CP, T and CPT Violation

in

Future LBL Experiments

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based on
PH, M. Lindner and W. Winter, hep-ph/0204352

Outline

in vacuum

- CP violation in neutrino oscillation could be large
- the CP-odd probability difference $\Delta P_{\alpha\beta}^{CP} = P_{(\alpha\to\beta)} - P_{(\overline{\alpha}\to\overline{\beta})}$ and the T-odd probability difference $\Delta P_{\alpha\beta}^{T} = P_{(\alpha\to\beta)} - P_{(\beta\to\alpha)}$ are equal and a direct measure of CP violation

in matter

- matter also induces CP violation
- asymmetric matter profile also induces T violation

$\Longrightarrow$ $\Delta P_{\alpha\beta}^{CP}$ and $\Delta P_{\alpha\beta}^{T}$ are no longer a direct measure

in reality

- smallness of CP effects, suppressed by θ_{13} and Δm_{21}^2
- systematic uncertainties of any real experiment
- correlation with the other oscillation parameters
- existence of degenerate solutions

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, Phys. Rev. D **64** (2001) 053003.

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

Setups

JHF-SK	JHF-HK	NuFact-I	NuFact-II
$22.5\,\mathrm{kt}$ water Cherenkov	$1\,000\,\mathrm{kt}$ water Cherenkov	$10\,\mathrm{kt}$ magnetized iron calorimeter	$50\,\mathrm{kt}$ magnetized iron calorimeter
$0.75\,\mathrm{MW}$ target power	$4\,\mathrm{MW}$ target power	$0.75\,\mathrm{MW}$ target power	$4\,\mathrm{MW}$ 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

Systematical Errors

Signal

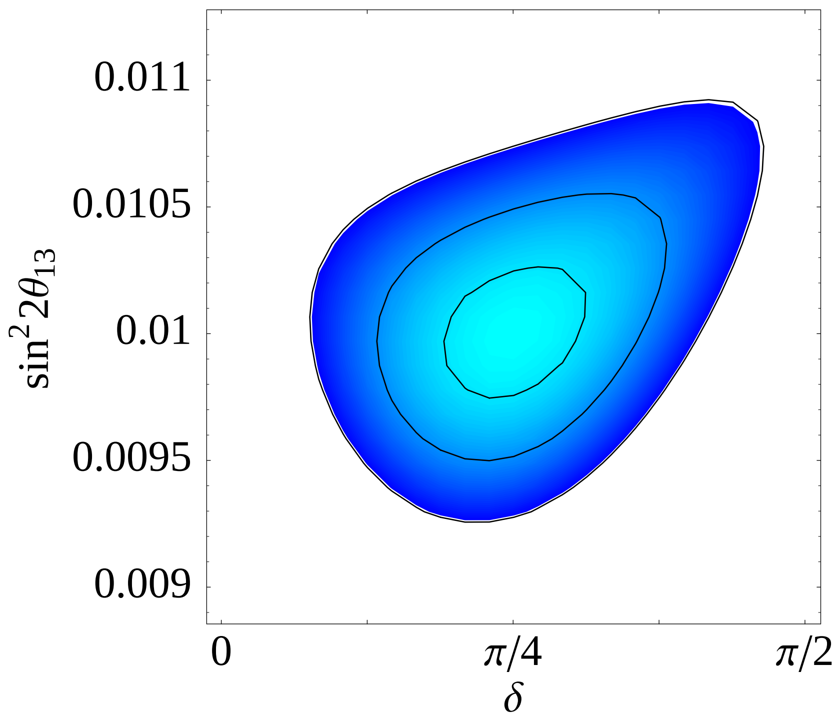
- use the energy information
- use appearance and disappearance
- appearance channel is a relative measurement
  - overall normalization error of 5% is okay
  - energy calibration error of 5% is okay

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

Correlations



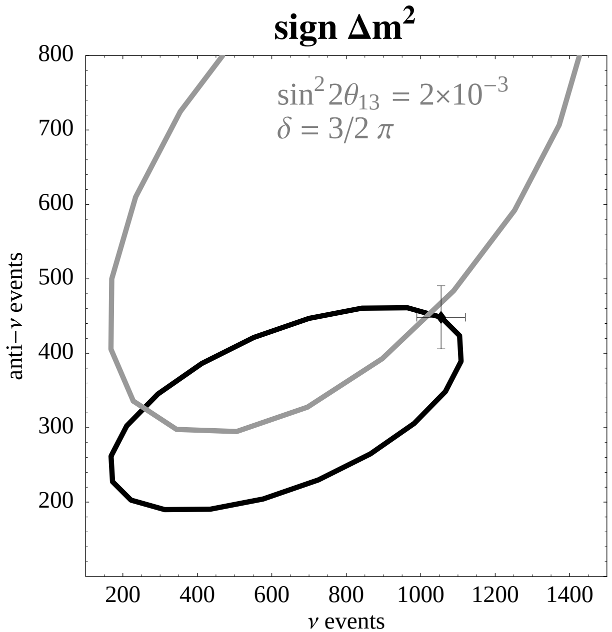
- multi-parameter problem
- highly non-linear
- complex topology

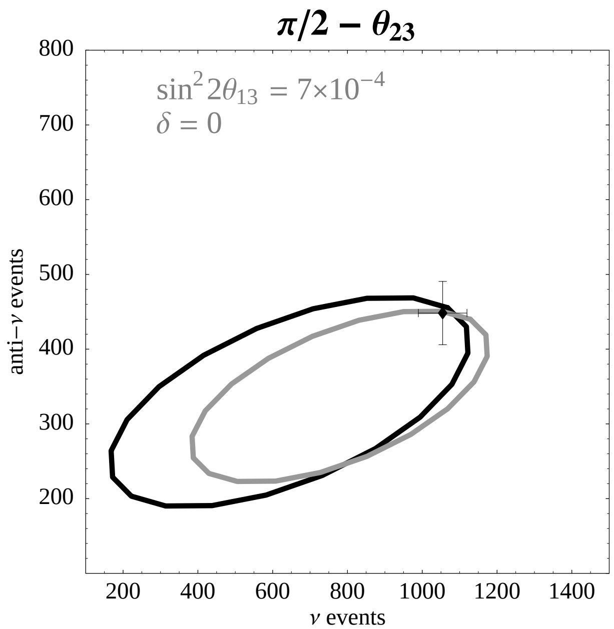
$\Rightarrow$ use all available information

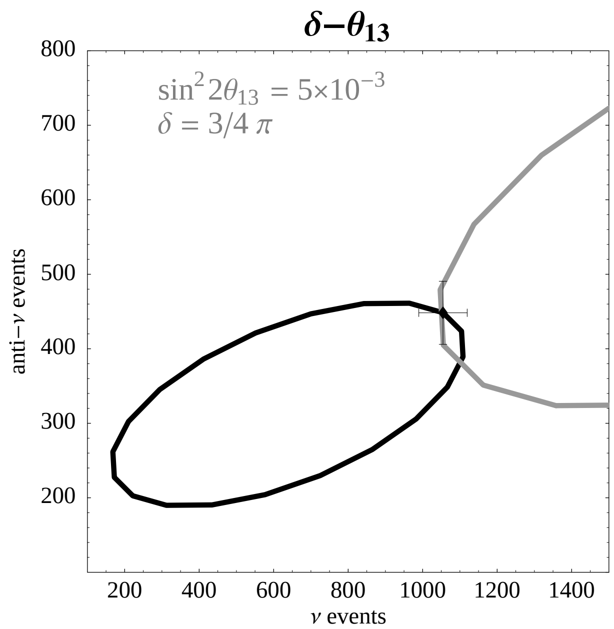
- appearance & disappearance channels
- energy information
- external input
  - KamLand, 15% on Δm^2_{21}
  - geophysics, 5% on matter density

Degeneracies

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







$\sin\delta$ 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 $\overline{\nu}$

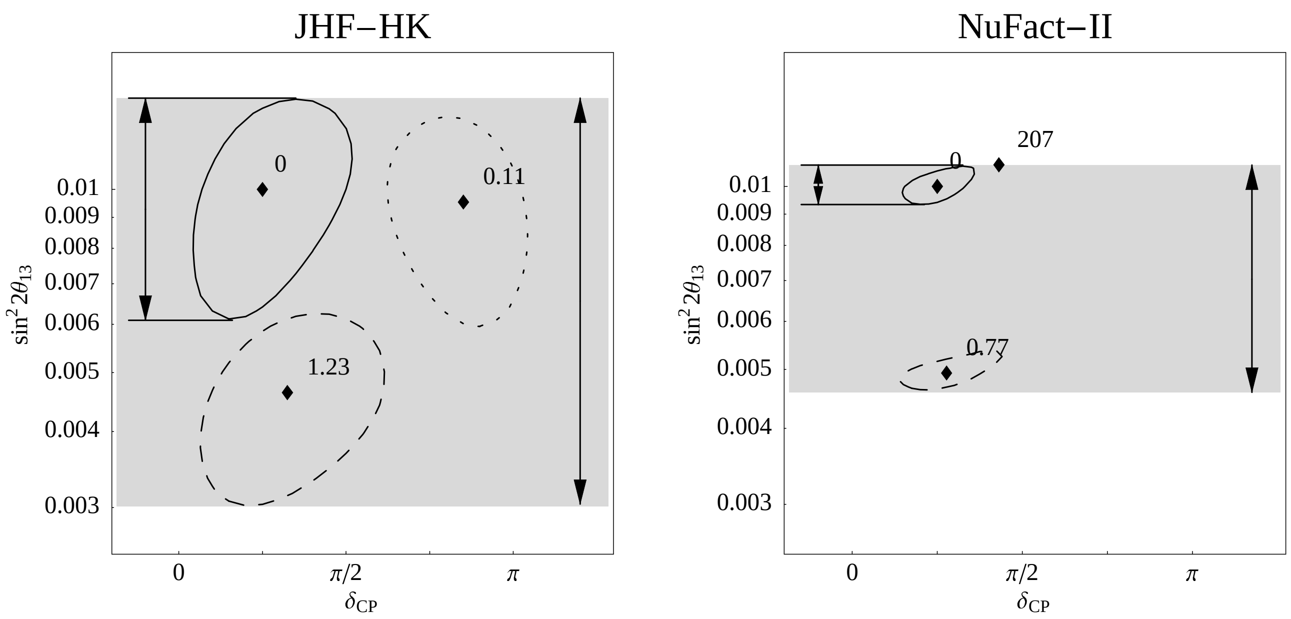
$\Longrightarrow$ δ' and θ'_{13}

H. Minakata and H. Nunokawa, JHEP **0110** (2001) 001.

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

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

Do They Really Exist?



- some show up in the fit
- depends on statistics
- depends on detector performance – esp. at low energies
- depends on energy resolution
- depends on strength of MSW-effect

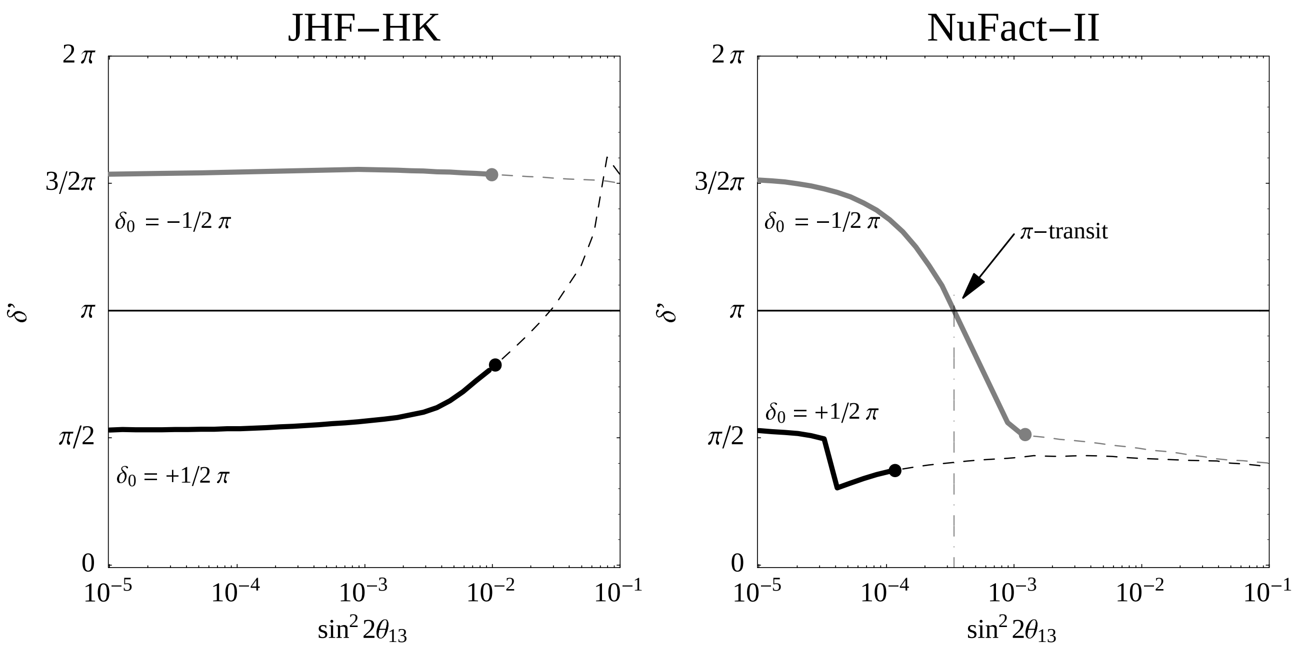
disconnected, multiple solutions

No general rule how to quote an error or sensitivity limit – appropriate choice on case by case base

A. Donini, D. Meloni and P. Migliozzi, hep-ph/0206034.

V. Barger, D. Marfatia and K. Whisnant, hep-ph/0206038.

The Mass Hierarchy Problem

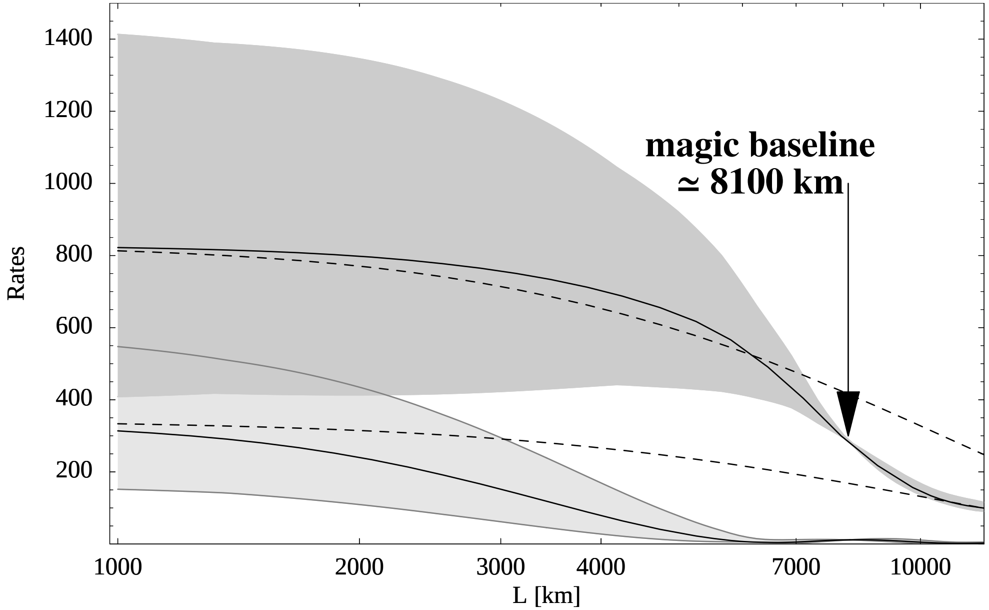


- in general two solutions with opposite sign of Δm^2_{31} and different δ_{CP}
- sufficient matter-effects allow to reject the wrong solution

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

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

Magic Baseline

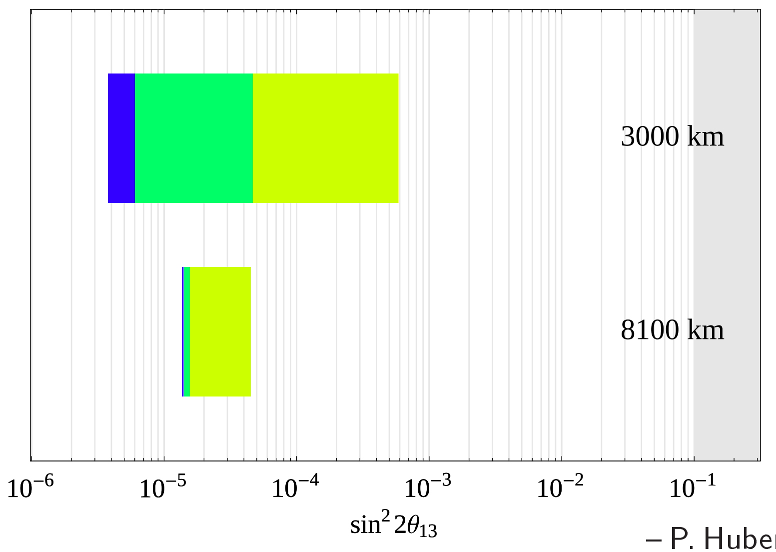


$$P_{\nu_e\to\nu_\mu} \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$
$$\pm \quad \alpha \quad \sin(\hat{A}\Delta)\sin\delta \times f_1$$
$$+ \quad \alpha \quad \sin(\hat{A}\Delta)\cos\delta \times f_2$$
$$+ \quad \alpha^2 \quad \sin^2(\hat{A}\Delta) \times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

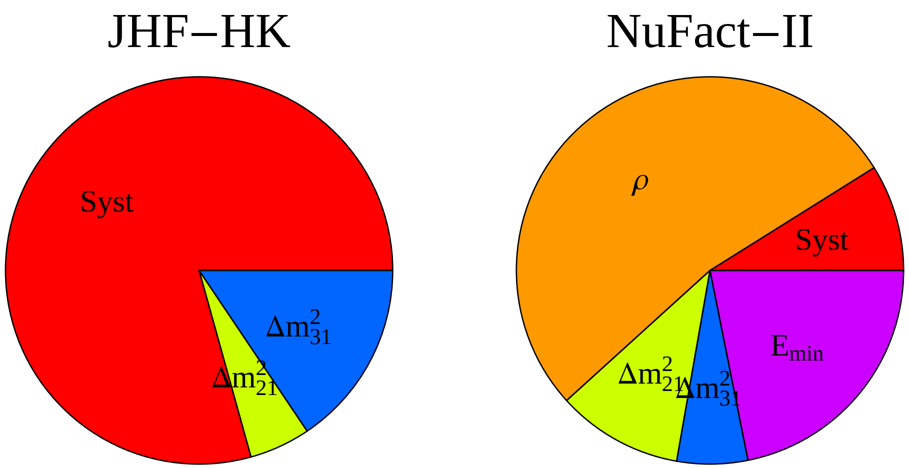
$$\boxed{\sin(\hat{A}\Delta) = 0 \Leftrightarrow \hat{A}\Delta = n\pi \Leftrightarrow VL/2 = n\pi}$$

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).



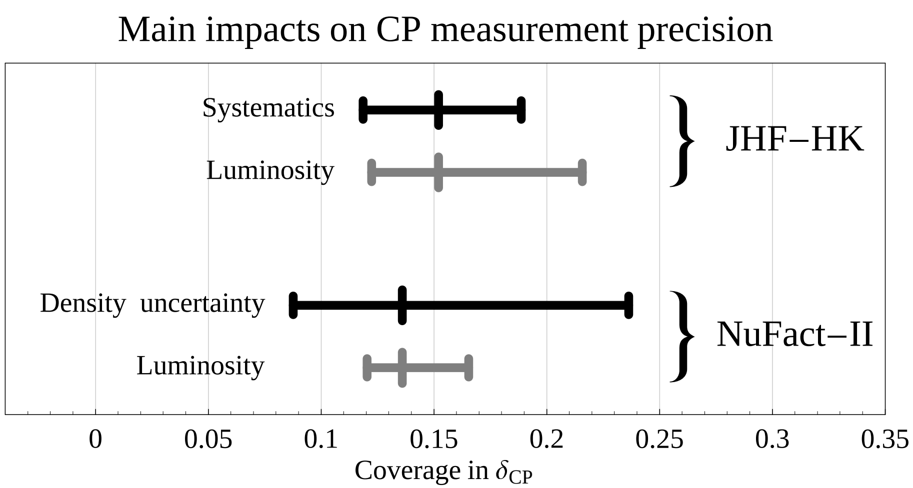
δ_{CP} – Impact Factors



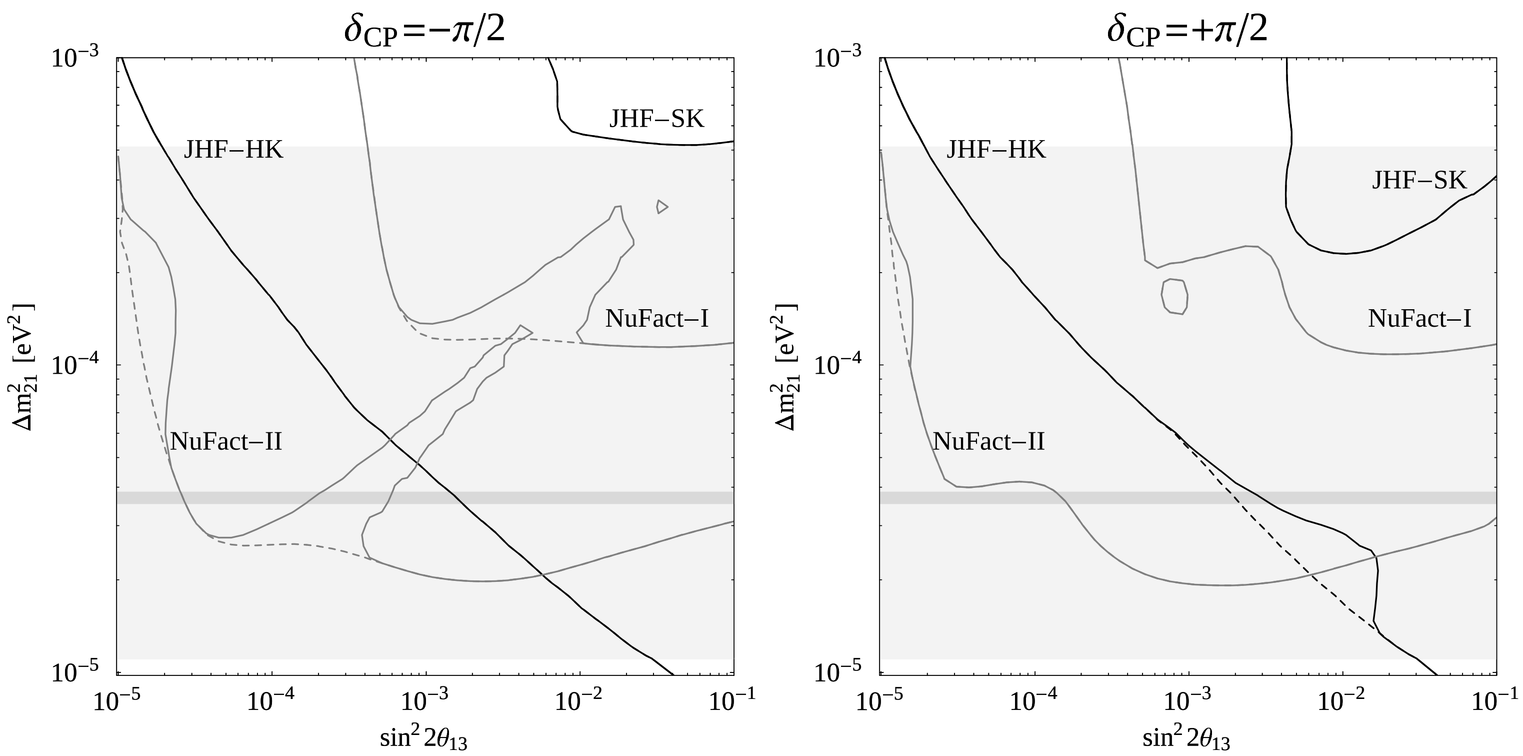
- relative contribution of controllable factors
- background uncertainty for Superbeams
- matter uncertainty for NuFact

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

- Superbeams – systematics
- NuFact – matter uncertainty

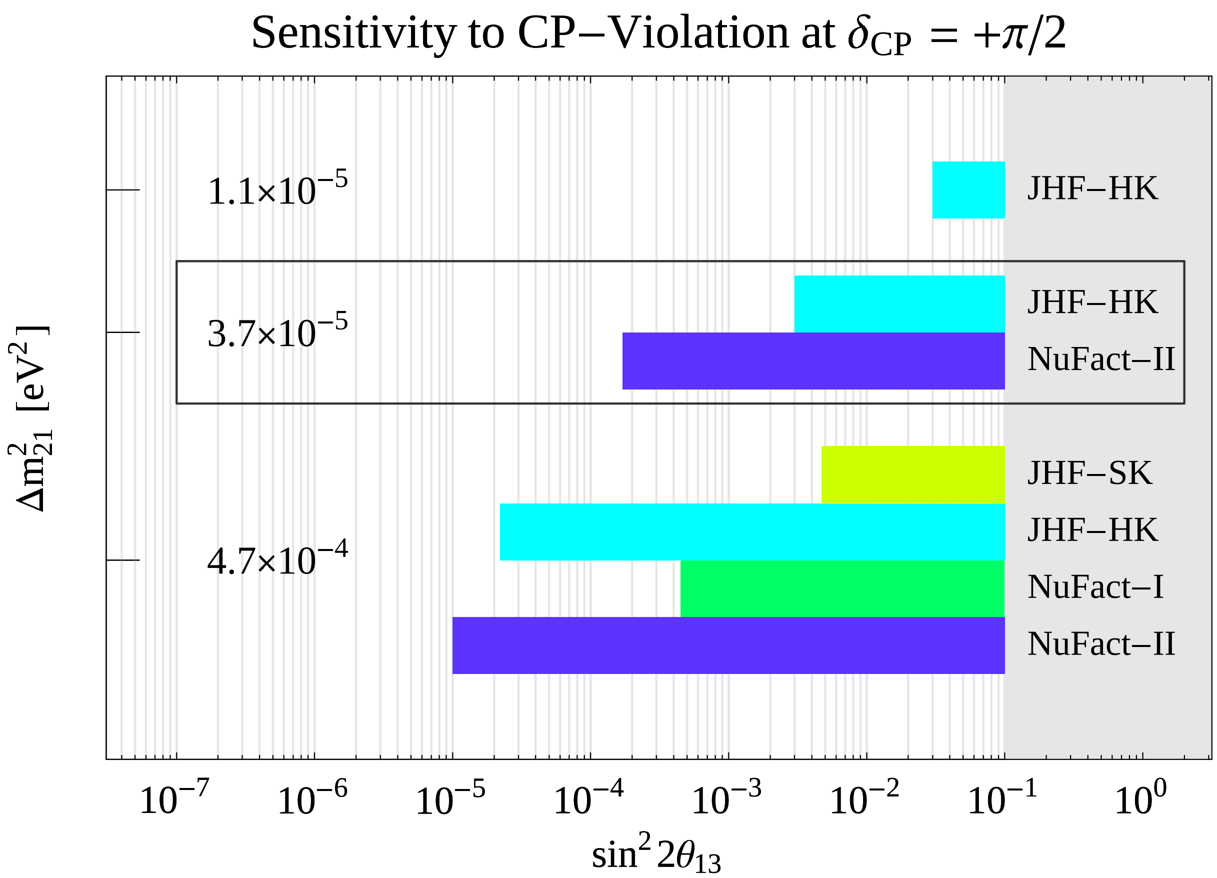


$\delta_{\rm CP}$ – Sensitivity



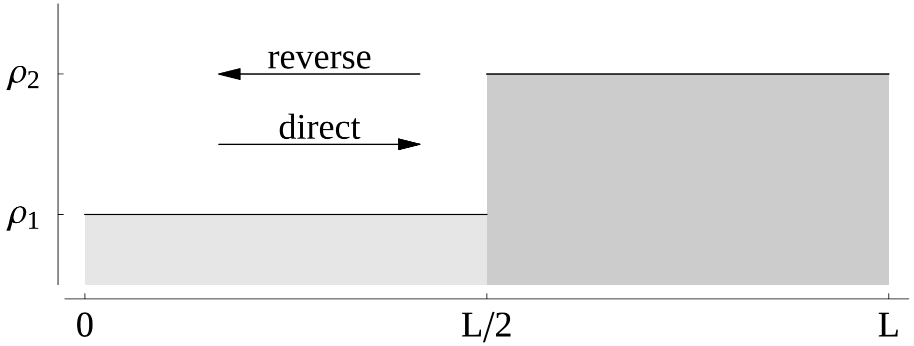
- degeneracies taken into account
- valleys due to π–transit
- high luminosity mandatory to cover LMA–range
- even if Superbeams do not see θ_{13} $(\sin^2 2\theta_{13} < 10^{-3})$ NuFact can go up to two orders of magnitude lower !

Summary – δ_{CP}



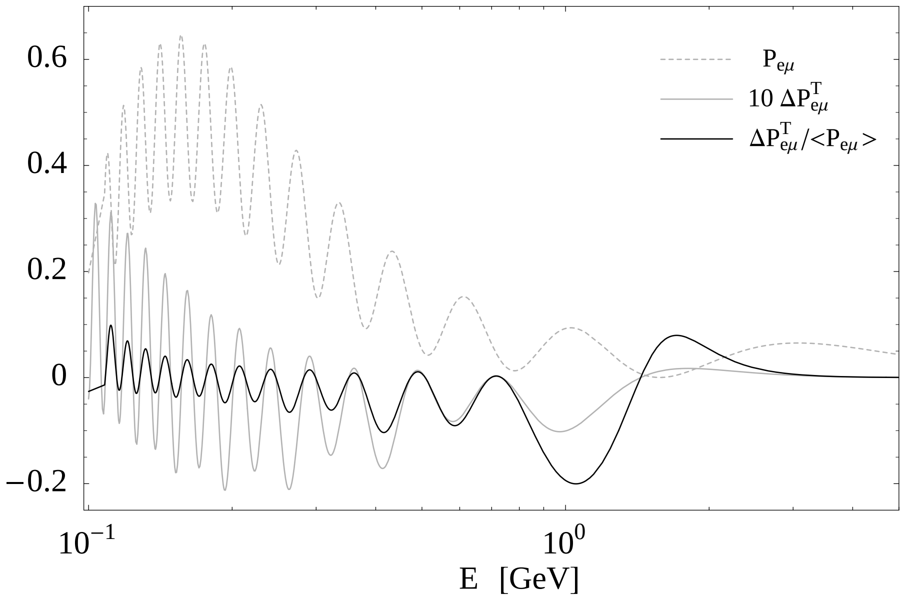
- needs luminosity (expensive)
- Superbeams have a real potential to see first evidence
- NuFact-II is the tool
- depends strongly on Δm^2_{21}

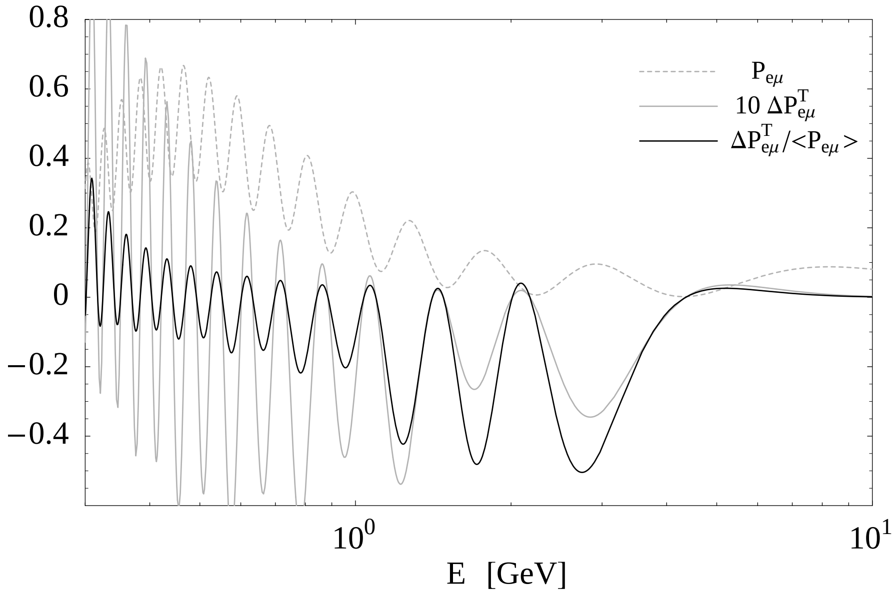
T violation



$$\Delta P^T_{\alpha\beta} = P^{\rm dir}_{(\alpha\to\beta)} - P^{\rm dir}_{(\beta\to\alpha)}$$

$$\Delta P_{\alpha\beta} = P^{\rm dir}_{(\alpha\to\beta)} - P^{\rm rev}_{(\beta\to\alpha)}$$





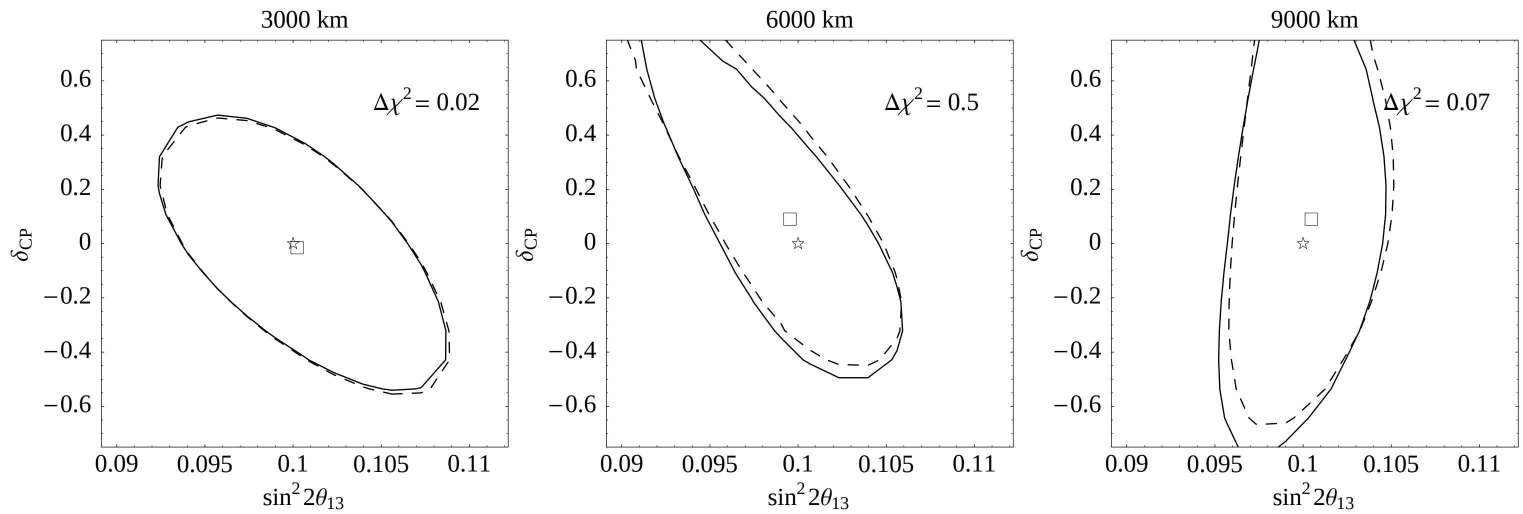
$\rho_1 = 1\,\mathrm{g\,cm^{-3}}$, $\rho_2 = 3\,\mathrm{g\,cm^{-3}}$, $L = 1\,500\,\mathrm{km}$ $\rho_1 = 1\,\mathrm{g\,cm^{-3}}$, $\rho_2 = 3\,\mathrm{g\,cm^{-3}}$, $L = 3\,000\,\mathrm{km}$

E. Akhmedov, PH, M. Lindner and T. Ohlsson, Nucl. Phys. B **608** (2001) 394.

P. M. Fishbane and P. Kaus, Phys. Lett. B **506** (2001) 275.

T violation

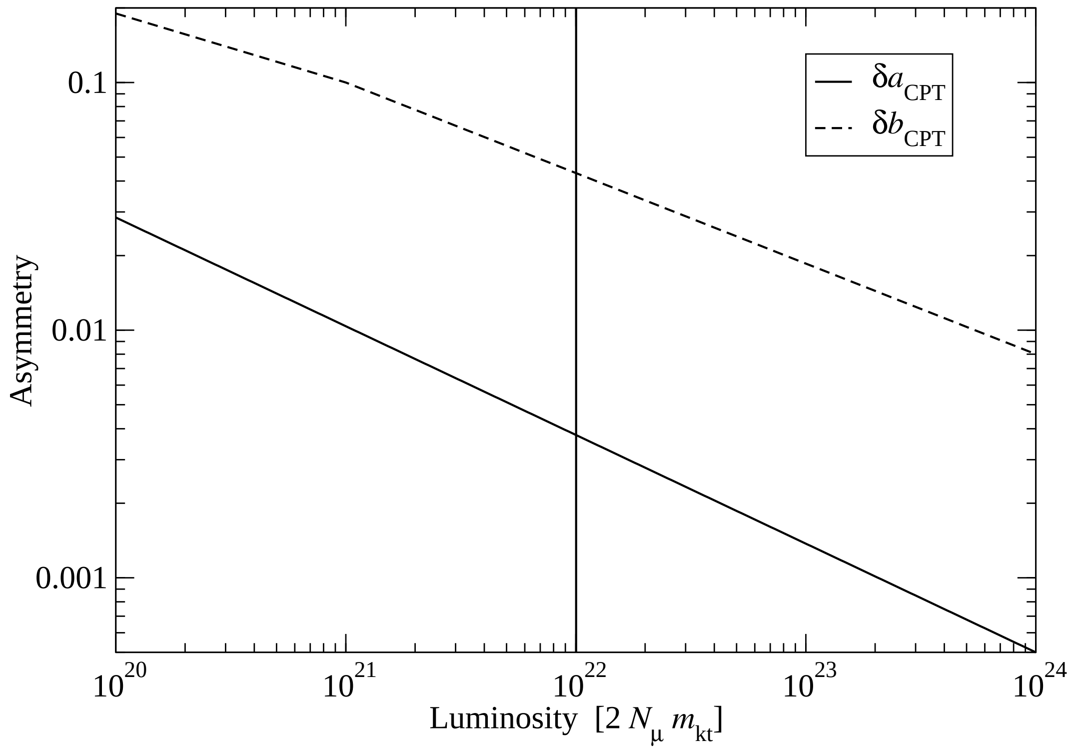
NuFact – can matter induced T violation mimic intrinsic CP violation?



$$\rho_1 = 3\,\mathrm{g\,cm}^{-3},\ \rho_2 = 3.3\,\mathrm{g\,cm}^{-3}$$

- this is the worst case
- at this level of accuracy
  matter induced T violation is of no concern

CPT violation



- different θ for ν and $\overline{\nu}$
- different Δm^2 for ν and $\overline{\nu}$

$$a_{\text{CPT}} = \frac{|m_3 - \overline{m}_3|}{(m_3)_{\text{average}}}$$

$$b_{\text{CPT}} = \frac{|\theta_{23} - \overline{\theta}_{23}|}{(\theta_{23})_{\text{average}}}$$

- neutrinos can be very sensitive to new physics
- in seesaw models a_{CPT} and b_{CPT} probe CPT violation at the scale of M_R
- in extra dimensions ν_R lives in the bulk $\Leftrightarrow$ CPT violation

S. M. Bilenky *et al.*, Phys. Rev. D **65** (2002) 073024.

Conclusion

- CP violation can be large
- it is possible to see it
- though it is very tough to do so

- high statistics
- very good detector
- low systematics

$\Longrightarrow$ money & time

NuFact is the tool to study $\not{C}\not{P}$

the necessary effort depends crucially on Δm^2_{21} $\Longrightarrow$

we are waiting for KamLand