Improving our knowledge on neutrino mixing parameters

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Neutrino Physics with Liquid Argon TPCs

Yale University

11-12 July 2006

Outline

- neutrino oscillation
- neutrino sources
- experiments in the next 10 years
- resolving correlations and degeneracies
- summary

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 $\theta_{12} \sim 0.55$

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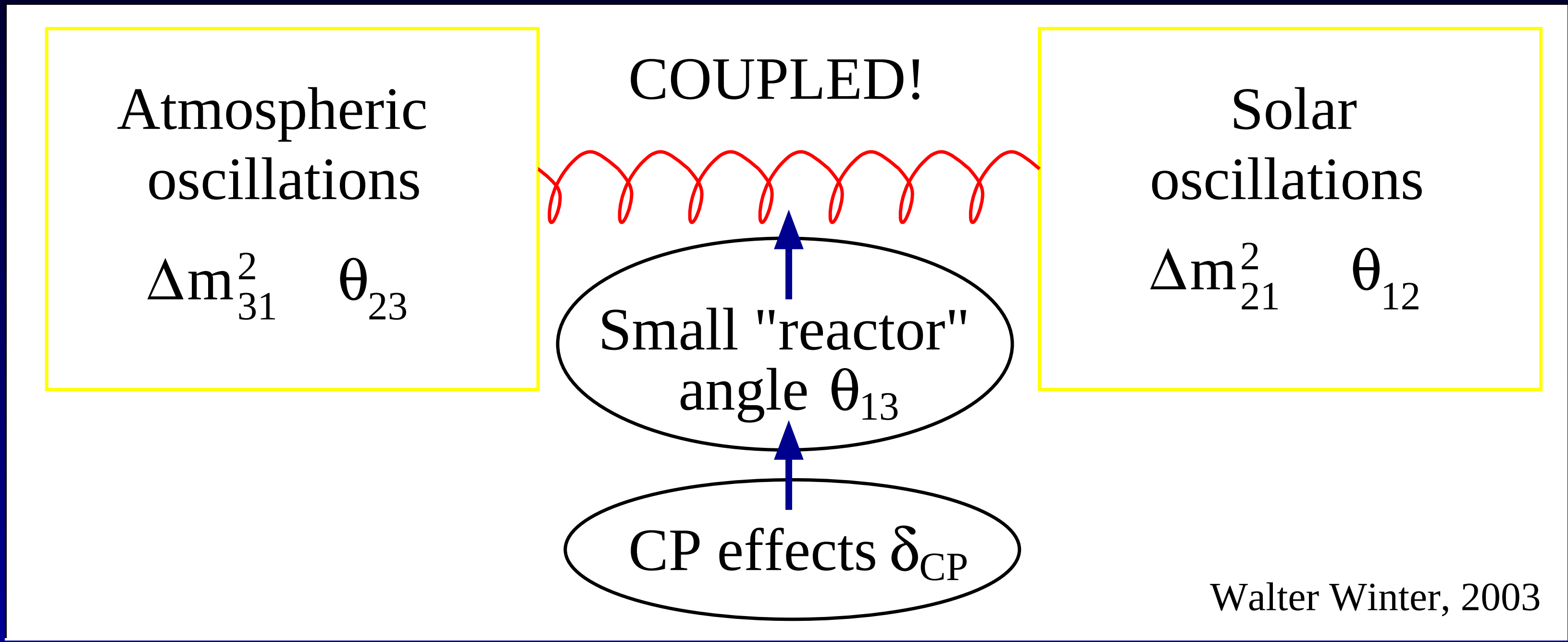
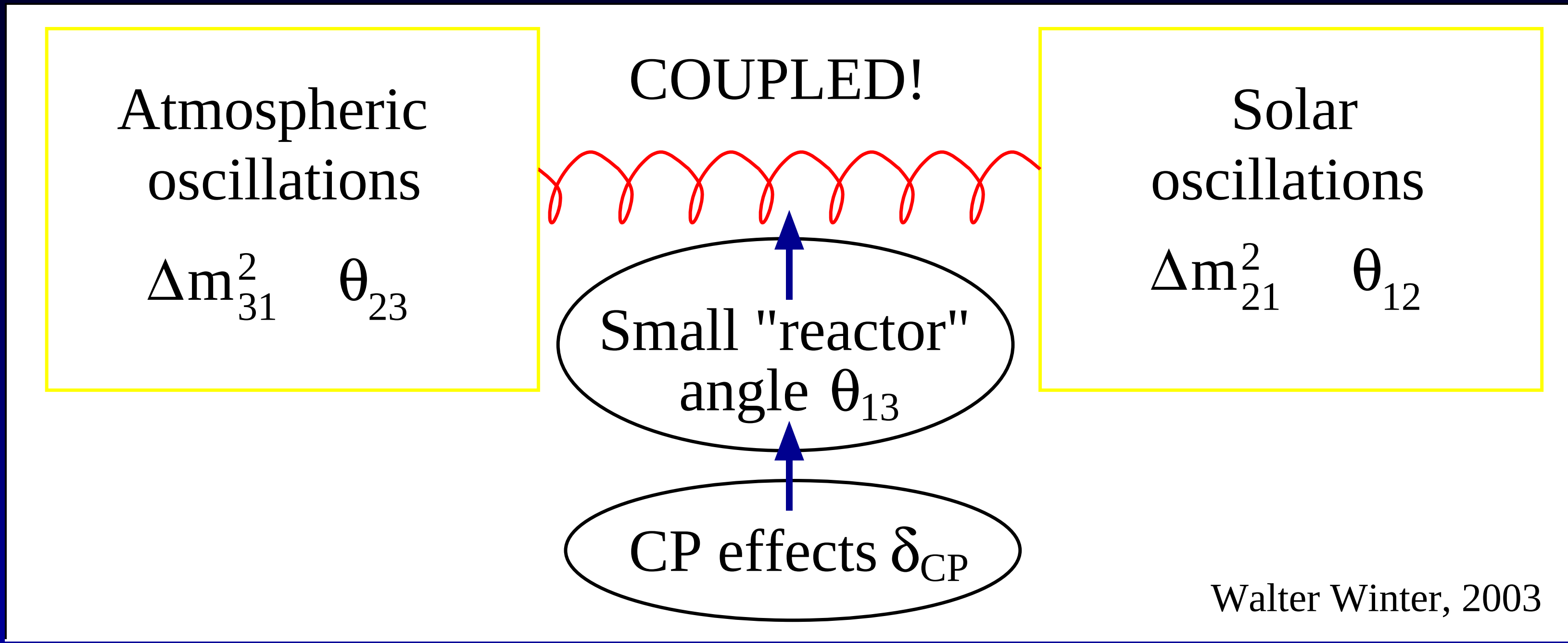
What we don't know

- status of LSND evidence
- 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 $\Leftrightarrow$ signΔm^2_{31}
- CP effects $\Leftrightarrow$ δ

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

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

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

last term negligible for $\frac{\Delta m_{31}^2 L}{4E_\nu} \sim \pi/2$ 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 $\nu_\mu \to \nu_e$

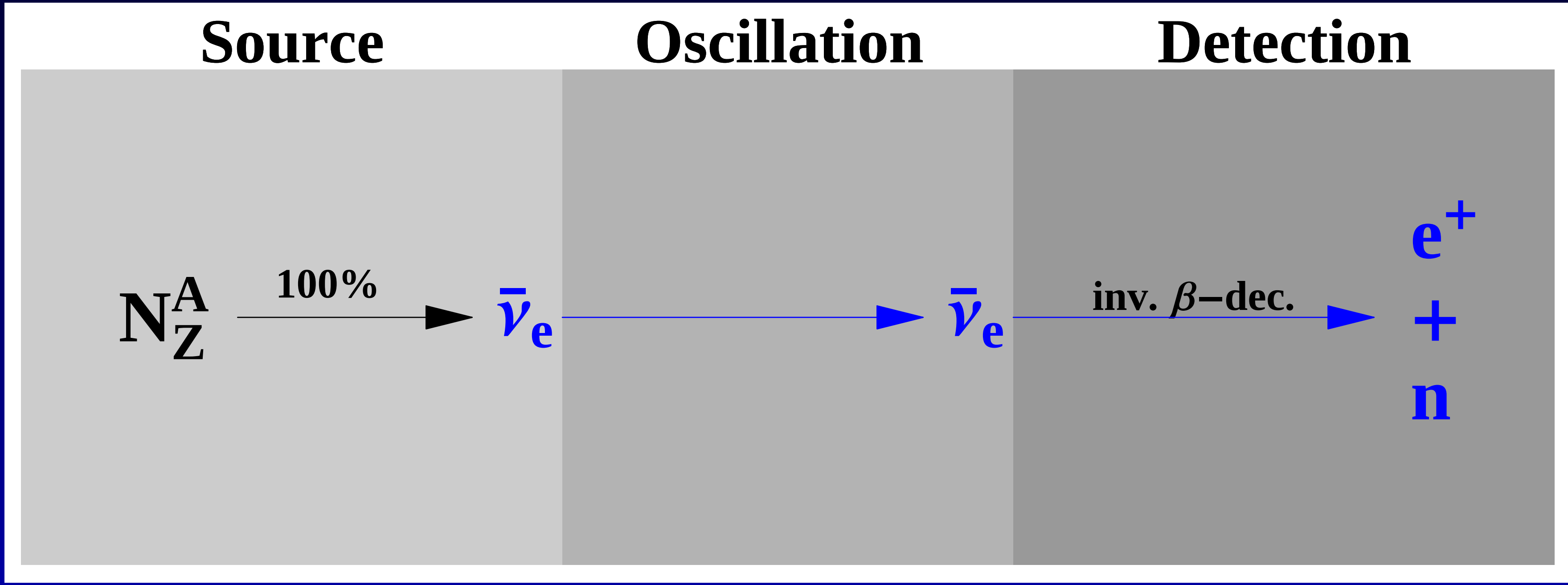
$$
\begin{aligned}
P_{\mu e} \simeq\; & \sin^2 2\theta_{13}\, \sin^2\theta_{23} \sin^2\Delta_{31} \\
\mp\; & \alpha\, \sin 2\theta_{12}\, \sin 2\theta_{13}\, \sin\delta\, \sin 2\theta_{23}\, \Delta_{31}\, \sin^2\Delta_{31} \\
-\; & \alpha\, \sin 2\theta_{12}\, \sin 2\theta_{13}\, \cos\delta\, \sin 2\theta_{23}\,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

with

$$
\alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}\,, \qquad \Delta_{31} \equiv \frac{\Delta m_{31}^2 L}{4E_\nu}
$$

How-to make neutrinos I

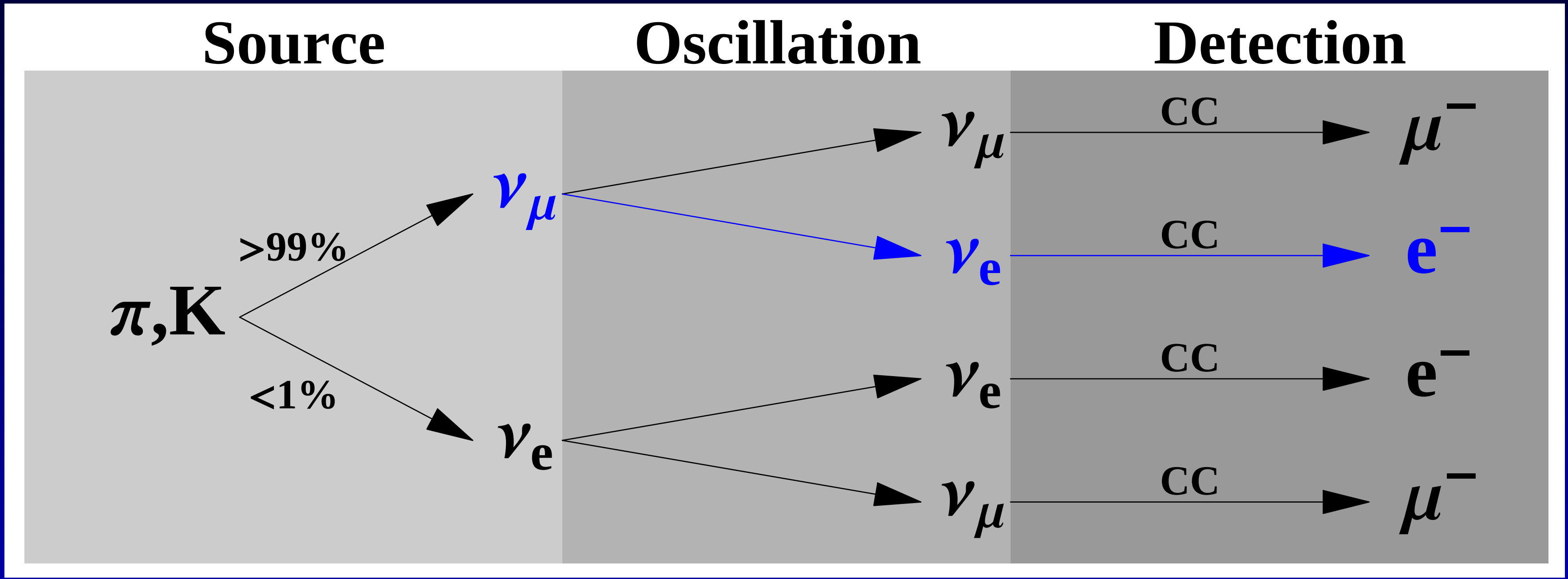
Nuclear reactor



- $E_\nu = 2 - 8\,\mathrm{MeV}$, 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

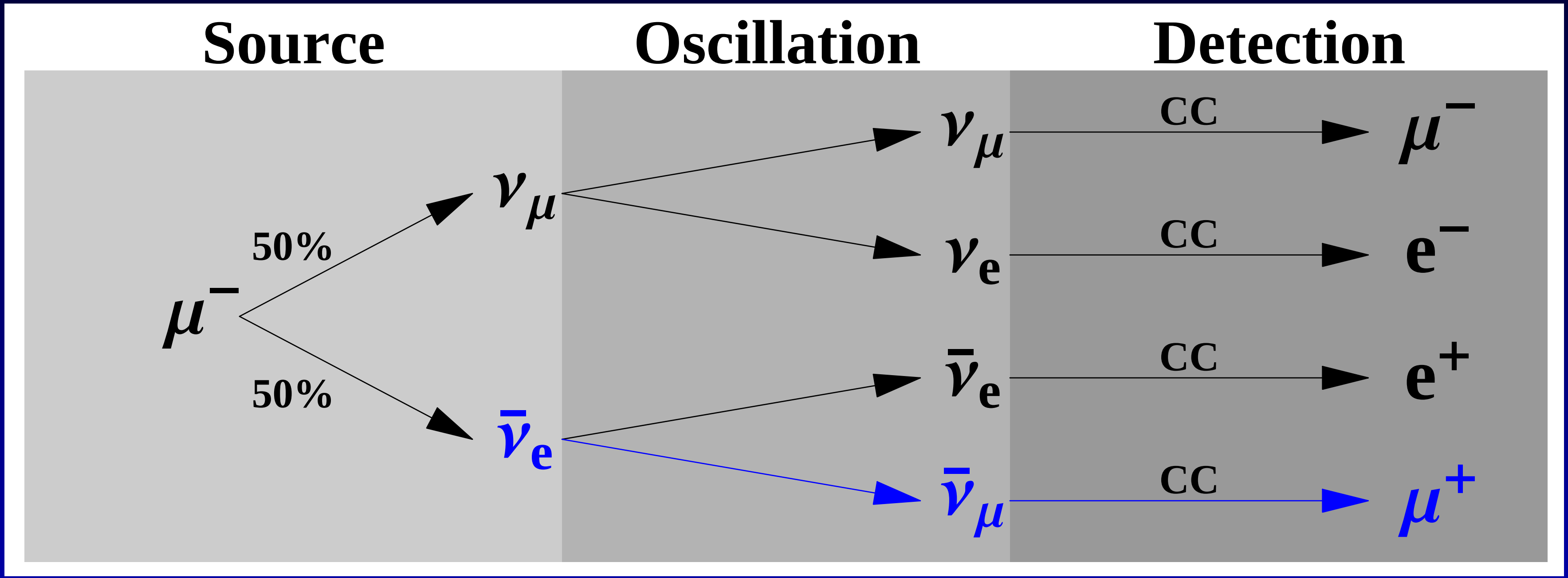
Superbeam



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

How-to make neutrinos III

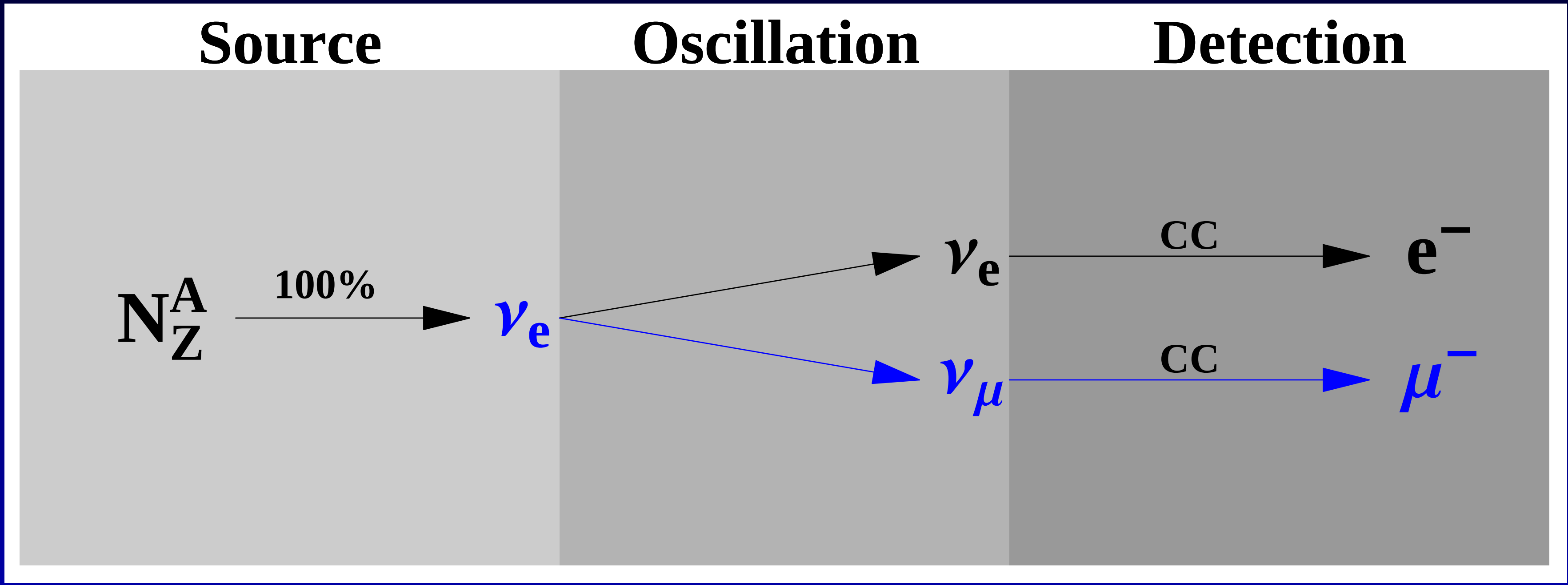
Neutrino factory



- $E_\nu = 20 - 50\,\mathrm{GeV}$, 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

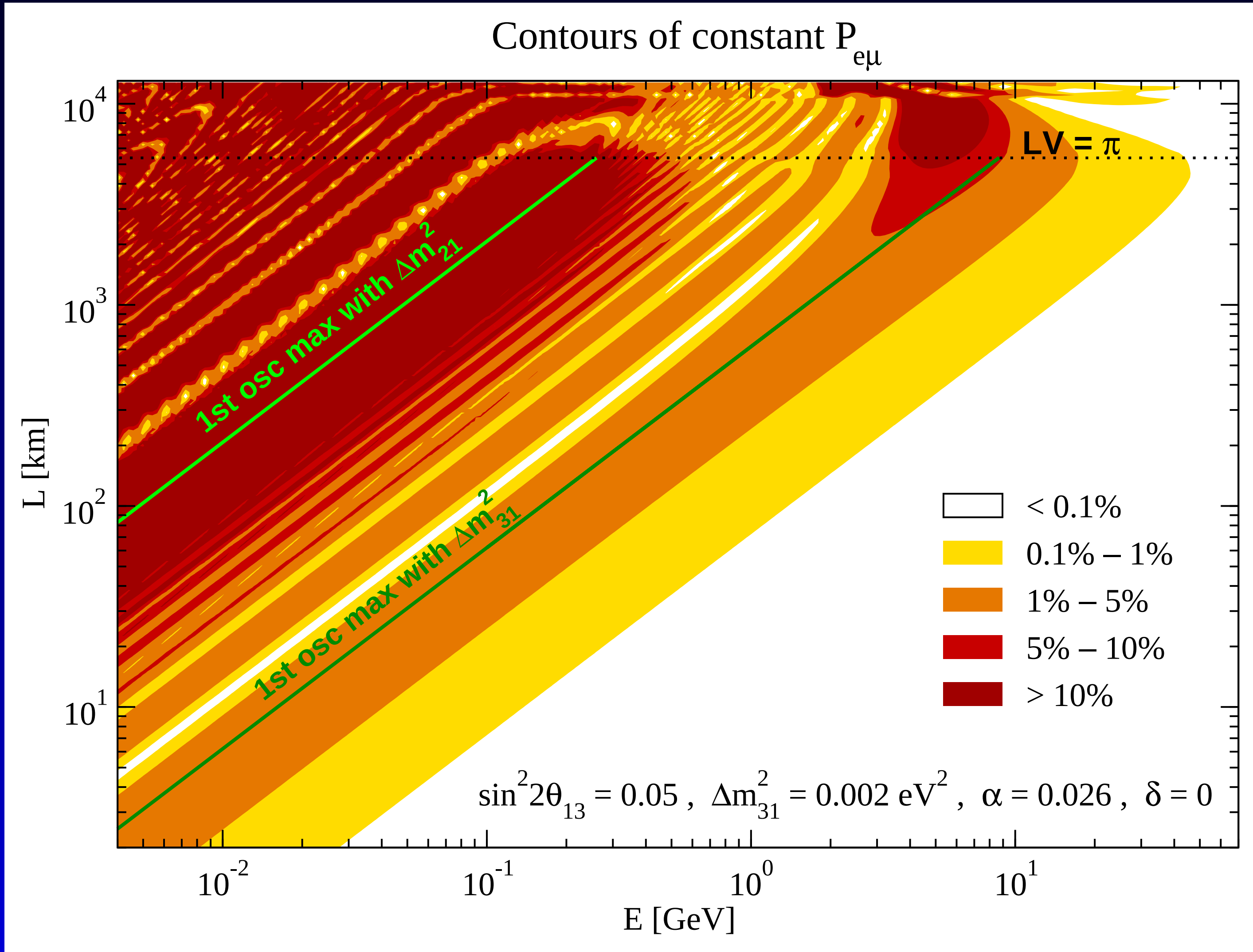


figure by T. Schwetz

L/E of the planned experiments

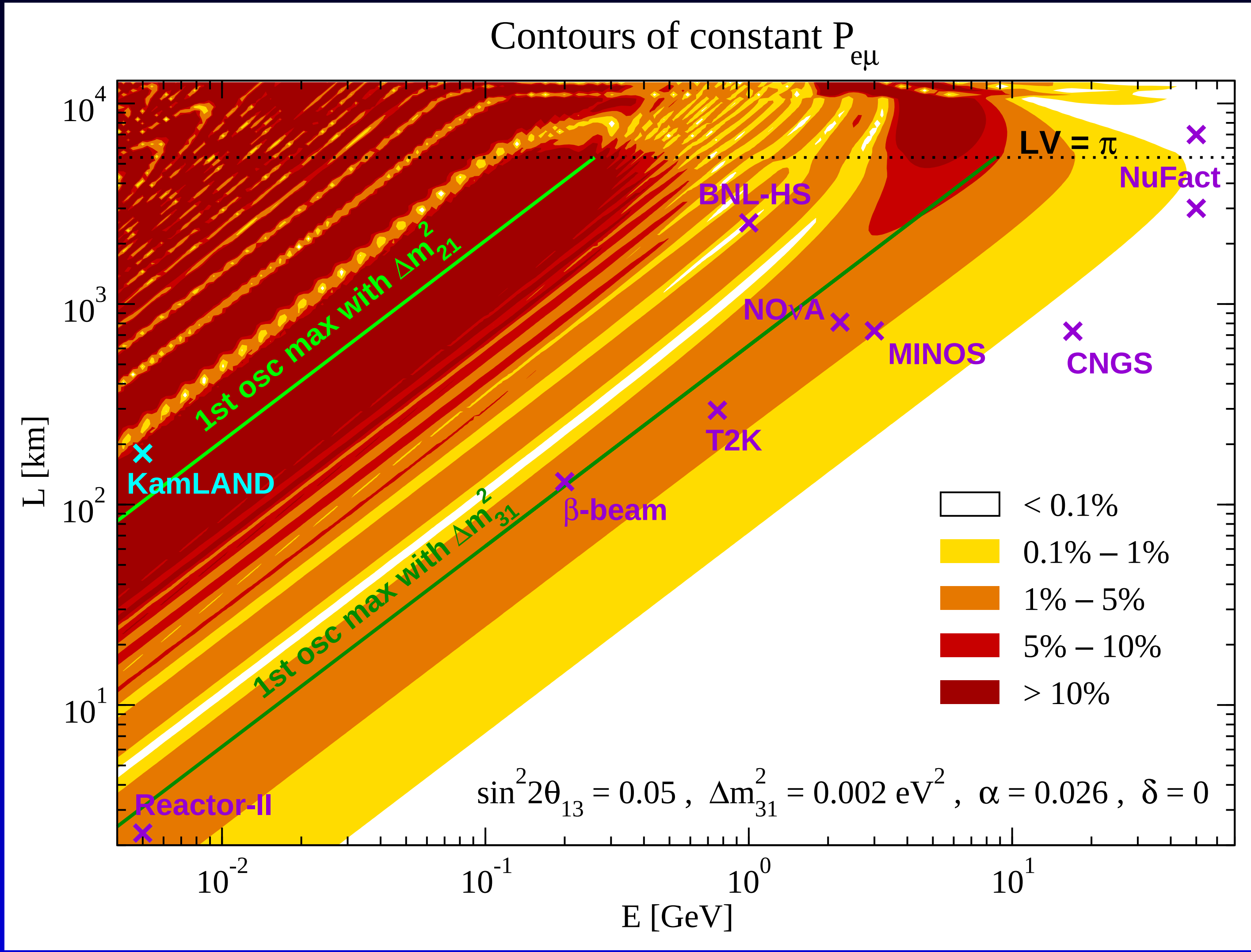


figure by T. Schwetz

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

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ICARUS	$732\,\text{km}$	$17\,\text{GeV}$	$5\,\text{yr}$	$\nu_\mu \to \nu_e, \nu_\mu, \nu_\tau$
OPERA	$732\,\text{km}$	$17\,\text{GeV}$	$5\,\text{yr}$	$\nu_\mu \to \nu_e, \nu_\mu, \nu_\tau$
Off-axis superbeams:				
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CNGS: CERN to Gran Sasso, ν_τ appearance

ICARUS: 2.35 kt liquid argon TPC
OPERA: 1.65 kt emulsion cloud chamber

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Off-axis superbeams:				
T2K	$295\,\text{km}$	$0.76\,\text{GeV}$	$5\,\text{yr}$	$\nu_\mu \to \nu_e, \nu_\mu$
NOνA	$812\,\text{km}$	$2.22\,\text{GeV}$	$5\,\text{yr}$	$\nu_\mu \to \nu_e, \nu_\mu$
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°

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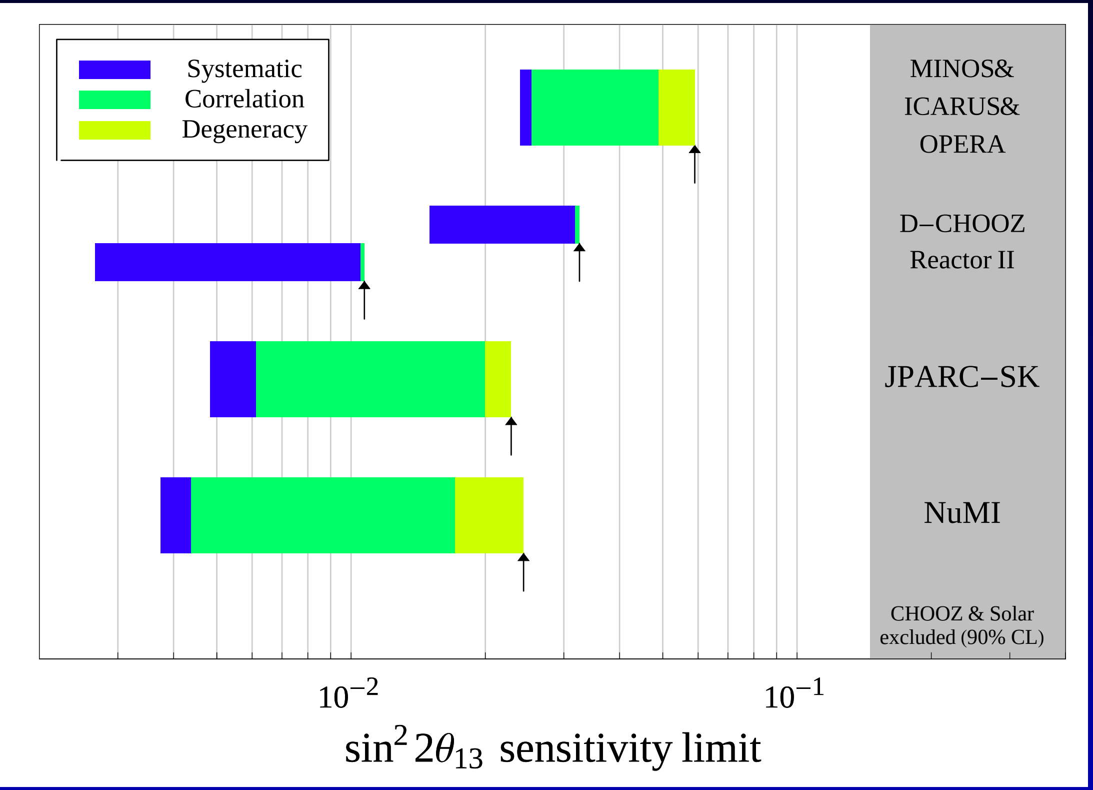
Reactor experiments with near and far detectors:				
D-Chooz	$1.05\,\text{km}$	$\sim 4\,\text{MeV}$	$3\,\text{yr}$	$\nu_e \to \nu_e$
Reactor-II	$1.70\,\text{km}$	$\sim 4\,\text{MeV}$	$5\,\text{yr}$	$\nu_e \to \nu_e$

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

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

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



true values:

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

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

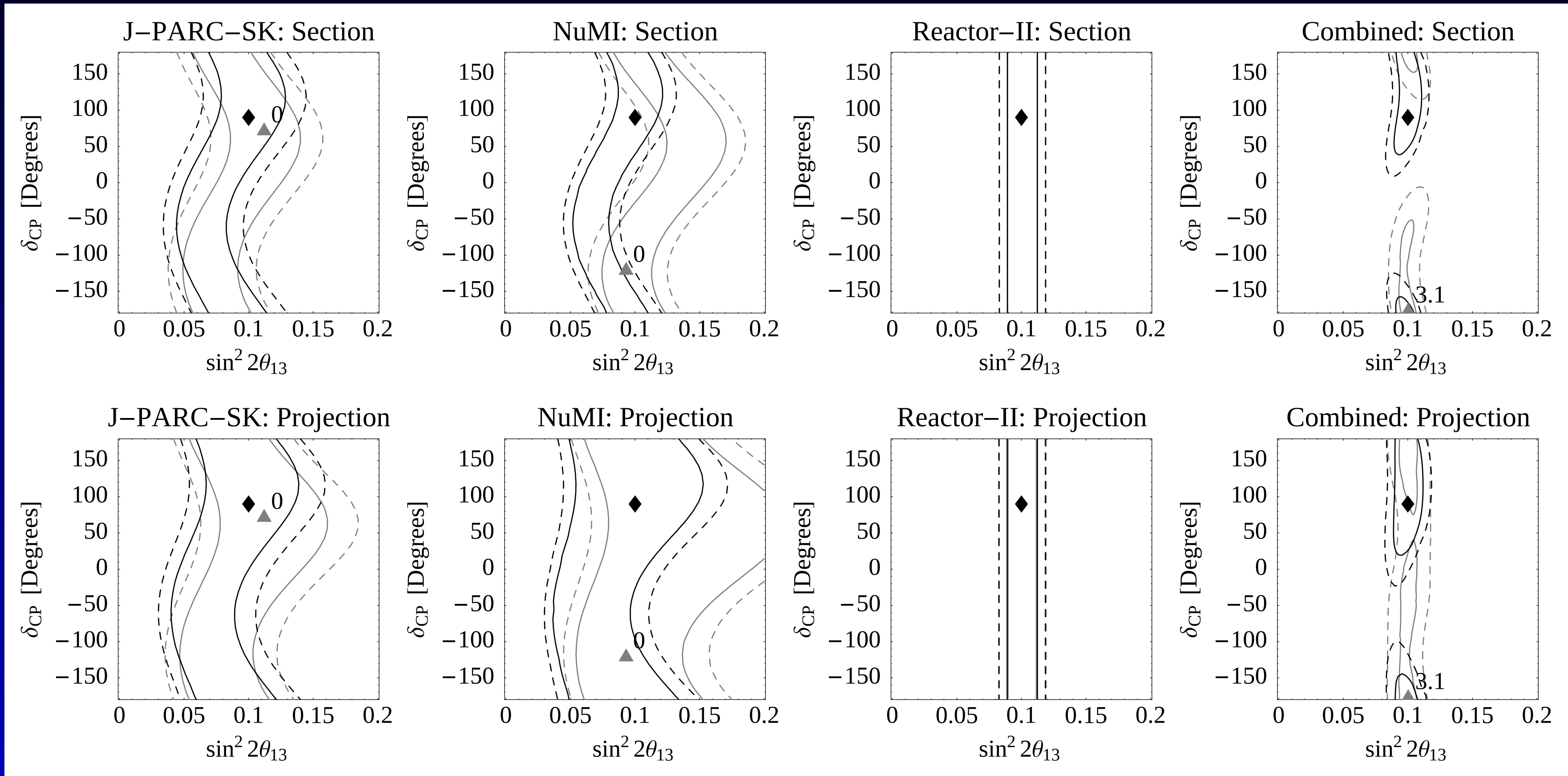
$\sin^2 2\theta_{13} = 0.0$

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

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

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

If $\sin^2 2\theta_{13}$ is large . . .



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

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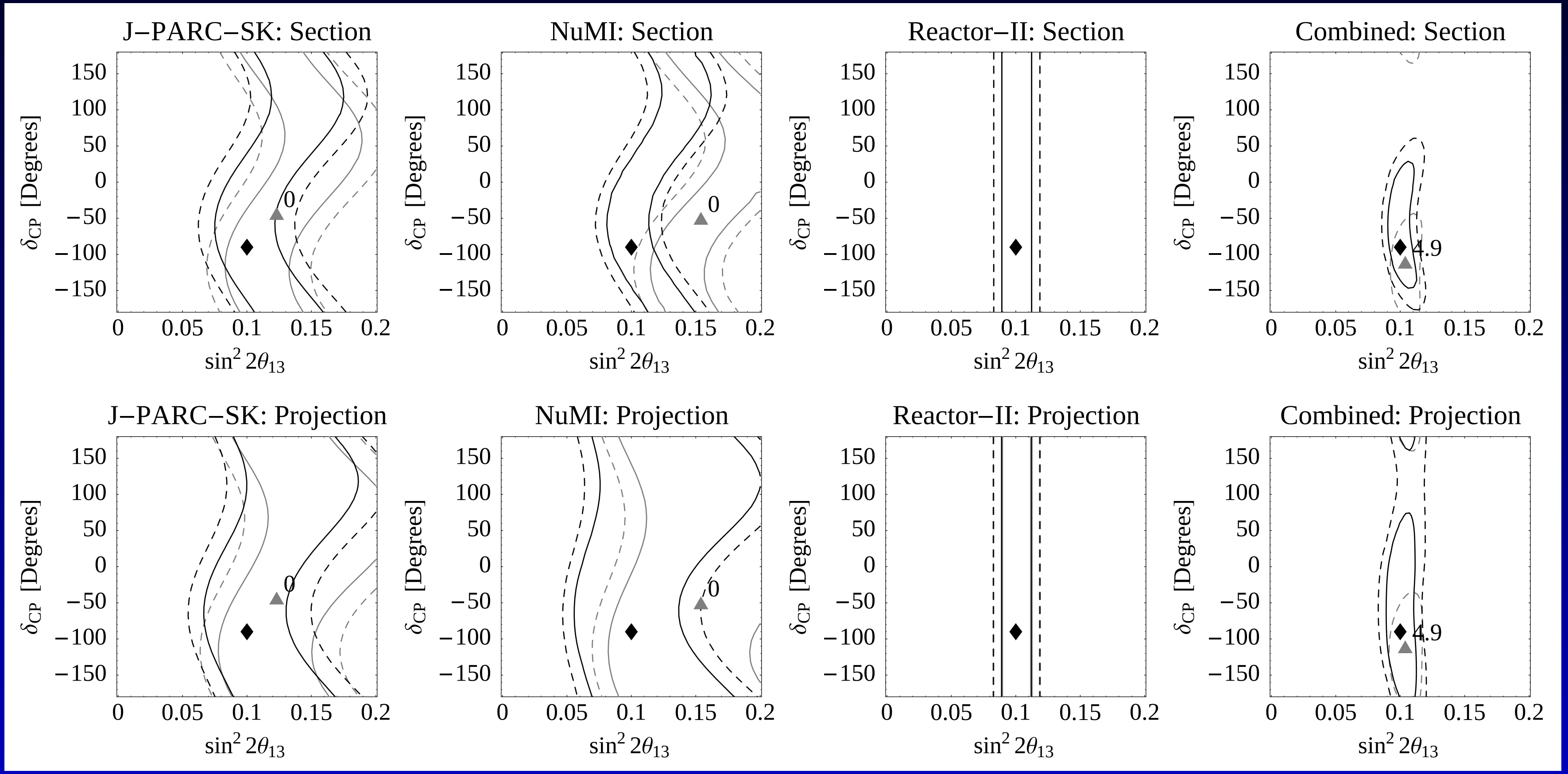


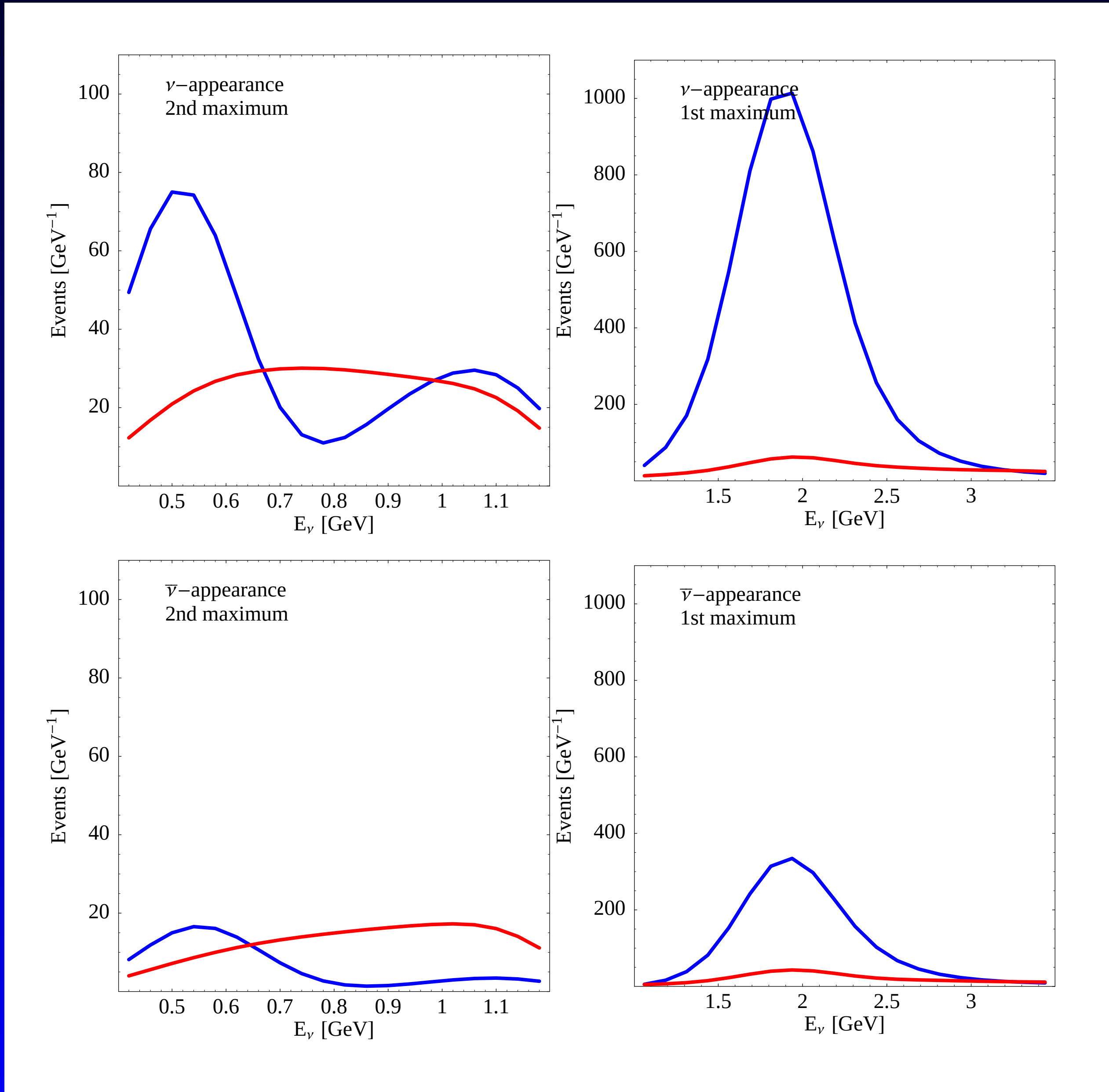
PH, Lindner, Rolinec, Schwetz, Winter, Phys. Rev. D70 (2004) 073014

Resolving correlations and degeneracies

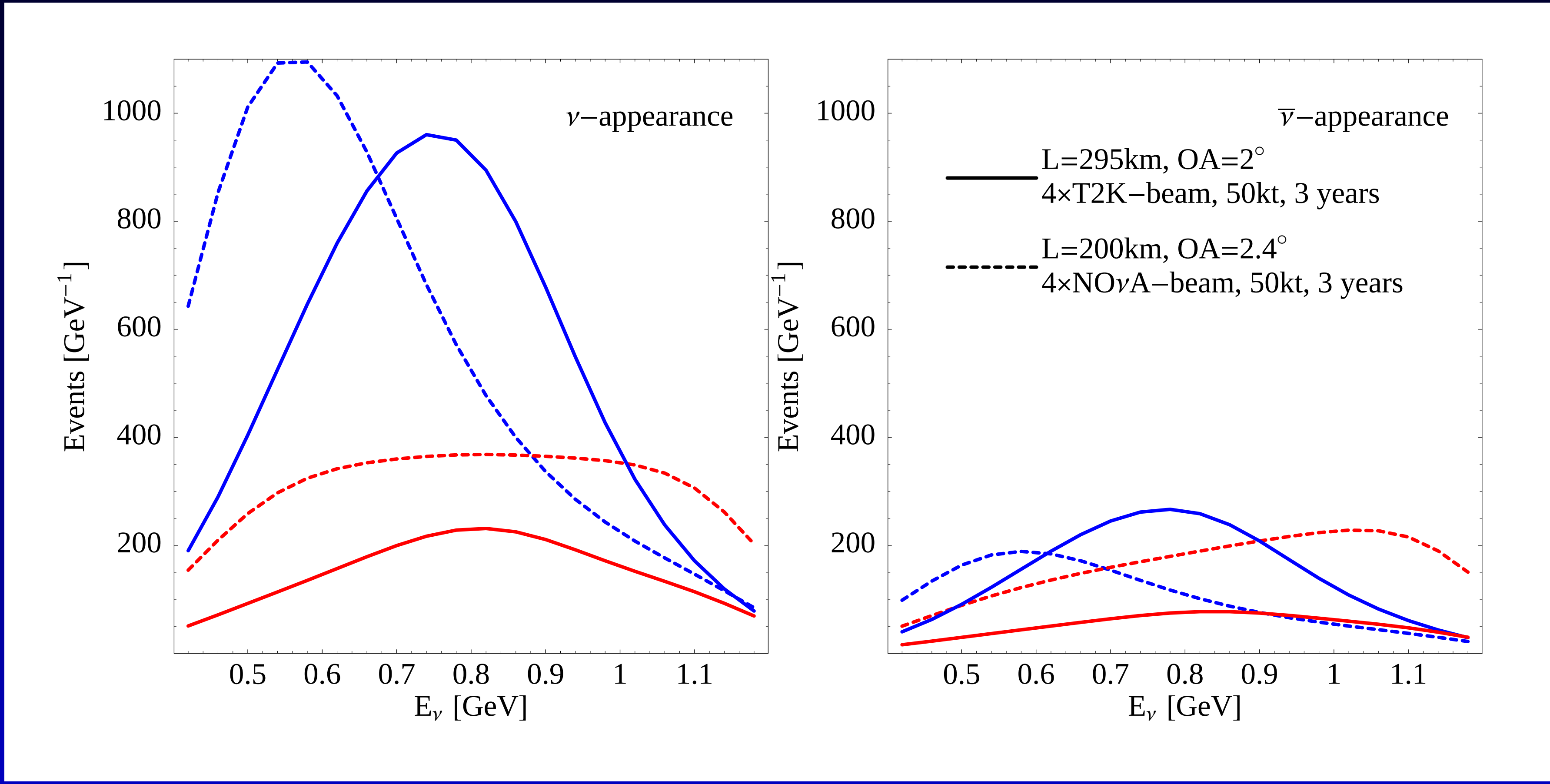
Possible strategies

- Combination of different baselines
  - Second oscillation maximum (**NOνA**)
  - Same L/E – different baseline (**T2K**, Super-**NOνA**)
  - Magic baseline – neutrino factory
- Combination of different energies – use of energy spectrum (wide band beam)
- Combination of different channels – mainly relevant for neutrino factories only ($\nu_e \longrightarrow \nu_\tau$)

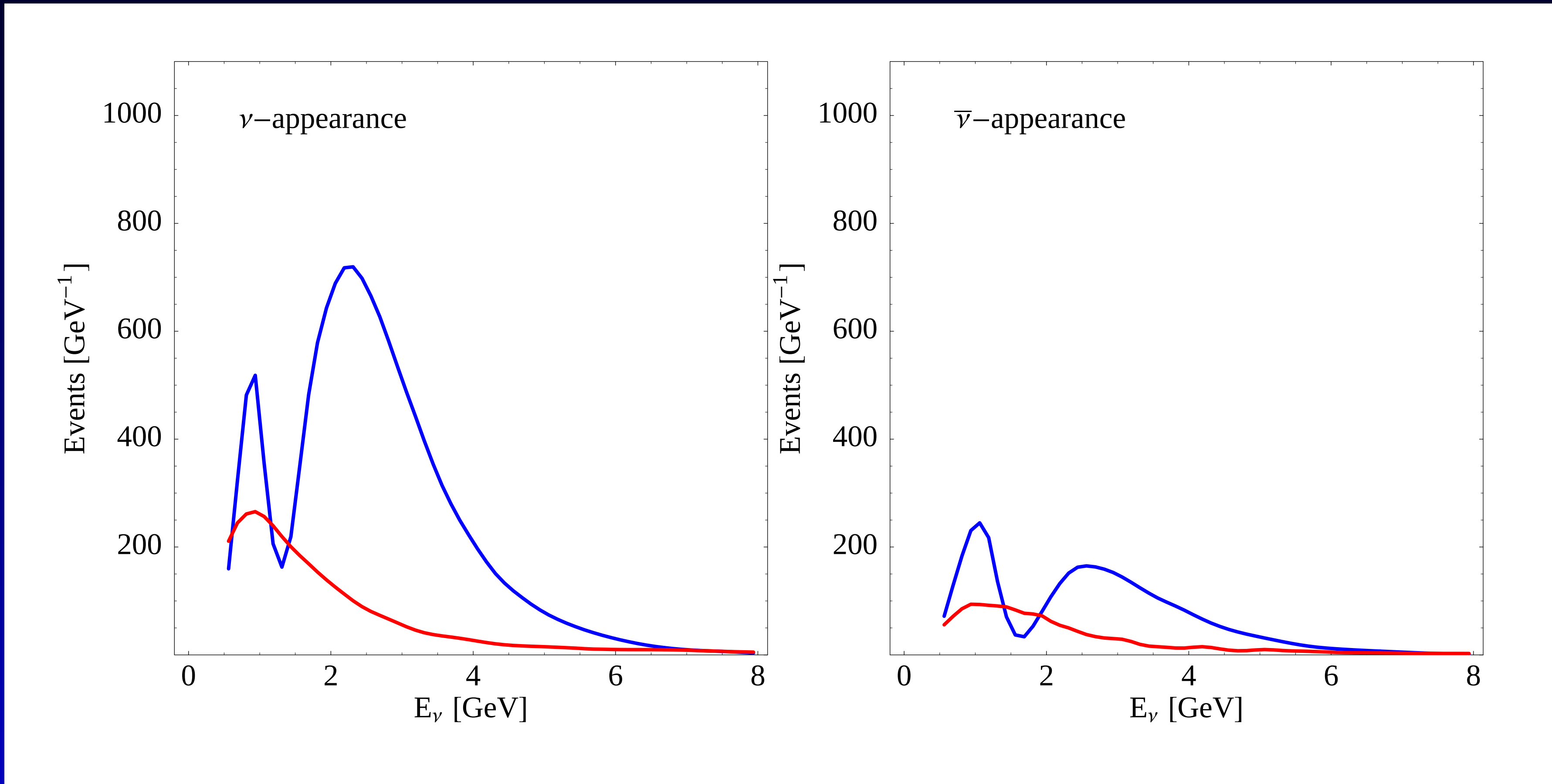
NOνA and the 2^{nd} peak



Super-NOνA and T2K

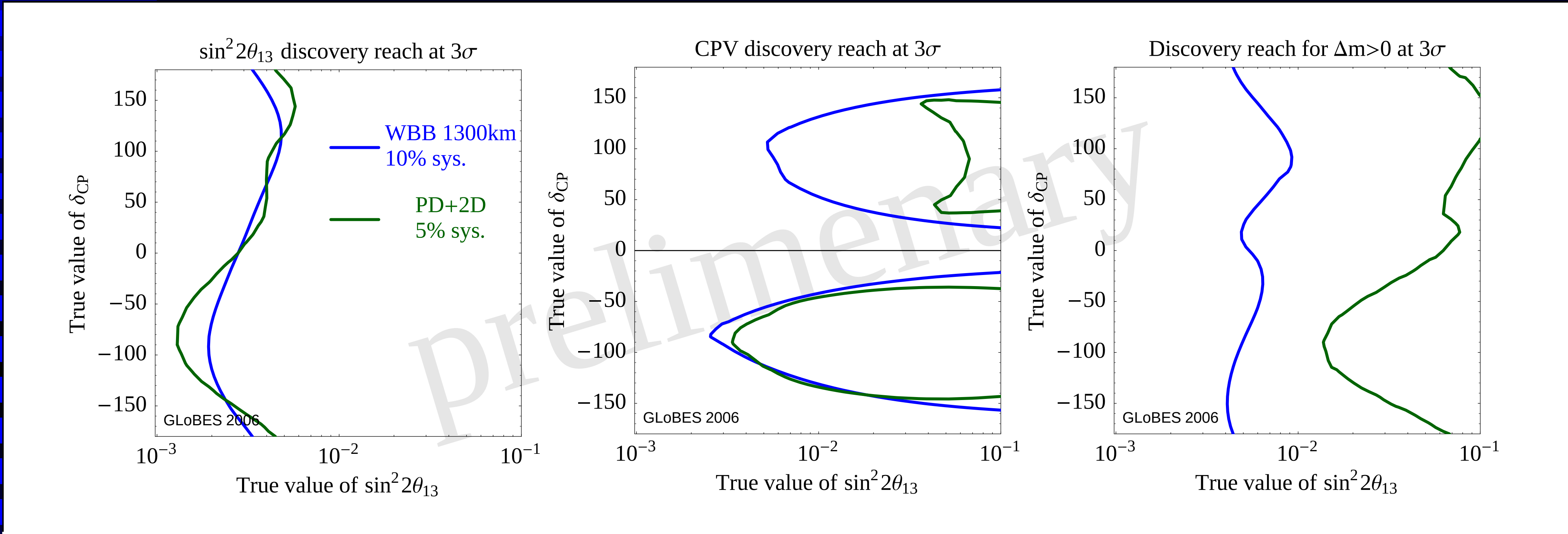


Wide band beam



$P = 1\,\mathrm{MW}$, $500\,\mathrm{kt}$ water Cherenkov detector, π^0 suppression verifi ed by Super-K MC, $5 \times 10^7\mathrm{s}$ neutrino running, $5 \times 10^7\mathrm{s}$ anti-neutrino running

Performance comparison

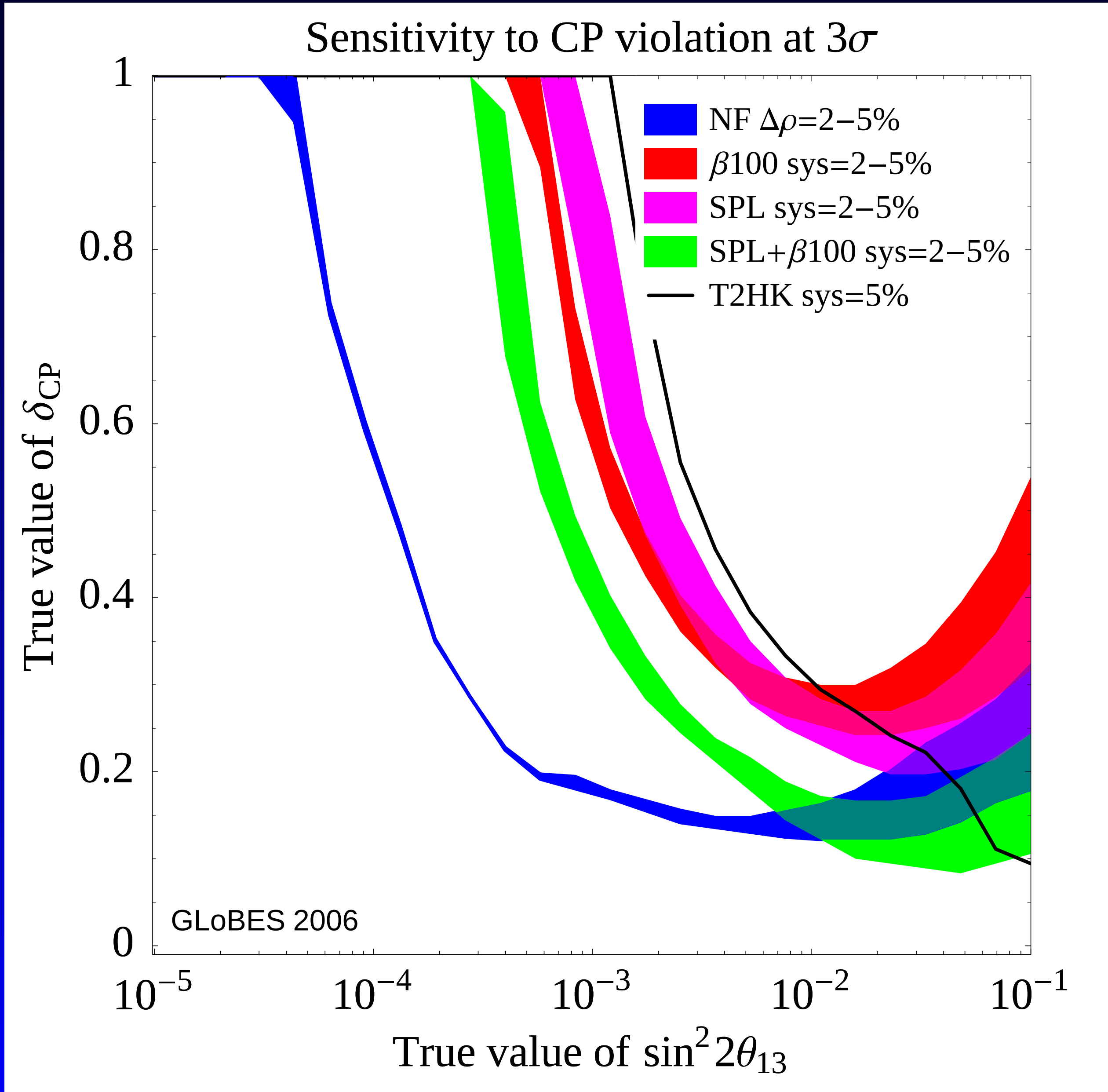


work in progress together with V. Barger, M. Bishai, M. Dierckxsens, M. Diwan, C. Lewis, D. Marfatia, B. Viren and W. Winter

Summary

Summary

- **T2K**, DoubleChooz, Daya Bay and **NOνA** can discover $\sin^2 2\theta_{13} > 0.01$
- they can not access the mass hierarchy or CP violation (even in combination requires fine-tuning)
- higher statistics needed $\longrightarrow$ more powerful beams, larger/more effiecient detectors
- anti-neutrino running essential
- additional information required $\longrightarrow$ energy spectrum or combination of baselines


Sensitivity to CP violation at 3σ
NF Δρ=2−5%
β100 sys=2−5%
SPL sys=2−5%
SPL+β100 sys=2−5%
T2HK sys=5%
GLoBES 2006
True value of δ_{CP}
True value of $\sin^2 2\theta_{13}$
1
0.8
0.6
0.4
0.2
0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}