Phenomenological aspects of LBL physics: the role of of large theta13

IOP meeting on Future Long Baseline Neutrino experiments
QMUL
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Outline

1. Neutrino properties: questions for the future and the discovery of theta13

2. Theoretical aspects of long baseline neutrino oscillations

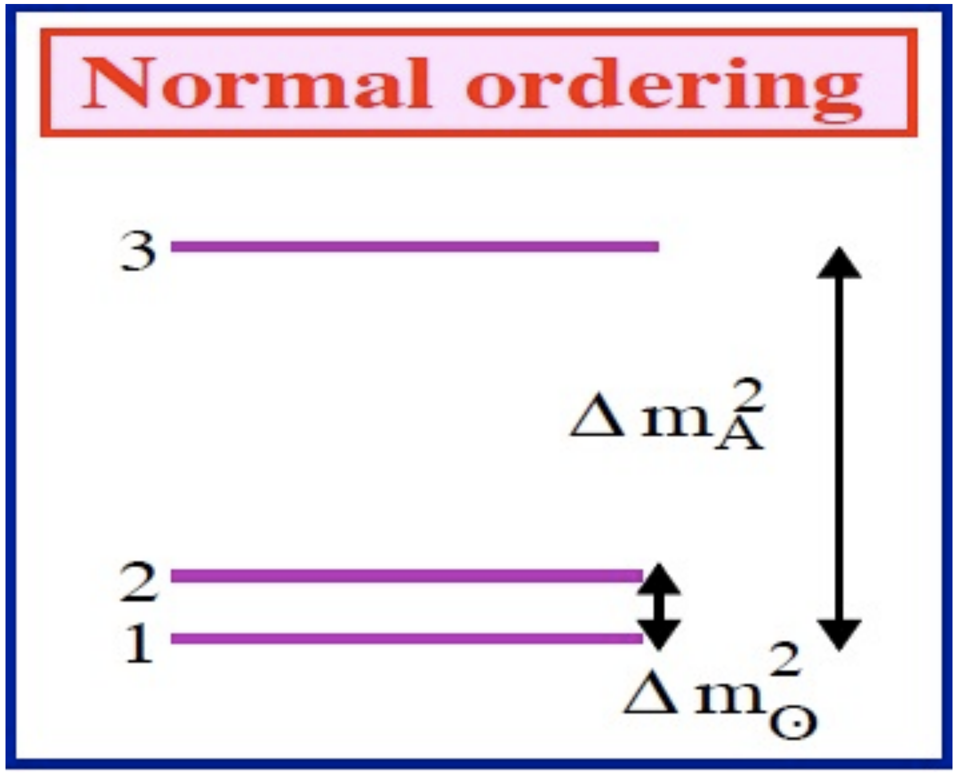
3. Longbaseline neutrino oscillation experiments: comparison of facilities

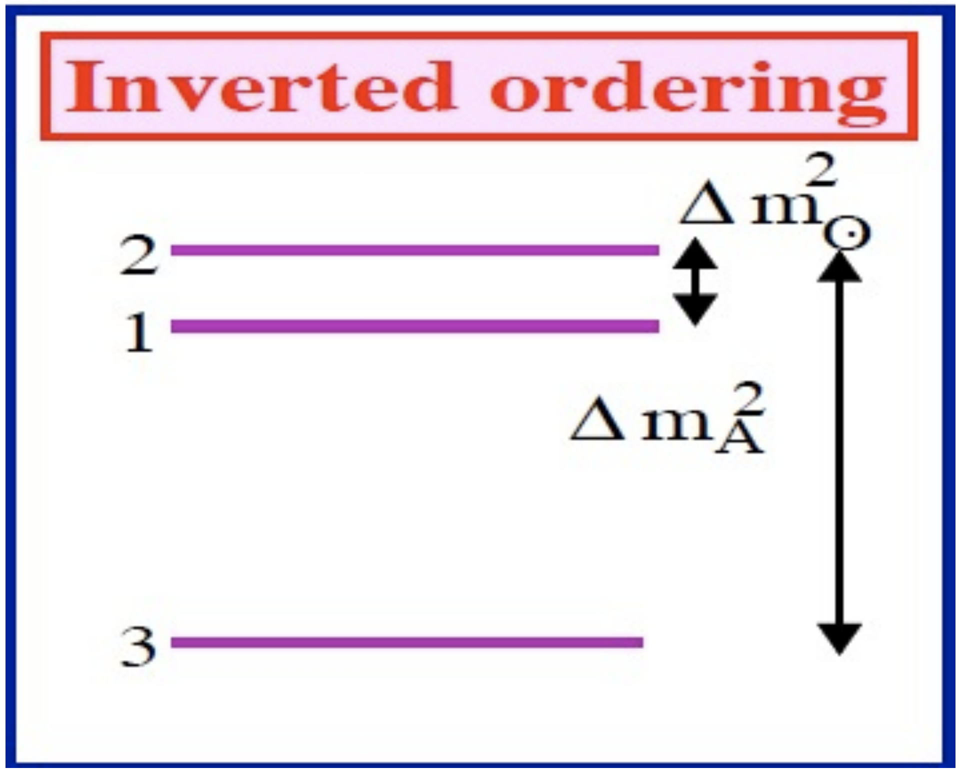
4. Neutrino parameters precision measurements

4. Conclusions

Present status of (standard) neutrino physics

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





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

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

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

Neutrino mixing

The Pontecorvo-Maki-Nakagawa-Sakata mixing matrix:

$$U = \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, reactor } \theta_\odot \sim 30^o} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atm, Acc. } \theta_A \sim 45^o}$$

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}}_{\text{CPV phase}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor, Acc. } \theta_{13} \sim 9^o} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}}_{\text{CPV Majorana phases}}$$

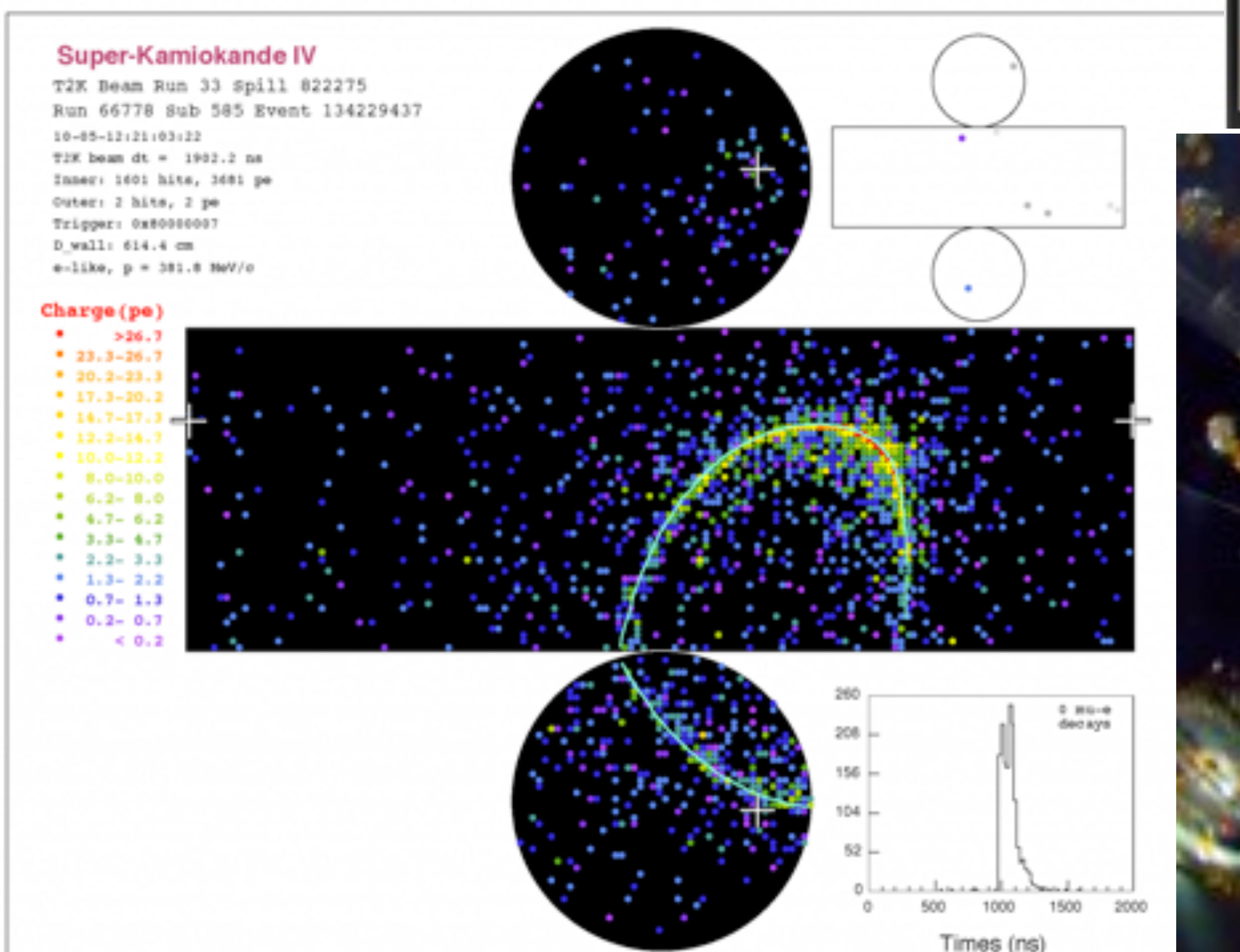
CP-symmetry is one of the important symmetries in particle physics and a necessary condition for leptogenesis. It is broken in the quark sector.

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

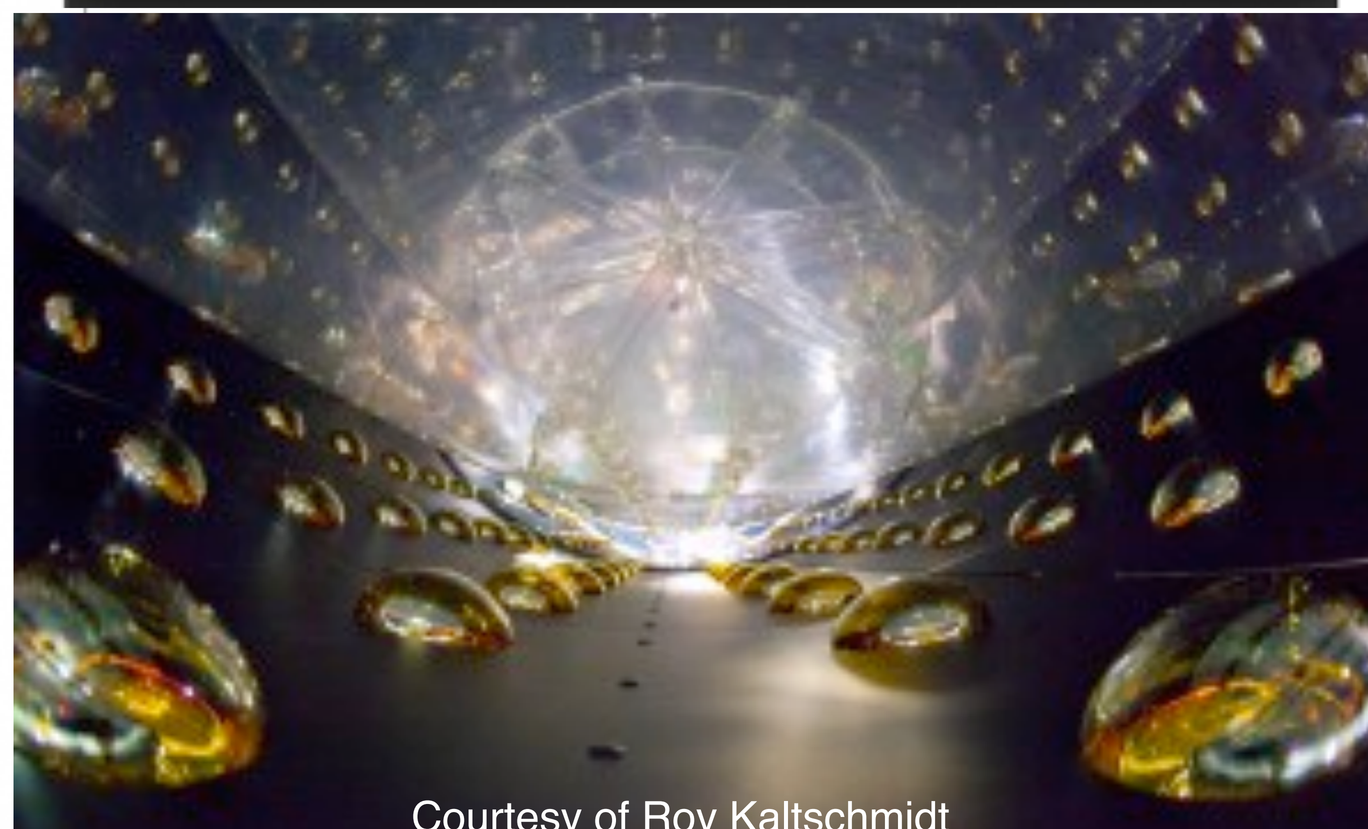
$$P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})$$

CP-conservation requires U is real $\Rightarrow \delta = 0, \pi$

In 2012, previous hints (DoubleCHOOZ, T2K, MINOS) for a nonzero third mixing angle were confirmed by Daya Bay and RENO: important discovery.

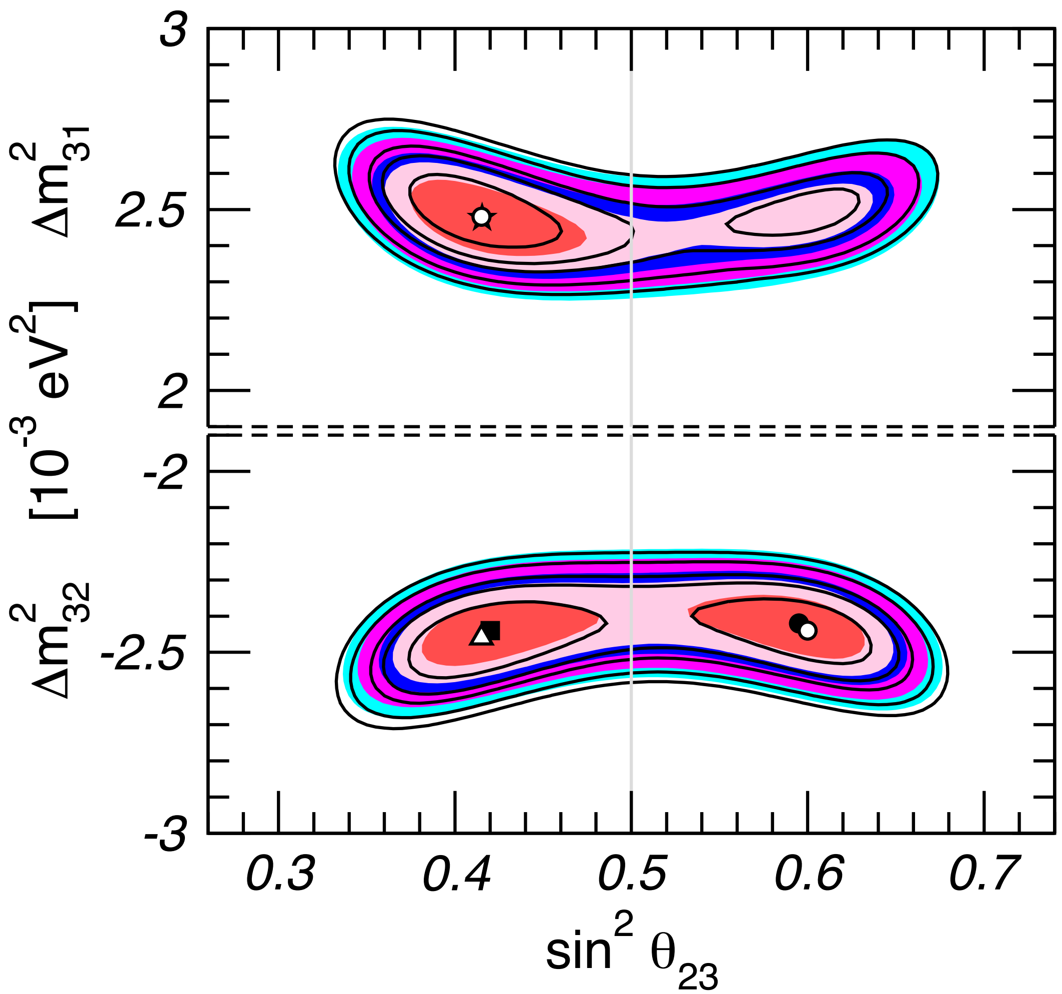


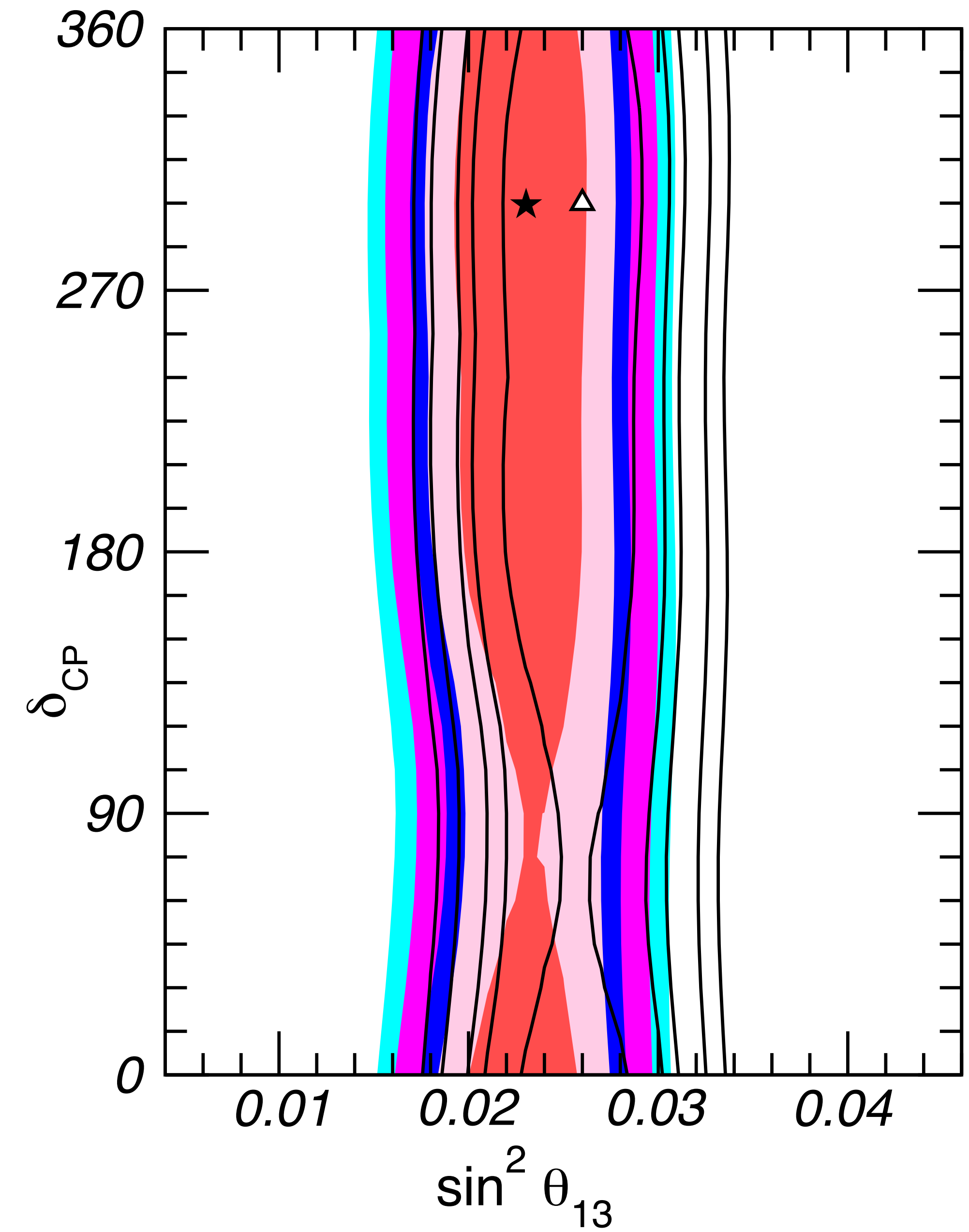
T2K event in 2011


Courtesy of Roy Kaltschmidt

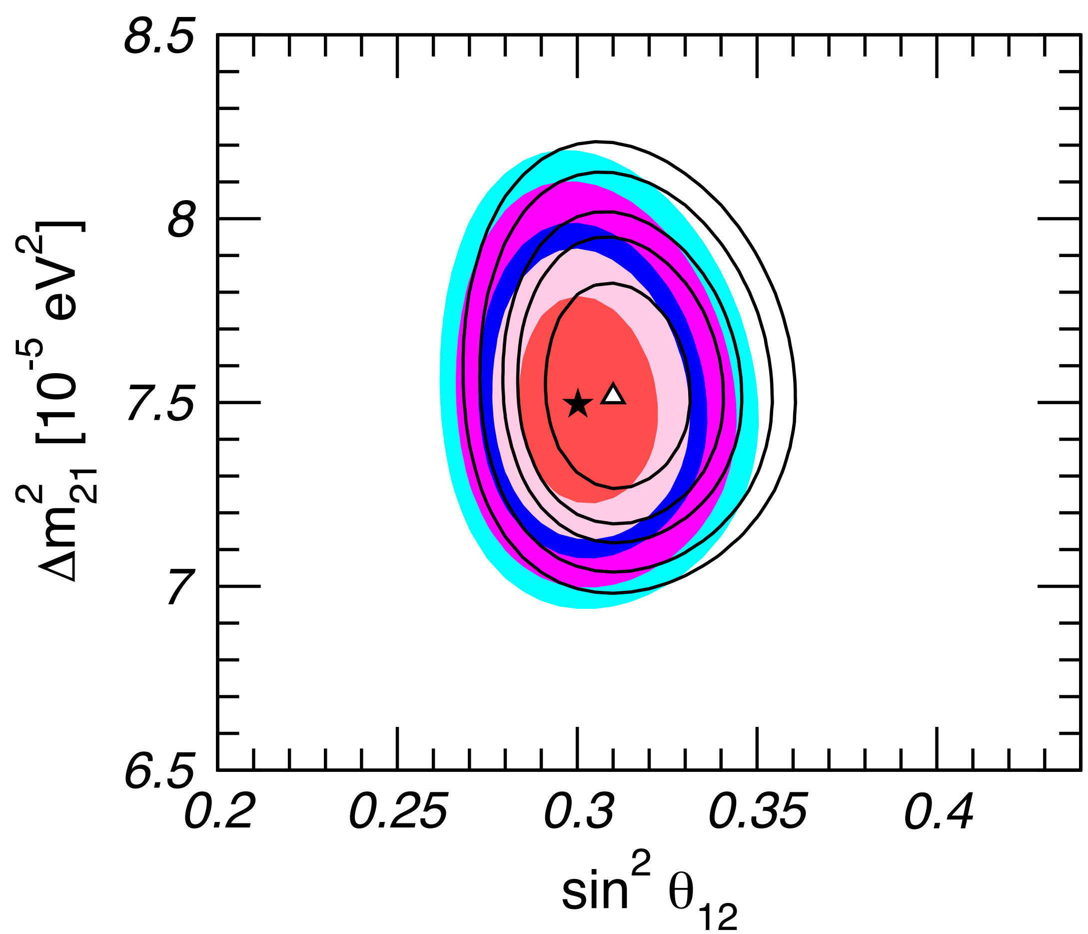
Daya Bay: reactor neutrino experiment in China

This discovery has very important implications for the future neutrino programme and our understanding of the origin of mixing.





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



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 (J. Hartnell'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? Do they suggest a underlying pattern?**

- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

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.**

Neutrino oscillations in matter

- When neutrinos travel through a medium, they interact with the background of electron, proton and neutrons and acquire an effective mass.

- Typically the background is CP and CPT violating, e.g. the Earth and the Sun contain only electrons, protons and neutrons, and the resulting oscillations are CP and CPT violating.

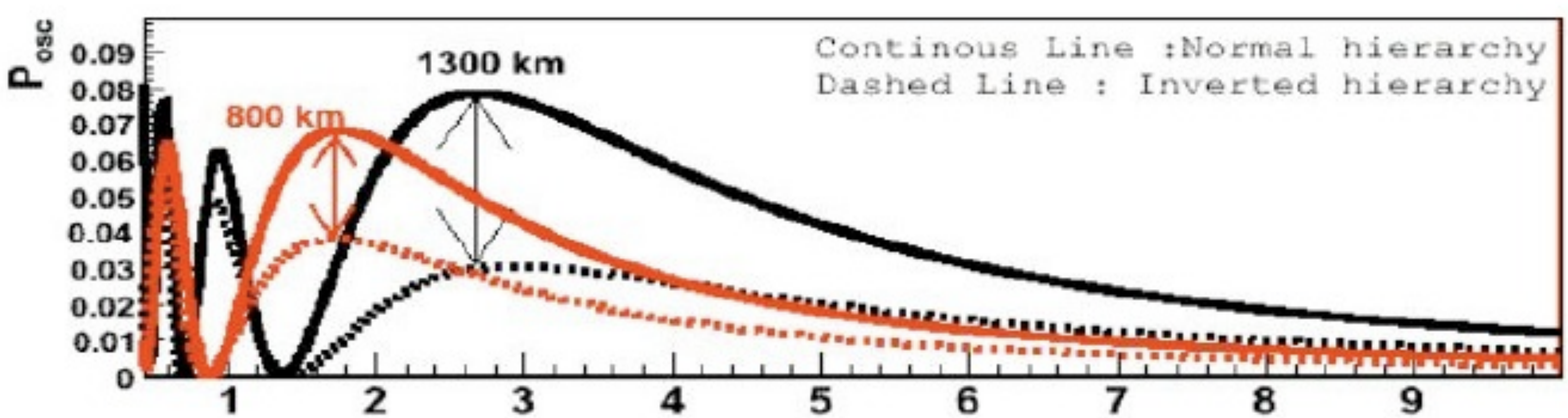
$$V = \sqrt{2} G_F (N_e - N_n/2)$$

$$P_{\nu_\mu \to \nu_e} = \sin^2\theta_{23} \sin^2 2\theta_{13}^m \sin^2 \frac{\Delta_{13}^m L}{2}$$

The mixing angle in matter is

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

- The enhancement of the neutrino oscillations probability is found for
  - neutrinos if $\Delta m^2 > 0$
  - antineutrinos if $\Delta m^2 < 0$



CPV effects

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

- $\boxed{\frac{\Delta m_{21}^2}{4E} L \ll 1}$, applies to atmospheric, reactor (CHOOZ...), current accelerator neutrino experiments

$$P(\nu_\alpha \to \nu_\beta) = 4 \left| U_{\alpha 3} U_{\beta 3} \right|^2 \sin^2 \left(\frac{\Delta m_{31}^2}{4E} L \right)$$

$$P(\nu_\mu \to \nu_e; t) = s_{23}^2 \sin^2(2\theta_{13}) \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

$$P(\nu_e \to \nu_e; t) = 1 - \sin^2(2\theta_{13}) \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

CP-violation will manifest itself in neutrino oscillations, due to the delta phase. 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 we have seen that effective 2-neutrino probabilities are CP-symmetric.

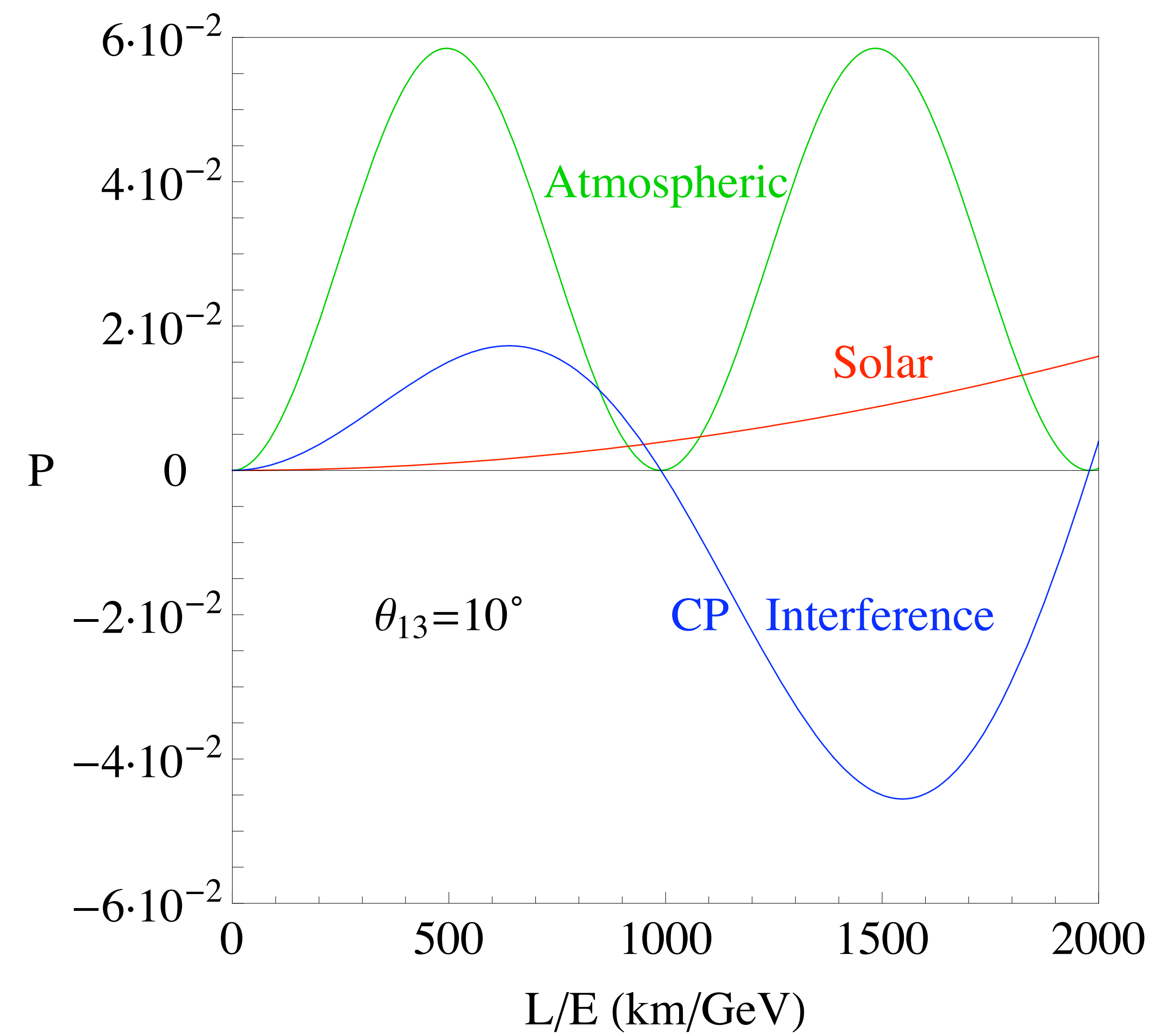
One can compute the probability in matter by expanding the full 3-neutrino oscillation probability.

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

CP-violation

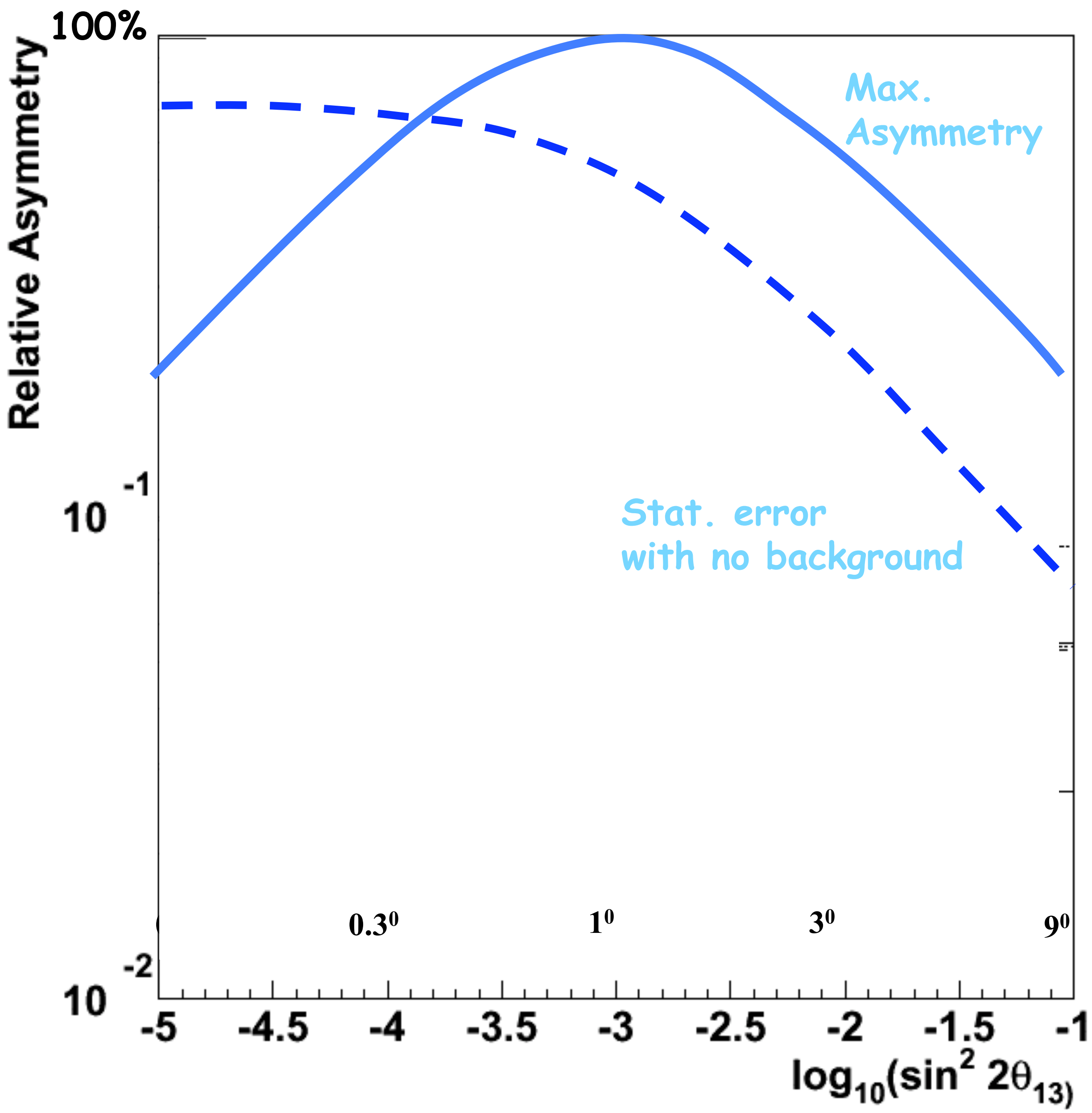
Matter effects

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

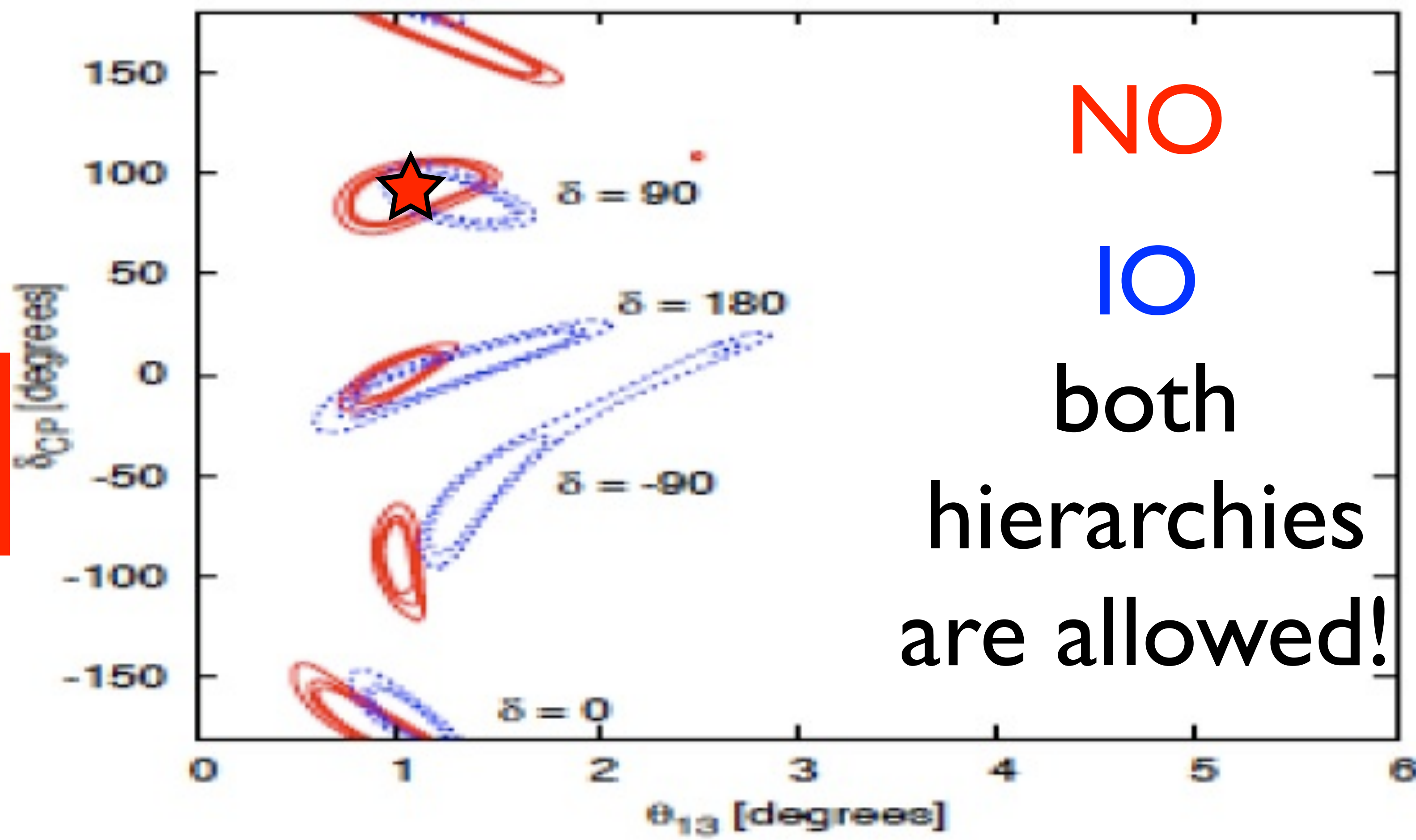
Degeneracies

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).

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

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

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



NO

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both hierarchies are allowed!

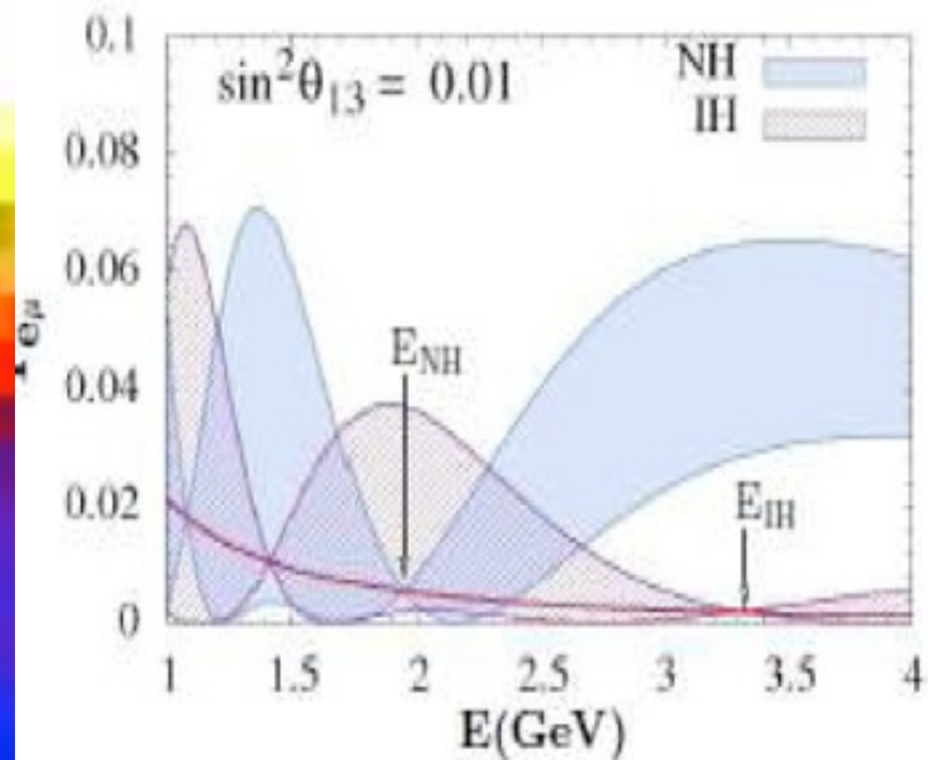
- (θ_{13}, δ) degeneracy (Koike, Ota, Sato; Burguet-Castell et al.)

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

Having information at different L/E can resolve this.

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

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



This degeneracy is broken by matter effects.

For ex. Bimagic baseline at L=2540 km
Excellent sensitivity to the hierarchy
A. Dighe et al., 1009.1093; Raut et al. 0908.3741; Joglekar et al. 1011.1146

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

Future long baseline experiments

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

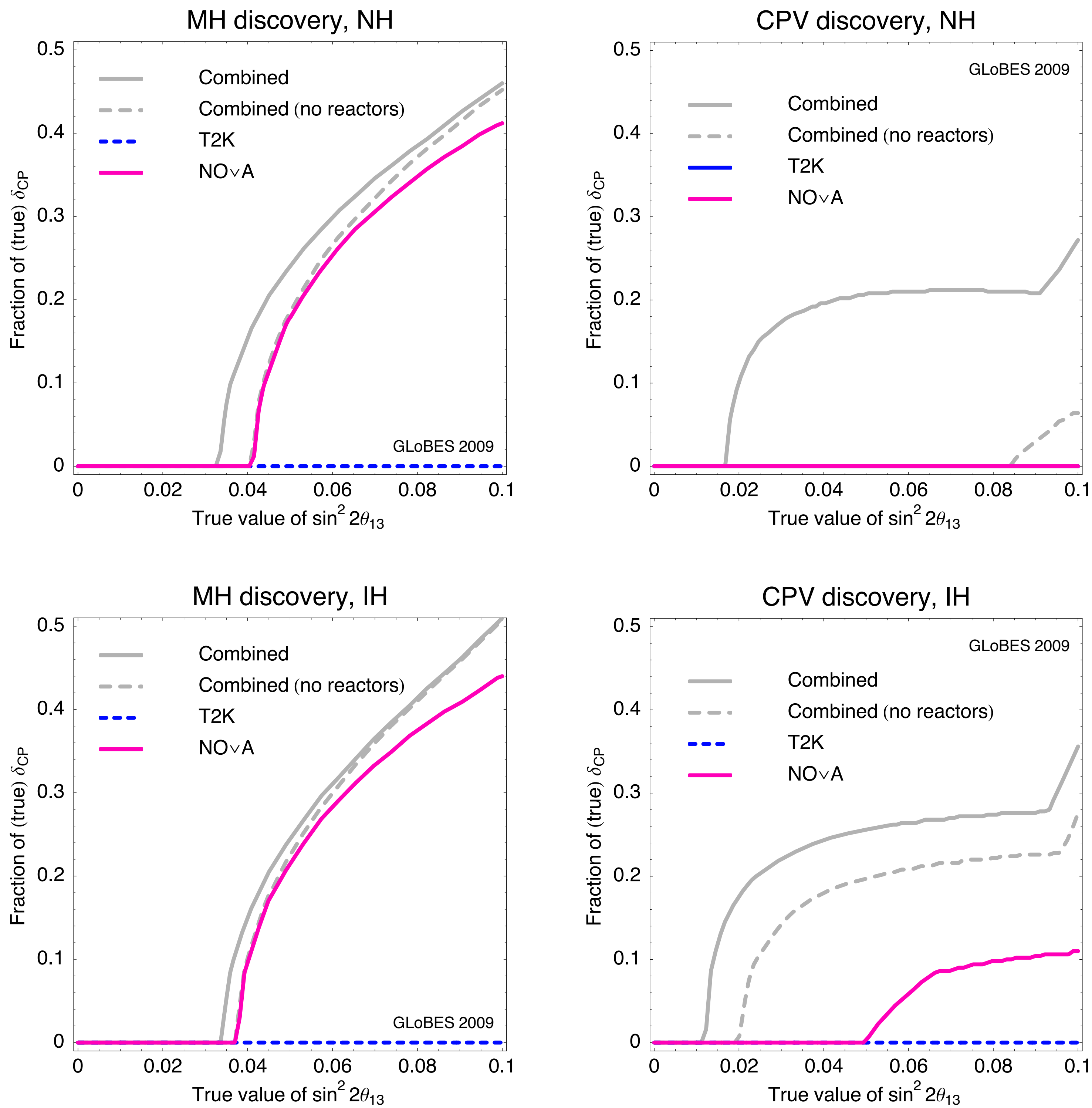
- **Betabeams**: Use electron neutrinos from high-gamma **ion decays**.

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

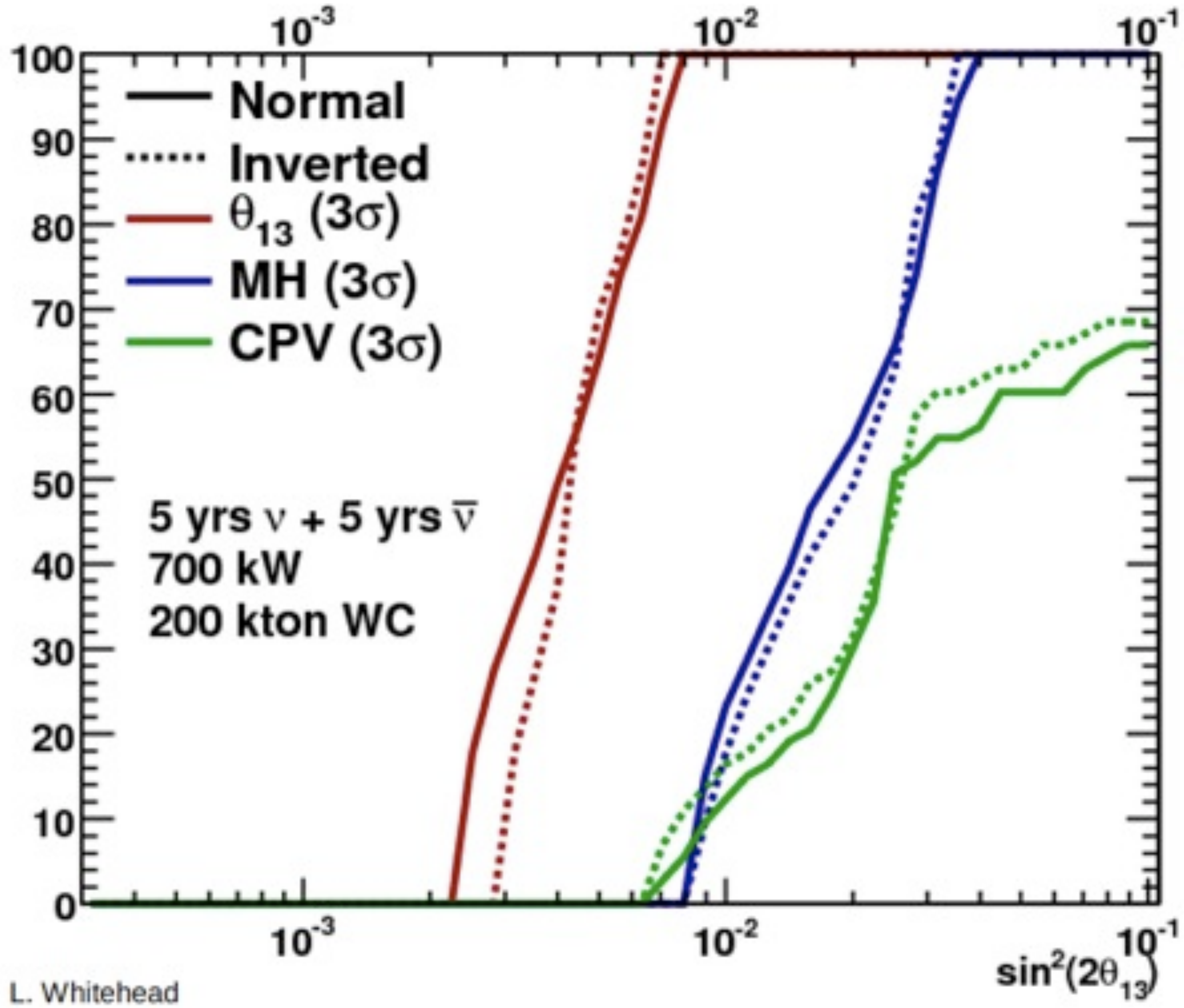
The physics reach of the facilities is actively studied at present in order to shape the future experimental neutrino program.

Superbeams

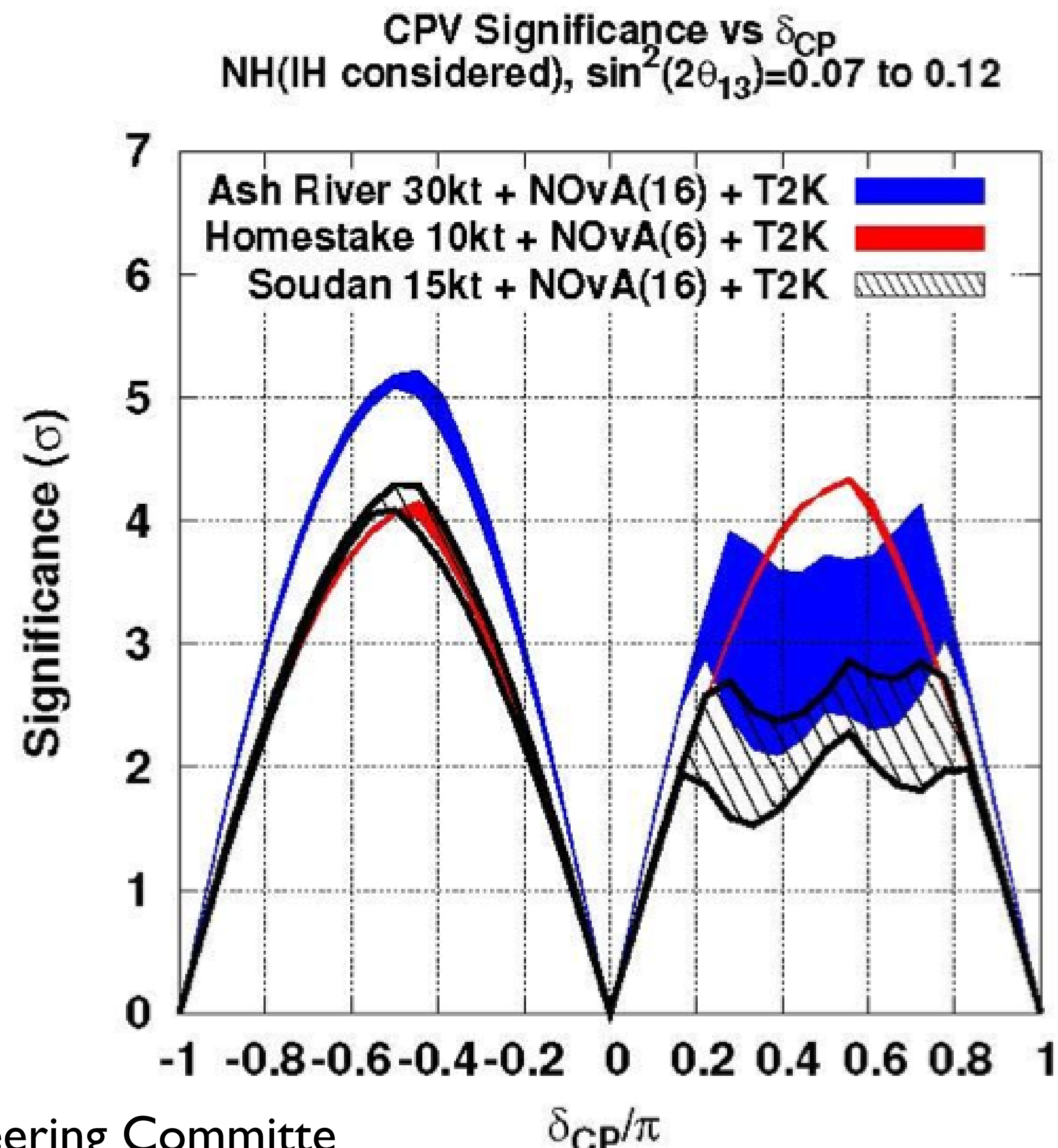
90% CL reach for T2K (0.75 MW 5 yrs), NOvA (0.7 MW, 3 yrs, nu+nubar, 15 kton detector)



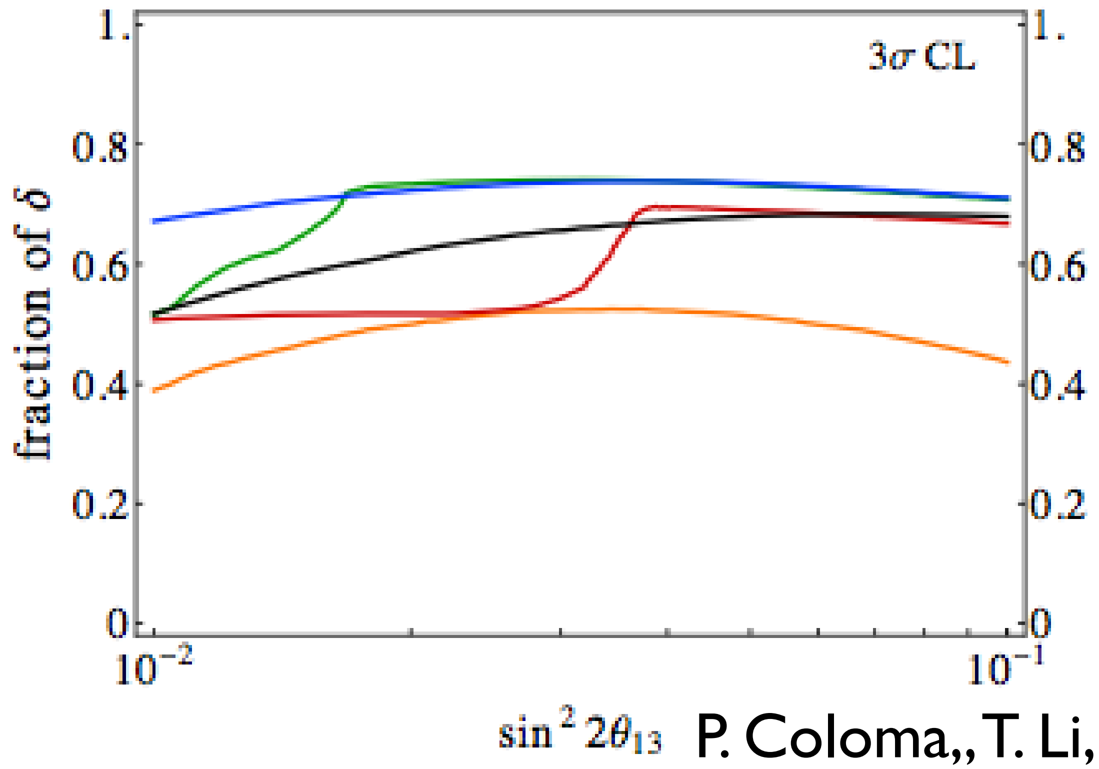
Huber at al., 2009



LBNE: Two detector options: 200 kton WC, 34 kton LiAr. At these energies they have very similar physics reach.

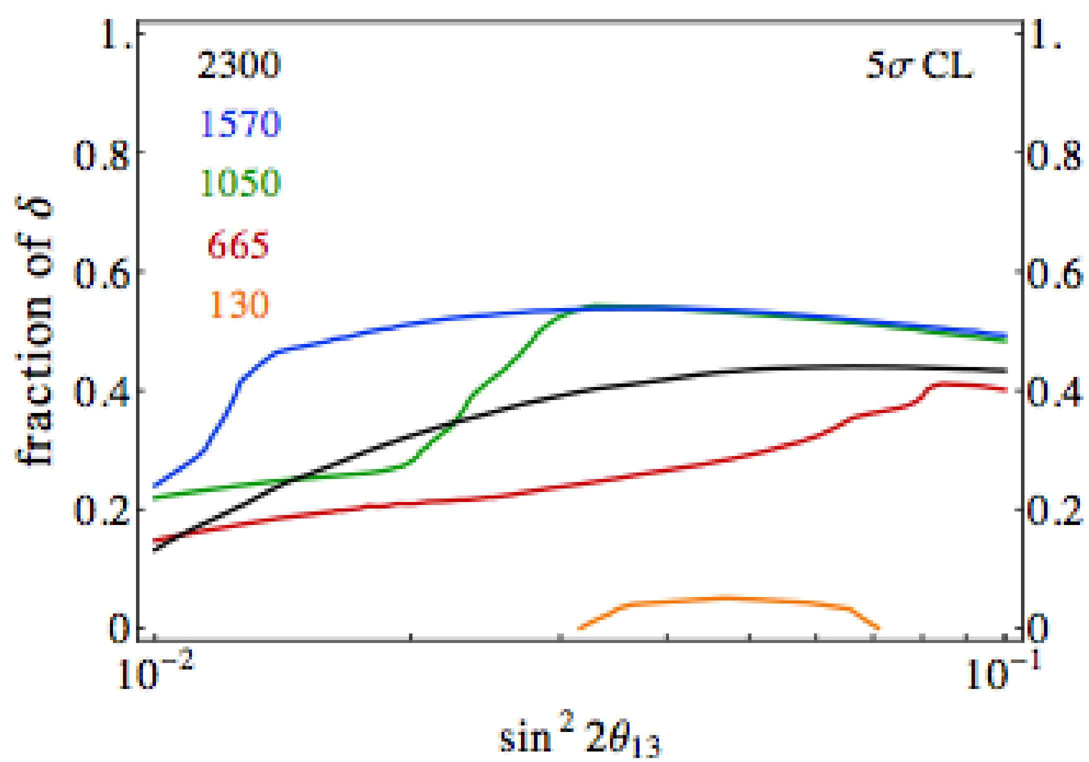


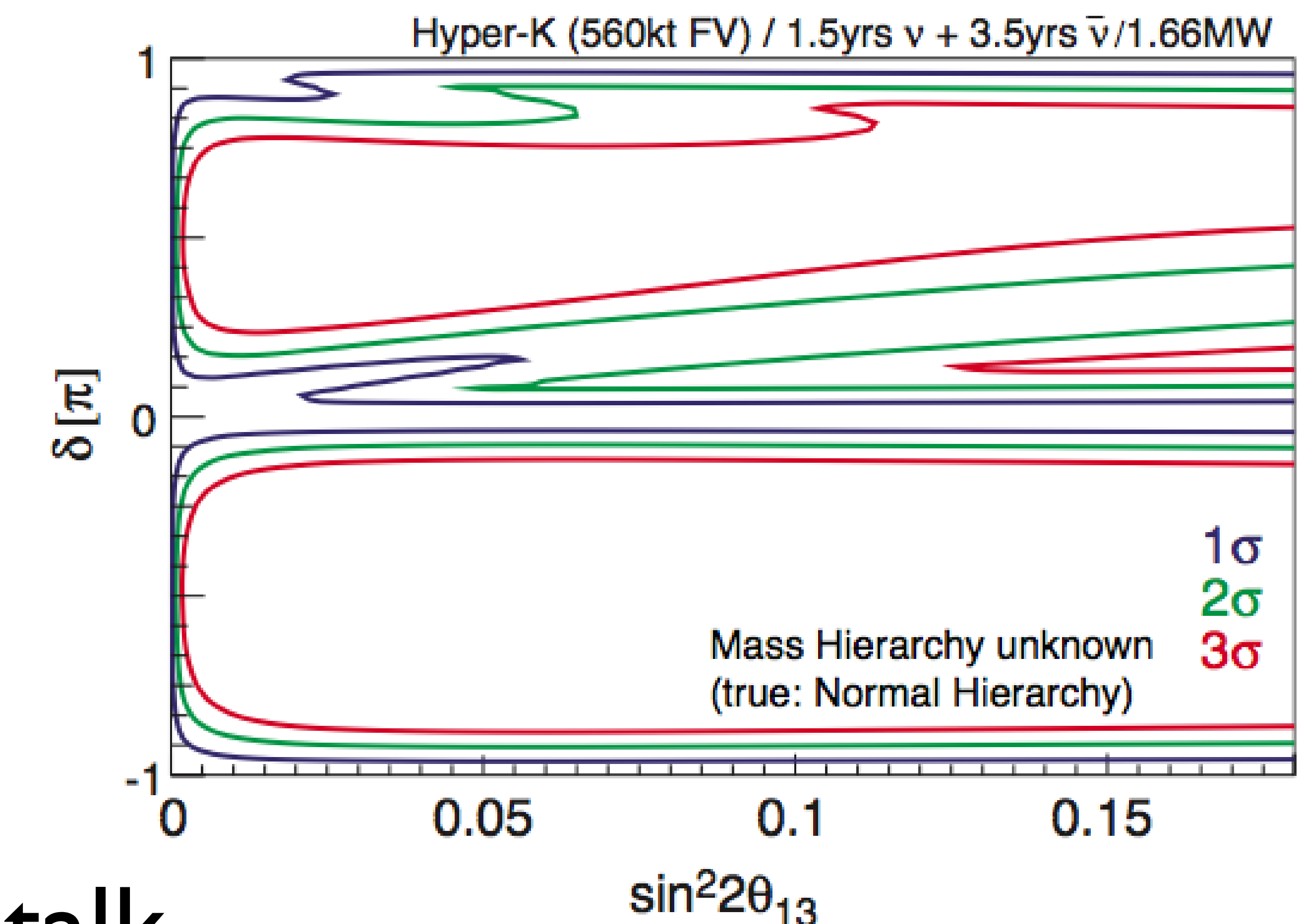
In 2012 a reconfiguration took place. Now the baseline choice is a 10 kton detector at Homestake. In October CD1 is expected. See J. Evans's talk.



P. Coloma,, T. Li, SP, 1206.4038

LBNO: Incremental approach for large theta13. Smaller detectors than the baseline choice (100 kton LAr, 500 Kton WC) to be upgraded. See N. McCauley's talk.



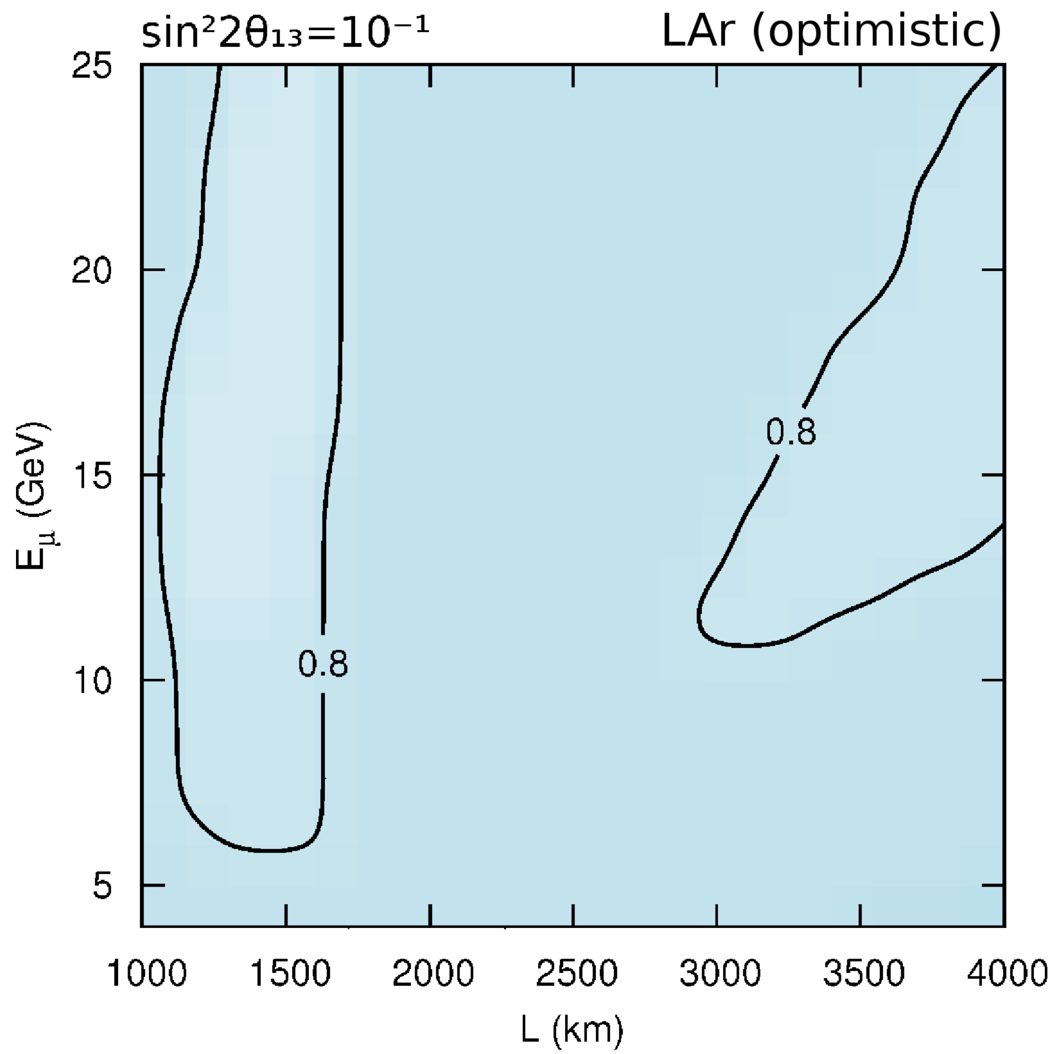


T2HK

See T. Nakaya's talk

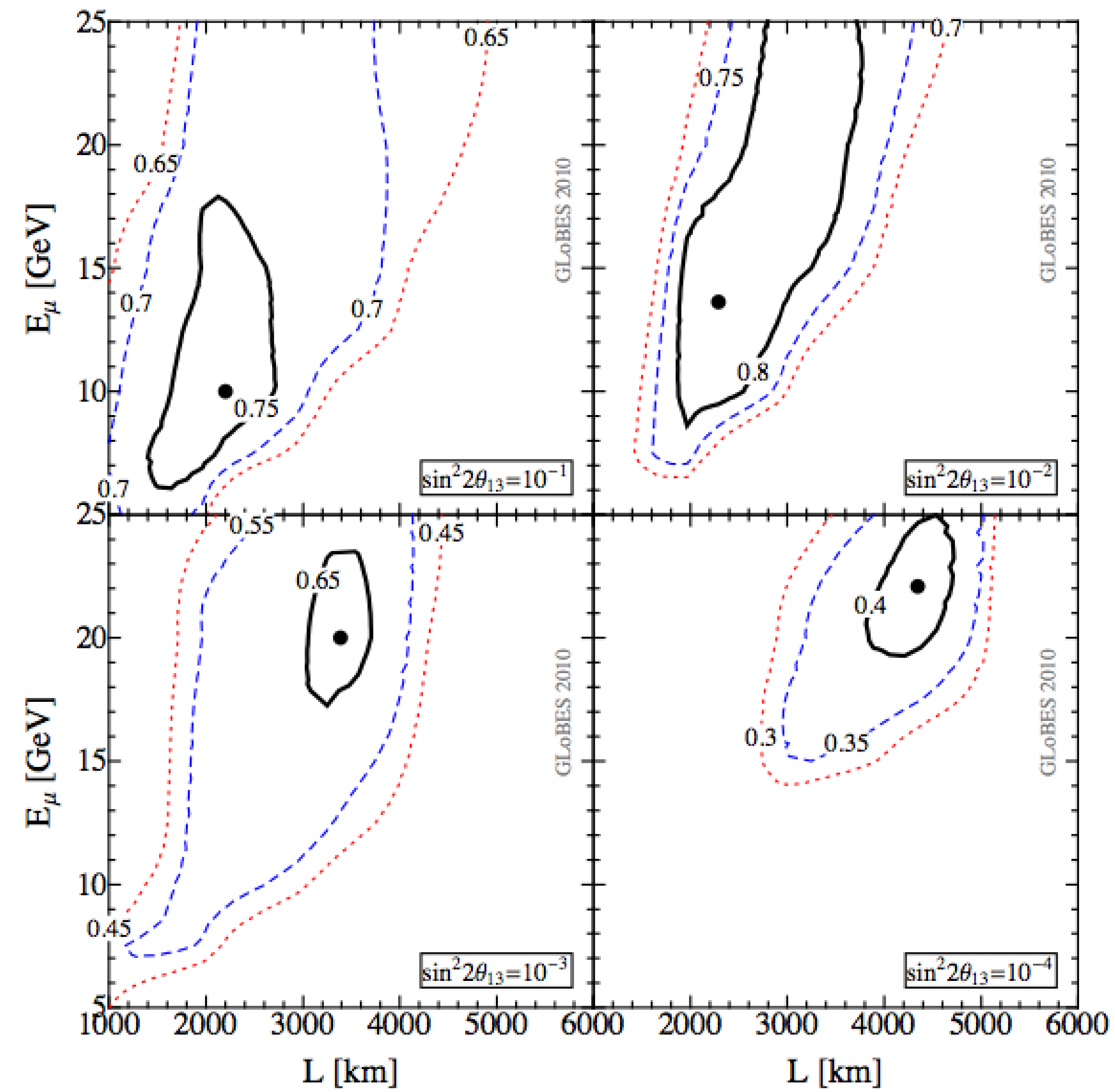
Neutrino Factory

See K. Long's talk



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

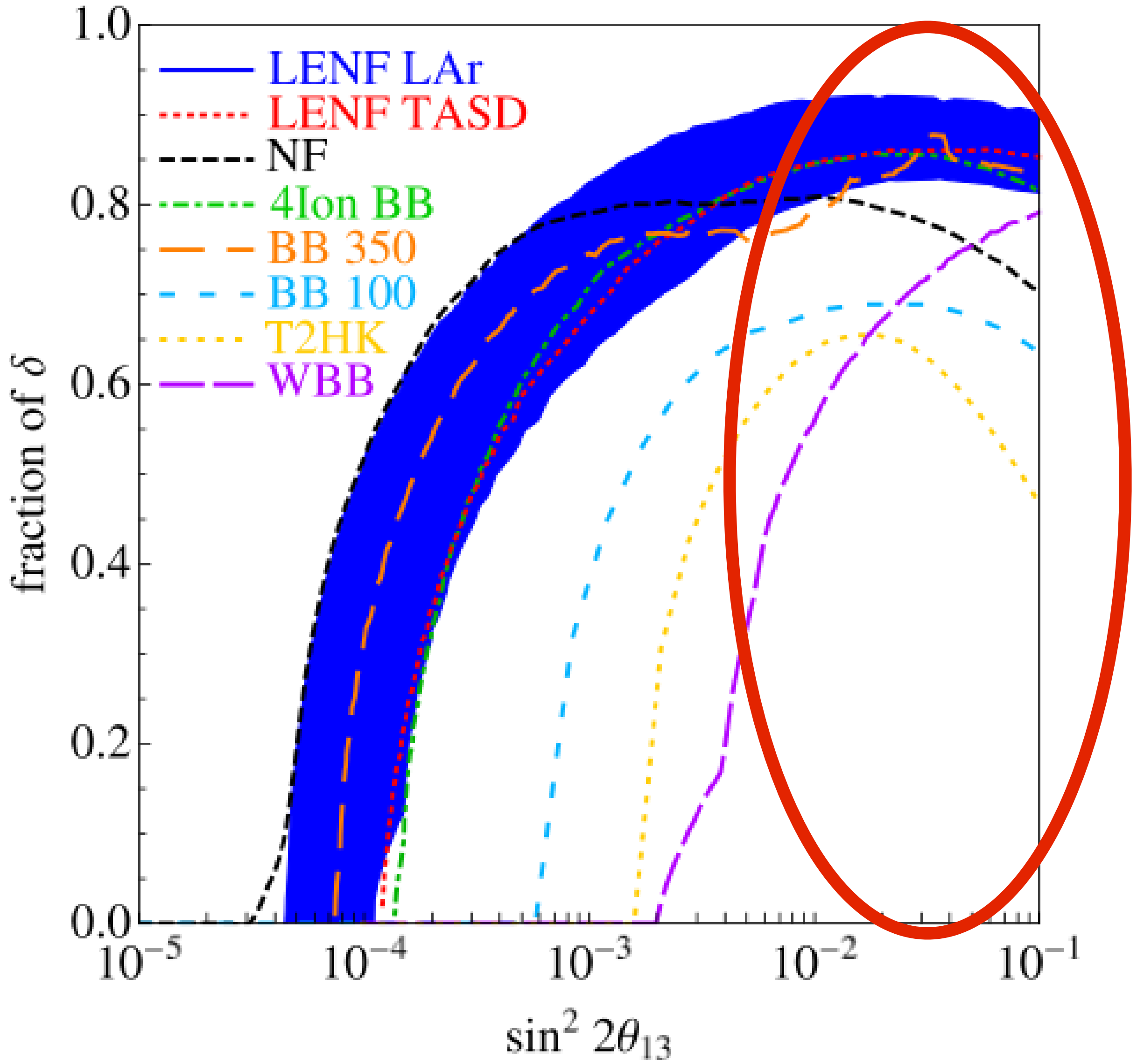
Excellent sensitivity for large theta13 rather independent from L and E. Ballett, SP 1201.6299



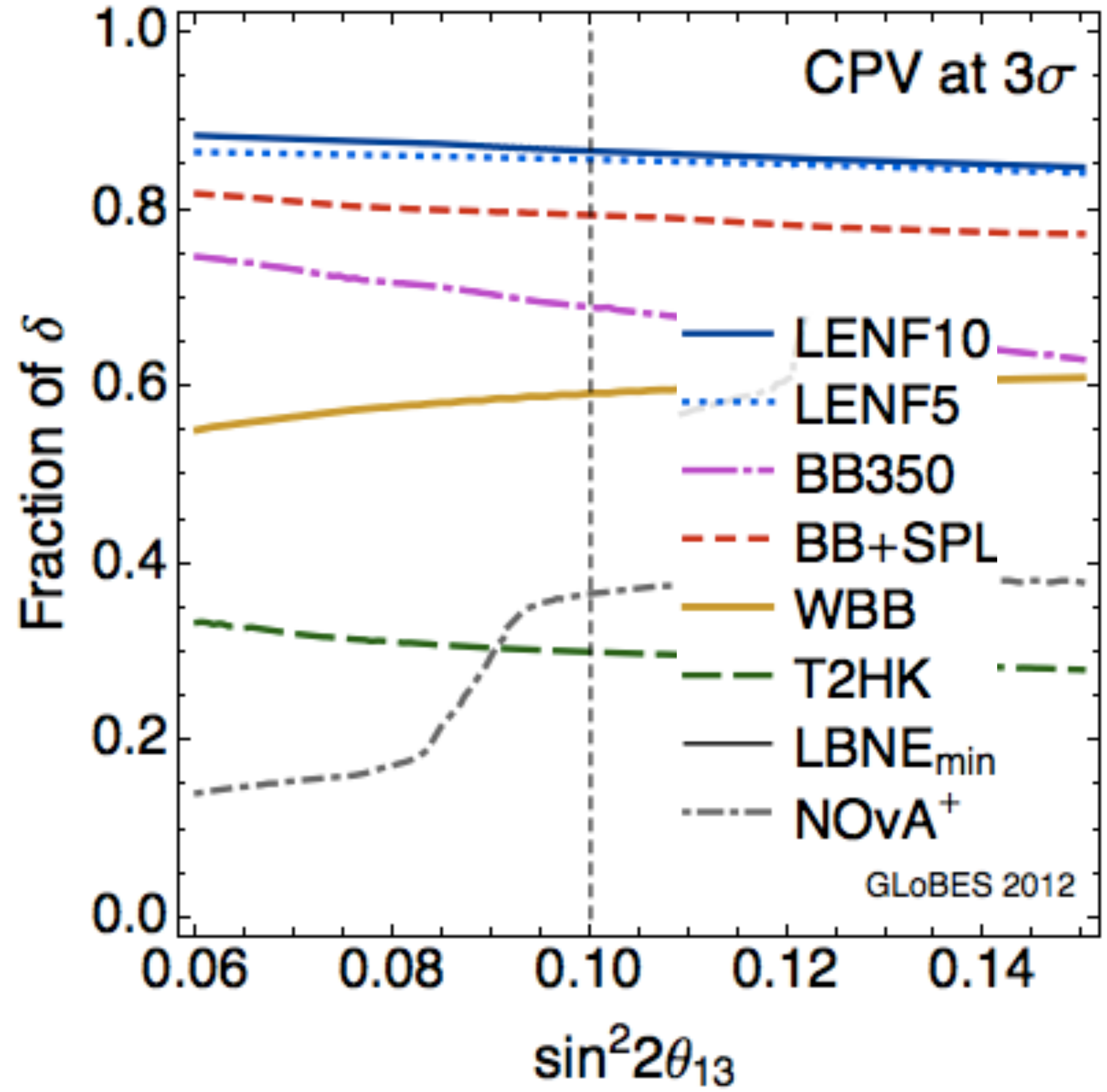
For a MIND detector, the optimal configuration is reached for L~2000 km and an energy which is not too high.

Agarwalla, Huber, Tang, Winter, 1012.1872

Comparison between facilities



Fernandez-Martinez et al., 0911.3776

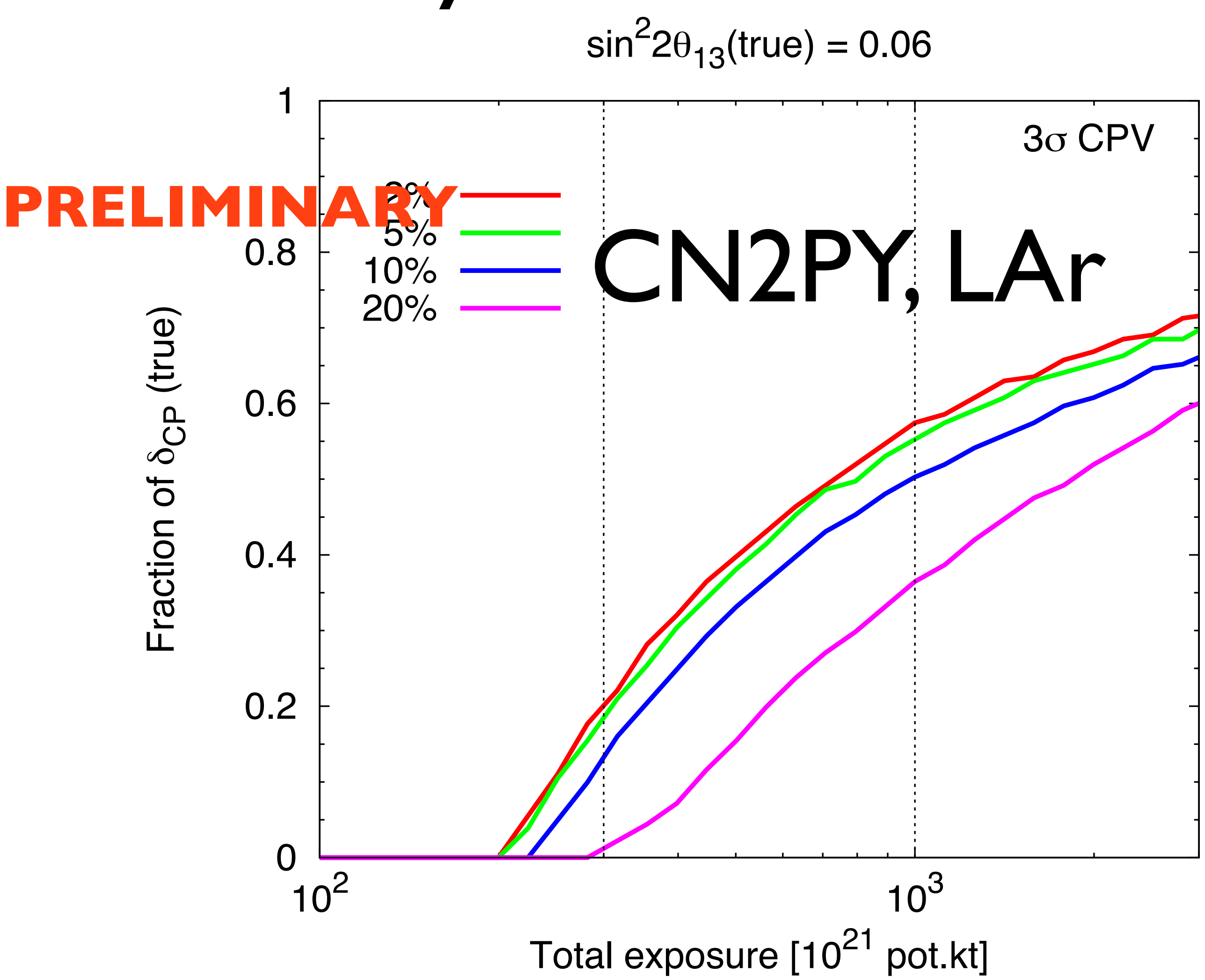


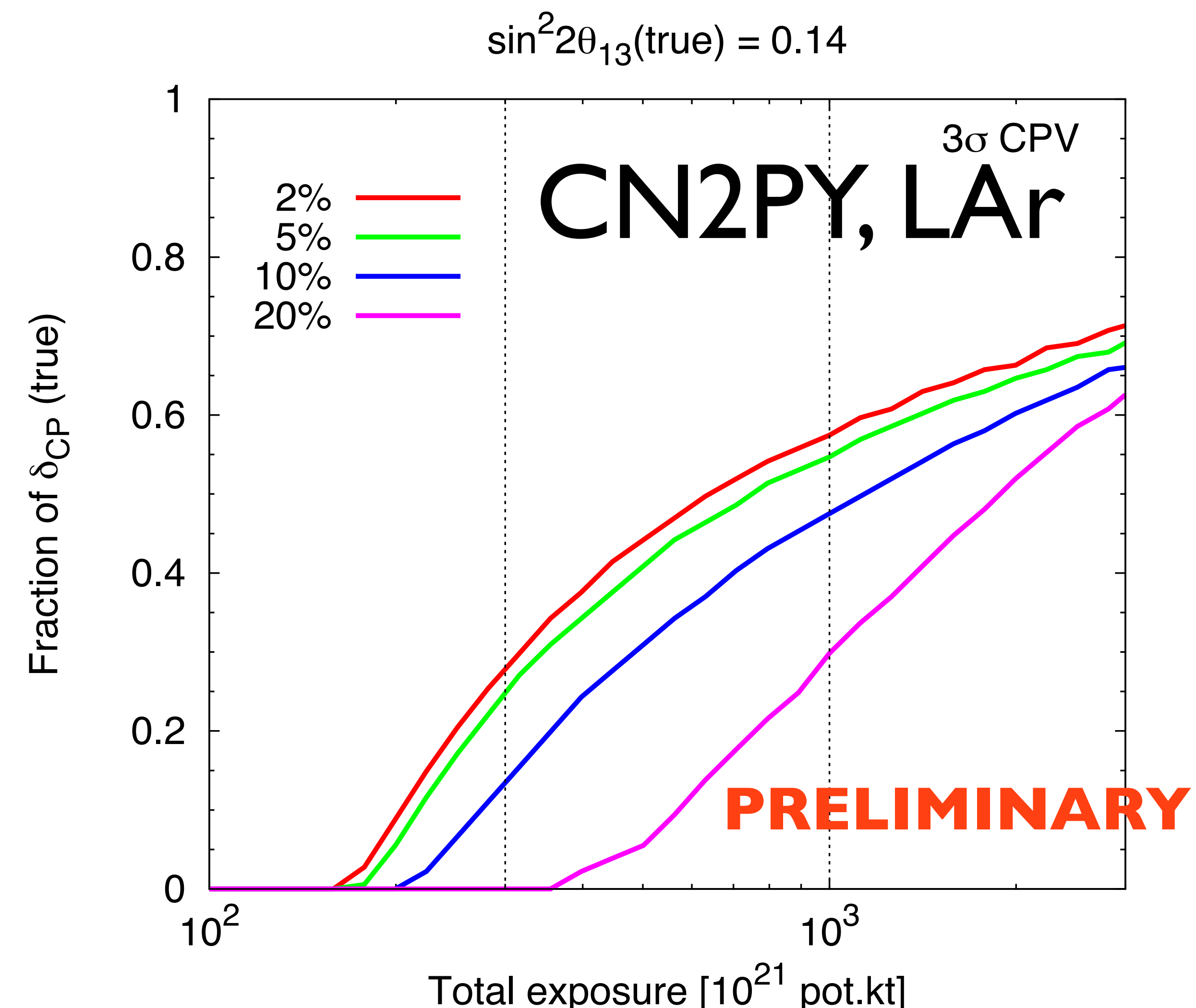
Coloma, Huber, Kopp, Winter, 1209.5973

Systematic errors

Systematic errors might become the limiting factor.

- The cross sections will be one of the dominant factors. See R. Terri's talk.
- The knowledge of the Earth matter profile introduces also an error. Typically, an uncertainty ~7% but for the CERN-Pyhasalmi baseline ~2% [Kozlovskaya et al., hep-ph/0305042].

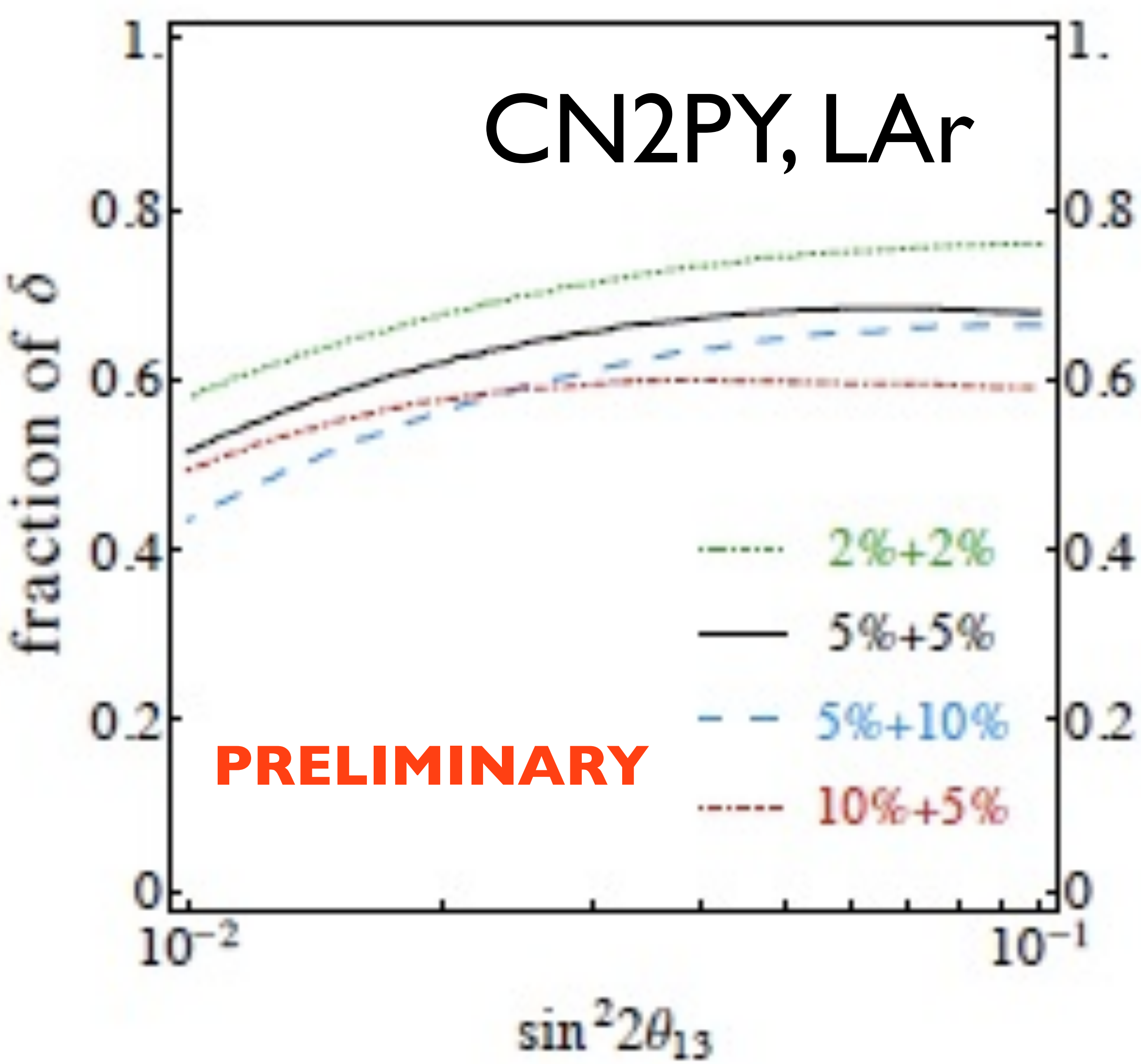




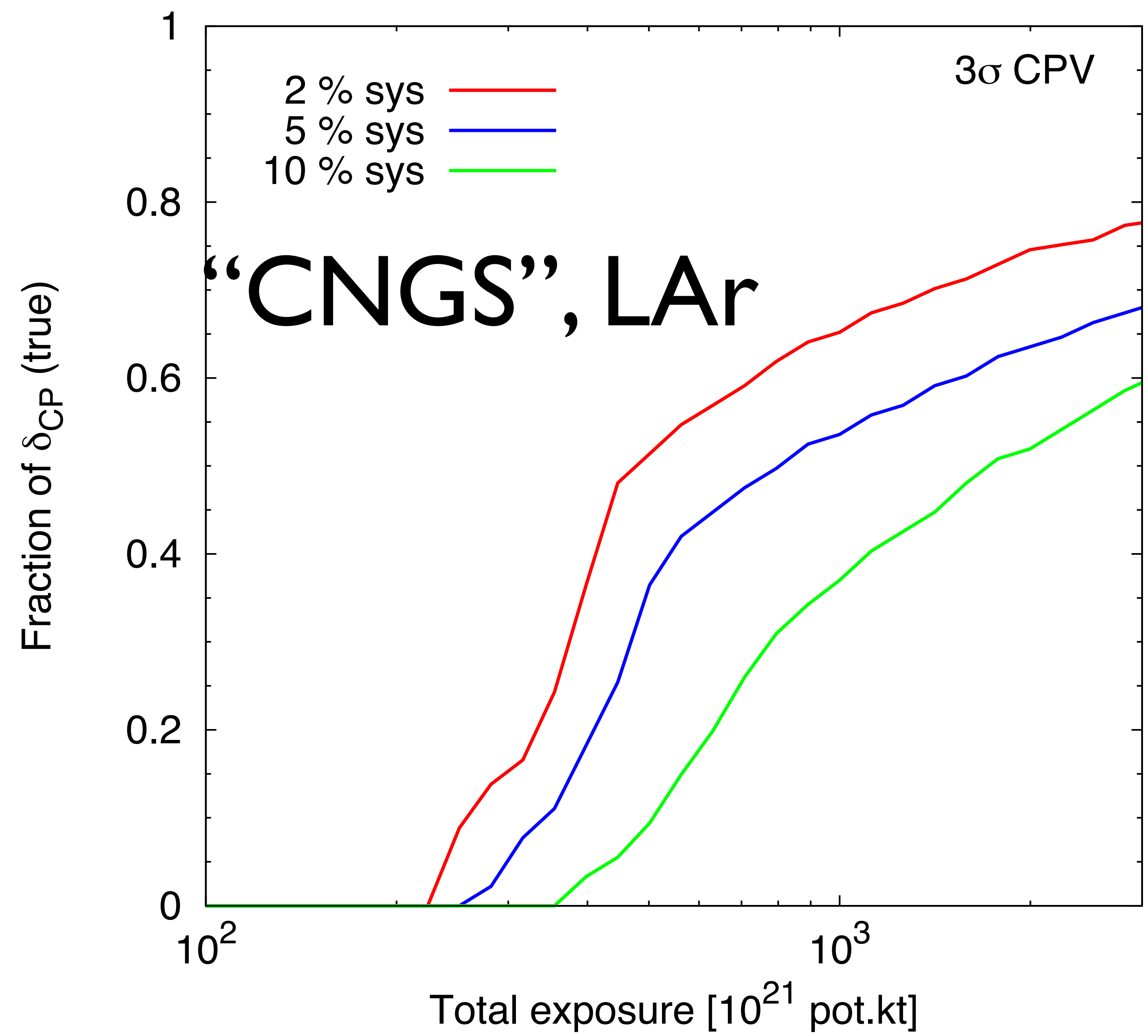
Coloma, Li, SP, in preparation; NOW2012

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

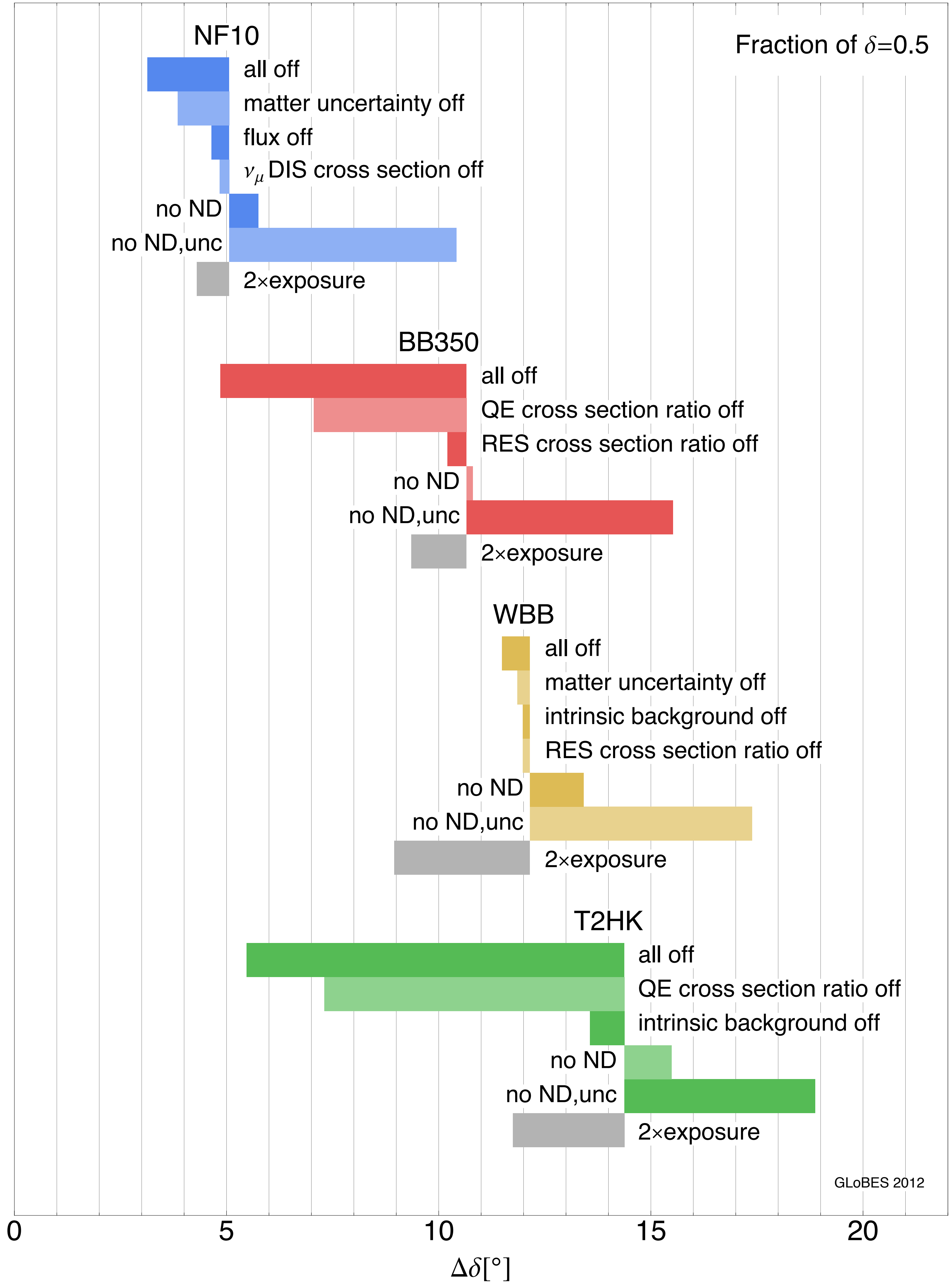
They have a large impact on the physics reach.



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.

Coloma, Huber, Kopp, Winter, 1209.5973

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

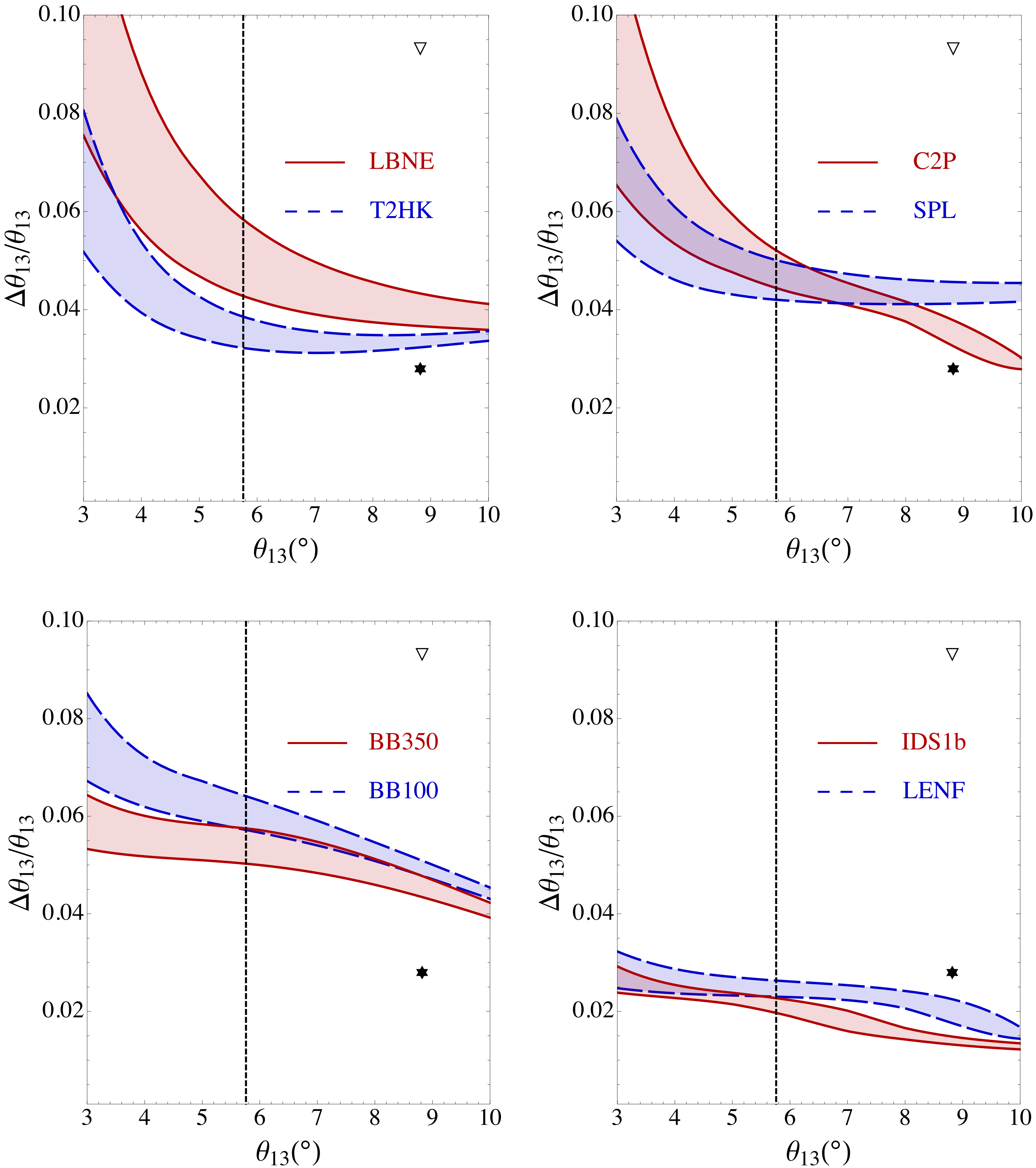
$$N_{\text{events}} \sim P_{\mu e} \sim \sin^2 2\theta_{13} \sim (\theta_{13})^2 \Rightarrow \Delta N \sim \theta_{13} \Delta\theta_{13}$$

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

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

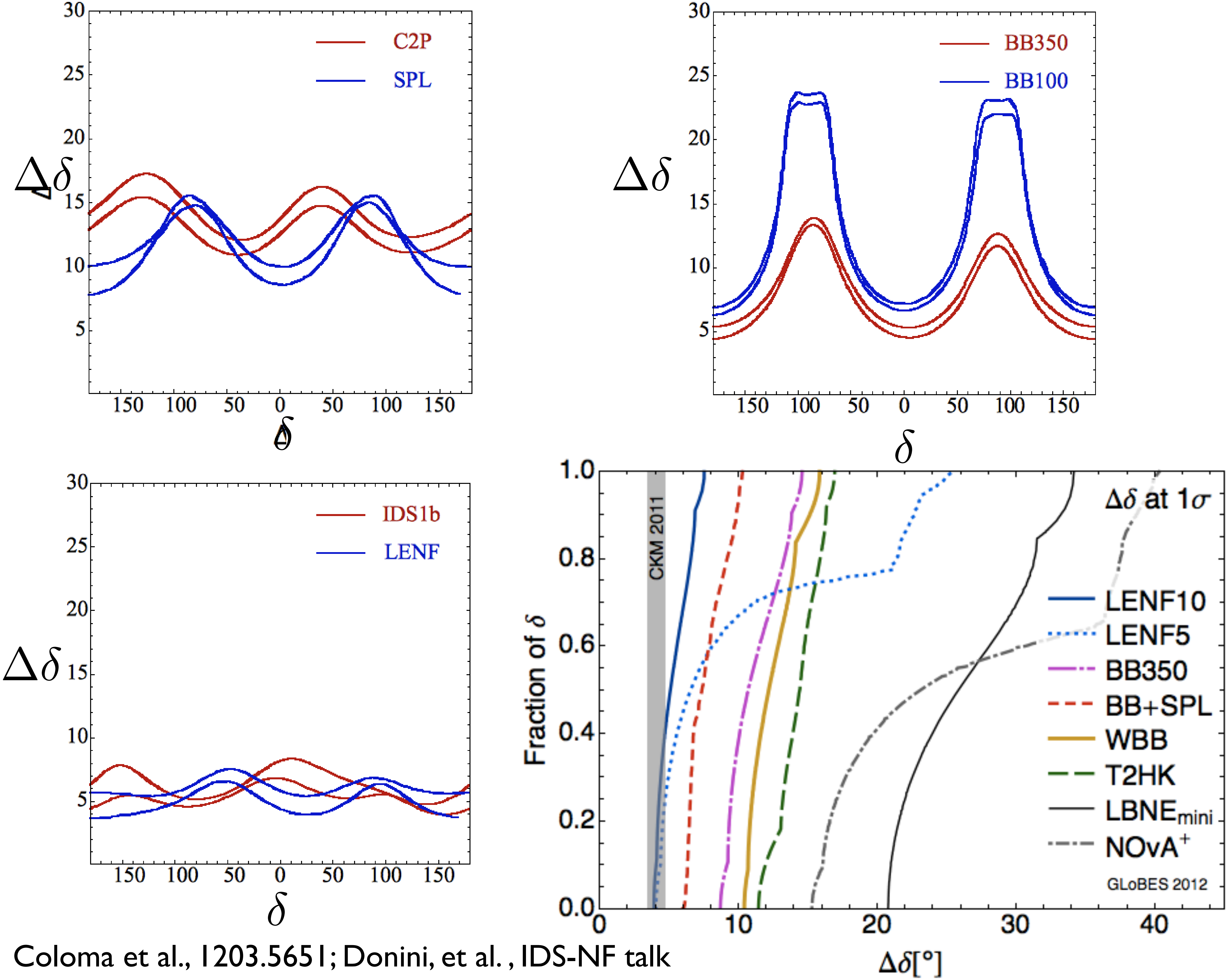
If that on the background: $\dfrac{\Delta\theta_{13}}{\theta_{13}} \sim \dfrac{1}{\theta_{13}^2}$

Coloma, Donini, Fernandez Martinez, Hernandez, 1203.5651



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



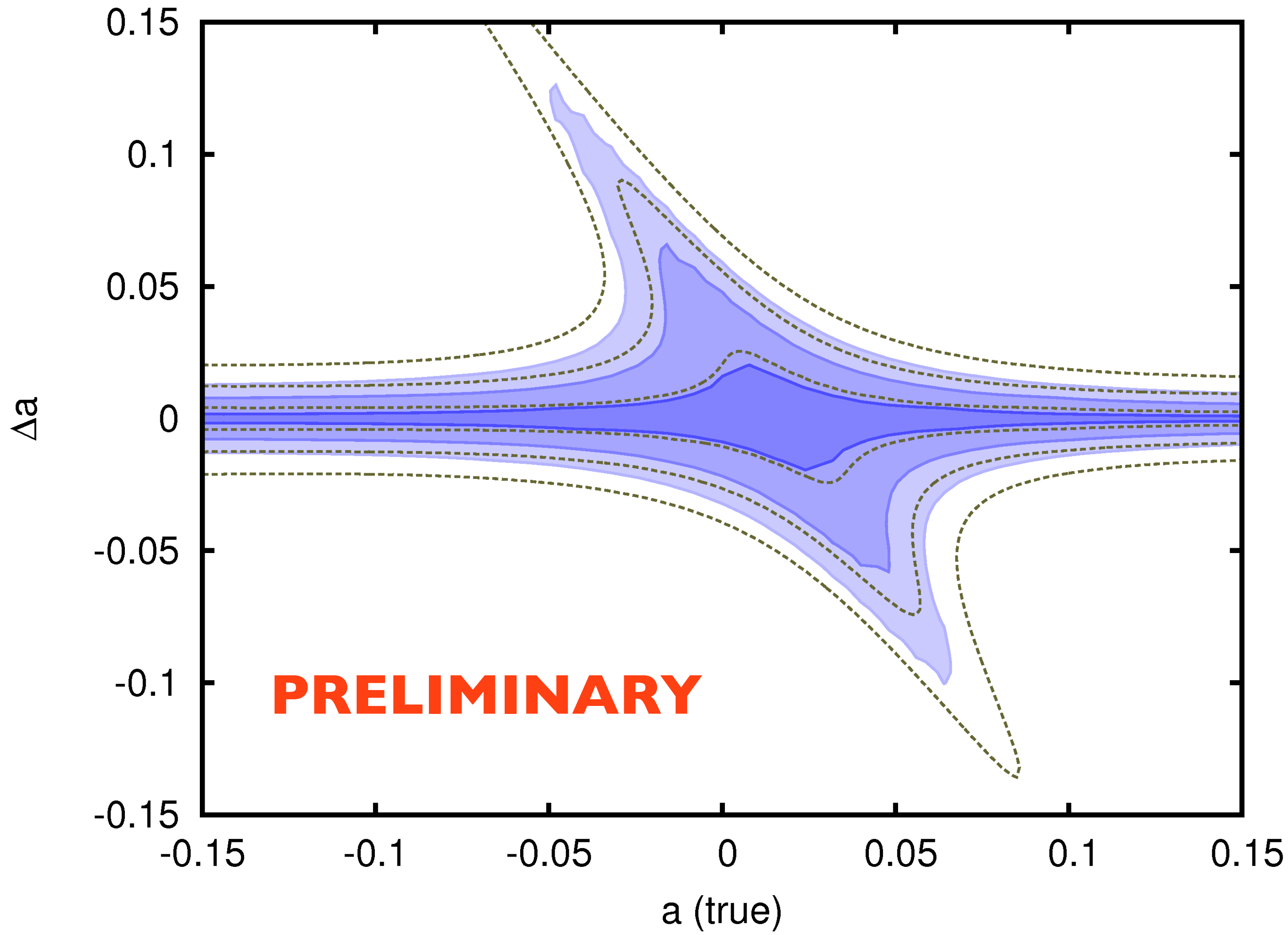
Coloma et al., 1203.5651; Donini, et al. , IDS-NF talk

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



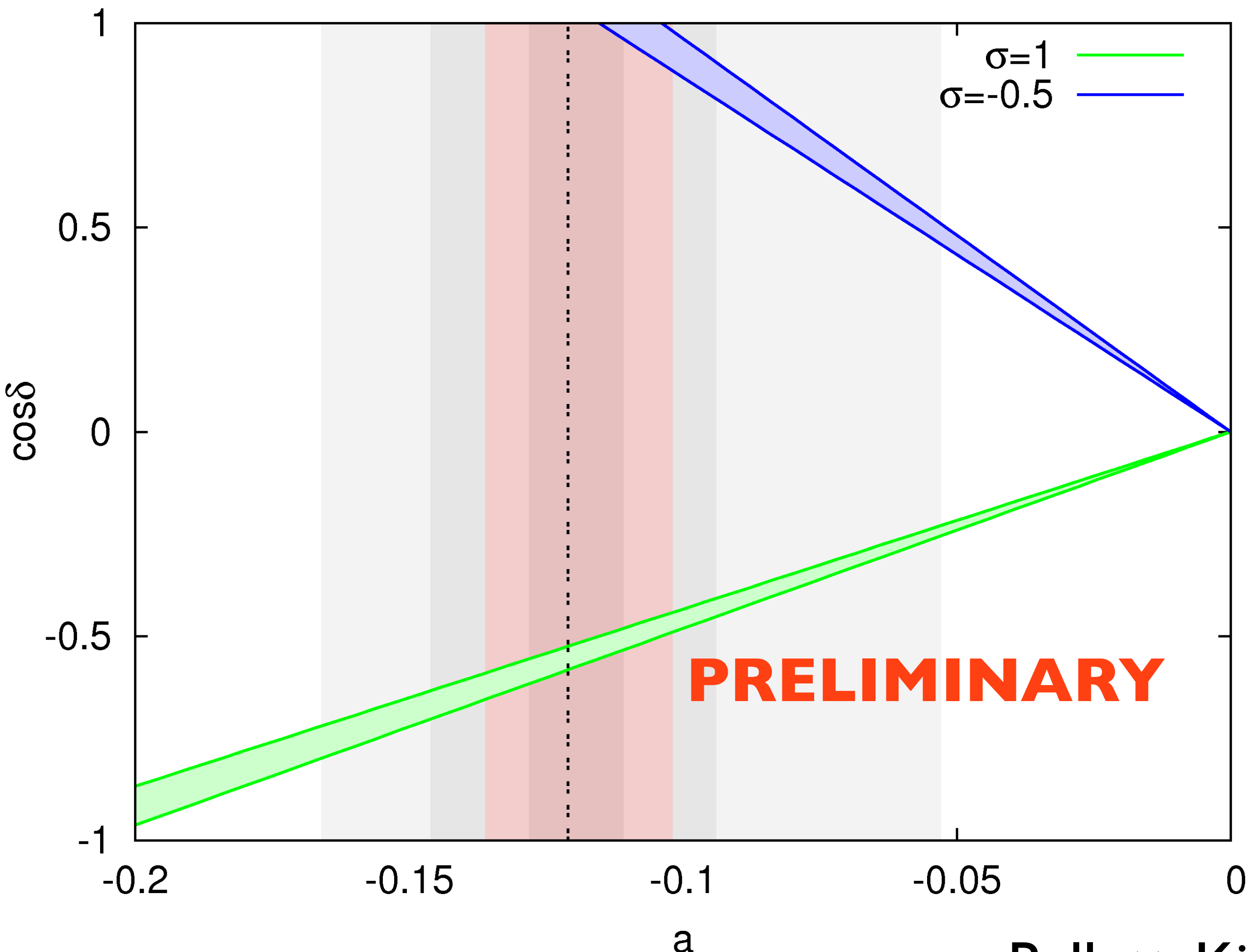
Dashed: WBB
Blue: LENF

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

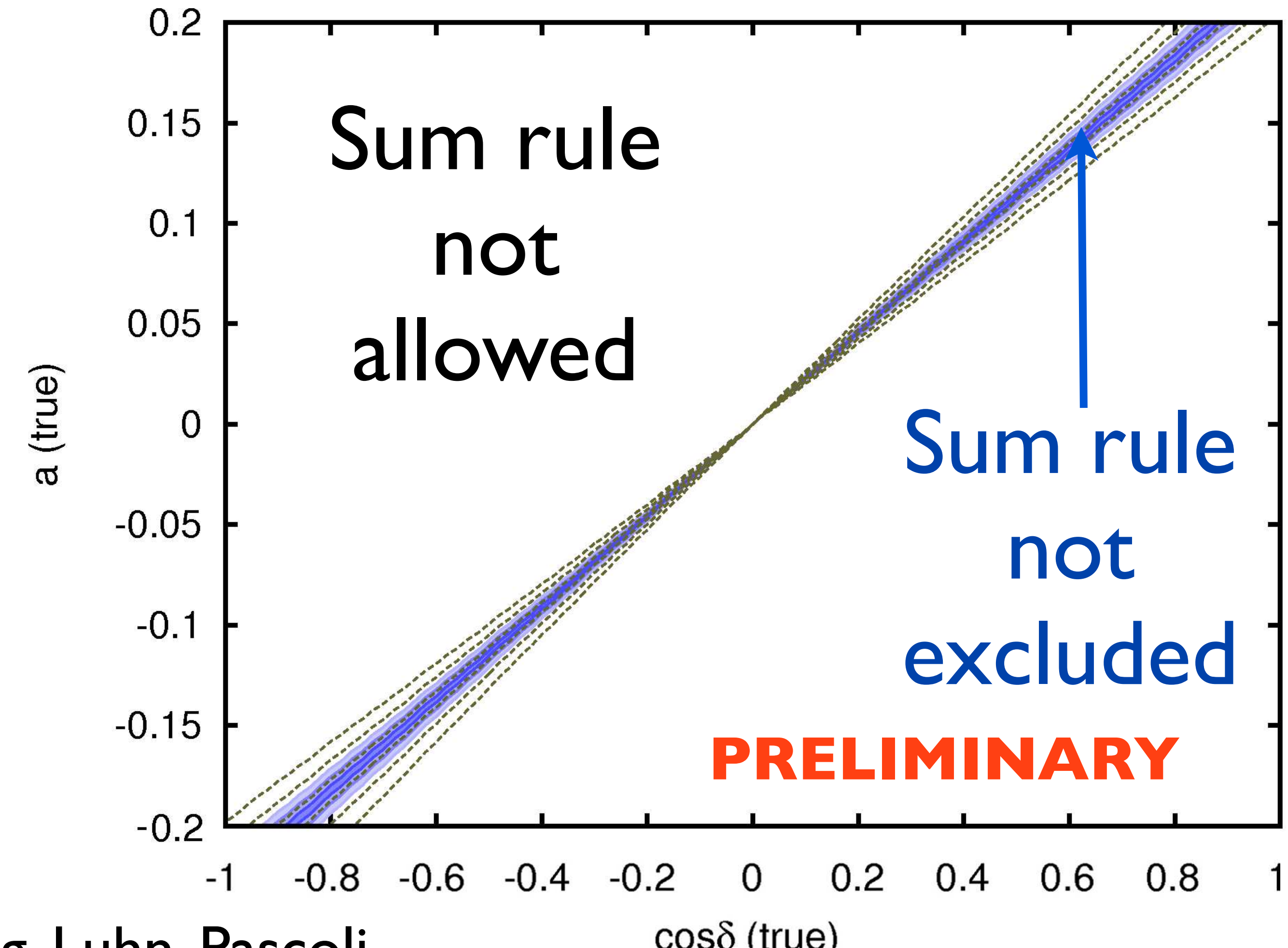
Deviation from these patterns is expected theoretically and is required by experimental data. Theoretical models typically lead to correlations between parameters (sum rules).

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

Current data



Future prospects:
Dashed: WBB, Blue: LENF



Ballett, King, Luhn, Pascoli, 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.

- Next generation superbeams, betabeams and/or neutrino factory will 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.