The Race for θ_{13}: Reactors versus Superbeams

Patrick Huber

Technische Universität München,
Max-Planck-Institut für Physik

in collaboration with
M. Lindner, T. Schwetz and W. Winter

based on
hep-ph/0303232

Max-Planck-Institut
für Physik
(Werner-Heisenberg-Institut)

Hunting $\theta_{13} \neq 0$ with New Reactor Experiments

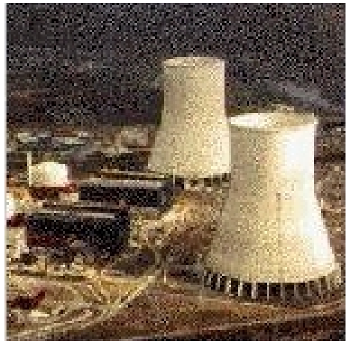
Many successful experiments

- Gösgen, G. Zacek *et al.*, Phys. Rev. **D34** (1986) 2621.
- Bugey, Y. Declais *et al.*, Nucl. Phys. **B434** (1995) 503.
- CHOOZ, M. Apollonio *et al.*, Phys. Lett. **B466** (1999) 415.
- Palo Verde, F. Boehm *et al.*, Phys. Rev. **D64** (2001) 112001.
- KamLAND, K. Eguchi *et al.*, Phys. Rev. Lett. **90** (2003) 021802.
- ...

Proposals for future reactor experiments

- V. Martemyanov, L. Mikaelyan, V. Sinev, V. Kopeikin, Y. Kozlov, hep-ex/0211070.
- H. Minakata, H. Sugiyama, O. Yasuda, K. Inoue, F. Suekane, hep-ph/0211111.
- M. Shaevitz, Talk at NOON 2003, Kanazawa, Japan.
- S. Schönert, T. Lasserre, L. Oberauer, Astropart. Phys. **18** (2003) 565, hep-ex/0203013.

The idea

 $\xrightarrow{\overline{\nu}_e}$ **near detector** (170m) $\xrightarrow{\overline{\nu}_e}$ **far detector** (1700m)

- detection of $\overline{\nu}_e$ by $\boxed{\overline{\nu}_e + p \rightarrow e^+ + n}$
- $E_\nu = E'_e + m_n - m_p$
- prompt energy: $E_{\text{prompt}} = E_{\text{kin}} + 2m_e$
- prompt positron energy and delayed γ from neutron capture
- **identical near and a far detectors $\Rightarrow$ look for distortions**
  - $\simeq$ eliminate reactor information / uncertainties (flux, spectrum)
  - eliminate x-section errors
  - relative precision is easier than absolute precision
- high event rates $\Rightarrow$ use rates and spectral information

The survival probability

– expand in small quantities

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

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

– atmospheric frequency is dominant

– most important:

- **No degeneracies!**
- **Practically no correlations!**
- **No matter effects!**

$\Rightarrow$ evaluate the potential on event rate basis...

The setup

- one reactor block (spread of individual reactors negligible)
- far detector at $1.7\,\mathrm{km}$, near detector at $\sim 170\,\mathrm{m}$
- identical near and far detectors ($\geq 10\times$ more events in the near than in the far detector)
- assume background free measurement Schönert, Lasserre, Oberauer, hep-ex/0203013.

- 62 bins in E_{prompt} from $1 - 7.2\,\mathrm{MeV}$, number of events in bin i:

$$N_i = \mathcal{N} \int dE_\nu\, \sigma(E_\nu)\varphi(E_\nu)\, P_{ee}(E_\nu) \int_i dE_e\, R(E_e, E_e')$$

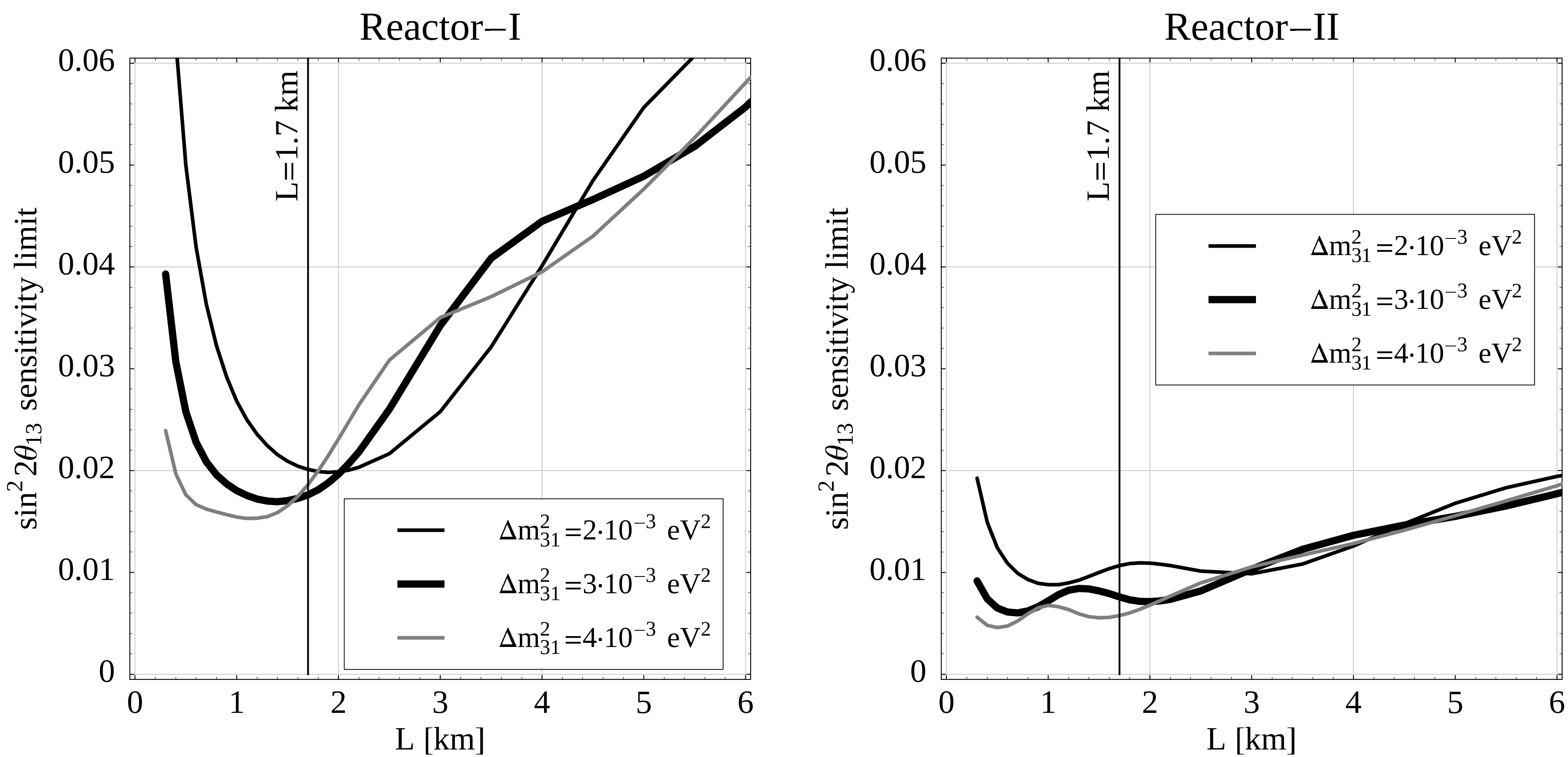
- R: energy resolution $5\%/\sqrt{E_e\,(\mathrm{MeV})}$
- $\mathcal{N} \propto$ integrated luminosity $\mathcal{L}$
- $\mathcal{L} \equiv$ detector mass $[\mathrm{t}] \times$ thermal reactor power $[\mathrm{GW}] \times$ running time $[\mathrm{y}]$

  $12\,\mathrm{t}$ detector, $7\,\mathrm{GW}$ thermal power, $5\,\mathrm{years}$ running time $\Rightarrow$ $400\,\mathrm{t\,GW\,y}$

  $250\,\mathrm{t}$ detector, $7\,\mathrm{GW}$ thermal power, $5\,\mathrm{years}$ running time $\Rightarrow$ $8000\,\mathrm{t\,GW\,y}$

Scenarios and optimal distance

setup	$\mathcal{L}$	# of events (no osc)	baseline
Reactor-I	400 t GW y	31 500	1.7 km
Reactor-II	8000 t GW y	630 000	1.7 km



Systematical errors

- absolute normalization error common to both detectors $\sigma_{\rm tot} \sim$ few %
  e.g., neutrino flux normalization, cross section uncertainty, ...
- relative normalization errors of the two detectors $\sigma_{\rm rel} \lesssim 1\%$
  e.g., error on the fiducial masses, ...

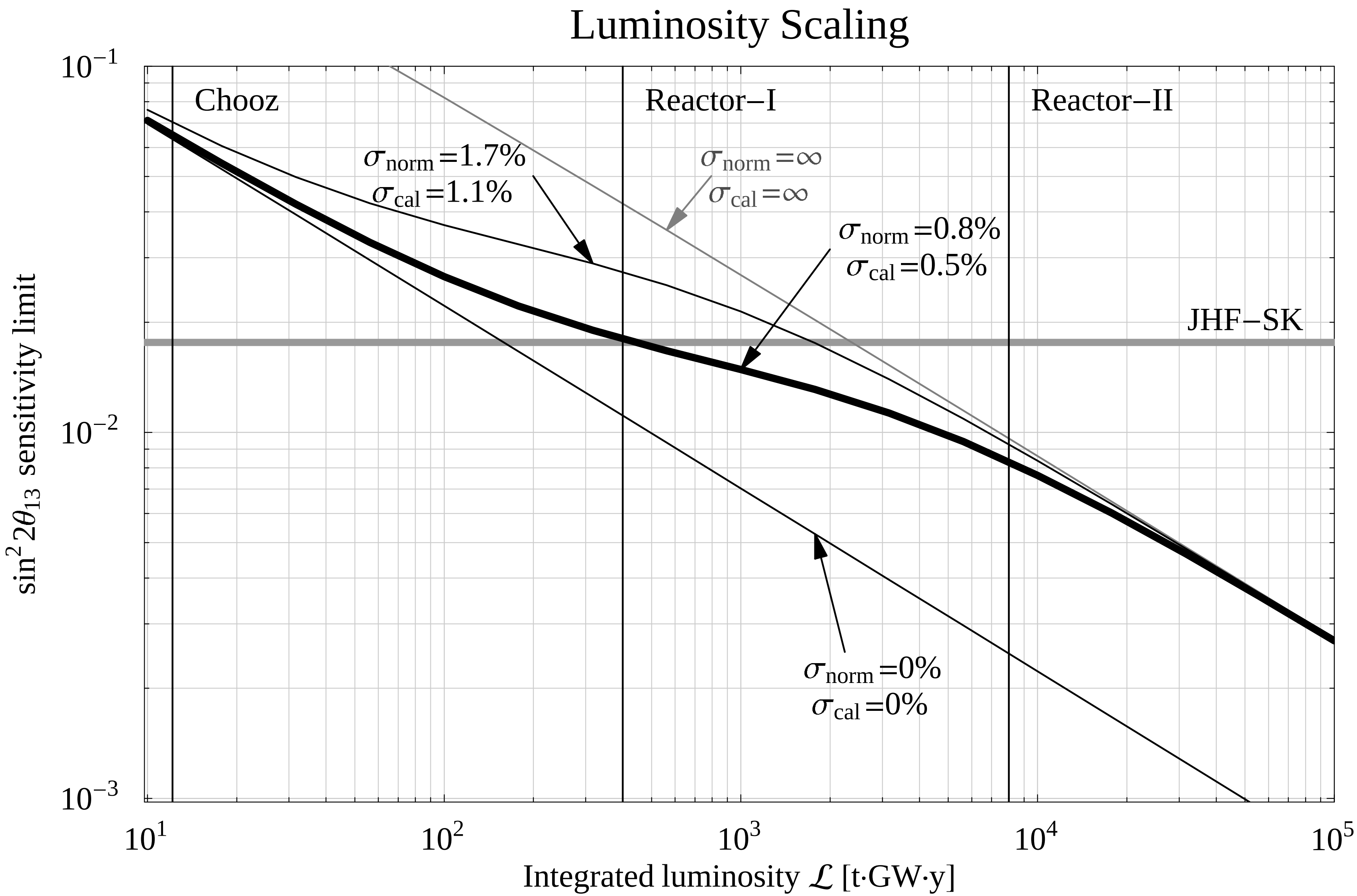
  $\Rightarrow$ effective normalization error for the far detector

$$\sigma^2_{\rm norm} \simeq \sigma^2_{\rm rel} + \left(\frac{1}{\sigma^2_{\rm tot}} + \frac{1}{\sigma^2_{\rm rel}} \right)^{-1}$$

  e.g.: $\sigma_{\rm tot} = 2\%$ and $\sigma_{\rm rel} = 0.6\%$ $\rightarrow$ $\sigma_{\rm norm} \simeq 0.8\%$

- energy calibration uncertainty $\sigma_{\rm cal} \sim 0.5\%$
- shape uncertainty of the expected energy spectrum $\sigma_{\rm shape} \sim {\rm few}\%$
  uncorrelated between energy bins, but correlated between detectors
- completely uncorrelated experimental bin-to-bin error $\sigma_{\rm exp} \lesssim 0.5\%$
  e.g., background uncertainty

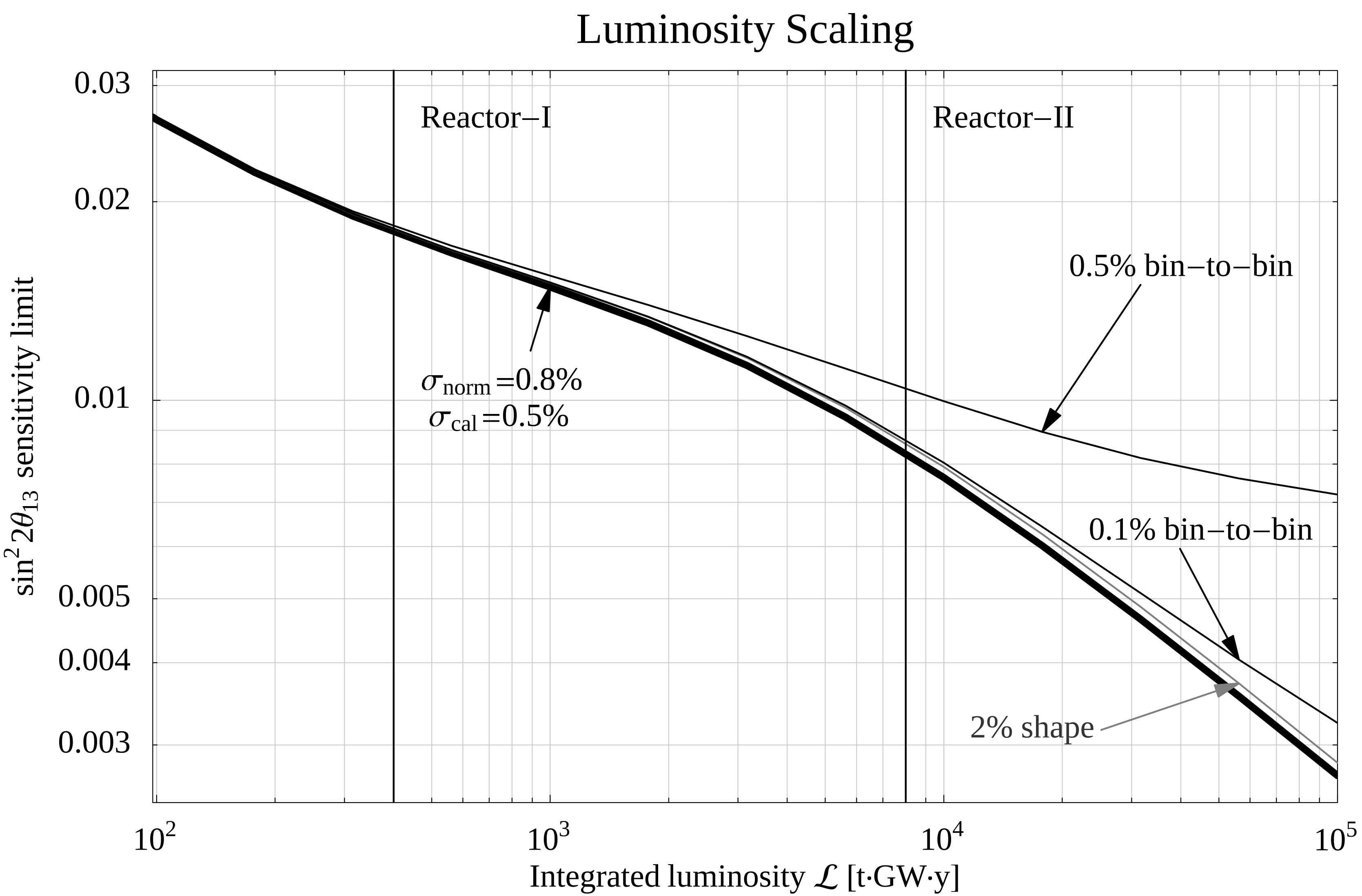
Sensitivity to $\sin^2 2\theta_{13}$ at 90% CL



Reactor-I: Limit depends crucially on σ_{norm}

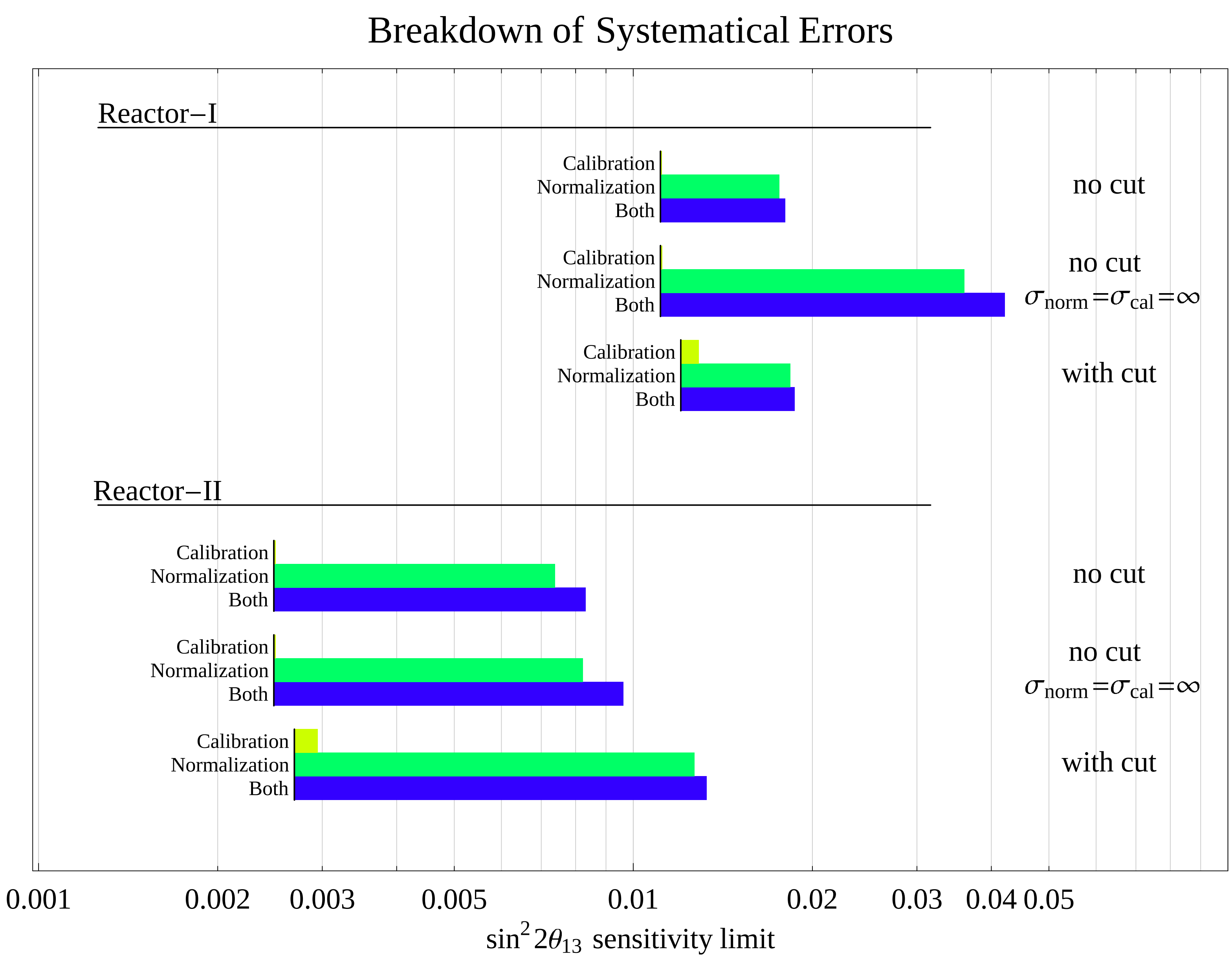
Reactor-II: essentially independent of σ_{norm}

Theoretical shape and experimental bin-to-bin errors



experimental bin-to-bin error: e.g. back ground uncertainty

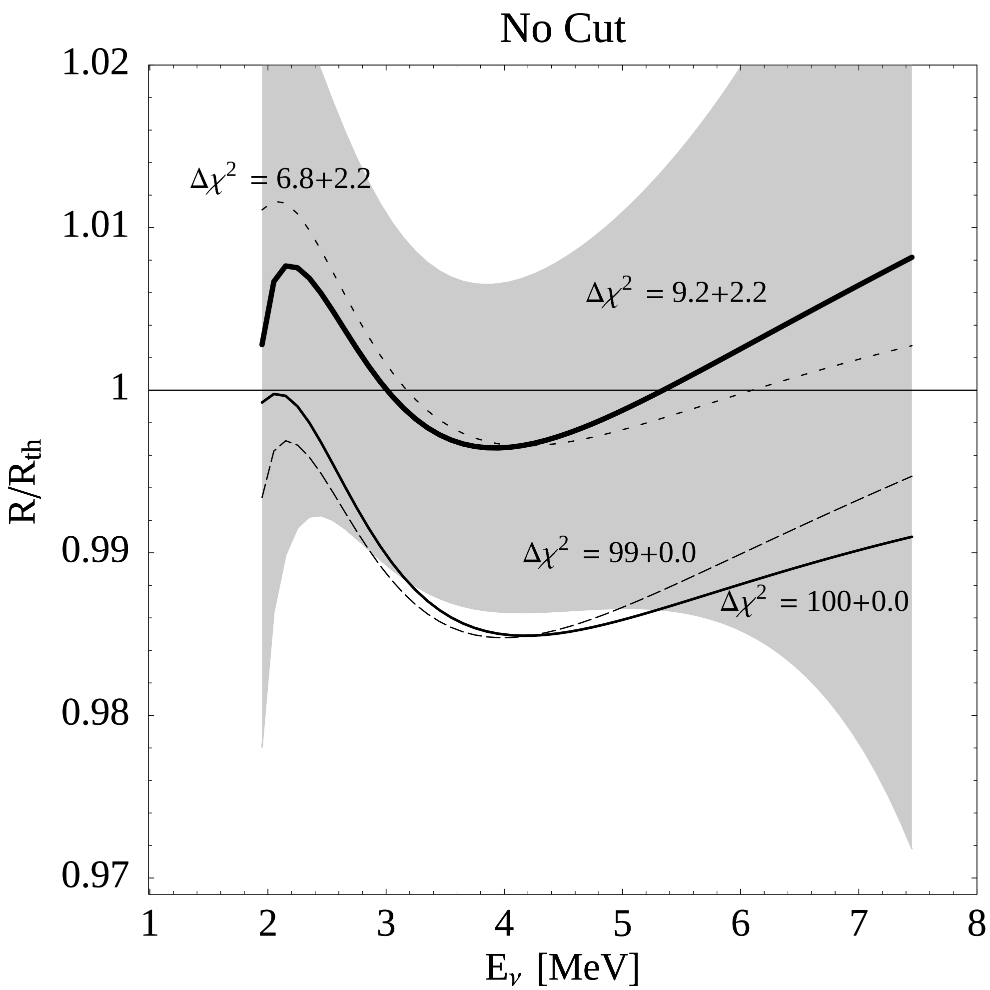
a BG of 1% of the signal, known within 10% $\rightarrow$ 0.1% exp. error

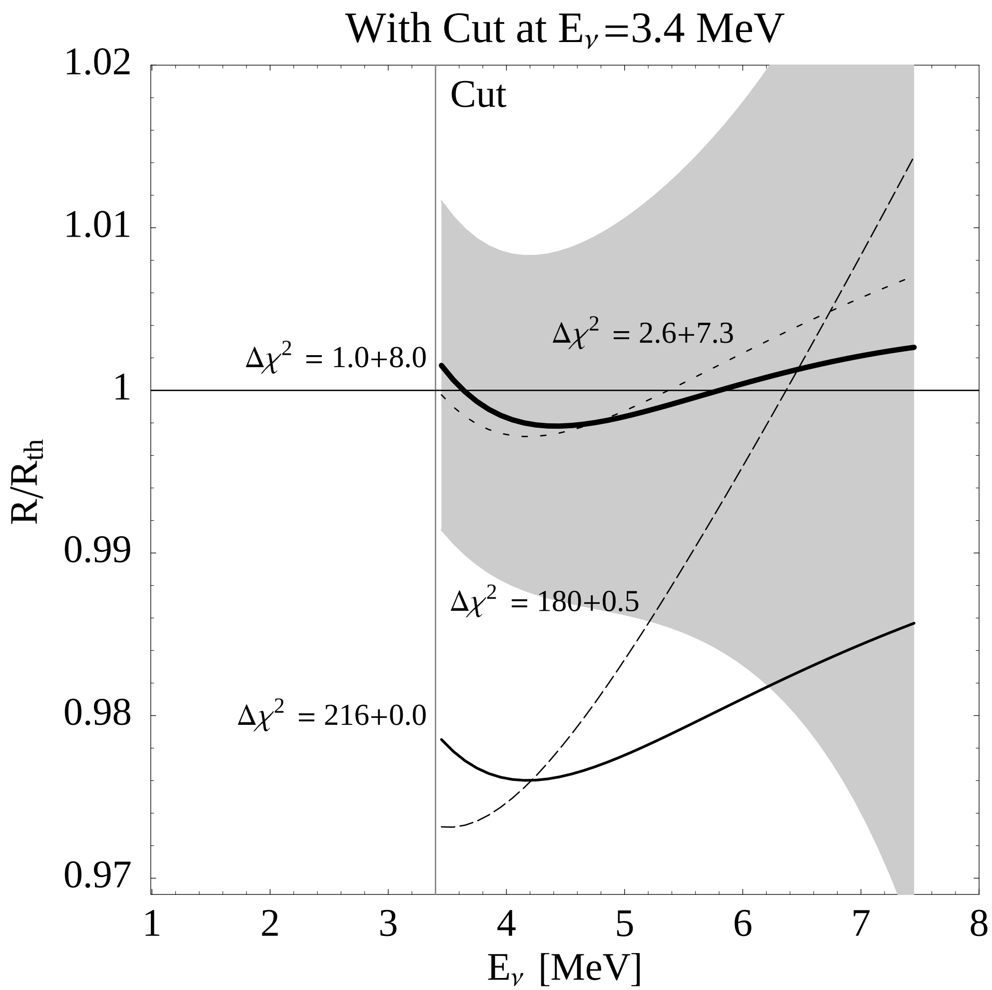


Reactor-I:
σ_{cal} and cut
not important
σ_{norm} important

Reactor-II:
σ_{cal} and σ_{norm}
not important
energy cut
some impact

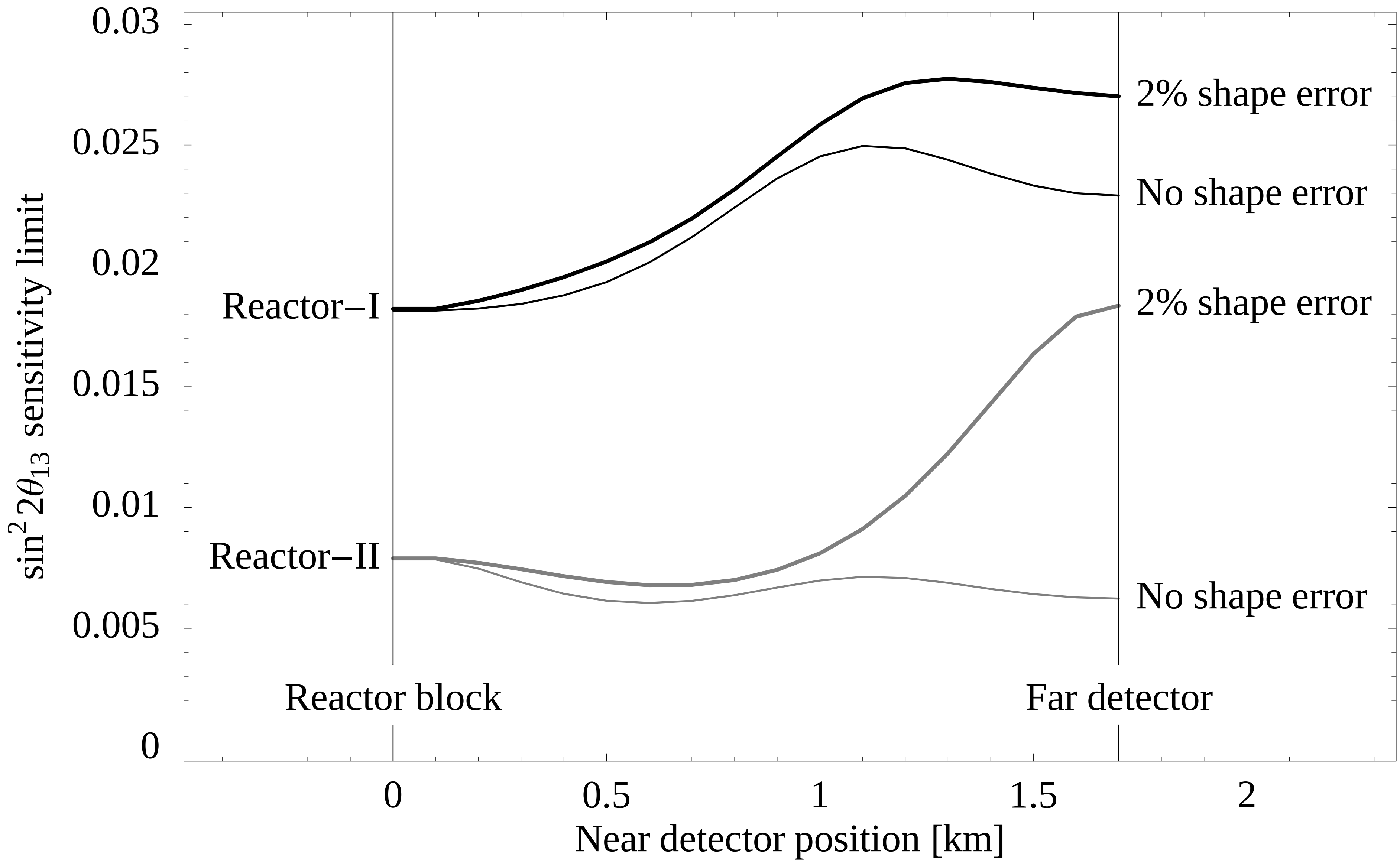
Effect of an energy cut





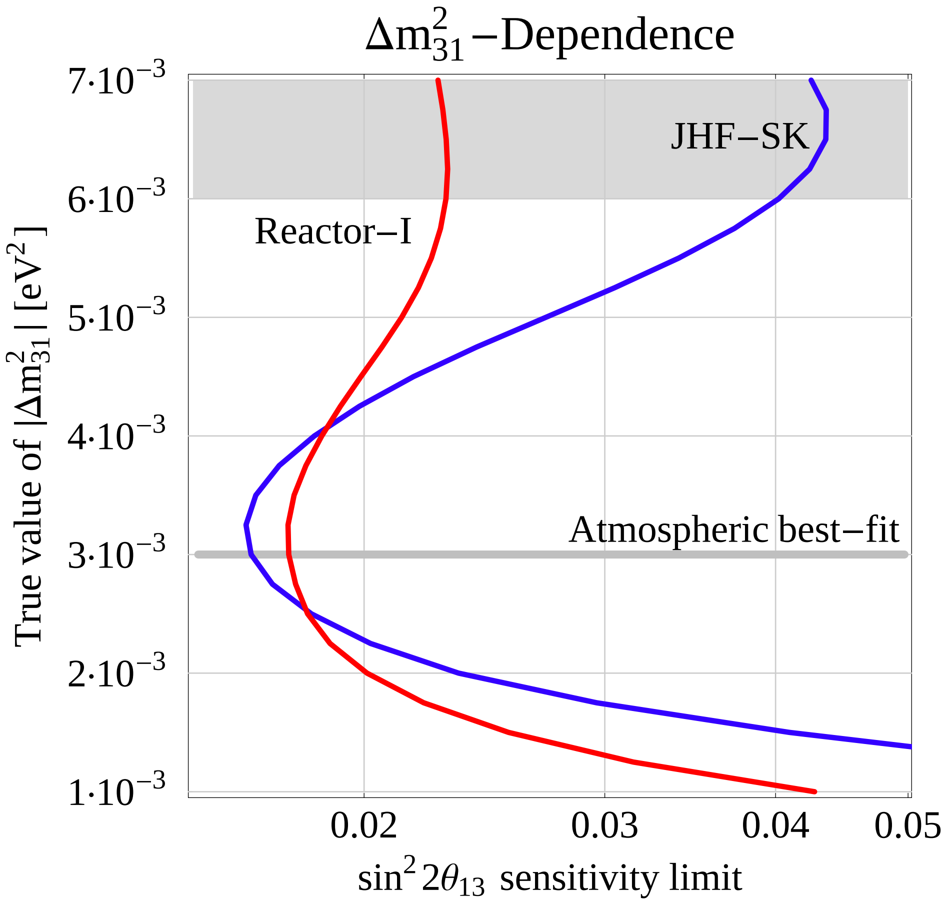
The position of the near detector

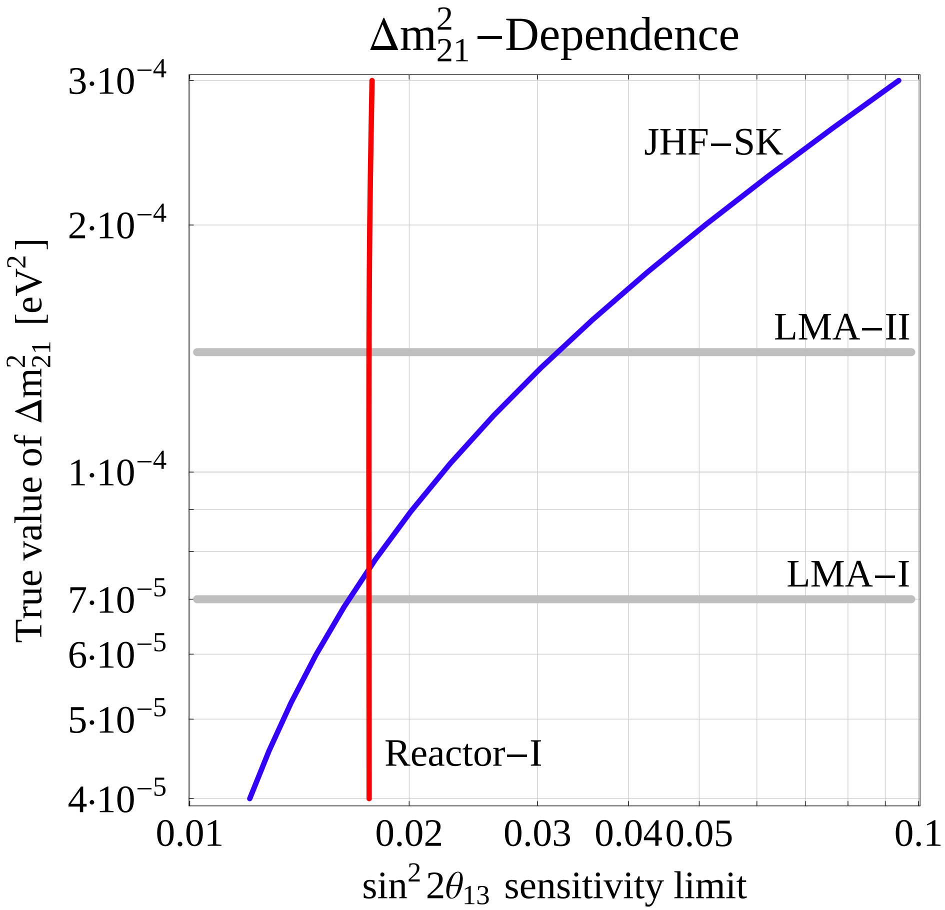
Real sites may not allow a near detector at $170\,\mathrm{m}$ (no-oscillation)$\Rightarrow$

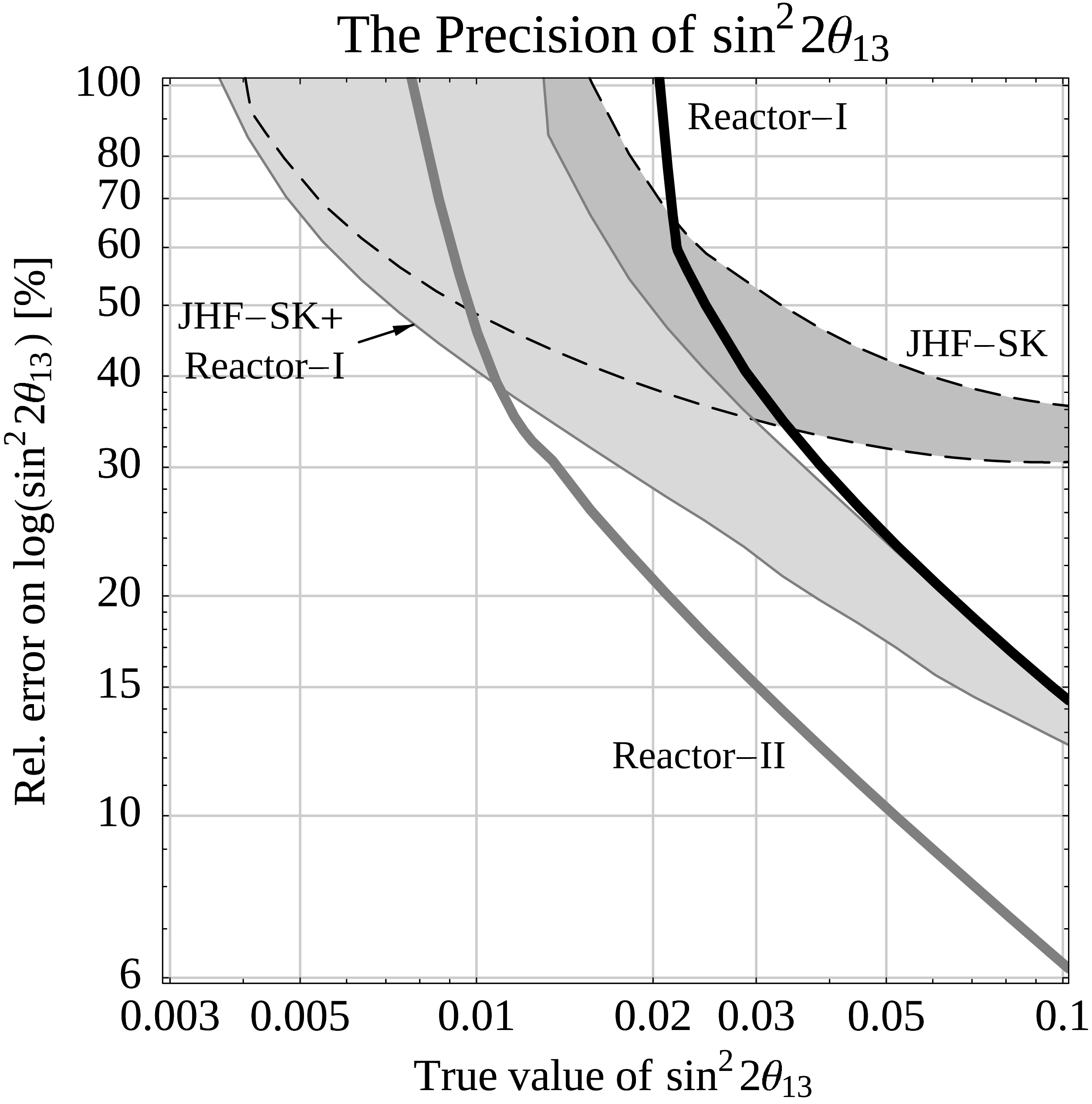


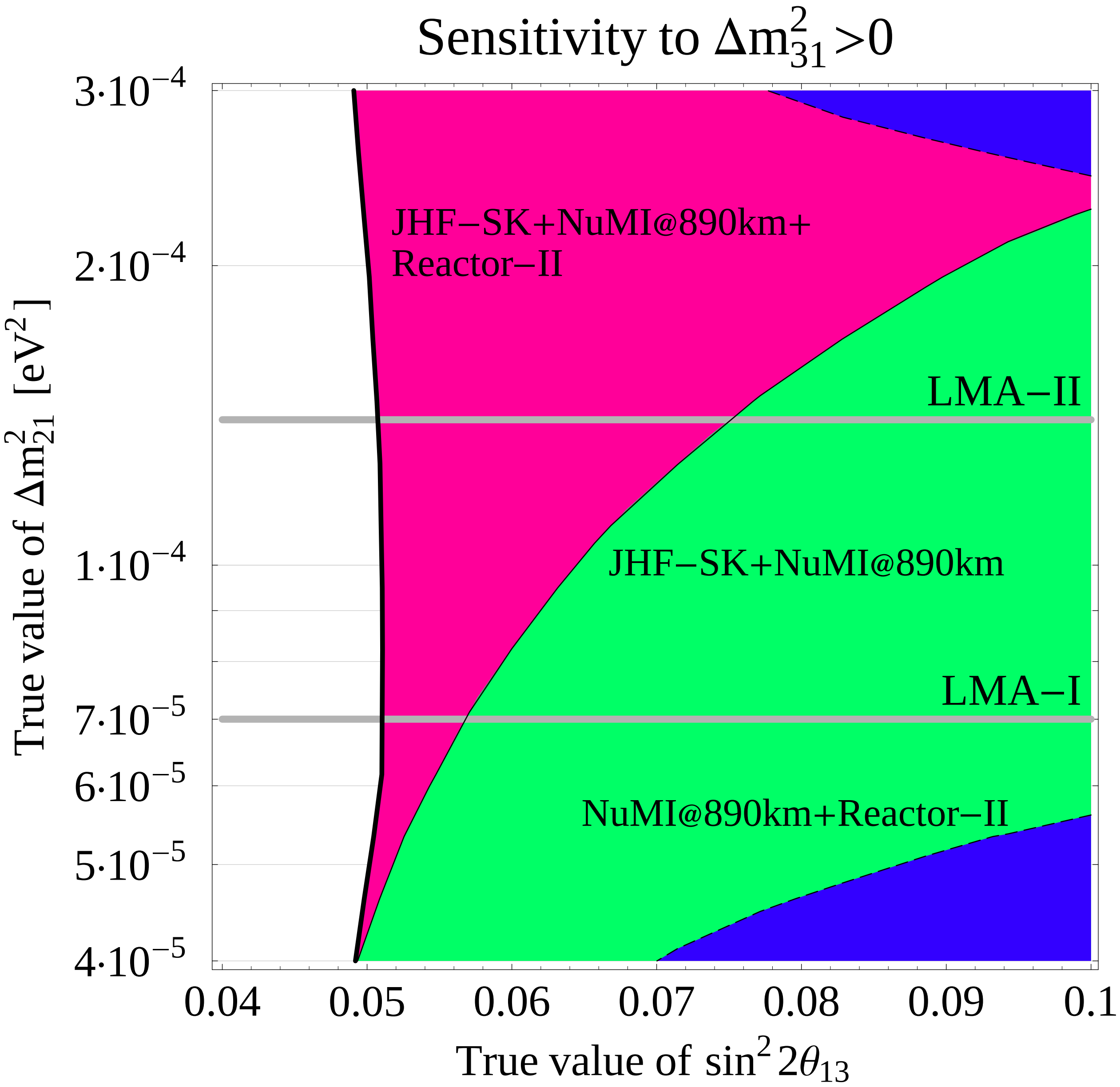
Comparison of Reactor and Superbeam experiments

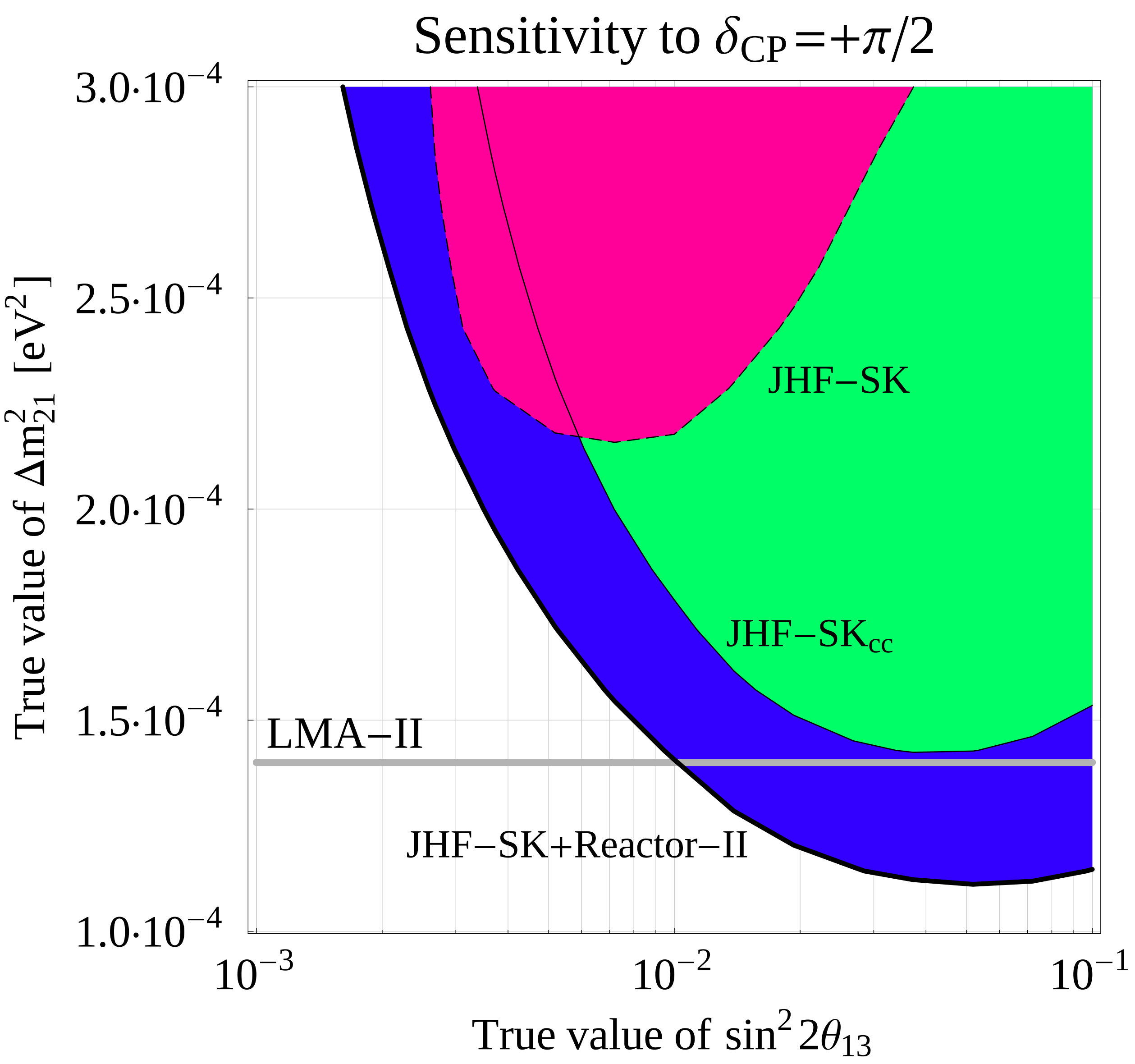
The sensitivity to $\sin^2 2\theta_{13}$ at 90% CL






The Precision of $\sin^2 2\theta_{13}$
Rel. error on $\log(\sin^2 2\theta_{13})$ [%]
100
80
70
60
50
40
30
20
15
10
6
0.003
0.005
0.01
0.02
0.03
0.05
0.1
True value of $\sin^2 2\theta_{13}$
Reactor−I
JHF−SK+
Reactor−I
JHF−SK
Reactor−II


Sensitivity to $\Delta m^2_{31}>0$
True value of Δm^2_{21} [eV^2]
$3\cdot10^{-4}$
$2\cdot10^{-4}$
$1\cdot10^{-4}$
$7\cdot10^{-5}$
$6\cdot10^{-5}$
$5\cdot10^{-5}$
$4\cdot10^{-5}$
0.04
0.05
0.06
0.07
0.08
0.09
0.1
True value of $\sin^2 2\theta_{13}$
JHF−SK+NuMI@890km+
Reactor−II
JHF−SK+NuMI@890km
NuMI@890km+Reactor−II
LMA−II
LMA−I


Sensitivity to $\delta_{CP}=+\pi/2$
True value of Δm^2_{21} [eV^2]
$3.0\cdot10^{-4}$
$2.5\cdot10^{-4}$
$2.0\cdot10^{-4}$
$1.5\cdot10^{-4}$
$1.0\cdot10^{-4}$
10^{-3}
10^{-2}
10^{-1}
True value of $\sin^2 2\theta_{13}$
JHF−SK
JHF−SK$_{cc}$
LMA−II
JHF−SK+Reactor−II

Summary – experiment

- a sensitivity of $\sin^2 2\theta_{13} \lesssim 10^{-2}$ seems reachable by reactor neutrino experiments
- near-far detector setup allows the efficient reduction of systematical effects (over-all normalization, shape uncertainty)
- Reactor-I ($\mathcal{L} \sim 400\,\mathrm{t\,GW\,y}$)
  limit depends sensible on a relative normalization error

  Reactor-II ($\mathcal{L} \sim 8000\,\mathrm{t\,GW\,y}$)
  limit is rather independent of the relative normalization error
- energy calibration error has no big effect
- experimental bin-to-bin uncorrelated systematical error
  should be $\lesssim 0.1\%$ for very large experiments ($\mathcal{L} \sim 10^4\,\mathrm{t\,GW\,y}$)

Summary – $\sin^2 2\theta_{13}$-limit

Reactors are highly competitive to first generation superbeams

statistical errors

$\Downarrow$

systematics

$\Downarrow$

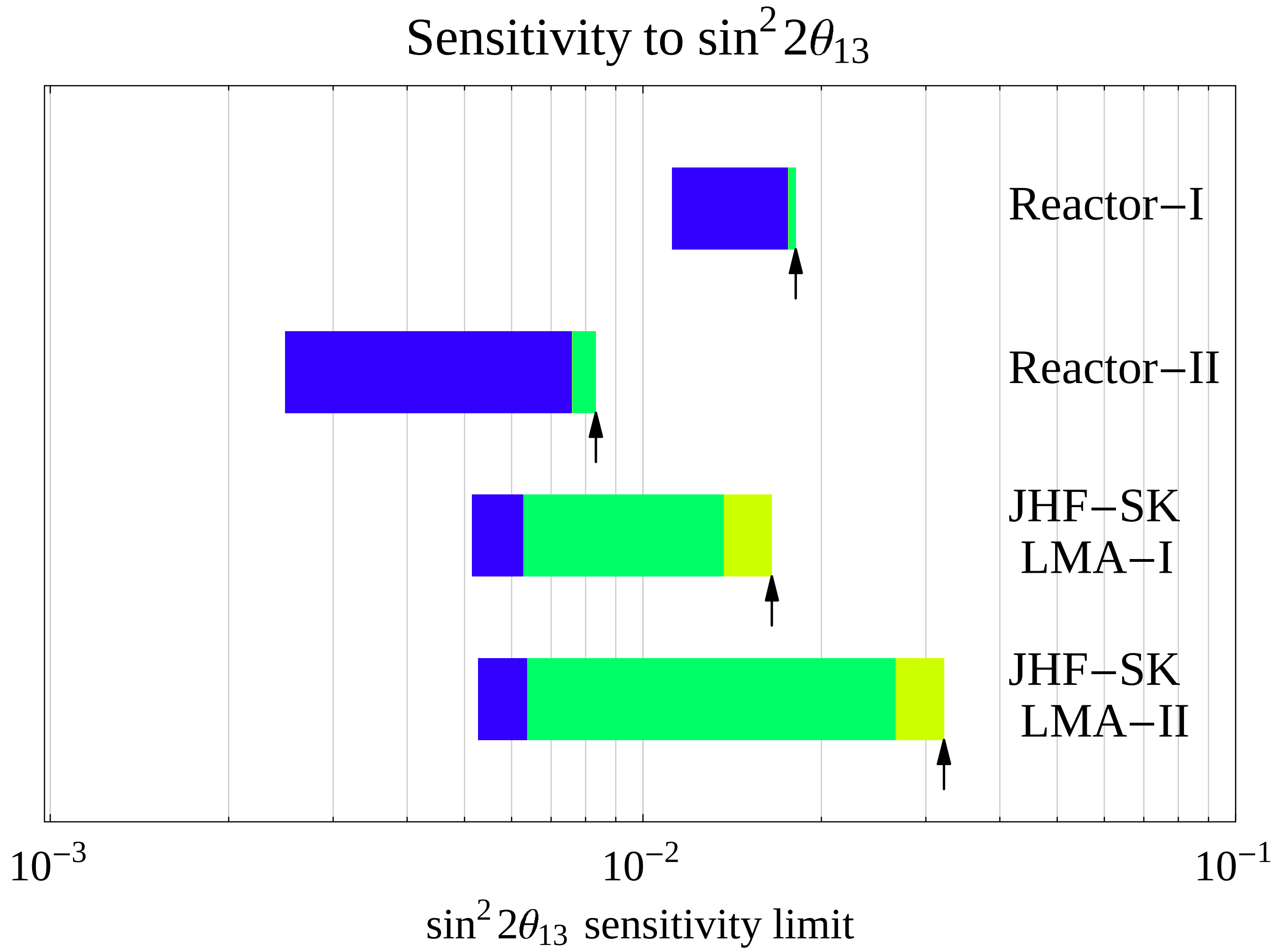
correlations

$\Downarrow$

degeneracies

$\Downarrow$

final result



– superbeam experiments suffer from correlations and degeneracies

.... especially for large Δm^2_{21}

Summary – Combination of reactor and superbeam

clean θ_{13} measurement of the reactor resolves degeneracies

- JHF-SK + NuMI@890km + Reactor-II:
  significantly improved sensitivity to the neutrino mass hierarchy
- JHF-SK + Reactor-II:
  better sensitivity for leptonic CP violation

Reactor neutrino experiments

- **are a very promising option to measure θ_{13}**
- **are complementary to the long-baseline program**

Degeneracies in $\nu_\mu \to \nu_e$

measurement of $\sin^2 2\theta_{13}$ in the $\nu_\mu \to \nu_e$ 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; Phys. Rev. **D66** (2002) 053007; P. Huber, M. Lindner, W. Winter, Nucl. Phys. **B645** (2002) 3; Nucl. Phys. **B654** (2003) 3.

oscillation probability in vacuum:

$$\begin{aligned} P_{\mu e} &\simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta_{31} \\ &\mp \alpha \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3\Delta_{31} \\ &- \alpha \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta_{31} \sin^2\Delta_{31} \\ &+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2\Delta_{31}, \end{aligned}$$

with

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

Analysis method

- we consider a general three flavour scenario
- parameters: $\Delta m^2_{21},\ \theta_{12},\ |\Delta m^2_{31}|,\ \theta_{23}, \theta_{13}, \delta\ , \mathrm{sgn}[\Delta m^2_{31}]$
- simulate “data” for fixed “true values” of oscillation parameters
- perform a 6-parameter fit, taking into account correlations and degenerate solutions
- external information:
  assume that $\Delta m^2_{21},\ \theta_{12},\ |\Delta m^2_{31}|$ are known within 10% at 1σ
  (KamLAND, K2K, MINOS, CNGS)

χ^2-analysis of reactor experiments with a near and far detector

systematical errors

- normalization error common to both detectors $\sigma_{\mathrm{tot}} \sim$ few %
  e.g., neutrino flux normalization, cross section uncertainty
- uncorrelated normalization errors of the detectors $\sigma_{\mathrm{rel}} \lesssim 1\%$
  e.g., error on the fiducial masses
- energy calibration uncertainty $\sigma_{\mathrm{cal}} \sim 0.5\%$
- shape uncertainty of the expected energy spectrum $\sigma_{\mathrm{shape}} \sim \mathrm{few}\%$
  uncorrelated between energy bins, but correlated between detectors
- completely uncorrelated experimental bin-to-bin error $\sigma_{\mathrm{exp}} \lesssim 0.5\%$
  e.g., background uncertainty

χ^2-function

$$\chi^2 = \sum_{A=N,F} \left\{ \sum_i \left[\frac{(T_i^A - O_i^A)^2}{O_i^A + \sigma_{\rm exp}^2 (O_i^A)^2} + \left(\frac{c_i}{\sigma_{\rm shape}} \right)^2 \right] + \left(\frac{b^A}{\sigma_{\rm rel}} \right)^2 + \left(\frac{g^A}{\sigma_{\rm cal}} \right)^2 \right\} + \left(\frac{a}{\sigma_{\rm tot}} \right)^2$$

$$\begin{aligned} T_i^F(\theta_{13}) &= (1 + a + b^F + c_i)\, N_i^F(\theta_{13}) + g^F M_i^F(\theta_{13}) \\ T_i^N &= (1 + a + b^N + c_i)\, N_i^N + g^N M_i^N \end{aligned}$$

$N_i^F(\theta_{13})$, N_i^N : predicted # of events in bin i of far and near detector

energy calibration: $E_{\rm obs} \to (1 + g^A) E_{\rm obs}$ and $M_i^A = \frac{\partial N_i^A}{\partial g^A}$

our “data”: $O_i^F = N_i^F(\theta_{13}^{\rm true})$ and $O_i^N = N_i^N$

χ^2-function

for $\sigma_{\mathrm{shape}} \lesssim 2\%$ and $\sigma_{\mathrm{exp}} \lesssim 0.1\%$ we can set $c_i = \sigma_{\mathrm{exp}} = 0$

$$\begin{aligned}\chi^2 &= \sum_i \frac{\left[T_i^F(\theta_{13},a,b^F,g^F)-O_i^F\right]^2}{O_i^F} + \left(\frac{b^F}{\sigma_{\mathrm{rel}}}\right)^2 + \left(\frac{g^F}{\sigma_{\mathrm{cal}}}\right)^2 \\ &+ \sum_i \frac{\left[(a+b^N)\,N_i^N+g^N M_i^N\right]^2}{N_i^N} + \left(\frac{b^N}{\sigma_{\mathrm{rel}}}\right)^2 + \left(\frac{g^N}{\sigma_{\mathrm{cal}}}\right)^2 + \left(\frac{a}{\sigma_{\mathrm{tot}}}\right)^2\end{aligned}$$

effective χ^2 for the far detector:

$$\chi^2_{\mathrm{eff}} = \sum_i \frac{(T_i^F - O_i^F)^2}{O_i^F} + \left(\frac{g^F}{\sigma_{\mathrm{cal}}}\right)^2 + \left(\frac{\alpha}{\sigma_{\mathrm{norm}}}\right)^2$$

$$T_i^F = (1+\alpha)\,N_i^F(\theta_{13}) + g^F M_i^F(\theta_{13})$$

for large # of events in the near detector $\sigma_{\mathrm{rel}} \gg 1/\sqrt{N_i^N}$:

$$\sigma^2_{\mathrm{norm}} \simeq \sigma^2_{\mathrm{rel}} + \left(\frac{1}{\sigma^2_{\mathrm{tot}}} + \frac{1}{\sigma^2_{\mathrm{rel}}}\right)^{-1}$$

Superbeam experiments

$\nu_\mu \to \nu_e$ appearance using an up-graded conventional ν_μ-beam

	JHF-SK Y. Itow *et al.*, hep-ex/0106019.	NuMI D. Ayres *et al.*, hep-ex/0210005.
beam		
baseline	$295\,\mathrm{km}$	$712\,\mathrm{km}$
target power	$0.77\,\mathrm{MW}$	$0.4\,\mathrm{MW}$
off-axis angle	2°	0.72°
mean energy	$0.76\,\mathrm{GeV}$	$2.22\,\mathrm{GeV}$
mean L/E	$385\,\mathrm{km\,GeV}^{-1}$	$320\,\mathrm{km\,GeV}^{-1}$
detector		
technology	water Cherenkov	low-Z calorimeter
fiducial mass	$22.5\,\mathrm{kt}$	$17\,\mathrm{kt}$
running period	5 years	5 years
events[1]		
signal	138	132
background	23	19

[1] at $\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{12} = 0.8$, $\Delta m^2_{31} = 3 \cdot 10^{-3}\,\mathrm{eV}^2$, $\Delta m^2_{21} = 5 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\delta_{CP} = 0$