Large θ_{13}: a window for CPV and the mass hierarchy

Enrique Fernández Martínez

Oscillation Parameters

- What we already know (1σ)
  - Solar sector
  - Atm. sector

$$\begin{cases} \Delta m^2_{21} = 7.62^{+0.19}_{-0.19} \cdot 10^{-5}\,\mathrm{eV}^2 \\ \sin^2\theta_{12} = 0.320^{+0.015}_{-0.017} \end{cases}$$

$$\begin{cases} \Delta m^2_{31} = 2.53^{+0.08}_{-0.10} \cdot 10^{-3} / -2.40^{+0.10}_{-0.07} \cdot 10^{-3}\ \mathrm{eV}^2 \\ \sin^2\theta_{23} = 0.49^{+0.08}_{-0.05} / 0.53^{+0.05}_{-0.07} \end{cases}$$

$$\sin^2\theta_{13} = 0.026^{+0.003}_{-0.004} / 0.027^{+0.003}_{-0.004}$$

D. V. Forero, M. Tortola, J. Valle 1205.4018
see also G.L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, A.M. Rotunno 1205.5254

Oscillation Parameters

- What we already know (1σ)
  - Solar sector $\begin{cases} \Delta m^2_{21} = 7.62^{+0.19}_{-0.19} \cdot 10^{-5}\,\mathrm{eV}^2 \\ \sin^2\theta_{12} = 0.320^{+0.015}_{-0.017} \end{cases}$
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  - $\sin^2\theta_{13} = 0.026^{+0.003}_{-0.004} / 0.027^{+0.003}_{-0.004}$
- What we still don't know
  - δ
  - Mass hierarchy $s_{atm} = sign\left(\Delta m^2_{31}\right)$

D. V. Forero, M. Tortola, J. Valle 1205.4018
see also G.L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, A.M. Rotunno 1205.5254

The Golden channel in matter

$$P\left(\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu\right) = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{atm}}{\tilde{B}_\mp}\right)^2 \sin\left(\frac{\tilde{B}_\mp L}{2}\right)^2$$

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{sol} L}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$

$$+ \tilde{J} \frac{\Delta_{sol}}{A} \frac{\Delta_{atm}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{atm} L}{2}\right)$$

Expanded in

$$\sin 2\theta_{13} \sim 0.3 \qquad \left(\frac{\Delta_{sol} L}{2}\right) \cong 0.05$$

where

$$\tilde{J} = \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \qquad \Delta_{atm} = \frac{\Delta m_{23}^2}{2E} \qquad \Delta_{sol} = \frac{\Delta m_{12}^2}{2E}$$

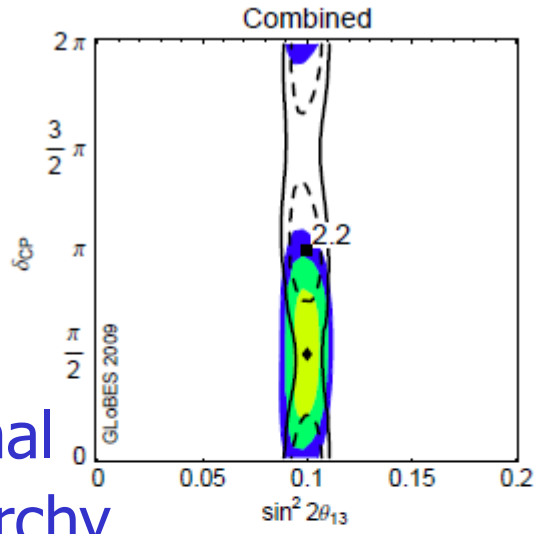
$$A = \sqrt{2} G_F n_e \qquad \tilde{B}_\mp = \left|A \mp \Delta_{atm}\right|$$

A. Cervera *et al.* hep-ph/0002108

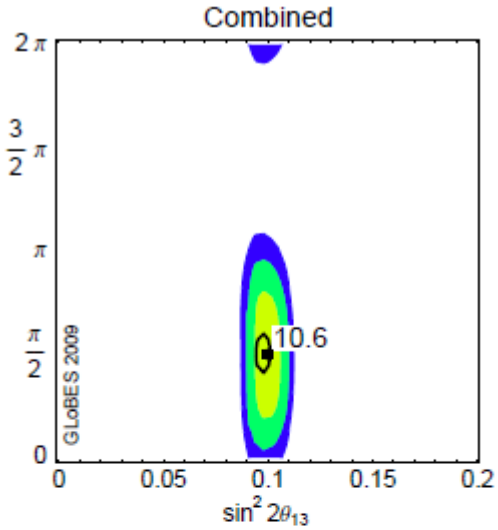
Sensitivities with present experiments

1, 2 and 3 σ

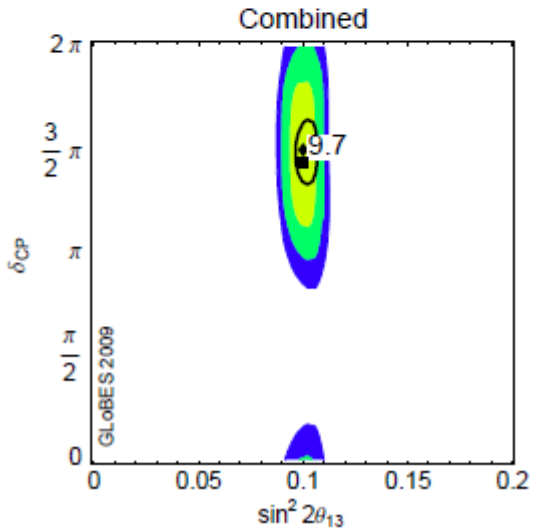
Normal hierarchy

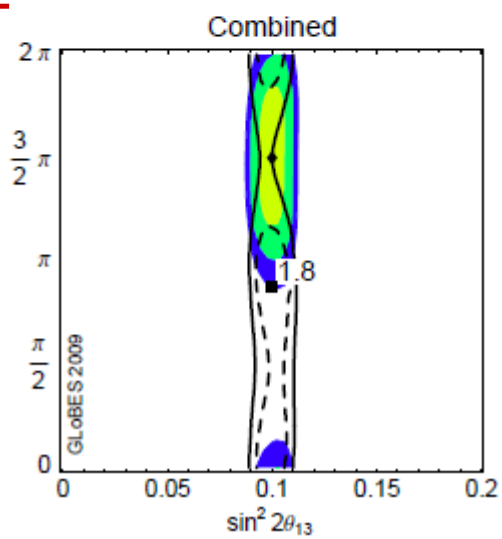


T2K+
Nova+
Daya Bay+
DChooz



Inverted hierarchy





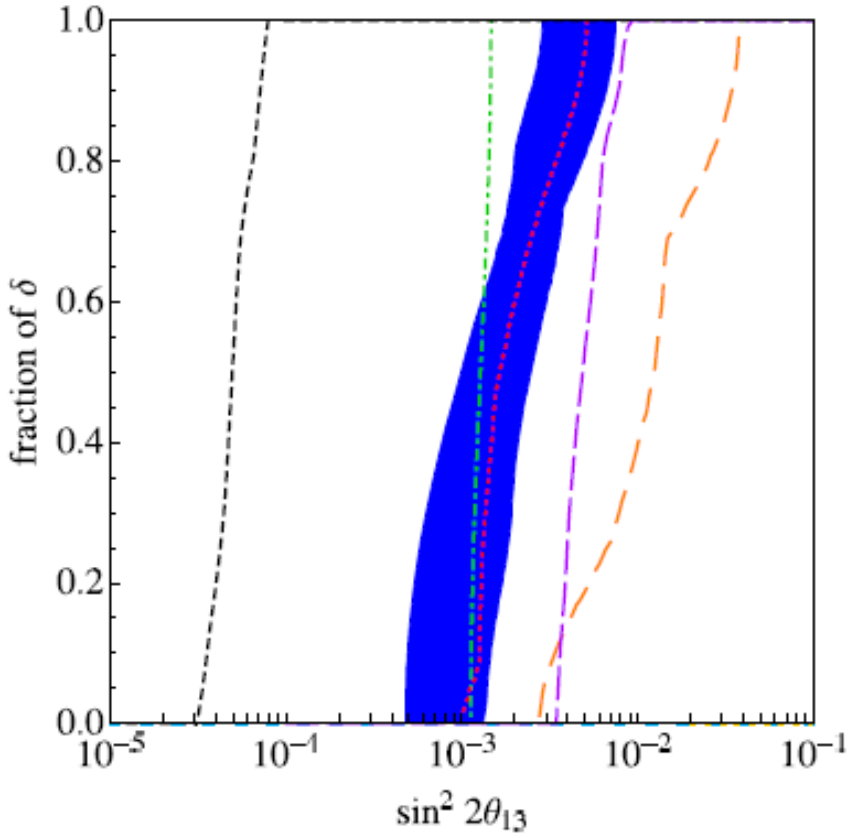
From P. Huber *et al.* 0907.1896

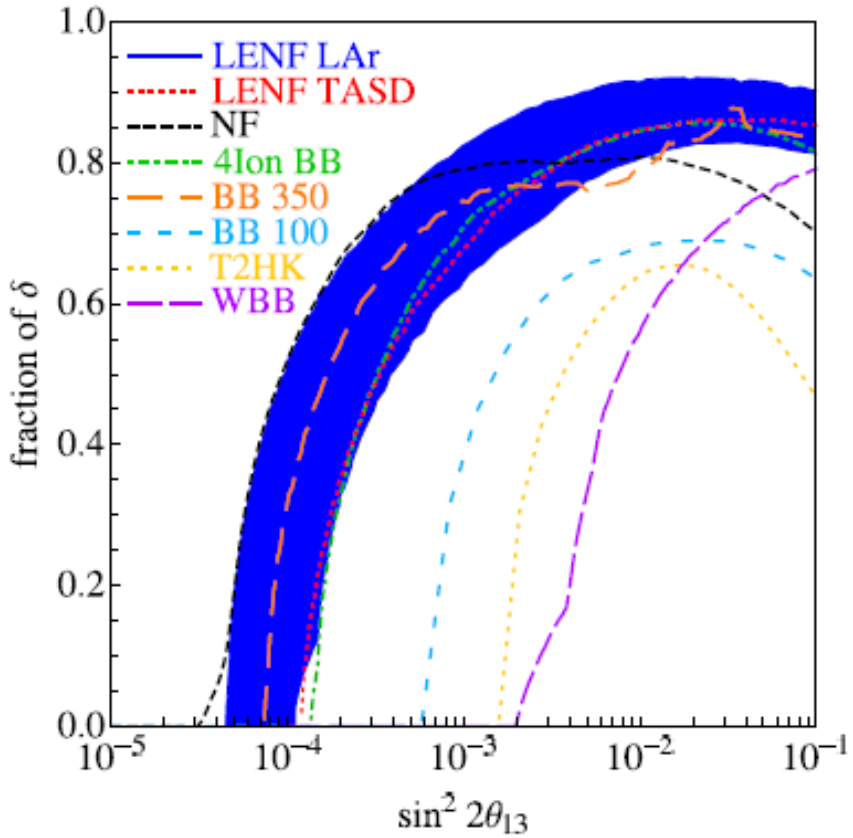
Sensitivities with future accelerators

Mass hierarchy

3 σ

CP violation



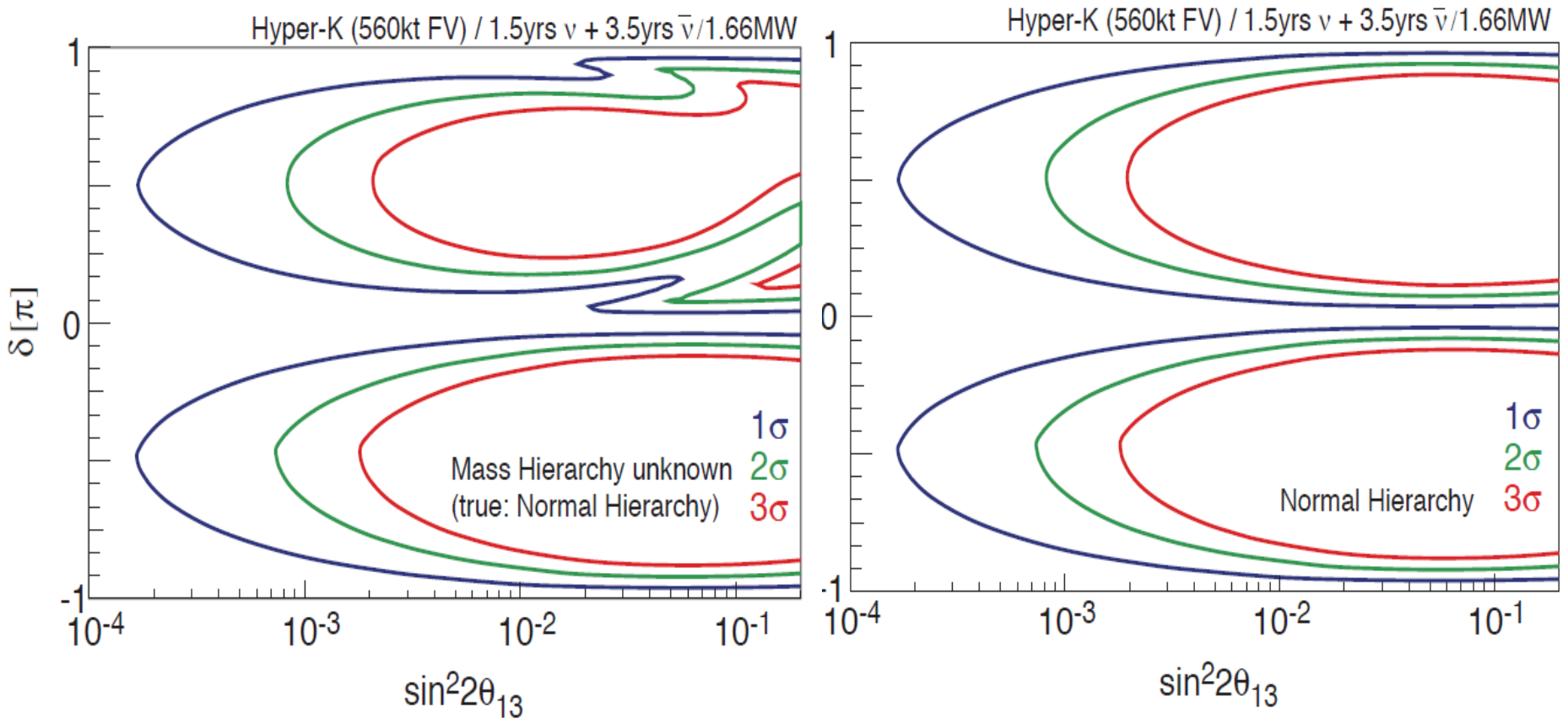


From EFM, T. Li, O. Mena and S. Pascoli 0911.3776

5 questions before we launch the large θ_{13} race

- 1. Do we need the mass hierarchy from the same machine that gives us δ?

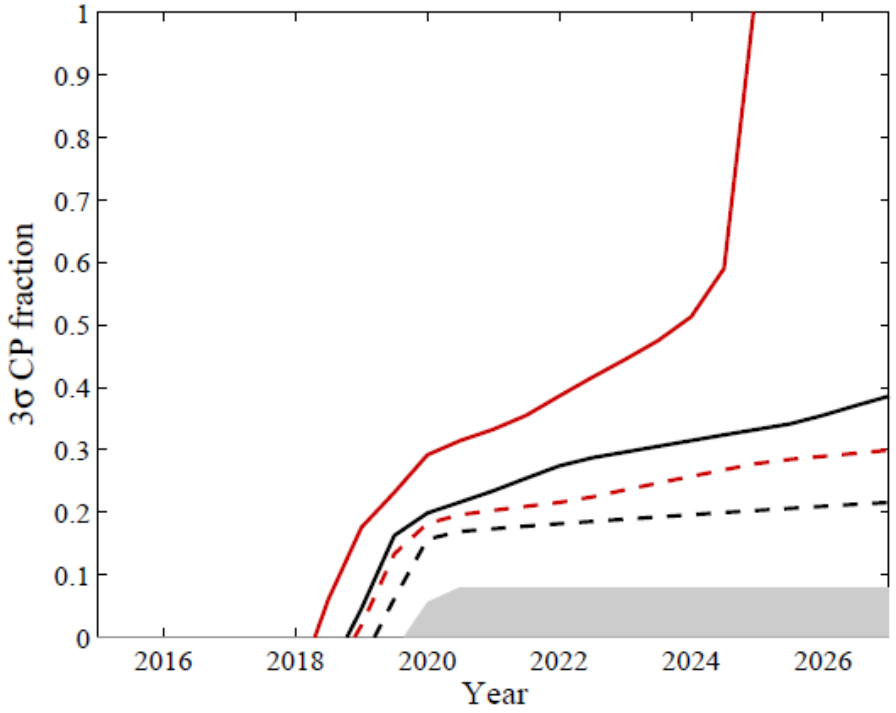
T2HK



K. Abe *et al.* HK LoI 1109.3262

Mass hierarchy with Nνa + T2K + INO

3 σ

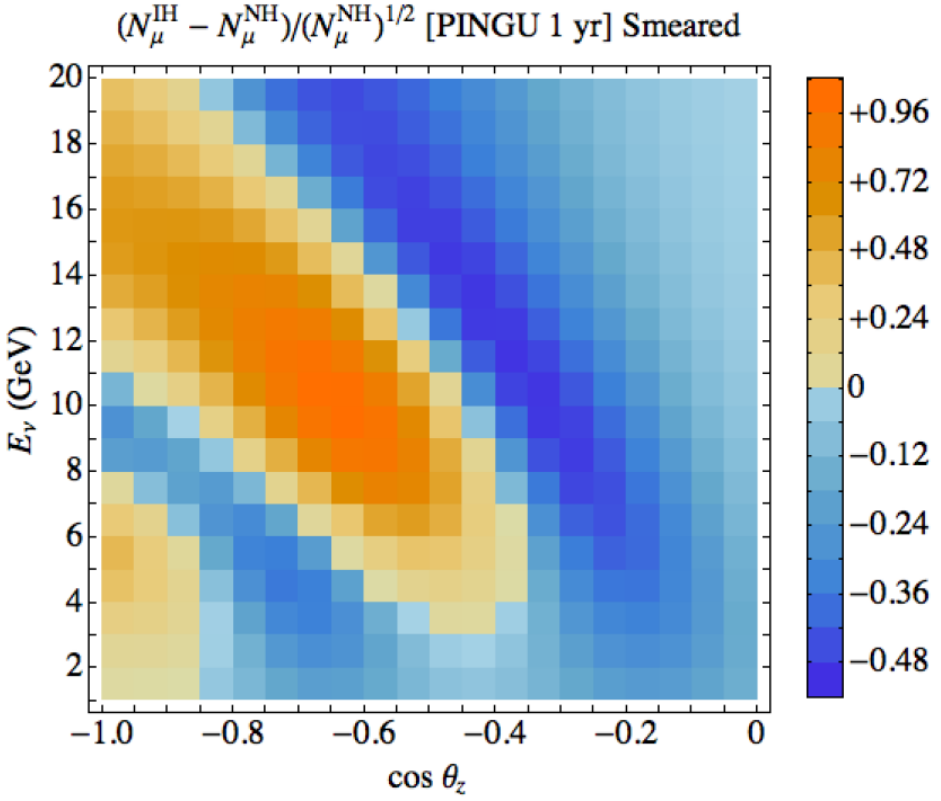


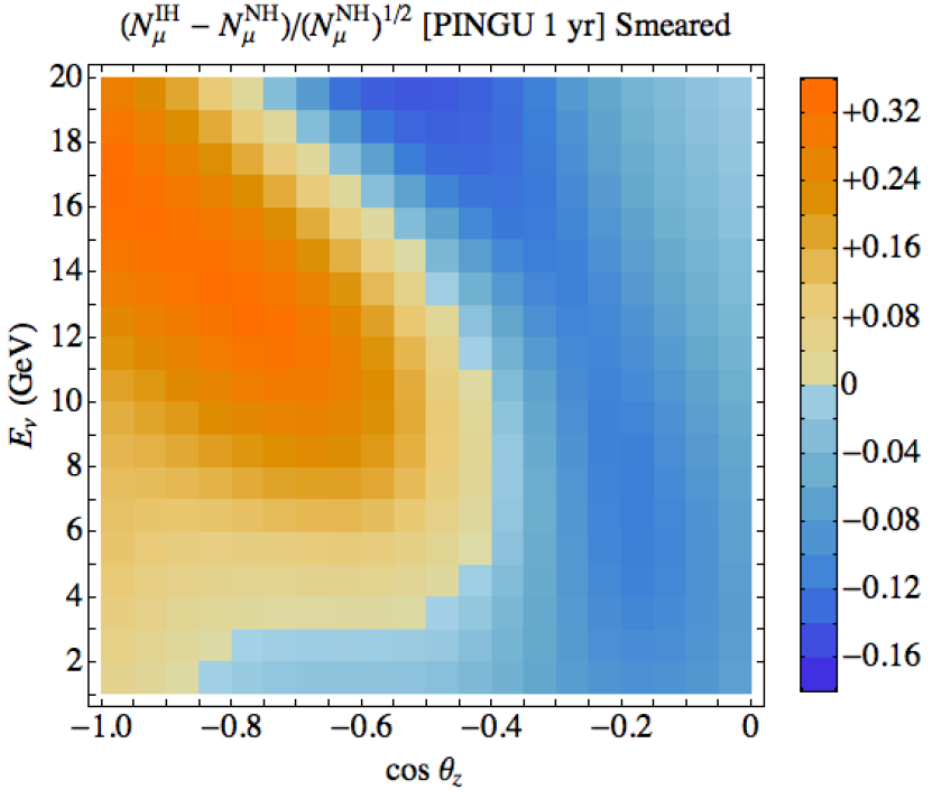
Red 100 kt INO Solid: high res INO ($\sigma_E/E = 0.10$, $\sigma_\theta = 10^o$)

Black 50 kt INO Dashed: low res INO ($\sigma_E/E = 0.15$, $\sigma_\theta = 15^o$)

From M. Blennow and T. Schwetz 1203.3388

Mass hierarchy with PINGU





σ_E=2 GeV, σ_θ=11.25º σ=5%

11σ

σ_E=4 GeV, σ_θ=22.5º σ=10%

3σ

From E. Kh. Akhmedov, S. Razzaque and A. Yu. Smirnov 1205.7071

5 questions before we launch the large θ_{13} race

- 1. Do we need the mass hierarchy from the same machine that gives us δ?
- 2. Downgrading: How much can we afford?

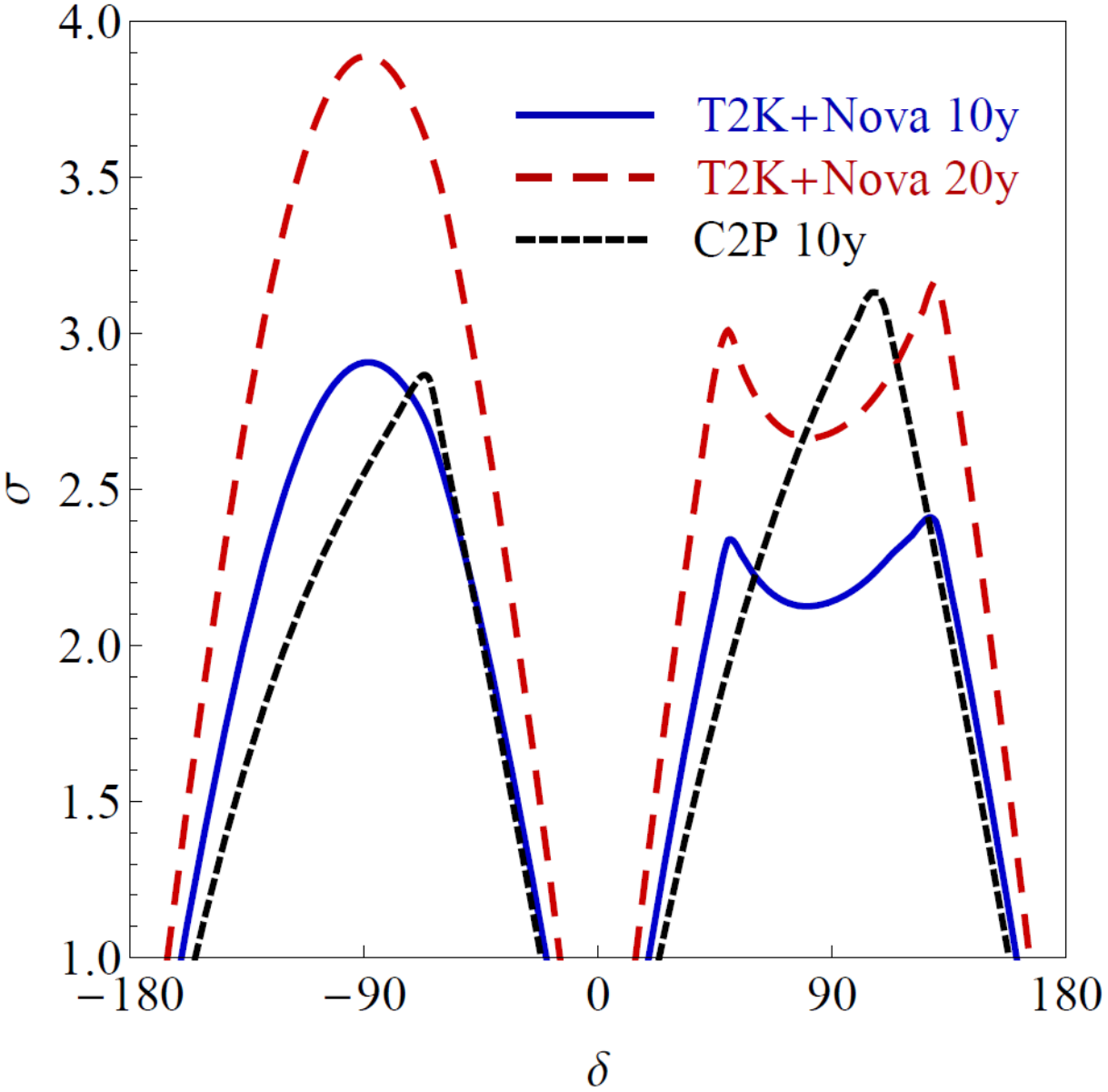
Downgrading is trendy in the large θ_{13} race!

	2001	2011	2012
T2HK:	4MW + 500 kt →	1.6MW + 500 kt →	0.7 MW? + 500 kt → ??

	2010	2012
LBNE:	2MW + 33 kt →	0.7MW + 17 kt? → ??

	2011	2012	2012
LBNO:	2MW + 100 kt →	2MW + 20 kt →	0.8MW + 20 kt → ??

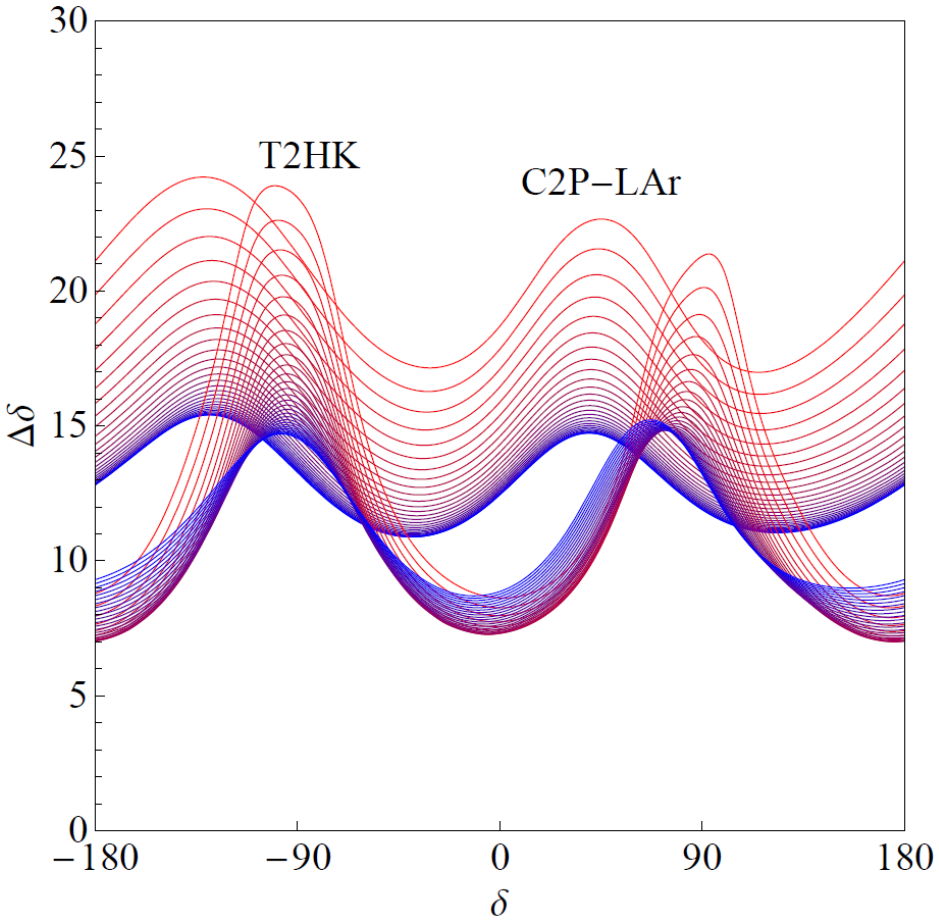
Danger!!! How much can we afford?

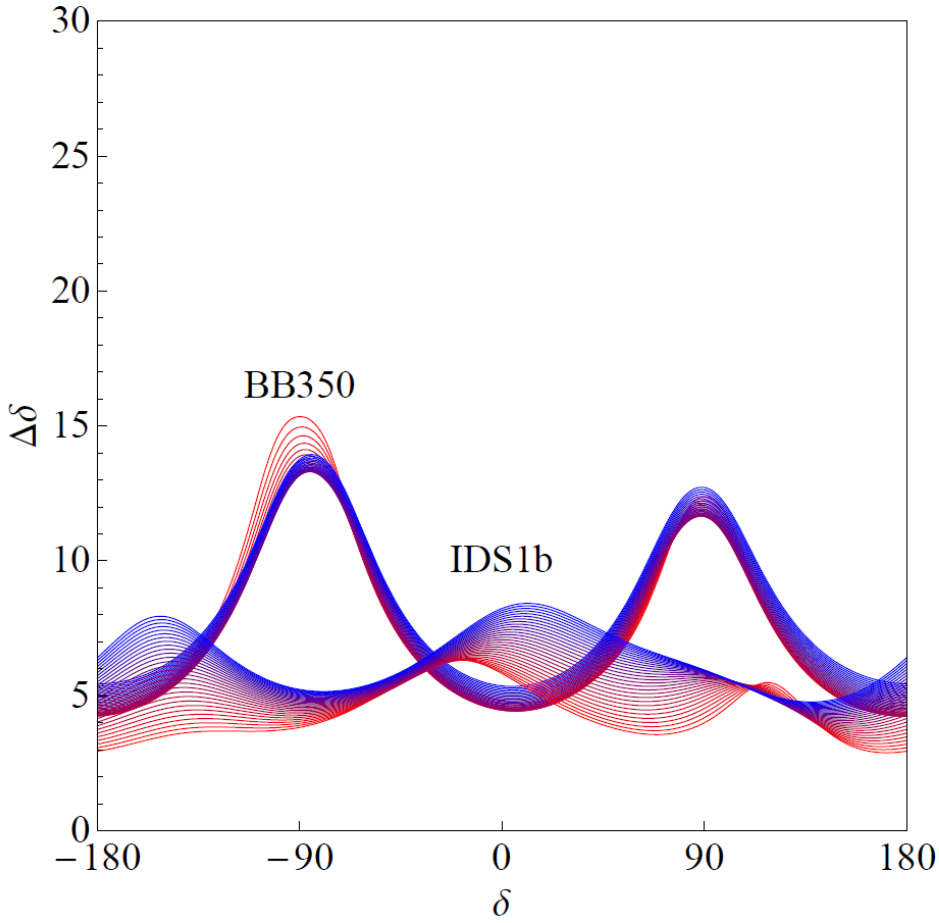


5 questions before we launch the large θ_{13} race

- 1. Do we need the mass hierarchy from the same machine that gives us δ?
- 2. Downgrading: How much can we afford?
- 3. Precision: New comparisons. How much?

Precision

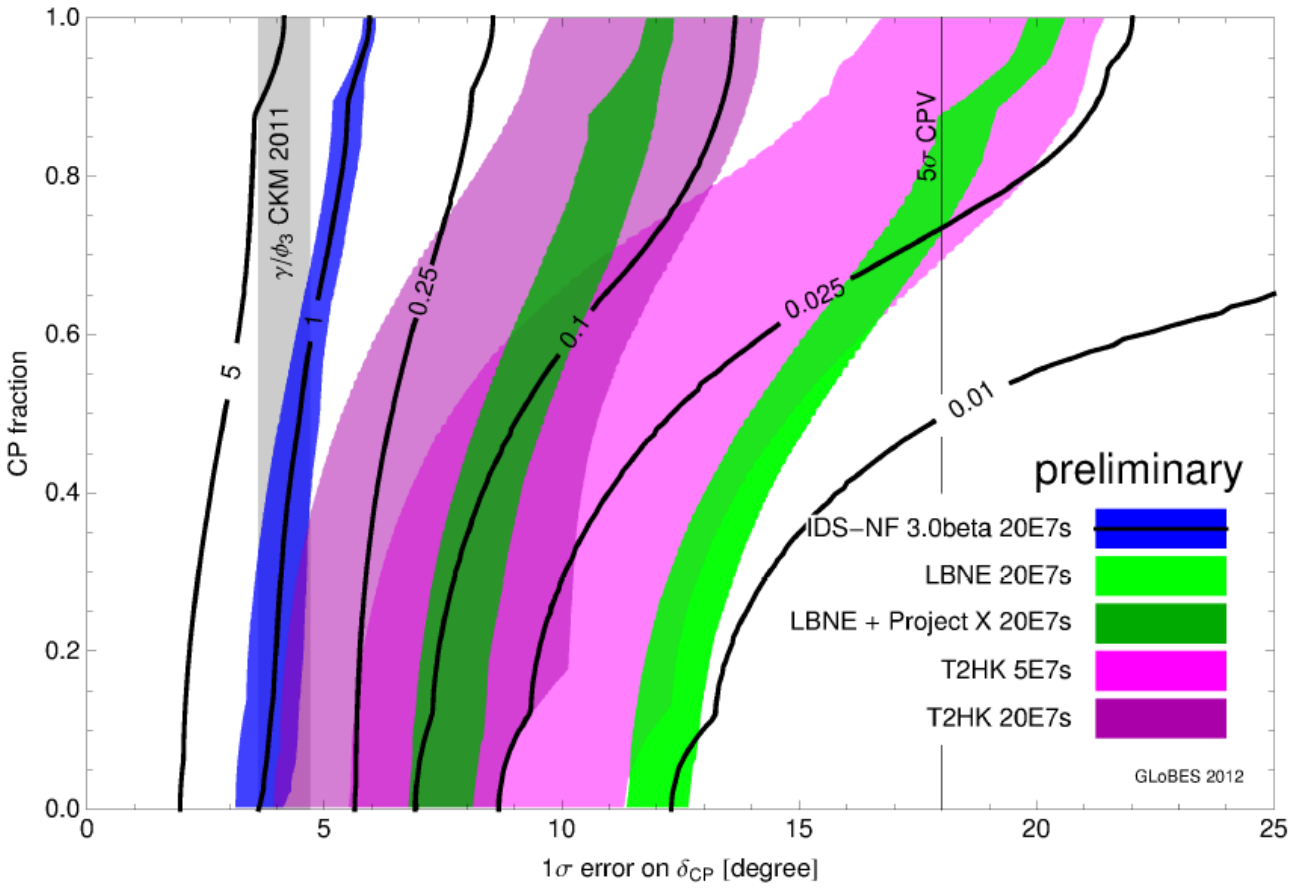




θ_{13}: 3º - 10º

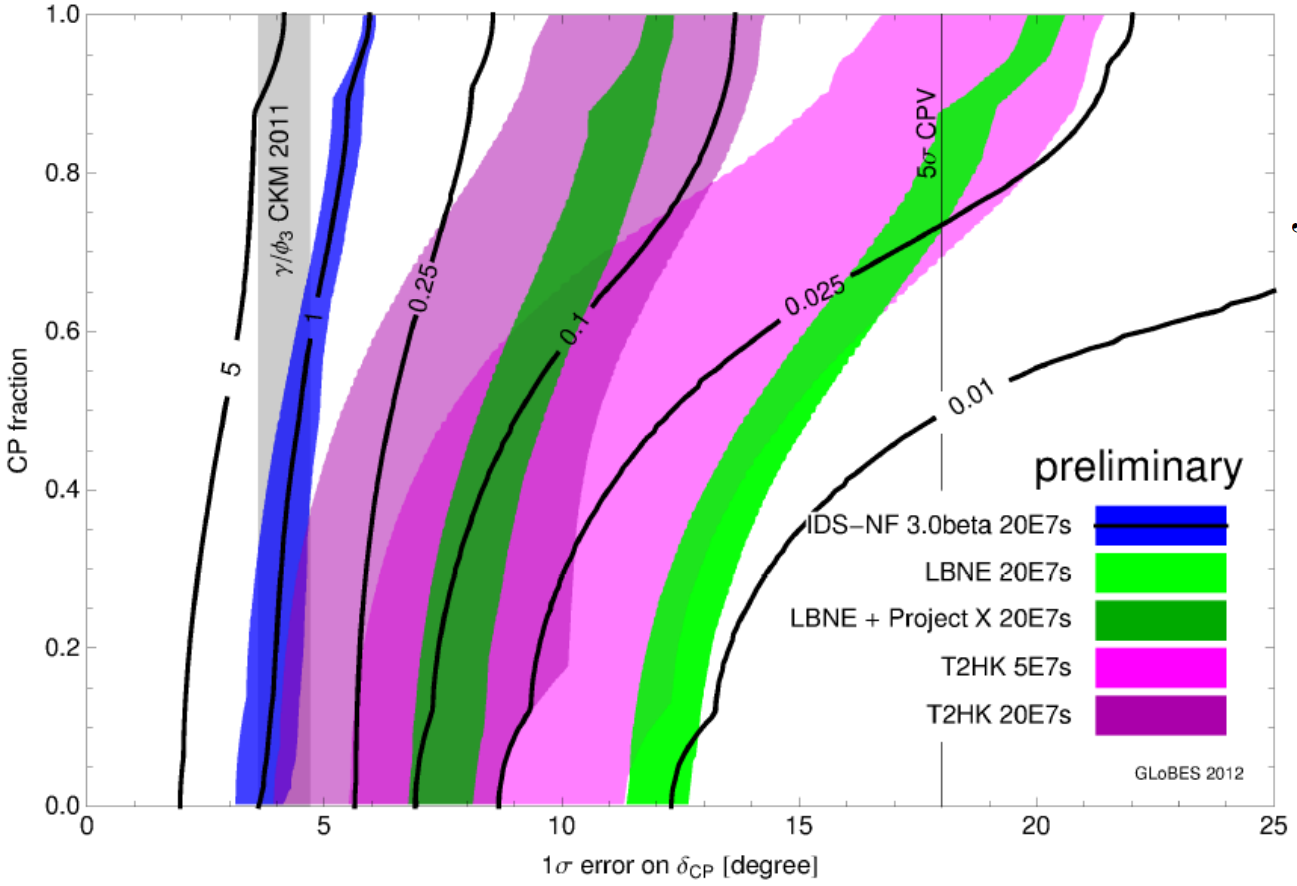
P. Coloma, A. Donini, EFM and P. Hernandez 1203.5651

How much precision we need?



P. Coloma, P. Huber, J. Kopp and W. Winter in preparation

How much precision we need?



For quarks

$$J = (2.91^{+0.19}_{-0.11}) \times 10^{-5}$$

For neutrinos

$$J = 0.29 \sin \delta$$

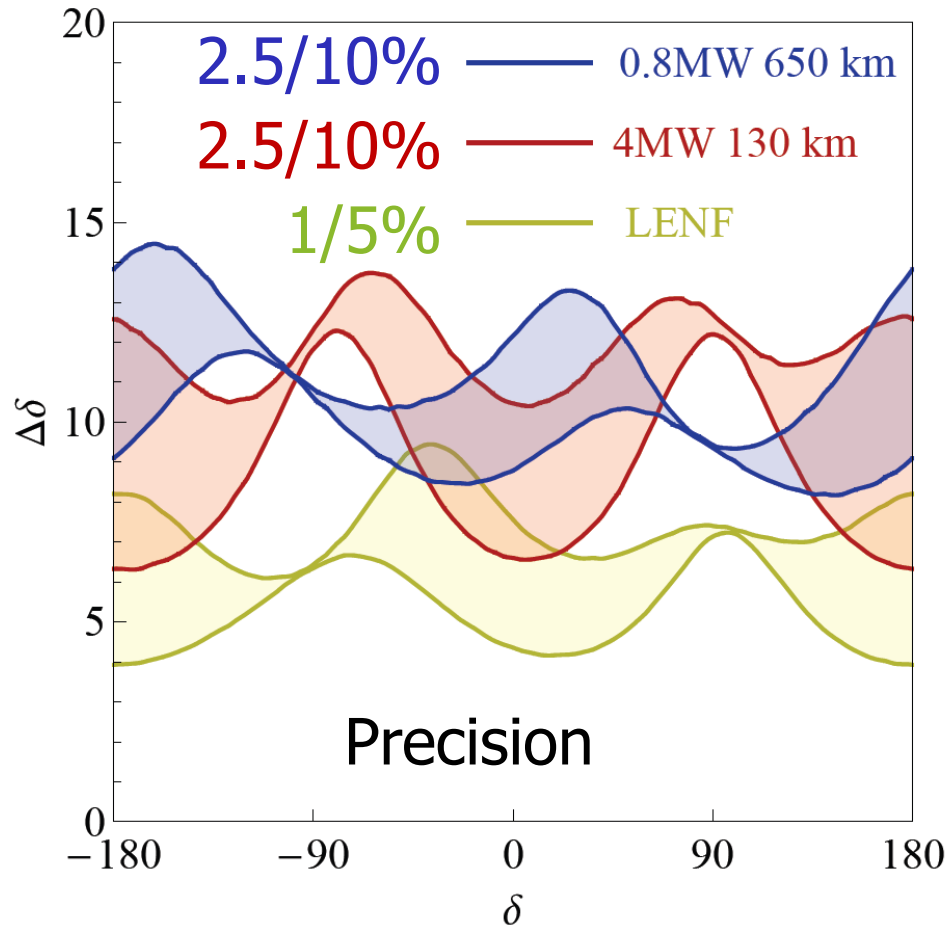
With this value of θ_{13} we cannot below J=10^{-2}

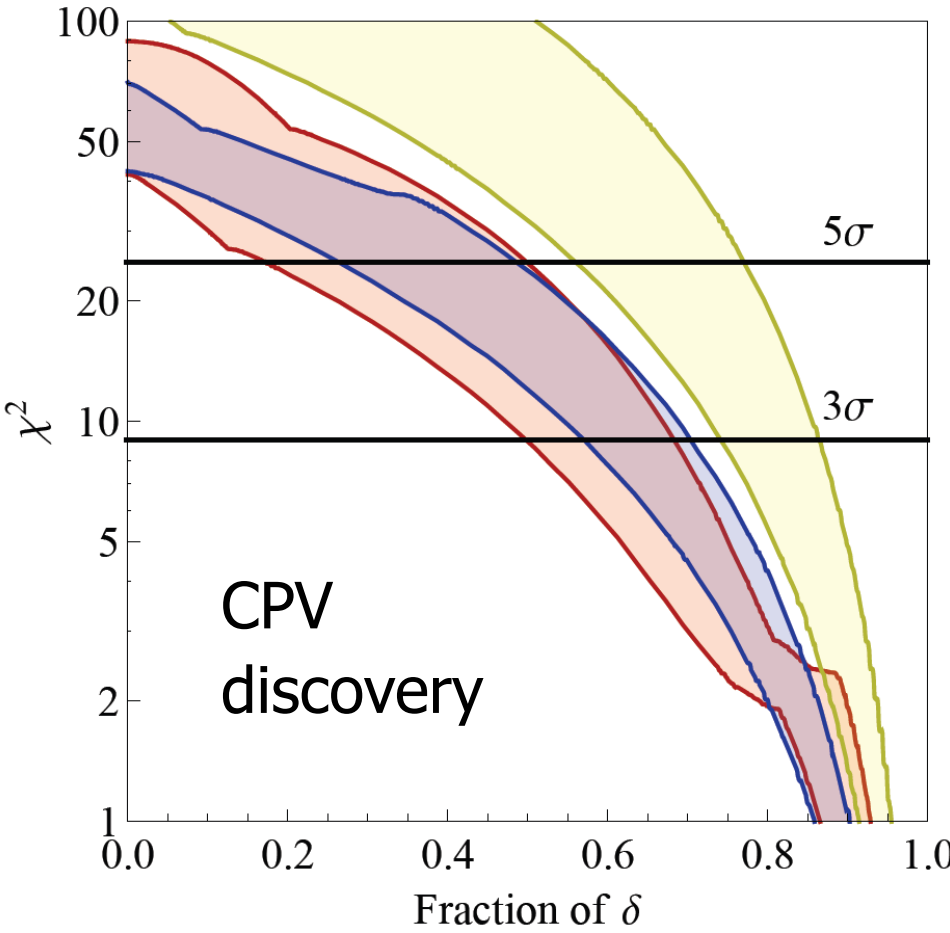
P. Coloma, P. Huber, J. Kopp and W. Winter in preparation

5 questions before we launch the large θ_{13} race

- 1. Do we need the mass hierarchy from the same machine that gives us δ?
- 2. Downgrading: How much can we afford?
- 3. Precision: New comparisons. How much?
- 4. Systematics!

Systematics





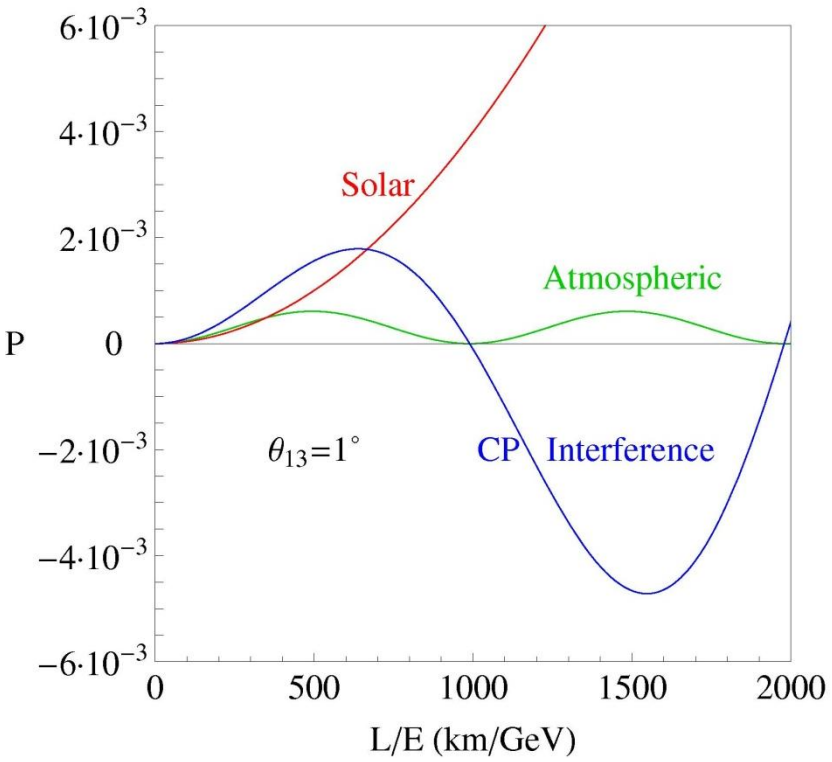
In many cases comparison of performance depends on sys

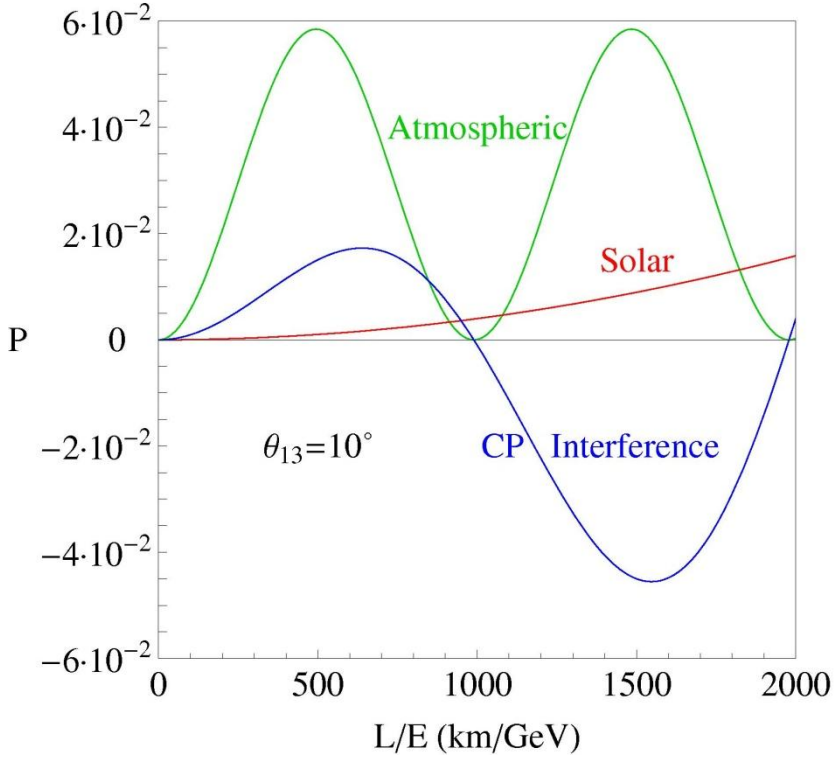
A precise knowledge of the sys is mandatory!!

5 questions before we launch the large θ_{13} race

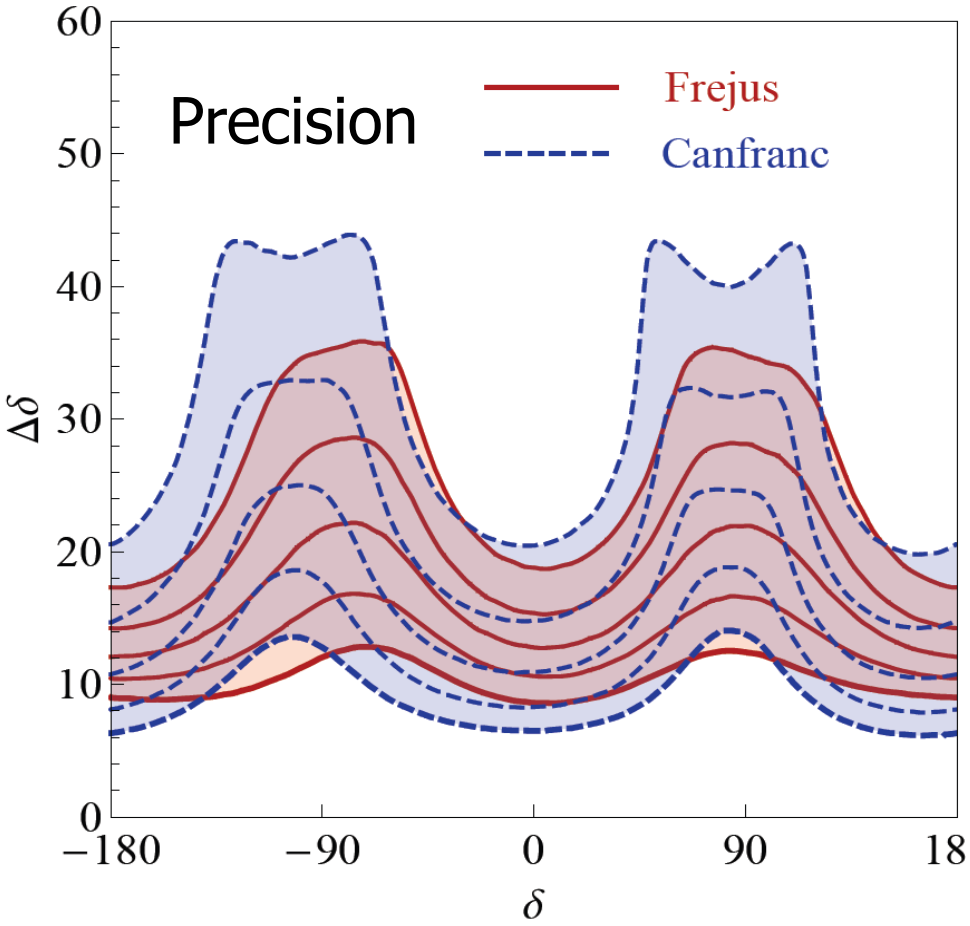
- 1. Do we need the mass hierarchy from the same machine that gives us δ?
- 2. Downgrading: How much can we afford?
- 3. Precision: New comparisons. How much?
- 4. Systematics!
- 5. New strategies for large θ_{13}?

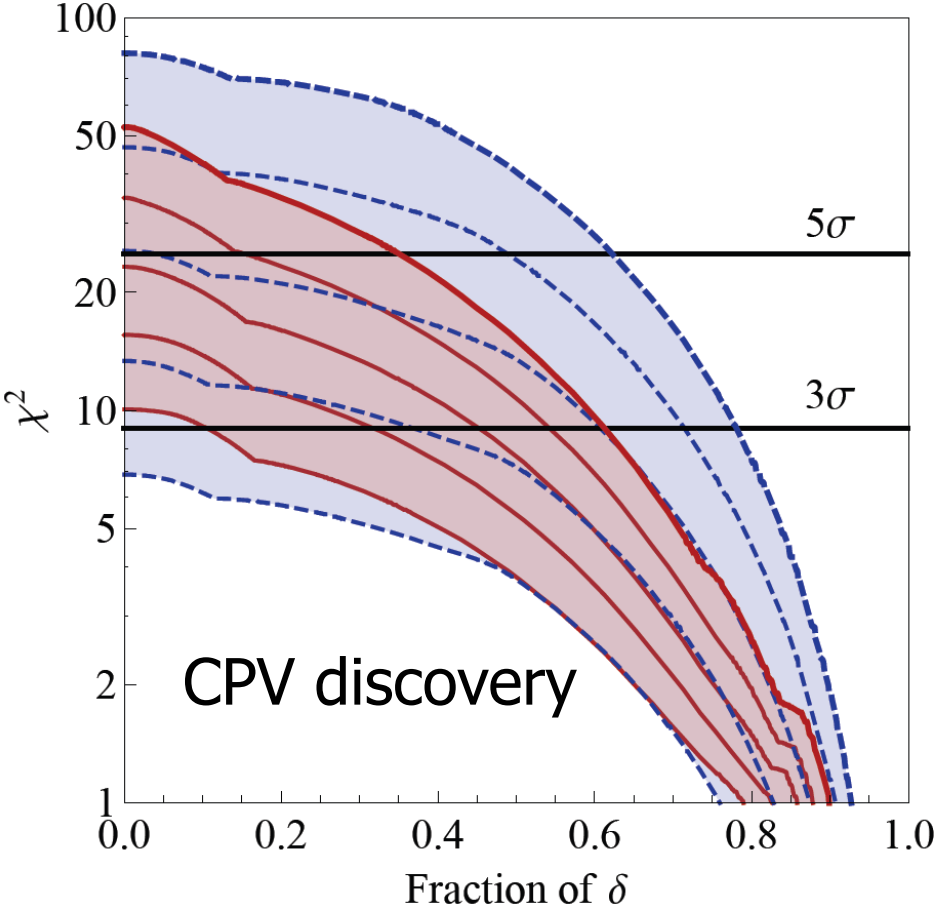
Optimization of facilities for large θ_{13}





SPL at Frejus vs Canfranc





Lines are reducing the statistics by factors of 2, 4, 8 and 16

For high statistics Canfranc much better

For very small statistics Frejus better

P. Coloma and EFM 1110.4583

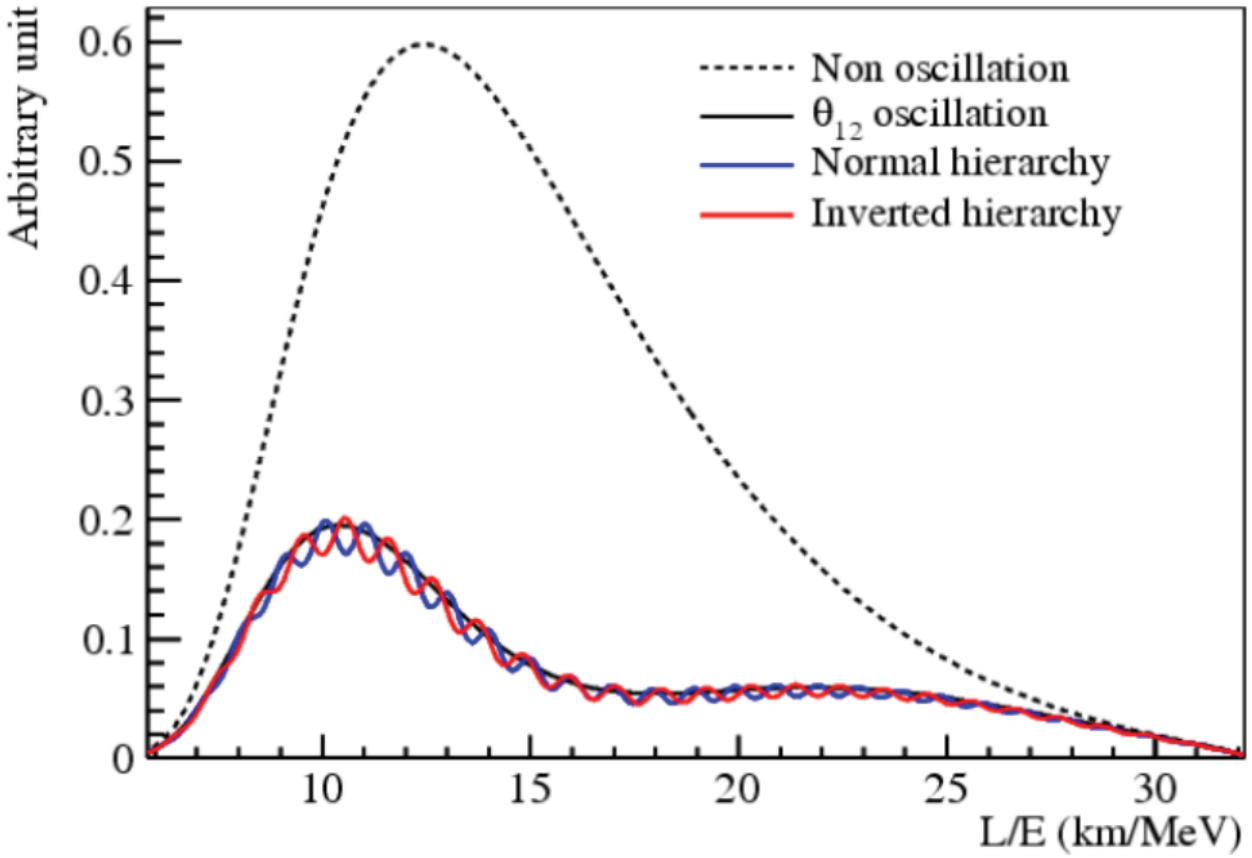
Conclusions

- The large value of θ_{13} discovered by Daya Bay opens the window to the measurement of the neutrino mass hierarchy and leptonic CP violation.

- T2K and Nova will provide the first ~90% CL indications over the next 8 years.

- We still need to "digest" the large θ_{13} news before committing. Important questions to answer:
  - Will we get the mass hierarchy from atmospherics?
  - What are the achievable systematics at each facility?
  - How much precision do we need?
  - How much can we afford to downgrade?

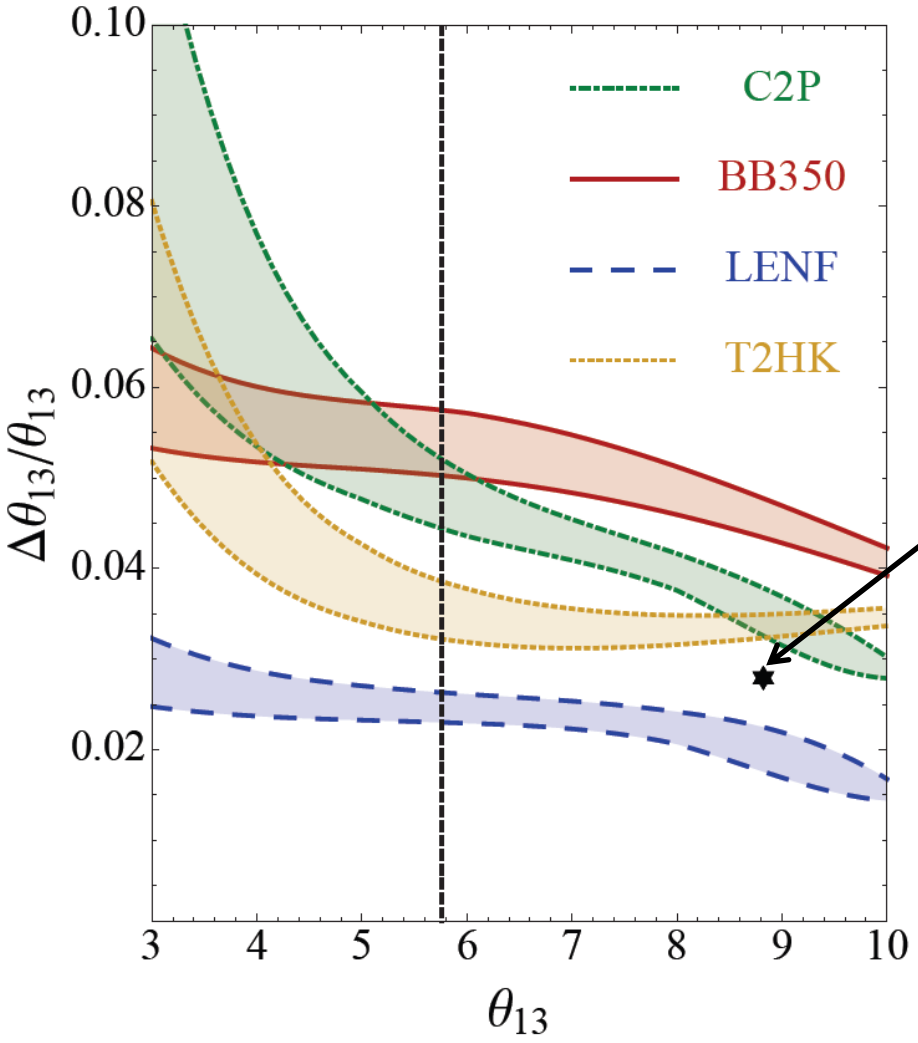
Daya-Bay II



Big detector ~20 kt
L = 60 km
Really good energy resolution

S.T. Petcov and M. Piai hep-ph/0112074
S.Choubey, S.T. Petcov and M. Piai hep-ph/0306017
J. Learned et al. hep-ex/0612022
L. Zhan, Y. Wang, J. Cao, L. Wen 0807.3203; 0901.2976

Precision: θ_{13}



Daya Bay only sys

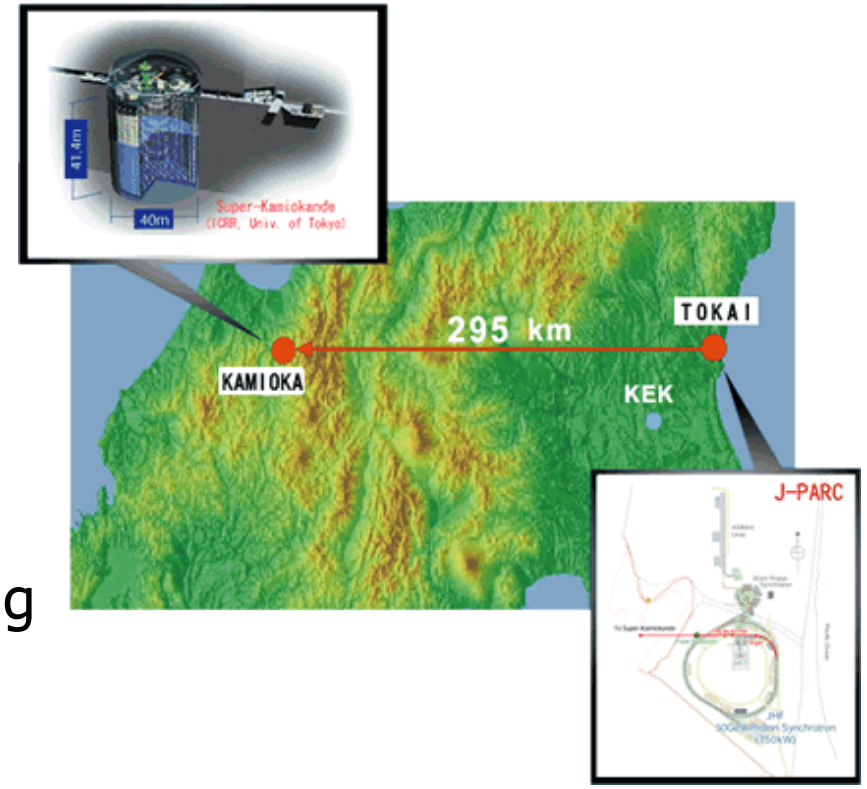
P. Coloma, A. Donini, EFM and P. Hernandez 1203.5651

Present (and near future) ν beams

- T2K: L=295 Km, E= 0.4-1.2 GeV

  SK 22 kt water Cerenkov detector

  ν_μ beam → no sensitivity to δ



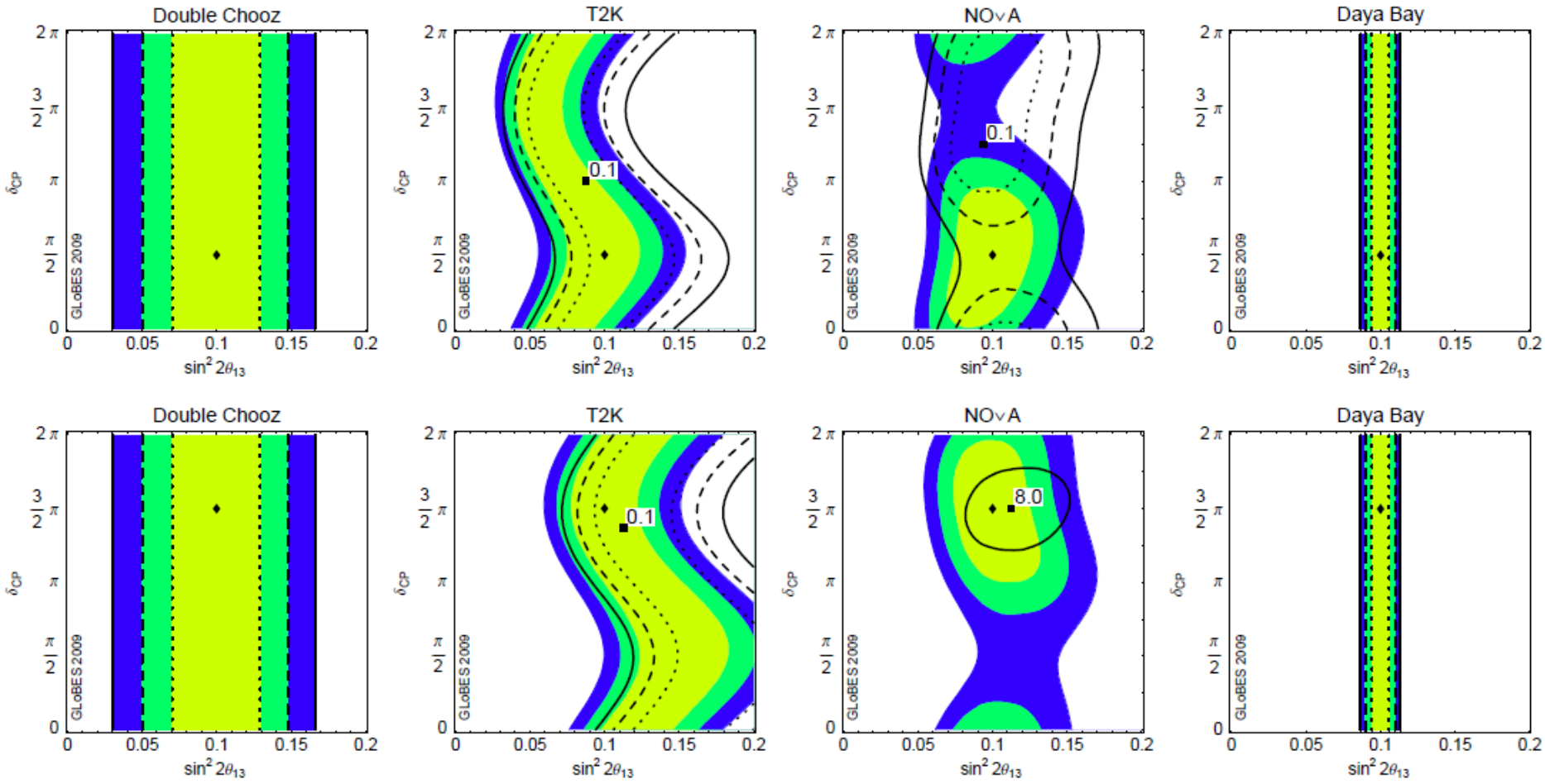
- Nova: L=810 Km E= 1.5-3 GeV

  3 + 3 yr run. 2013 starts data taking

  15 kt active scintillator detector

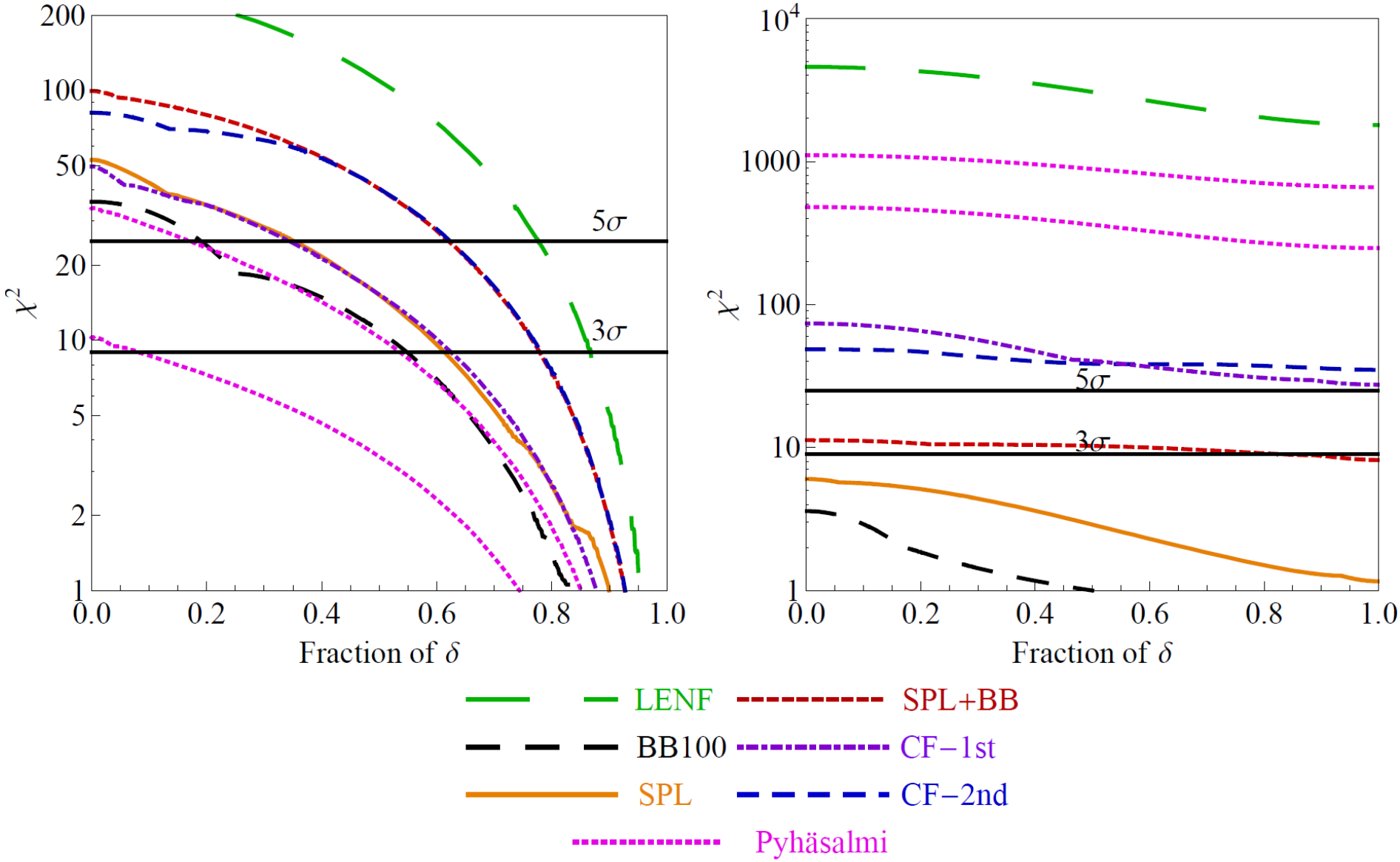
Sensitivities with present experiments

1, 2 and 3 σ

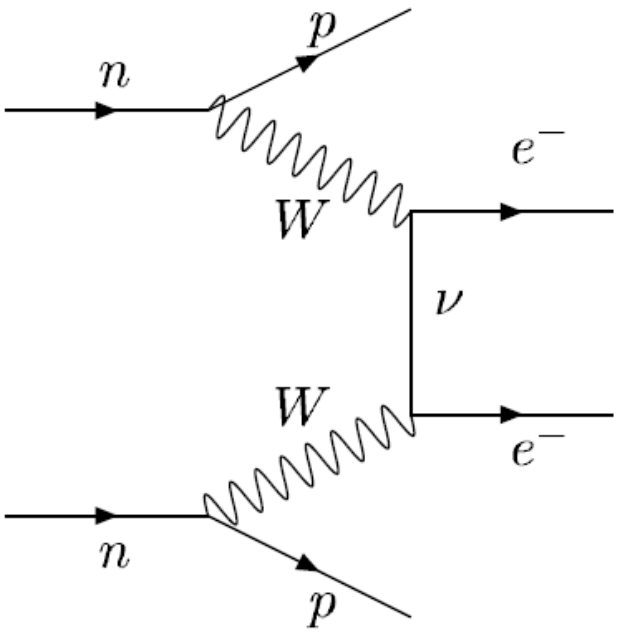


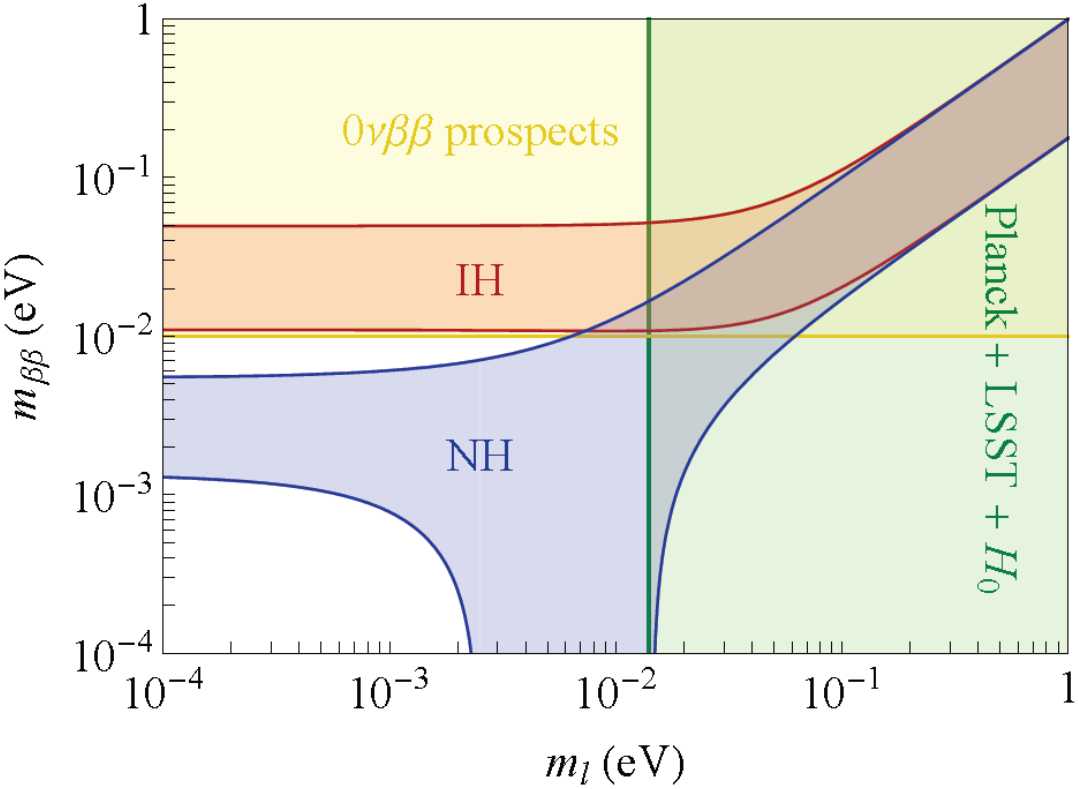
From P. Huber *et al.* 0907.1896

Final Comparison



Neutrinoless double β decay





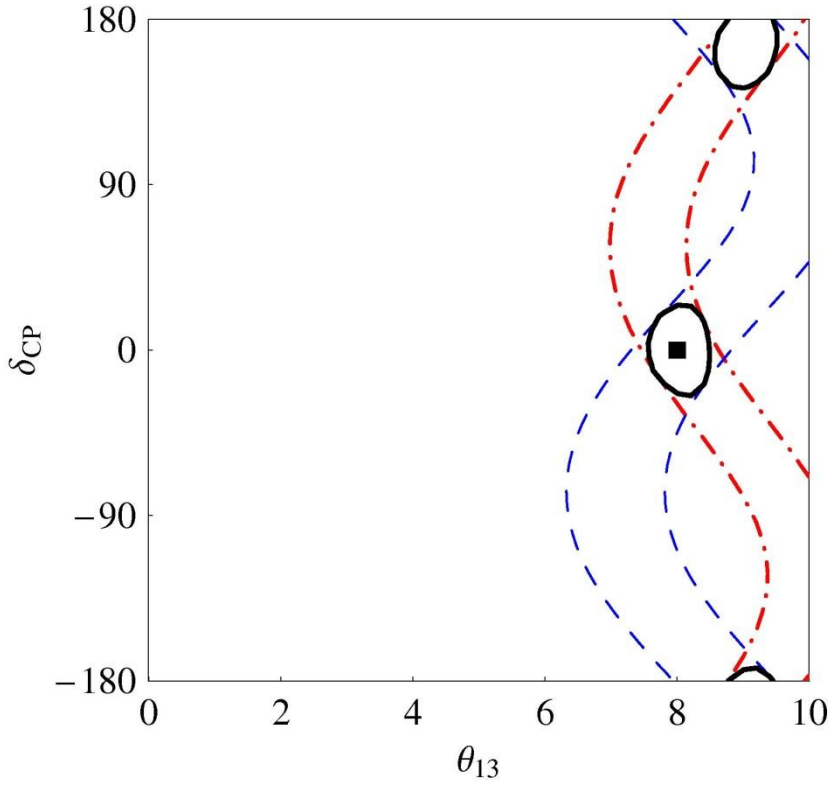
$$m_{\beta\beta} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha_1} + m_3 s_{13}^2 e^{2i\alpha_2}$$

Adapted from M. Blennow, EFM, J. Lopez and J. Menendez 1005.3240

Future with weak lensing from LSST (survey ~2020) and prospective 0νββ experiments

The degeneracy problem

- Black square = input "true" value
- There is a curve of solutions
- If we add antineutrinos the two curves intersect in 2 regions: The *true* solution and an *intrinsic degeneracy*



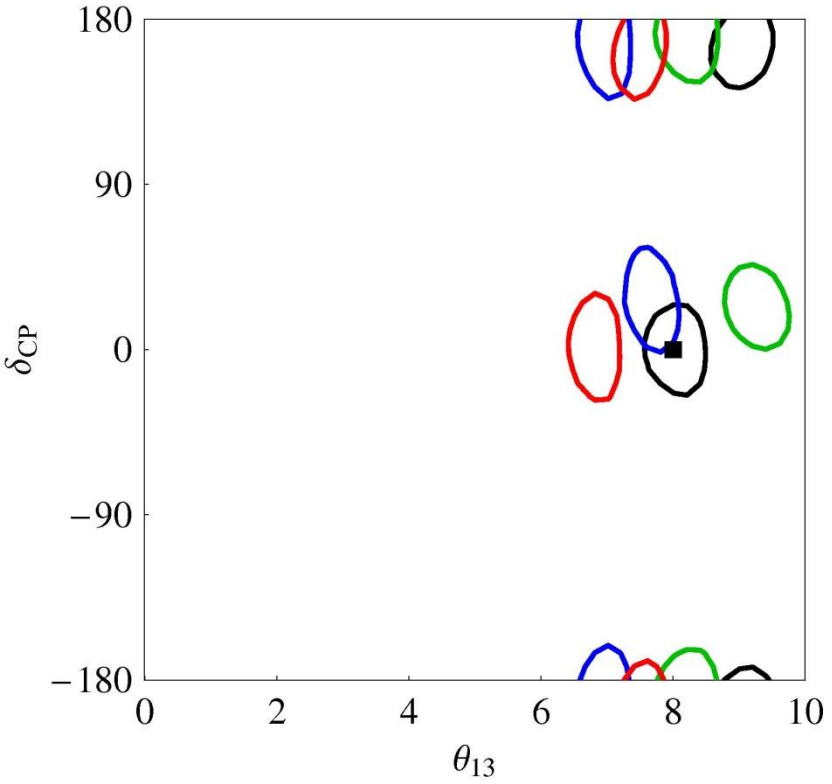
J. Burguet-Castell *et al.* hep-ph/0103258

The degeneracy problem

Two other unknown parameters: sign and oct

- There are 4 different sets of curves for different choices of sign and octant
- 2 Intersections each

Eightfold degeneracy:
Intrinsic sign octant mixed



H. Minakata and H. Nunokawa hep-ph/0108085
G.L.Fogli and E. Lisi hep-ph/9604415
V. Barger and D. Marfatia hep-ph/0112119

Super-Beams

- Intense conventional ν_μ beams from π decay with MW proton drivers

- T2HK: Beam power x2
  mass x25 (560 kt) Hyper-K
  Abe et al 1109.3262

- SPL: CERN - Frejus L=130 km
  E= 0.1-0.5 GeV
  500 kt water Cerenkov detector

- LBNE: Wide Band Beam
  E= 1-5 GeV
  Fnal – Dusel L=1300 km
  Liquid Ar detector 33.4 kt

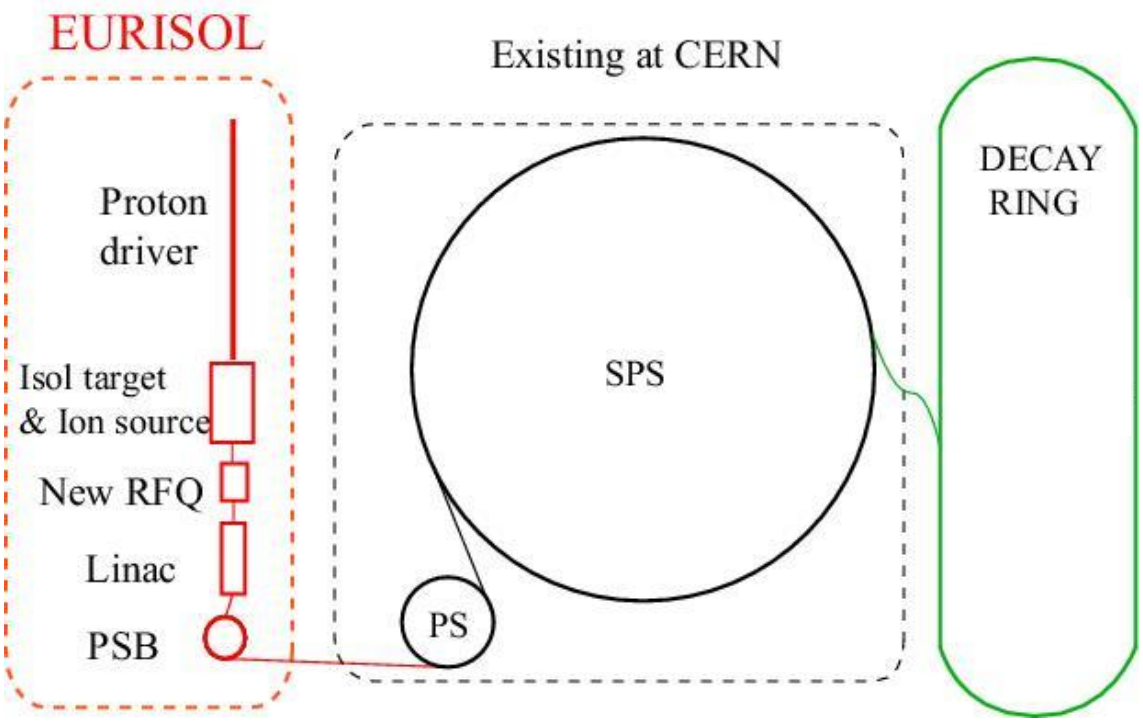
- LAGUNA-LBNO: Wide Band Beam E= 1-8 GeV
  CERN – Pyhäsalmi L=2300 km
  Liquid Ar detector 100 kt

β-Beams

Pure ν_e beams from the β decay of radiactive ions

$$^{6}He \rightarrow {}^{6}Li + \bar{\nu}_e + e^- \qquad {}^{18}Ne \rightarrow {}^{18}F + \nu_e + e^+$$

$$\nu_e \rightarrow \nu_\mu \qquad \nu_e \rightarrow \nu_e$$



P. Zucchelli 2002

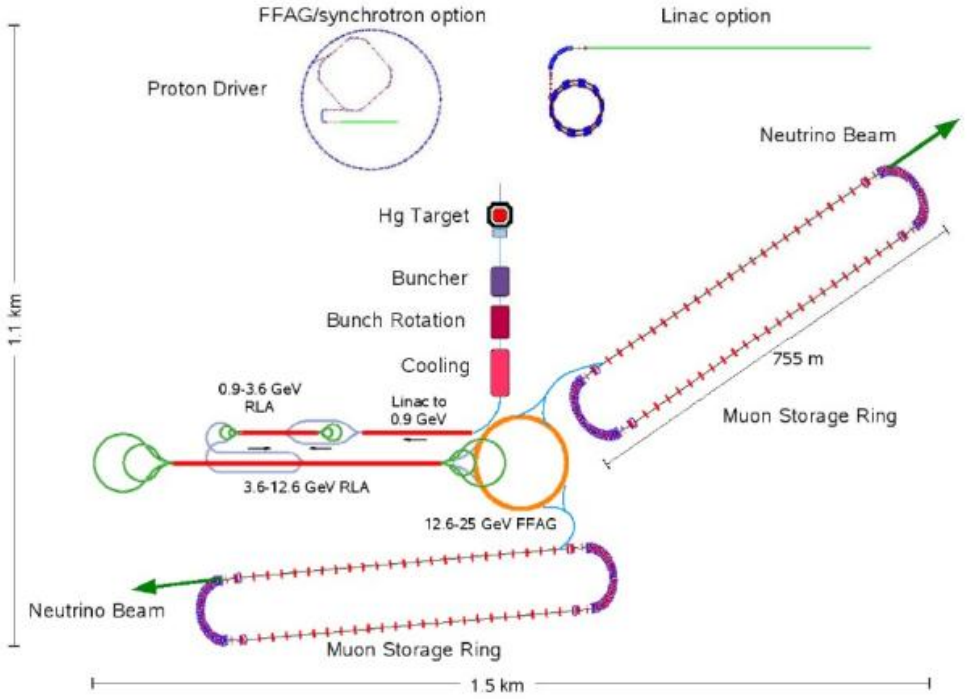
Neutrino Factory

- Pure ν_e and ν_μ from the μ decay accelated to 25 GeV

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \qquad L = 4000km$$

Lots of channels could be observed

- *golden channel:* $\nu_e \rightarrow \nu_\mu$
- *silver channel:* $\nu_e \rightarrow \nu_\tau$
- $\nu_\mu \rightarrow \nu_\mu$
- $\nu_\mu \rightarrow \nu_\tau$

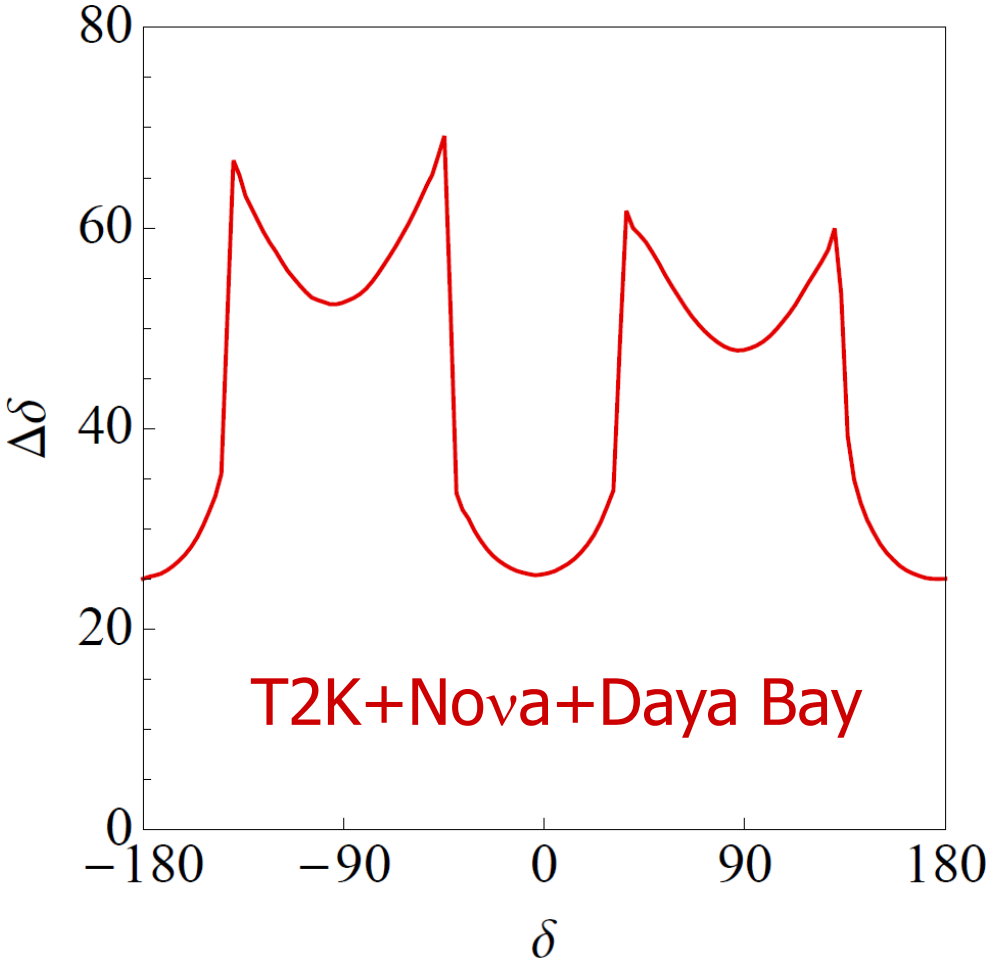


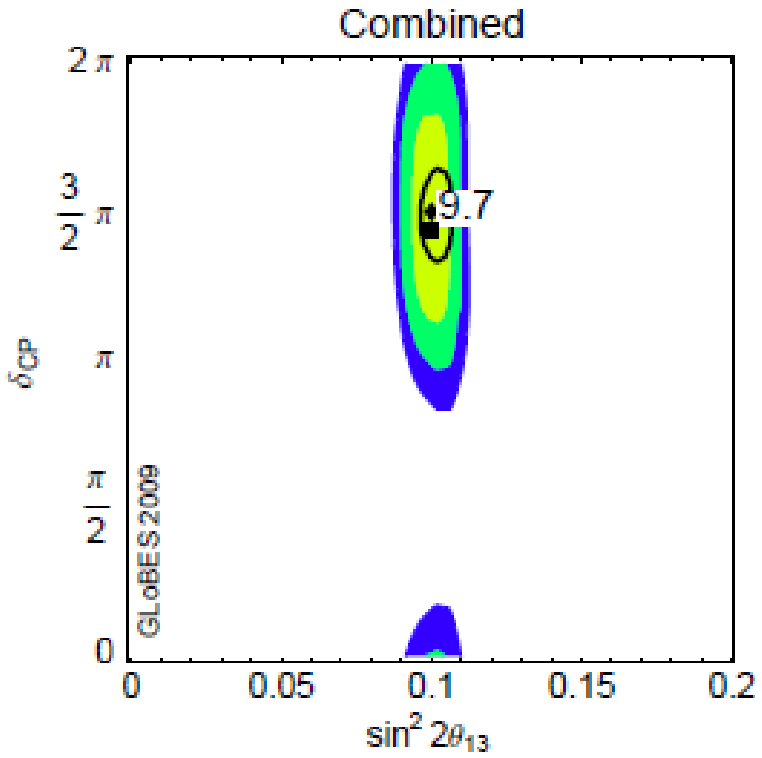
Needs to measure the lepton charge to identify the original flavour

Magnetized iron detector for $\nu_e \rightarrow \nu_\mu$ and ECC for $\nu_e \rightarrow \nu_\tau$

S. Geer hep-ex/9712290 A. de Rujula, B. Gavela and P. Hernandez hep-ex/9811390

Precision





From P. Huber *et al.* 0907.1896

P. Coloma, A. Donini, EFM and P. Hernandez 1203.5651