Leptonic CP violation at large θ_{13}

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LowNu 2011
6th International Workshop on Low energy neutrino physics
9-12, November, 2011
Seoul National University, South Korea

The Question

If $\sin^2 2\theta_{13} \sim 0.1$, as indicated by recent data, 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?
- Are new experiments beyond NOνA and T2K necessary?
- Are superbeams sufficient?

Eight-fold degeneracy

By measuring only two numbers n_ν and $n_{\bar\nu}$, the following solutions remain

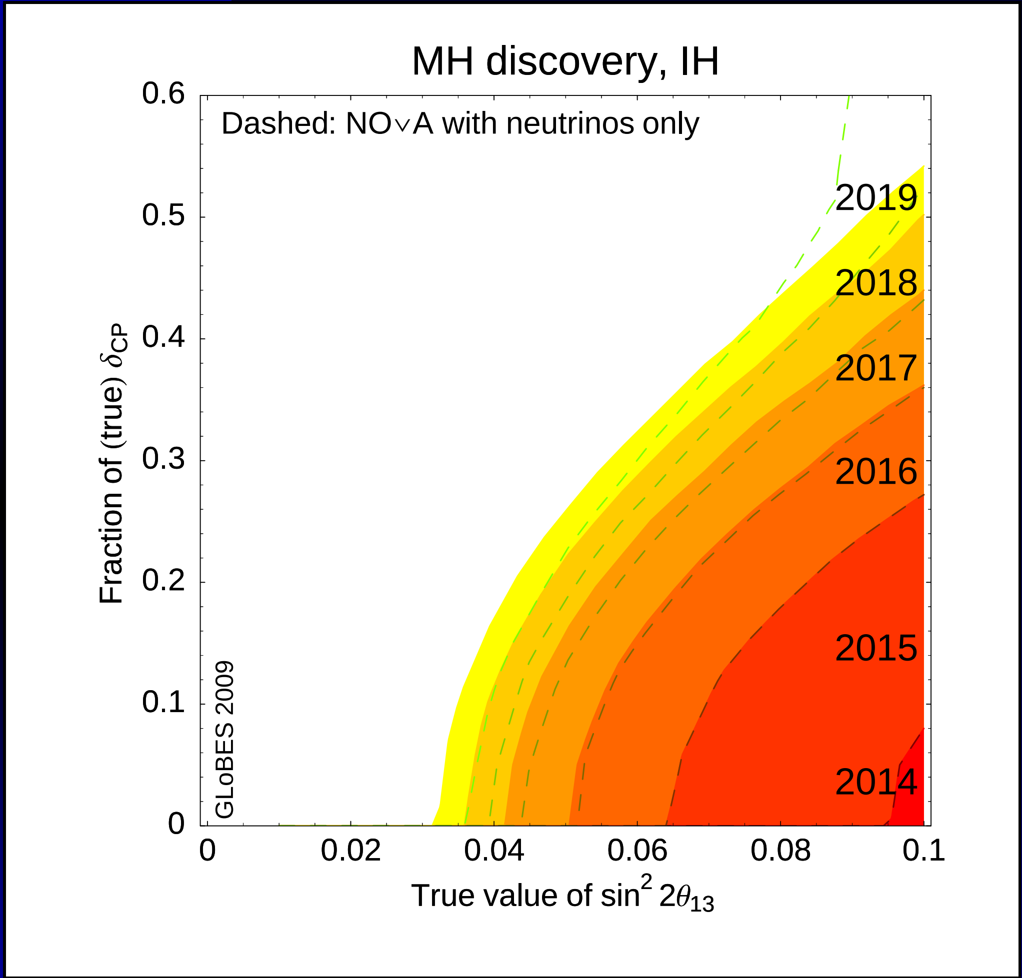
- intrinsic ambiguity for fixed α
- Disappearance determines only $|\Delta m^2_{31}| \Rightarrow$ $\mathcal{T}_s := \Delta m^2_{31} \rightarrow -\Delta m^2_{31}$
- Disappearance determines only $\sin^2 2\theta_{23} \Rightarrow$ $\mathcal{T}_t := \theta_{23} \rightarrow \pi/2 - \theta_{23}$
- Both transformations $\mathcal{T}_{st} := \mathcal{T}_s \oplus \mathcal{T}_t$

For studies of CP violation the sign ambiguity $\mathcal{T}_s$ poses the most severe problems.

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

Mass hierarchy

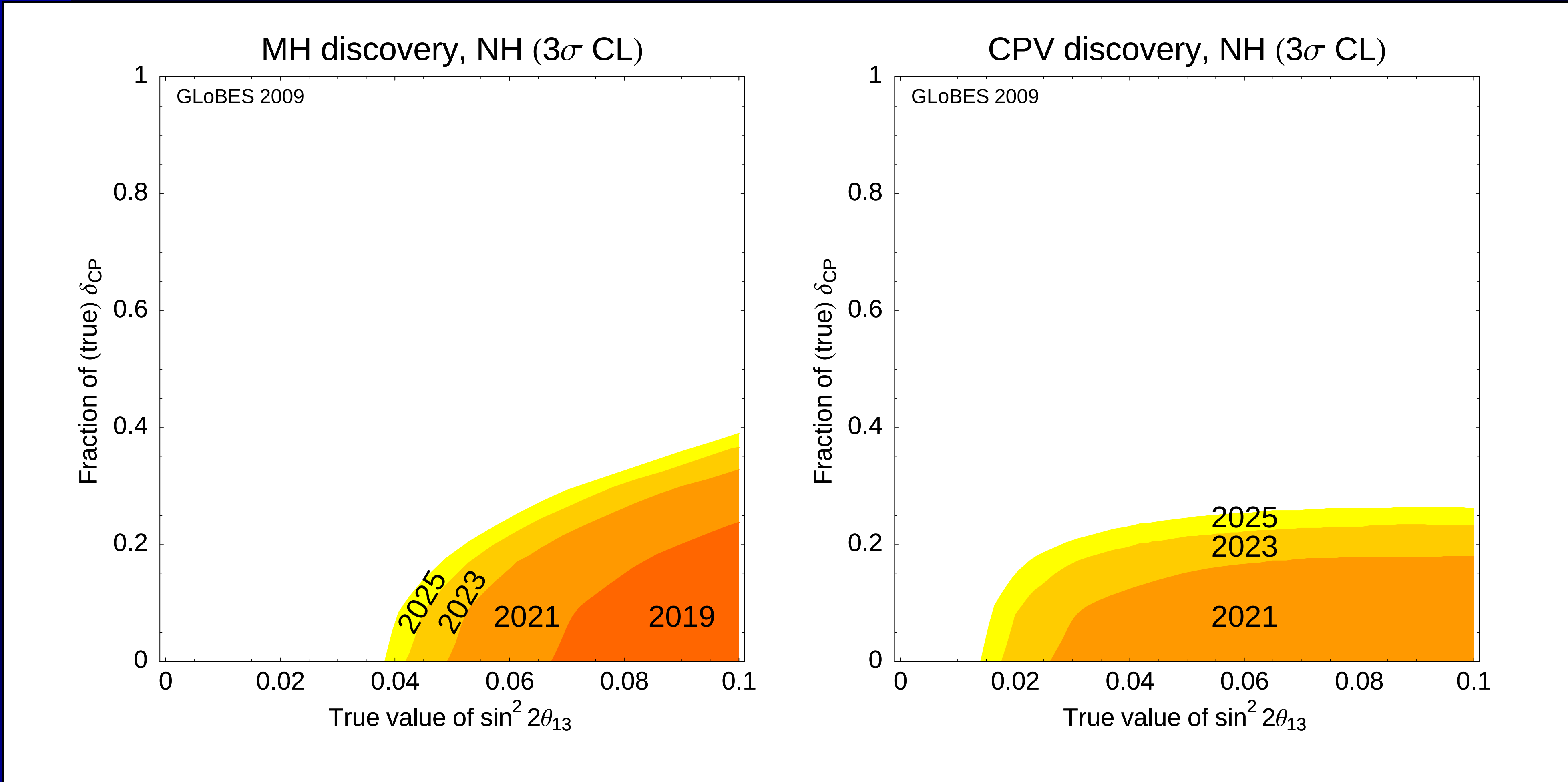


90% CL, combines T2K, NOνA, Daya Bay, Double Chooz and RENO At this CL MINOS and T2K have discovered $\theta_{13} \neq 0$!

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.

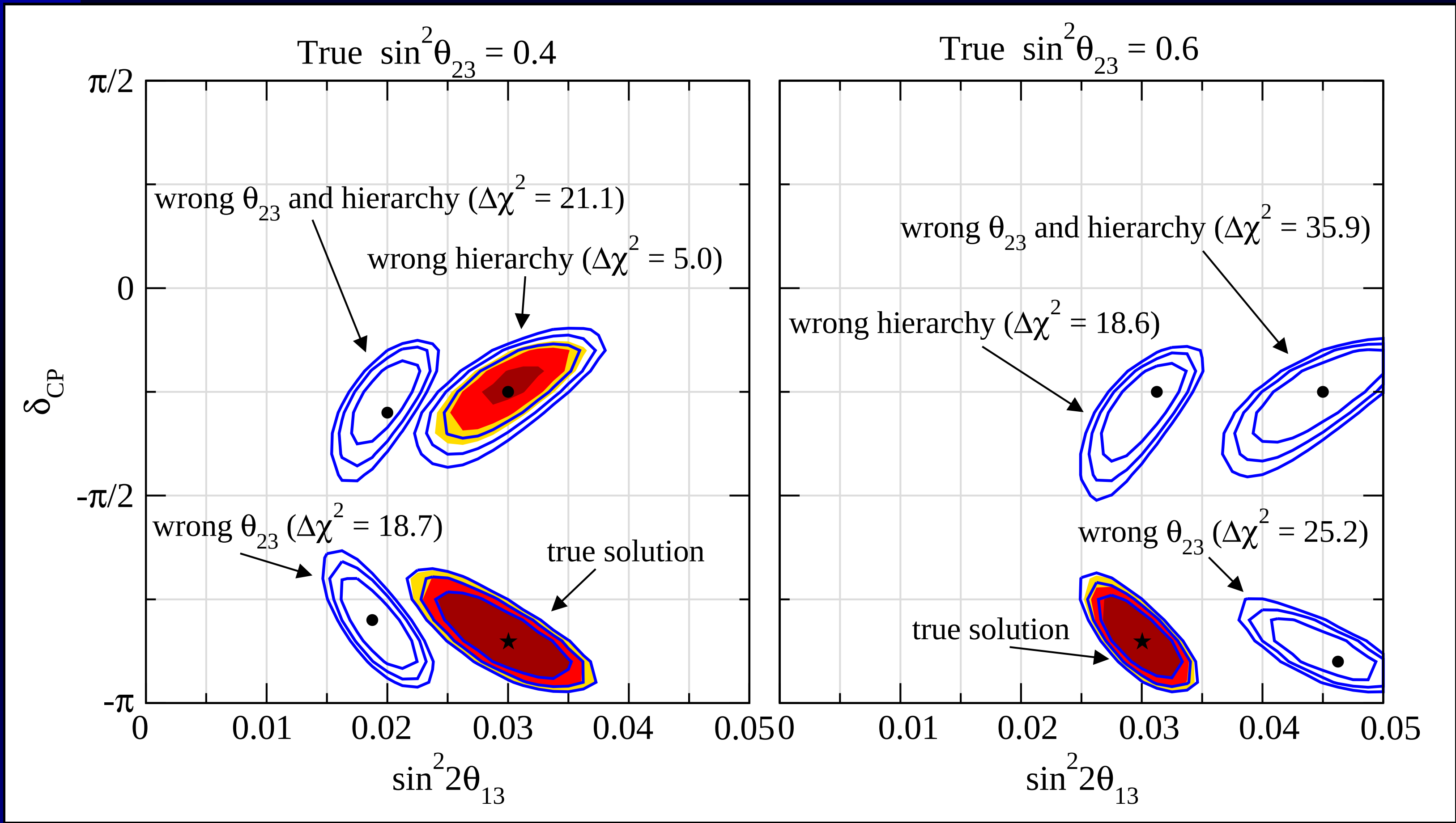
Atmospheric data

A number of new atmospheric data samples is on the horizon

- INO
- IceCube – Deep Core
- PINGU?
- next large (few 100 kt) water Cerenkov detectors

It has been shown in a large number of publications that all these data on their own but in particular in combination with data from beams is very effective in resolving degeneracies esp. at large θ_{13}.

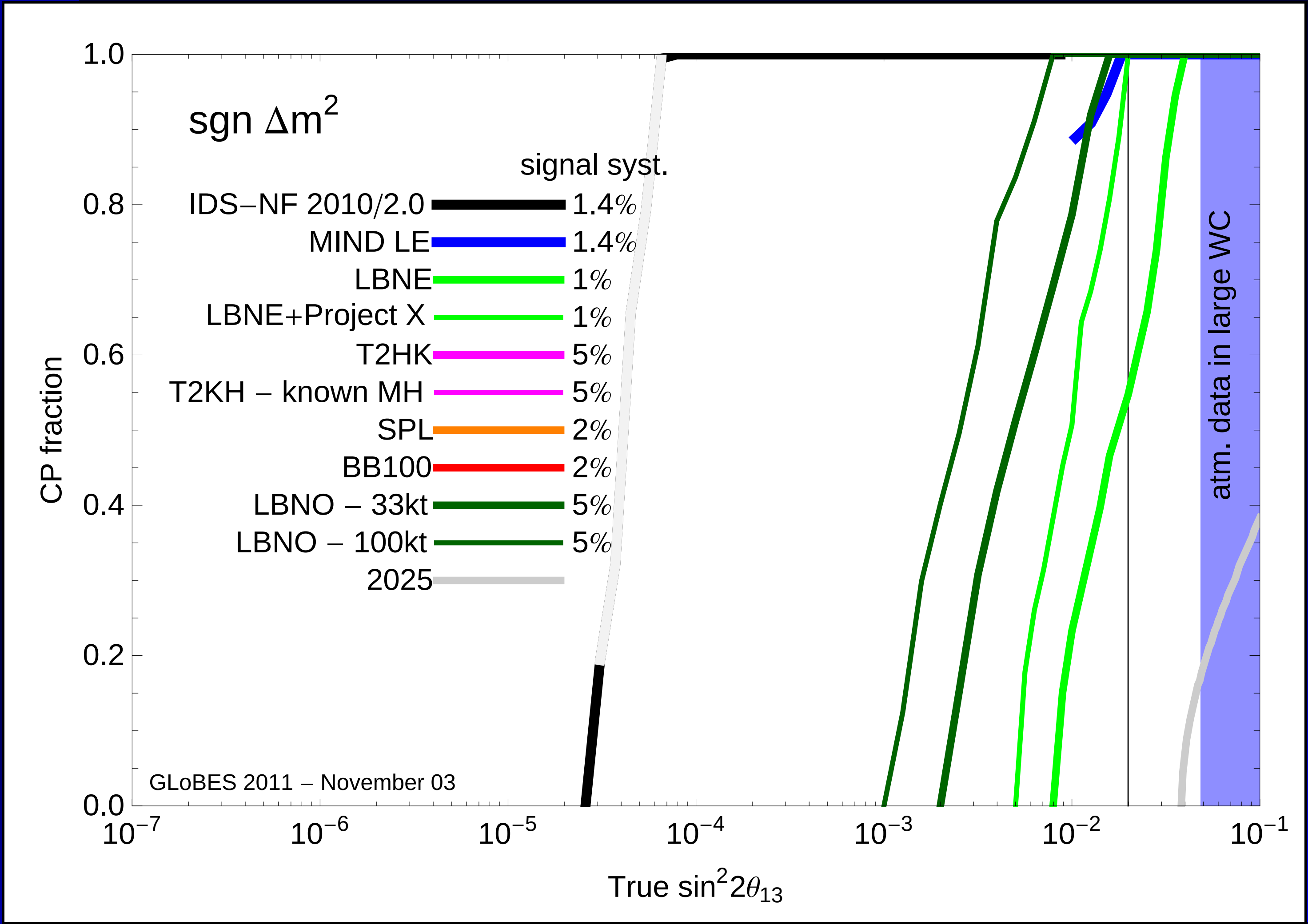
Atmospheric + LBL data



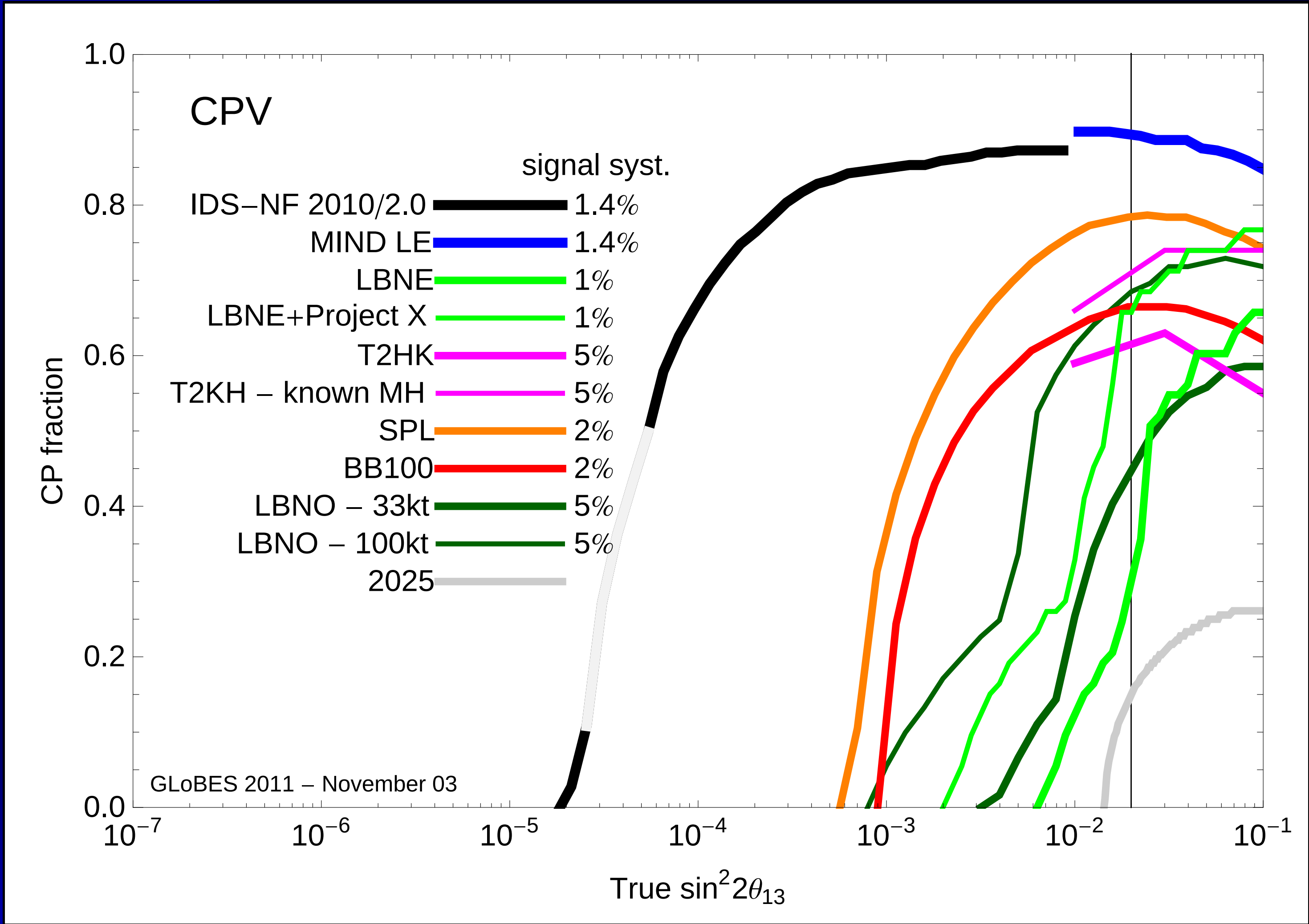
PH, Maltoni, Schwetz, Phys.Rev. D71 (2005) 053006

T2HK-like setup, 9 Mt yr atmospheric exposure

Mass hierarchy from LBL



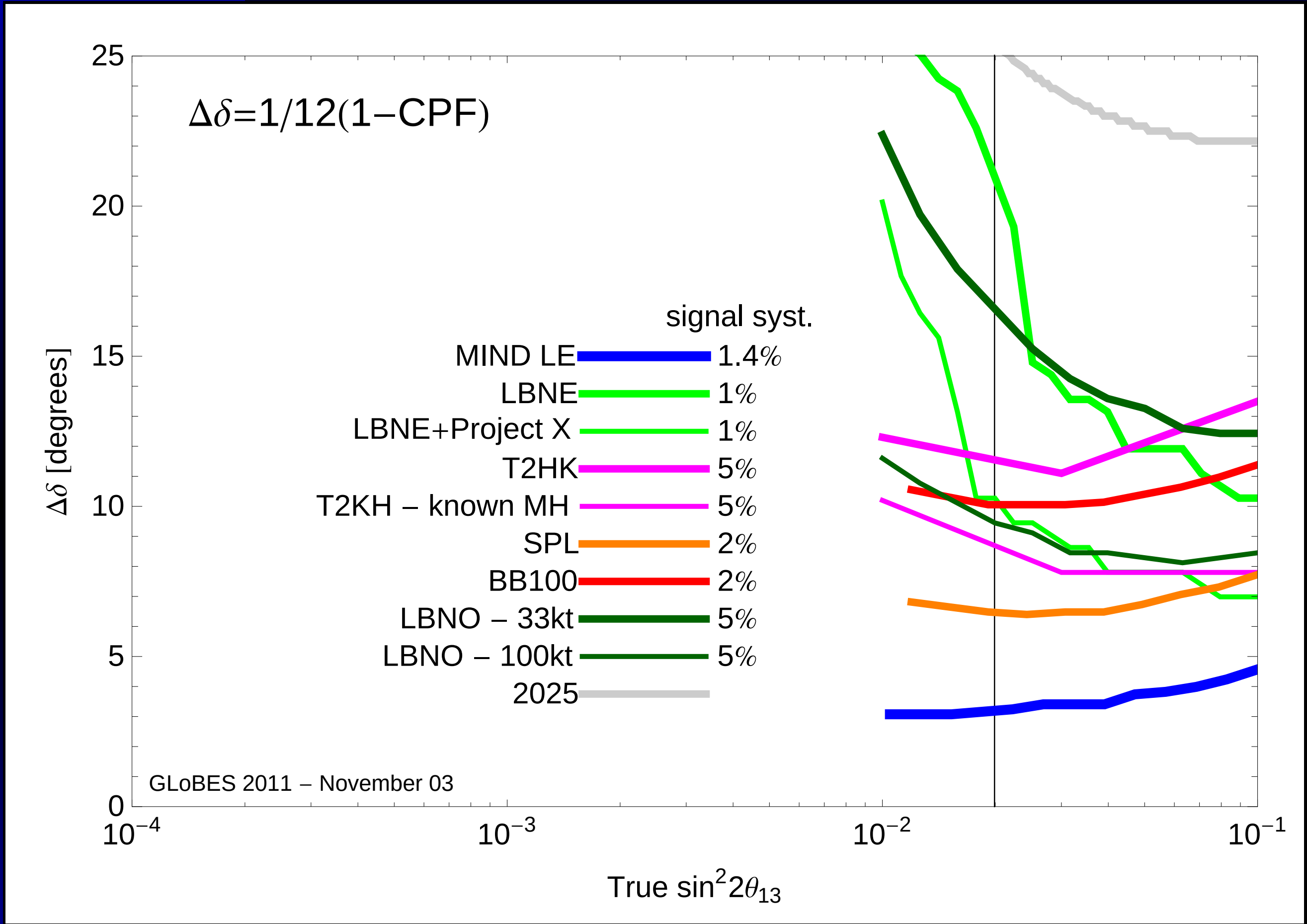
Are superbeams enough?



SB reach CPF of 0.25-0.8
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 $\Delta\delta = 6^\circ - 25^\circ$

NF $\Delta\delta = 3^\circ - 5^\circ$

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

This requires a MUCH more detailed analysis!

Systematics

When I speak of some quantity is ’known’ in the following I mean, known at a level of percent or better from an actual measurement or a theoretical calculation†

† *i.e.* from a controlled approximation, where the error term can be bounded reliably from above

The Idea

In order to measure CP violation and to break the correlation with θ_{13} 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 the percent level accuracy

The Reality

We do not measure probabilities, but event rates!

$$R^\alpha_\beta = N \int dE\, \Phi_\alpha(E)\, \sigma_\beta(E)\, \epsilon_\beta(E)\, P(\nu_\alpha \to \nu_\beta, E)$$

In order the reconstruct P, we have to know

- N – overall normalization (fiducial mass)
- Φ_α – flux of ν_α
- σ_β – x-section for ν_β
- ϵ_β – detection efficiency for ν_β

Note: $\sigma_\beta \epsilon_\beta$ always appears in that combination, hence we can define an effective cross section $\tilde{\sigma}_\beta := \sigma_\beta \epsilon_\beta$

The Problem

Even if we ignore all energy dependencies of efficiencies, x-sections *etc.*, we generally can not expect to know any ϕ or any $\tilde{\sigma}$. Also, we won't know any kind of ratio

$$\frac{\Phi_\alpha}{\Phi_{\bar{\alpha}}} \quad \text{or} \quad \frac{\Phi_\alpha}{\Phi_\beta}$$

nor

$$\frac{\tilde{\sigma}_\alpha}{\tilde{\sigma}_{\bar{\alpha}}} \quad \text{or} \quad \frac{\tilde{\sigma}_\alpha}{\tilde{\sigma}_\beta}$$

Note: Even if we may be able to know σ_e/σ_μ from theory, we won't know the corresponding ratio of efficiencies ϵ_e/ϵ_μ

The Solution

Measure the un-oscillated event rate at a near location and everything is fine, since all uncertainties will cancel, (provided the detectors are identical and have the same acceptance)

$$\frac{R^\alpha_\alpha(\text{far})L^2}{R^\alpha_\alpha(\text{near})} = \frac{N_\text{far}\Phi_\alpha\,\tilde{\sigma}_\alpha\,P(\nu_\alpha \to \nu_\alpha)}{N_\text{near}\Phi_\alpha\,\tilde{\sigma}_\alpha 1}$$

$$\frac{R^\alpha_\alpha(\text{far})L^2}{R^\alpha_\alpha(\text{near})} = \frac{N_\text{far}}{N_\text{near}}P(\nu_\alpha \to \nu_\alpha)$$

And the error on $\frac{N_\text{far}}{N_\text{near}}$ will cancel in the ν to $\bar{\nu}$ comparison.

Some practical issues

- same acceptance may require a not-so-near near detector
- near and far detector cannot be really identical
- some energy dependencies will remain

In principle all those factors can be controlled by careful design and analysis with good accuracy, see *e.g.* MINOS.

But ...

This all works only for disappearance measurements!

$$\frac{R^\alpha_\beta(\text{far})L^2}{R^\alpha_\beta(\text{near})} = \frac{N_\text{far}\Phi_\alpha\,\tilde{\sigma}_\beta\,P(\nu_\alpha \to \nu_\beta)}{N_\text{near}\Phi_\alpha\,\tilde{\sigma}_\alpha\,1}$$

$$\frac{R^\alpha_\beta(\text{far})L^2}{R^\alpha_\beta(\text{near})} = \frac{N_\text{far}\,\tilde{\sigma}_\beta\,P(\nu_\alpha \to \nu_\beta)}{N_\text{near}\,\tilde{\sigma}_\alpha\,1}$$

Since $\tilde{\sigma}$ will be different for ν and $\bar{\nu}$, this is a serious problem. And we can not measure $\tilde{\sigma}_\beta$ in a beam of ν_α.

Remarks

- this discussion completely neglected backgrounds
- the ν_e component of a superbeam will not help much, since Φ_μ/Φ_e is essentially unknown
- a β-beam can probably measure $\tilde{\sigma}_e$ but not $\tilde{\sigma}_\mu$
- and we really need to know the ratio (at least)

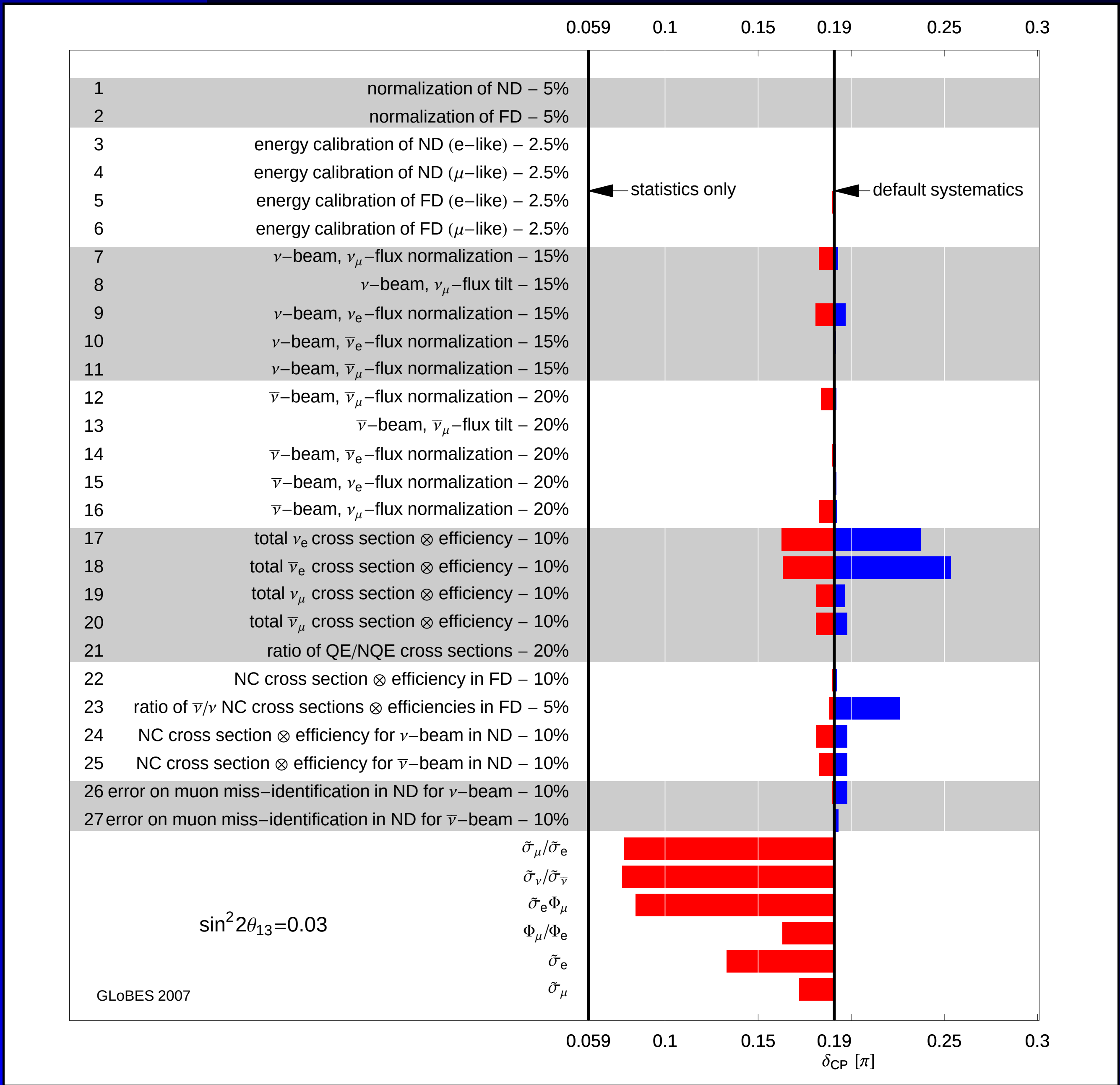
A detailed example . . .

Details to be found in PH, Mezzetto, Schwetz, JHEP 0803:021,2008., overall T2HK-like.

- WC far detector $m = 500\,\mathrm{kt}$ and $L = 295\,\mathrm{km}$
- WC near detector $m = 1\,\mathrm{kt}$ and $L = 2\,\mathrm{km}$
- same flux for near and far (except for L^2-scaling)
- same (energy dependent) efficiencies in both detectors

All sensitivity calculation are performed with GLoBES 3.0 – no degeneracies taken into account.

Systematical errors



These uncertainties are implemented using the so called pull-approach. We have all together 28 such pulls.

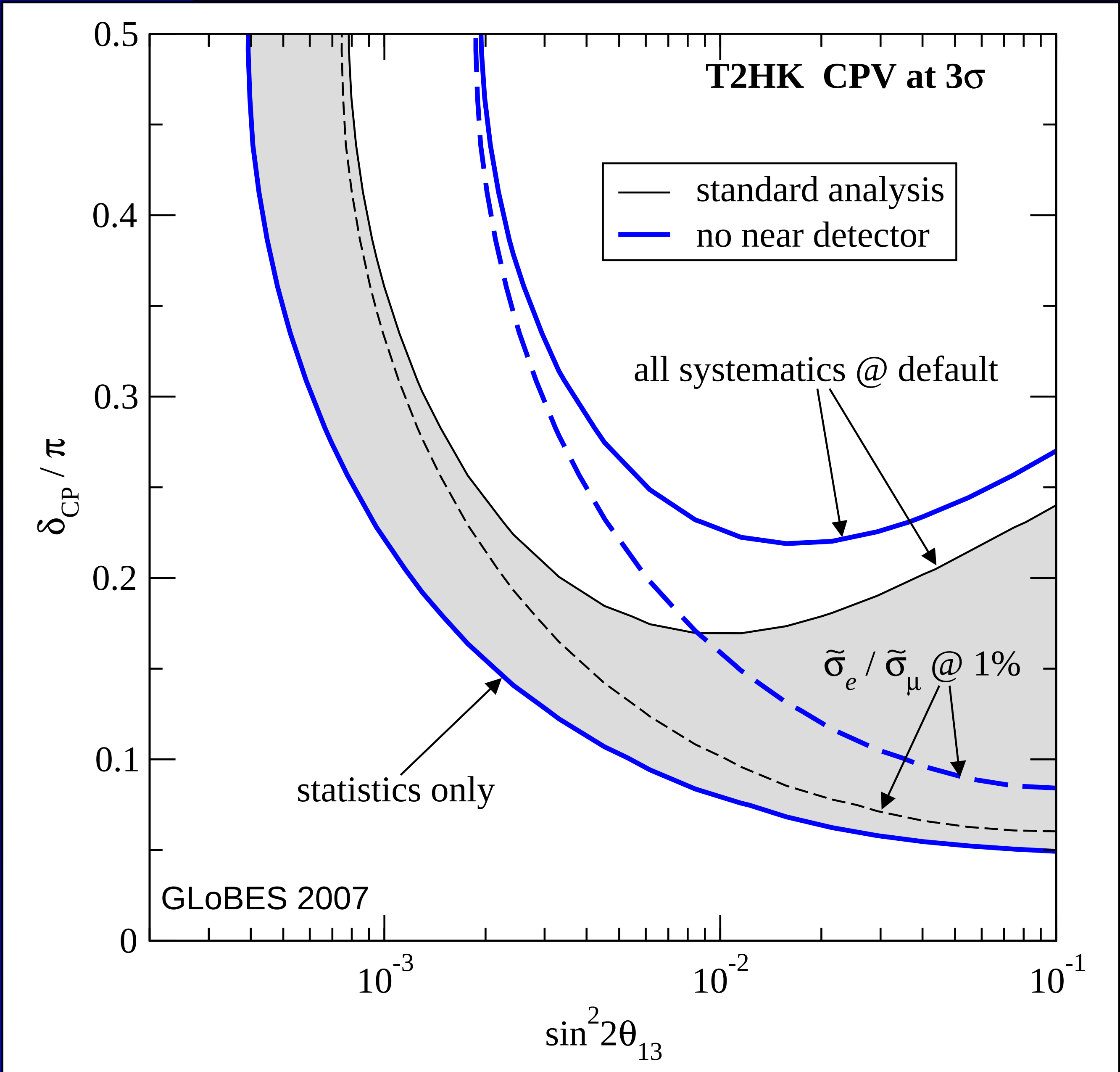
Here, no near detector

red – sys.=0
blue – 5× sys.

Disclaimer: I do not claim that any error actually will have that size in a real experiment nor that our simulation is exact.

The point of the following is to show that a near detector on its own won’t take care of all the systematics. Additional information will be needed!

Impact of Near Detector

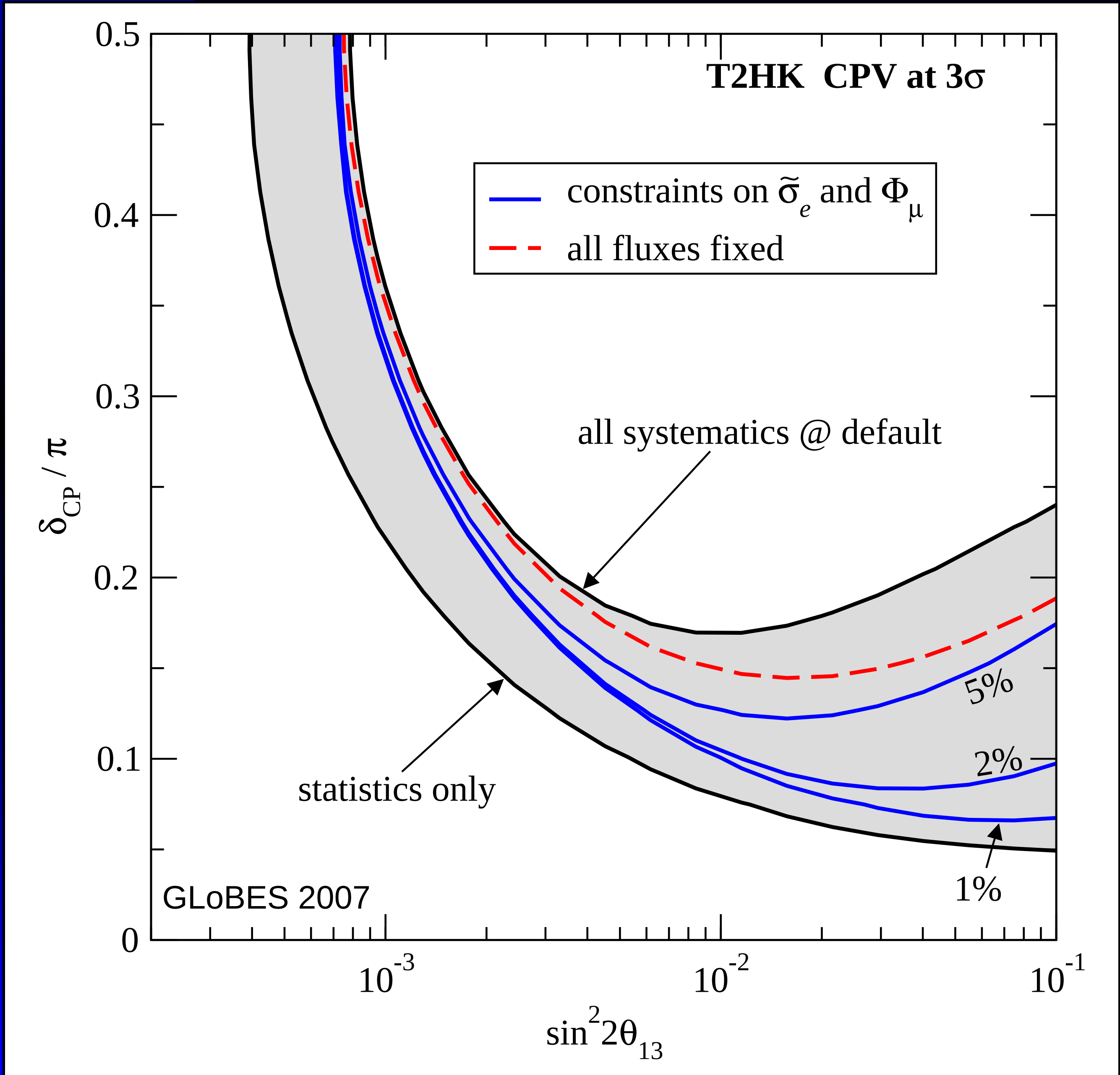


Near detector does not eliminate all systematics

$\tilde{\sigma}_\mu/\tilde{\sigma}_e$ is the by far most important parameter

Large θ_{13} is the most difficult region

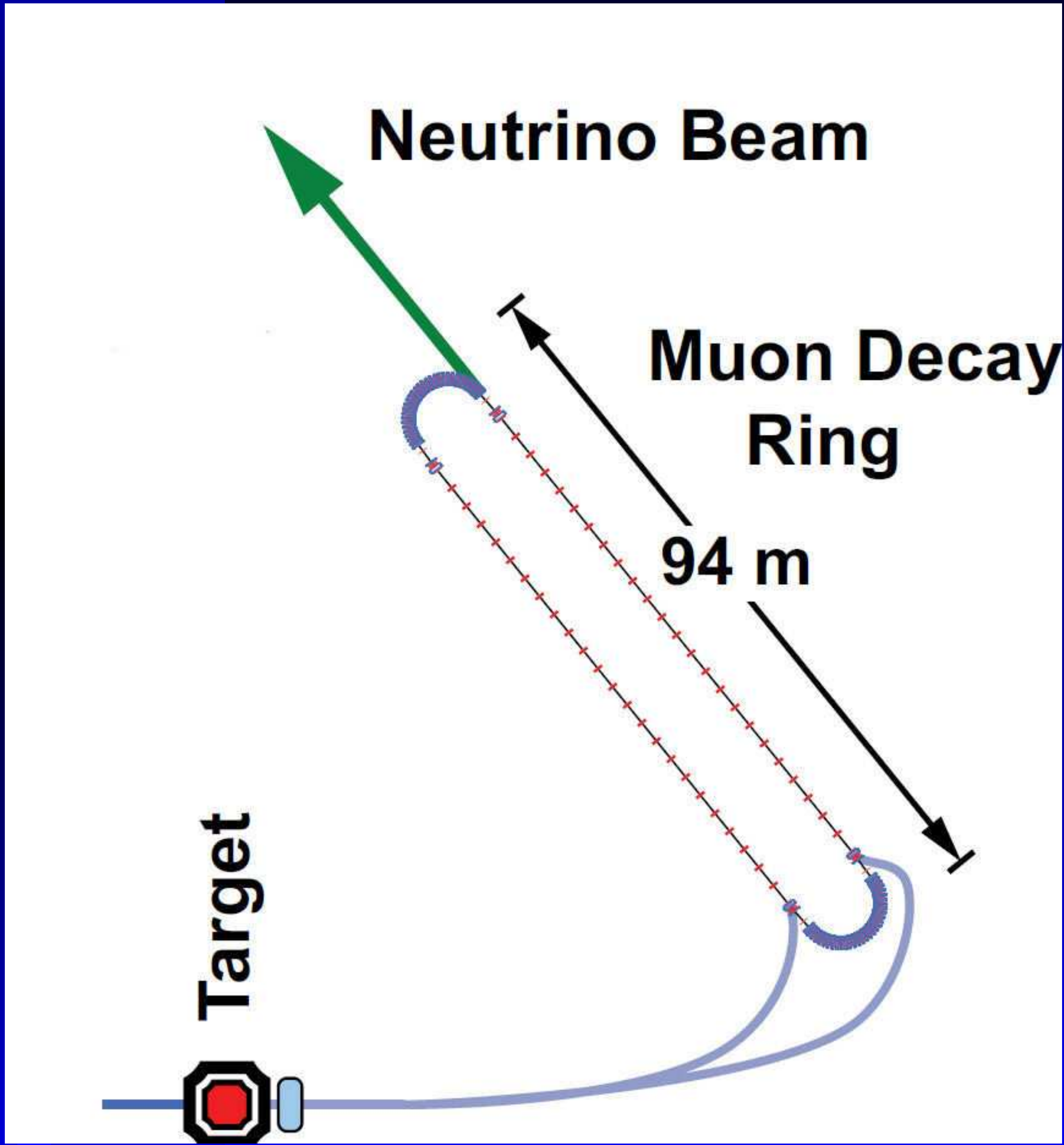
Impact of fluxes



Even perfectly know fluxes plus near detector do not eliminate systematics

Large θ_{13} is the most difficult region

Very Low Energy NF



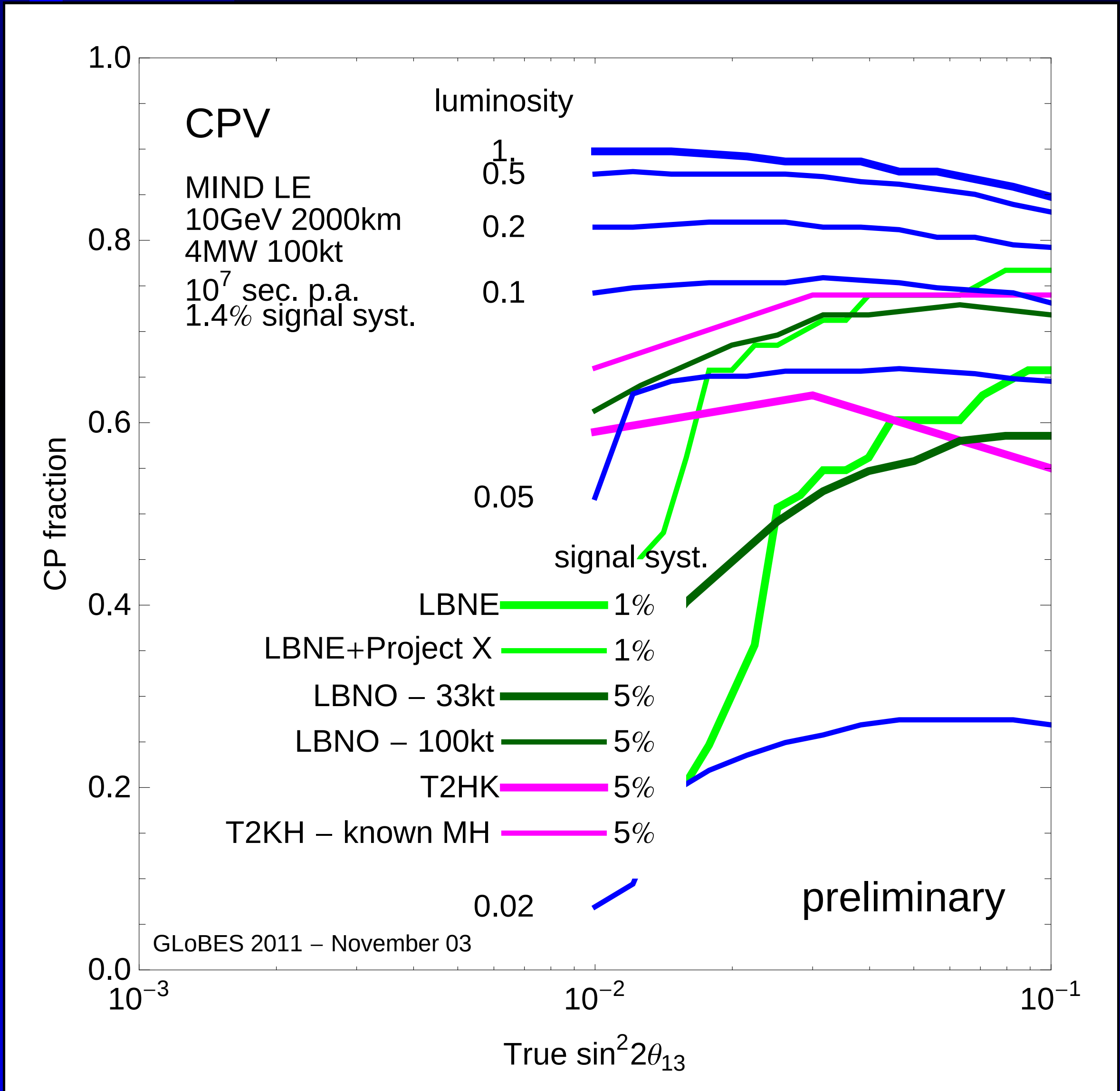
8 GeV protons from the FNAL booster on thick Be target – 3 GeV muon energy

In a 200 t near detector, 10^5 – 10^6 $\nu_\mu/\bar{\nu}_e$ CC events per year

Use of μ^-/μ^+ beams allows to measure $\tilde{\sigma}_\mu/\tilde{\sigma}_e$ and $\tilde{\sigma}_{\bar{\mu}}/\tilde{\sigma}_{\bar{e}}$

L^3NF

Low Luminosity Low energy Neutrino Factory



1/20-1/10 of luminosity - L^3NF as good as the best SB

⇒ Start somewhere between 1/20 and 1/10

⇒ No muon cooling

⇒ Use existing proton infrastructure at FNAL

⇒ Upgrade to full luminosity

Summary

- At large θ_{13} leptonic CP violation still can not be done by existing experiments
- At large θ_{13} many degeneracies can be resolved by atmospheric neutrino data
- At large θ_{13} systematics will be key to CP measurement
- Superbeams can not constraint the crucial $\tilde{\sigma}_\mu/\tilde{\sigma}_e$ and $\tilde{\sigma}_{\bar{\mu}}/\tilde{\sigma}_{\bar{e}}$ ratios in their near detector
- Neutrino factories will ultimately provide the best precision

References

- LBNE curves are provided by Sam Zeller as defined by the LBNE physics working group as of fall 2010 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 Euro-ν WP6 report 2011
- Amtospheric data sensitivity in large WC on mass hierarchy from Euro-ν WP6 report 2010
- Neutrino Factory curves are taken from the IDS-NF IDR
- 2025 data from PH, *et al.* JHEP 11 044 (2009).

Future Options

name	baseline	type	mass	power	sec. in year	years	sig. syst.
LBNE	1300	WC/LAr	200/33	0.7MW	2×10^7	5+5	1%
LBNE+ Pro. X	1300	WC/LAr	200/33	2.3MW	2×10^7	5+5	1%
LBNO 33kt	2300	LAr	33	1.7MW	1.7×10^7	5+5	5%
LBNO 100kt	2300	LAr	100	1.7MW	1.7×10^7	5+5	5%
T2HK	295	WC	560	1.66MW	1×10^7	2.1+2.9	5%
SPL	130	WC	440	4MW	1×10^7	2+8	2%
BB100	130	WC	440	1.1×10^{18} Ne	1×10^7	5+5	2%
				2.9×10^{18} He			
IDS-NF 2.0	4000+7500	MIND	100+50	4MW	1×10^7	5+5	1.4%
MIND LE	2000	MIND	100	4MW	1×10^7	5+5	1.4%