Impacts of precision measurement of neutrino mixing parameters

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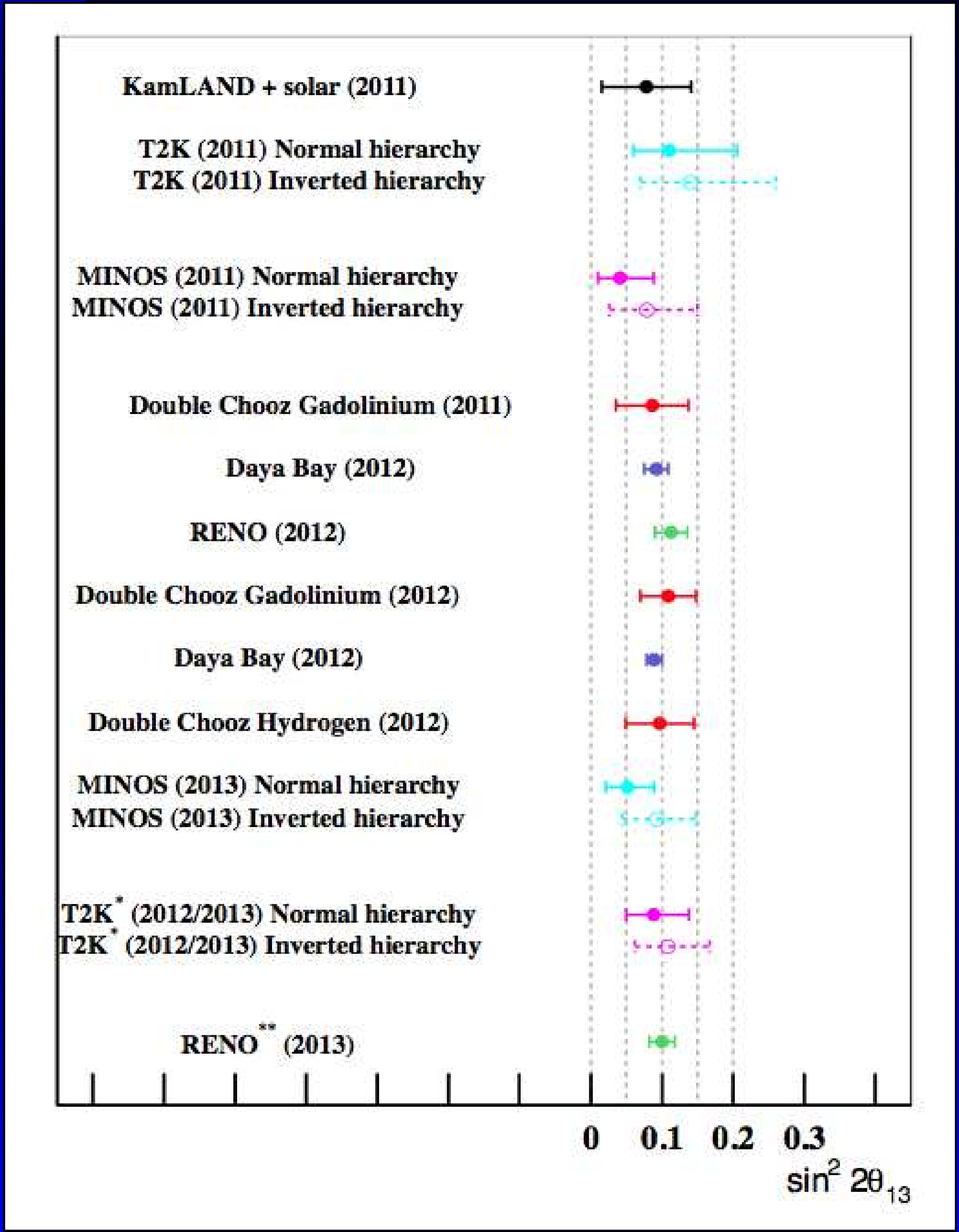
θ_{13} is large!



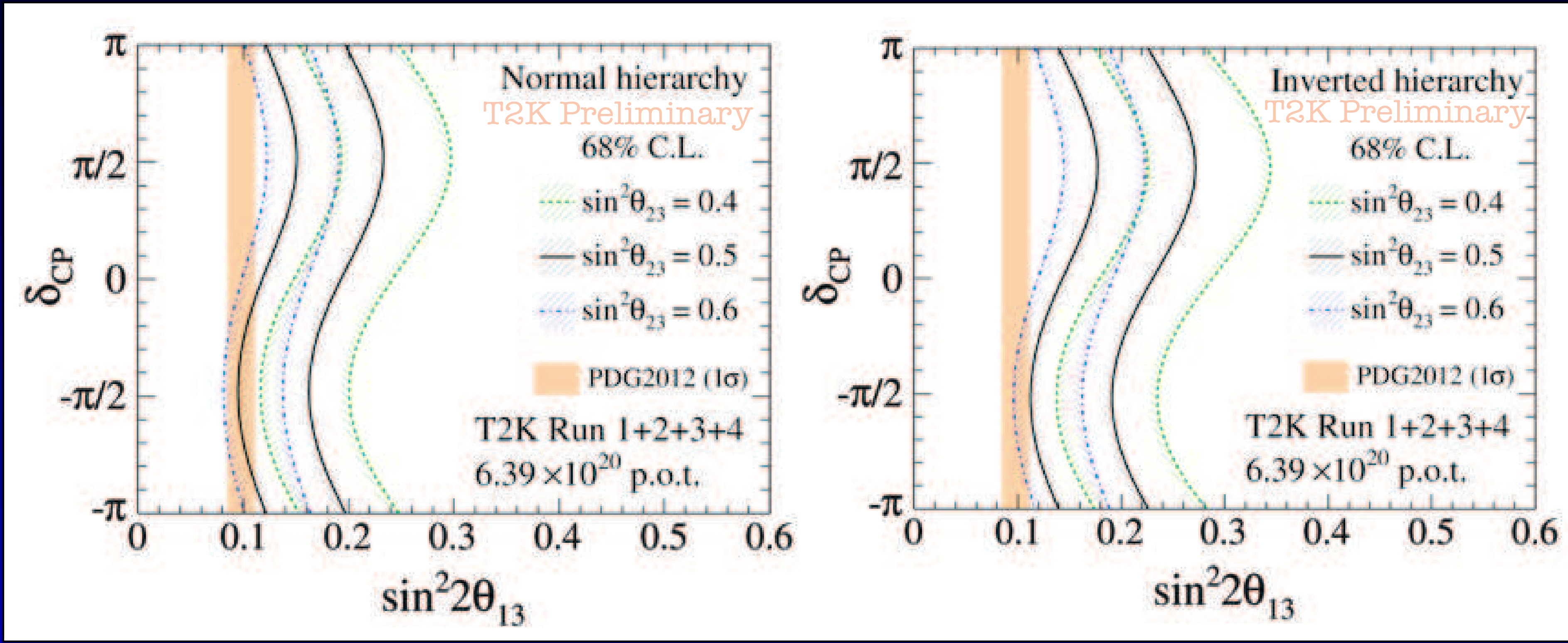
Many results from reactor and beam experiments

Some single results exceed 5 σ significance

All results agree well

NB – 2 years ago we had only 2 σ indications.

Latest results



First observation of ν_e appearance
First step towards leptonic CP violation
Comparison of reactor and accelerator measurements
important test of three flavor framework

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

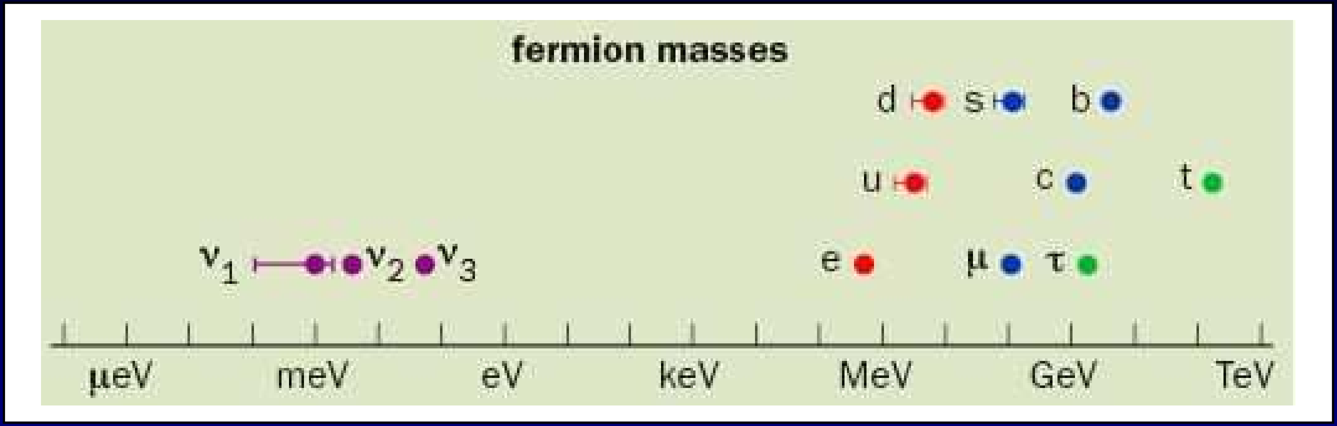
$$|U_{CKM}| = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

Neutrinos

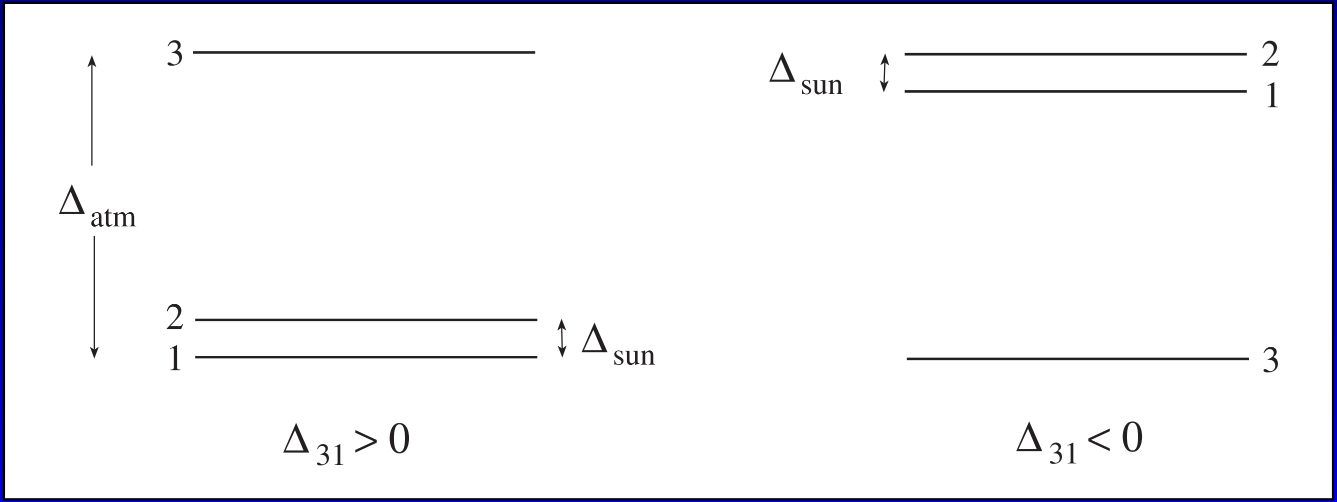
$$|U_\nu| = \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Fermion masses

Scale



Ordering – mass hierarchy



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

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

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

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

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

$$-\frac{1}{2}m_L(\bar{\psi}_L\psi_R^C + \bar{\psi}_R\psi_L^C) - \frac{1}{2}m_R(\bar{\psi}_R\psi_L^C + \bar{\psi}_L\psi_R^C)$$

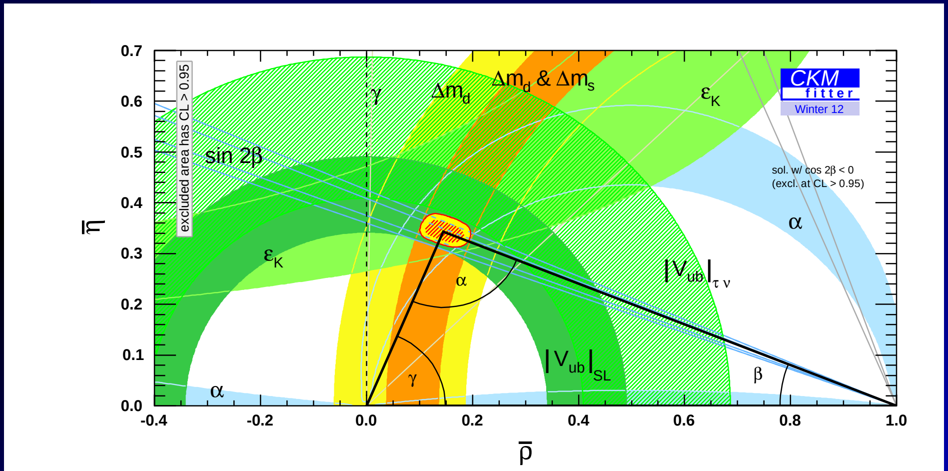
on top of the usual Dirac mass term

$$m_D(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

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
  - does not exist or
  - has a special flavor structure

and a vast number of parameter and model space excluded.

Neutrinos are very different from quarks, therefore precision measurements will yield very different answers, relating to physics at scales inaccessible by any collider.

Precision matters

Precision measurements allow to

- detect deviations from "standard" framework – *e.g.* mismatch between reactor and accelerator measurement for θ_{13} would indicate non-standard interactions
- test predictions from theories – *e.g.* $\theta_{12}^{\nu} + \theta_{12}^{\mathrm{CKM}} = \pi/4$

As such the target precision is entirely driven by models of new physics in relation to the standard framework. Thus, it is very difficult (impossible?) to establish model-independent goals for precision.

In the following I will focus on one example. . .

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

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

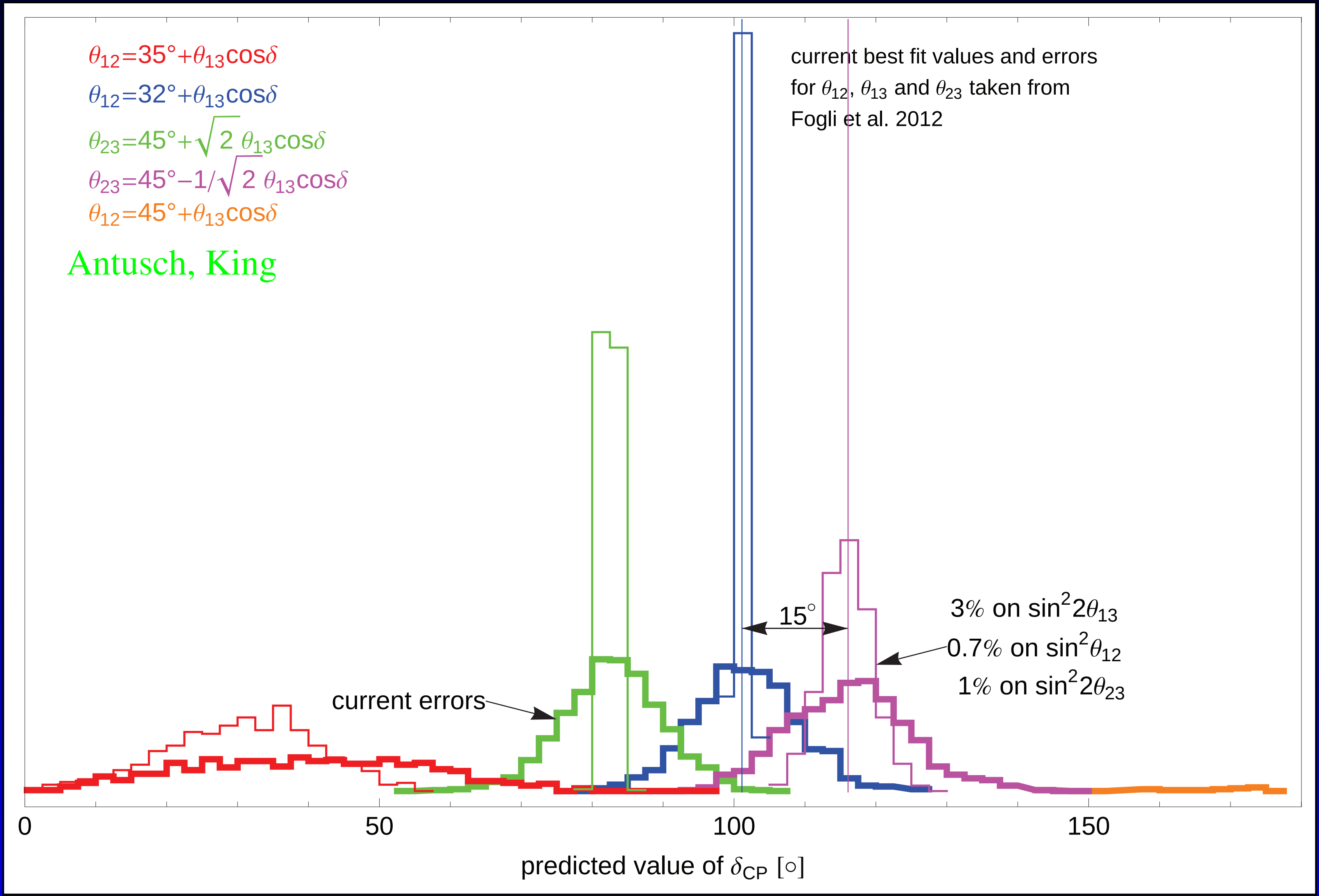
predicts flat distribution in δ_{CP}

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

CPV in oscillation

Like in the quark sector mixing can cause CP violation

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$$

The size of this effect is proportional to

$$J_{CP} = \frac{1}{8} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\delta$$

but the asymmetry

$$\frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \propto \frac{1}{\sin 2\theta_{13}}$$

The experimentally most suitable transition to study CP violation is $\nu_e \leftrightarrow \nu_\mu$.

CPV from matter

The charged current interaction of ν_e with the electrons creates a potential for ν_e

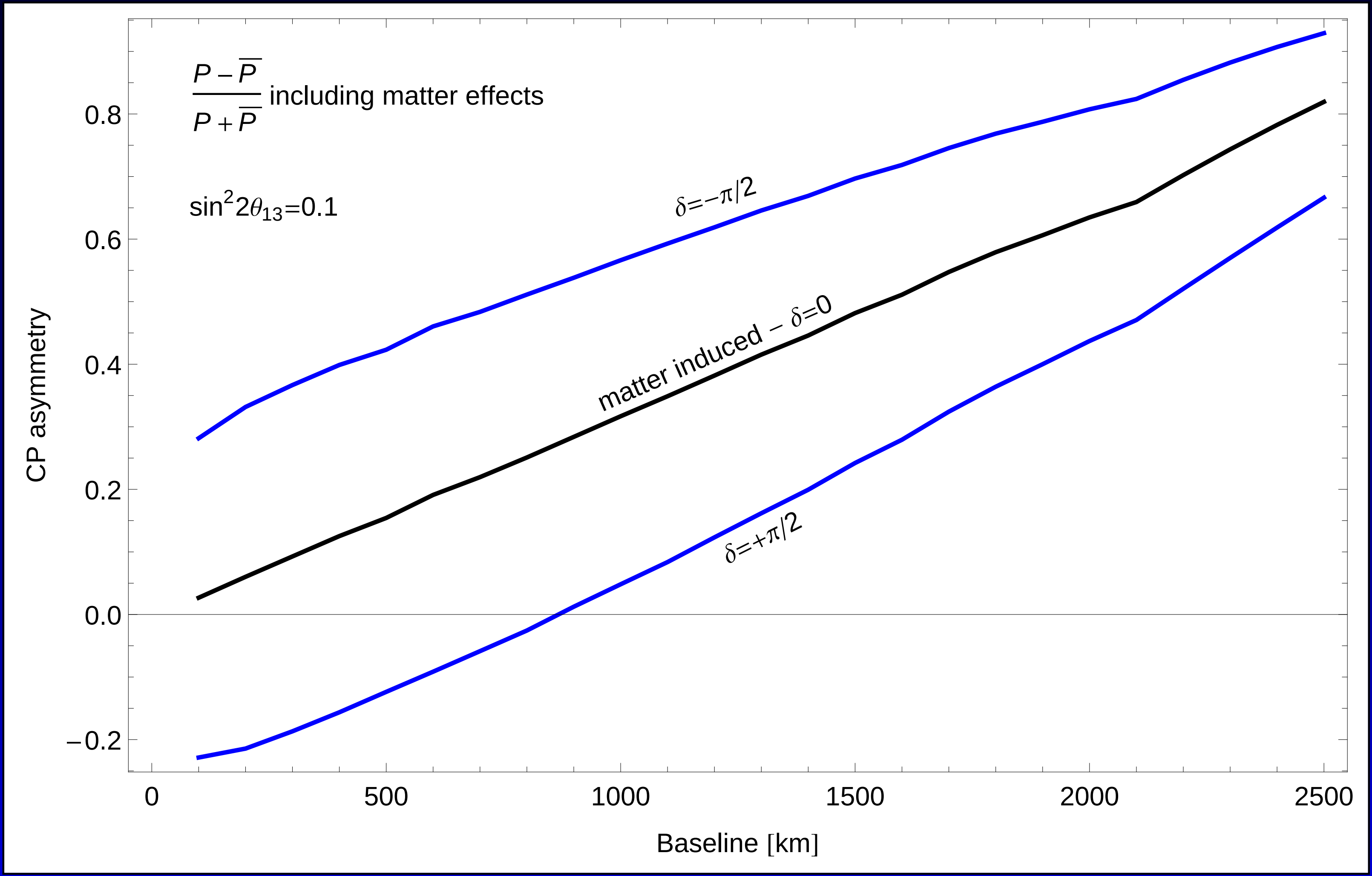
$$A = \pm 2\sqrt{2} G_F \cdot E \cdot n_e$$

where $+$ is for ν and $-$ for $\bar{\nu}$.
This potential gives rise to an additional phase for ν_e and thus changes the oscillation probability. This has two consequences

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$$

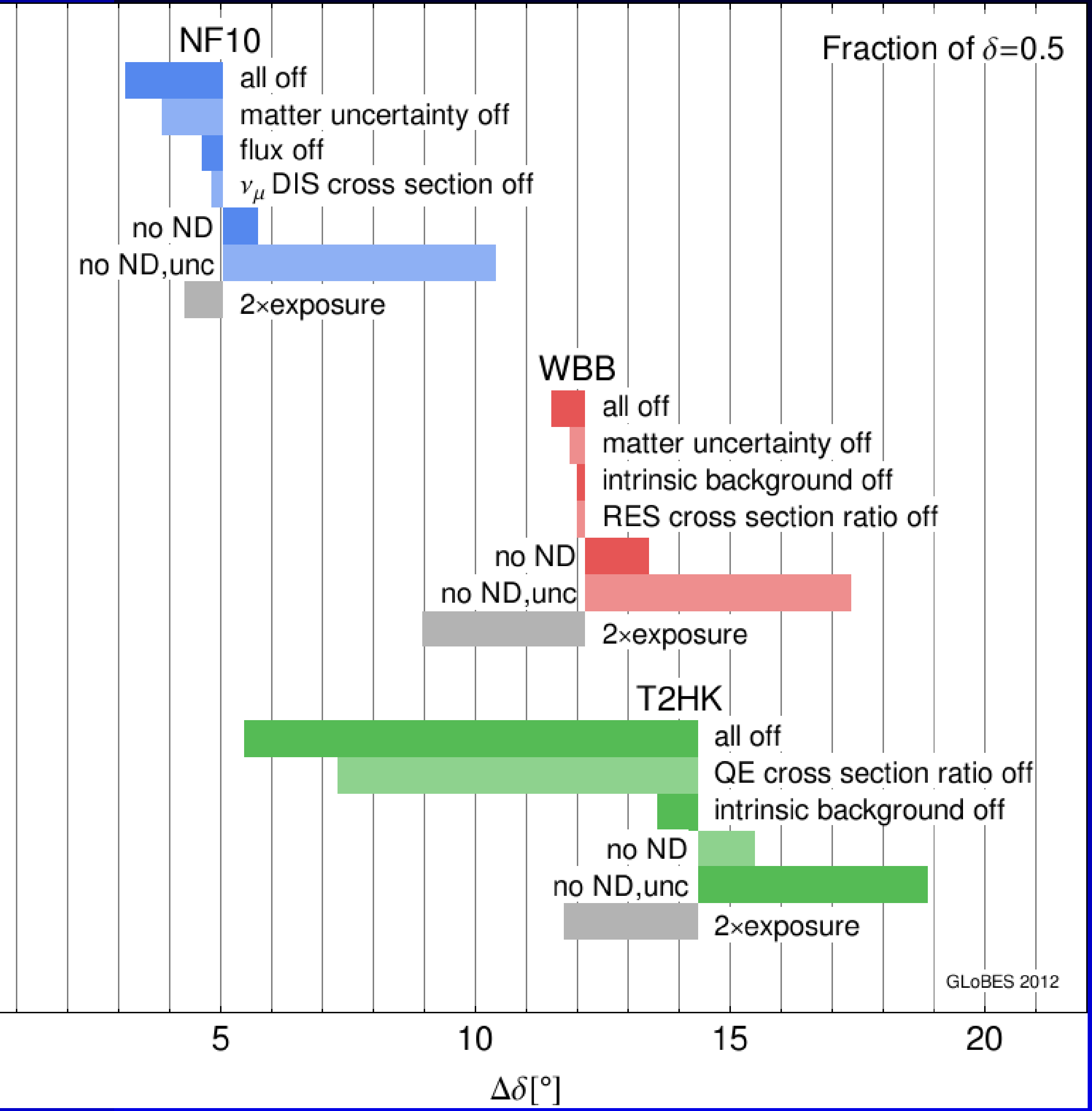
even if $\delta = 0$, since the potential distinguishes neutrinos from anti-neutrinos.

CP asymmetry



For 1300 km the asymmetry is about 65%, with 40% from matter and ±25% from genuine CPV.

Systematics



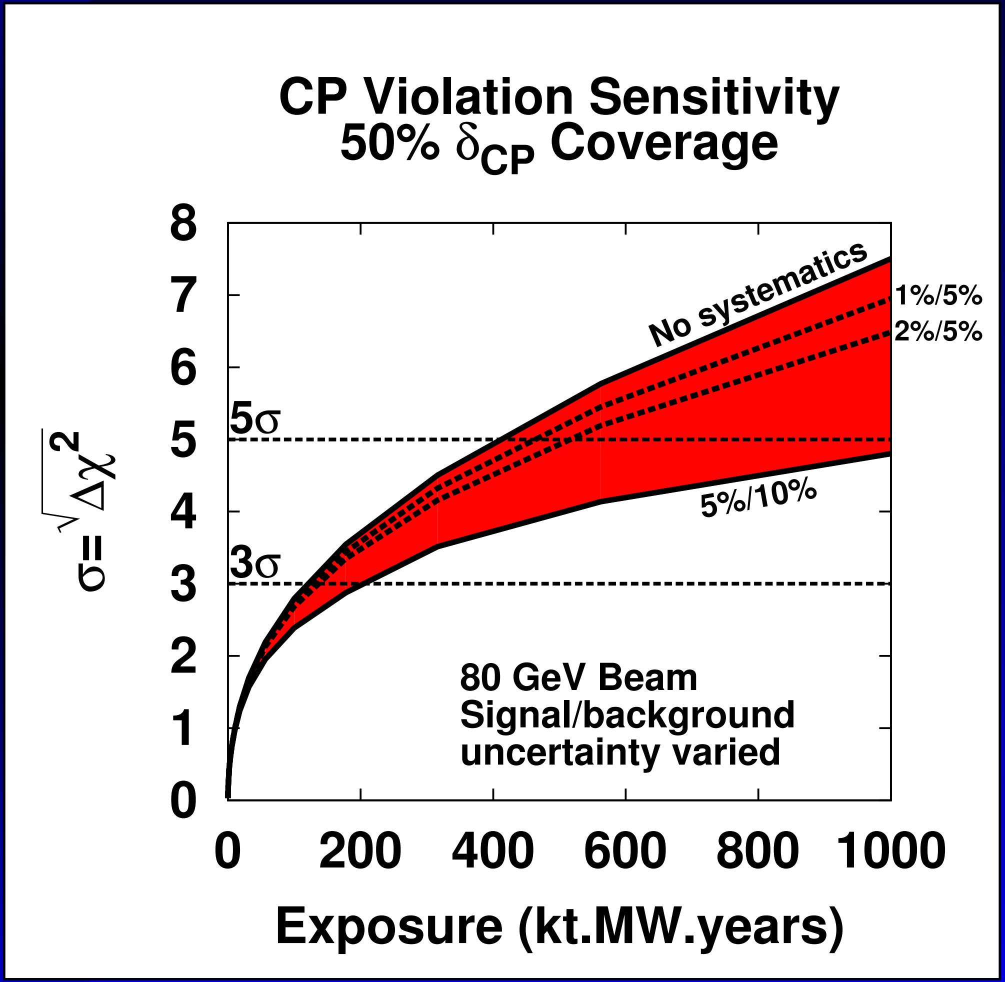
arXiv:1209.5973

Neutrino factories will reach 10 000 events in appearance mode

Percent level systematic accuracy needed

Scaling with luminosity is strongly affected by systematics

Luminosity scaling

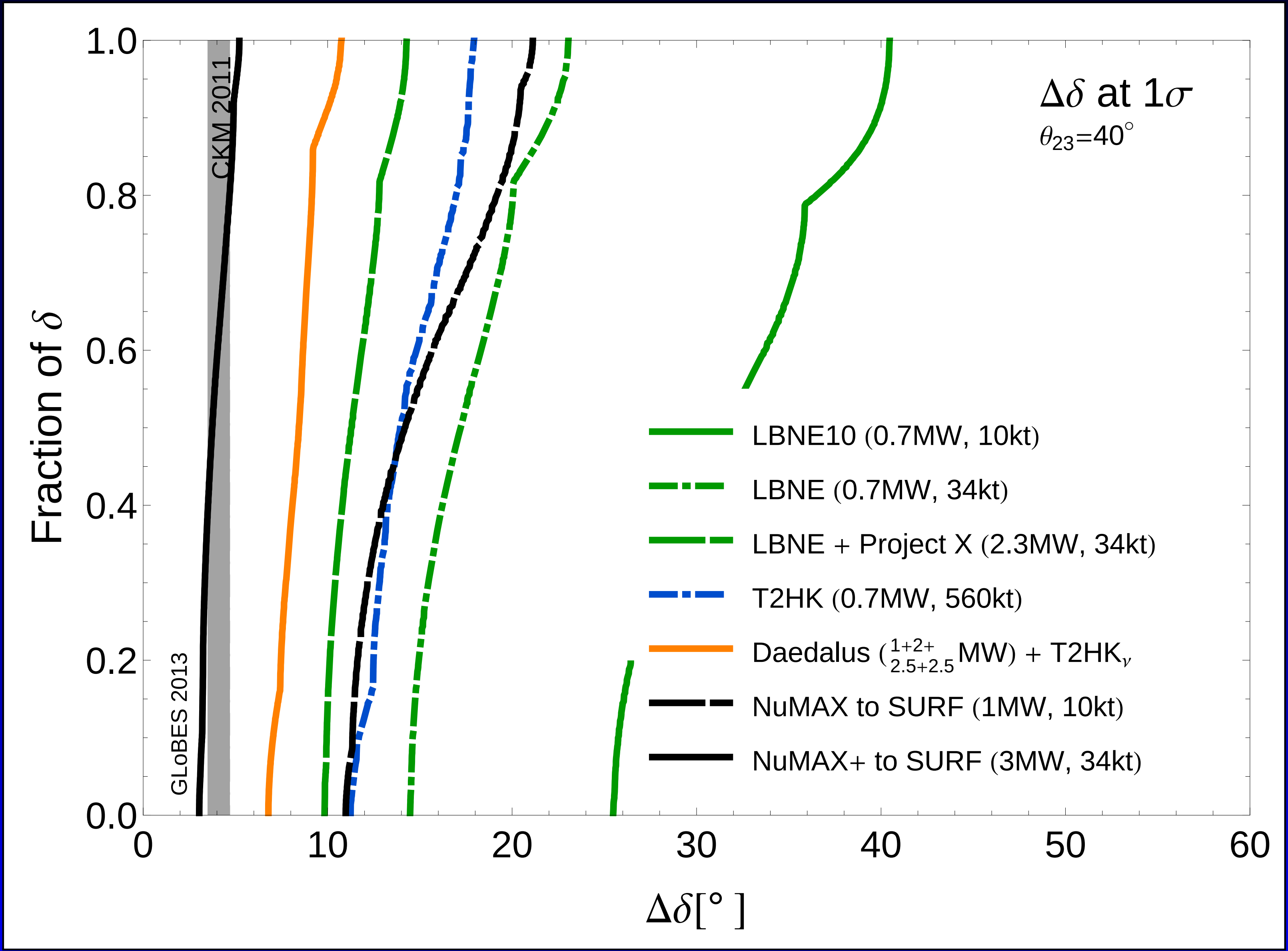


arXiv:1307.7335

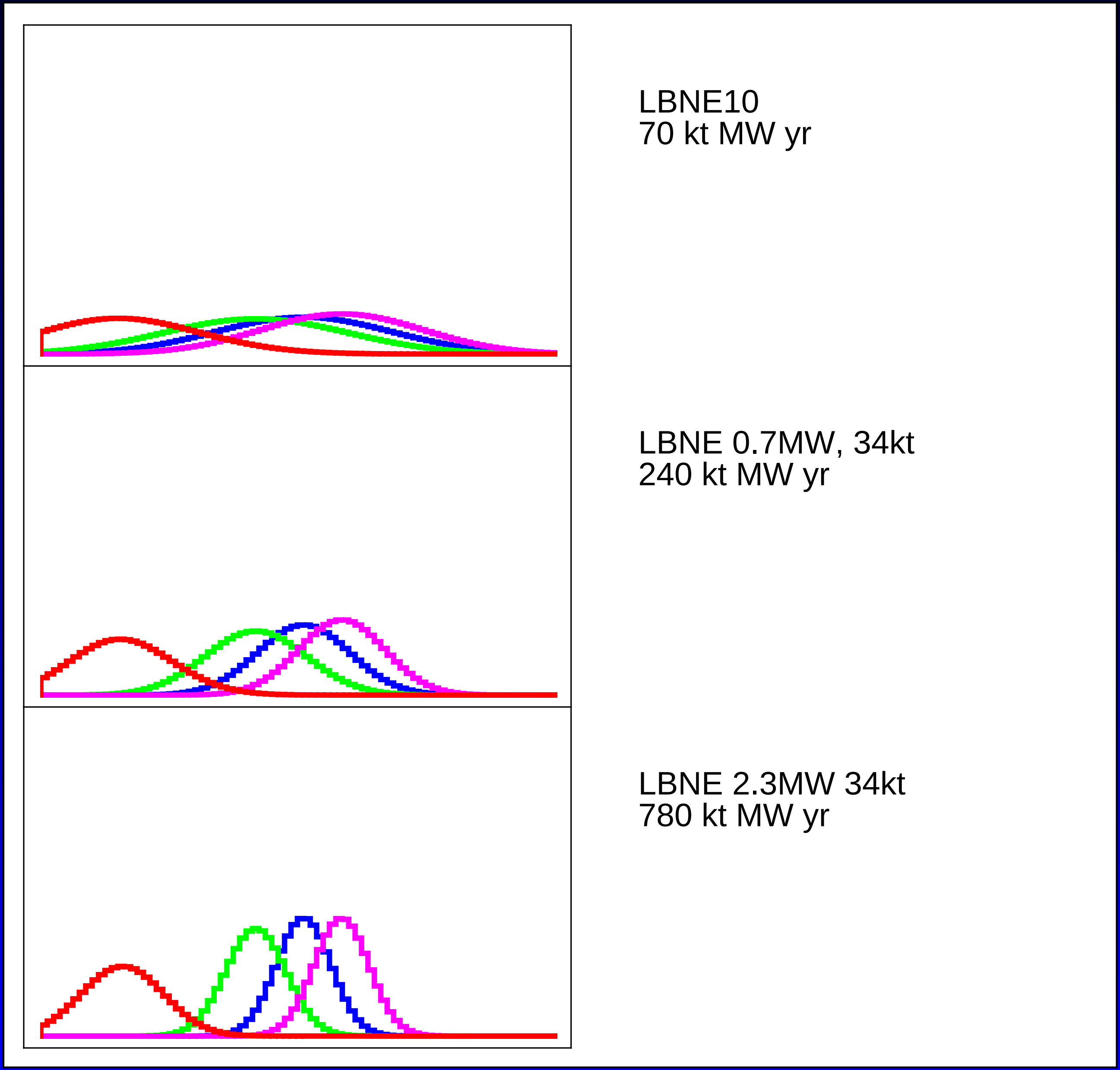
Extrapolating super-beam performances beyond several 100 kt MW years is entirely dependent on the assumptions on systematics!

LBNE10 – 70 kt MW yr
LBNE – 238 kt MW yr
LBNE + Project X – 782 kt MW yr
T2HK –3920 kt MW yr
NuMAX+ 34kt – 1020 kt MW yr

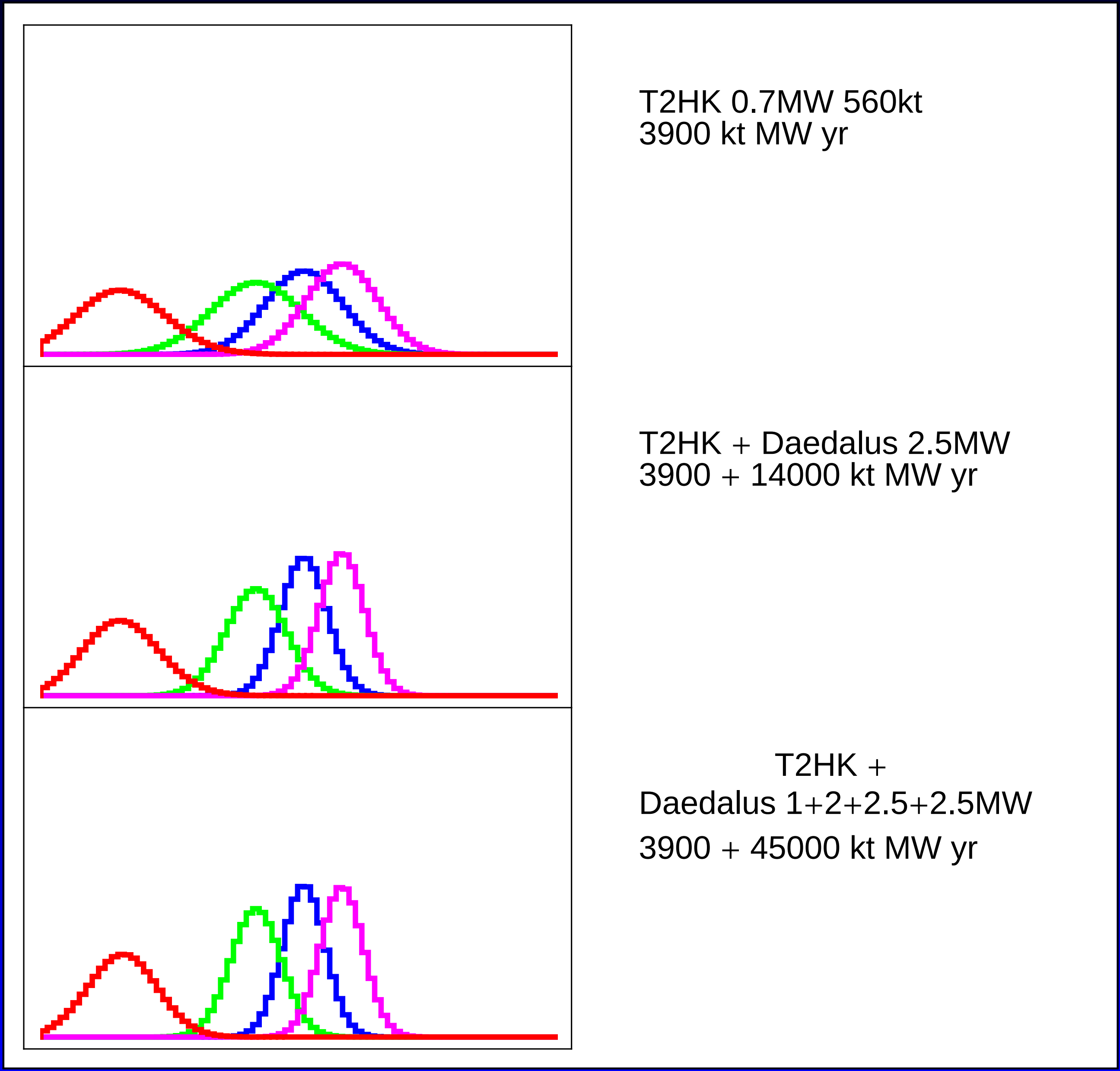
Is 5° feasible?



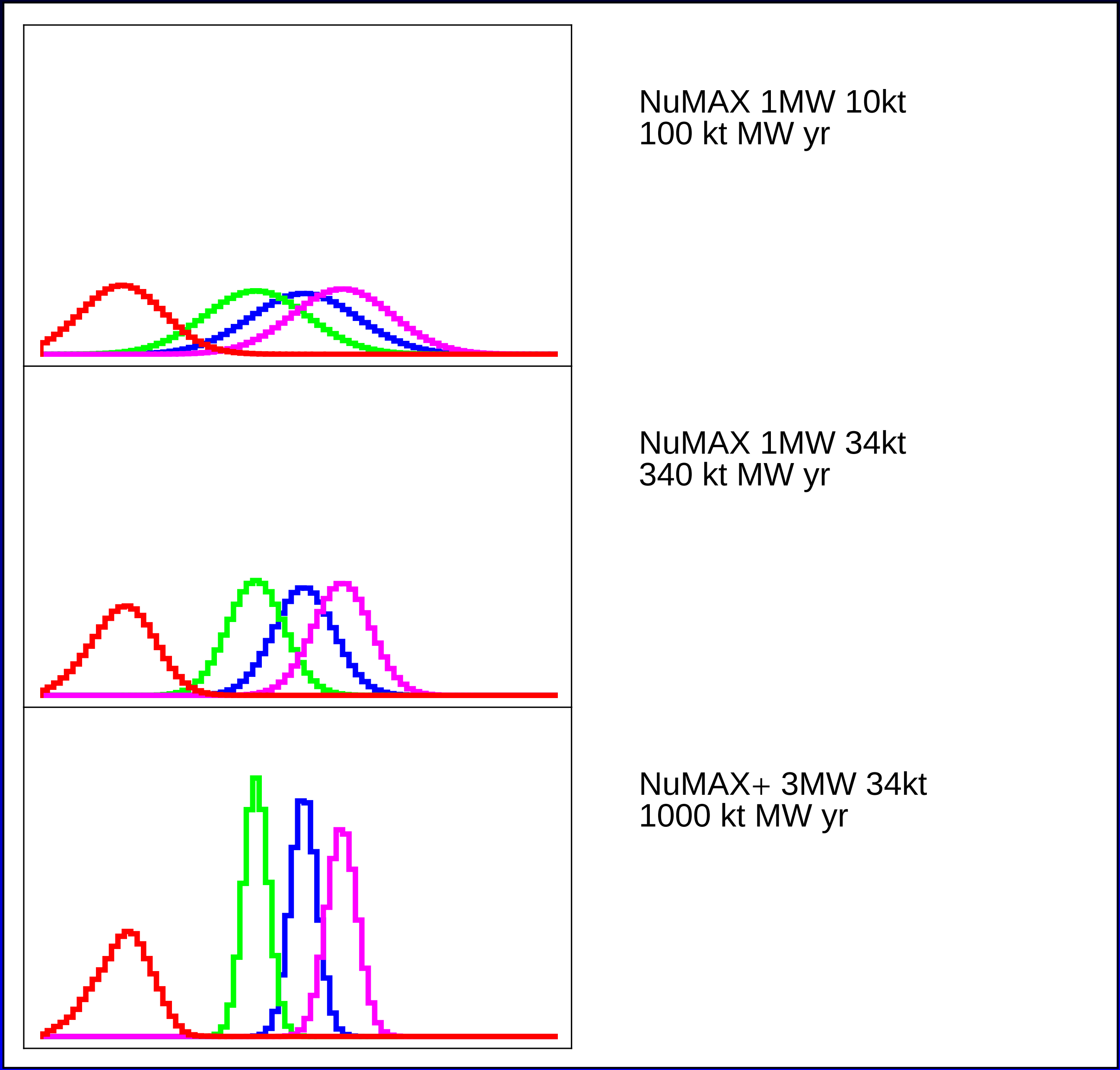
Sumrules and LBNE



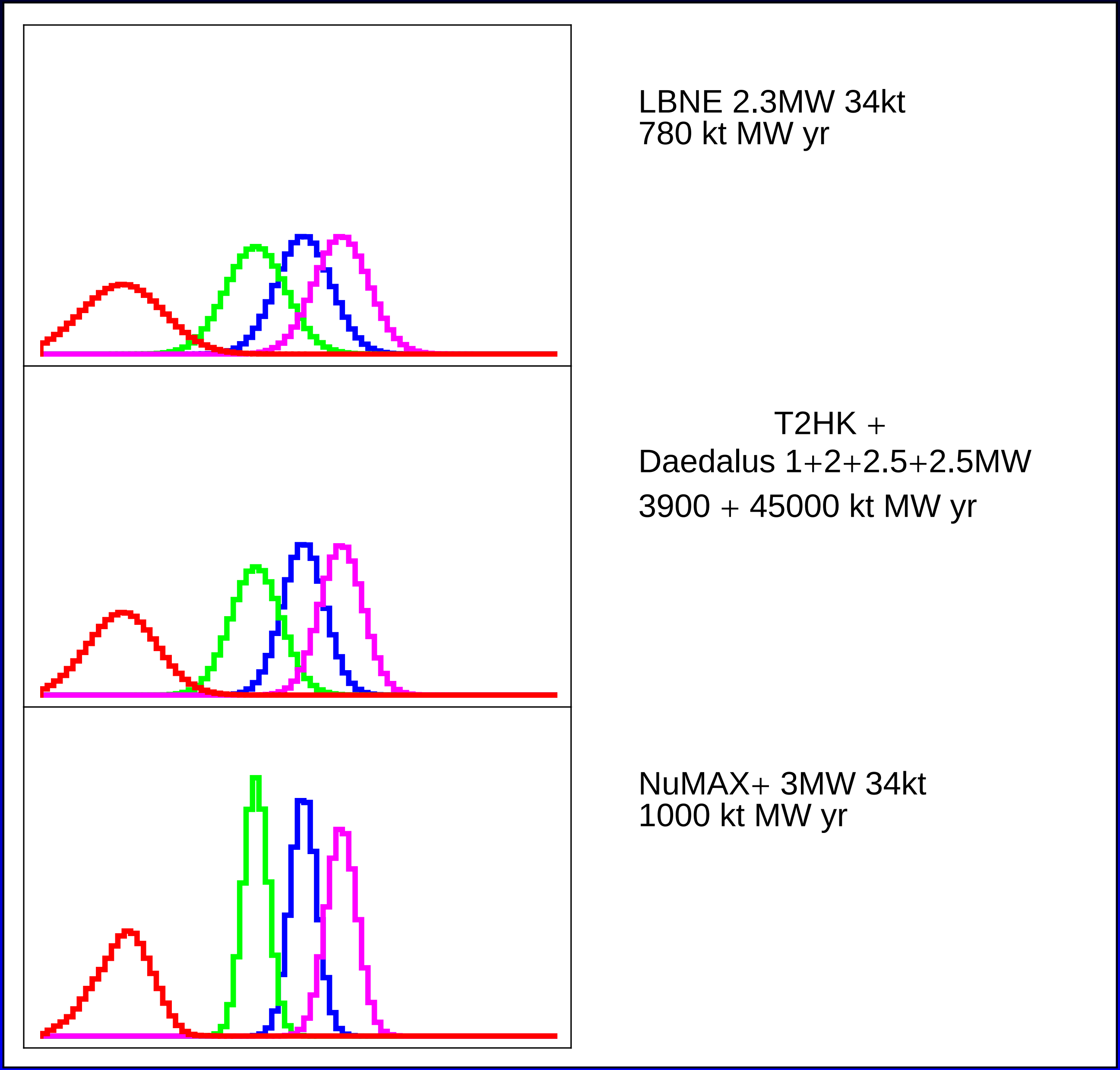
Sumrules and T2HK



Sumrules and NuMAX



Sumrules comparison



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
- High precision counteracts the indirect nature of neutrino measurements
- Precision statements tend to be model-dependent

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