The Race for θ_{13}: Reactors versus Superbeams

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Introduction

– mass parameters: $m_1,\ m_2,\ m_3$ **or** $m_1,\ \Delta m^2_{21},\ |\Delta m^2_{31}|,\ sign(\Delta m^2_{31})$

– mixings:

$$\mathbf{U} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \cdot \mathbf{diag}(\mathbf{e^{i\Phi_1}}, \mathbf{e^{i\Phi_2}}, \mathbf{1})$$

– parameter determination schedule

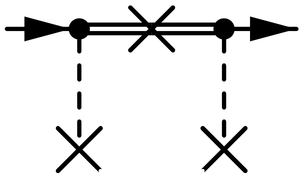
$\theta_{23},\ \lvert\Delta m^2_{31}\rvert$	atmospheric ν-experiments, K2K, MINOS, CNGS
$\theta_{12},\ \Delta m^2_{21}$	solar ν-experiments, KamLAND
θ_{13}	upper bound from CHOOZ: $\sin^2 2\theta_{13} < 0.1$
absolute mass scale	upper bound(s)
sgn[Δm^2_{31}], δ	superbeams, neutrino factories
Φ_1, Φ_2	$0\nu\beta\beta$ + ?

$\Rightarrow$ **next steps:** 1) neutrino mass scale
2) θ_{13} $\Leftrightarrow$ 3-flavour effects, ..., leptonic CP-violation

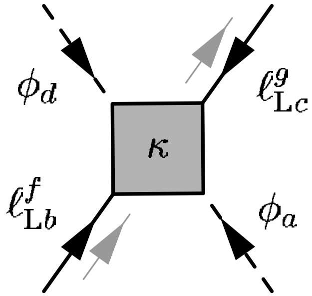
How small could θ_{13} be?

- **neutrino mass models** $\Rightarrow$ diagonalization of "textures"
  - $\theta_{ij} = \mathcal{O}(1)$ or maybe suppressed by mass hierarchies $10^{-1} \ldots 10^{-2}$
  - texture parameters may allow $\theta_{13} \equiv 0$ $\Leftrightarrow$ parameter tuning
  - $\theta_{12} \sim \theta_{23} \sim 1$ and $\theta_{13} \ll 10^{-2}$ $\Rightarrow$ special reason (symmetry, ...)

- **RGE:** Even for $\theta_{13} = 0$ at the GUT scale $\Rightarrow$ evolution to $\theta_{13} \neq 0$ at low energies
  - $d = 5$ **neutrino mass operator** $\Rightarrow$ integrating out all heavy dof, e.g. M_R:



$\Rightarrow$

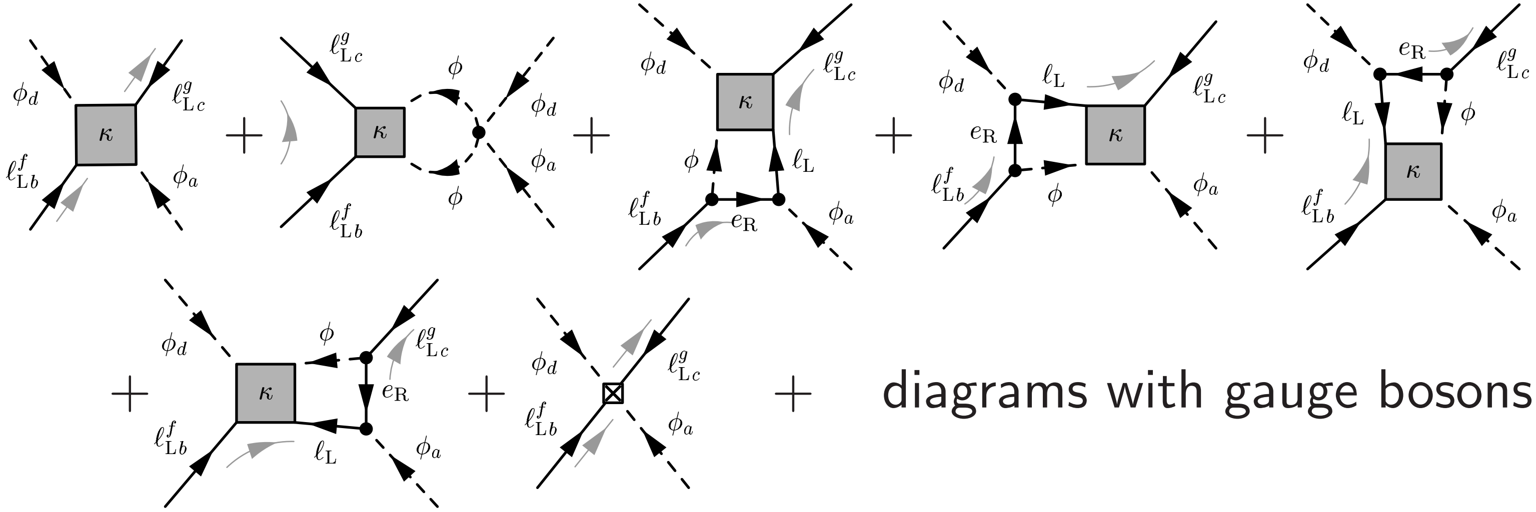


$\Leftrightarrow$ $\mathcal{L}_{mass} = \kappa \cdot \overline{\nu}^C_L \nu_L \Phi^T \Phi$

  - only light degrees of freedom $\Rightarrow$ ν_L, Φ
  - κ is dimension-full , e.g. $\kappa \simeq \frac{1}{M_R}$, $\langle\Phi\rangle = v \Rightarrow$ neutrino masses $\sim \kappa v^2$

- **Comparison of theory and experiment:**
  - **experiment:** masses, mixings at low energies (in the future very precise!)
  - **theory:** $\Rightarrow$ models at high energies

- **RGE-evolution at 1-loop: SM, MSSM, 2HSM**



νew β-function(s):

non-diagonal $\Leftrightarrow$ running mixings

$$16\pi^2\,\beta_\kappa = -\frac{3}{2}\,\kappa\,(Y_e^\dagger Y_e) - \frac{3}{2}(Y_e^\dagger Y_e)^T\kappa + \lambda\kappa - 3g_2^2\kappa$$
$$+2\,\mathrm{Tr}(Y_e^\dagger Y_e)\,\kappa + 6\,\mathrm{Tr}(Y_u^\dagger Y_u)\,\kappa + 6\,\mathrm{Tr}(Y_d^\dagger Y_d)\,\kappa$$

Yukawa-matrices

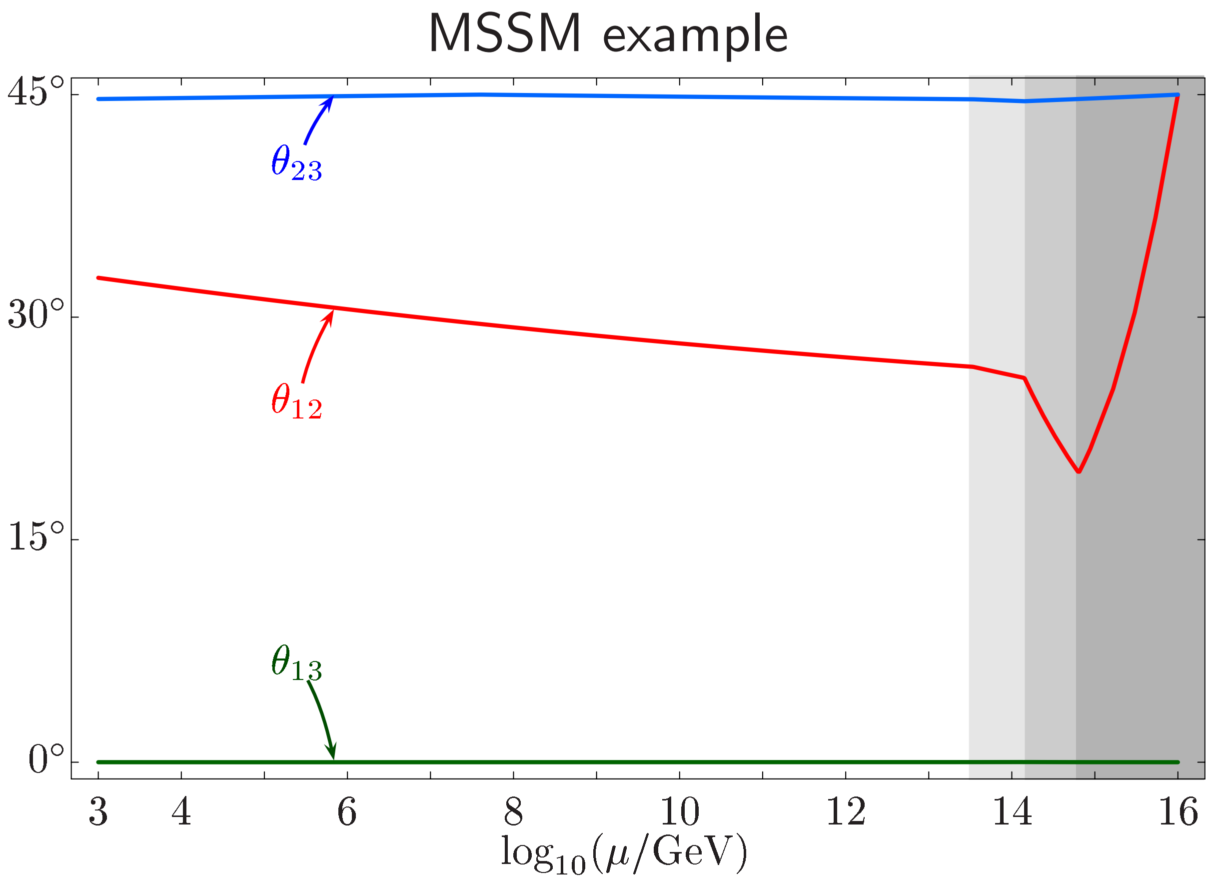
Babu, Leung, Pantaleone
Chankowski, Pluciennik
Antusch, Drees, Kersten, ML, Ratz, PLB 519 (2001) 238 and PLB 525 (2002) 130

• **Example: RG-evolution of bi-maximal mixings at the GUT-scale**

atmospheric → ← **bi-maximal**

solar →

Chooz limit → ← **small**



$\Rightarrow \quad \frac{\dot\theta_{12}}{\dot\theta_{23}} \simeq \frac{\Delta m^2_{31}}{\Delta m^2_{21}} \times \ldots \quad \Leftrightarrow \quad \theta_{12}$ runs more than θ_{23}

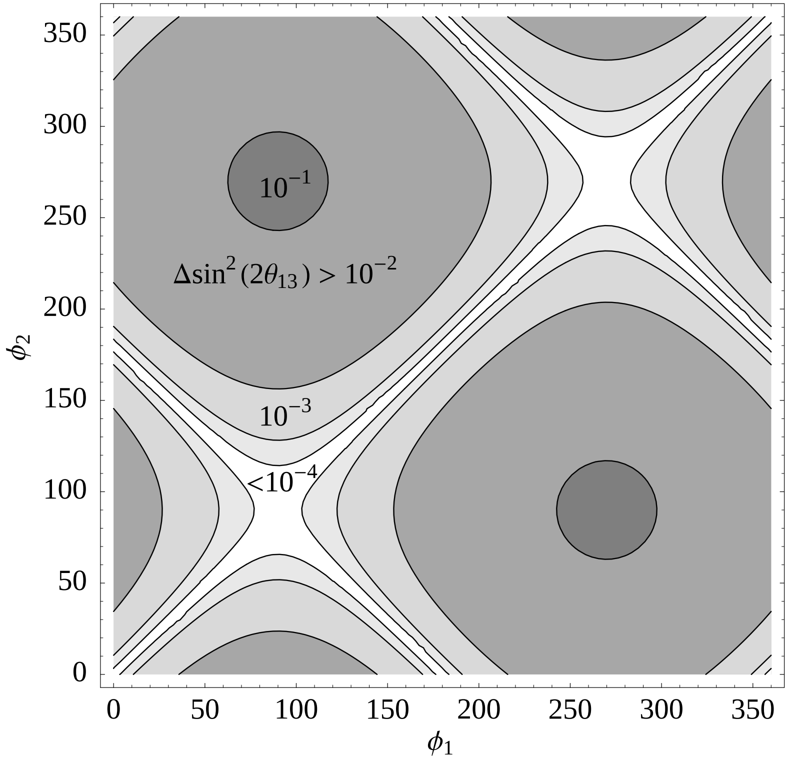
$\Rightarrow$ **deviation from bi-maximality can be explained by RGE**

Antusch, Kersten, ML, Ratz, Phys.Lett. B544 (2002) 1

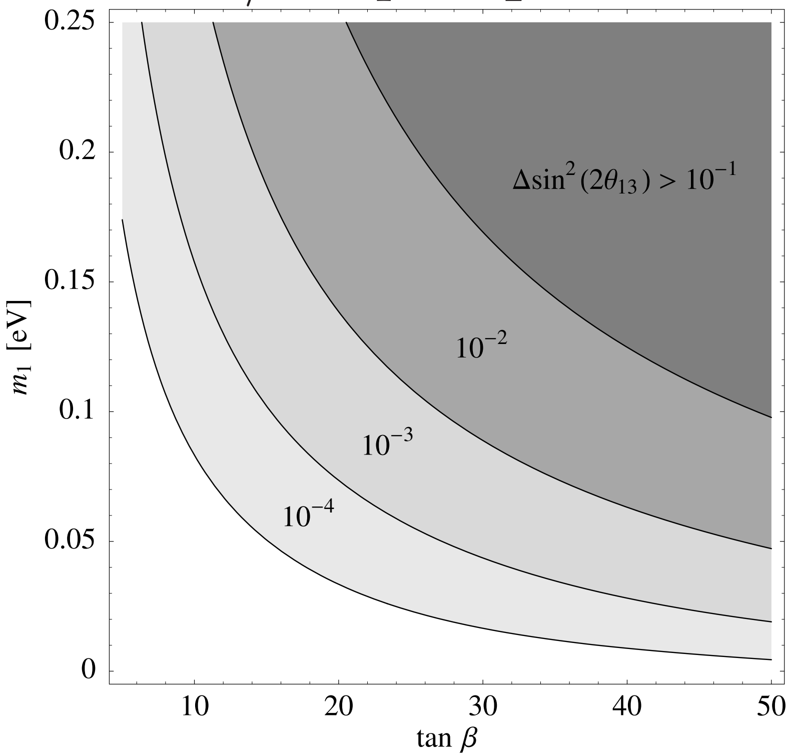
- **How big are the RGE effects for θ_{13}?** $\Rightarrow$ change of θ_{13} in MSSM

$$\dot{\theta}_{13} \simeq \frac{y_\tau^2 \sin 2\theta_{12} \sin 2\theta_{23} m_3}{32\pi^2 \Delta m^2_{\rm atm}} \left[m_1 \cos(\Phi_1 - \delta) - m_2 \cos(\Phi_2 - \delta) - m_3 \frac{\Delta m^2_{sol}}{\Delta m^2_{atm}} \cos\delta \right]$$

$\tan\beta = 50$, $m_1 = 0.1$ eV, $\delta = \pi/2$



$\delta = \pi/2$, $\Phi_1 - \Phi_2 = \pi$

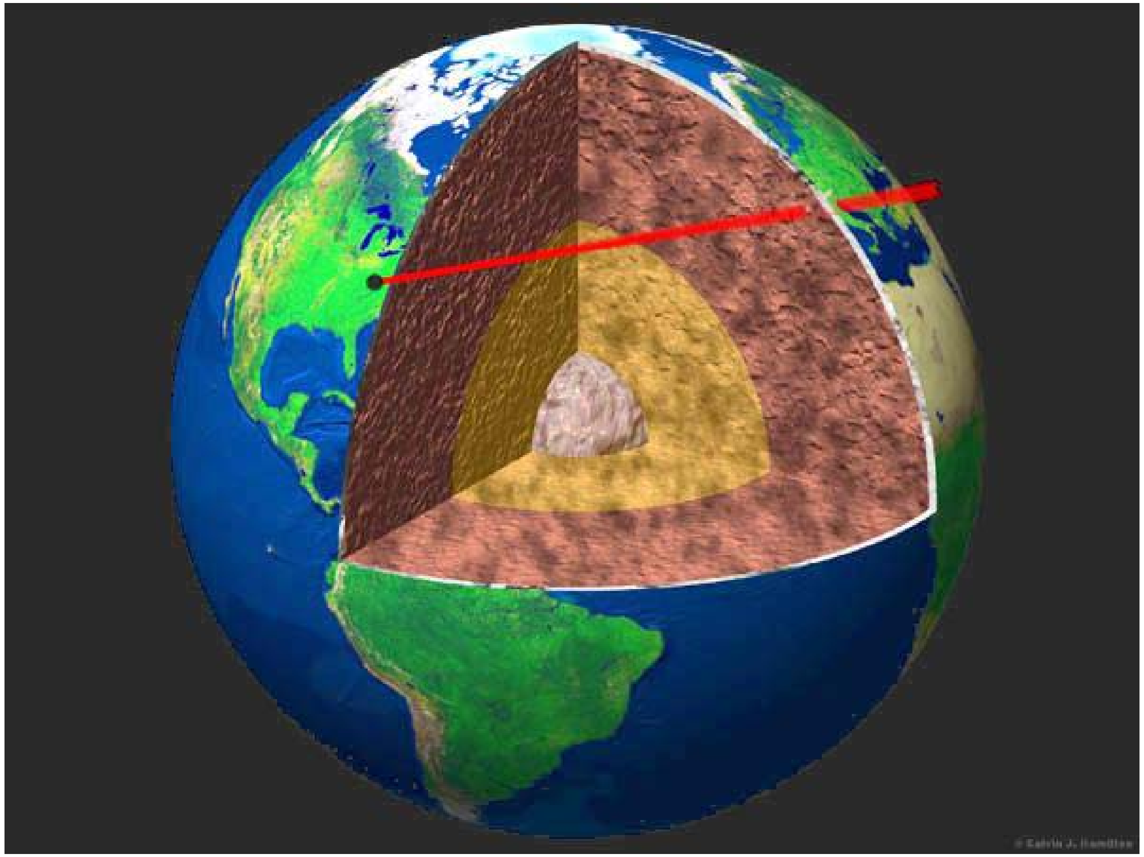


$\Rightarrow$ even for $\theta_{13} = 0$ at the GUT scale **one can often have** $\Delta\sin^2(2\theta_{13}) \geq 10^{-2}$

$\Rightarrow$ without tuning: typical size of θ_{13} from RGE $\Rightarrow$ sensitivity to $\sin^2(2\theta_{13}) \simeq 10^{-2}$

Antusch, Kersten, ML, Ratz, to appear soon

Hunting $\theta_{13} \neq 0$ with Long Baseline Experiments



Precision!

Source	$\otimes$	**Oscillation**	$\otimes$	**Detector**

- neutrino energy E
- flux and spectrum
- flavour composition
- contamination
- symmetric $\nu/\overline{\nu}$ operation

- oscillation channels
- realistic baselines
- MSW matter profile

- effective mass, material
- threshold, resolution
- particle ID (flavour, charge, event reconstruction, ...)
- backgrounds
- x-sections (at low E)

- **Analytic understanding (qualitative)**
  - $\Delta = \Delta m_{31}^2 L/4E$
  - matter effects $\hat{A} = A/\Delta m_{31}^2 = 2VE/\Delta m_{31}^2;\ \ V = \sqrt{2} G_F n_e$
  - expand oscillation probabilities in $\alpha = \Delta m_{21}^2/\Delta m_{31}^2$ and $\sin^2 2\theta_{13}$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\Delta + 2\,\alpha\,\cos^2\theta_{13}\cos^2\theta_{12}\sin^2 2\theta_{23}\Delta\cos\Delta$$

$$\begin{aligned}
P(\nu_\mu \to \nu_e) \approx\ & \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
\mp\ & \sin\delta_{CP}\ \alpha\sin 2\theta_{12}\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{23}\sin(\Delta)\frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\ & \cos\delta_{CP}\ \alpha\sin 2\theta_{12}\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{23}\cos(\Delta)\frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\ & \alpha^2\sin^2 2\theta_{12}\cos^2\theta_{23}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}$$

Cervera, Donini, Gavela, Gomez Cadenas, Hernandez, Mena, Rigolin
Freund, Huber, ML
Freund

• Simplification for vacuum: $V = 0$

$\Delta = \Delta m^2_{31} L/4E$

$\Rightarrow$ expansion in powers of $\alpha = \Delta m^2_{21}/\Delta m^2_{31} \simeq 10^{-2}$ and $\sin\theta_{13} \leq 10^{-1}$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;\approx\; & \sin^2 2\theta_{13} \sin^2\theta_{23} \quad \sin^2(\Delta) \\
\mp\; & \sin\delta_{\rm CP}\; \alpha\; \sin 2\theta_{13} \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{23} \sin^3(\Delta) \\
+\; & \cos\delta_{\rm CP}\; \alpha\; \sin 2\theta_{13} \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{23} \cos(\Delta) \sin^2(\Delta) \\
+\; & \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \sin^2(\Delta) \\
+\; & \mathcal{O}(\epsilon^3)
\end{aligned}
$$

– most interesting: $\sin^2 2\theta_{13} \simeq \alpha \cdot \sin^2 2\theta_{12} = \sin^2 2\theta_{12} \Delta m^2_{21}/\Delta m^2_{31}$

– parameter correlations

– depends on solar parameters only via the product $\Delta m^2_{21} \cdot \sin 2\theta_{12}$

– degeneracies: $(\delta_{CP} - \theta_{13})$, $(\delta_{CP} - sign(\Delta m^2_{31}))$, $(\theta_{23} - \frac{\pi}{2} - \theta_{23})$

– $\mathcal{O}(\epsilon^3)$ corrections $\Leftrightarrow$ relative contributions $\mathcal{O}(\epsilon)$

• Event rate simulations

– naive probability based statements are easily many orders of magnitude off

– include all relevant aspects in event rate simulations:
statistics, systematics, backgrounds, efficiencies, resolution, threshold, x-sections, ...

– general three flavour scenario including matter effects (and errors)

– parameters: Δm^2_{21}, θ_{12}, $|\Delta m^2_{31}|$, θ_{23}, θ_{13}, δ , $\mathrm{sgn}[\Delta m^2_{31}]$ and assume that Δm^2_{21}, θ_{12} are known within 10% at 1σ (KamLAND, K2K, MINOS, CNGS)

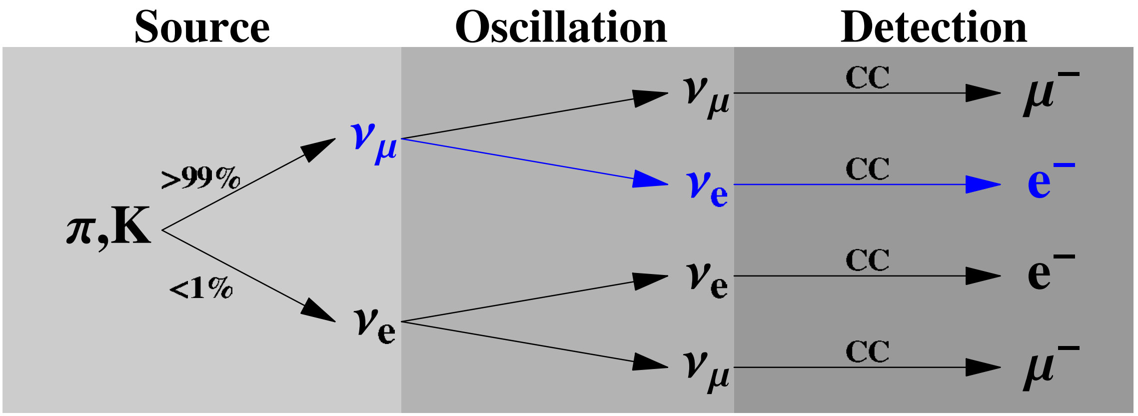
– simulate "data" for fixed "true values" of oscillation parameters

– perform 6-parameter fit:
take into account correlations and degeneracies
include available external information **and their errors**
determine sensitivity, precision etc.

– optimization for individual experiments and combinations

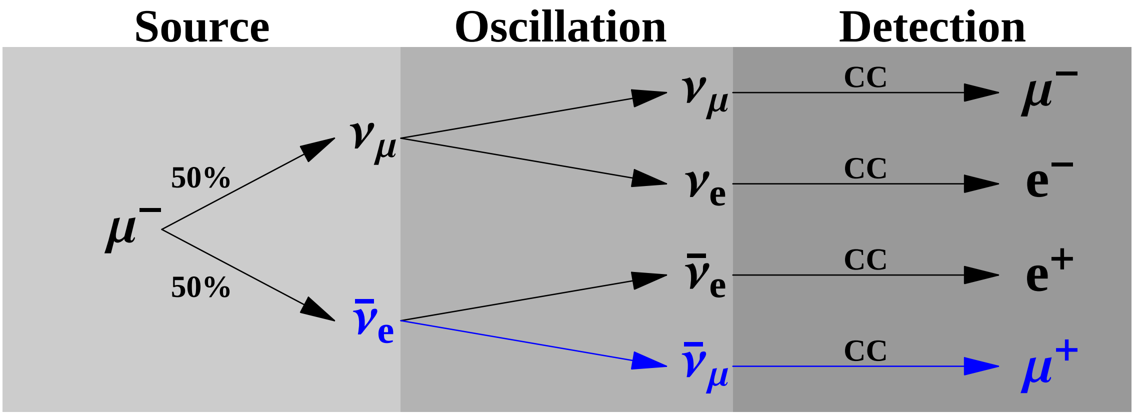
– compare different scenarios on the same footing

- **Conventional ν-Beams from Beam Dumps $\Rightarrow$ Superbeams**



$\nu_\mu \to \nu_e$ oscillation most interesting
ν_e contamination $\Leftrightarrow$ off-axis
good electron detection efficiency
good NC background rejection
near detector
$\overline{\nu}$-beam $\simeq$ different experiment

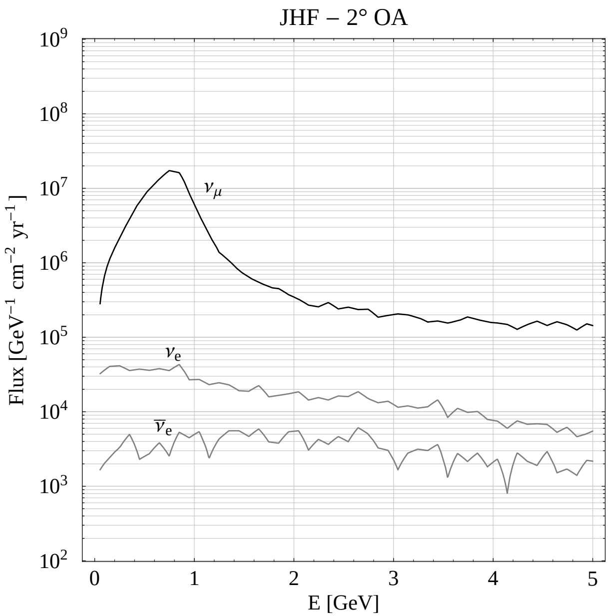
- **Neutrino Factories**



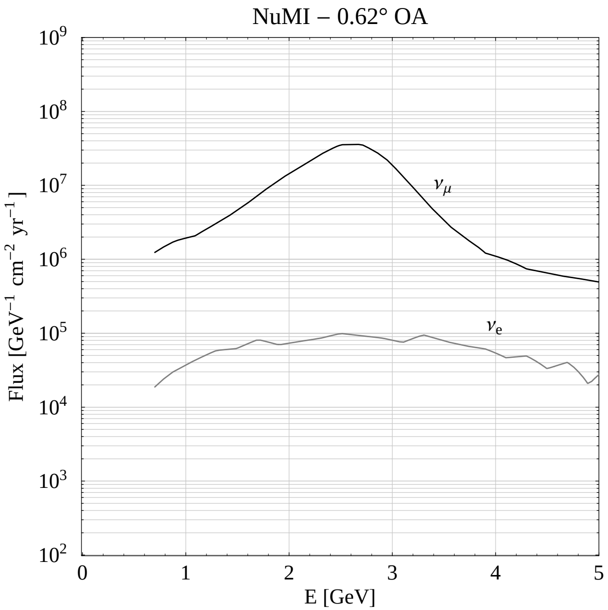
$\overline{\nu}_e \to \overline{\nu}_\mu$ oscillation most interesting
excellent beam properties
very good charge ID required
good NC background rejection
μ^+ mode very symmetric

- **The Sources**

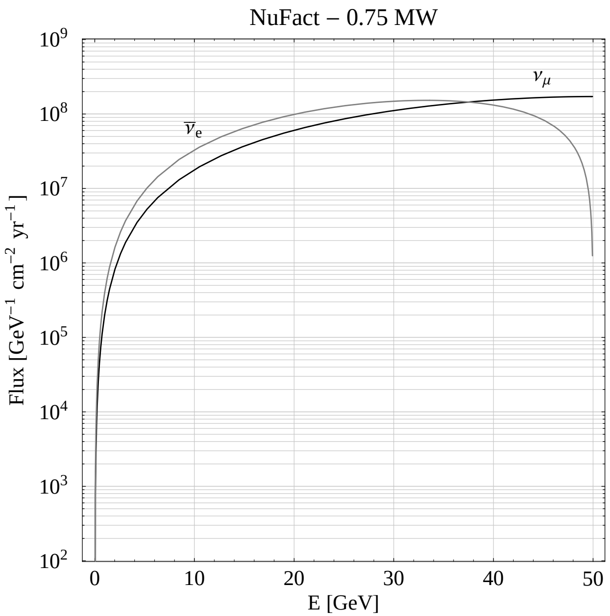
JHF	NuMI off-axis	NuFact



- mean energy $0.51\,\mathrm{GeV}$
- peak intensity $1.7 \cdot 10^7\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{yr}^{-1}$ at $0.78\,\mathrm{GeV}$
- ν_μ/ν_e-ratio at peak 0.2%



- mean energy $2.78\,\mathrm{GeV}$
- peak intensity $3.6 \cdot 10^7\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{yr}^{-1}$ at $2.18\,\mathrm{GeV}$
- ν_μ/ν_e-ratio at peak 0.2%



- mean energy $30\,\mathrm{GeV}$
- peak intensity $1.5 \cdot 10^8\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{yr}^{-1}$ at $33.33\,\mathrm{GeV}$
- ν_μ/ν_e-ratio at peak 83%

Uncertainties in flux and ν_e–background

Uncertainties in flux

Itow et al. Para, Szleper Geer

Detectors

	water Cherenkov = SK (HK)	low-Z calorimeter	magnetized iron calorimeter
fiducial mass	$22.5\,\mathrm{kt}\ (1\,000\,\mathrm{kt})$	$20\,\mathrm{kt}$	$10\,\mathrm{kt}\ (50\,\mathrm{kt})$
energy range	$0.4 - 1.2\,\mathrm{GeV}$	$1 - 5\,\mathrm{GeV}$	$4 - 50\,\mathrm{GeV}$
energy resolution	5%	10%	20%
signal efficiency	0.5	0.5	0.45
NC rejection	0.01	0.001	$< 10^{-5}$
CID	–	–	$< 10^{-5}$
backround uncertainty	5%	5%	5%

– threshold effects for the magnetized iron calorimeter
linear rise of the efficiency between $4\,\mathrm{GeV}$ and $20\,\mathrm{GeV}$

– liquid Argon TPC ?

5 Scenarios

	JHF-SK	NuMI	NuFact-I
detector	water cherenkov	low-Z calorimeter	10kt magnetized iron calorimter
baseline	$295\,\mathrm{km}$	$735\,\mathrm{km}$	$3\,000\,\mathrm{km}$
matter density	$2.8\,\mathrm{g\,cm}^{-3}$	$2.8\,\mathrm{g\,cm}^{-3}$	$3.5\,\mathrm{g\,cm}^{-3}$
L/E_{peak}	$378\,\mathrm{km\,GeV}^{-1}$	$337\,\mathrm{km\,GeV}^{-1}$	$90\,\mathrm{km\,GeV}^{-1}$

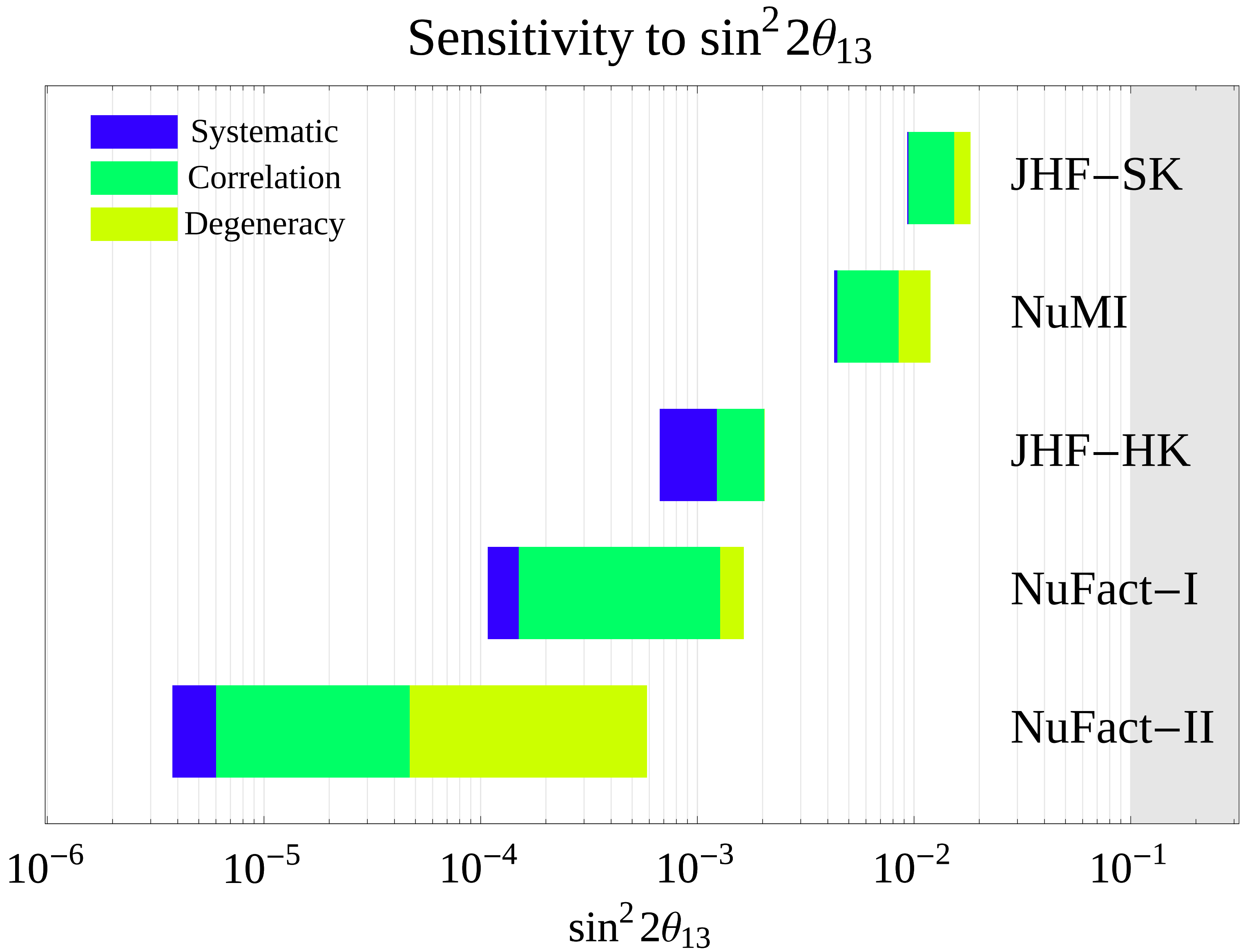
- JHF-HK $\Rightarrow$ $\simeq 95$ times more luminosity than JHF-SK plus anti-neutrino running
- NuFact-II $\Rightarrow$ $\simeq 42$ times more luminosity than NuFact-I

Itow et al., A. Para, A. Blondel et al.

	JHF-SK	NuMI	JHF-HK	NuFact-I	NuFact-II
signal	139.0	387.5	13 180.0	1 522.8	64 932.6
background	23.3	53.3	2 204.6	4.2	180.3
S/N	6	6	6	360	360

- **Compare the setups** Huber, ML, Winter, NPB 645 (2002) 3

statistical errors
⇓
systematics
⇓
correlations
⇓
degeneracies
⇓
final result



– Different sensitivity reductions by systematics
– Correlations & degeneracies lead to severe limitations
– Improvements by combining experiments

Sensitivity to the sign of Δm^2_{31}

statistical errors

$\Downarrow$

systematics

$\Downarrow$

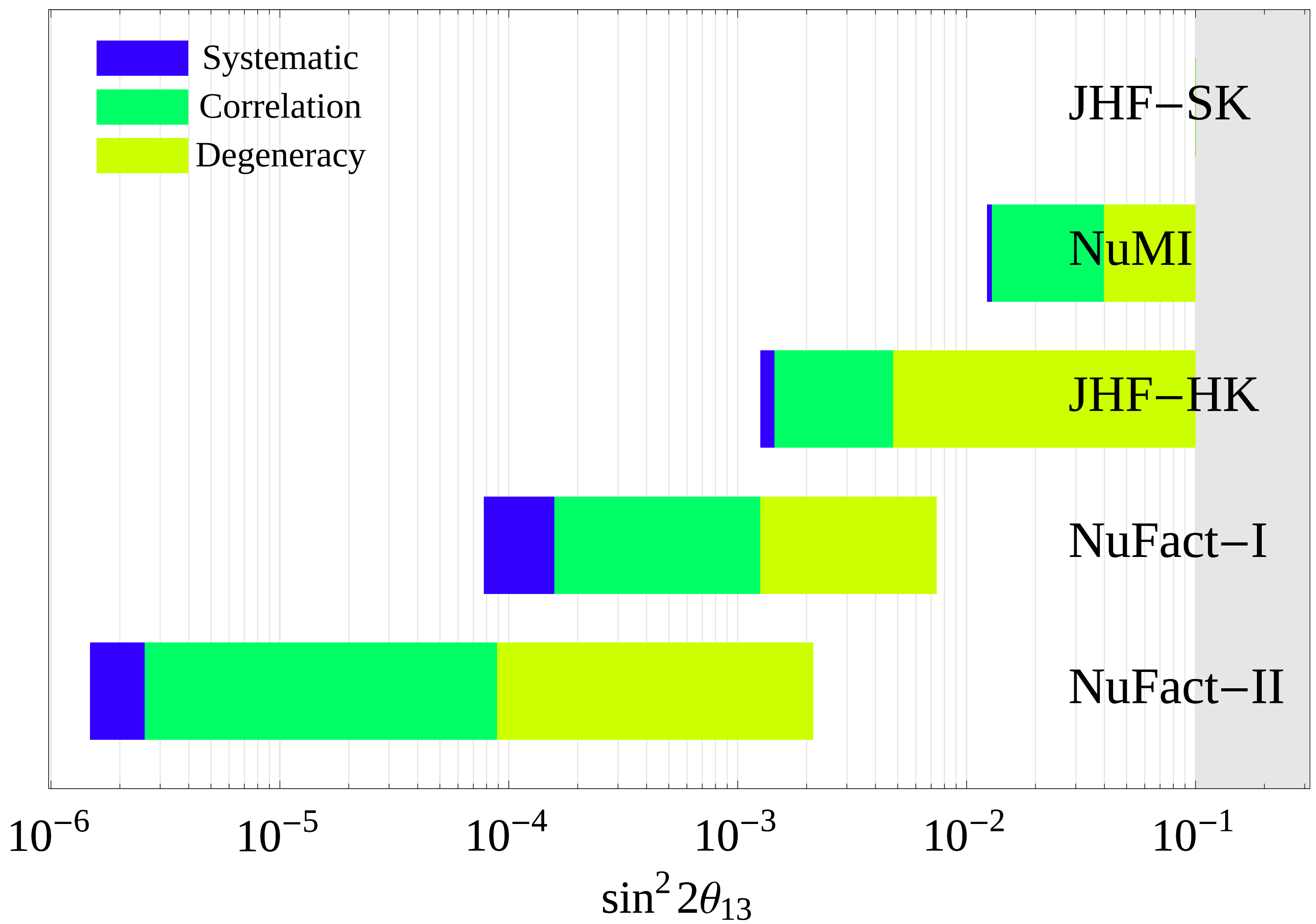
correlations

$\Downarrow$

degeneracies

$\Downarrow$

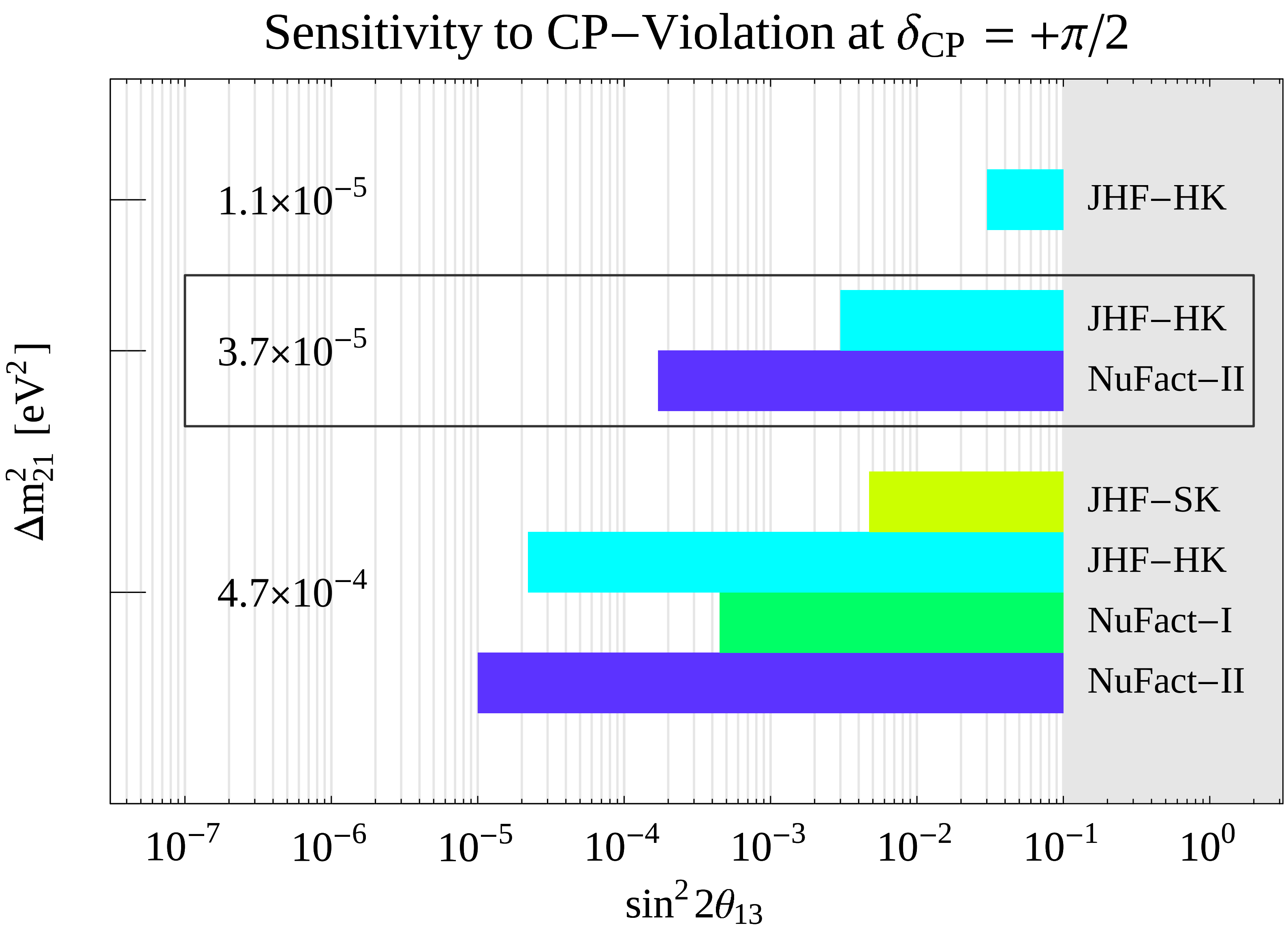
final result



- $sign(\Delta m^2_{31})$ very hard to determine with superbeams
- degeneracies with δ_{CP} are the main problem

$\Rightarrow$ combine experiments! Huber, ML, Winter, NPB 645 (2002) 3

Measurements of CP-violation



– CP violation with high luminosity superbeams feasable

– sensitivity is δ_{CP} dependent

Huber, ML, Winter, NPB 645 (2002) 3

• Combine the Next Generation of LBL Experiments

Huber, ML, Winter, NPB 654 (2003) 3

- $\nu_\mu \to \nu_e$ appearance using an up-graded conventional ν_μ-beam
- **JHF-SK** combined with **NuMI off-axis** as given in LOIs

	JHF-SK	NuMI
	Y.Itow et al. hep-ex/0106019	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

Typical S/B results:

	JHF-SK	NuMI
Signal	137.8	132.0
Bckgd.	22.6	19.0

- variation-1: NuMI at 890 km and 950 km $\Leftrightarrow$ matter effects
- variation-2: neutrino running only (ν) or mixed ν-$\overline{\nu}$ mode (c)

Sensitivity to $\sin^2 2\theta_{13}$ for JHF−SK & NuMI

statistical errors

⇓

systematics

⇓

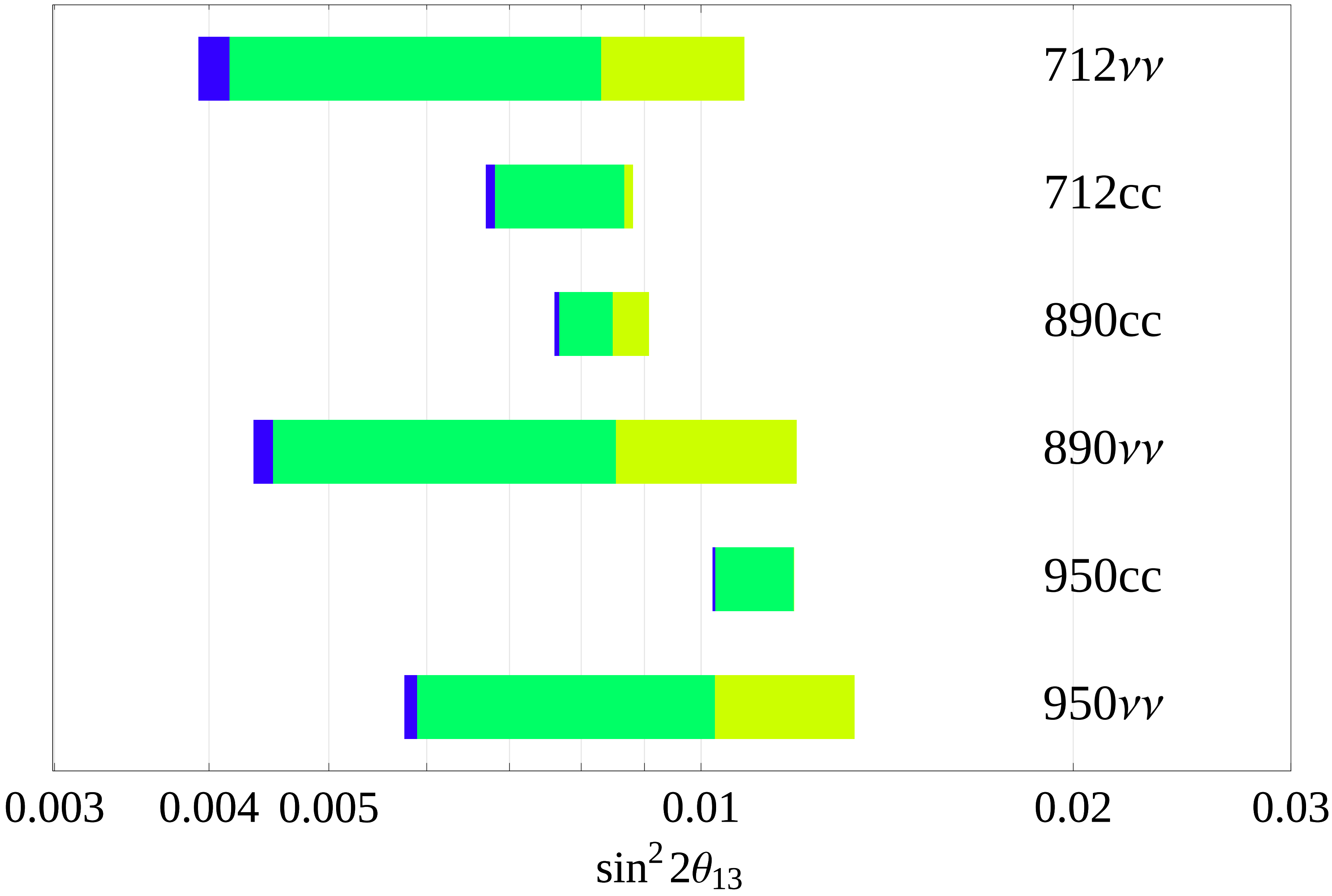
correlations

⇓

degeneracies

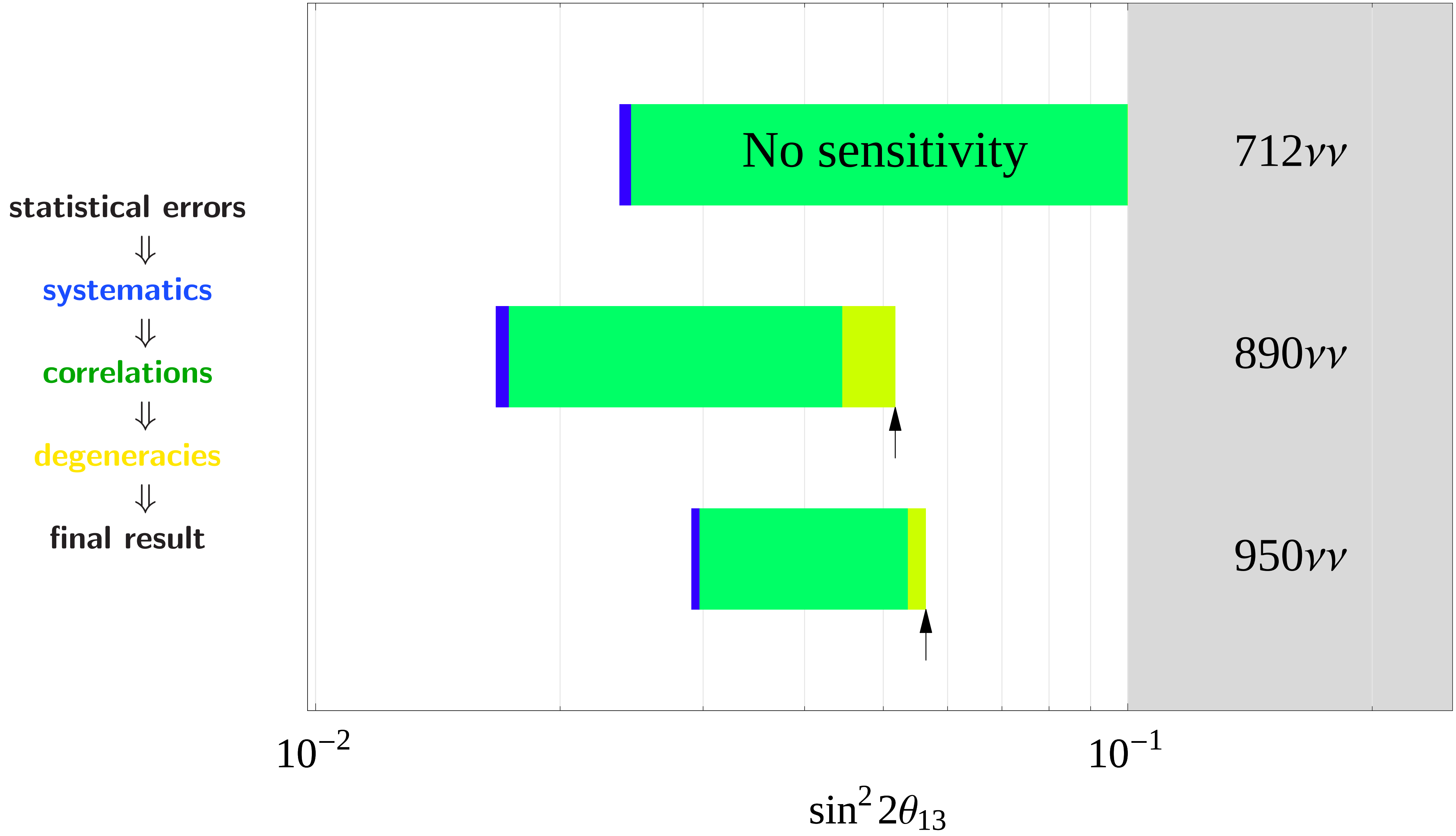
⇓

final result



labels: NuMI-baseline(km) JHF-mode(ν,c) NuMI-mode(ν,c)

Sensitivity to sgn (Δm^2_{31}) for JHF−SK & NuMI



labels: NuMI-baseline(km) JHF-mode(ν,c) NuMI-mode(ν,c)

Sensitivity to CP violation for JHF−SK & NuMI

statistical errors

⇓

systematics

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correlations

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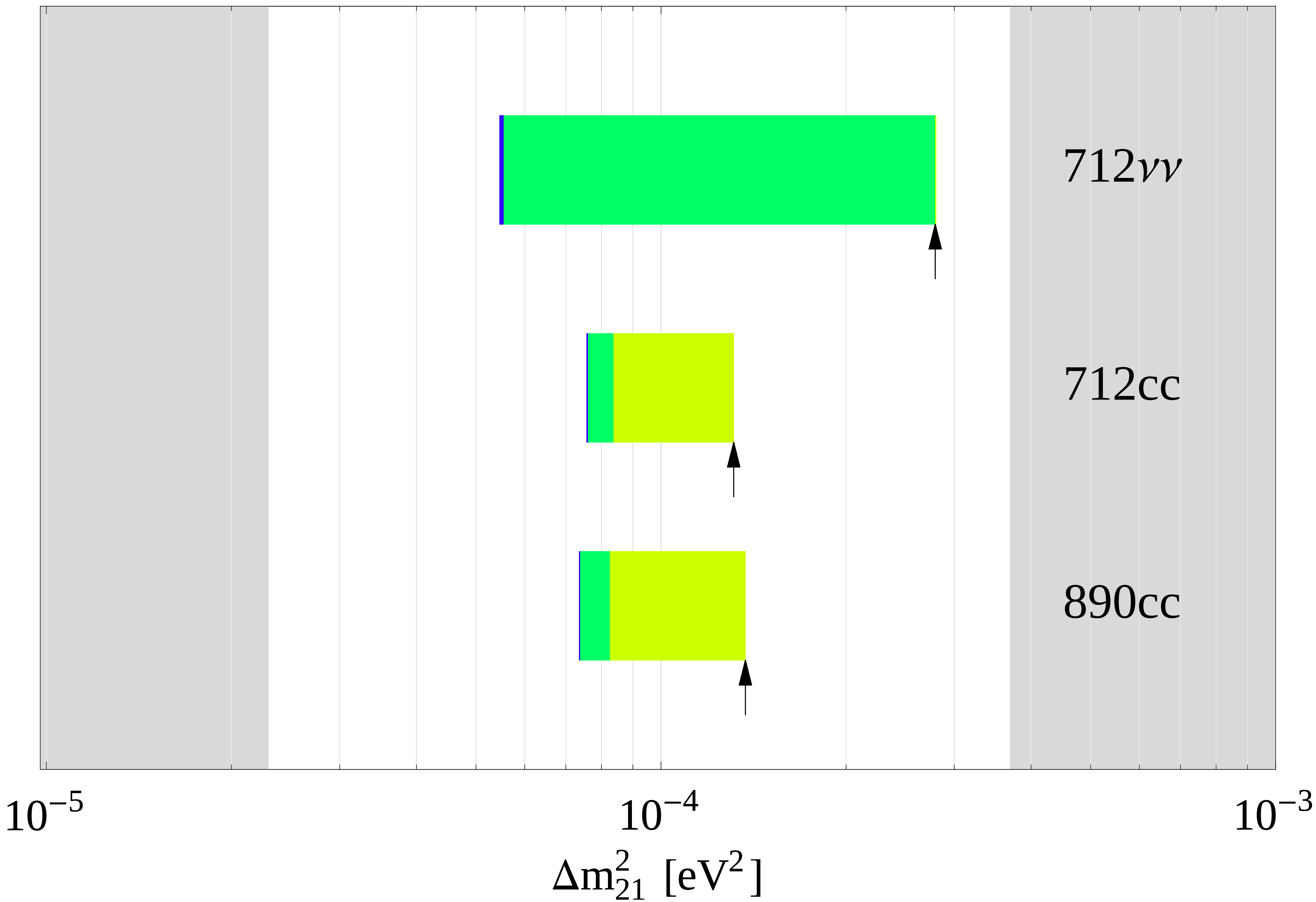
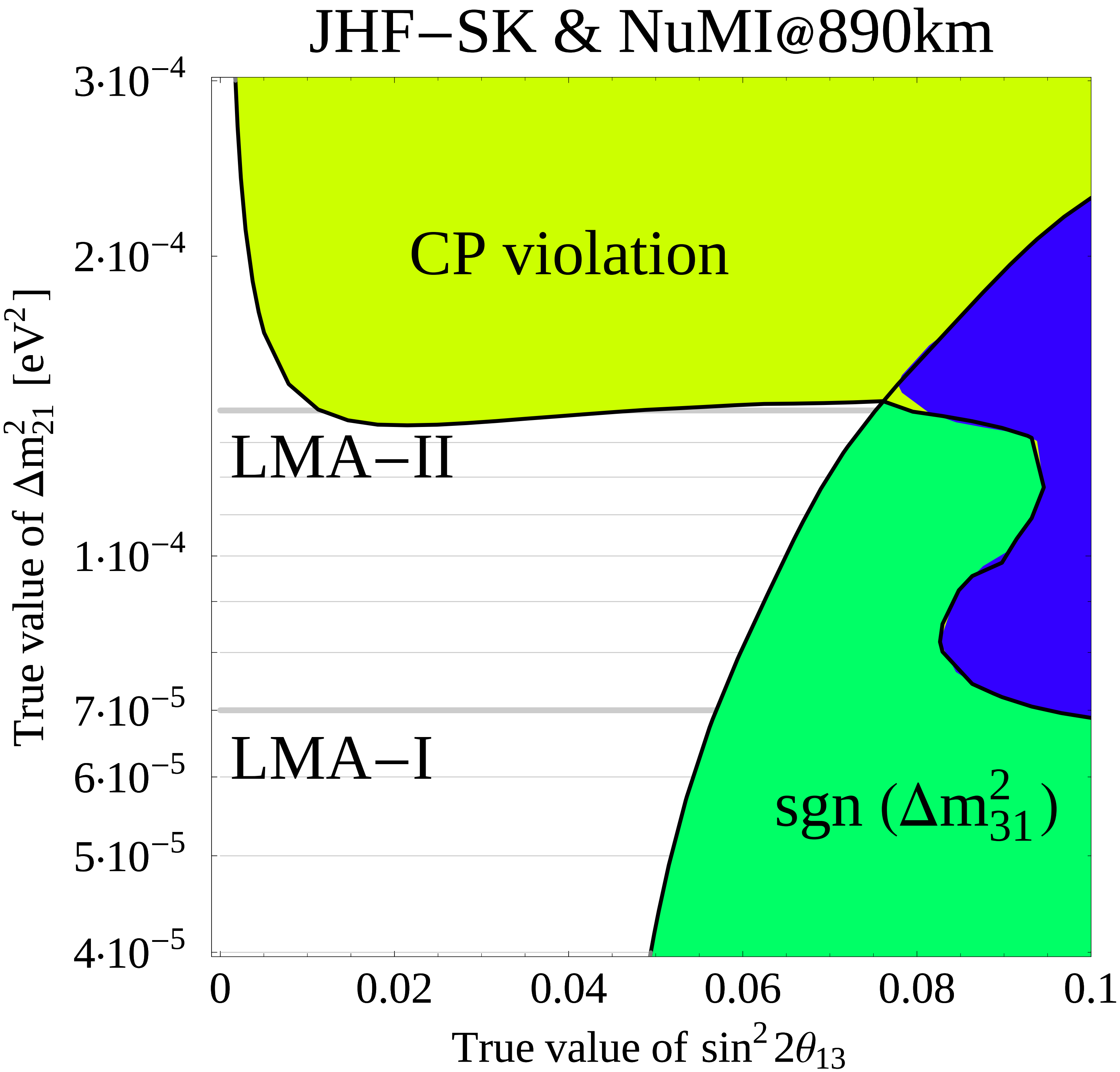
degeneracies

⇓

final result



labels: NuMI-baseline(km) JHF-mode(ν,c) NuMI-mode(ν,c)


JHF−SK & NuMI@890km
CP violation
LMA−II
LMA−I
sgn (Δm^2_{31})
$3\cdot10^{-4}$
$2\cdot10^{-4}$
$1\cdot10^{-4}$
$7\cdot10^{-5}$
$6\cdot10^{-5}$
$5\cdot10^{-5}$
$4\cdot10^{-5}$
0
0.02
0.04
0.06
0.08
0.1
True value of Δm^2_{21} [eV^2]
True value of $\sin^2 2\theta_{13}$

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, 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

detailed study | Huber, ML, Schwetz, Winter, hep-ph/0303232

- **The idea:**

$\overset{\overline{\nu}_e}{\Longrightarrow}$ **near detector** (170m) $\overset{\overline{\nu}_e}{\Longrightarrow}$ **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: $E_{\rm prompt} = E_{\rm kin} + 2m_e$

– 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

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

  - last term negligible for $\frac{\Delta m^2_{31} L}{4E_\nu} \sim \pi/2$ and $\sin^2 2\theta_{13} \gtrsim 10^{-3}$
  - 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 km , near detector at $\sim$ 170 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 $E_{\rm prompt}$ from 1 to 7.2 MeV, number of events in bin i:

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

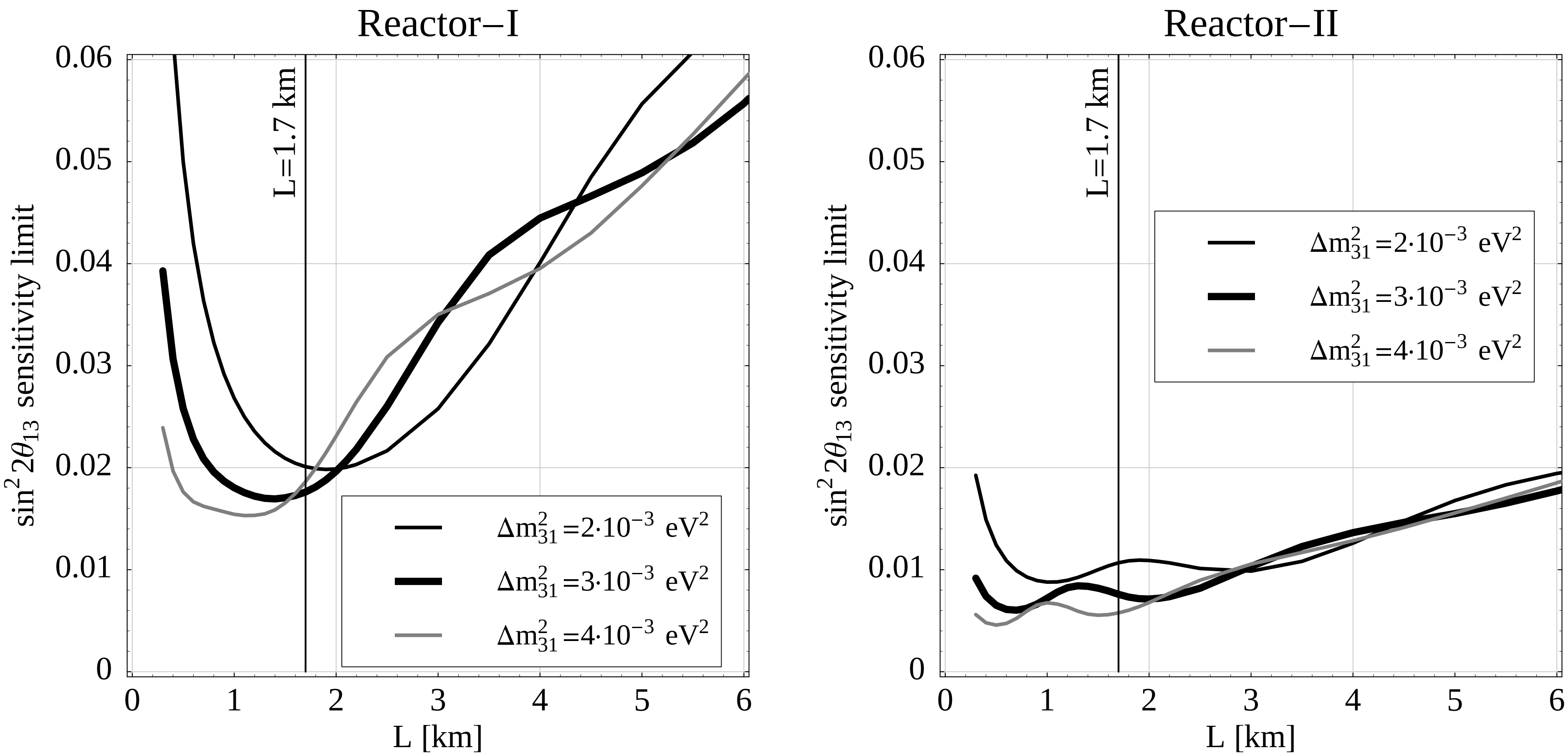
  - R: energy resolution $5\%/\sqrt{E_e(\mathrm{MeV})}$
  - $\mathcal{N} \propto$ integrated luminosity $\mathcal{L}$
  - $\mathcal{L} \equiv$ detector mass [t] $\times$ thermal reactor power [GW] $\times$ running time [y]

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

    250t detector, 7 GW thermal power, 5 years running time $\Rightarrow$ 8000 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 normalisation error common to both detectors $\sigma_{\text{tot}} \sim$ few %
  e.g., neutrino flux normalisation, cross section uncertainty, ...

  – relative normalisation errors of the two detectors $\sigma_{\text{rel}} \lesssim 1\%$
  e.g., error on the fiducial masses, ...

  $\Rightarrow$ effective normalisation error for the far detector

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

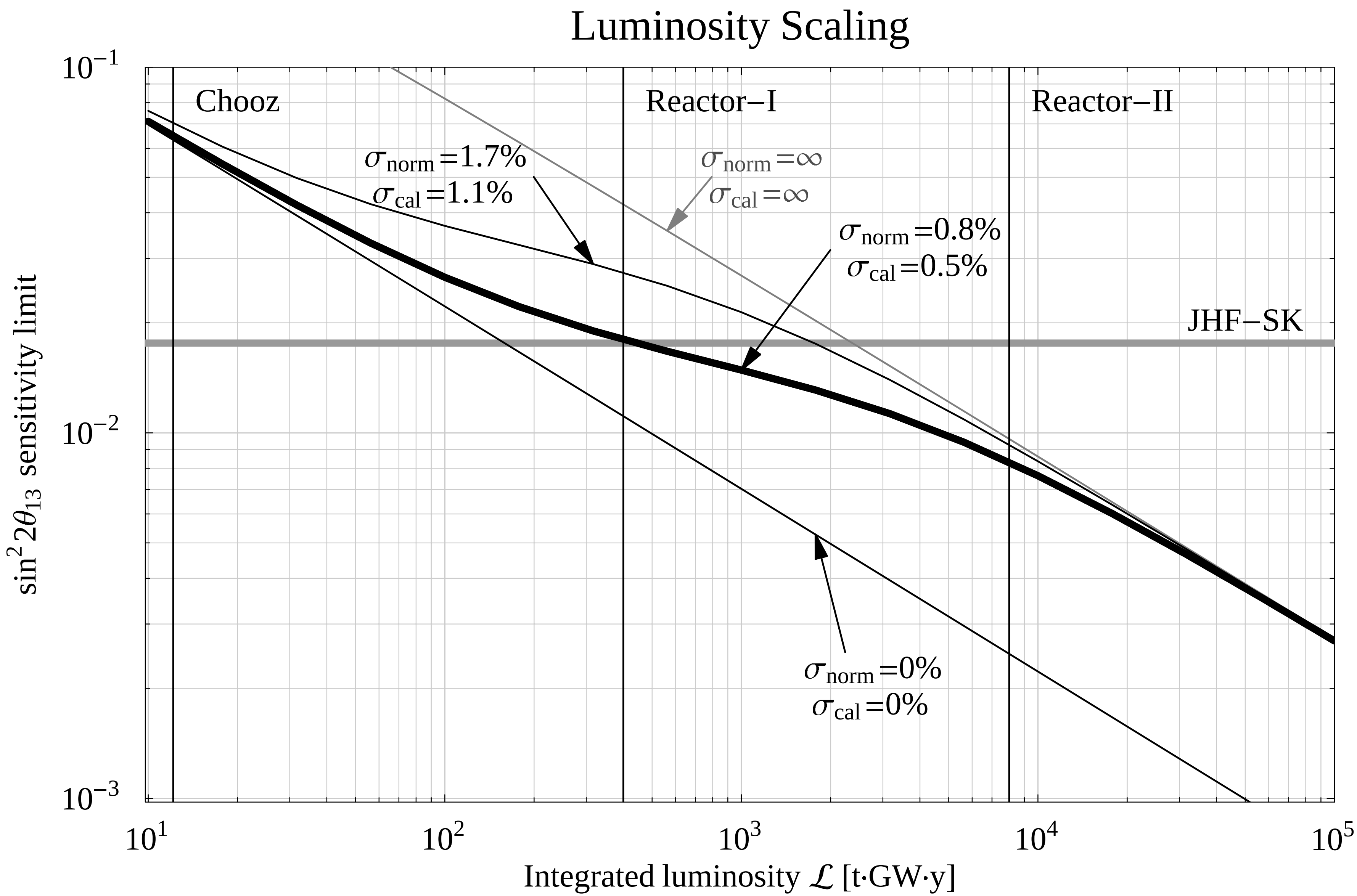
  e.g.: $\sigma_{\text{tot}} = 2\%$ and $\sigma_{\text{rel}} = 0.6\% \quad \rightarrow \quad \sigma_{\text{norm}} \simeq 0.8\%$

  – energy calibration uncertainty $\sigma_{\text{cal}} \sim 0.5\%$

  – shape uncertainty of the expected energy spectrum $\sigma_{\text{shape}} \sim \text{few}\%$
  uncorrelated between energy bins, but correlated between detectors

  – completely uncorrelated experimental bin-to-bin error $\sigma_{\text{exp}} \lesssim 0.5\%$
  e.g., background uncertainty

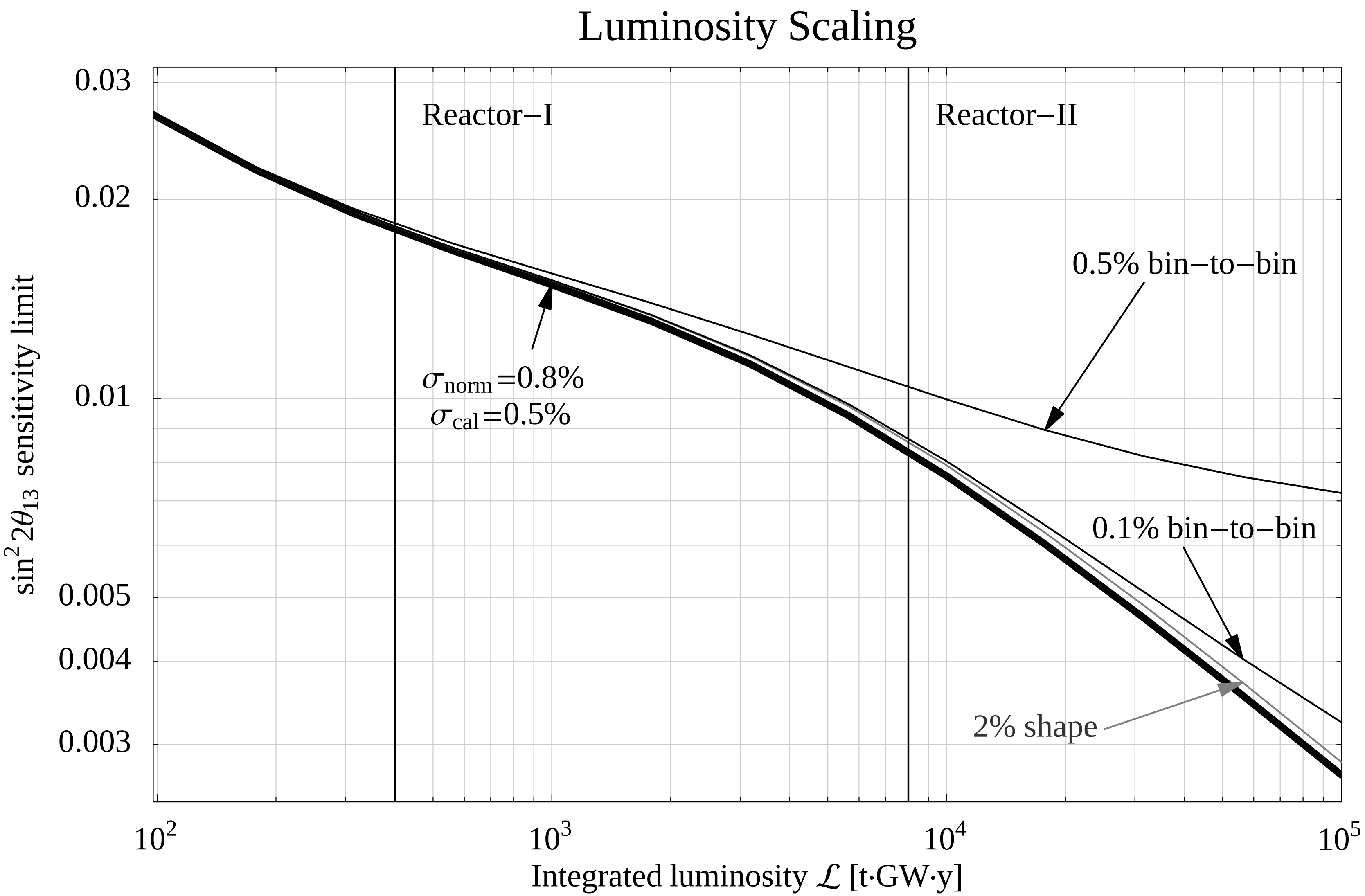
- **Sensitivity to $\sin^2 2\theta_{13}$ at 90% CL**



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

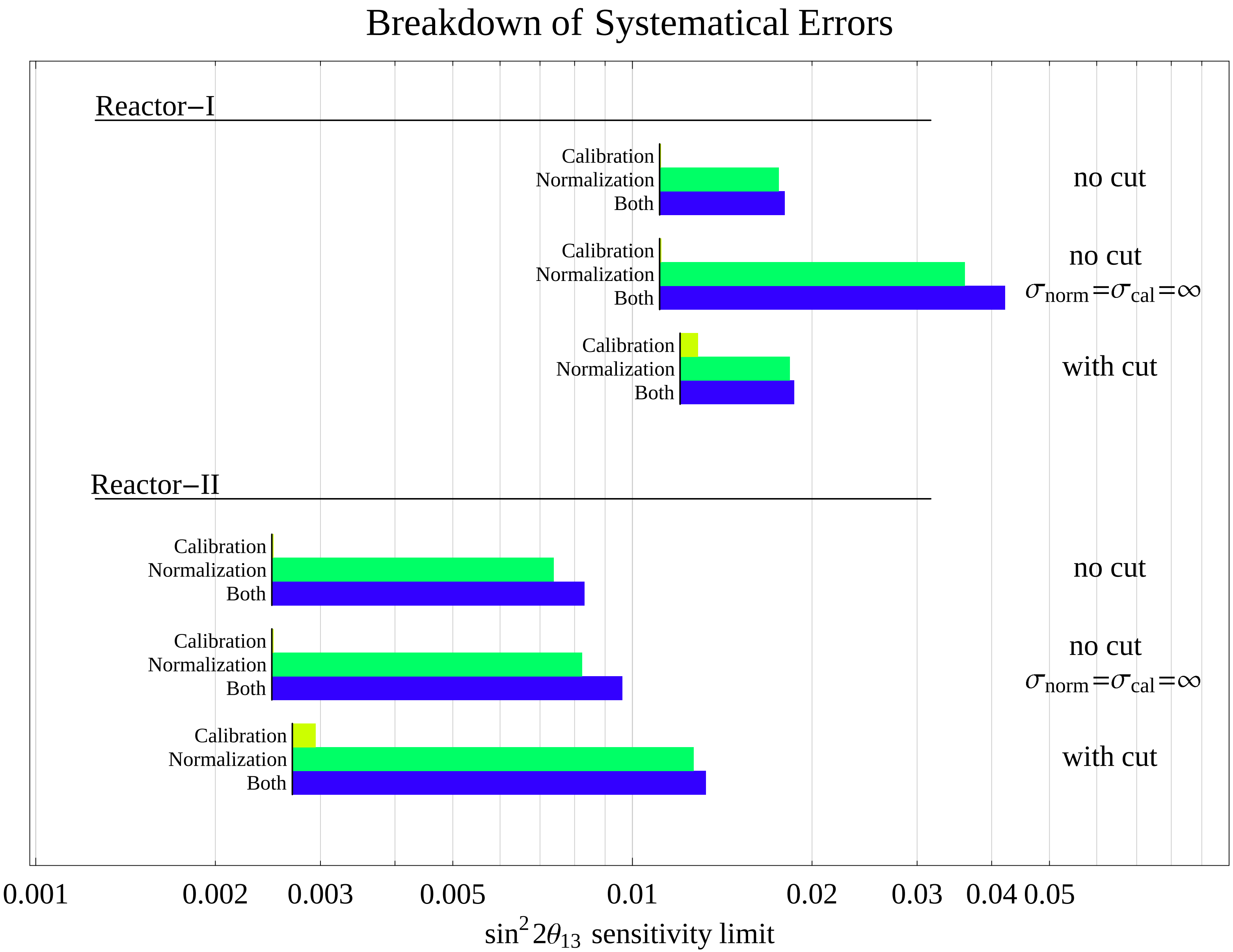
Reactor-II: essentially independent of σ_{norm}

- **Theoretical shape and experimental bin-to-bin errors**



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

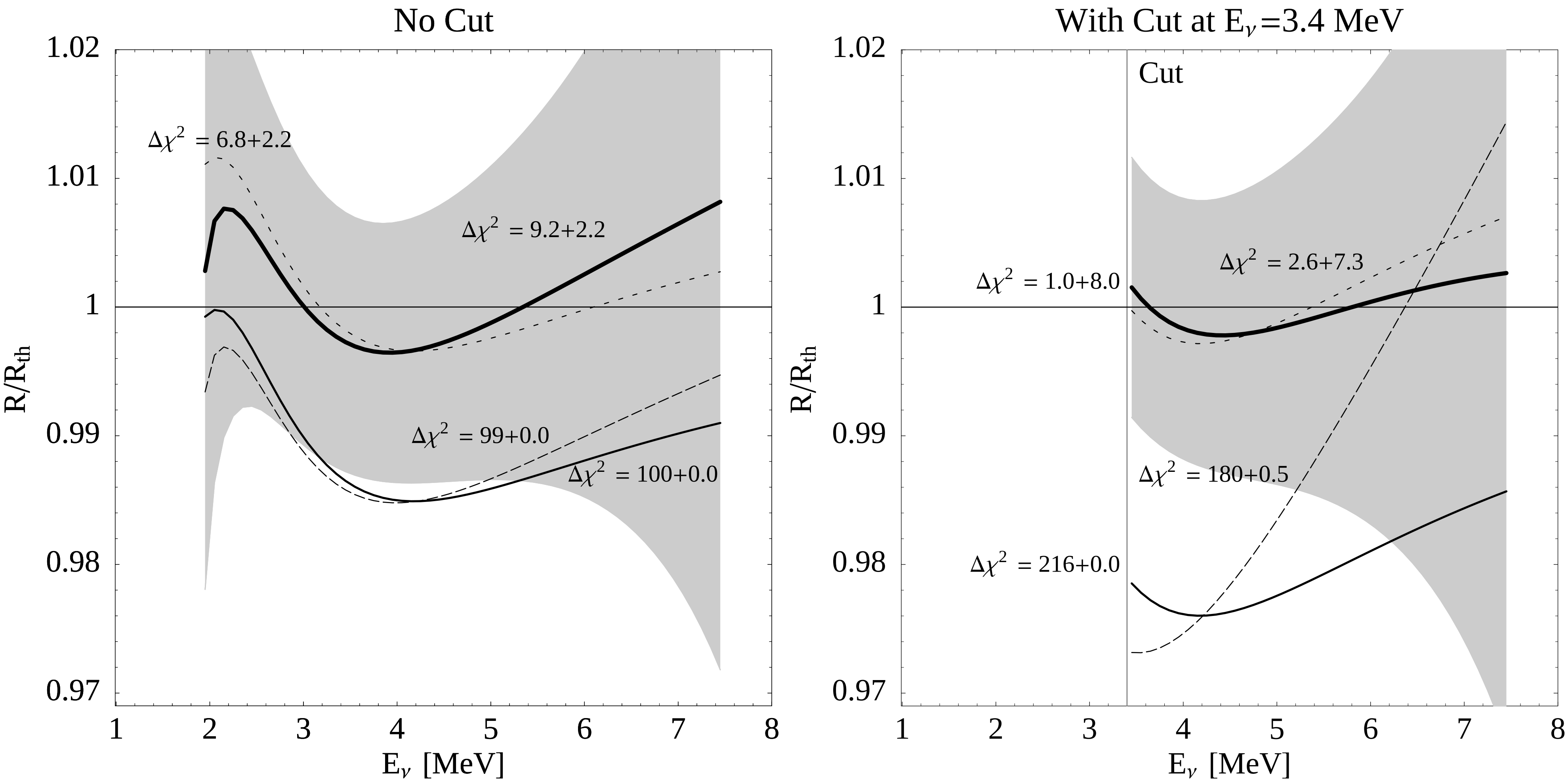
a BG of 1% of the signal, known within 10% $\longrightarrow$ 0.1% exp. error



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

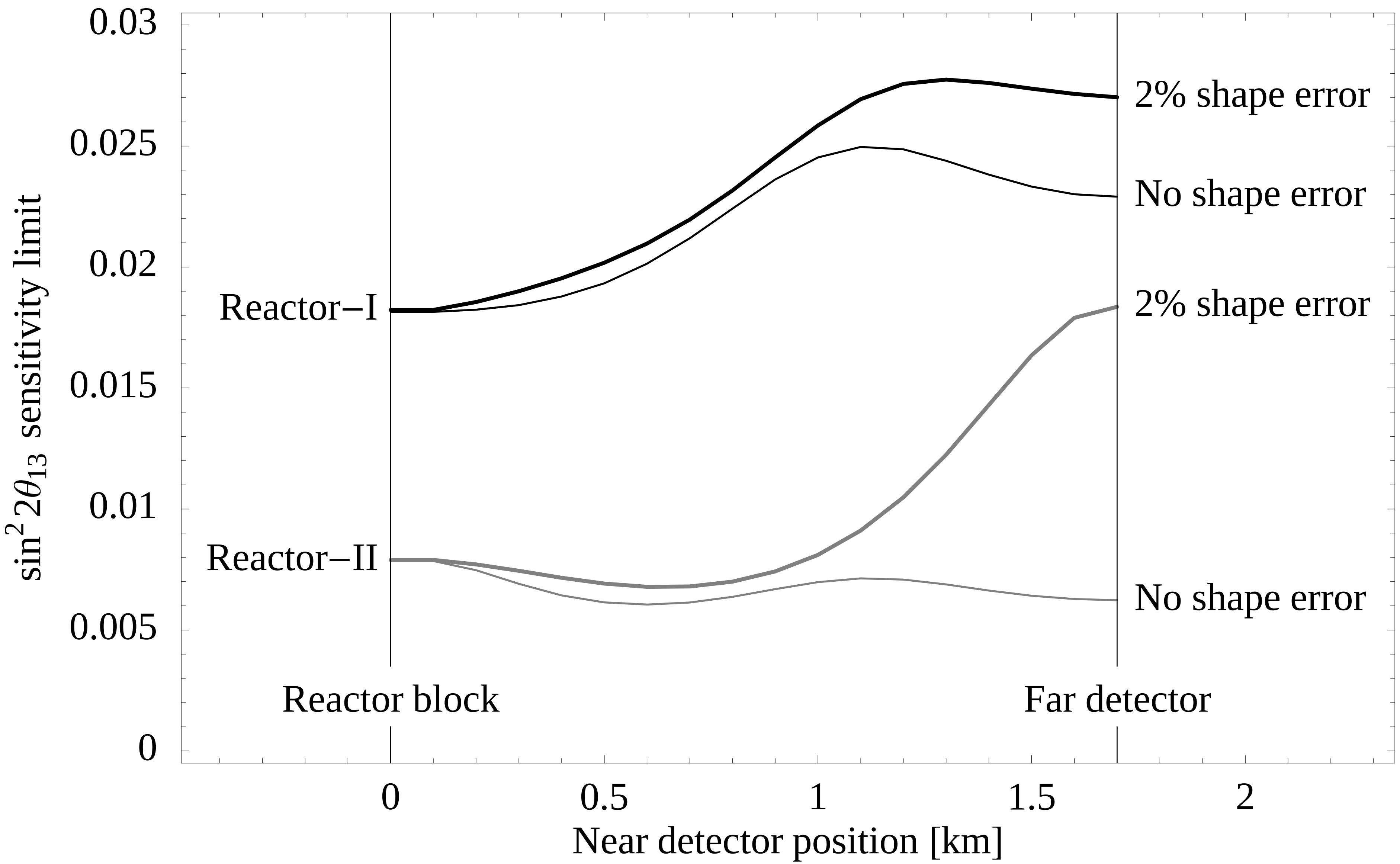
Reactor-II:
σ_{cal} and σ_{norm}
not important
energy cut
some impact

• Effect of an energy cut



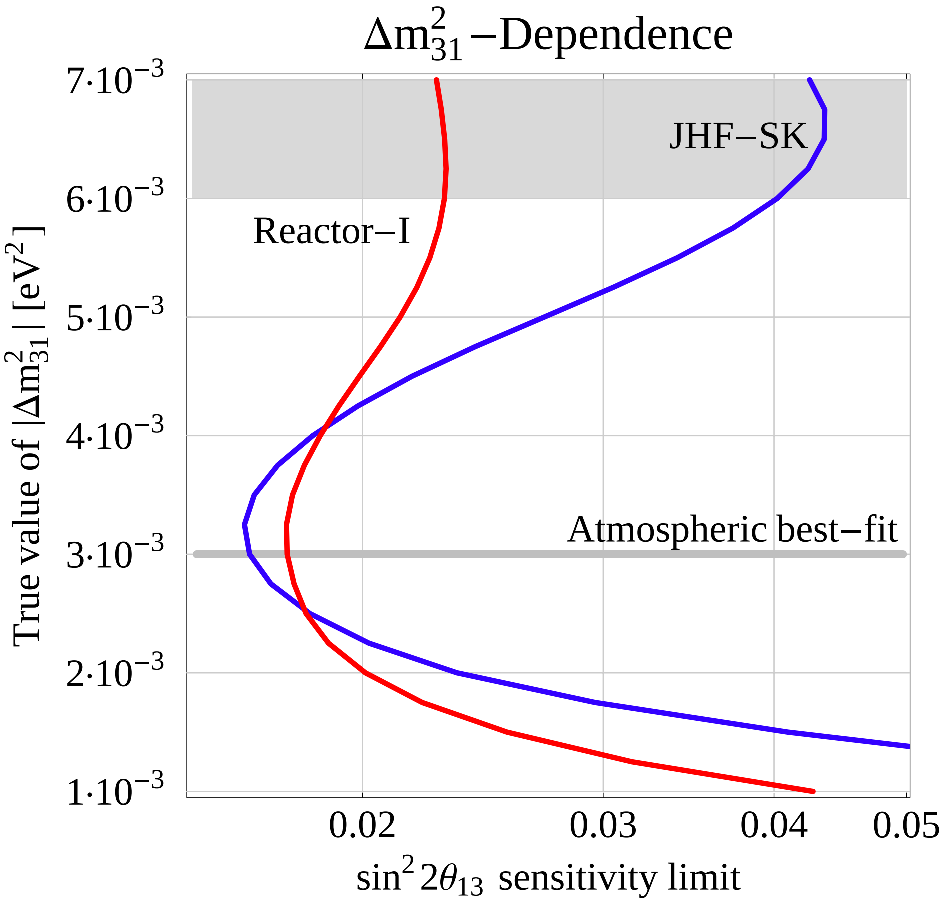
- **The position of the near detector**

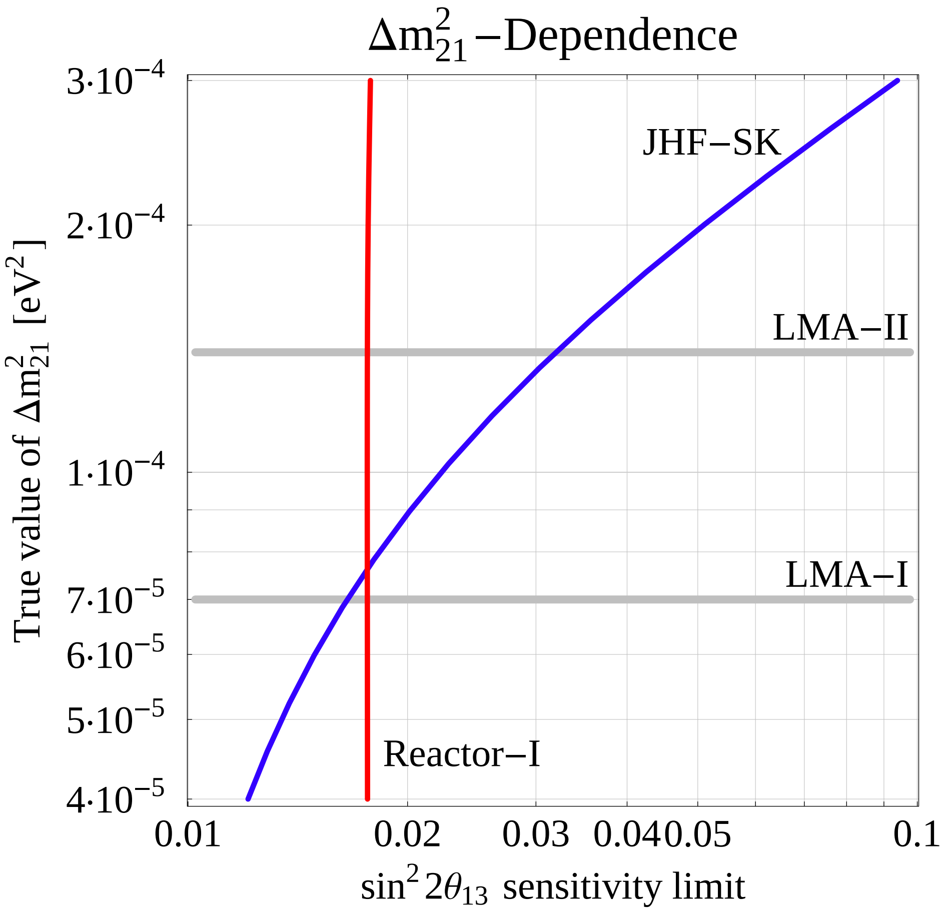
Real sites may not allow a near detector at 0.17 km (no-oscillation)⇒



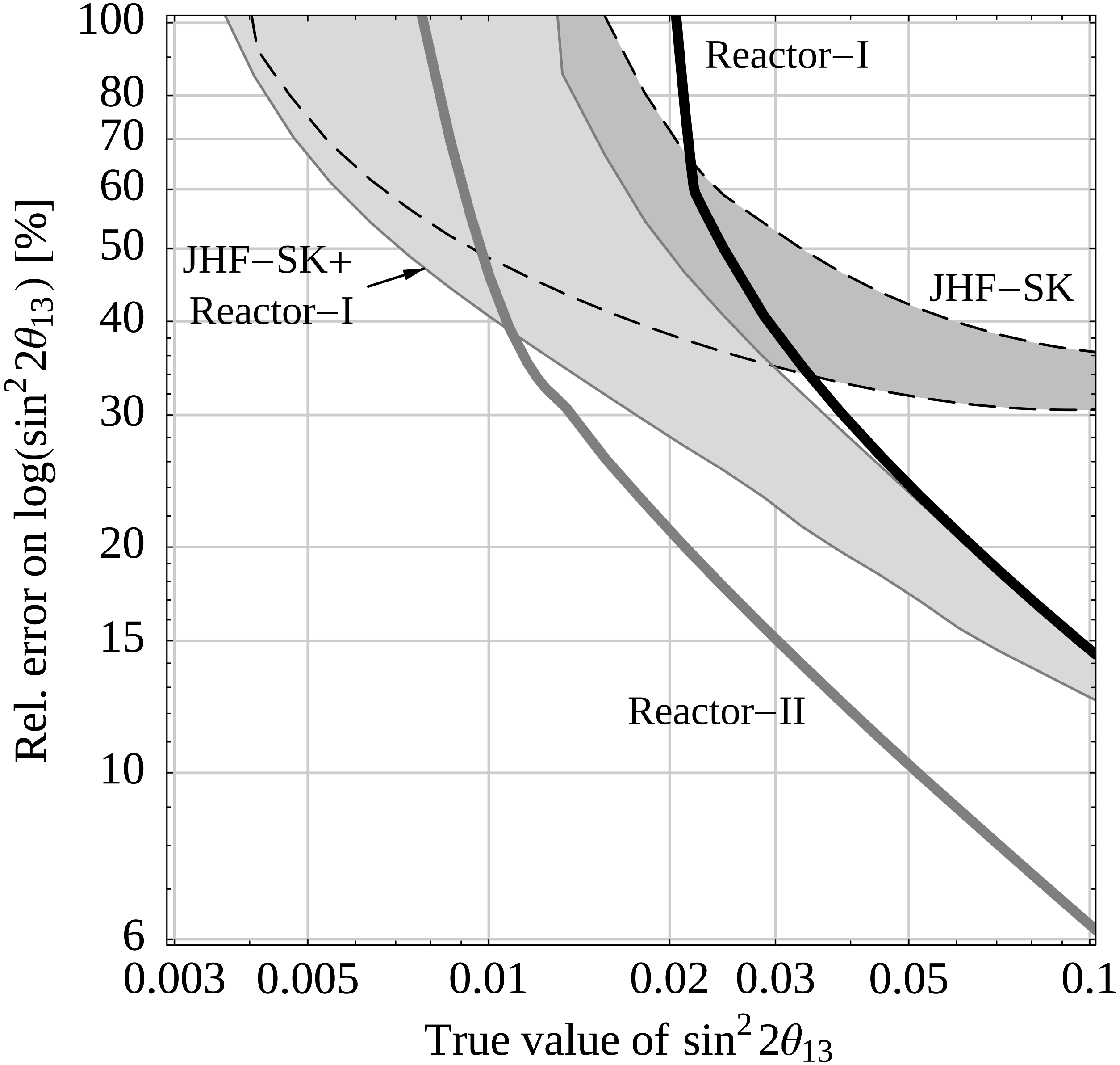
Comparison of Reactor and Superbeam experiments

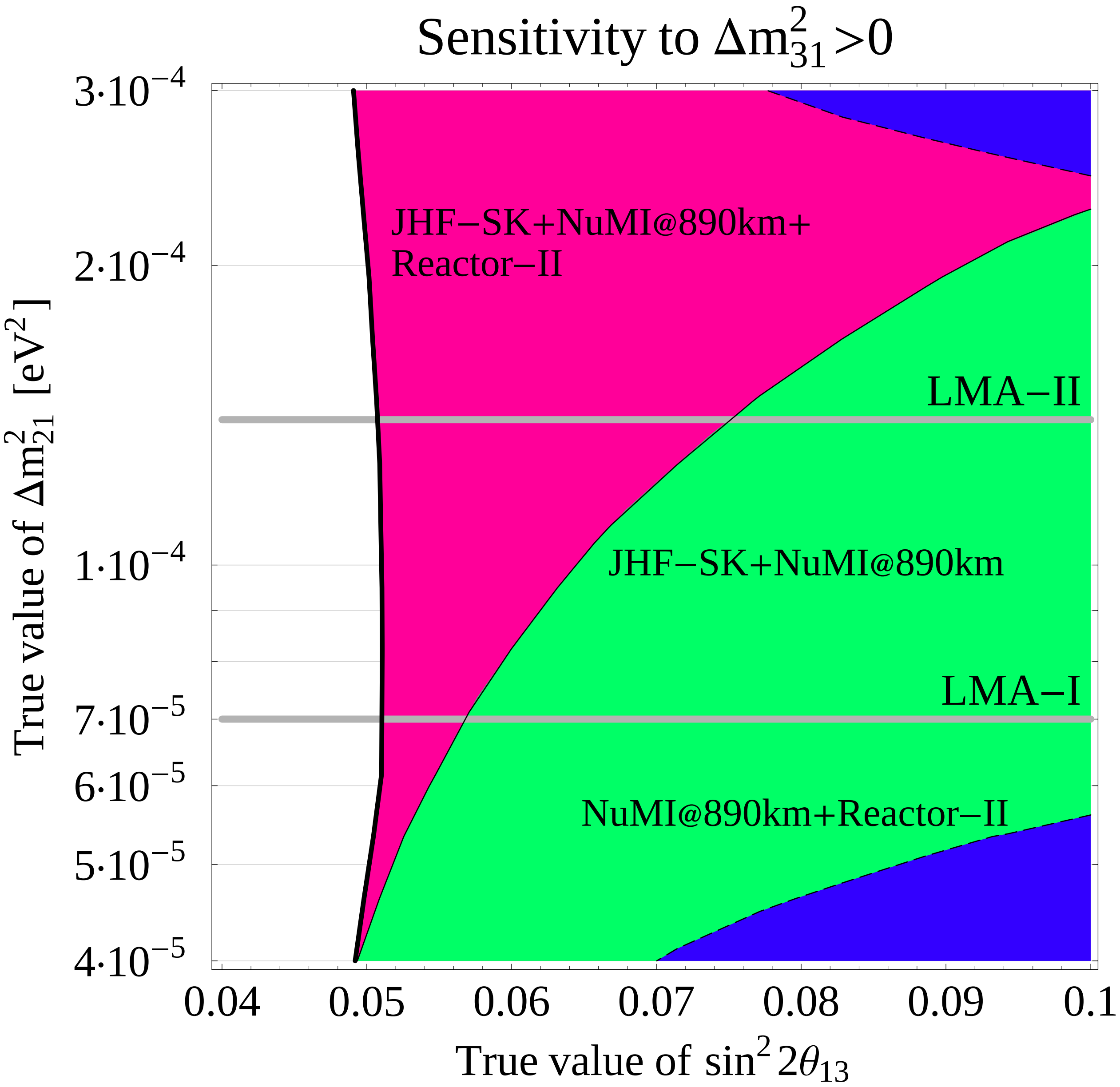
- **The sensitivity to $\sin^2 2\theta_{13}$ at 90% CL**

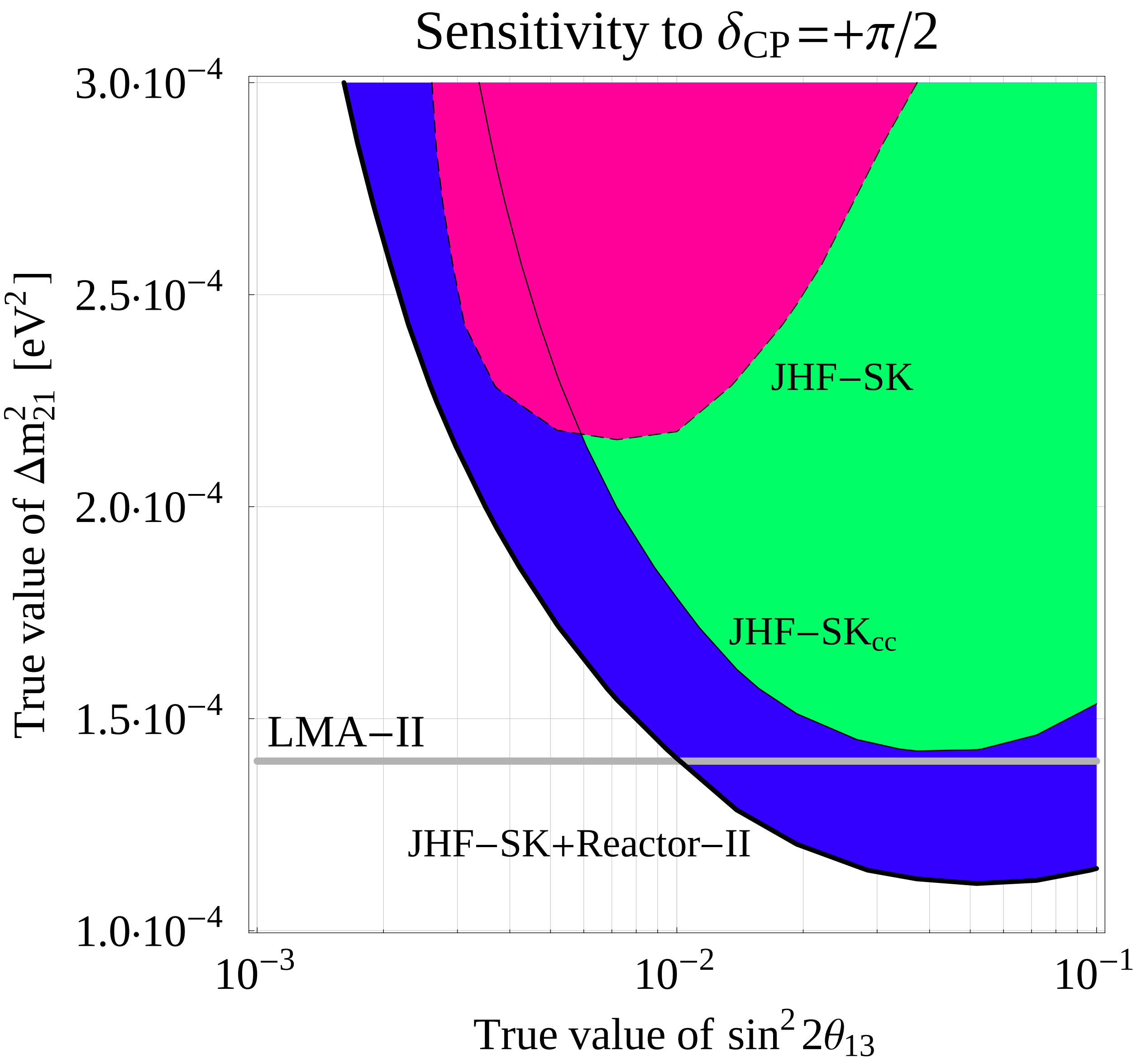




The Precision of $\sin^2 2\theta_{13}$




Sensitivity to Δm²31 >0
3·10−4
2·10−4
1·10−4
7·10−5
6·10−5
5·10−5
4·10−5
True value of Δm²21 [eV²]
0.04
0.05
0.06
0.07
0.08
0.09
0.1
True value of sin² 2θ13
JHF−SK+NuMI@890km+
Reactor−II
LMA−II
JHF−SK+NuMI@890km
LMA−I
NuMI@890km+Reactor−II



Sensitivity to $\delta_{CP}=+\pi/2$
$3.0\cdot10^{-4}$
$2.5\cdot10^{-4}$
$2.0\cdot10^{-4}$
$1.5\cdot10^{-4}$
$1.0\cdot10^{-4}$
True value of Δm^2_{21} [eV^2]
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

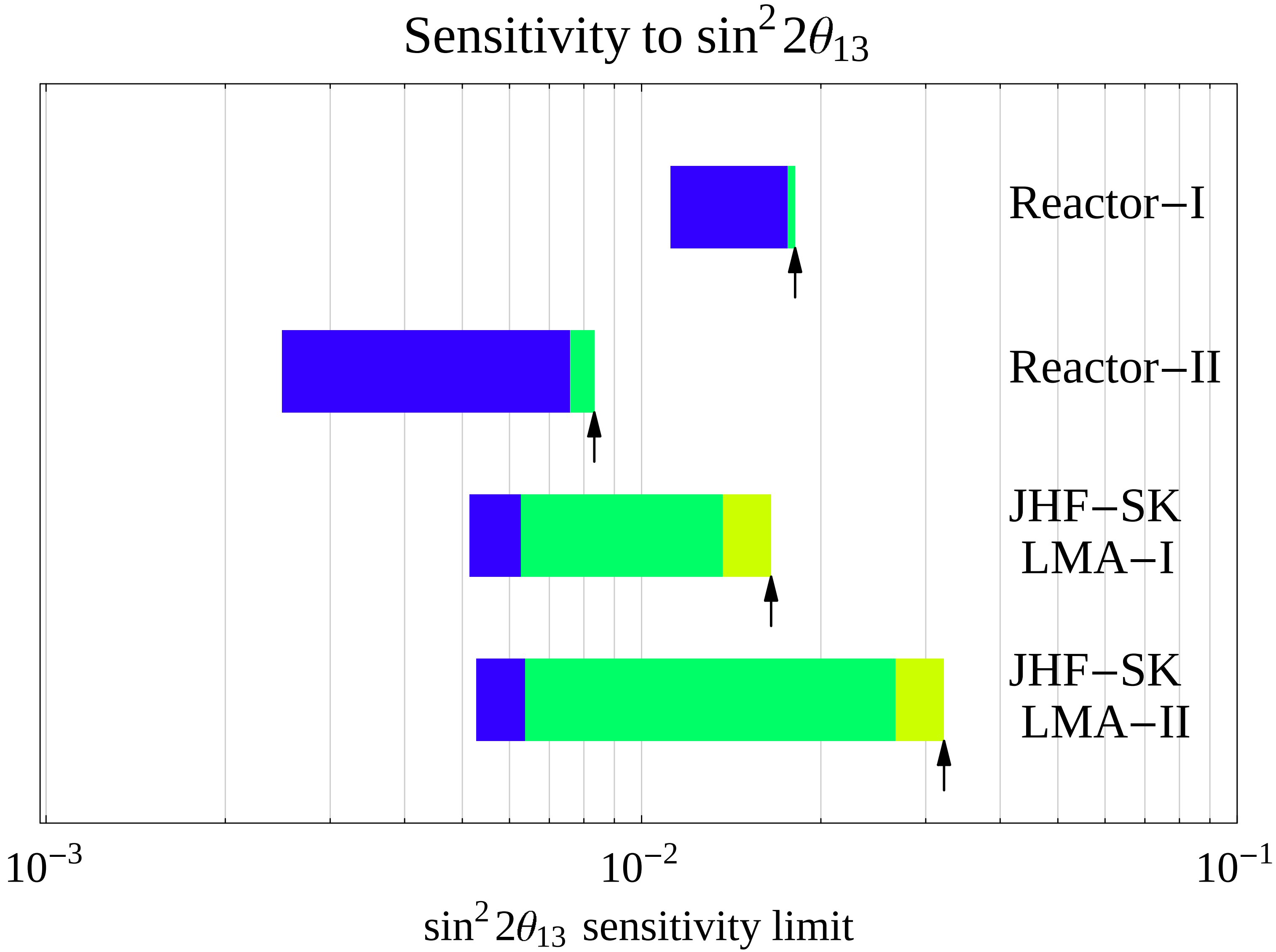
Summary

- 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 normalisation, shape uncertainty)
- Reactor-I ($\mathcal{L} \sim$ 400 t GW y)
  limit depends sensible on a relative normalisation error

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

- $\sin^2 2\theta_{13}$-limit is highly competitive to first generation superbeams

statistical errors
⇓
systematics
⇓
correlations
⇓
degeneracies
⇓
final result



– superbeam experiments suffer from correlations and degeneracies
.... especially for large Δm^2_{21}

- Combined analysis of reactor and superbeam experiments:
  - 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**