The physics case for LBL in EUROPE to search for CPV

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Outline

1. Neutrino properties: questions for the future

2. Phenomenology of LBL experiments

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

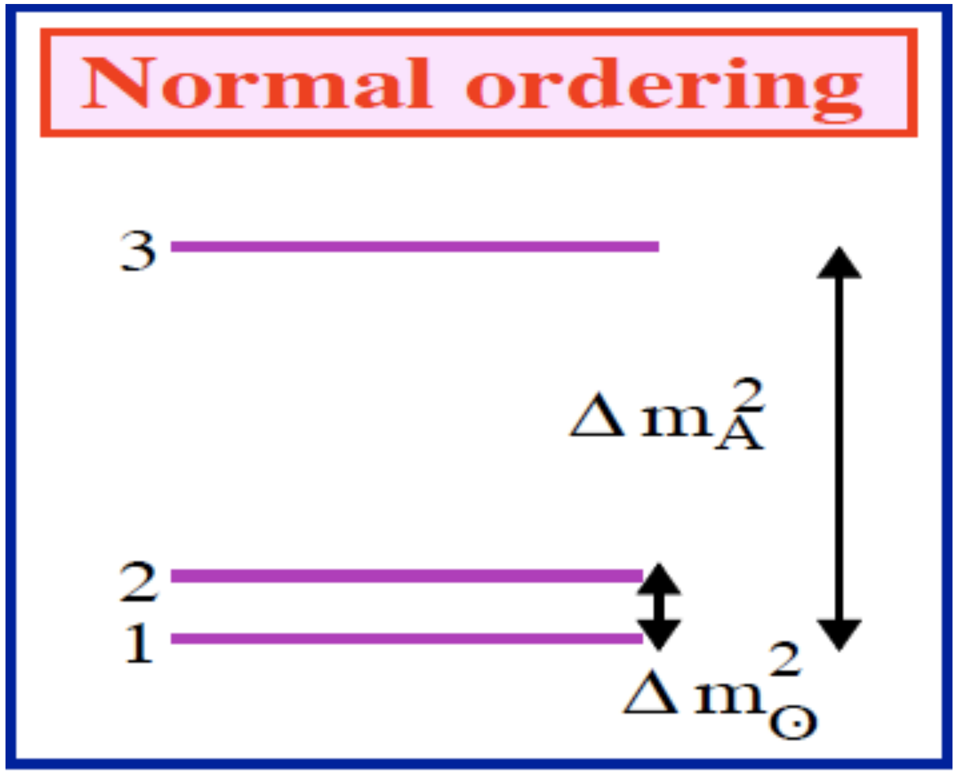
4. Systematic errors

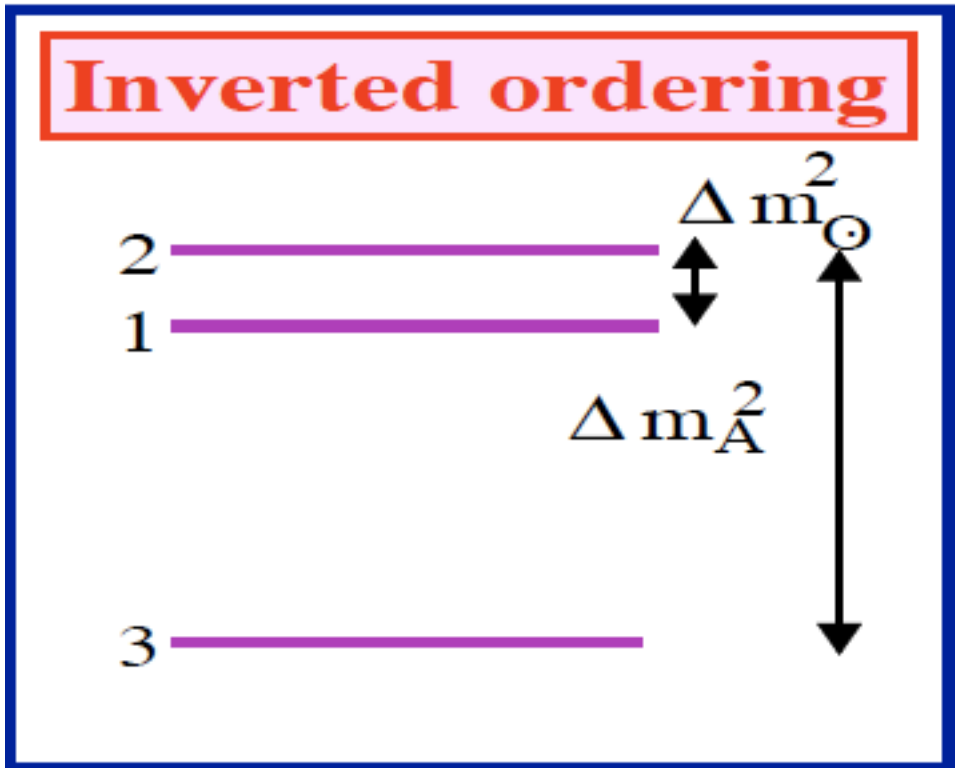
5. Precision measurements

6. Conclusions and outlook

Present status of (standard) neutrino physics

$\Delta m_{\rm s}^2 \ll \Delta m_{\rm A}^2$ implies at least 3 massive neutrinos.





$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm sol}^2}$$
$$m_3 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2 - \Delta m_{\rm sol}^2}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

Measuring the masses requires: $m_{\rm min}$ and the ordering.

Mixing is described by a unitary mixing matrix.

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

$\text{Solar, reactor } \theta_{\odot} \sim 30^o$ $\quad$ $\text{Atm, Acc. } \theta_A \sim 45^o$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}$$

CPV phase $\quad$ $\text{Reactor, Acc. } \theta_{13} \sim 9^o$ $\quad$ $\text{CPV Majorana phases}$

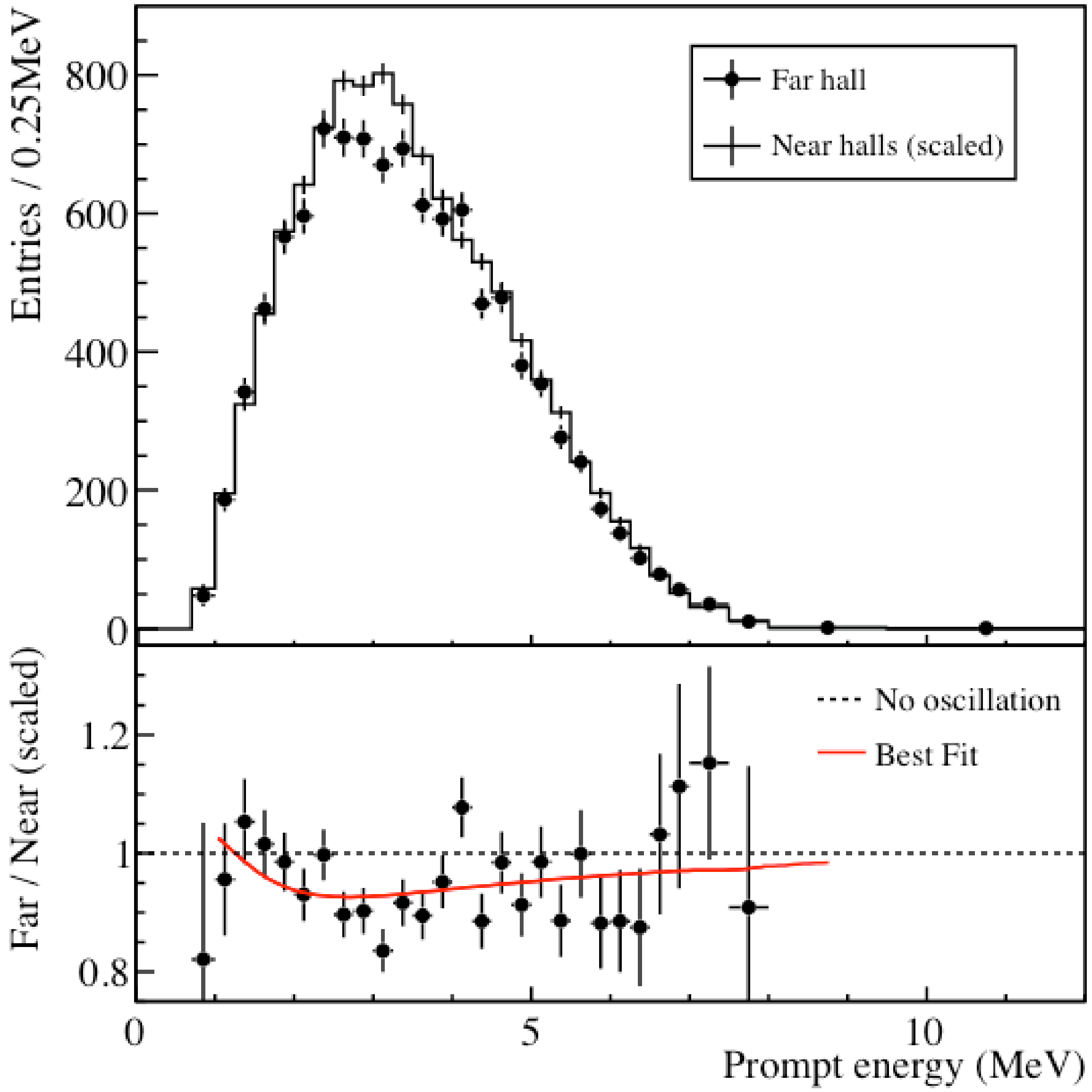
>5 sigma discovery of non-zero θ_{13}

If $U \neq U^*$, there is leptonic CP-violation

$$P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})$$

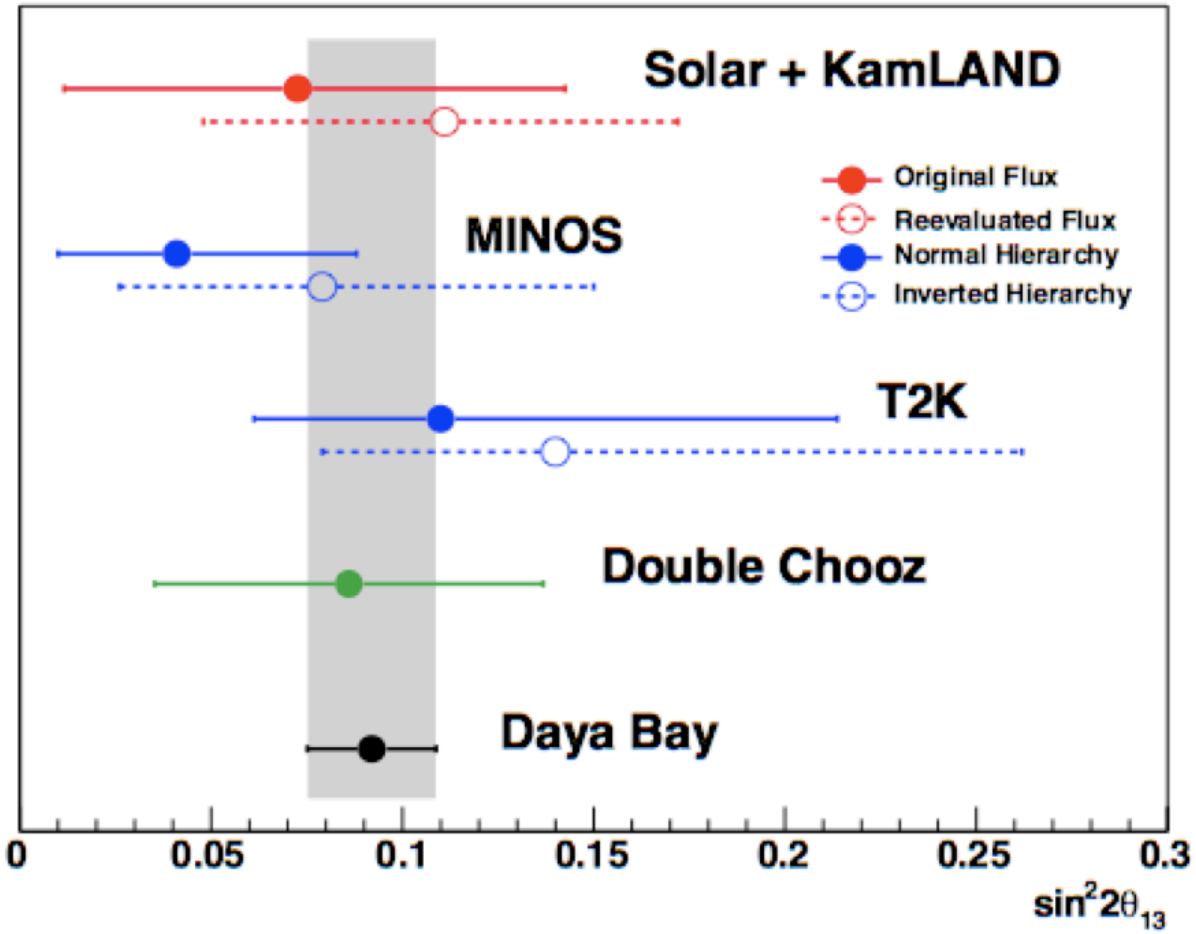
This is a fundamental question to answer and is related to the flavour problem, and to leptogenesis and the possible origin of the baryon asymmetry of the Universe.

In 2011, the first hints of large θ_{13} were found in T2K, MINOS and DoubleCHOOZ. Daya Bay (!) and RENO have confirmed these hints and discovered this angle.



The Daya Bay Collaboration, 1203.1669

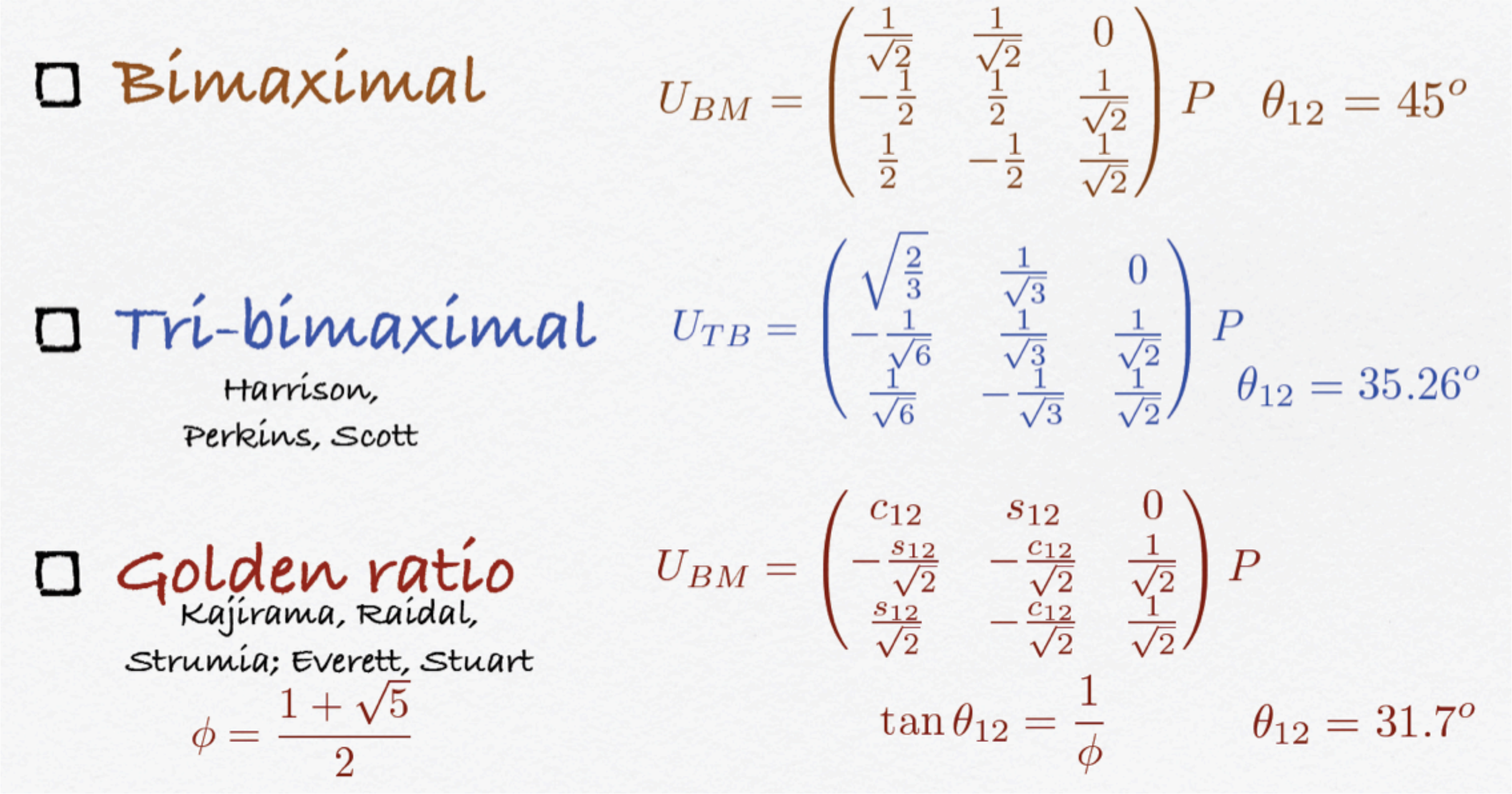
See Fogli's talk for first combined analysis of all data



$$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$$

This has critical implications for LBL.

The precise values of the mixing angles have a strong theoretical impact for understanding the flavour problem. Symmetry motivated patterns:



☐ **Bimaximal**

$$U_{BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} P \qquad \theta_{12} = 45^o$$

☐ **Tri-bimaximal**

Harrison, Perkins, Scott

$$U_{TB} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} P \qquad \theta_{12} = 35.26^o$$

☐ **Golden ratio**

Kajirama, Raidal, Strumia; Everett, Stuart

$$U_{BM} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -\frac{s_{12}}{\sqrt{2}} & -\frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{s_{12}}{\sqrt{2}} & -\frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} P$$

$$\phi = \frac{1+\sqrt{5}}{2} \qquad \tan\theta_{12} = \frac{1}{\phi} \qquad \theta_{12} = 31.7^o$$

Thanks to S. King

Deviation from these patterns is expected theoretically, e.g. GUTs, and is required by experimental data. Theoretical models typically lead to correlations between parameters (sum rules) or specific predictions for their values. Minakata's talk

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 theta13 and of delta.
- **What are the precise values of mixing angles (tribimaximal mixing?)?**
- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

Long baseline neutrino oscillations

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

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

Matter effects

CP violation

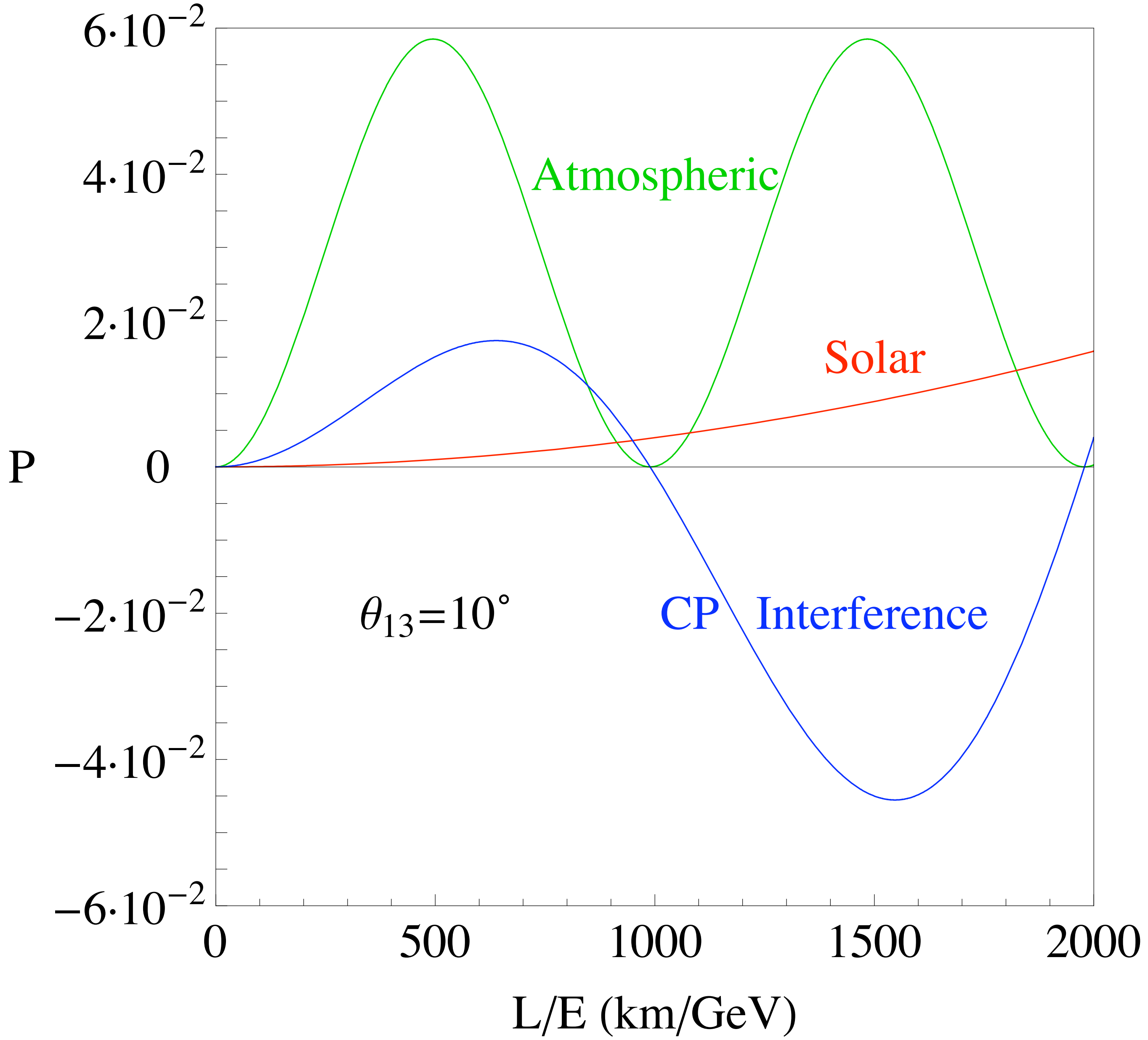
in order to establish

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

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



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).

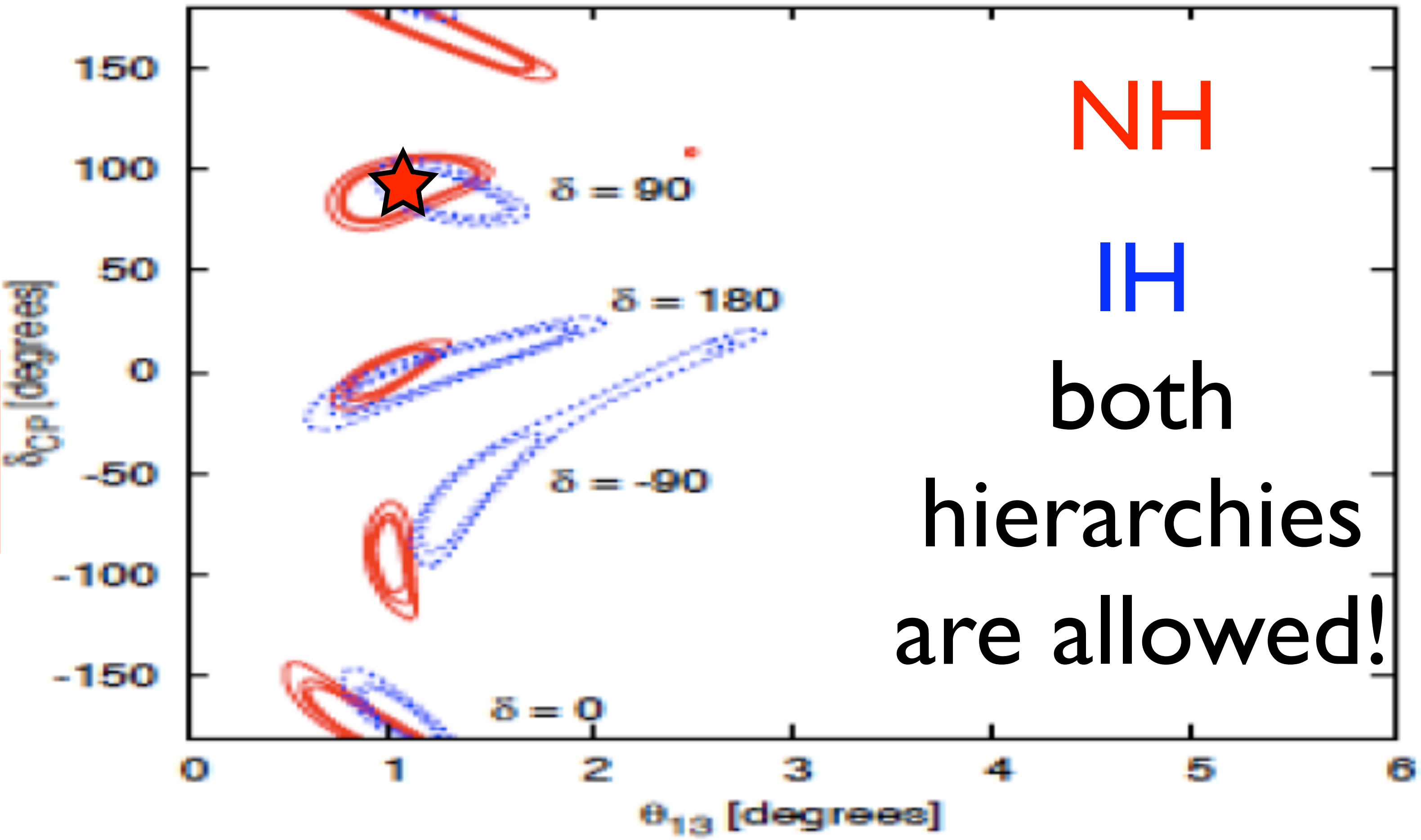
$$\boxed{\theta_{13}, \delta, \mathrm{sgn}(\Delta m^2_{31}), \theta_{23}}$$

$$\downarrow$$

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

$$\uparrow$$

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



both hierarchies are allowed!

- (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 estavlish the mass hierarchy. It can broken by matter effects.

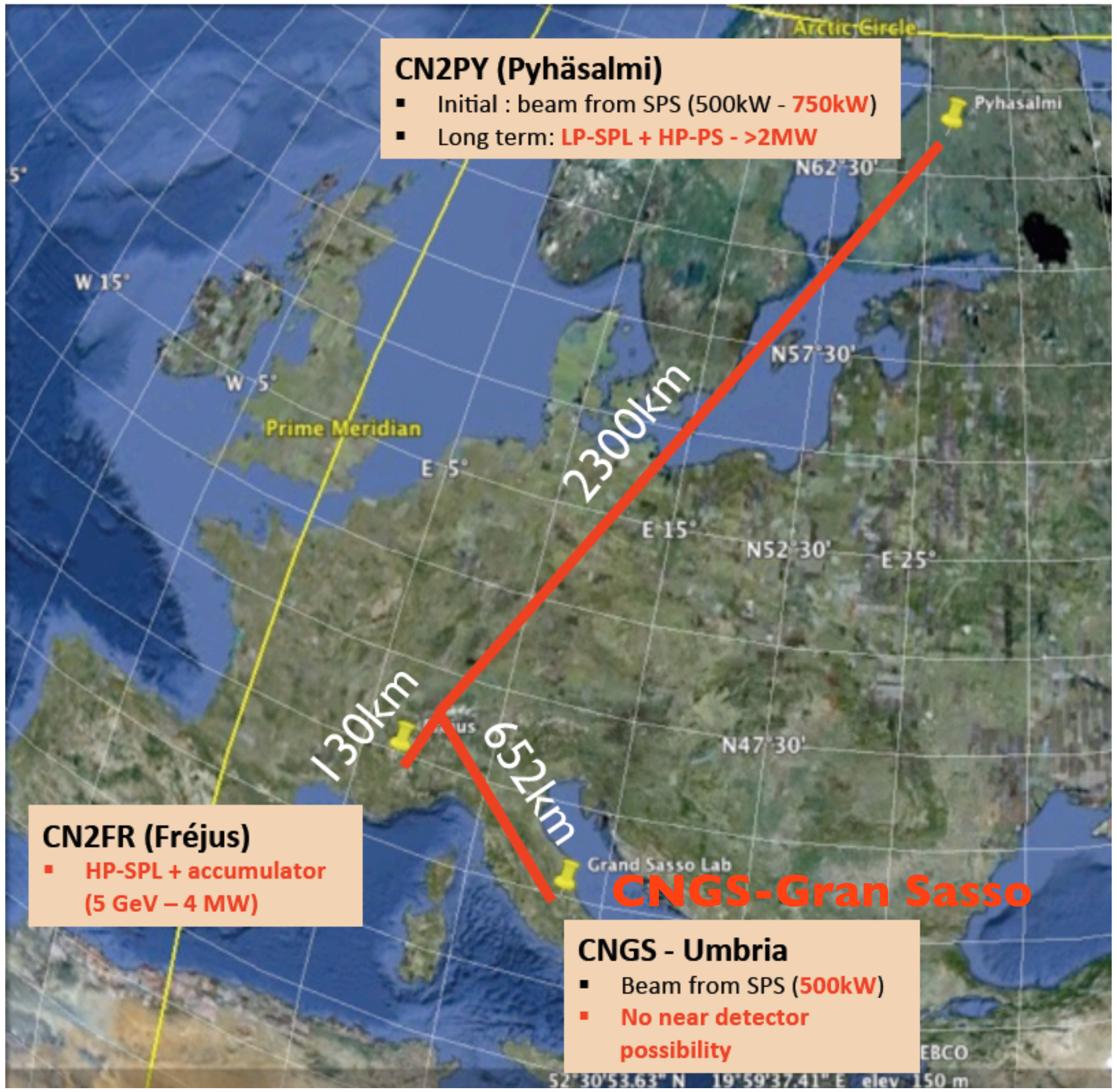
- the octant of θ_{23} (low E data) (Fogli, Lisi)

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. 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)
- CERN-Gran Sasso (Umbria): ~650-700 km, E~1.3 GeV.

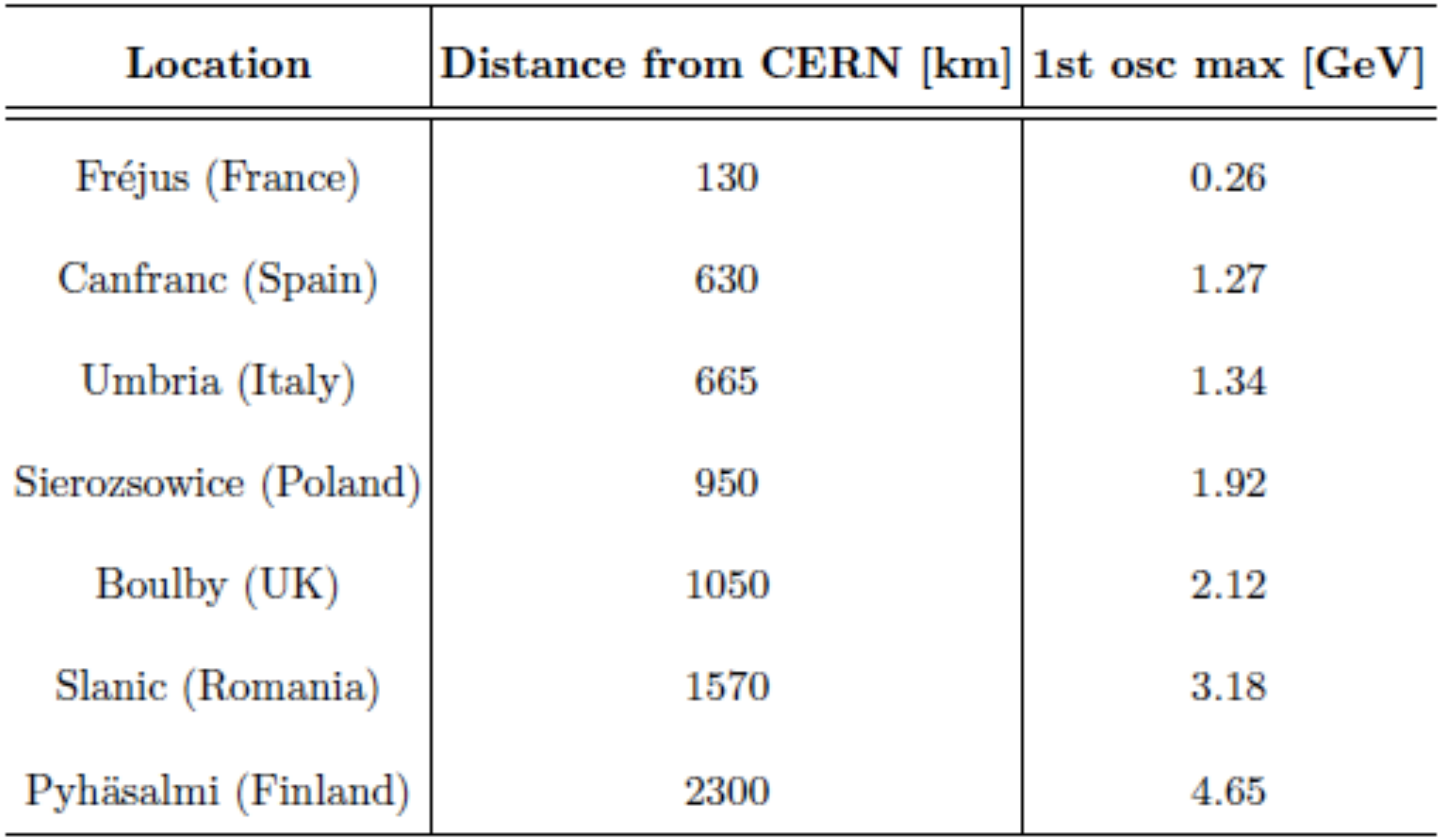
See also work by Huber, Schwetz, Kopp, Winter, Donini, Hernandez, Fernandez Martinez...


CN2PY (Pyhäsalmi)
- Initial : beam from SPS (500kW - 750kW)
- Long term: LP-SPL + HP-PS - >2MW

CN2FR (Fréjus)
- HP-SPL + accumulator (5 GeV – 4 MW)

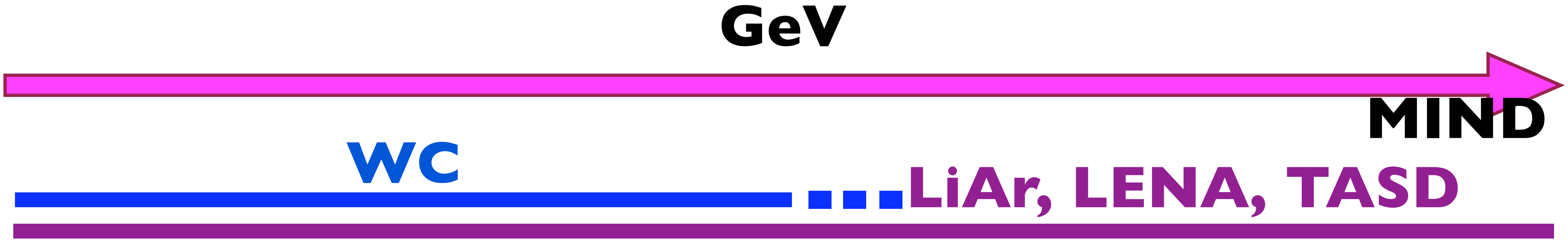
CNGS - Umbria
- Beam from SPS (500kW)
- No near detector possibility

Thanks to Rubbia; old LAGUNA-LBNO



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

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.



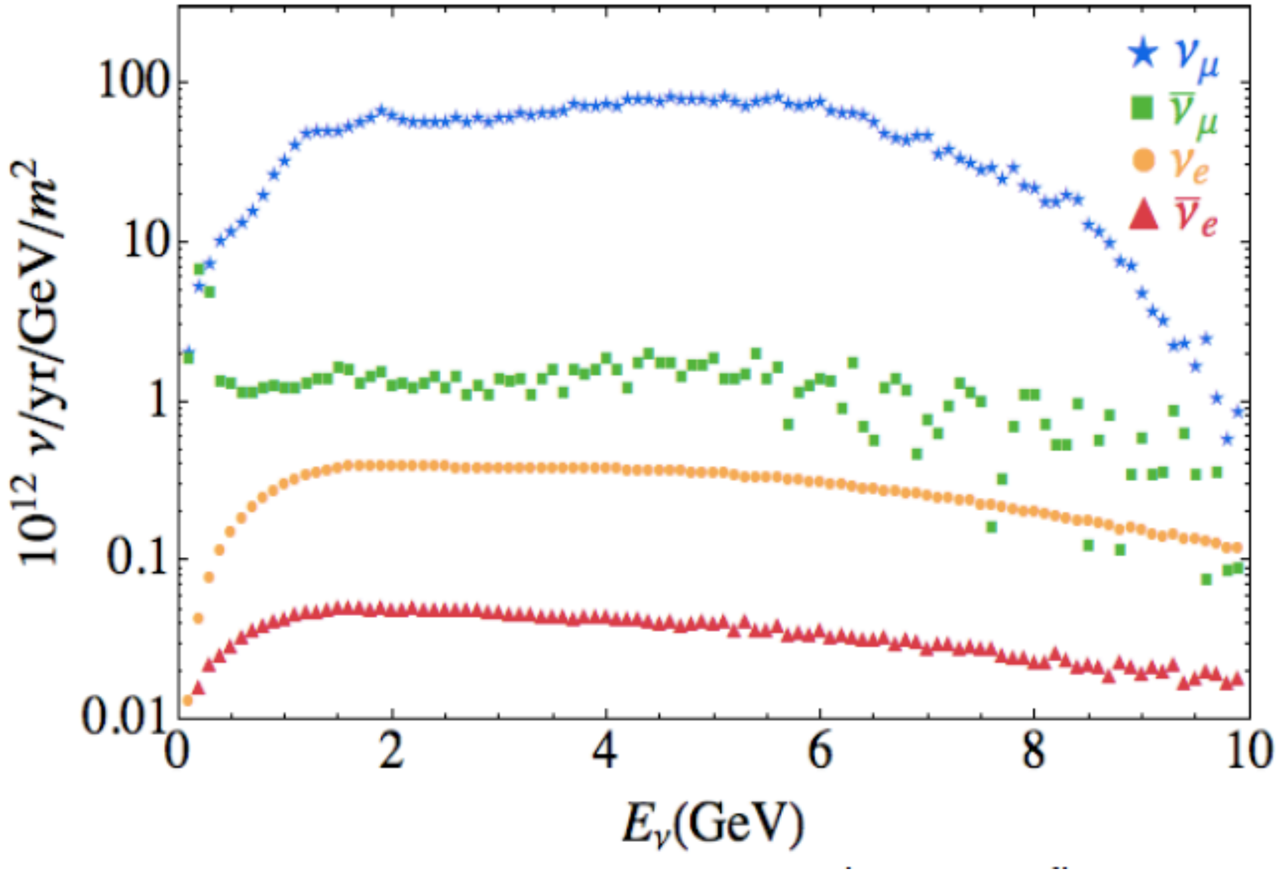
The beam

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

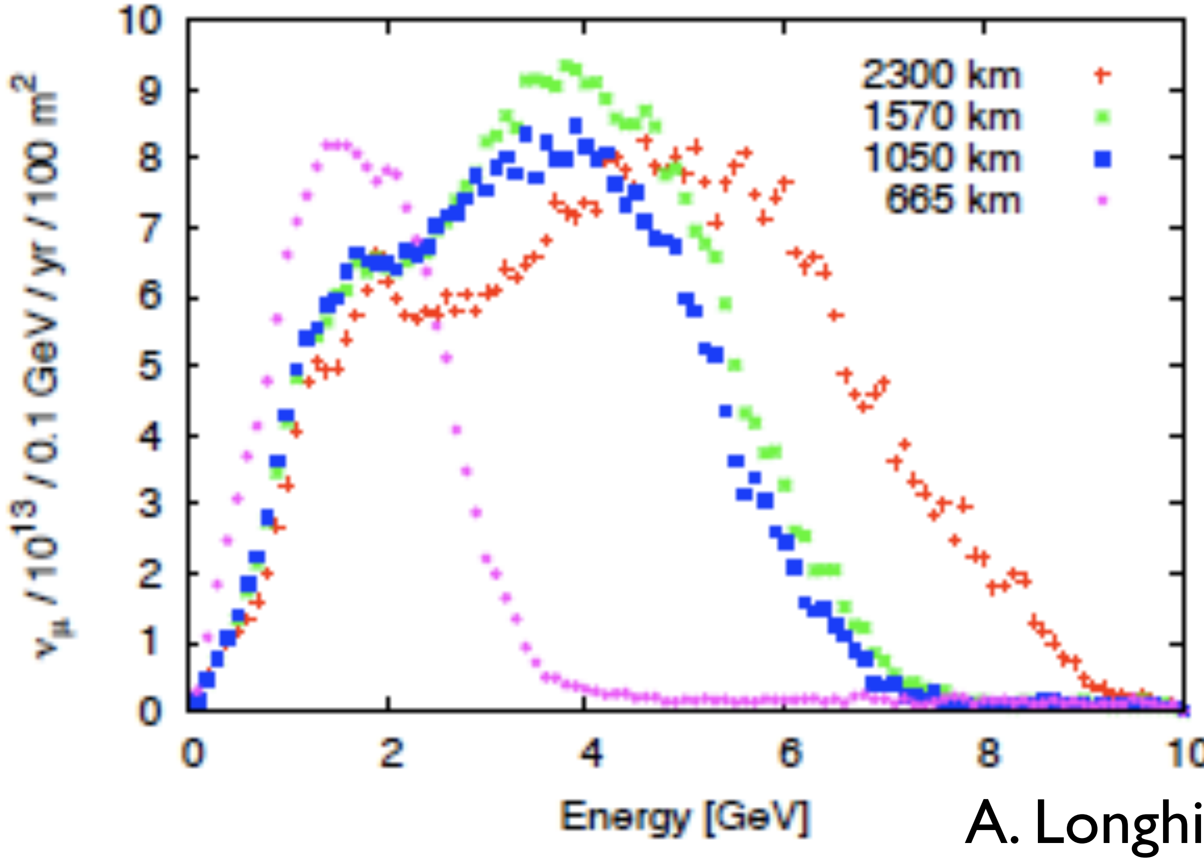
Thanks to I. Efthymiopoulos

Phyasalmi (0.8-2.3 MW)

A. Longhin, PoS ICHEP2010 (2010) 325



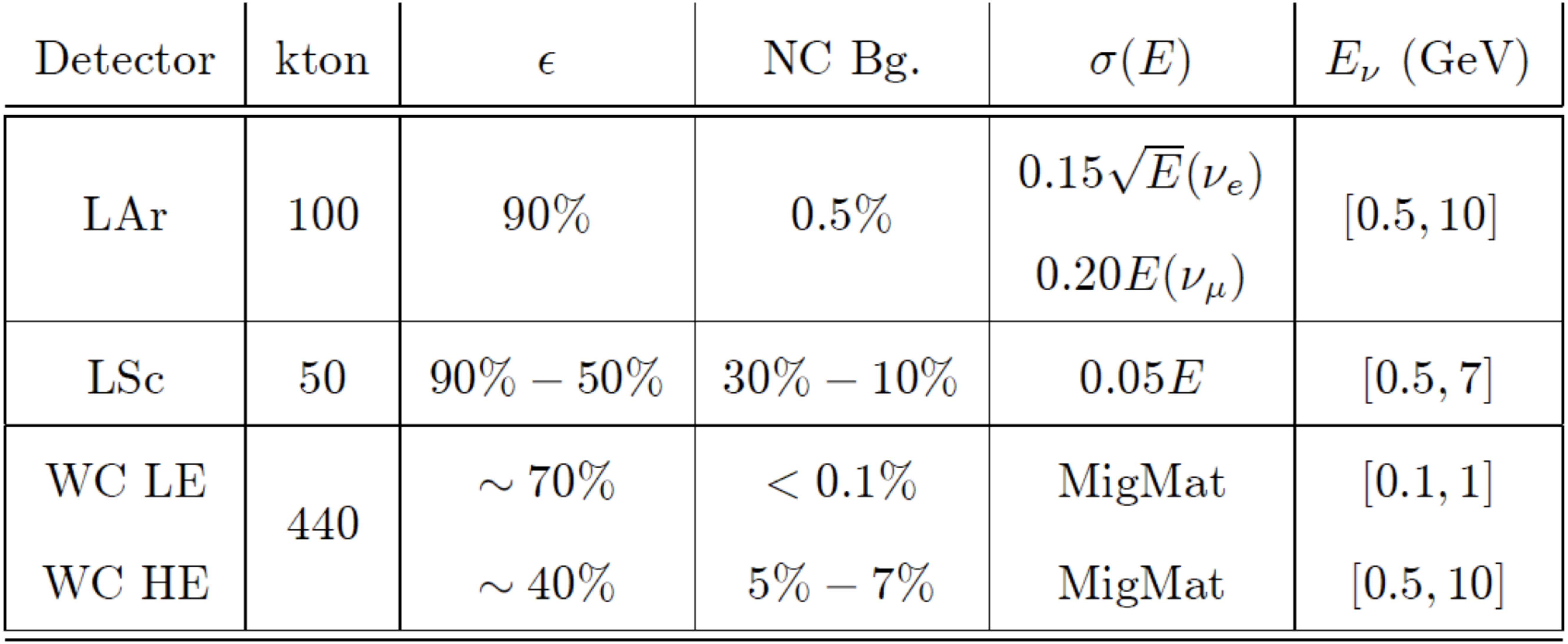
Different baselines



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	$[0.5, 10]$

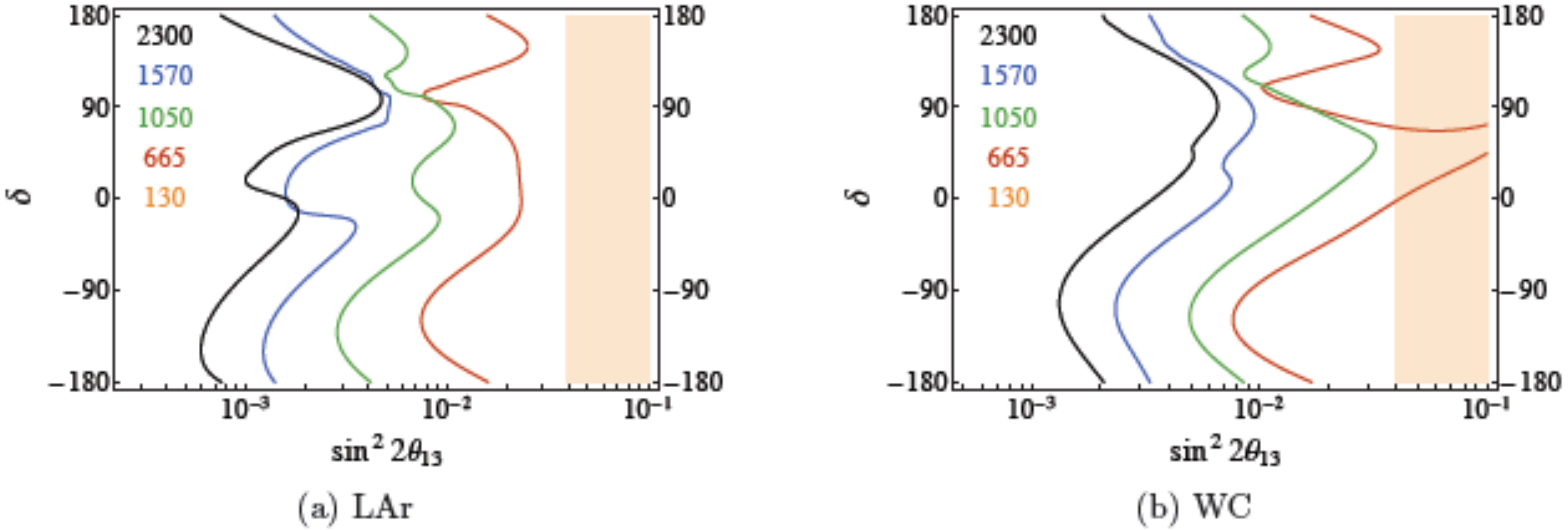
In LAGUNA, the simulation of the WC is not optimised for ~650 km as it has a threshold at 500 MeV.

In Coloma’s et al. plots, additional NC backgrounds have been introduced for LAr and charge mis-ID and WC size has been increased to 500 kton.

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

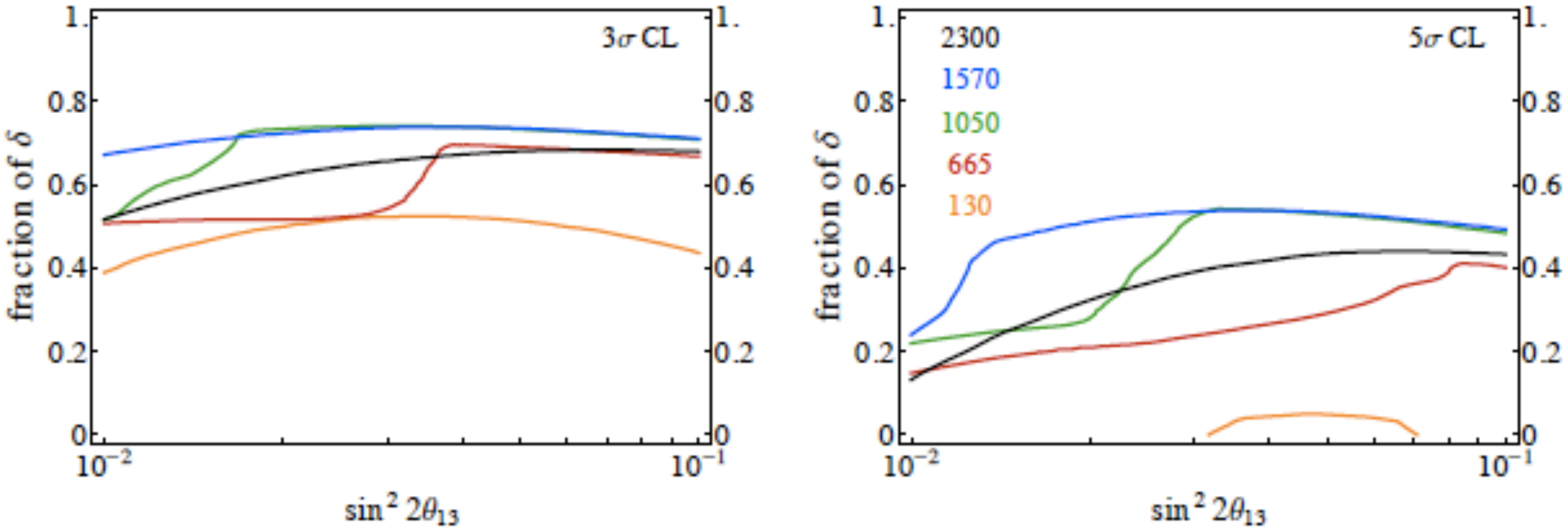
(b) WC

PRELIMINARY

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

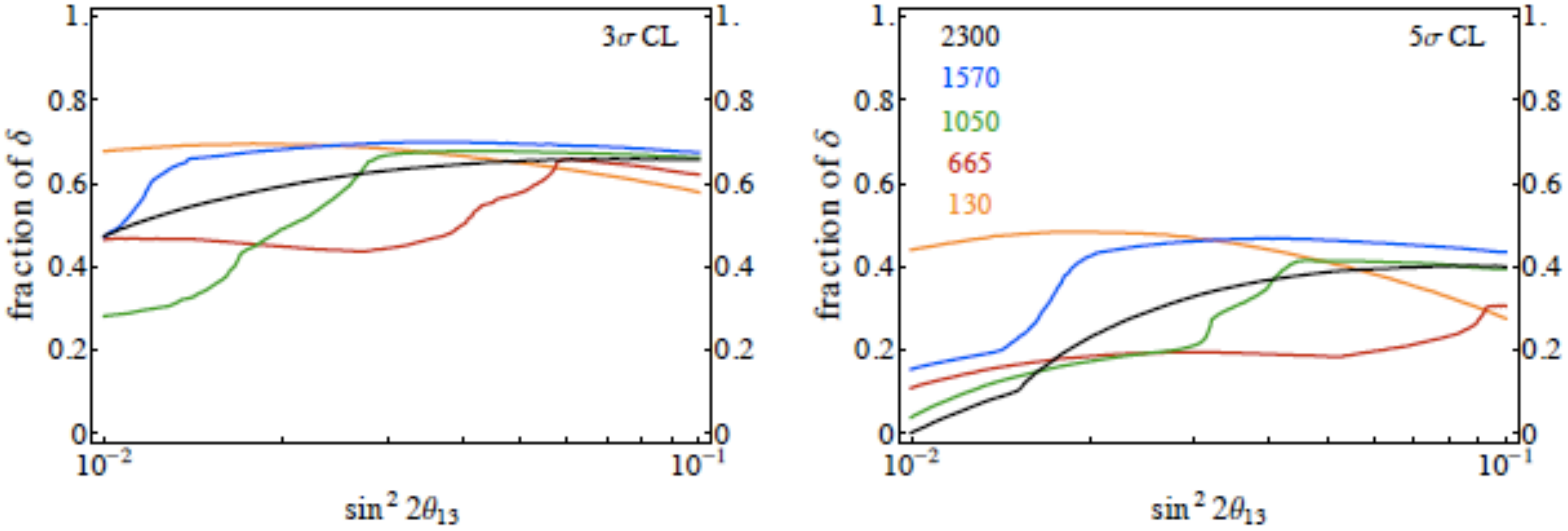
Comparison between baselines

The determination of CPV



(a) LAr

PRELIMINARY

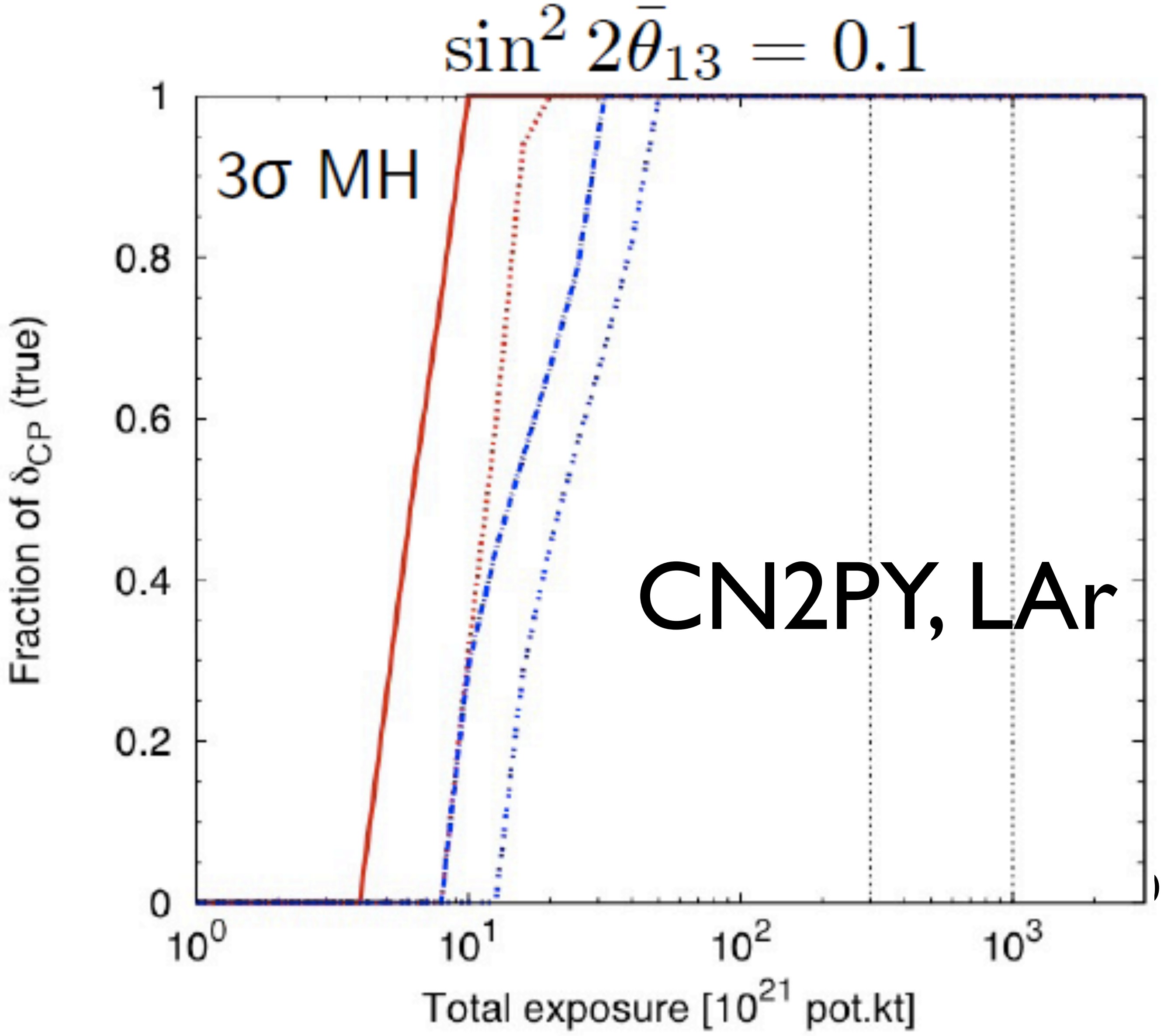


(b) WC

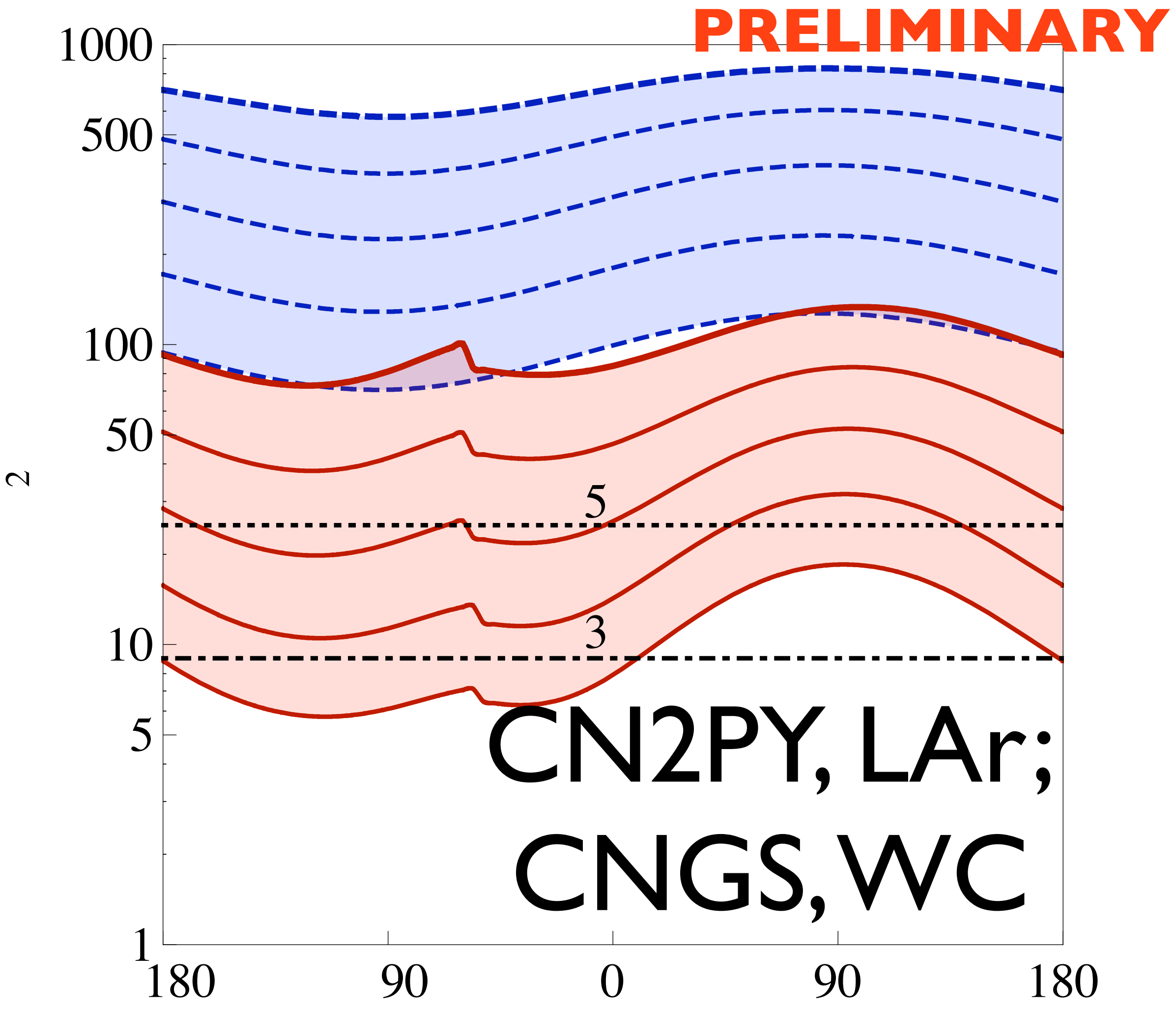
Coloma, Li, SP, in preparation; LAGUNA-LBNO

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).

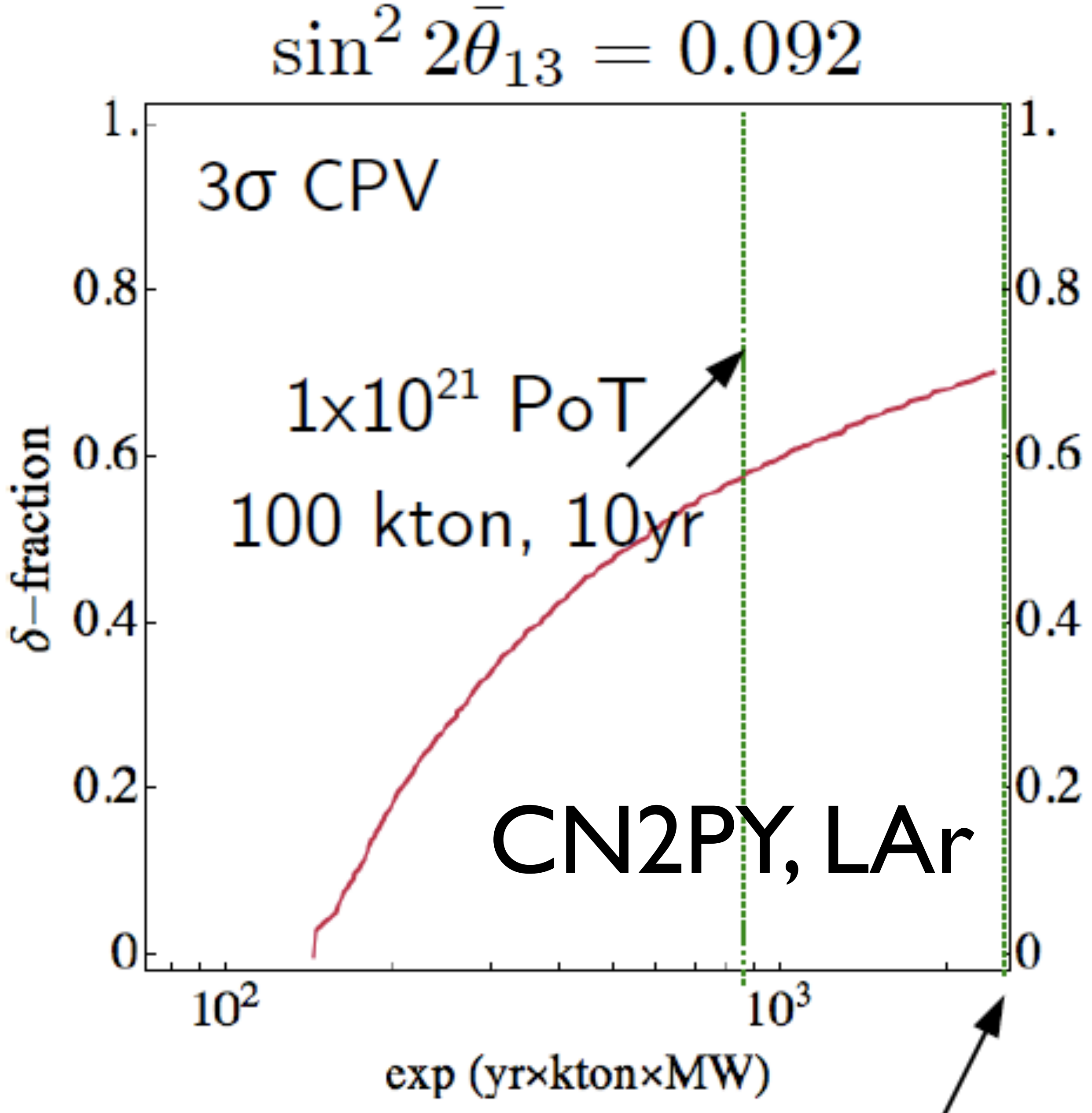


Agarwalla, Li, Rubbia



Coloma, Fernandez-Martinez, Labarga

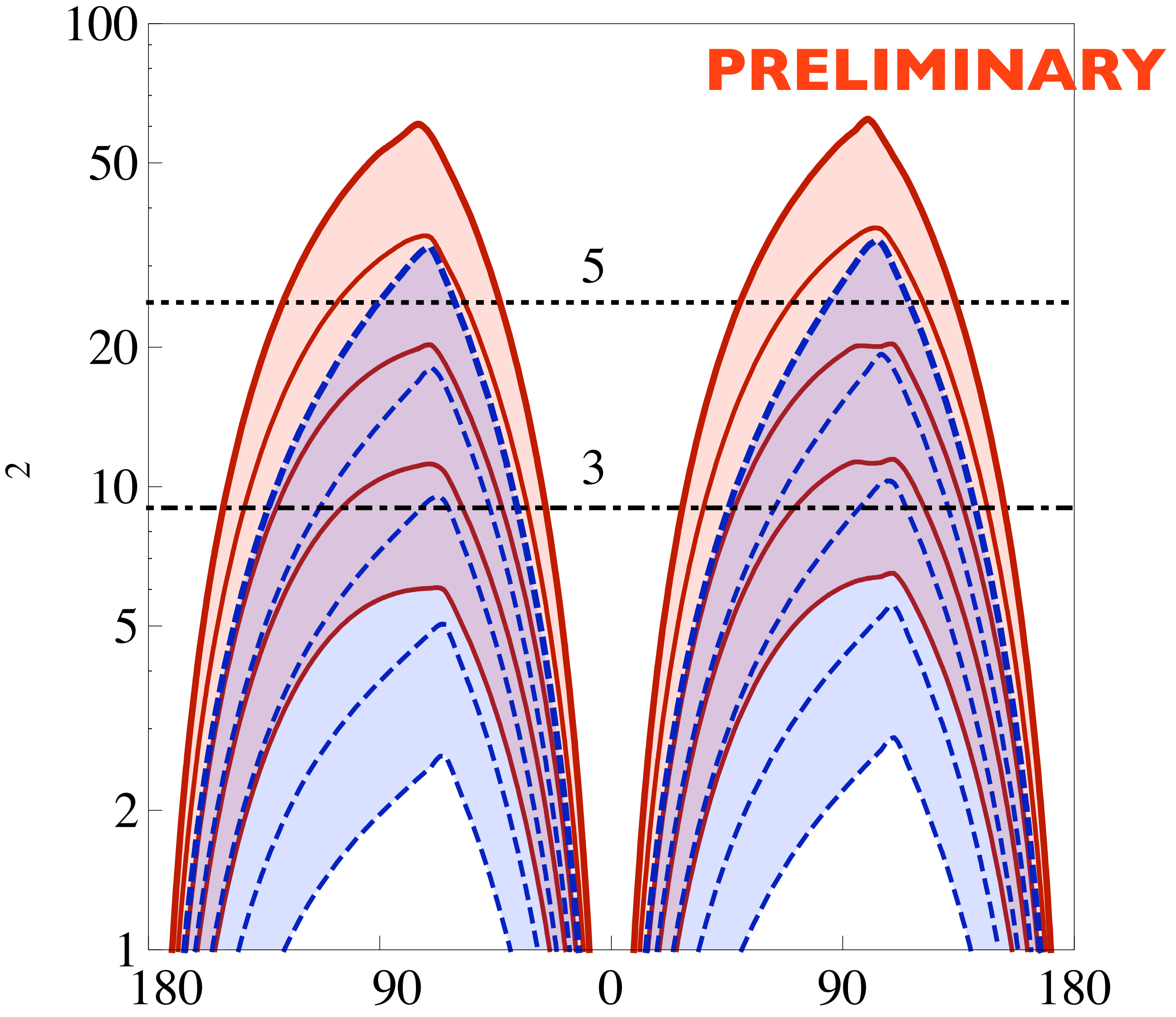
Discovering CPV will be more difficult and higher exposures are needed.



Coloma, Li, SP

3×10^{21} PoT

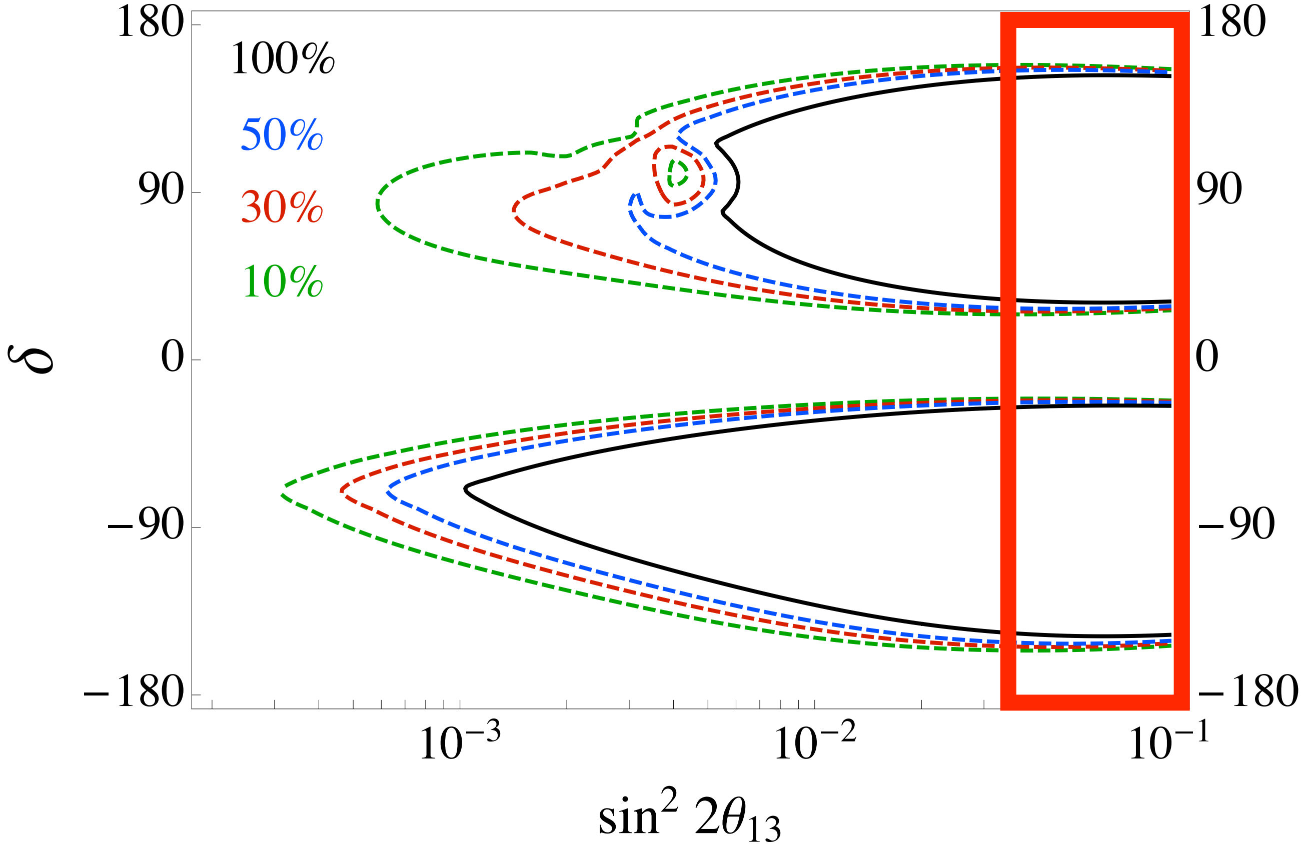
100 kton, 10yr



CN2PY, LAr;
CNGS, WC

Coloma, Fernandez-Martinez, Labarga

Backgrounds

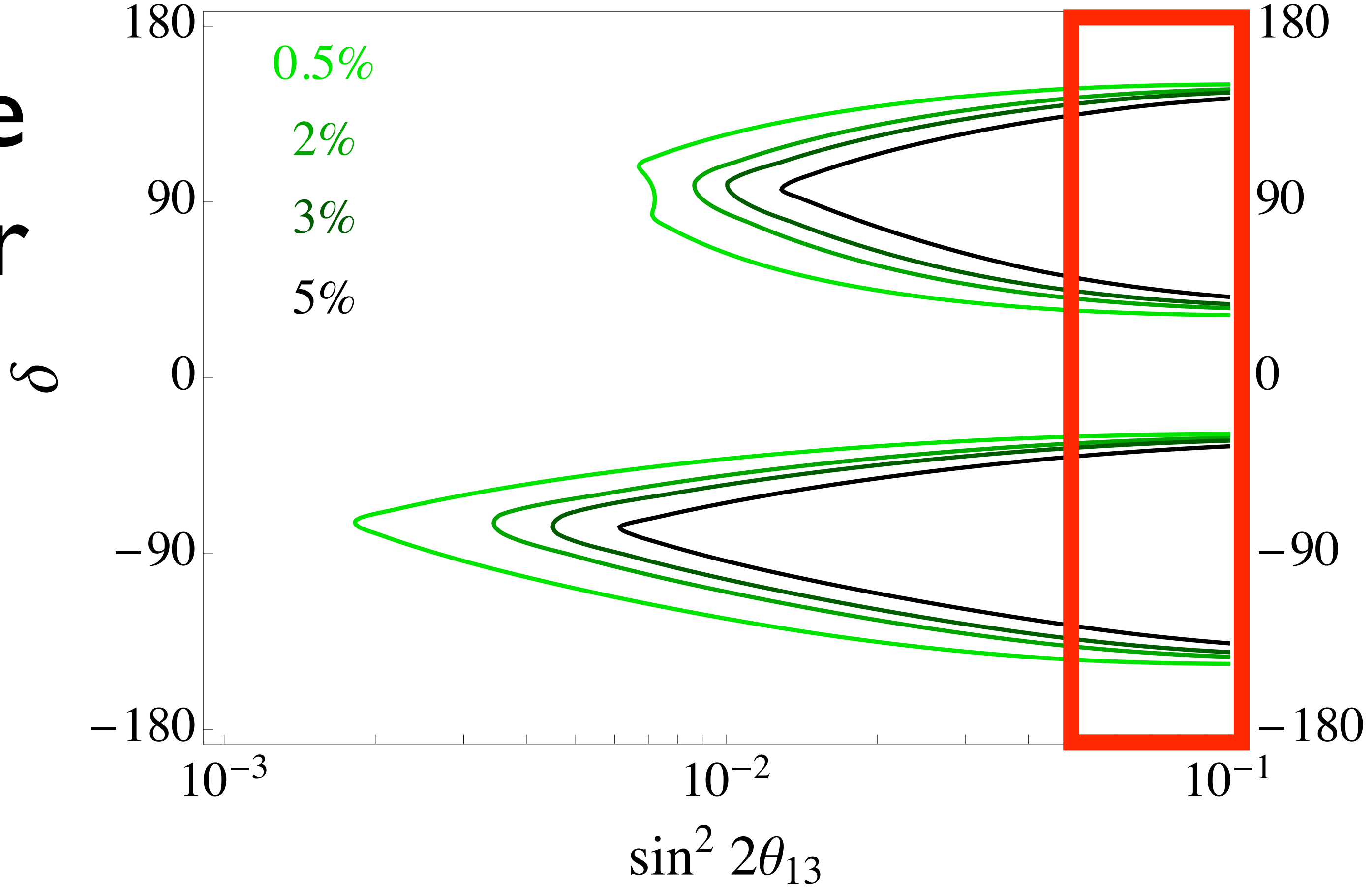


The intrinsic electron neutrino background is typically <1% level and does not affect the sensitivity significantly.

Coloma, Li, SP

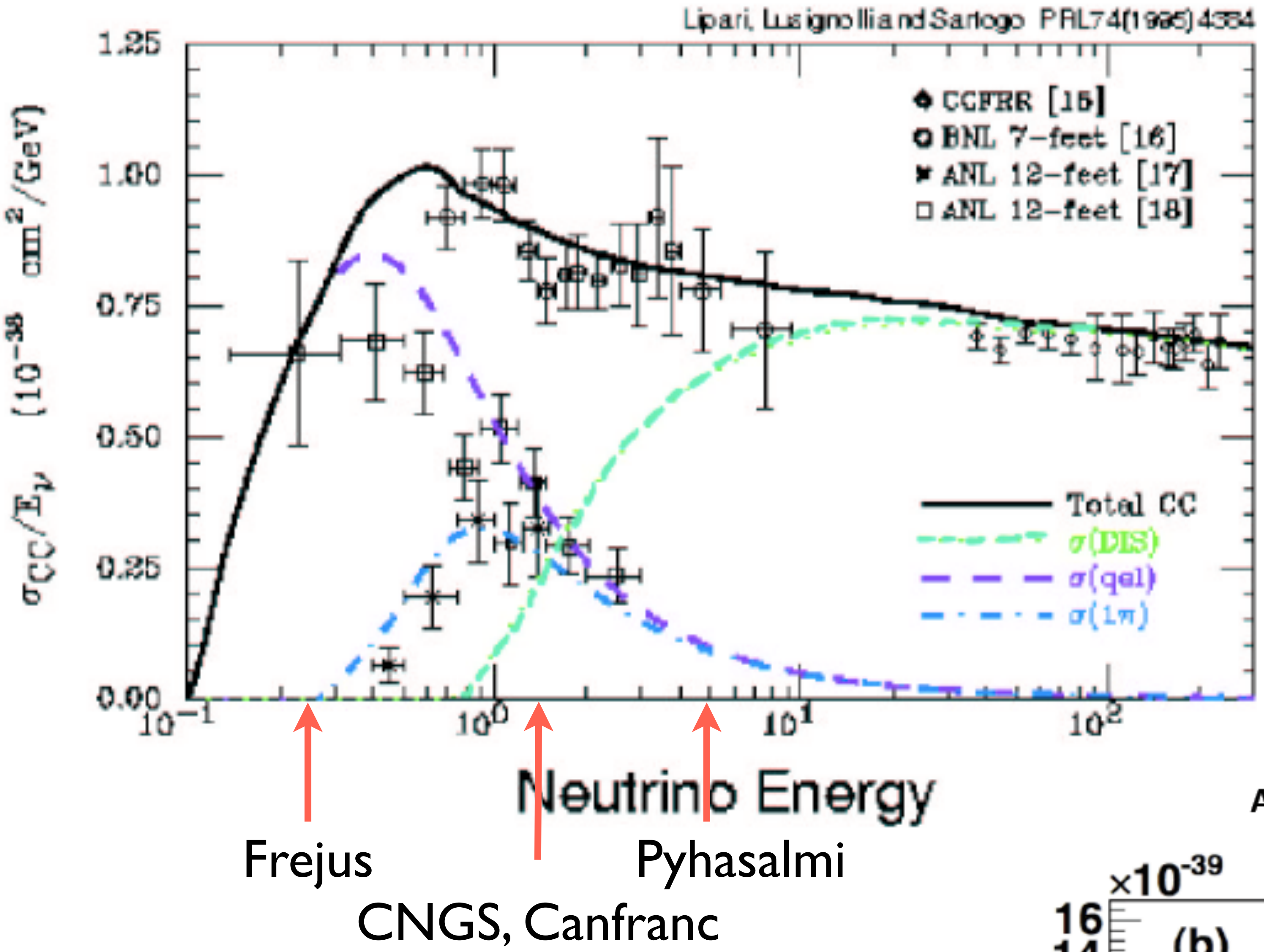
The NC backgrounds are particularly important for CPV searches.

50 kton detector with excellent energy resolution



Systematic errors

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



Lipari, Lusignolli and Sartogo PRL74(1995)4384

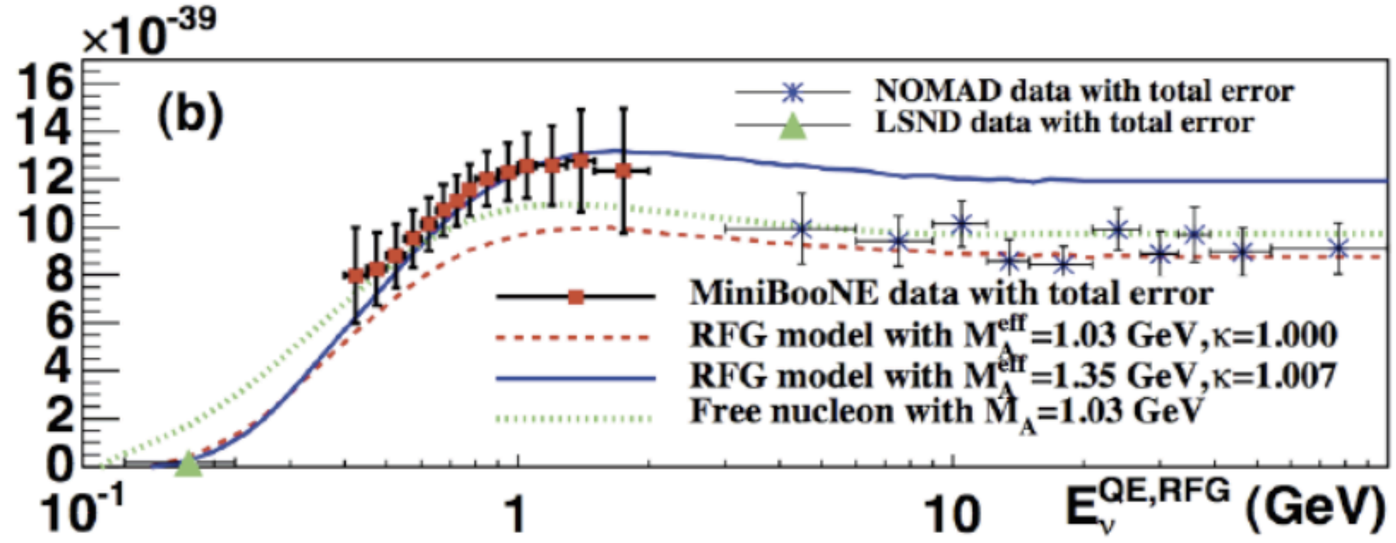
Frejus

CNGS, Canfranc

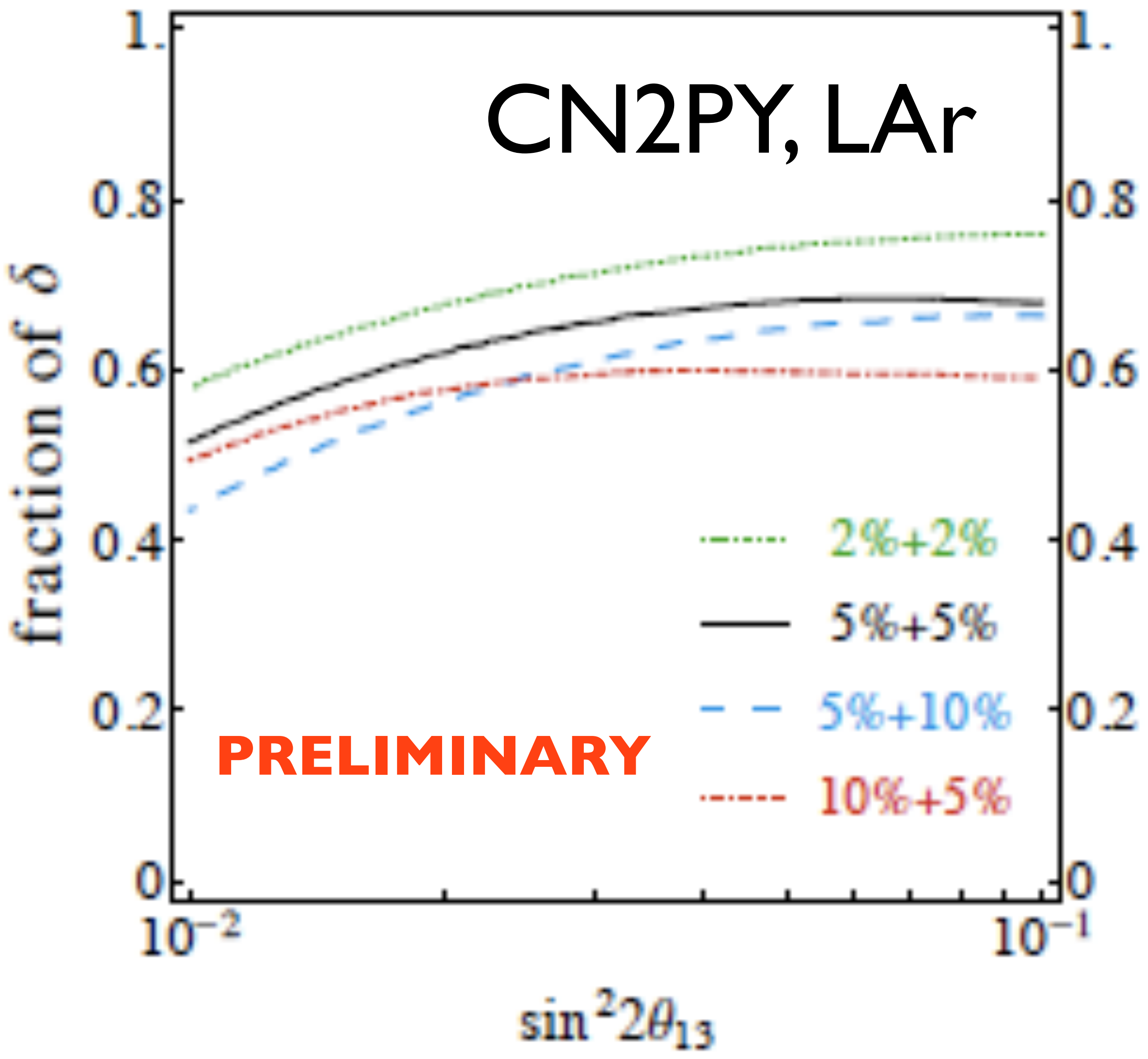
Pyhasalmi

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

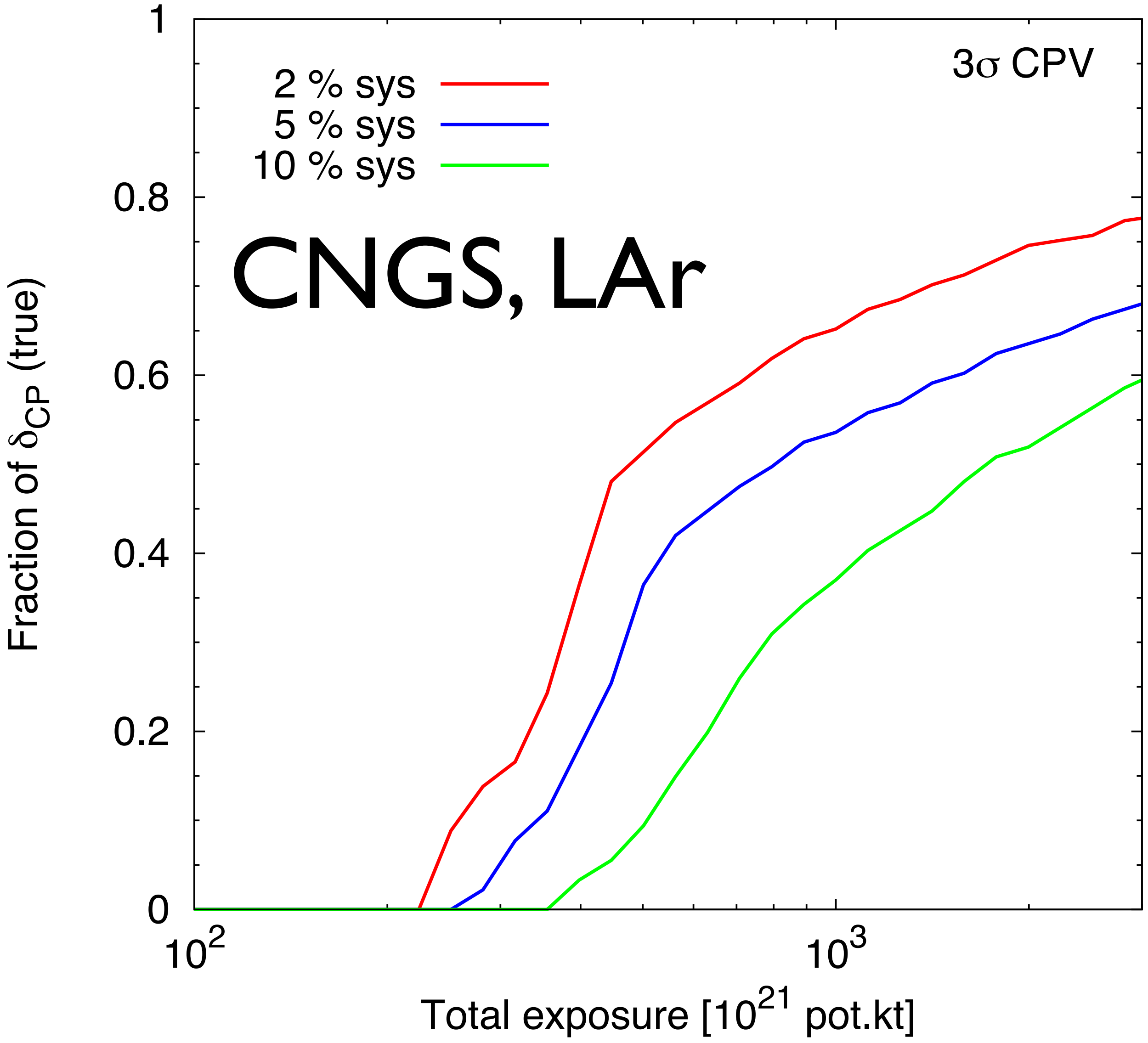
A.A. Aguilar-Arevalo, Phys. Rev. D81, 092005 (2010).



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, in preparation



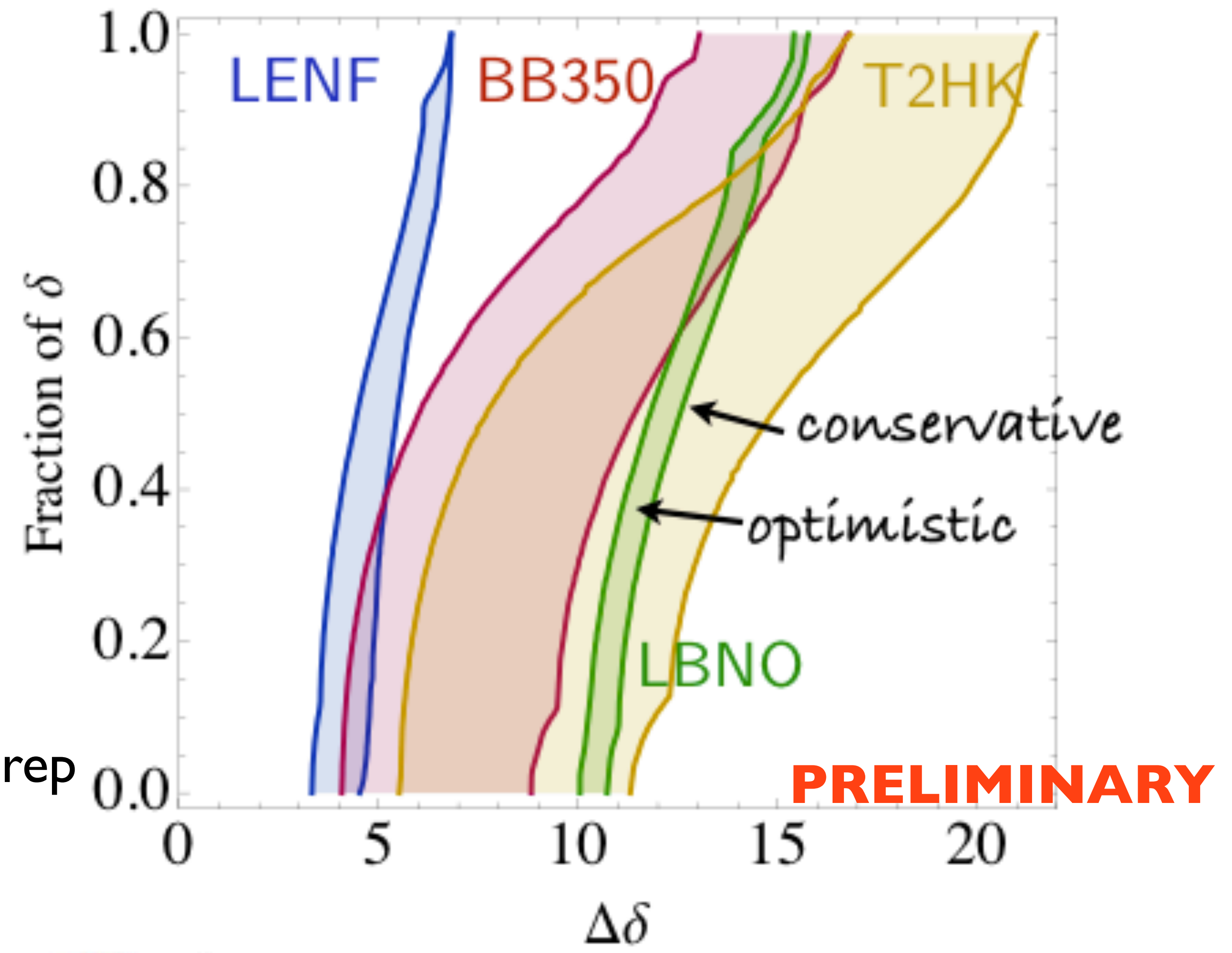
Thanks to T. Li

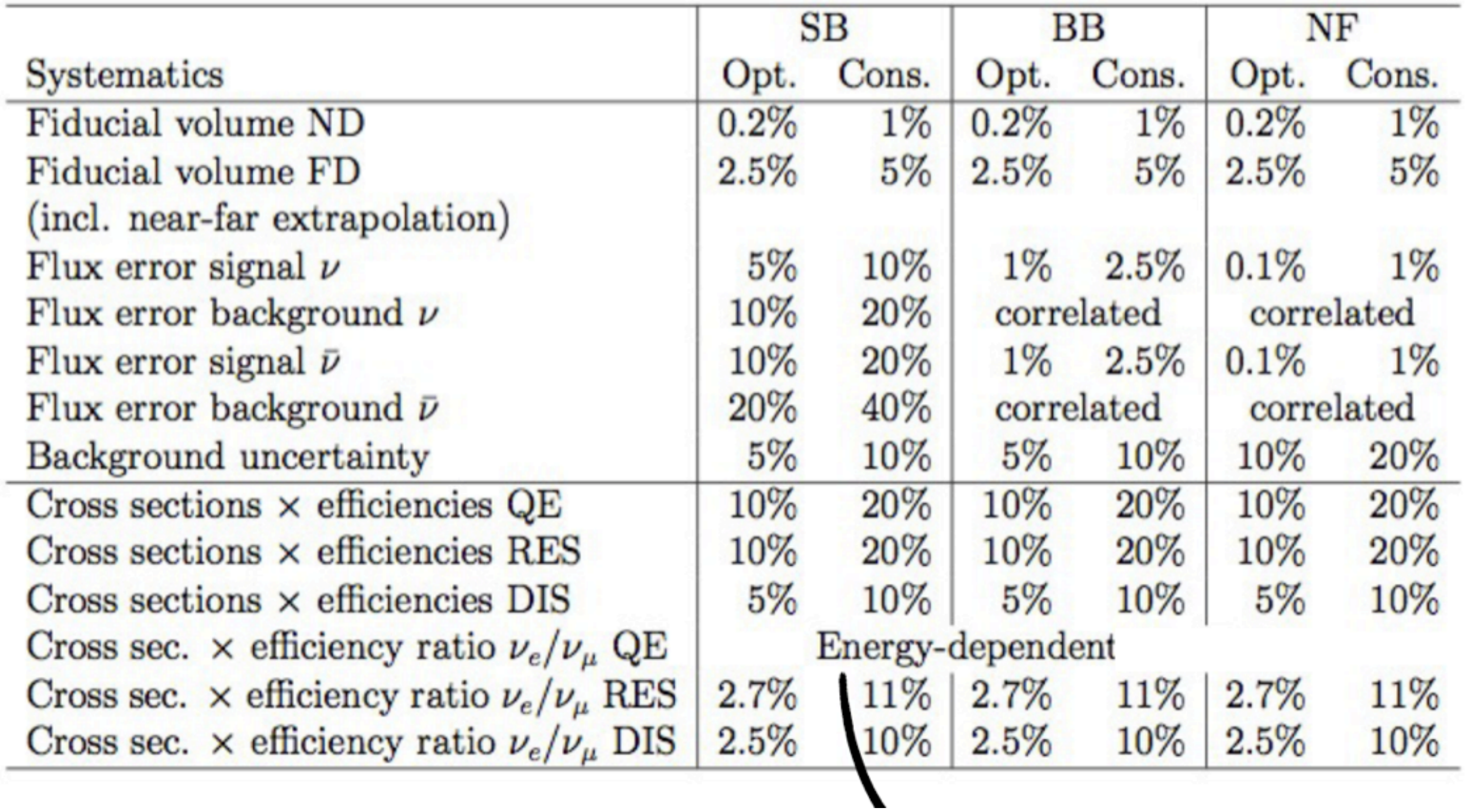
Difference between optimistic and pessimistic assumptions (two-det case):

$$L_{ND} \sim 1-2 \text{ km}$$

$$M_{ND} \sim 25-100 \text{ tons}$$

Coloma, Huber, Kopp, Winter, in prep





Systematics	SB Opt.	SB Cons.	BB Opt.	BB Cons.	NF Opt.	NF Cons.
Fiducial volume ND	0.2%	1%	0.2%	1%	0.2%	1%
Fiducial volume FD (incl. near-far extrapolation)	2.5%	5%	2.5%	5%	2.5%	5%
Flux error signal ν	5%	10%	1%	2.5%	0.1%	1%
Flux error background ν	10%	20%	correlated		correlated	
Flux error signal $\bar{\nu}$	10%	20%	1%	2.5%	0.1%	1%
Flux error background $\bar{\nu}$	20%	40%	correlated		correlated	
Background uncertainty	5%	10%	5%	10%	10%	20%
Cross sections × efficiencies QE	10%	20%	10%	20%	10%	20%
Cross sections × efficiencies RES	10%	20%	10%	20%	10%	20%
Cross sections × efficiencies DIS	5%	10%	5%	10%	5%	10%
Cross sec. × efficiency ratio ν_e/ν_μ QE		Energy-dependent				
Cross sec. × efficiency ratio ν_e/ν_μ RES	2.7%	11%	2.7%	11%	2.7%	11%
Cross sec. × efficiency ratio ν_e/ν_μ DIS	2.5%	10%	2.5%	10%	2.5%	10%

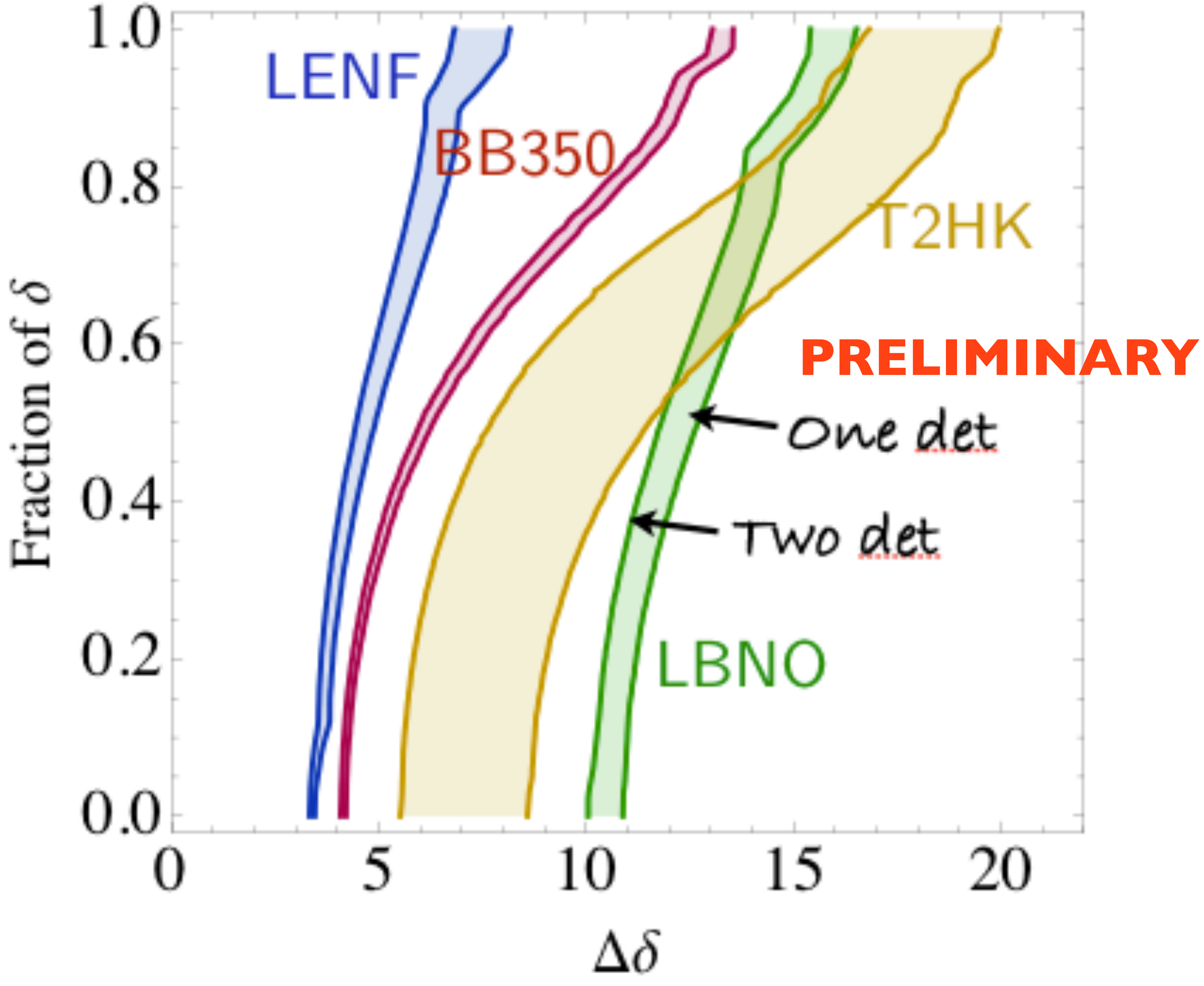
Good energy resolution, wide band beam, additional input will help in reducing the impact of systematic errors.

The near detector(s) will help in reducing the impact of systematic errors by measuring the flux, the intrinsic background contamination....

Difference between 1 detector and 2 detectors (optimistic case):

$$L_{ND} \sim 1 - 2 \text{ km}$$

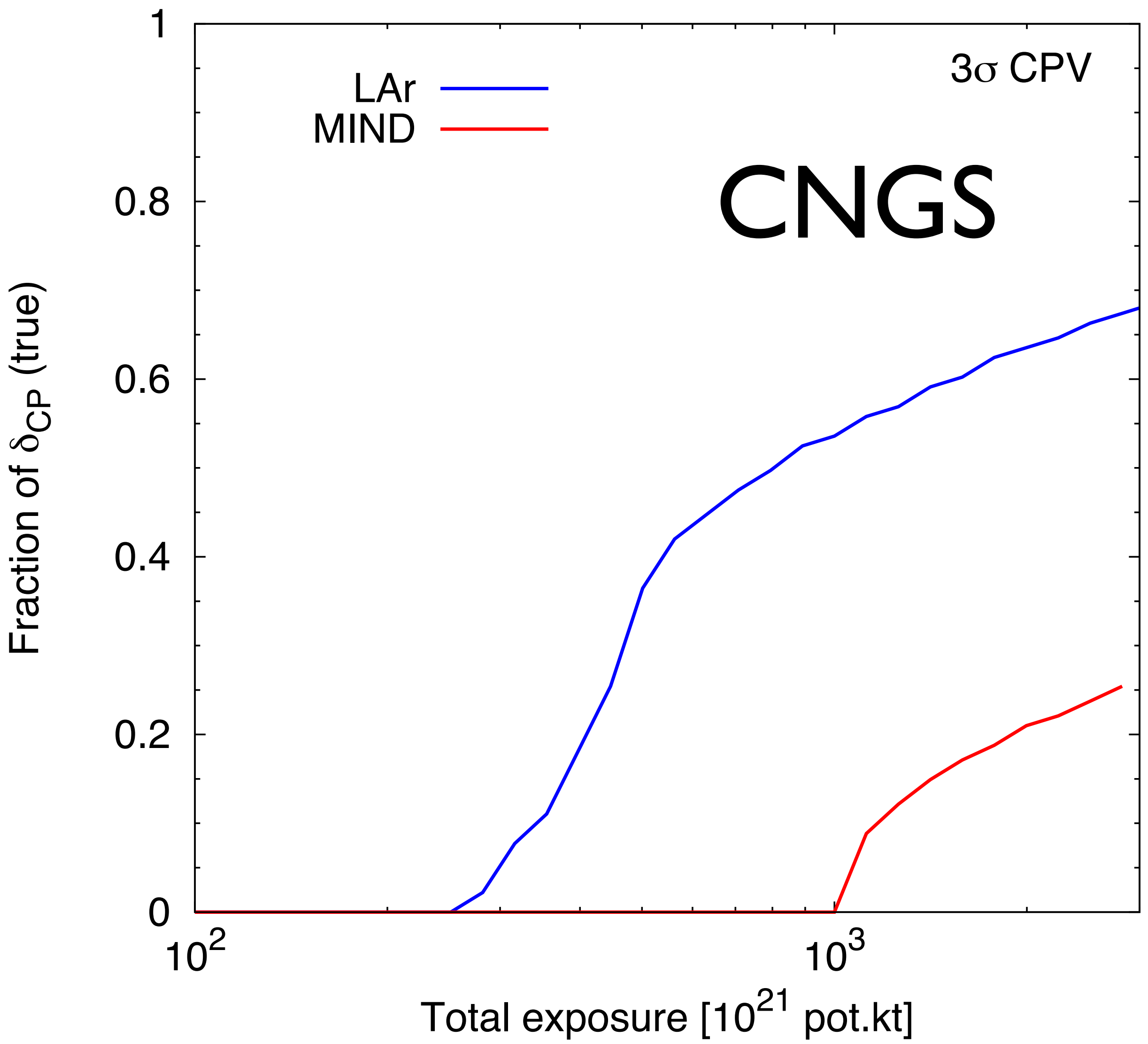
$$M_{ND} \sim 25 - 100 \text{ tons}$$



Coloma, Huber, Kopp, Winter

Comparison between different detector choices.

A detector with low threshold, good energy resolution and excellent NC background rejection is needed to search for CPV.

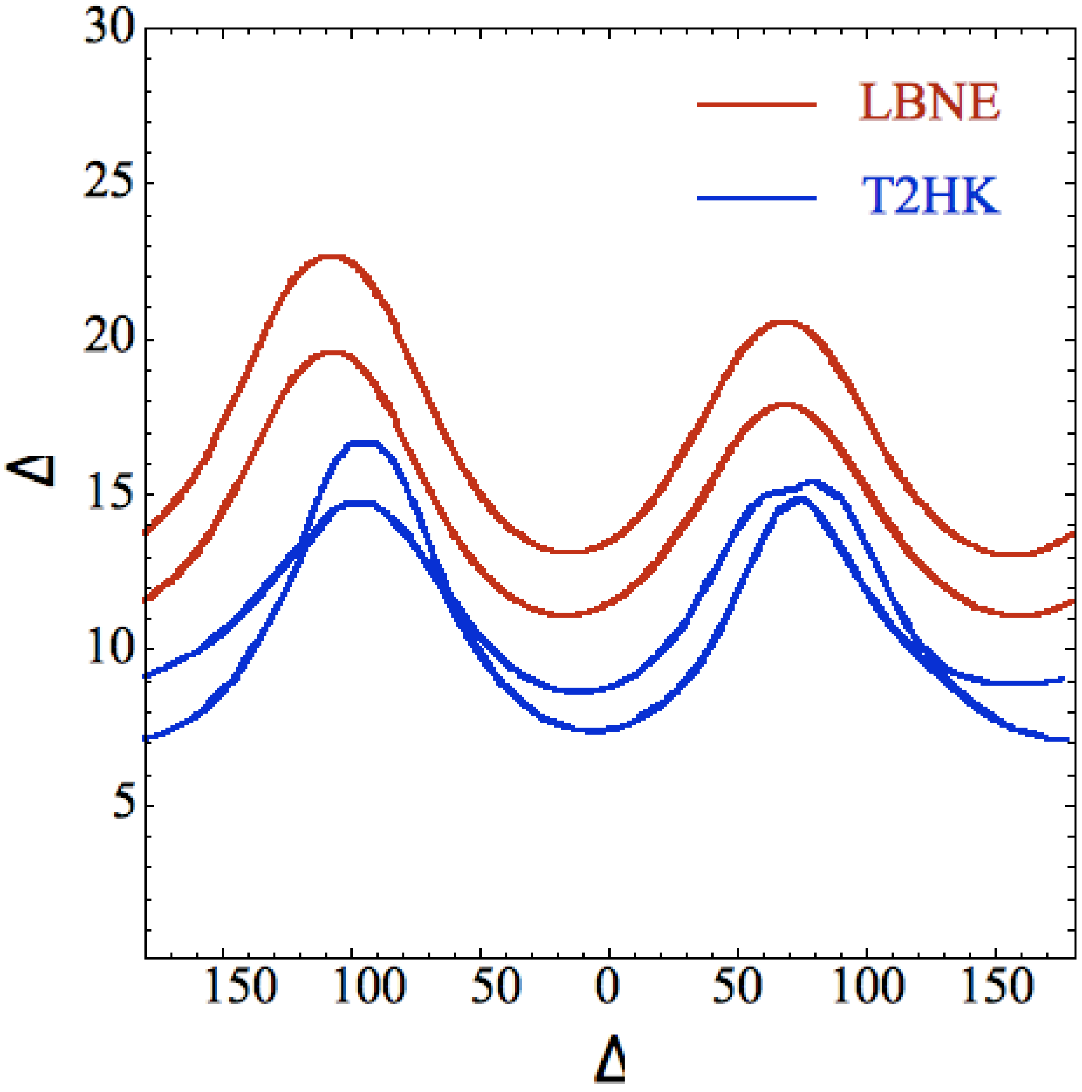


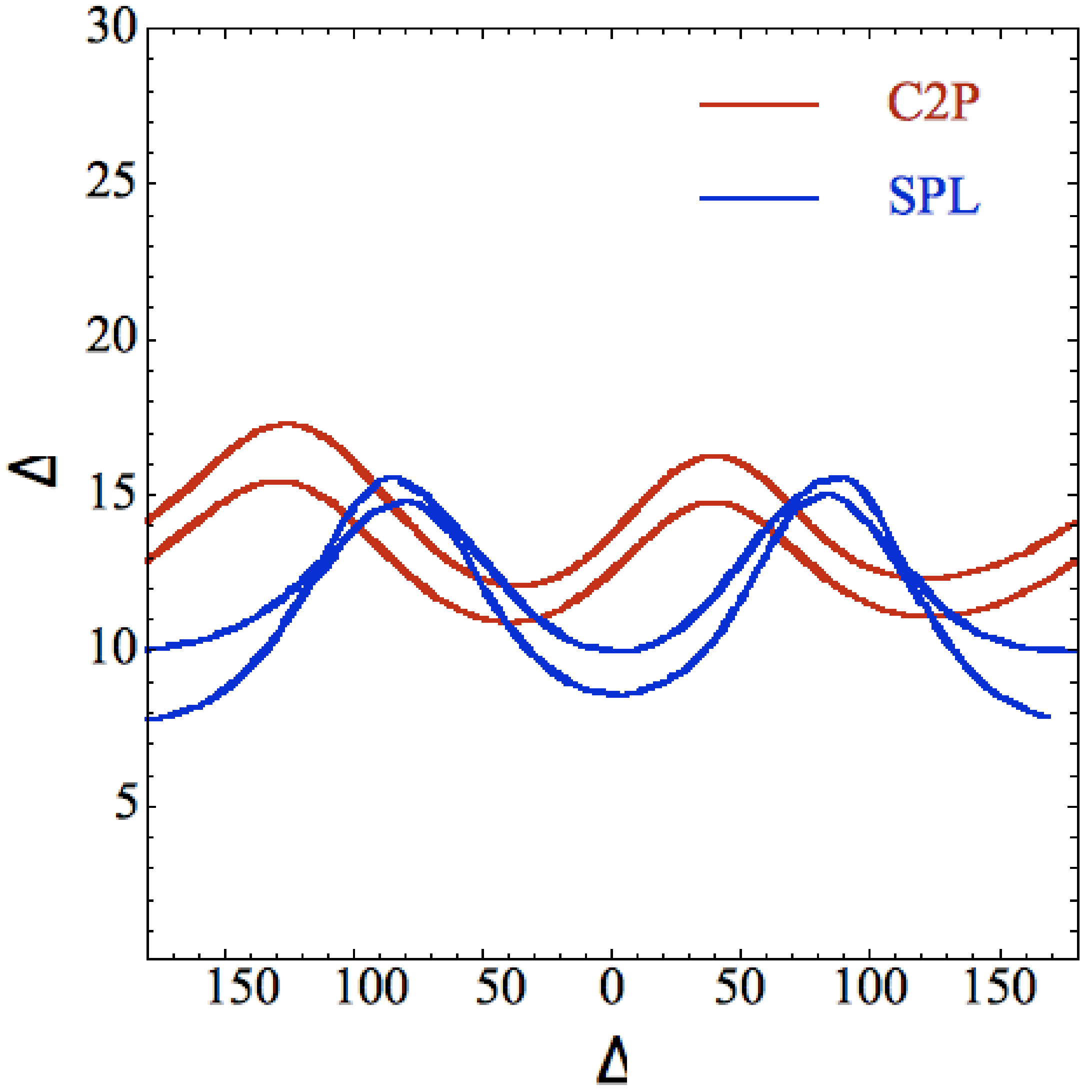
The information on the low energy part of the spectrum is critical for CPV searches.

Thanks to T. Li

Precision measurements of oscillation parameters

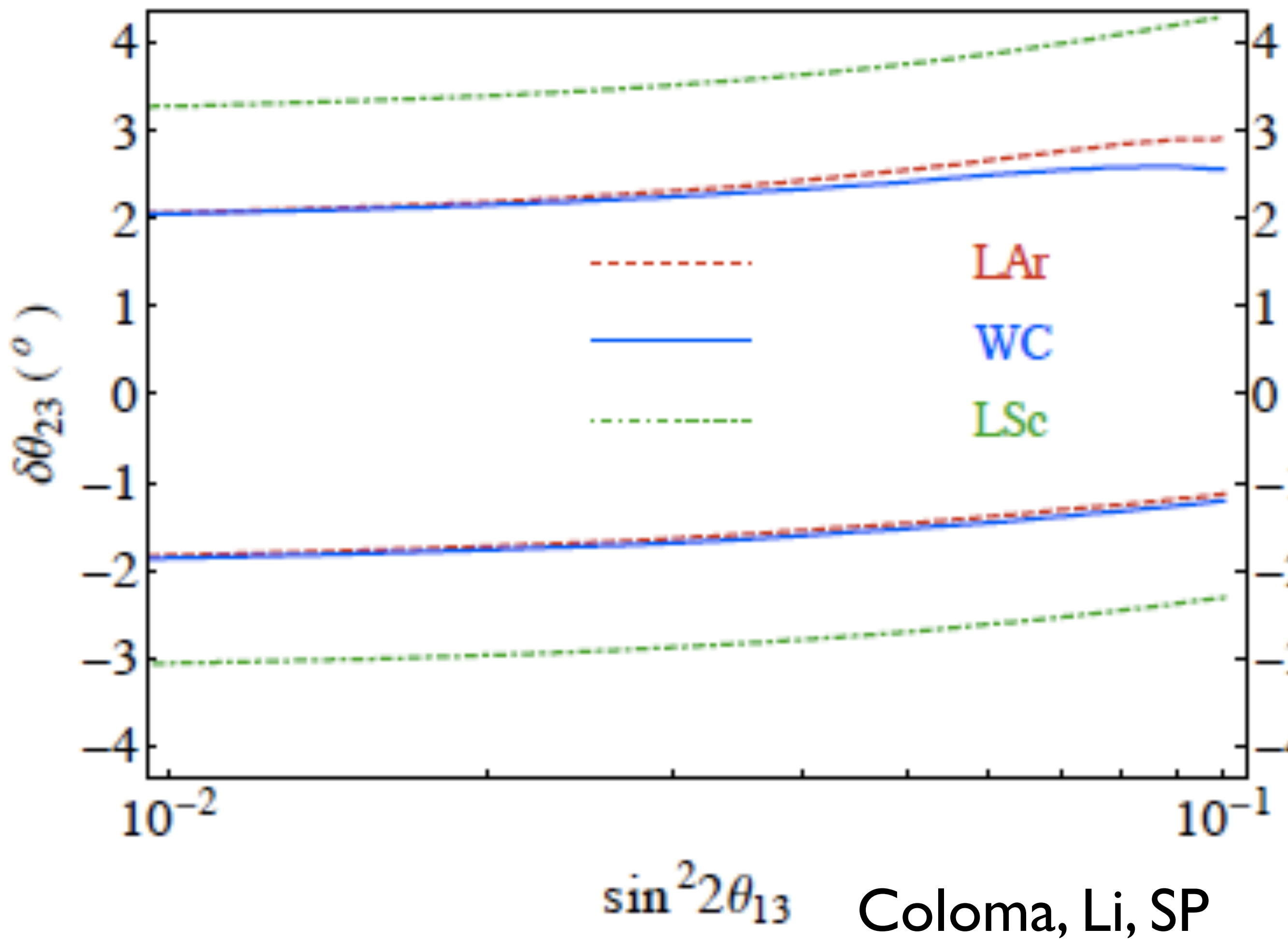
The precision measurement of the oscillation parameters will become very important once the mass hierarchy and CPV are established. LBL experiments can give information on $\theta_{23},\ \theta_{13},\ \delta$.



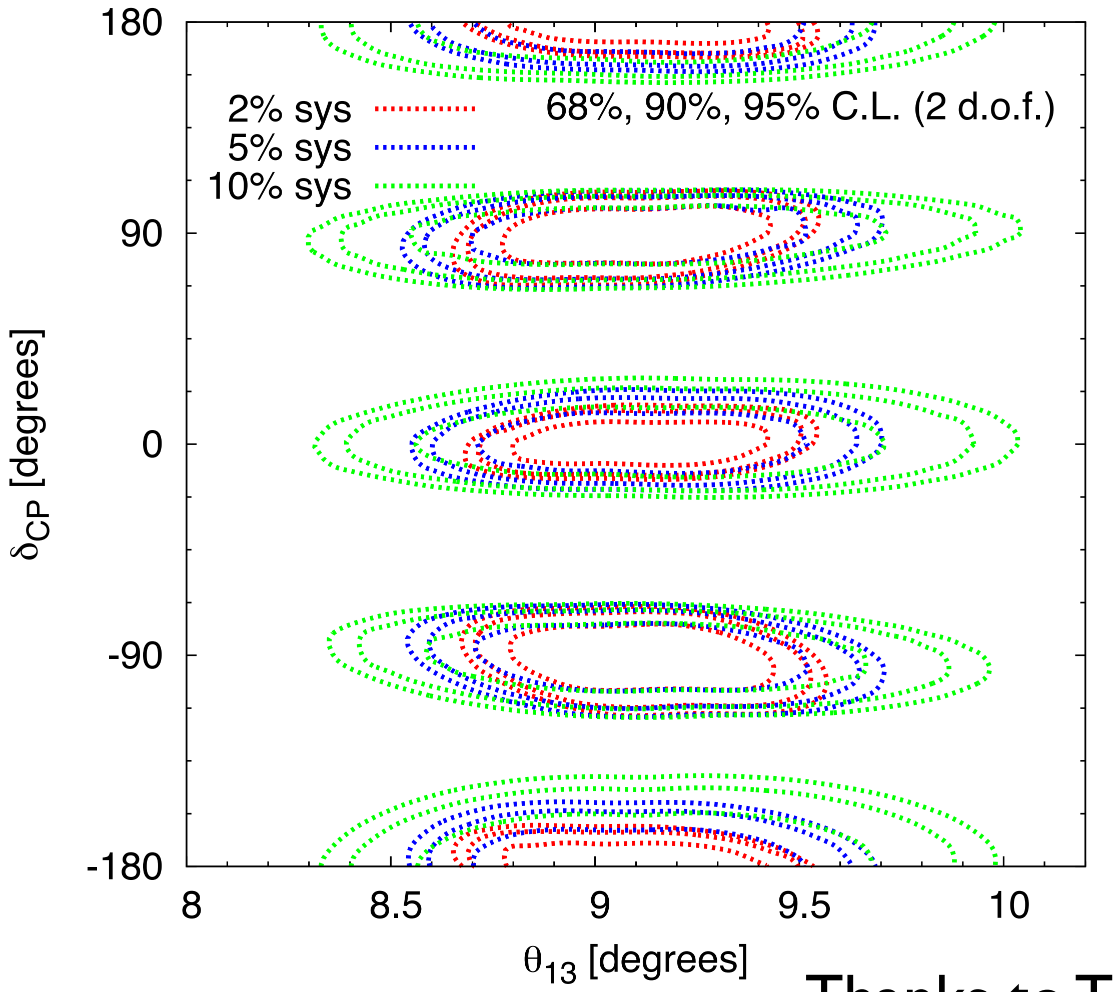


Coloma et al., 1203.5651; Donini, et al. , IDS-NF talk

In addition to delta, the study of sum rules and possible mixing patterns requires a precise measurement of the atmospheric and solar mixing angles and of theta13.



Coloma, Li, SP

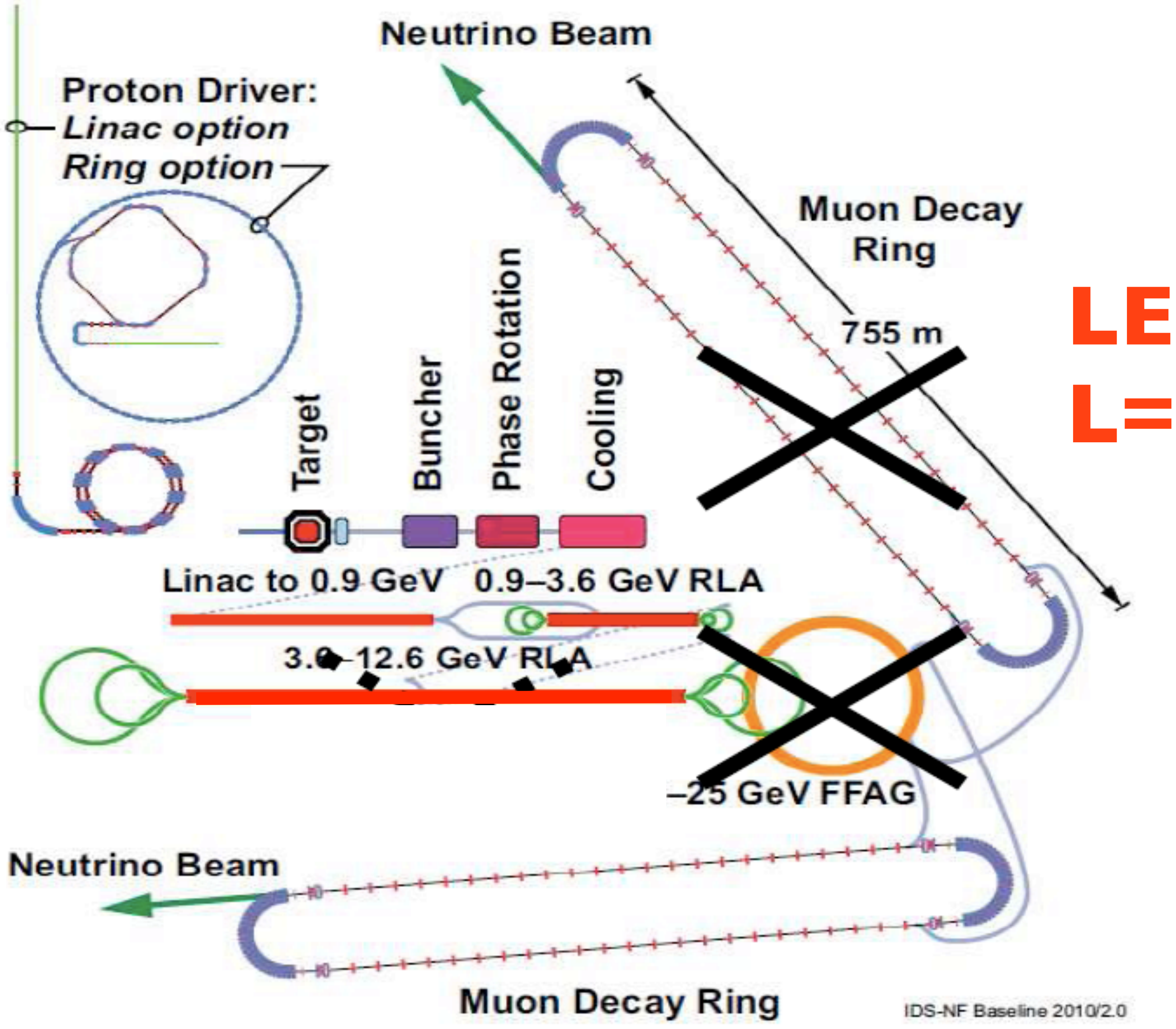


Thanks to T. Li

The first preliminary studies have been carried out but much more detailed analysis are required to fully understand the physics reach of different facilities.

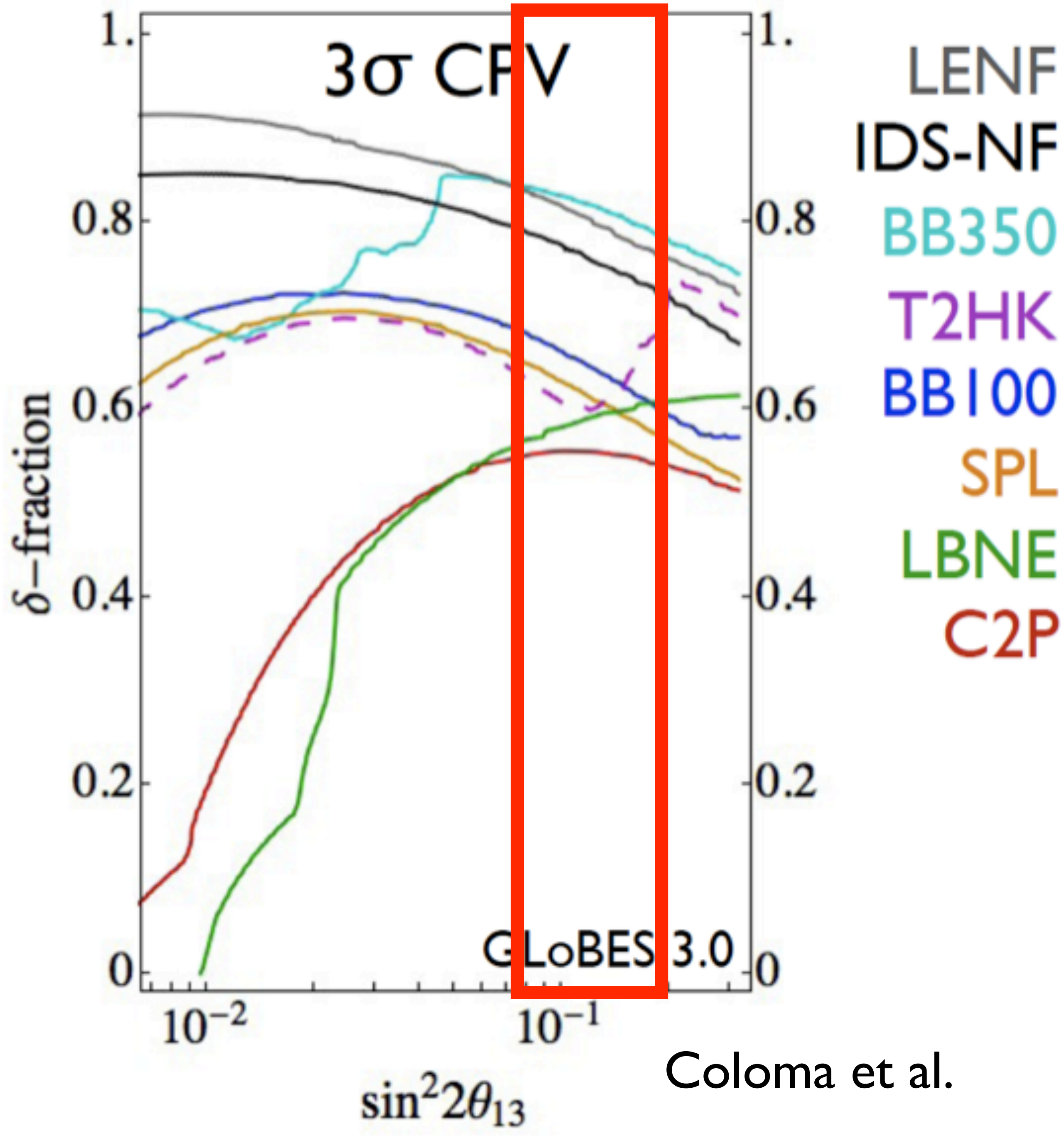
More sensitive facilities could be considered for the future.

- **beta beams:** neutrinos are produced in beta decays of highly accelerated ions.
- **neutrino factory:** neutrinos produced in muon decays. It needs a magnetised detector



LENF: E=10 GeV and L=2000 km

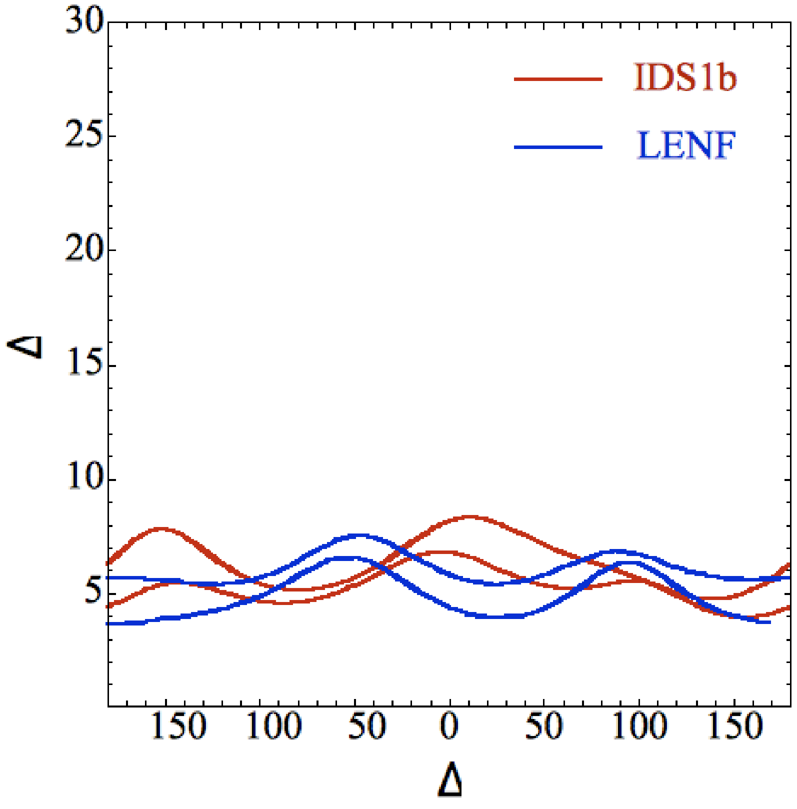
Future facilities can improve on the searches for CPV and provide excellent measurements of the oscillation parameters.

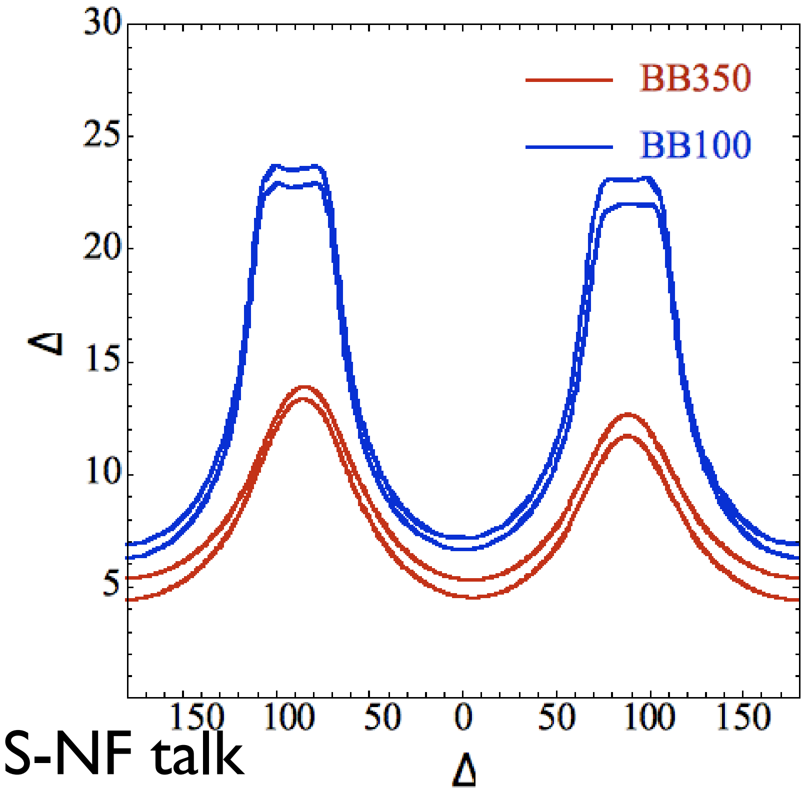


1%sys

5% sys

Coloma et al.





Donini, et al., IDS-NF talk

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 between setups should be done with great care.