Resolving degeneracies for different values of θ_{13}

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Introduction: neutrino oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \underbrace{\sum_{i=1}^{3} \sum_{\substack{j=1 \\ i>j}}^{3} \mathrm{Re}\, J_{ij}^{\alpha\beta} \sin^2 \Delta_{ij}}_{\mathrm{CP-conserving}} - 2 \underbrace{\sum_{i=1}^{3} \sum_{\substack{j=1 \\ i>j}}^{3} \mathrm{Im}\, J_{ij}^{\alpha\beta} \sin 2\Delta_{ij}}_{\mathrm{CP-violating}}$$

with

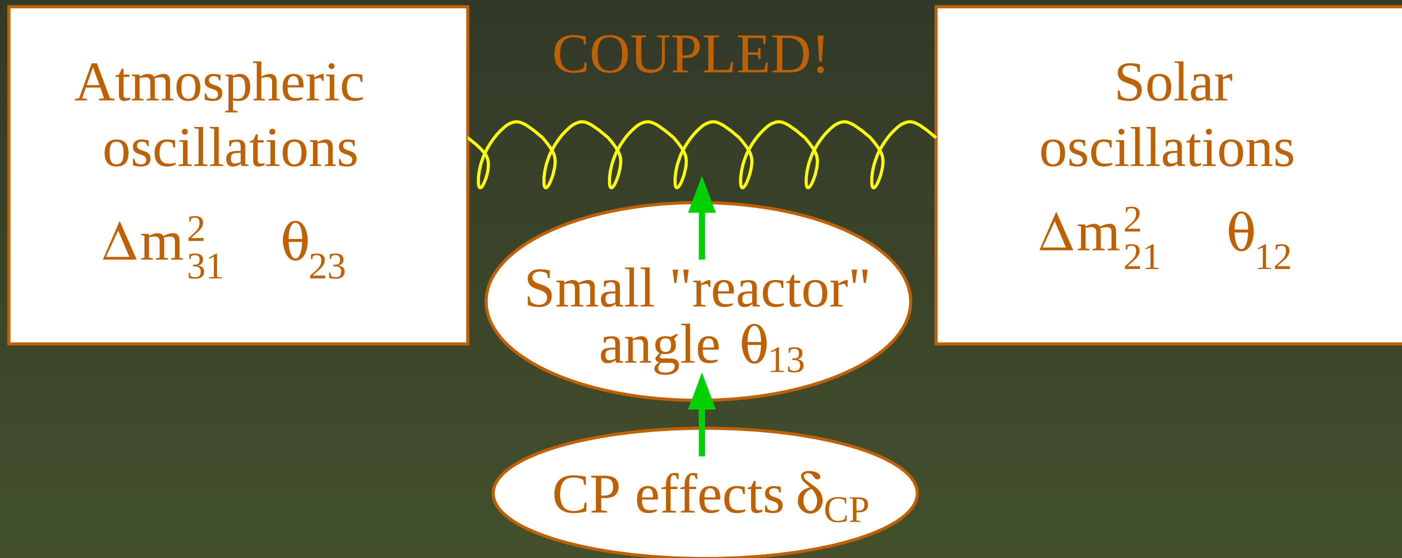
$$J_{ij}^{\alpha\beta} \equiv U_{\alpha i} U_{\alpha j}^* U_{\beta i}^* U_{\beta j}, \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E} \equiv \frac{\left(m_i^2 - m_j^2\right) L}{4E},$$

$$U = \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta} & c_{23} c_{13} \end{pmatrix}.$$

$\rightarrow$ Six parameters: Δm_{31}^2, Δm_{21}^2, θ_{23}, θ_{12}, θ_{13}, δ_{CP}

Classification of oscillation parameters

... with mass hierarchy $|\Delta m^2_{21}| \ll |\Delta m^2_{31}|$ and $\sin^2 2\theta_{13} \lesssim 0.1$:

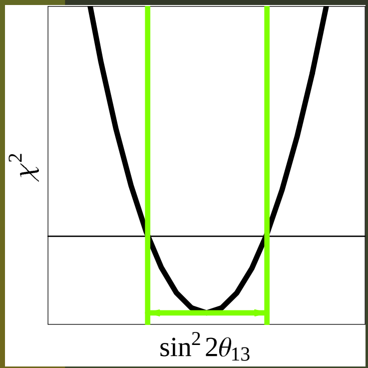


Future important experiments: (examples)	- Beams (K2K, MINOS, CNGS) - Superbeams - ν-Factories	- Beams? - Reactor (θ_{13}) - Superbeams - ν-Factories	- KamLAND - Solar exp.

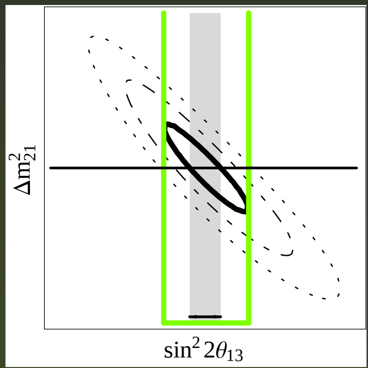
Most interesting for future LBL: θ_{13}, $\mathrm{sgn}(\Delta m^2_{31})$, δ_{CP}

Impact factors to the measurement

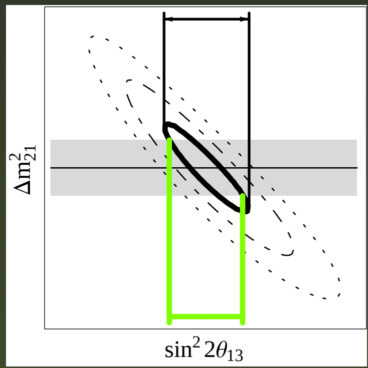
1. Statistical errors



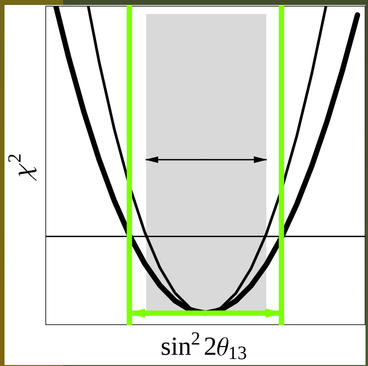
3. Correlations



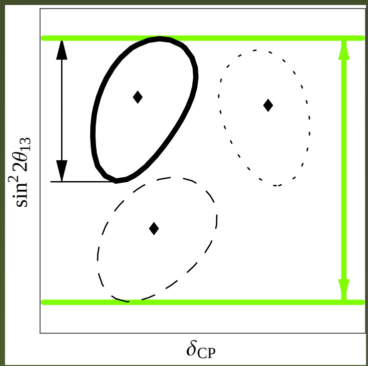
5. External input



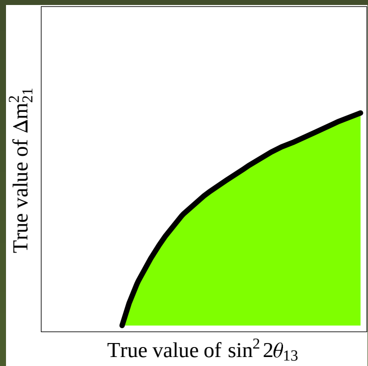
2. Systematics



4. Degeneracies



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

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

Statistical errors

$\Downarrow$

Systematics

$\Downarrow$

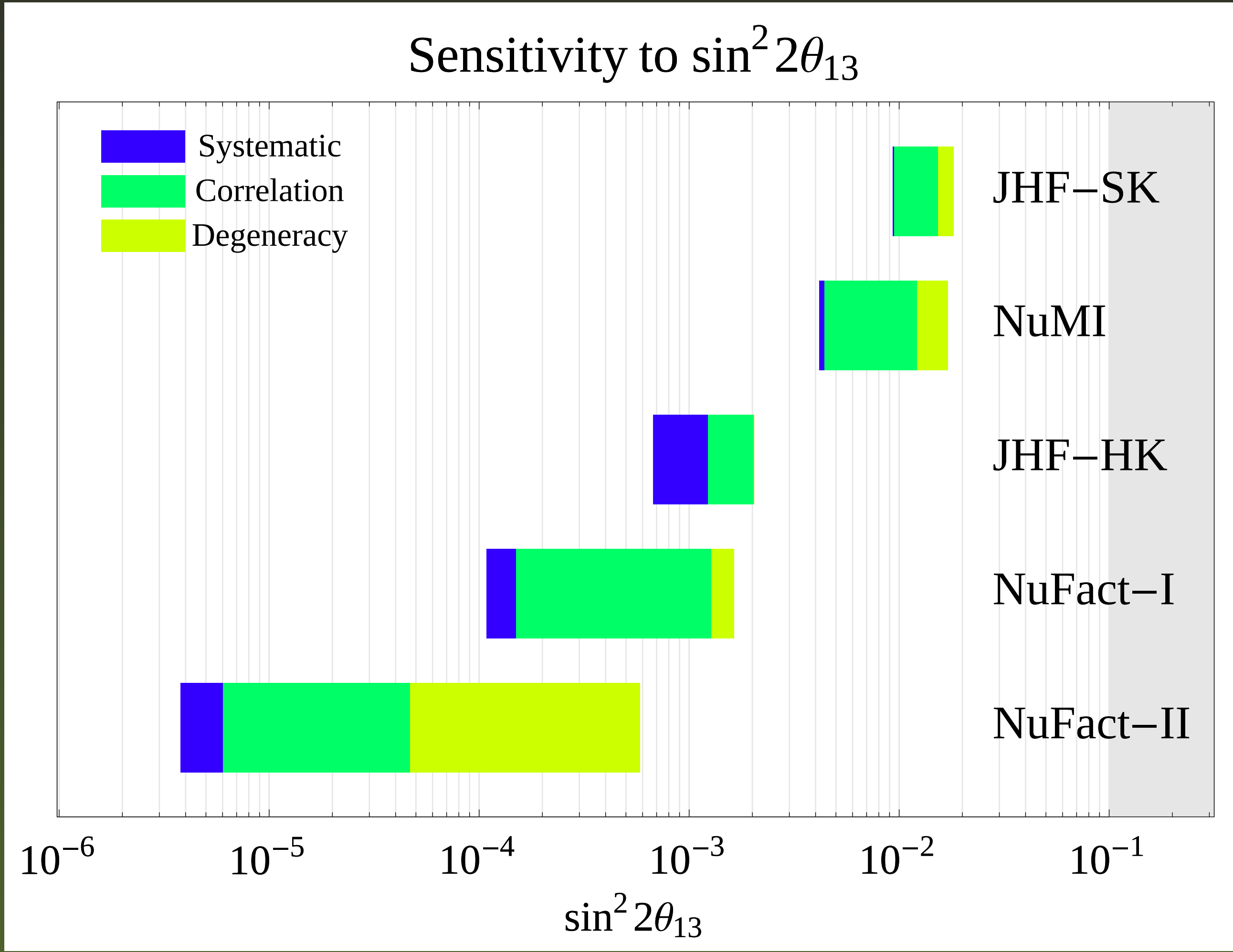
Correlations

$\Downarrow$

Degeneracies

$\Downarrow$

Final result



$\rightarrow$ Correlations and degeneracies to be reduced by clever combinations!

(Huber, Lindner, Winter, NPB 645/3, 2002, hep-ph/0204352)

The appearance channels

LBL exp: interesting information in $P_{\mathrm{app}} = P_{e\mu}, P_{\mu e}, P_{\bar{e}\bar{\mu}}$, or $P_{\bar{\mu}\bar{e}}$

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

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

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

$\rightarrow$ The true values of $\sin^2 2\theta_{13}$ and Δm_{21}^2 change the relative weights!

(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) $\underline{\mathrm{sgn}(\Delta m_{31}^2)\text{-degeneracy}}$ (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) $\underline{(\theta_{23}, \frac{\pi}{2} - \theta_{23})\text{-degeneracy}}$ (Fogli, Lisi, 1996)
Does not appear for current best-fit value $\theta_{23} = \pi/2$

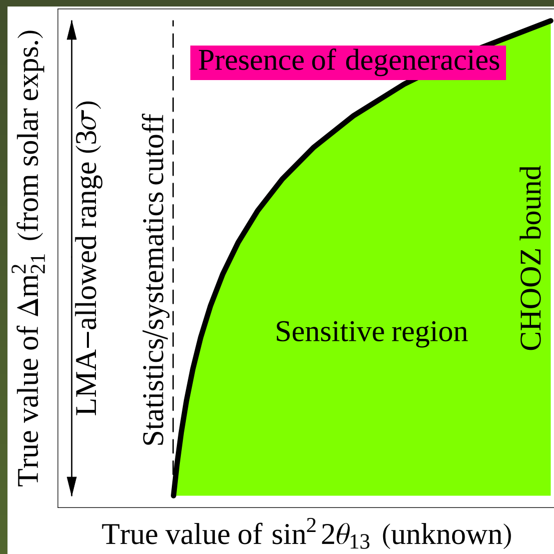
3) $\underline{(\delta, \theta_{13})\text{-degeneracy}}$ (Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, 2001)
Important for neutrino factories because of good energy resolution and statistics

The parameters of interest (illustrated)

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

- Main information in first term
- First term enhanced by matter effects (Resonance: $\hat{A} \rightarrow 1$)
- Spoilt by degeneracies for large α
- Insufficient Δm^2_{21} $\rightarrow$ correlations with α/α^2-terms

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

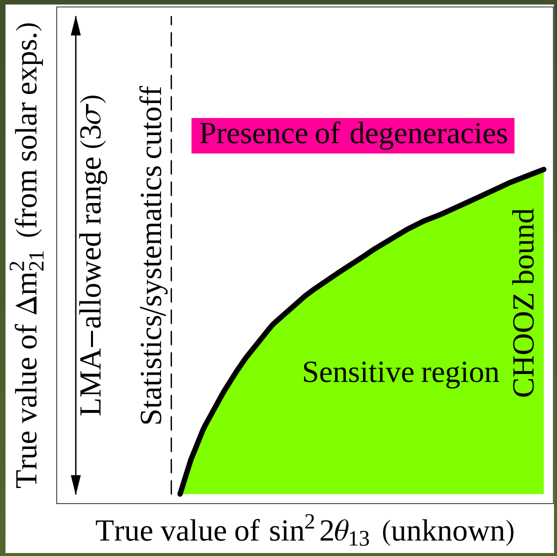


The parameters of interest (illustrated)

$\mathrm{sgn}(\Delta m_{31}^2)$

- Main information in first term through matter effects
- Biggest influence at resonance $\hat{A} \to 1$
- Spoilt by $\mathrm{sgn}(\Delta m_{31}^2)$-degeneracy for large α
- True value of δ_{CP} relevant!

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

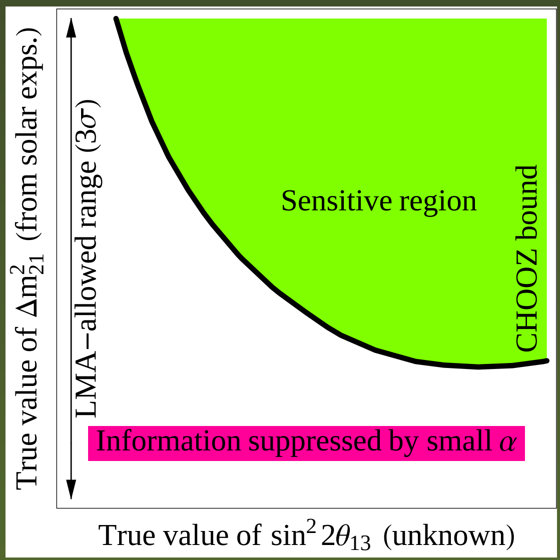


The parameters of interest (illustrated)

δ_{CP}

- Main information in second and third terms
- Other terms act as background
- Large $\sin 2\theta_{13}$ and Δm^2_{21} required

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



Different scales of $\sin^2 2\theta_{13}$

True value of $\sin^2 2\theta_{13}$:

CHOOZ bound	10^{-1}	10^{-2}	10^{-3}	10^{-4}

Timescale???

CHOOZ bound	2000	2010	2025	2040

Sensitive Experiments:				
	- Conventional Beams - Reactor experiments - Superbeams	- Superbeam-Upgrades - ν-Factories - Reactor upgrades?	- ν-Factories	- ν-Factories? - Theoretical reason for $\sin^2 2\theta_{13} \equiv 0$?

$\rightarrow$ Experiments to resolve degs. “selected” by true value of $\sin^2 2\theta_{13}$

$\rightarrow$ Combinations of experiments with similar capabilities!

Resolving degs: $\sin^2 2\theta_{13} \sim 10^{-2} - 10^{-1}$

Options:

- Combinations of first-generation superbeams

  (Whisnant, Yang, Young, 2002)

  (Barger, Marfatia, Whisnant, 2002)

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

  (Minakata, Nunokawa, Parke, 2003)

- Reactor experiments and Superbeams

  (Minakata, Sugiyama, Yasuda, Inoue, Suekane, 2002)

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

- Others!?

Example: Synergies JHF-SK + NuMI

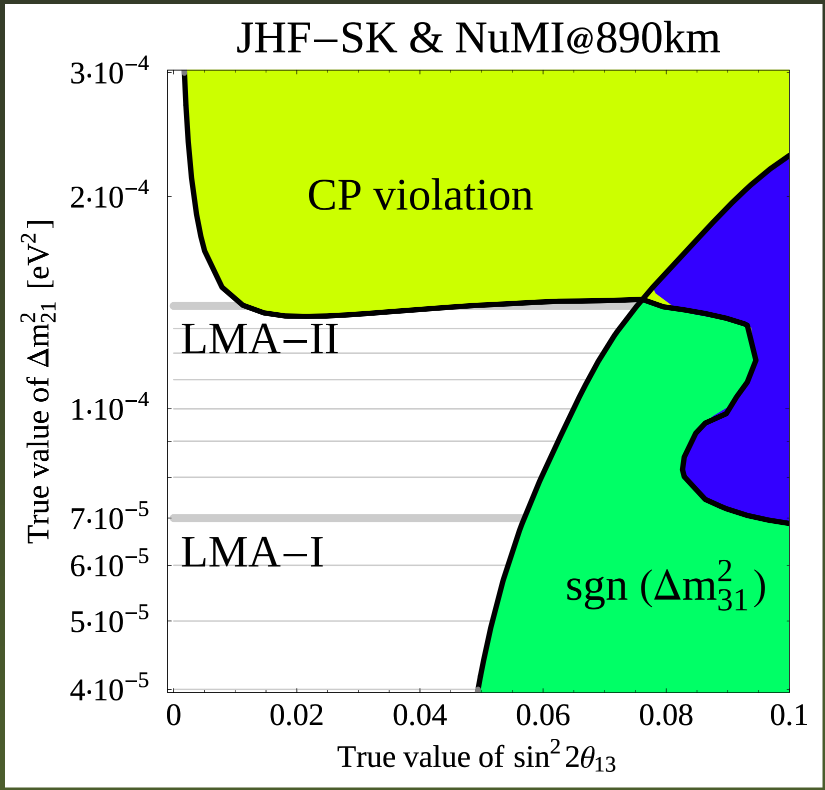
... as in LOIs (Itow et al, 2001; Ayres et al, 2002), 5 years running time

Initial situation:

- No sensitivity to the mass hierarchy
- Both optimized for similar params
- Only marginal CP sensitivity

Possible modifications:

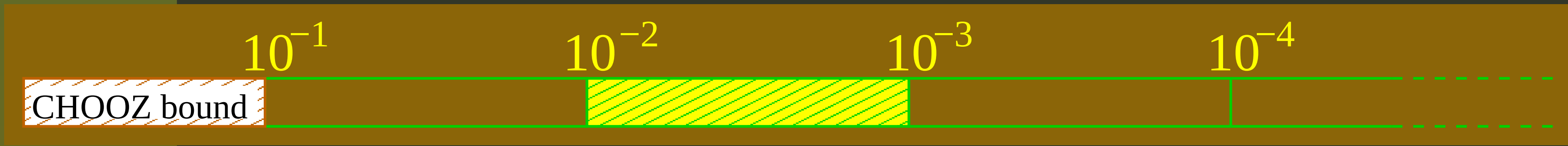
- For δ_{CP}: partial antineutrino running (especially JHF-SK!)
- For mass hierarchy: NuMI@longer baseline (here: 890 km for OA 0.72° alternatively: 950 km for OA 0.97°)



90% CL

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

Resolving degs: $\sin^2 2\theta_{13} \sim 10^{-3} - 10^{-2}$



Options:

- Combinations of superbeam upgrades

  (Barger, Marfatia, Whisnant, 2002)

- Superbeam upgrade and neutrino factory

  (Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, 2002)

- Neutrino factory with “silver channels”

  (Donini, Meloni, Migliozzi, 2002; Autiero et al, 2003)

- Superbeam at “magic baseline” (comes later)

  (Asratyan, Davidenko, Dolgolenko, Kaftanov, Kubantsev, Verebryusov, 2003)

- Others!?

Resolving degs: $\sin^2 2\theta_{13} \sim 10^{-4} - 10^{-3}$

$\sin(\hat{A}\Delta) \equiv 0$: "Magic baseline"

(not $\hat{A} \rightarrow 1$ = Matter resonance!)

$\rightarrow$ Correlations/degs. disappear

$\rightarrow$ Independent of E, osc. params

$\rightarrow$ Evaluates to $\sqrt{2} G_F n_e L = 2\pi$,

$L_{\mathrm{magic}} \simeq 7\,630\,\mathrm{km}$ (average density)

$L_{\mathrm{magic}} \simeq 7\,250\,\mathrm{km}$ (PREM profile)

However: no CP at L_{magic}!

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

Lipari, 2000; Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, 2001; Barger, Marfatia, Whisnant, 2002; Huber/Lindner, 2002; Huber, Winter, 2003

Example: NuFact-II

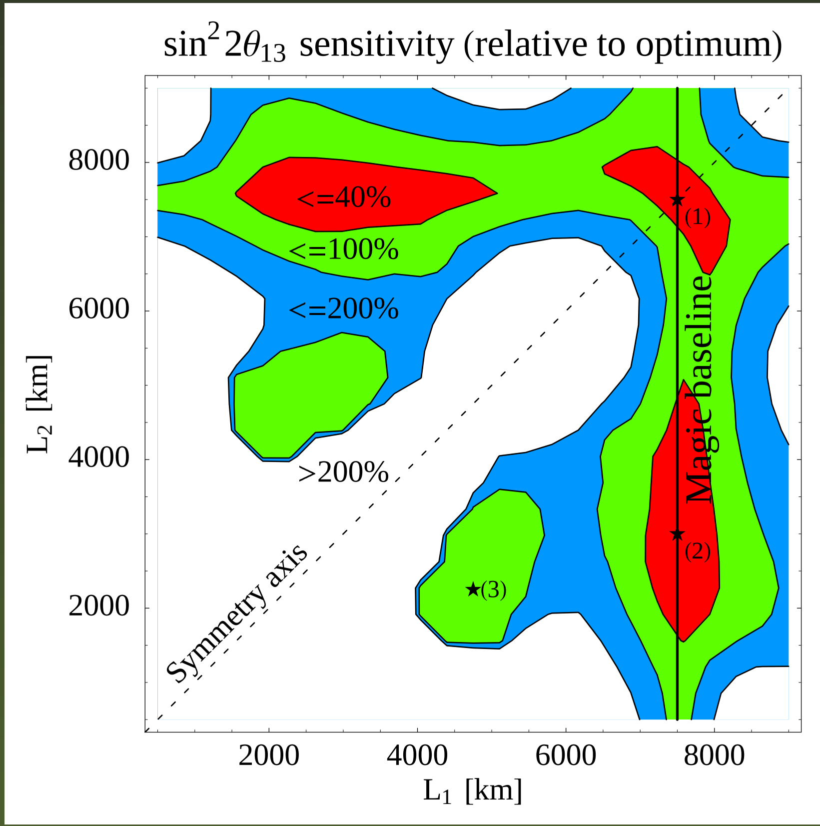
... as a "large" neutrino factory

- Detector: magnetized iron calorimeter
- Detector mass: $50\,\mathrm{kt}$
- Running time: $4\,\mathrm{y}$ neutrinos plus $4\,\mathrm{y}$ antineutrinos
- Standard baseline: $3\,000\,\mathrm{km}$ (to be varied)
- Target power: $4\,\mathrm{MW}$
  ($\sim 5.3 \cdot 10^{20}$ useful muon decays/year)
- 5% matter density uncertainty assumed

Now: split detector mass into two equal pieces of $25\,\mathrm{kt}$ placed at L_1 and L_2

Full analysis and the magic baseline

... for $\sin^2 2\theta_{13}$-sensitivity limit in two baseline space (L_1, L_2)
(incl. correlations and degeneracies)



3σ CL, LMA-I

Three local minima:

(1) $L_1 \simeq L_2 \simeq 7\,500\,\mathrm{km}$:

$\rightarrow$ No CP measurement possible!

(2) $L_1 \simeq 7\,500\,\mathrm{km}$, $L_2 \simeq 3\,000\,\mathrm{km}$:

$\rightarrow$ Stable minimum

$\rightarrow$ Independent of osc. parameters

(3) $L_1 \simeq 4\,750\,\mathrm{km}$, $L_2 \simeq 2\,250\,\mathrm{km}$:

$\rightarrow$ Preferred by statistics

$\rightarrow$ Depends on osc. parameters

$\rightarrow$ Unstable $(\delta_{CP}, \theta_{13})$-degeneracy

(Huber, Winter, 2003, PRD, to be published, hep-ph/0301257)

Magic baseline: Main results

Magic baseline $L \sim 7\,500$ km compared to $L = 3\,000$ km:

a) $L_1 = L_2 = 3\,000$ km:

$\rightarrow$ Poor $\mathrm{sgn}(\Delta m^2_{31})$ measurement

$\rightarrow$ High risk of unknown Δm^2_{21}

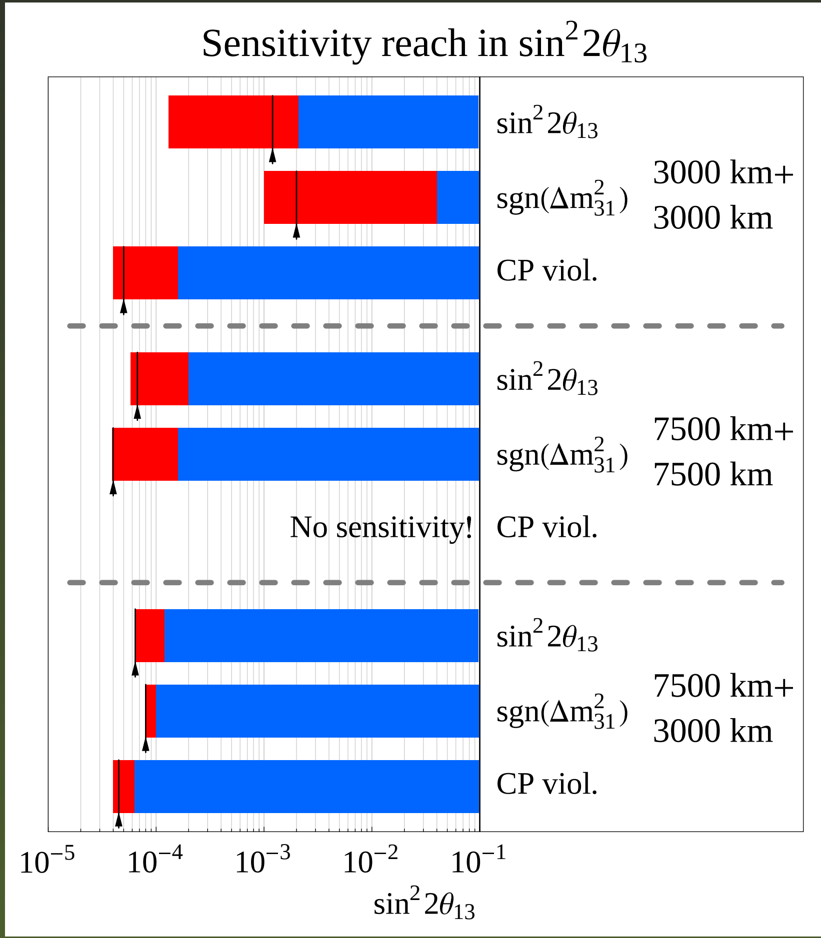
b) $L_1 = L_2 = 7\,500$ km

$\rightarrow$ No CP sensitivity

c) $L_1 = 7\,500$ km, $L_2 \simeq 3\,000$ km:

$\rightarrow$ Excellent for all parameters

esp. between $\sin^2 2\theta_{13} \sim 10^{-4} - 10^{-3}$



(Figure: 3σ CL; Red bars by variation of Δm^2_{21} in KamLAND-allowed 3σ-range; Arrows: LMA-I best-fit)

(Huber, Winter, 2003, PRD, to be published, hep-ph/0301257)

Difference to Long-Baseline strategy!?

Example: only JHF-SK is running and finds $\sin^2 2\theta_{13} = 0.07$

$\rightarrow$ Options depend on solar data:

LMA-I: - Mass hierarchy determination with 2nd superbeam possible

- No CP sensitivity with first-generation superbeams

  $\rightarrow$ Superbeam-Upgrade!?

LMA-II: - No certain mass hierarchy determination with 2nd superbeam

  $\rightarrow$ Additional reactor experiment!?

- CP sensitivity with JHF-SK (ν running)+reactor experiment or JHF-SK only with very extensive ν+$\bar{\nu}$ running

However: If $\sin^2 2\theta_{13} = 0.07 \not\Rightarrow$ JHF-SK finds it (HLMA, LOW-ATM)
$\rightarrow$ Reactor experiments to test this range for sure!

Summary and conclusions

- Discussion based upon true value of $\sin^2 2\theta_{13}$
  $\rightarrow$ "Selects" the experiments, which are sensitive
  $\rightarrow$ These can be combined to resolve degeneracies
- Long-Baseline strategy slightly different
  $\rightarrow$ Depends on when $\sin^2 2\theta_{13}$ is found and the experiments/information available at that time
- Now most interesting: $\sin^2 2\theta_{13} \sim 10^{-2} - 10^{-1}$
  $\rightarrow$ Later decisions based on results in this range
  $\rightarrow$ New technologies will change discussion
- We discussed a logarithmic scale of $\sin^2 2\theta_{13}$
  $\rightarrow$ Is this an appropriate representation?
  $\rightarrow$ Linear scale from linear mass models in flavor space?