Physics and Optimisation of a Neutrino Factory

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Outline

- CP measurements
  - CP coverage
  - CP scaling & CP pattern
  - Improving the performance
- Beta-Beams and other alternatives
  - θ_{13}
  - CP measurements
  - Mass hierarchy
- Summary & Conclusion

Leptonic CP violation

Size of CP effects is proportional to

- $\sin 2\theta_{13}$
  - will determine experimental strategy
  - $\sin^2 2\theta_{13}$ needs to be $> 10^{-5}$
- $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$
  - solar neutrinos puzzle solved by LMA
  - $0.024 < \alpha < 0.06$
- $\sin 2\theta_{12}$
  - $0.84 < \sin 2\theta_{12} < 0.97$

How to evaluate CP sensitivity

- Choose a value for all oscillation parameters, called ‘true value’
- Simulate data for those true values
- Perform a fit to these data
- Project the resulting $\Delta\chi^2$ onto the δ_{CP}-axis

Choosing true values

- 6 oscillation parameters
  $$\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{\mathrm{CP}}$$
- Allowed ranges are of the same order than the central value
- Results strongly depend on the initial point

True value will be denoted by the sub/super-script 0. Unless otherwise stated

$$(\Delta m^2_{31})^0 = +2.5\cdot 10^{-3}\,\mathrm{eV} \quad (\Delta m^2_{21})^0 = +8.2\cdot 10^{-4}\,\mathrm{eV}$$

$$\sin^2 2\theta^0_{23} = 1 \quad \sin^2 2\theta^0_{12} = 0.82$$

Simulating data

- Appearance channels
- Backgrounds
- Spectrum – energy resolution
- Disappearance channels
- Matter effects

Fitting the data

- How many parameters
- Matter density uncertainty
- Systematic effects

All those things are done with

GLoBES

`http://www.ph.tum.de/~globes`

The neutrino factory

We assume a neutrino factory with

- $50\,\mathrm{GeV}$ muon energy
- 10^{21} useful muon decays per year
- 4 years neutrino & 4 years anti-neutrino running

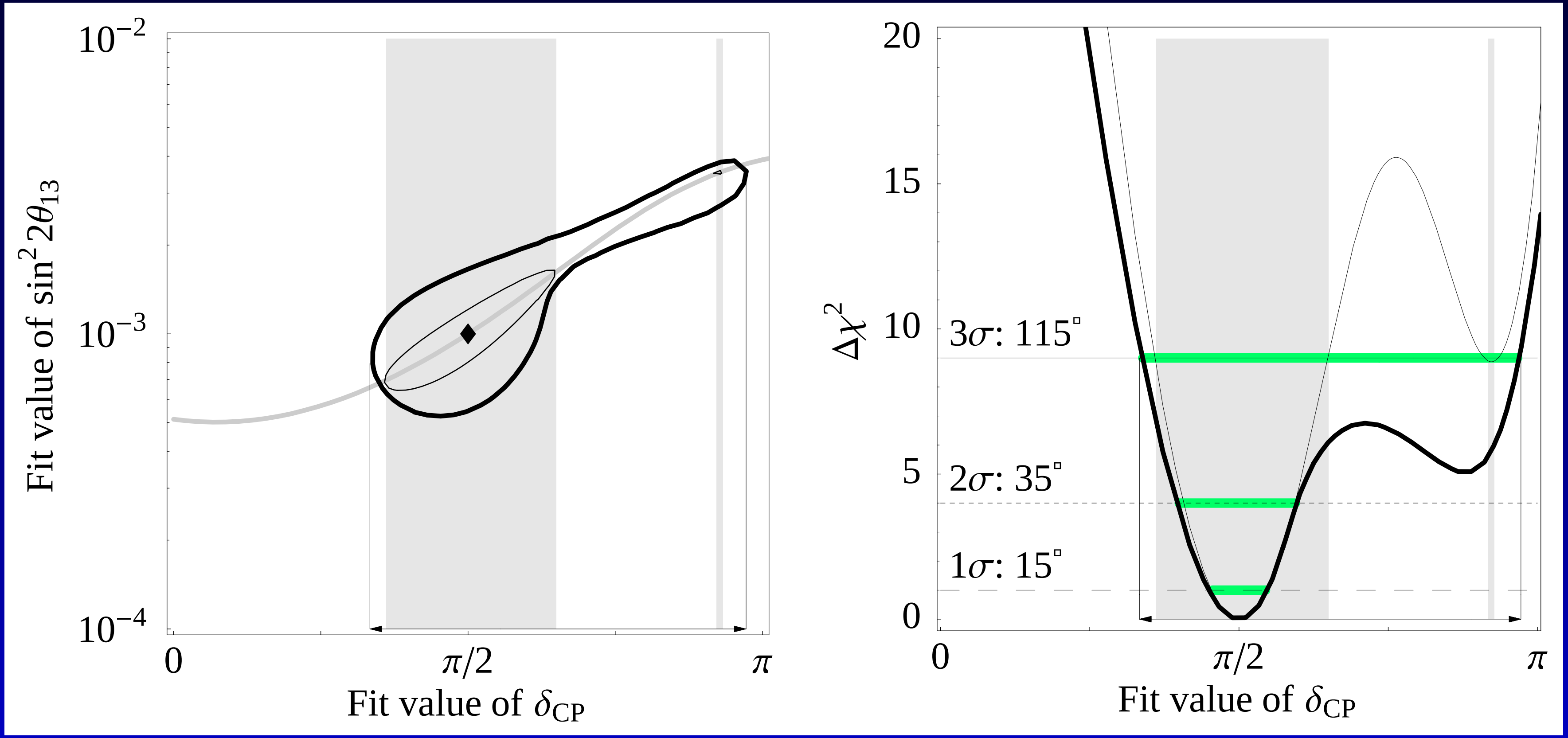
We assume a detector with

- $50\,\mathrm{kt}$ fiducial mass
- an energy threshold at $4\,\mathrm{GeV}$ rising till $20\,\mathrm{GeV}$
- energy resolution $\delta E_\nu / E_\nu = 0.15$

The following results are taken from
PH, M. Lindner, W. Winter, JHEP **0505** (2005) 020.

CP coverage

NuFact-II

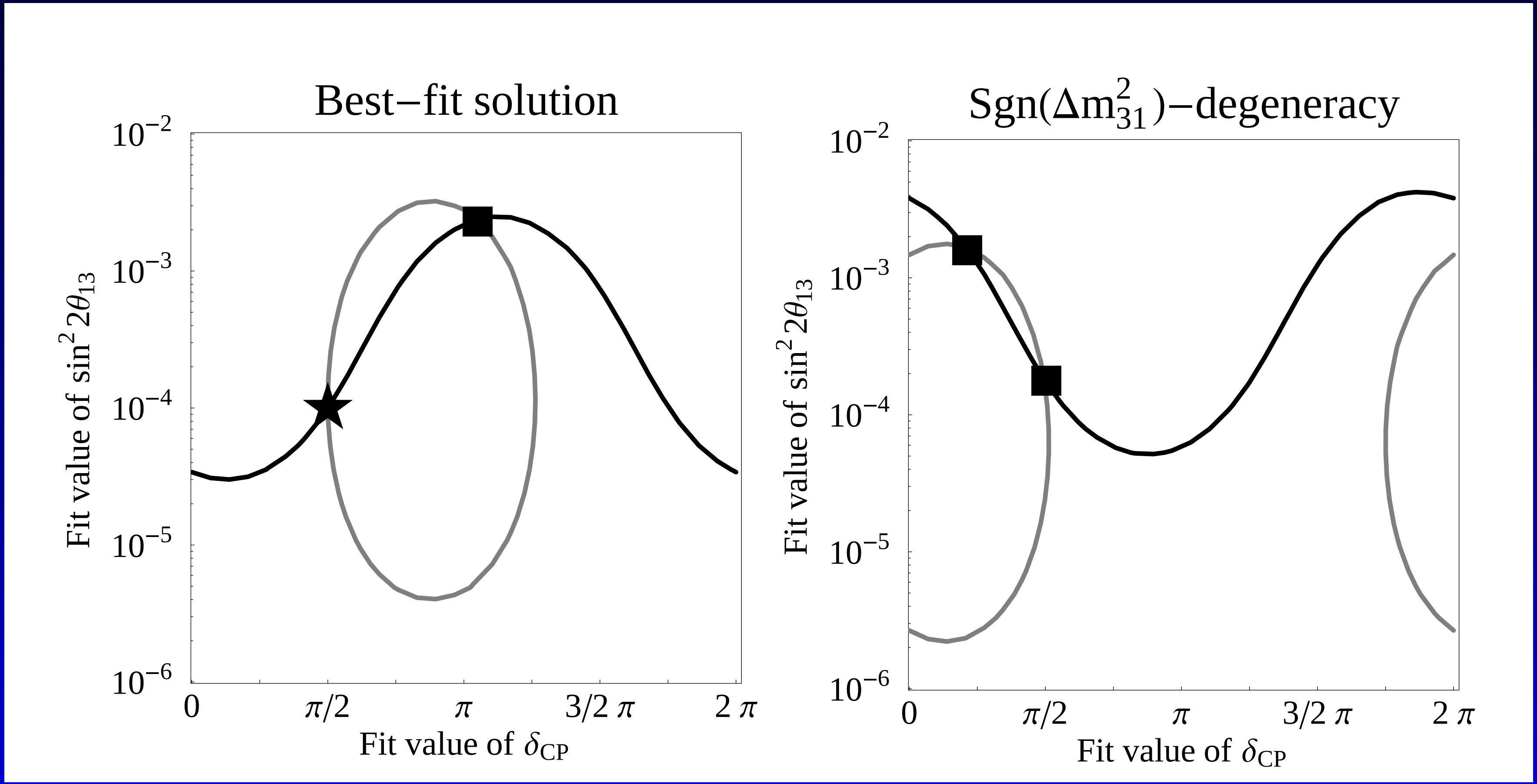


CP coverage:

total length of the allowed region(s) in δ_{CP}

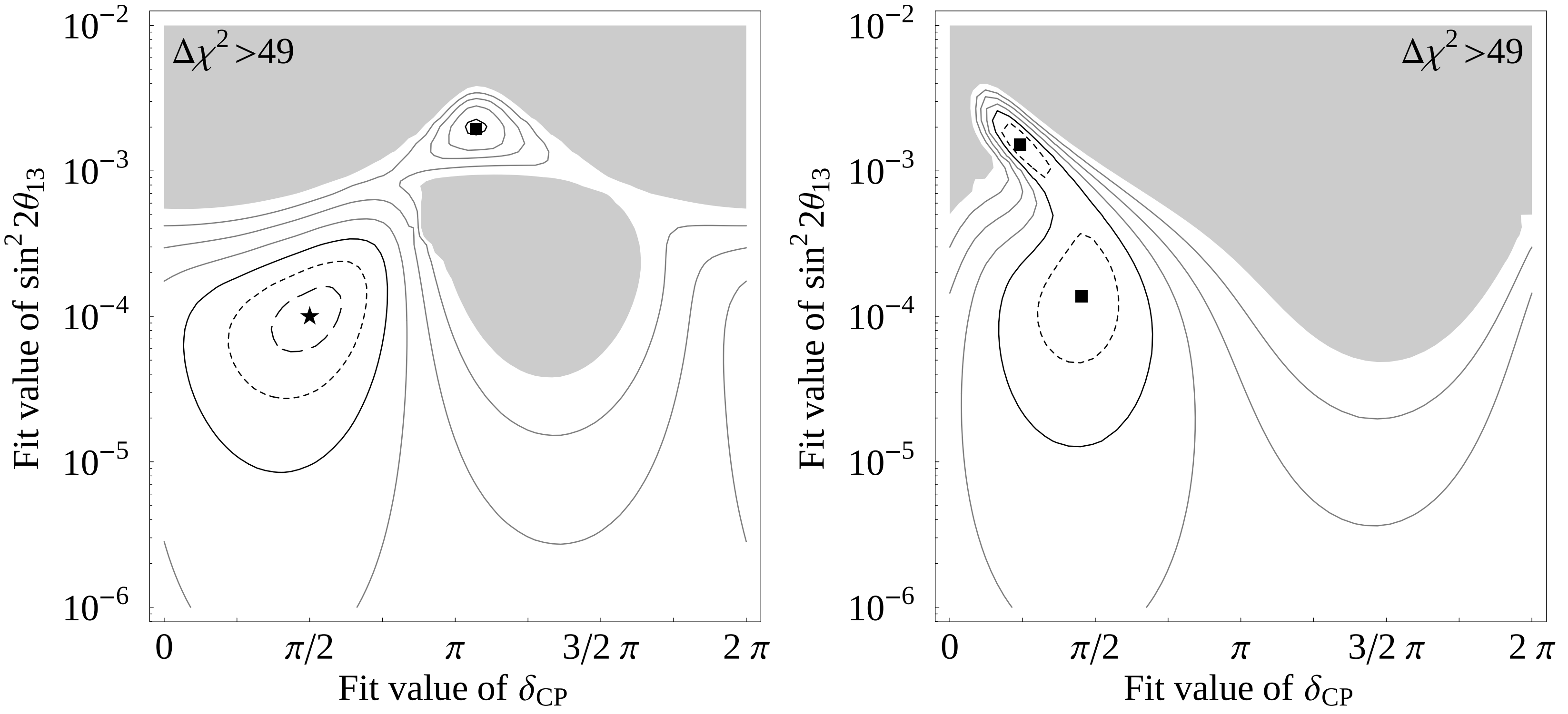
Spotting degeneracies

Total appearance rates



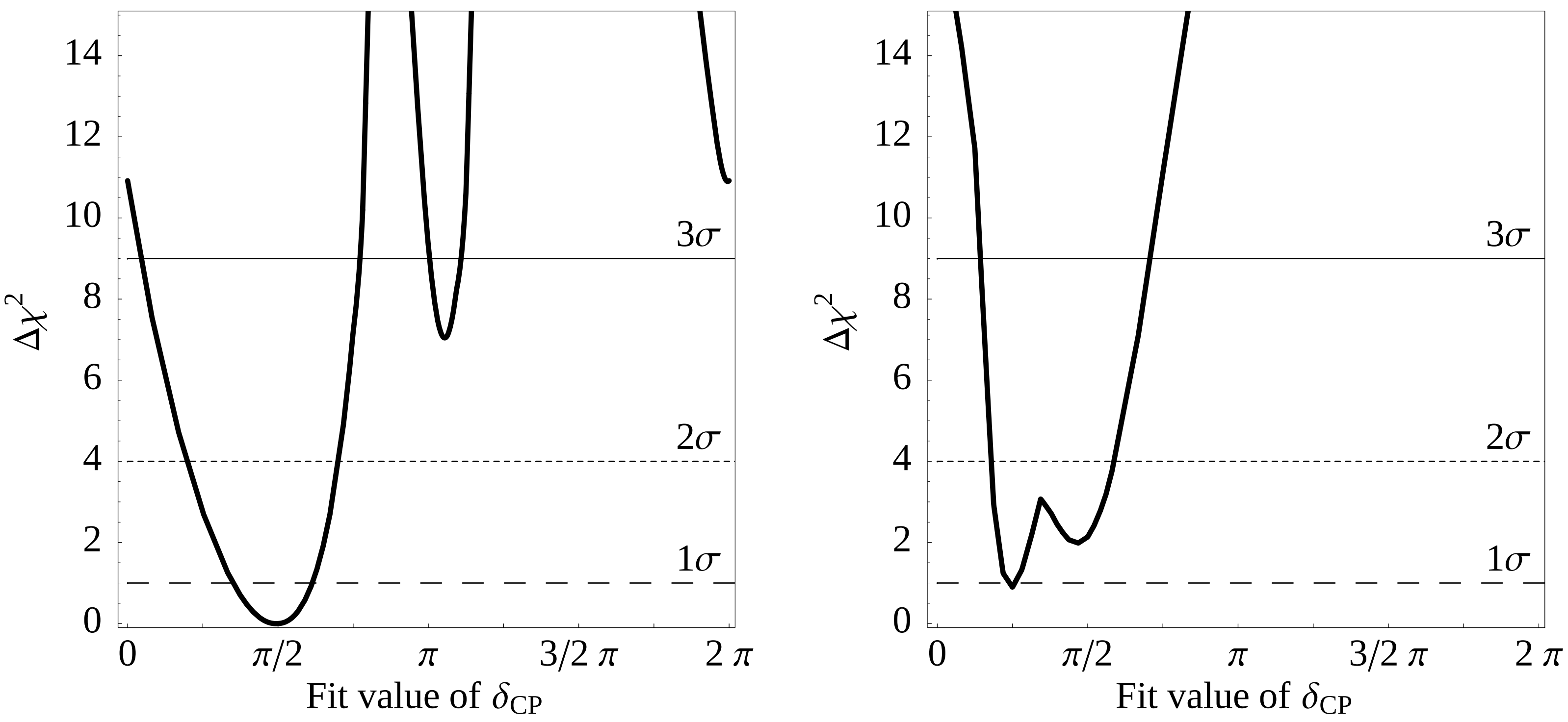
Spotting degeneracies

Find the local minima in the full $\Delta\chi^2$



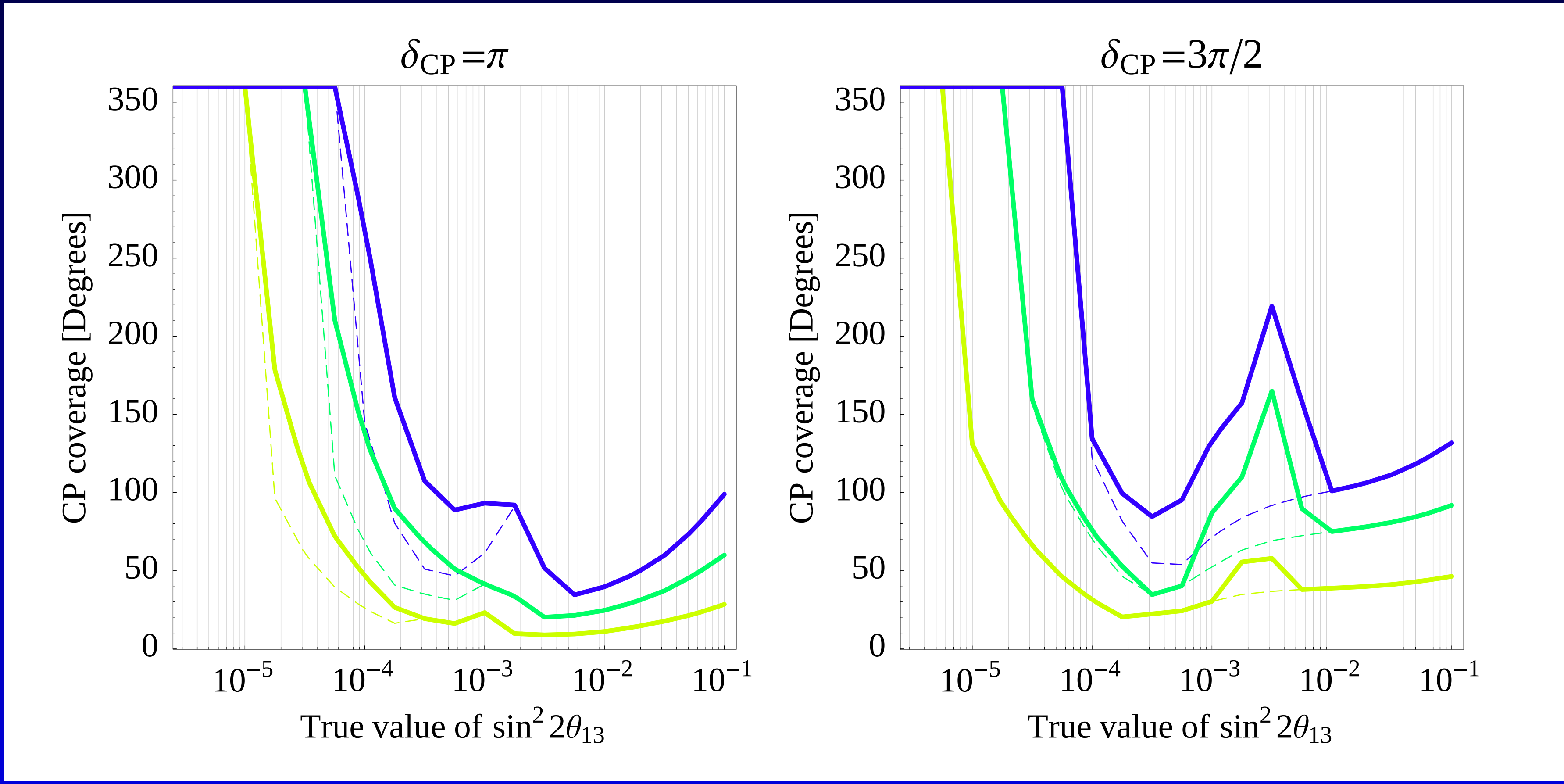
Spotting degeneracies

Project onto δ_{CP}-axis



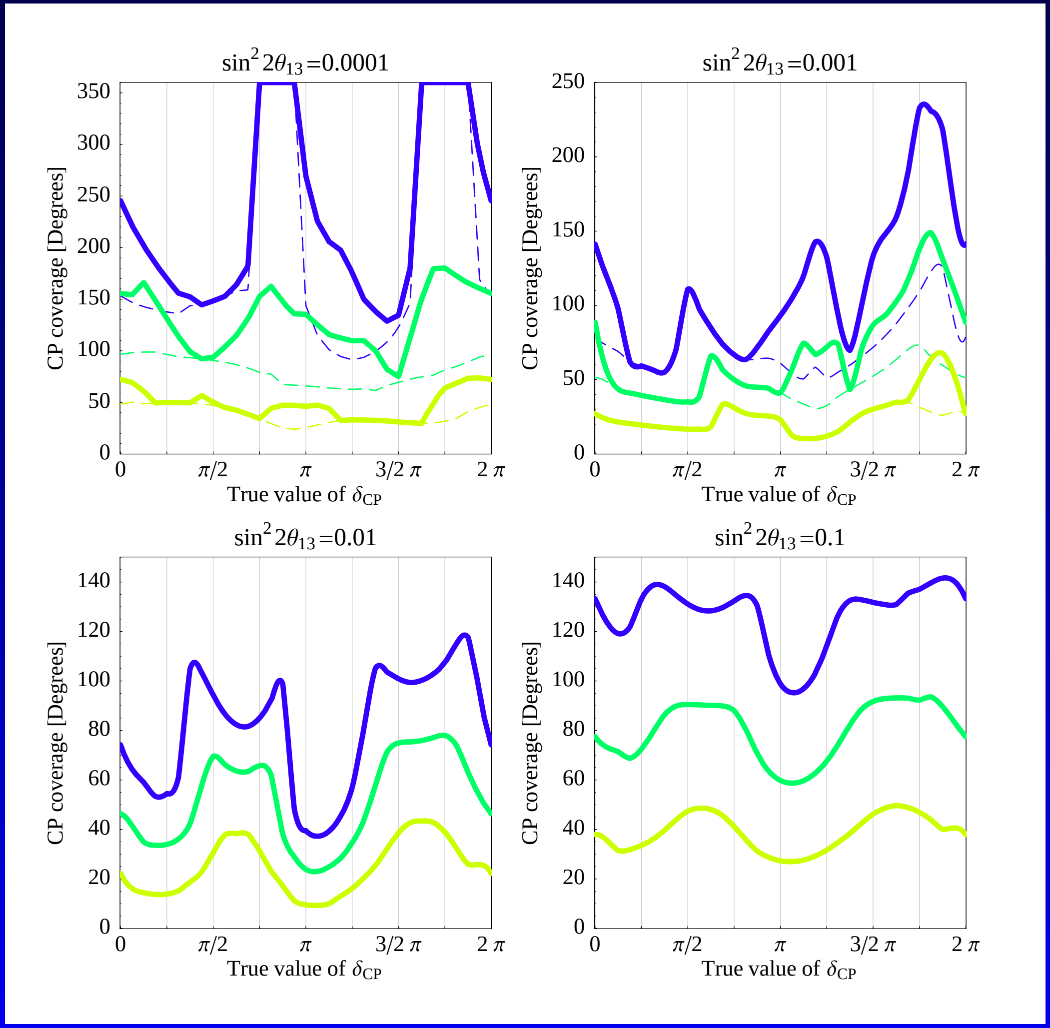
CP scaling

Variation of the CP coverage as a function of θ_{13}^0 with δ^0 fixed



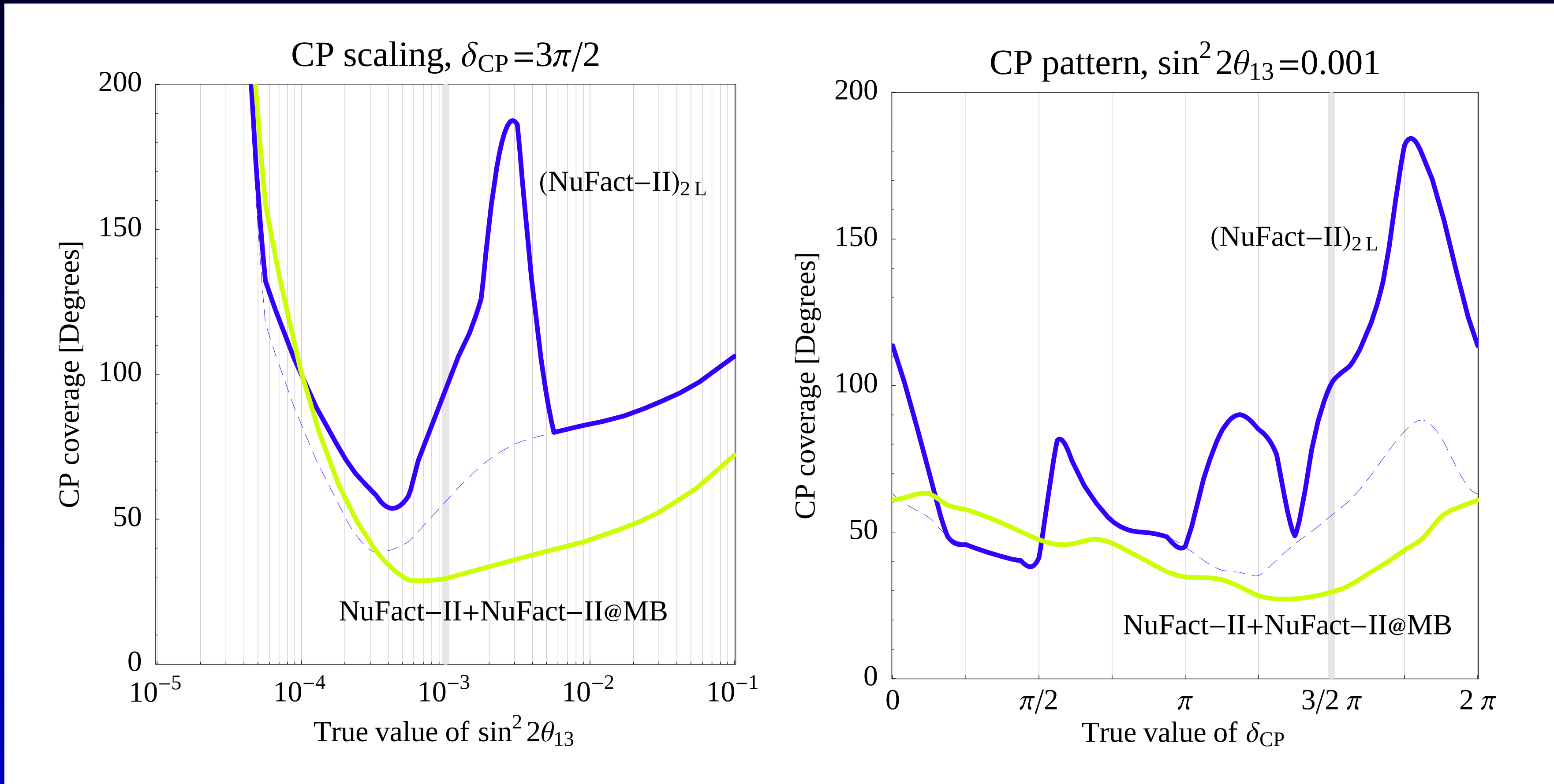
CP pattern

Variation of the CP coverage as a function of δ^0 with θ_{13}^0 fixed



Large variations in CP coverage, esp. for small θ_{13}^0 and high CL

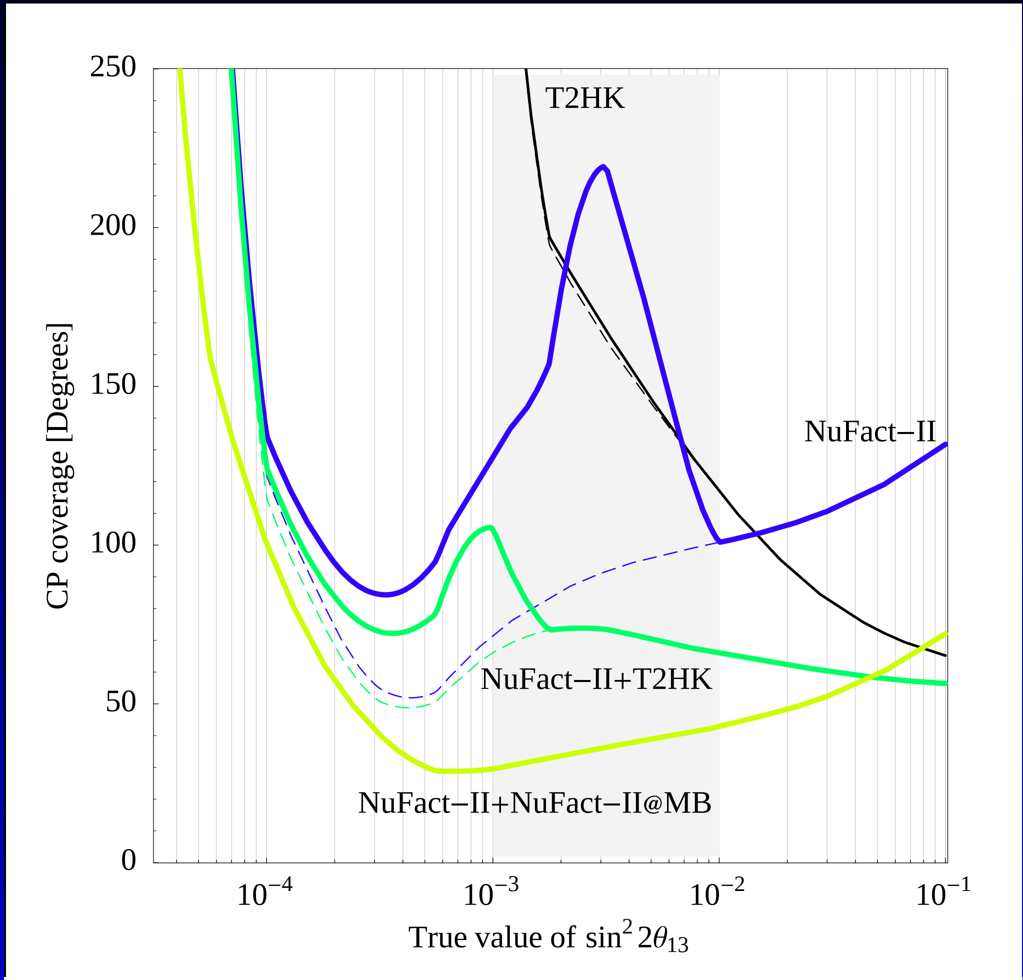
Improving the performance I



The magic baseline of 7 500 km eliminates the risk of the being at the wrong place in parameter space

PH and W. Winter, Phys. Rev. D **68** (2003) 037301.

Improving the performance II



$\sin^2 2\theta_{13} \geq 10^{-2}$
T2HK outperforms NF

$10^{-3} \leq \sin^2 2\theta_{13} \leq 10^{-2}$
true synergy

$\sin^2 2\theta_{13} \leq 10^{-3}$
only NF contributes

J. Burguet-Castell, *et al.*, Nucl. Phys. B **646** (2002) 301

Beta-beam I

For the Beta-beam we assume

- $1.1 \cdot 10^{18}$ neutrinos (^{18}Ne) and $2.9 \cdot 10^{18}$ (^{6}He) anti-neutrinos per year
- same γ for both
- running time of 8 years
- flux independent of γ

We will used two different detector technologies:

Water Cherenkov for low γ

Totally active scintillator *á la* NOνA for medium to high γ

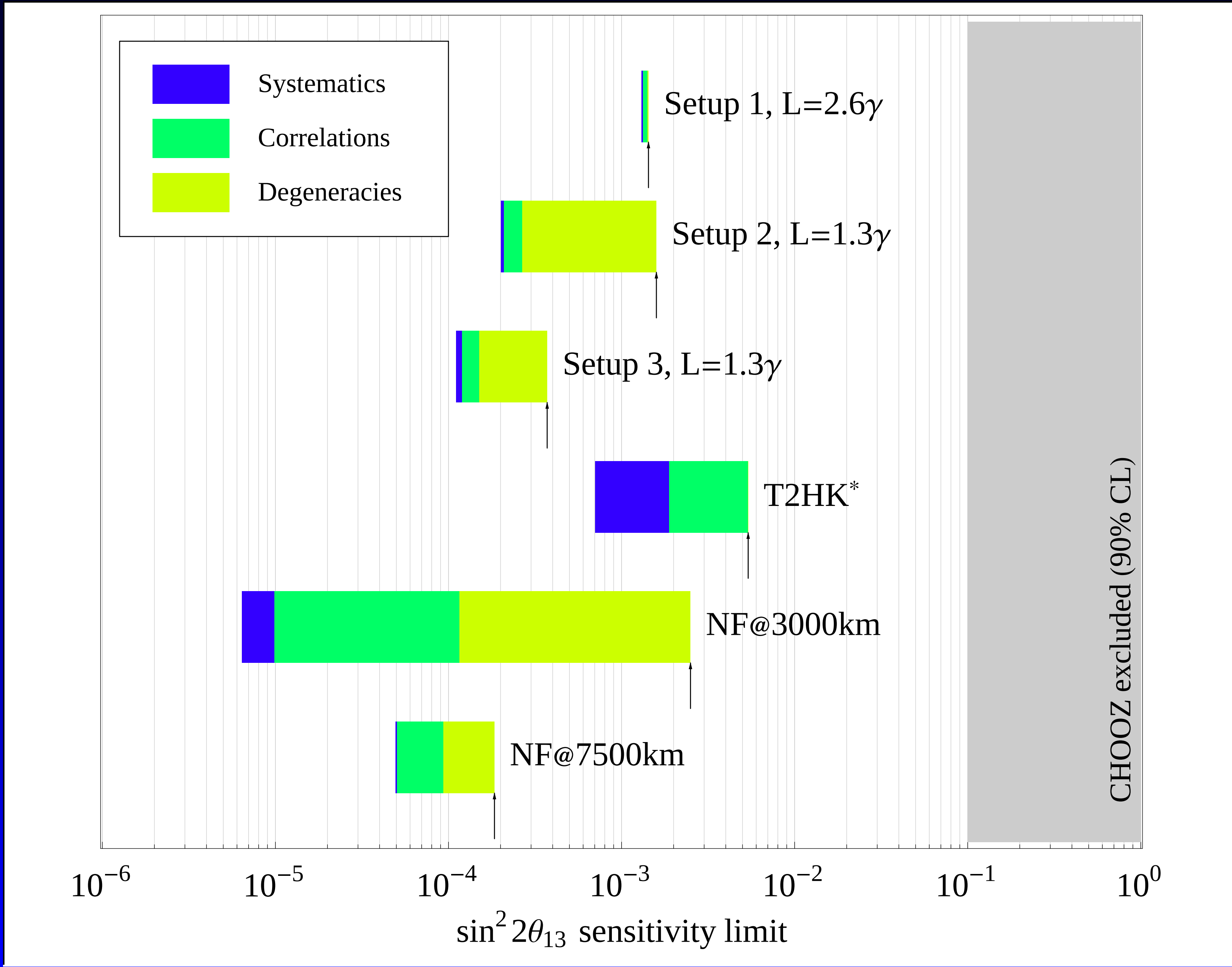
Beta-beam II

These are the setups

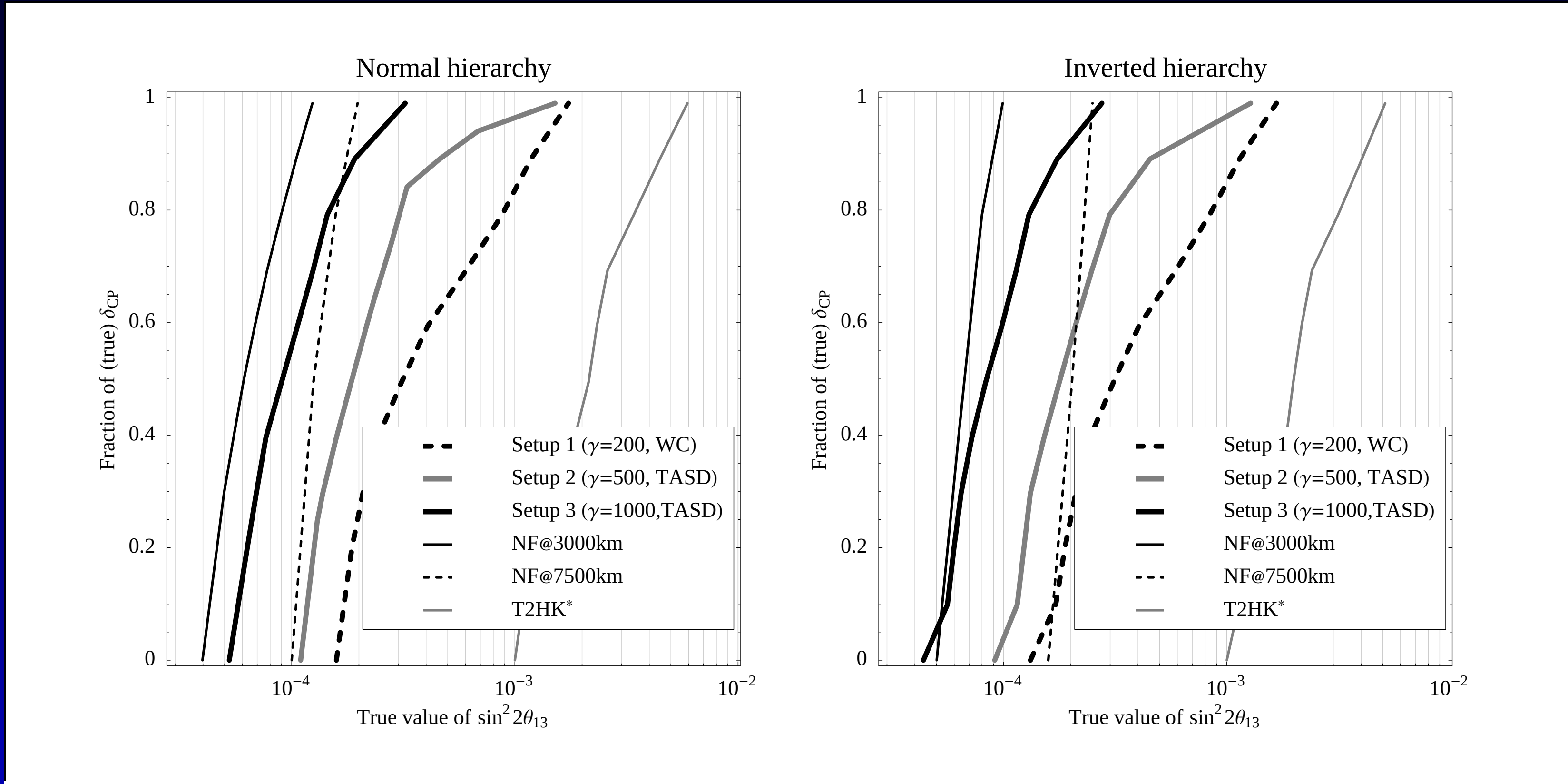
#	1	2	3
type	WC	TASD	TASD
m [kt]	500	50	50
γ	200	500	1000
L [km]	520	650	1000
ν signal	1983	2807	7416
ν background	105	31	95

The following results are taken from PH, M. Lindner, M. Rolinec, W. Winter, hep-ph/0506237.

$\sin^2 2\theta_{13}$ **sensitivity** – $\theta_{13}^0 = 0$

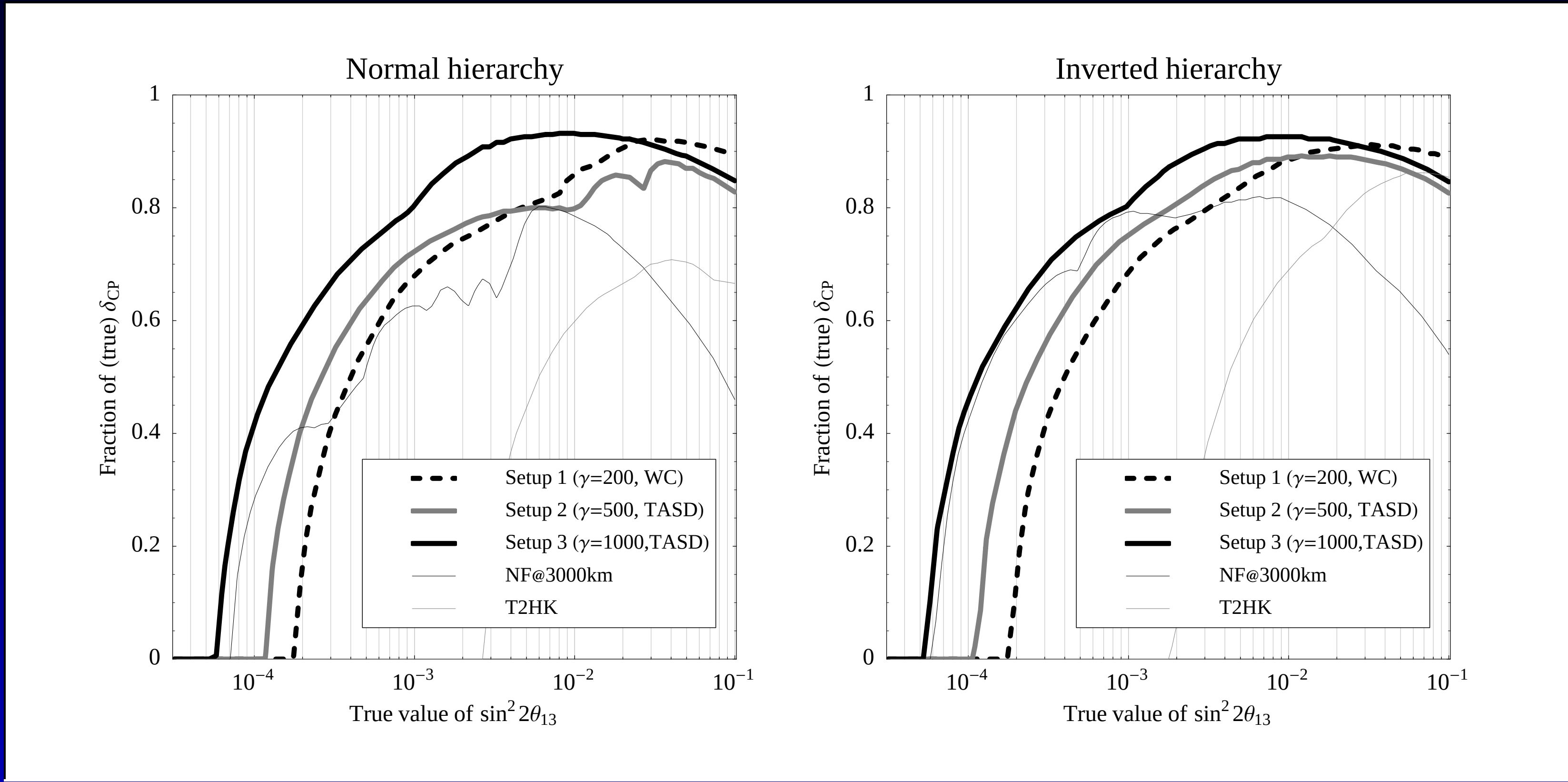


$\sin^2 2\theta_{13}$ discovery – $\theta_{13}^0 \neq 0$



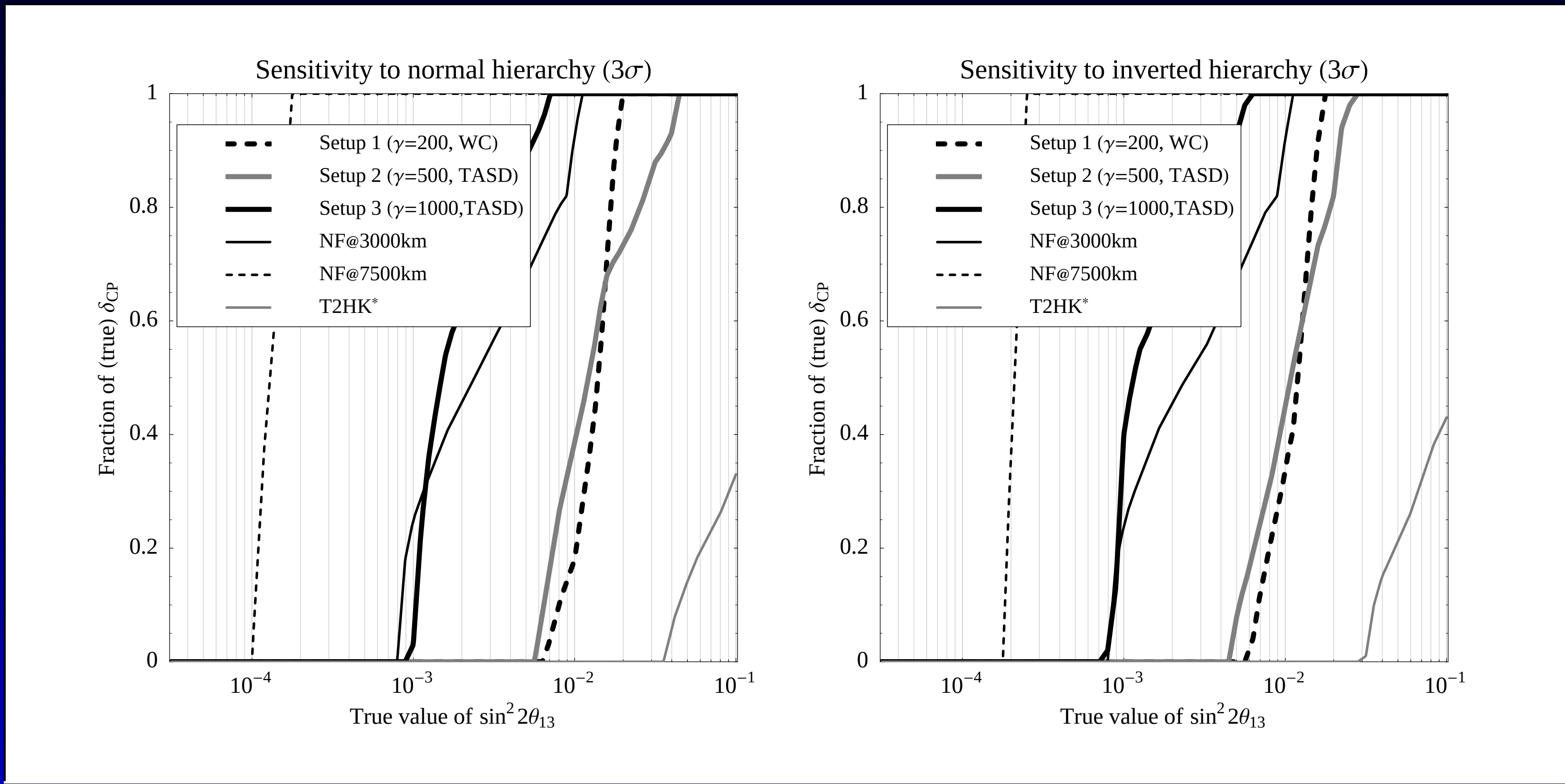
- good discovery potential at 3 000 km
- only high-γ beta-beams are comparable
- T2HK* background/systematic limited

CP violation



- Beta-beam performs very well, for all γs
- Neutrino factory handicapped by error on matter density

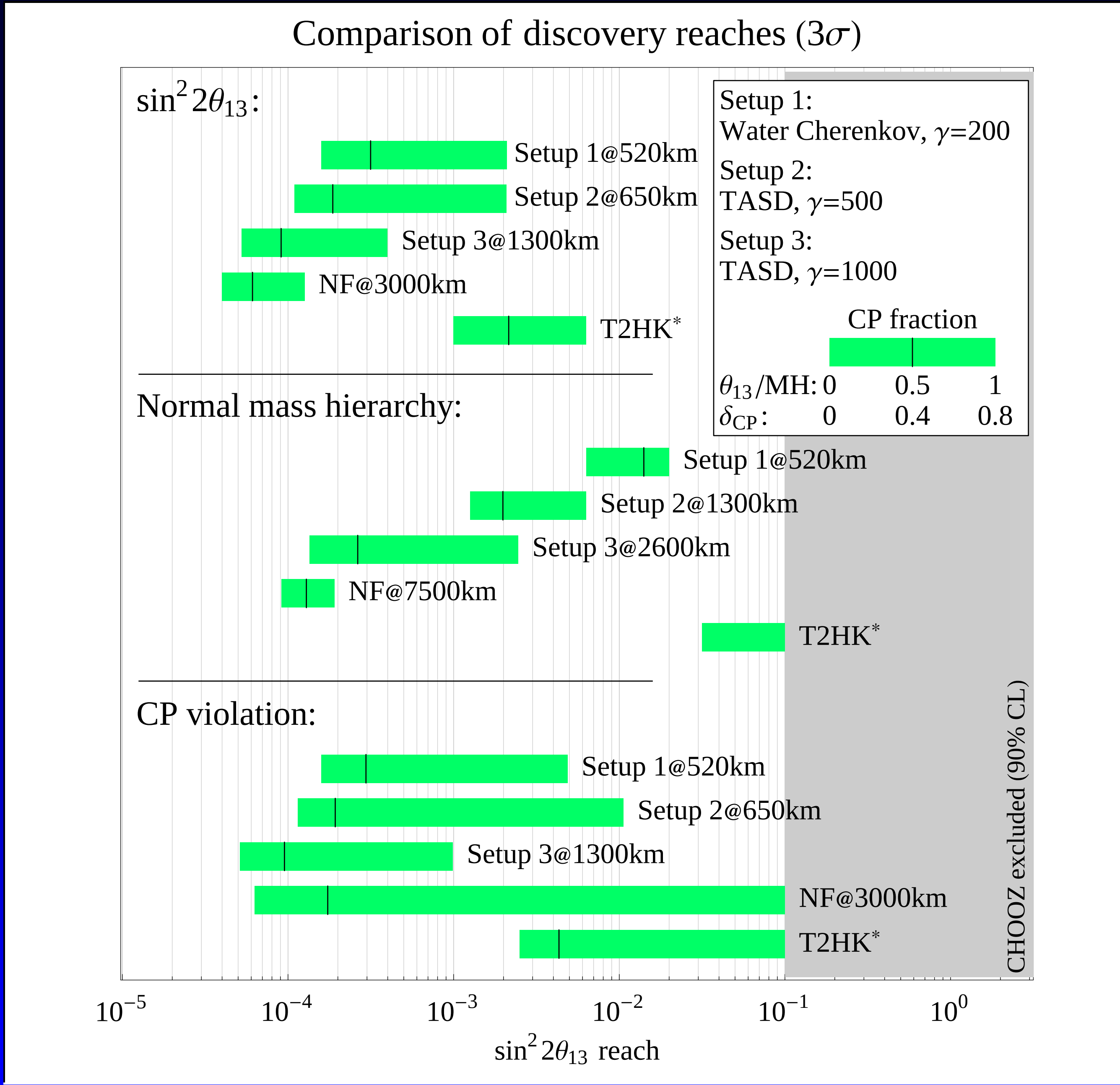
Mass hierarchy



- NF with very long baselines is optimal
- T2HK*, too short baseline $\longrightarrow$ NOνA and BNL
- Only high-γ beta-beam is useful

Summary & Conclusion

Summary



Comparison of discovery reaches (3σ)
$\sin^2 2\theta_{13}$:
Setup 1@520km
Setup 2@650km
Setup 3@1300km
NF@3000km
T2HK*
Normal mass hierarchy:
Setup 1@520km
Setup 2@1300km
Setup 3@2600km
NF@7500km
T2HK*
CP violation:
Setup 1@520km
Setup 2@650km
Setup 3@1300km
NF@3000km
T2HK*
Setup 1:
Water Cherenkov, γ=200
Setup 2:
TASD, γ=500
Setup 3:
TASD, γ=1000
CP fraction
θ_{13}/MH: 0 0.5 1
δ_{CP}: 0 0.4 0.8
CHOOZ excluded (90% CL)
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
$\sin^2 2\theta_{13}$ reach

Conclusion

Caveat – this talk is based on assumptions

- luminosities
- γ, muon energy
- detectors, backgrounds, ...

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For a conclusion you need to answer

- How large is θ_{13}?
- What does one want to measure?
- What are realistic design parameters?

Conclusion

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- luminosities
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For a conclusion you need to answer

- How large is θ_{13}?
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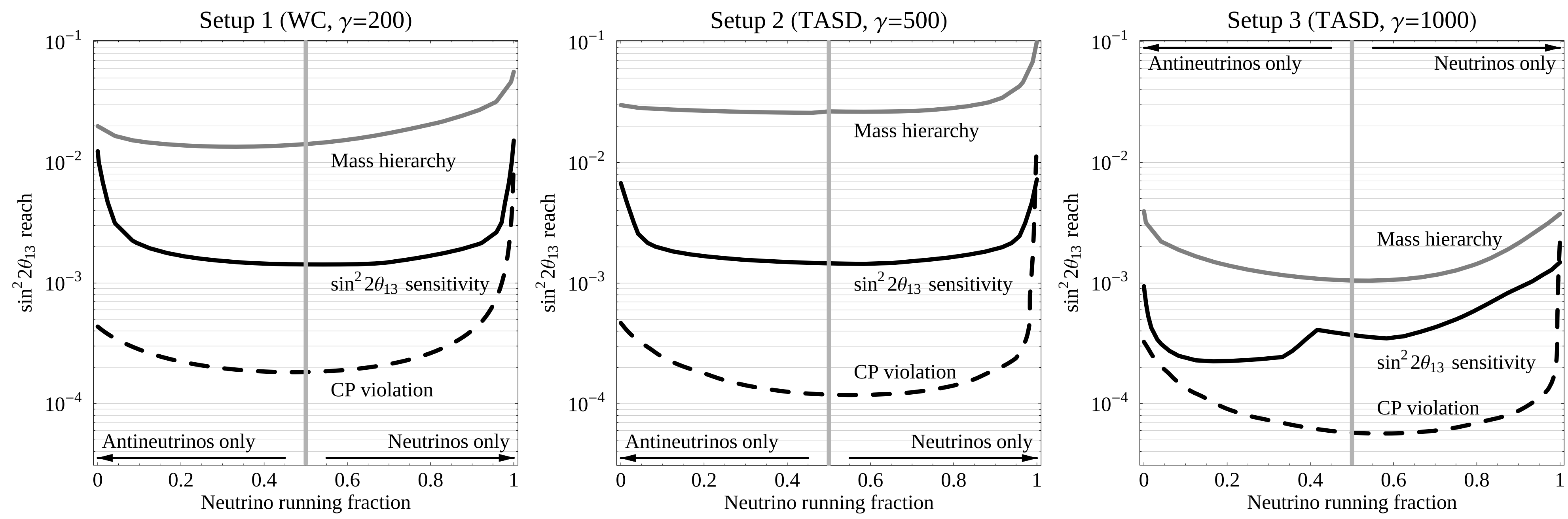
The “best” experiment may be the one,

you actually can build

Backup Slides

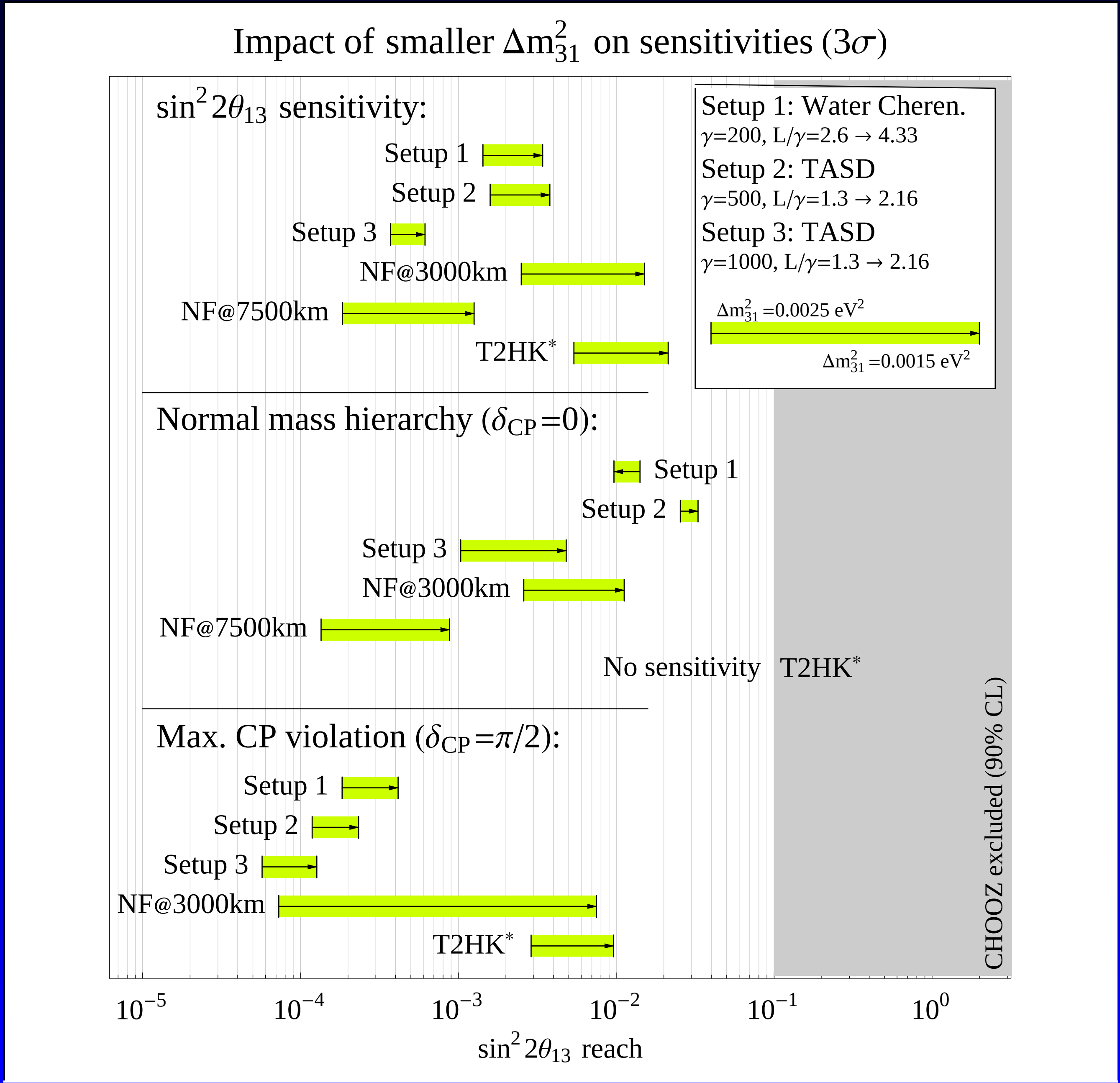
Changing the $\nu/\bar{\nu}$-ratio



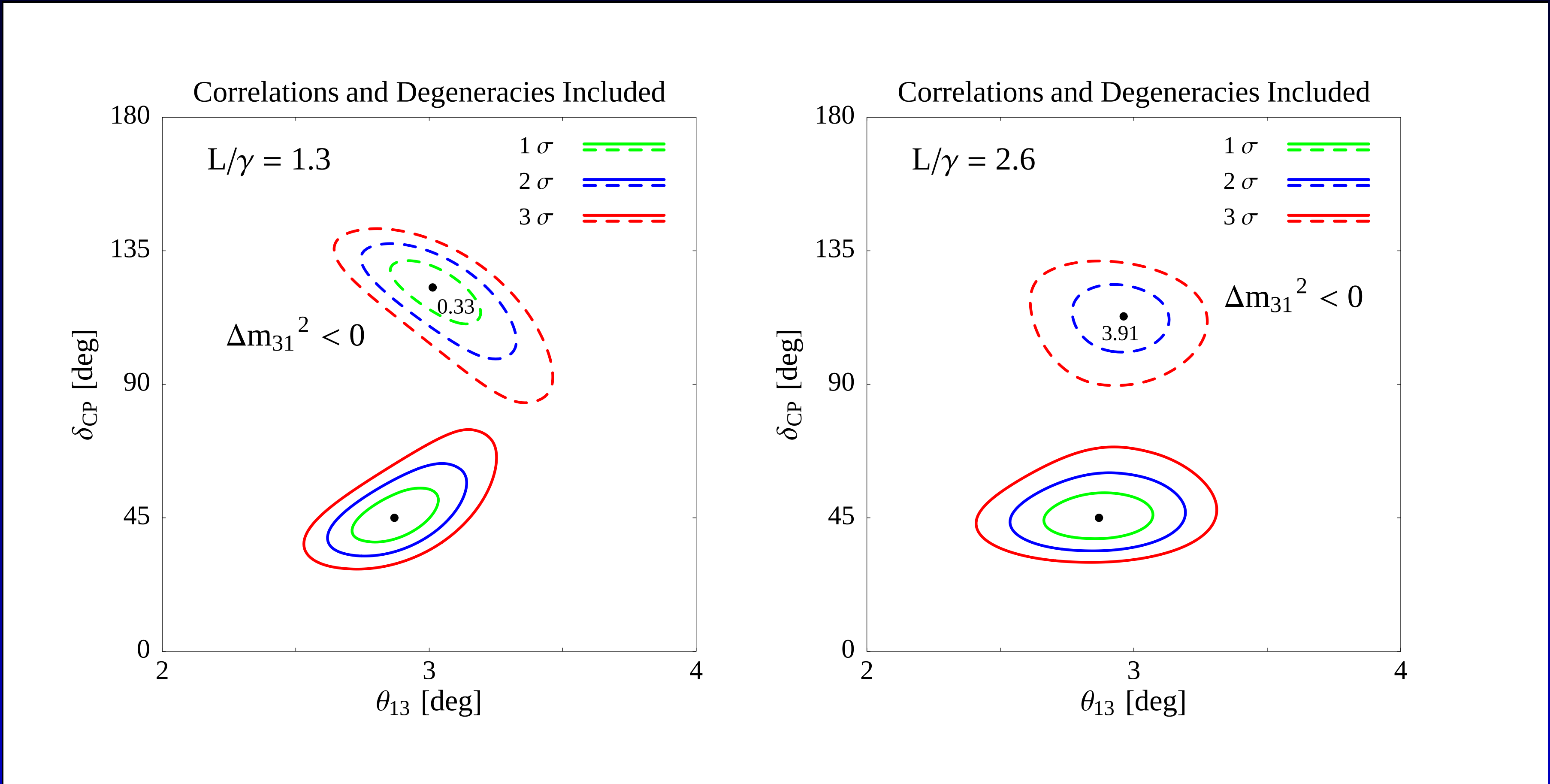
$3\,\sigma$ CL

- 5-10% ν-running is sufficient
- having only ν is much worse
- a factor 30 less in ν is too much, but a factor 20 may already be tolerable

Impact of $\Delta m^2_{31} = 1.5 \cdot 10^{-3}\,\mathrm{eV}^2$

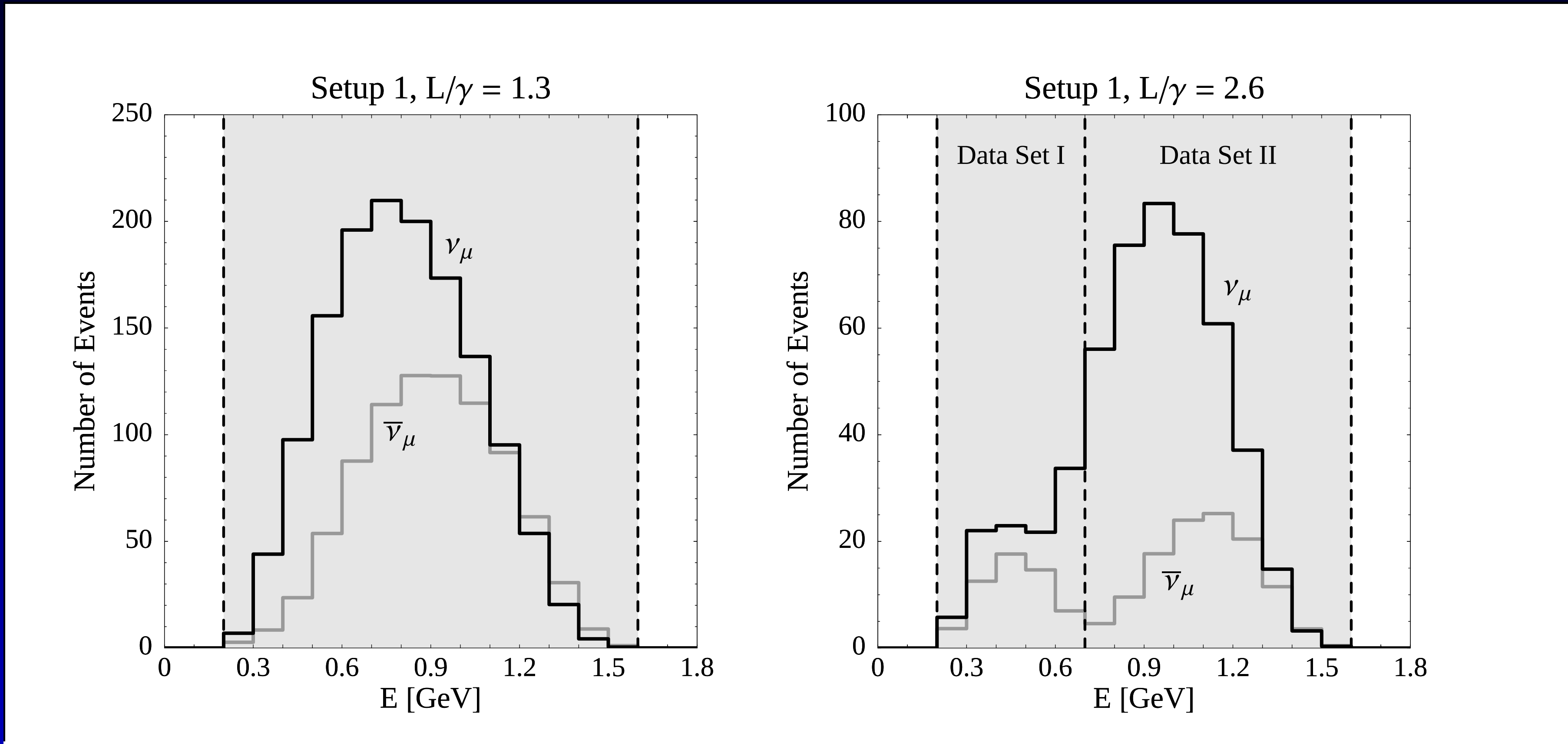


Why $L = 520\,\mathrm{km}$ in setup I?



- less correlation of δ and θ_{13}
- better rejection of wrong sign solution

Why $L = 520\,\mathrm{km}$ ... – continued



- double peak feature
- data sets I+II have different correlations
- data sets I+II have different sign degeneracy

Our parameterization – WC

Water Cherenkov

	Appearance		Disappearance	
	ν	$\bar{\nu}$	ν	$\bar{\nu}$
signal eff.	0.55	0.75	0.55	0.75
background eff.	0.003	0.0025	0.003	0.0025
signal err.	2.5%	2.5%	2.5%	2.5%
background err.	5%	5%	5%	5%

J. Burguet-Castell, *et al.*, arXiv:hep-ph/0503021.

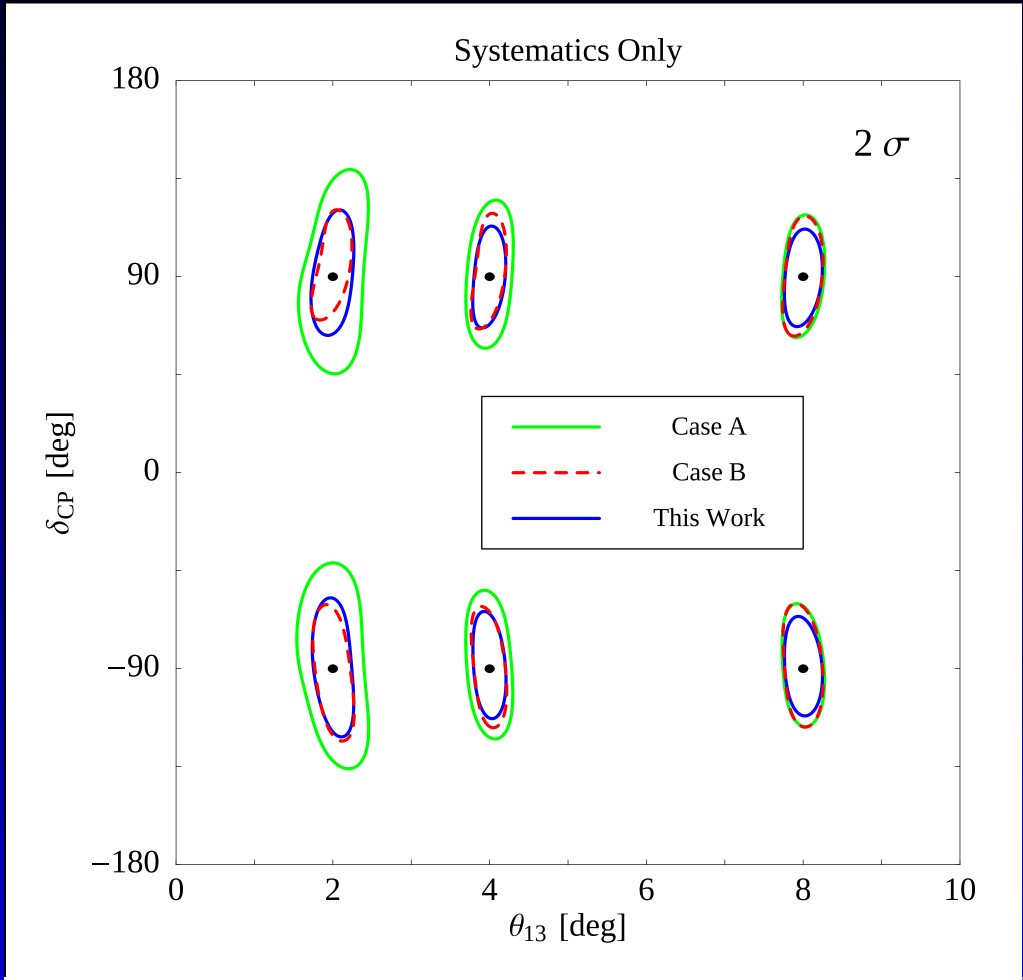
Our parameterization – TASD

Totally active scintillator

	Appearance		Disappearance	
	ν	$\bar{\nu}$	ν	$\bar{\nu}$
signal eff.	0.8	0.8	0.2	0.2
background eff.	0.001	0.001	0.001	0.001
signal err.	2.5%	2.5%	2.5%	2.5%
background err.	5%	5%	5%	5%

D. S. Ayres *et al.* [NOvA Collaboration], arXiv:hep-ex/0503053.

Comparison with literature



case A: M. Mezzetto, J. Phys. G **29**, 1771 (2003).

case B: J. Burguet-Castell, *et al.*, arXiv:hep-ph/0503021.