LBL projects and neutrino CP violation in Europe

NOW 2012

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Outline

1. Phenomenology of LBL experiments

2. LBL options in Europe: comparisons for mass hierarchy and CPV

3. Systematic errors

4. Precision measurements

5. Conclusions and outlook

Phenomenology questions for the future

- What is the nature of neutrinos? Dirac vs Majorana?
- **What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of of delta.
- **What are the precise values of mixing angles? Do they suggest a underlying pattern?**
- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

The discovery of theta13 is crucial for this programme.

Long baseline neutrino oscillations

Long baseline neutrino oscillation experiments will aim at studying the subdominant channels $\nu_{\mu,e} \to \nu_{e,\mu}$ $\bar{\nu}_{\mu,e} \to \bar{\nu}_{e,\mu}$

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

Matter effects

CP violation

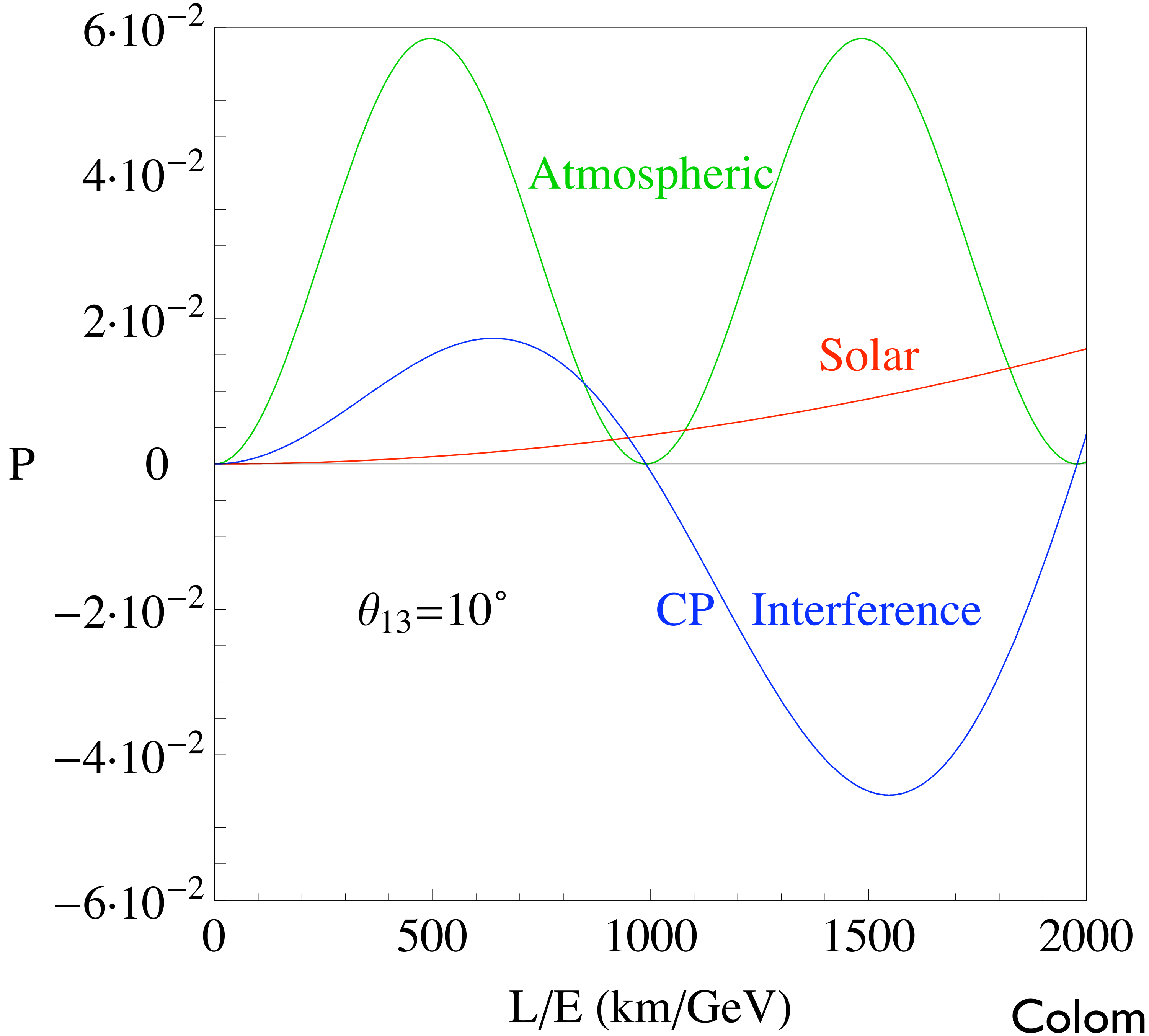
in order to establish

1. **The mass hierarchy**
2. **Leptonic CPV**
3. **Precise values for the mixing parameters**
4. **Non-standard effects.**

CP-violation

A measure of CPV effects is given by

$$A_{CP} = \frac{P(\nu_l \to \nu_{l'}) - P(\bar{\nu}_l \to \bar{\nu}_{l'})}{P(\nu_l \to \nu_{l'}) + P(\bar{\nu}_l \to \bar{\nu}_{l'})} \propto J_{CP} \propto \sin\theta_{13} \sin\delta$$



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

Coloma and Fernandez-Martinez, 2011

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).

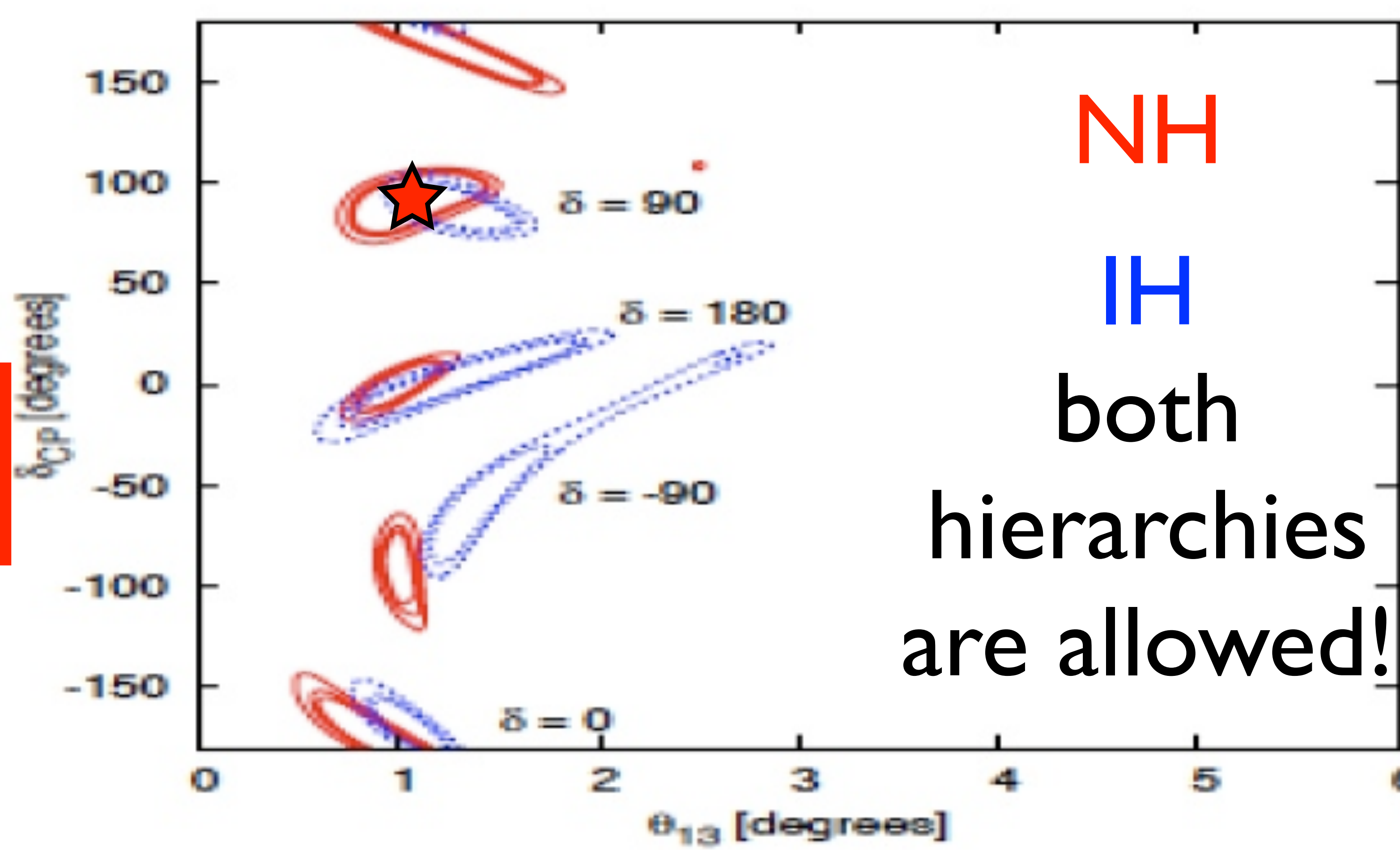
$$\boxed{\theta_{13}, \delta, \mathrm{sgn}(\Delta m^2_{31}), \theta_{23}}$$

$$\downarrow$$

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

$$\uparrow$$

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



- (θ_{13}, δ) degeneracy (Koike, Ota, Sato; Burguet-Castell et al.; Minakata et al.)

$$\begin{aligned} \delta' &= \pi - \delta \\ \theta'_{13} &= \theta_{13} + \cos\delta \sin 2\theta_{12} \frac{\Delta m^2_{12} L}{4E} \cot\theta_{23} \cot \frac{\Delta m^2_{13} L}{4E} \end{aligned}$$

Having information at different L/E , e.g. with a wide band beam, can resolve this degeneracy.

- sign(Δm^2_{31}) vs CPV (matter effects). In vacuum

$$\delta' \rightarrow \pi - \delta \qquad \mathrm{sign}'(\Delta m^2_{13}) \rightarrow -\mathrm{sign}(\Delta m^2_{13})$$

This degeneracy is severe as it hinders the ability to establish the mass hierarchy. It can broken by matter effects.

- the octant of θ_{23} (low E data) (Fogli, Lisi)

Phenomenological studies of neutrino properties in LBL experiments

In Europe several possible baselines can be considered. A detailed study of possible large underground facilities was done in LAGUNA.

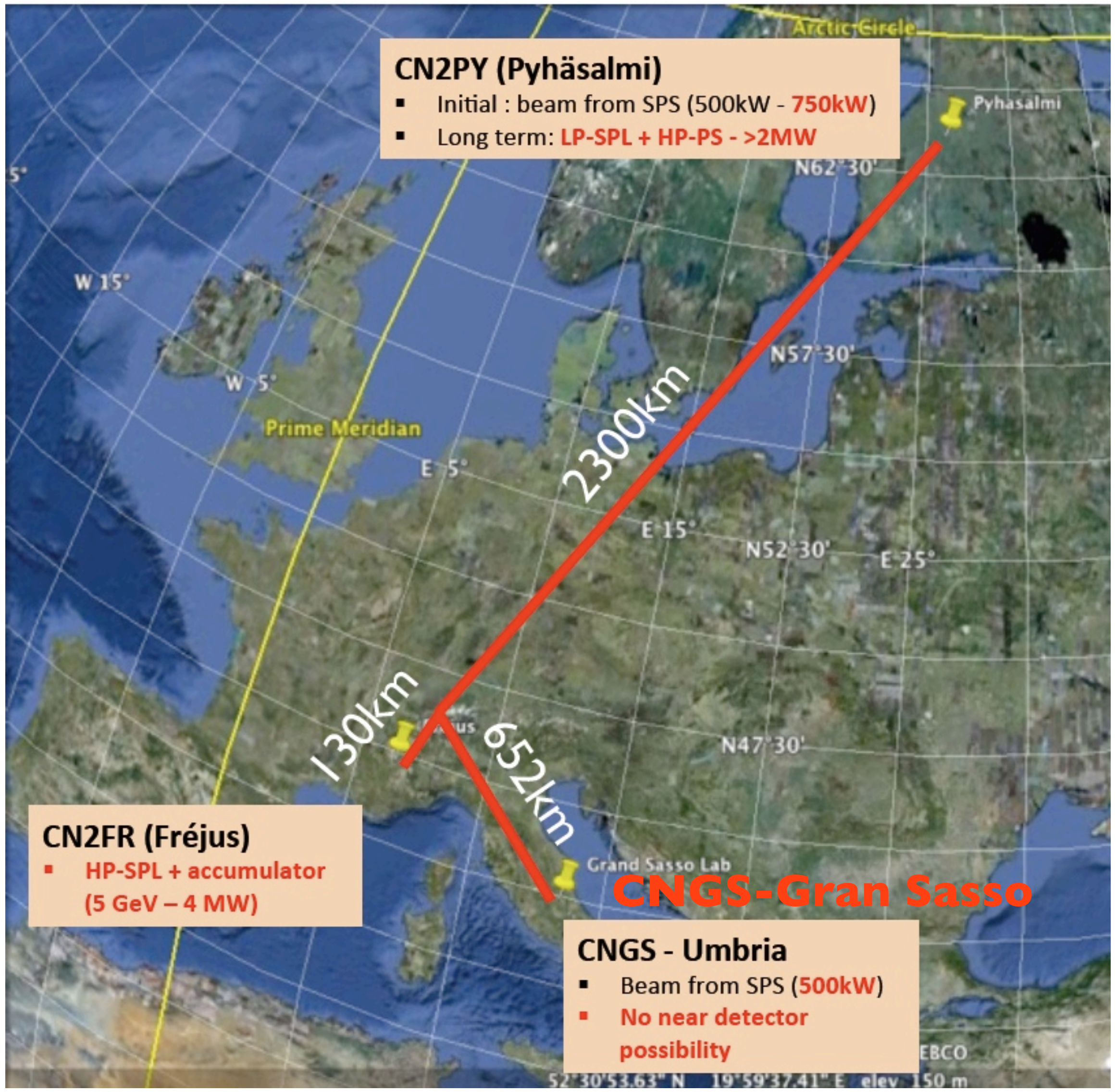
Location	Distance from CERN [km]	1st osc max [GeV]
Fréjus (France)	130	0.26
Canfranc (Spain)	630	1.27
Umbria (Italy)	665	1.34
Sierozsowice (Poland)	950	1.92
Boulby (UK)	1050	2.12
Slanic (Romania)	1570	3.18
Pyhäsalmi (Finland)	2300	4.65

See also work by Huber, Schwetz, Kopp, Winter, Donini, Hernandez, Fernandez Martinez...

Particularly interesting baselines are:

• CERN-Pyhasalmi: 2300 km, high energy neutrinos, (Long term synergy with NF)

• CERN-Frejus: 130 km, ~300 MeV neutrinos, (Long term synergy with Betabeam)



Thanks to Rubbia; old LAGUNA-LBNO

The baseline determines the energy of the beam and viceversa: exploit first oscillation maximum for best sensitivity. The energy and the oscillation channels impact on the type of detector used.

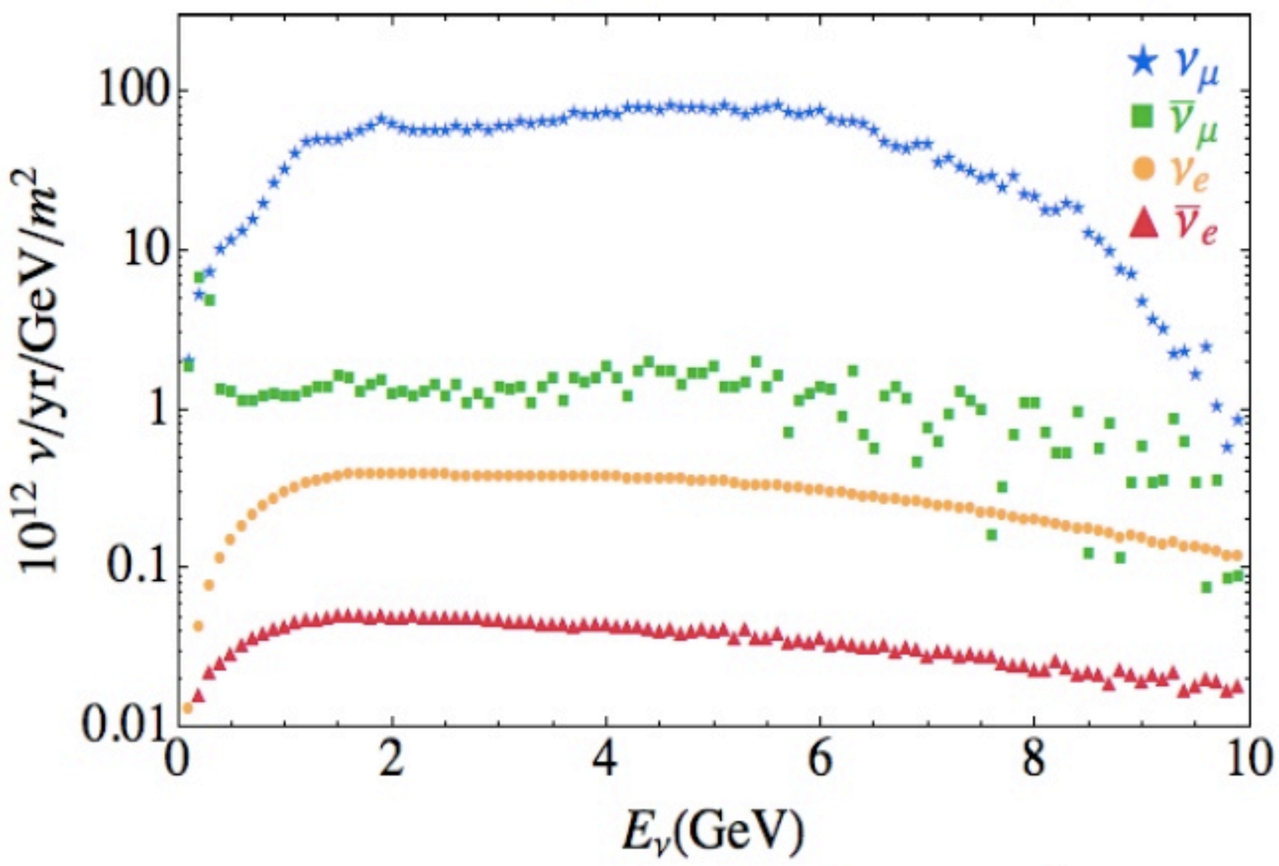
The beam

At present the SPS delivers 4.5 10^19 pot/year. This could be improved to 8 10^19 pot/year.

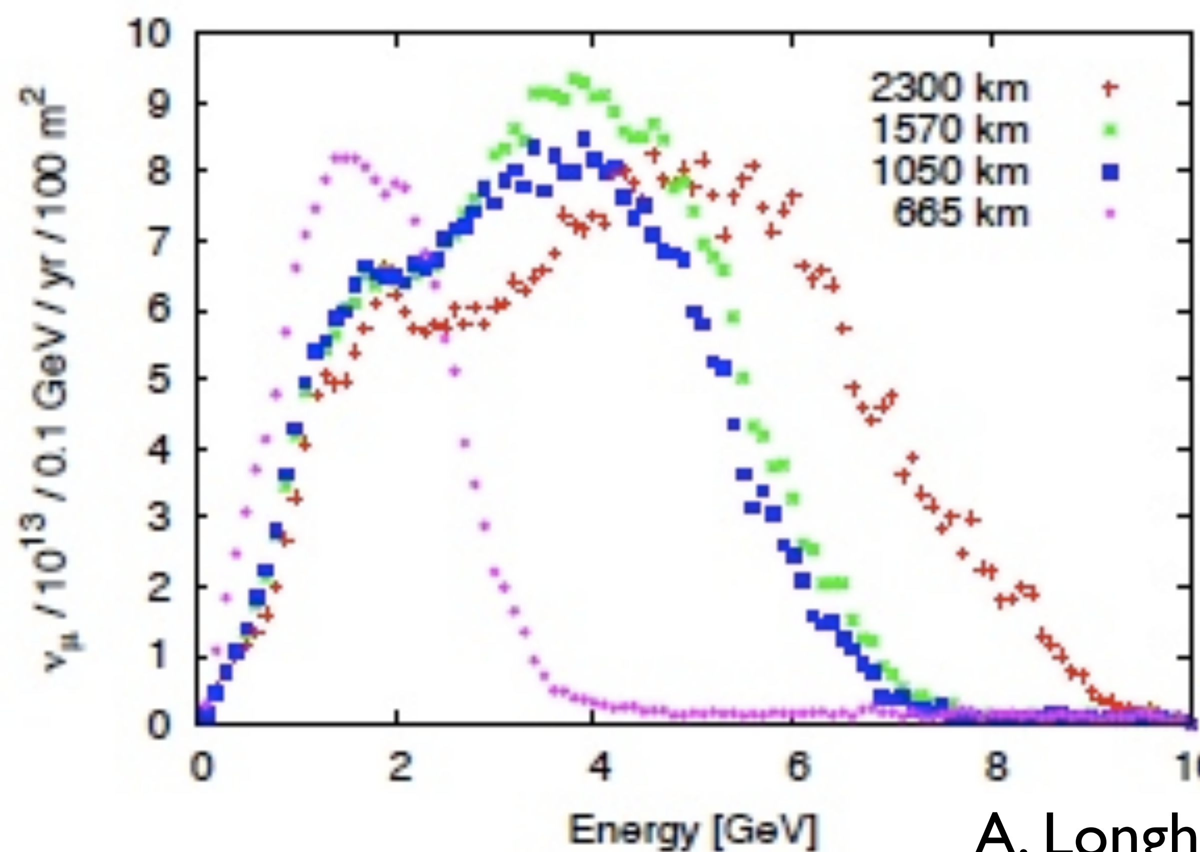
Thanks to I. Efthymiopoulos

Pyhasalmi (0.8-2.3 MW)

A. Longhin, PoS ICHEP2010 (2010) 325



Different baselines



A. Longhin

Beam parameters (except Frejus, 4 MW): 1e21 PoT, 50 GeV, for 10^7 useful secs/yr, 10 years of data taking.

The detector performance

Detector	kton	ϵ	NC Bg.	$\sigma(E)$	E_ν (GeV)
LAr	100	90%	0.5%	$0.15\sqrt{E}(\nu_e)$ $0.20E(\nu_\mu)$	$[0.5, 10]$
LSc	50	$90\% - 50\%$	$30\% - 10\%$	$0.05E$	$[0.5, 7]$
WC LE	440	$\sim 70\%$	$< 0.1\%$	MigMat	$[0.1, 1]$
WC HE		$\sim 40\%$	$5\% - 7\%$	MigMat	$[0.5, 10]$

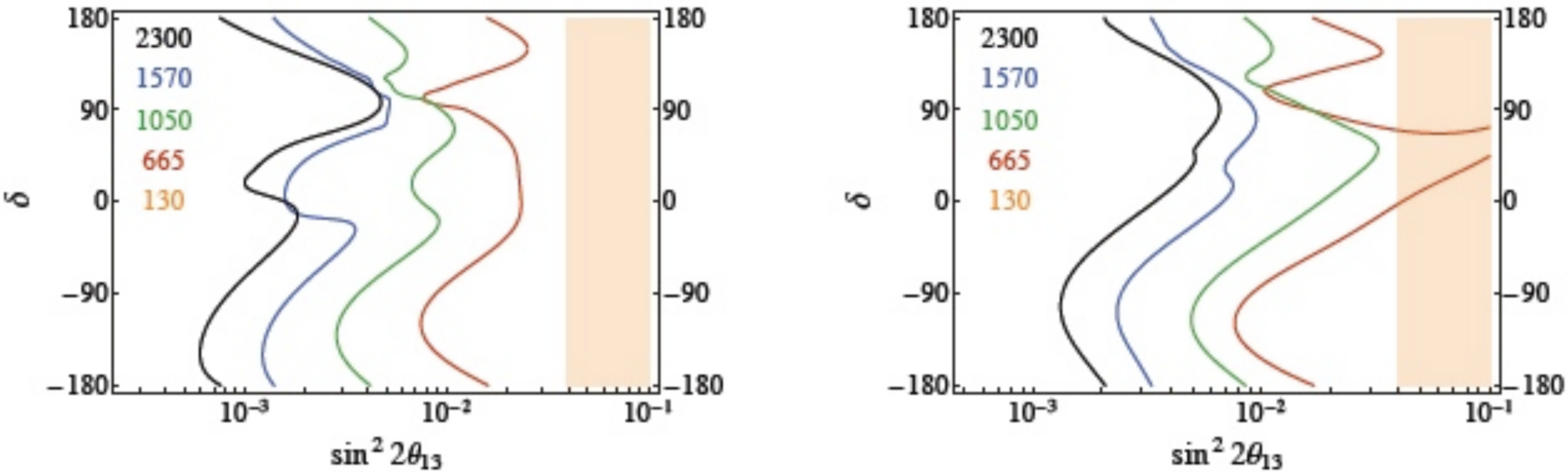
Detailed simulations of the detector performance are currently ongoing in LAGUNA-LBNO.

See talks by T. Patzak and M. Wurm.

Comparison between baselines

The determination of the mass hierarchy

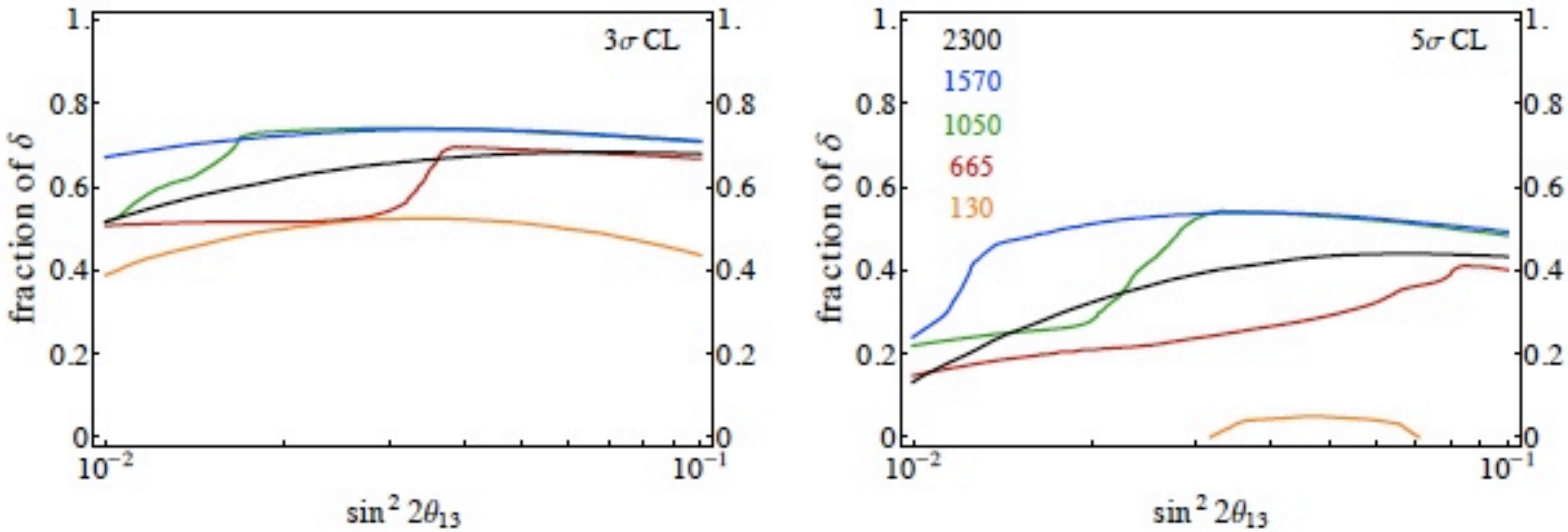
The hierarchy is determined thanks to matter effects, which increase with distance and energy. Longer baselines are preferred.



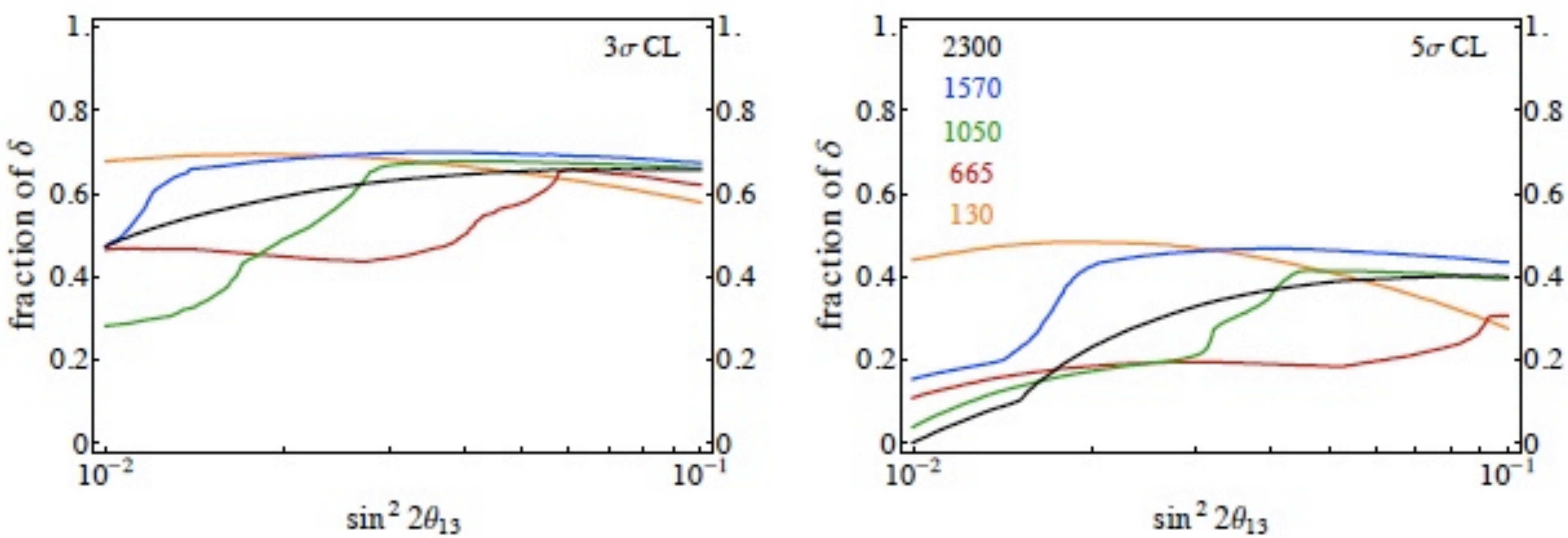
(a) LAr Coloma, Li, SP, 1206.4038; LAGUNA-LBNO (b) WC

A LSc detector at Pyhasalmi could also have sensitivity to the mass hierarchy. See M. Wurm's talk.

The determination of CPV



(a) LAr



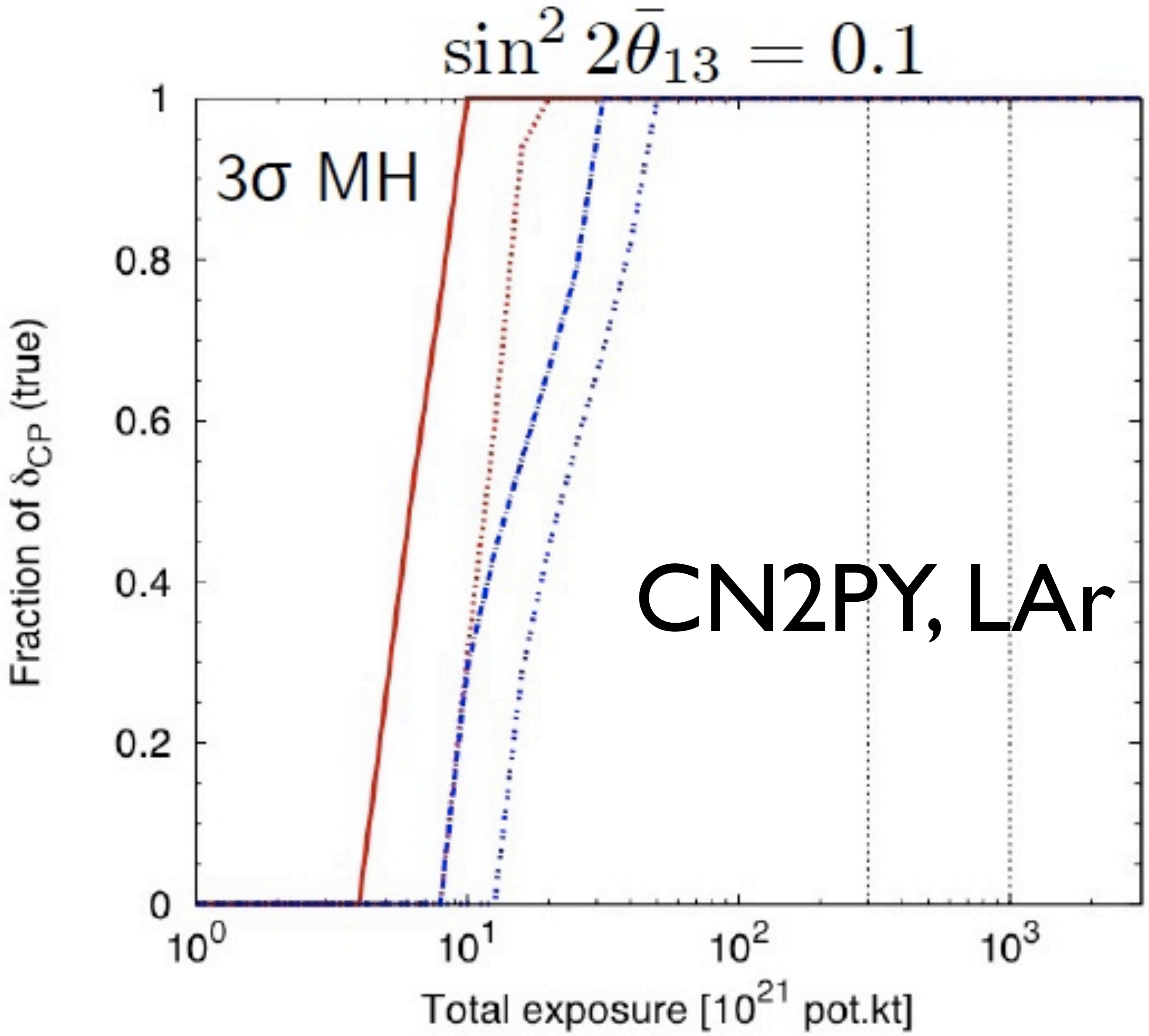
(b) WC

Coloma, Li, SP, 1206.4038; LAGUNA-LBNO

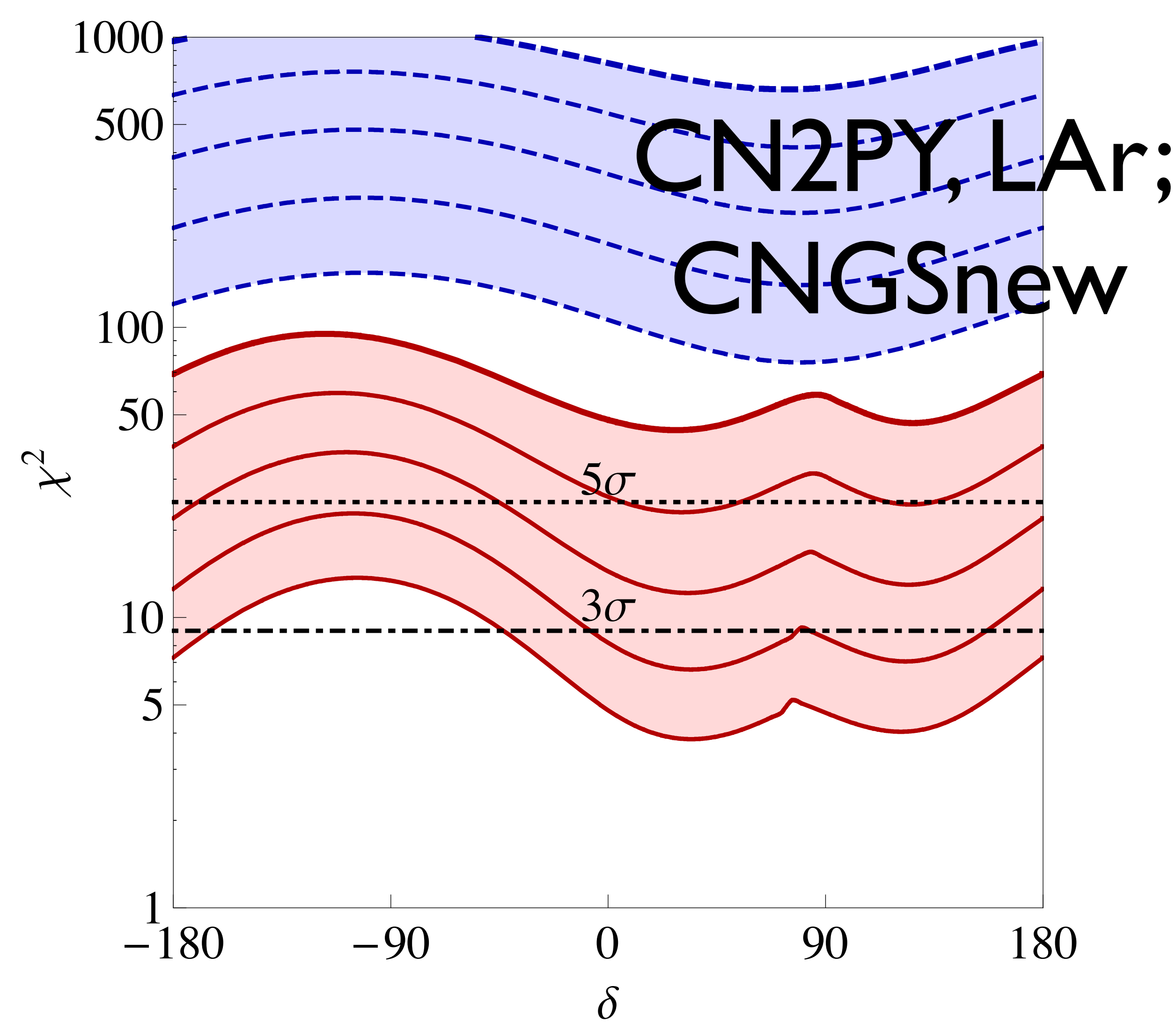
See also the results presented by T. Patzak.

Incremental approach for large theta13

For large θ_{13}, it is possible to consider smaller detectors than the baseline choice (100 kton LAr, 500 Kton WC) in a staged incremental approach. The mass hierarchy can be determined for small exposures (=small detector).

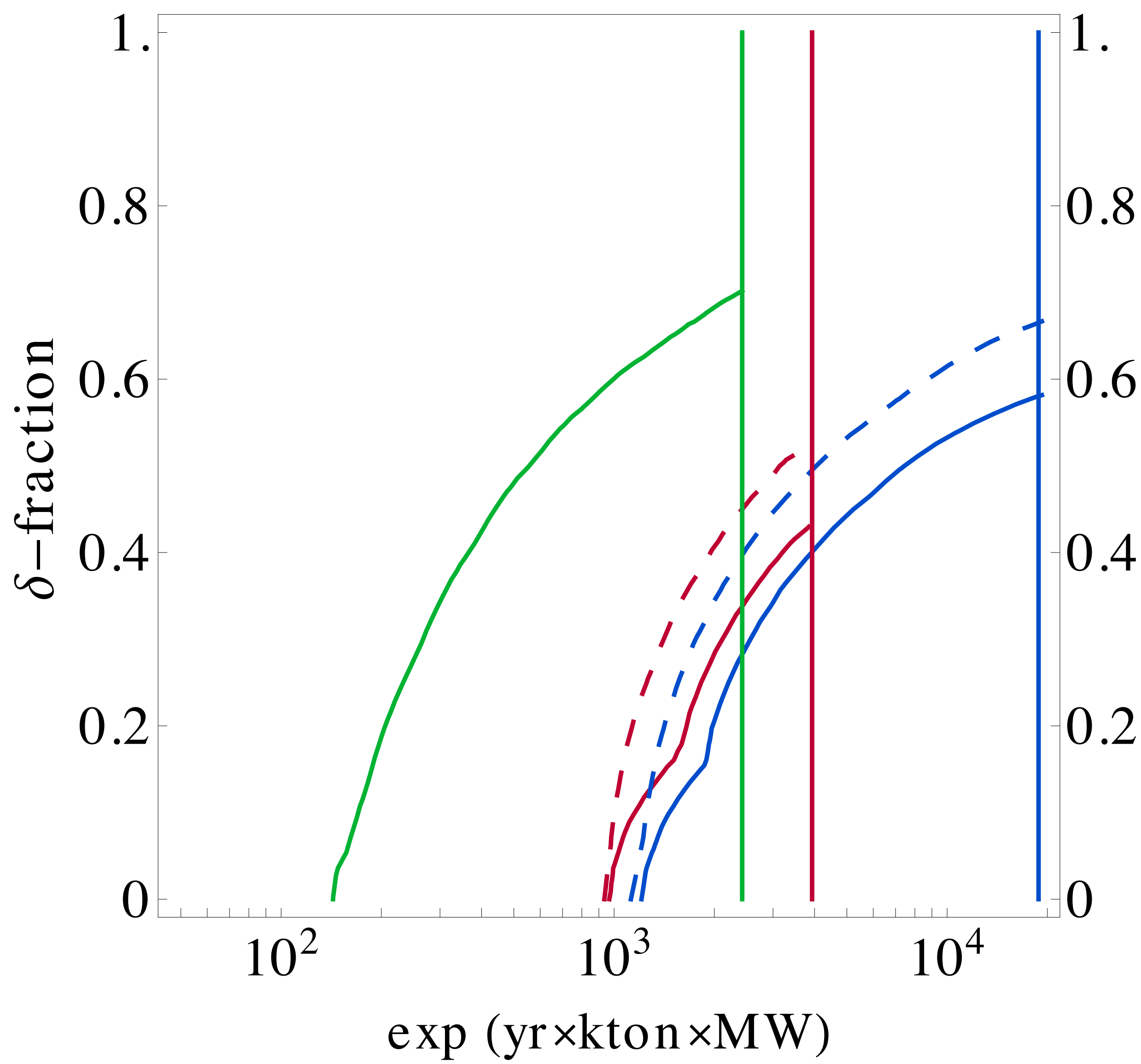


Agarwalla, Li, Rubbia, 1109.6526



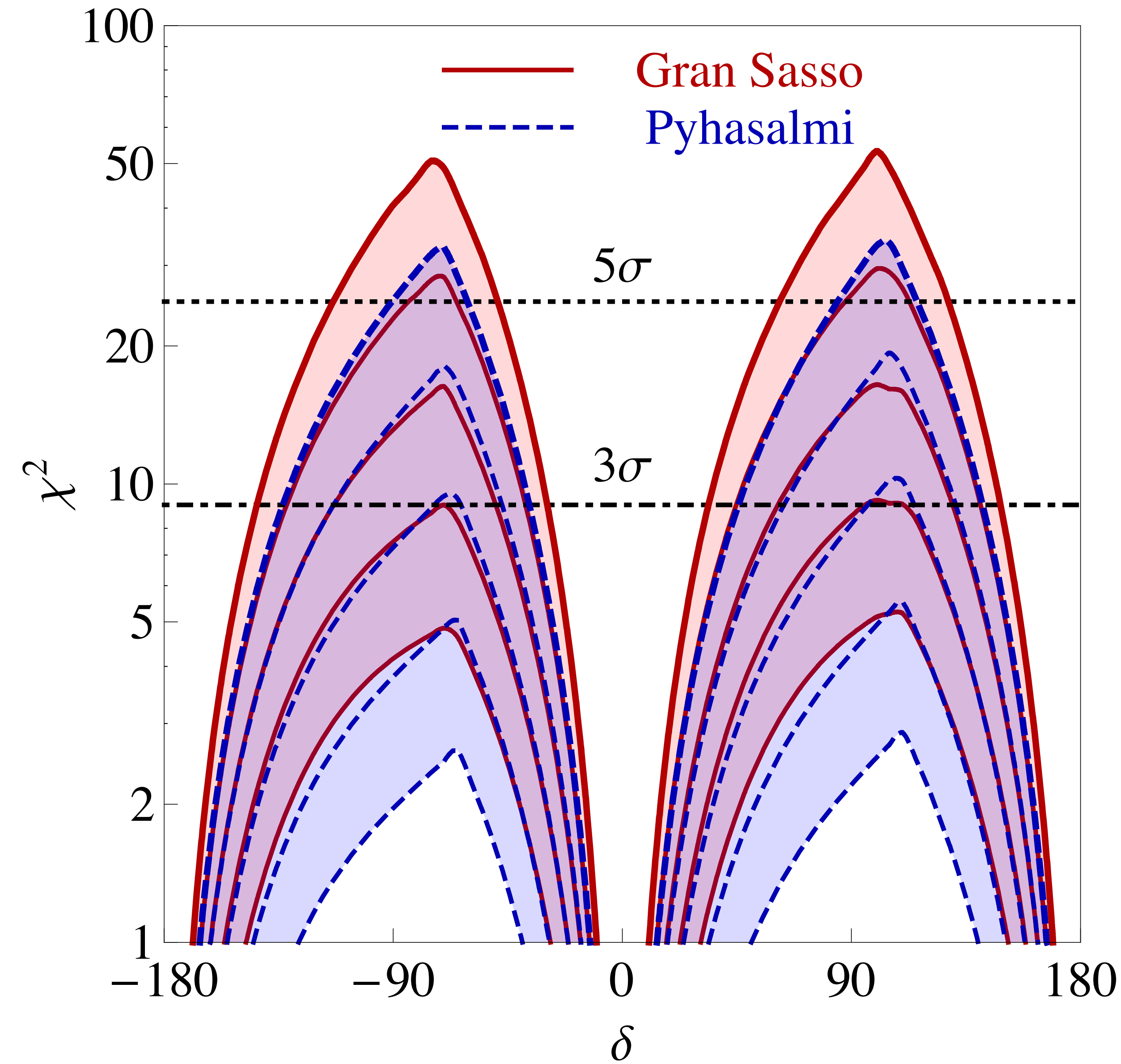
Coloma, Fernandez-Martinez, Labarga, 1206.0475

Discovering CPV will be more difficult and higher exposures are needed.



CN2PY, LAr; CN2Fr, LAr; CN2Fr, WC

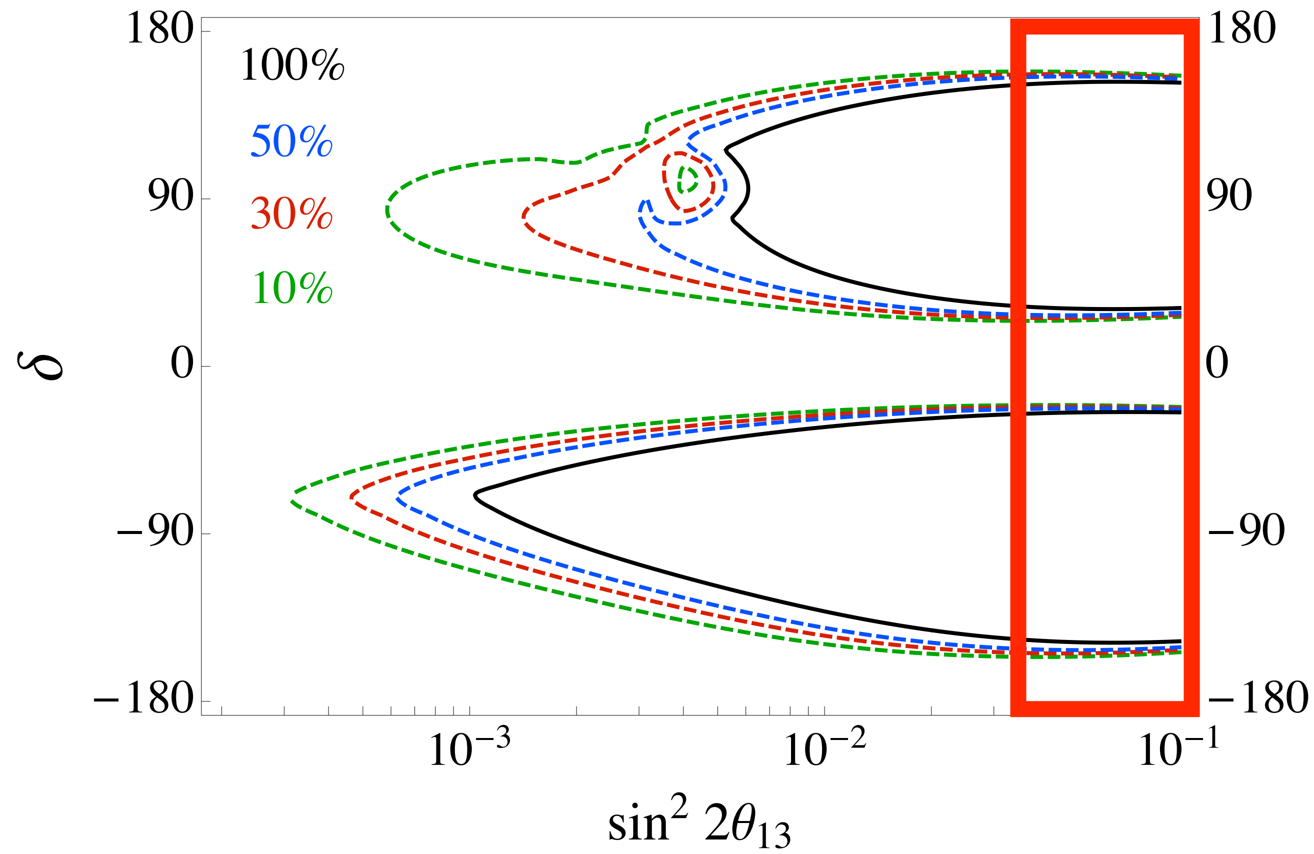
Coloma, Li, SP, 1206.4038; LAGUNA-LBNO



CN2PY, LAr; CN2GSnew, WC

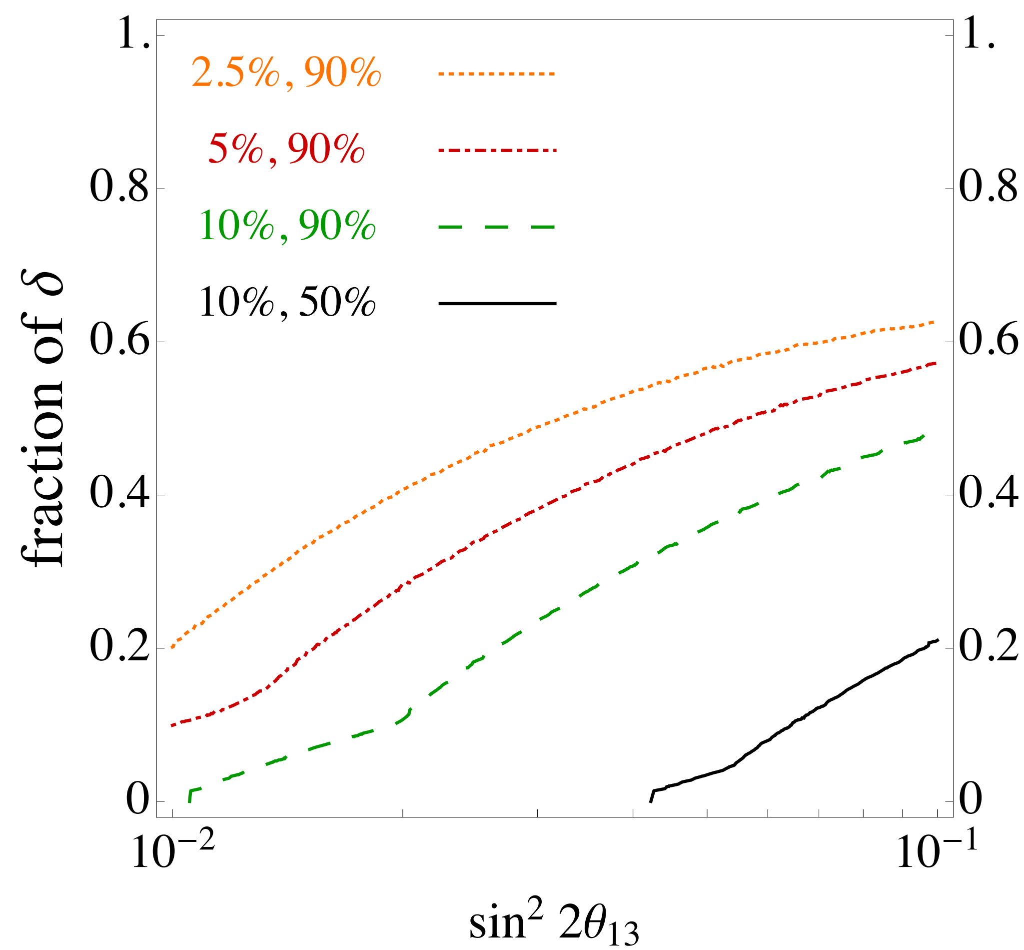
Coloma, Fernandez-Martinez, Labarga

Backgrounds



The intrinsic electron neutrino background is typically <1% level and does not affect the sensitivity significantly.

Coloma, Li, SP



The NC backgrounds are particularly important for CPV searches.

Coloma, Li, SP, 1206.4038; LAGUNA-LBNO

Systematic errors

Systematic errors might become the limiting factor for the physics reach. They arise from beam and detector effects.

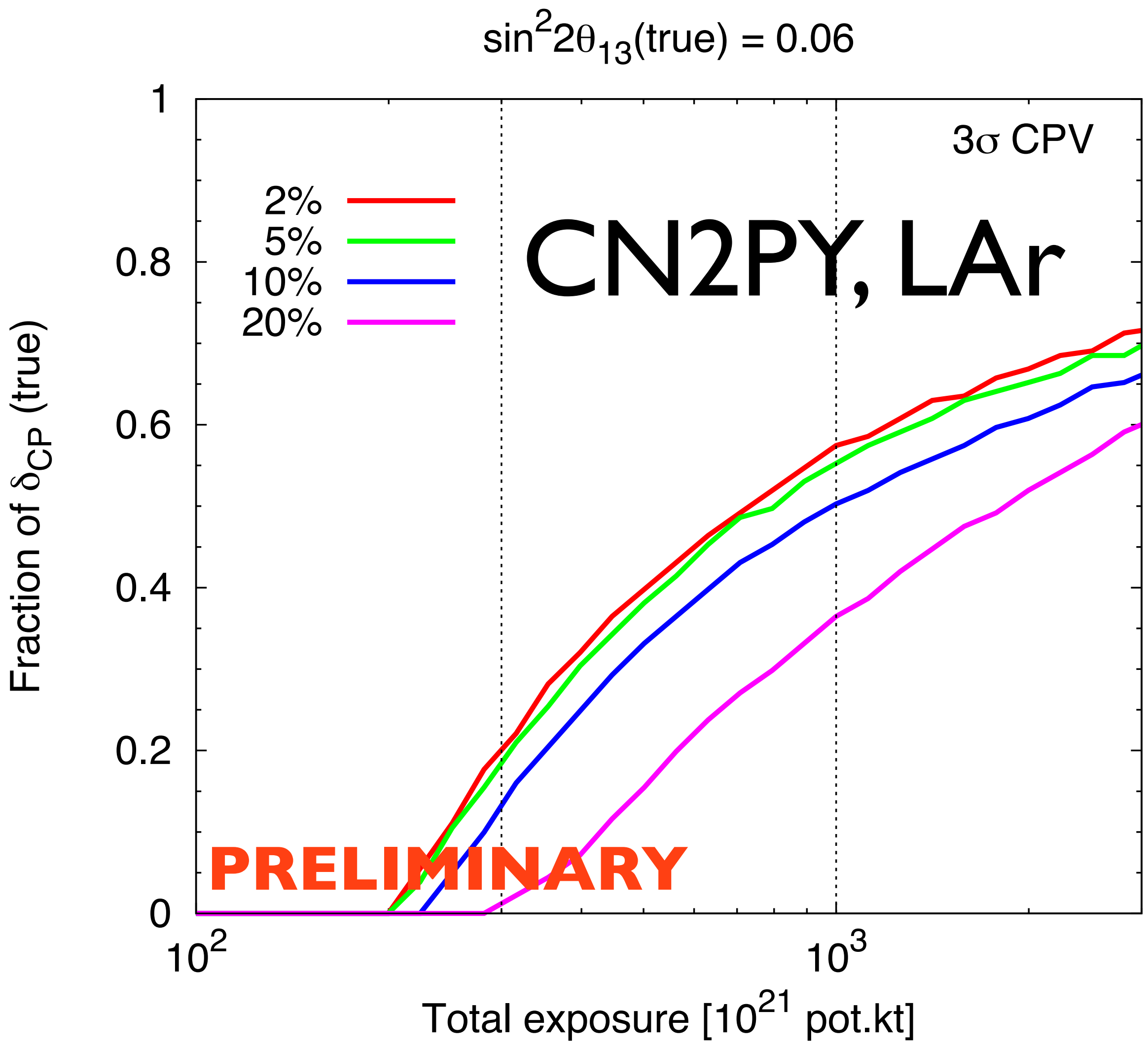
- The knowledge of the cross sections will be one of the dominant factors.

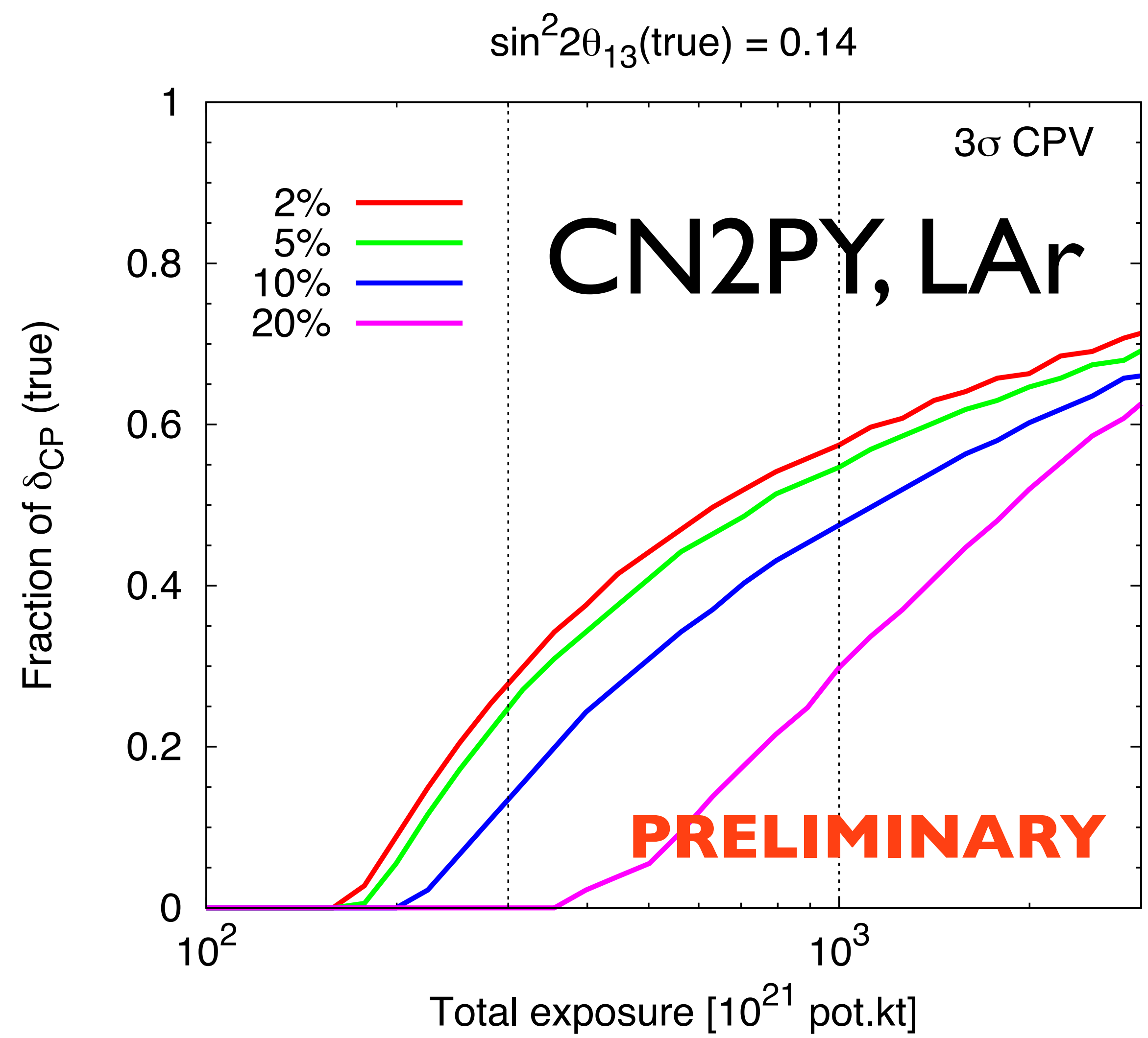
- The knowledge of the Earth matter profile introduces also an error. Typically, it is known with an uncertainty ~7% [Geller, Hara, hep-ph/0111342] but for the CERN-Pyhasalmi baseline within ~2% [Kozlovskaya, Peltoniemi, Sarkamo, hep-ph/0305042].

  - For the hierarchy measurement it does not have large impact.

  - It is important for CPV searches, as matter effects and CPV are partially degenerate.

We have assumed a 5% systematic error on the signal and background and varied the uncertainty on the Earth matter profile.

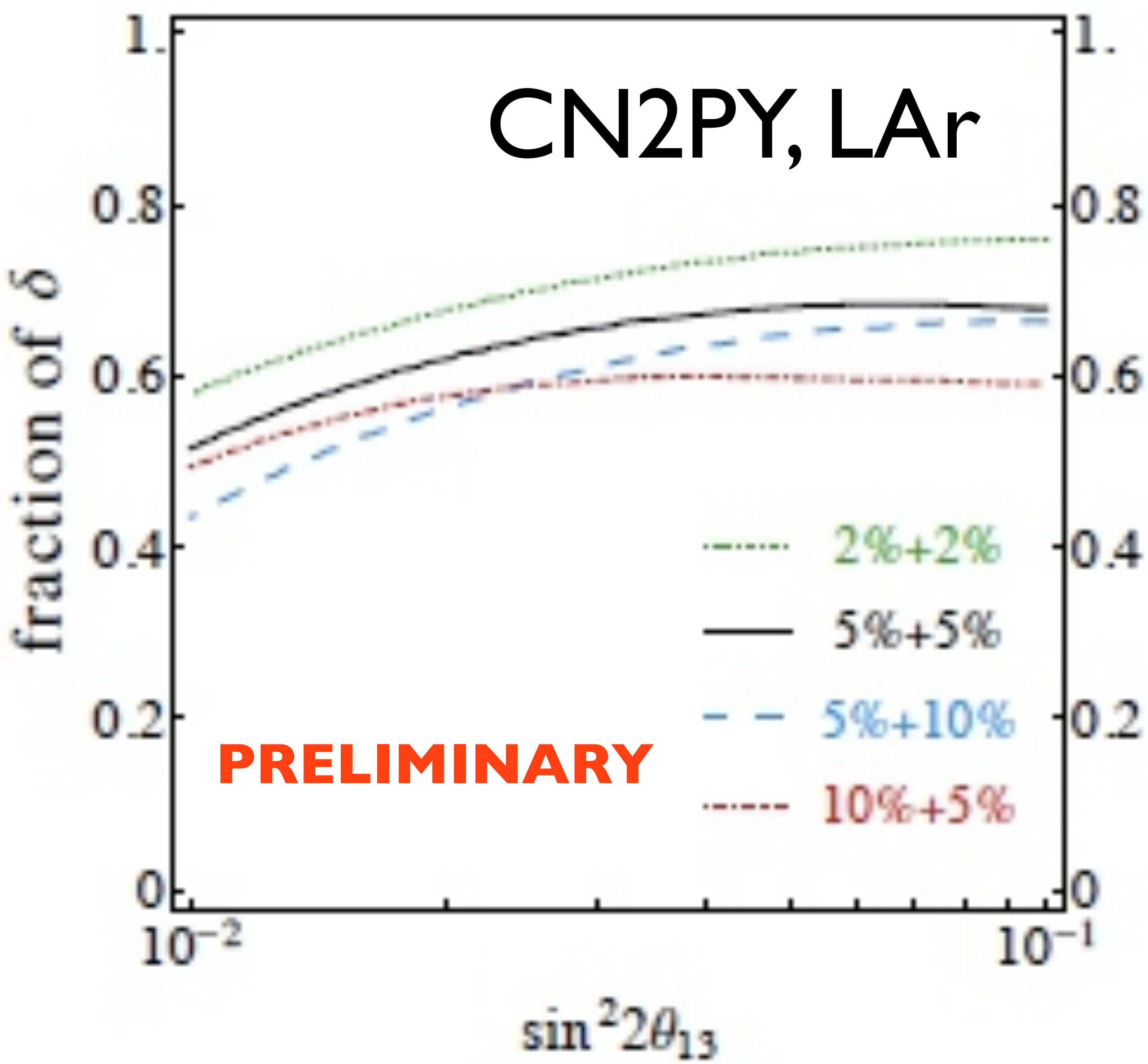




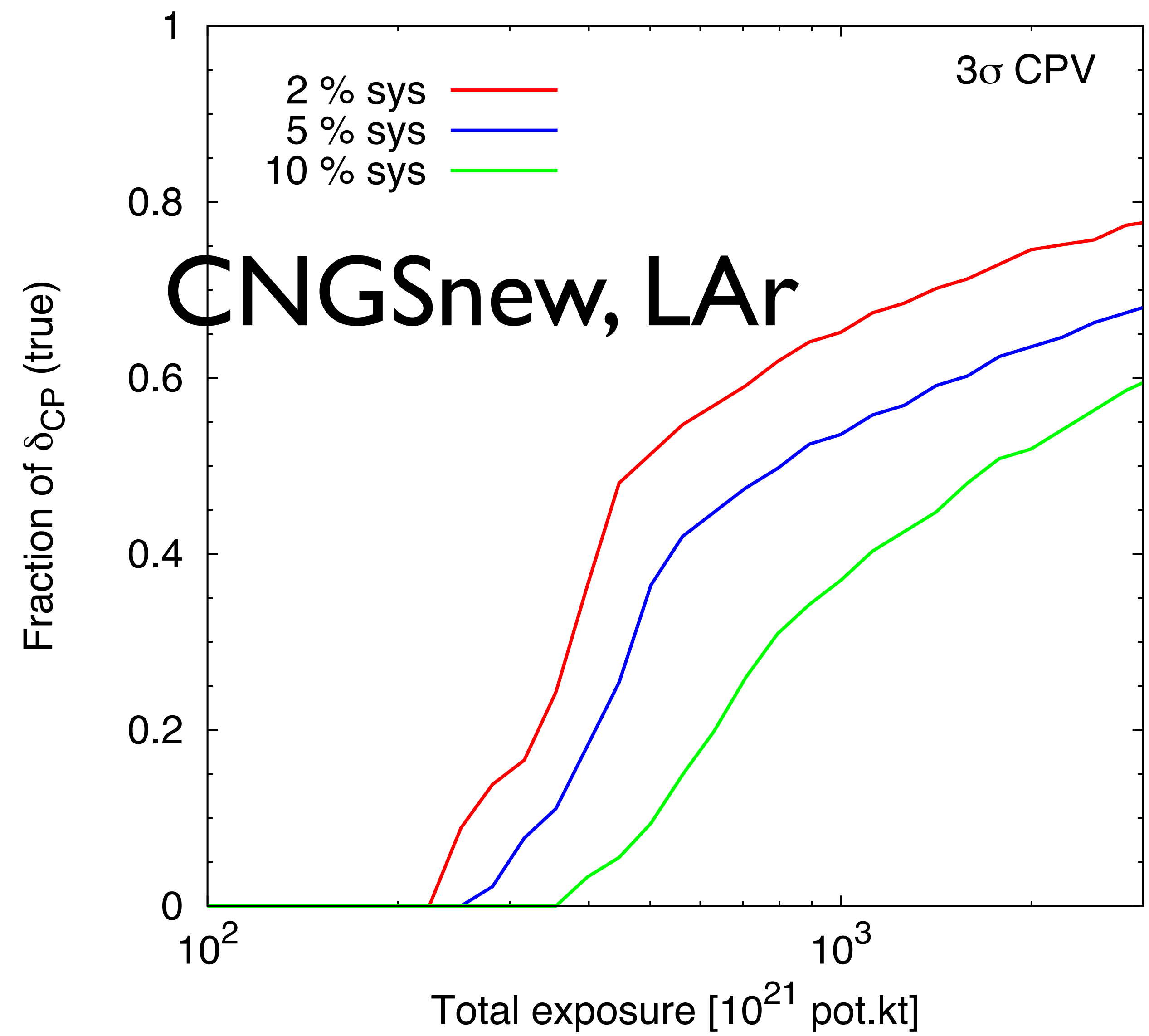
Coloma, Li, SP, in preparation; LAGUNA-LBNO Oxford meeting

At present most of the studies consider an overall systematic error which includes: fiducial mass, flux, cross section, efficiency, ... errors.

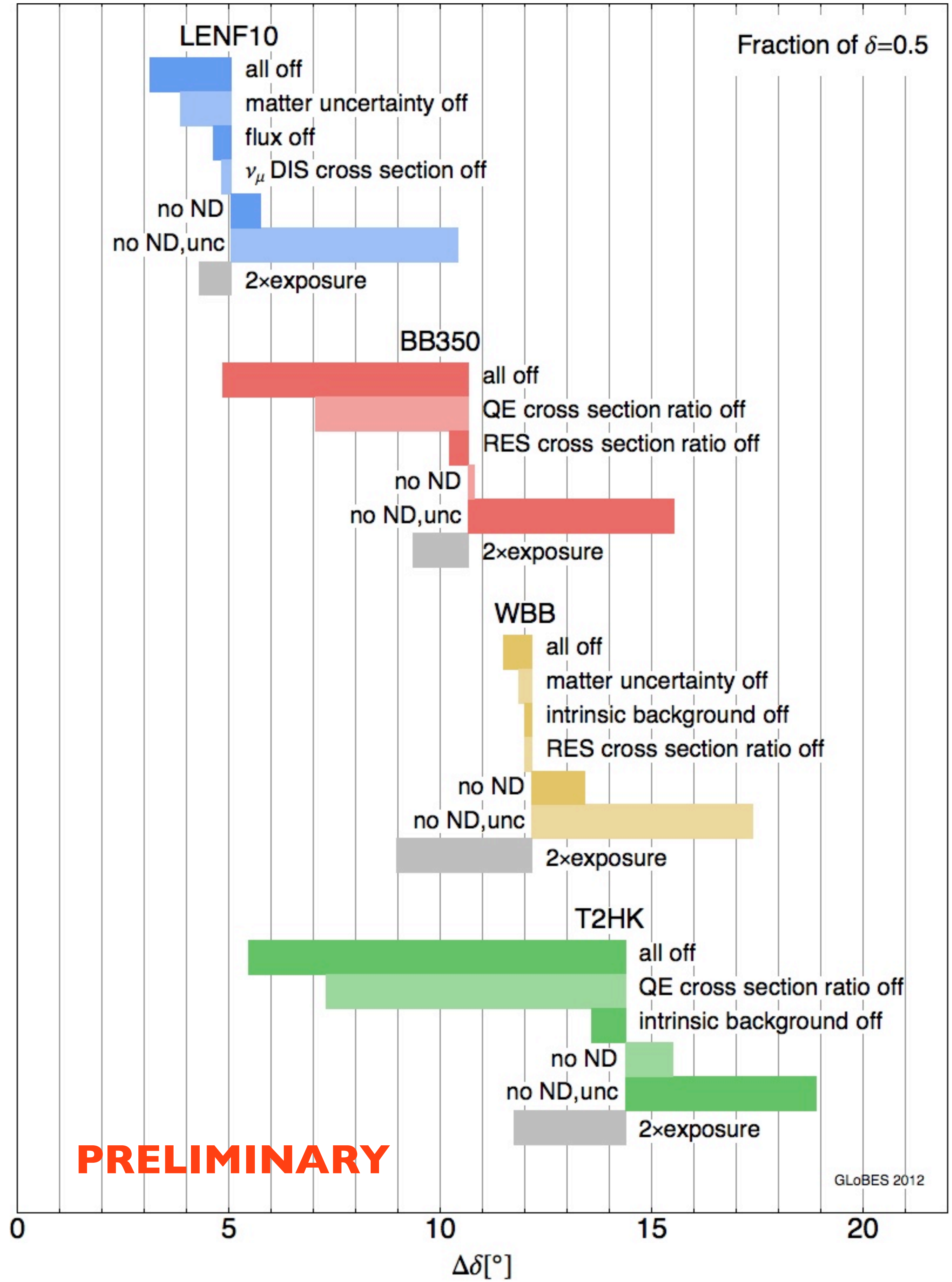
They have a large impact on the physics reach.



Coloma, Li, SP, 1206.4038; LAGUNA-LBNO



Thanks to T. Li

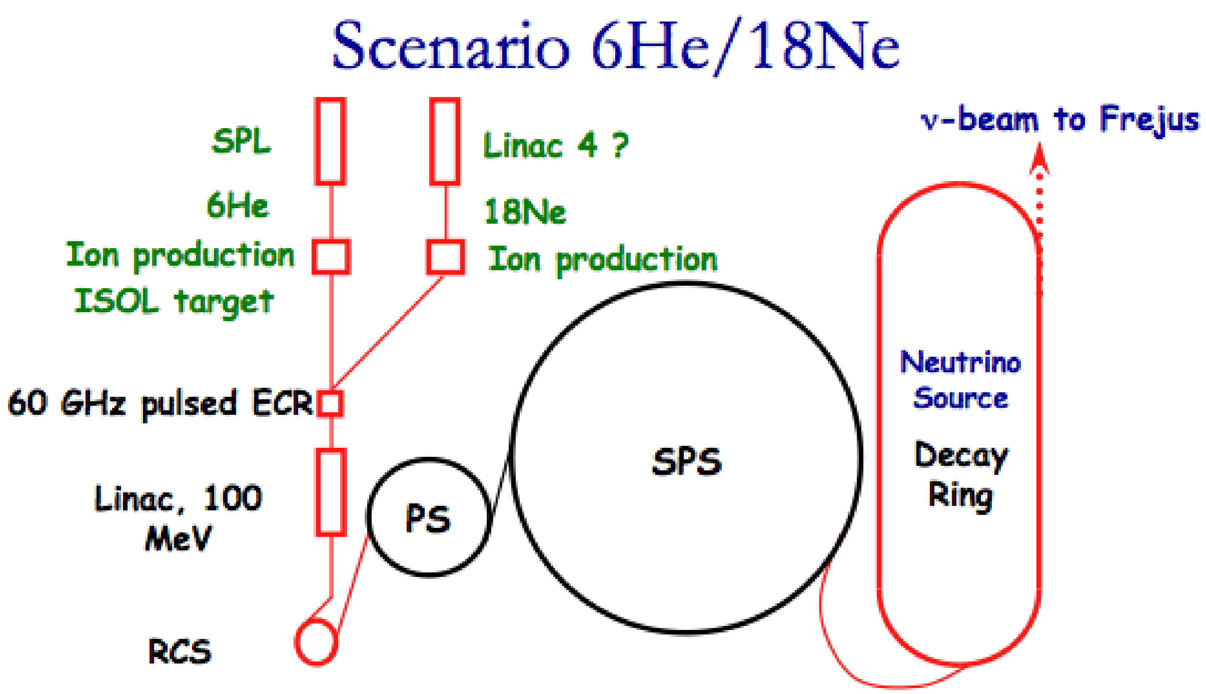


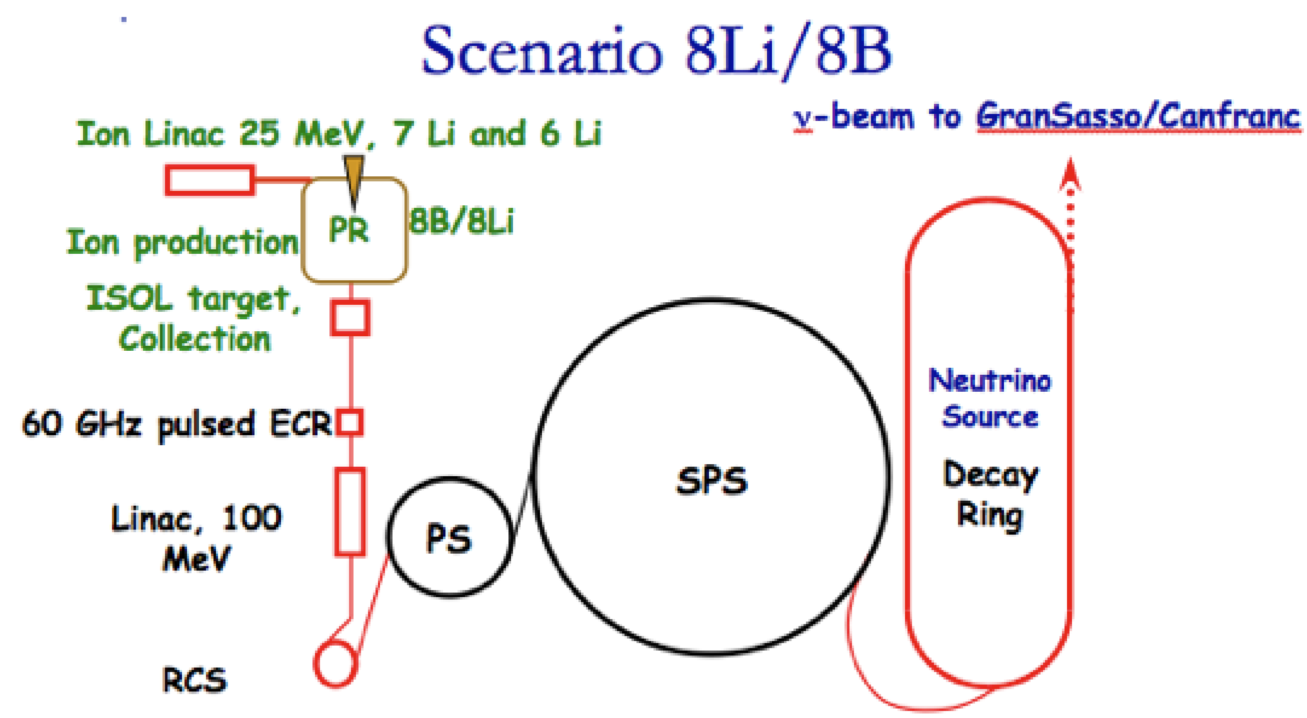
Good energy resolution, wide band beam, additional input will help in reducing the impact of systematic errors. The near detector(s) will play an important role.

Thanks to Coloma, Huber, Kopp, Winter, in preparation

Future projects:
Betabeams and Neutrino Factory
Betabeams

Electron neutrinos from beta decays of highly accelerated ions. Pure beam but difficult to achieve high neutrino fluxes. Studied in detail within EUROnu.



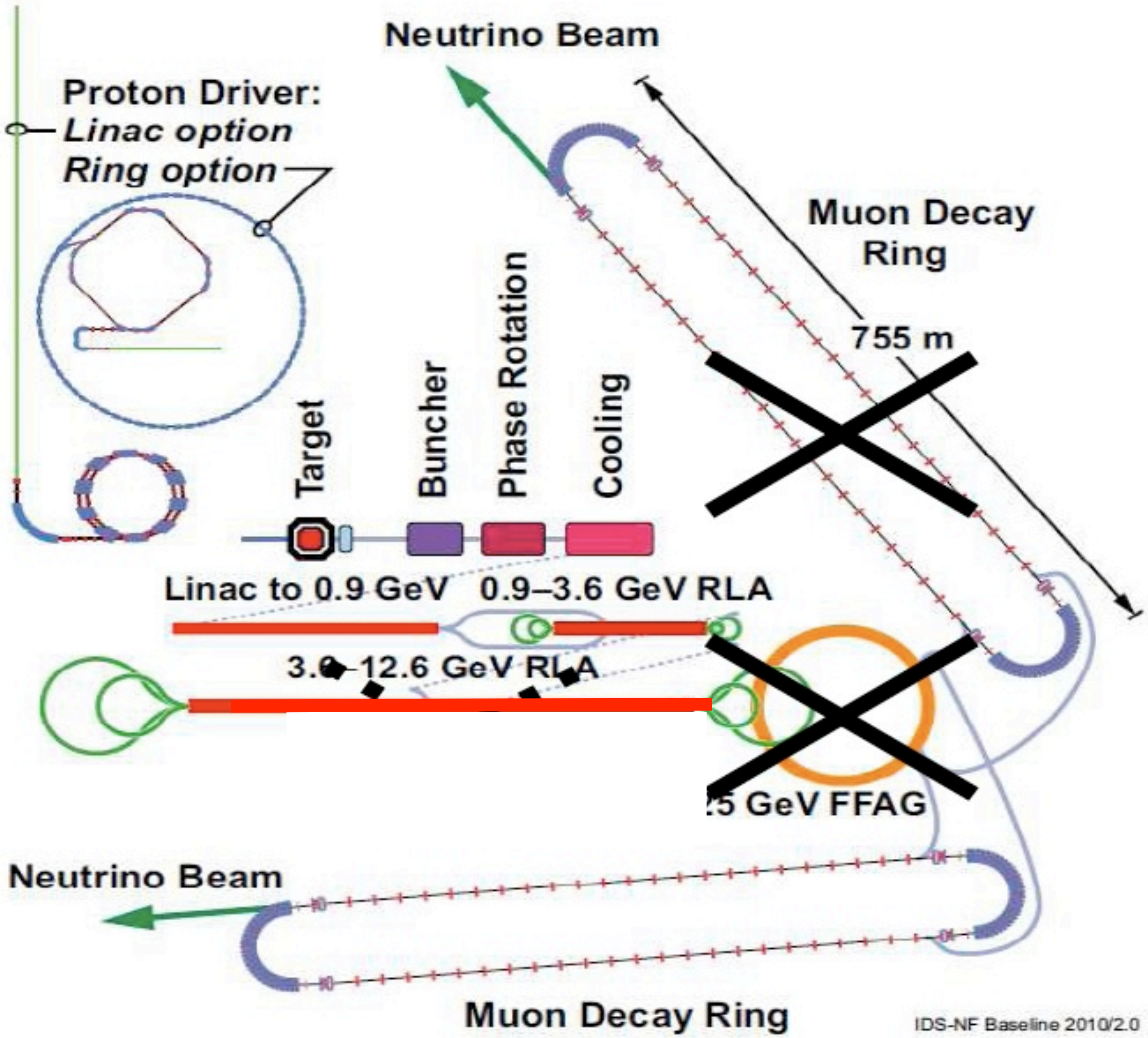


Various options have been considered for high gamma beta beams. They require an upgraded SPS or the LHC.

Neutrino factory

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

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

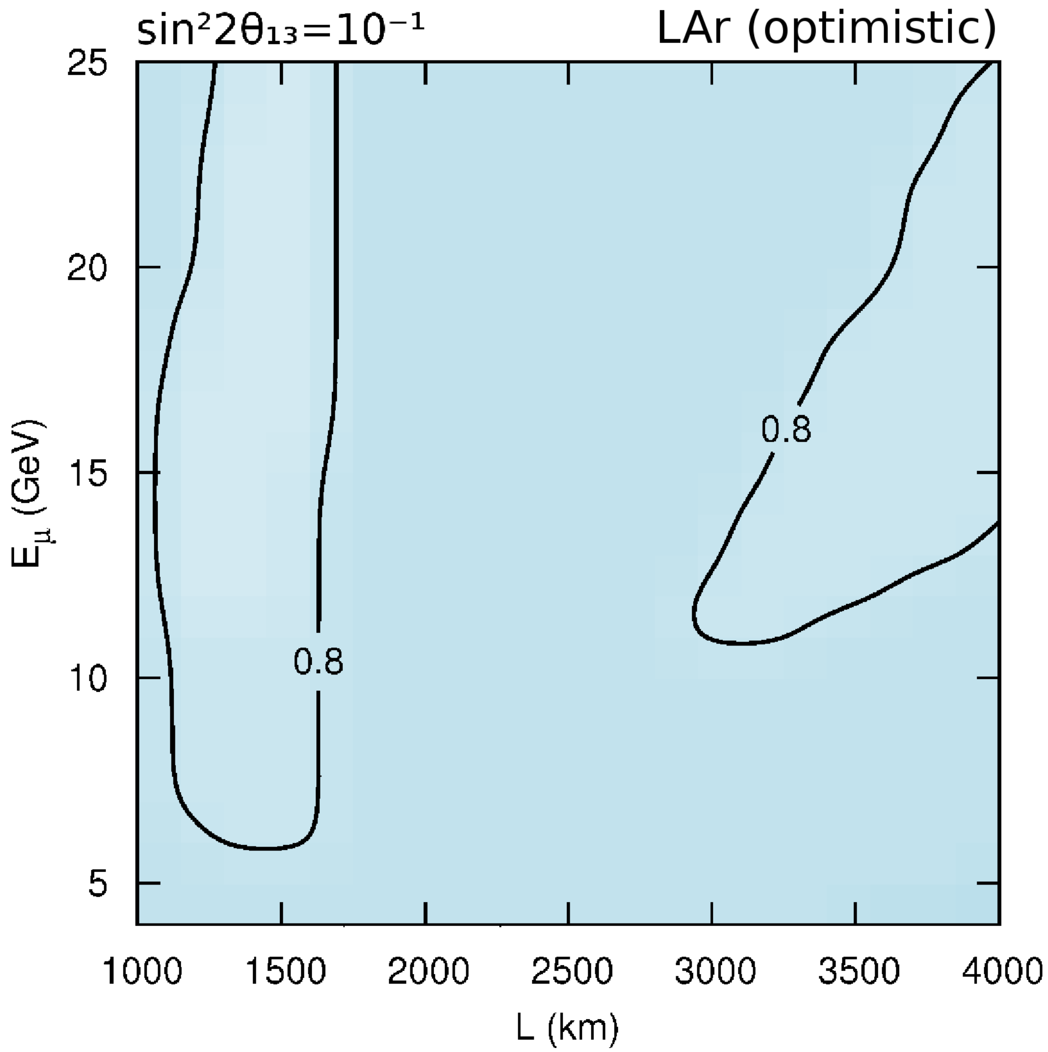


New baseline for IDS-NF (Apr 2012):

LENF:

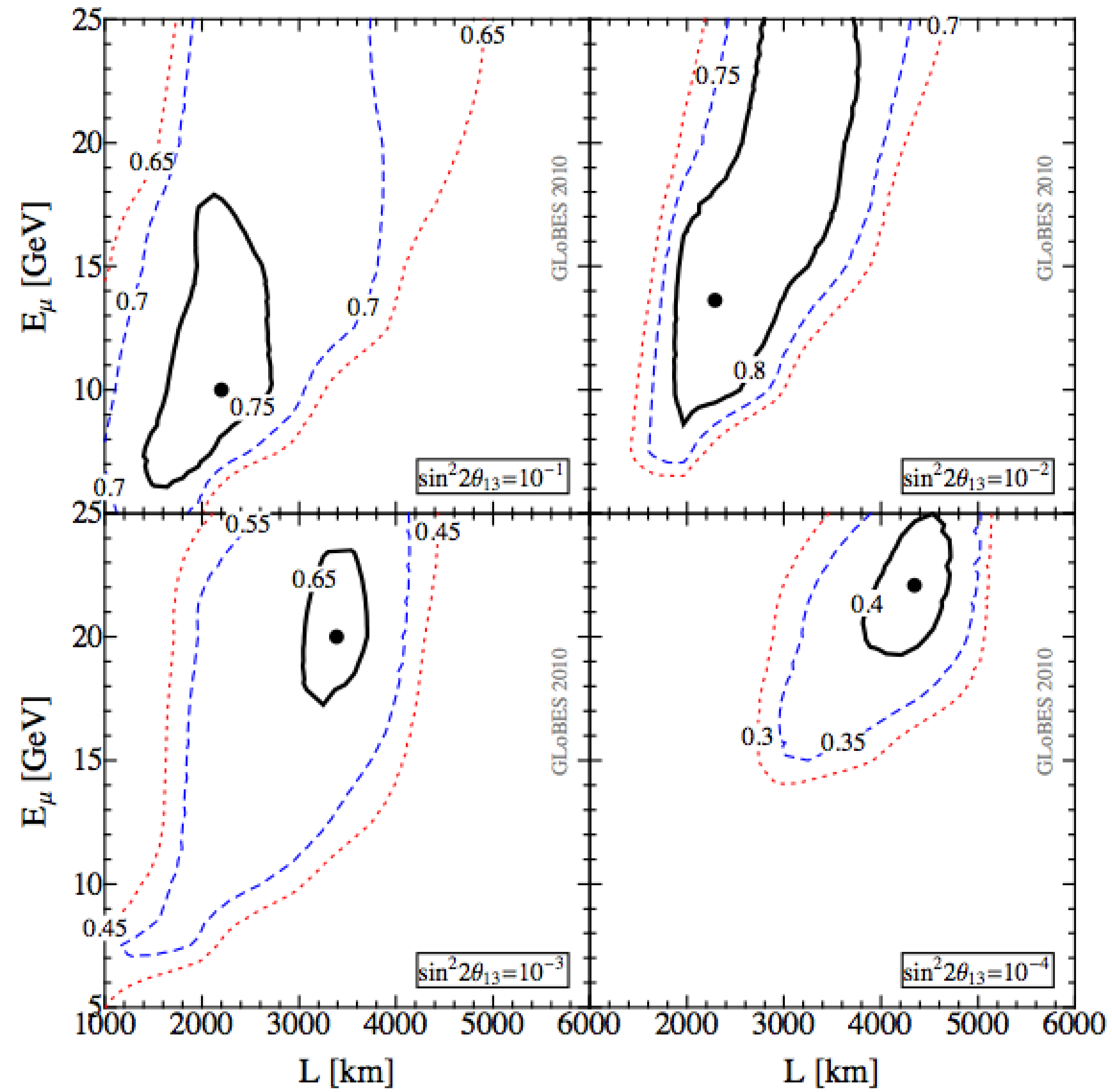
E=10 GeV and L=2000 km with MIND

Sensitivity to CP-violation.



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

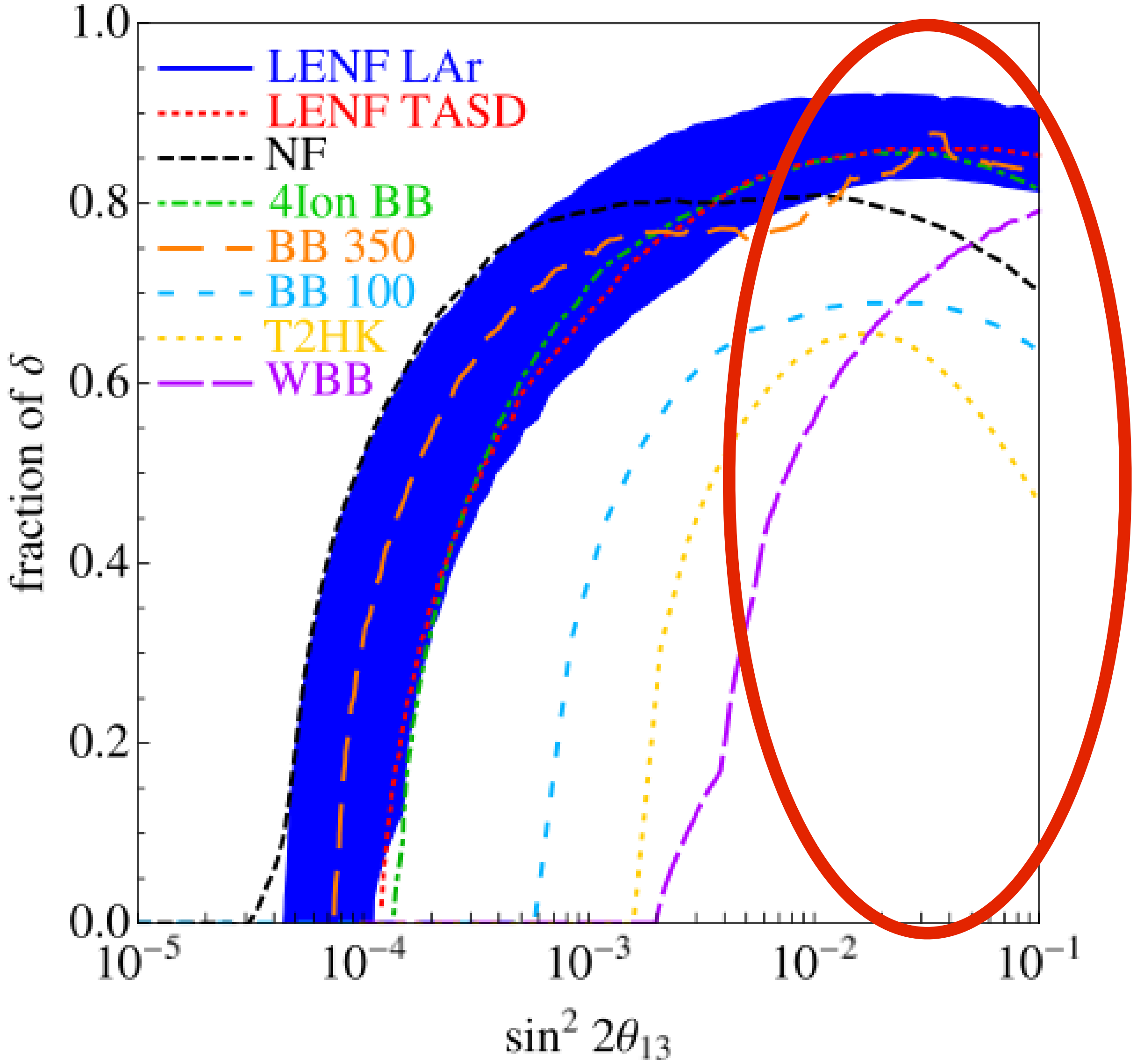
Excellent sensitivity for large theta13 rather independent from L and E. Ballett, SP, 1201.6299



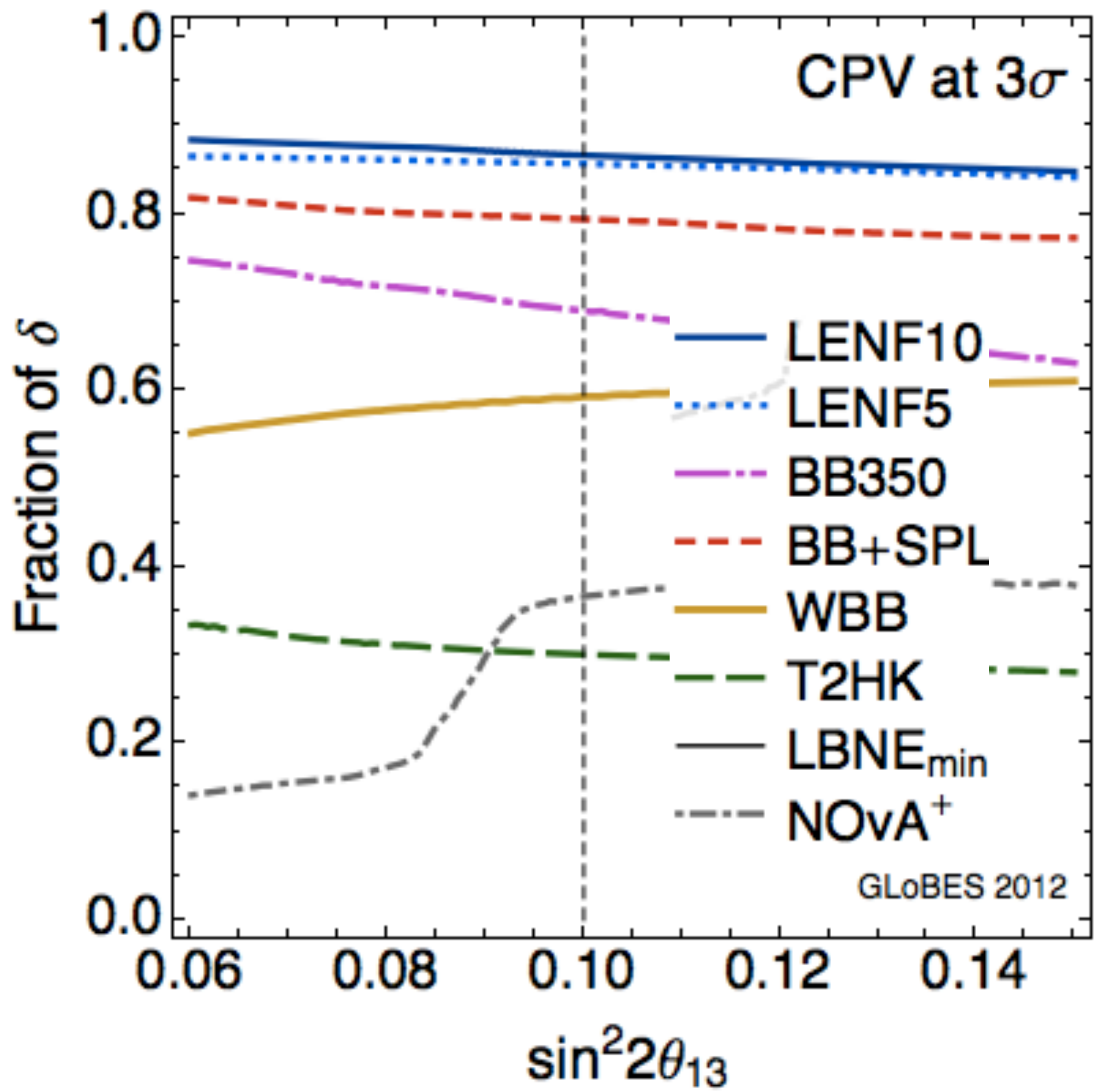
For a MIND detector, the optimal configuration is reached for L~2000 km and an energy which is not too high.

Agarwalla, Huber, Tang, Winter, 1012.1872

Comparison of different facilities



Fernandez-Martinez et al., 0911.3776



Thanks to Coloma, Huber, Kopp, Winter, in preparation

The ultimate sensitivity could be provided by the neutrino factory. Different timescales, technological challenges and costs should be taken into account.

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

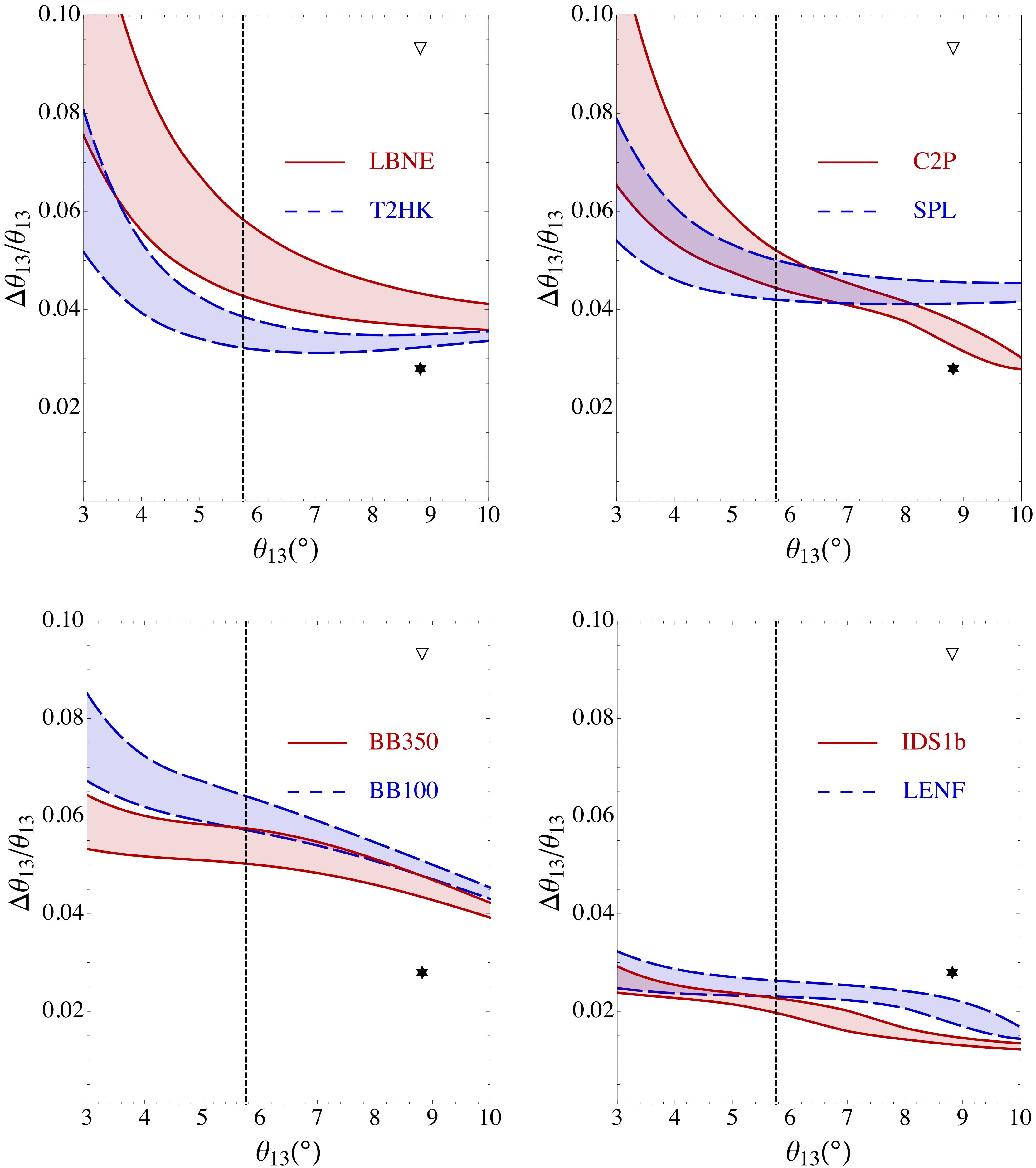
$$N_{\rm events} \sim P_{\mu e} \sim \sin^2 2\theta_{13} \sim (\theta_{13})^2 \Rightarrow \Delta N \sim \theta_{13}\Delta\theta_{13}$$

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

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

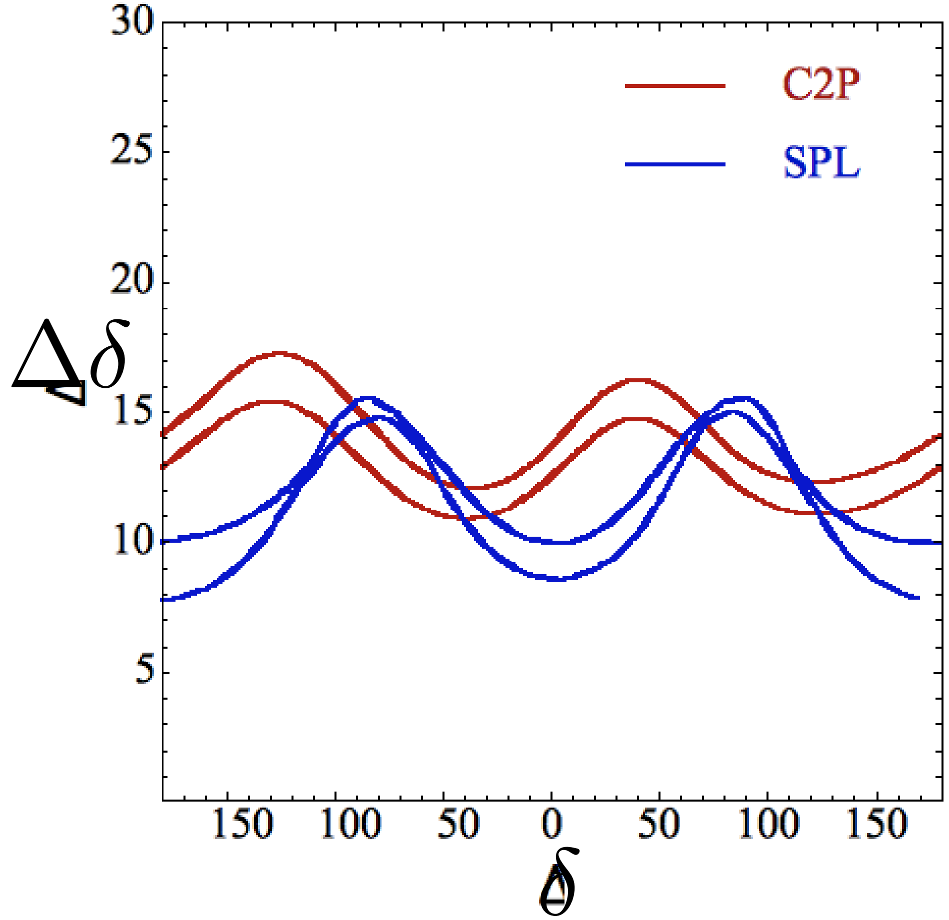
If that on the background: $$\frac{\Delta\theta_{13}}{\theta_{13}} \sim \frac{1}{\theta_{13}^2}$$

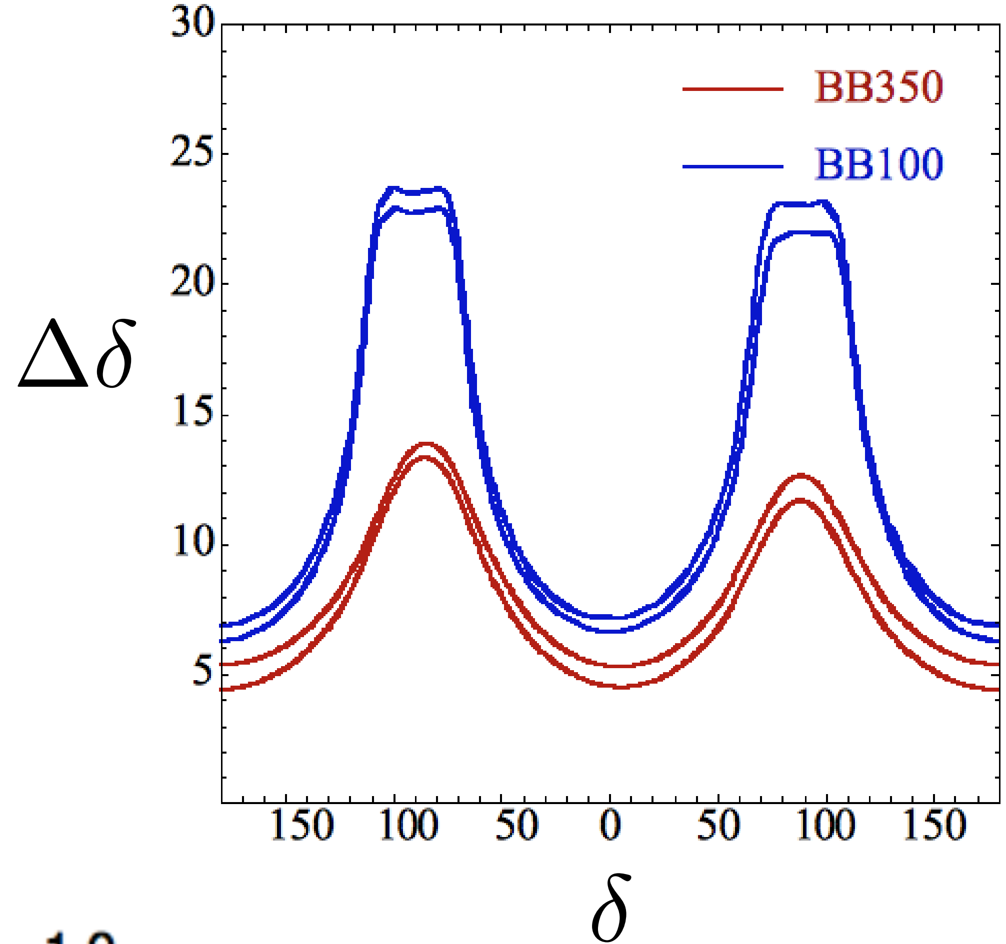
Coloma, Donini, Fernandez Martinez, Hernandez, 1203.5651



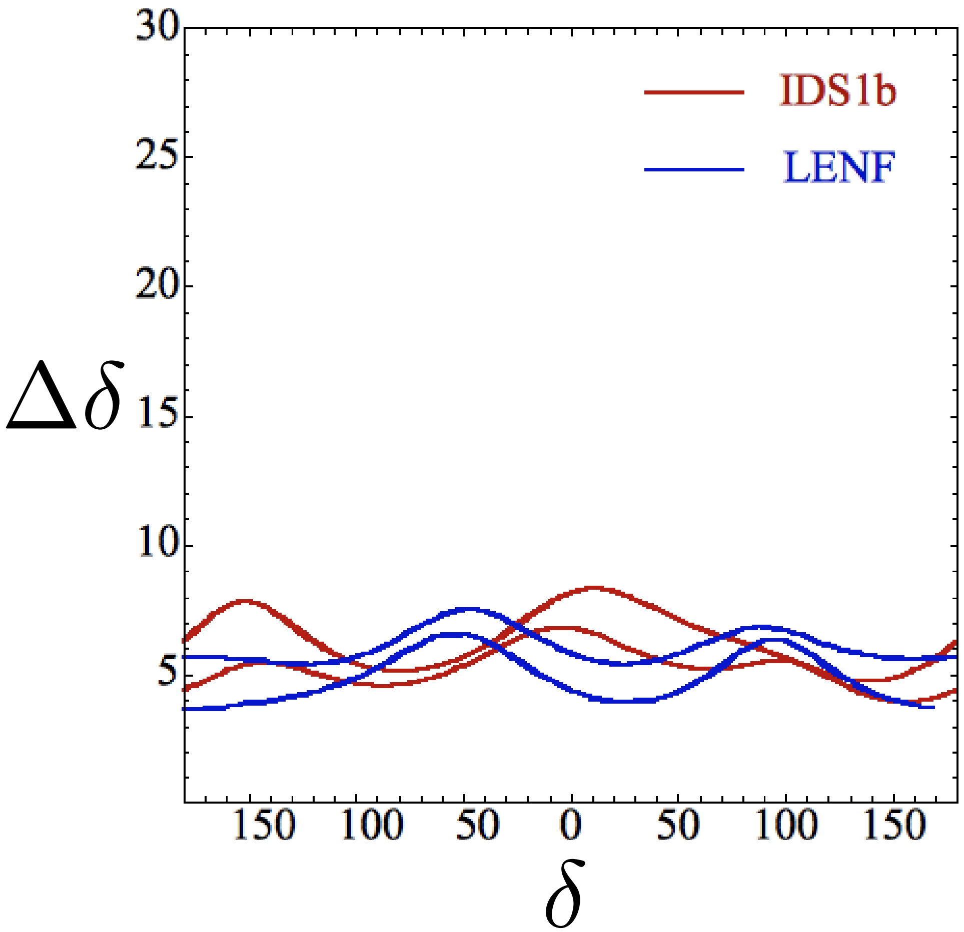
The best measurement of theta13 will be provided by Daya Bay, unaffected by degeneracies, and it could be marginally improved by LENF.

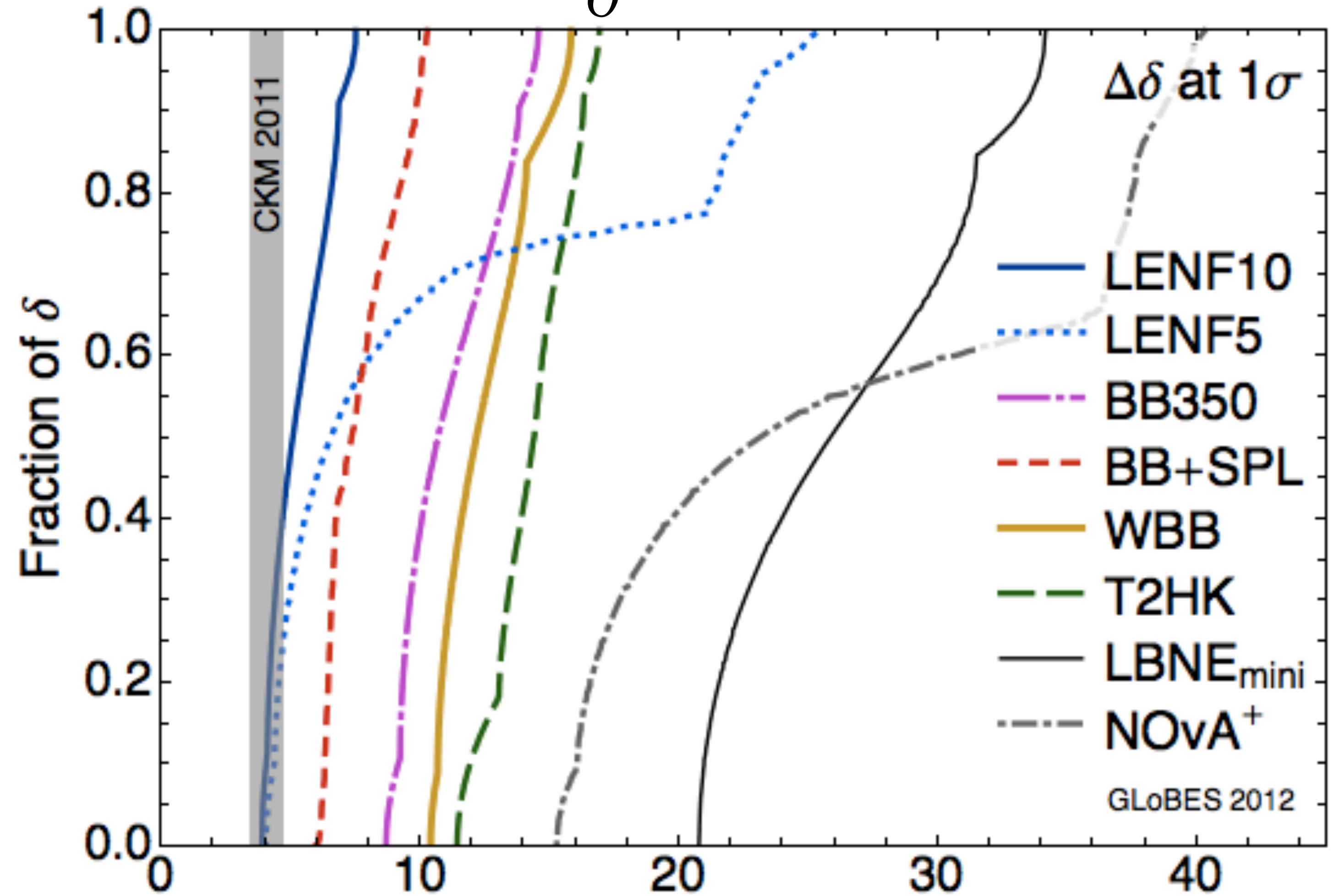
Coloma, Donini, Fernandez Martinez, Hernandez, 1203.5651





Coloma et al., 1203.5651; Donini, et al. , IDS-NF talk





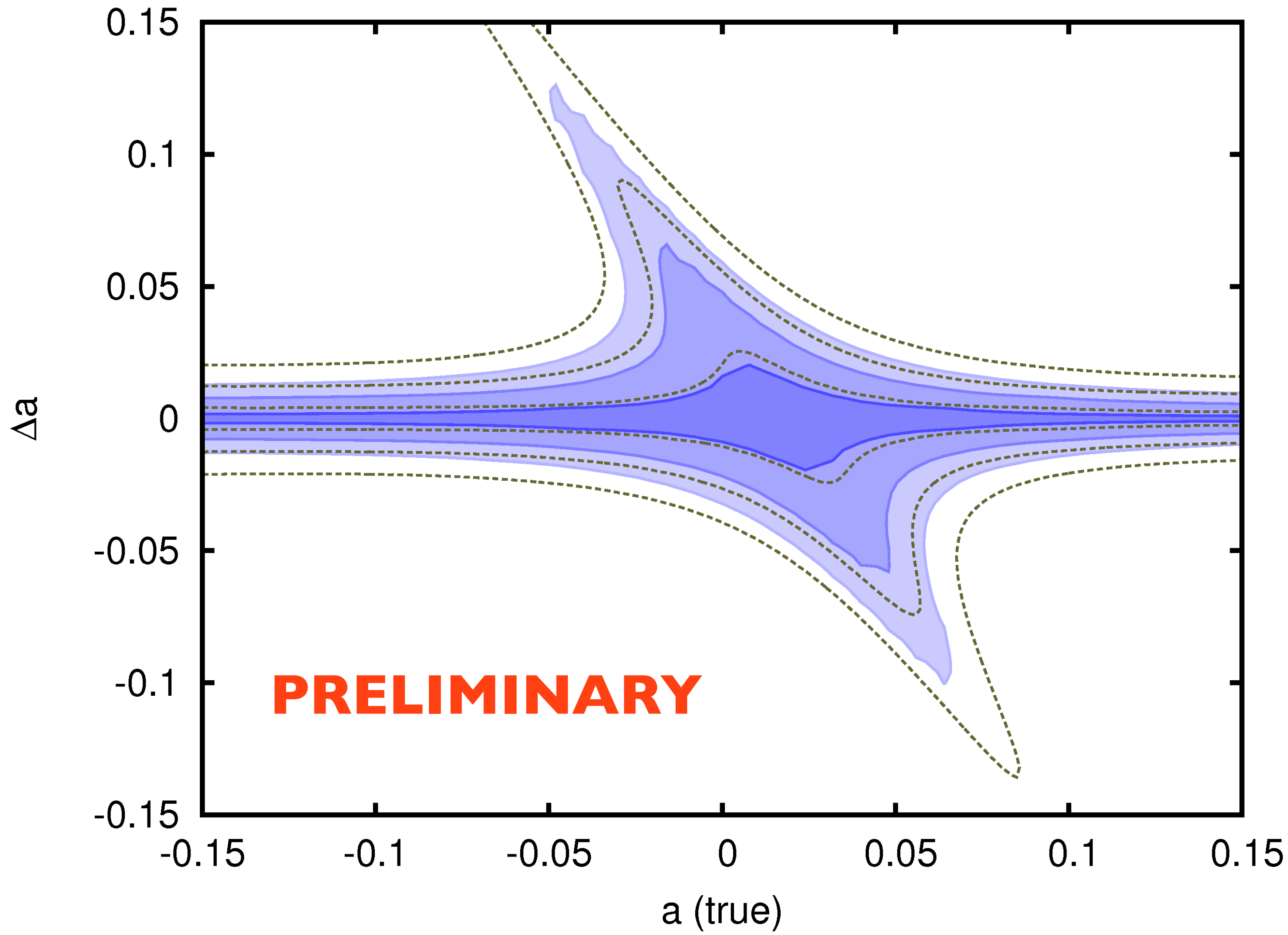
Thanks to Coloma, Huber, Kopp, Winter, in preparation

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:

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

King, 0710.0530



Dashed: WBB

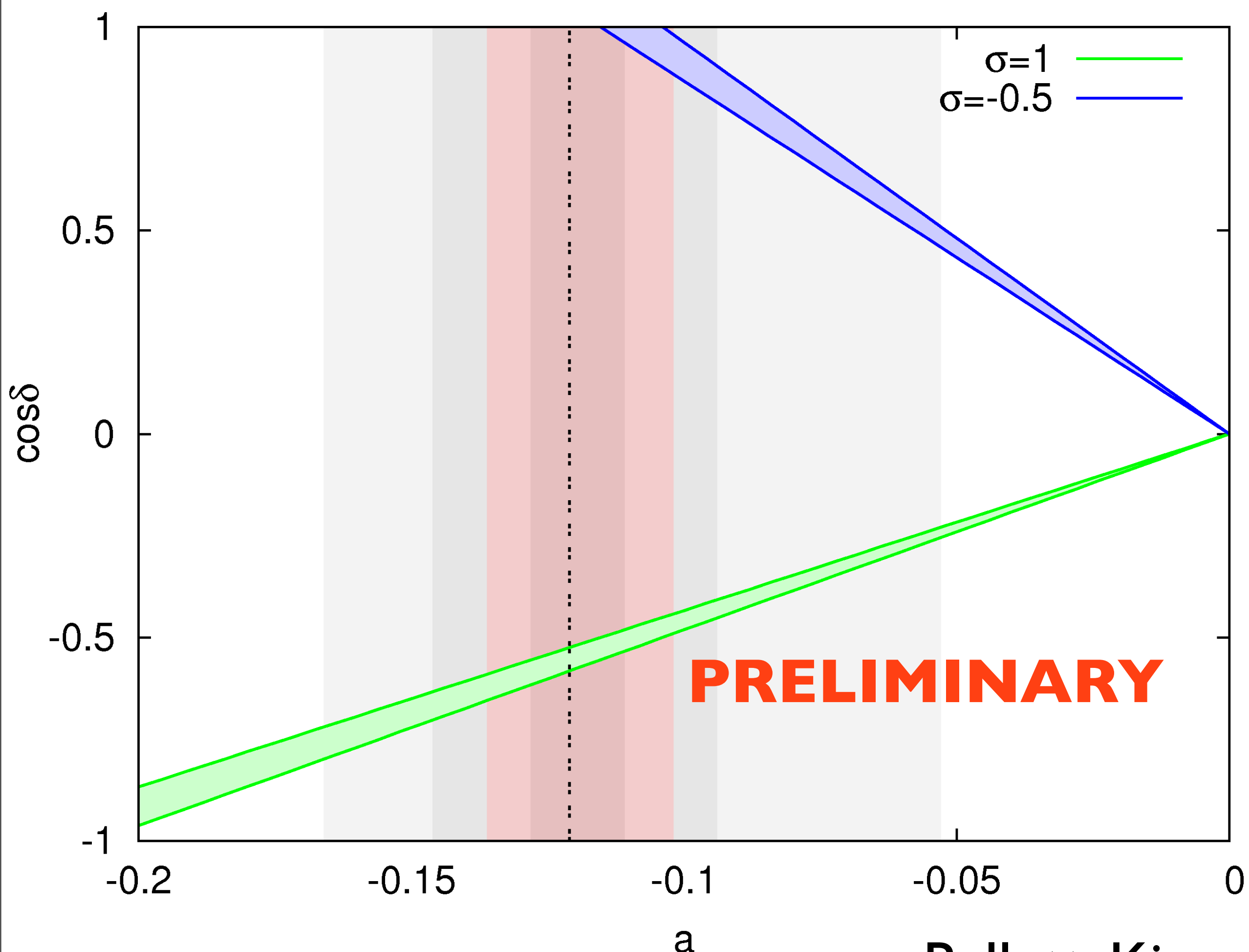
Blue: LENF

Ballett, King, Luhn, SP, Schmidt, in prep

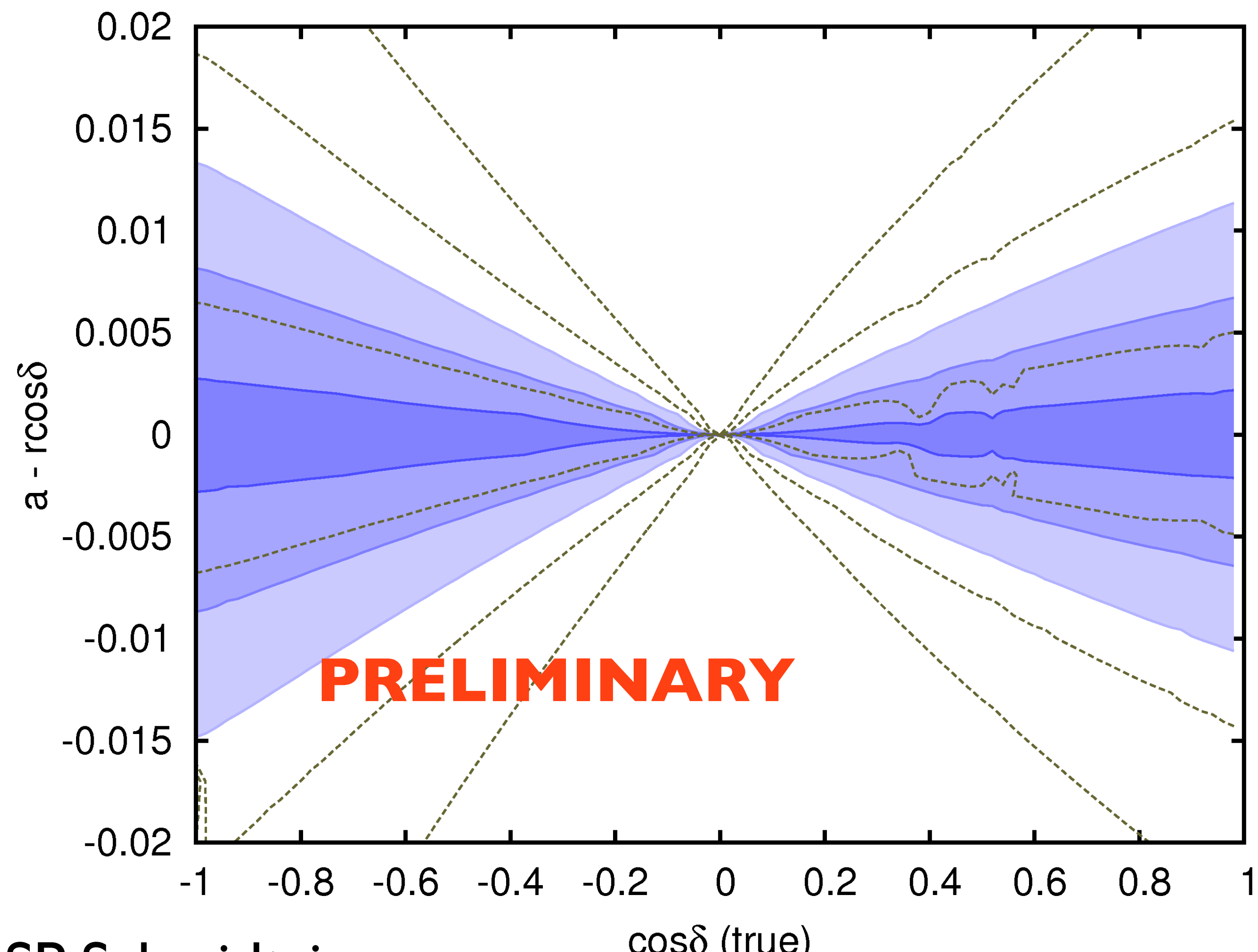
Deviation from these patterns is expected theoretically and is required by experimental data. Theoretical models typically lead to correlations between parameters (sum rules).

$$a = \sigma r \cos\delta \qquad \sigma = 1, -1/2$$

Current data



Future prospects:
Dashed: WBB, Blue: LENF



Ballett, King, Luhn, SP, Schmidt, in prep

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.

- A common LBL EU programme could address the mass hierarchy, CPV searches and precision measurements of the oscillation parameters.

- The study of the physics reach of a facility requires a detailed understanding of beam, detector performance, systematic errors and backgrounds. Comparisons should be done with great care.

Thanks to Coloma, Huber, Kopp, Winter, Ballett, King, Luhn, Schmidt, Li!