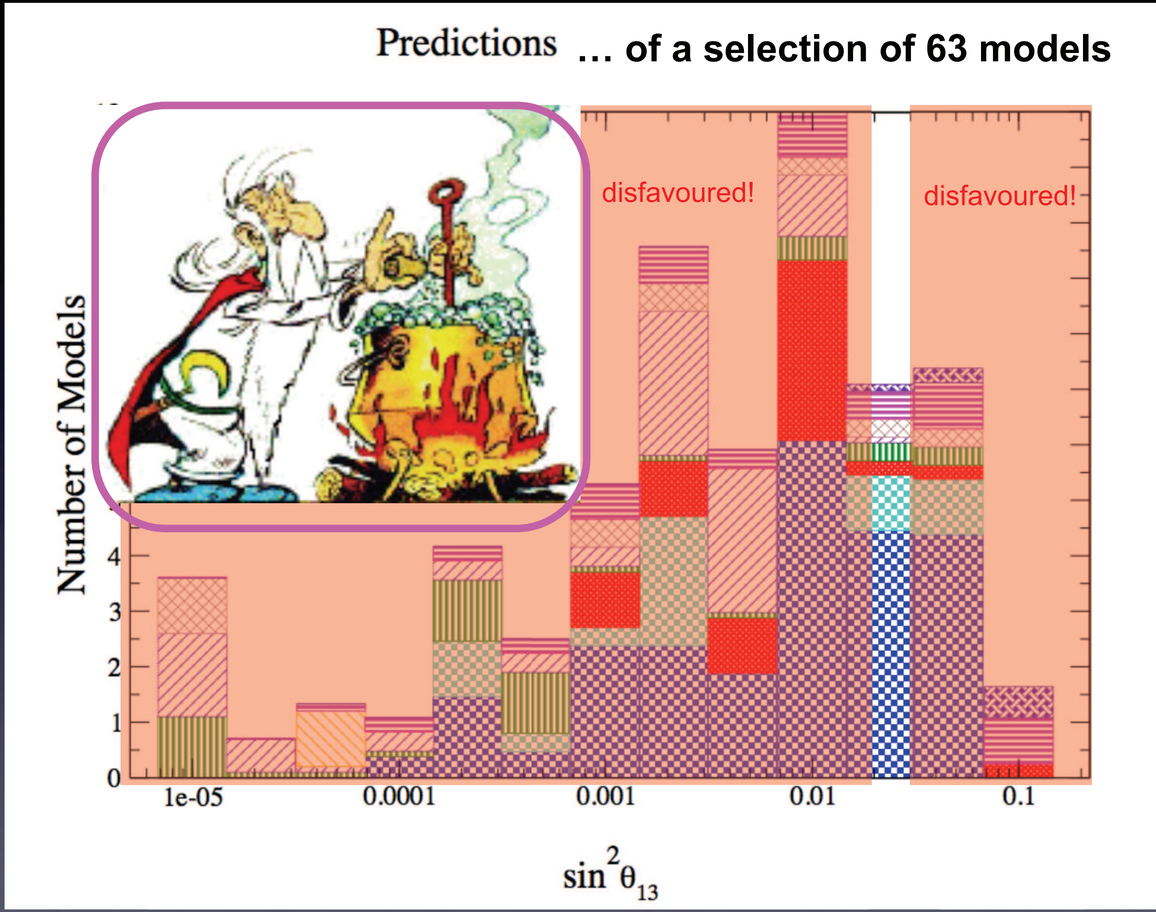


Figure shows only a small subset of the existing models … !

based on figure from Albright, Mu-Chun Chen ('06)

Antusch, 2012

Measuring leptonic CPV

In order to measure CP violation we need to reconstruct one out of these

$$P(\nu_\mu \to \nu_e) \text{ or } P(\nu_e \to \nu_\mu)$$

and one out of these

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \text{ or } P(\bar{\nu}_e \to \bar{\nu}_\mu)$$

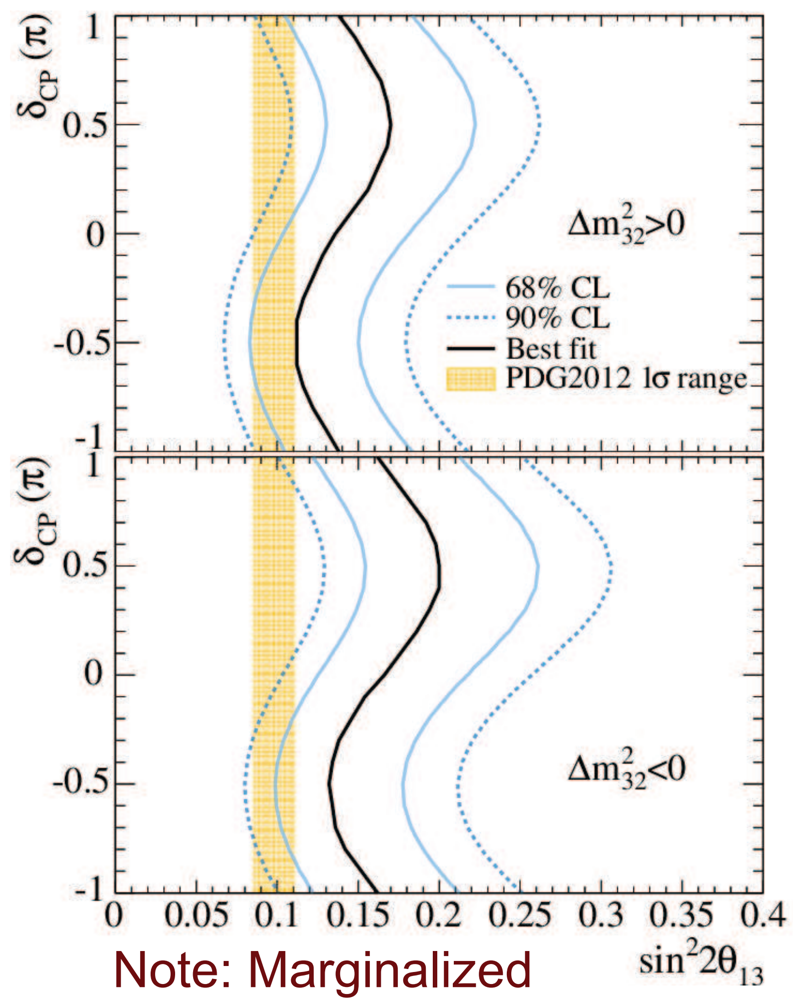
and we'd like to do that at percent level accuracy. Note,

$$\frac{\bar{P} - P}{\bar{P} + P} \propto \frac{1}{\sin\theta_{13}}$$

First hints for CP violation?

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

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



Note: Marginalized over θ_{23} and Δm^2_{32}

Walters, Neutrino 2014

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, 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

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

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 – anywhere from keV to the Planck scale is possible.

Neutrino masses are different

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

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

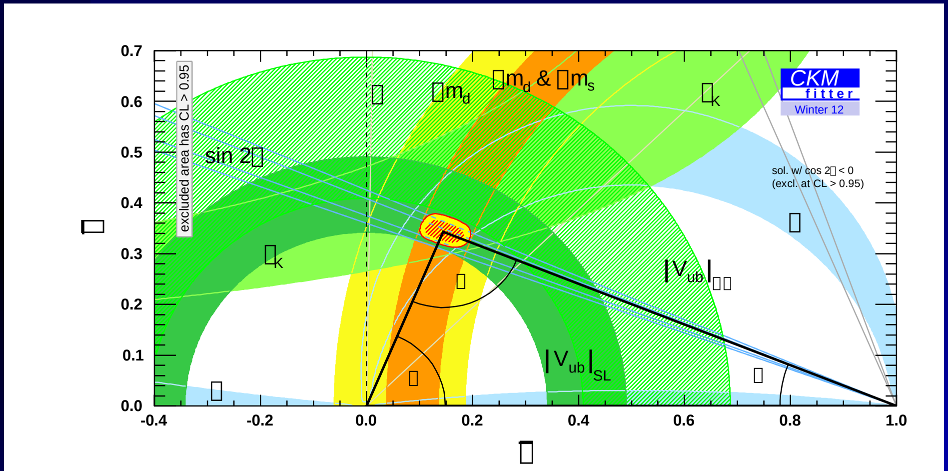
on top of the usual Dirac mass term

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

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.

What did we learn from that?

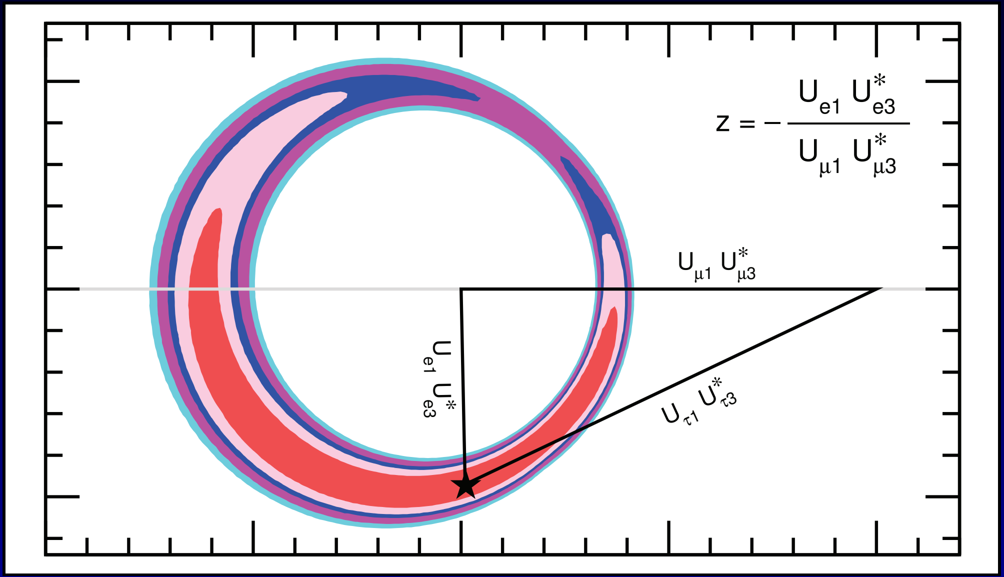
Our expectations where to find BSM physics are driven by models – but we should not confuse the number of models with the likelihood for discovery.



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

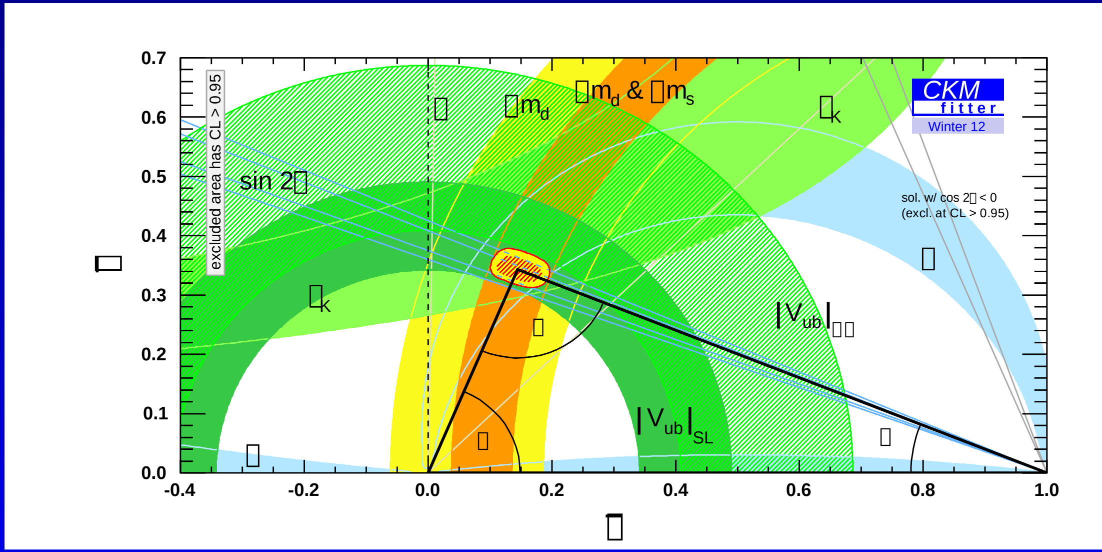
and a vast number of parameter and model space excluded.
Neutrinos are very different from quarks, therefore precision measurements will yield very different answers ⇒ complementary to collider searches

Unitarity triangles



Neutrino sector

Gonzalez-Garcia, Maltoni, Schwetz, 2014



Quark sector

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…

Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

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

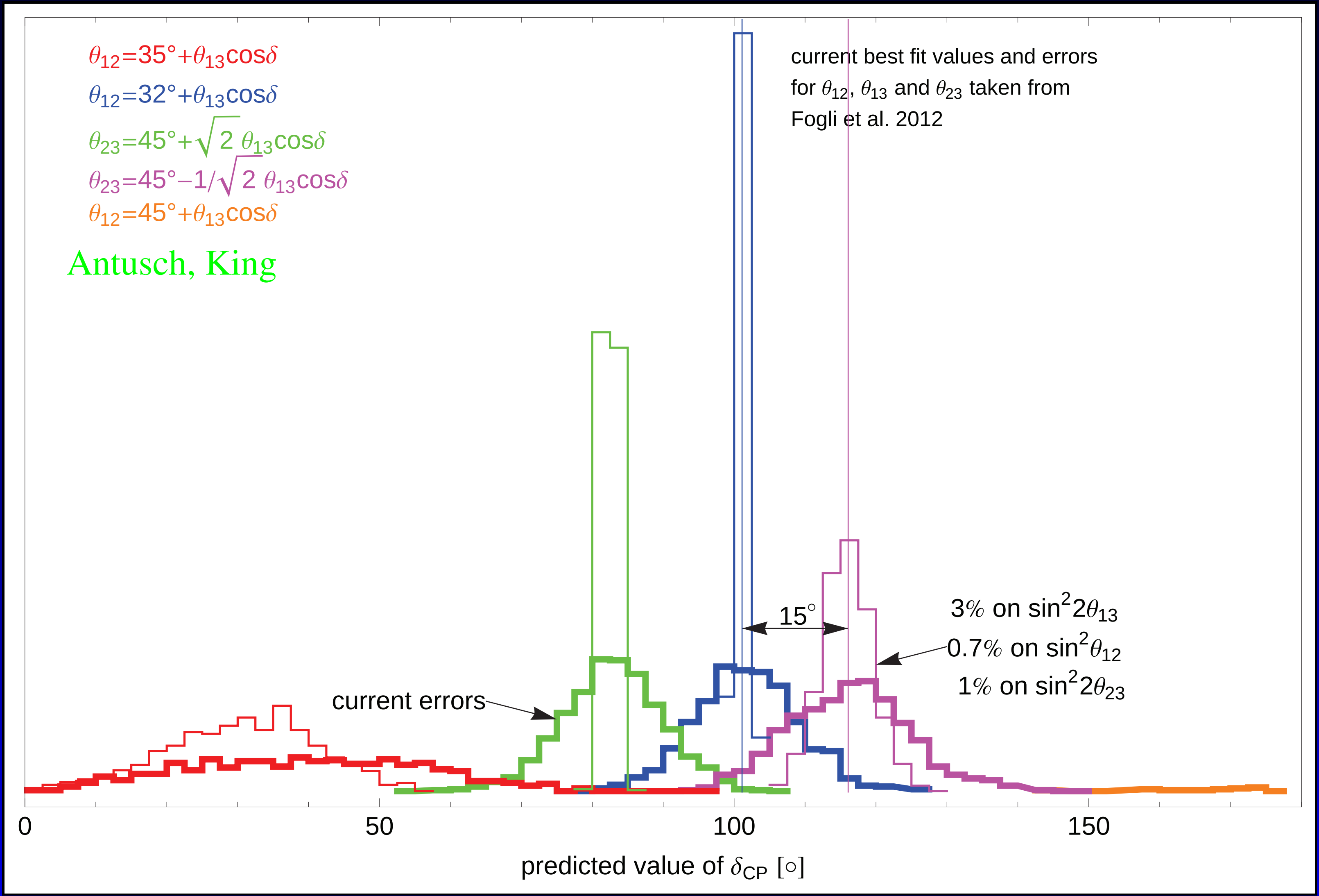
predicts flat distribution in δ_{CP}

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

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

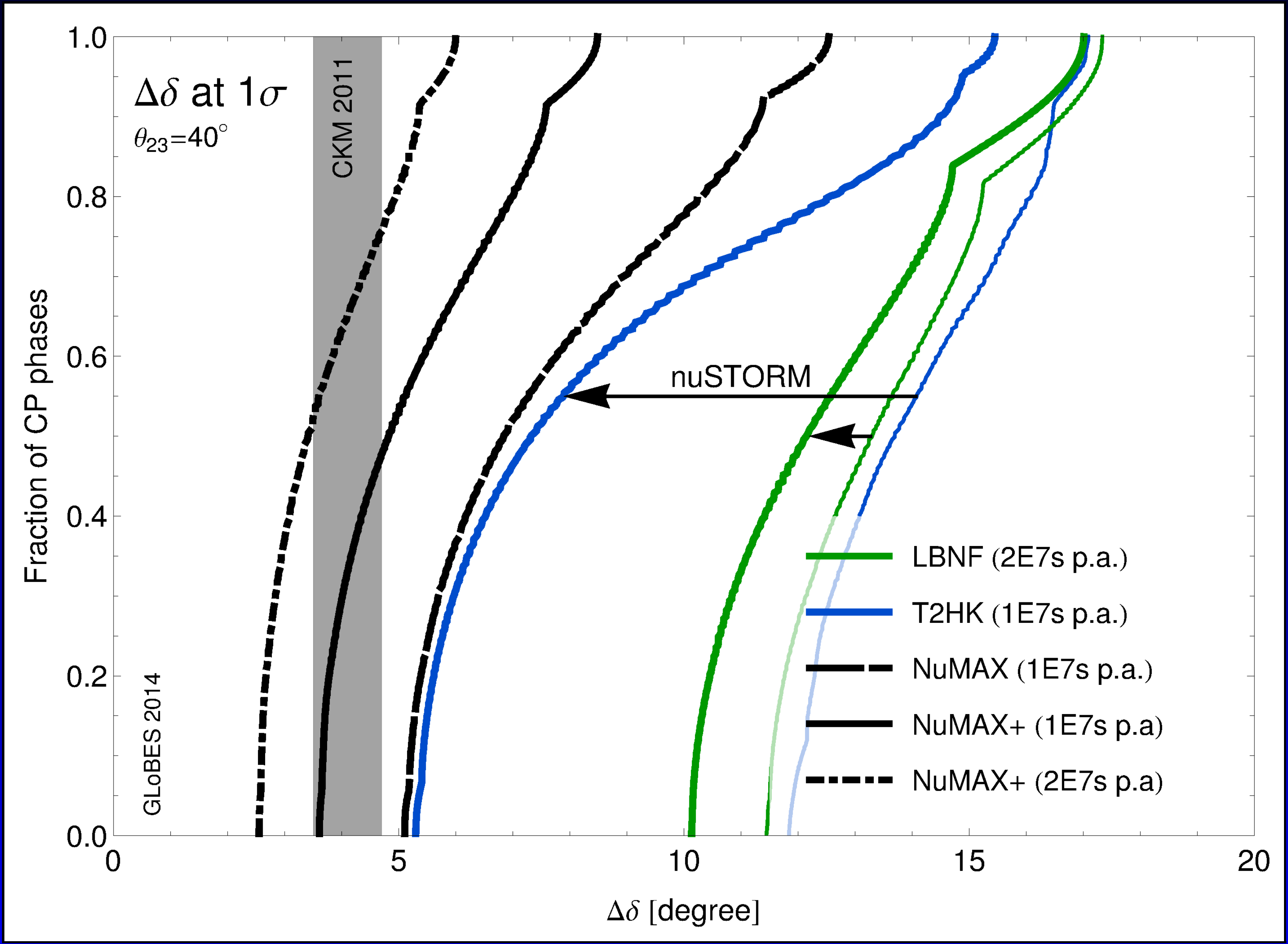
to still fit data, obviously corrections are needed – predictivity?

Sum rules



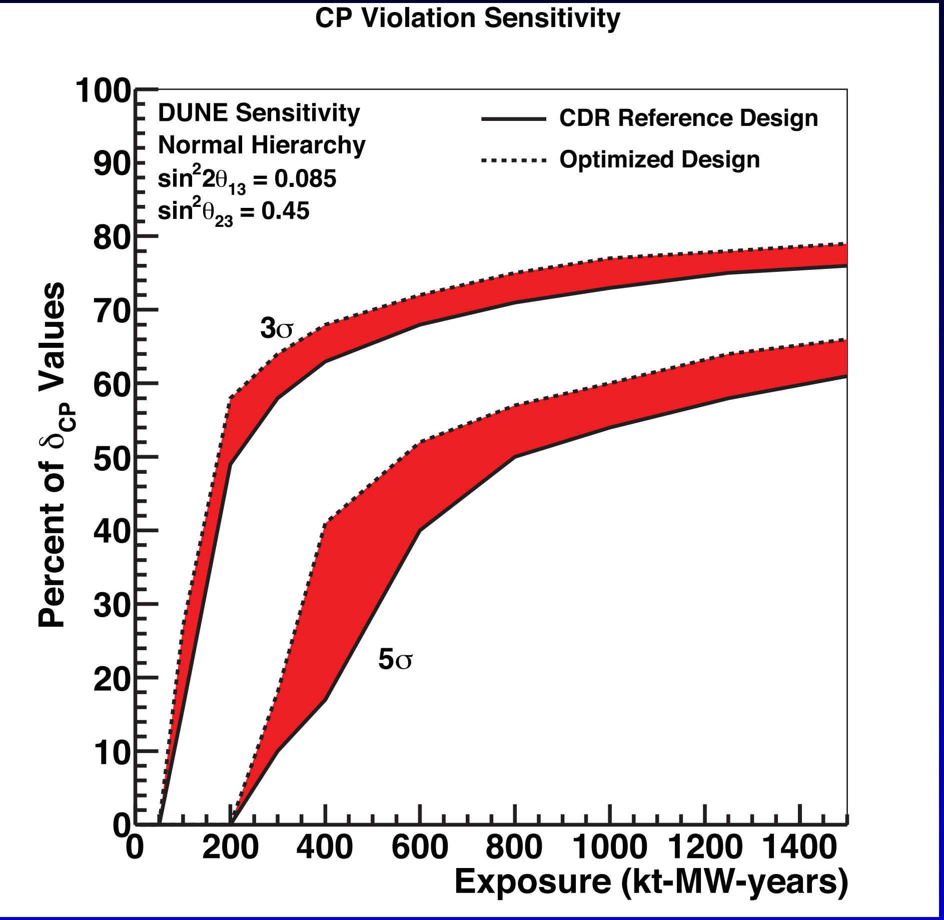
$3\,\sigma$ resolution of 15° distance requires 5° error. NB – smaller error on θ_{12} requires dedicated experiment like JUNO

Is 5° feasible?



PH, Bross, Palmer

DUNE



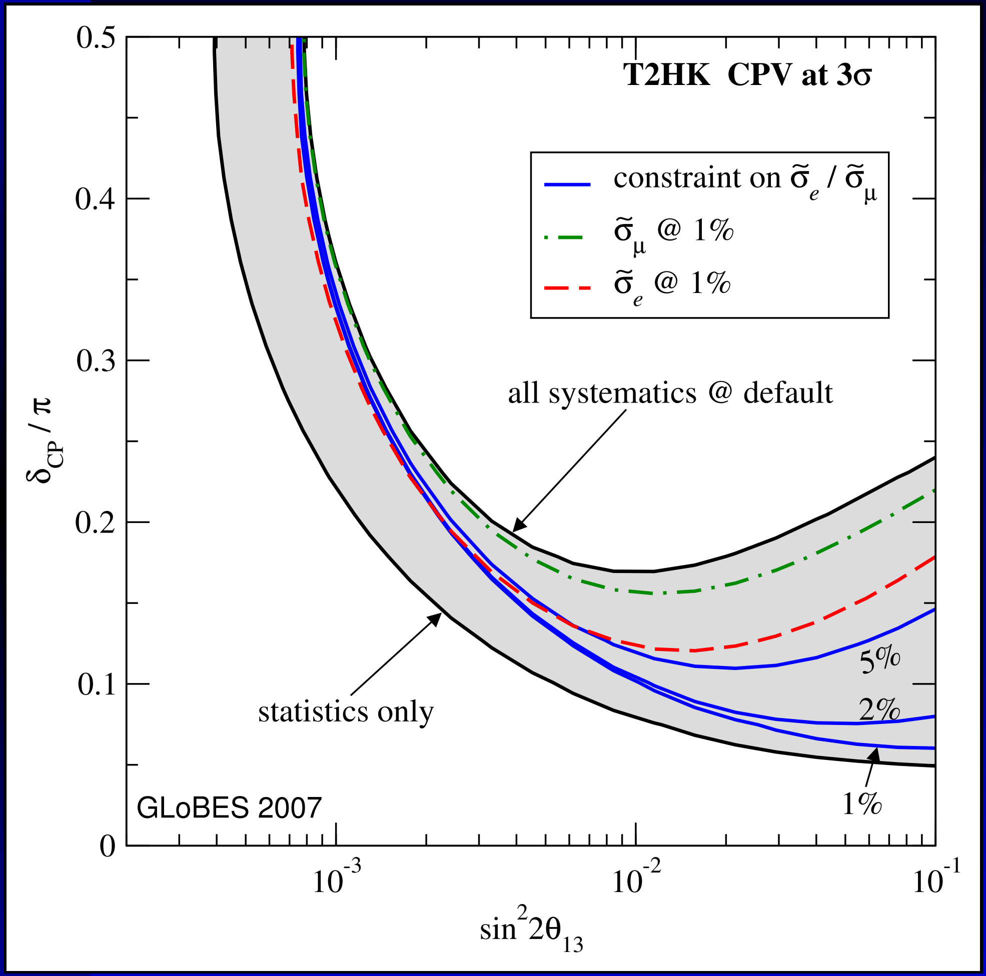
One year at 1.2 MW and 40 kt corresponds to 48 kt MW y

Beam upgrade to 2.3 MW foreseen

At 1000 MW kt y reaches 8-12° CP phase accuracy

Scheduled start of data taking 2026

Neutrino cross sections



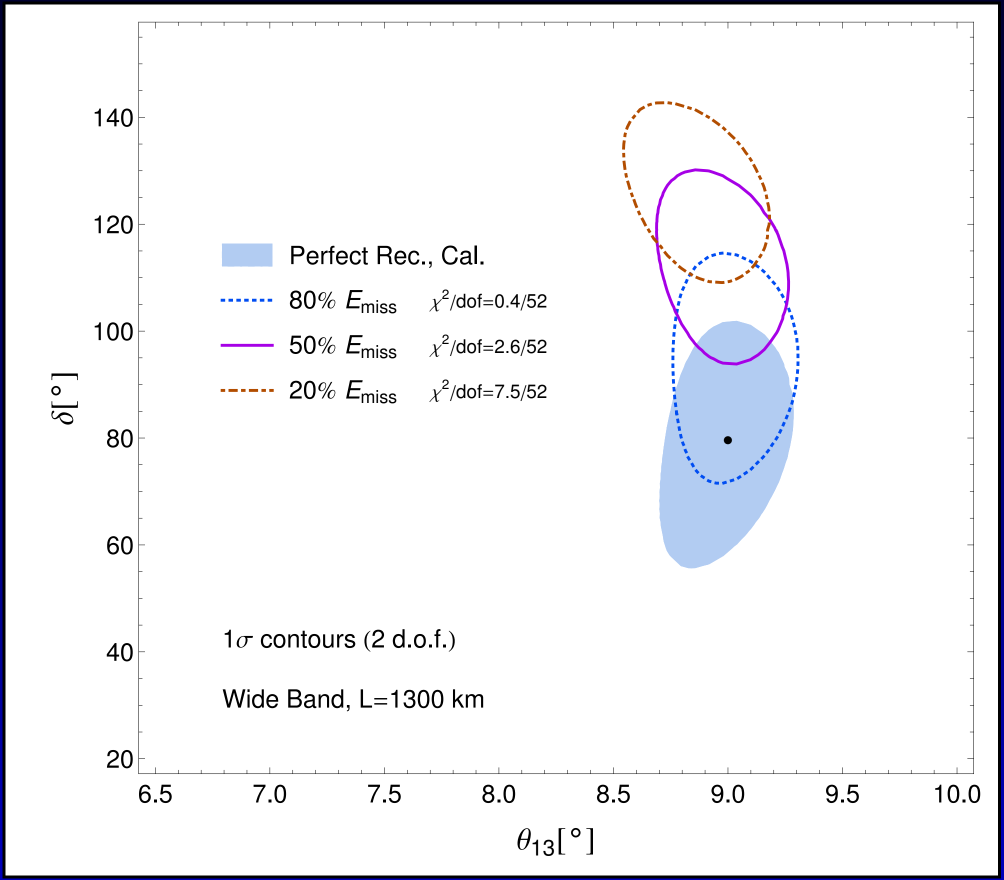
Using current cross section uncertainties and a perfect near detector.

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

PH, Mezzetto, Schwetz, 2007

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.*, in preparation

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. Currently, there are two major approaches

Greens function Monte Carlo: numerically "exact" solutions for light nuclei ($A \leq 12$) and non-relativistic kinematics.

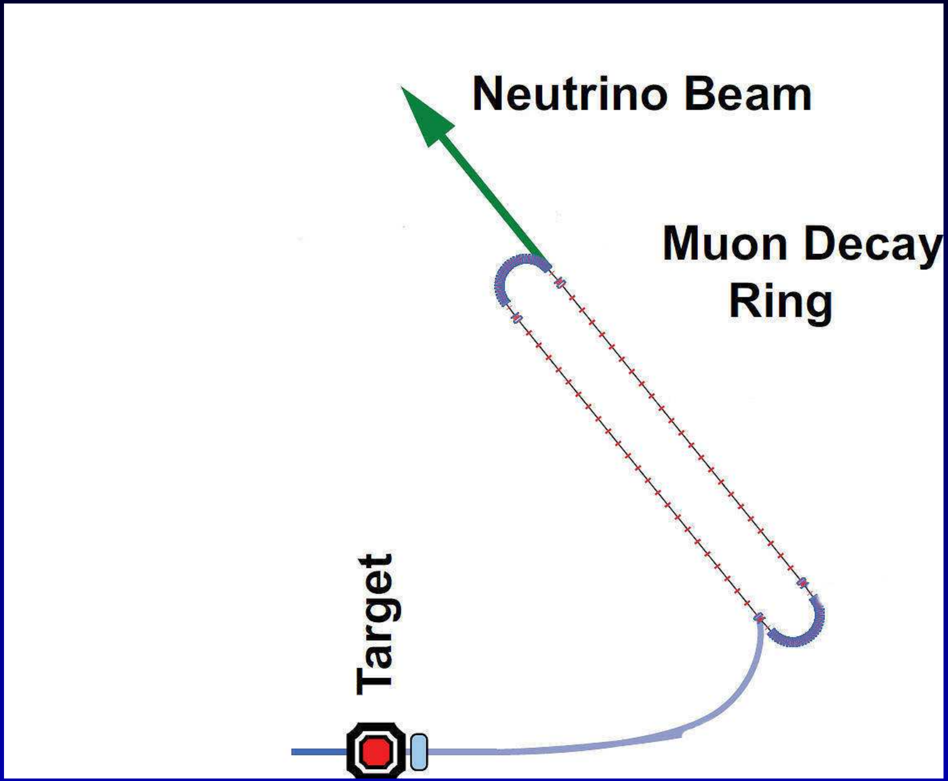
Spectral functions: use information on the initial state from electron-scattering data.

Both techniques are not controlled approximations and thus to trust theory at x% we have to experimentally test the theory at x% – ultimately, precision cross section measurements are unavoidable.

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.

Summary

- Neutrino oscillation is solid evidence for new physics
- Current data allows $\mathcal{O}(1)$ corrections to three flavor framework
- Precision measurements have the best potential to uncover even “newer” physics
- Sterile neutrinos?

Neutrinos have provided us with many surprises and neutrinos are still largely unexplored !