

Neutrino Factories

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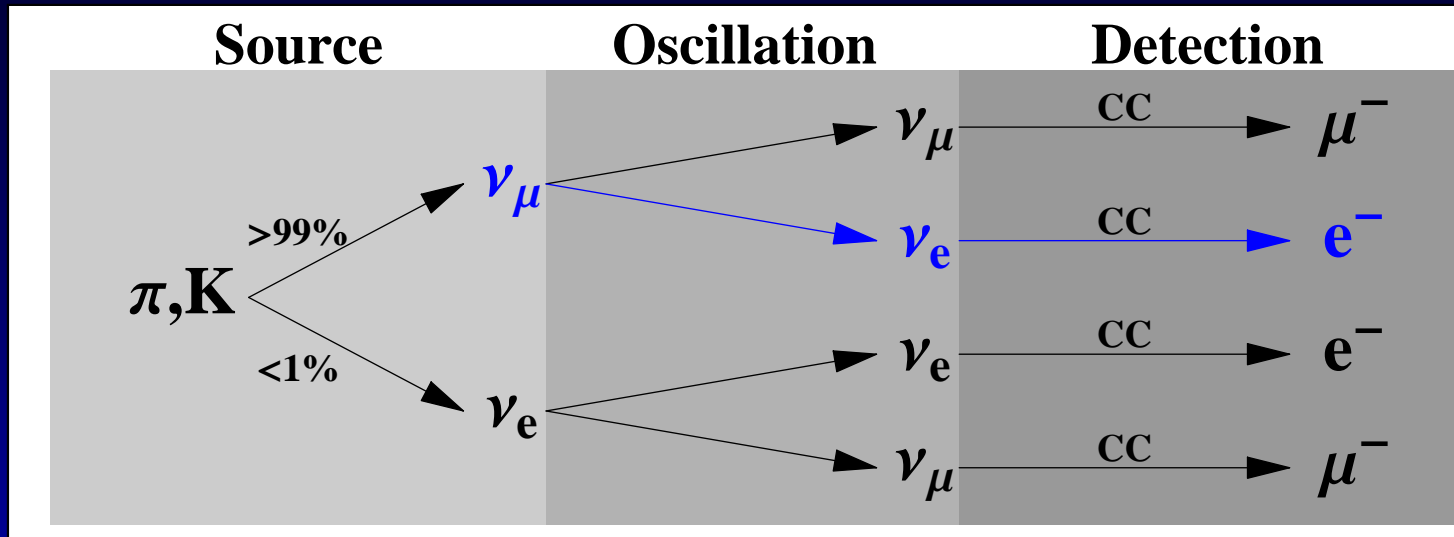
Outline

- What is a neutrino factory?
- Why should you care about neutrinos?
 - Neutrino mass is BSM
 - Window to theory of flavor
 - New interactions
 - Fermion portal aka sterile neutrinos
- Summary & Outlook

TLDR - a neutrino factory is the mother of all neutrino beams.

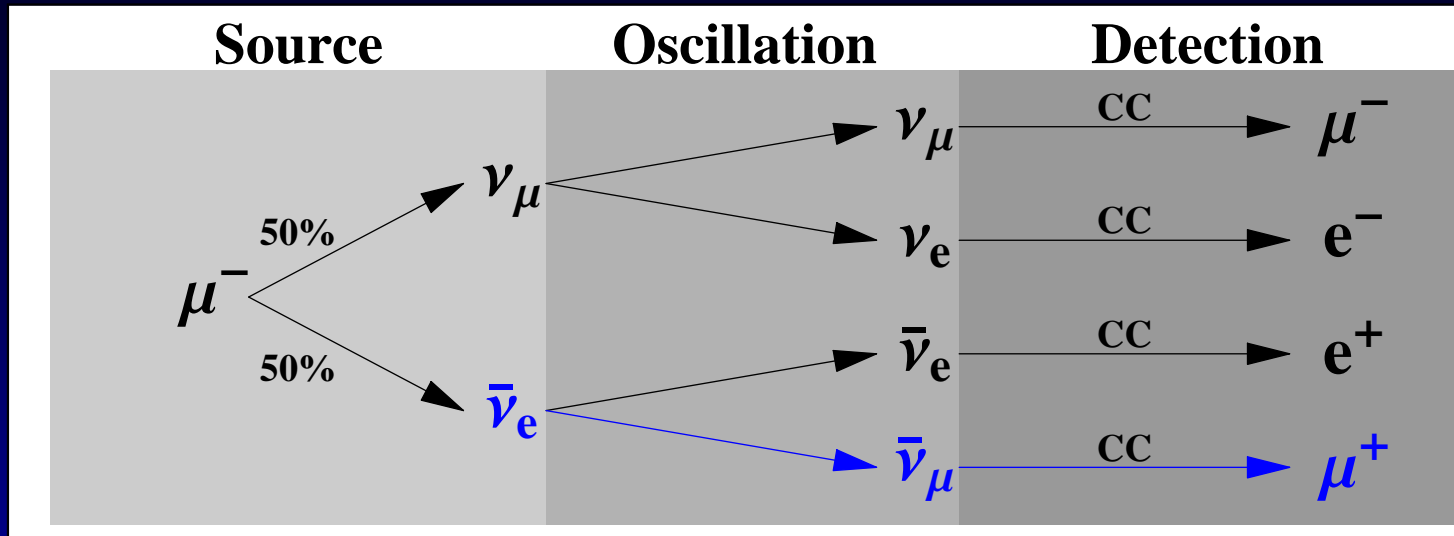
Traditional beam

Neutrino beam from π -decay



- primary ν_μ flux constrained to 5-15%
- ν_e component known to about 20%
- anti-neutrino beam systematically different – large wrong sign contamination
- ν_e difficult to distinguish from NC events

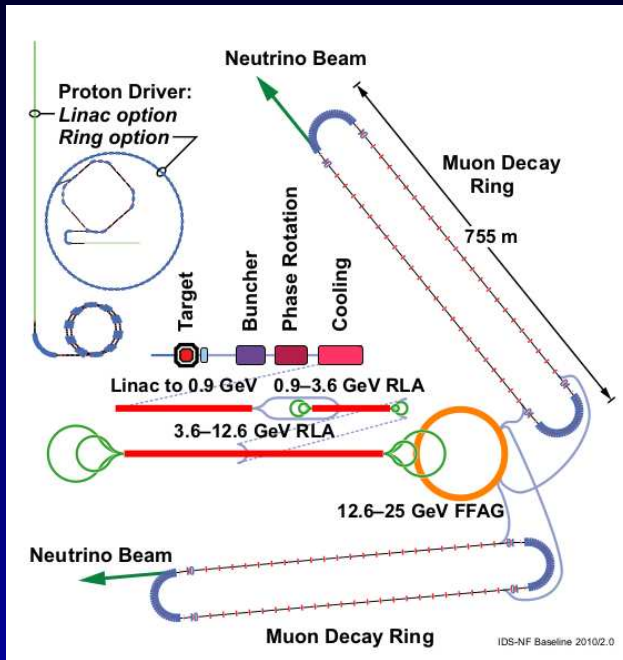
Neutrino factory beam



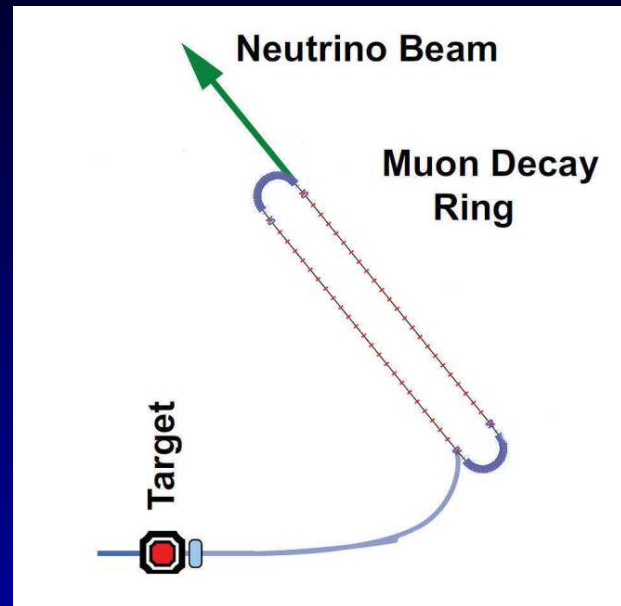
This requires a detector which can distinguish μ^+ from $\mu^- \Rightarrow$ magnetic field of around 1T

- beam known to $\%$ -level or better
- muon detection very clean
- multitude of channels available, including ν_τ

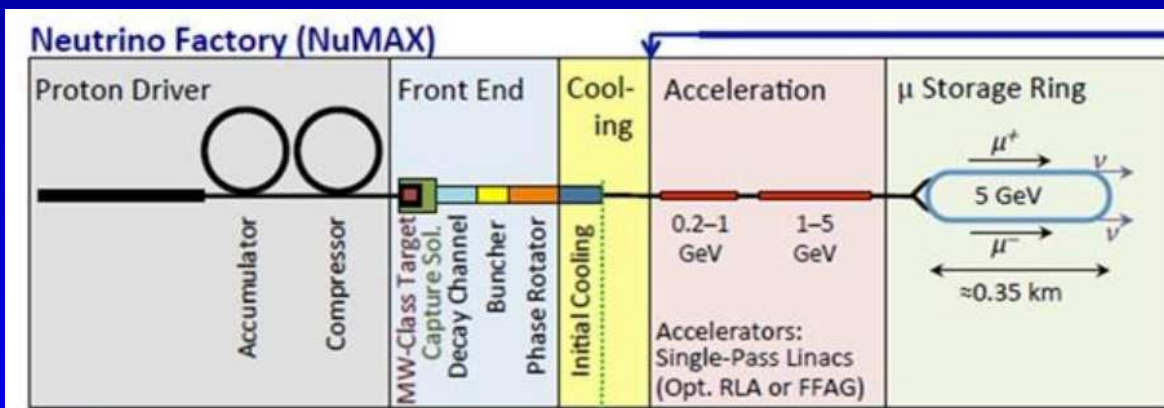
Neutrino factories



IDS, 2010



nuSTORM, 2012



MAP/MASS, 2013

muon cooling for high luminosity

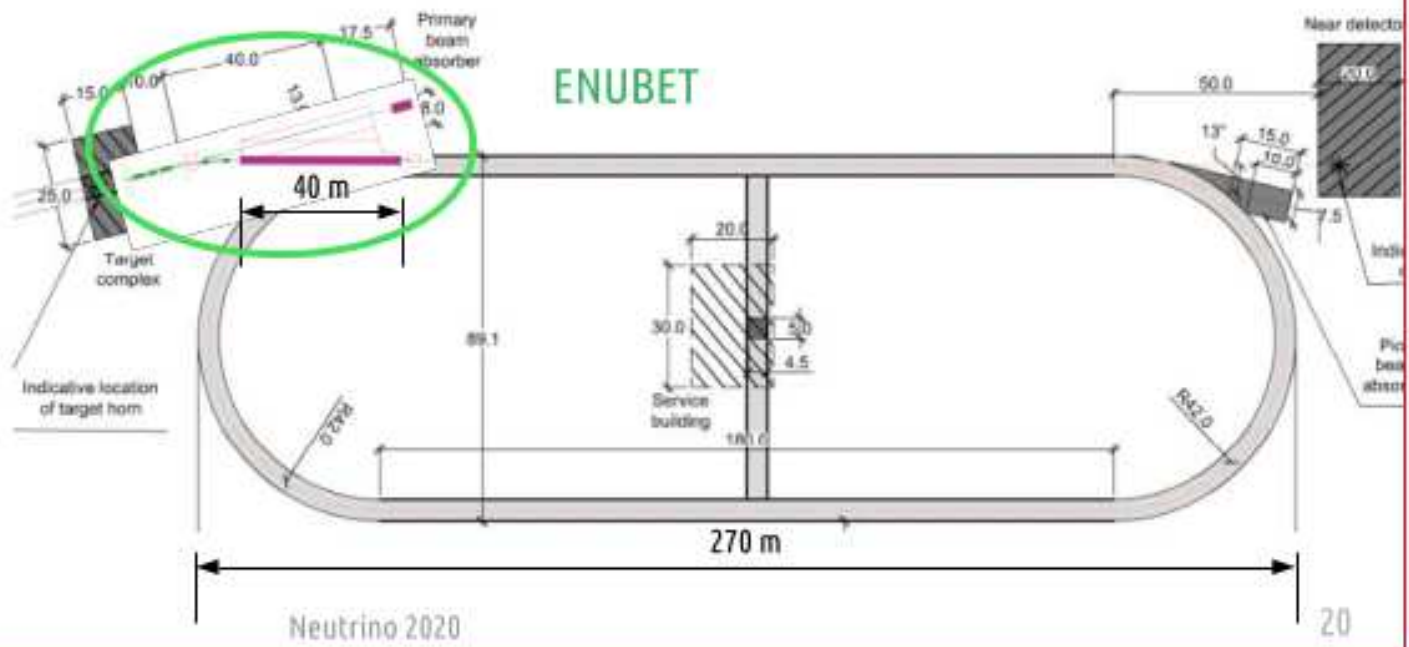
high energy for BSM physics

nuSTORM & ENUBET



	Decay region	Hadron dump	Proton extraction	Target, sec. transfer line, p-dump	Neutrino detector
ENUBET	~40 m. Instrumented.	Yes. Dumps muons in addition preventing a (small) ν_e pollution to $K_{e3} - \nu_e$	Slow, 400 GeV (flexible)	Yes, similar	~100 m (some flexibility)
nuSTORM	Replaced by straight section of the ring (180 m).	No. Muons are kept: the most interesting flux parents.	Fast, 100 GeV	Yes, similar	> 300 m from target (ring straight section)

- Different concepts, budget, geometry.
- Main synergy: target facility, 1st stage of meson focusing, proton dump.



Neutrinos are massive – so what?

Neutrinos in the Standard Model (SM) are strictly massless \Leftrightarrow neutrino oscillation is BSM physics!

... yes, this is not SUSY, large extra dimensions or anyone's favorite BSM model, but it **IS the only** laboratory-based proof for the incompleteness of the SM.

Alas, it is indirect evidence: no energy scale, no symmetry, no new interaction, no new particles are seen in the laboratory.

Neutrinos in a nutshell

$m_\nu \lesssim 1 \text{ eV}$, could be Dirac or Majorana

Quarks

Neutrinos

$$|U_{CKM}| = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix} \quad |U_\nu| = \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Majorana mass term allows for things like seesaw and could be simple explanation why mixings so different.

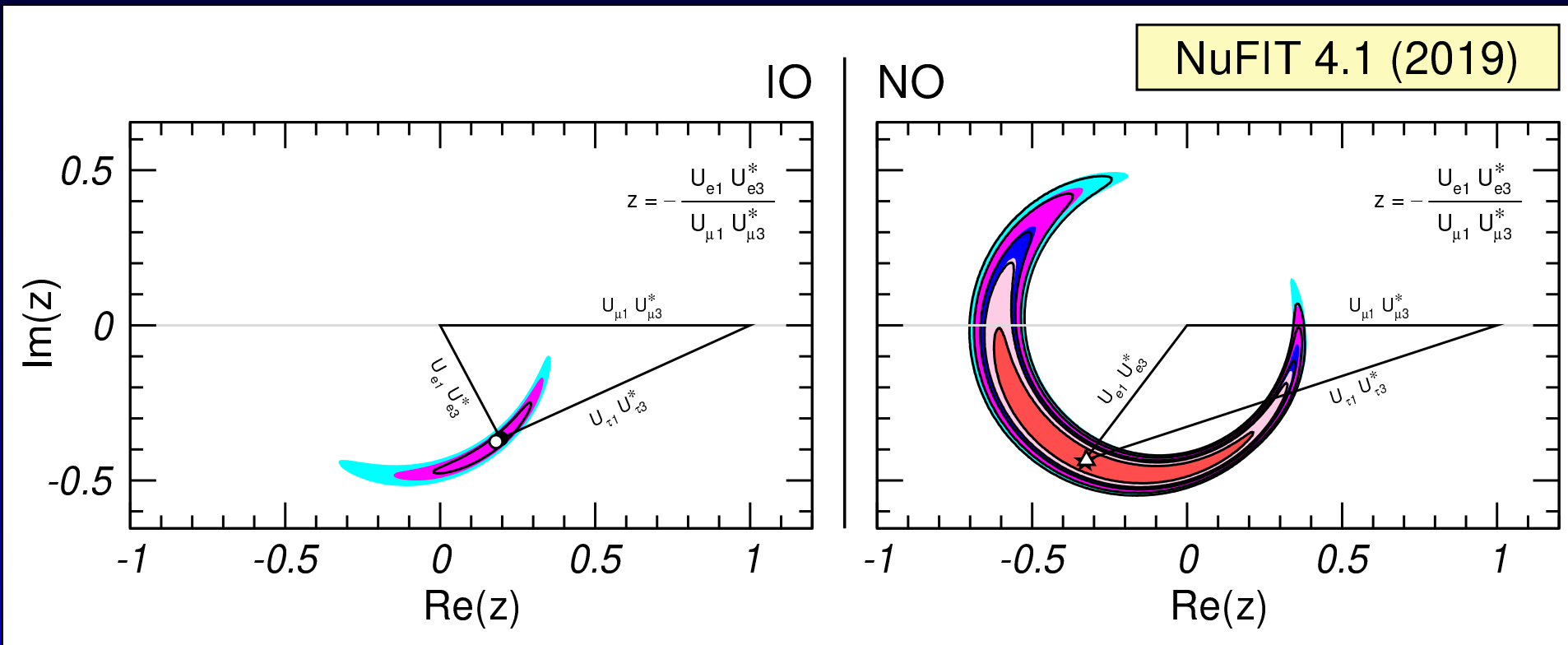
CP violation

There are only very few parameters in the ν SM 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...

Unitarity triangles



We currently have no way to directly measure any of sides containing ν_{τ} .

Non-standard interactions

NSI are the workhorse for BSM physics in the neutrino sector. They can be parameterized by terms like this

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

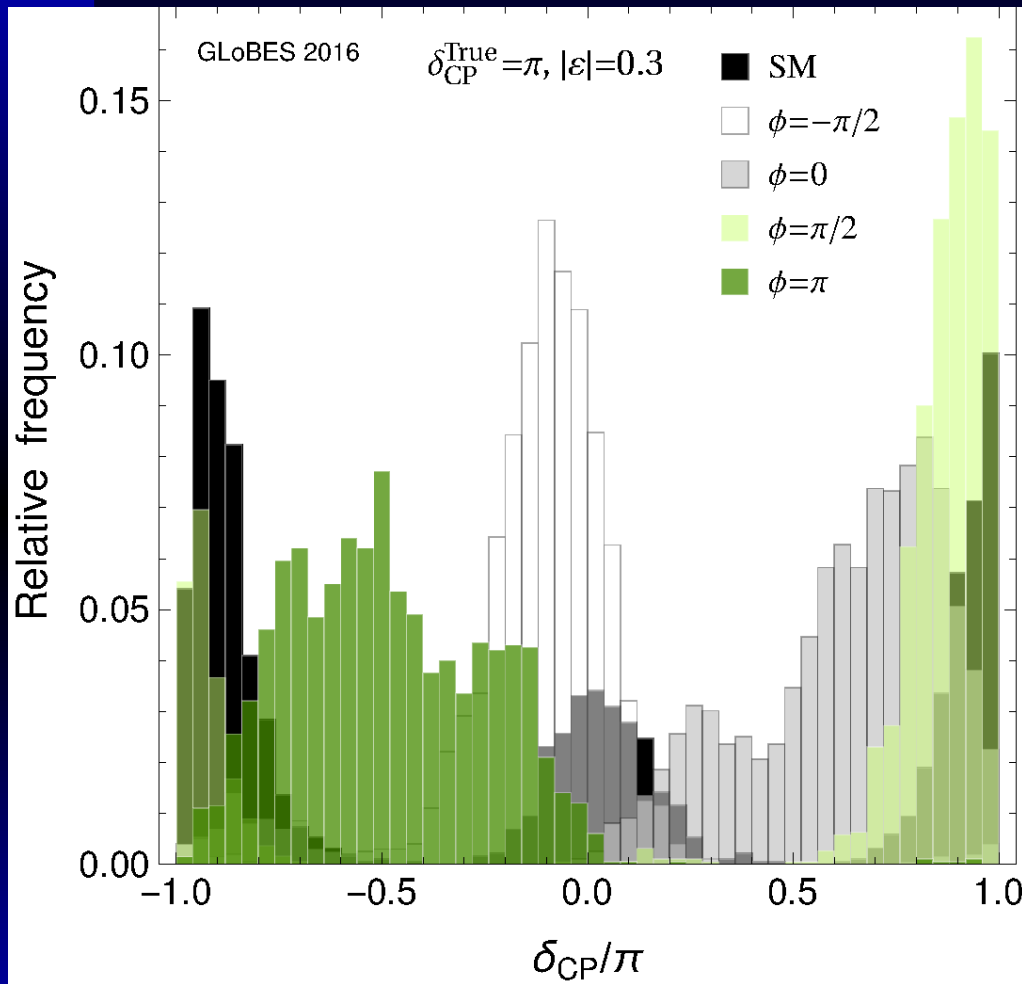
Wolfenstein, 1978

NB – difficult to build UV-complete models with large effects, e.g Farzan, 2015

Systematic matching to SM EFT also possible, resulting in relationships between the naive ϵ 's.

Falkowski, González-Alonso, Tabrizi, 2019

Impact on three flavors

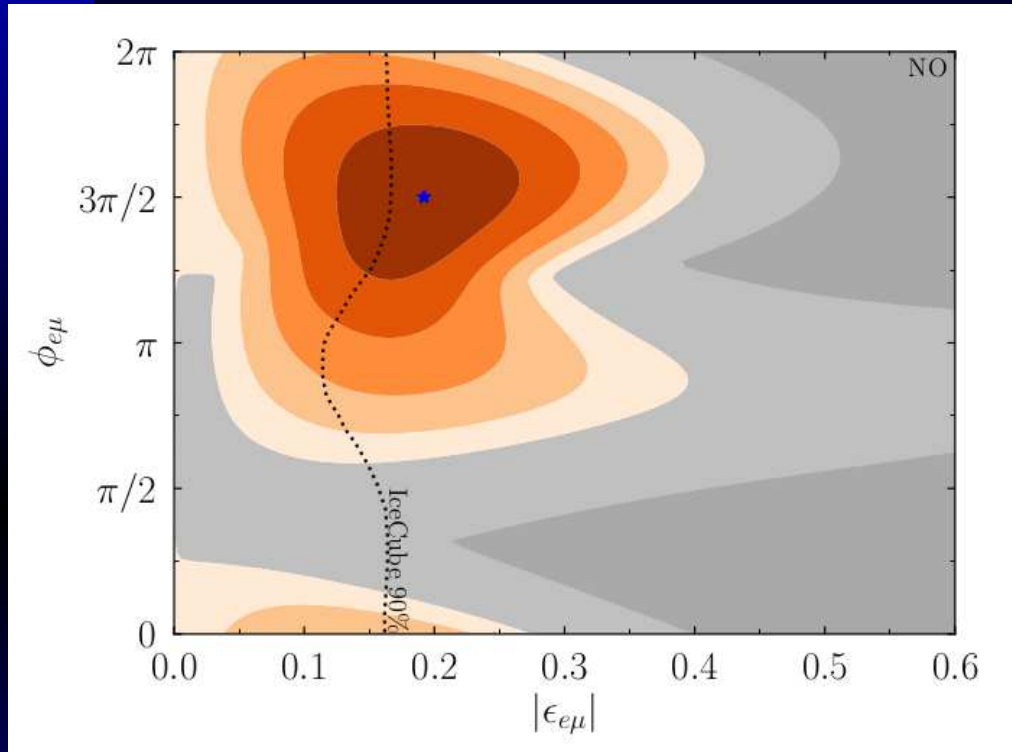


Three flavor analysis are not safe from these effects!

PH, D. Vanegas, 2016

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

NSI 2020



2020 NOvA and T2K data is slight tension

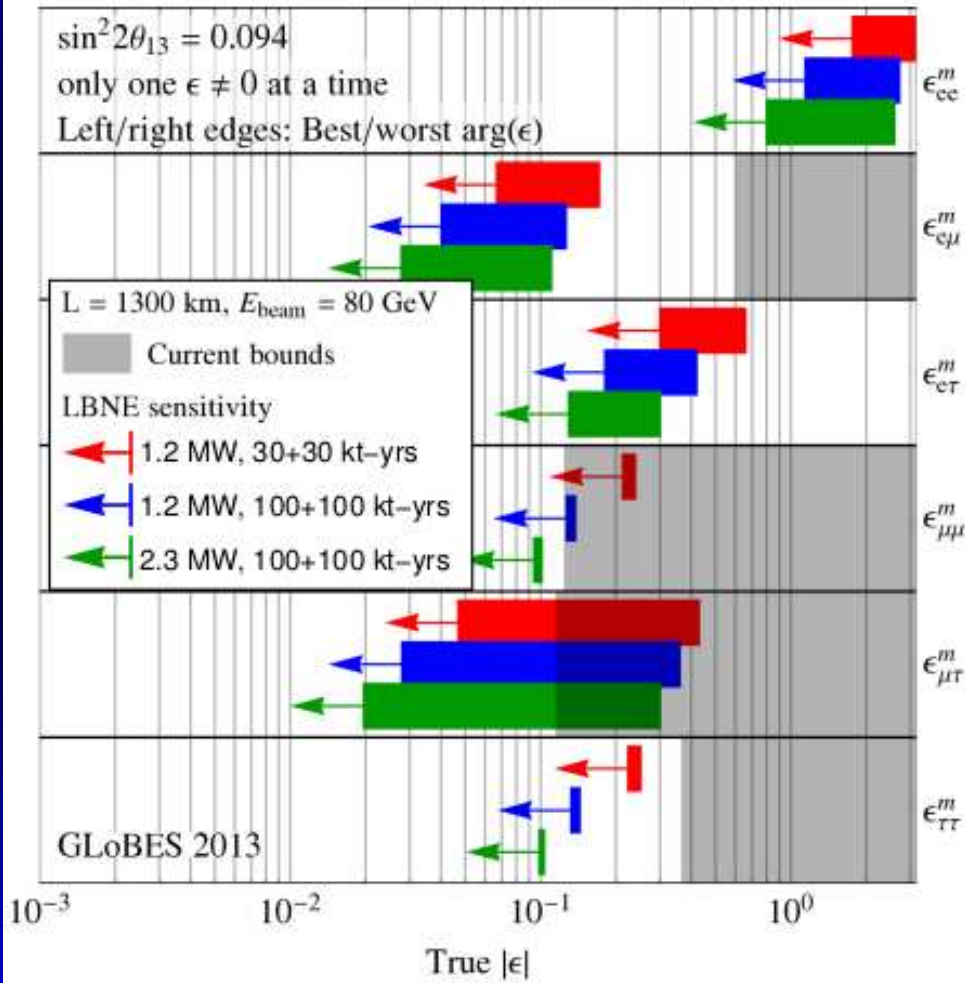
CP violating NSI could be the explanation.

Gehrlein, Denton, Pestes, 2020

Every time T2HK & DUNE find different values for oscillation parameters the same game will be played and we'll never know if it's real or just systematics.

DUNE & NSI

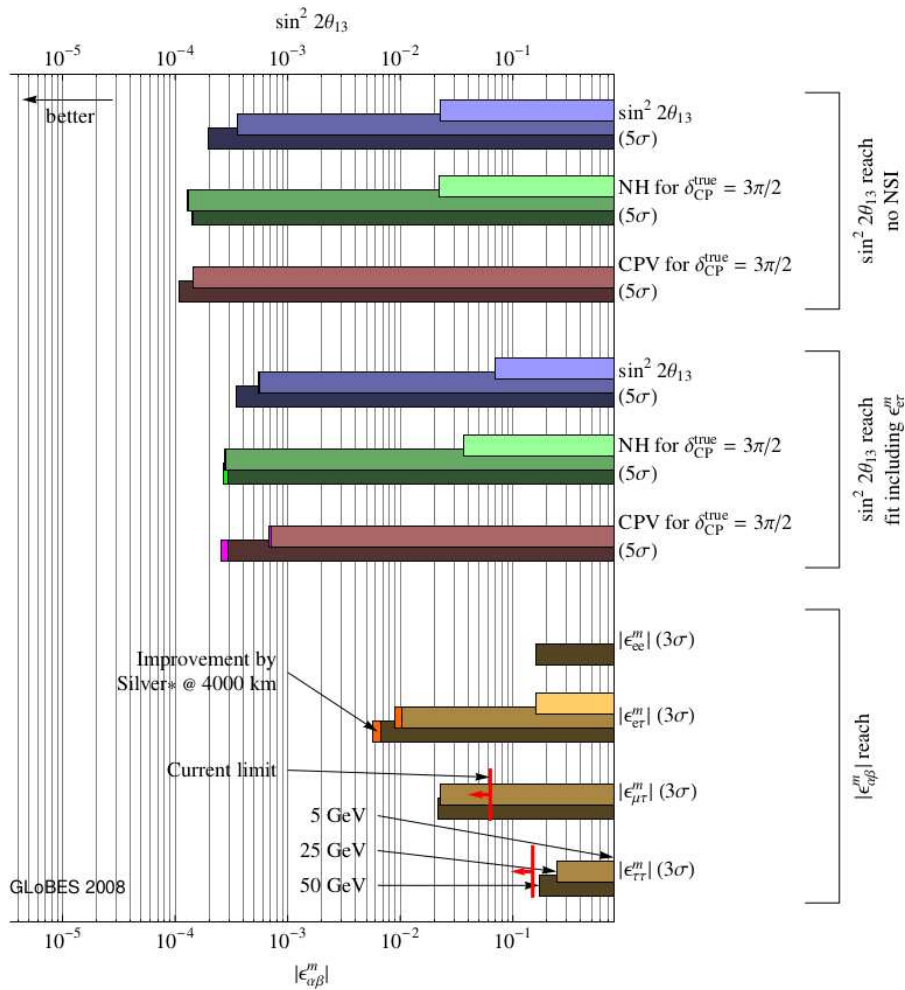
NC NSI discovery reach (3σ C.L.)



NC NSI modifies matter effects

Only one NSI parameter at a time.

Neutrino factory & NSI



Includes correlation between NSI parameters

Generally, one order of magnitude improvement with respect to DUNE/T2HK

Improves further with ν_τ detection in near detector *Antusch et al. 2009.*

Kopp, Ota, Winter, 2008

Flavor models

Simplest un-model – anarchy **Murayama, Naba, DeGouvea**

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

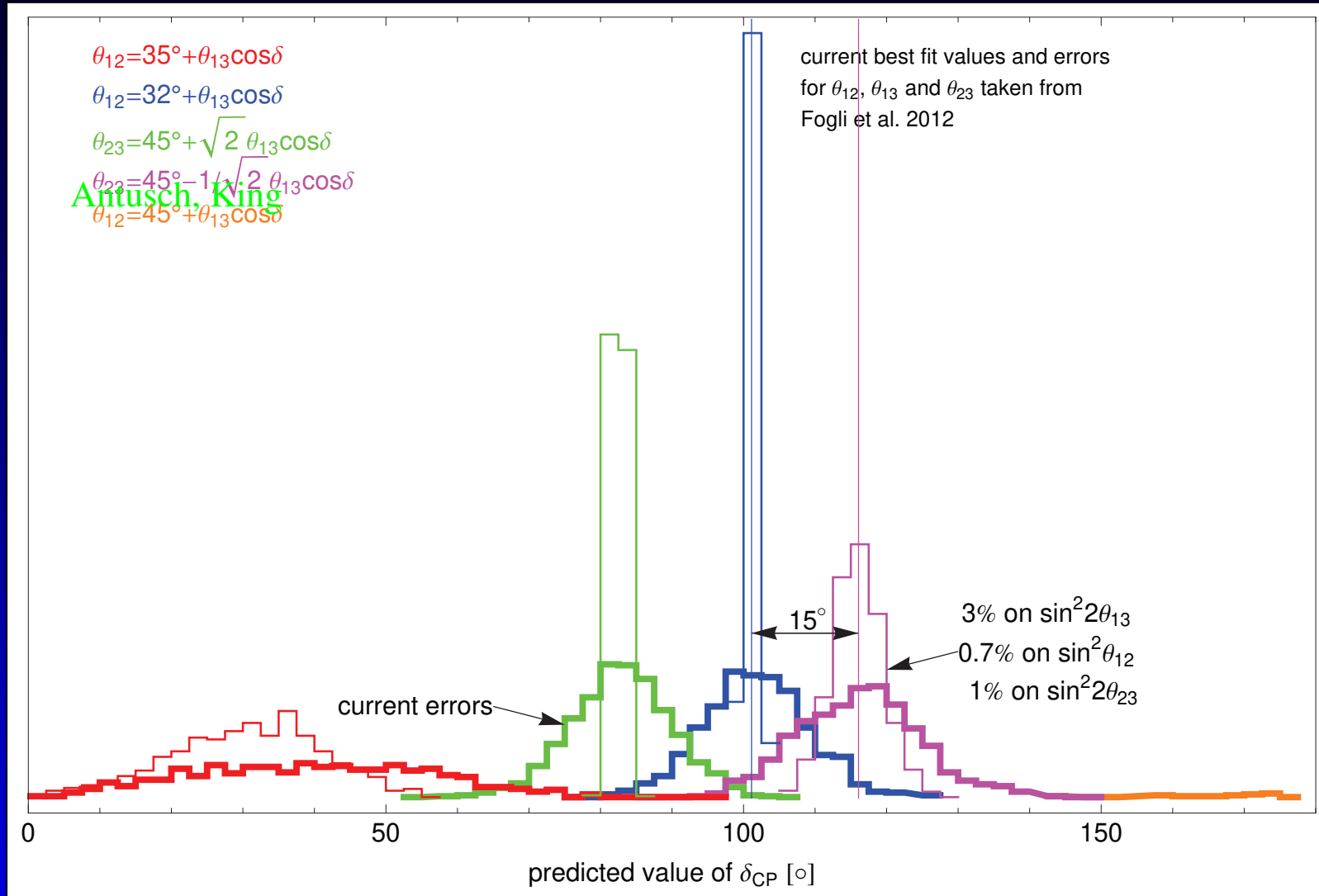
predicts flat distribution in δ_{CP}

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

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

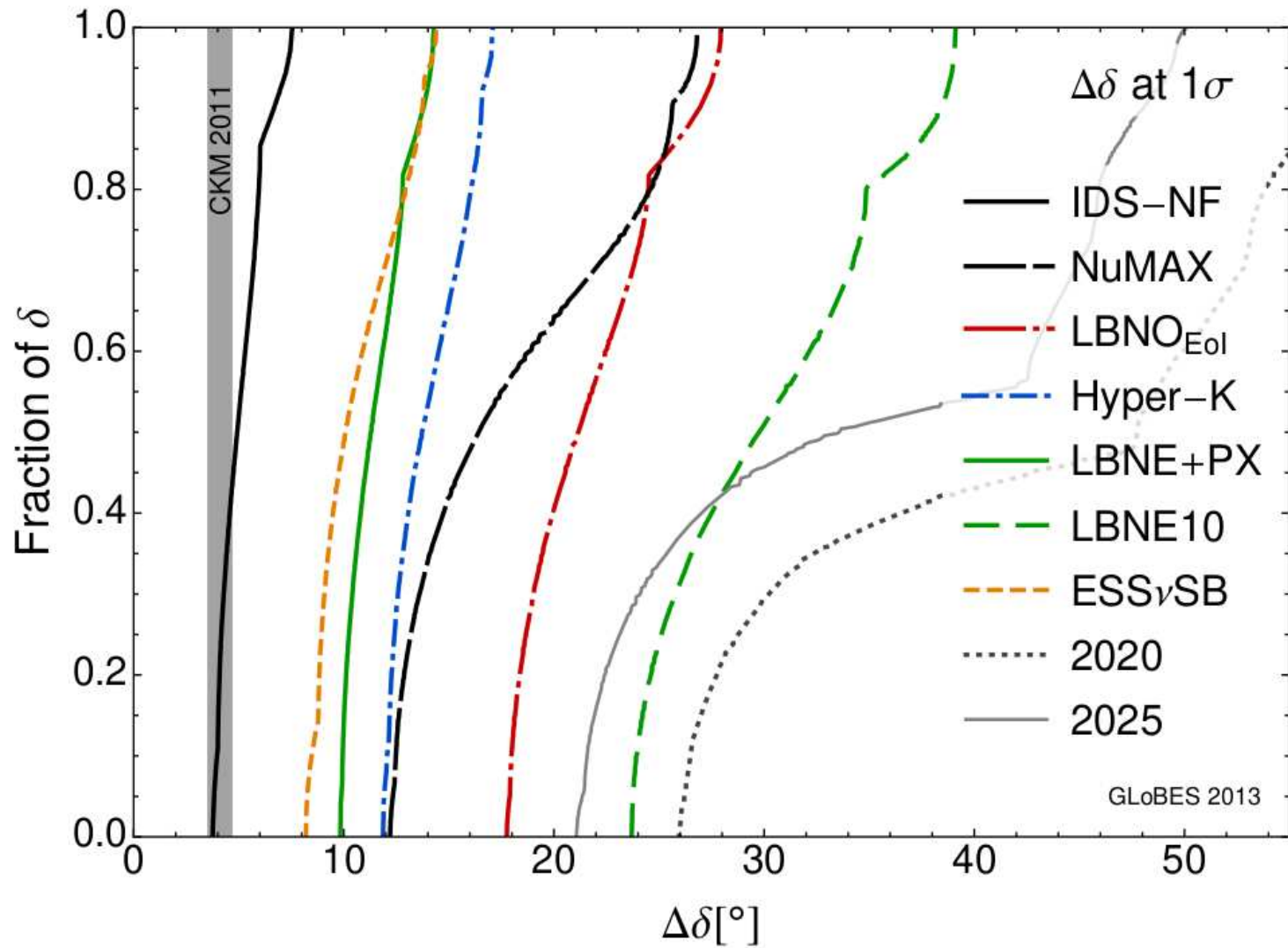
obviously corrections are needed – predictivity?

Sum rules

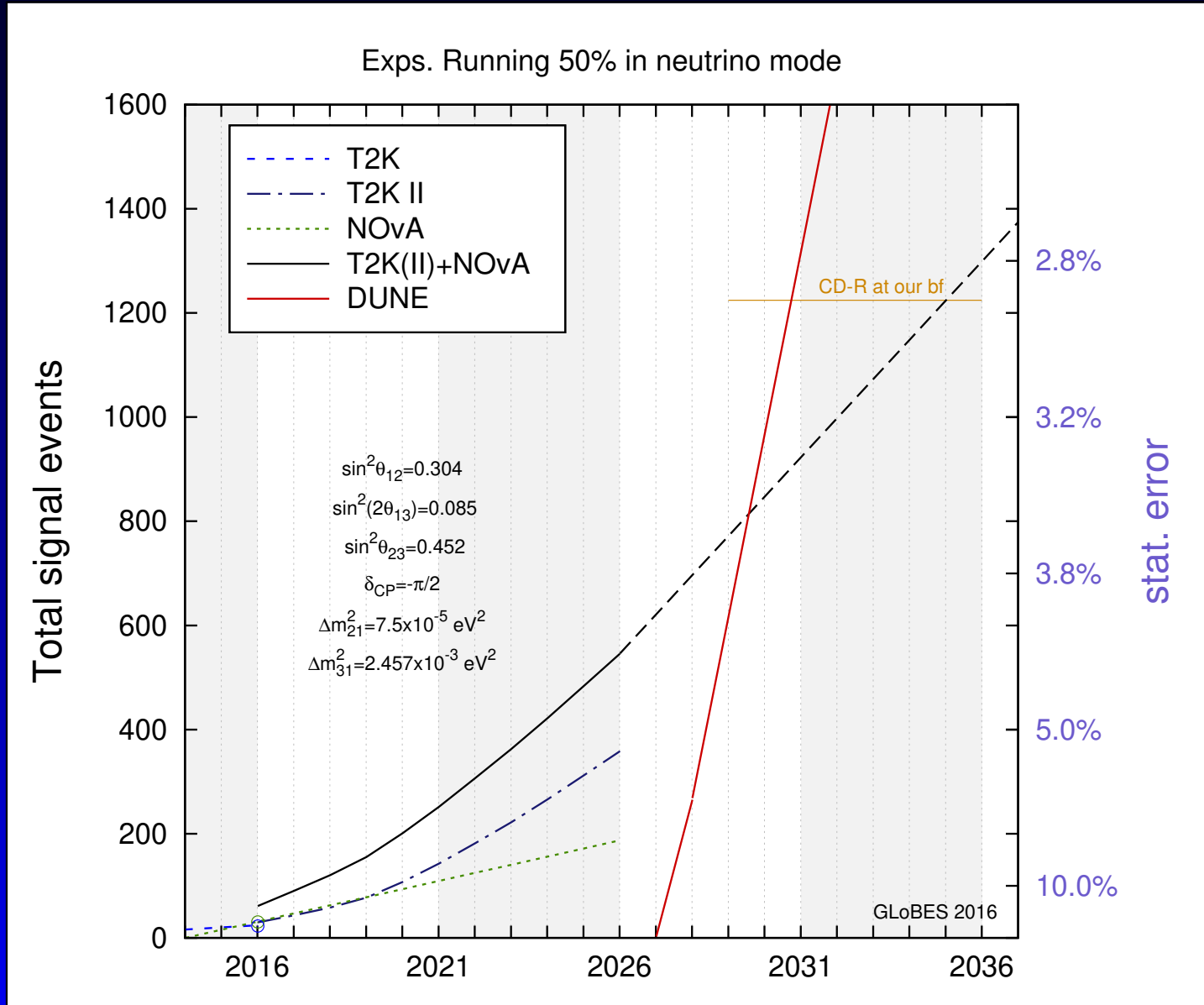


NB – smaller error on θ_{12} requires dedicated experiment like JUNO

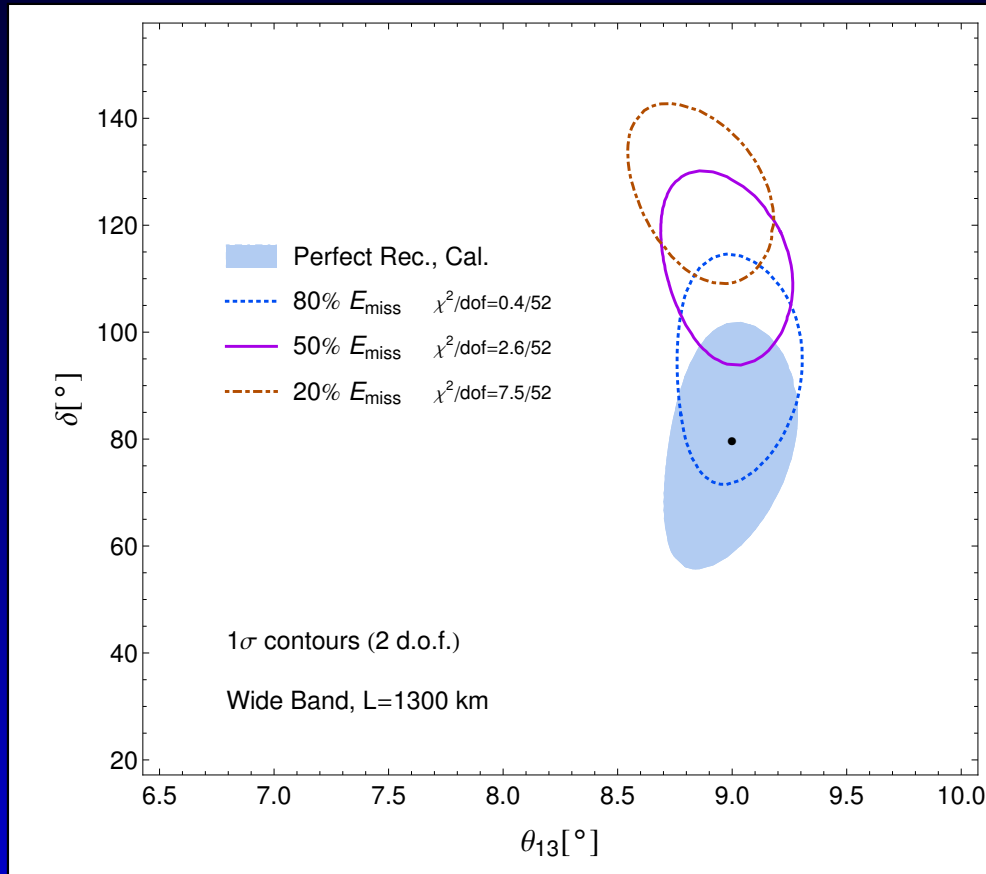
Is 5° feasible?



The way forward



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

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 working on this...

Without being anchored by data, any result will be based on assumptions and uncontrolled approximations.



Requires a novel precision, high-luminosity neutrino source \Rightarrow nuSTORM & ENUBET

The big question

Things the Standard Model does NOT explain

- Neutrino mass
- Dark matter
- Baryon asymmetry
- Dark energy
- Gravity

50 years of ideas, most have been retired by flavor physics and LHC results

Is there anything within our means we can find?

NB: None of the neutrino properties & discoveries was anticipated by theory.

Outlook

- Neutrino physics has a lot of room for surprises, so it makes sense to push sensitivities even after DUNE/T2HK.
- Persistent hints for new degrees of freedom around 1-10 eV.
- A neutrino factory would be a “must fund” if:
 - the eV-scale anomalies are confirmed,
 - T2HK and DUNE find different oscillation parameters, **which is basically guaranteed**
 - a robust theory of flavor emerges.

A neutrino factory has strong synergies with muon collider R&D and could help to motivate the necessary investment.