Long baseline neutrino experiments: the neutrino factory

IPP13

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IPPP - Durham University

Outline

1. Theoretical aspects of long baseline neutrino oscillations: CPV and matter effects

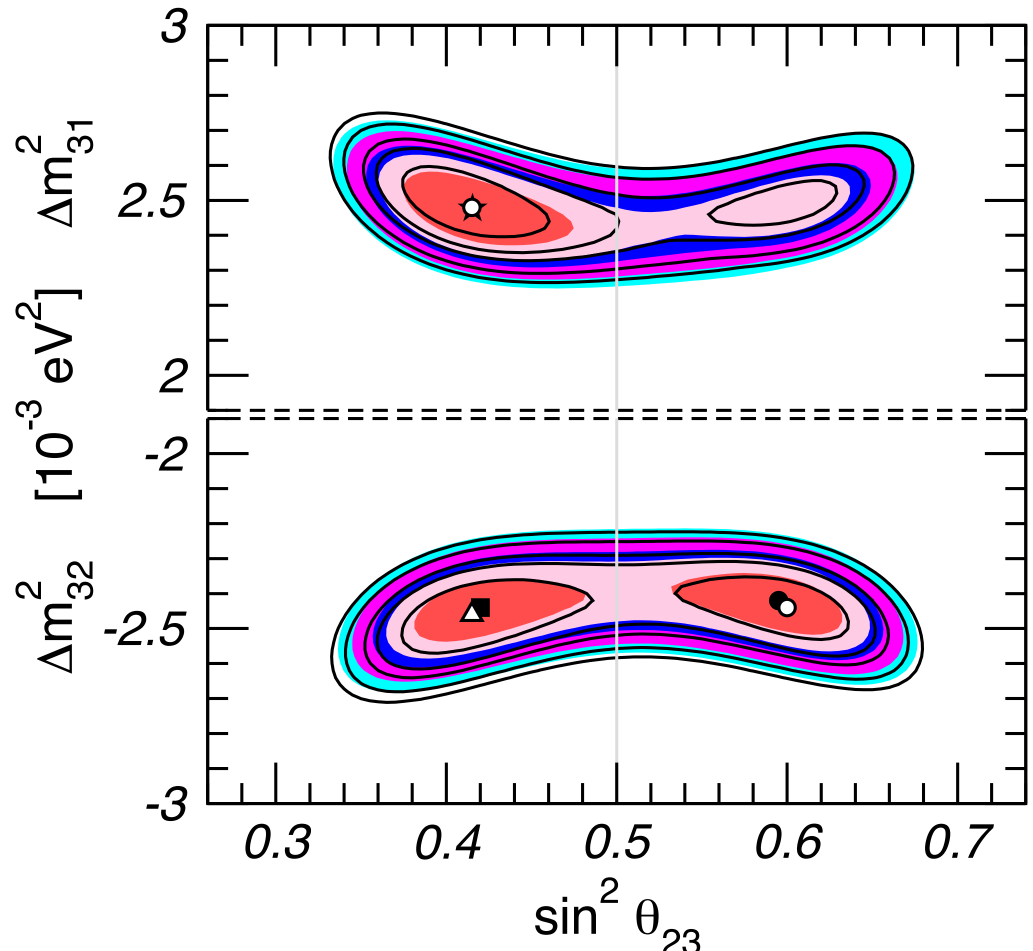
2. Long baseline neutrino oscillation experiments

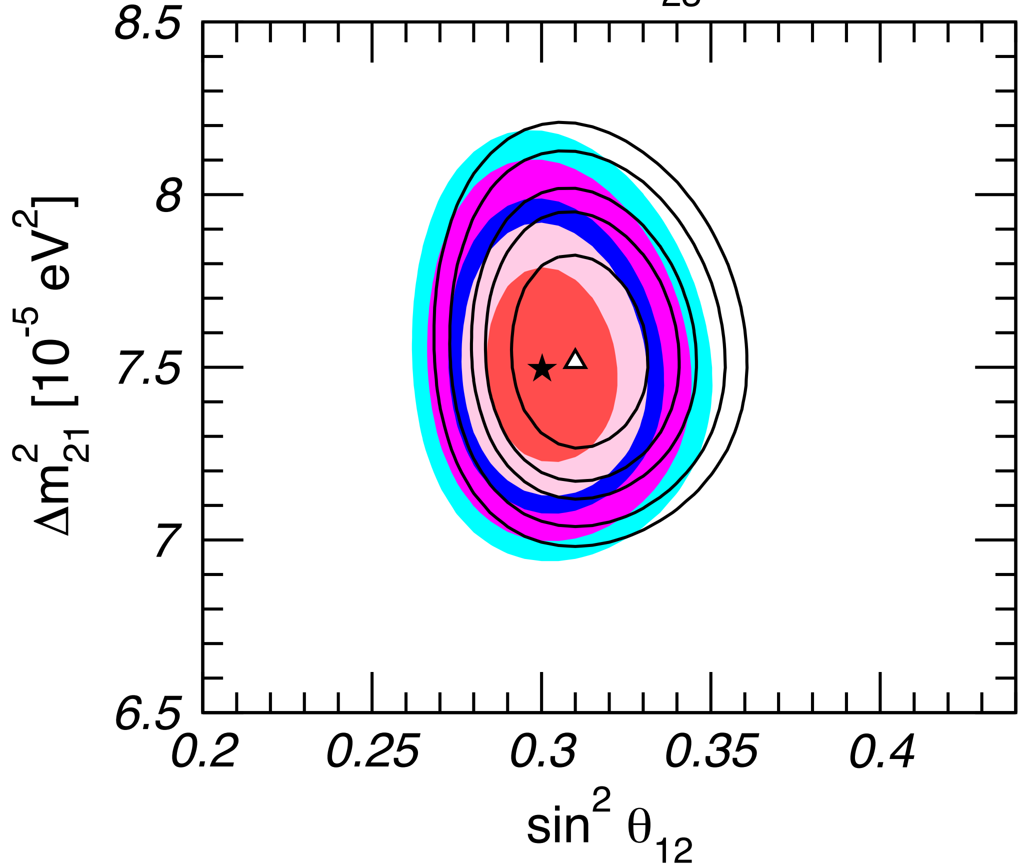
3. The neutrino factory:

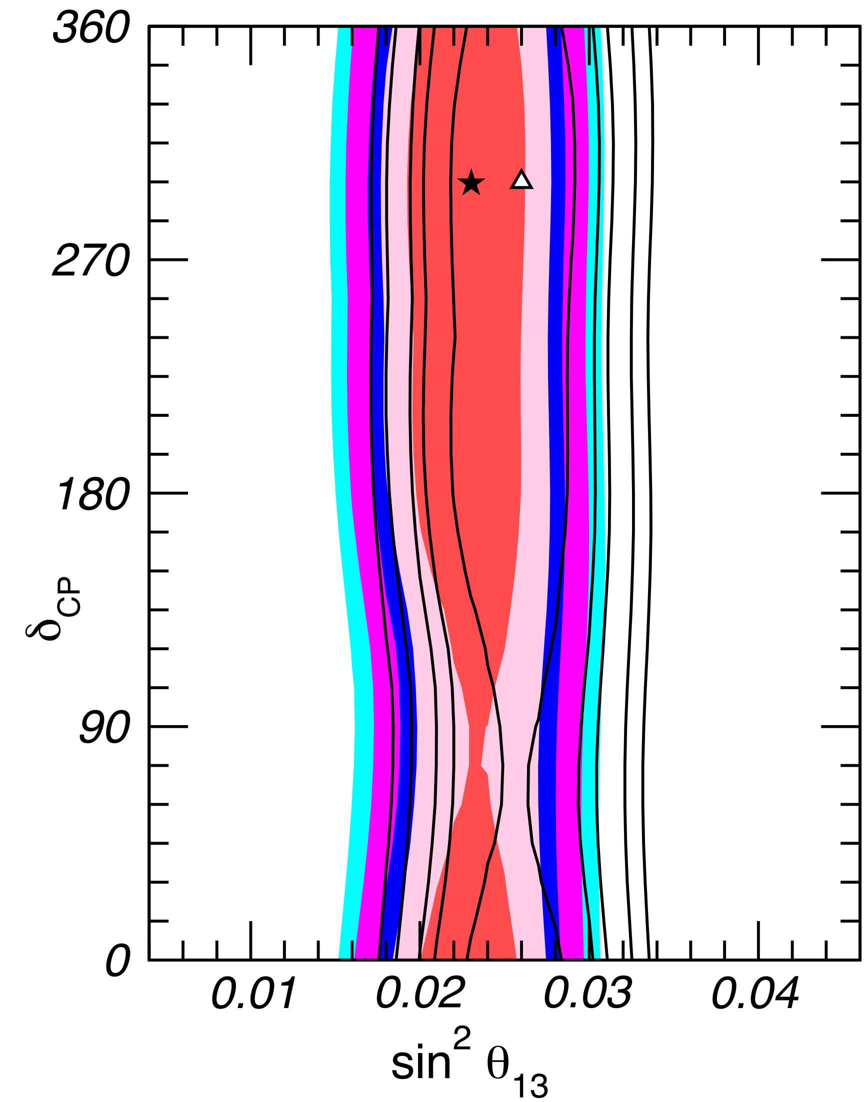
- mass hierarchy and CPV reach
- CPV: optimisation of L and E
- precision measurements
- non-standard effects

4. Conclusions and outlook

Present status of neutrino parameters







M. C. Gonzalez-Garcia et al., 1209.3023

Discovery of theta13! All oscillation parameters are measured with good precision, except for the mass hierarchy and the delta phase. One needs to check the 3-neutrino paradigm.

Long baseline neutrino oscillations

Long baseline neutrino oscillation experiments (T2K, LBNE, EU superbeams, neutrino factories and beta beams) will aim at studying the subdominant channels

$$\nu_{\mu,e} \longrightarrow \nu_{e,\mu} \quad \bar{\nu}_{\mu,e} \longrightarrow \bar{\nu}_{e,\mu}$$

$$P(\nu_\mu \to \nu_e) \sim \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

for negligible matter and CPV effects.

in order to establish

1. **the mixing angles (θ_{13})**
2. **the mass hierarchy**
3. **Leptonic CPV**
4. **Non-standard effects.**

See also Agarwalla's talk

CPV effects in neutrino oscillations

In many experimental situations the probabilities can be approximated for 2 neutrinos. In this case there are no CPV effects. The CP-asymmetry:

$$P(\nu_\mu \to \nu_e; t) - P(\bar{\nu}_\mu \to \bar{\nu}_e; t) =$$

$$= 4 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \left[\sin\left(\frac{\Delta m_{21}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{23}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \right]$$

- CP-violation requires all angles to be nonzero.
- It is proportional to the sine of the delta phase.
- If one can neglect Δm_{21}^2, the asymmetry goes to zero as effective 2-neutrino probabilities are CP-symmetric.

Neutrino oscillations in matter

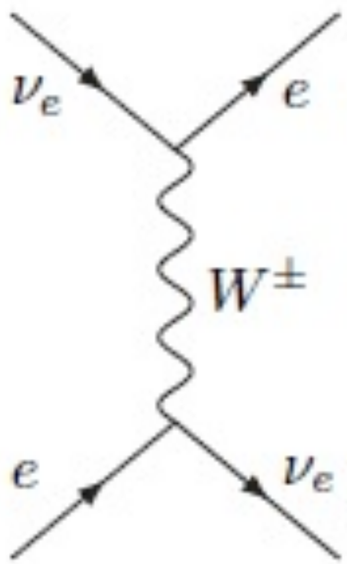
- When neutrinos travel in media, they interact with the background of electron, proton and neutrons and acquire an effective mass and oscillations are modified.
- Typically the background is CP and CPT violating and the resulting oscillations are CP and CPT violating.

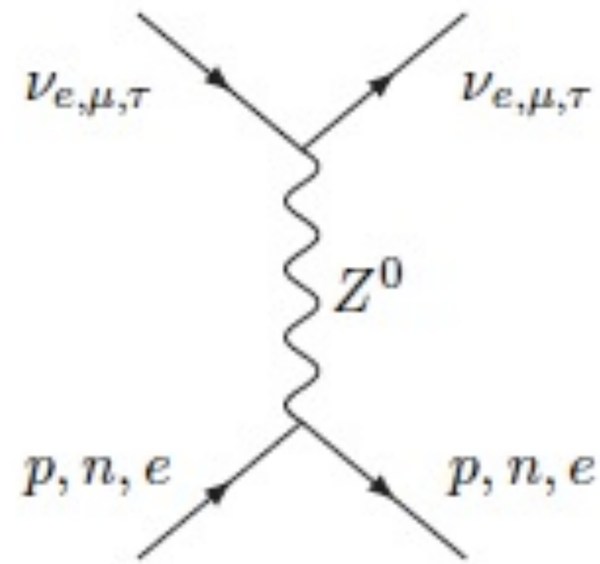
Neutrinos undergo forward elastic scattering. [L. Wolfenstein, Phys. Rev. D 17, 2369 (1978); ibid. D 20, 2634 (1979), S. P. Mikheyev, A. Yu Smirnov, Sov. J. Nucl. Phys. 42 (1986) 913.]

$$\mathcal{L}_{4-f} = -2\sqrt{2} G_F (\bar{\nu}_{eL} \gamma^\rho \nu_{eL})(\bar{e}_L \gamma_\rho e_L) + \cdots$$

If additional interactions were present, these would modify the matter effects we observe.

Electron neutrinos have CC and NC interactions, while muon and tau neutrinos only the latter.





For a useful discussion, see E. Akhmedov, hep-ph/0001264; A. de Gouvea, hep-ph/0411274.

We treat the electrons as a background: $\langle \bar{e}\gamma_0 e \rangle = N_e$.

medium	A_{CC} for $\nu_e, \bar{\nu}_e$ only	A_{NC} for $\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau}$
$e, \bar{e}$	$\pm\sqrt{2}G_F(N_e - N_{\bar{e}})$	$\mp\sqrt{2}G_F(N_e - N_{\bar{e}})(1 - 4s_W^2)/2$
$p, \bar{p}$	0	$\pm\sqrt{2}G_F(N_p - N_{\bar{p}})(1 - 4s_W^2)/2$
$n, \bar{n}$	0	$\mp\sqrt{2}G_F(N_n - N_{\bar{n}})/2$
ordinary matter	$\pm\sqrt{2}G_F N_e$	$\mp\sqrt{2}G_F N_n/2$

Strumia and Vissani

The full Hamiltonian in matter can then be obtained by adding the potential terms, diagonal in the flavour basis. For electron and muon neutrinos

$$i\frac{d}{dt}\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix}$$

For antineutrinos the potential has the opposite sign.

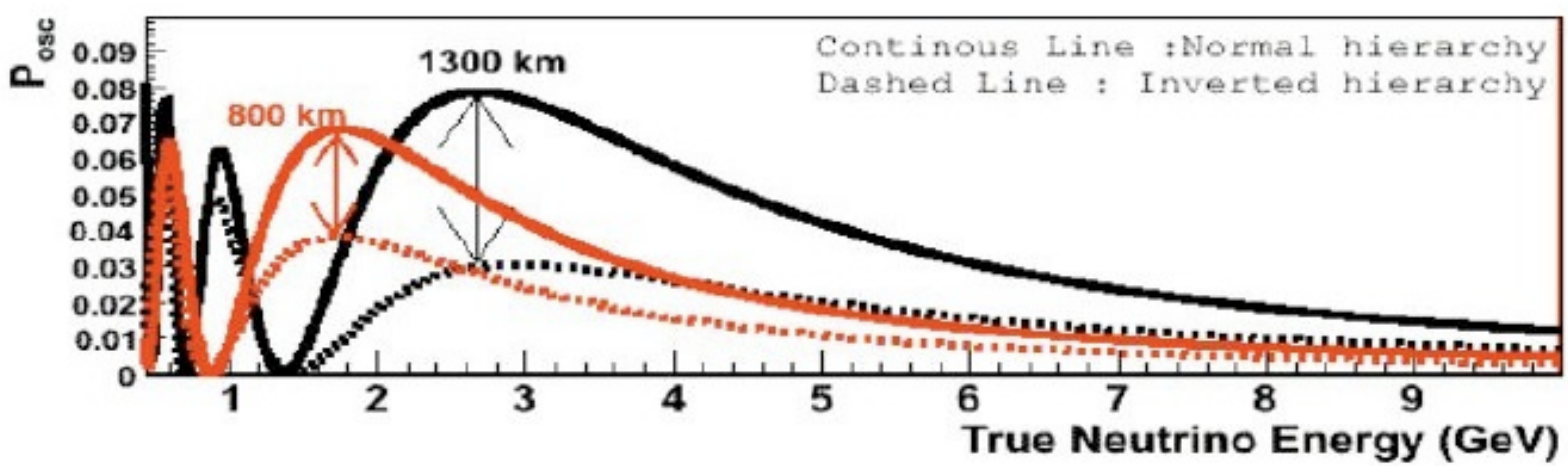
- The diagonal basis and the flavour basis are related by a unitary matrix with angle in matter

$$\tan(2\theta_m) = \frac{\frac{\Delta m^2}{2E}\sin(2\theta)}{\frac{\Delta m^2}{2E}\cos(2\theta) - \sqrt{2}G_F N_e}$$

- If $\sqrt{2}G_F N_e \gg \frac{\Delta m^2}{2E}\cos(2\theta)$, matter effects dominate and oscillations are suppressed.

- If $\sqrt{2}G_F N_e = \frac{\Delta m^2}{2E}\cos 2\theta$: resonance $\theta_m = \pi/4$

- The resonance condition can be satisfied for
  - neutrinos if $\Delta m^2 > 0$
  - antineutrinos if $\Delta m^2 < 0$



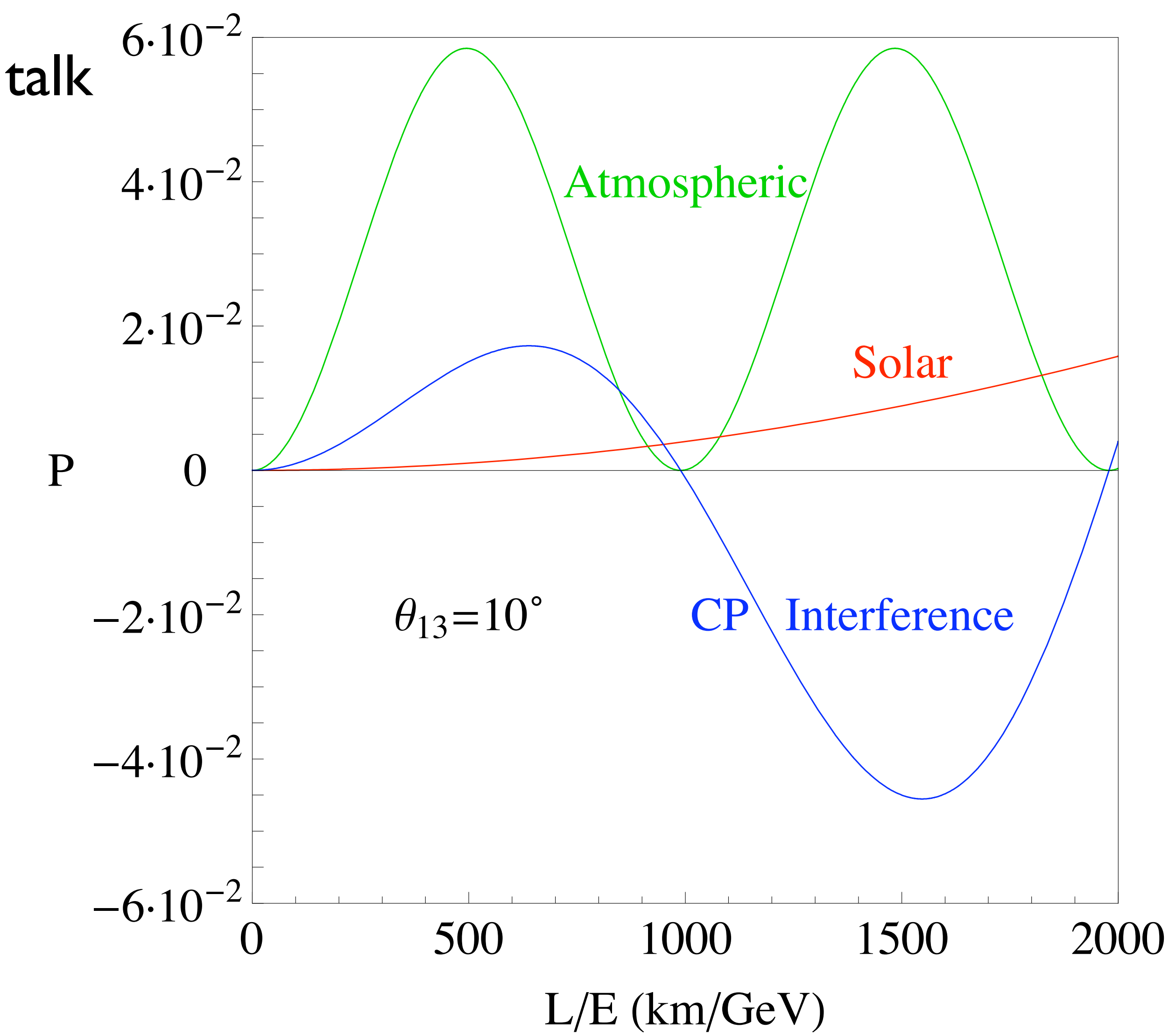
One can compute the probability in matter by expanding the full 3-neutrino oscillation probability.

$$P(\bar{P}) \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{A\mp\Delta_{13}}\right)^2 \sin^2 \frac{(A\mp\Delta_{13})L}{2}$$
$$+ \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{A\mp\Delta_{13}} \sin\frac{AL}{2} \sin\frac{(A\mp\Delta_{13})L}{2} \cos\left(\mp\delta + \frac{\Delta_{13}L}{2}\right)$$
$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2 \frac{AL}{2}$$

CP-violation

Matter effects

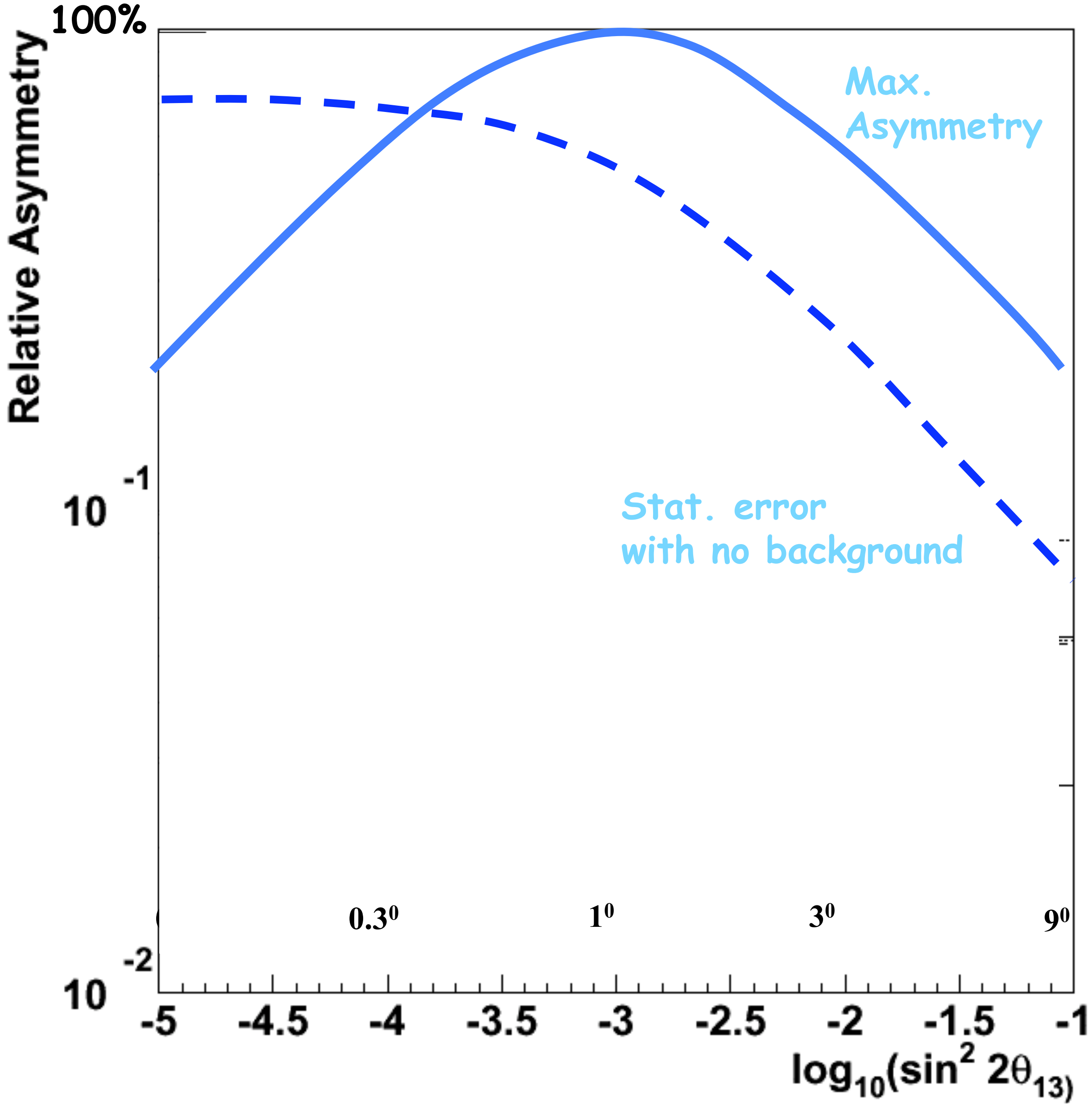
See also Agarwalla's talk



The CPV effect depend on energy and they become more important at low energy.

Coloma and Fernandez-Martinez, 2011

For large θ_{13}, it is a subdominant effect with respect to the dominant atmospheric term.



The CP asymmetry peaks for sin^2 2 theta13 ~0.001. Large theta13 makes its searches possible but not ideal.

A. Blondel

Degeneracies

The determination of CPV and the mass ordering is complicated by the issue of **degeneracies**: different sets of parameters which provide an equally good fit to the data (eight-fold degeneracies).

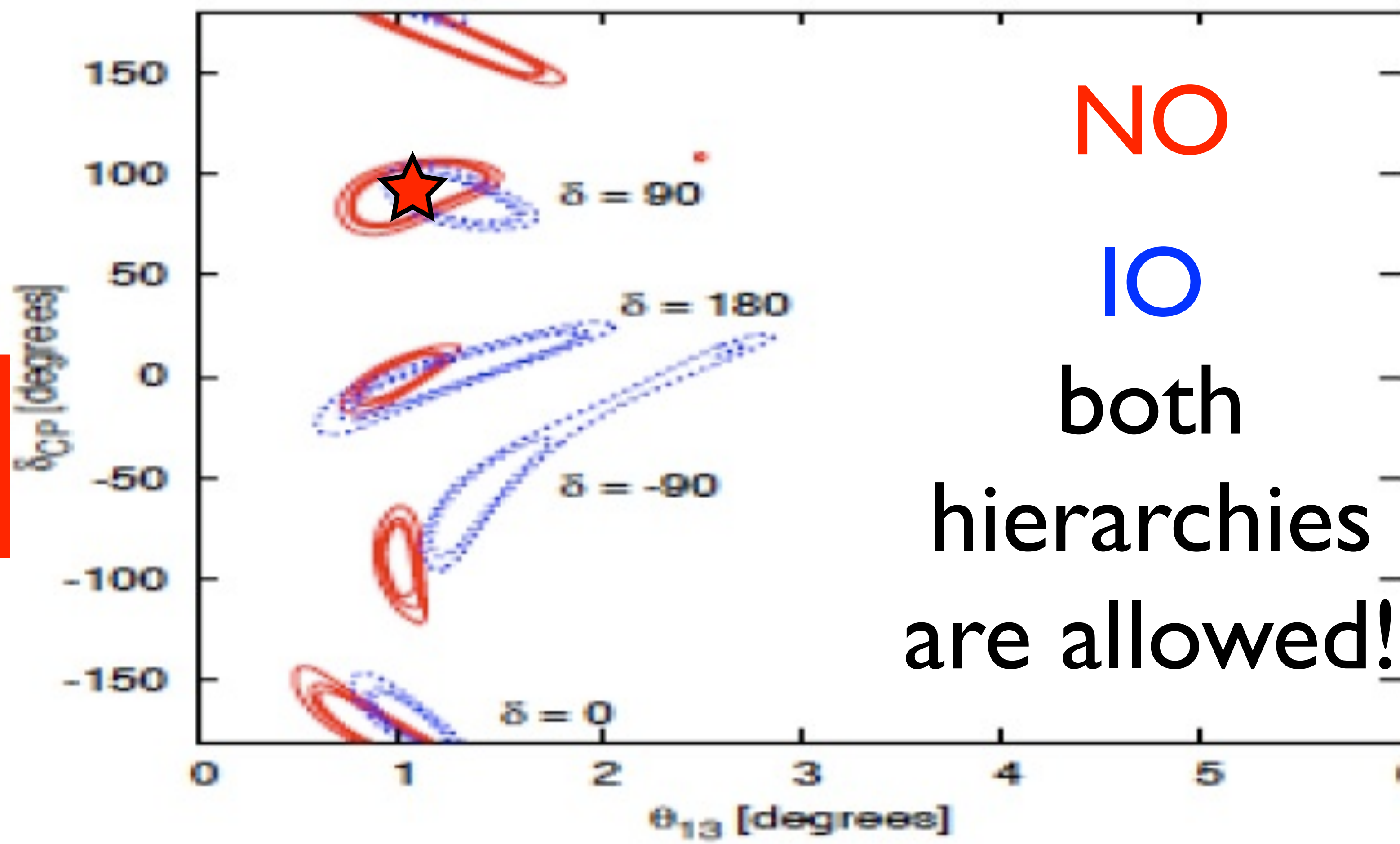
$$\theta_{13}, \delta, \mathrm{sgn}(\Delta m^2_{31}), \theta_{23}$$

↓

$$P(L/E) \quad \text{and} \quad \bar{P}(L/E)$$

↑

$$\theta'_{13}, \delta', \mathrm{sgn}'(\Delta m^2_{31}), \theta'_{23}$$



Future long baseline experiments

- **Superbeams**: T2K, NOvA, LBNE, SPL, LAGUNA. Use very intense muon neutrino beams from **pion decay** and search for electron neutrino appearance.

- **Betabeams**: Use electron neutrinos from high-gamma **ion decays**.

- **Neutrino factory**: Use muon and electron neutrinos from **high-gamma muon decays** and need a magnetised detector.

Medium term

Long term

The physics reach of the facilities is actively studied at present in order to shape the future experimental neutrino program.

See also Choudhary's talk

Neutrino flux and baseline

- **Neutrino flux:** High flux is crucial.
- **Beam Backgrounds:** The beam is known to a high degree: for large theta13, the nue contamination in superbeams is subdominant and the neutrino factory has negligible intrinsic background.
- **Dispersion effects:** the flux scales as $1/L^2$
- **Matter effects:** The longer the baseline the stronger matter effects (A) and increased sensitivity to the type of neutrino mass hierarchy.

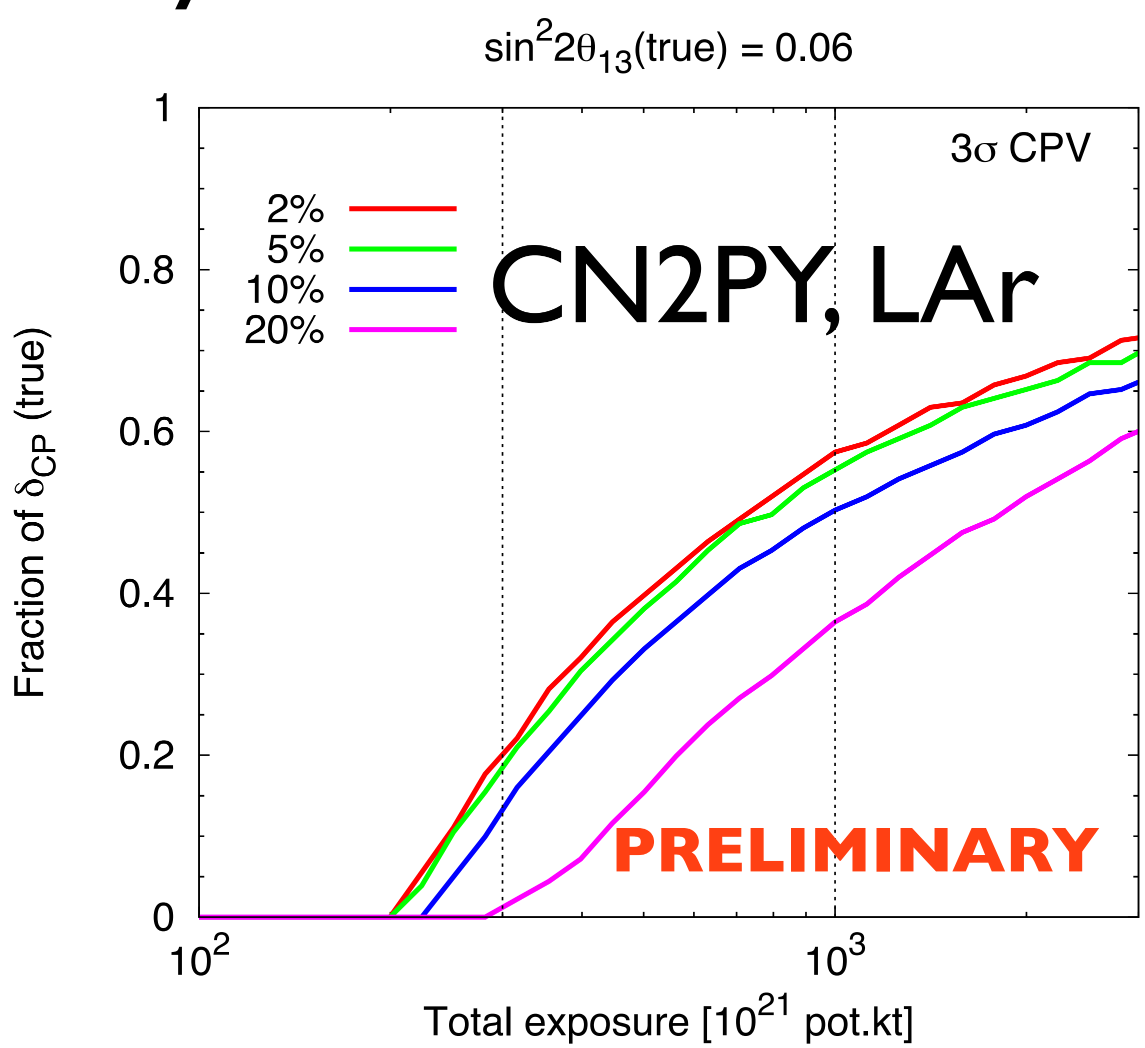
Detector

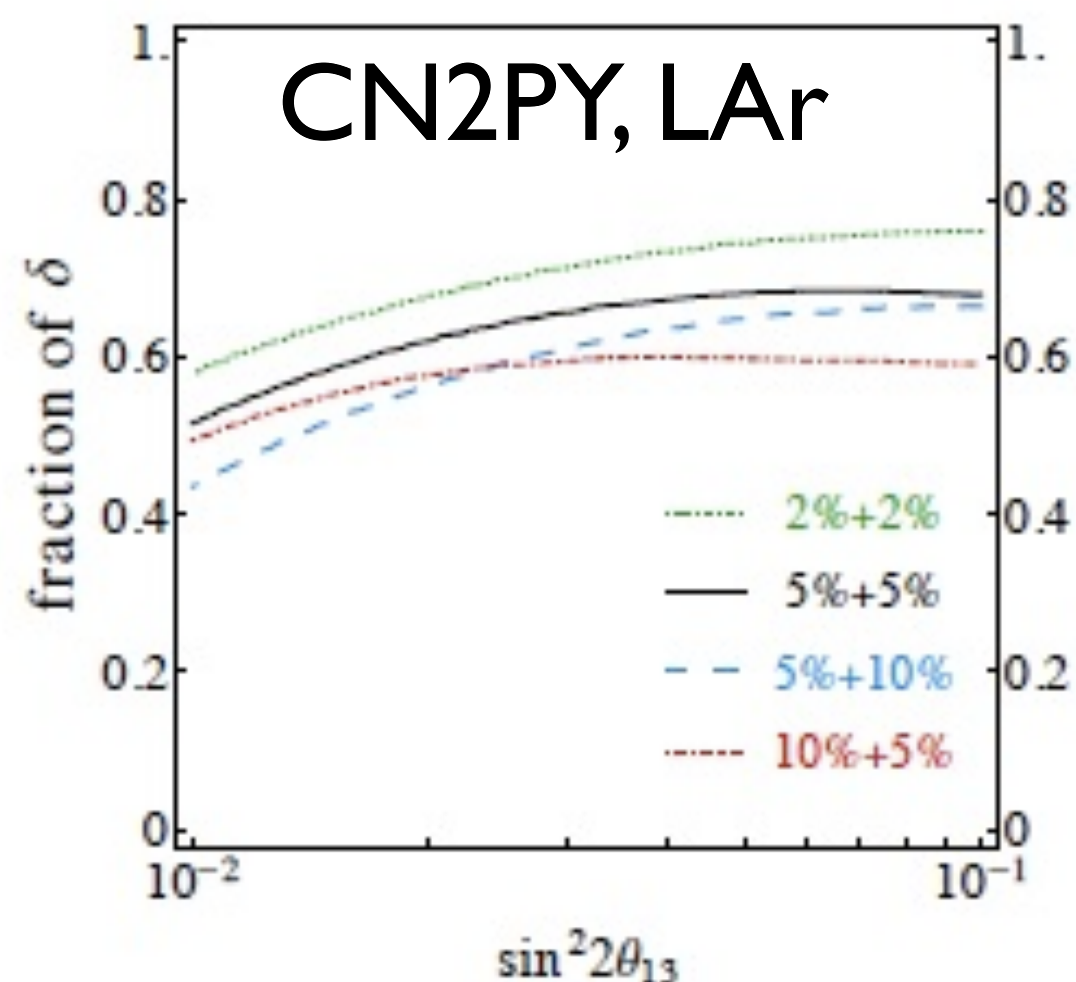
- Detection Cross section: scales with energy $\propto E_\nu$
- Backgrounds: NC in superbeams is important, and charge mis-id and tau neutrino contamination in neutrino factory
- Detector performance: plays a crucial role in the performance. Particularly important are the low energy efficiency (LENF), energy resolution
- Systematic errors: might be the ultimate limiting factor. Importance of near detector, independent measurements.

Systematic errors

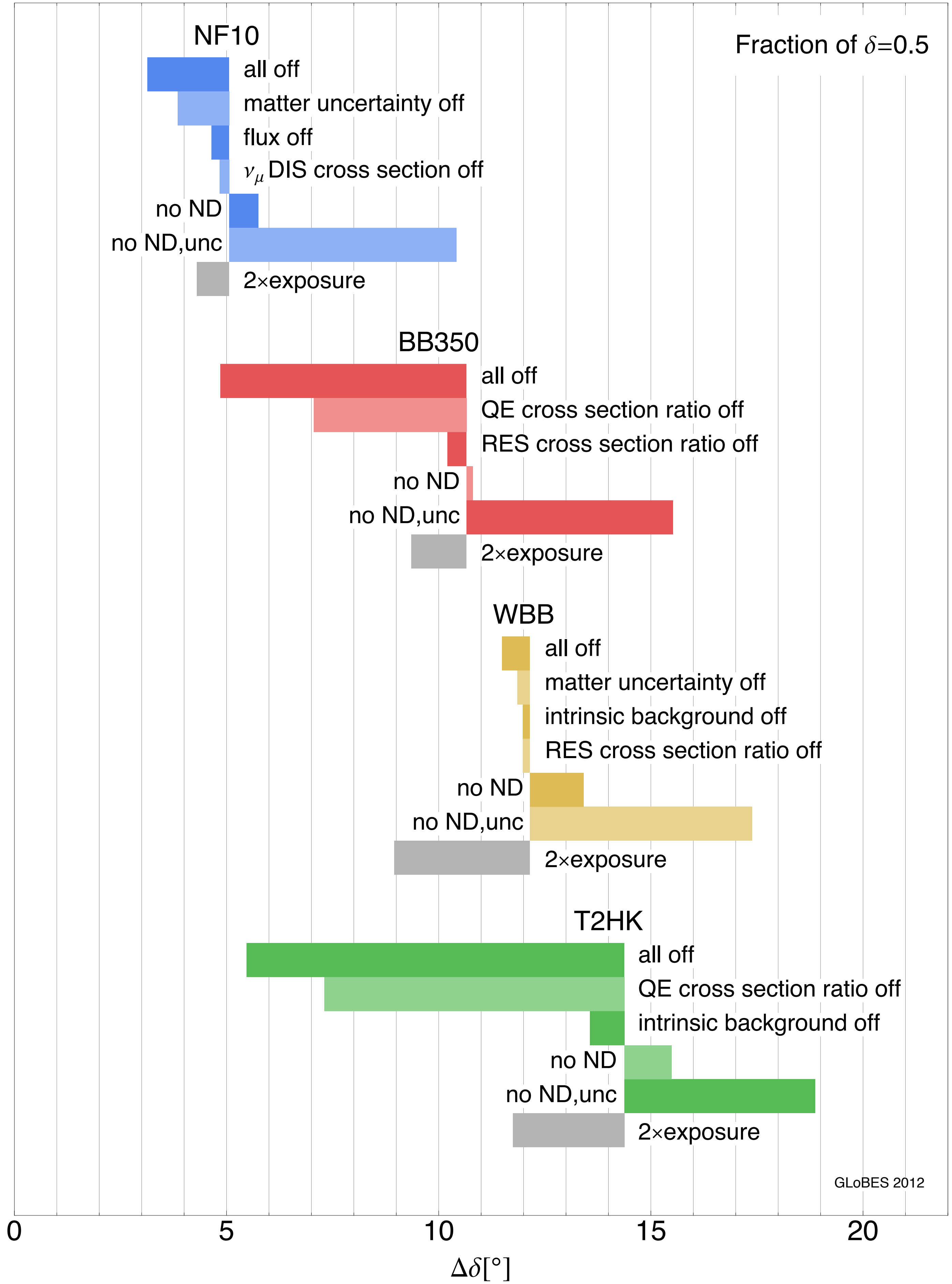
- The cross sections will be one of the dominant factors.

- The knowledge of the Earth matter profile introduces also an error for experiments with long baselines. Typically, an uncertainty ~7% but e.g. for the CERN-Pyhasalmi baseline ~2% [Kozlovskaya et al., hep-ph/0305042].





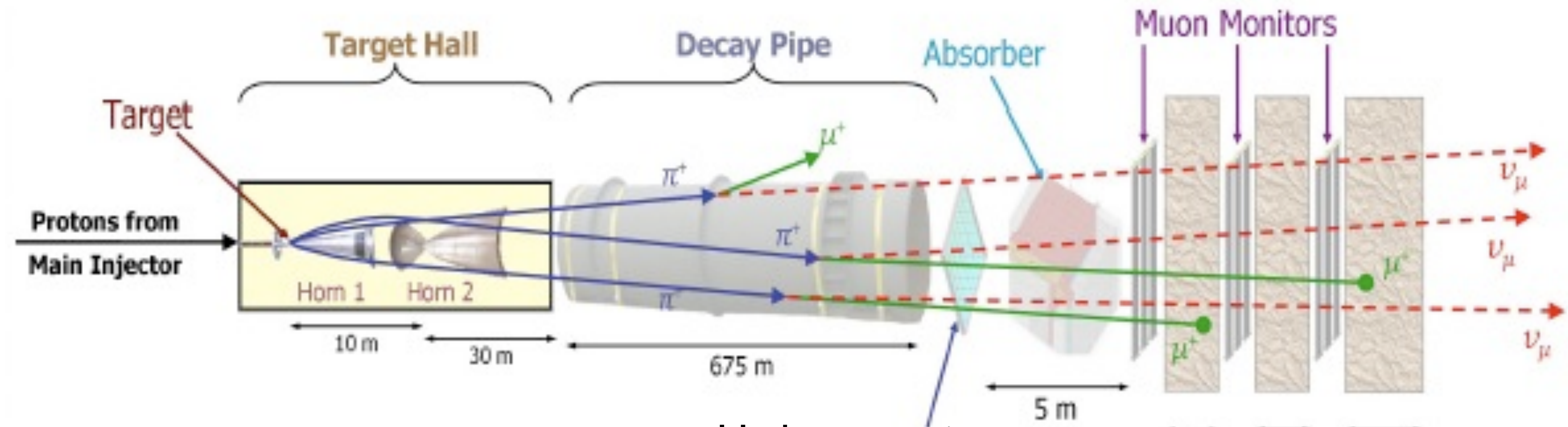
Coloma, Li, SP, in preparation; NOW2012



Good energy resolution, wide band beam, additional input will help in reducing the impact of systematic errors. The near detector(s) will play an important role.

Coloma, Huber, Kopp, Winter, 1209.5973

Superbeams



[www-numi.fnal.gov]

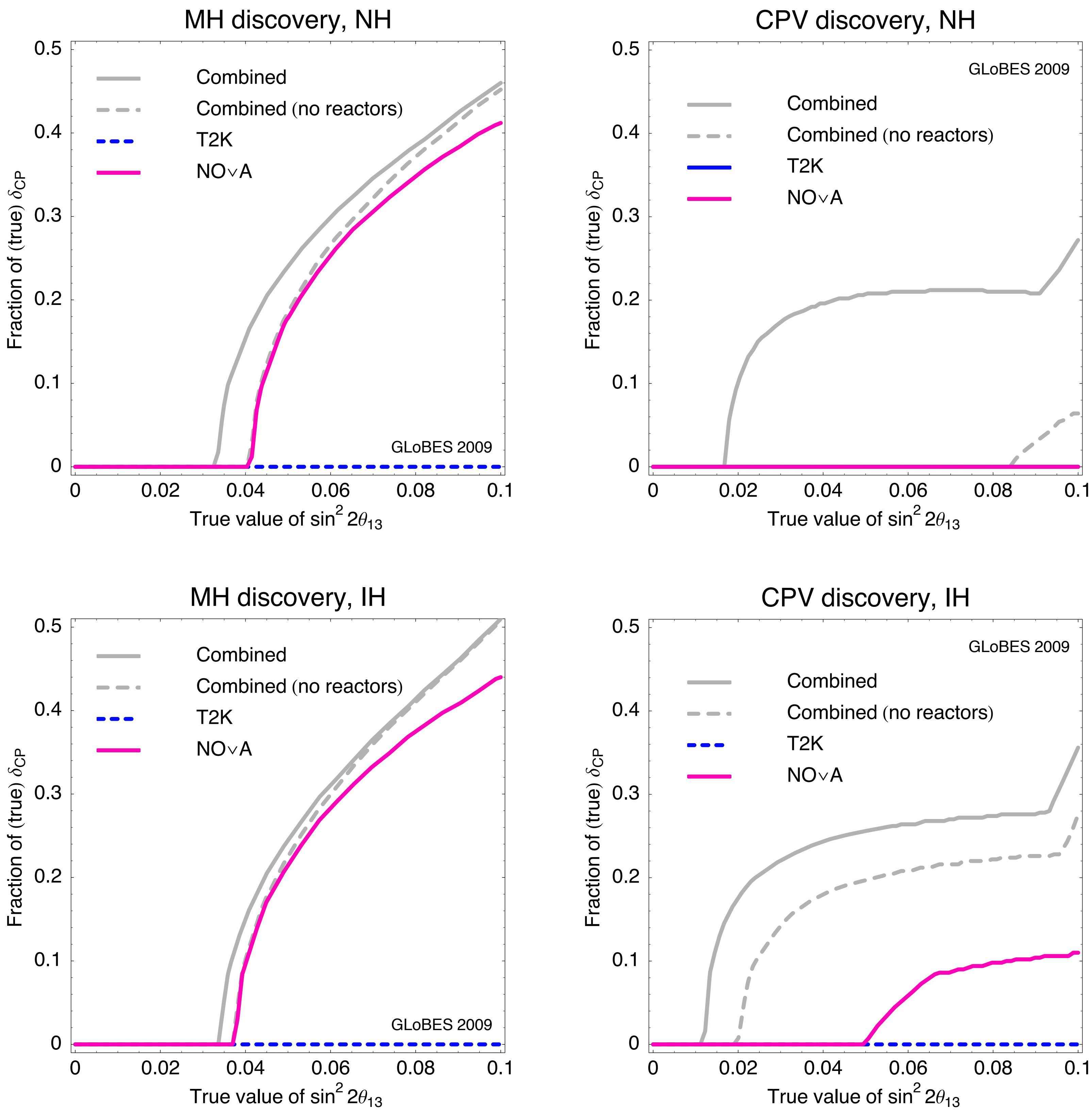
Muon neutrinos come from pion decays with high fluxes and large detectors (T2K, NOvA, T2K-II, LBNE, SPL in EUROnu, LAGUNA-LBNO) at L~100-2000 km.

T2K
off-axis
L= 295 km

T. Kobayashi

NOvA
off-axis
L=810 km

90% CL reach for T2K (0.75 MW 5 yrs), NOvA (0.7 MW, 3 yrs, nu+nubar, 15 kton detector)



T2K and NOvA

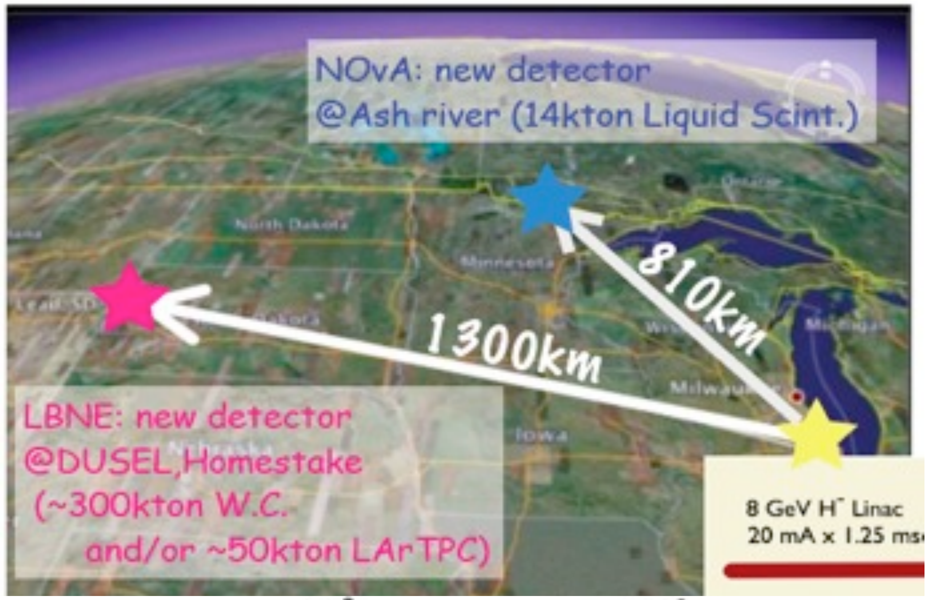
Goals: get some information about the mass hierarchy and open the hunt for CP-violation.

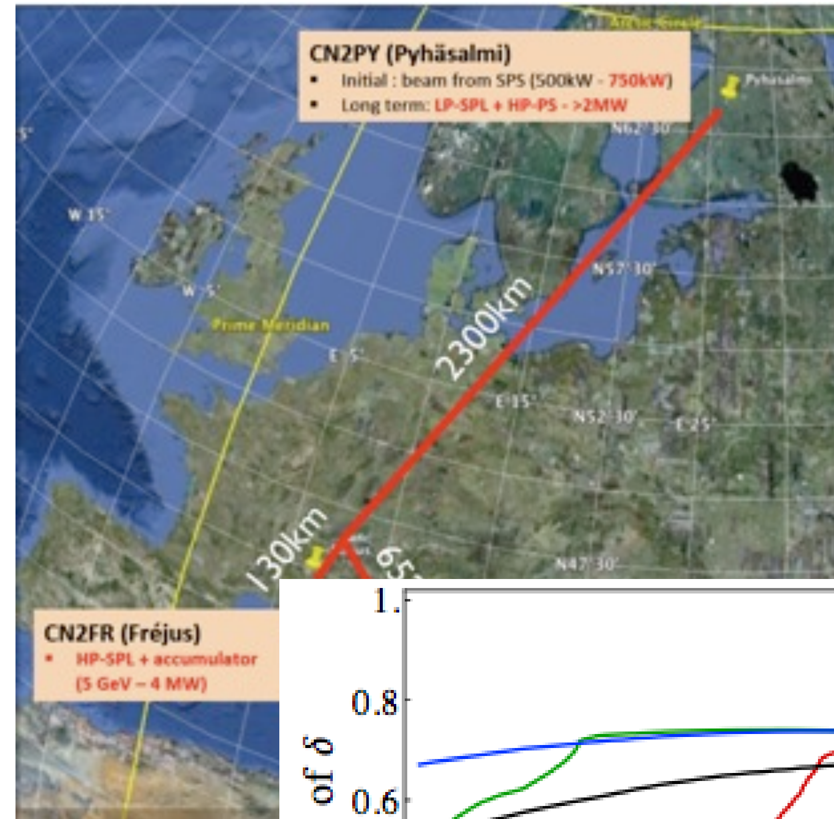
- In Feb 24 2010, first T2K event was seen in SK!

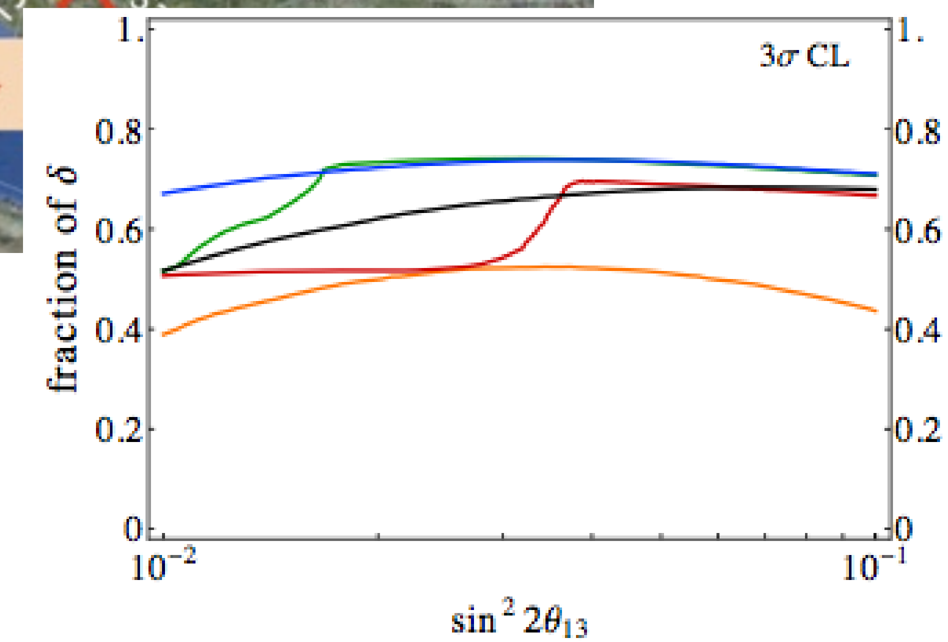
- NOvA will start data taking in 2013 and be completed by 2014.

Huber at al., 2009

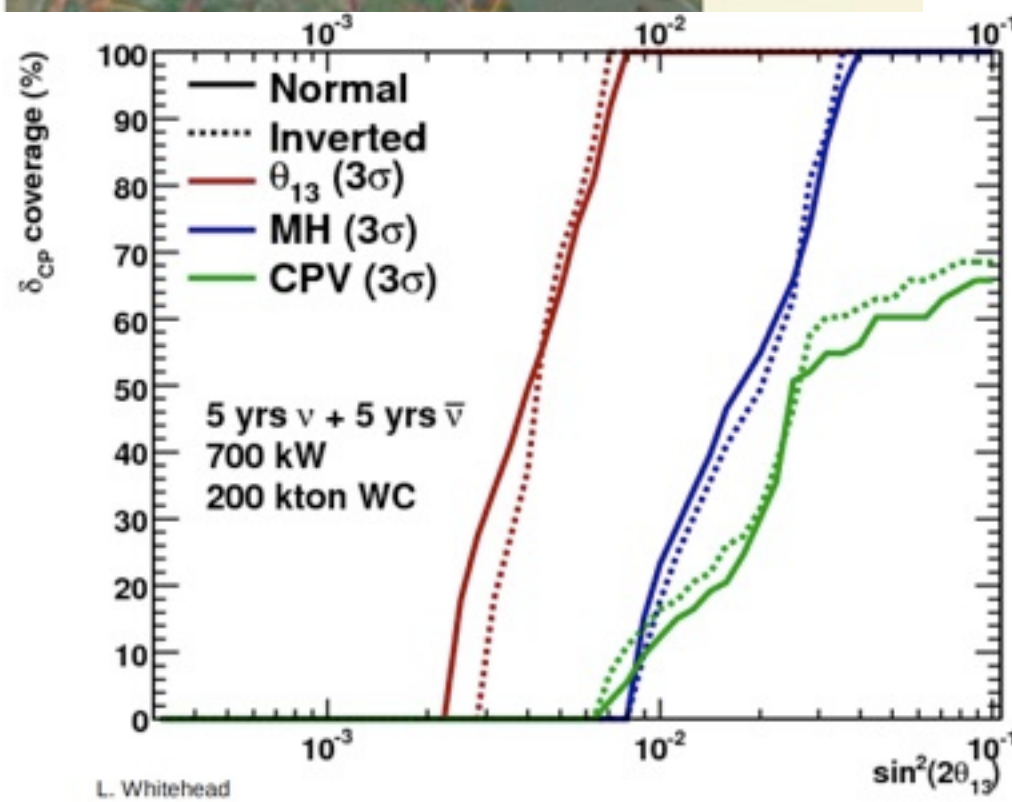
LBNE, LBNO, T2HK Goals: CPV and matter effects

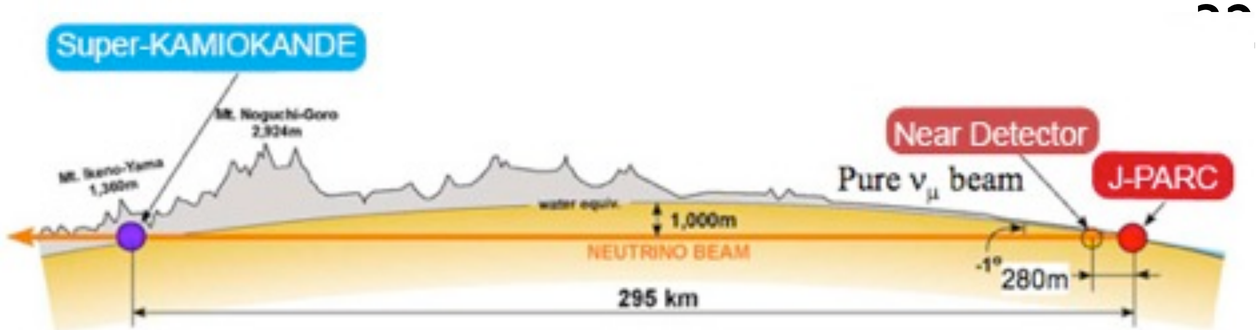




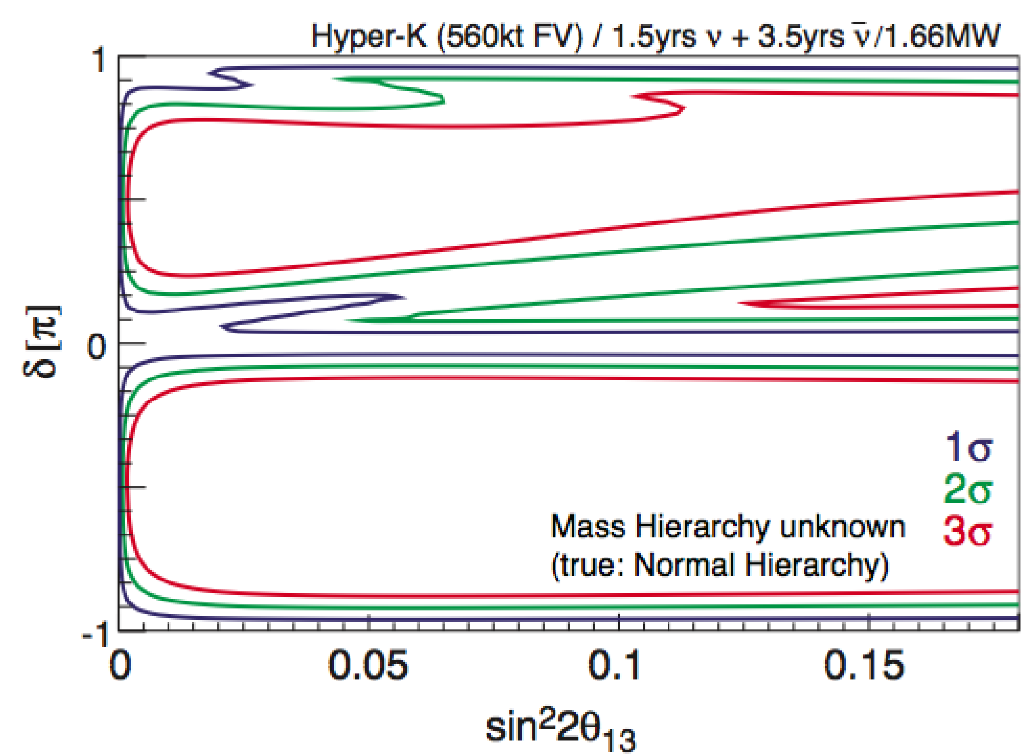


P. Coloma, T. Li, SP, 1206.4038





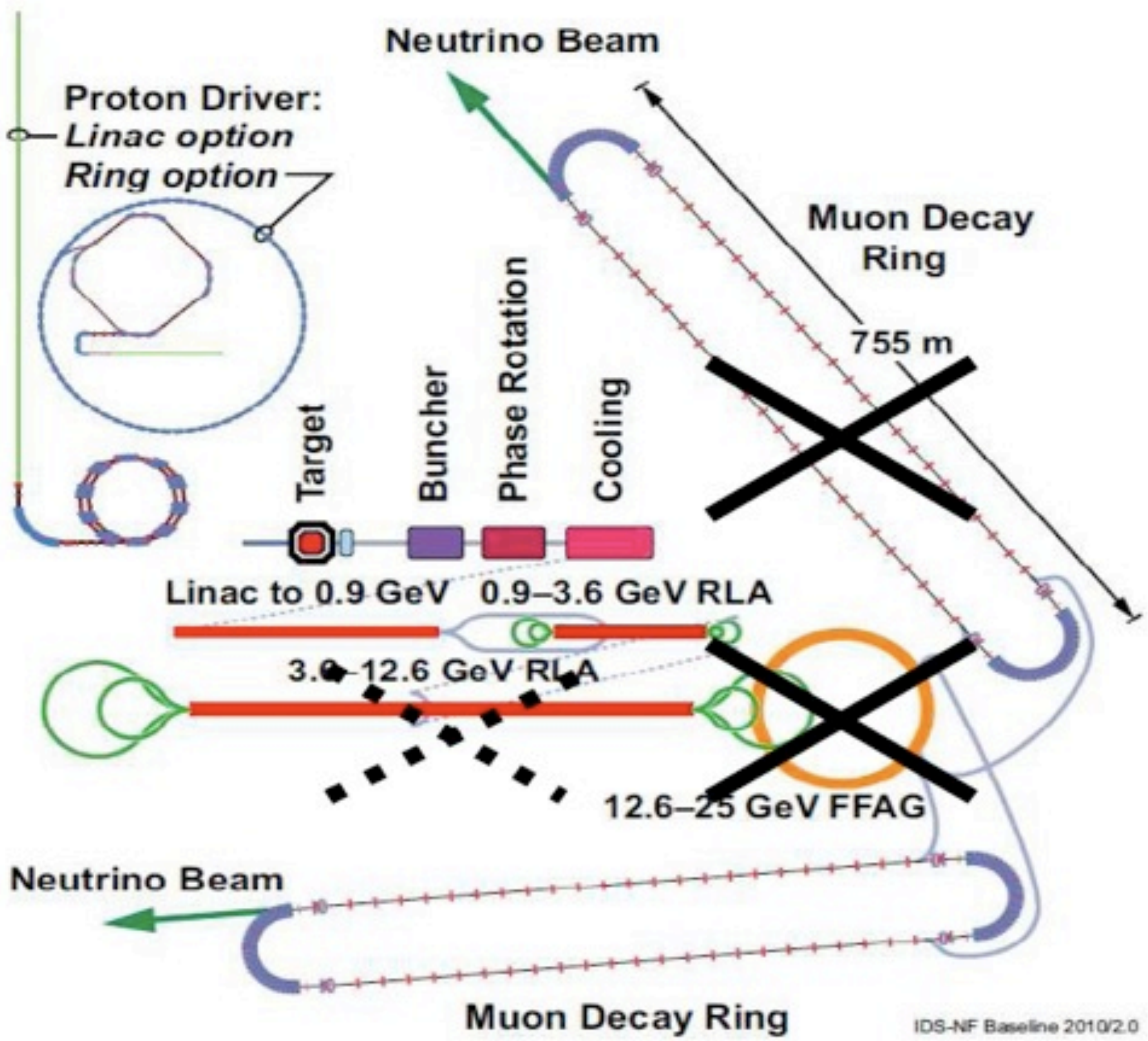
Abe et al., 1109.3262.



Neutrino factory

Neutrino factory: Neutrinos from muon decays at L~1500-7000 km. Pure beam and multiple oscillation channels but needs magnetised detector (MIND, LAr).

See e.g. de Rujula, Gavela, Hernandez; Cervera et al.; Freund, Huber, Lindner; Rubbia ....



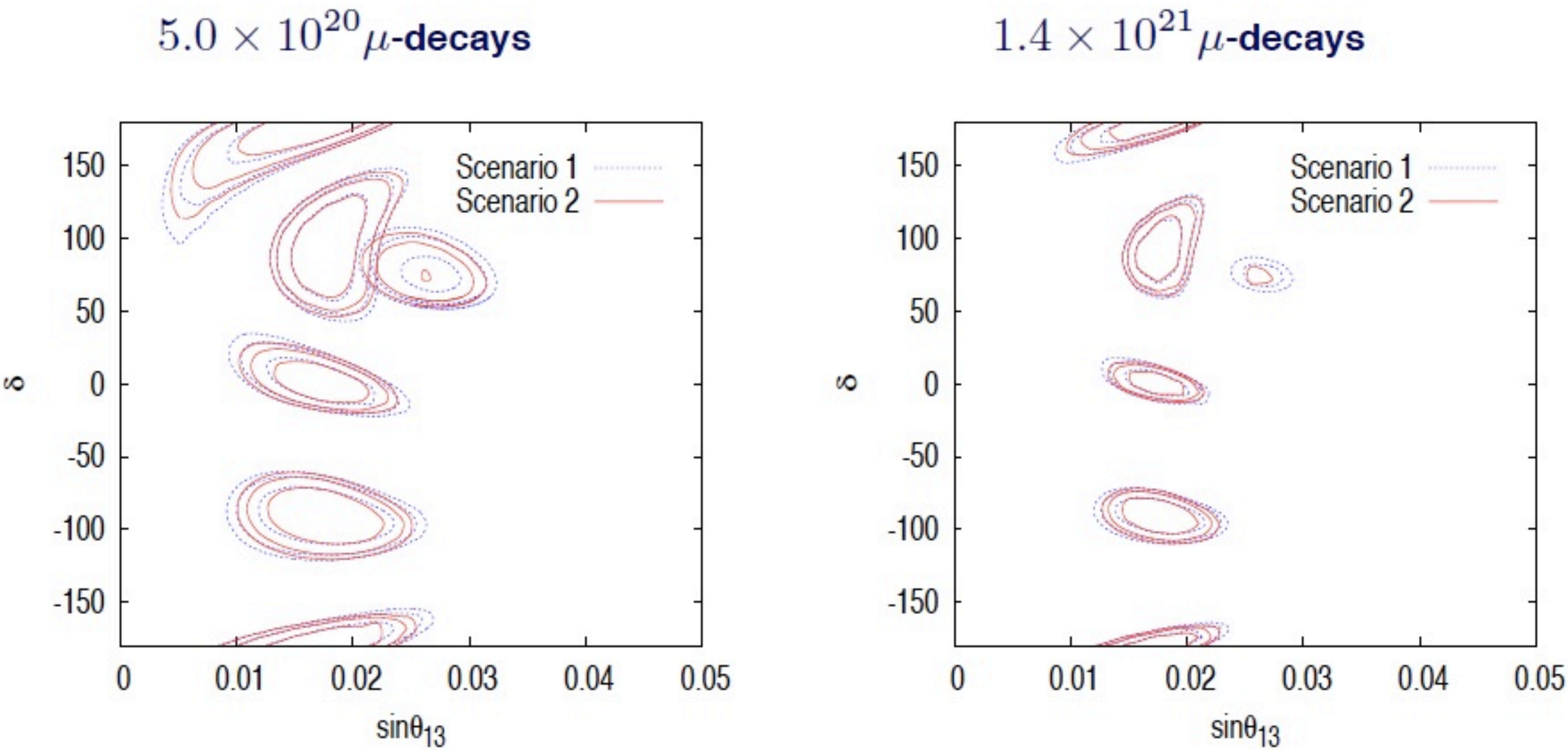
New baseline for IDS-NF (Apr 2012):

LENF:

E=10 GeV and L=2000 km with MIND

First LENF proposed in 2007 Geer, Mena, Pascoli

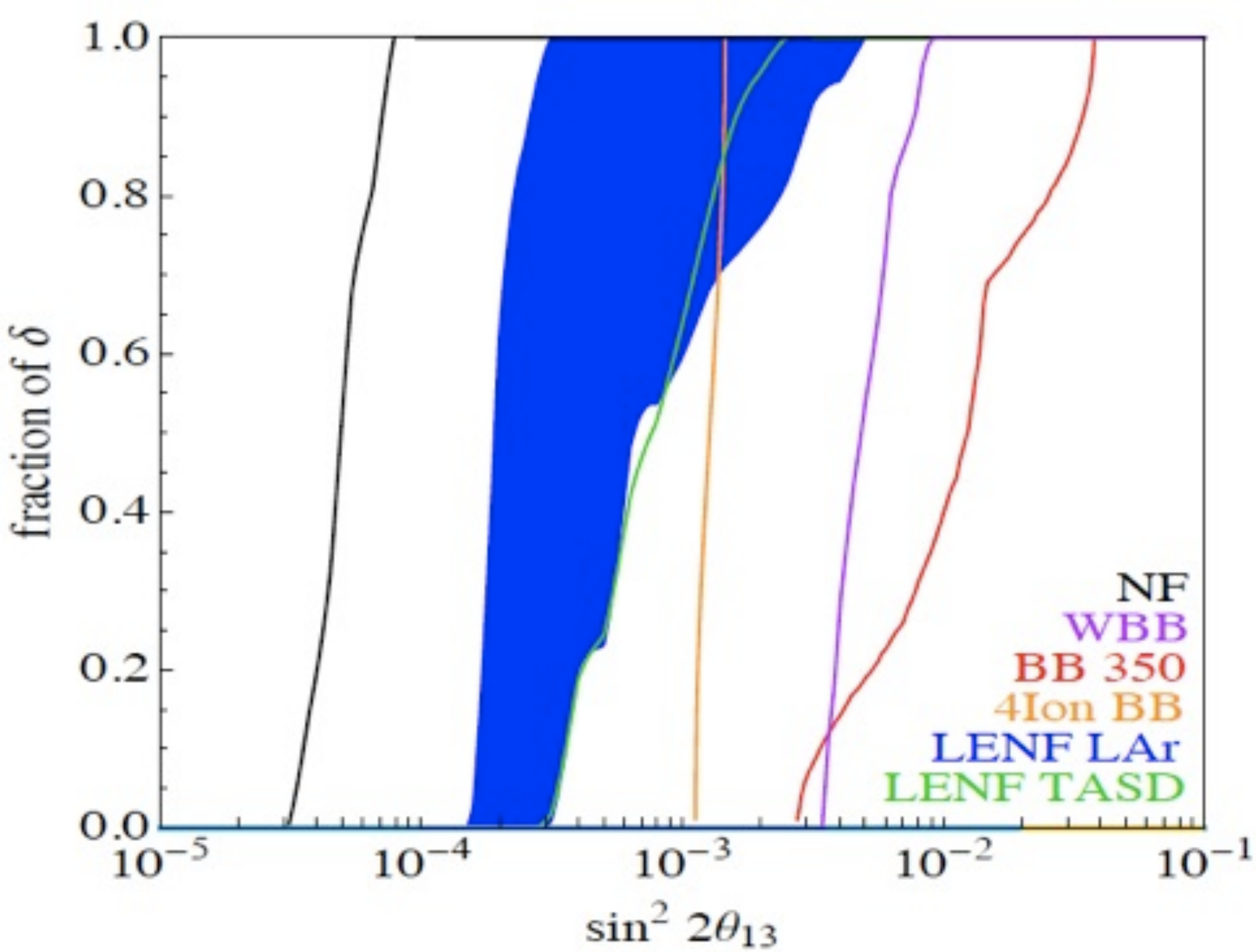
Effect of statistics (LENF 20 kton TASD)



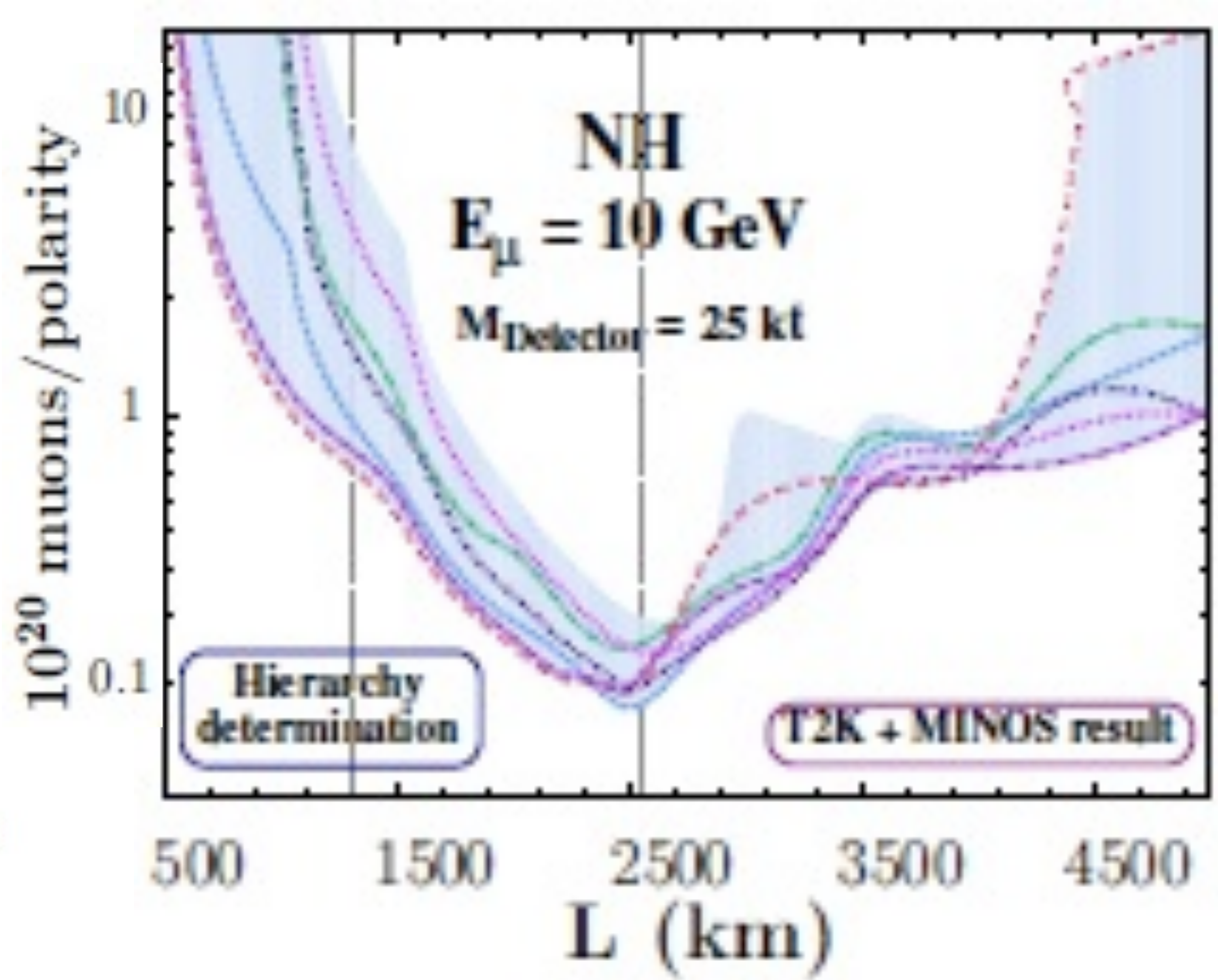
Fernandez-Martinez et al., 0911.3776

The number of events dominates the sensitivity.

Sensitivity to mass hierarchy



Fernandez-Martinez et al., 0911.3776

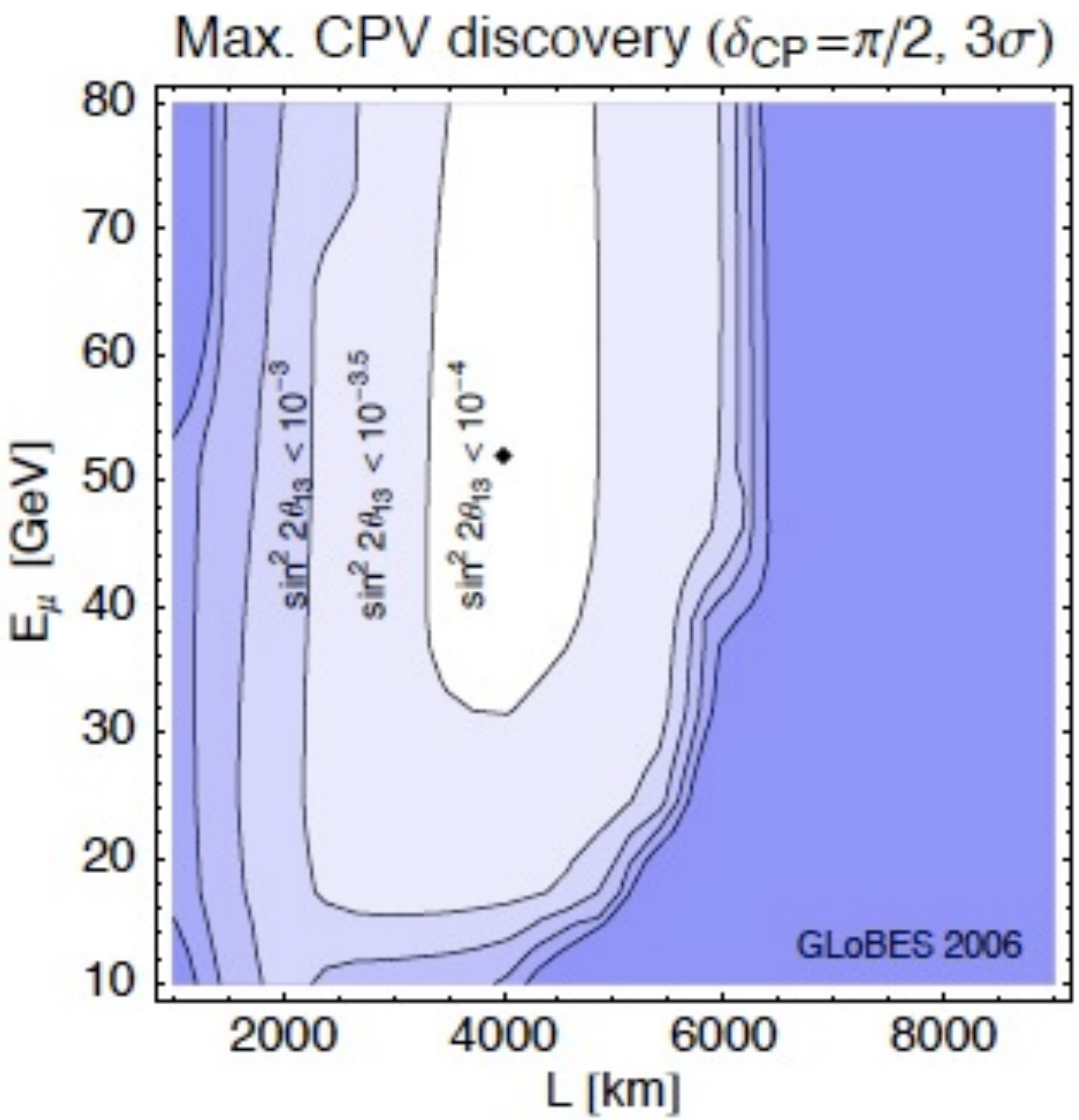


Dighe, Goswami, Ray, 1110.3289

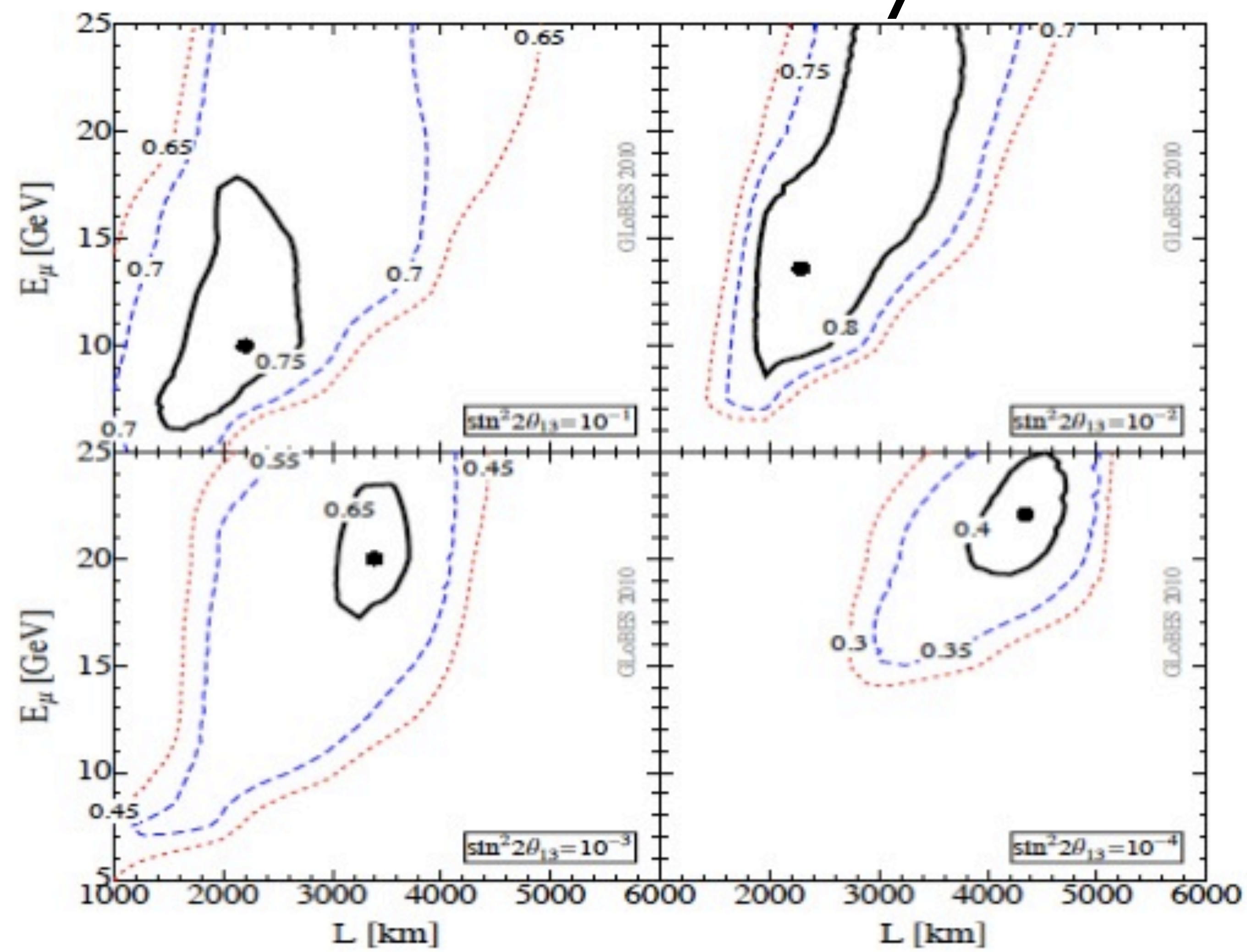
A LENF (E~10 GeV, L~2000 km) can determine the type of mass hierarchy for all values of delta.

CPV searches: optimisation studies

An optimisation of the NF using one MIND detector (low efficiency at low energies) was performed.



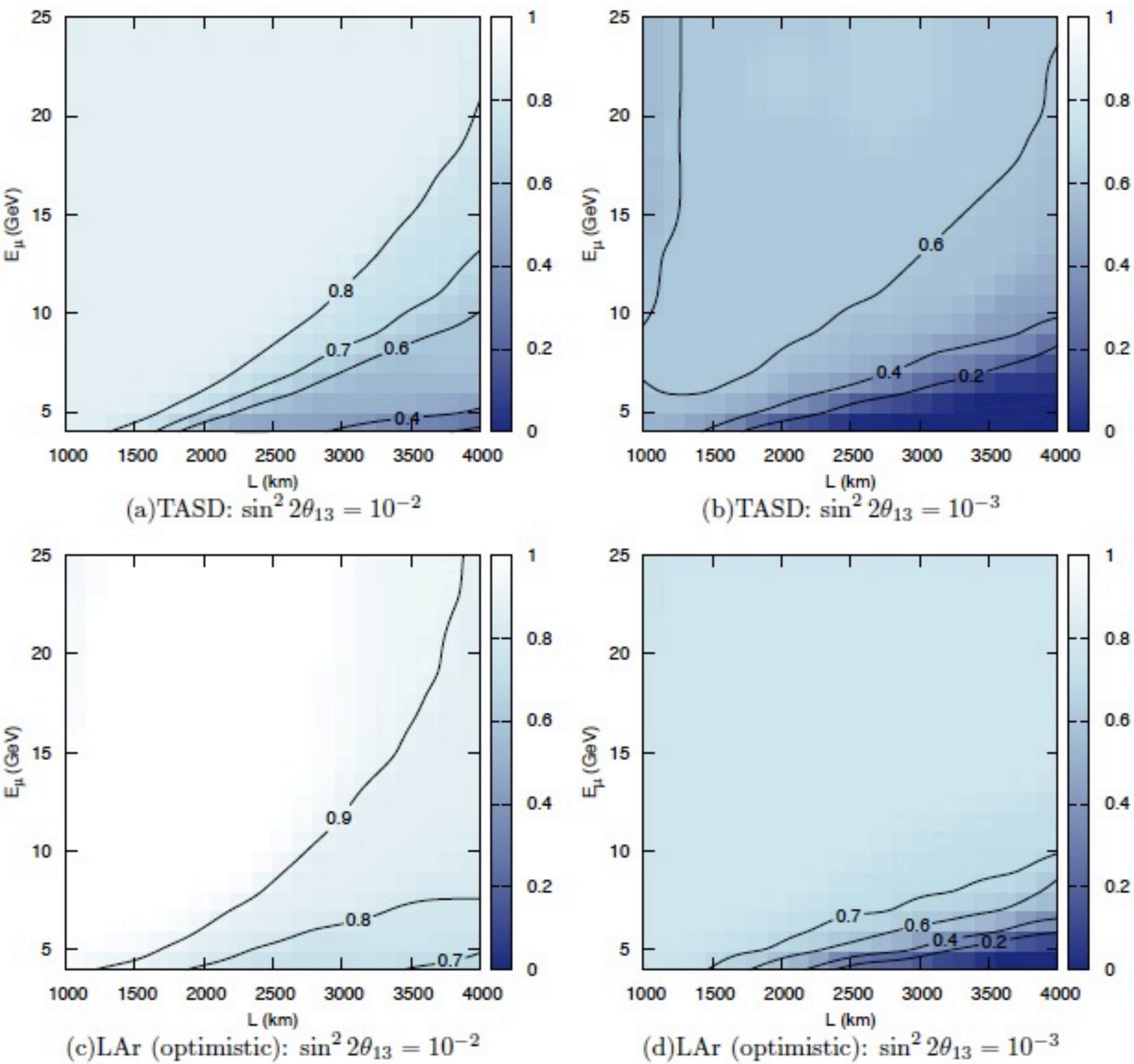
CPV sensitivity



Huber et al., hep-ph/0606119

Agarwalla, Huber, Tang, Winter, 1012.1872

As θ_{13} decreases the optimal energy and baseline shift towards the HENF configuration.

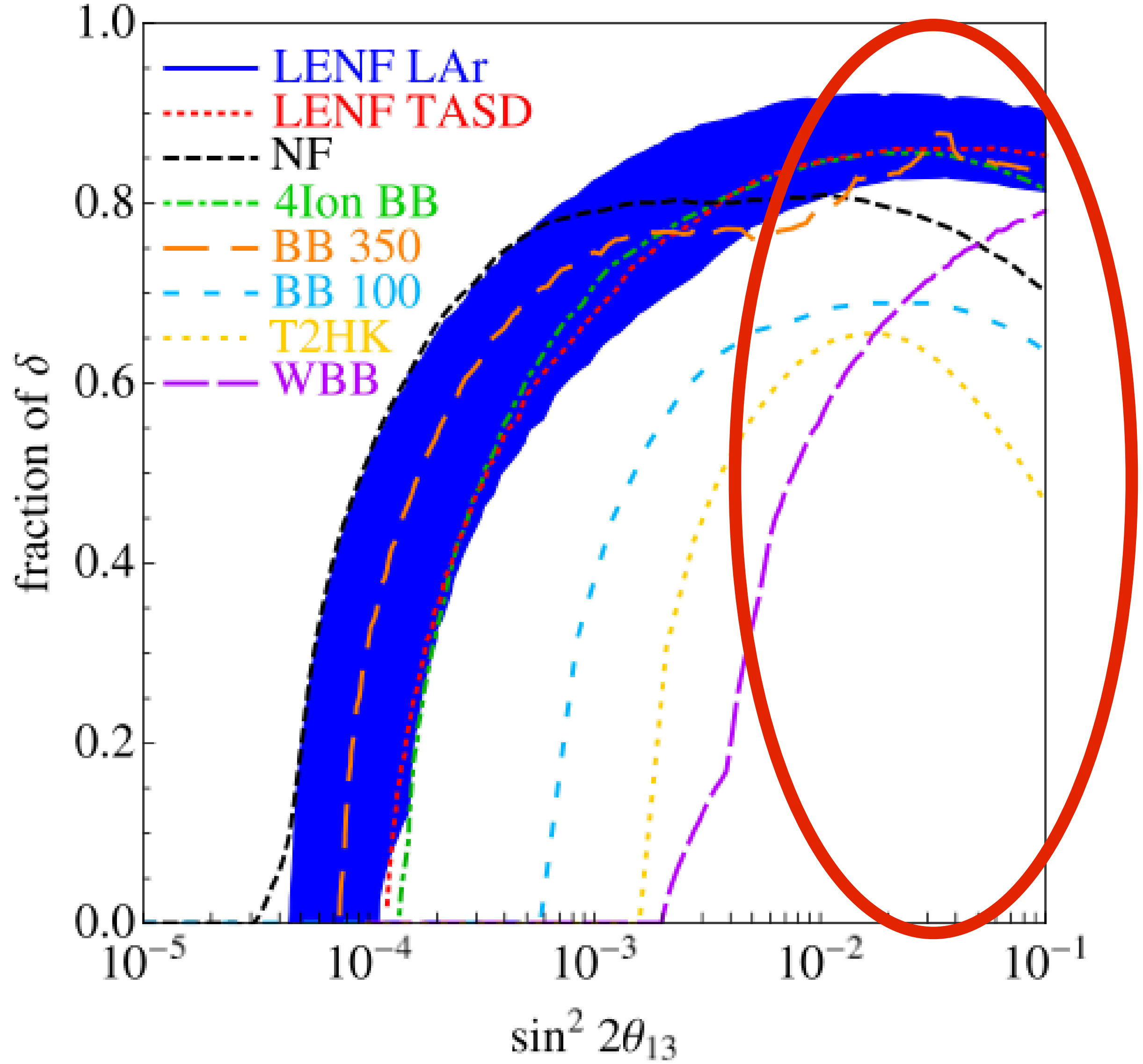


TASD and LAr detectors.

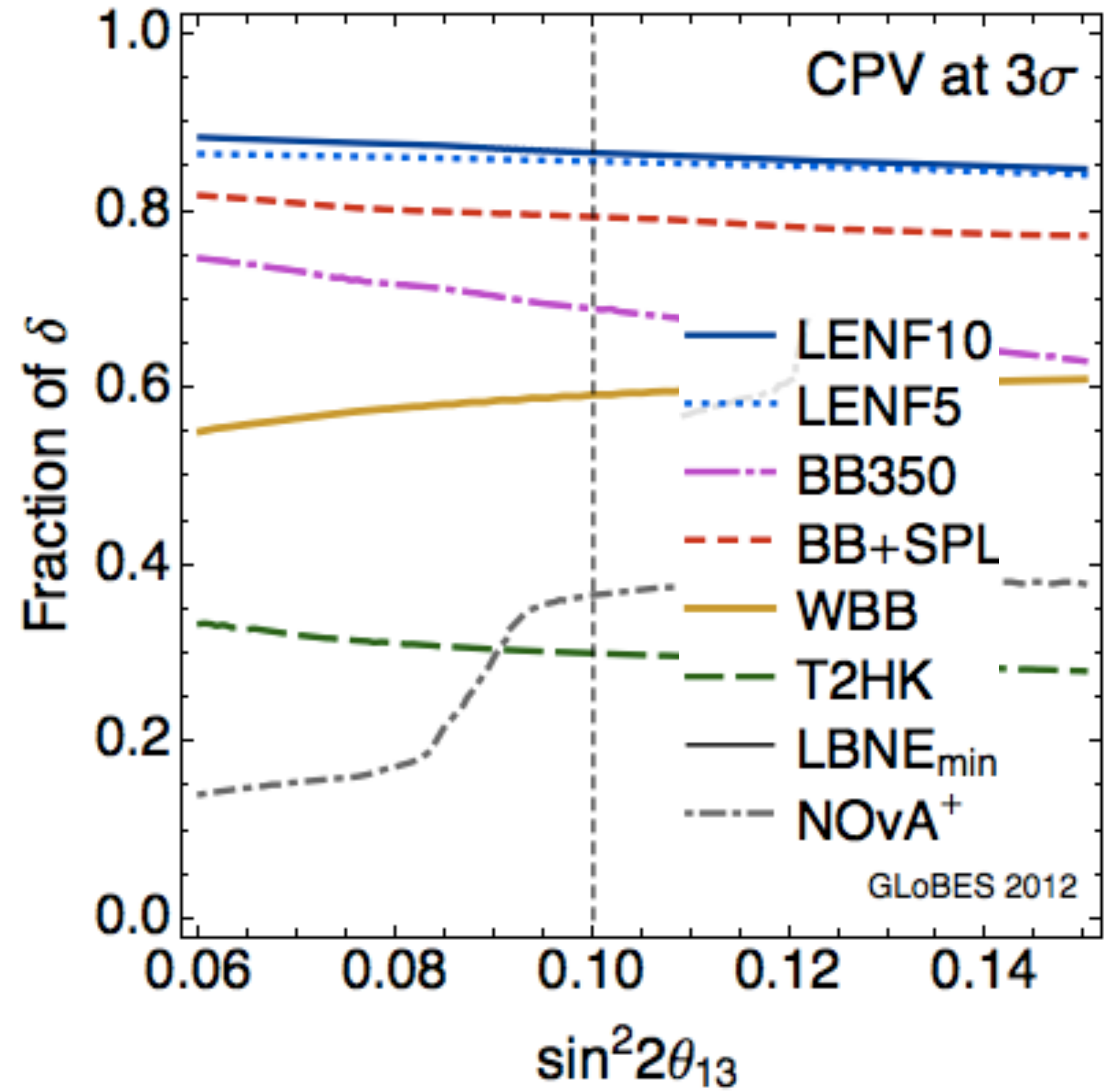
Lines show the fraction of delta for which CPV can be determined.

Excellent sensitivity for large θ_{13} rather independent from L and E.

P. Ballett, SP, 1201.6299



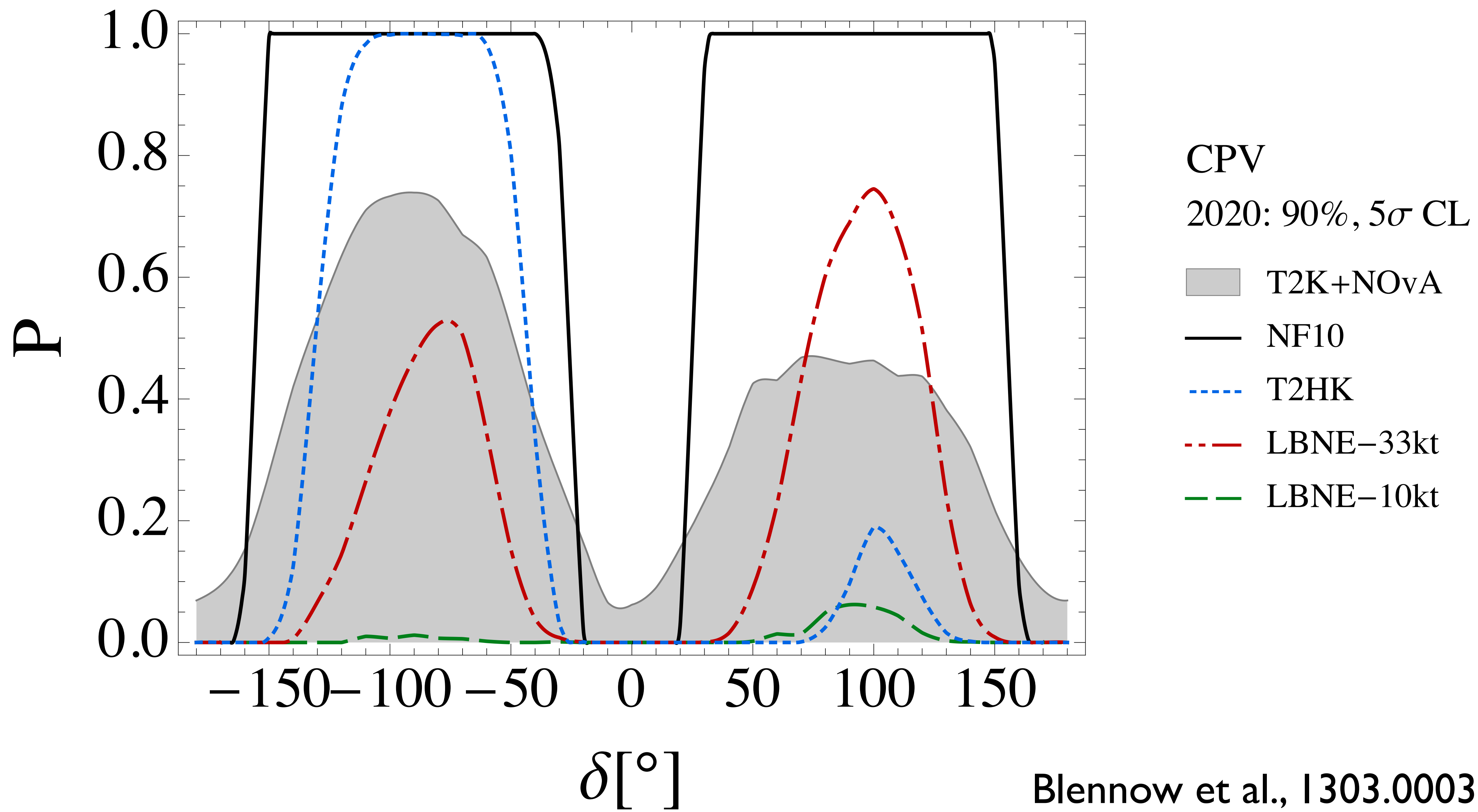
Fernandez-Martinez et al., 0911.3776



Coloma, Huber, Kopp, Winter, 1209.5973

The ultimate sensitivity could be provided by the neutrino factory.

LENF10 vs T2K and NOvA



Blennow et al., 1303.0003

If T2K and NOvA find a hint of CPV, then the LENF10 will have an excellent chance to discover CPV.

Precision measurements of oscillation parameters

The precision measurement of the oscillation parameters will become very important once the mass hierarchy and CPV are established. LBL experiments can give information on $\theta_{23},\ \theta_{13},\ \delta$.

The expected precision on theta13 can be related to

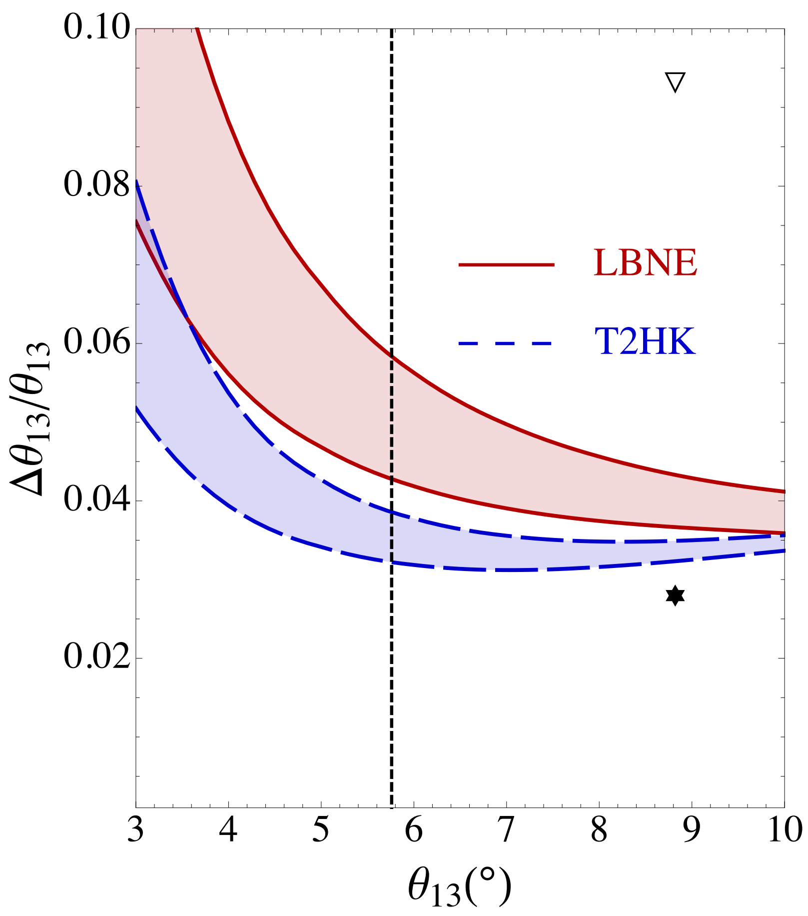
$$N_{\rm events} \sim P_{\mu e} \sim \sin^2 2\theta_{13} \sim (\theta_{13})^2 \Rightarrow \Delta N \sim \theta_{13} \Delta\theta_{13}$$

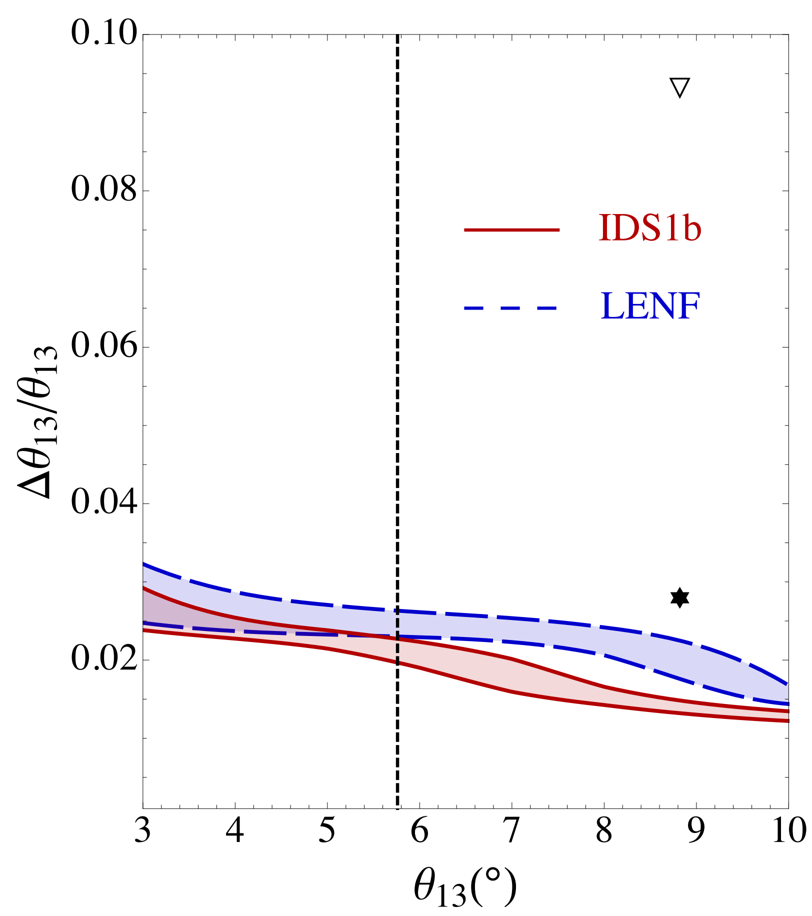
If the statistical error dominates: $\dfrac{\Delta\theta_{13}}{\theta_{13}} \sim \dfrac{1}{\theta_{13}}$

If the systematic error on the signal does: $\dfrac{\Delta\theta_{13}}{\theta_{13}} \sim \text{constant}$

If that on the background: $\dfrac{\Delta\theta_{13}}{\theta_{13}} \sim \dfrac{1}{\theta_{13}^2}$

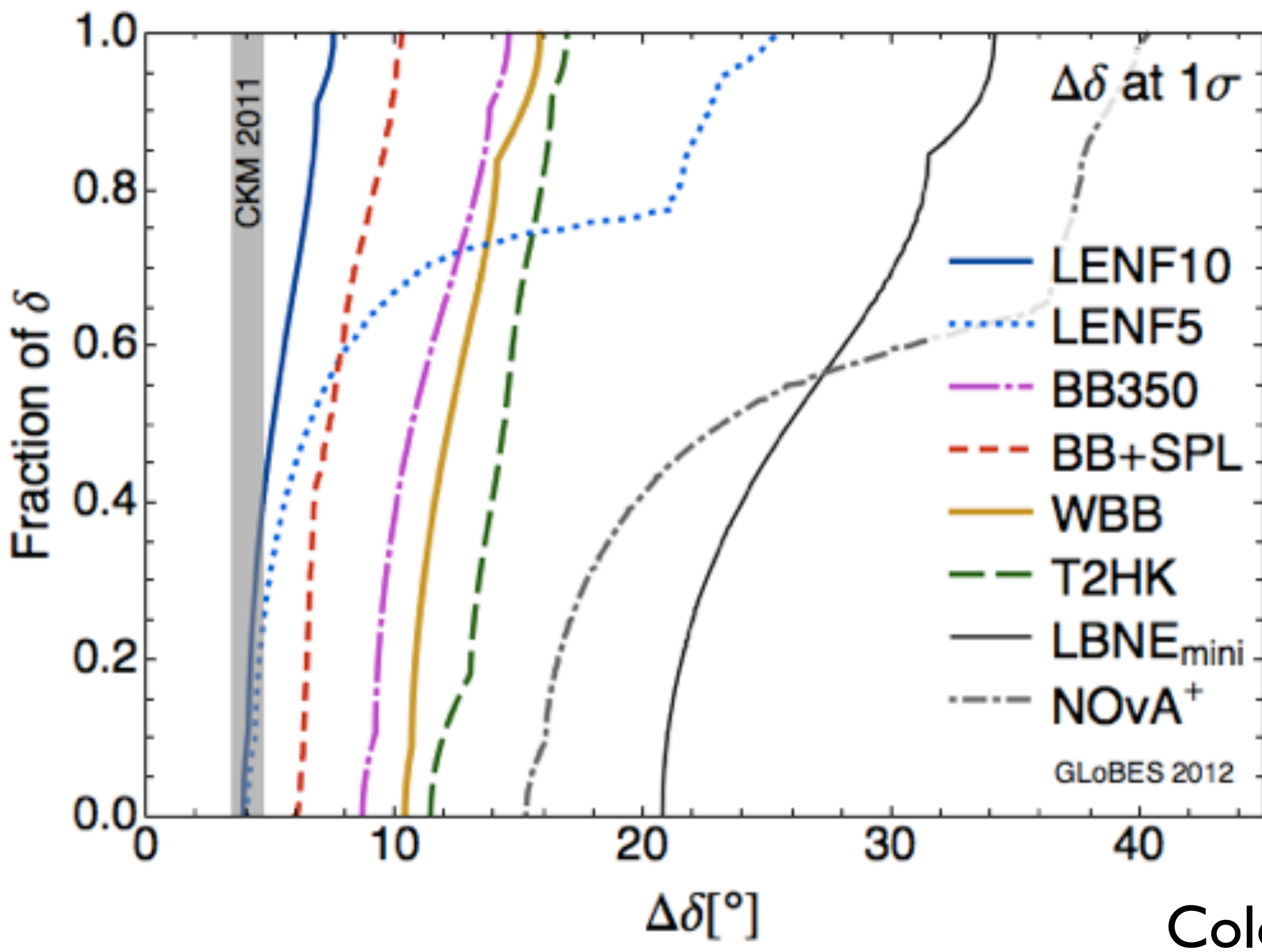
Coloma, Donini, Fernandez Martinez, Hernandez, 1203.5651





Coloma, Donini, Fernandez Martinez, Hernandez, 1203.5651

The best measurement of theta13 will be provided by Daya Bay, unaffected by degeneracies, and it could be marginally improved by LENF.



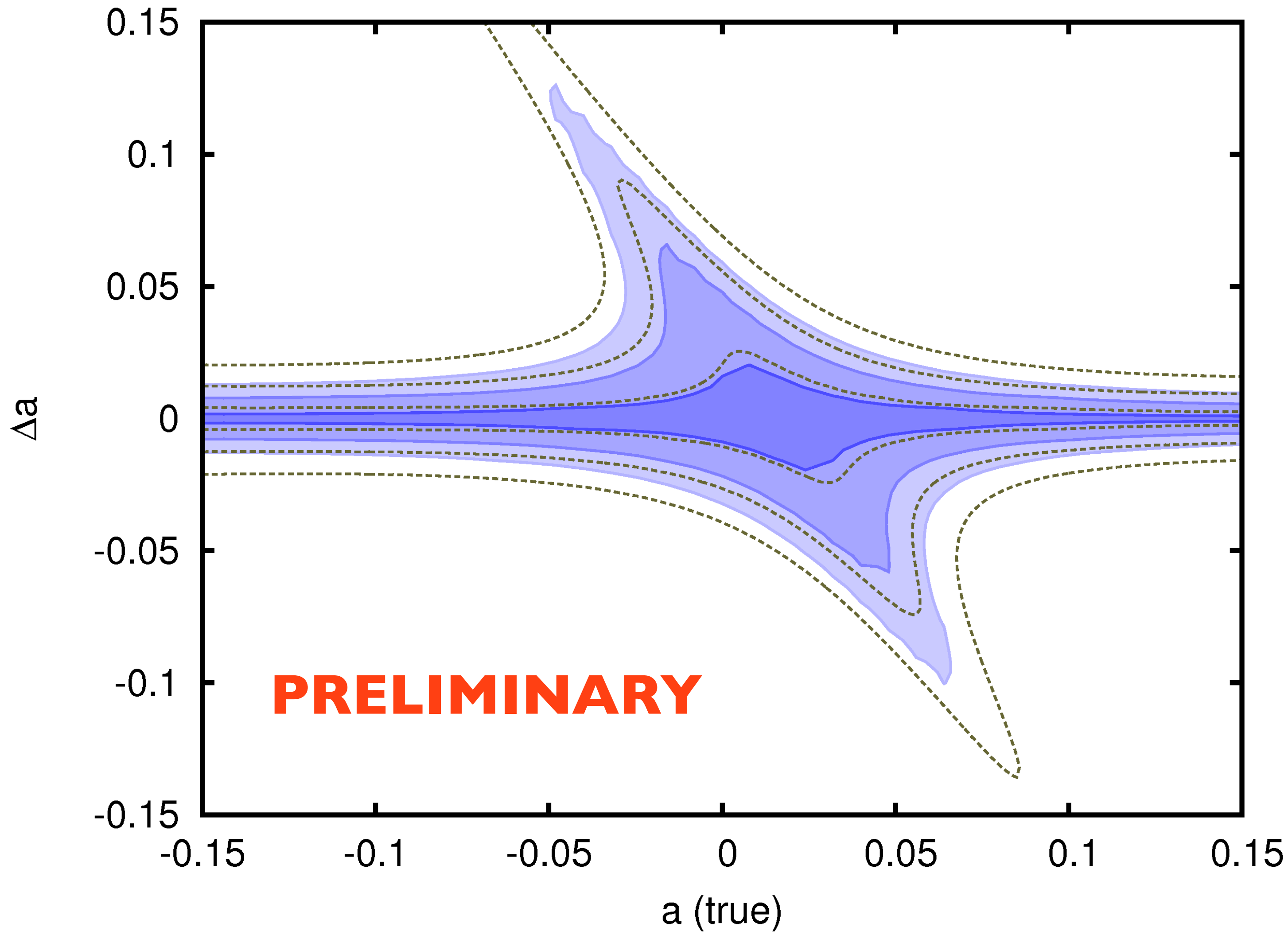
Coloma, Huber, Kopp, Winter, 1209.5973

In addition to delta, the study of sum rules and possible mixing patterns requires a precise measurement of the atmospheric and solar mixing angles.

Useful parameterisation:

King, 0710.0530

$$\sin\theta_{12} = \frac{1+s}{\sqrt{3}}, \quad \sin\theta_{13} = \frac{r}{\sqrt{2}}, \quad \sin\theta_{23} = \frac{1+a}{\sqrt{2}}$$



Current data:

$$-0.07 \leq s \leq -0.01$$
$$0.21 \leq r \leq 0.23,$$
$$-0.15 \leq a \leq -0.07$$

Dashed: WBB

Blue: LENF

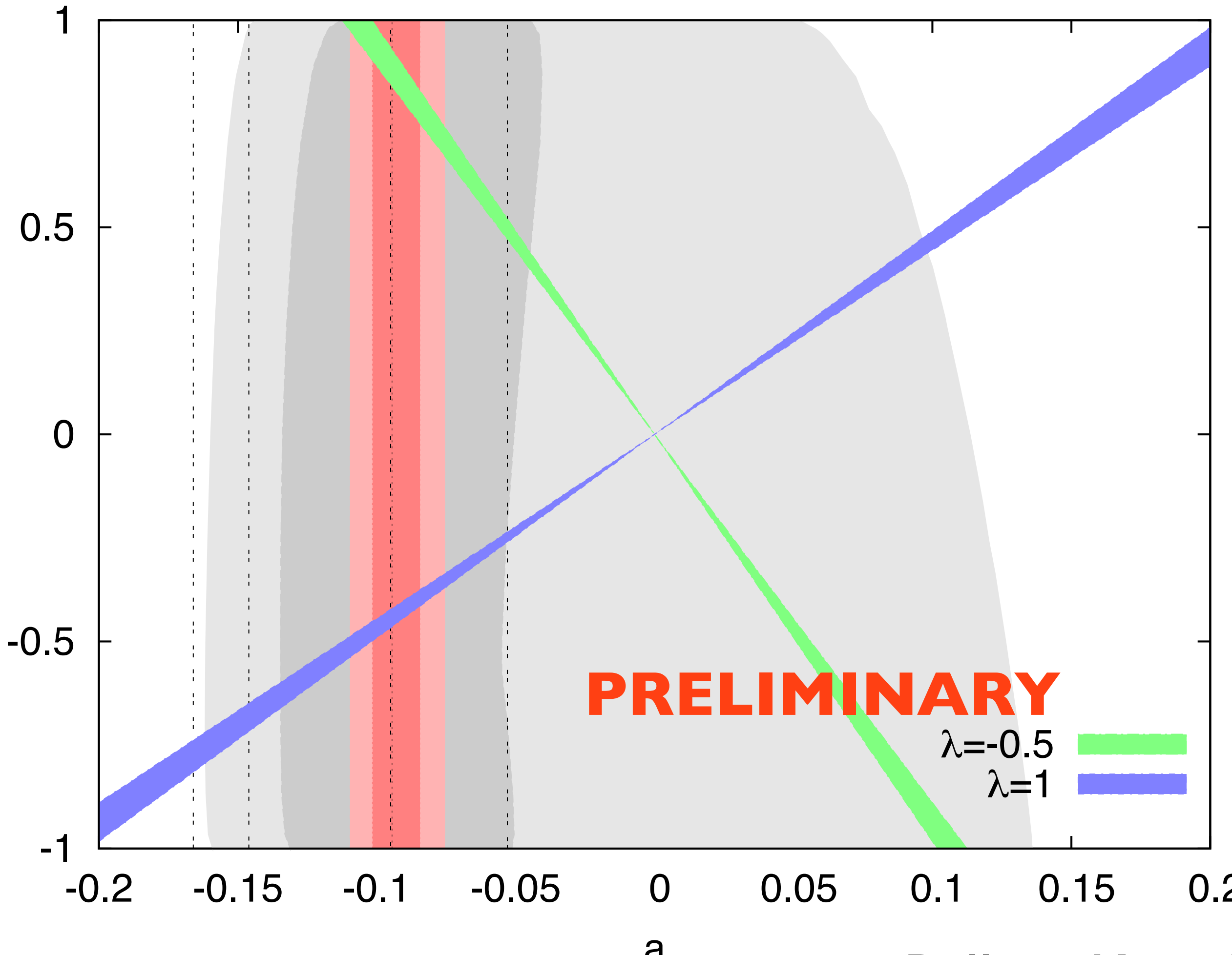
Ballett, King, Luhn, Pascoli, Schmidt, in prep

Theoretical models typically lead to correlations between parameters (sum rules).

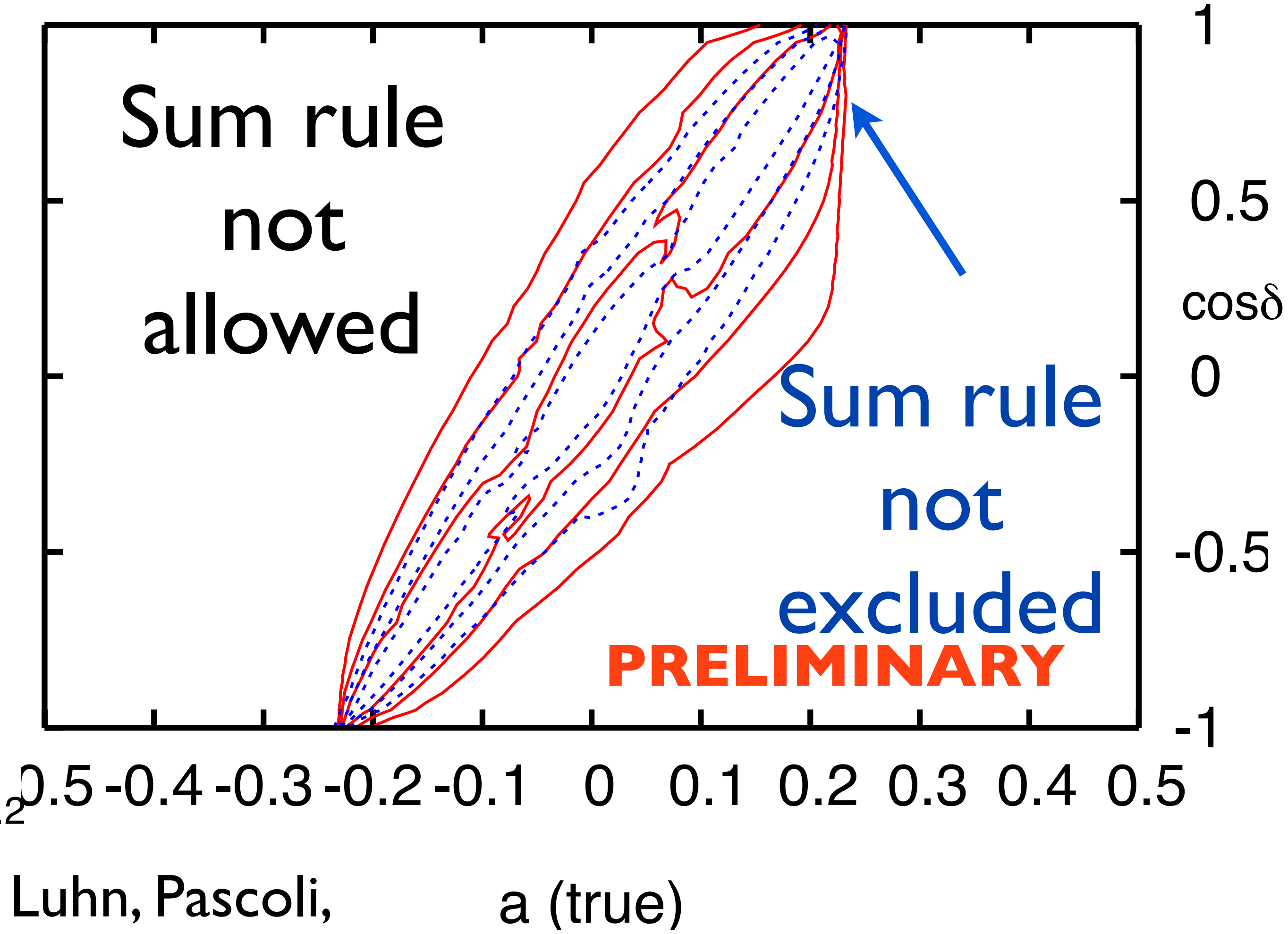
$$a = a_0 + \lambda r \cos\delta, \qquad \lambda = 1, -1/2$$

G_f	m	T_α–S_i	s	a_0	λ
A_4	3	T_e–S_2	0.010	0.000	−0.500
	3	T_μ–S_2	0.012	0.000	−0.500
	3	T_τ–S_2	0.012	0.000	−0.500
S_4	3	T_e–S_1	−0.012	0.000	1.000
	4	T_μ–S_2	−0.124	−0.179	−0.408
	4	T_τ–S_2	−0.124	0.179	−0.408
A_5	5	T_e–S_1	−0.118	0.000	1.144
	5	T_e–S_2	−0.079	0.000	−0.437
	5	T_μ–S_2	0.054	0.084	−0.532
	5	T_τ–S_2	0.054	−0.084	−0.532

Current data



Future prospects



Ballett, King, Luhn, Pascoli, Schmidt, in prep

Going beyond the standard 3 neutrino mixing scenario

A plethora of hints of physics beyond 3 neutrino mixing and SM interactions is present.

LSND appearance experiment

MiniBooNE neutrino and antineutrino results

Reactor anomaly

If confirmed, it would lead to a radical shift in our understanding of neutrino and physics BSM and would require a reanalysis of the reach of future neutrino oscillation experiments.

Sterile neutrinos

Sterile neutrinos could be present in extensions of the SM with masses from sub-eV to GUT scale. Of phenomenological interest for oscillations are those with sub-eV to multi-eV masses (LSND, MiniBooNE). New angles and CPV phases appear

$$U = R_{34}(\theta_{34}, 0)\, R_{24}(\theta_{24}, 0)\, R_{14}(\theta_{14}, 0)\, R_{23}(\theta_{23}, \delta_3)\, R_{13}(\theta_{13}, \delta_2)\, R_{12}(\theta_{12}, \delta_1)$$

The near detector plays an important role as it can lead to sensitivity to oscillations with large masses:

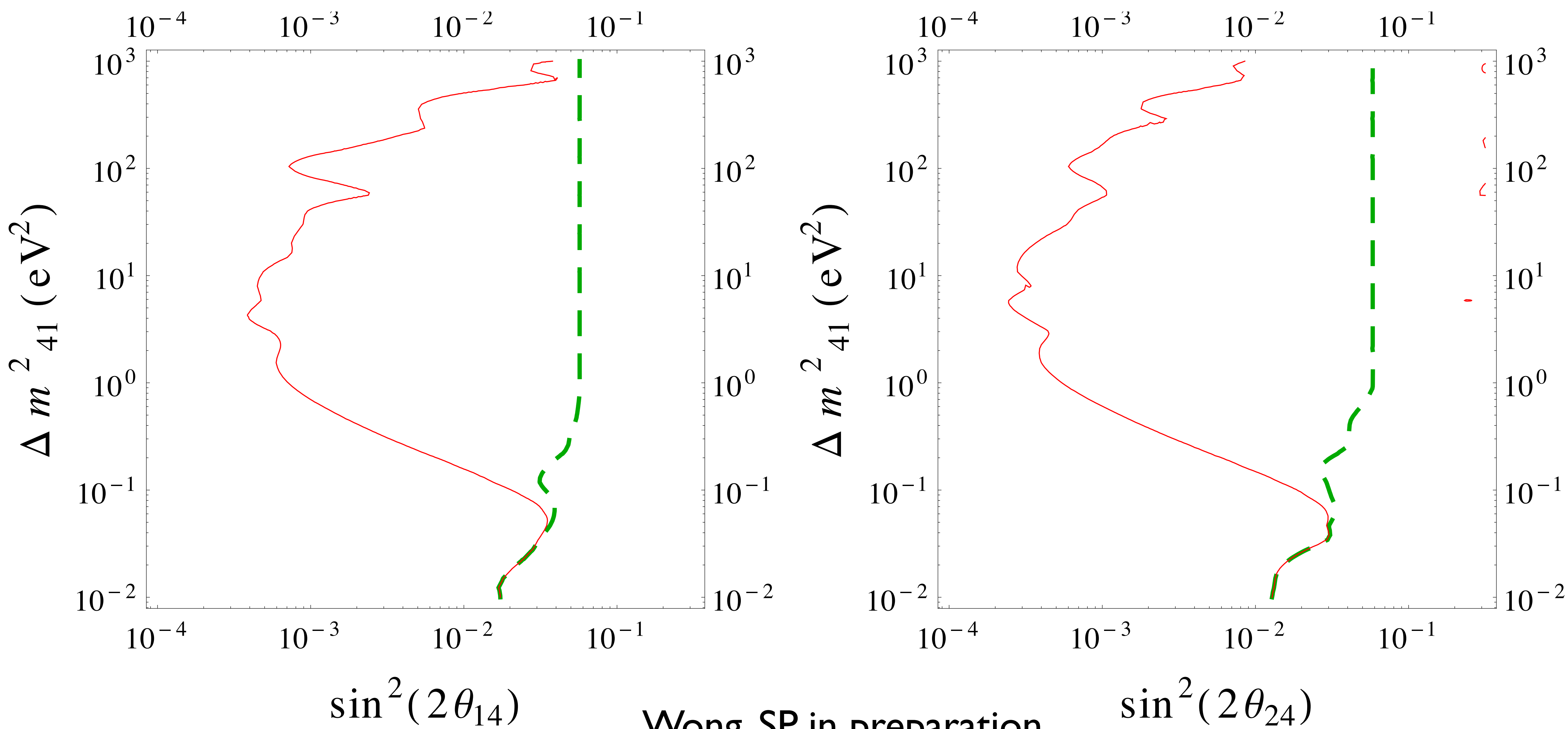
$$P_{e\mu} = 4c_{14}^2 s_{14}^2 s_{24}^2 \sin^2\Delta_{41}$$

$$P_{ee} = 1 - \sin^2(2\theta_{14}) \sin^2\Delta_{41}$$

$$P_{\mu\tau} = 4c_{14}^2 c_{24}^2 s_{24}^2 s_{34}^2 \sin^2\Delta_{41}$$

Sensitivities to the sterile neutrino parameters using a near detector at 2 km.

See e.g. Meloni, Tang, Winter, 1007.2419. Also, Donini et al., Antusch et al., Tang and Winter...



Wong, SP, in preparation

No sensitivity to the third angle as there is no sensitivity to the tau-channel.

NSI

NSI appear as additional effects in the H:

$$\hat{H}^{fl} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{pmatrix} U^\dagger \pm A \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

NSI can arise in extensions of the SM. For instance D=6 operators typically lead to

$$\mathcal{O}^6 = \frac{1}{\Lambda^2} \left(L_\sigma \gamma^\lambda L_\rho\right) \left(L_\psi \gamma_\lambda L_\zeta\right) \longleftrightarrow \epsilon \sim g^2 M_W^2 / (g_{NSI}^2 M_{NSI}^2)$$

Strong bounds arise from oscillations, pion decay, CKM unitarity..., typically <0.001, 0.1, and at the loop-level, if charged current processes cannot be avoided.

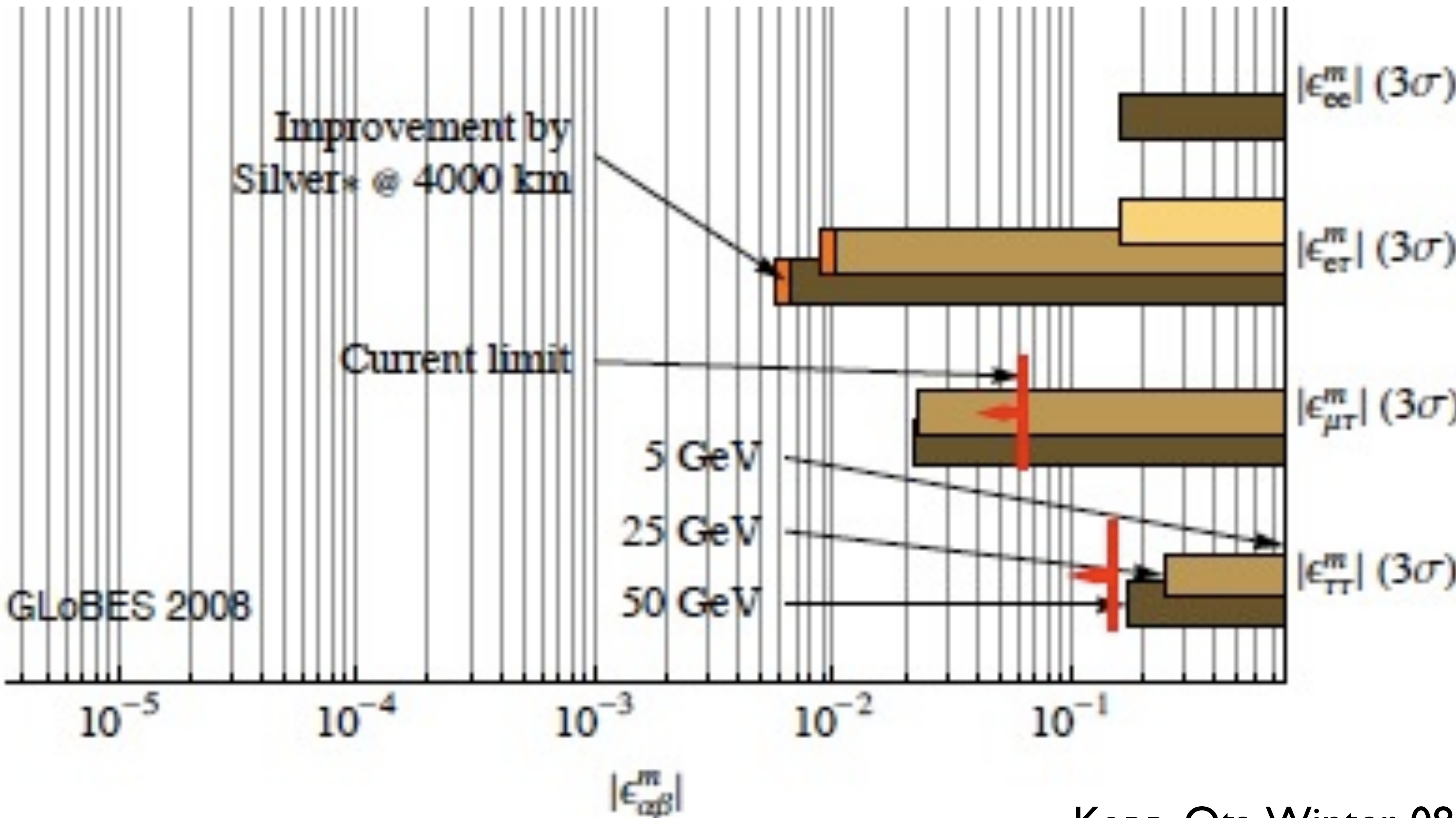
LBL experiments are also sensitive to NSI at source, propagation and detection (Grossman, 95):

matter effects

$$
\begin{aligned}
P_{\nu_e \to \nu_\mu} \simeq\ & \frac{s_{213}^2 s_{23}^2}{\left(1 - \frac{A}{\Delta_{31}}\right)^2} \\
& + \frac{s_{213} c_{13} s_{212} s_{223}}{1 - \frac{A}{\Delta_{31}}} \frac{\Delta_{21}}{A} \sin\left(\frac{AL}{2}\right) \cos\left(\frac{\pi + AL}{2} - \delta\right) \\
& - 4\varepsilon_{e\mu} \frac{s_{213} c_{23} s_{23}^2}{1 - \frac{A}{\Delta_{31}}} \sin\left(\frac{AL}{2}\right) \cos\left(\frac{\pi + AL}{2} - \delta + \phi_{e\mu}\right) \\
& - 4\varepsilon_{e\tau} \frac{s_{213} c_{23} s_{23}^2}{1 - \frac{A}{\Delta_{31}}} \sin\left(\frac{AL}{2}\right) \cos\left(\frac{\pi + AL}{2} - \delta + \phi_{e\tau}\right)
\end{aligned}
$$

The longer baseline (higher energy), the better the physics reach as NSI effects become more important.

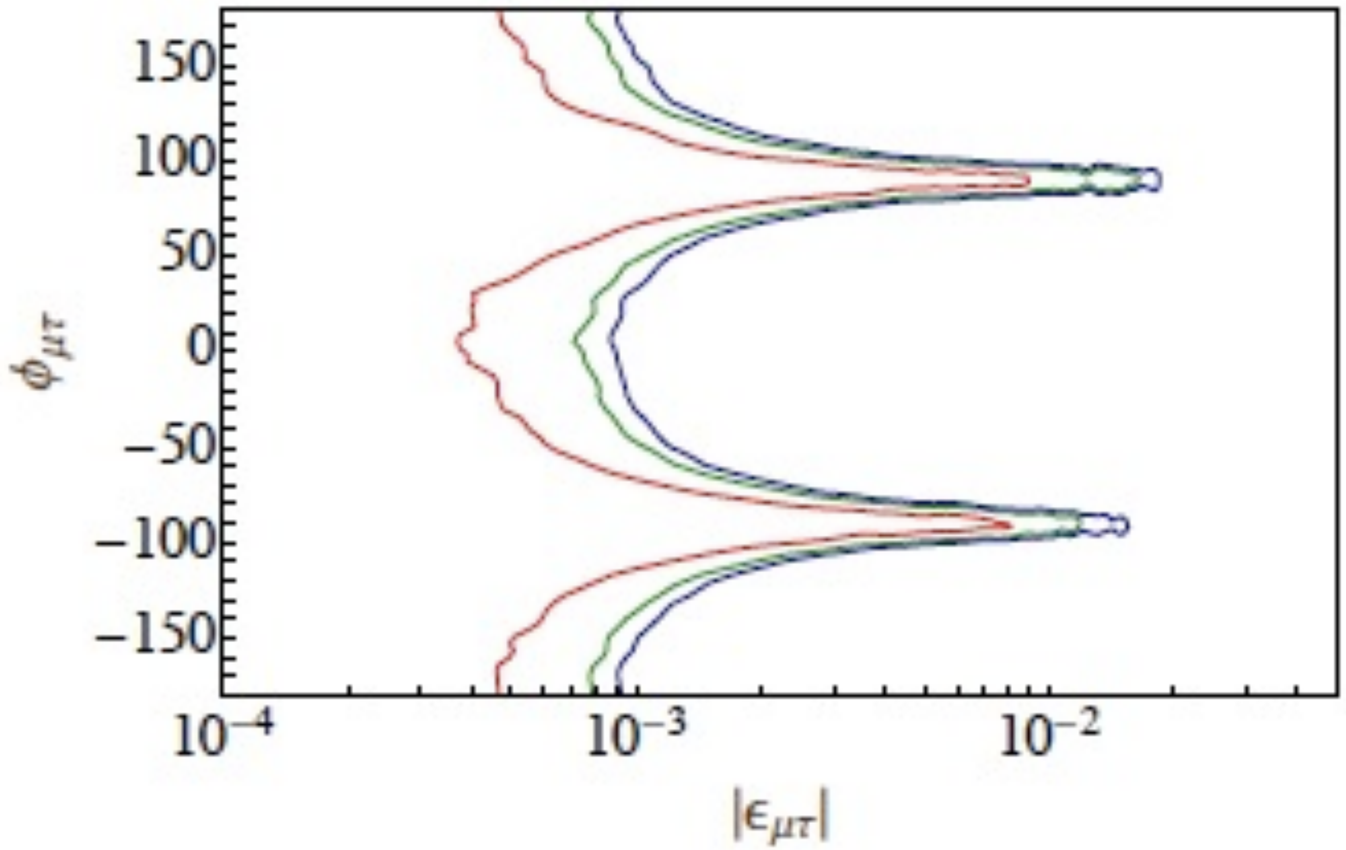
The HENF provides the best sensitivity to NSI:



Kopp, Ota, Winter, 0804.2261

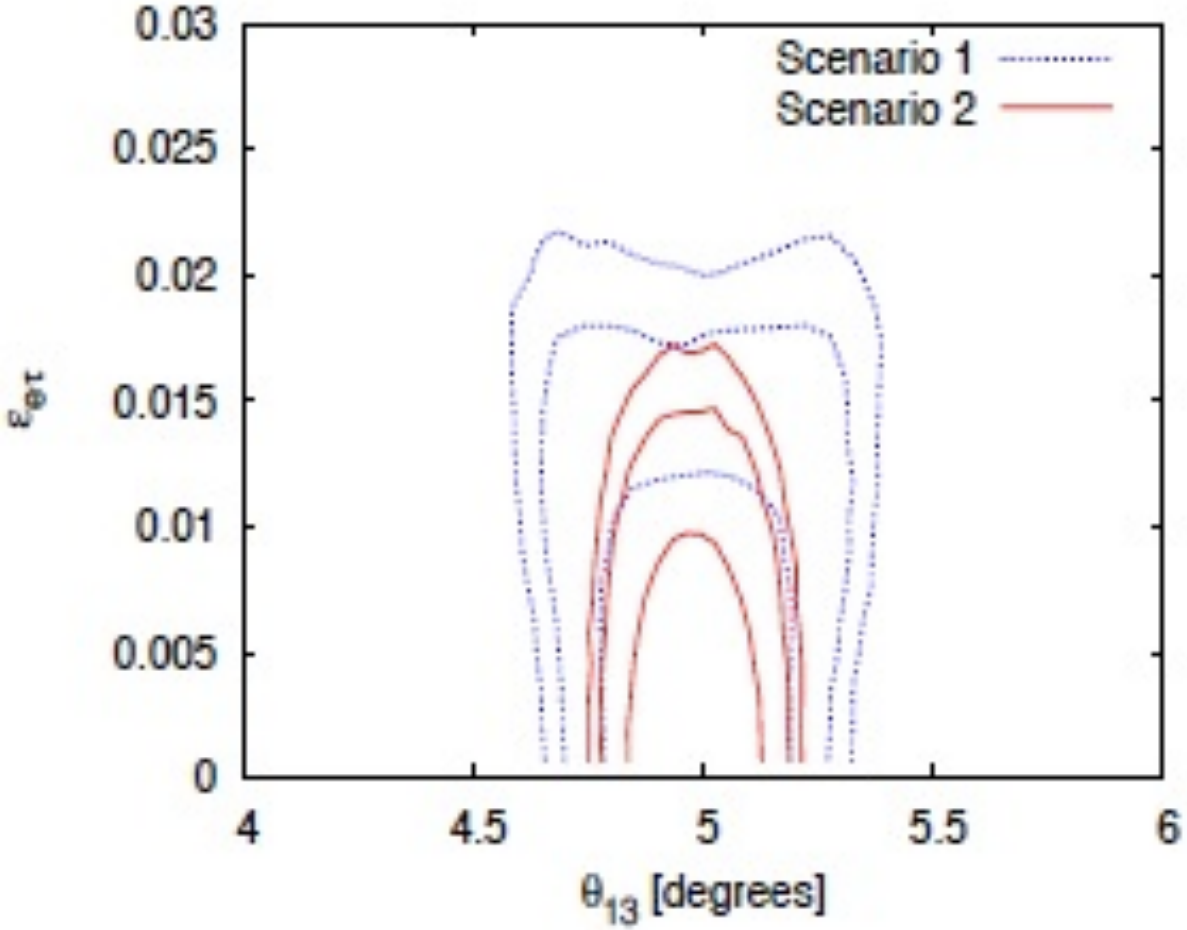
This analysis assumes two MIND detectors and therefore the reach for E=5 GeV is very limited.

New phases appear in the new interactions and correlations with other parameters need to be taken into account.



Coloma, Donini, Lopez-Pavon and Minakata, 1105.5936

The LENF has also good sensitivity. The inclusion of the platinum channel helps in resolving degeneracies and to improve the sensitivity.



Li, Pascoli et al., in preparation

(d) $\theta_{13} = 5°$, sensitivity to $\varepsilon_{e\tau}$.

Conclusions

- In the past few years, the neutrino oscillation parameters have been measured with good precision. The recent discovery of non-zero θ_{13} has important implications for LBL experiments.
- Next generation superbeams, betabeams and/or neutrino factory will address the mass hierarchy, CPV searches and precision measurements of the oscillation parameters. The NF is the ultimate facility.
- The study of the physics reach of a facility requires a detailed understanding of beam, detector performance, systematic errors and backgrounds. Comparisons between setups should be done with great care.