Superbeam vs. Neutrino Factory

correlations, uncertainties degeneracies

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based on
hep-ph/0204352

Motivation

$\boxed{\text{neutrinos oscillate} \Longrightarrow \text{(at least) 6 additional fundamental parameters}}$

LBL experiments offer the unique possibility to study in detail:

- atmospherical parameters $\Longrightarrow$ Δm^2_{31} and θ_{23}
- subleading oscillations $\Longrightarrow$ θ_{13}
- mass hierarchy $\Longrightarrow$ $\mathrm{sign}\Delta m^2_{31}$
- three neutrino effects $\Longrightarrow$ δ_{CP}

But:

The size of θ_{13} will determine if any experiment can answer those fundamental questions

Outline

Comparison of different experiments

- Superbeams vs. Neutrino Factories
- initial and advanced setups
- identical boundary conditions
  - running time, target power, confidence levels etc.
  - equal level of sophistication in the analysis

Impact factors - which controllable factors determine the physics potential

- luminosity (i.e. money)
- systematical effects
- quality of external input

Full three flavour analysis

- 6 physical parameters
- systematical uncertainties
- external input
- correlations
- degeneracies

Appearance Probability

Analytic approximation of the appearance probability –
expansion in powers of $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$

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

$$\Delta = \Delta m^2_{31}L/4E;\ \hat{A} = A/\Delta m^2_{31} = 2VE/\Delta m^2_{31};\ V = \sqrt{2}G_F n_e.$$

$\boxed{P_{\nu_e\to\nu_\mu} \text{ depends on solar parameters only via the product } \sin 2\theta_{12}\cdot\Delta m^2_{21}}$

M. Freund, hep-ph/0103300.

A. Cervera *et al.*, Nucl. Phys. **B579** (2000) 17.

Simulation of LBL Experiments

Source $\otimes$ Oscillation $\otimes$ Detector

Source

- neutrino energy , flux and spectrum
- neutrino flavour composition (and contamination)
- operation of neutrino and anti-neutrino modes

Oscillation

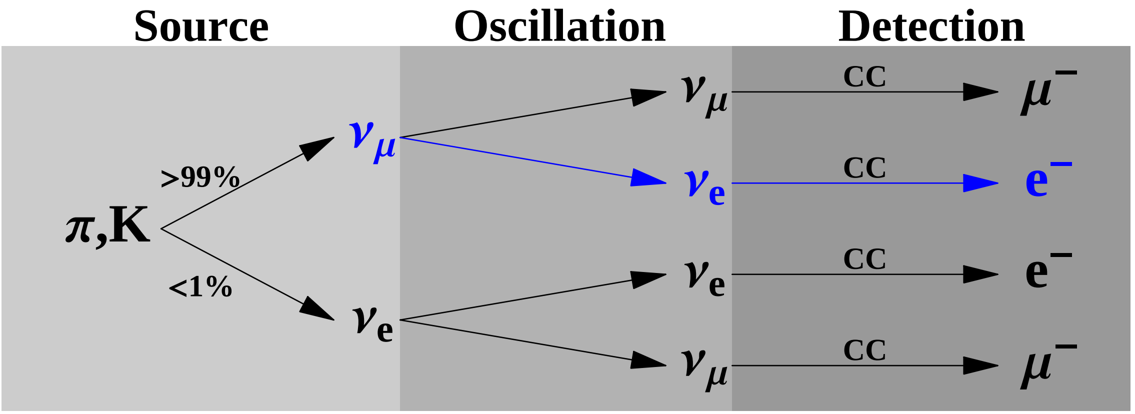
- initial and final flavour $\Leftrightarrow$ oscillation channels
- oscillation parameters: mass splittings, angles and phase
- baseline, matter profile, ...

Detector

- fiducial mass, material, energy threshold and resolution
- particle ID (flavour, charge, event reconstruction, ...)
- x-sections

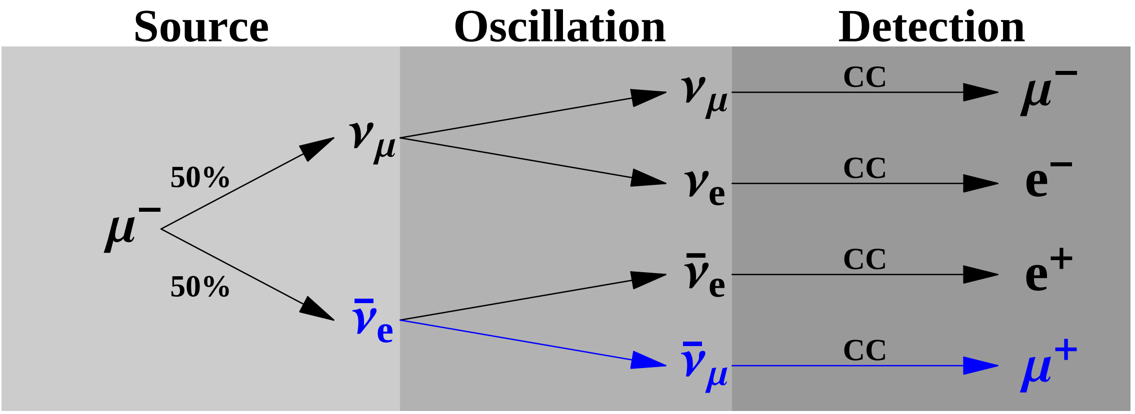
Possible Signals

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

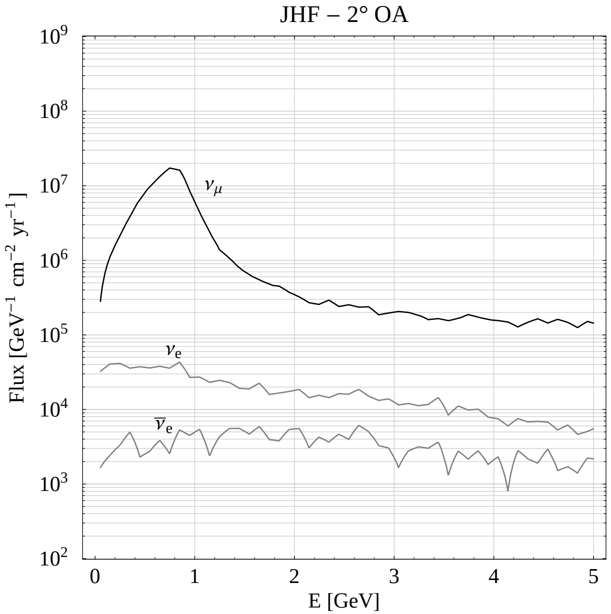
Neutrino Factories



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

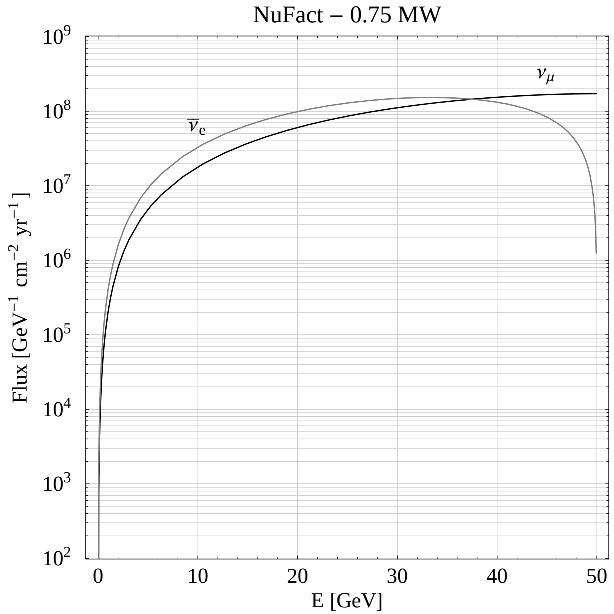
Our Analysis – Source

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%

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%

$\boxed{\text{Uncertainties in flux and } \nu_e\text{–background}}$

Our Analysis – Oscillation

JHF
- $295\,\mathrm{km}$ baseline
- $L/E_{\text{peak}} = 378\,\mathrm{km\,GeV}^{-1}$
- matter density $\rho = 2.8\,\mathrm{g\,cm}^{-3}$

NuFact
- $3\,000\,\mathrm{km}$ baseline
- $L/E_{\text{peak}} = 90\,\mathrm{km\,GeV}^{-1}$
- matter density $\rho = 3.5\,\mathrm{g\,cm}^{-3}$

$P_{\nu_\mu \to \nu_e}$ depends on solar parameters via the product

$$\pi_{\text{sol}} := \sin 2\theta_{12} \cdot \Delta m^2_{21}$$

thus we use this π_{sol} as parameter –
this is the only approximation in the treatment of the oscillation

- full 3 neutrino calculation in matter
- we allow for errors on all parameters, including the matter density
- for solar parameters we assume KamLand input
- CP-phase δ_{CP} is unconstrained

Uncertainties on all parameters

Our Analysis – Detector

JHF

- water Cherenkov detector – SuperK
- fiducial mass $22.5\,(1\,000)\,\mathrm{kt}$
- running period of $5\,(8)$ years
- NC-rejection ~ 0.01
- energy range $0.4 - 1.2\,\mathrm{GeV}$
- constant efficiency
- efficiency for $\nu_e \sim 0.5$
- 61% QE-interactions at E_{peak}
- energy resolution $\delta E = 5\%$
- 5% uncertainty on all backgrounds

NuFact

- magnetized iron calorimeter
- fiducial mass $10\,(50)\,\mathrm{kt}$
- running period of $5\,(8)$ years
- NC-rejection $< 10^{-5}$
- energy range $4 - 50\,\mathrm{GeV}$
- linear rise of efficiency from $4 - 20\,\mathrm{GeV}$
- efficiency for $\nu_\mu \sim 0.4$
- DIS
- energy resolution $\delta E = 15\%$
- 5% uncertainty on all backgrounds

Y. Itow *et al.*, hep-ex/0106019.

A. Blondel *et al.*, Nucl. Instrum. Meth. **A451**, 102 (2000).

Setups

JHF-SK	JHF-HK	NuFact-I	NuFact-II
22.5 kt water Cherenkov	1 000 kt water Cherenkov	10 kt magnetized iron calorimeter	50 kt magnetized iron calorimeter
0.75 MW target power	4 MW target power	0.75 MW target power	4 MW target power
5 years	8 years	5 years	8 years
139.0 signal	13 180.0 signal	1 522.8 signal	64 932.6 signal
23.3 background	2 204.6 background	4.2 background	180.3 background

Statistics

- Poissonian statistics $\chi^2 = \sum_{i=1}^{b} \left(2[\langle x_i \rangle - x_i] + 2\, x_i \log \frac{x_i}{\langle x_i \rangle} \right)$
- parameterization of systematical uncertainties

$$
\begin{aligned}
s_i &= s_i(n_s, t_s) = s_i^0\,(1 + n_s + t_s \cdot E_i/(E_{\mathsf{max}} - E_{\mathsf{min}})) \\
b_i &= b_i(n_b, t_b) = b_i^0\,(1 + n_b + t_b \cdot E_i/(E_{\mathsf{max}} - E_{\mathsf{min}})) \\
x_i &= x_i(n_s, t_s, n_b, t_b) = s_i(n_s, t_s) + b_i(n_b, t_b) \\
\chi^2_\alpha &= \chi^2_\alpha(\lambda, \rho; n_s^\alpha, t_s^\alpha, n_b^\alpha, t_b^\alpha)
\end{aligned}
$$

- integrating out the nuisance parameters

$$
\hat{\chi}^2_\alpha(\lambda, \rho) = \min_{n_s^\alpha, t_s^\alpha, n_b^\alpha, t_b^\alpha} \left(\chi^2_\alpha(\lambda, \rho; n_s^\alpha, t_s^\alpha, n_b^\alpha, t_b^\alpha) + \frac{(n_s^\alpha)^2}{\sigma^2_{n_s^\alpha}} + \frac{(t_s^\alpha)^2}{\sigma^2_{t_s^\alpha}} + \frac{(n_b^\alpha)^2}{\sigma^2_{n_b^\alpha}} + \frac{(t_b^\alpha)^2}{\sigma^2_{t_b^\alpha}} \right)
$$

Statistics

- projection on the parameter of interest – taking into account additional information

$$\chi^2_{\mathsf{F}}(\eta) \quad = \quad \min_{\overline{\lambda},\rho} \left(\sum_{\alpha} \hat{\chi}^2_{\alpha}(\lambda,\rho) + \frac{(\rho-\rho^0)^2}{\sigma^2_\rho} + \frac{(\pi_{\mathsf{sol}}-\pi^0_{\mathsf{sol}})^2}{\sigma^2_{\pi_{\mathsf{sol}}}} \right)$$

- external information from KamLand and geophysics

$$\sigma_{\pi_{\mathsf{sol}}} = 0.15\,\pi^0_{\mathsf{sol}} \quad \text{and} \quad \sigma_\rho = 0.05\,\rho^0$$

- 6 parameters remain

$$\lambda = (\rho, \pi_{\mathsf{sol}}, \Delta m^2_{31}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$$

R. J. Geller and T. Hara, hep-ph/0111342.

M. C. Gonzalez-Garcia and C. Peña-Garay, Phys. Lett. **B527**, 199 (2002).

1

4×10^{-6}

Systematical Errors

Signal

- use the energy information
- use appearance and disappearance
- appearance channel is a relative measurement
  - overall normalization error of 5% is okay
  - energy calibration error of 5% is okay

Background

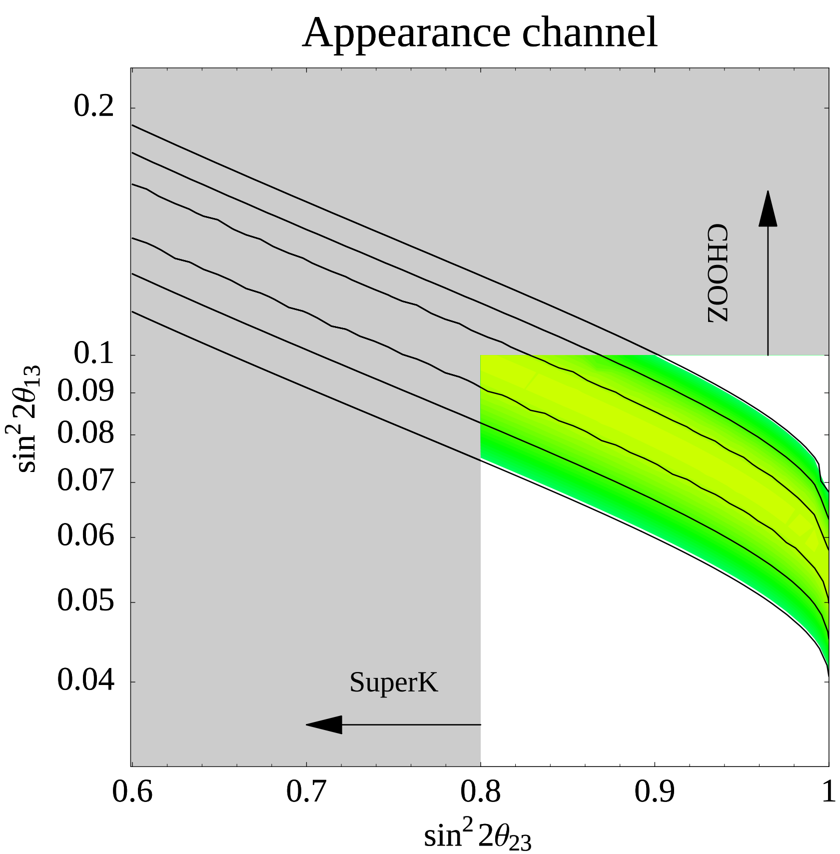
- magnitude of backgrounds limits sensitivity for Superbeams
- energy information helps to reduce the impact of the background
- background uncertainty becomes important when $\sigma_{b_n} \geq 1/\sqrt{b}$
  for $\sigma_{b_n} = 5\% \Leftrightarrow b = 400$

Background uncertainty important for high statistics experiments

1.6

$6{\times}10^{-6}$

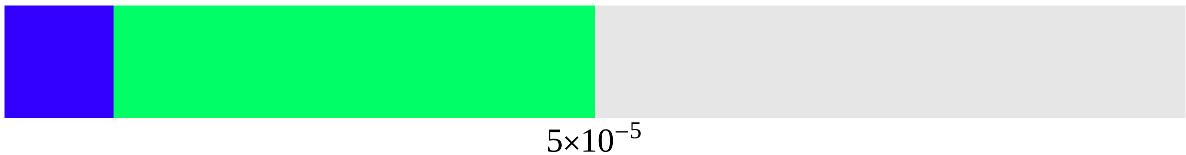
Correlations



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

$\Rightarrow$ use all available information

- appearance & disappearance channels
- energy information
- external input



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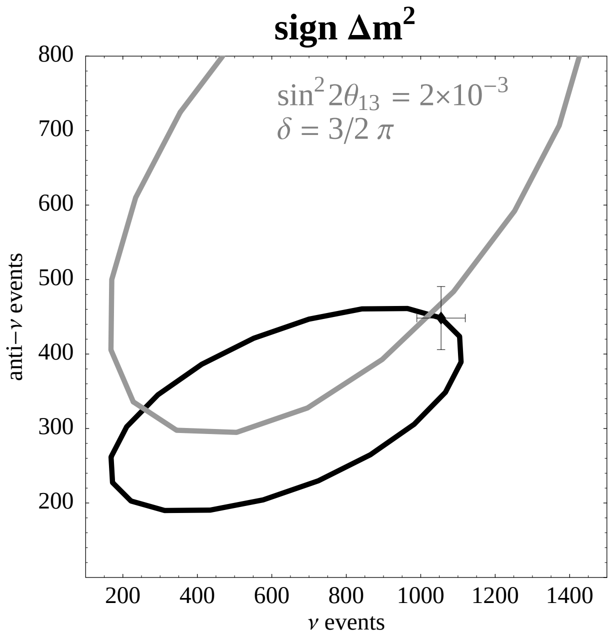
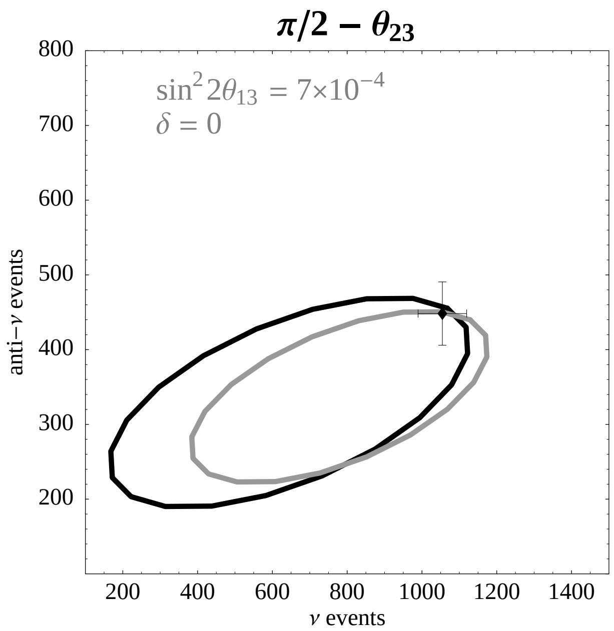
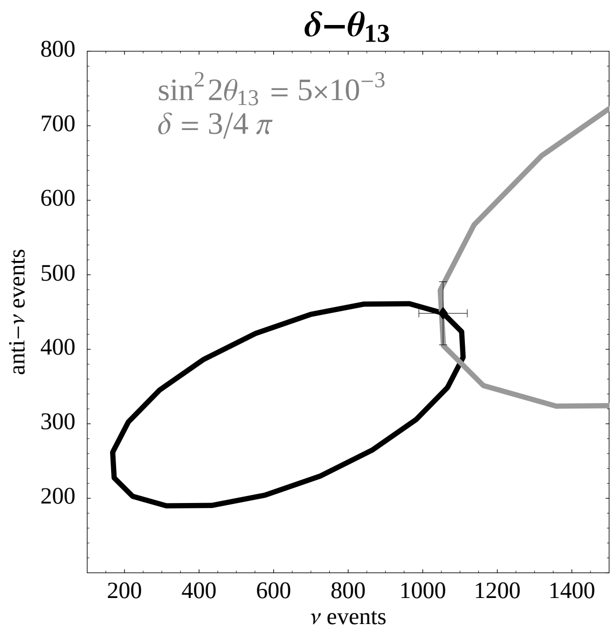
Degeneracies

Starting values: $\sin^2 2\theta_{13} = 1 \cdot 10^{-3}$ and $\delta_{\mathrm{CP}} = 0$







$\sin\delta$ and $\mathrm{sign}\Delta m^2_{31}$ act different on ν and $\overline{\nu}$

- matter effect

$\Longrightarrow$ δ' and opposite sign

$\sin^2 2\theta_{23}$ in $\nu_\mu \to \nu_\mu$ is symmetric around $\pi/4$

$\sin^2\theta_{23}$ in $\nu_e \to \nu_\mu$ is not

$\Longrightarrow$ θ'_{13} and θ'_{23}

$\sin 2\theta_{13}, \cos\delta, \sin\delta$

- two solutions with identical event rates for ν and $\overline{\nu}$

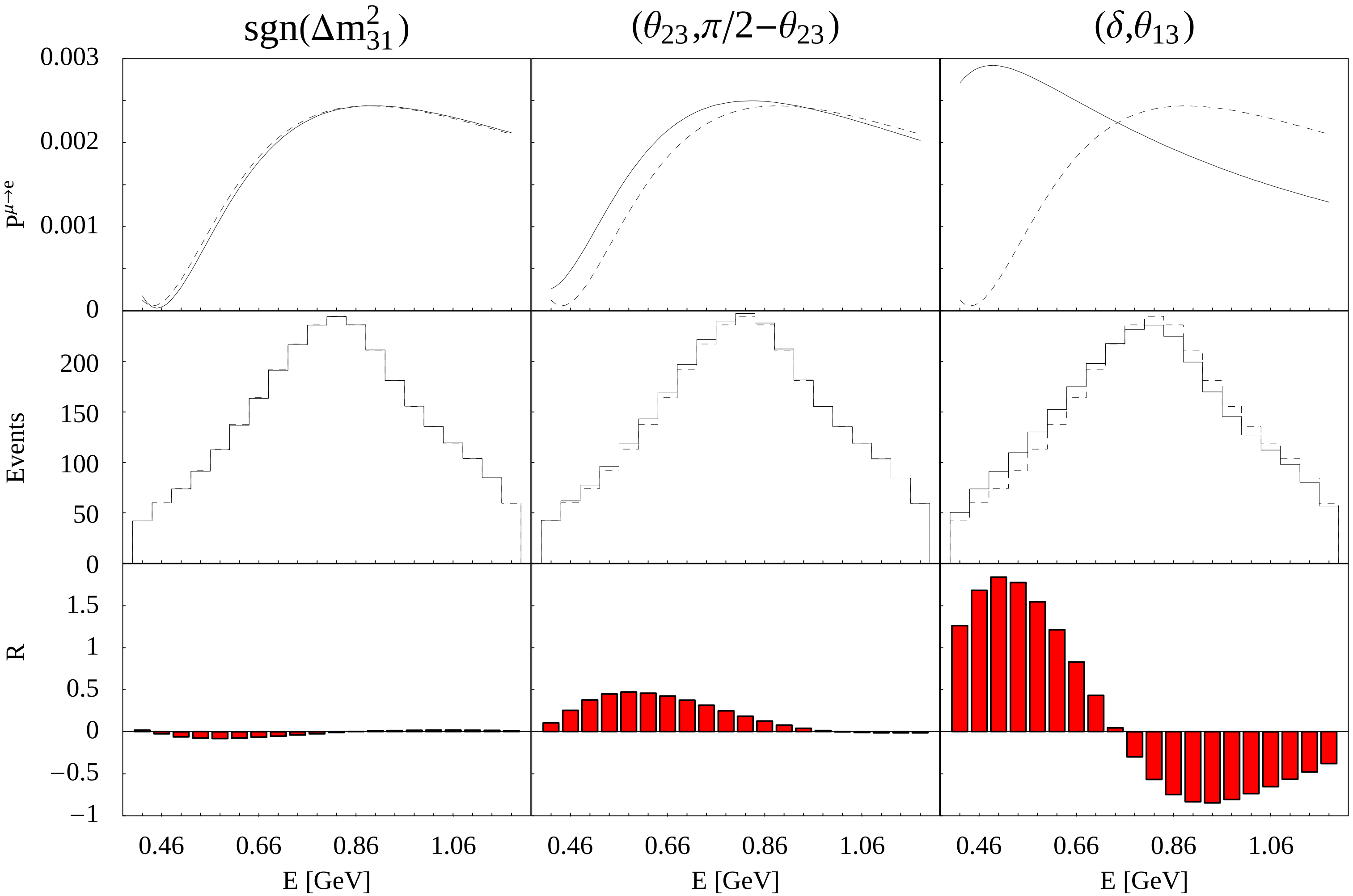
$\Longrightarrow$ δ' and θ'_{13}

J. Burguet-Castell *et al.*, Nucl. Phys. **B608**, 301 (2001).

V. Barger *et al.*, Phys. Rev. **D65**, 073023 (2002).

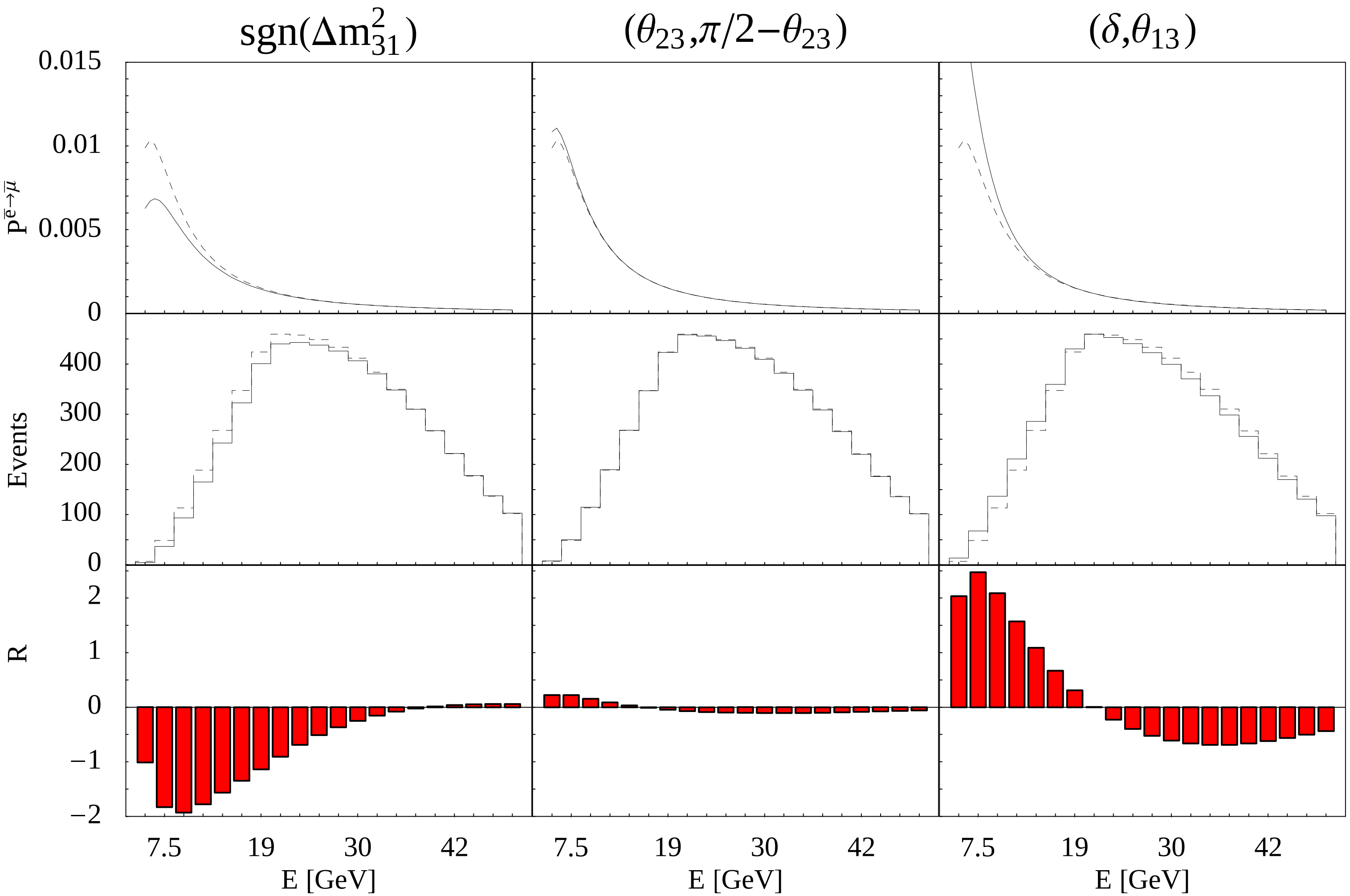
Degeneracies

Superbeam

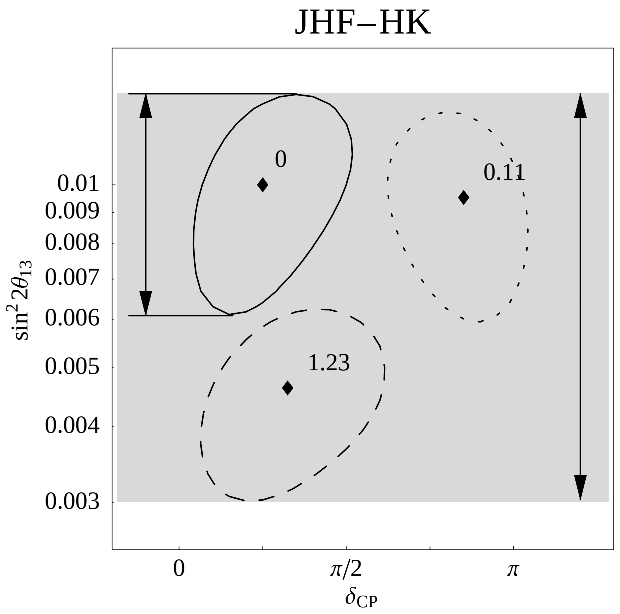


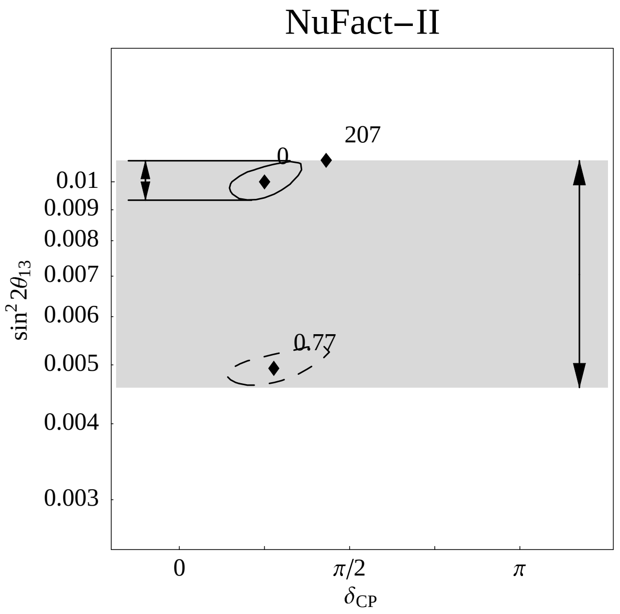
Degeneracies

NuFact



Do They Really Exist?





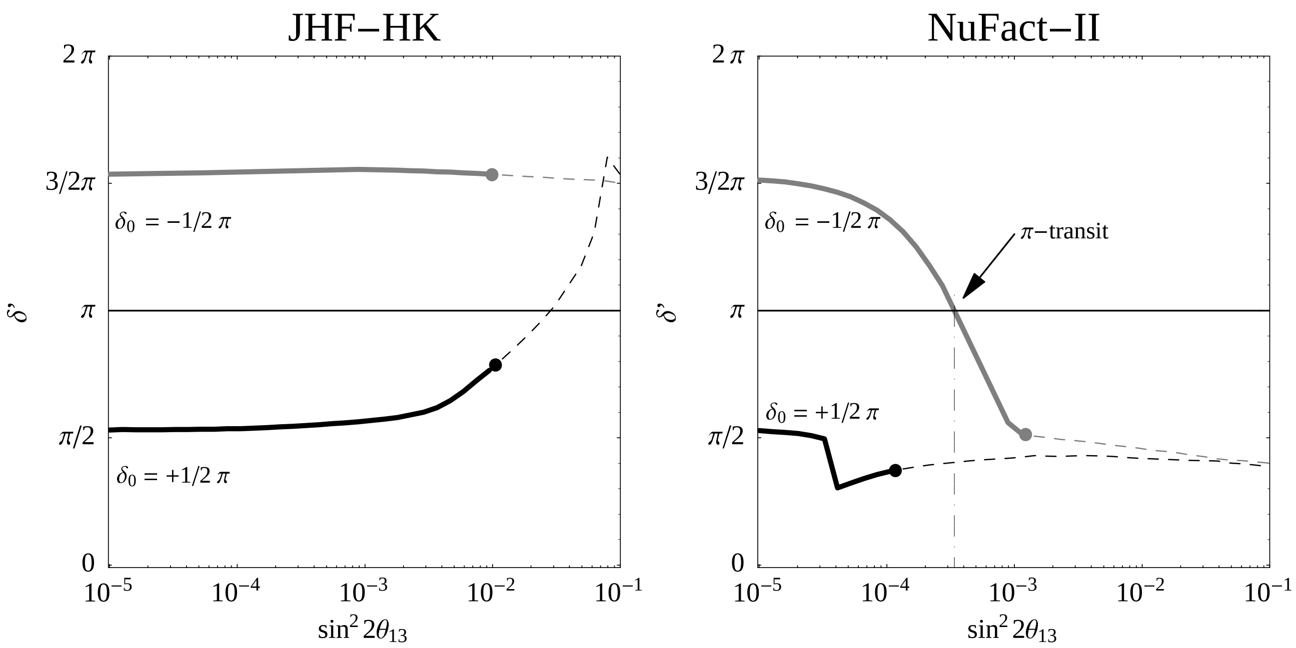
- some show up in the fit
- depends on statistics
- depends on detector performance
- depends on strength of MSW-effect
- depends on energy resolution

disconnected, multiple solutions

No general rule how to quote an error or sensitivity limit –

appropriate choice on case by case base

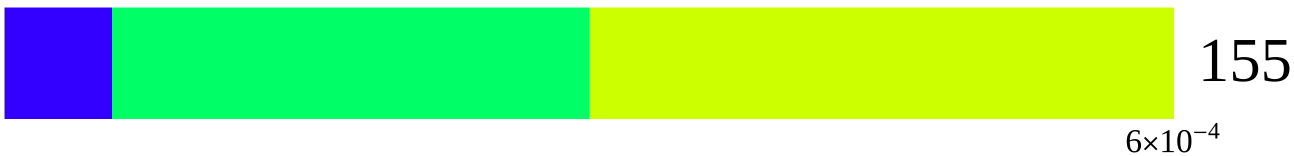
The Mass Hierarchy Problem



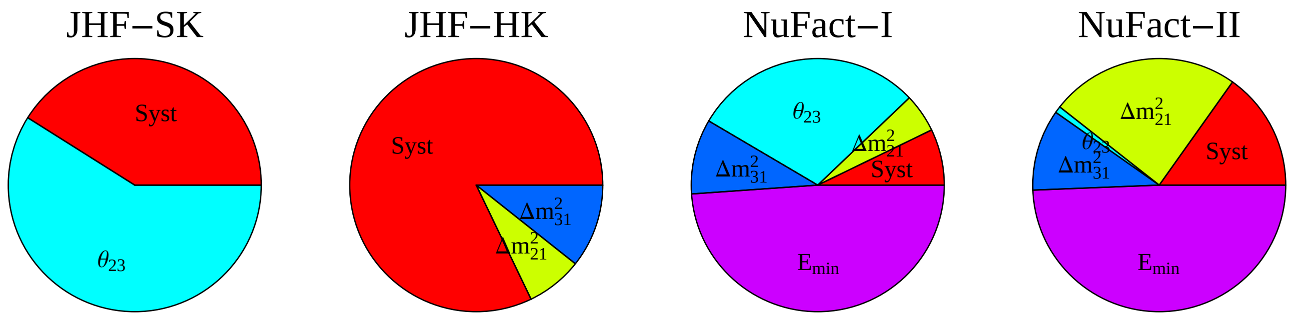
- in general two solutions with opposite sign of Δm^2_{31} and different δ_{CP}
- sufficient matter-effects allow to reject the wrong solution

$\boxed{\delta_{\mathrm{CP}} \text{ gets continously mapped to any } \delta_{\mathrm{CP}}\text{‘}}$

"π–transit" $\Longleftrightarrow$ maximal $\cancel{CP}$ is mapped to CP–conservation



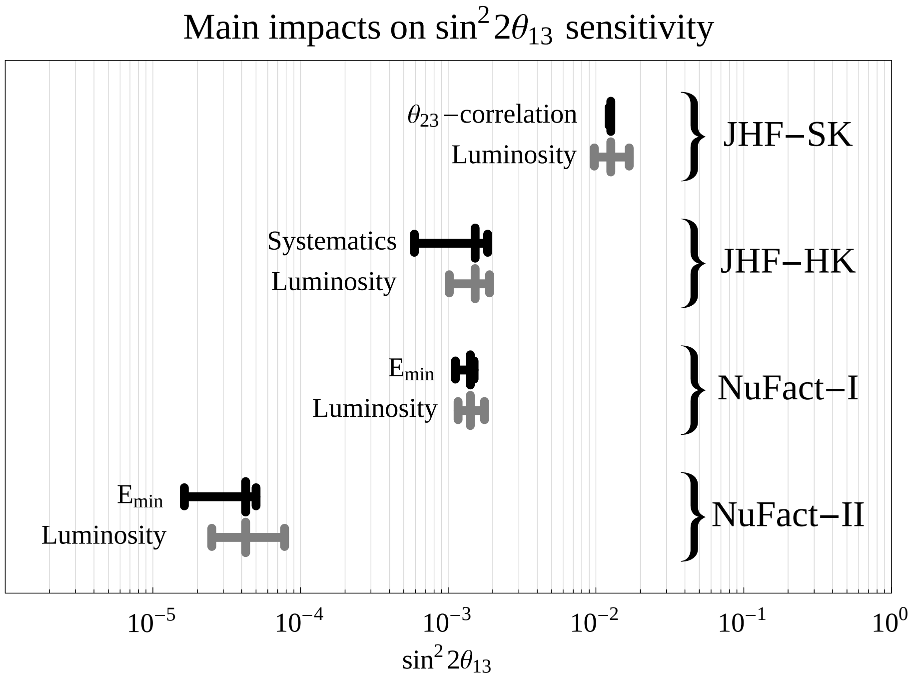
$\sin^2 2\theta_{13}$ – Impact Factors



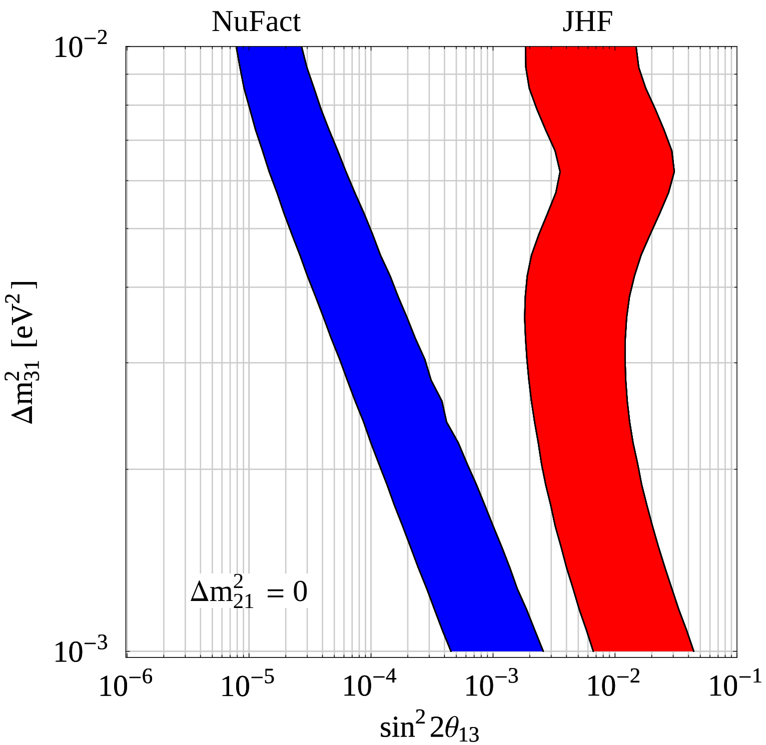
- relative contribution of controllable factors
- background uncertainty for Superbeams
- threshold effects for NuFact

variation of main impact factors
$\Longleftrightarrow$ variation of luminosity

- Superbeams – systematics
- NuFact – low energies

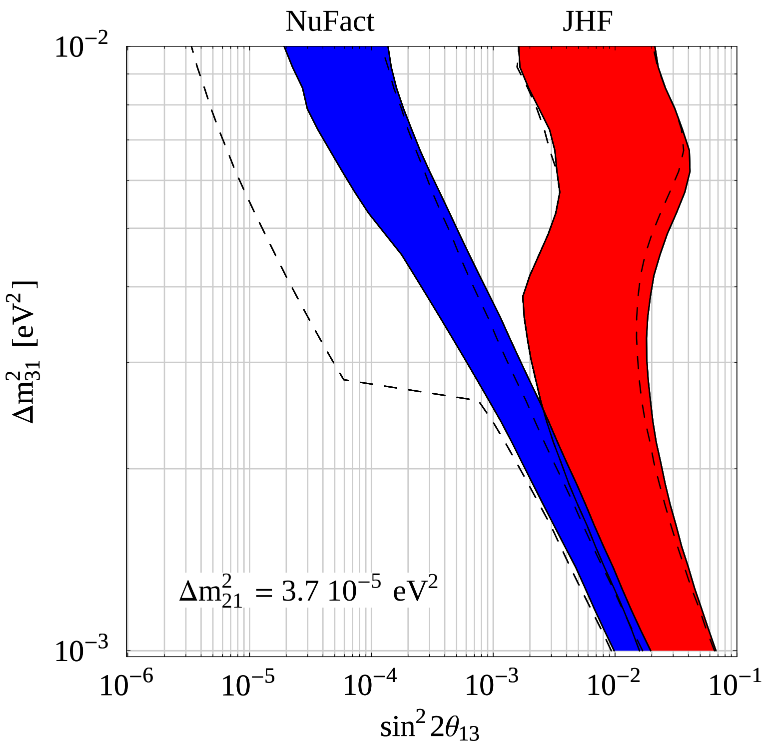


$\Delta m^2_{21} = 0$



- no problems due to $\delta_{\rm CP}$

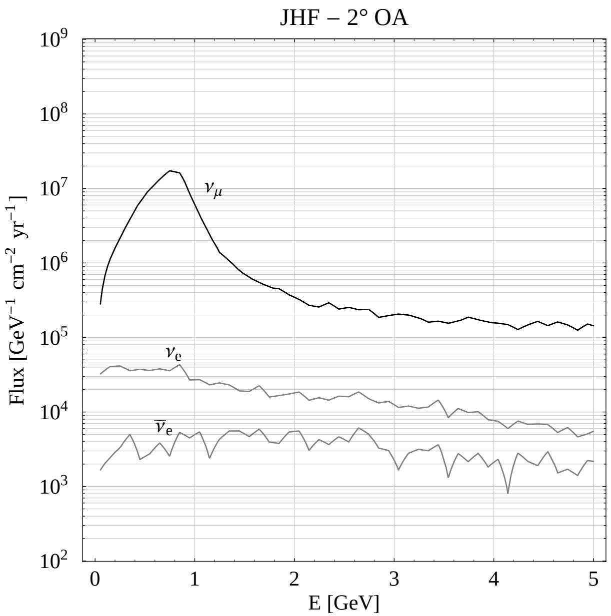
$\Delta m^2_{21} = 3.7 \cdot 10^{-5}\,\mathrm{eV}^2$



- dashed line shows result neglecting $\pi/2 - \theta_{23}$ degeneracy

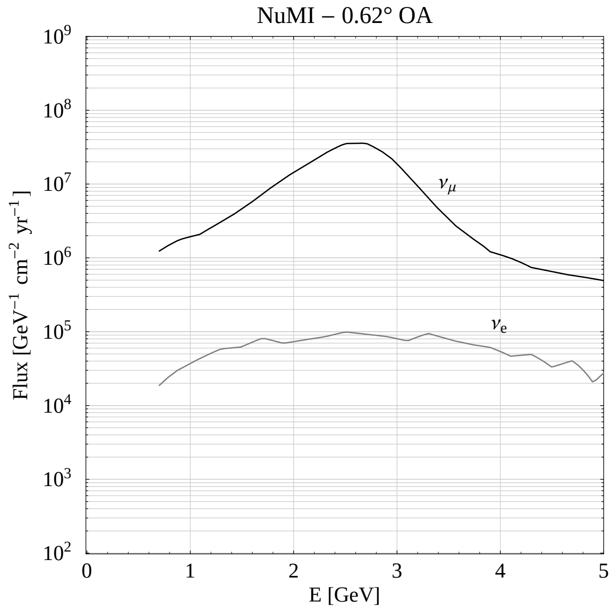
JHF vs. NuMI

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%

Uncertainties in flux and ν_e–background

JHF vs. NuMI

JHF

- $295\,\mathrm{km}$
- water Cherenkov detector – SuperK
- fiducial mass $22.5\,\mathrm{kt}$
- running period of 5 years
- NC-rejection ~ 0.01
- efficiency for $\nu_e \sim 0.5$
- 61% QE-interactions at E_{peak}
- energy range $0.4 - 1.2\,\mathrm{GeV}$
- energy resolution $\delta E = 5\%$
- 5% uncertainty on all backgrounds

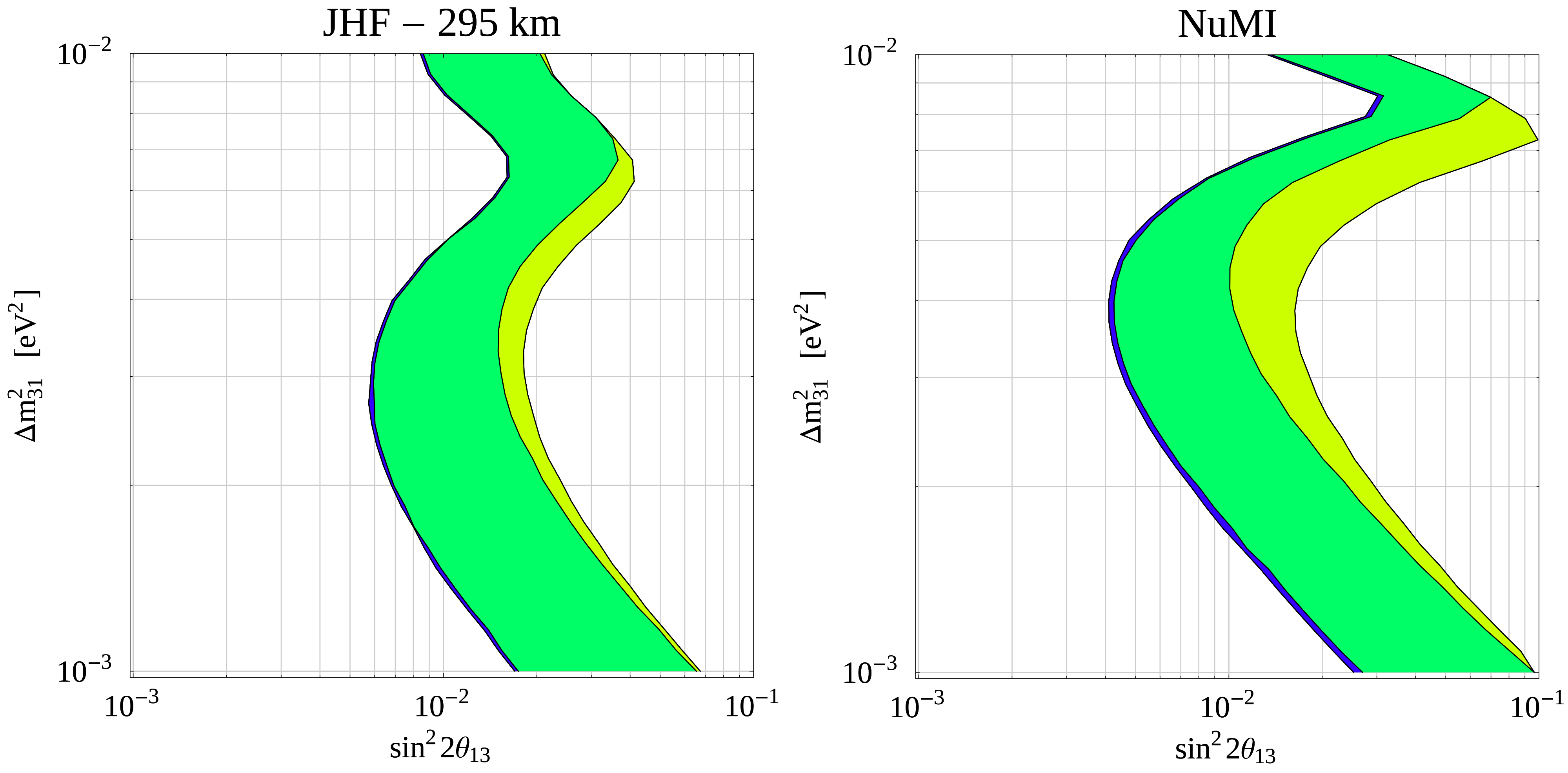
NuMI

- $712\,\mathrm{km}$
- low-Z calorimeter
- fiducial mass $17\,\mathrm{kt}$
- running period of 5 years
- NC-rejection ~ 0.001
- efficiency for $\nu_e \sim 0.4$
- 22% QE-interactions at E_{peak}
- energy range $1.6 - 2.8\,\mathrm{GeV}$
- energy resolution $\delta E = 16\%$
- 10% uncertainty on all backgrounds

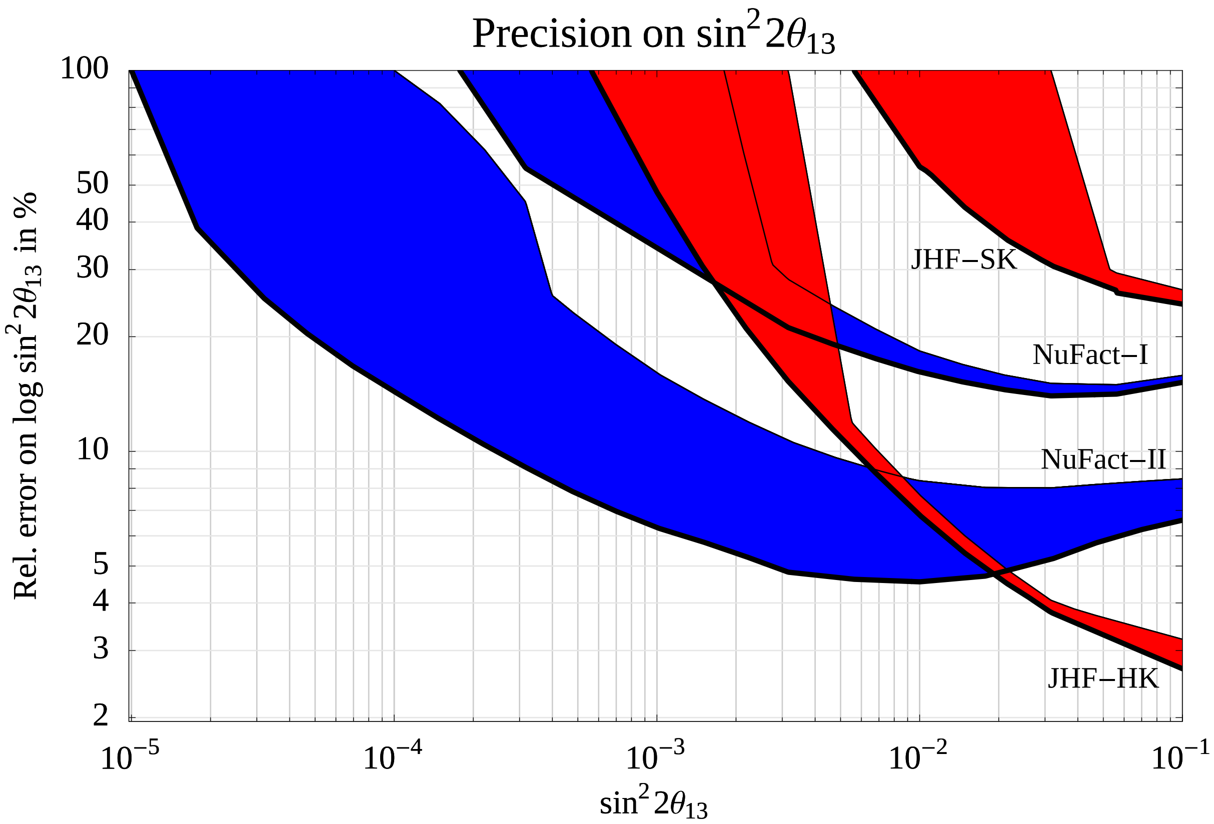
Y. Itow *et al.*, hep-ex/0106019.

A. Para and M. Szleper, hep-ex/0110001, hep-ex/0110032.

JHF vs. NuMI

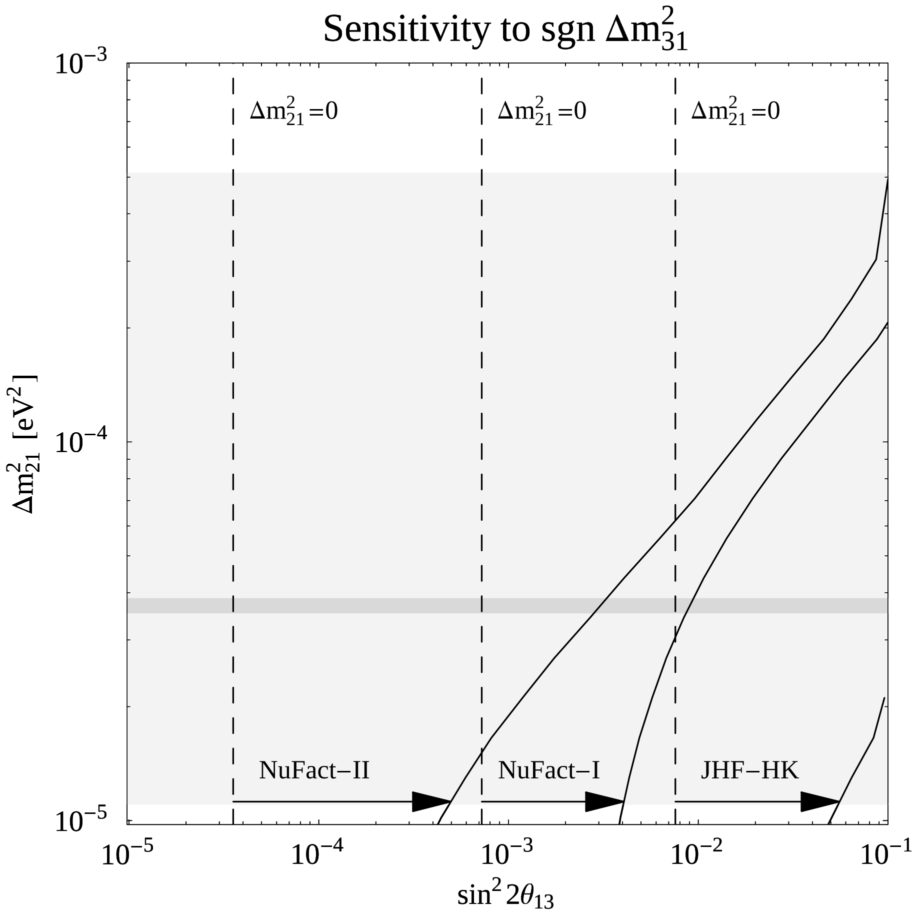

JHF – 295 km
NuMI
10^{-2}
10^{-3}
Δm^2_{31} [eV^2]
10^{-3}
10^{-2}
10^{-1}
$\sin^2 2\theta_{13}$

$\sin^2 2\theta_{13}$ – Accuracy



- local minima only
- bands due to δ_{CP}
- upward bending for $\sin^2 2\theta_{13} > 10^{-2}$ due to matter uncertainty

$\mathrm{sign}\Delta m^2_{31}$ – a Difficult Task



- degeneracy with δ_{CP} determines the sensitivity
- bigger Δm^2_{21}

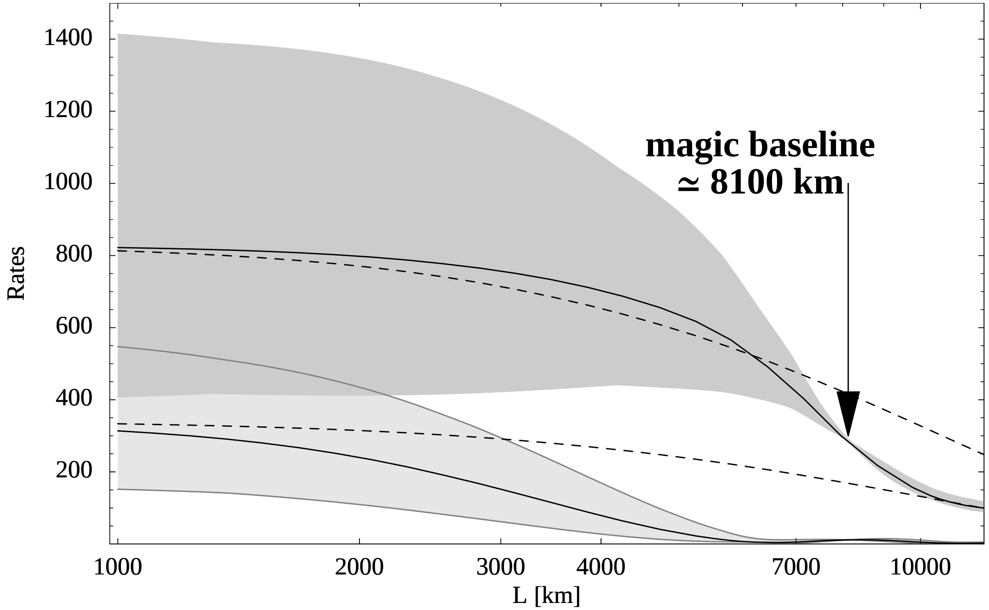
$\Longrightarrow$ more CP–effects

$\Longrightarrow$ more confusion

$\Longrightarrow$ several orders of magnitude loss in sensitivity

Very long baseline $> 7\,000\,\mathrm{km}$ is needed

Magic Baseline



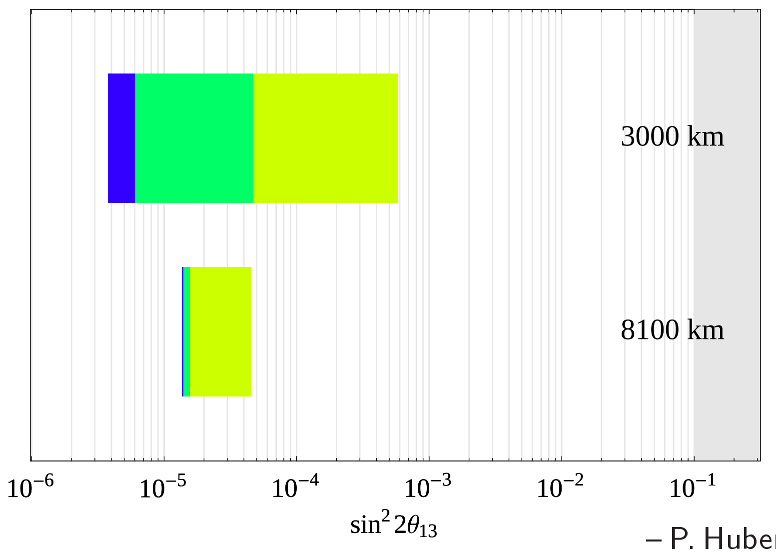
$$
\begin{aligned}
P_{\nu_e\to\nu_\mu} \quad &\approx \quad \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta) \\
&\pm \quad \alpha \quad \sin(\hat{A}\Delta)\sin\delta \times f_1 \\
&+ \quad \alpha \quad \sin(\hat{A}\Delta)\cos\delta \times f_2 \\
&+ \quad \alpha^2 \quad \sin^2(\hat{A}\Delta) \times f_3
\end{aligned}
$$

$$\boxed{\sin(\hat{A}\Delta) = 0 \Leftrightarrow \hat{A}\Delta = n\pi \Leftrightarrow VL/2 = n\pi}$$

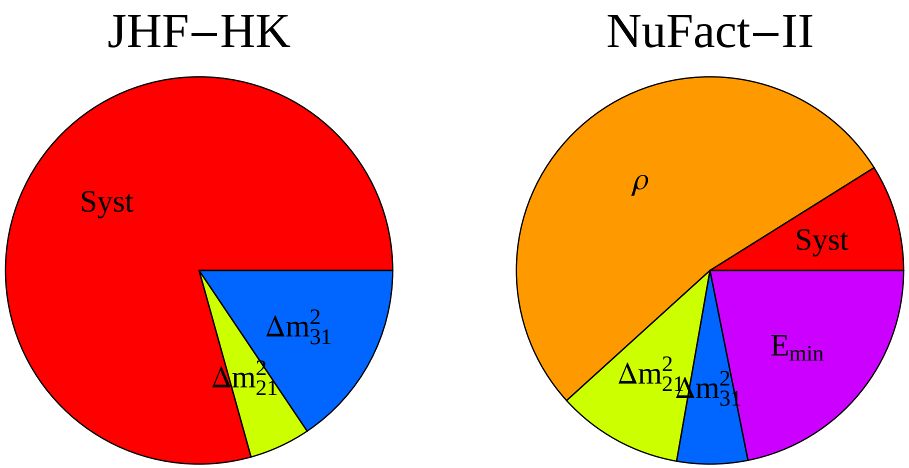
this relation gives a magic baseline $\simeq 8\,100\,\mathrm{km}$
where all effects due to α and δ_{CP} vanish
independent of energy and mass splittings

V. Barger *et al.*, Phys. Rev. **D65**, 073023 (2002).

Sensitivity to $\sin^2 2\theta_{13}$ for NuFact–II



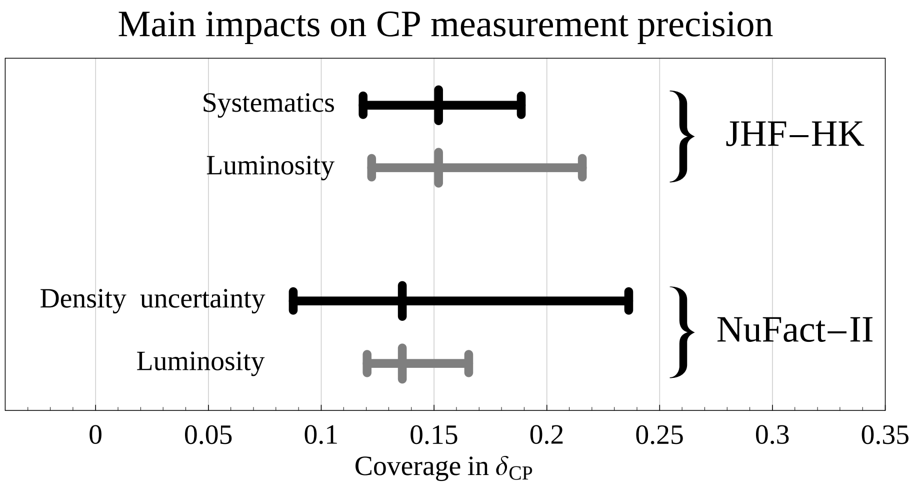
δ_{CP} – Impact Factors



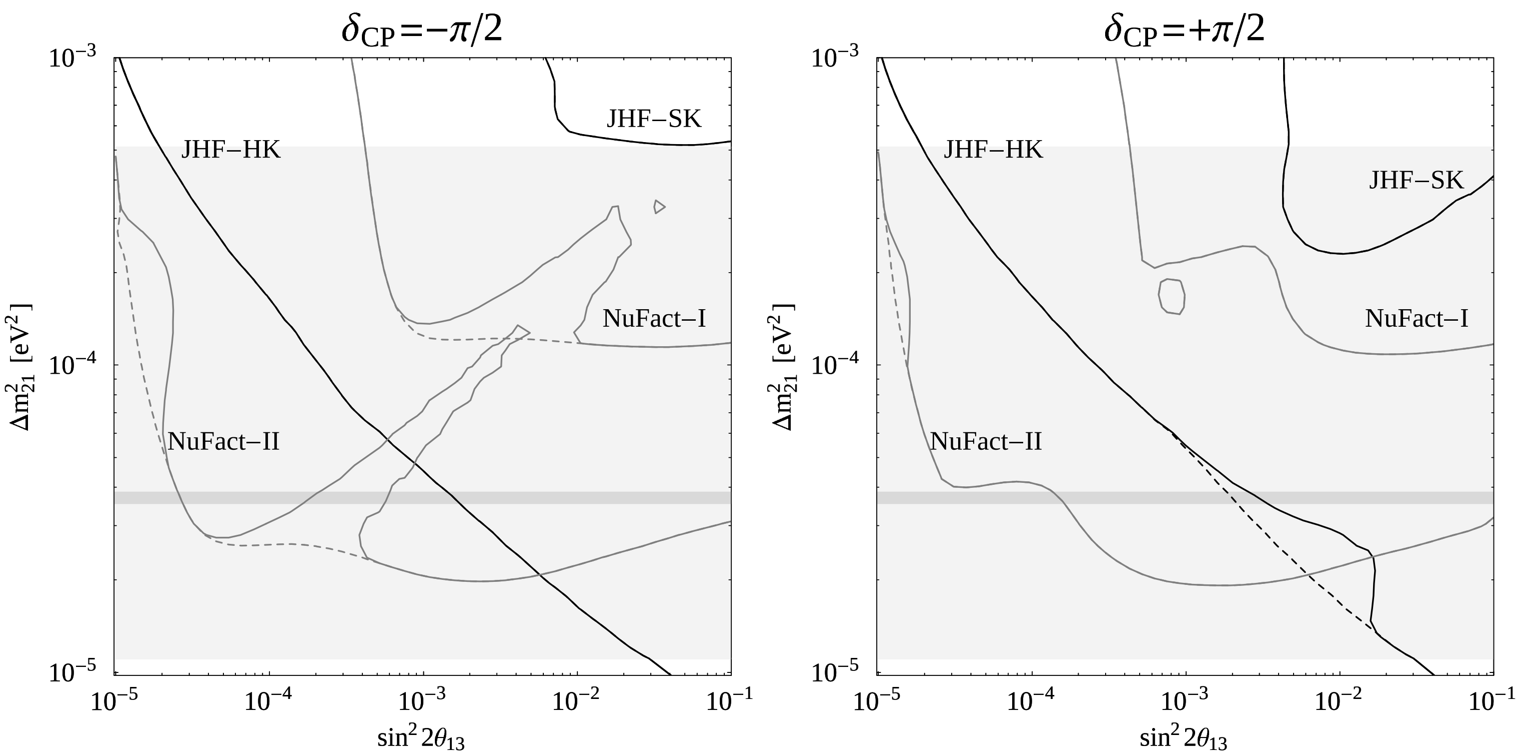
- relative contribution of controllable factors
- background uncertainty for Superbeams
- matter uncertainty for NuFact

variation of main impact factors
$\Longleftrightarrow$ variation of luminosity

- Superbeams – systematics
- NuFact – matter uncertainty

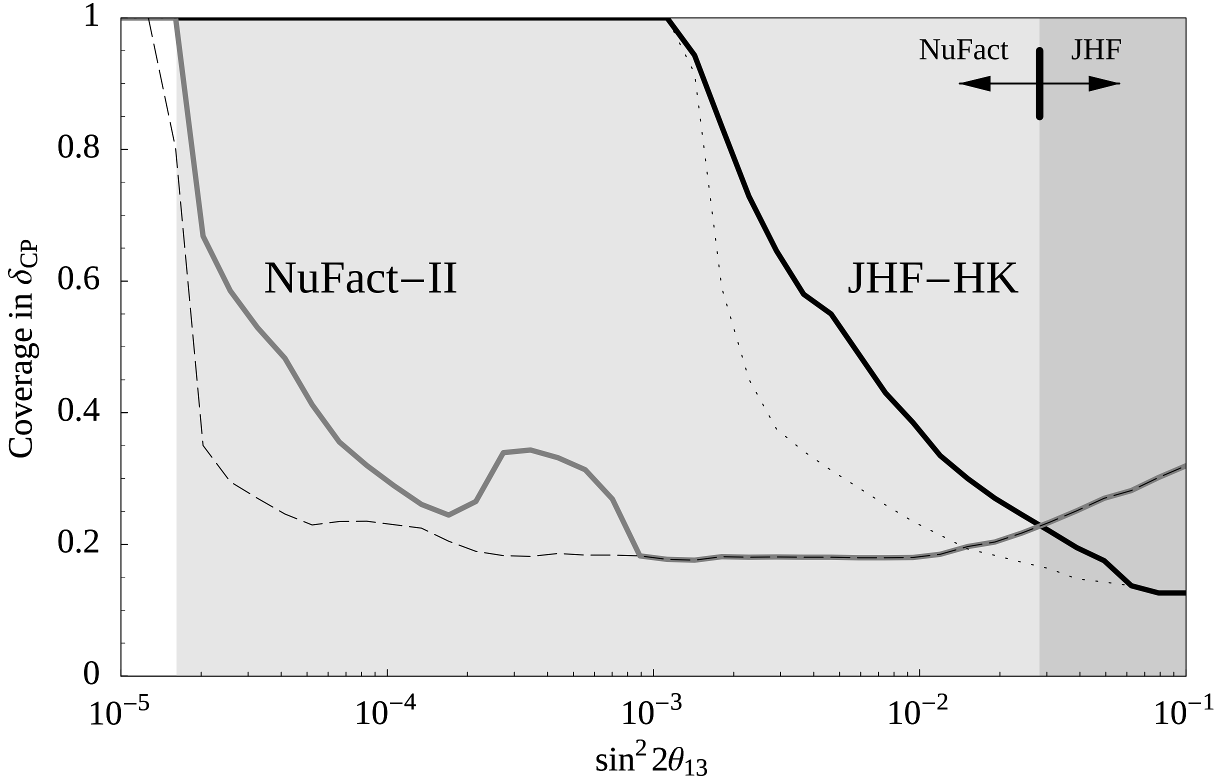


δ_{CP} – Sensitivity



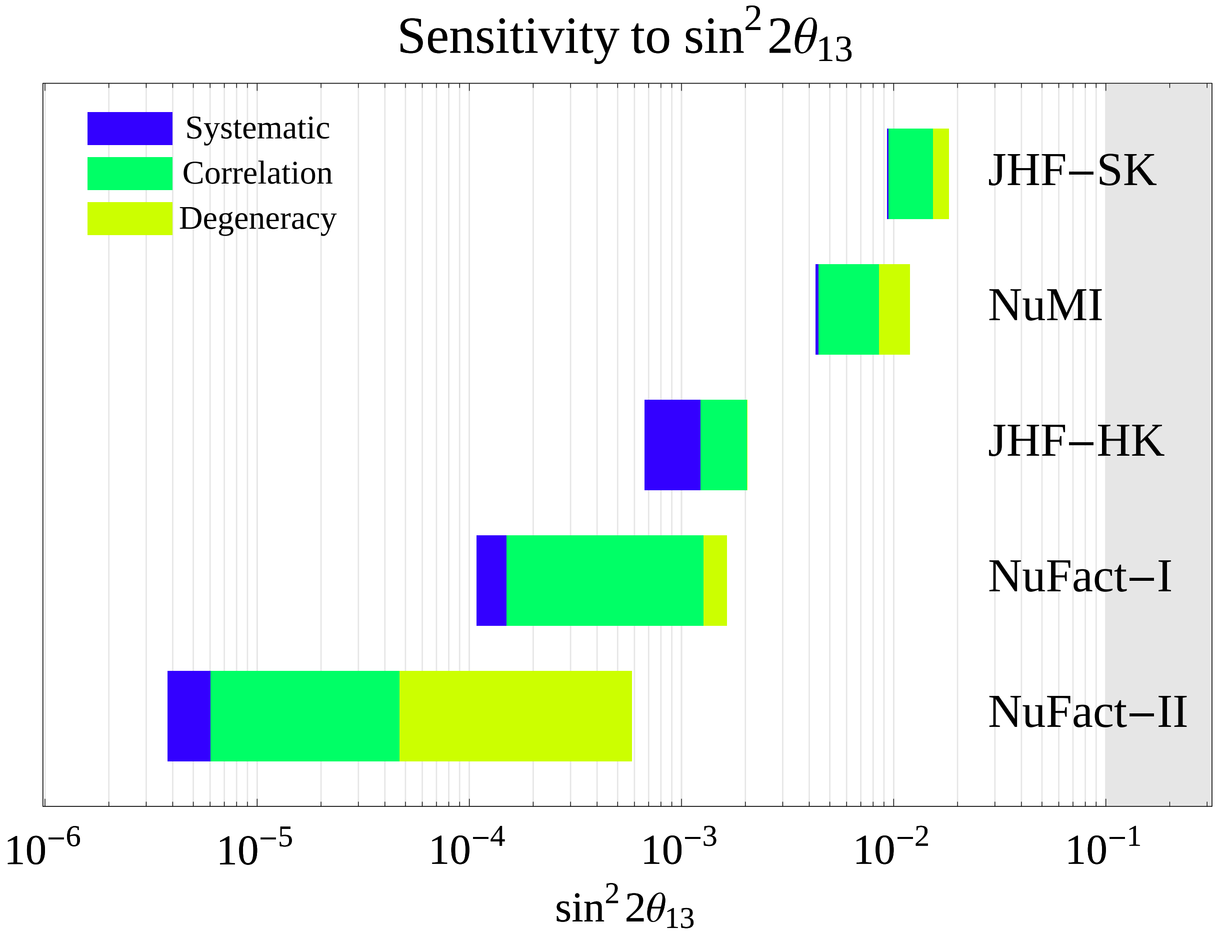
- degeneracies taken into account
- valleys due to π–transit
- high luminosity mandatory to cover LMA–range
- even if Superbeams do not see θ_{13} $(\sin^2 2\theta_{13} < 10^{-3})$
  NuFact can go up to two orders of magnitude lower !

δ_{CP} – Accuracy



- with degeneracies
- upward bending for $\sin^2 2\theta_{13} > 10^{-2}$ due to matter uncertainty
- bump due to π–transit
- NuFact is better in most cases

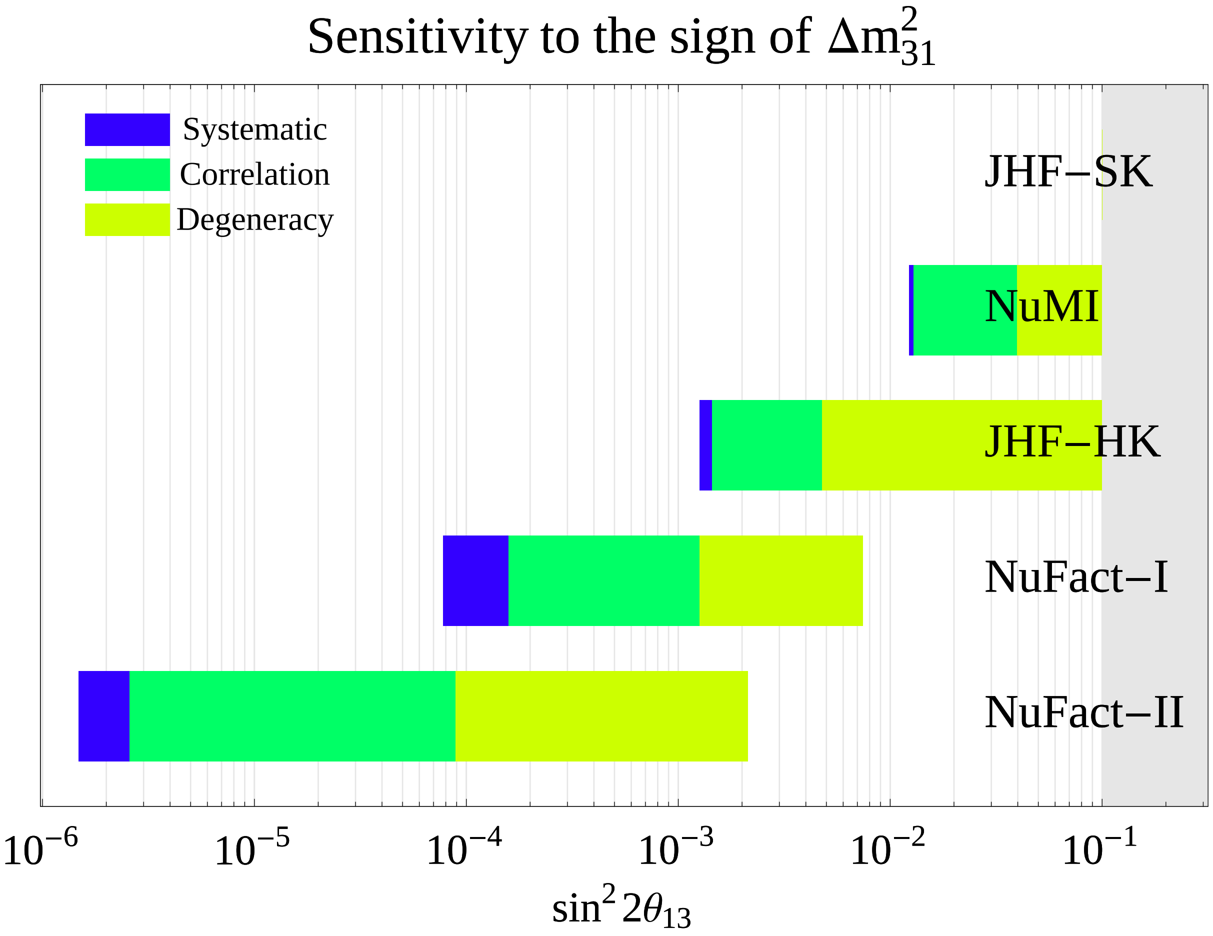
Summary – $\sin^2 2\theta_{13}$



- JHF-SK and NuMI statistics limited
- JHF-HK systematics limited
- NuFact far away from systematic limit
- correlations and degeneracies require a clever setup

$\Longrightarrow$ e.g. magic baseline

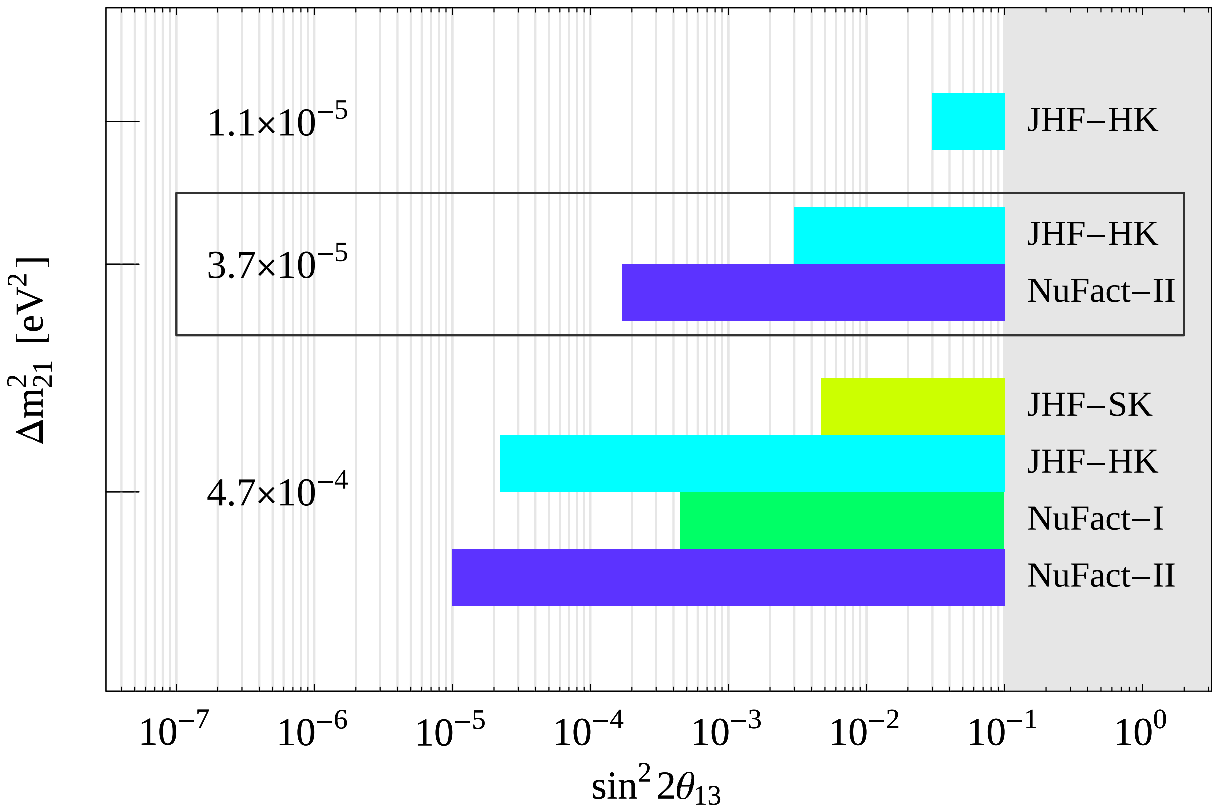
Summary – $\mathrm{sign}\Delta m^2_{31}$



- hard with Superbeams
- δ-degeneracy has to be resolved
- NuFact $\Longrightarrow$ magic baseline

Summary – δ_{CP}

Sensitivity to CP–Violation at $\delta_{CP} = +\pi/2$



- needs luminosity (expensive)
- JHF-HK has a real potential
- NuFact-II is the tool

Conclusion

Analysis

- θ_{13} determination is already involved
- correlations extremely important esp. with δ_{CP}
- degeneracies exist also in a full analysis
- strong interplay between mass hierarchy and δ_{CP}

further clever ideas needed

see e.g. talk by O. Mena

Comparison

- next generation of LBL experiments one order of magnitude below CHOOZ
- Superbeam can be pushed one further order of magnitude
- NuFact can go much further down to $\geq 10^{-5}$
- mass hierarchy requires high energies and long baselines
- CP needs luminosity

U_{MNS} can be measured