Improving our knowledge on neutrino mixing parameters

Patrick Huber

University of Wisconsin – Madison

Brookhaven National Laboratory

15th September 2005

Outline

- neutrino oscillation
- neutrino sources
- experiments in the next 10 years
- BNL neutrino beam
- summary & conclusion

Neutrino oscillation

What we know

- $|\Delta m^2_{31}| \sim 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$ and $\theta_{23} \sim \pi/4$
- $\Delta m^2_{21} \sim 8 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\theta_{12} \sim 0.55$

Neutrino oscillation

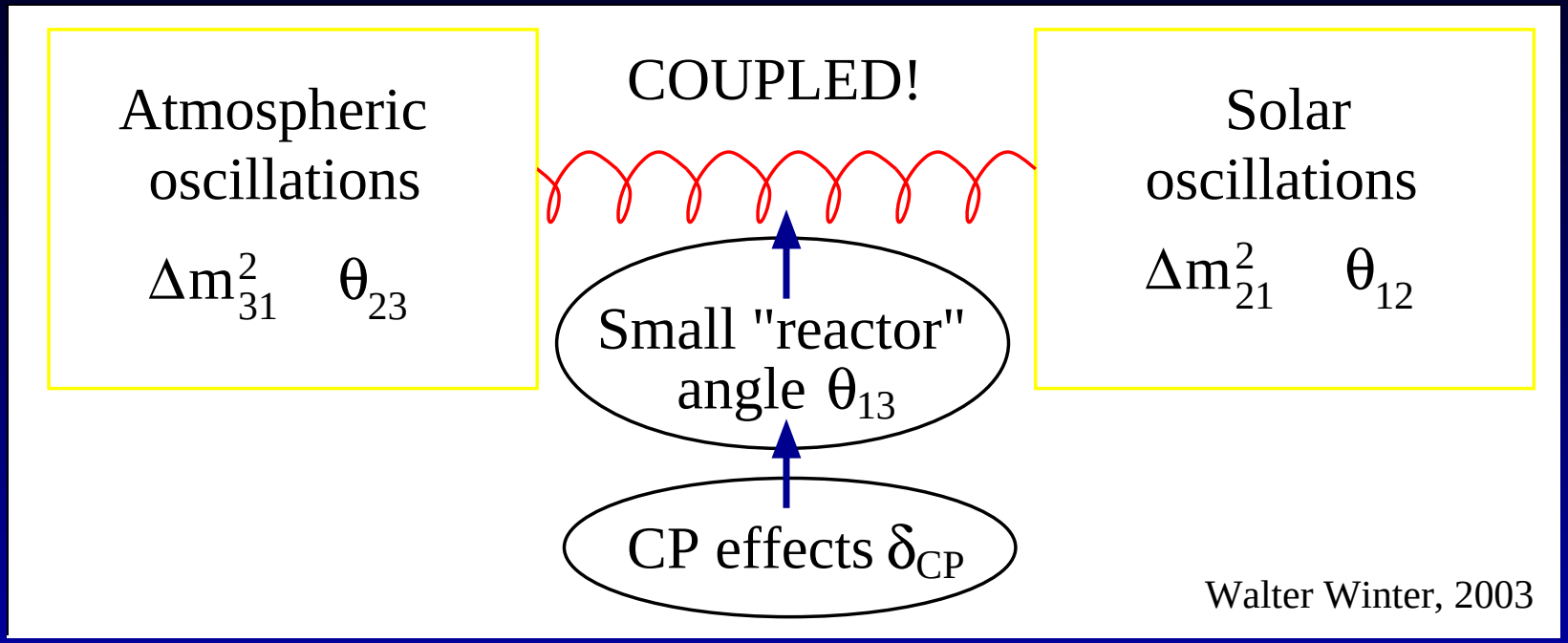
What we know

- $|\Delta m^2_{31}| \sim 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$ and $\theta_{23} \sim \pi/4$
- $\Delta m^2_{21} \sim 8 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\theta_{12} \sim 0.55$

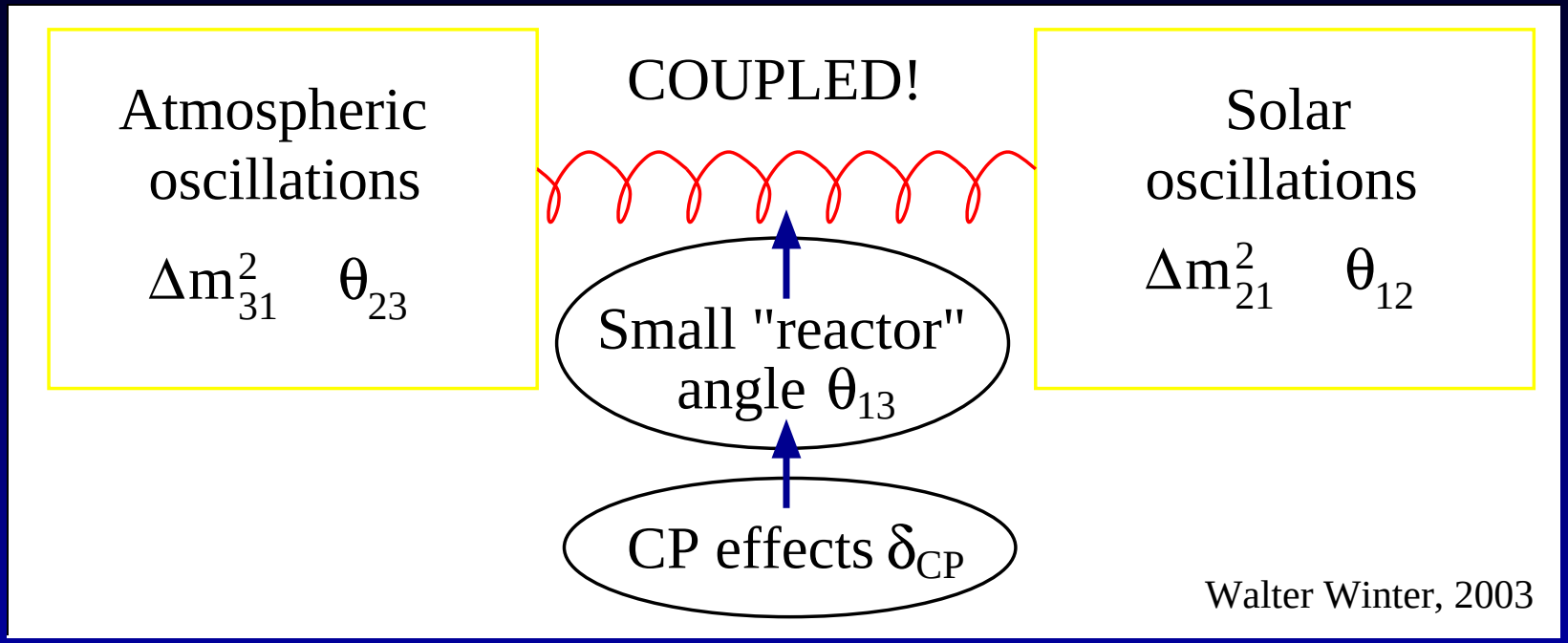
What we don't know

- θ_{13}
- δ
- $\mathrm{sign}\Delta m^2_{31}$

The role of θ_{13}



The role of θ_{13}



Finite θ_{13} is necessary for

- matter effects $\Leftrightarrow \mathrm{sign}\Delta m^2_{31}$
- CP effects $\Leftrightarrow \delta$

Measuring θ_{13} by $\bar{\nu}_e \longrightarrow \bar{\nu}_e$

"Clean" measurement of $\sin^2 2\theta_{13}$:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \, \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \left(\frac{\Delta m^2_{21} L}{4E_\nu} \right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

last term negligible for $\frac{\Delta m^2_{31} L}{4E_\nu} \sim \pi/2$ and $\sin^2 2\theta_{13} \gtrsim 10^{-3}$

determination of θ_{13} is free of correlations and degeneracies

PH, M. Lindner, T. Schwetz and W. Winter, Nucl. Phys. B **665** (2003) 487 [hep-ph/0303232]

H. Minakata, H. Sugiyama, O. Yasuda, K. Inoue and F. Suekane, Phys. Rev. D **68** (2003) 033017

Using $\nu_\mu \rightarrow \nu_e$

The measurement of θ_{13}, δ and the mass hierarchy with the $\nu_\mu \rightarrow \nu_e$ appearance channel suffers from correlations and degeneracies:

G.L. Fogli, E. Lisi, Phys. Rev. D54 (1996) 3667
J. Burguet-Castell et al., Nucl. Phys. B608 (2001) 301
H. Minakata, H. Nunokawa, JHEP 10 (2001) 001
V.Barger, D.Marfatia, K.Whisnant, Phys. Rev. D65 (2002) 073023; D66 (2002) 053007
PH, M.Lindner, W.Winter, Nucl. Phys. B645 (2002) 3; Nucl. Phys. B654 (2003) 3

Not $\sin^2 2\theta_{13}$, but only a specific parameter combination is measured very accurately

Using $\nu_\mu \longrightarrow \nu_e$

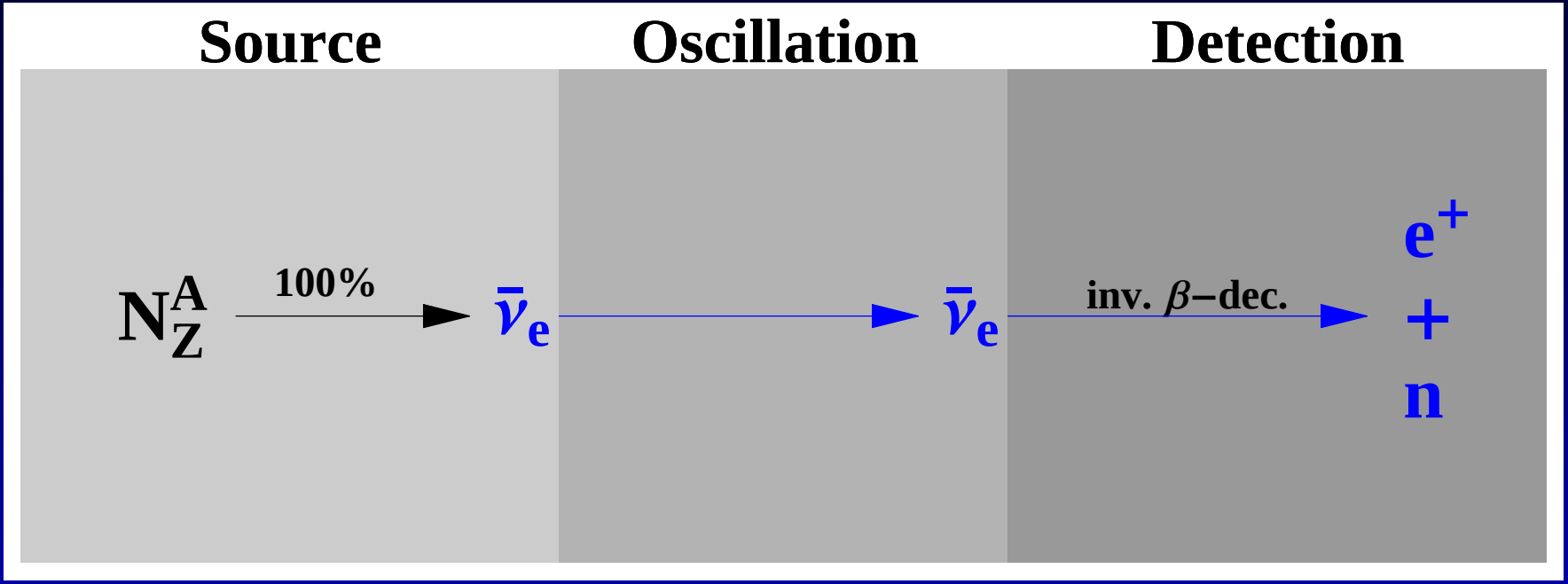
$$
\begin{aligned}
P_{\mu e} &\simeq \sin^2 2\theta_{13}\, \sin^2\theta_{23} \sin^2\Delta_{31} \\
&\mp \alpha\, \sin 2\theta_{12}\, \sin 2\theta_{13}\, \sin\delta\, \sin 2\theta_{23}\, \Delta_{31}\, \sin^2\Delta_{31} \\
&- \alpha\, \sin 2\theta_{12}\, \sin 2\theta_{13}\, \cos\delta\, \sin 2\theta_{23}\, \Delta_{31}\, \cos\Delta_{31} \sin\Delta_{31} \\
&+ \alpha^2\, \sin^2 2\theta_{12}\, \cos^2\theta_{23}\, \Delta_{31}^2,
\end{aligned}
$$

with

$$
\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}, \quad \Delta_{31} \equiv \frac{\Delta m^2_{31} L}{4E_\nu}
$$

How-to make neutrinos I

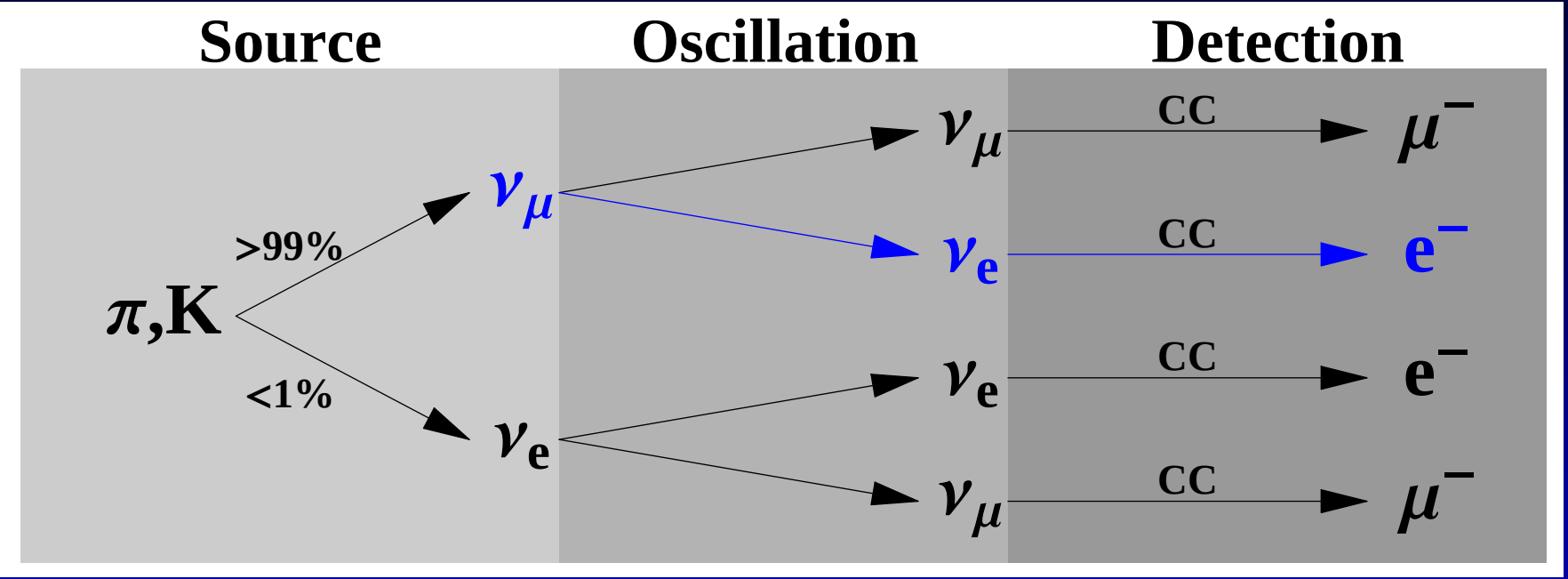
Nuclear reactor



- $E_\nu = 2 - 8\,\mathrm{MeV}$, only $\bar{\nu}_e$ (no anti-reactors)
- Inverse β-decay gives unique signature
- Disappearance measurement requires very good control of systematics

How-to make neutrinos II

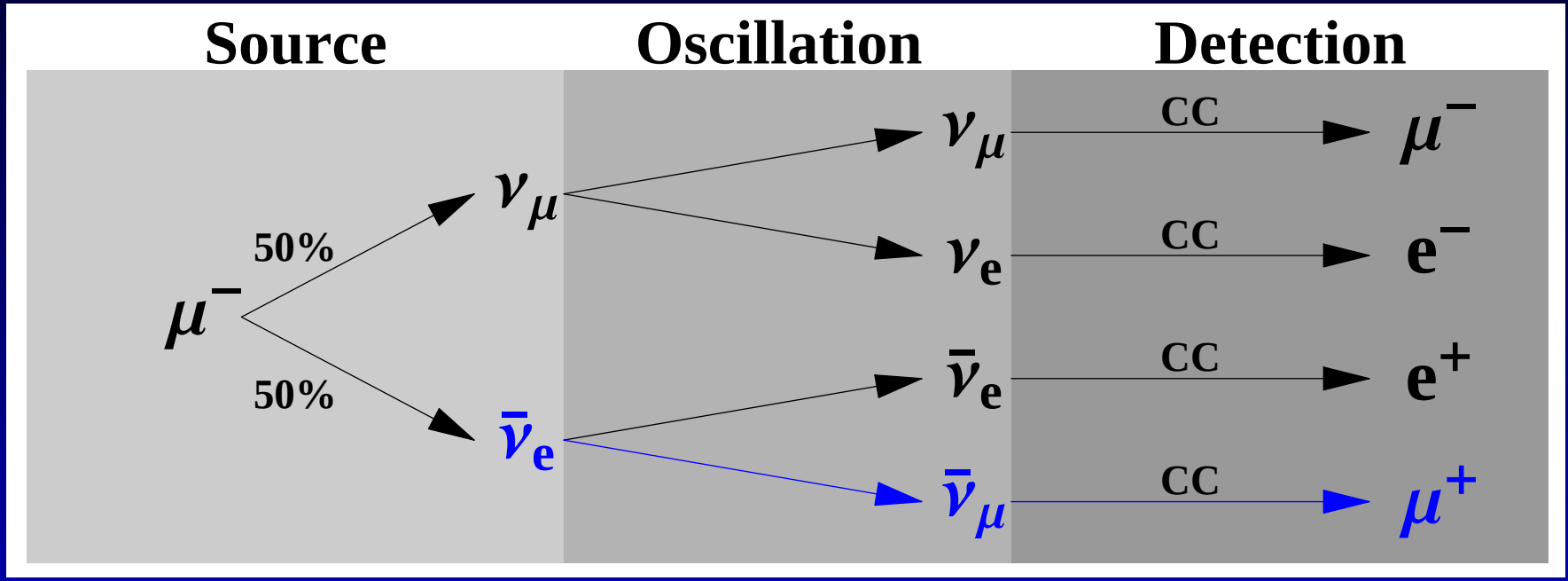
Superbeam



- $E_\nu = 0.5 - 25\,\mathrm{GeV}$, both ν and $\bar{\nu}$
- Intrinsic beam ν_e are irreducible background
- NC background
- Appearance measurement

How-to make neutrinos III

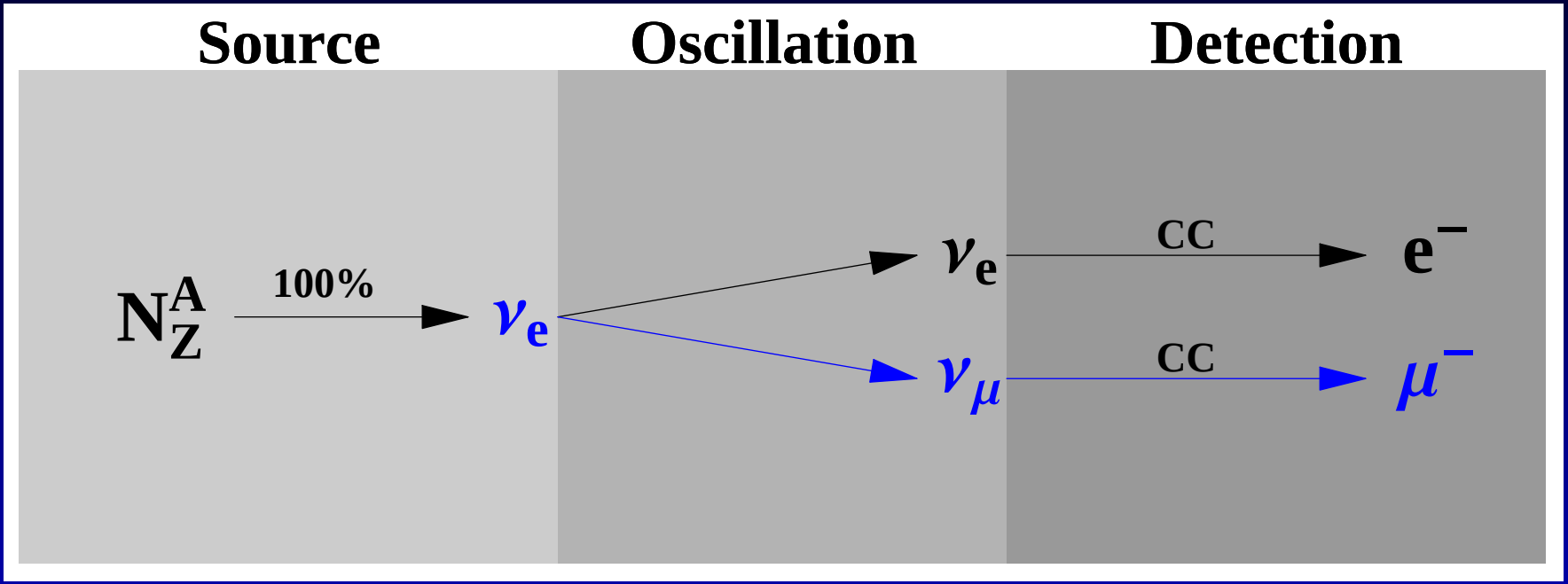
Neutrino factory



- $E_\nu = 20 - 50\,\mathrm{GeV}$, both ν and $\bar{\nu}$
- Muon charge ID
- NC background
- Appearance measurement

How-to make neutrinos IV

β-beam



- $E_\nu = 0.2 - 5\,\mathrm{GeV}$, both ν and $\bar{\nu}$
- Low energy x-sections
- NC background
- Appearance measurement

L/E of the planned experiments

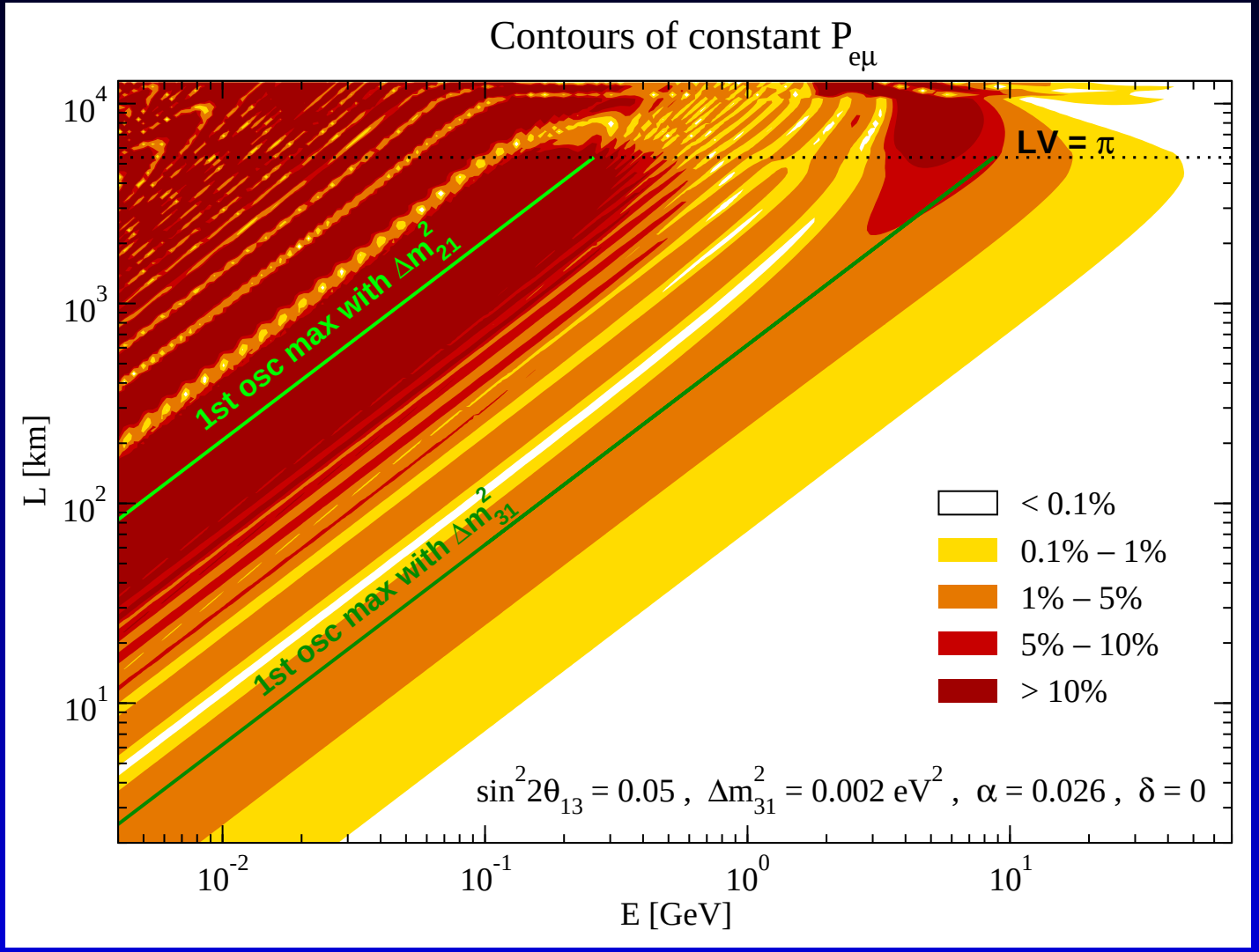


figure by T. Schwetz

L/E of the planned experiments

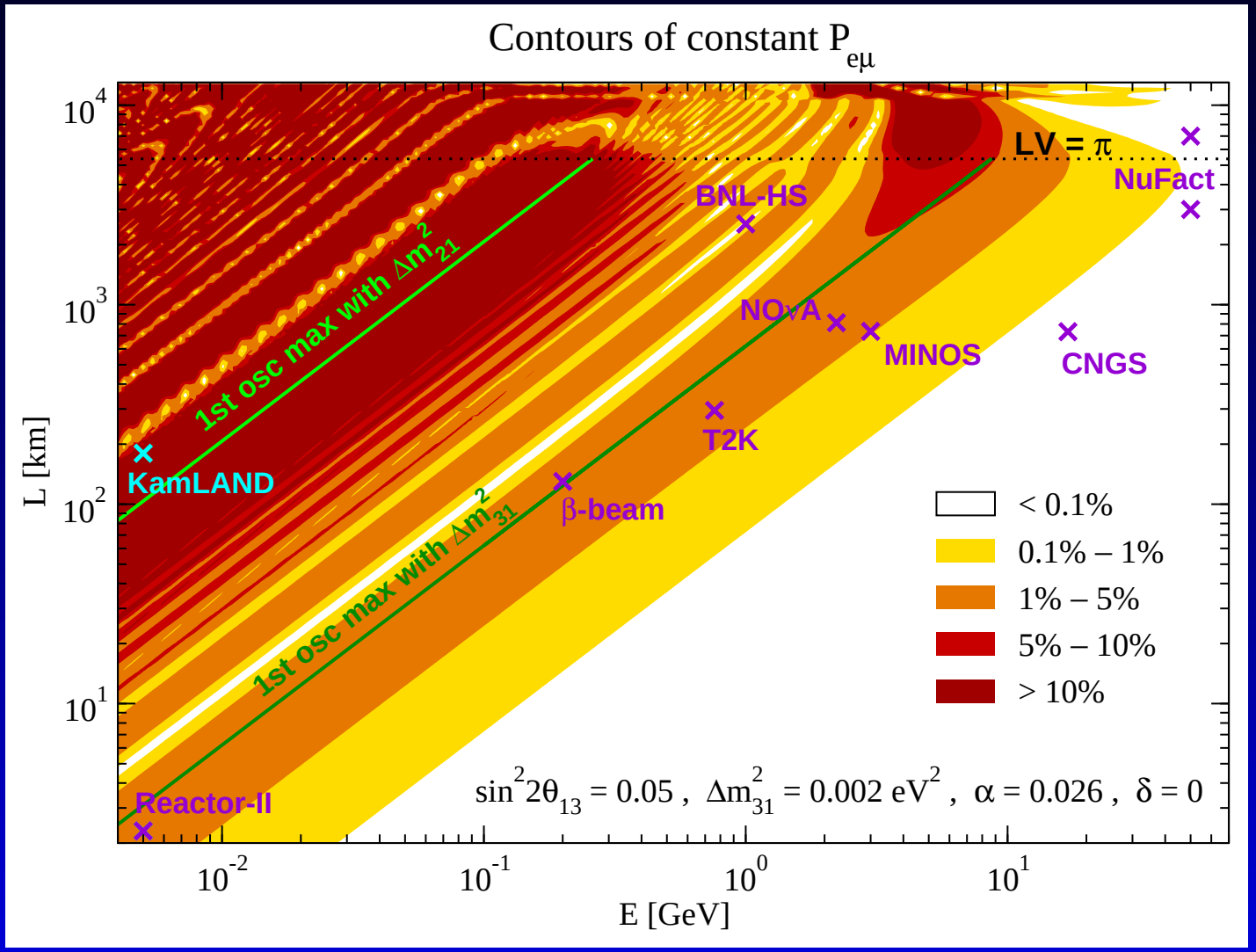


figure by T. Schwetz

General analysis strategy

Event rate calculation

- Efficiencies
- Backgrounds
- Energy response

Data

- Appearance channels
- Disappearance channels
- Energy information
- External information

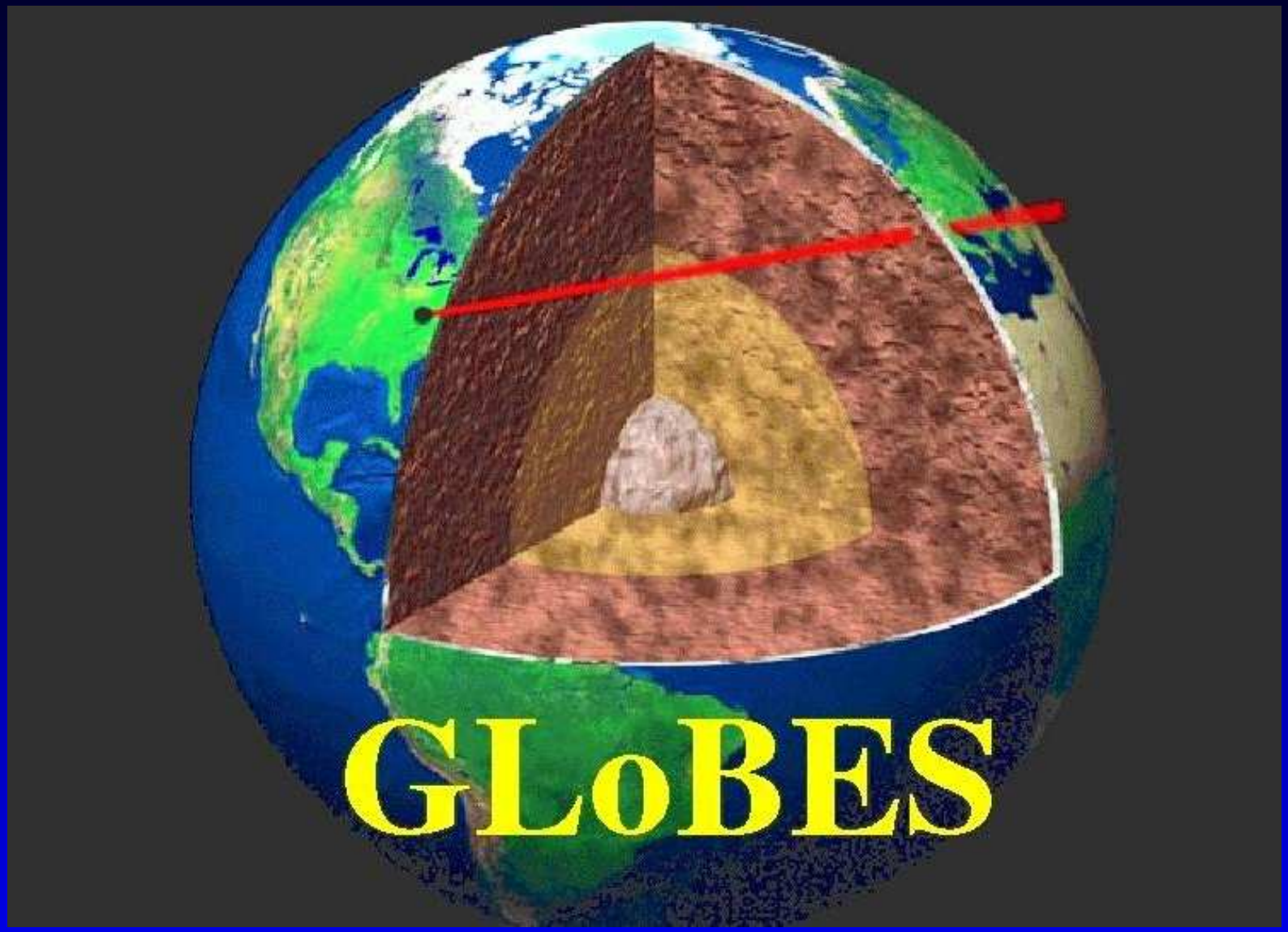
General analysis strategy

Analysis

- Systematics
- Correlations
- Matter density uncertainties
- Degeneracies

Comparison

- Parameters of interest
- Figure(s) of merit
- Risk function


GLoBES

General Long Baseline Experiment Simulator

GLoBES is a software package designed for

- Simulation
- Analysis
- Comparison

of neutrino oscillation experiments

GLoBES

GLoBES has been used for simulating

- MINOS, CNGS
- Reactor experiments, Double-CHOOZ
- T2K
- NOvA
- JHF-HK (T2K upgrade)
- Neutrino factory
- β-beam
- BNL neutrino project

GLoBES

GLoBES is developed, documented and maintained by

- Patrick Huber
- Joachim Kopp
- Manfred Lindner
- Mark Rolinec
- Walter Winter

The GLoBES tar-ball for GNU/Linux as well as an extensive manual are available since August 1st 2004 at

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

The Next Generation

Experiments in the next 10 y

Conventional beam experiments:

Off-axis superbeams:

Reactor experiments with near and far detectors:

Experiments in the next 10 y

Label	L	$\langle E_\nu \rangle$	$t_{\rm run}$	channel
Conventional beam experiments:				
MINOS	$735\,\mathrm{km}$	$3\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_\mu, \nu_e$
Off-axis superbeams:				
Reactor experiments with near and far detectors:				

MINOS:
Fermilab to Soudan mine, 5.4 kt magnetized iron calorimeter

Experiments in the next 10 y

Label	L	$\langle E_\nu \rangle$	$t_{\rm run}$	channel
Conventional beam experiments:				
MINOS	$735\,\mathrm{km}$	$3\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_\mu, \nu_e$
ICARUS	$732\,\mathrm{km}$	$17\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_e, \nu_\mu, \nu_\tau$
OPERA	$732\,\mathrm{km}$	$17\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_e, \nu_\mu, \nu_\tau$
Off-axis superbeams:				
Reactor experiments with near and far detectors:				

CNGS: CERN to Gran Sasso, ν_τ appearance
ICARUS: 2.35 kt liquid argon TPC
OPERA: 1.65 kt emulsion cloud chamber

Experiments in the next 10 y

Label	L	$\langle E_\nu \rangle$	$t_{\rm run}$	channel
Conventional beam experiments:				
MINOS	$735\,\mathrm{km}$	$3\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_\mu, \nu_e$
ICARUS	$732\,\mathrm{km}$	$17\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_e, \nu_\mu, \nu_\tau$
OPERA	$732\,\mathrm{km}$	$17\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_e, \nu_\mu, \nu_\tau$
Off-axis superbeams:				
T2K	$295\,\mathrm{km}$	$0.76\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_e, \nu_\mu$
NOνA	$812\,\mathrm{km}$	$2.22\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_e, \nu_\mu$
Reactor experiments with near and far detectors:				

T2K: Tokai (JPARC) to Kamioka (SK) 22.5 kt water Cherenkov

NOνA: 50 kt low-Z-calorimeter, off-axis angle of 0.72°

Experiments in the next 10 y

Label	L	$\langle E_\nu \rangle$	$t_{\rm run}$	channel
Conventional beam experiments:				
MINOS	$735\,\mathrm{km}$	$3\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_\mu, \nu_e$
ICARUS	$732\,\mathrm{km}$	$17\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_e, \nu_\mu, \nu_\tau$
OPERA	$732\,\mathrm{km}$	$17\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_e, \nu_\mu, \nu_\tau$
Off-axis superbeams:				
T2K	$295\,\mathrm{km}$	$0.76\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_e, \nu_\mu$
NOνA	$812\,\mathrm{km}$	$2.22\,\mathrm{GeV}$	$5\,\mathrm{yr}$	$\nu_\mu \to \nu_e, \nu_\mu$
Reactor experiments with near and far detectors:				
D-Chooz	$1.05\,\mathrm{km}$	$\sim 4\,\mathrm{MeV}$	$3\,\mathrm{yr}$	$\nu_e \to \nu_e$
Reactor-II	$1.70\,\mathrm{km}$	$\sim 4\,\mathrm{MeV}$	$5\,\mathrm{yr}$	$\nu_e \to \nu_e$

D-Chooz: new experiment at Chooz site (60 000 events)

Reactor-II: optimized reactor experiment (630 000 events)

θ_{13}-sensitivity

How to compute the θ_{13}-sensitivity

θ_{13}-sensitivity

How to compute the θ_{13}-sensitivity

- Simulate data with $\theta_{13} = 0$

θ_{13}-sensitivity

How to compute the θ_{13}-sensitivity

- Simulate data with $\theta_{13} = 0$
- Include statistical errors

θ_{13}-sensitivity

How to compute the θ_{13}-sensitivity

- Simulate data with $\theta_{13} = 0$
- Include statistical errors
- Include systematical errors

θ_{13}-sensitivity

How to compute the θ_{13}-sensitivity

- Simulate data with $\theta_{13} = 0$
- Include statistical errors
- Include systematical errors
- Include correlations

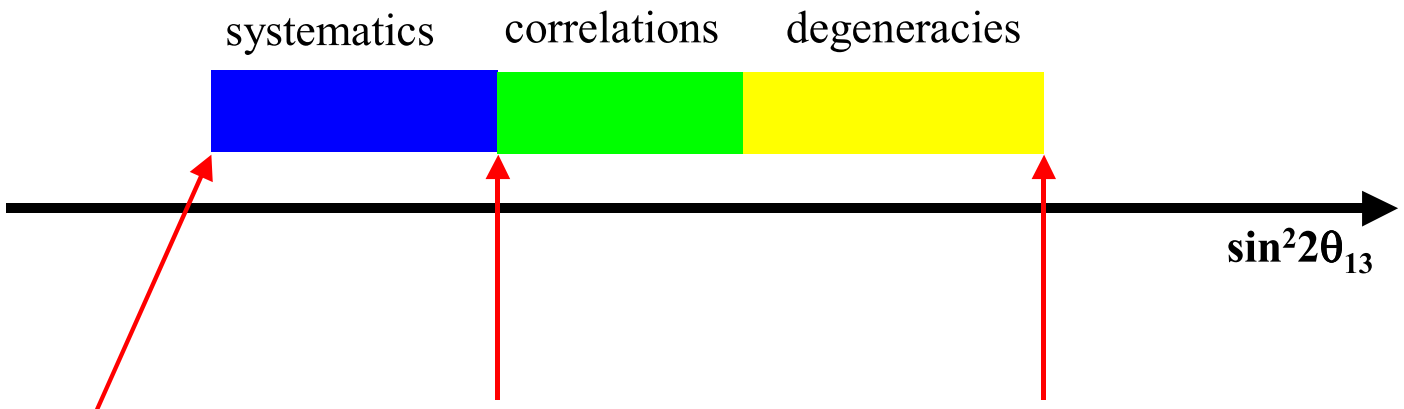
θ_{13}-sensitivity

How to compute the θ_{13}-sensitivity

- Simulate data with $\theta_{13} = 0$
- Include statistical errors
- Include systematical errors
- Include correlations
- Include degeneracies

θ_{13}-sensitivity

Sensitivitiy Plots



statistical limit
(all parameters fixed)

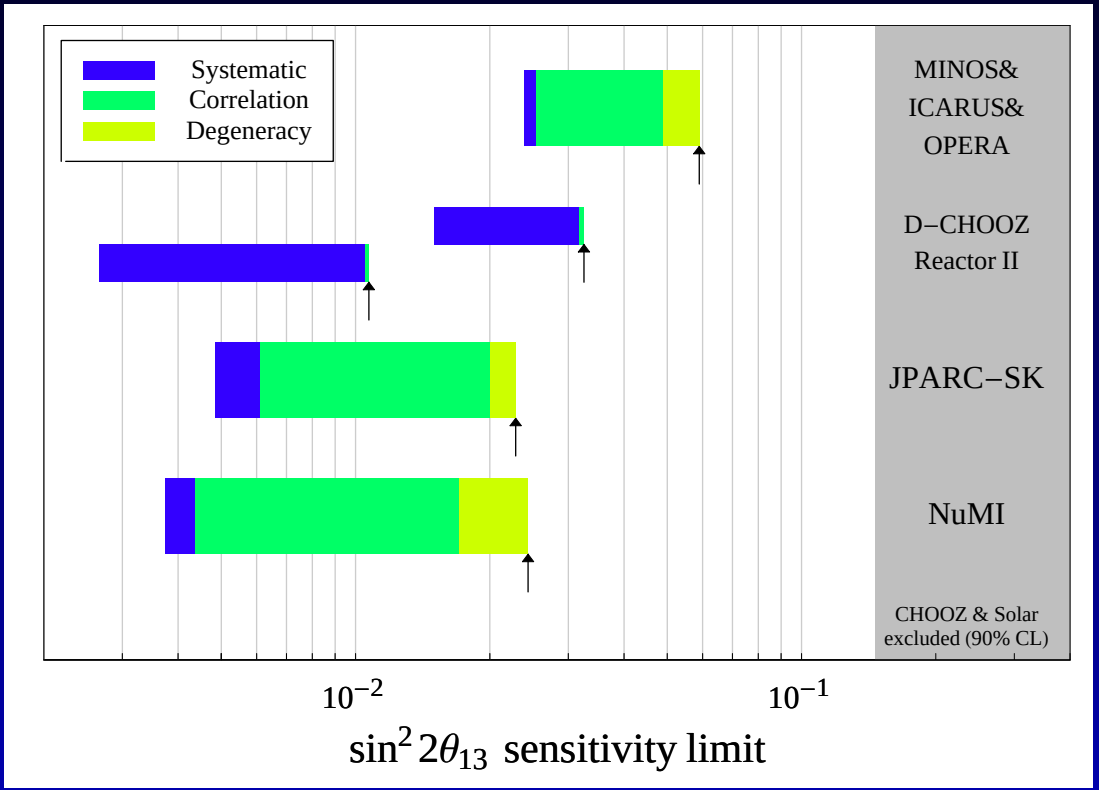
limit for $(\sin^2 2\theta_{13})_{eff}$

limit for $\sin^2 2\theta_{13}$ from *THIS* experiment only

precise knowledge of some parameter combination = precision of the experiment

synergies = combine with other experiments
➔ gain more than statistics

$\sin^2 2\theta_{13}$ within the next ten years



true values:

$\sin^2 2\theta_{12} = 0.8$

$\sin^2 2\theta_{23} = 1.0$

$\sin^2 2\theta_{13} = 0.0$

$\Delta m^2_{21} = 7.0 \cdot 10^{-5}\ \text{eV}^2$

$\Delta m^2_{31} = 2.0 \cdot 10^{-3}\ \text{eV}^2$

PH, Lindner, Rolinec, Schwetz, Winter, Phys. Rev. D70 (2004) 073014

The BNL neutrino beam

Concept

work in progress together with V. Barger, M. Bishai, M. Dierckxsens, M. Diwan, C. Lewis, D. Marfatia and B. Viren

- protons with $E > 20\,\mathrm{GeV}$ and $P \sim 1\,\mathrm{MW}$
  $\Rightarrow$ high power wide band beam
- $500\,\mathrm{kt}$ water Cherenkov detector
- baseline $L \sim 1000 - 3000\,\mathrm{km}$

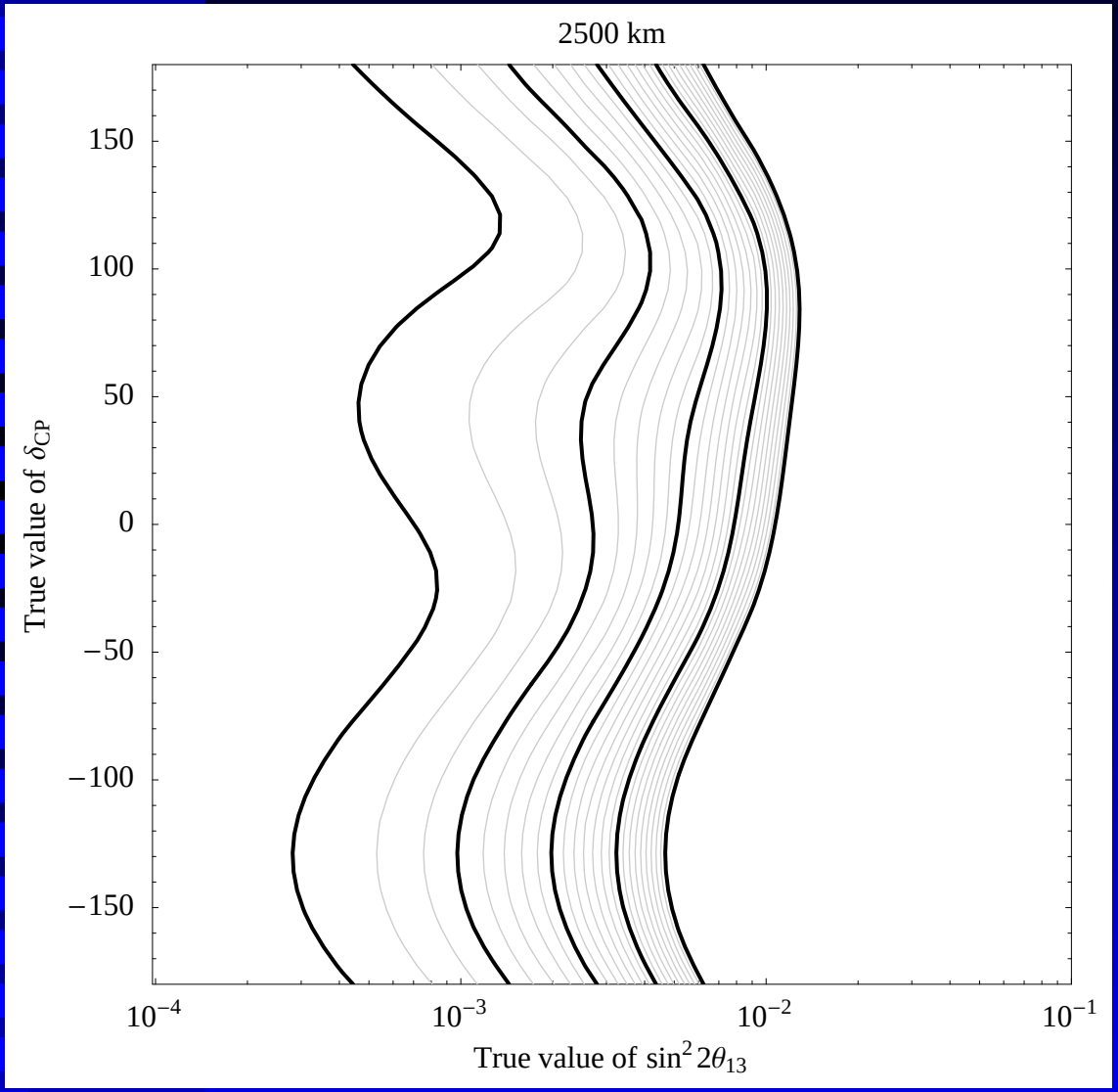
Our study

specifically we assume

- protons with $E = 28\,\mathrm{GeV}$ and $P = 1\,\mathrm{MW}$
- $500\,\mathrm{kt}$ water Cherenkov detector
- π^0 suppression verified by Super-K MC
- $5 \times 10^7 \mathrm{s}$ neutrino running
- $5 \times 10^7 \mathrm{s}$ anti-neutrino running
- 10% uncertainty on the background
- 5% matter density uncertainty

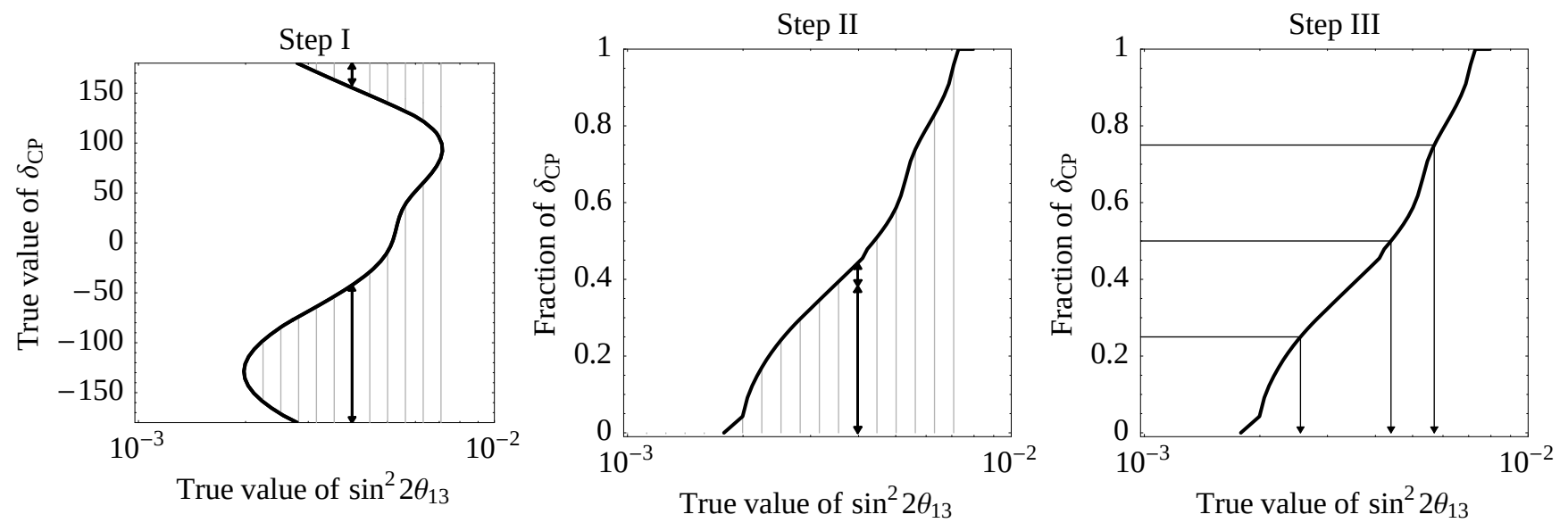
full analysis with GLoBES

Discovery of θ_{13}



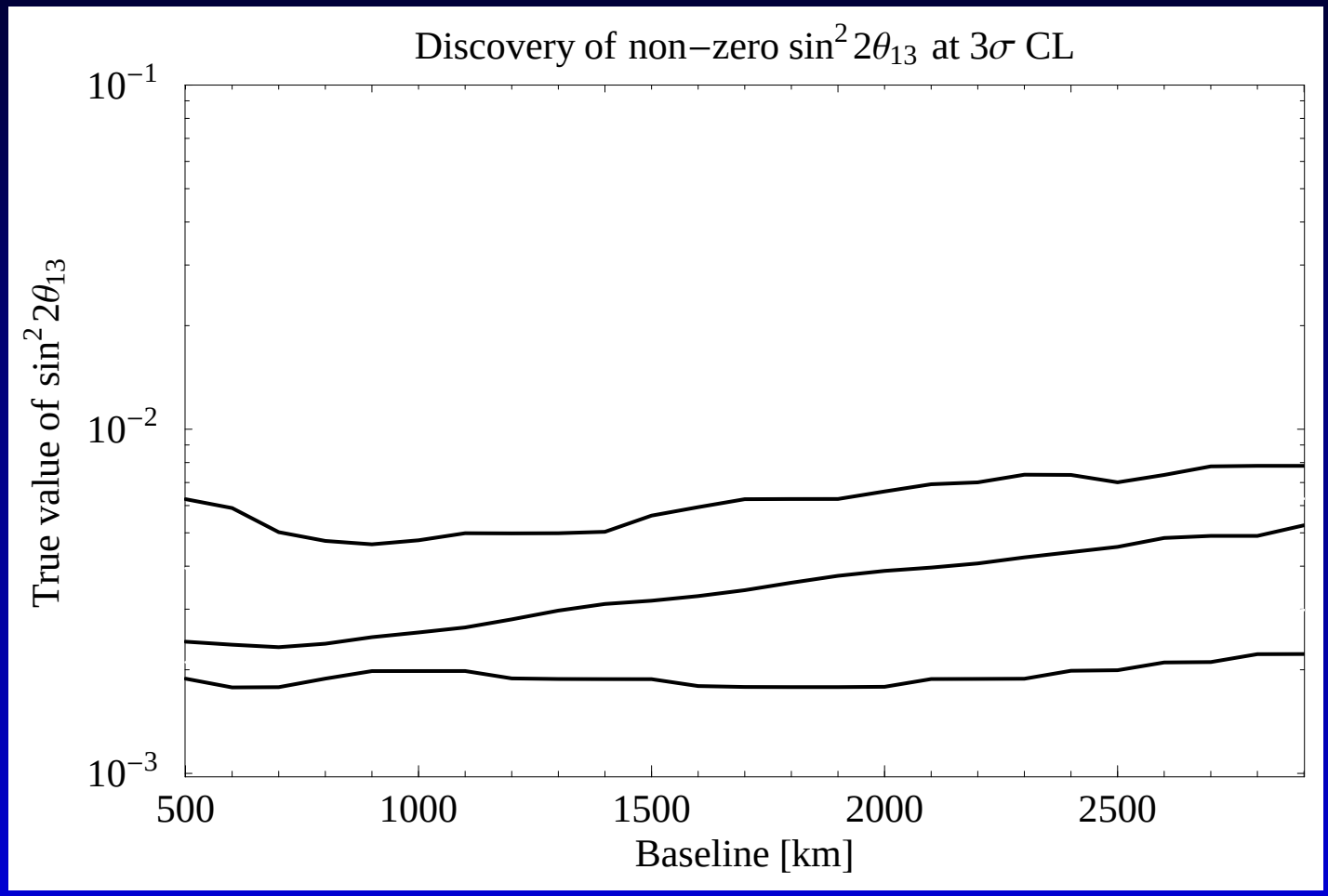
- simulate data for δ and $\theta_{13} \neq 0$
- try to fit them with $\theta_{13} = 0$
- repeat the fit for the wrong hierarchy
- take the smallest χ^2

CP fraction



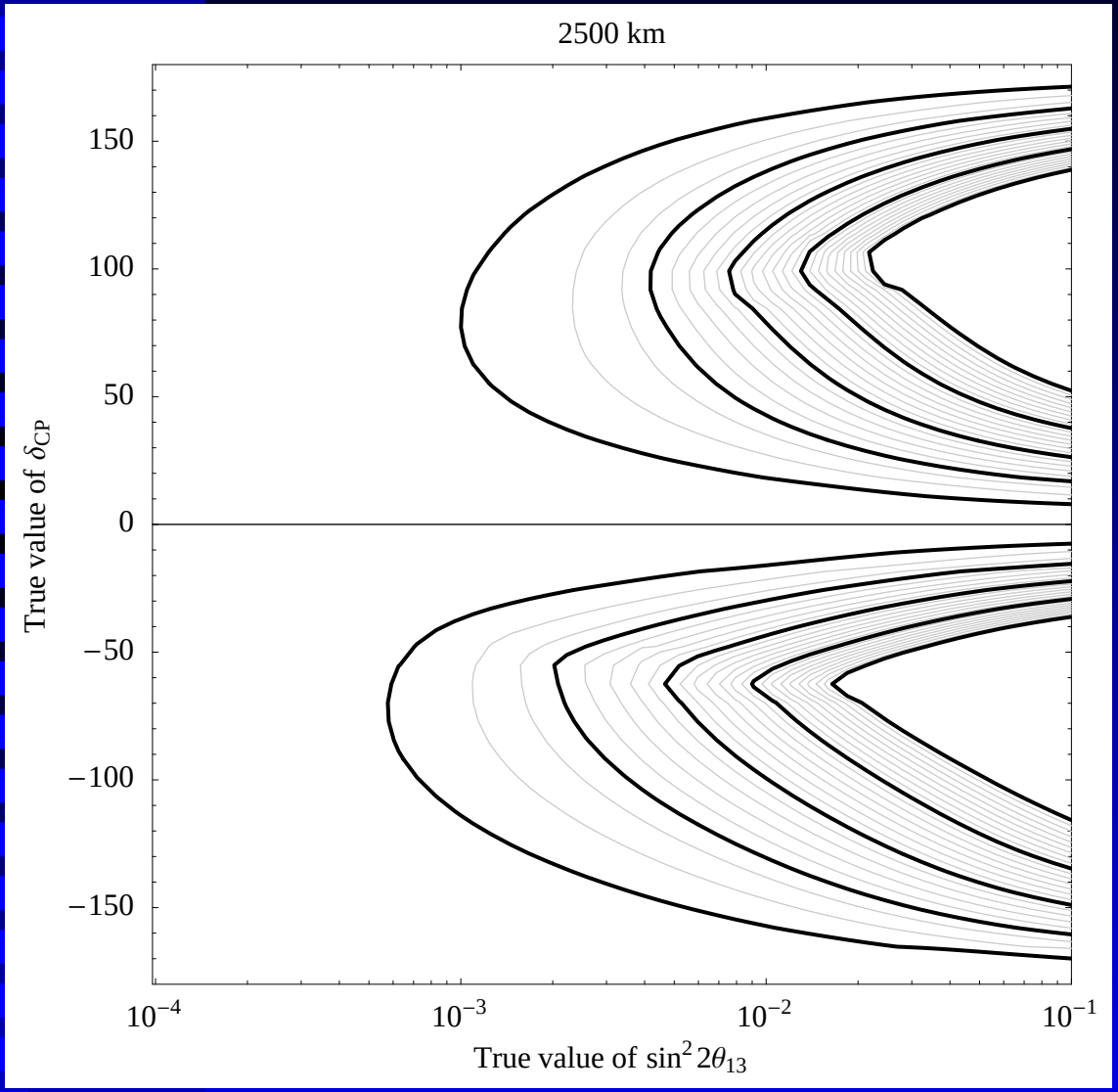
- reduces 2D plot to 3 points
- allows unbiased comparison
- allows risk assessment
- CPF = 1, worst case – guaranteed sensitivity
- CPF =0, best case

Baseline dependence



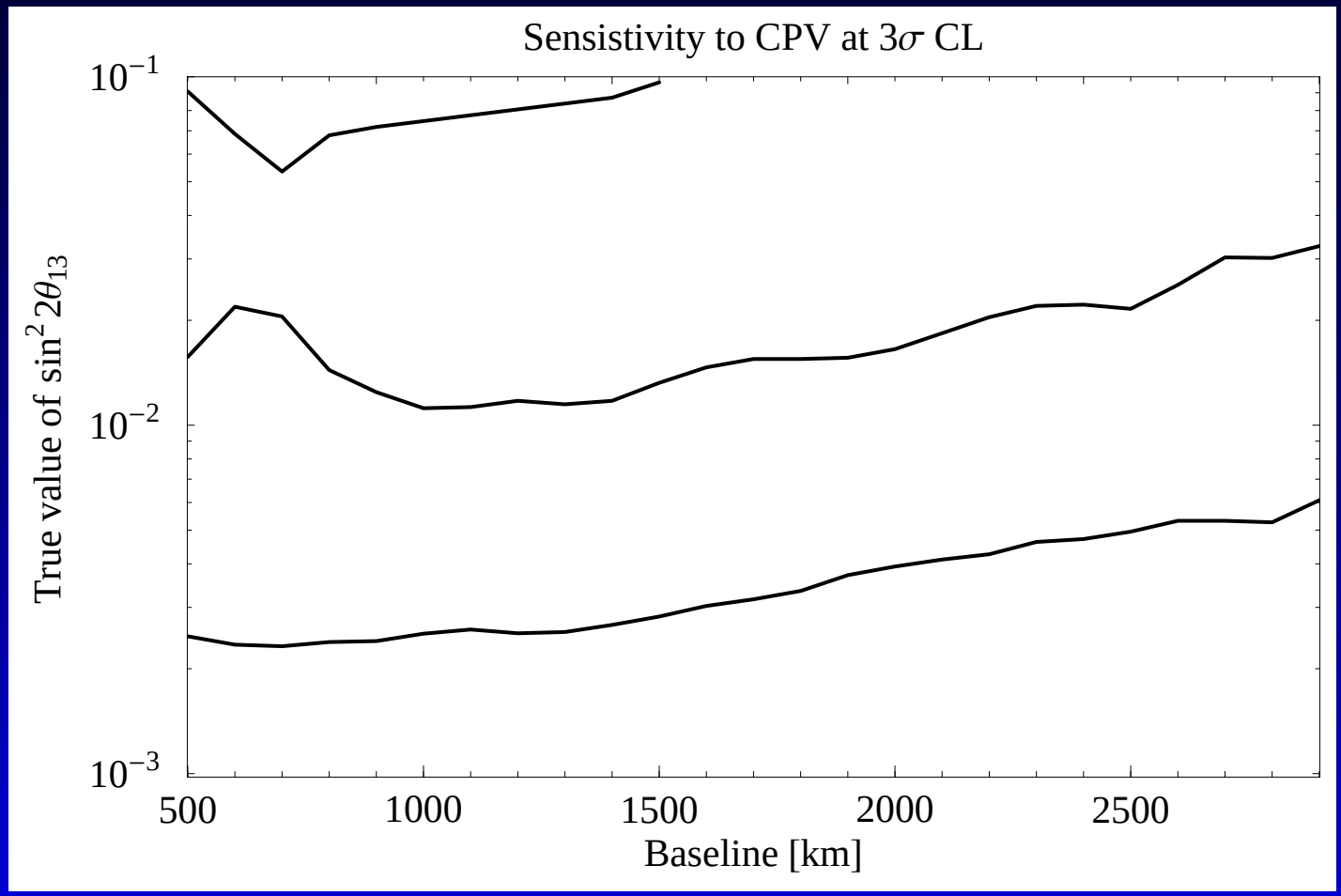
- weak baseline dependence

Discovery of CP violation



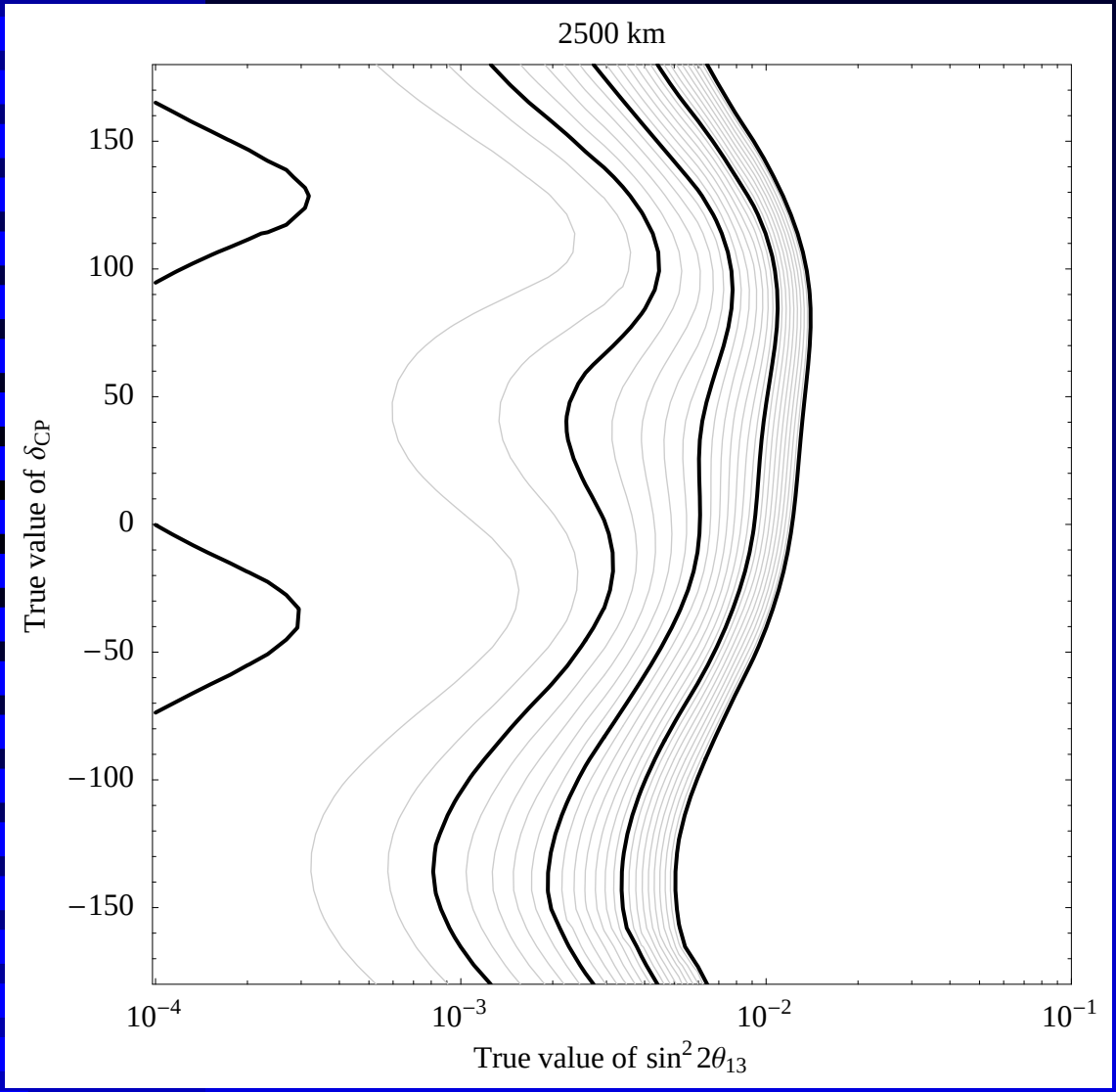
- simulate data for $\delta \neq 0, \pi$ and θ_{13}
- try to fit them with $\delta = 0, \pi$
- repeat the fit for the wrong hierarchy
- take the smallest χ^2

Baseline dependence



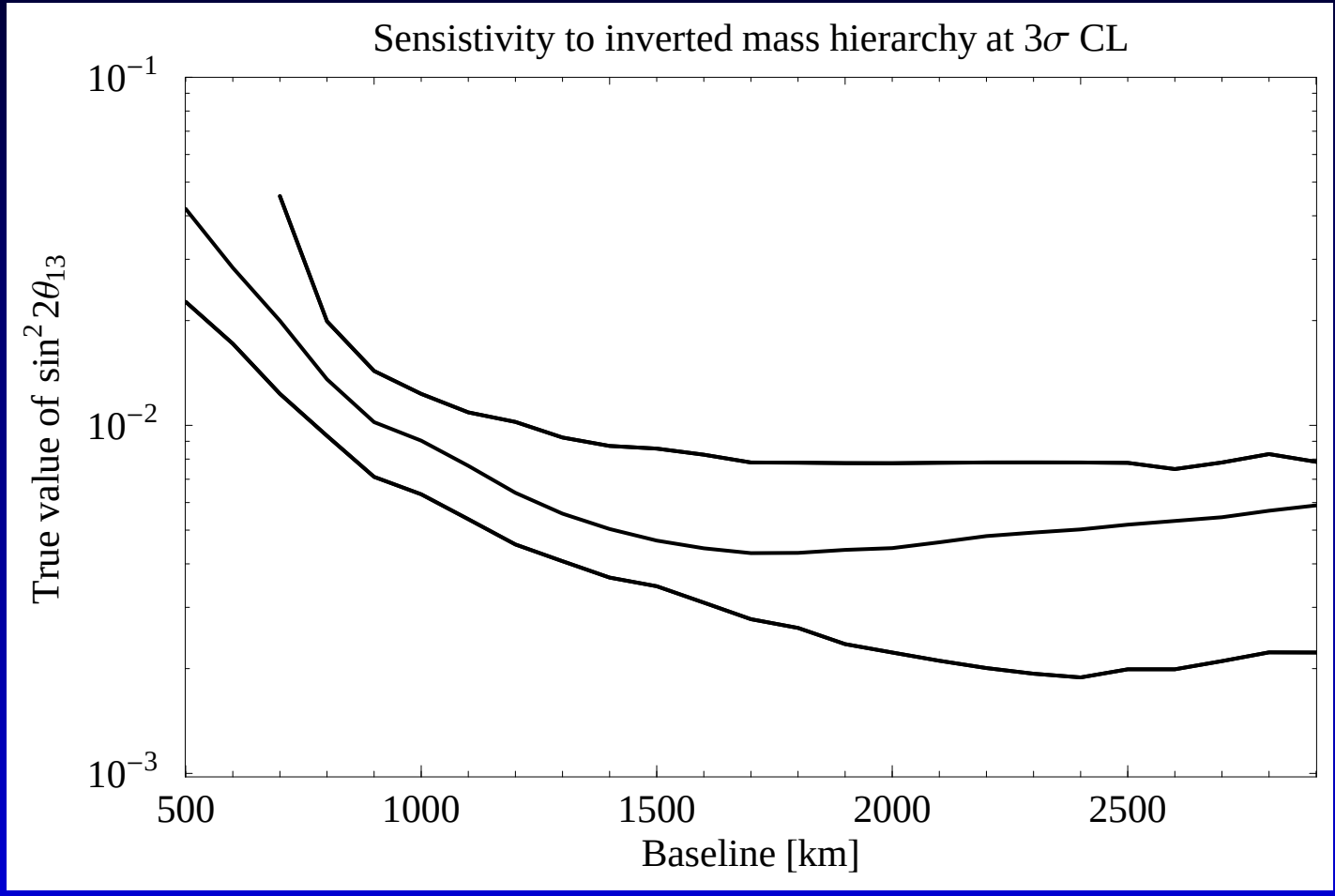
- baselines between 1000 and 2000 km are very similar

Determination of the mass hierarchy



- simulate data for δ and θ_{13}
- try to fit with the wrong hierarchy

Baseline dependence

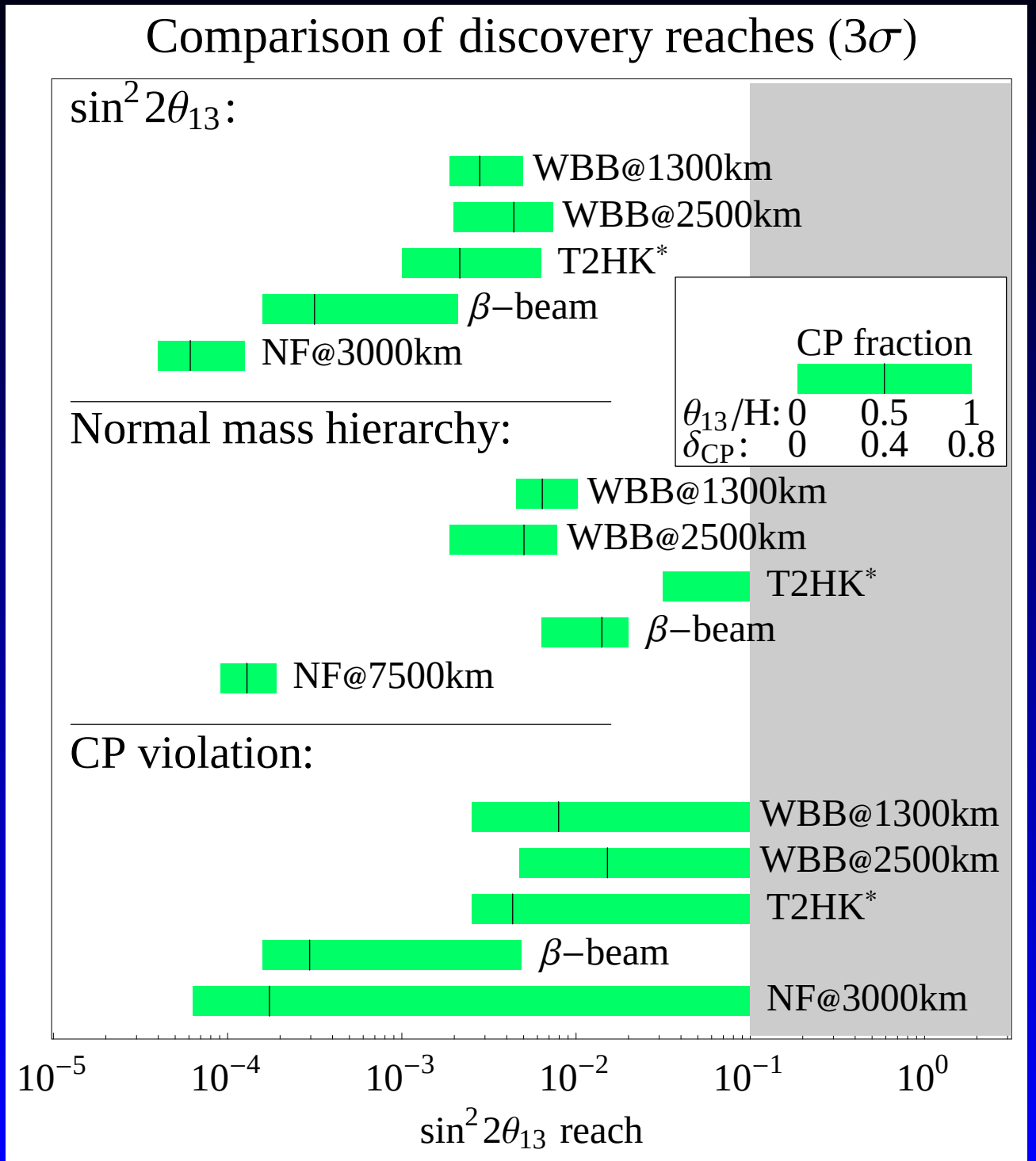


- long baselines are clearly favored

Summary

Wide band beam

- backgrounds are under control
- full analysis corroborates earlier findings
- baselines above $1000\,\mathrm{km}$ are preferred
- wide band beams are very competitive



β-beam, T2HK* and NF numbers are taken from PH, M. Lindner and W. Winter, JHEP **0505**, 020 (2005)