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Neutrino Oscillation Phenomenology - II

Thomas Schwetz

CERN

Outline - Part II

- Introduction
  Overview of upcoming LBL exps. and ideas for the future
- General comments on the LBL osc. probability
- Leading atmospheric parameters
- The measurement of θ_{13}
  reactor vs accelerator experiments
- The problem of degeneracies
  combined determination θ_{13}, $\delta_{\rm CP}$, the octant of θ_{23} and the neutrino mass hierarchy

LBL experiments in the next ten years

Conventional beam experiments:

Reactor experiments with near and far detectors:

Off-axis superbeams:

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Label	L	$\langle E_\nu \rangle$	mass	channel
Conventional beam experiments:				
MINOS	$735\,\mathrm{km}$	$3\,\mathrm{GeV}$	$5.4\,\mathrm{kt}$	$\nu_\mu \to \nu_\mu, \nu_e$
Reactor experiments with near and far detectors:				
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MINOS:
Fermilab to Soudan mine, 5.4 kt magnetized iron calorimeter

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CNGS: CERN to Gran Sasso, ν_τ appearance

OPERA: 1.65 kt emulsion cloud chamber

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D-Chooz	$1.05\,\mathrm{km}$	$\sim 4\,\mathrm{MeV}$	$\sim 10\,\mathrm{kt}$	$\bar\nu_e \to \bar\nu_e$
Reactor-II	$1.70\,\mathrm{km}$	$\sim 4\,\mathrm{MeV}$	$\sim 200\,\mathrm{kt}$	$\bar\nu_e \to \bar\nu_e$
Off-axis superbeams:				

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

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

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Off-axis superbeams:				
T2K	$295\,\mathrm{km}$	$0.76\,\mathrm{GeV}$	$22.5\,\mathrm{kt}$	$\nu_\mu \to \nu_e, \nu_\mu$
NOνA	$812\,\mathrm{km}$	$2.22\,\mathrm{GeV}$	$50\,\mathrm{kt}$	$\nu_\mu \to \nu_e, \nu_\mu$

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

NOνA: 50 kt TASD detector, off-axis angle of 0.72°

LBL experiments beyond ten years

- superbeam upgardes $(\nu_\mu \to \nu_e, \nu_\mu) + (\bar{\nu}_\mu \to \bar{\nu}_e, \bar{\nu}_\mu)$

  T2HK: beam 0.77 $\to$ 4 MW, SK (22.5 kt) $\to$ HK (500 kt)

  NOνA: proton driver, second detector

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  WBB: wideband beam, $E_\nu \sim \mathrm{GeV}, L \gtrsim 1000\,\mathrm{km}$

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- neutrino factory (**NuFact**) $(\nu_e, \nu_\mu \to \nu_\mu) + (\bar{\nu}_e, \bar{\nu}_\mu \to \bar{\nu}_\mu)$
  $E_\nu \sim 20 - 50\,\mathrm{GeV},\ 1000\,\mathrm{km} \lesssim L \lesssim 7000\,\mathrm{km}$

General comments on LBL oscillation probabilities

LBL probabilities

three-flavour effects are small:

$$\theta_{13} \ll 1 \,, \qquad \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \approx 0.03 \ll 1$$

LBL probabilities

2-flavour osc probability in constant matter:

$$P = \frac{\sin^2 2\theta}{C^2} \sin^2 C\Delta \,, \quad C \equiv \sqrt{\sin^2 2\theta + (\cos 2\theta - A)^2}$$

with $\Delta \equiv \frac{\Delta m^2 L}{4E}$, $A \equiv \frac{2EV}{\Delta m^2}$

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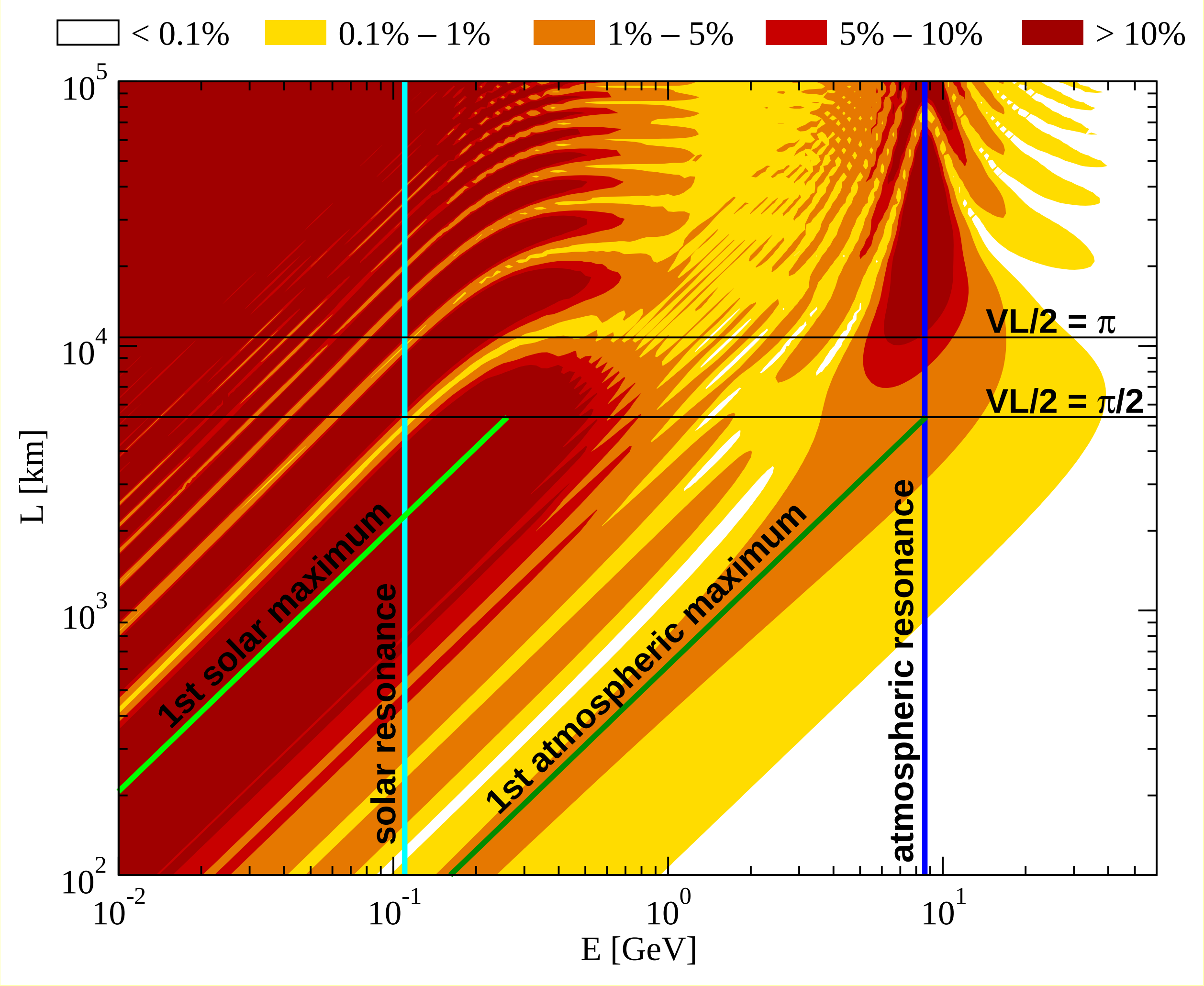
$\Delta = (n + \frac{1}{2})\pi$: oscillation maximum in vacuum

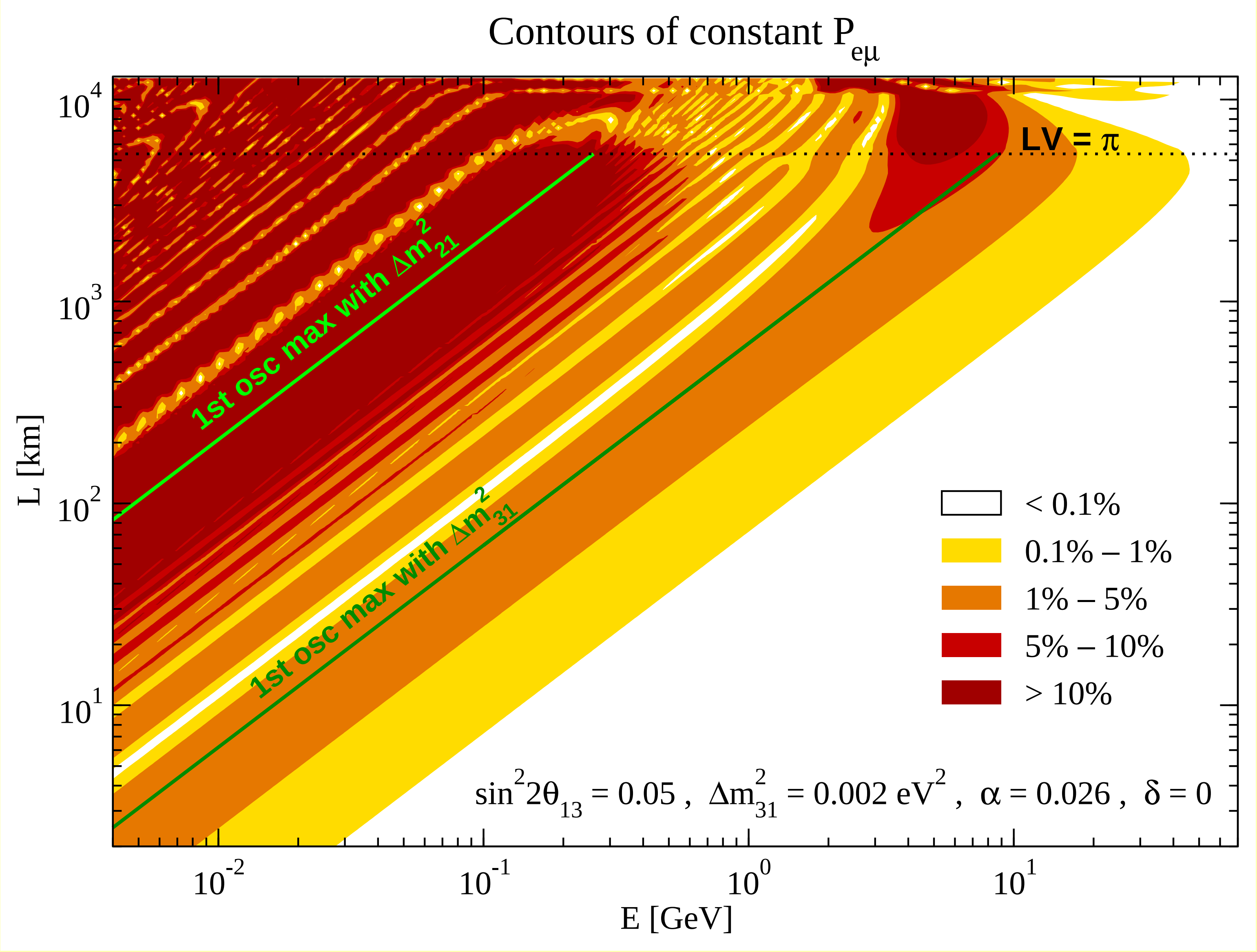
$A = \cos 2\theta$: resonance, $E_{res} = \cos 2\theta \frac{\Delta m^2}{2V}$

LBL probabilities – const. matter



contours of $P_{e\mu}$ for $\sin^2 2\theta_{13} = 0.02$, $\Delta m^2_{31} = 0.002$eV^2, $\alpha = 0.03$, $\theta_{12} = 33°$, $\theta_{23} = 45°$, $\delta_{\rm CP} = 0$, and constant matter dentsity of $\rho = 3$ g/cm^3

LBL probabilities – earth matter profile



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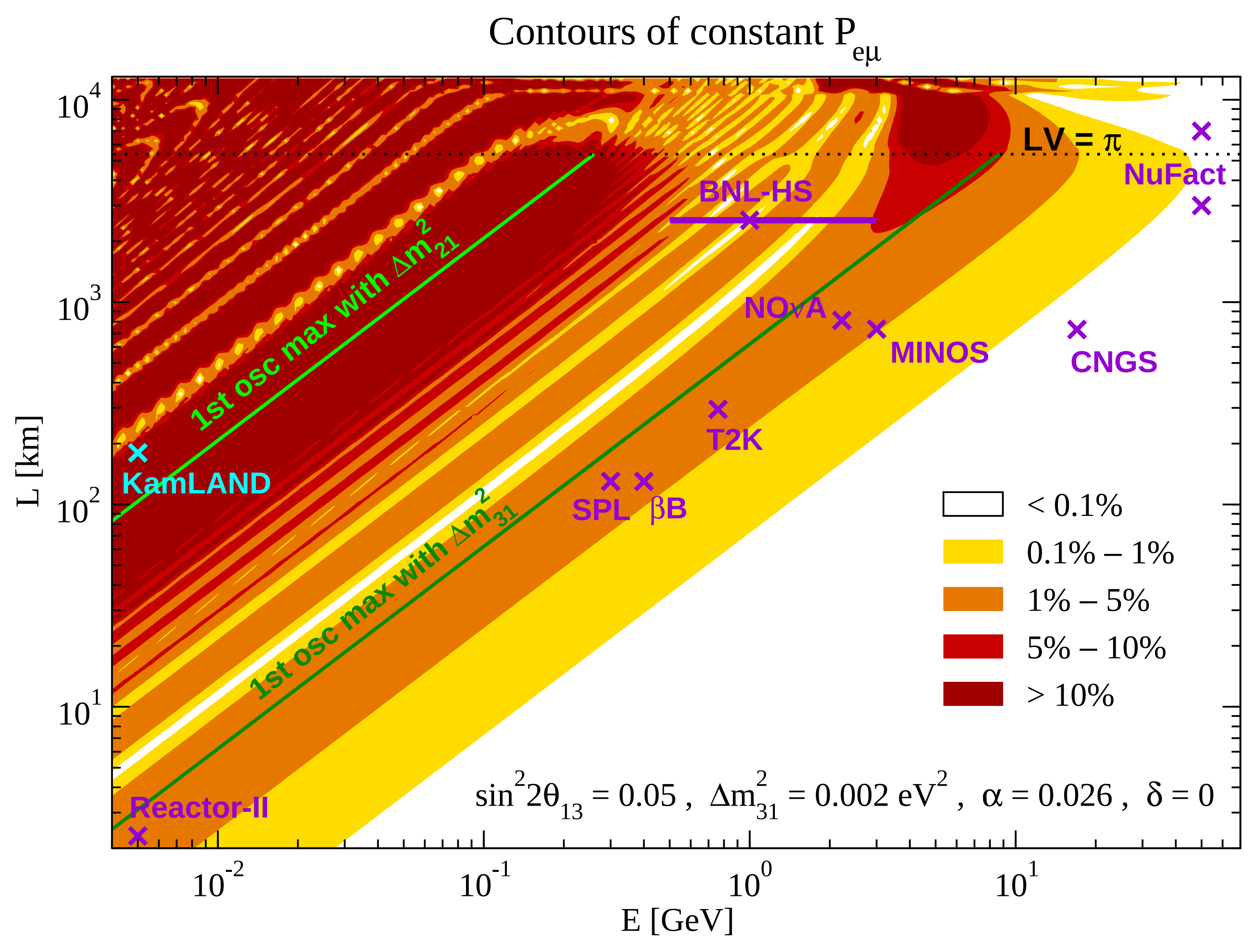


Improving on the ‘atmospheric’ parameters

θ_{23} and $|\Delta m^2_{31}|$

Atmospheric parameters $|\Delta m^2_{13}|$ *and* θ_{23}

determined in ν_μ-disappearance experiments:

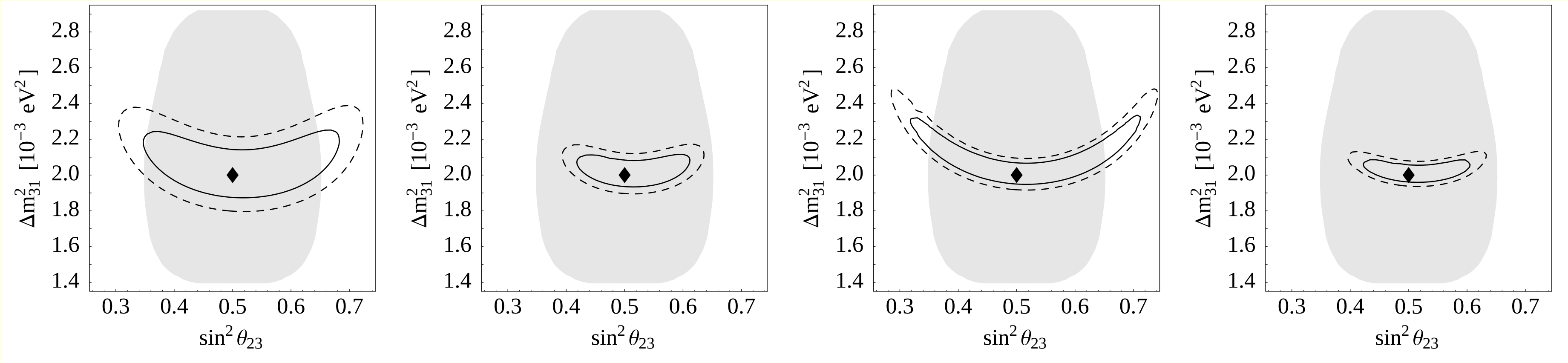
$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \Delta + \mathcal{O}(\alpha, s_{13}\alpha, s_{13}^2)$$

- large number of events $\rightarrow$ small stat. errors
- $\sin^2 2\theta_{23}$ large $\rightarrow$ large effect

Atmospheric parameters $|\Delta m^2_{13}|$ *and* θ_{23}

ν_μ-disappearance in LBL accelerator experiments

MINOS+CNGS **T2K** **NOνA*** combined



* **NOνA** with TASD slightly better

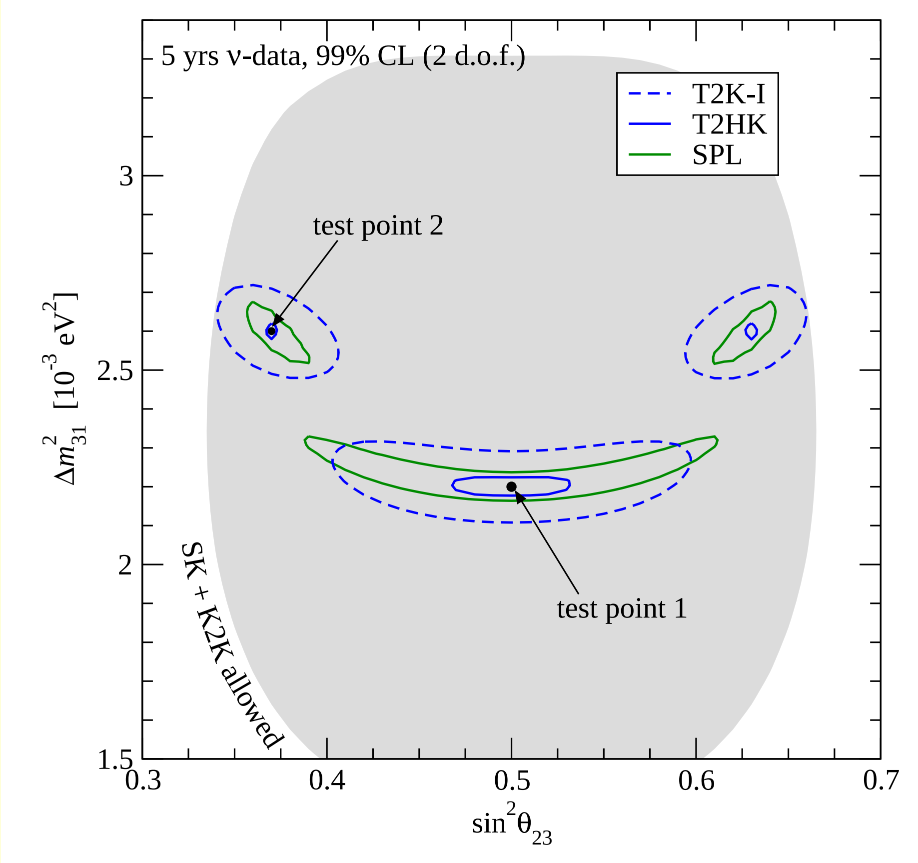
Atmospheric parameters $|\Delta m^2_{13}|$ *and* θ_{23}

going beyond 10 yrs:

subsequent generation of LBL experiments like

T2HK, **SPL**, **NuFact**

will provide a sub-% determination of $|\Delta m^2|$ and $\sin^2 2\theta_{23}$!



Atmospheric parameters $|\Delta m^2_{13}|$ *and* θ_{23}

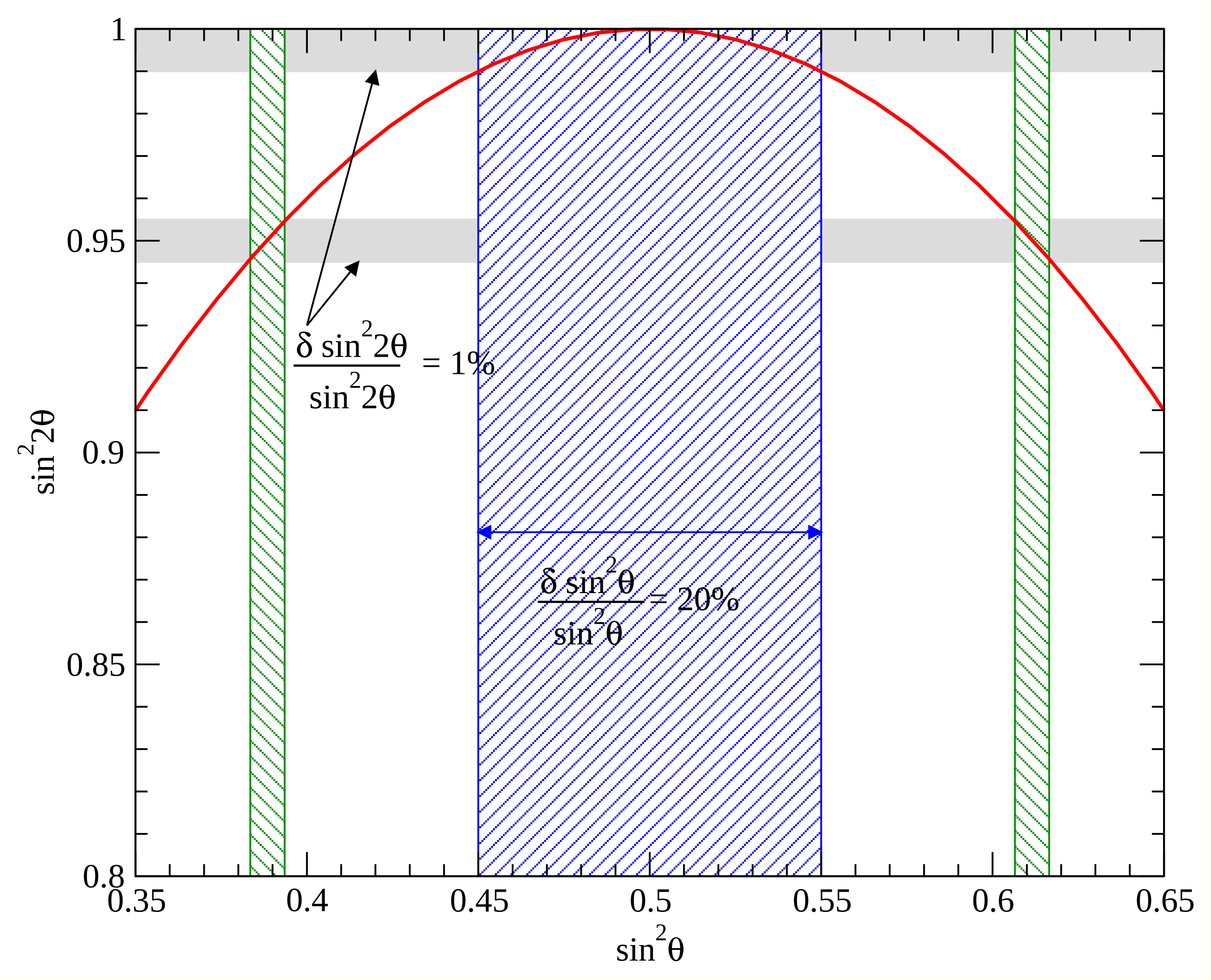
$$P_{\mu\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

$|\Delta m^2_{31}|$ and $\sin^2 2\theta_{23}$ are measured very precisely by energy spectral information

BUT:

- no information on sign(Δm^2_{31})
- cannot distinguish between first and second octant, two possibilities: θ_{23} and $\pi - \theta_{23}$
- if $\sin^2 2\theta_{23} \approx 1$ accuracy on $\sin^2 \theta_{23}$ becomes poor

Atmospheric parameters $|\Delta m^2_{13}|$ *and* θ_{23}



Determination of θ_{13}

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- naively one would expect $\theta_{12} \sim \theta_{23} \sim \theta_{13}$
  $\rightarrow \theta_{13}$ around the corner
- $\theta_{13} \ll 1$ hint for some symmetry
- relatively large θ_{13} opens the possibilty to observe generic 3-flavour effects (CP-violation)

Measuring θ_{13}

- $\bar{\nu}_e \to \bar{\nu}_e$ disappearance reactor experiments with near and far detectors
  Double-Chooz, Daya Bay

- LBL $\nu_\mu \to \nu_e$ (or $\nu_e \to \nu_\mu$) appearance experiments
  MINOS, **T2K**, **NOνA**, **T2HK**, **WBB**, **SPL**, **βB**, **NuFact**

Measuring θ_{13} by $\nu_\mu \to \nu_e$ at beams

The measurement of θ_{13} with the $\nu_\mu \to \nu_e$ 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
P.Huber, M.Lindner, W.Winter, Nucl. Phys. B645 (2002) 3; Nucl. Phys. B654 (2003) 3
and many more

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

The LBL appearance oscillation probability

$$
\begin{aligned}
P_{\mu e} \;\simeq\;& \sin^2 2\theta_{13} \, \sin^2\theta_{23} \, \frac{\sin^2(1-A)\Delta}{(1-A)^2} \\
&+ \sin 2\theta_{13} \, \hat\alpha \, \sin 2\theta_{23} \, \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\Delta + \delta_{\mathrm{CP}}) \\
&+ \hat\alpha^2 \, \cos^2\theta_{23} \, \frac{\sin^2 A\Delta}{A^2}
\end{aligned}
$$

with

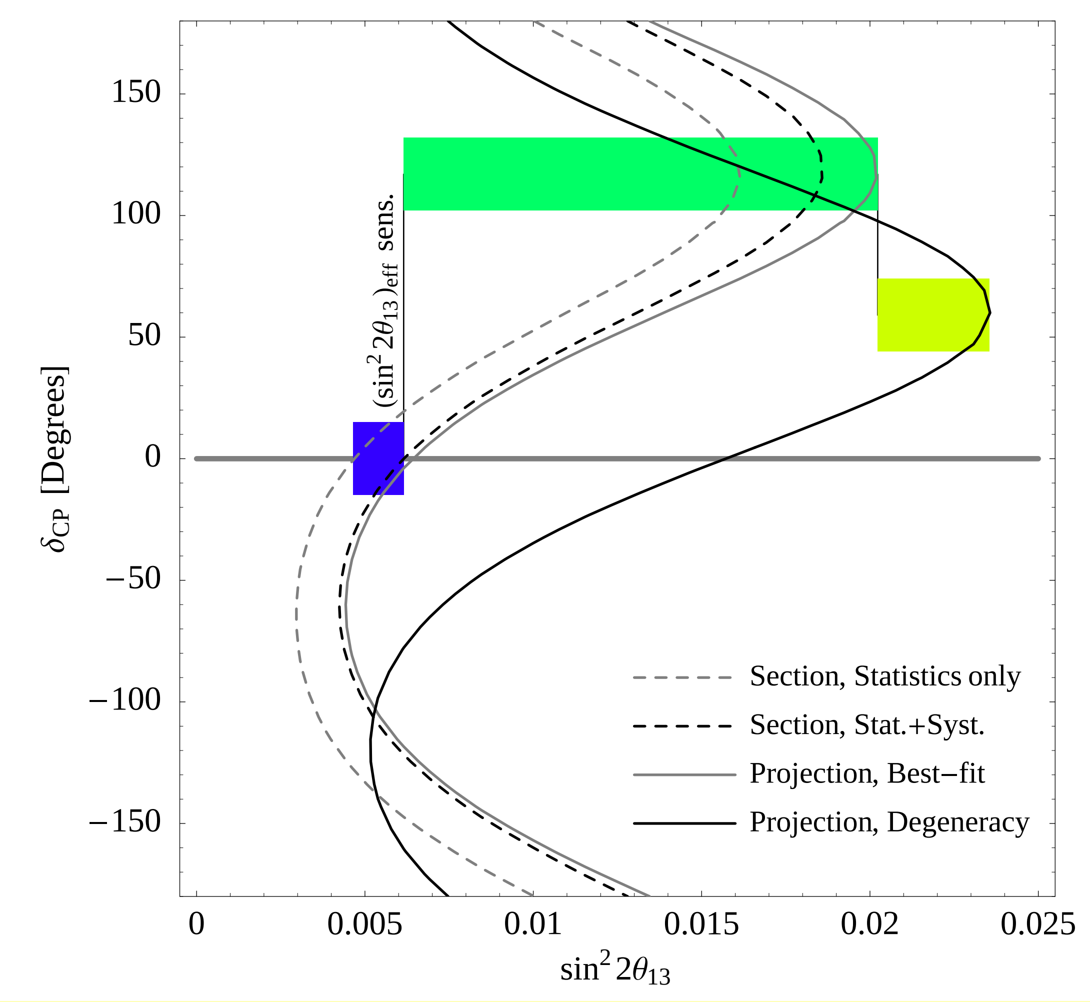
$$
\Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}\,, \qquad \hat\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sin 2\theta_{12}\,, \qquad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}}
$$

anti-ν: $\delta_{\mathrm{CP}} \to -\delta_{\mathrm{CP}}$, $A \to -A$, $\quad P_{e\mu}$: $\delta_{\mathrm{CP}} \to -\delta_{\mathrm{CP}}$

other hierarchy: $\Delta \to -\Delta$, $A \to -A$, $\hat\alpha \to -\hat\alpha$

Measuring θ_{13} by $\nu_\mu \to \nu_e$ at beams

T2K: $\delta - \theta_{13}$ correlation:



Measuring $\sin^2 2\theta_{13}$ *at reactors*

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

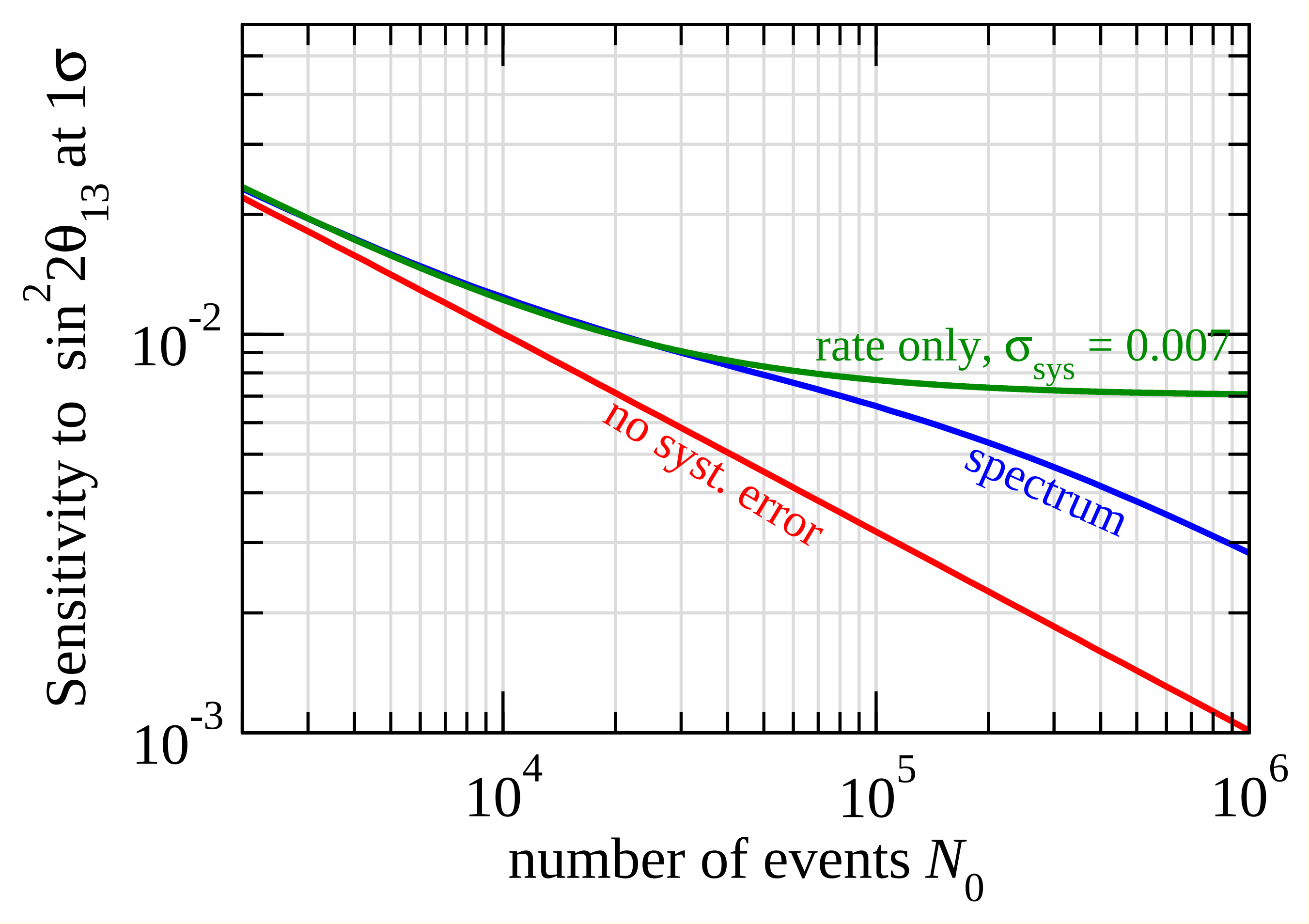
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \, \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \left(\frac{\Delta m^2_{21} L}{4E_\nu} \right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

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

P. Huber, 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

Measuring $\sin^2 2\theta_{13}$ *at reactors - 2*

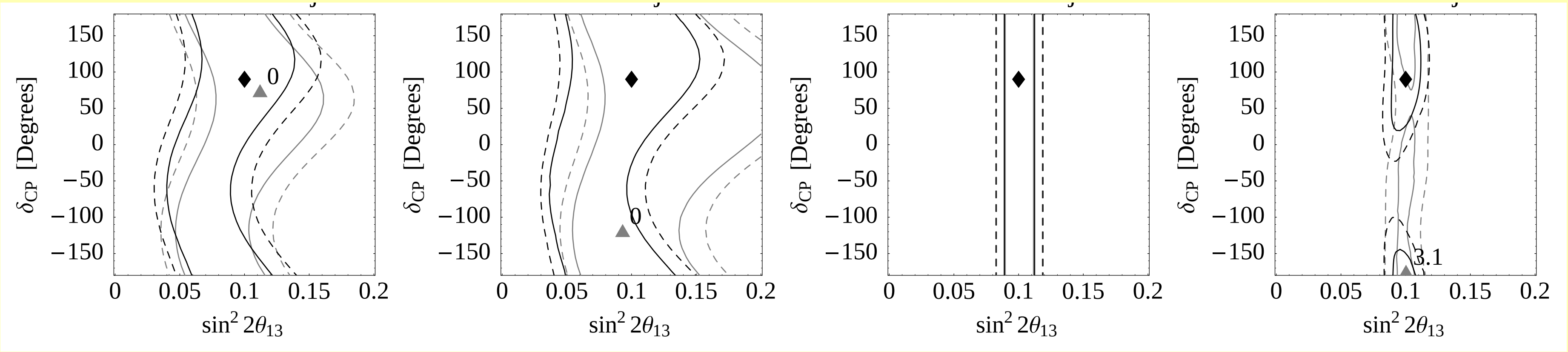


rate only limit at $n\sigma$: $\sin^2 2\theta_{13} < n\sqrt{\frac{1}{N_0} + \sigma_{sys}^2}$

Measuring $\sin^2 2\theta_{13}$ *at beams or reactors*

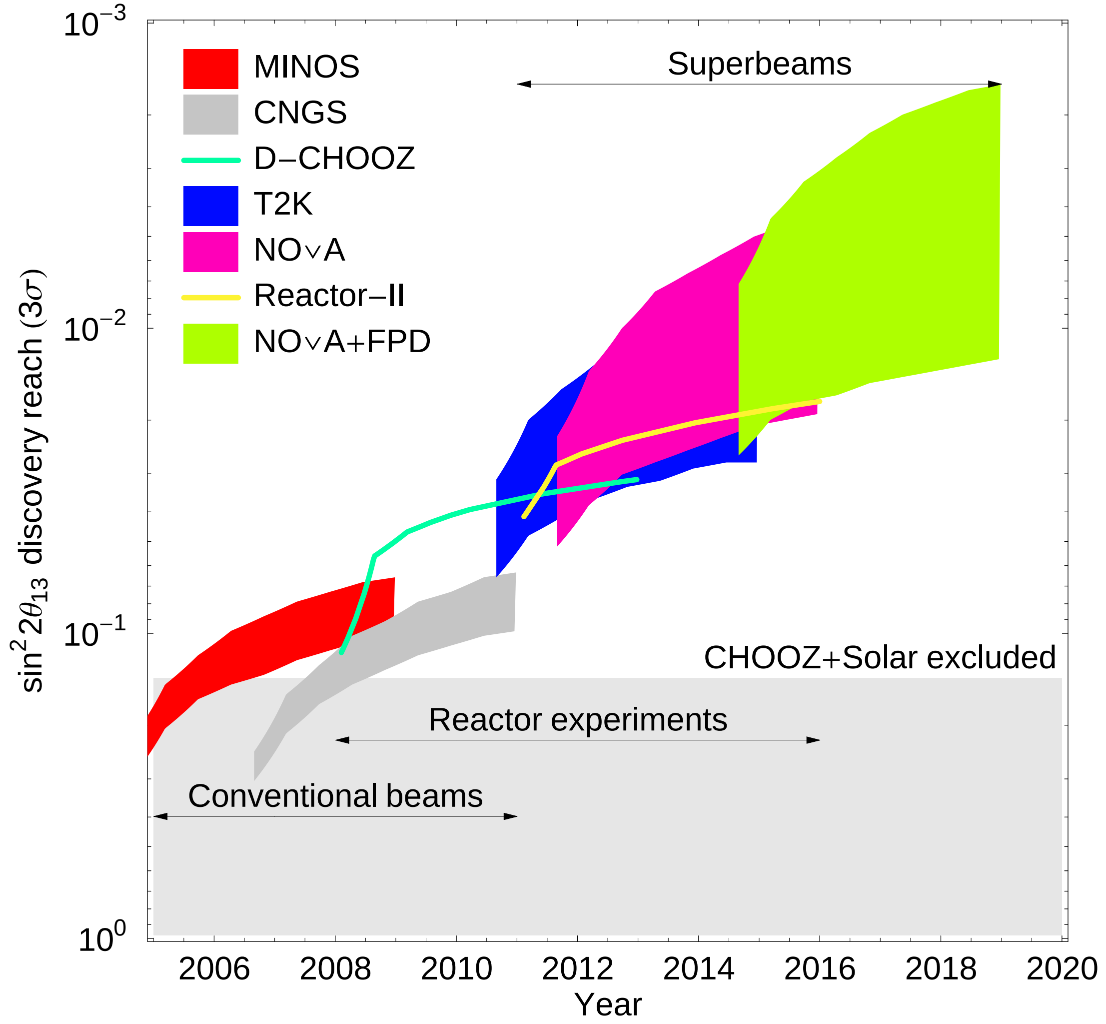
assume $\sin^2 2\theta_{13} = 0.1$

T2K **NOνA** **Reactor-II** combined



Huber, Lindner, Rolinec, Schwetz, Winter, hep-ph/0403068

The $\sin^2 2\theta_{13}$-sensitivity evolution

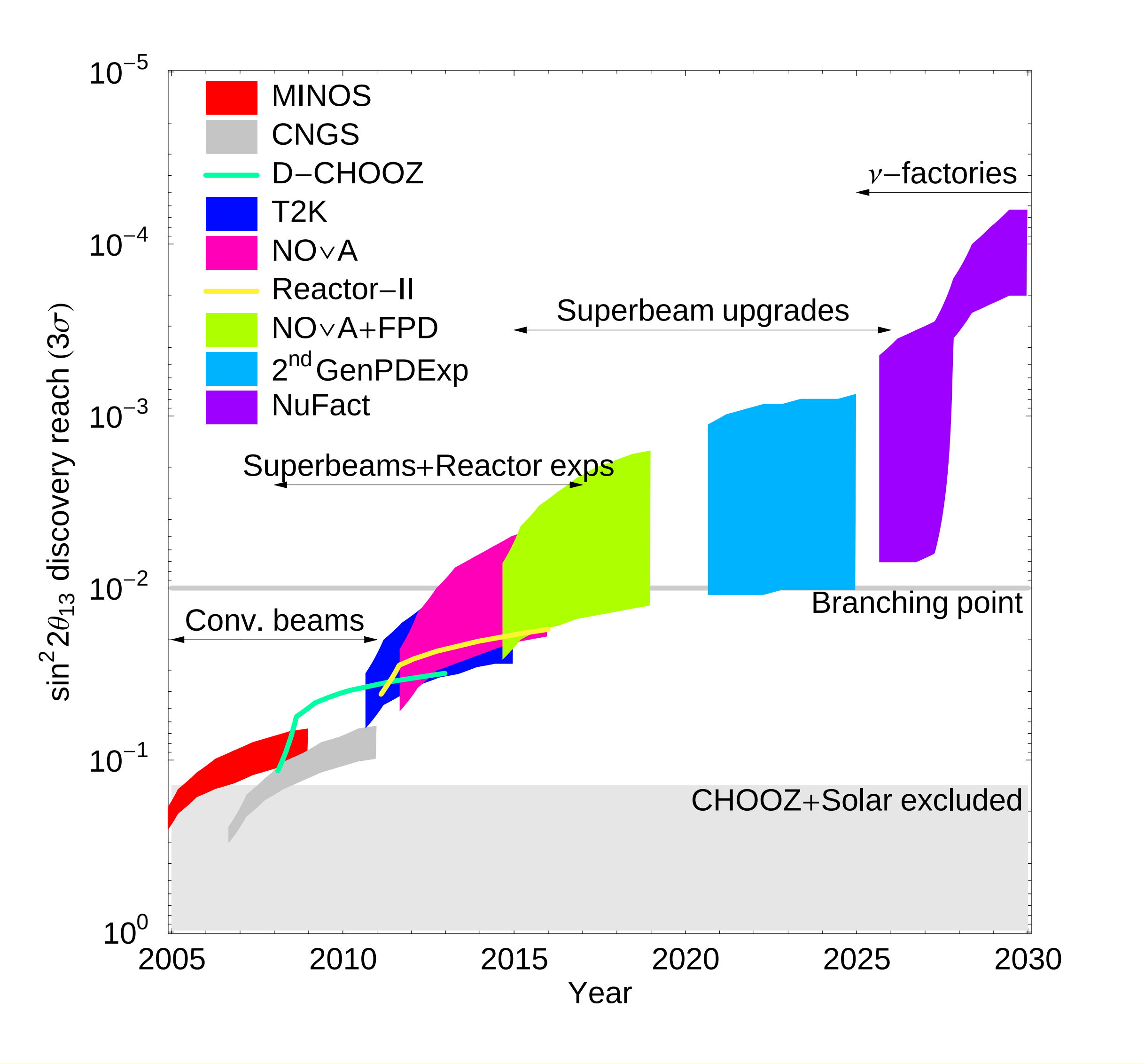


plot by W. Winter from
Albrow et al., hep-ex/0509019

$\Delta m^2_{31} = +2.5 \times 10^{-3}$ eV^2
$\sin^2 2\theta_{23} = 1$

FPD = Fermilab Proton Driver
LBL exps.: neutrinos only
2^{nd}GenPDExp = T2HK
NuFact anti-ν after 2.5 yr

The $\sin^2 2\theta_{13}$*-sensitivity evolution*



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CP violation in neutrino oscillations

CP violation

CP asymmetry in vacuum:

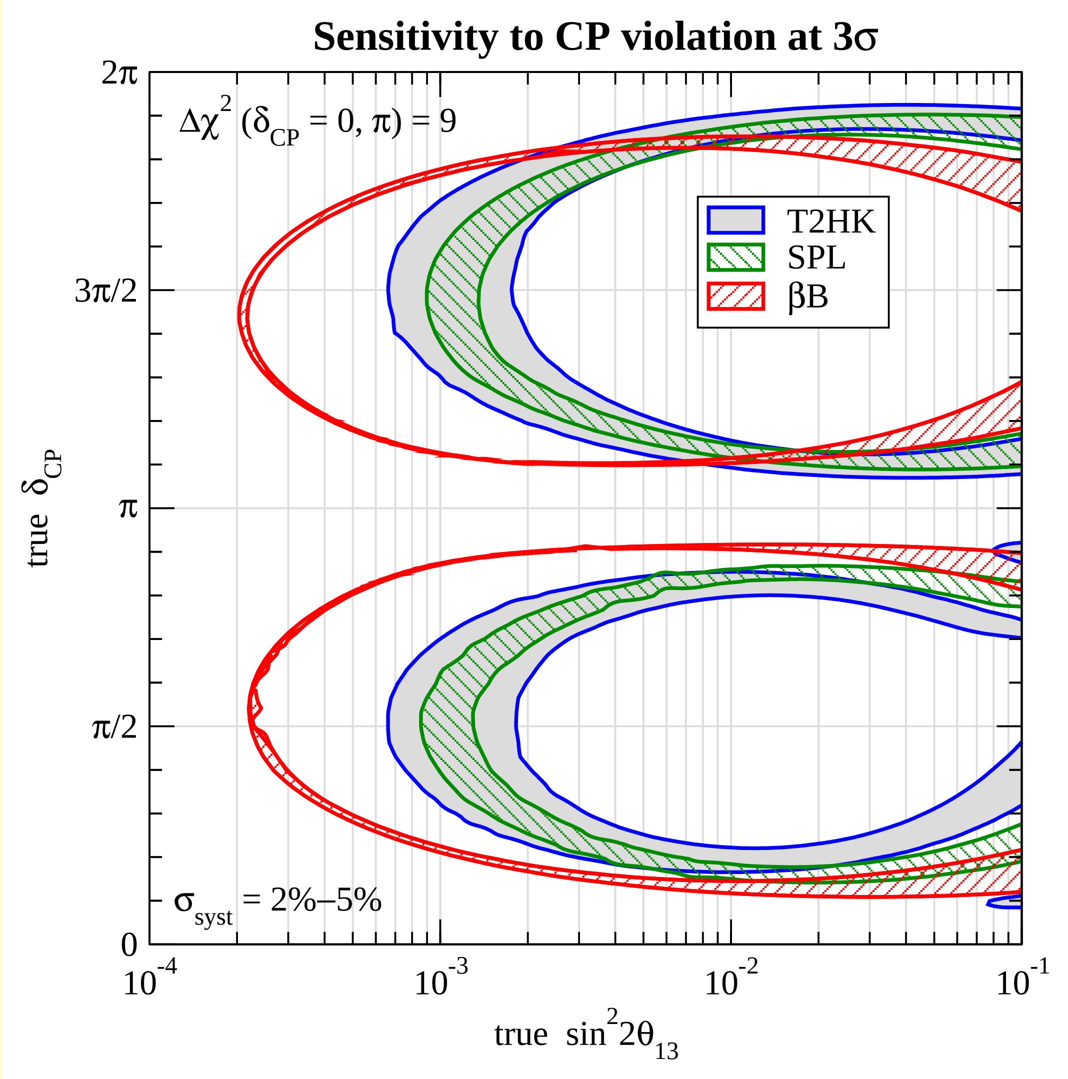
$$P_{\bar\nu_\mu\to\bar\nu_e} - P_{\nu_\mu\to\nu_e} =$$
$$2\sin 2\theta_{13}\ \hat\alpha\ \sin 2\theta_{23}\ \Delta\sin^2\Delta\sin\delta_{\rm CP}$$

with

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}\,, \quad \hat\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}\sin 2\theta_{12}$$

values of $\delta_{\rm CP} \neq 0, \pi$ introduce CP violation

Sensitivity to CP violation



Campagne, Maltoni, Mezzetto, Schwetz, hep-ph/0603172

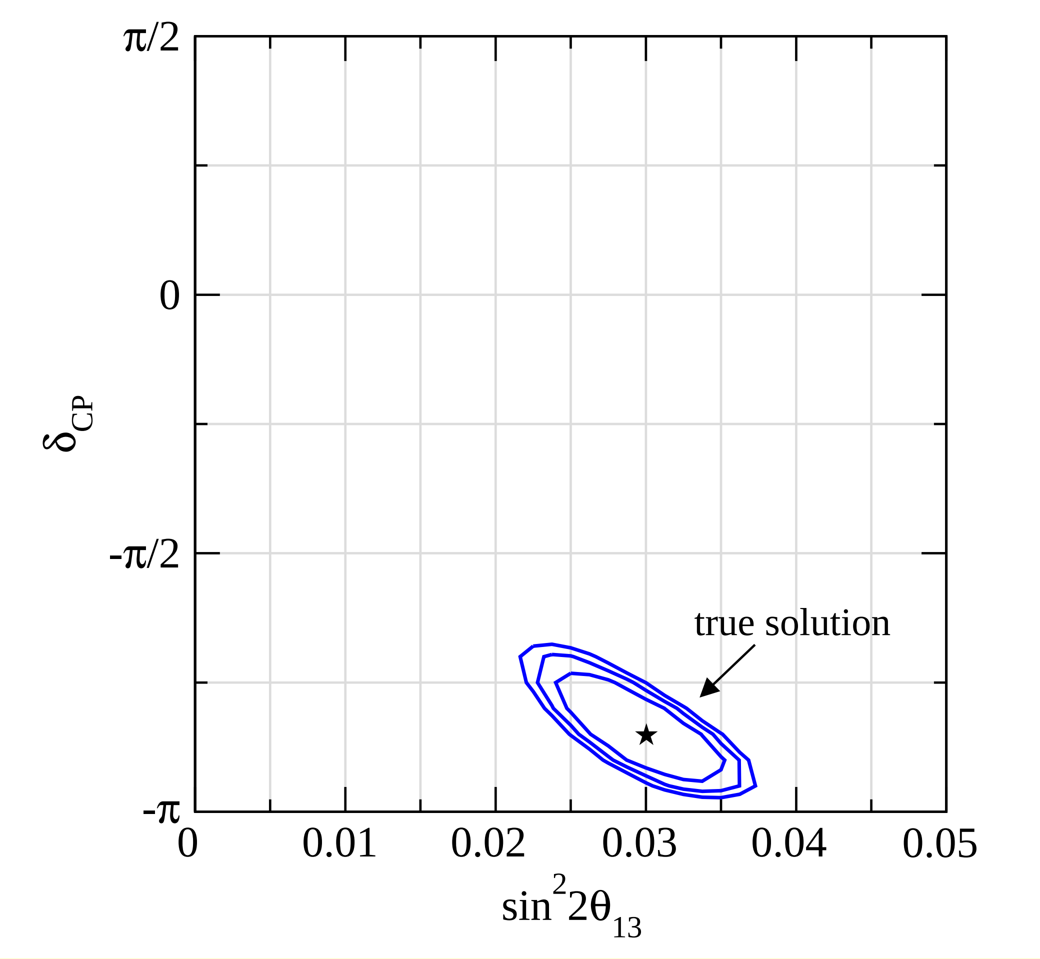
Determination of θ_{13}, $\delta_{\rm CP}$, sgn(Δm^2_{31})

or the problem of

Degeneracies

Illustration of degeneracies

Example: **T2HK** experiment



True values:

$\sin^2 2\theta_{13} = 0.03$

$\delta_{\rm CP} = -0.85\pi$

$\sin^2 \theta_{23} = 0.4$

$\Delta m^2_{31} = 2.2 \times 10^{-3}$eV^2

Illustration of degeneracies

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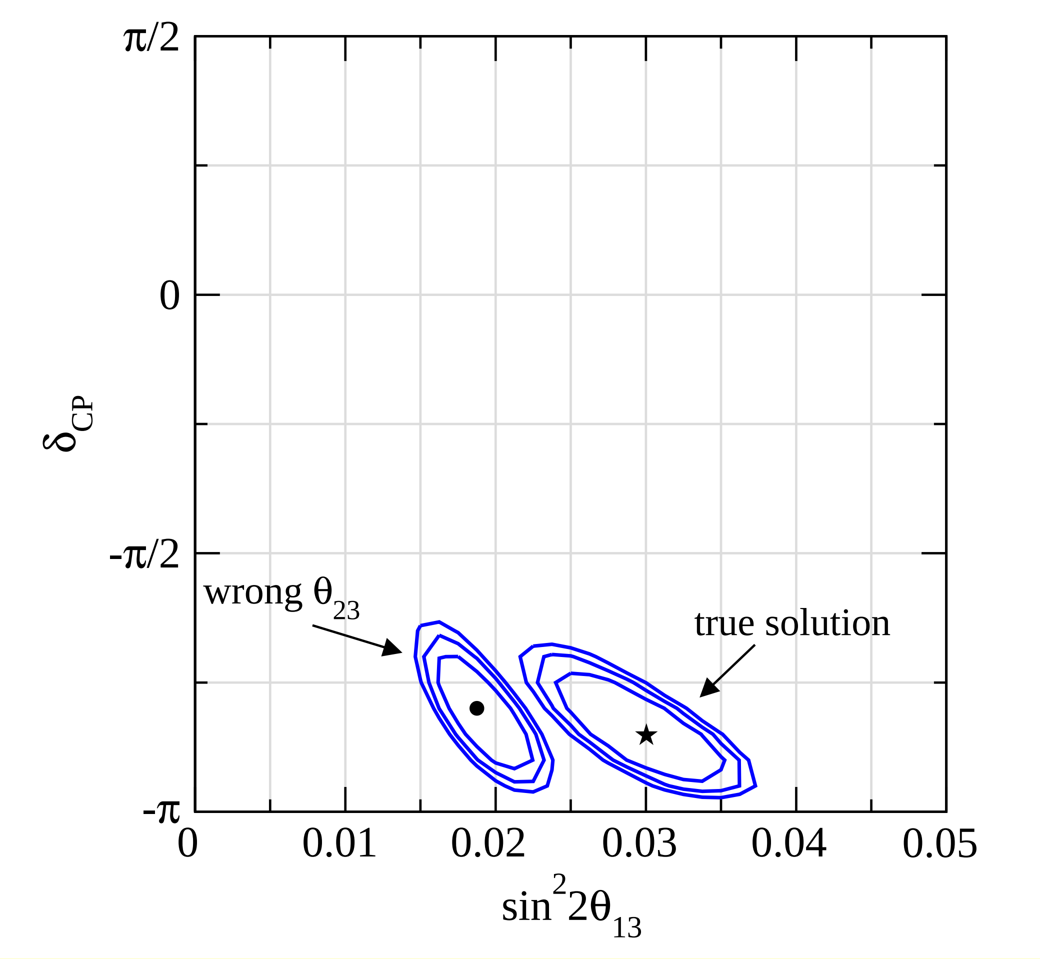

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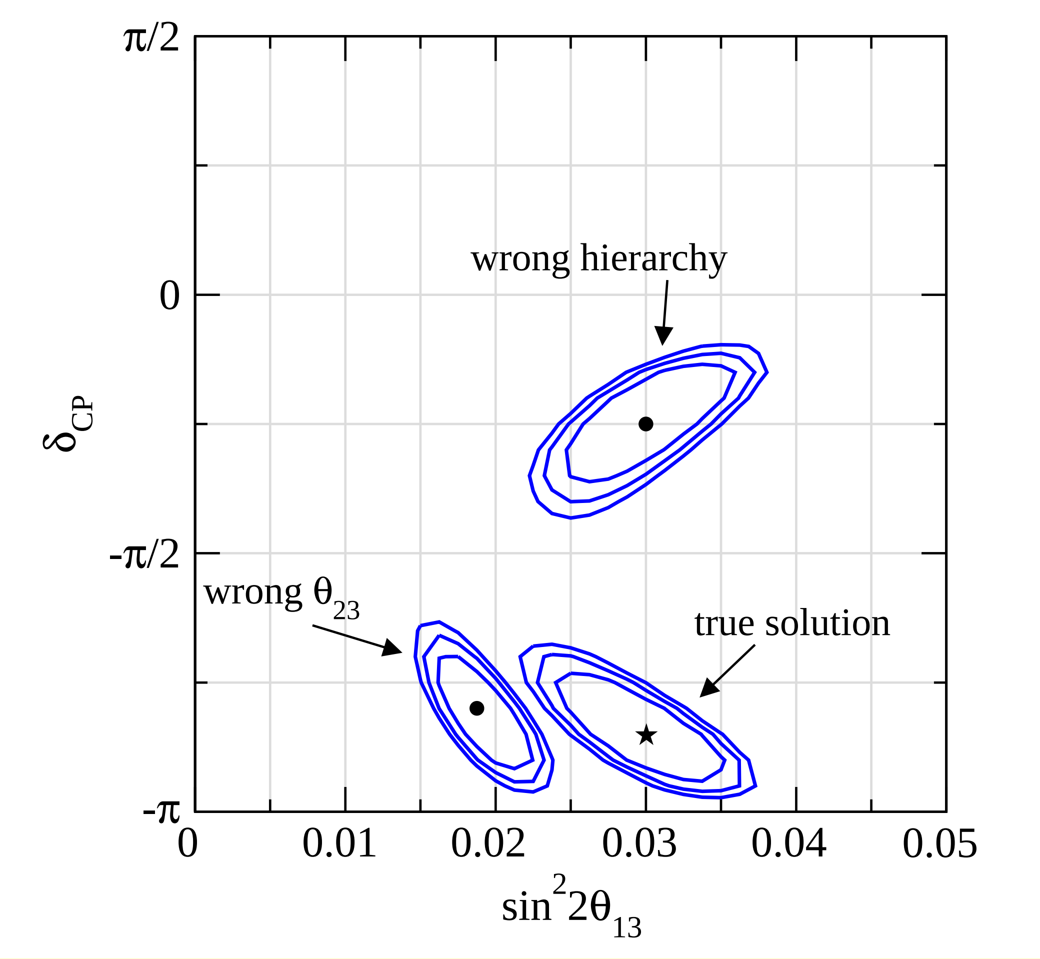

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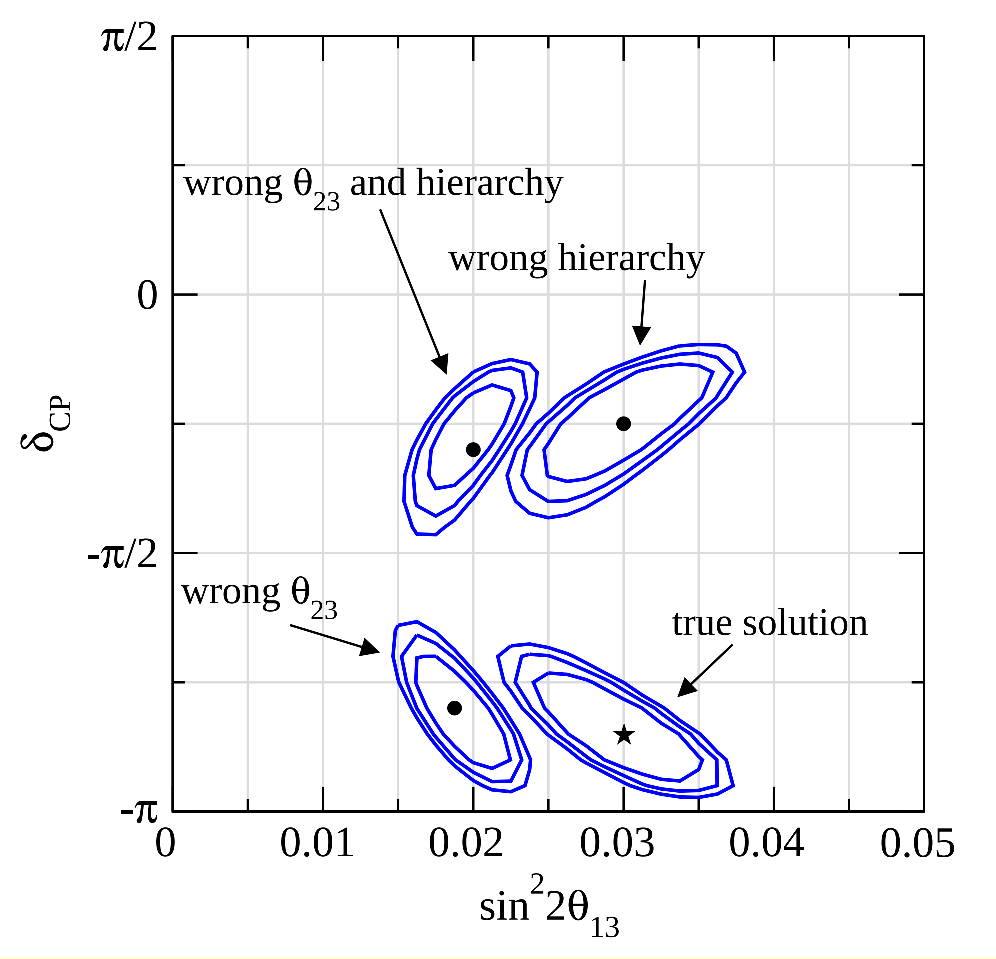

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The eight-fold degeneracy

- ambiguities in the determination of θ_{13} and $\delta_{\rm CP}$
- can involve an ambiguity between CP conserving and CP violating values of $\delta_{\rm CP}$
- the sign(Δm^2_{31}) is not determined (neutrino mass hierarchy)
- the octant of θ_{23} is not determined

Resolving the degeneracies

several possibilities to resolve the degeneracies are known:

- combining information from detectors at different baselines
- using additional oscillation chanels ($\nu_e \to \nu_\tau$)
- spectral information (wideband beam)
- adding information on θ_{13} from a reactor experiment
- adding information from (Mt scale) atmospheric neutrino experiments
- ...

Determination of the neutrino mass hierarchy

Matter effect and the mass hierarchy

the vacuum oscillation probability is invariant under

$$\Delta m^2_{31} \to -\Delta m^2_{31} \qquad \delta_{\rm CP} \to \pi - \delta_{\rm CP}$$

Matter effect and the mass hierarchy

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$$\Delta m^2_{31} \to -\Delta m^2_{31} \qquad \delta_{\rm CP} \to \pi - \delta_{\rm CP}$$

the key to resolve the hierarchy degeneracy is the matter effect

resonance condition for $\nu_\mu \to \nu_e$ oscillations:

$$A \equiv \pm \frac{2EV}{\Delta m^2_{31}} = \cos 2\theta_{13} \approx 1$$

can be fulfi lled for

neutrinos if $\Delta m^2_{31} > 0$ (normal hierarchy)

anti-neutrinos if $\Delta m^2_{31} < 0$ (inverted hierarchy)

Resolving the hierarchy degeneracy

need an experiment with "large" matter effect:

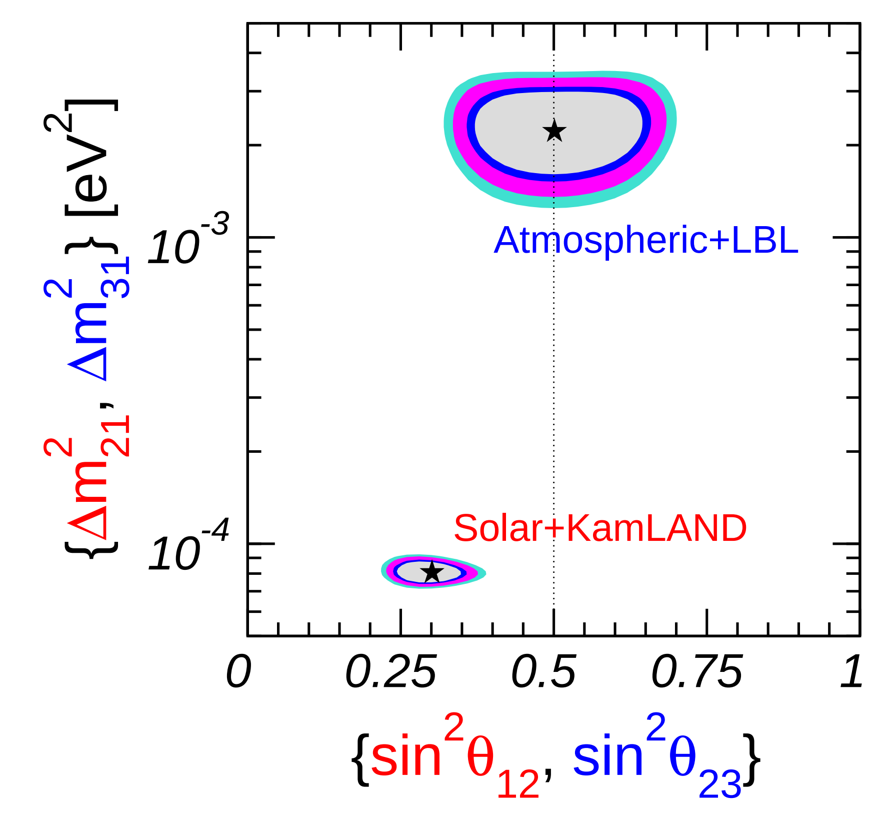
- baselines $\gtrsim 1000$ km
- energies $\gtrsim 10$ GeV (close to resonance energy)

and check whether the resonance is for neutrinos or anti-neutrinos

To conclude...

To conclude. . .

prestent status



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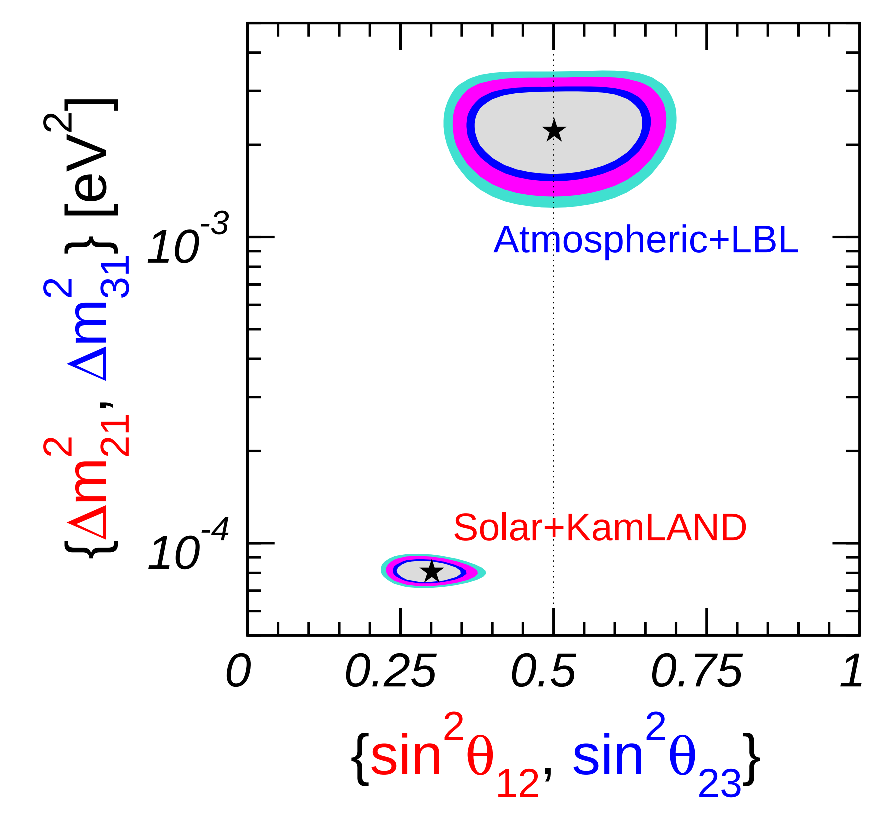
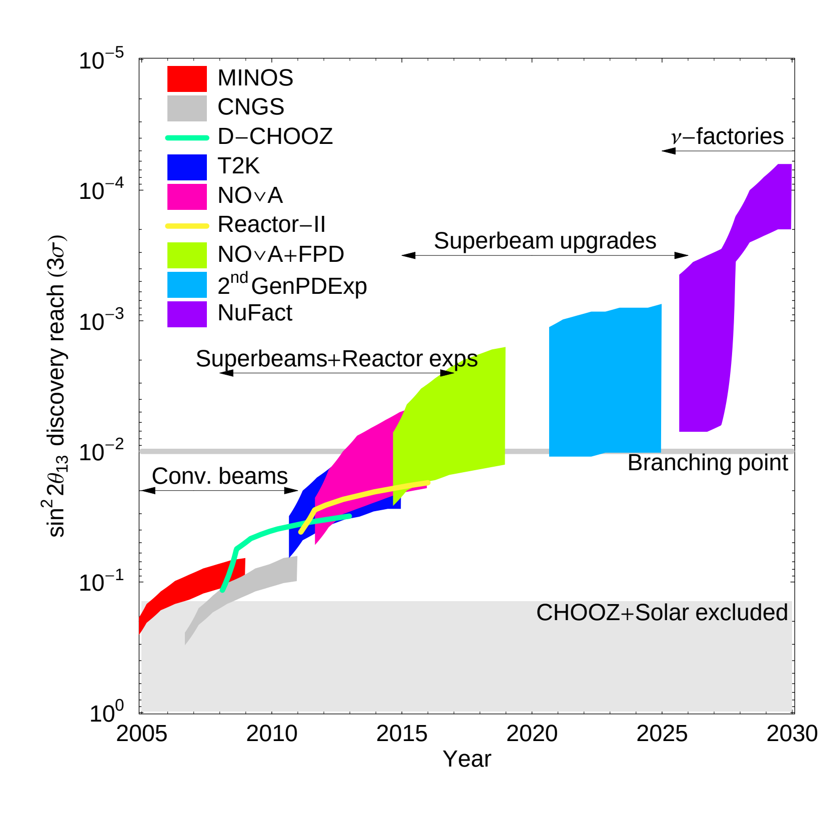
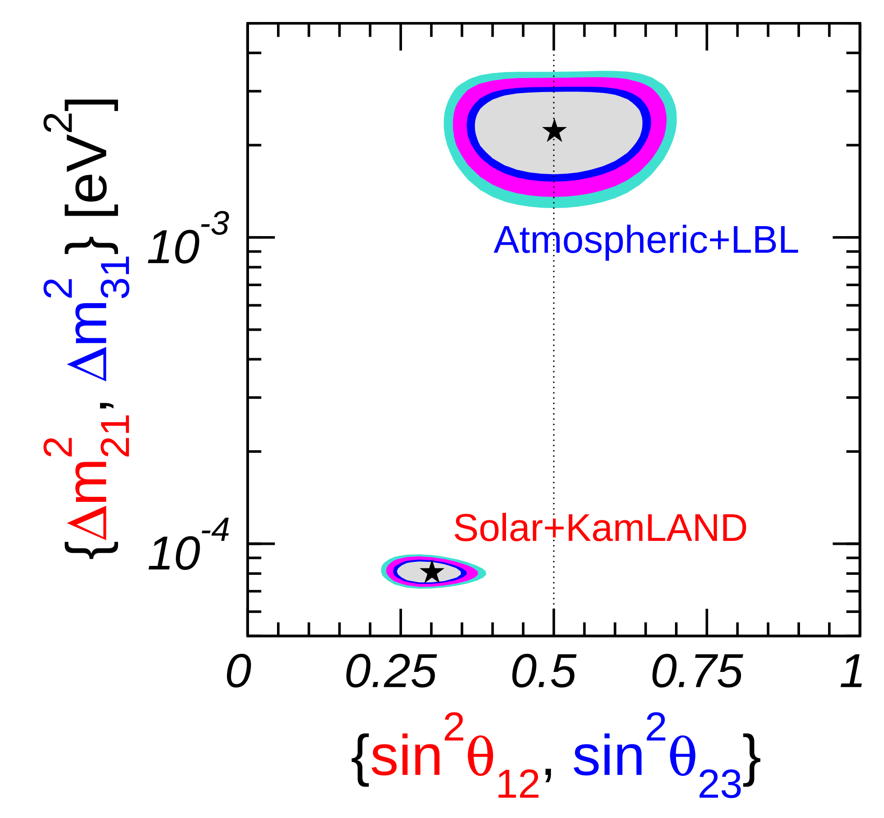


future

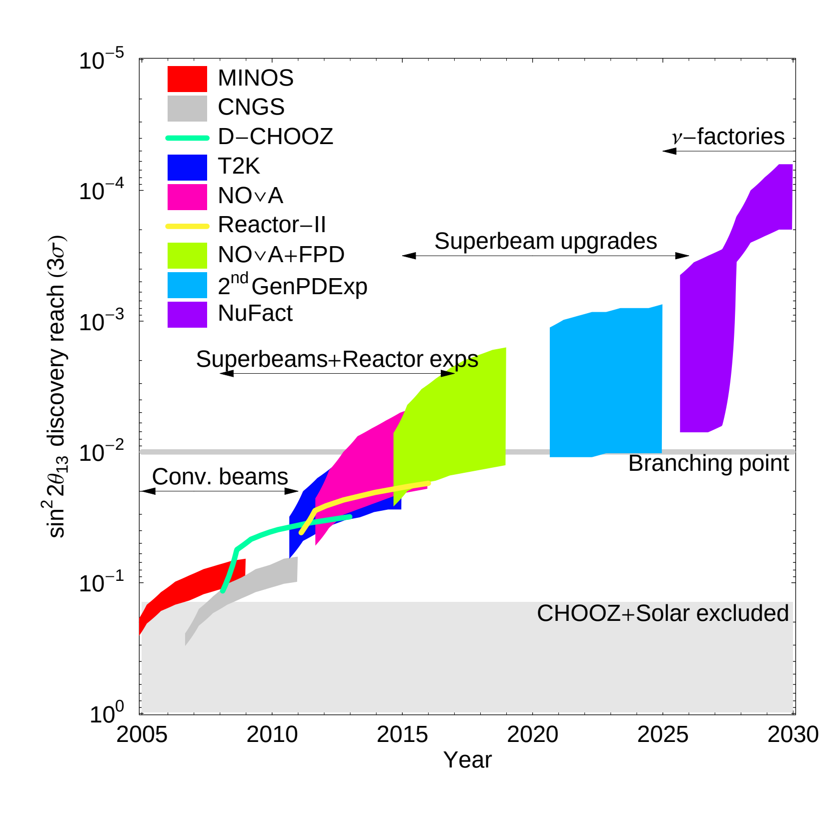


To conclude. . .

prestent status



future



Thanks for your attention!