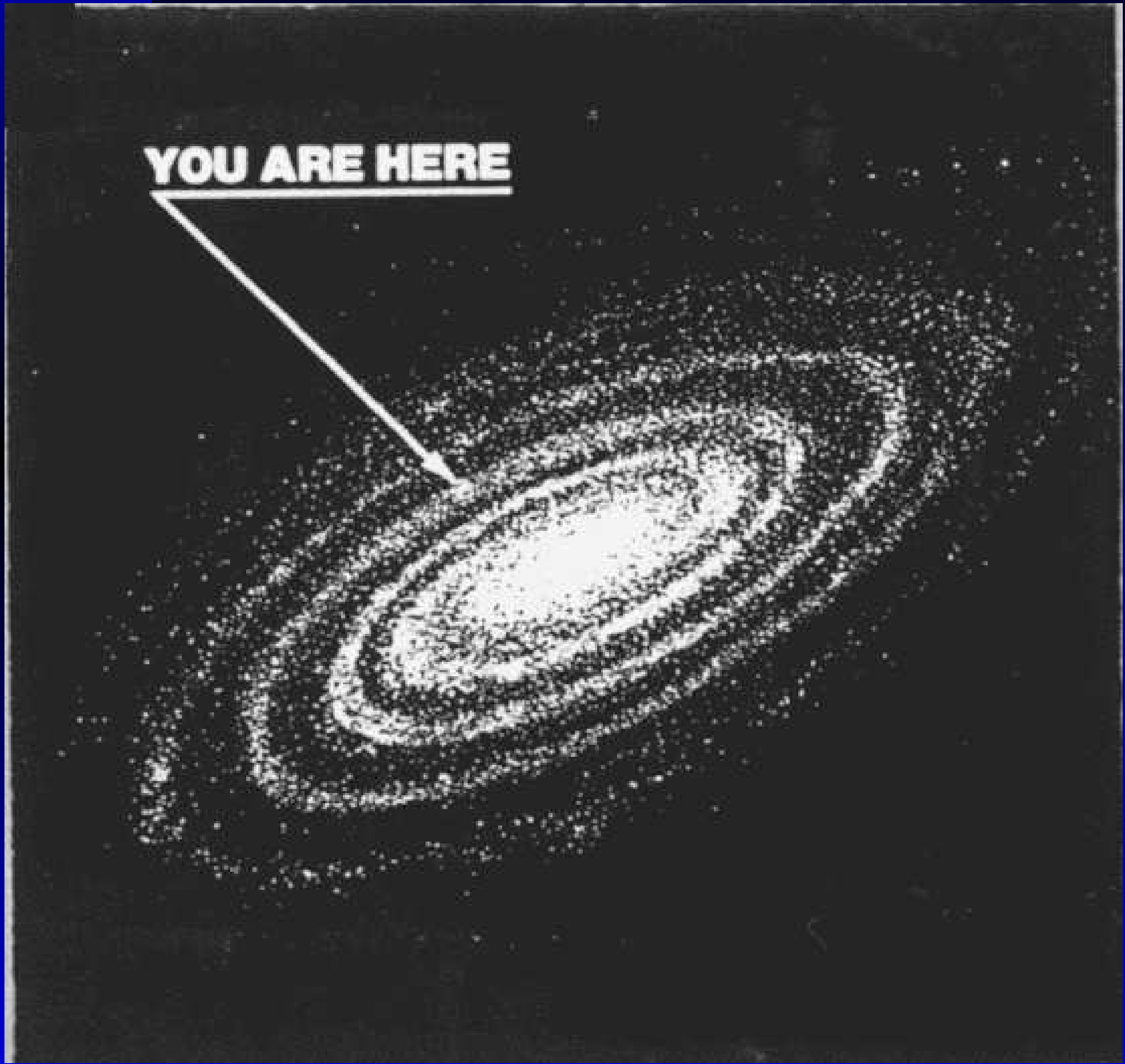


Patrick Huber

Center for Neutrino Physics
at Virginia Tech

NuFact 2012
International Workshop on
Neutrino Factories,
Super Beams
and Beta Beams
July 23-28, 2012

Williamsburg, VA USA

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 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

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

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.

What we want to learn

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

Given the current state of the theory of neutrinos we can not say with confidence that any one quantity is more fundamental than any other.

Large θ_{13} – implications

The Daya Bay result is

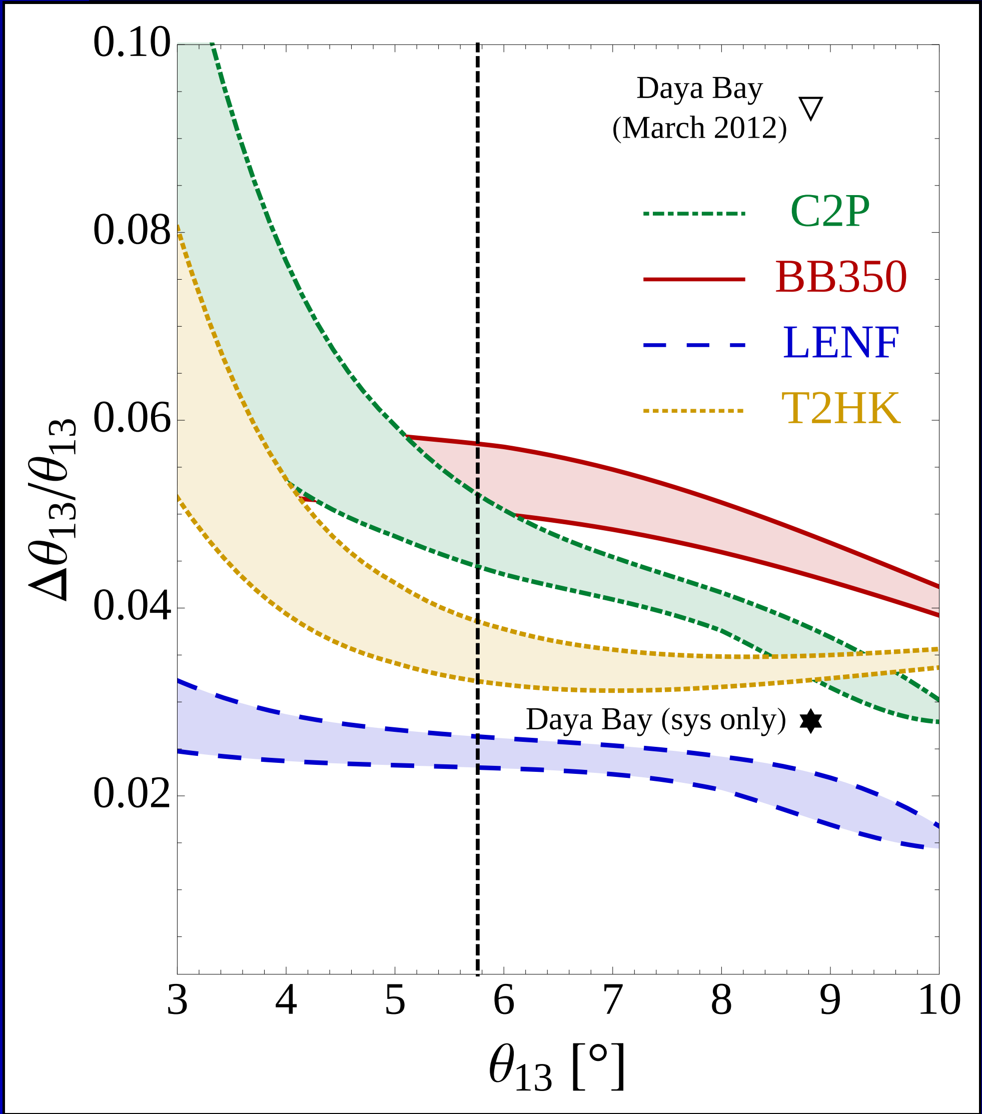
$$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst}) \,,$$

which translates into a more than $5\,\sigma$ exclusion of $\theta_{13} = 0$, confirmed by RENO. What are the implications for future facilities?

In general, this raises the following questions

- Will the mass hierarchy have been determined?
- Are new experiments beyond NOνA and T2K necessary?
- Are superbeams sufficient?

θ_{13}



FAPP θ_{13} will be known to very high accuracy

At $\sin^2 2\theta_{13} = 0.1$ the measurement error at T2K will be 10%

At $\sin^2 2\theta_{13} = 0.1$ the measurement error at Daya Bay will be <5%

Agreement of values of θ_{13} from reactors (disappearance) and beams (appearance) constitutes a critical test of the 3 flavor framework

P. Coloma, A. Donini, E. Fernandez-Martinez, P. Hernandez, arXiv:1203.5651

Large θ_{13} and new physics

In looking for new physics (NP) we generally have

$$P = |A_{\rm SM} + A_{\rm NP}|^2 = A_{\rm SM}^2 + 2A_{\rm SM}A_{\rm NP} + A_{\rm NP}^2$$

With large θ_{13} we have $A_{\rm SM} \gg A_{\rm NP}$ and thus

$$P \simeq A_{\rm SM}^2 + 2A_{\rm SM}A_{\rm NP}$$

which depends linearly on the new physics amplitude, $A_{\rm NP}$

Note, there is not reason to expect the NP to be CP conserving.

Phenomenology of 3×3 active oscillations

CP violation

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 $\nu_e \leftrightarrow \nu_\mu$.

Matter effects

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

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

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

Matter effects

The second consequence of the matter potential is that there can be a resonant conversion – the MSW effect. The condition for the resonance is

$$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\rm res}^{\rm Earth} = 6 - 8\,\mathrm{GeV}$$

Obviously the occurrence of this resonance depends on the signs of both sides in this equation. Thus oscillation becomes sensitive to the mass ordering

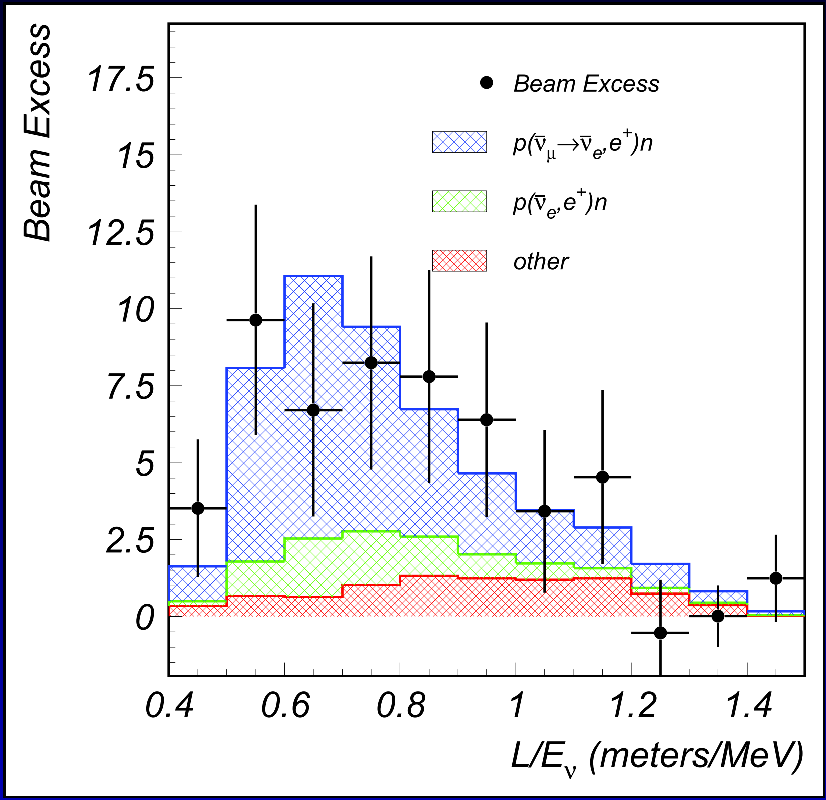
	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

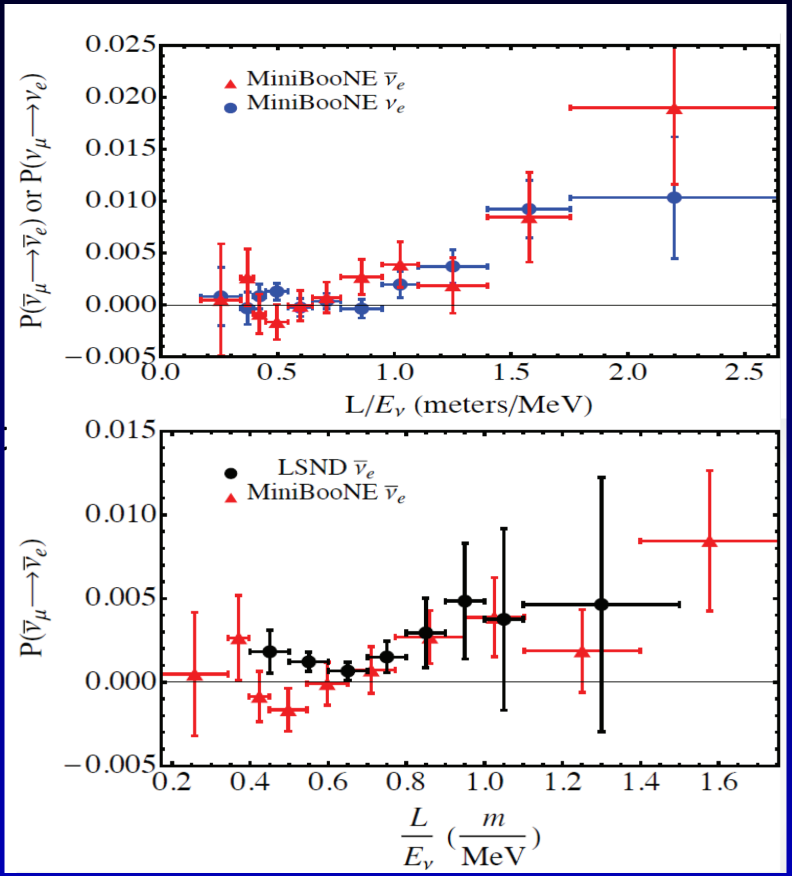
Consequences for experiments

- need to measure 2 out of $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$, $P(\nu_e \to \nu_\mu)$ and $P(\bar{\nu}_e \to \bar{\nu}_\mu)$
- need more than 1 energy and/or 1 baseline
- matter resonance at $6 - 8\,\mathrm{GeV}$
- matter effects sizable for $L > 1\,000\,\mathrm{km}$
- large θ_{13} implies small CP asymmetries
  $\Rightarrow$ need for small systematics

Short-baseline anomalies

LSND and MiniBooNE

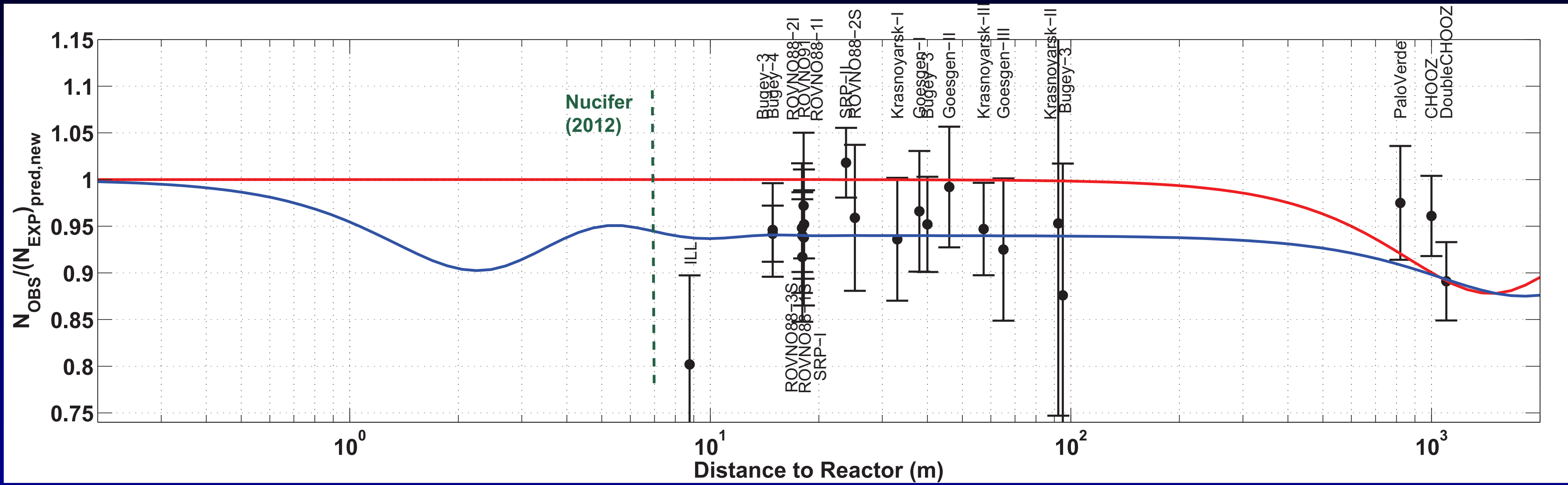




$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq 0.003$$

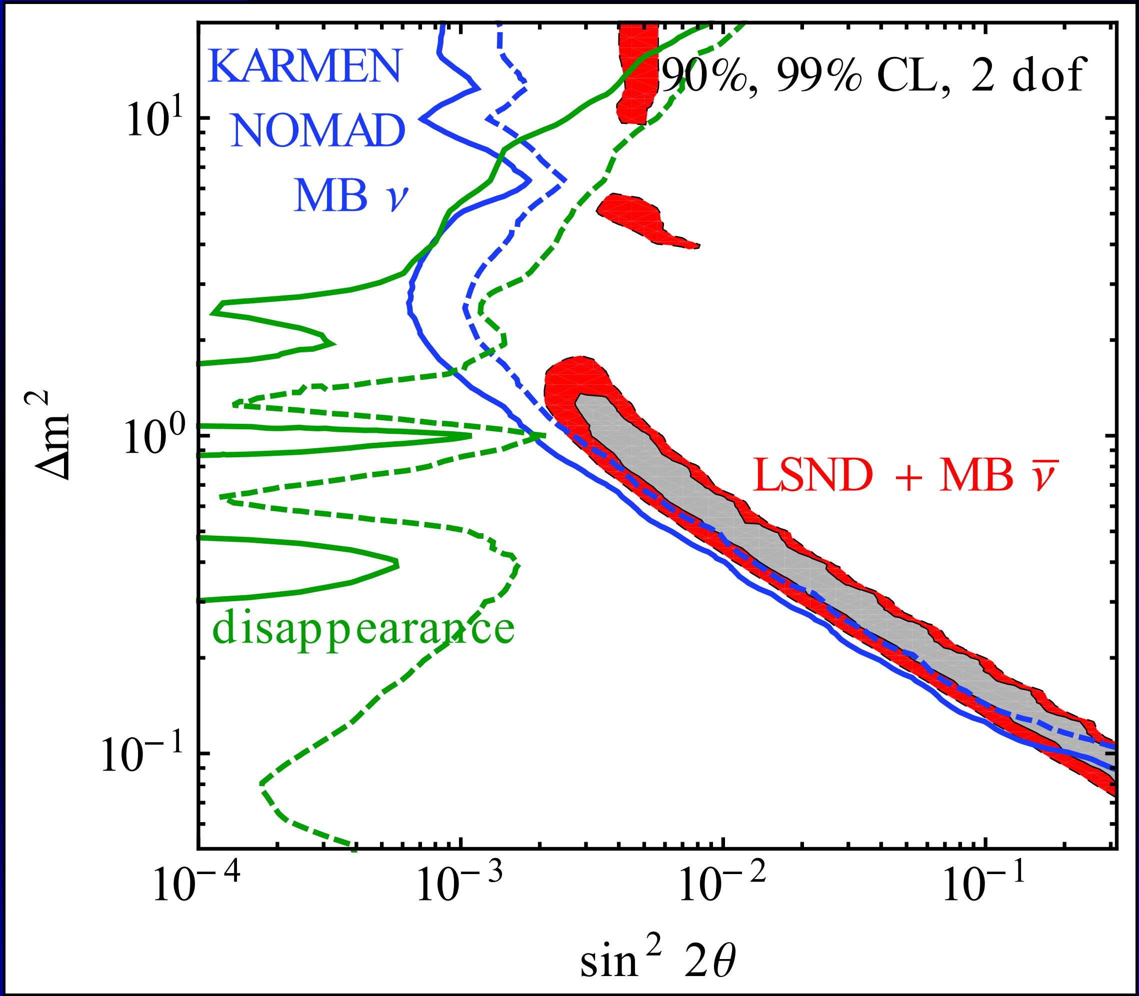
Tension between neutrino and antineutrino signals?

Reactor and Gallium anomalies



	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R_B^k	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm ^{+0.084}_{-0.078}$
R_H^k	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm ^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0		1.47	
source height [m]	2.7	2.38	0.72	

Disappearance constraints



Absence of effects in

- atmospheric
- Bugey
- CDHS
- MINOS
- …

data creates considerable tension in 3+N sterile neutrino models

More details can be found in the sterile neutrino white paper, arXiv:1204.5379.

Sterile oscillation

In general, in a 3+N sterile neutrino oscillation model one finds that the energy averaged probabilities obey the following inequality

$$P(\nu_\mu \to \nu_e) \leq 4 P(\nu_e \to \nu_e) P(\nu_\mu \to \nu_\mu)$$

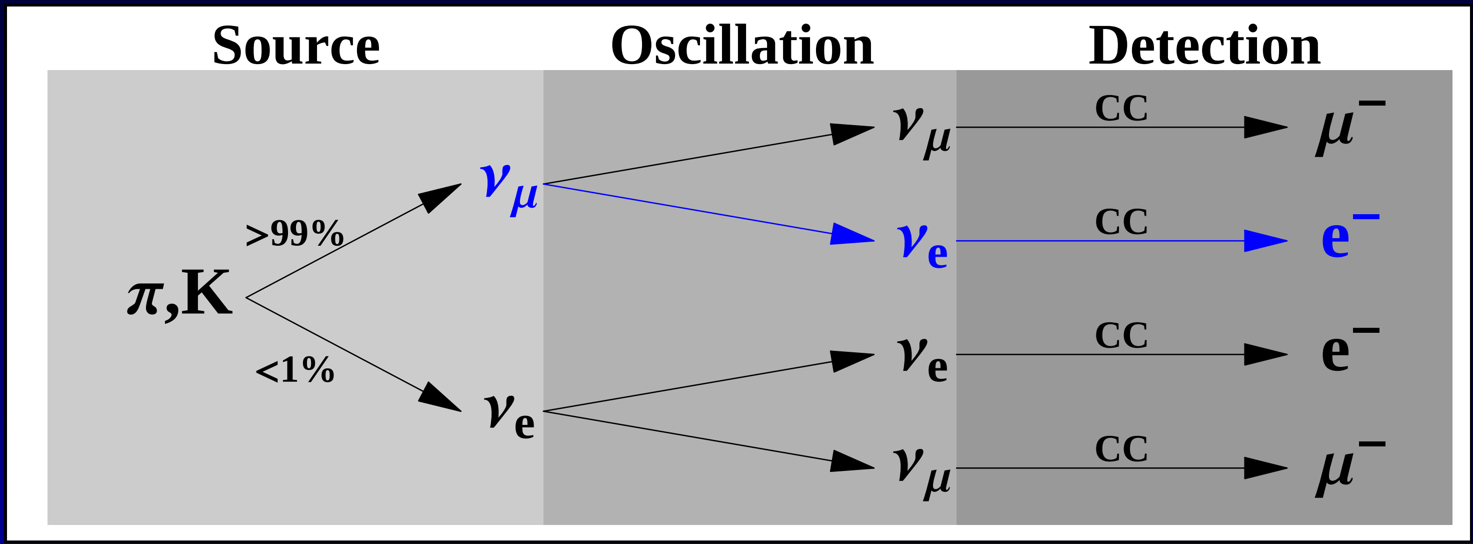
independent of CP transformations. Therefore, a stringent test of the model is to measure

- $P(\nu_\mu \to \nu_e)$ – appearance
- $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ – appearance
- $P(\nu_\mu \to \nu_\mu)$ or $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ – disappearance
- $P(\nu_e \to \nu_e)$ or $P(\bar{\nu}_e \to \bar{\nu}_e)$ – disappearance

Neutrino sources

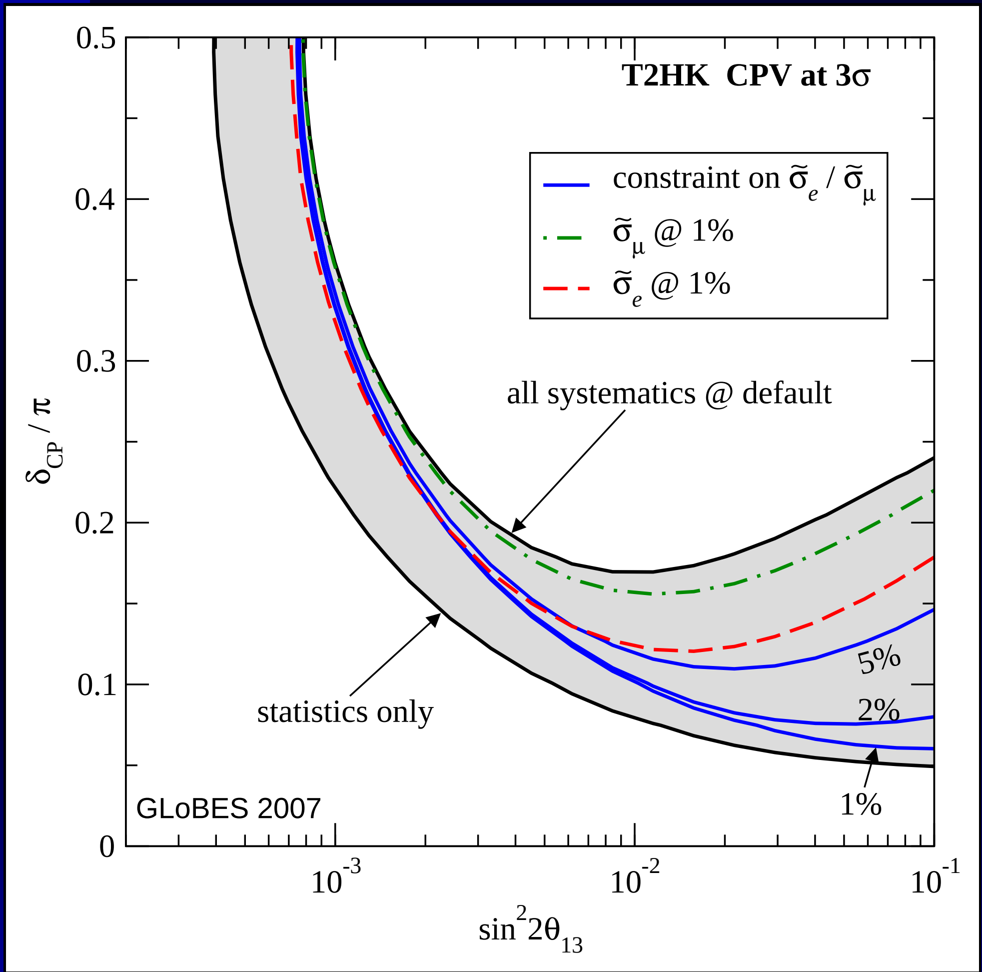
Traditional beam

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

ν_e/ν_μ x-sections

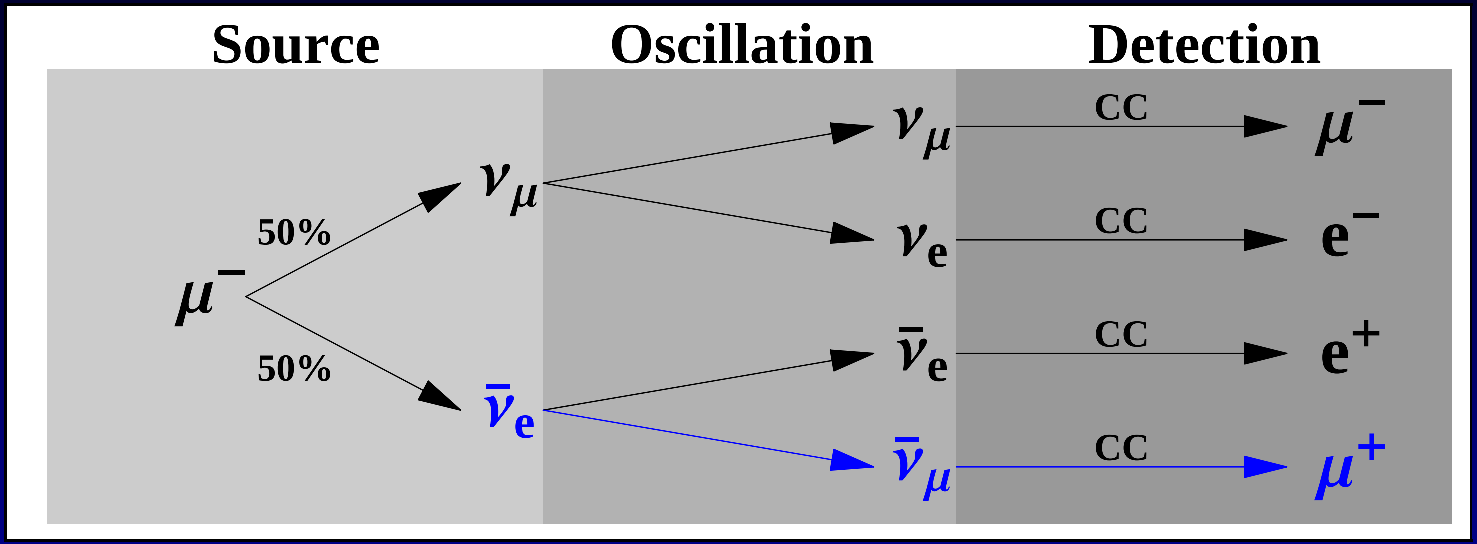


PH, M. Mezzetto, T. Schwetz
arXiv:0711.2950

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

Large θ_{13} most difficult region.

Neutrino factory beam



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

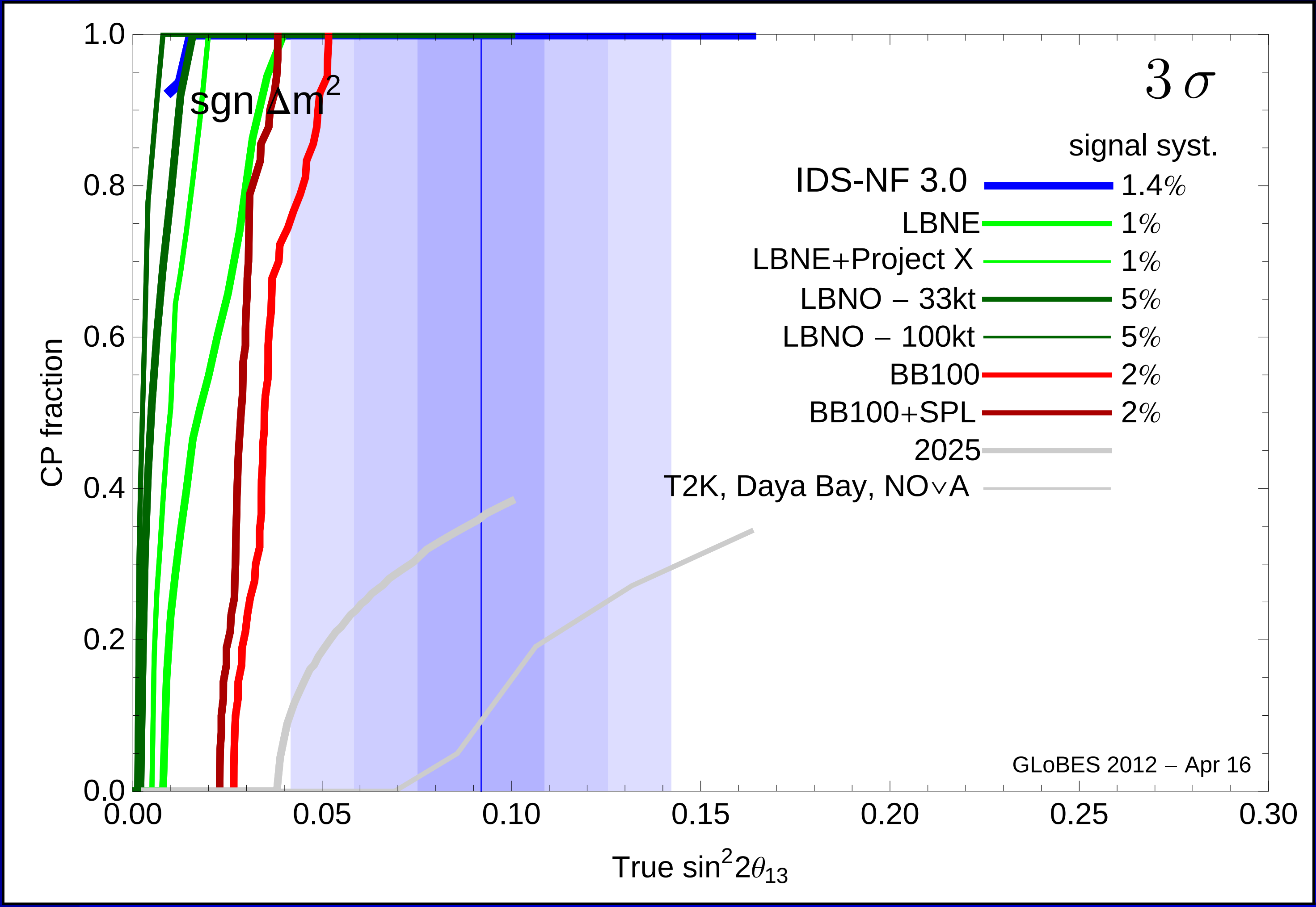
- beam known to %-level or better
- muon detection very clean
- multitude of channels available

Long-baseline oscillations

Mass hierarchy I

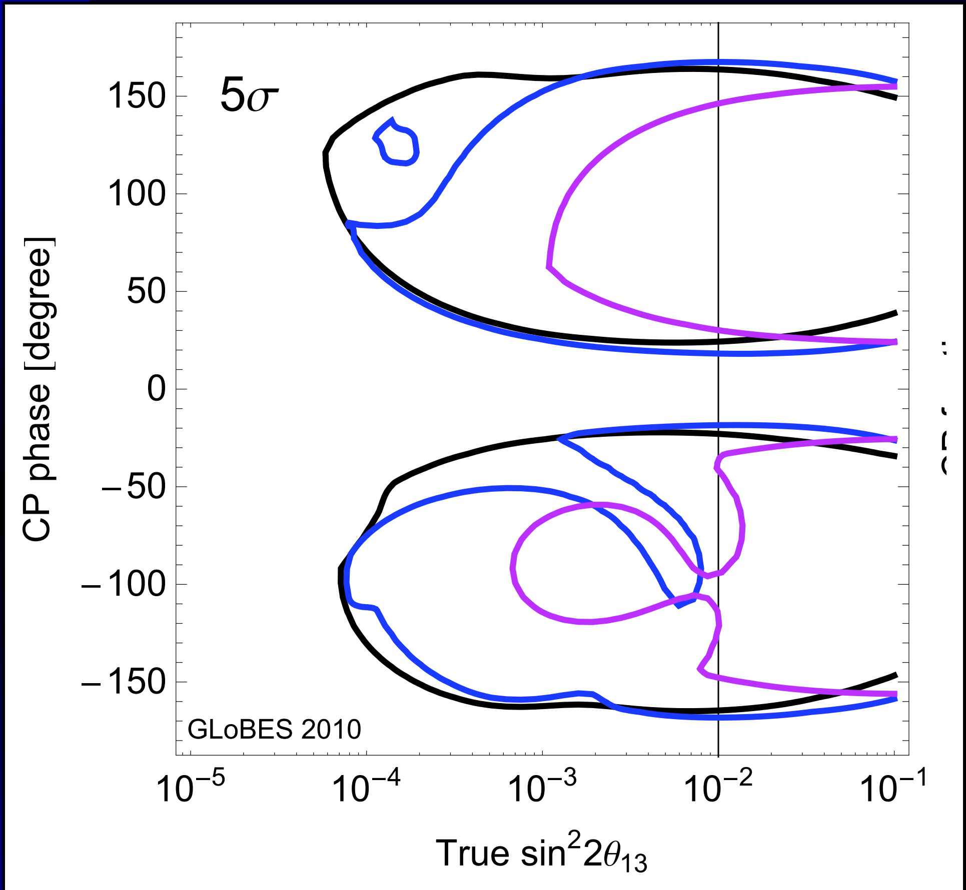
- Given the large value of θ_{13} mass hierarchy can be done in many different ways
- PINGU, ICAL, Daya Bay 2, HK atmospheric data, ...
- It seems to be the general opinion that mass hierarchy will be determined at some level w/o a new long baseline experiment
- What about new physics, *e.g.* NC-like new interactions?

Mass hierarchy II



Mass hierarchy is no longer a distinguishing feature!

CP violation vs CP precision

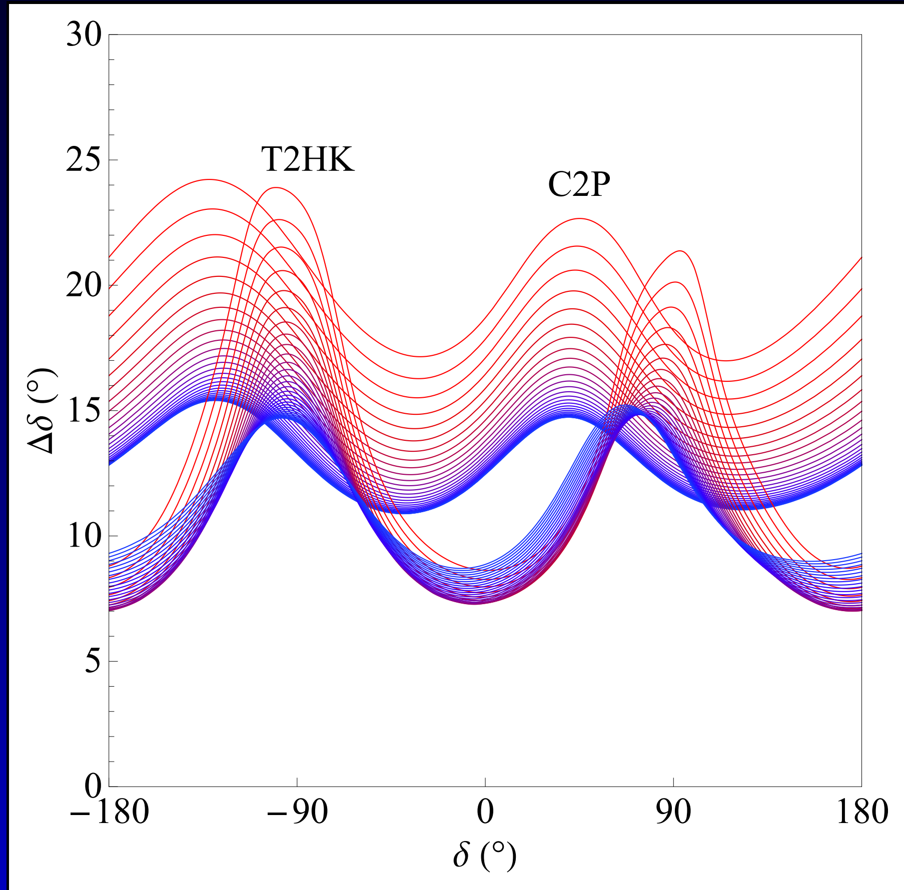


IDS-NF IDR

+ can show θ_{13} dependence

+ naturally include degeneracies

- region of no sensitivity



Coloma *et al.* 2012

+ can show δ dependence

+ no gaps in sensivity

- hard to include degeneracies

Discovery of CP conservation

The QCD vacuum structure induces the following term in the Lagrangian

$$\theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

This term violates CP and knowing nothing else we would expect θ to be $\mathcal{O}(1)$, *i.e.* there should be CP violation in QCD beyond mixing.

However, the absence of a neutron electric dipole moment constrains $\theta < 10^{-10}$. This is the “strong CP problem”.

CP conservation as a surprise!

Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

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

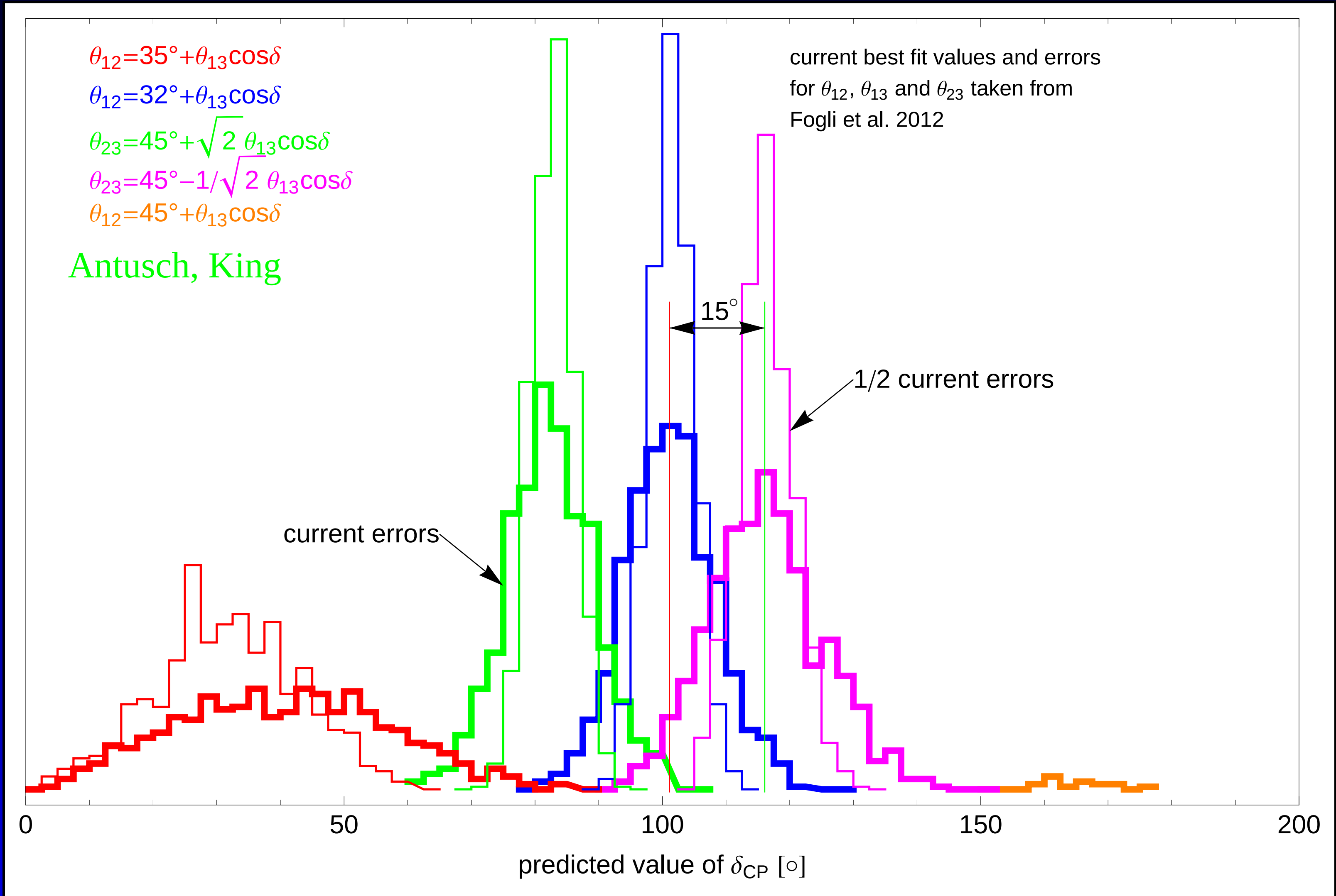
predicts flat distribution in δ_{CP}

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

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

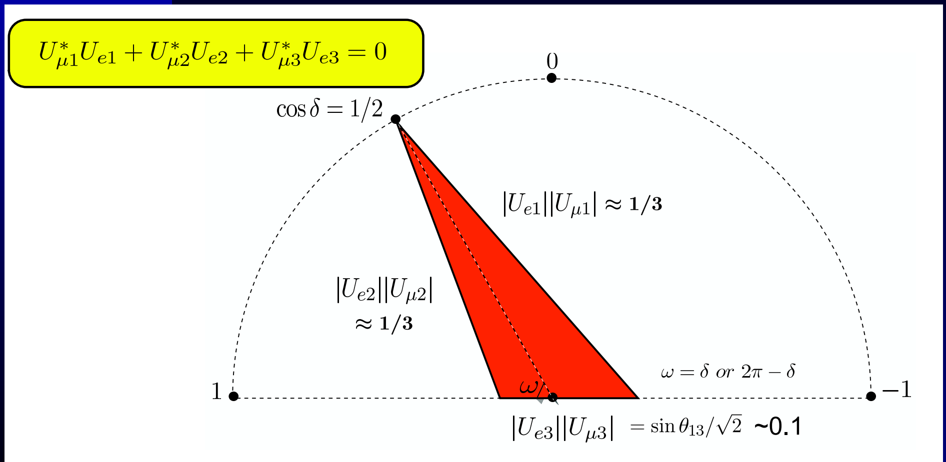
to still fit data, obviously corrections are needed

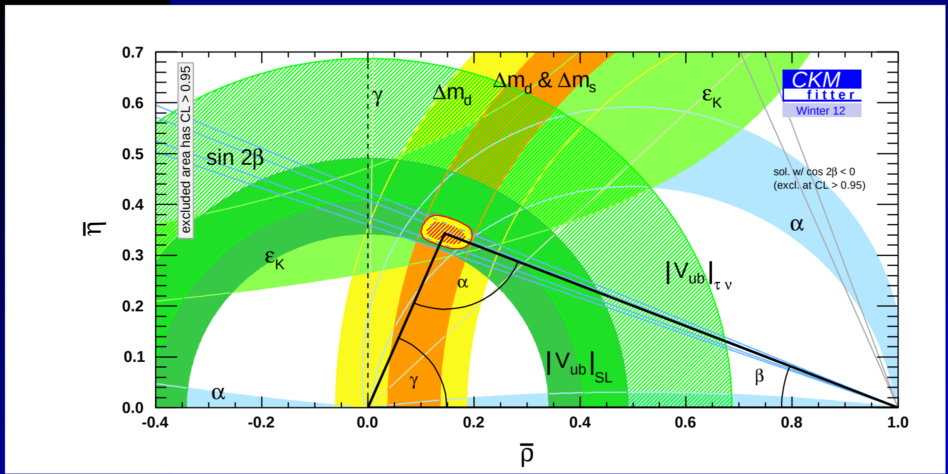
Sum rules



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

Figure of merit

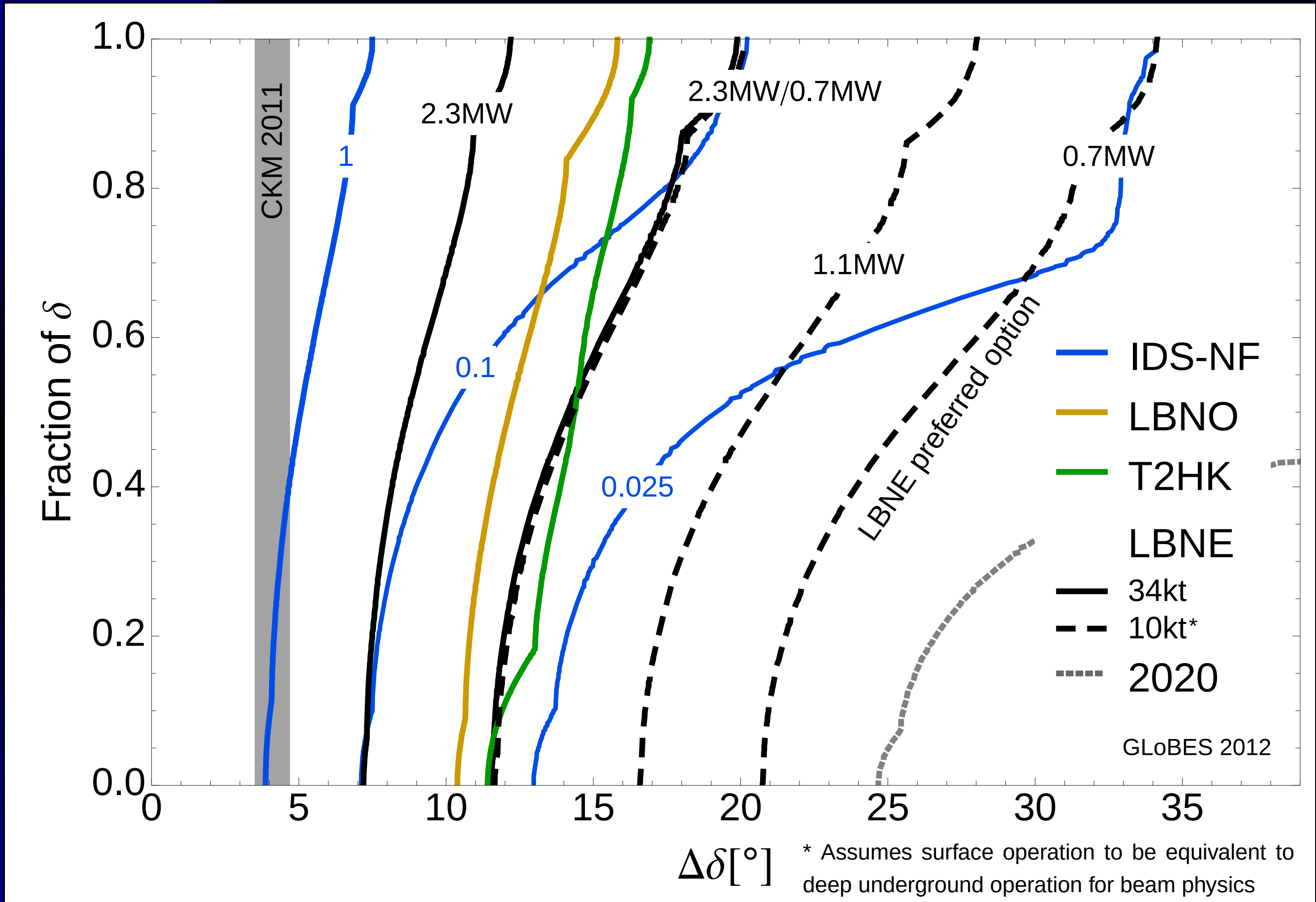




We should use CP precision as figure of merit

- experimentally challenging yet achievable
- direct relation to systematics
- directly related to the unitarity triangle
- most susceptible to new physics

CP precision



* Assumes surface operation to be equivalent to deep underground operation for beam physics

2020 – T2K, NOνA and Daya Bay nominal runs

LBNE – 1300 km, 34 kt
0.7 MW, 2×10^8 s

LBNO – 2300 km, 100 kt
0.8 MW, 1×10^8 s

T2HK – 295 km, 560 kt
0.7 MW, 1.2×10^8 s

all masses are fiducial

LBNO EOI submitted to CERN – 20 kt LAr + MIND, similar beam power to above

P. Coloma, PH, J. Kopp, W. Winter, in preparation

0.025 IDS-NF – 700kW, no cooling, 2×10^8 s running time, 10-15 kt detector

Corollary

- New facilities are indispensable to fully exploit the discovery of neutrino oscillation and to study the short-baseline anomalies
- Mass hierarchy at large θ_{13} is no longer a main decision criterion
- Stop using “disovery reach for CP violation”
- CP phase is never easy to measure – especially for the largest values of θ_{13}
- muon based options clearly outperform any other technology both for short- and long-baseline physics

A comment on staging –

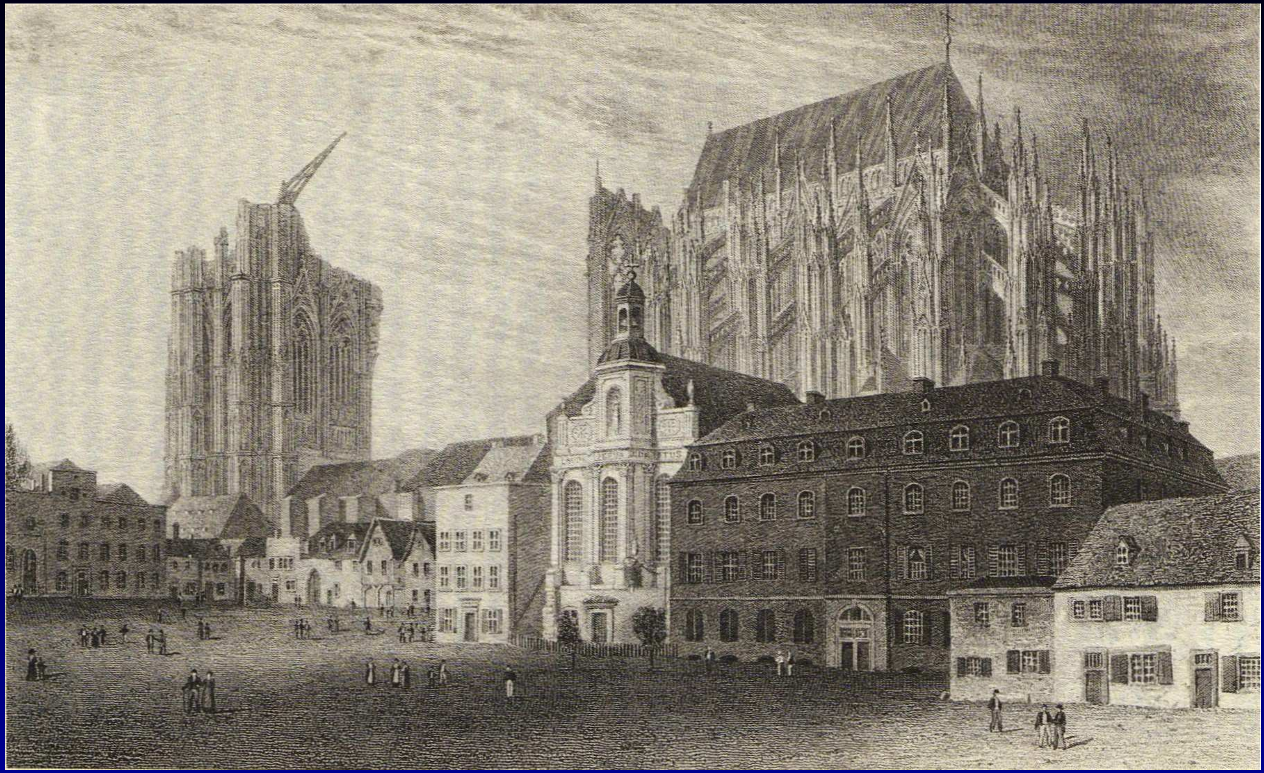
a tale from German history

Konrad von Hochstaden Archbishop of Cologne

1248 A.D. Konrad inaugurated a civil engineering project to build a Gothic cathedral...

1517 A.D. – M. Luther announces a "new theory" and construction came to a halt in the early 16th century

Phase I



Project status
1824 A.D.

The community (= citizens of Cologne) managed to raise 2/3 of the funds required, about $1B in today’s currency, and construction resumed.

Phase N

1880 A.D. the cathedral was finished

a mere 632 years after inception of the project...

Lessons learned

Assuming that our future is in building Gothic cathedrals, ...

- good motivation transcending day-to-day politics
- multi-generational, phased approach
- phase n does not imply that phase $n + 1$ follows (immediately)
- re-assess program based on new developments
- community involvement

As a consequence, each phase will have to be able to stand on its own or on the $n - 1$ previous phases.

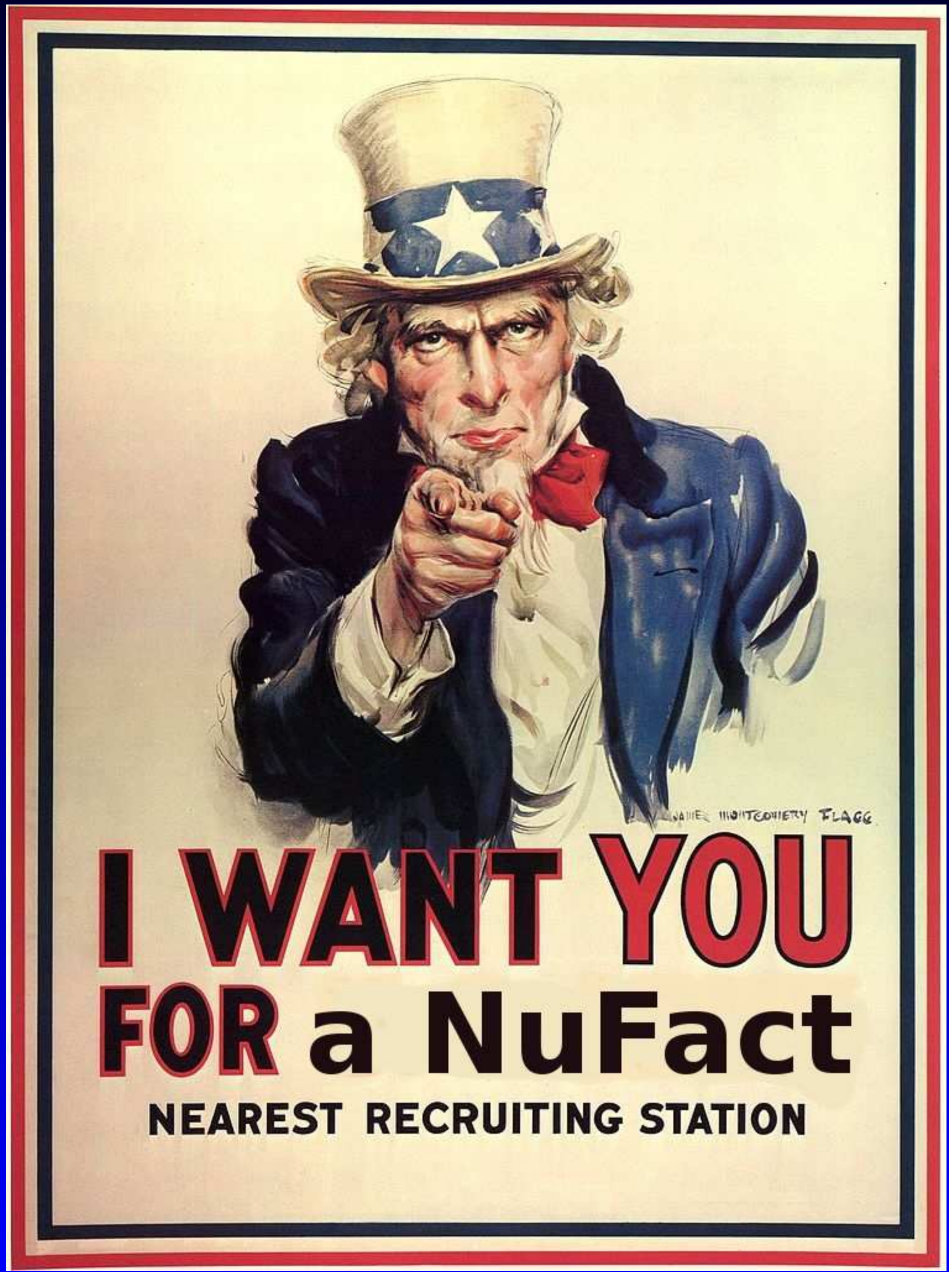
Note, that the staff and funding of the cathedral works (Dombauhütte) always shrank and grew in proportion to the actual activities!

One way forward

A staged, muon based program

- νSTORM – resolve the SBL anomalies and if discovery, precise measurements of NP, necessary to control systematics in superbeam experiments
- Low luminosity neutrino factory (700kW beam, no cooling, 10-20 kt detector) – on par with most superbeams
- Low energy neutrino factory – better than any superbeam
- Full neutrino factory – ultimate precision

provides excellent, unique physics in each phase!



If not this community, who else?