The physics potential of the next generation of long-baseline experiments

NuMi Off-axis meeting, Cambridge, UK

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Based upon ...

- **Superbeams versus Neutrino Factories**
  by Patrick Huber, Manfred Lindner, WW
  Nucl. Phys. B 645 (2002) 3, hep-ph/0204352
- **Synergies between the first-generation JHF-SK and NuMI superbeam experiments**
  by Patrick Huber, Manfred Lindner, WW
  Nucl. Phys. B 654 (2003) 3, hep-ph/0211300
- **Reactor Neutrino Experiments Compared to Superbeams**
  by Patrick Huber, Manfred Lindner, Thomas Schwetz, WW
  Nucl. Phys. B 665 (2003) 487, hep-ph/0303232
- **Understanding CP phase-dependent measurements at neutrino superbeams in terms of bi-rate graphs**
  by WW, hep-ph/0310307

Contents

- Introduction
- First-generation superbeams: JHF-SK and NuMI
- Reactor experiments with two detectors
- The $\sin^2 2\theta_{13}$-sensitivity limit
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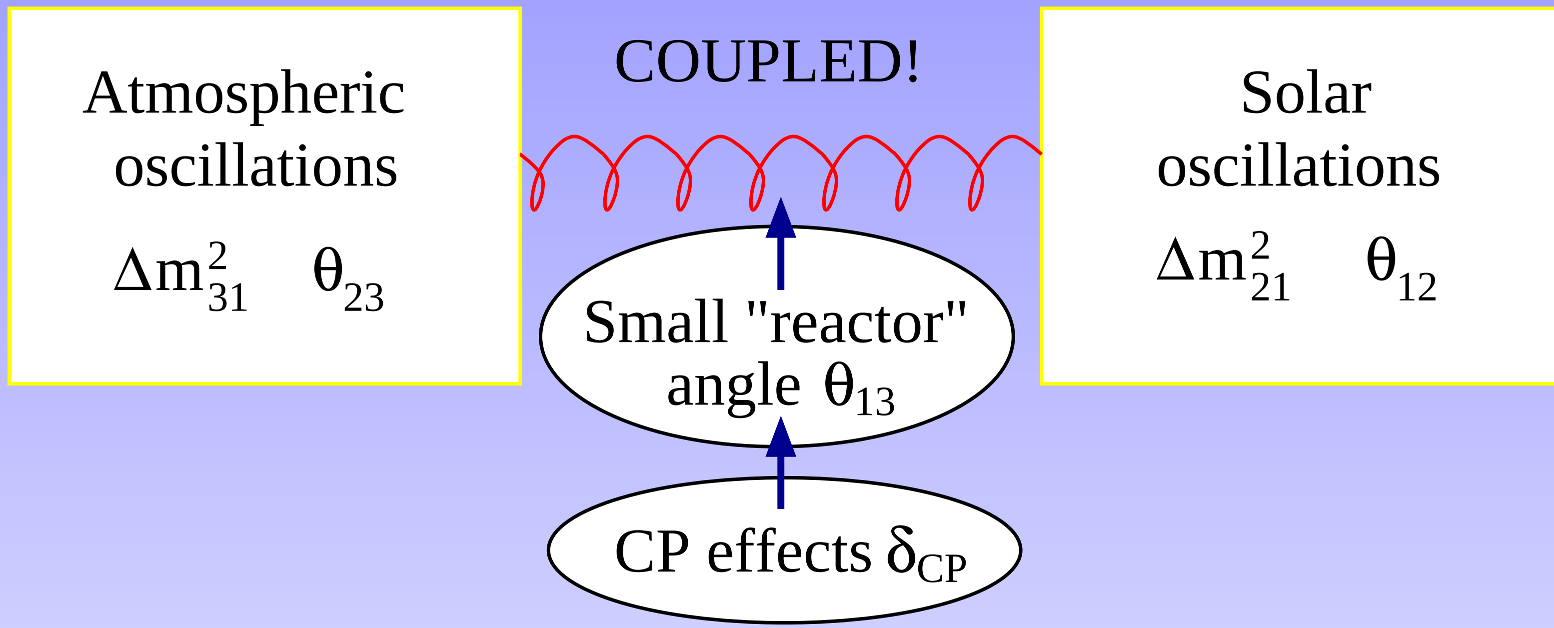
- CP measurements at LMA-I !?!
- Summary and conclusions

Introduction: Neutrino oscillations



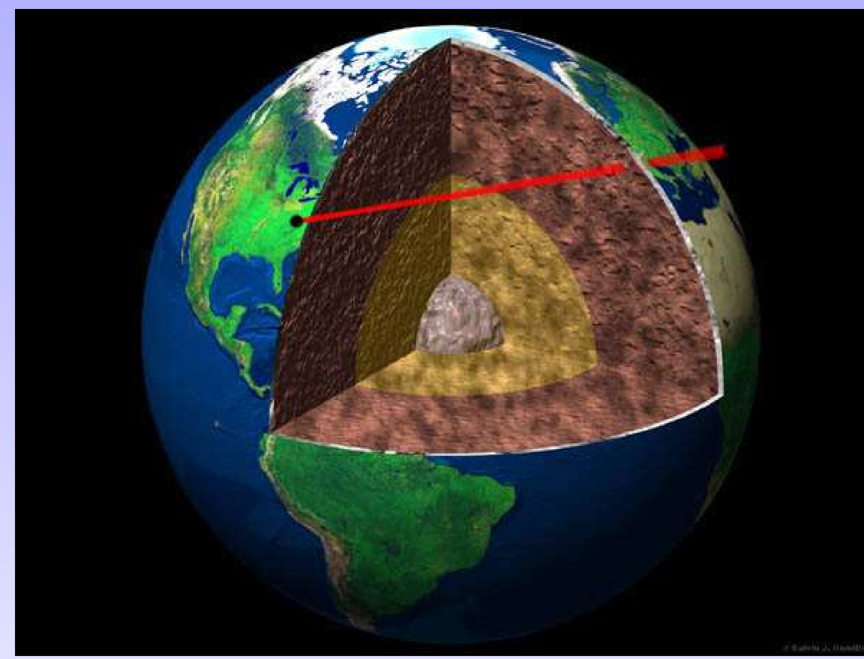
Most interesting for future LBL: θ_{13}, $\mathrm{sgn}(\Delta m^2_{31})$, δ_{CP}

Critical for three-flavor effects: Magnitude of θ_{13}

$\Rightarrow$ Find $\theta_{13} > 0$
$\Rightarrow$ Reactor experiment or superbeam?

Introduction: Future LBL experiments

- L, E chosen that in oscillation maximum:
  $\Delta m^2_{31} L/E = \mathcal{O}(1)$
  $\rightarrow L \sim 1\,\mathrm{km} - 8\,000\,\mathrm{km}$
  $\rightarrow E \sim 1\,\mathrm{MeV} - 50\,\mathrm{GeV}$
- Artificial neutrino source: Reactor, Accelerator
  $\rightarrow$ well-known flux, flavor composition, ...
- Often: near detector for better control of systematics



Examples for future LBL exps

	Reactor exp.	Superbeam	Neutrino Factory
Timescale	$\lesssim 2015$	$\lesssim 2015$	> 2015
Source	Reactor	Accelerator	Accelerator
ν-production	Semi-leptonic	Semi-leptonic	Leptonic
	$n \rightarrow p + e^- + \bar{\nu}_e$	$\pi, K \underset{>99\%}{\rightarrow} \mu + \nu_\mu$	$\mu \rightarrow e + \bar{\nu}_e + \nu_\mu$
Constraints	Systematics	Systematics	Statistics
Challenges	Knowledge of detector	Backgrounds	Target power, muon cooling
ν-energies	$\sim 4\,\mathrm{MeV}$	$\sim 1\,\mathrm{GeV}$	$\sim 50\,\mathrm{GeV}$
Baselines	$1 - 2\,\mathrm{km}$	$300 - 1\,000\,\mathrm{km}$	$700 - 7\,500\,\mathrm{km}$

First-generation superbeams

	JHF-SK	NuMI
Beam		
Baseline	295 km	a) 712 km b) 890 km c) 950 km
Off-axis angle	2°	a)b) 0.72° c) 0.97°
Target Power	0.77 MW	0.4 MW
Detector		
Technology	Water Cherenkov	Low-Z calorimeter
Fiducial mass	22.5 kt	50 kt
Running period	5 years	5 years

... similar to LOIs (Itow et al, 2001; Ayres et al, 2002)

(Simulation description: Huber, Lindner, Winter, NPB 654, 2002, 3, hep-ph/0211300)

Superbeams: Appearance channels

Interesting information in $P_{\mathrm{app}} = P_{\mu e}$ or $P_{\bar{\mu}\bar{e}}$

To second order in $\sin 2\theta_{13}$ and the hierarchy parameter $\alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$:

$$
\begin{aligned}
P_{\mathrm{app}} &\simeq \sin^2 2\theta_{13}\, \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
&\pm \alpha \sin 2\theta_{13}\, \xi \sin\delta_{\mathrm{CP}} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \alpha \sin 2\theta_{13}\, \xi \cos\delta_{\mathrm{CP}} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2},
\end{aligned}
$$

$\Delta \equiv \frac{\Delta m_{31}^2 L}{4E}$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$, $\hat{A} \equiv \pm \frac{2\sqrt{2} G_F n_e E}{\Delta m_{31}^2}$.

$\rightarrow \sin^2 2\theta_{13}$, δ_{CP}, and mass hierarchy (via $\hat{A}$) measurements!

(Cervera et al., 2000; Freund, Huber, Lindner, 2000; Freund, 2001)

Problems with degeneracies

Especially for large α and $\sin 2\theta_{13}$ all terms act simultaneously
$\rightarrow$ A different parameter value in one term can often be compensated by a different parameter value in another term
$\rightarrow$ There exists an "eight-fold" degeneracy (Barger, Marfatia, Whisnant, 2001):

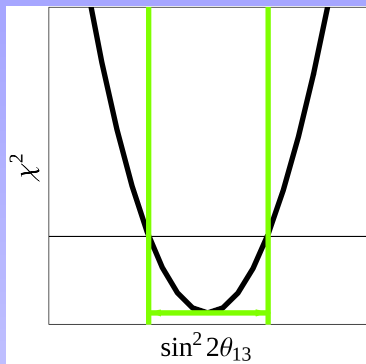
1) $\text{sgn}(\Delta m_{31}^2)$-degeneracy (Minakata, Nunokawa, 2001)
Most important for us: solution for opposite sign of Δm_{31}^2 spoils especially mass hierarchy and $\sin^2 2\theta_{13}$ measurements

2) $(\theta_{23}, \frac{\pi}{2} - \theta_{23})$-degeneracy (Fogli, Lisi, 1996)
Does not appear for current best-fit value $\theta_{23} = \pi/4$

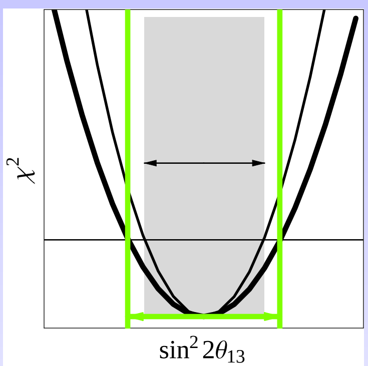
3) (δ, θ_{13})-degeneracy (Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, 2001)
Important for neutrino factories because of good energy resolution and statistics

Superbeams: Impact factors

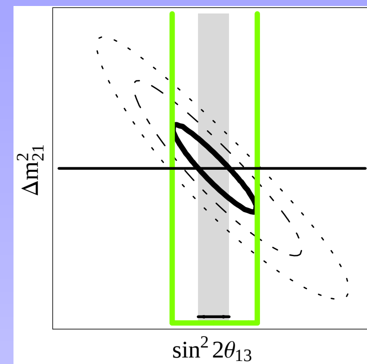
1. Statistical errors



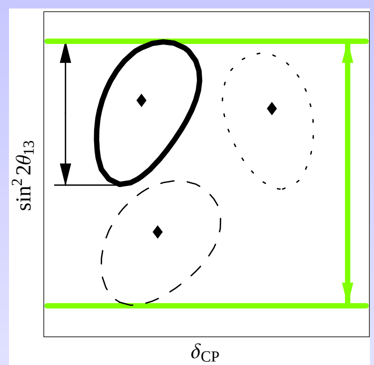
2. Systematics



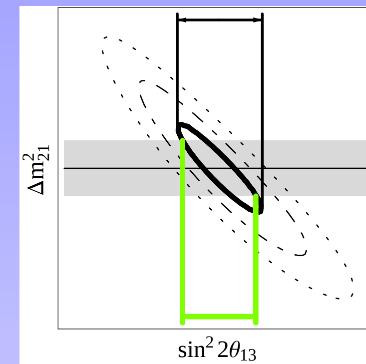
3. Correlations



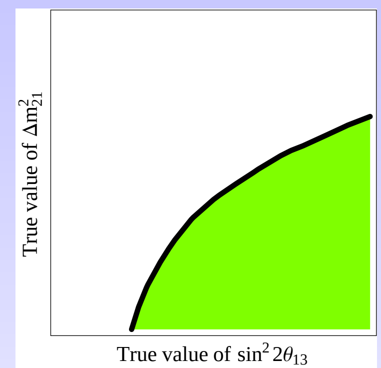
4. Degeneracies



5. External input



6. True values



Determined by R&D of experiment

Controllable by L, E, combinations, ...

No influence by experiment

For a more detailed discussion: see Secs. 3 and 5 of hep-ph/0204352

The new player: Reactor experiments

$\xrightarrow{\bar{\nu}_e}$ **near det.** ($\lesssim 500\,\mathrm{m}$) $\xrightarrow{\bar{\nu}_e}$ **far det.** ($\sim 1.7\,\mathrm{km}$)

Key ideas:

1) Build detector much *bigger* than CHOOZ
$\longrightarrow$ KamLAND etc.: it is possible to build such a detector

2) Use additional *near detector* (without oscillations!)
$\longrightarrow$ Eliminate uncertainties
$\longrightarrow$ Relative precision is easier than absolute precision

3) Use *identical* near and far detectors
$\longrightarrow$ Eliminate correlated errors (e.g., shape uncertainty)

(Martemyanov et al, 2002, Minakata et al, 2002, Huber et al, 2003, Schönert et al, 2003, ...)

Reactor setups: Examples

	Reactor-I	Reactor-II
Integrated luminosity	$400\,\mathrm{t\,GW\,y}$	$8000\,\mathrm{t\,GW\,y}$
Unoscillated events	$31\,493$	$629\,867$
σ_{norm}	0.8%	0.8%
σ_{cal}	0.5%	0.5%
Baseline	$1.7\,\mathrm{km}$	$1.7\,\mathrm{km}$
Detector equivalent (for $2\,\mathrm{y}$ and $10\,\mathrm{GW}$)	$4\times$ CHOOZ	KamLAND

(Luminosities given in detector mass [t] $\times$ thermal reactor power [GW] $\times$ running time [y])

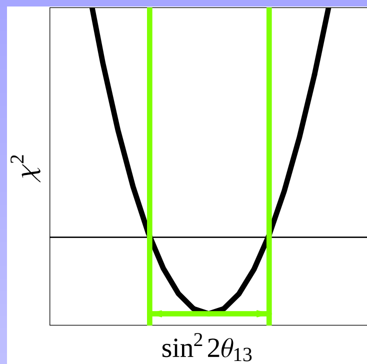
Additional assumptions:

- Background-free measurement (Schönert, Lasserre, Oberauer, hep-ex/0203013)
- Identical near and far detectors
- 100 % detection efficiency ($\longrightarrow$ maybe re-scaling)

(Huber, Lindner, Schwetz, Winter, NPB 665, 2003, 487, hep-ph/0303232)

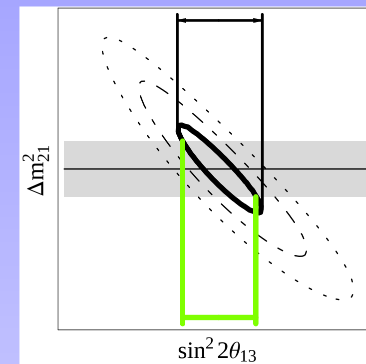
Reactor experiments: Impact factors

1. Statistical errors

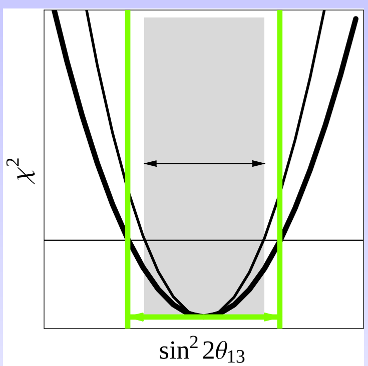


5. External input

Only $\Delta m_{31}^2 \longrightarrow$ to about 30-50%



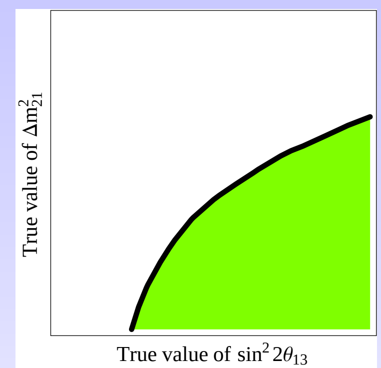
2. Systematics



$\longleftarrow$ Critical!

6. True values

Quite robust (later) $\longrightarrow$



Determined by R&D of experiment

No influence by experiment

True and fit parameter values

True parameter values: Used to compute the reference rate vector

→ Replace data for the analysis of future experiments

→ Provided by nature within current limits

Fit parameter values: Used to fit the reference rate vector

→ Determine prec. of quantities of interest (fixed ref. rate vector)

→ Lead to correlations

Correlations in "theorist's language":

The precision for a set of k parameters is obtained by the projection of the n-dim. fit manifold onto the k-dim. hyperplane ($1 \leq k < n$)

Ex.: Projection onto $\sin^2 2\theta_{13}$-axis (1D) or $\sin^2 2\theta_{13}$-δ_{CP}-plane (2D)

Difference to "cut" through fit manifold:

No correlations, computed for fixed oscillation parameters

Definition: $\sin^2 2\theta_{13}$-sensitivity

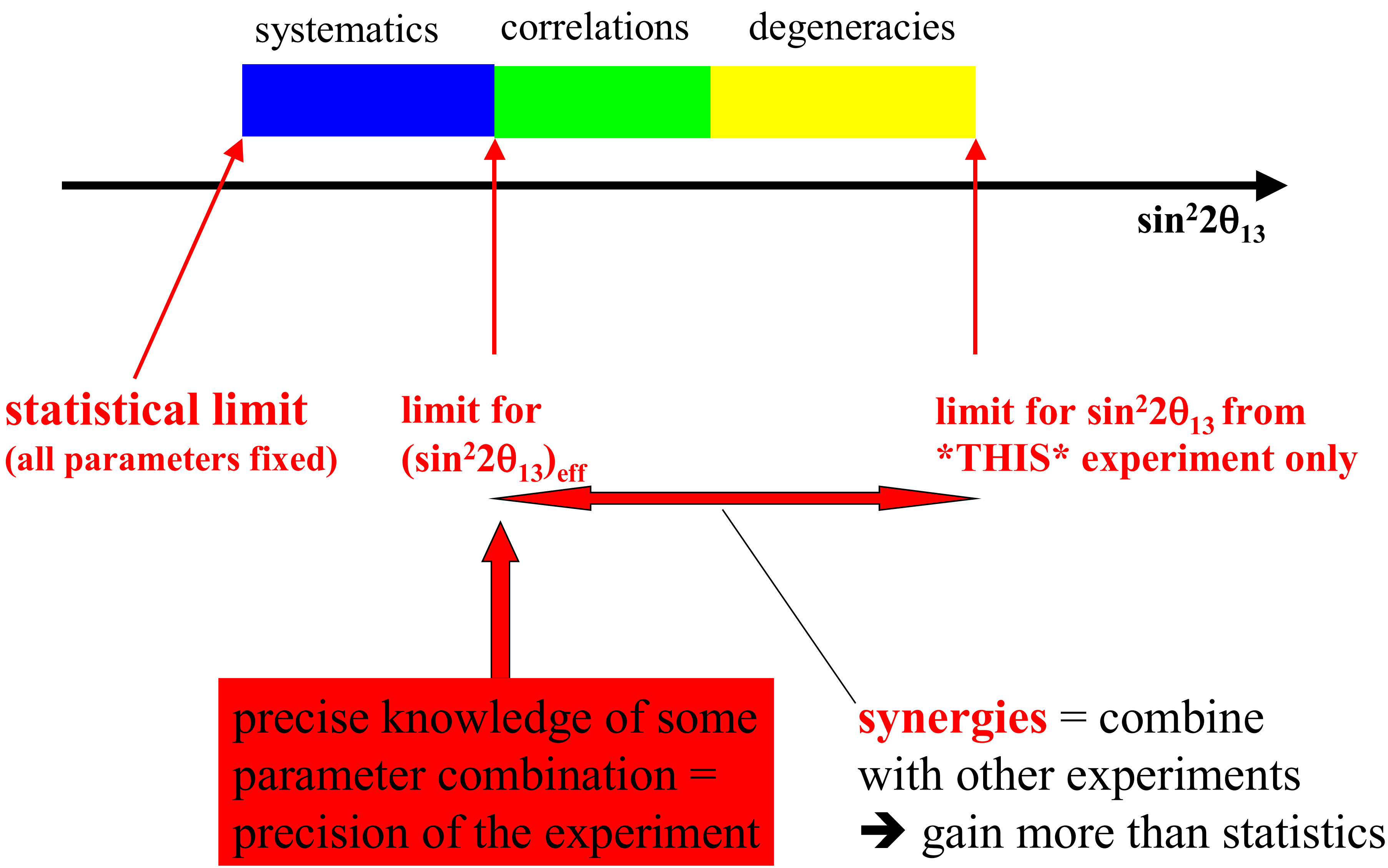
We define:

The $\sin^2 2\theta_{13}$-sensitivity limit is the largest fit value of $\sin^2 2\theta_{13}$, which fits the true value $\sin^2 2\theta_{13} = 0$ at the chosen CL.

Advantages:

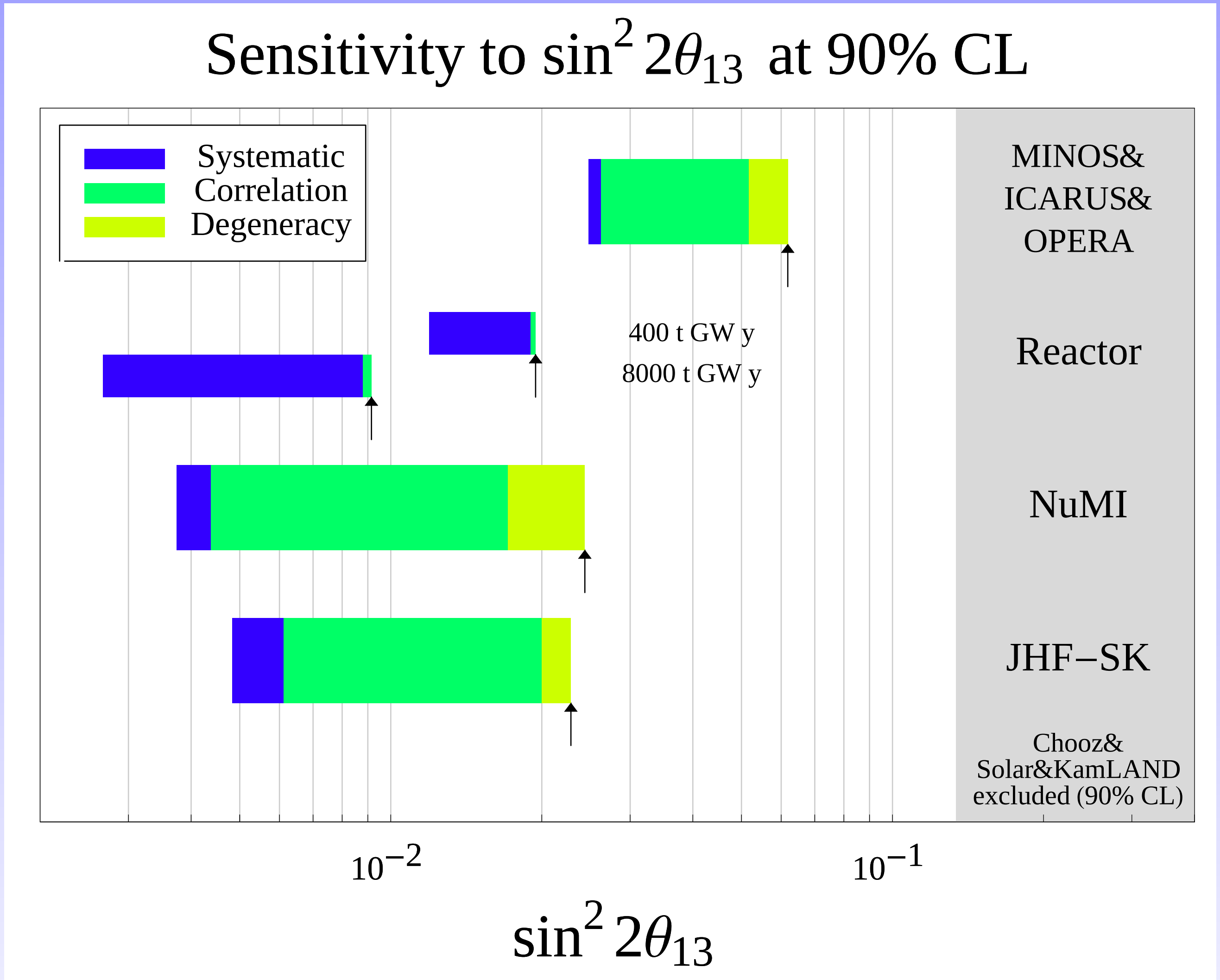
- ✓ Reference rate vector is computed for $\sin^2 2\theta_{13} = 0$
  $\rightarrow$ No dependence on the true value of δ_{CP}
- ✓ Guaranteed range, in which $\sin^2 2\theta_{13}$ will be found (at CL)
  $\rightarrow$ Covers all degeneracies (reference rate vector equal!)
- ✓ Straightforward inclusion of $\mathrm{sgn}(\Delta m^2_{31})$-degeneracy
  $\rightarrow$ Sensitivity limit does not depend on mass hierarchy
- ✓ Inclusion of correlations by projection onto $\sin^2 2\theta_{13}$-axis

Sensitivitiy Plots



(Courtesy of Manfred Lindner)

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



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

NuMI as in proposal

(+8% target power),

MINOS etc.:

5 yr running time

(Huber et al,

in preparation;

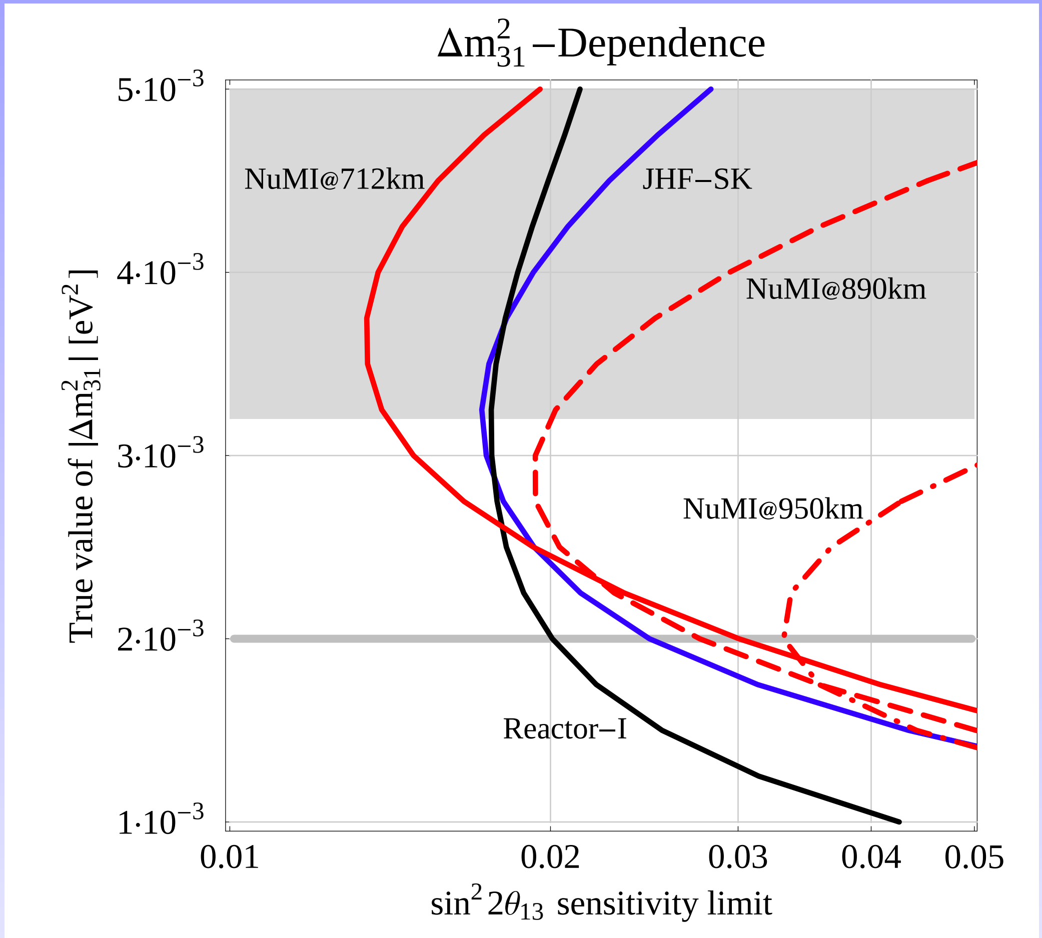
Courtesy of

Marc Rolinec)

→ Superbeam (1st gen.) dominated by correlations and degeneracies

→ Reactor experiments dominated by systematics

$\sin^2 2\theta_{13}$-sens.: Δm^2_{31}-dependence



90% CL, unpublished

Includes correlations and degeneracies!

(Similar figure without NuMIin hep-ph/0303232)

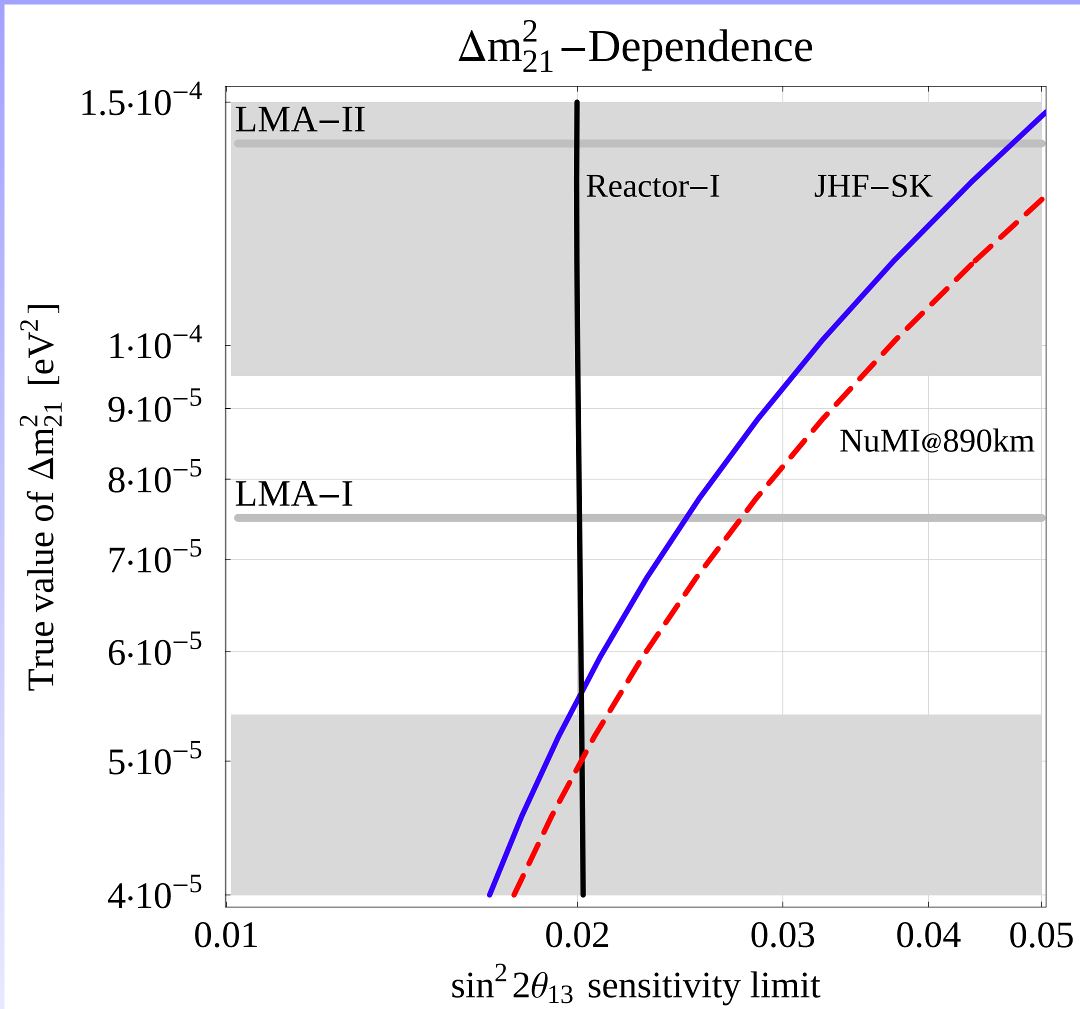
→ REACTOR-I very robust (broad spectrum)

→ Rel. improvement to CHOOZ bound important! (Breaks away for small Δm^2_{31})

→ NuMI: sharper spectrum; peak position depends on L, E

→ At $\Delta m^2_{31} = 2\cdot10^{-3}\,\mathrm{eV}^2$ hardly difference among options; NuMI@890km best

$\sin^2 2\theta_{13}$-sens.: Δm^2_{21}-dependence



$\rightarrow$ Reactor experiment hardly affected by Δm^2_{21}

$\rightarrow$ Superbeams: Correlations become important for large Δm^2_{21}

$\rightarrow$ Is the timescale the most critical issue for NuMI???

$\Delta m^2_{31} = 2 \cdot 10^{-3}\,\mathrm{eV}^2$, 90% CL, unpublished

Includes correlations and degeneracies!

(Similar figure without NuMIin hep-ph/0303232)

What reactor experiments cannot do

- ✓ No measurement of Δm_{31}^2 independent of $\sin^2 2\theta_{13}$
- ✓ No measurement of θ_{23}
- ✓ No matter effects, no mass hierarchy sensitivity
- ✓ No sensitivity to δ_{CP}
- ✓ No flavor transitions $\nu_\alpha \rightarrow \nu_\beta$ observable

$\rightarrow$ What can NuMI off-axis do and the others not?

For example: Mass hierarchy sensitivity

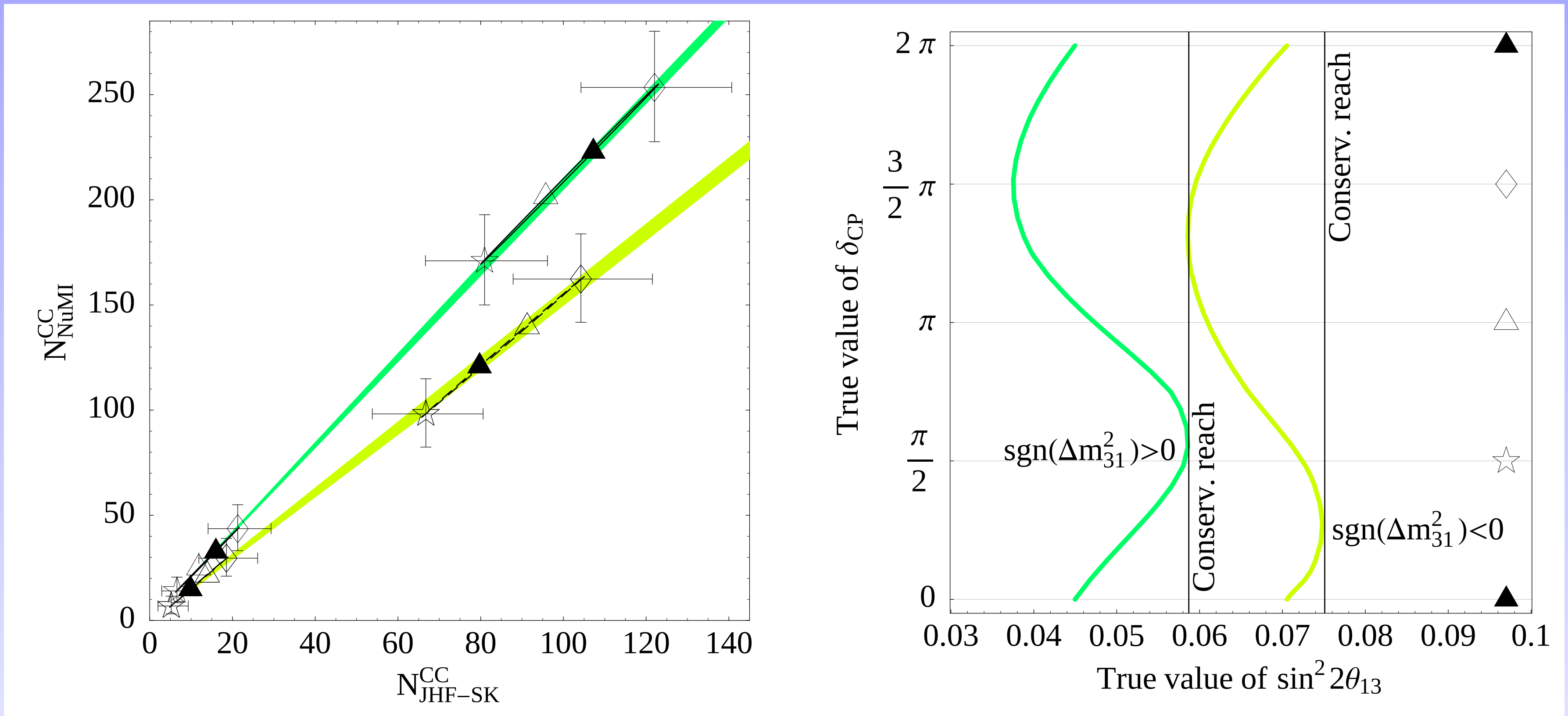
$\rightarrow$ Put detector to longer baseline $L \gg 712\,\mathrm{km}$

(Barger, Marfatia, Whisnant, hep-ph/0210428; Huber, Lindner, Winter, hep-ph/0211300)

(Minakata, Nunokawa, Parke, hep-ph/0301210)

Mass hierarchy sensitivity reach

JHF-SK + NuMI@890km, 50kt:



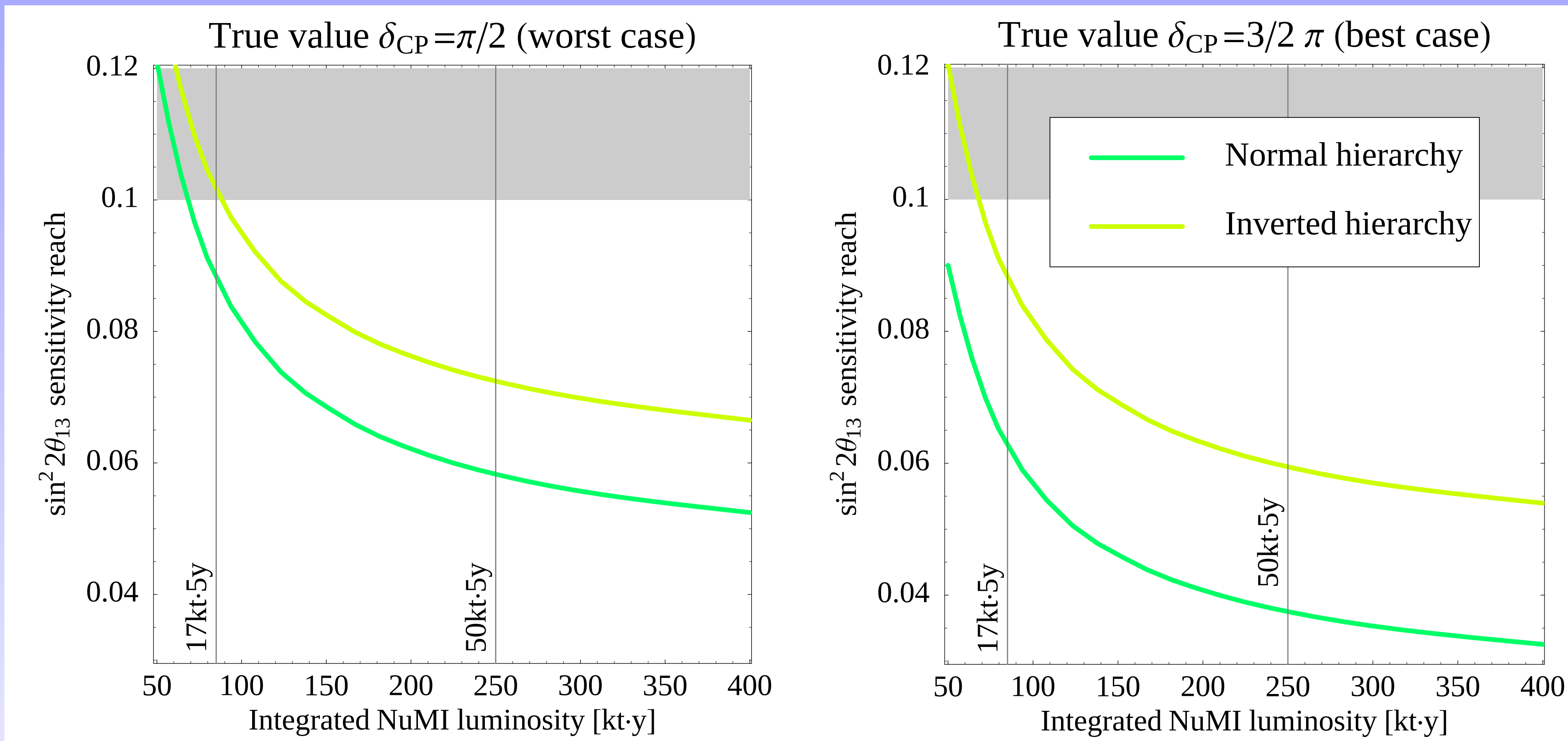
$\Delta m^2_{31} = 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$, 90% CL (Winter, hep-ph/0310307)

"Conservative reach": This can be done in any case!

For bi-probability graphs, see also Minakata, Nunokawa, Parke, hep-ph/0301210

Mass hierarchy: Luminosity scaling

JHF-SK + NuMI@890km, $\sin^2 2\theta_{13}$-sensitivity reach:



$\Delta m^2_{31} = 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$, 90% CL

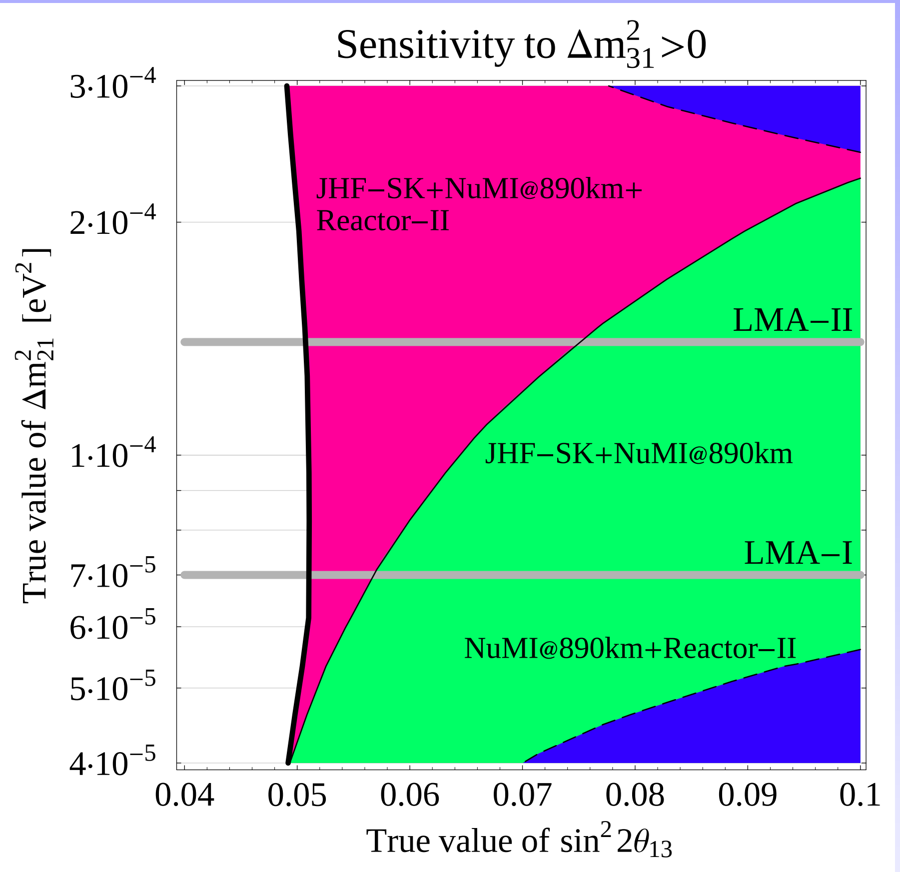
(Winter, hep-ph/0310307)

$\longrightarrow$ 50 kt detector very useful!

Mass hierarchy sensitivity: Synergies

→ "How many experiments do we need for that?"

- ✓ JHF-SK or NuMI@712km alone: No sensitivity
- ✓ JHF-SK+NuMI: Put NuMI to longer baseline
- ✓ Strong dependence on Δm^2_{21} can be resolved by large reactor experiment
- ✓ Three exps optimal!

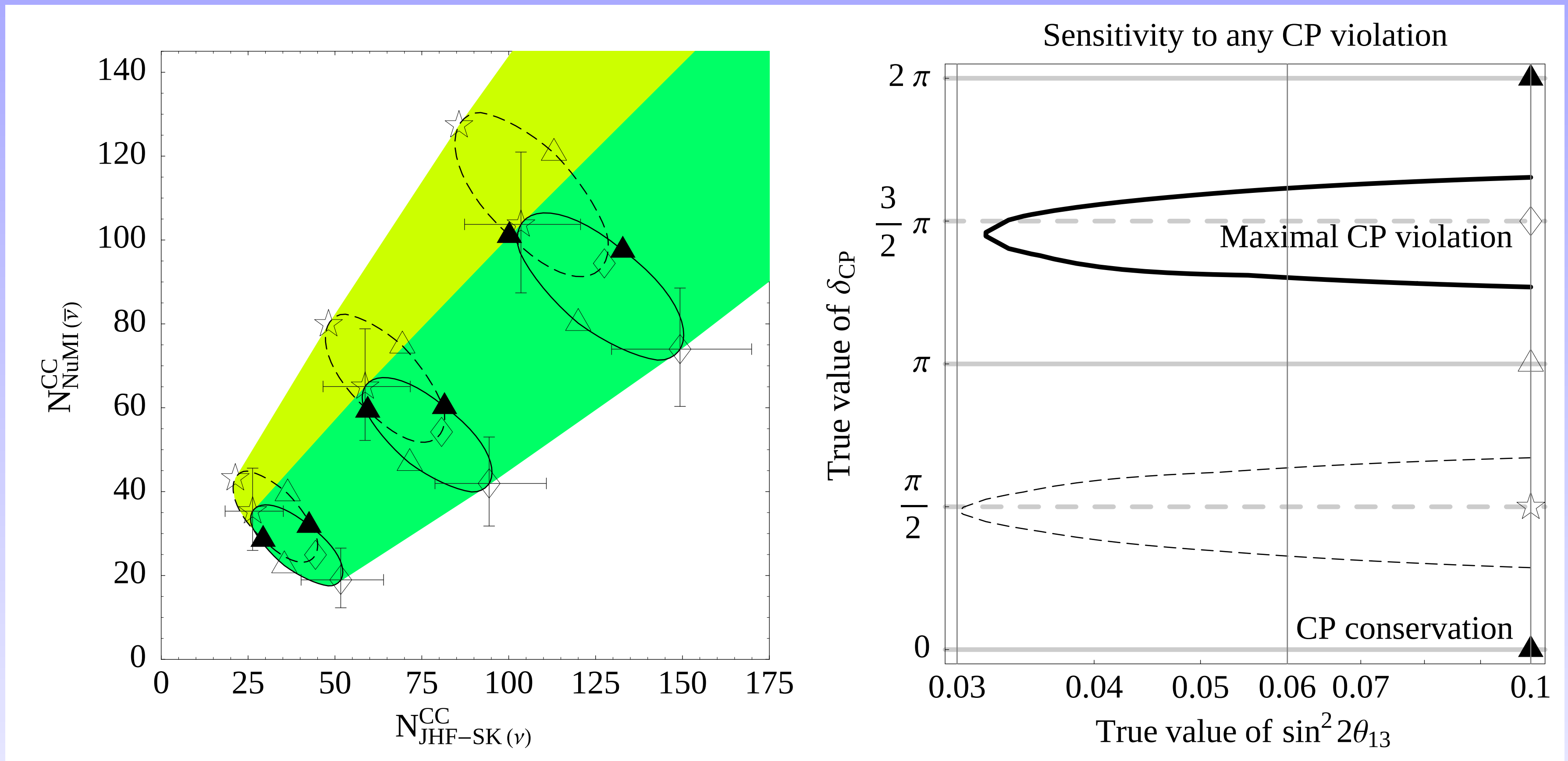


Conservative reach, 17 kt NuMI detector only!, $\Delta m^2_{31} = 3 \cdot 10^{-3}\,\mathrm{eV}^2$, 90% CL

(Huber, Lindner, Winter, hep-ph/0211300; Huber, Lindner, Schwetz, Winter, hep-ph/0303232)

What about CP violation at LMA-I?

Example: JHF-SK (ν)+ NuMI@712km, 50kt, $\bar{\nu}$ only:



$\Delta m^2_{31} = 2.5 \cdot 10^{-3}\,\text{eV}^2$, 90% CL, dashed=no degeneracy (Winter, hep-ph/0310307)

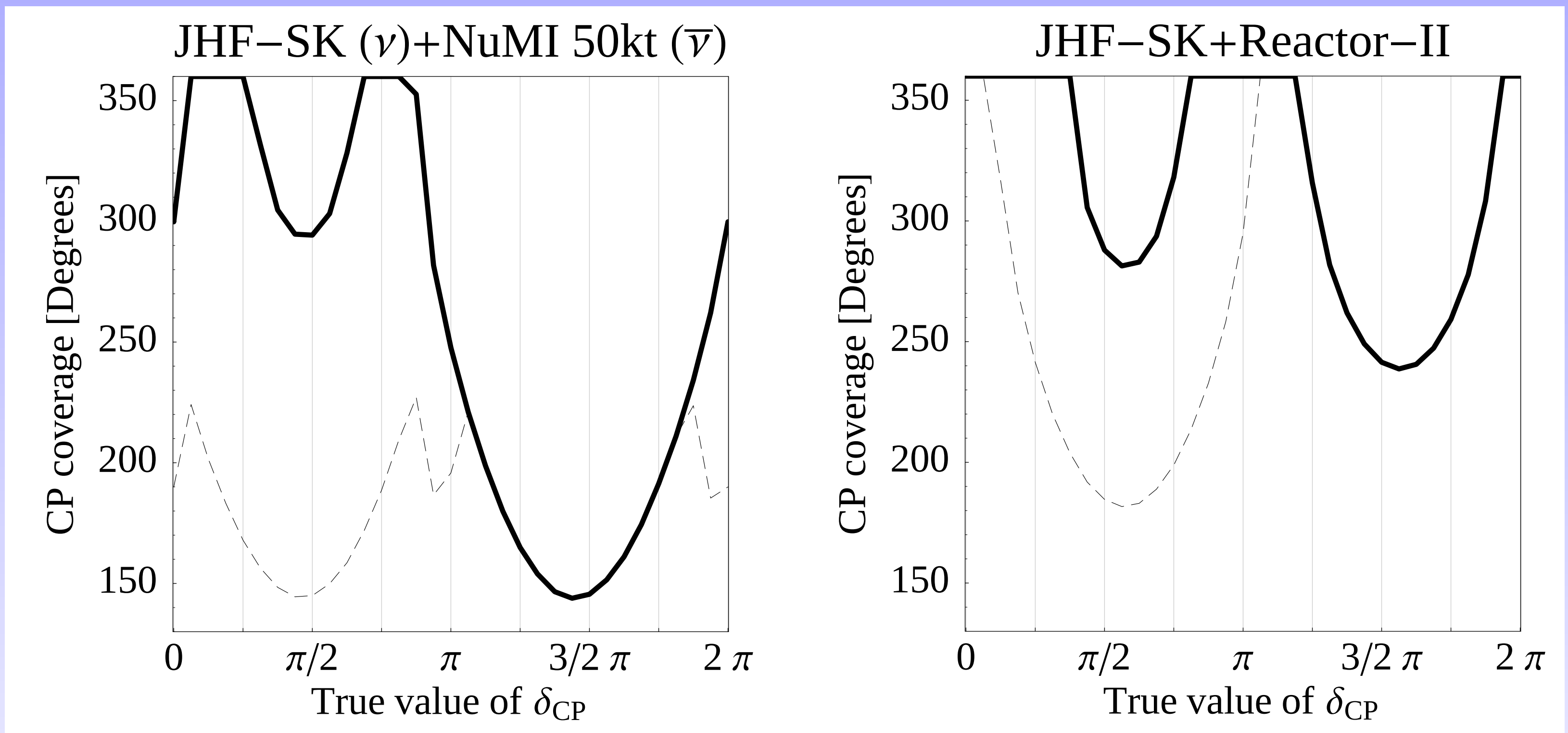
$\rightarrow$ In spite of optimized setup only marginal sensitivity close to $3/2\pi$

$\rightarrow$ But: $\bar{\nu}$-running could be replaced by REACTOR-II!

Can we learn sth about $\delta_{\rm CP}$ at all?

"CP coverage" of 360° = no information on $\delta_{\rm CP}$

Examples: CP patterns = CP coverage as fct. of True value of $\delta_{\rm CP}$



$\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{31} = 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$, 90% CL, dashed=no deg. (Winter, hep-ph/0310307)

→ Though no CP violation may be possible, certain regions of the "CP circle" could be excluded if one is lucky!

Summary (simplified)

	JHF-SK	NuMI	Reactor exp.
Δm^2_{31}, θ_{23}	Good	Good	Poor
θ_{13}-sensitivity	Param.-dep.	Param.-dep.	Robust
Matter effects	Almost none	712km / $\gg$712km	None
Mass hierarchy	None	None	None
	Good (NuMI@890km)		
	Very good (NuMI@890km), indep. of Δm^2_{21}		
CP violation	Marginal, close to $\delta_{CP} = 3/2\pi$ only		
CP precision	Marginal, but for all values of δ_{CP}: $< 360°$		
Flavor trans.	Yes	Yes	No
Spectral info.	Marginal	Marginal	Good

Conclusions

- ✓ All experiment types needed: Synergies, Complementarity
- ✓ For $\sin^2 2\theta_{13}$, a reactor experiment would be very competitive
- ✓ NuMI: Long baseline $\gg 712\,\mathrm{km}$ interesting to make its physics potential unique
  $\rightarrow$ Mass hierarchy sensitivity/matter effects
- ✓ In principle: Lower energy/large OA angle possible
  But: over-proportional loss of events
- ✓ CP-sensitivity as a "by-product" for large $\sin^2 2\theta_{13}$!?
  $\rightarrow$ Reactor-II instead of long $\bar{\nu}$-running?