The Physics Potential of Future Long Baseline Experiments

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The Motivation for LBL Precision Experiments

- **Atmospheric Δm^2: $E_\nu \simeq 10$ GeV** $\Rightarrow$ **oscillation at $\mathcal{O}(1000)$ km**
- **Solar Δm^2 most likely LMA** $\Rightarrow$ **$\simeq$ 10 –1000 times longer baseline**

  $\Rightarrow$ **interesting LBL experiments on Earth**

- **Source and detector are under control** $\Rightarrow$ **precise conditions**
- **Good statistics and small theoretical uncertainties**

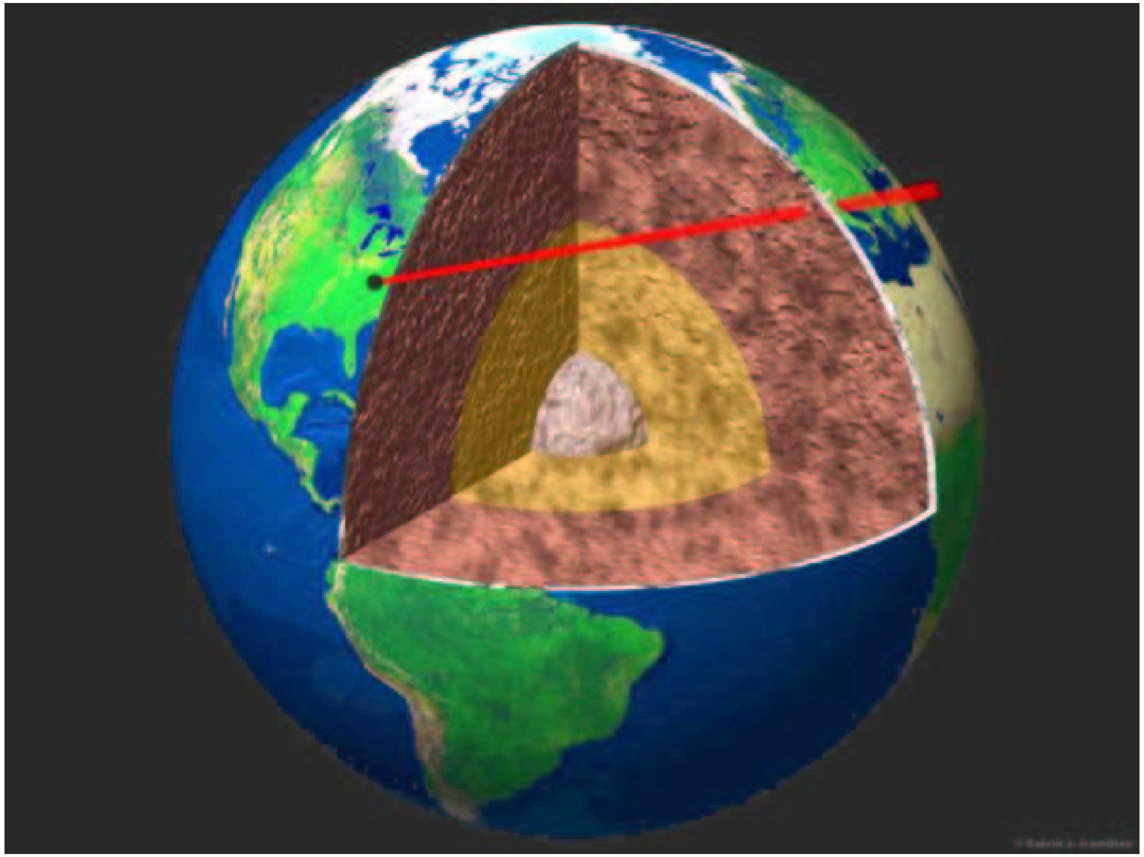
  $\Rightarrow$ **precision neutrino physics**

  $\Rightarrow$ **detailed tests of 3 neutrino oscillation $\oplus$ NSI, FCNC, $> 3\nu$, CPT, ...**

  $\Rightarrow$ **θ_{13}, matter effects, sign(Δm^2)**

  $\Rightarrow$ **LMA: Leptonic CP violation**

Promising physics, not easy, ..., possible, in stages



Precision!

Source	⊗	**Oscillation**	⊗	**Detector**

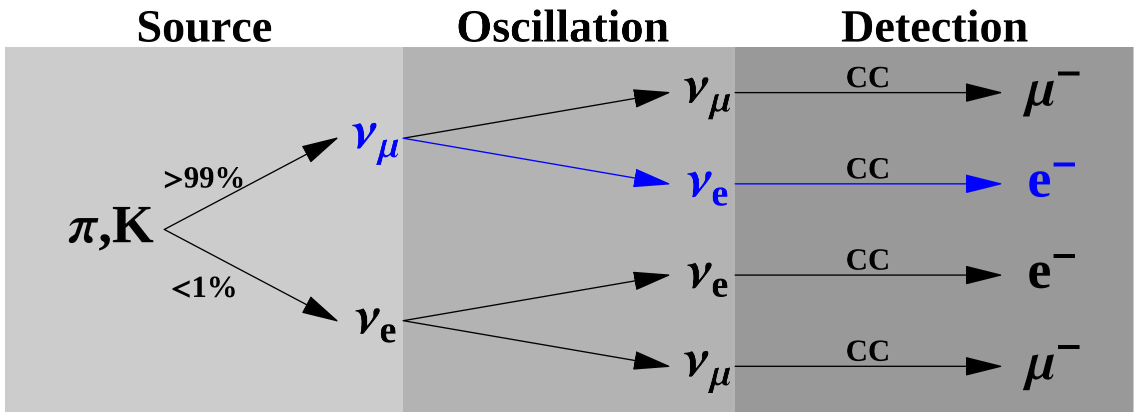
- neutrino energy E
- flux and spectrum
- flavour composition
- contamination
- symmetric $\nu/\overline{\nu}$ operation

- oscillation channels
- realistic baselines
- MSW matter profile

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

Sources, Oscillation and Detection

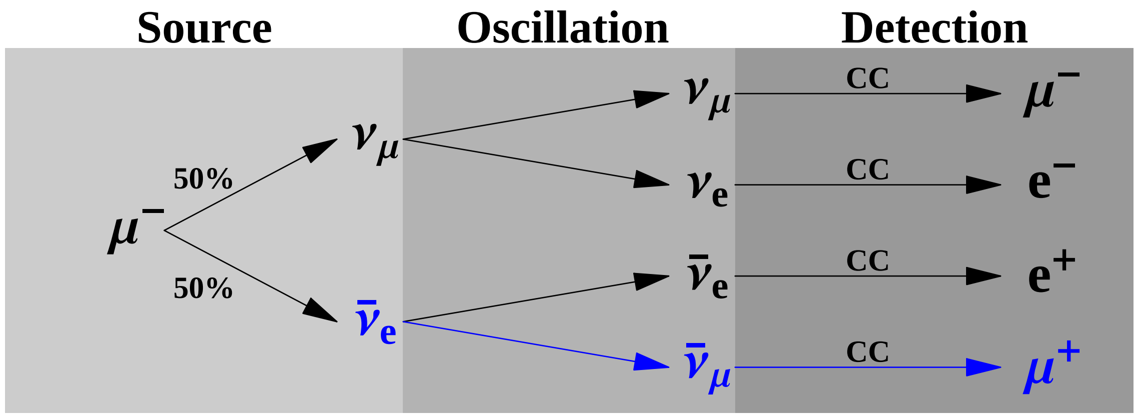
A) Conventional ν-Beams from Beam Dumps $\Rightarrow$ Superbeams



$\nu_\mu \to \nu_e$ 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

B) Neutrino Factories

Geer



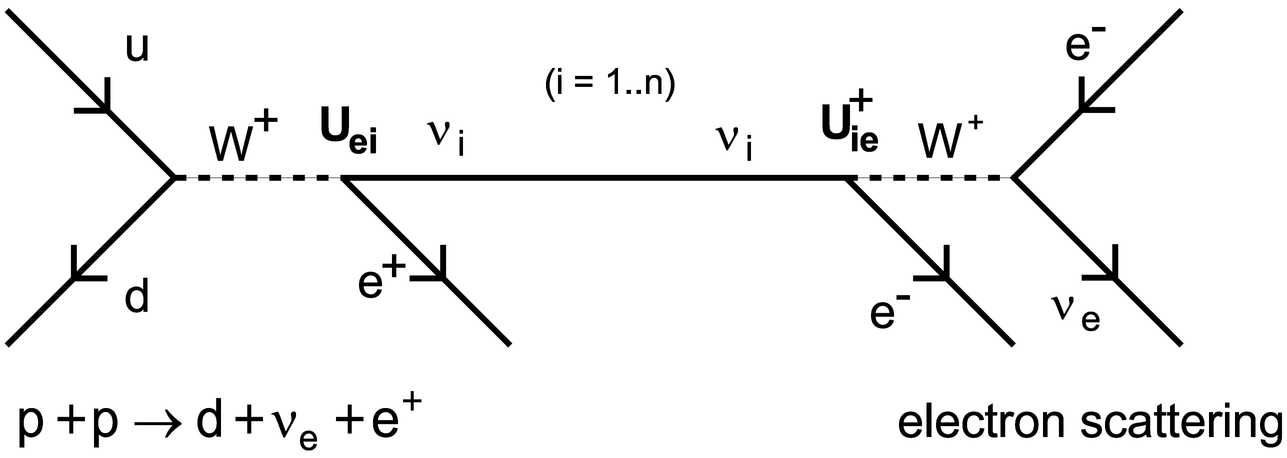
$\overline{\nu}_e \to \overline{\nu}_\mu$ oscillation most interesting
excellent beam properties
very good charge ID required
good NC background rejection
μ^+ mode very symmetric

C) Radioactive Beams ?

Pure ν_e or $\overline{\nu}_e$ beam from β decay, $\gamma \simeq 100$ Zuchelli

Neutrino Oscillations for $N = 2$

Production
Propagation
Detection



2 Flavours ν_e, ν_μ:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

flavour states = mixing matrix · mass eigenstates

Probability:

$$P(\nu_\mu \to \nu_e) = |\langle \nu_\mu(t)|\nu_e(t=0)\rangle|^2 = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$N \geq 2$ with CP and Matter Effects

Precision: $N = 2$ description insufficient $\Rightarrow$ modifications

- $2 \rightarrow 3$ neutrino framework $\Rightarrow$ more parameters & CP effects
- MSW: parameter mapping in matter

$$\Rightarrow \quad P(\nu_{e_l} \rightarrow \nu_{e_m}) = \underbrace{\delta_{lm} - 4 \sum_{i>j} \mathrm{Re} J_{ij}^{e_l e_m} \sin^2 \Delta_{ij}}_{P_{CP}} \underbrace{-2 \sum_{i>j} \mathrm{Im} J_{ij}^{e_l e_m} \sin 2\Delta_{ij}}_{P_{\not{CP}}}$$

Shorthands: $J_{ij}^{e_l e_m} := U_{li} U_{lj}^* U_{mi}^* U_{mj} \qquad \Delta_{ij} := \frac{\Delta m_{ij}^2 L}{4E}$

Neutrinos: $P(\nu_{e_l} \rightarrow \nu_{e_m}) = P_{CP} + P_{\not{CP}}$

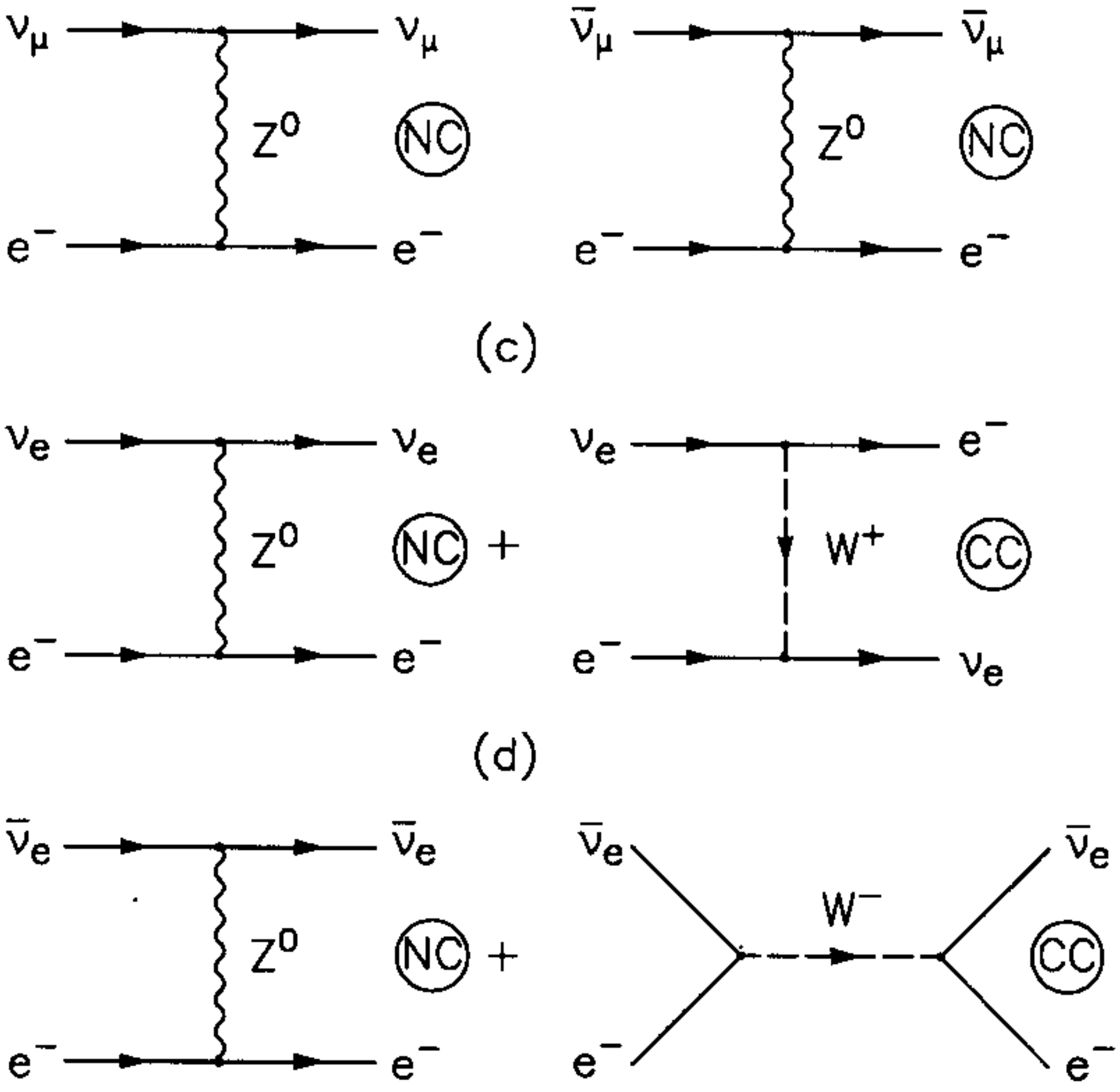
Antineutrinos: $P(\overline{\nu}_{e_l} \rightarrow \overline{\nu}_{e_m}) = P_{CP} - P_{\not{CP}}$

$\Rightarrow$ **e.g. CP Asymmetries:**

$$\mathbf{a}^{\mathrm{CP}} := \frac{\mathrm{P}(\nu_{e_l} \rightarrow \nu_{e_m}) - \mathrm{P}(\overline{\nu}_{e_l} \rightarrow \overline{\nu}_{e_m})}{\mathrm{P}(\nu_{e_l} \rightarrow \nu_{e_m}) + \mathrm{P}(\overline{\nu}_{e_l} \rightarrow \overline{\nu}_{e_m})} = \frac{P_{\not{CP}}}{P_{CP}}$$

Matter Effects and MSW Resonance

Mikheyev-Smirnov-Wolfenstein: coherent forward scattering



$\mathcal{L}_{NC}$ **= flavour universal**

$\mathcal{L}_{CC} = \sqrt{2} G_F n_e \quad \Leftrightarrow \quad$ **only** ν_e

MSW-resonance energy(Δm^2_{31})

Earth: $\mathbf{E_{res} \simeq 10}$ **GeV**

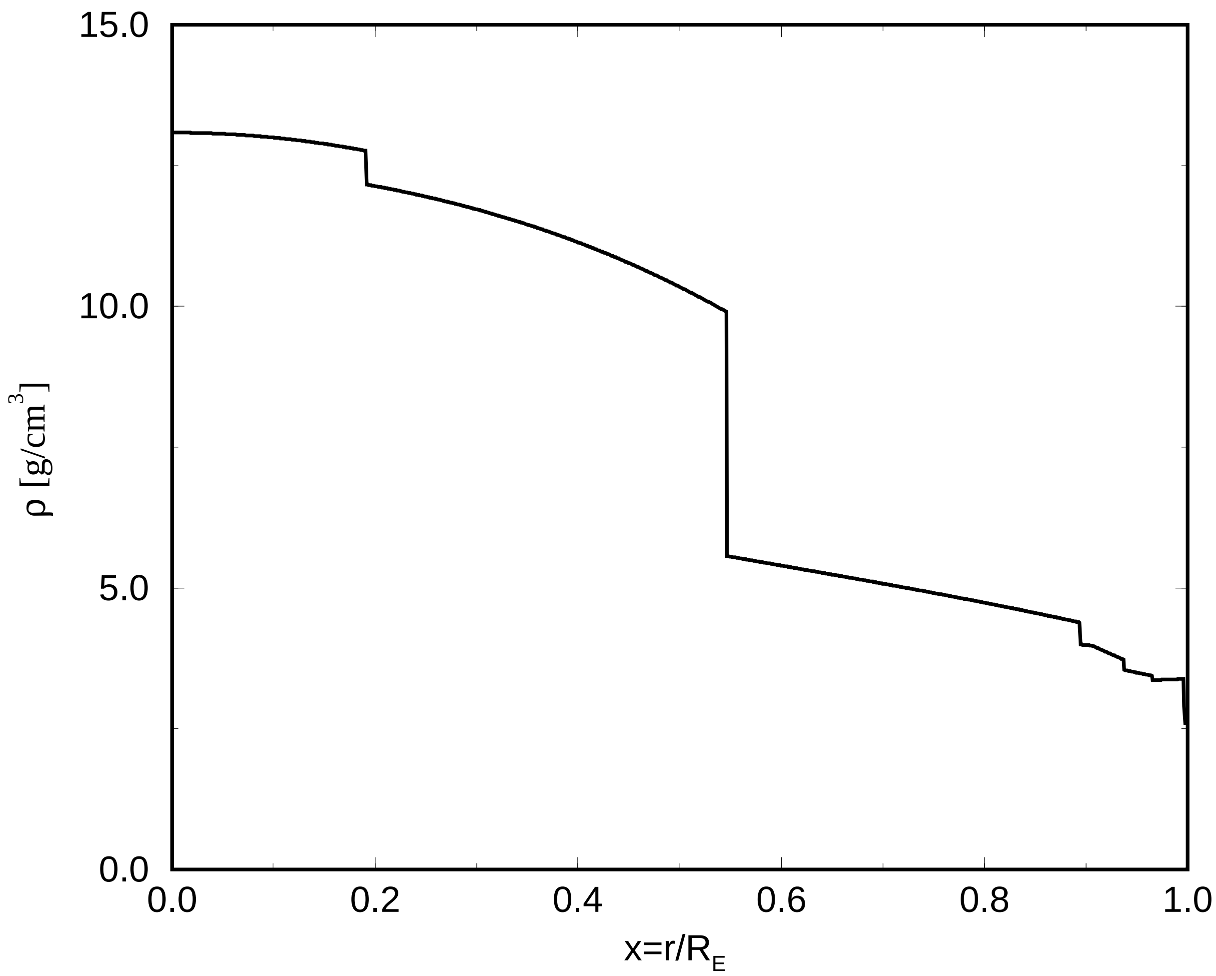
dominated by average density

$\rho = \rho_{\text{average}} + \delta\rho$

Baseline & MSW Matter Effects

Beams in Earth Matter:
$\Rightarrow$ **electron density profile as function of radius** Stacy
density errors Geller & Hara

Large L $\Rightarrow$ steep angles
$L = 2800$ **km** $\Leftrightarrow$ 13^o
$L = 7300$ **km** $\Leftrightarrow$ 35^o
$L = 12750$ **km** $\Leftrightarrow$ 90^o
$L \leq \mathcal{O}(10\ 000\ \mathrm{km})$ $\Leftrightarrow$ **mantle**



- $E_{resonance} \simeq 10 - 15$ **GeV, matter effects grow with distance L**
- **Average density profile uncertainties decrease with L** $\Rightarrow$ $\simeq 5\%$ **error**

$\Delta m^2_{12} \simeq 0$, $Y = e^-$/**nucleon** ρ =**matter density** m_n =**nucleon mass**

In Flavour Basis:

$$H_0 + \delta \mathbf{H}_{CC} + \delta \mathbf{H}_{NC} = \frac{1}{2E}\mathbf{U}\begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix}\mathbf{U^T} + \frac{1}{2E}\begin{pmatrix} \mathbf{A}+\mathbf{A}' & 0 & 0 \\ 0 & \mathbf{A}' & 0 \\ 0 & 0 & \mathbf{A}' \end{pmatrix}$$

$$\mathbf{A} = \pm \frac{\mathbf{2\sqrt{2}G_F Y \rho E}}{\mathbf{m_n}},$$

"$+$" for $\nu \oplus$ matter **and** $\overline{\nu} \oplus \overline{\text{matter}}$

$\mathbf{U} = R_{23}R_{13}R_{12} \to \mathbf{U}' \Rightarrow$ **1-3 subspace parameter mapping**

$$\sin^2 2\theta'_{13} = \frac{\sin^2 2\theta_{13}}{C^2_\pm}$$

$$\Delta m^2_{31,m} = \Delta m^2 C_\pm$$

$$\Delta m^2_{32,m} = \frac{\Delta m^2 \ (C_\pm + 1) + A}{2}$$

$$\Delta m^2_{21,m} = \frac{\Delta m^2 \ (C_\pm - 1) - A}{2}$$

$$C^2_\pm = \left(\frac{A}{\Delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta$$

$\Rightarrow$ **Different mappings for neutrinos and antineutrinos**

⇒ **All CP-violating effects are proportional to:**

1) $8J_{\rm CP} = \cos\theta_{13}\sin(2\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})\sin\delta$

2) $\sin\Delta_{12}\sin\Delta_{23}\sin\Delta_{31} \Rightarrow$ **3 different masses required**

$P_{\not{CP}}$ **is suppressed by:**

- **small solar $\Delta m^2_{\rm sun}$:** $\sin\Delta_{12} \approx \Delta_{12} \ll 1$
- **small mixing angles:** $\sin^2 2\theta_{13} \ll 1$
- **in addition for SMA:** $\theta_{\rm sun} \simeq \theta_{12}$

P_{CP} **is not suppressed by** $\Delta_{12} = \frac{\Delta m^2_{12}\ L}{4E}$

Sizable CP effects:

3 Neutrinos ⇒ LMA-MSW (most likely)
4 Neutrinos ⇒ always

Qualitative Analytic Understanding

- **full numerical simulation**
- $\Delta = \Delta m^2_{31} L/4E$
- **qualitative understanding** $\Rightarrow$ **expand in** $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ **and** $\sin^2 2\theta_{13}$
- **matter effects** $\hat{A} = A/\Delta m^2_{31} = 2VE/\Delta m^2_{31};\ \ V = \sqrt{2}G_F n_e$

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

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

Freund

Cervera & Donini & Gavela & Gomez Cadenas & Hernandez & Mena & Rigolin

Freund & Huber & ML

The Importance of θ_{13}

CHOOZ $\Rightarrow$ θ_{13} **is small:** $\sin^2 2\theta_{13} < 0.1$

All effects in the $\nu_e \rightarrow \nu_\mu$**-transition depend crucially on** θ_{13} **:**

- **the total transition rate**
- **matter effects**
- **the effects due to the sign of** Δm^2_{31}
- **CP violating effects**

The size of θ_{13} **determines if these effects can be studied**

Errors, Degeneracies and Correlations

Look at expansion in powers of $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ **and** $\sin\theta_{13}$; $\Delta = \Delta m^2_{31} L/4E$; $V = 0$

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

- **depends on solar parameters only via the product** $\Delta m^2_{21} \cdot \sin 2\theta_{12}$
- **most interesting:** $\sin^2 2\theta_{13} \simeq \alpha \cdot \sin^2 2\theta_{12} = \sin^2 2\theta_{12} \Delta m^2_{21}/\Delta m^2_{31}$
- **degeneracies**: **(**$\delta_{CP} - \theta_{13}$**), (**$\delta_{CP} - sign(\Delta m^2_{31})$**), (**$\theta_{23} - \frac{\pi}{2} - \theta_{23}$**)**
- $\alpha^2 = (\Delta m^2_{21})^2/(\Delta m^2_{31})^2$ **term dominates for tiny** $\sin^2 2\theta_{13}$ $\Leftrightarrow$ **error of** Δm^2_{21}

The Potential of Future LBL Setups

Physis input:

- full numerical 3-ν simulation and analytic understanding
- matter density profile and errors taken into account
- error correlations included (no fixed unknown parameters)

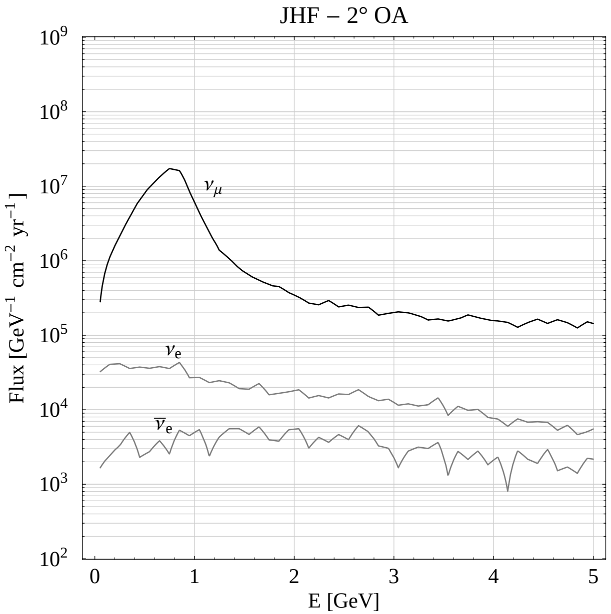
Analysis:

- MC for all possible input parameters
- combined fit of appearance and disappearance channels for both polarities
- fit spectral information and/or total rates
- adequate statistical methods (small event rates/bin):
  - $\Rightarrow$ Poissonian statistics
  - $\Rightarrow$ parameterization of systematical uncertainties
  - $\Rightarrow$ integrating out the nuisance parameters
  - $\Rightarrow$ projection on the parameter of interest
  - $\Rightarrow$ external information from KamLand (=LMA) and geophysics
  - $\Rightarrow$ 6 remaining parameters

$\Rightarrow$ Extract parameters and (correlated) errors $\Leftrightarrow$ sensitivity

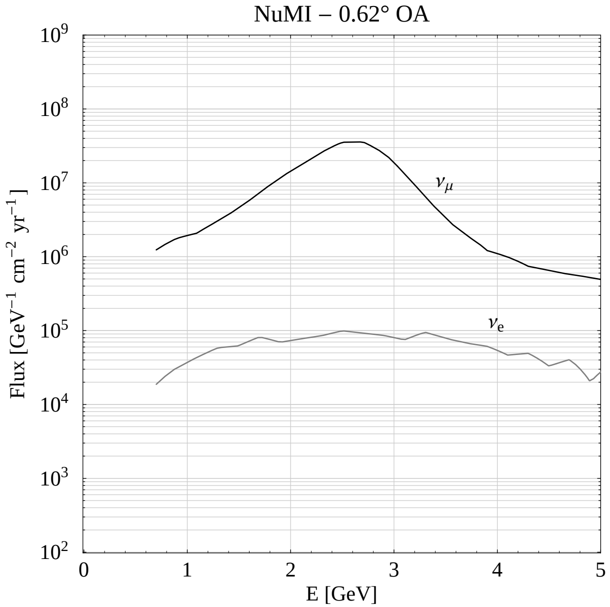
The Sources

JHF



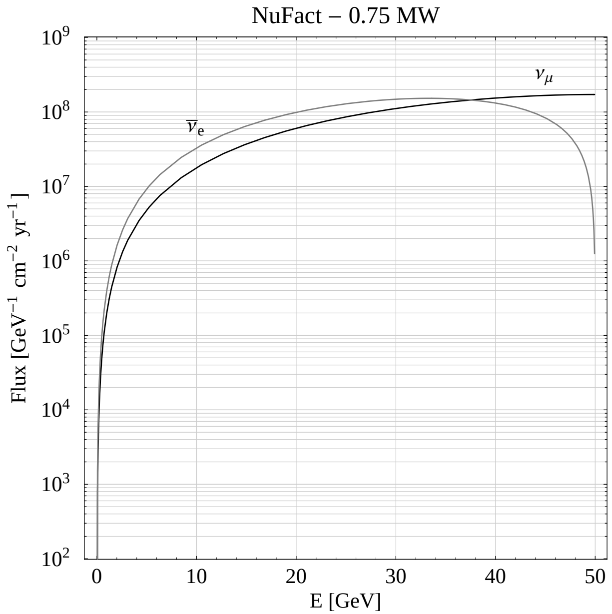
- **mean energy** $0.51\,\mathrm{GeV}$
- **peak intensity** $1.7 \cdot 10^7\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{yr}^{-1}$ **at** $0.78\,\mathrm{GeV}$
- ν_μ/ν_e**-ratio at peak** 0.2%

NuMI



- **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%

NuFact



- **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	$22.5\,\text{kt}$ $(1\,000\,\text{kt})$	$20\,\text{kt}$	$10\,\text{kt}$ $(50\,\text{kt})$
energy range	$0.4 - 1.2\,\text{GeV}$	$1 - 5\,\text{GeV}$	$4 - 50\,\text{GeV}$
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** $4\,\text{GeV}$ **and** $20\,\text{GeV}$

- **liquid Argon TPC ?**

5 Considered 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}	$378\,\mathrm{km\,GeV^{-1}}$	$337\,\mathrm{km\,GeV^{-1}}$	$90\,\mathrm{km\,GeV^{-1}}$

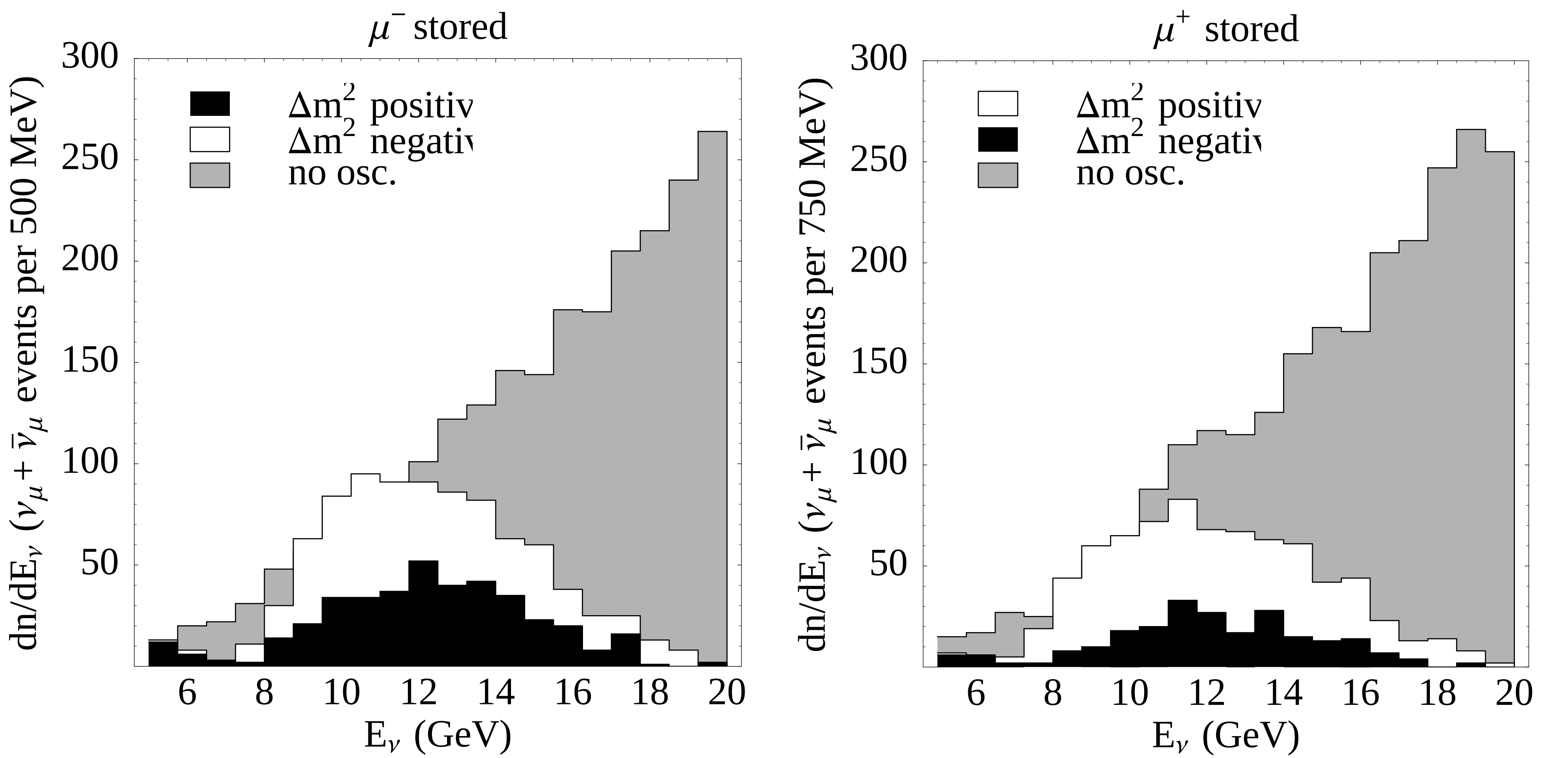
- **JHF-HK** $\Rightarrow$ $\simeq 95$ **times more luminosity than JHF-SK plus anti-neutrino running**
- **NuFact-II** $\Rightarrow$ $\simeq 42$ **times more luminosity than NuFact-I**

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

Disappearance Channels: Qualitative Picture

Large event rates ⇒ **spectral information** ⇒ **NuFact example:**



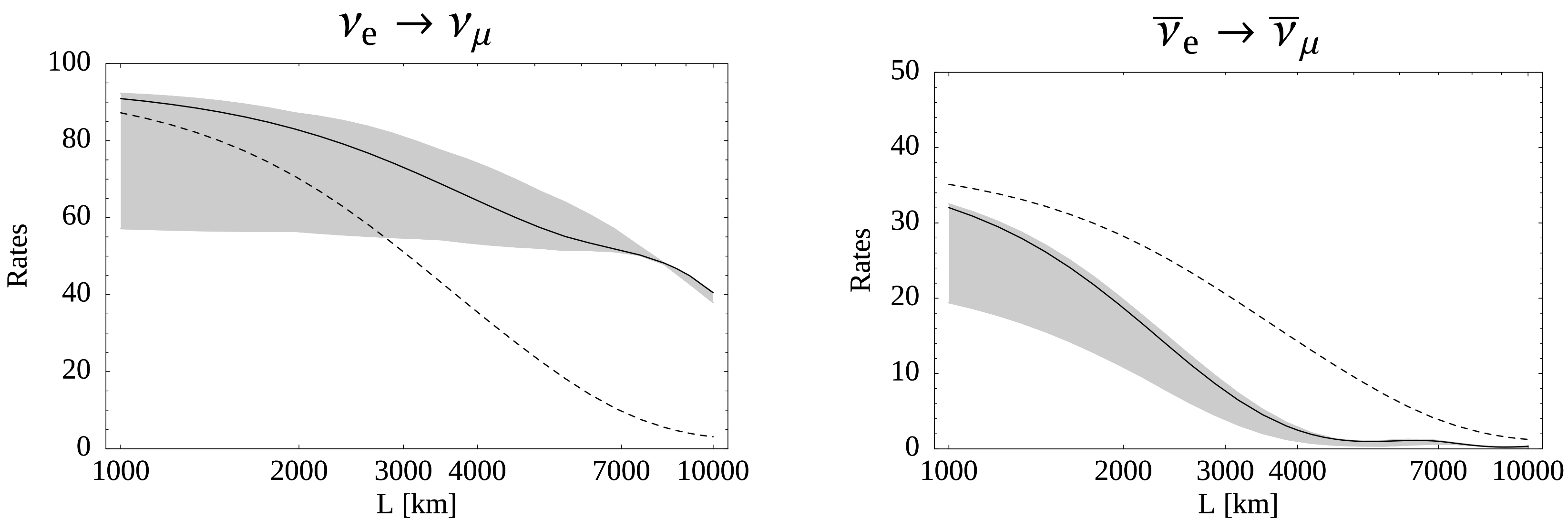
⇒ Δm^2_{31}, θ_{23} **and for not too small** θ_{13} **also** $sign(\Delta m^2_{31})$

Cervera et al., Barger & Geer & Raja & Whisnant, DeRujula et al., Donini et al., Bueno & Campanelli & Rubbia, Albright et al.. Yasuda, Minakata, Shrock et al., Barenboim & De Gouvea & Szleper & Velasco, Freund & ML & Petcov & Romanino, Freund & Huber & ML, ...

Appearance Channels: Qualitative Picture

Small event rates $\Rightarrow$ total rates & little spectral information

NuFact:
$E_\mu = 50$ **GeV**
$\sin^2 2\theta_{13} = 0.01$
LMA



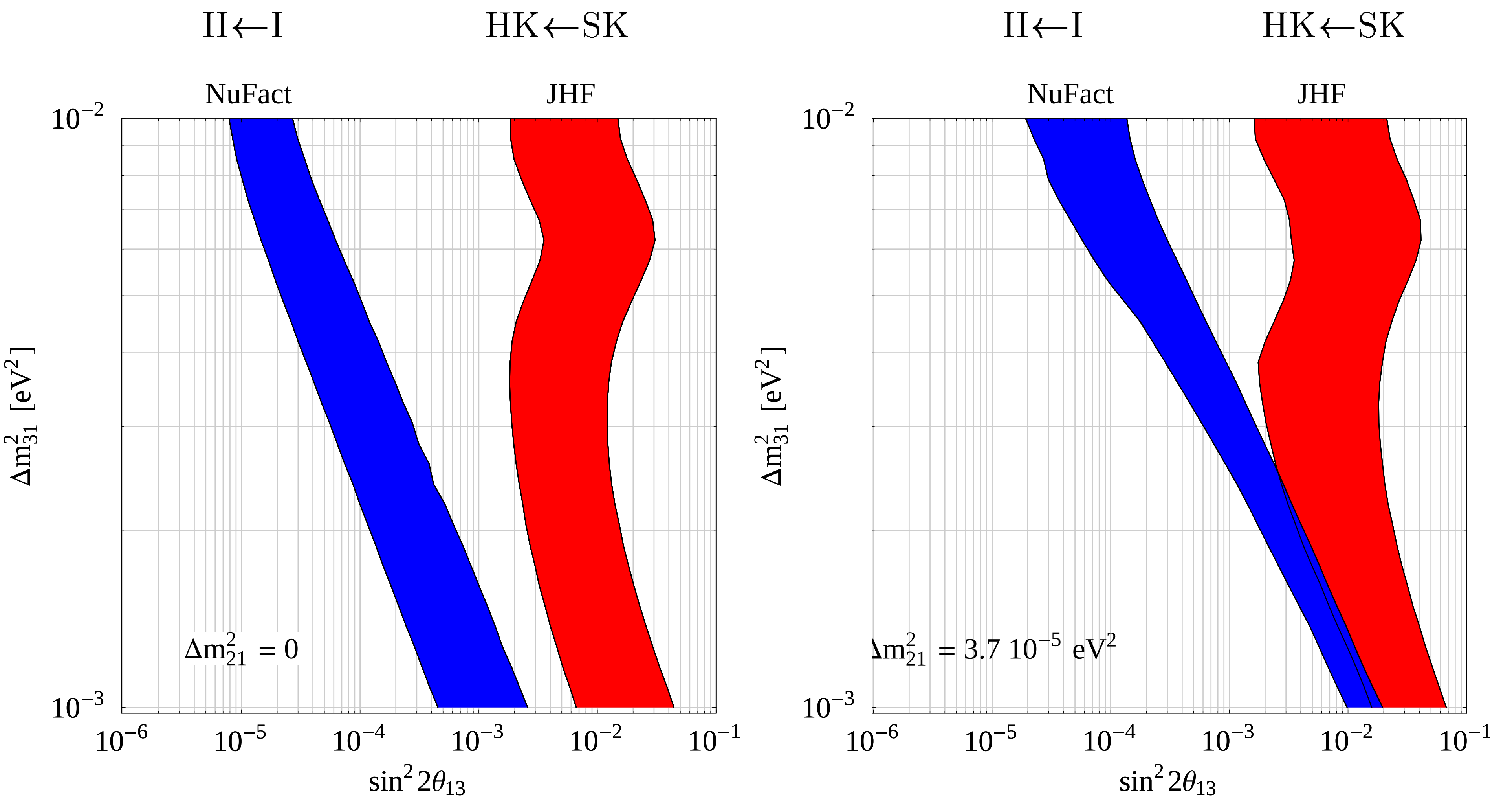
solid lines=matter ($\delta = 0$), dashed lines=vacuum ($\delta = 0$), grey band=all CP phases

Comparable matter and $\not{C}\not{P}$ effects $\Rightarrow$ separation
CP-phase $\Rightarrow$ short(er) baseline
matter effects, sign of δm^2 $\Rightarrow$ large L

For all solar solutions: θ_{13} and maybe $sign(\Delta m^2_{31})$
For LMA without external input: $\simeq \theta_{12}$, $\simeq \Delta m^2_{21}$
With external input for θ_{12} and Δm^2_{21}: $\Rightarrow$ δ_{CP}

Sub-Leading Parameters: $\sin^2 2\theta_{13}$ Sensitivity

All parameter correlations must be taken into account



- **sizable Δm^2_{31} and Δm^2_{21} dependence of sensitivity limits**
- **up to an order of magnitude difference**
- **effect strongest for short baselines**

Impact of Systematical Errors

Signal

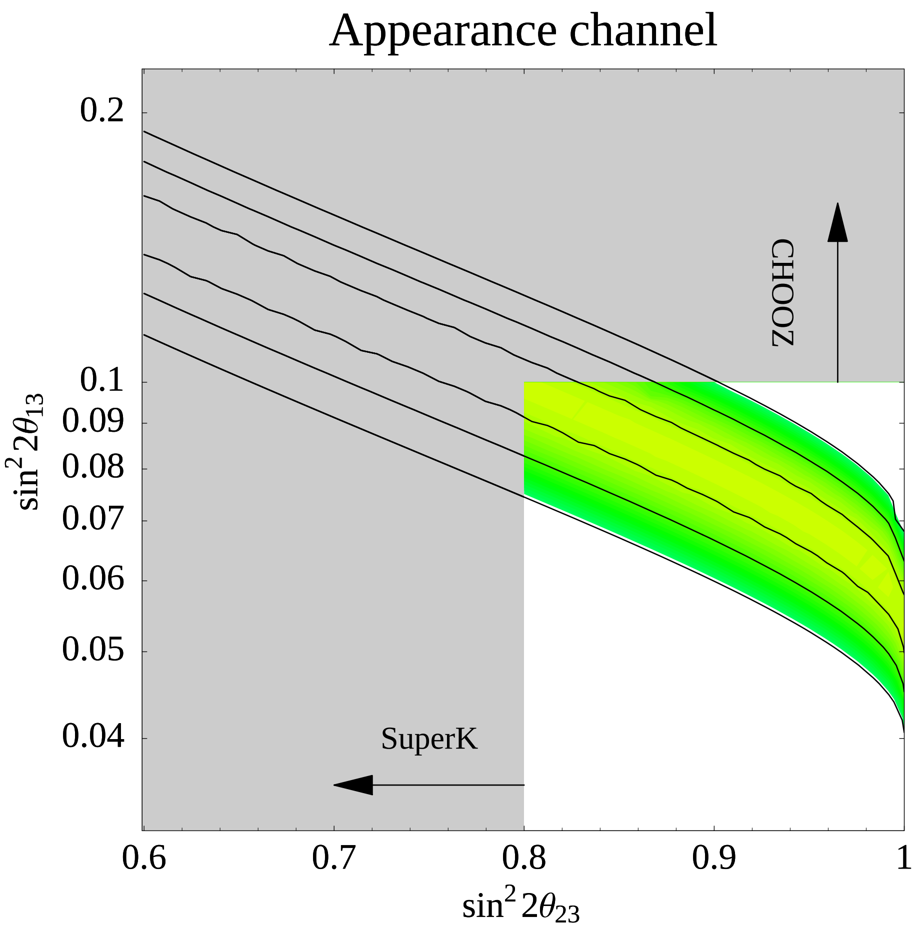
- use the information in the energy spectrum
- overall normalization error of 5% is acceptable
- energy calibration error of 5% is acceptable

Background

- backgrounds limit sensitivity
- energy spectrum helps to reduce the impact of the background
- background uncertainty becomes important when $\sigma_{b_n} \geq 1/\sqrt{b}$
  for $\sigma_{b_n} = 5\% \Leftrightarrow b = 400$

Background uncertainties may dominate high statistics experiments

Impact of Correlations



⇐ **Eample**

- **multi-parameter problem**
- **highly non-linear**
- **complex topology**

⇒ **use all available information:**

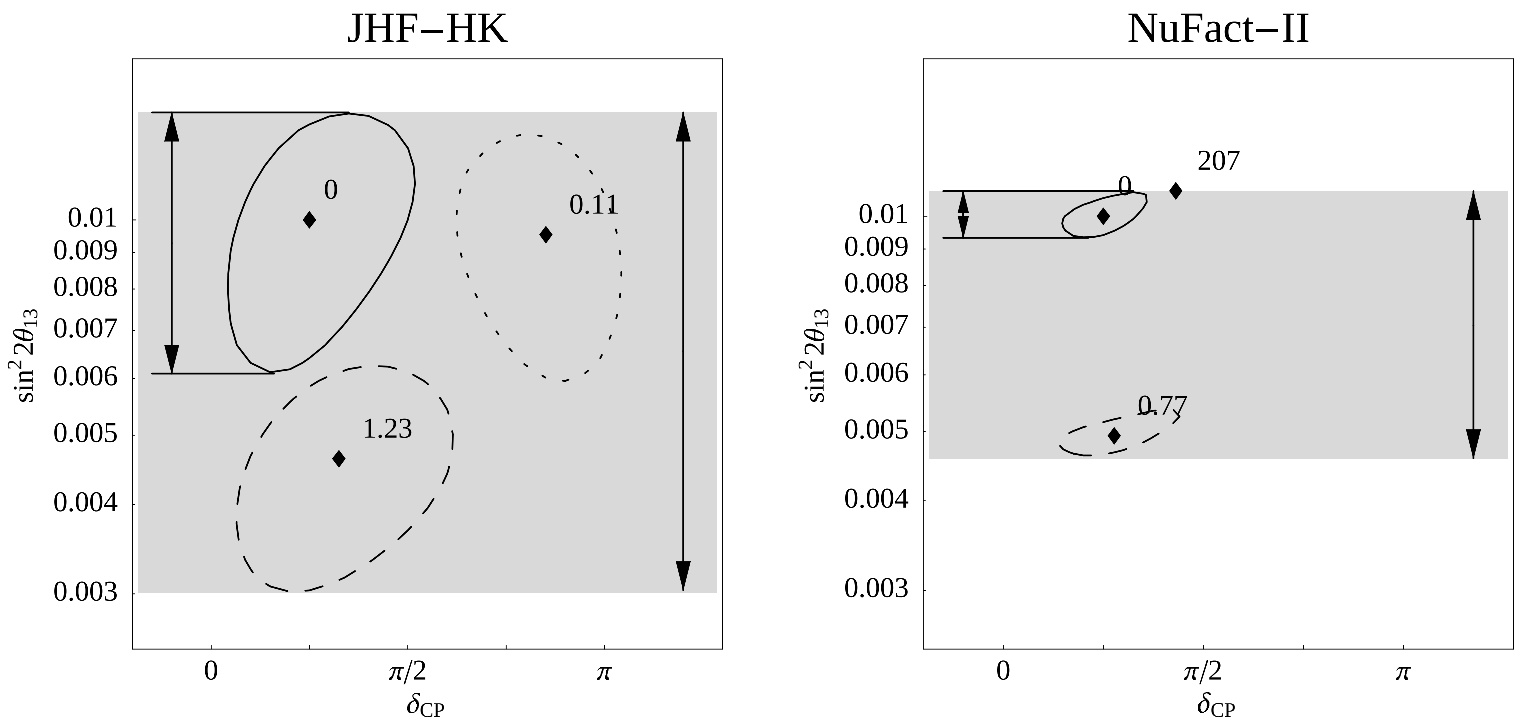
- **appearance & disappearance channel**
- **energy information**
- **external input**

Impact of Degeneracies

Complex parameter dependence in appearance probabilities $\Rightarrow$ multiple solutions

3 degeneracies:

- $\delta_{\rm CP}$-θ_{13}
- $\delta_{\rm CP}$-${\rm sgn}\Delta m^2_{31}$
- θ_{23}-$\pi/2-\theta_{23}$



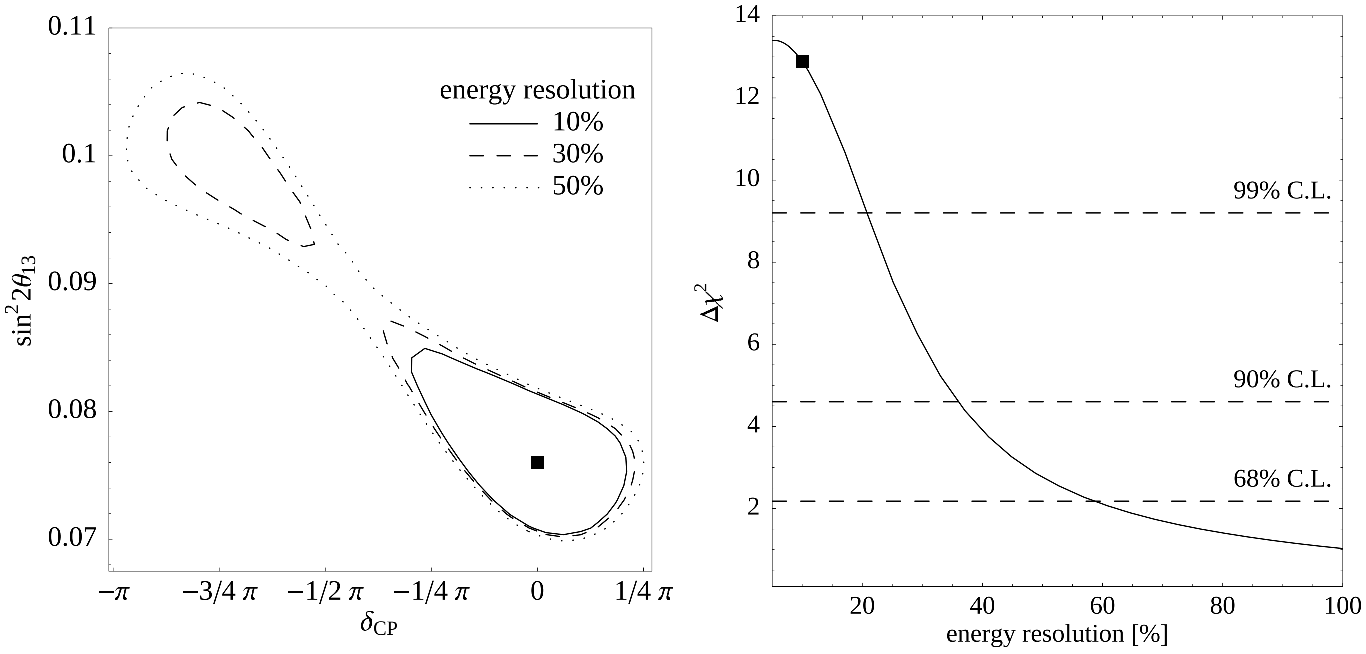
Full analysis:

- $\delta_{\rm CP}$-θ_{13} **is transformed to a correlation $\Leftrightarrow$ neutrino beam only**
- $\delta_{\rm CP}$-${\rm sgn}\Delta m^2_{31}$ **remains**
- θ_{23}-$\pi/2-\theta_{23}$ **remains**
- **combined or seperate regions**

Cervera et al., Barger et al., Burguett-Castell et al., Minakata et al., Huber, ML, Winter

Medium Baseline & Good Resolution

Correlation of $\delta_{\rm CP}$ with θ_{13}



$$E = 50\,\text{GeV},\ L = 3\,000\,\text{km},\ \Delta m^2_{21} = 10^{-4}\,\text{eV}^2$$

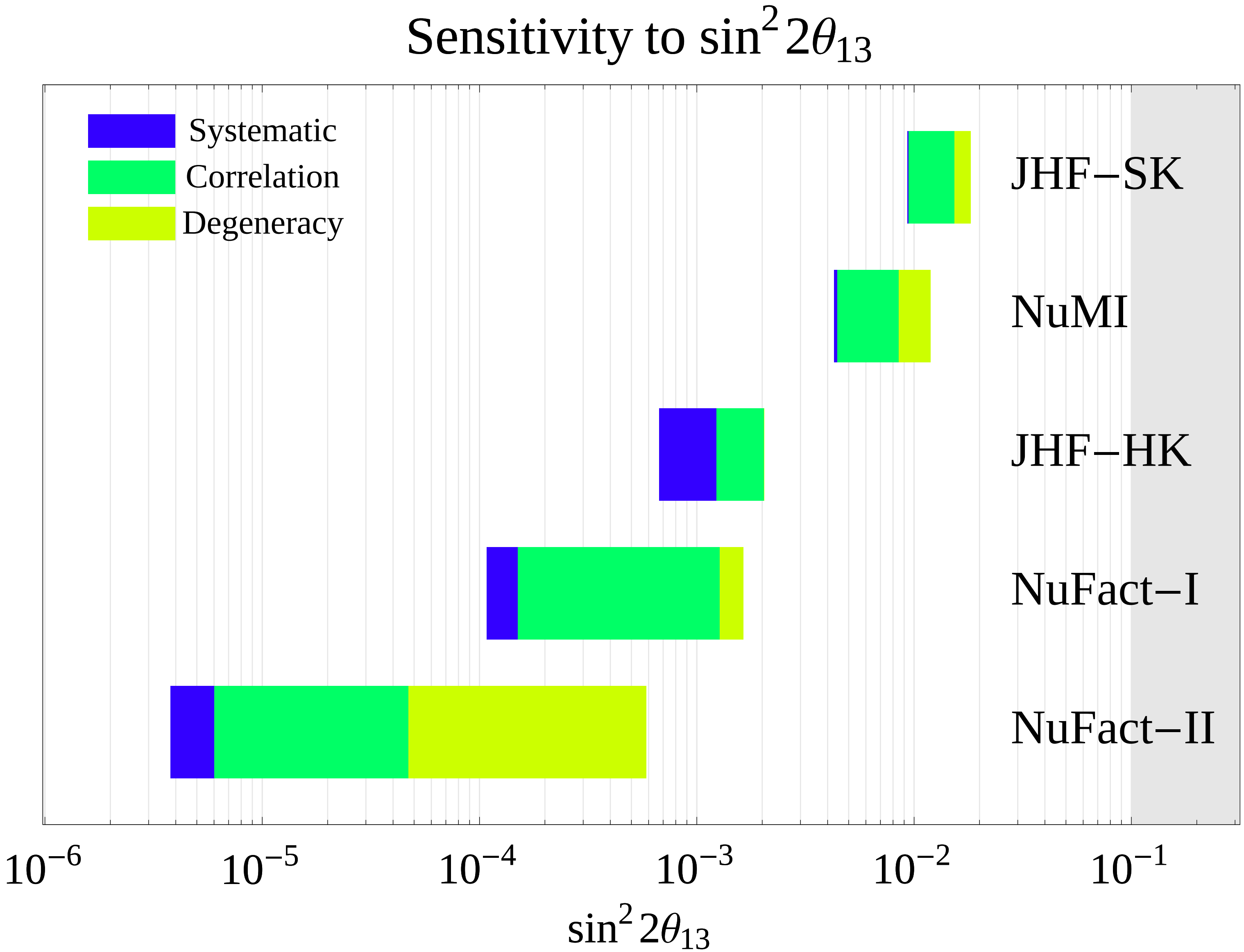
- two degenerate solutions
- depends strongly on energy resolution
- degeneracy lifted for energy resolution better than 25%

degeneracy can be resolved with spectral information ⇔ resolution & flux

Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, Freund, Huber, ML

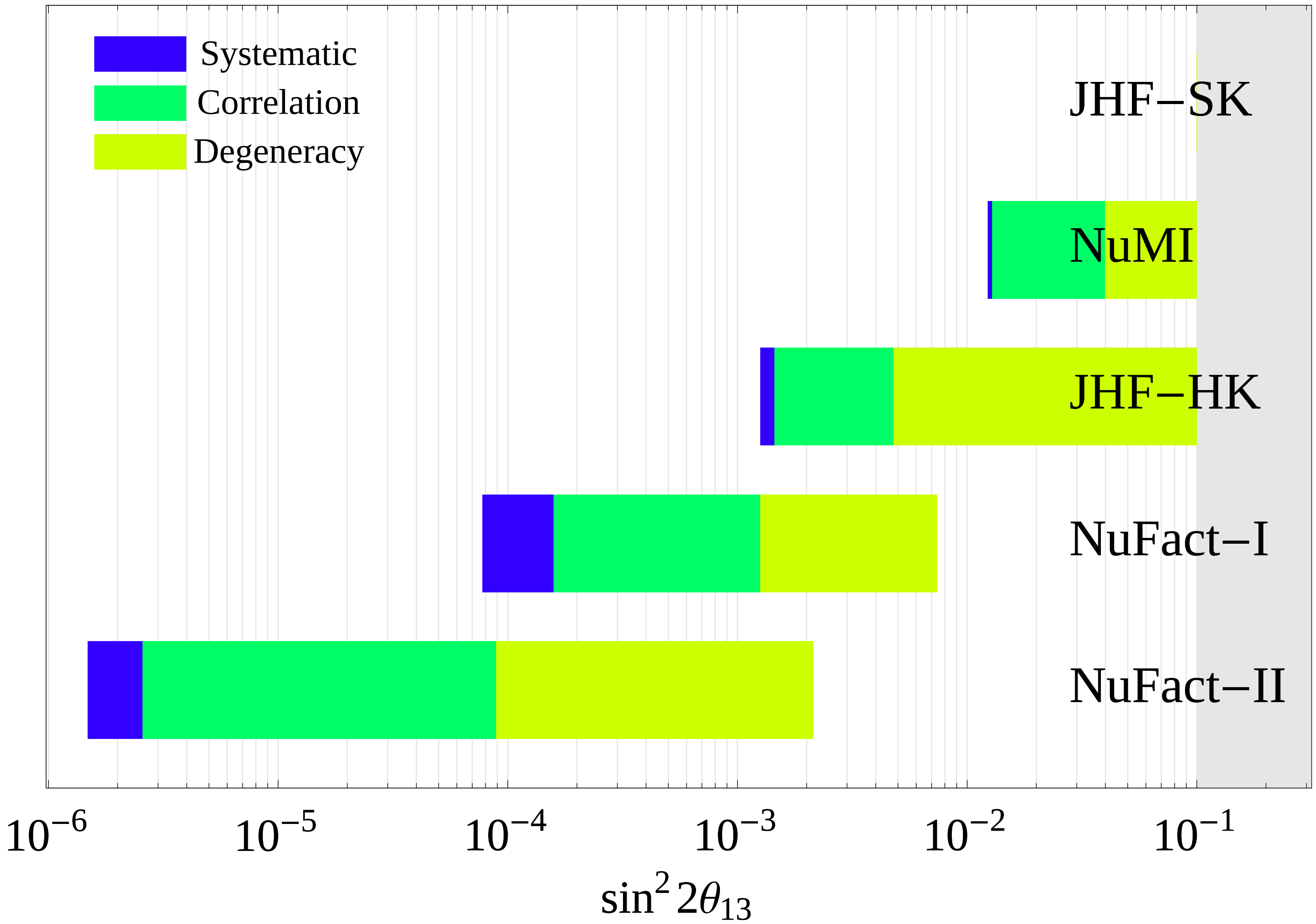
Comparative study including all effects

Huber, ML, Winter, hep-ph/0204352



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

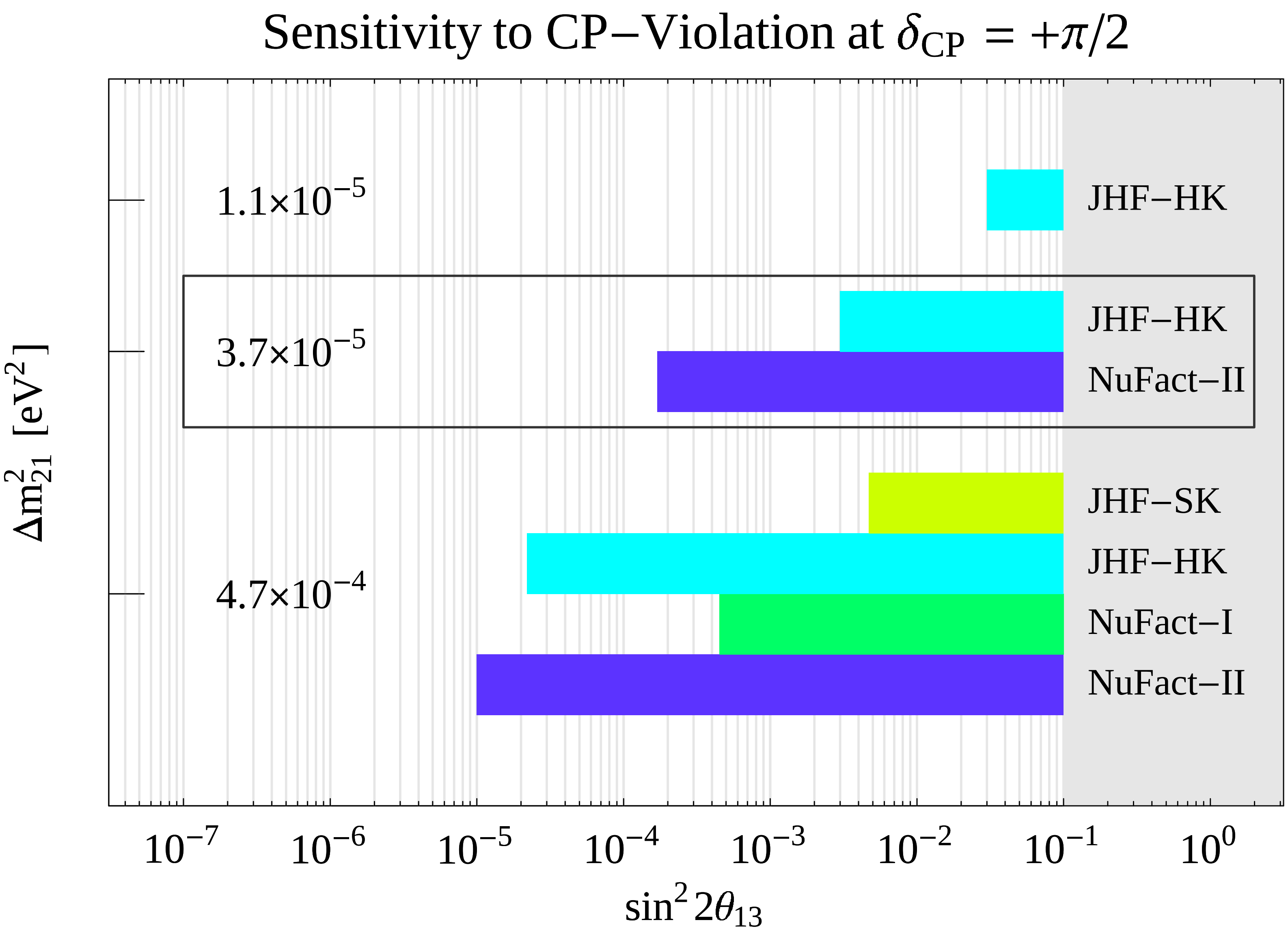
Sensitivity to the sign of Δm^2_{31}



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

$\Rightarrow$ **combine experiments!** **Huber, ML, Winter, hep-ph/0204352**

Measurements of CP-violation



- **CP violation** with high luminosity superbeams **feasable**
- **sensitivity is δ_{CP} dependent**

Huber, ML, Winter, hep-ph/0204352

Conclusions

Future LBL experiments ⇒ precision 3ν-Oscillation:

- requires very precise knowledge of the neutrio source
- in addition to detectors, oscillation framework (3ν, matter, ...)

⇒ "Laboratory" Sources: Reactors, β-beams, superbeams, neutrino factories

- known $\Delta m^2_{\rm atm}$, $E_\nu \simeq 1 - 100$ GeV ⇒ baselines 100...10000km
- is very promising and possible in stages ⇒ Δm^2_{31}, θ_{23}, θ_{13}, δ_{CP}
- Earth matter effects ⇒ complication & chance

Unique Impact on Physics:

- precise masses and mixings w/o hadronic uncertainties
- NSI, FCNC, $> 3\nu$, CPT, ... ⇒ very interesting limits
- very valuable flavour information ⇔ models of masses and mixings
- Dirac & Majorana masses ⇔ information on see-saw scales
- CP violation ⇔ leptogenesis: baryon asymmetry of the universe

⇒ Very Promising Future for LBL Neutrino Physics