θ_{13} and beyond

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Disclaimer

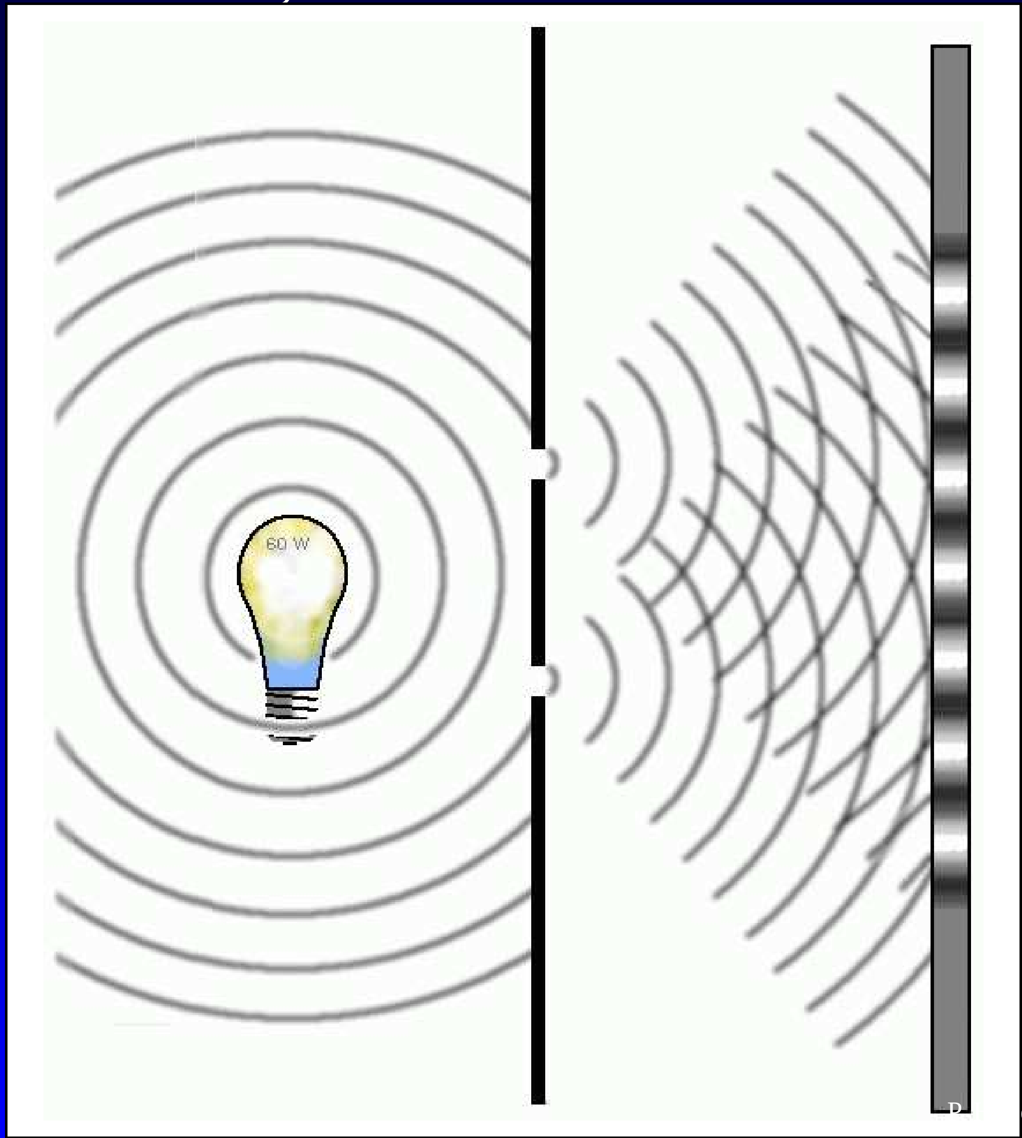
In this talk, I will not talk about

- superluminal neutrinos aka the Phantom of the OPERA
- sterile neutrinos
- data supporting large θ_{13} – see next talks

and not because, these are not very fascinating topics, but because I have only 25 minutes...

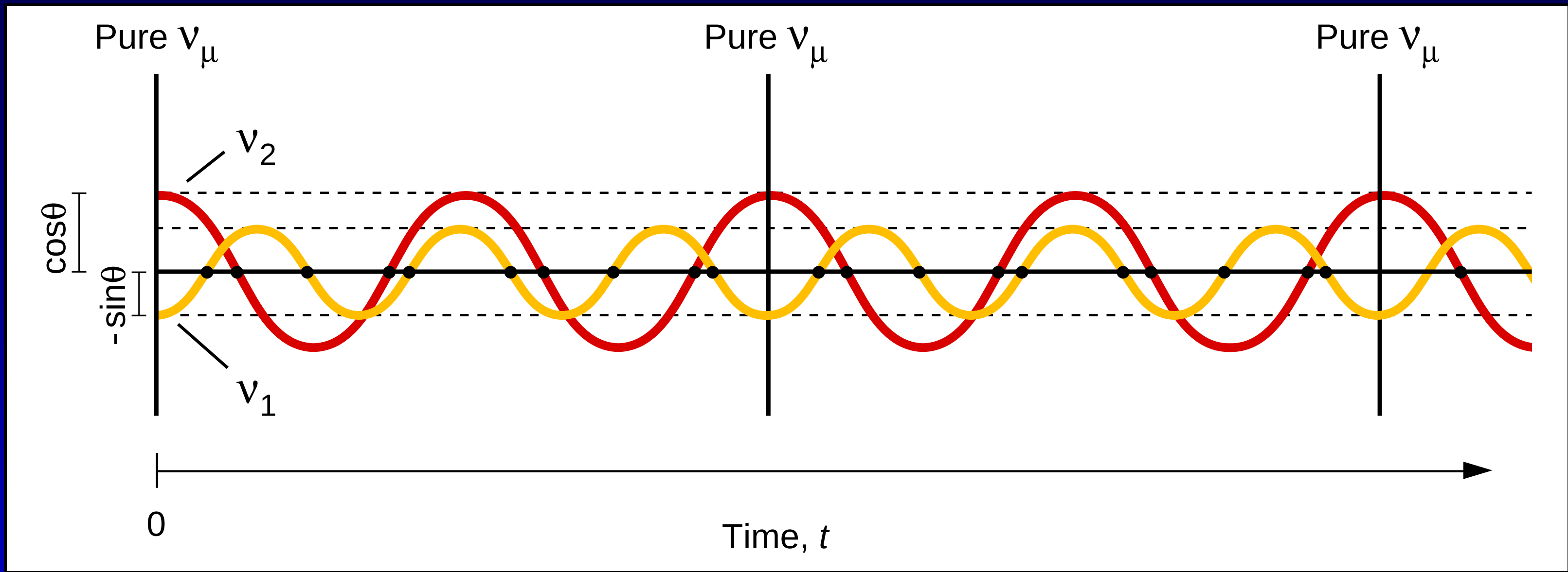
Neutrino oscillation

Neutrino oscillation is a quantum mechanical interference phenomenon, like electrons in the double slit experiment.



Neutrino oscillation

In the case of the neutrino there are two beams because the production process produces a superposition of two mass states ν_1 and ν_2.

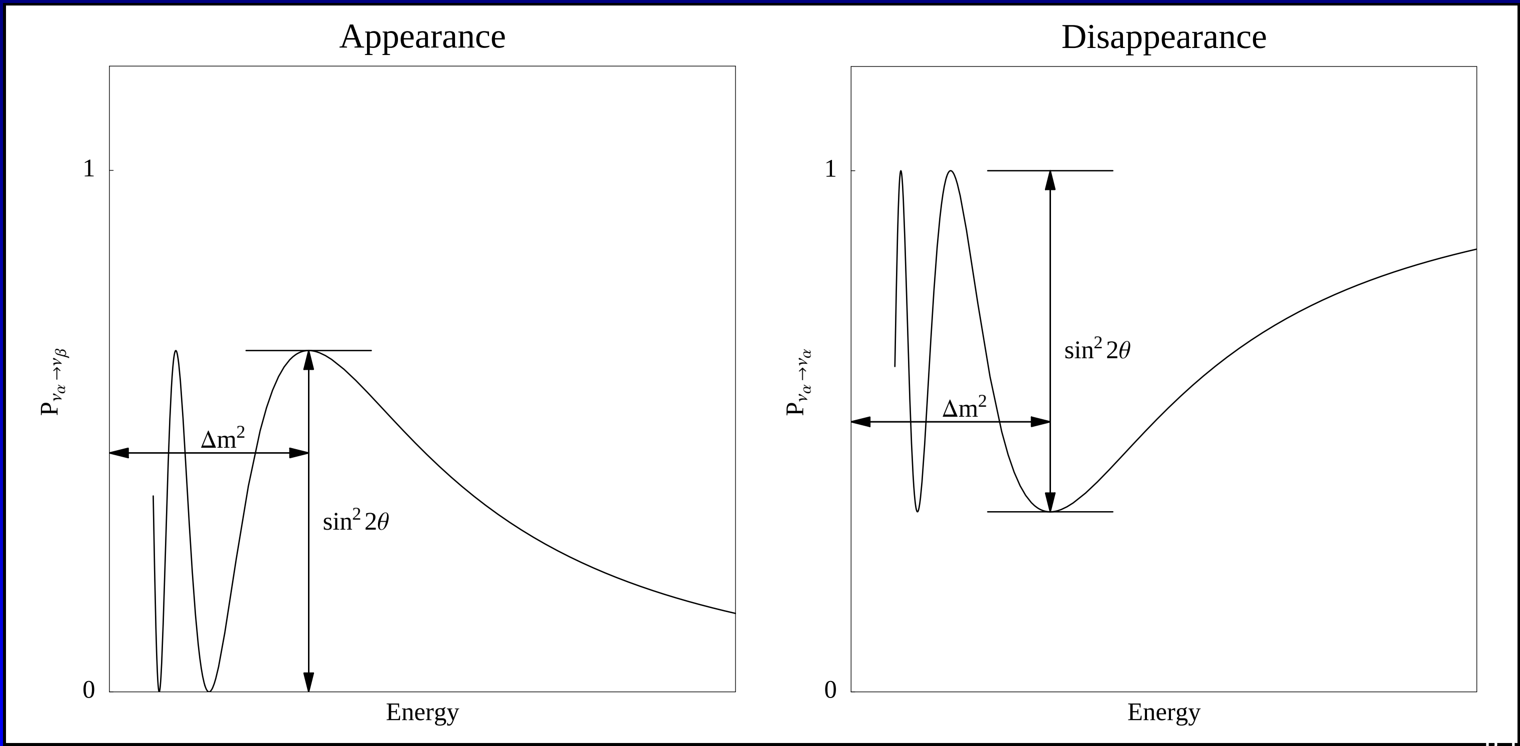


If the masses of these two states are different then they will take different times to reach the same point and there will be a phase difference and hence interference.

Neutrino oscillation

The oscillation probability is given by

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2 \frac{\overbrace{m_2^2 - m_1^2}^{=:\Delta m^2} L}{4E}$$



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

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

The experimentally most suitable transition to study CP violation is $\nu_e \leftrightarrow \nu_\mu$, which is only available in beam experiments.

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

Status quo

- Conversion of ν_e from the Sun into $\nu_\mu + \nu_\tau$
- Disappearance of $\bar{\nu}_e$ from nuclear reactors at a distance of $\sim 200\,\mathrm{km}$
- Disappearance of ν_μ from the Atmosphere
- Disappearance of ν_μ from a neutrino beam
- No disappearance of $\bar{\nu}_e$ from nuclear reactors at a distance of $\sim 1\,\mathrm{km}$

Status quo

A common framework for all the neutrino data, except for the things I said I would not talk about, is oscillation.

- $\Delta m^2_{21} \sim 8 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m^2_{31} \sim 2 \cdot 10^{-3}\,\mathrm{eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \lesssim 0.15$

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.

Status quo

Quarks

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

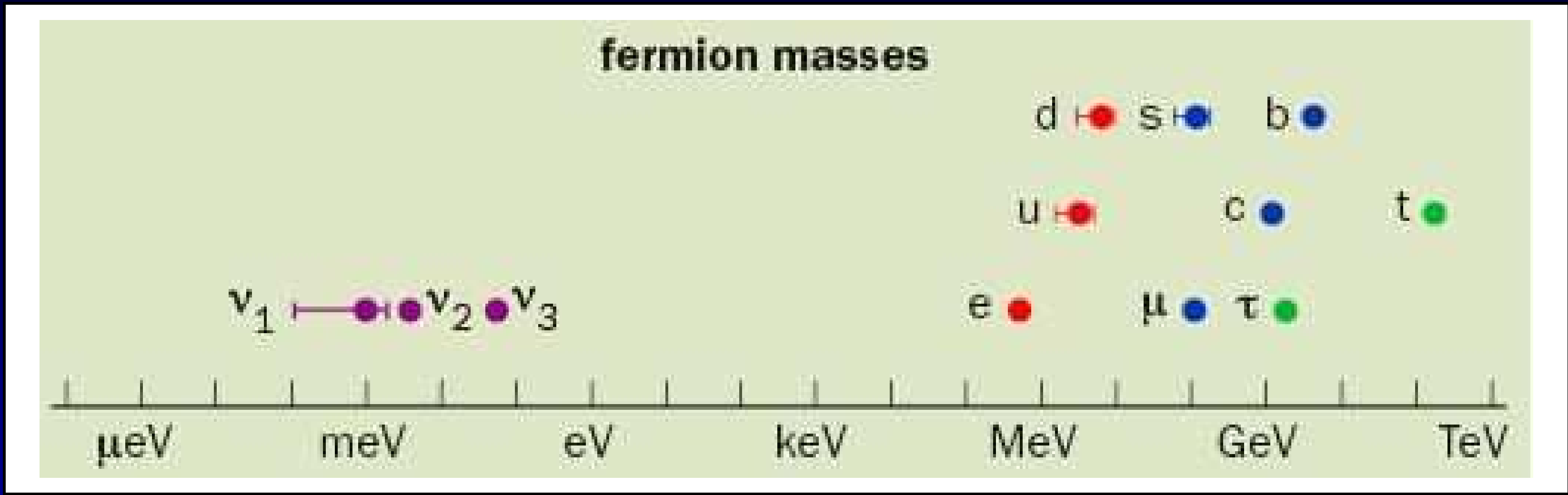
Neutrinos

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

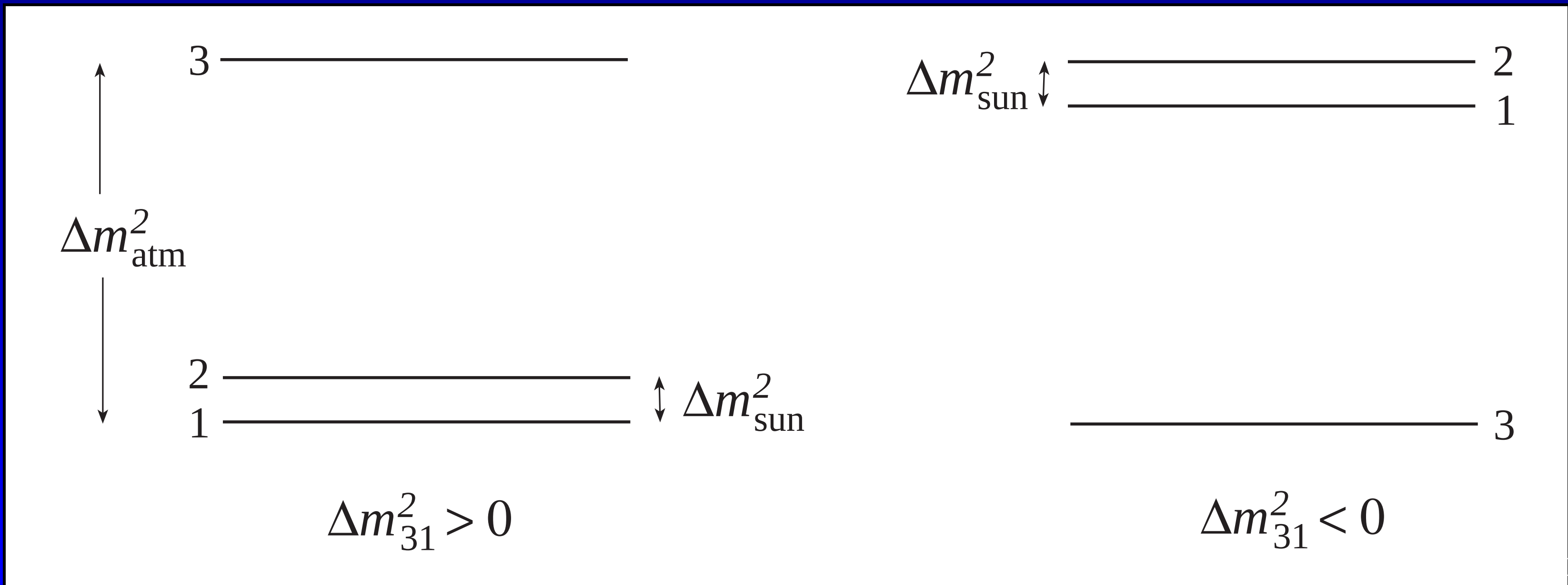
Why are neutrino mixings so large?

Status quo

Mass hierarchy in the SM



What makes neutrinos so much lighter?



What we can learn

In the context of neutrino oscillation experiments

- $\sin^2 2\theta_{13}$
- δ_{CP}
- mass hierarchy
- $\theta_{23} = \pi/4$, $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$?
- Exotica (NSI, sterile neutrinos, CPT violation)

It is very difficult to rank those measurements in their relative importance, with exception of $\sin^2 2\theta_{13}$ since its size has practical implications beyond theory.

The current generation

Setup	t_ν [yr]	$t_{\bar{\nu}}$ [yr]	P_{Th} or P_{Target}	L [km]	Detector	m_{Det}
Double Chooz	-	3	8.6 GW	1.05	L. scint.	8.3 t
Daya Bay	-	3	17.4 GW	1.7	L. scint.	80 t
RENO	-	3	16.4 GW	1.4	L. scint.	15.4 t
T2K	5	-	0.75 MW	295	Water	22.5 kt
NOνA	3	3	0.7 MW	810	TASD	15 kt

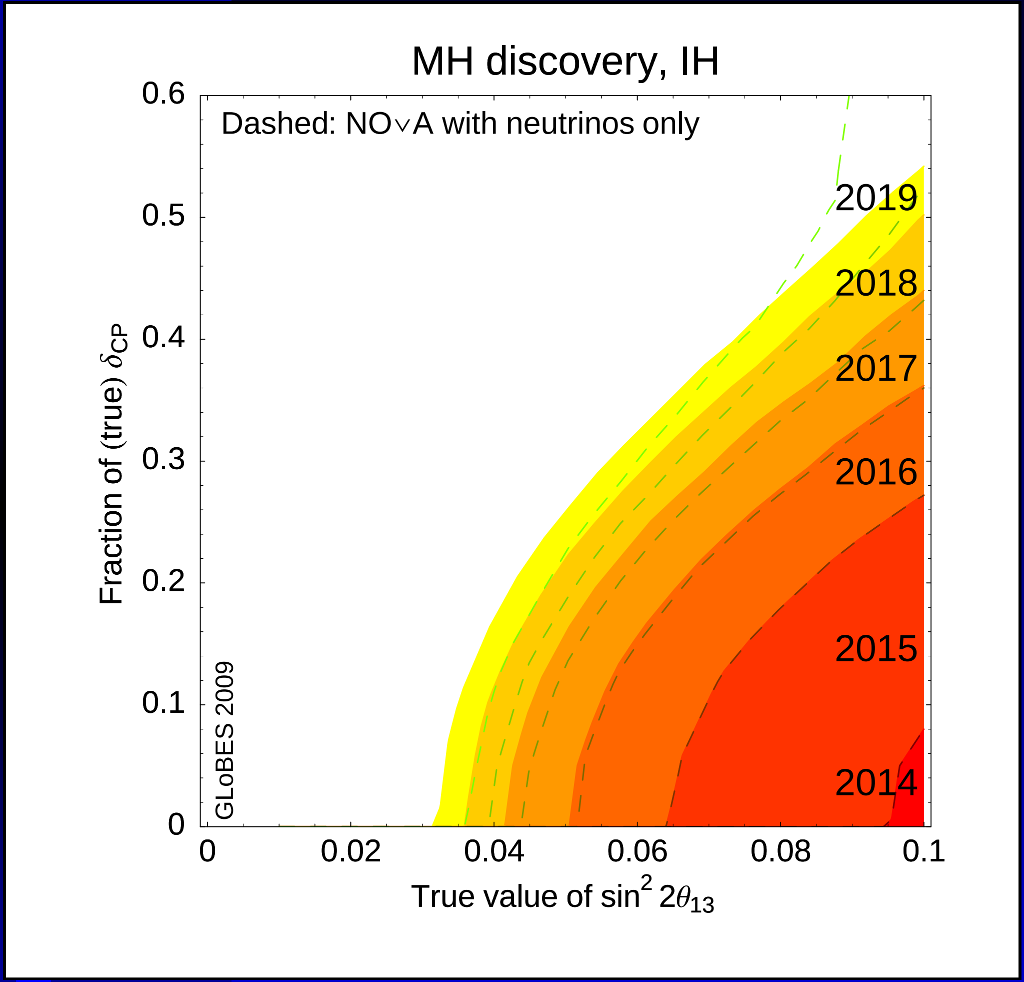
The Issue

If $\sin^2\theta_{13} > 0.01$, as hinted by recent data (see the following talks), what are the implications for future facilities?

I break this question down into the following more focused questions:

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

Mass hierarchy

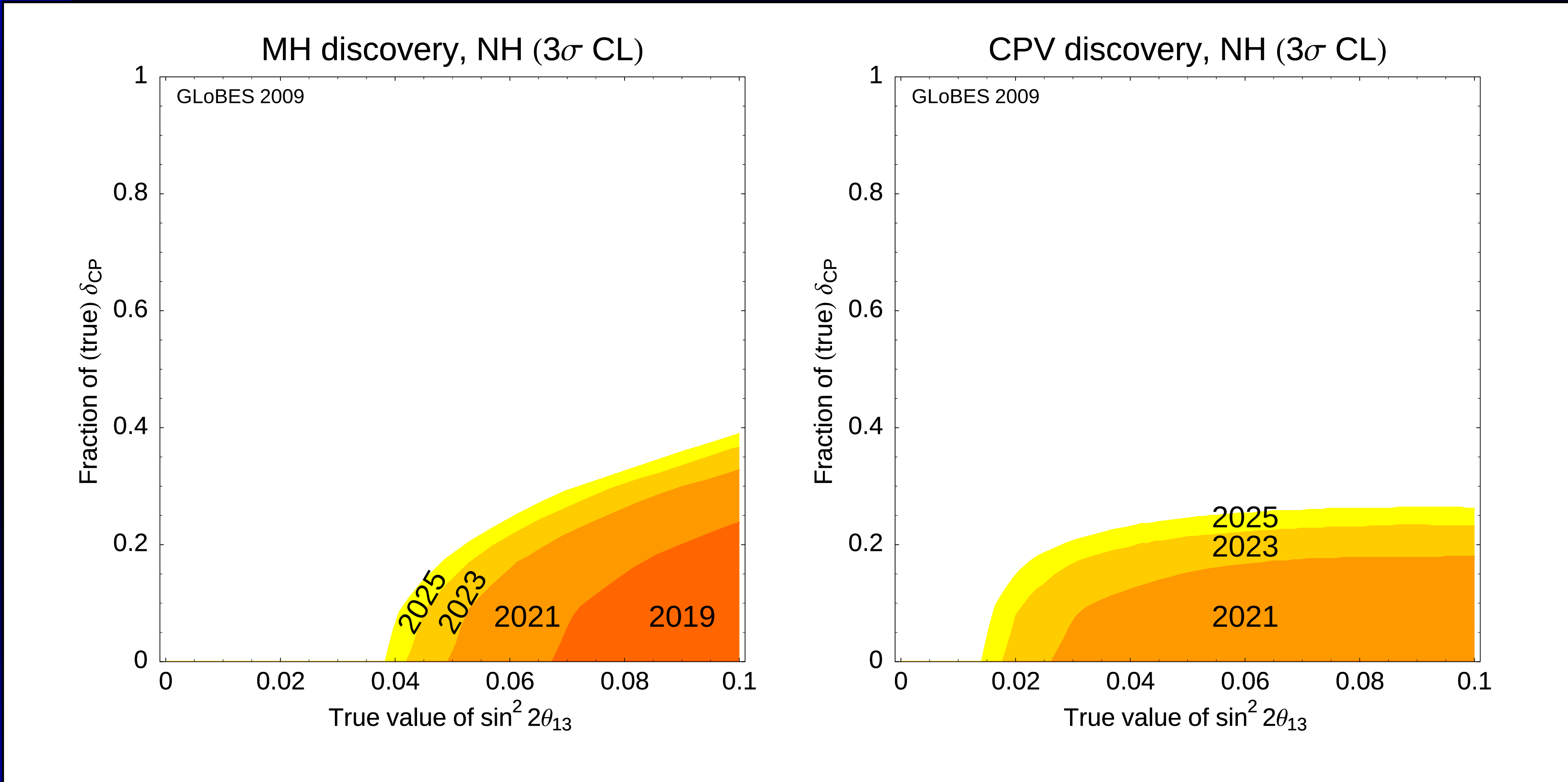


90% CL, combines T2K, NOνA, Daya Bay, Double Chooz and RENO At this CL MINOS and T2K have discovered $\theta_{13} \neq 0$!

At $3\,\sigma$ this plot would be essentially empty!

PH, M. Lindner, T. Schwetz, W. Winter, JHEP 11 044 (2009), arXiv:0907.1896.

CPV without new experiments?



PH, M. Lindner, T. Schwetz, W. Winter, JHEP 11 044 (2009), arXiv:0907.1896.

Includes Project X and T2K running at 1.7 MW.

2025

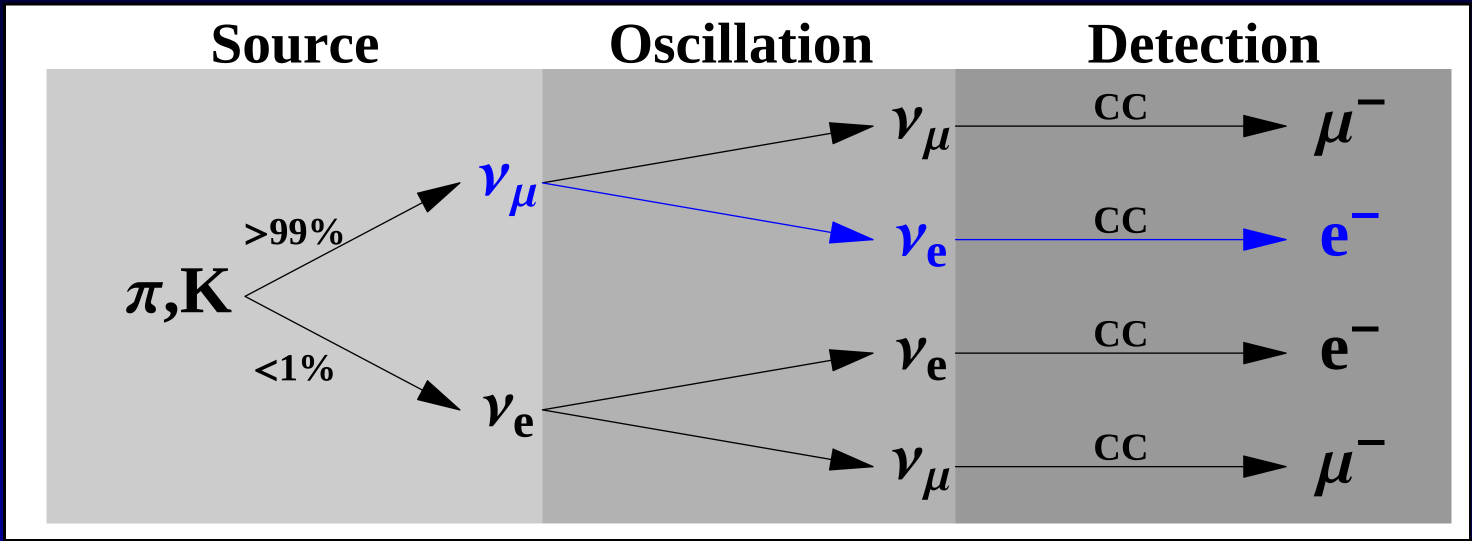
Knowledge in 2025 without new facilities at $3\,\sigma$ CL

- $\theta_{23} = \pi/4$ – for maximal mixing $45^\circ \pm 4^\circ$
- size of θ_{13} – if $\sin^2 2\theta_{13} > 0.01$
- mass hierarchy – if $\sin^2 2\theta_{13} > 0.04$ for at most 30% of all CP phases
- CP violation in leptons – if $\sin^2 2\theta_{13} > 0.02$ for at most 20% of all CP phases

Even for the largest currently allowed θ_{13} more than 70% of parameter space are not accessible.

Superbeams

Neutrino beam from π-decay



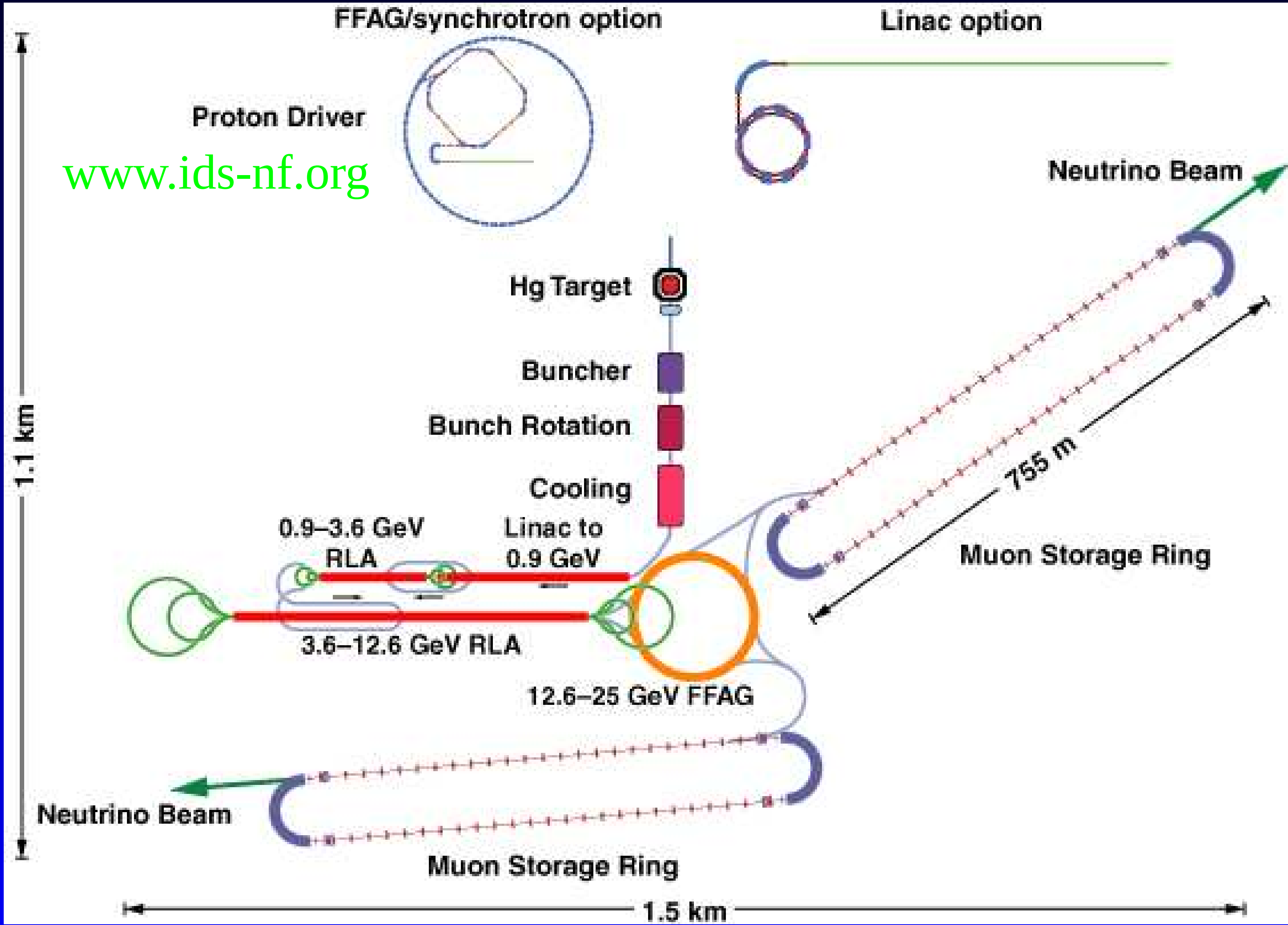
They are called 'super'

- beam power $\sim 1\,\mathrm{MW}$
- detectors mass $\sim 100\,\mathrm{kt}$
- running time of the experiment $\sim$ 10 years
- price

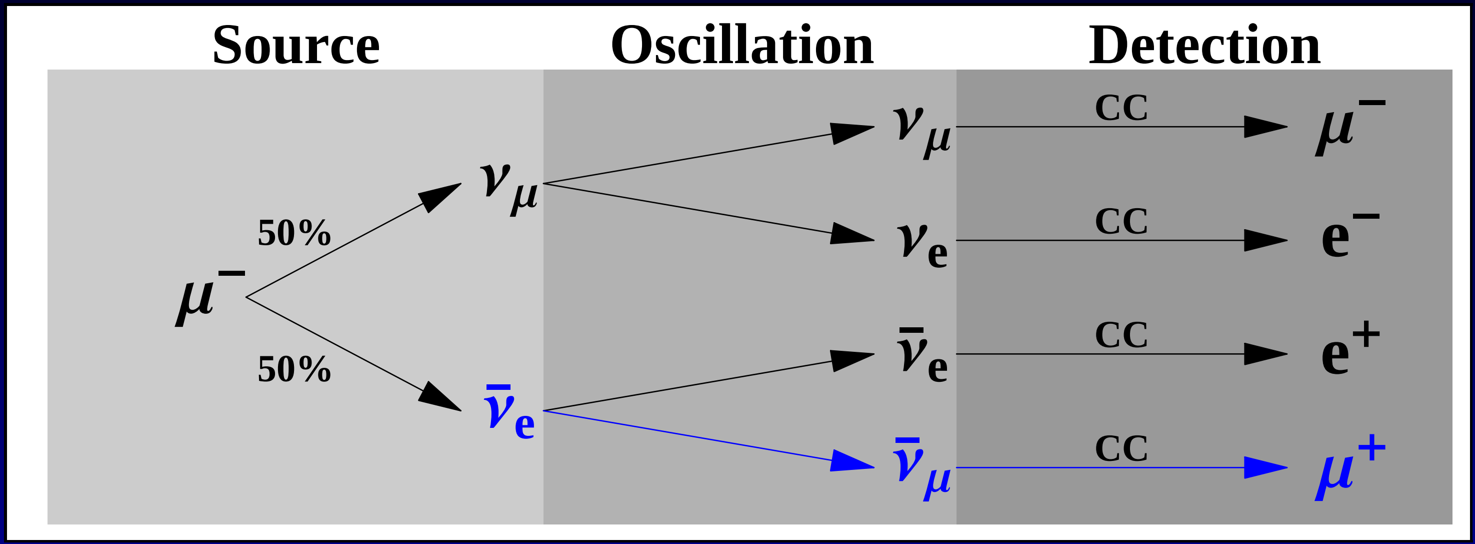
Challenges

- beam power $\sim 1\,\mathrm{MW}$
- detectors mass $\sim 100\,\mathrm{kt}$
- at large θ_{13} – systematics & precision

Neutrino Factory



Signal



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

- above 3 GeV – iron calorimeter like MINOS
- below 3 GeV – magnetized, totally active, fine grained scintillator

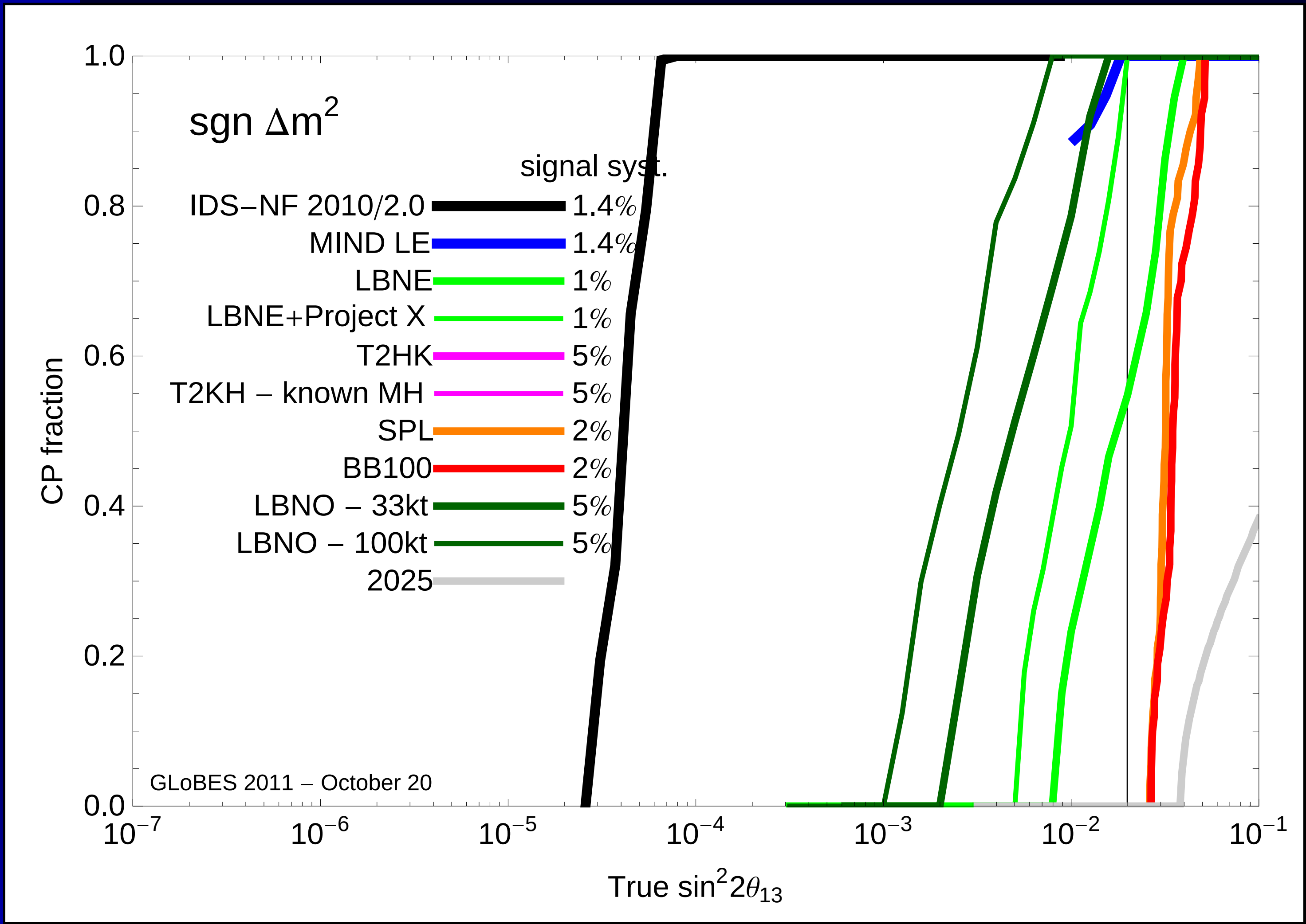
Challenges

- muon production (MERIT)
- muon cooling (MICE, MuCool)
- muon acceleration (EMMA)

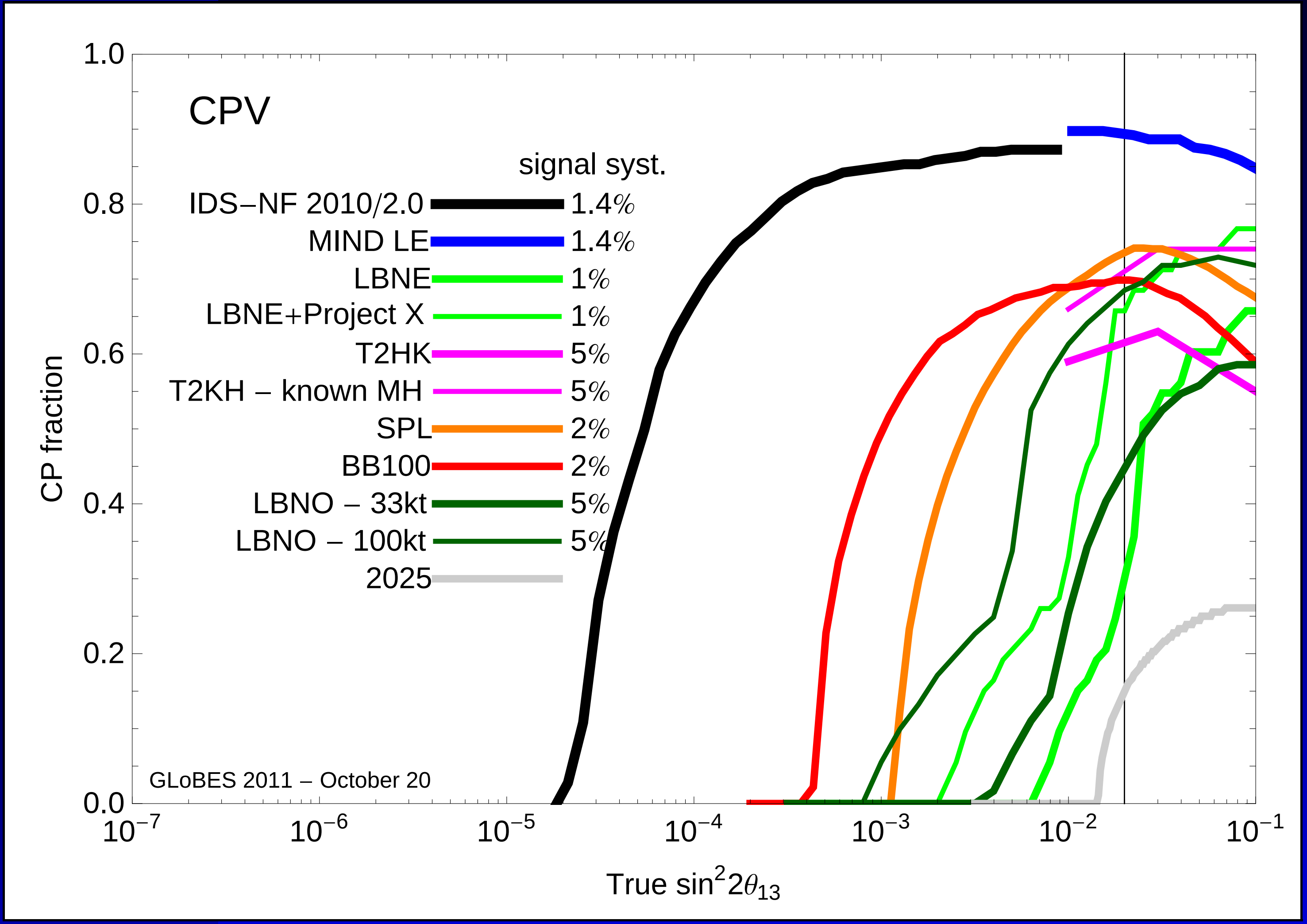
All these step are necessary for a muon collider, too. Active R&D effort, which will yield a reference design report by 2012.

International Design Study for a Neutrino Factory (IDS-NF): www.ids-nf.org

Are superbeams enough?



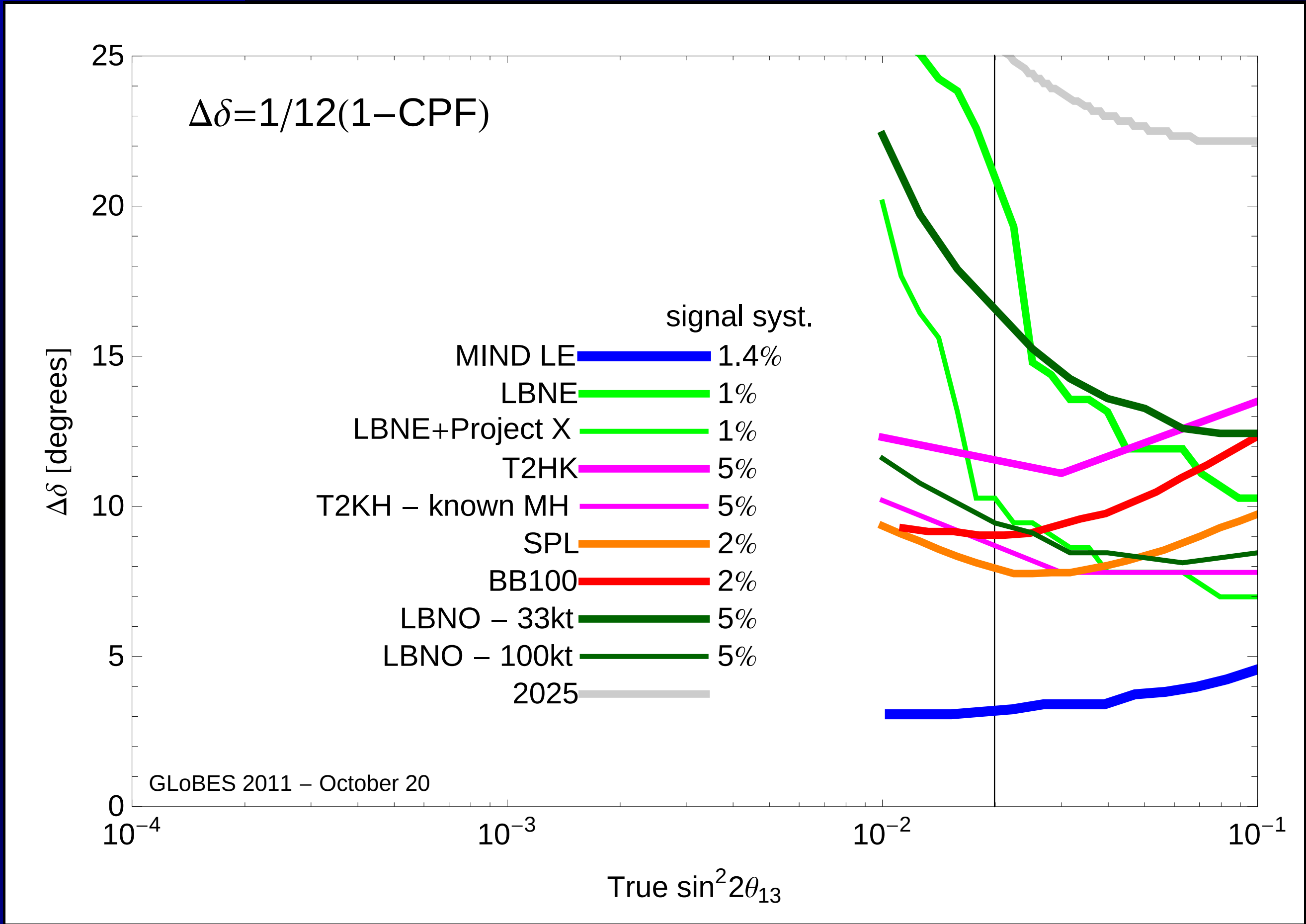
Are superbeams enough?



SB reach CPF of 0.15-0.77
NF reaches CPF of 0.85-0.9

NF best for **all** values of θ_{13}!

Are superbeams enough?



$$\Delta\delta \simeq \frac{1}{12}(1 - \mathrm{CPF})$$
SB $\Delta\delta = 7^\circ - 25^\circ$
NF $\Delta\delta = 3^\circ - 5^\circ$

BUT, wildely different assumptions about systematics, this comparison is not valid!

This requires a MUCH more detailed analysis!

Summary

- New facilities are indispensable to fully exploit the discovery of neutrino oscillation
- CP violation is never easy to measure – even for the largest values of θ_{13}
- Mass hierarchy needs long baseline and multi-GeV beams
- In the large θ_{13} case – systematics will be key!

Given sufficient resources, it seems likely that neutrino mixing can be quantitatively understood at a level similar to the quark sector, which ultimately will allow us to shed light onto the flavor puzzle.

References

- LBNE curves are provided by Sam Zeller as defined by the LBNE physics working group as of fall 2011 and have been computed by Lisa Whitehead
- LBNO curves are taken from Agarwalla, *et al.* arXiv:1109.6526 and have been provided by Tracey Li
- T2HK curves are taken from the T2HK LOI.
- SPL and beta beam curves (BB100) are taken from the Euroν report arXiv:1005.3146
- Neutrino Factory curves are taken from the IDS-NF IDR
- 2025 data from PH, *et al.* JHEP 11 044 (2009).
- current 3σ lower limit on $\sin^2 2\theta_{13}$, Fogli, *et al.* arXiv:1106.6028