Comparison of EURONU facilities & beyond

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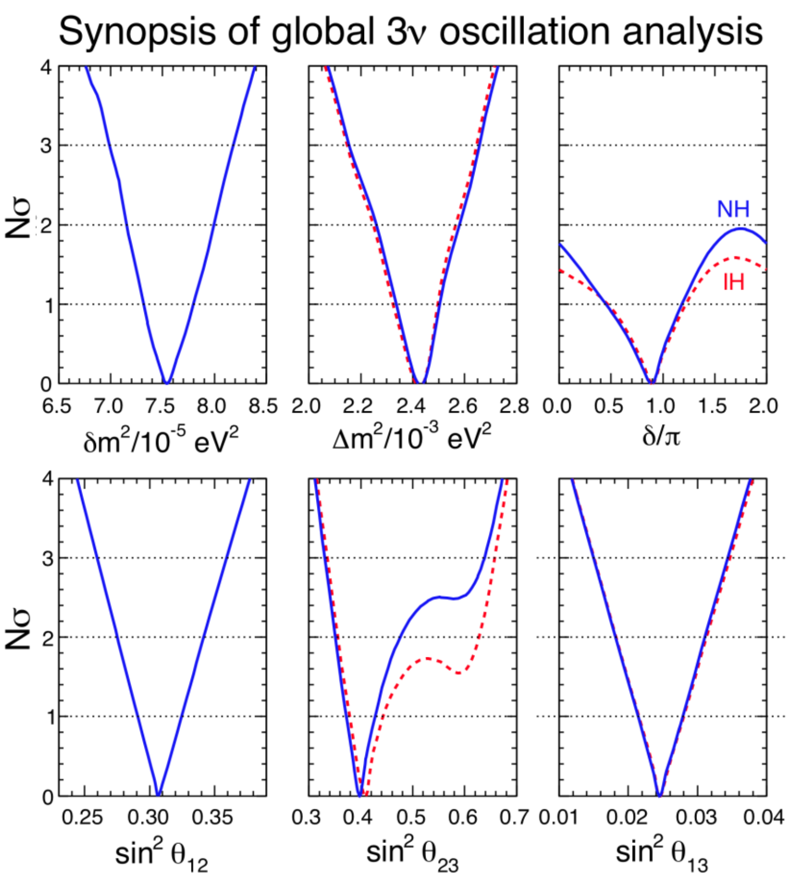
SM + massive ν_s

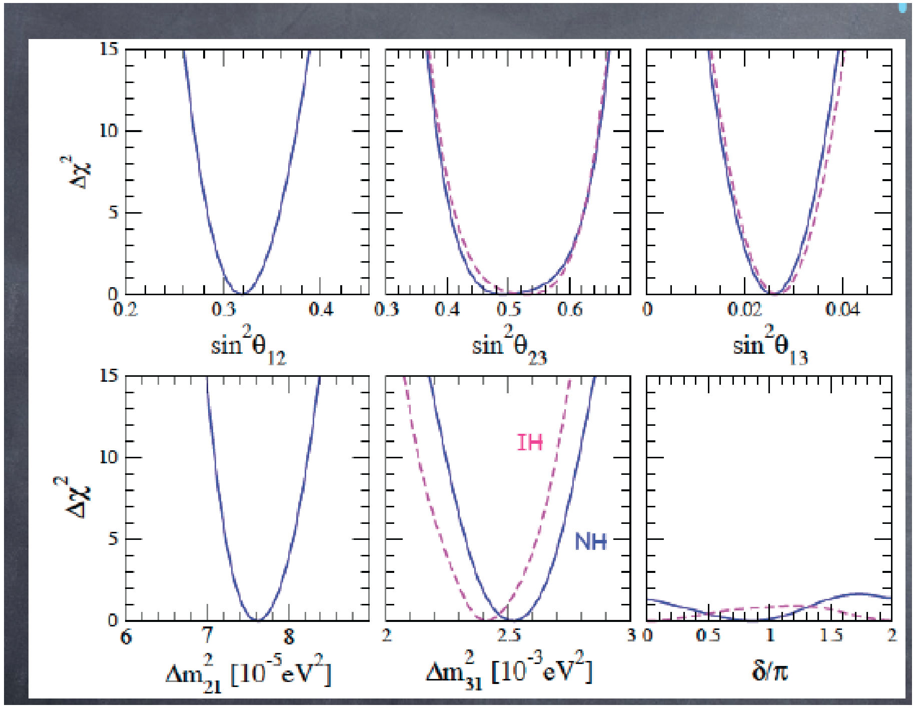
3ν mixing: $$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



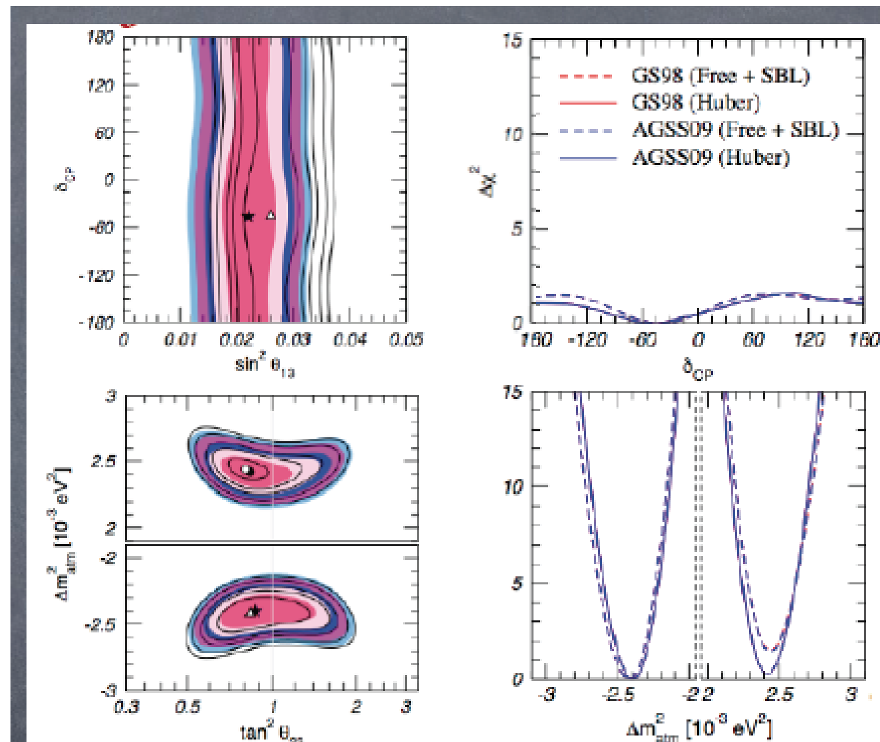
Fogli et al 2012 (after T2K, Double-CHOOZ, Daya Bay, RENO)

First ~2σ hint of δ & 1st octant !!

Hints not clear yet…very dependent on atmospheric data analyses



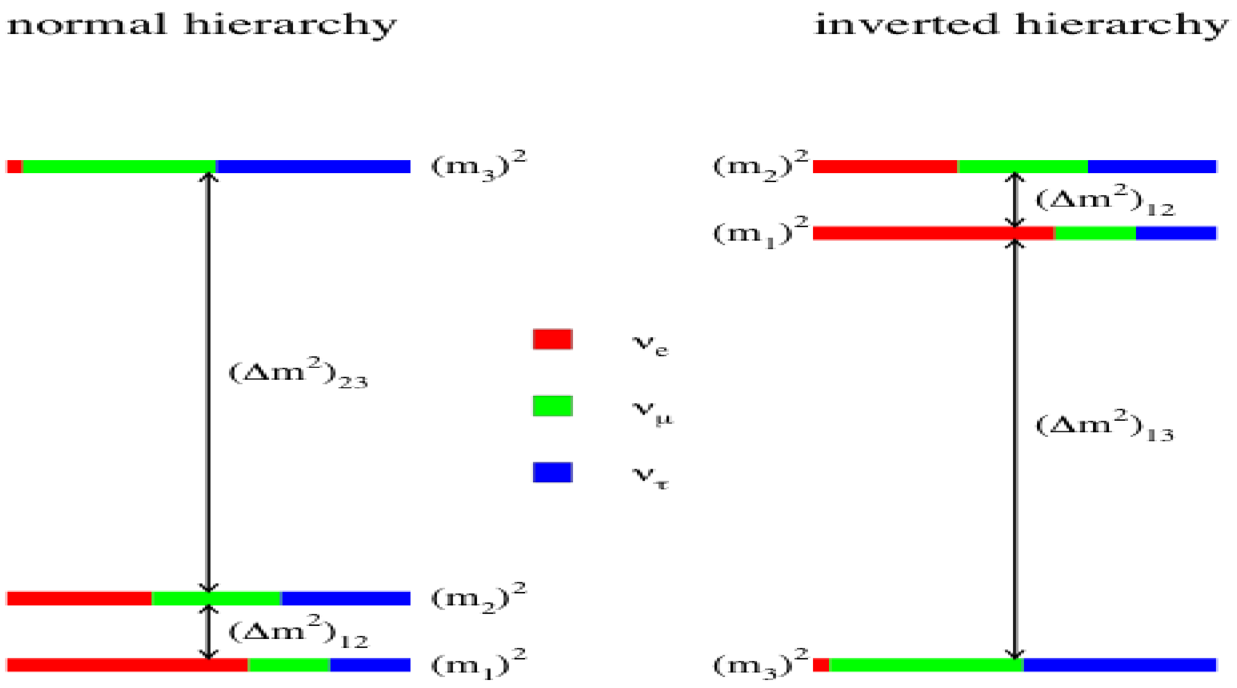
Tortola et al



Gonzalez-Garcia et al

The art of the possible

We should at least measure the 3 active ν mass matrix



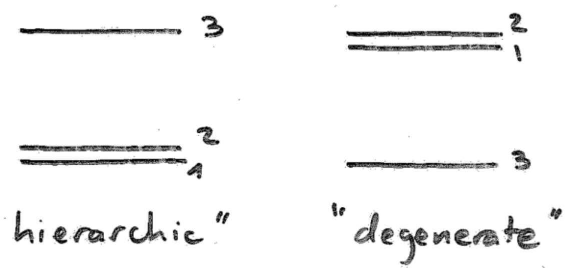
Masses	Angles	CP-phases
m_1^2 , m_2^2, m_3^2	$\theta_{12},\theta_{23},\theta_{13}$	δ (α_1, α_2)

Golden measurements in Nufact:

θ_{13} link between solar & atmospheric anomalies

$\mathrm{sign}(\Delta m^2_{23})$ ν mass spectrum $\equiv$ ν mass matrix

(see also Barger et al.)



δ CP̸ in lepton sector

Wrong sign μ's :	$\nu_e \to \nu_\mu$ (μ^+ beam)
	$\bar{\nu}_e \to \bar{\nu}_\mu$ (μ^- beam)

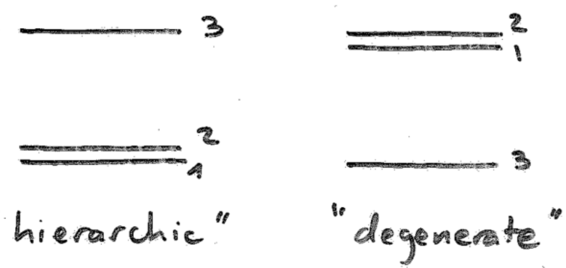
Circa '99

Golden measurements in Nufact:

θ_{13} — link between solar & atmospheric anomalies ✔

$\text{sign}(\Delta m^2_{23})$ — ν mass spectrum $\equiv$ ν mass matri

(see also Barger et al.)



δ — $\not{CP}$ in lepton sector

Wrong sign μ's :	$\nu_e \to \nu_\mu$ (μ^+ beam)
	$\bar{\nu}_e \to \bar{\nu}_\mu$ (μ^- beam)

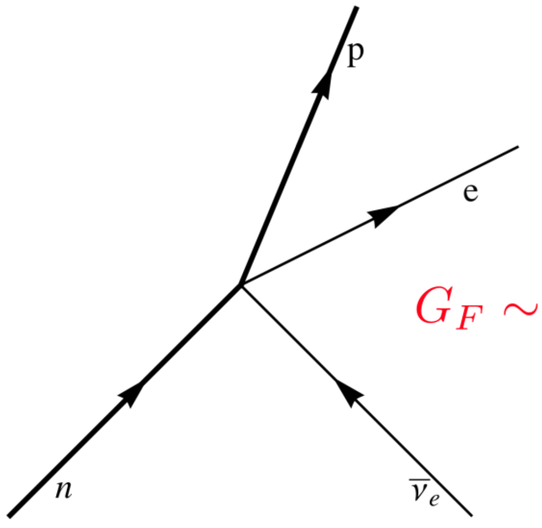
Circa '99

- Majorana nature of neutrinos -> new physics scale (Λ) & L non-conservation
- Absolute neutrino mass scale $m_\nu \approx \Lambda^{-1}$
- Leptonic CP violation

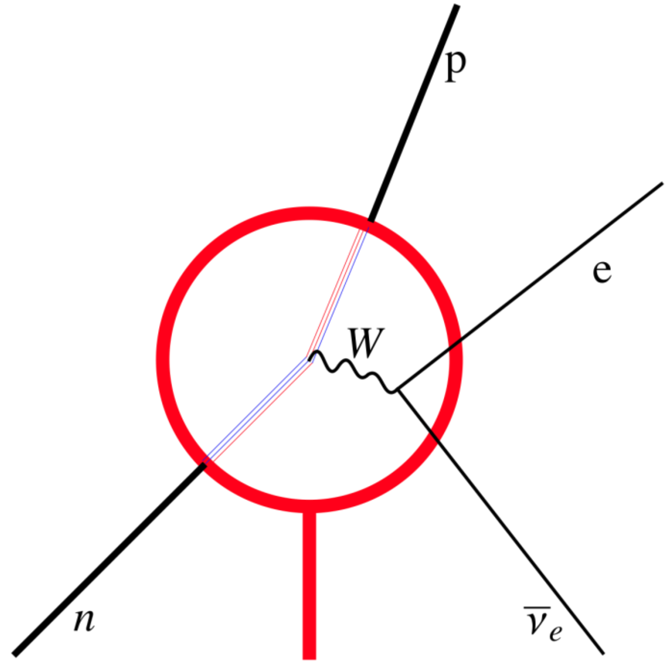
Implications for matter/antimatter asymmetry, dark matter, LSS, flavour puzzle…

Hierarchy essential for reconstructing the underlying model of neutrino masses & predictions for other observables

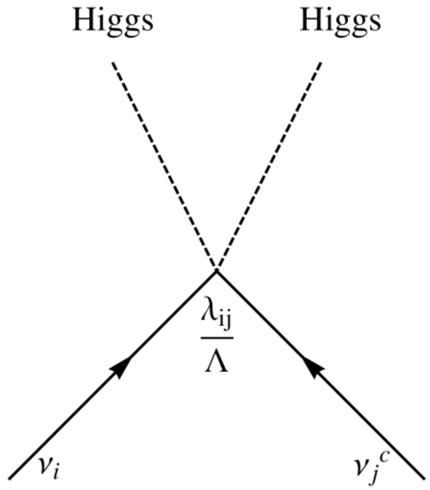
We do not know what physics is responsible for neutrino masses!



$$G_F \sim \frac{1}{M_W^2}$$

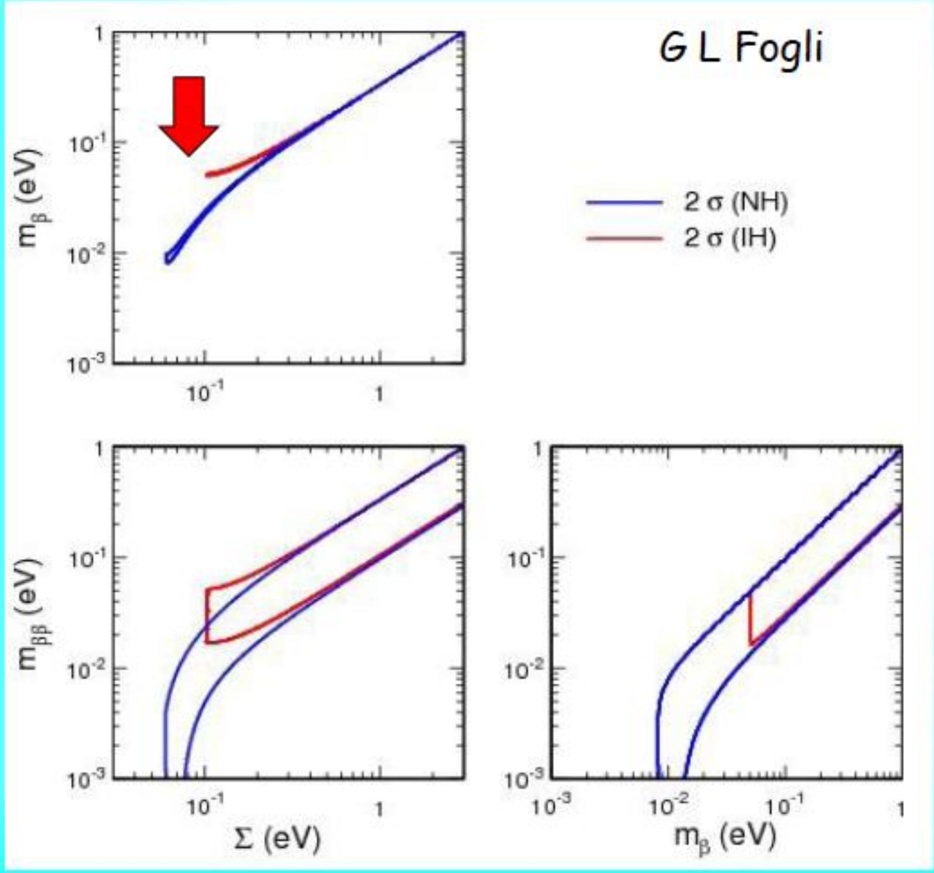


SM



νSM ?

Cosmology and hierarchy



Planck?

Hierarchy has very important implications !!

Leptonic CP violation (in vacuum)

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23}\, L}{2}\right) \equiv P^{atmos}$$

$$+ \quad c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12}\, L}{2}\right) \equiv P^{solar}$$

$$+\tilde{J} \quad \cos\left(\pm\delta - \frac{\Delta_{23}\, L}{2}\right) \frac{\Delta_{12}\, L}{2} \sin\left(\frac{\Delta_{23}\, L}{2}\right) \equiv P^{inter}$$

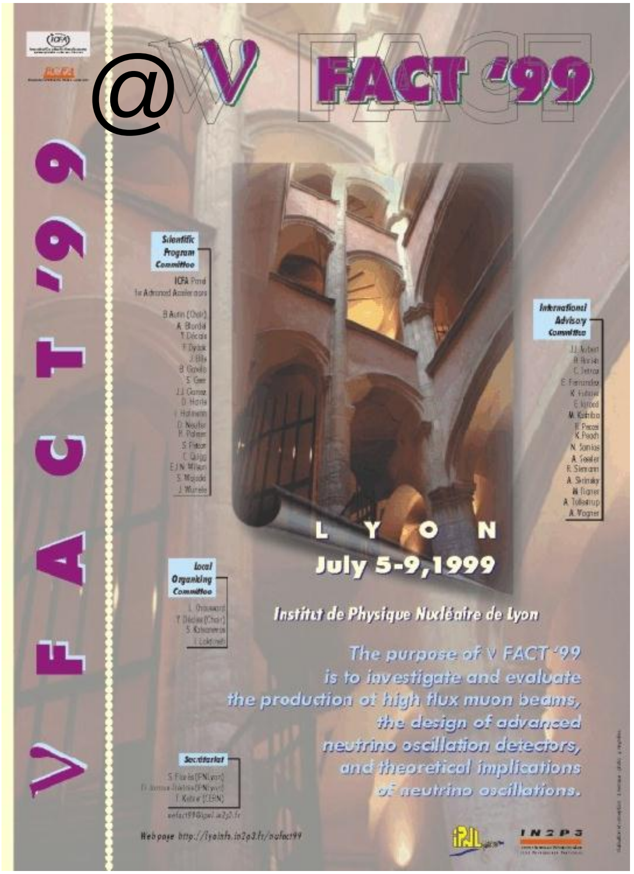
$$\tilde{J} \equiv c_{13} \; \sin 2\theta_{13} \; \sin 2\theta_{12} \; \sin 2\theta_{23}$$

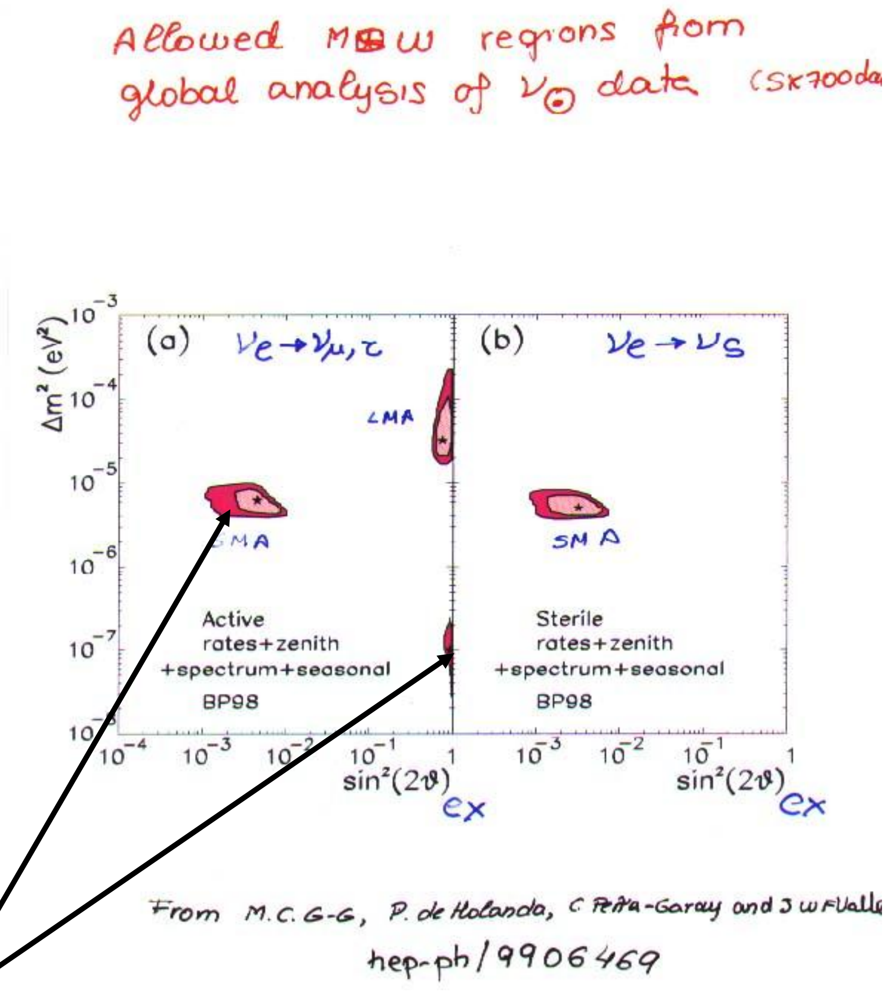
$$P^{atmos} \gg P^{solar} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} \sim \frac{\Delta_{12} L}{\sin 2\theta_{13}}$$

$$P^{solar} \gg P^{atmos} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} \sim \frac{\sin 2\theta_{13}}{\Delta_{12} L}$$

$$P^{solar} \simeq P^{atmos} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} = O(1)$$

So far so good…





It would have been impossible to measure CP violation!

Leptonic CP violation (in vacuum)

$$P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23}\,L}{2}\right) \equiv P^{atmos}$$

$$+ \quad c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12}\,L}{2}\right) \equiv P^{solar}$$

$$+\tilde{J} \quad \cos\left(\pm\delta - \frac{\Delta_{23}\,L}{2}\right) \frac{\Delta_{12}\,L}{2} \sin\left(\frac{\Delta_{23}\,L}{2}\right) \equiv P^{inter}$$

$$\tilde{J} \equiv c_{13} \; \sin 2\theta_{13} \; \sin 2\theta_{12} \; \sin 2\theta_{23}$$

θ_{13} measurement

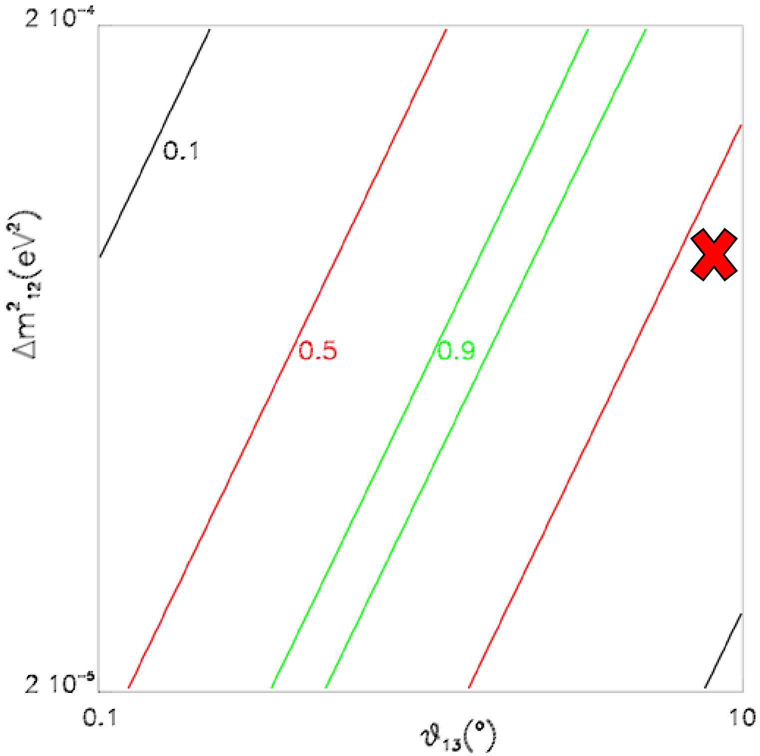
$$P^{atmos} \gg P^{solar} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} \sim \frac{\Delta_{12}L}{\sin 2\theta_{13}}$$

$$P^{solar} \gg P^{atmos} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} \sim \frac{\sin 2\theta_{13}}{\Delta_{12}L}$$

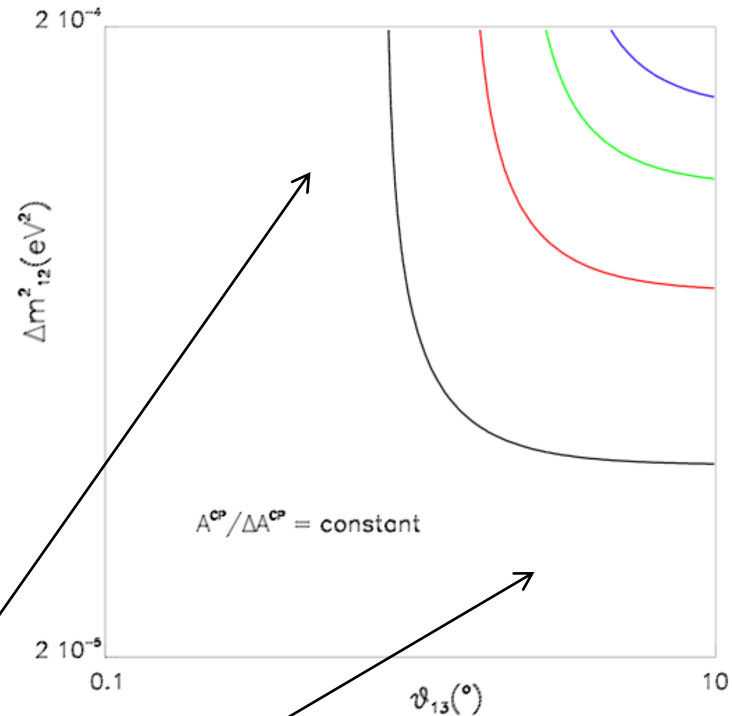
$$P^{solar} \simeq P^{atmos} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} = O(1)$$

CP asymmetries can be very large in $\nu_e \longleftrightarrow \nu_\mu$

Asymmetry



Significance



Out of reach: if not large enough θ_{13}

Out of reach: if not large solar splitting

Hierarchy via Matter effects

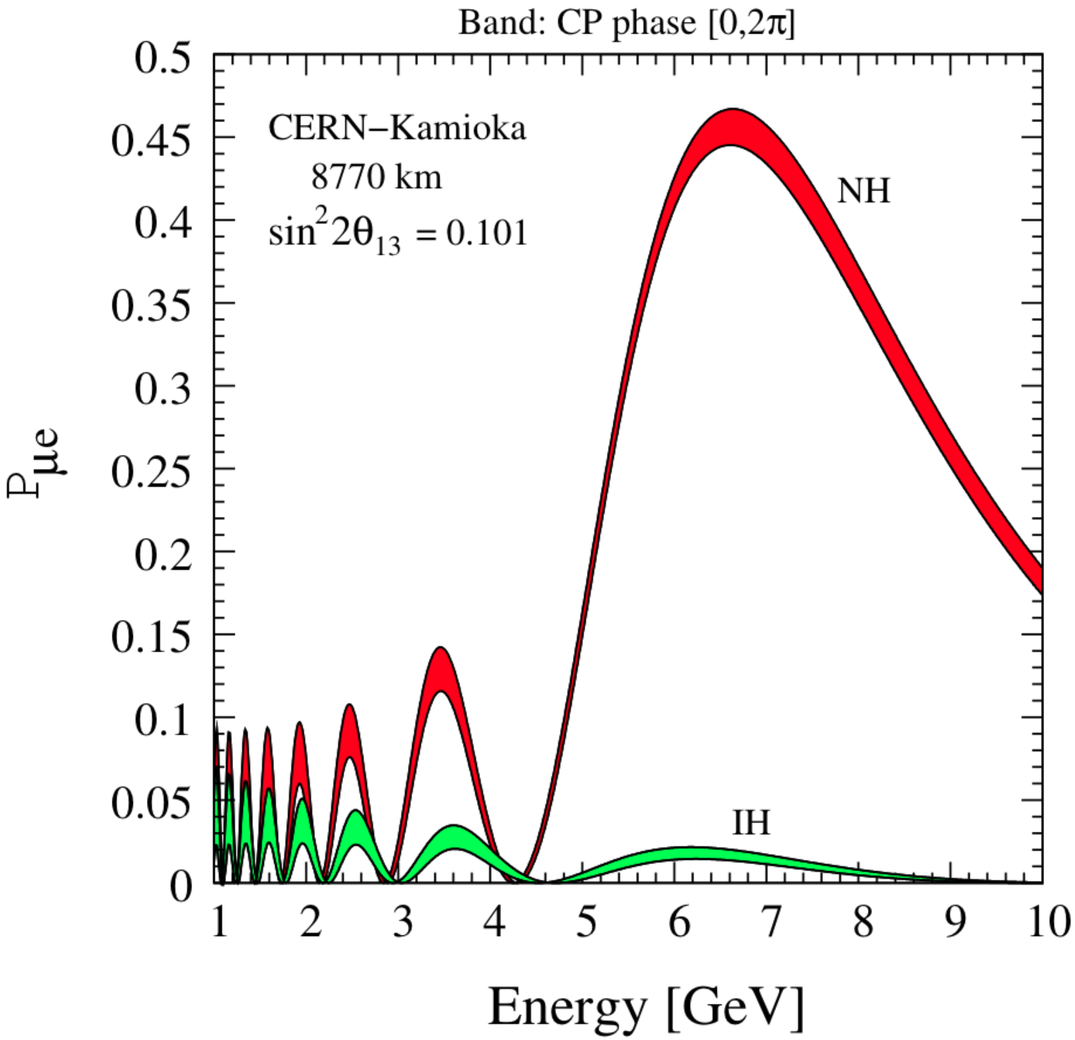
At second order in $\varepsilon = \theta_{13}$ or Δm^2_{12}

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s^2_{23}\,\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2\,\sin^2\left(\frac{B_\pm L}{2}\right)$$
$$+c^2_{23}\,\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\left(\frac{AL}{2}\right)$$
$$+\tilde{J}\,\frac{\Delta_{12}}{A}\,\sin\left(\frac{AL}{2}\right)\frac{\Delta_{13}}{B_\pm}\,\sin\left(\frac{B_\pm L}{2}\right)\,\cos\left(\pm\delta - \frac{\Delta_{13}L}{2}\right)$$

Cervera et al ‘00

$$B_\pm = |A \pm \Delta_{13}| \qquad \Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$

MSW effect for ν or $\bar{\nu}$ depending on sign(Δm^2_{13})



$$E_{\text{res}} \equiv \frac{\Delta m^2_{31} \cos 2\theta_{13}}{2\sqrt{2} G_F n_e},$$

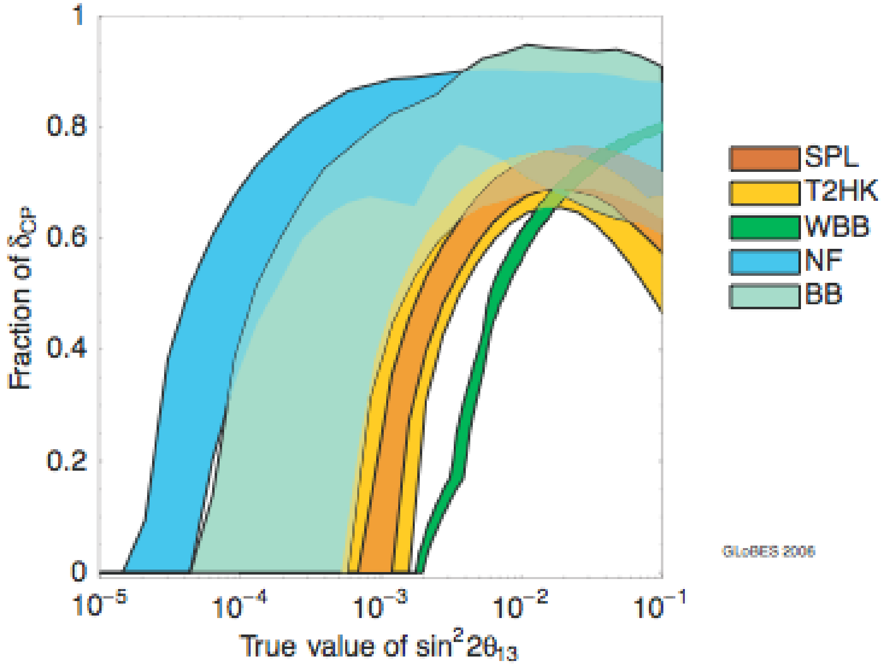
$$n_e(L) L|_{L_{\max}} = \frac{\pi}{\sqrt{2} G_F \tan 2\theta_{13}}$$

Spectacular MSW effect at O(6GeV) and very long baselines

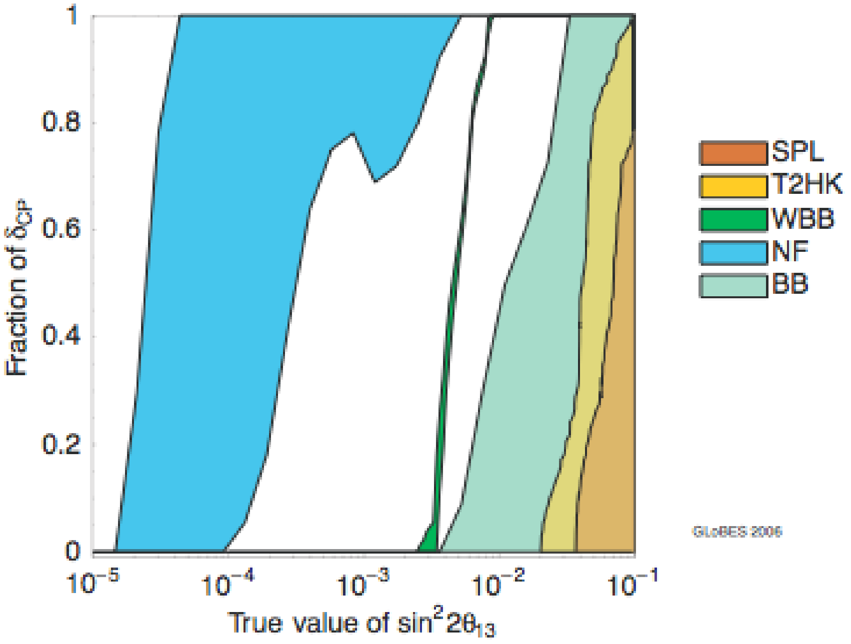
PRE-EURONU

Nothing would have worked had $\sin^2 2\theta_{13} < 10^{-5}$ …

CP phase



Hierarchy



The choice would have been easier had $\sin^2 2q_{13} < 10^{-3}$ …

In light of large θ_{13} CP violation requires optimally

1)Precise golden appearance measurements ν and ν

2)Spectral information (degeneracies…)

3)Small matter effects (shorter baselines)

4)E/L in atmospheric range (higher E, larger stat)

5)Precision always useful: more coverage in δ -> more precise determination of the parameter

In light of large θ_{13} hierarchy requires optimally

1)Golden appearance measurement (eg. ν)
(two channels better for strong confirmation)

2) No spectral information required if energy near resonance
5-6 GeV range

3) Very long baselines >O(7000)km

4) Digital measurement: precision not relevant!

Hierarchy + CP violation in one go

compromise …

Makes all sense if only one ultimate machine….

does it if hierarchy can be measured earlier ?

Or if more than two experiments ?

Can hierarchy be measured earlier ?

Very easy, very clean for moderate SB + moderate detector + but sufficiently long baseline !

Examples (5σ):

0.8MW(LBNO), 2.2y + 20kton LAr+ L=2300km ($\nu/\bar{\nu}$)

0.8MW(LBNO) , 4.5y + SuperK + L=8000km (only ν)

0.8MW(LBNO), 10y + 500kton WC + L=650km ($\nu/\bar{\nu}$)

0.8MW(LBNE), 10y+ 17kton LAr+ L=1500km ($\nu/\bar{\nu}$)

Atmospheric data contain this golden signal but hard to dig:

$\nu_e, \nu_e, \nu_\mu, \nu_\mu$

Examples: INO 25kton/50kton x 10yr

HK 0.6Mton x 10yr

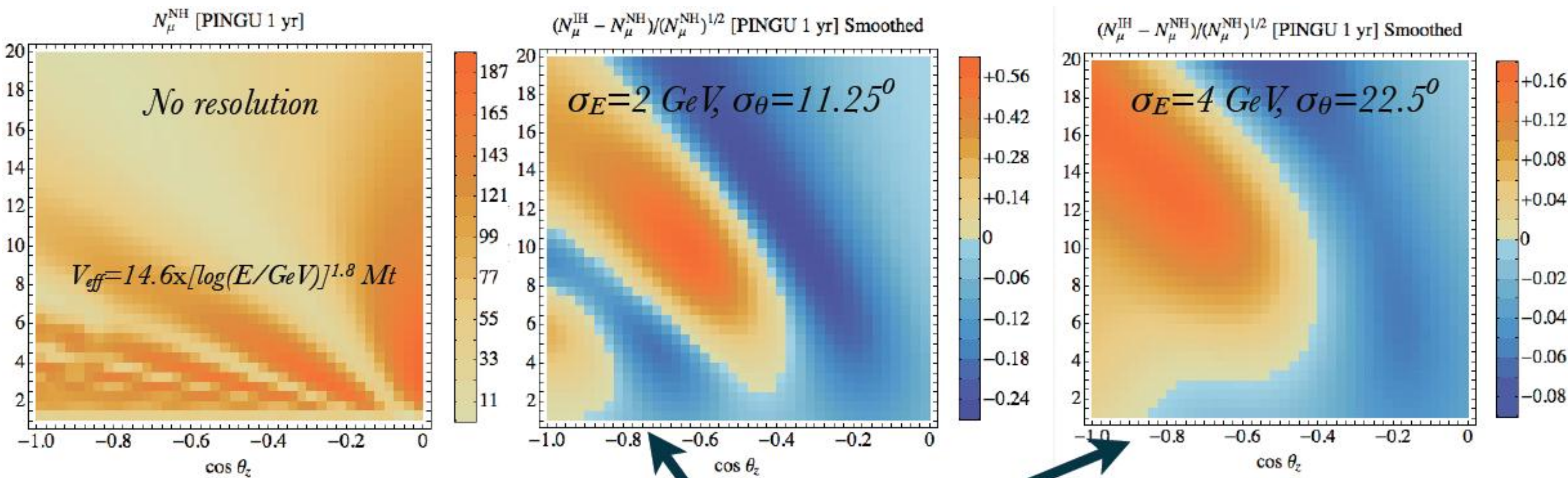
- *MH will be measured at INO at ~2σ by 2022 (250 kton-yr) and at ~2.7σ by 2027 (500 kton-yr data)*
- *MH will be measured at HK at ~3σ by 2028 (2.8 Mton-yr) and at >4σ by 2033 (5.6 Mton-yr data)*

Neutrino 2012 *Sandhya Choubey* *June 5, 2012*

25kton LAr + magnetized x 10y ~5σ

These are not moderate detectors!!!

PINGU @ ICECUBE



Akhmedov, Smirnov, Razzaque, 1206.7071

- *20 additional strings in the Deep Core, threshold reduced to ~ 1 GeV*
- *Multi-mton vol allows for 3σ to 11σ hierarchy sensitivity in 5 yrs for 10% and 5% bin-to-bin uncorr systematic errors respectively*

Atmospheric neutrino reach not easy and very systematics limited, but on the other hand they have a chance….

Is a O(10y) SB project that ONLY aims at the hierarchy (digital measurement) justified ?

CP violation is a longer shot which will require a ultimate machine…

Ultimate machines:

Nufact: 50GeV -> 25 GeV -> 10 GeV, 100kton MIND

BetaB: γ=100 (γ=350) –> γ=100, 0.5Mton WC

Superbeams:

JParc-HK (4MW -> 750kW, Mton WC/100kt LAr)
SPL (4MW, 0.5 Mton WC)
LBNE (700kW, 34ktLAr-> 10kt+surface)
LBNO (1.6MW -> 0.8MW, 100kt LAr-> 20kt LAr)

	L	$N_\nu/N_{\bar\nu}$	$B_\nu/B_{\bar\nu}$	$\langle E_\nu\rangle/\langle E_{\bar\nu}\rangle$	$\delta E_\nu/\delta E_{\bar\nu}$	$\hat{A}$
T2K	295	$2.6/0\ \times 10^3$	46/0	0.72/–	0.27/–	0.02
NOνA	810	$1.1/0.7\ \times 10^3$	10/11	2.02/2.04	0.43/0.42	0.14
T2HK	295	$4.3/1.3\ \times 10^5$	$4.3/1.5\ \times 10^3$	0.79/0.80	0.18/0.18	0.022
LBNE	1290	$2.3/0.9\ \times 10^4$	302/201	3.55/3.50	1.38/1.33	0.30
SPL	130	$2.5/1.6\ \times 10^5$	$1.1/1.2\ \times 10^3$	0.59/0.57	0.20/0.21	0.017
C2P	2300	$2.4/1.1\ \times 10^4$	210/129	5.04/5.15	1.65/1.59	0.48
BB100	130	$2.9/4.4\ \times 10^4$	$0.6/1.2\ \times 10^3$	0.47/0.45	0.18/0.18	0.013
BB350	650	$5.0/9.2\ \times 10^4$	372/432	1.53/1.61	0.45/0.45	0.11
LENF	2000	$8.1/5.3\ \times 10^5$	48/81	6.75/6.78	1.81/1.79	0.63
IDS1b	4000	$1.9/1.2\ \times 10^6$	154/196	16.85/16.86	4.57/4.55	1.65

Standard analysis

Example: A = normalization, x = $\sigma_\nu / \sigma_{\bar{\nu}}$

$$\chi^2(\theta_{13}, \delta, ..., A, x) = \sum_i \left(\frac{N_i(\theta_{13}, \delta, ..., A, x) - n_i}{\sigma_i} \right)^2 + \frac{(A-1)^2}{\sigma_A^2} + \frac{(x-1)^2}{\sigma_x^2}$$

Add as many parameters as required by physics/detector.

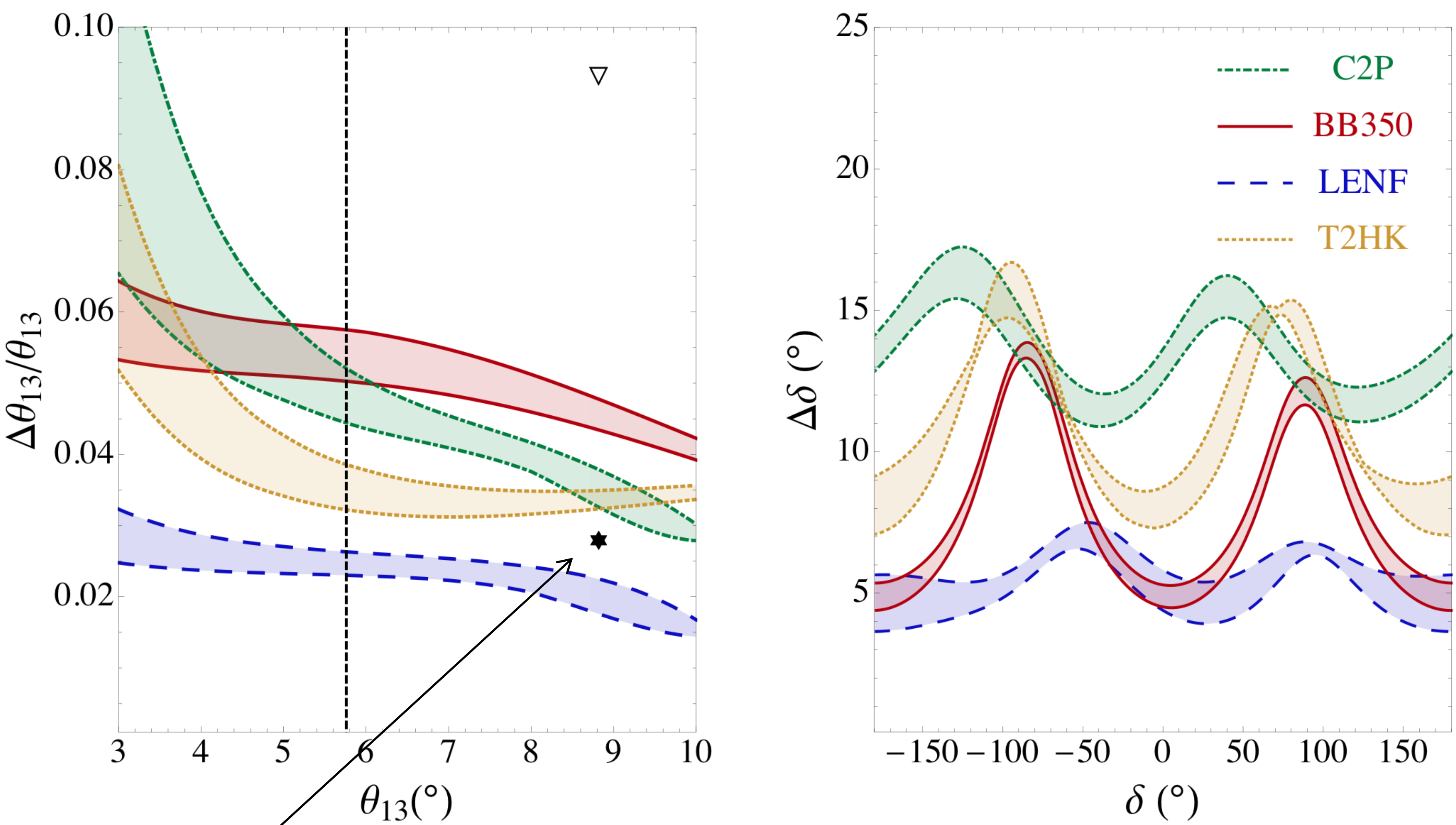
$$\begin{aligned} N_\alpha &= \int_{E_\alpha}^{E_\alpha + \Delta E} dE_\nu^r \int_0^\infty dE_\nu M(E_\nu^r, E_\nu) \sigma(E_\nu) P_{osc}(E_\nu, \{\theta_{ij}, \Delta m_{ij}^2\}) \left. \frac{d\Phi}{d\cos\theta}(E_\nu) \right|_{\theta \simeq 0} \\ &\simeq \sum_{\alpha,\beta} M_{\alpha\beta} \sigma(E_\beta) P_{osc}(E_\beta, \{\theta_{ij}, \Delta m_{ij}^2\}) \left. \frac{d\Phi}{d\cos\theta}(E_\beta) \right|_{\theta \simeq 0} \end{aligned}$$

Systematic error assumptions in following plots:

Superbeams: 5% eff, 5% bckgnd

Beta-beam, Nufact: 2.5% eff, 5% bckgnd

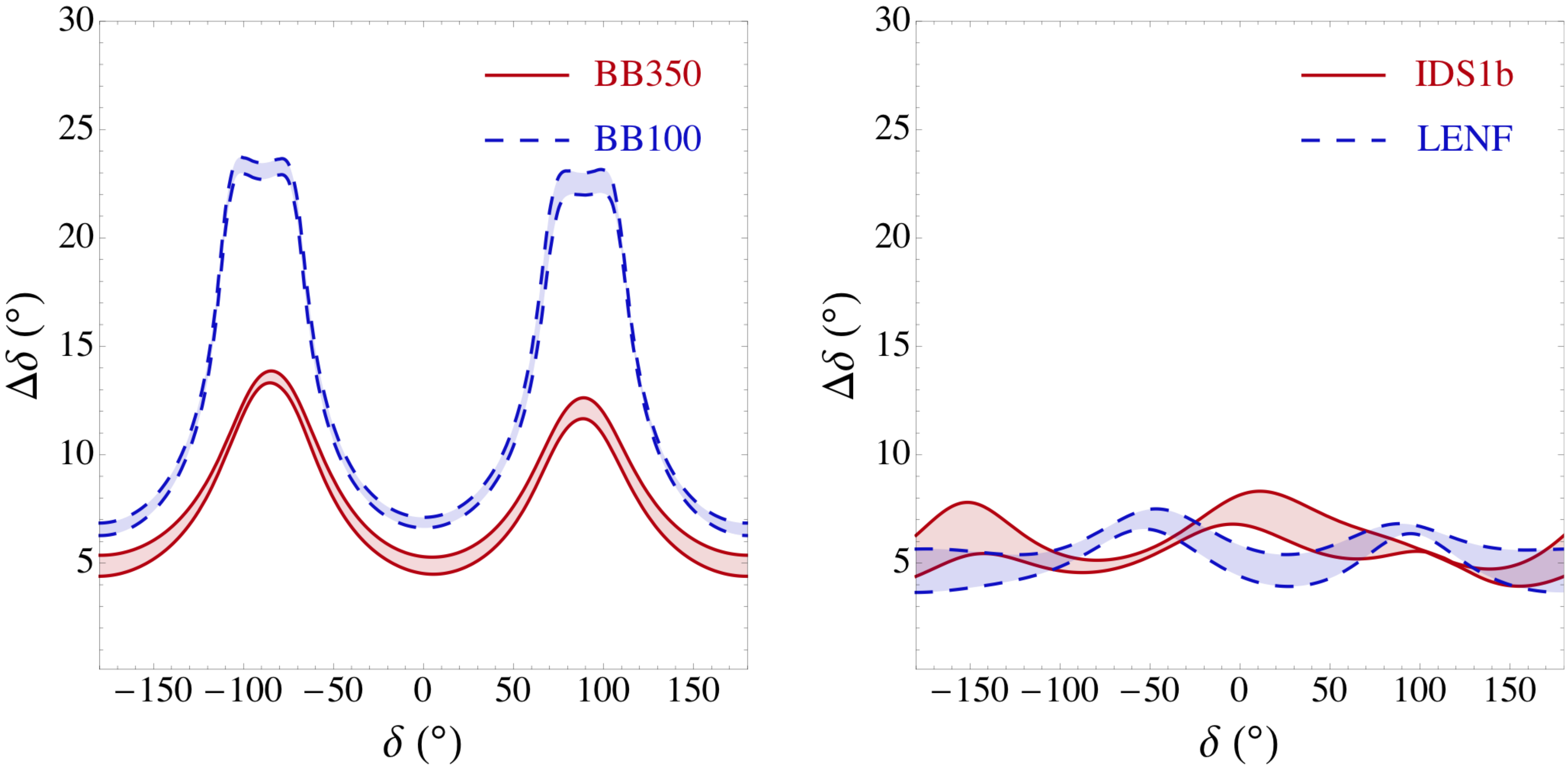
Large θ_{13}: from discovery reach to precision



Daya Bay limit !

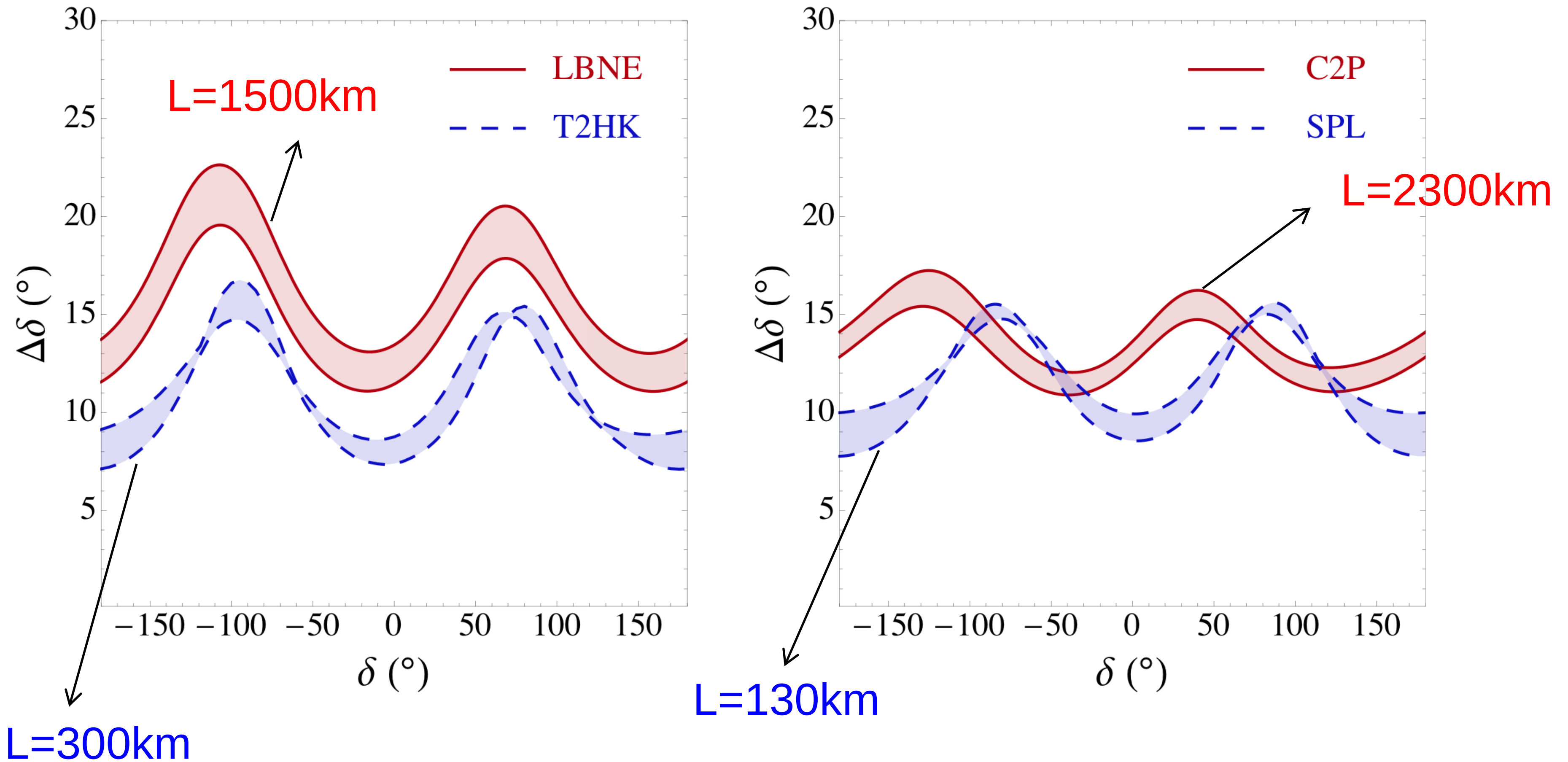
Coloma, Donini, Fernandez-Martinez,PH arXiv:1203.5651

Nufact: 25 GeV (IDS1b), 10 GeV (LENF)



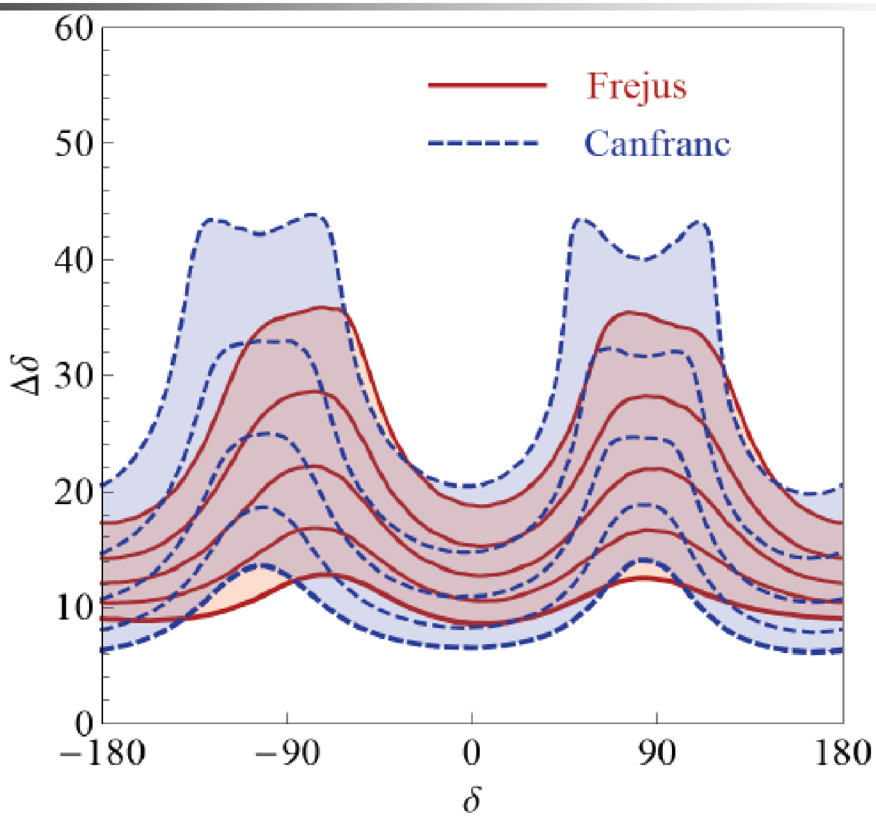
BB: not so good in precision …
(not enough spectral info, statistics)

Superbeams here and there (really super)



Shorter baselines outperform longer ones for precision (obviously not matter) but SPL baseline maybe not fully optimal…

SPL at Frejus vs Canfranc: precision



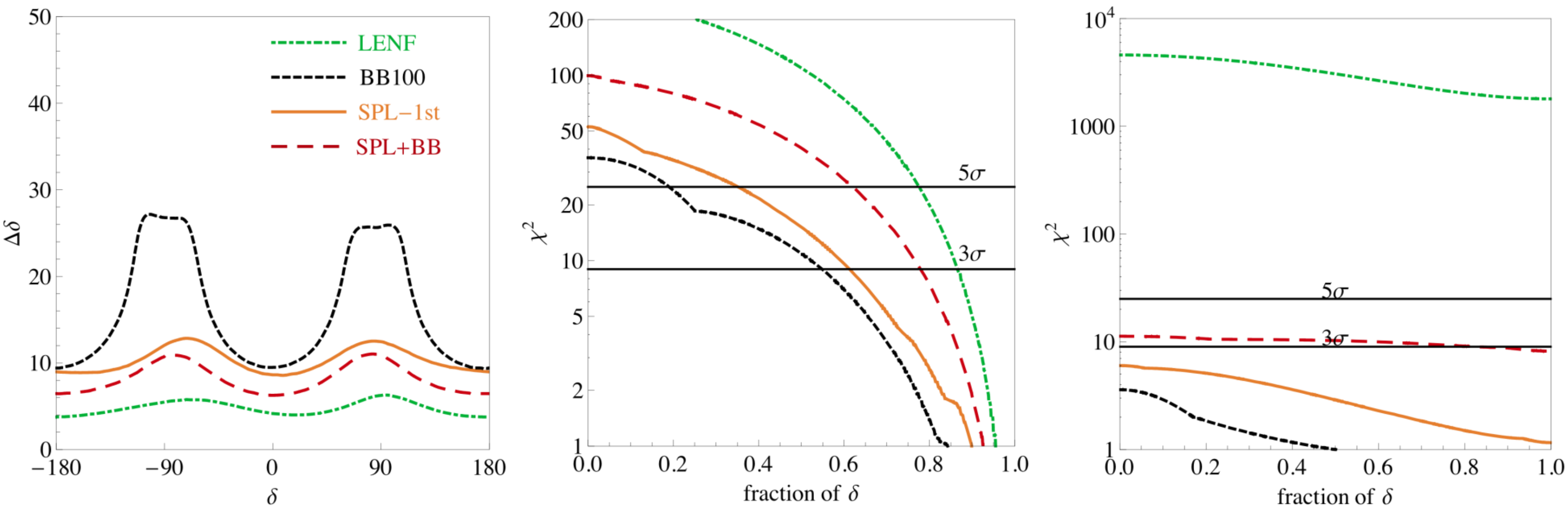
Lines are reducing the statistics by factors of 2, 4, 8 and 16

For high statistics Canfranc generally better measurement

For small statistics Frejus is preferable P. Coloma and EFM 1110.4583

If this would be a minor change for SPL design maybe worth it ?

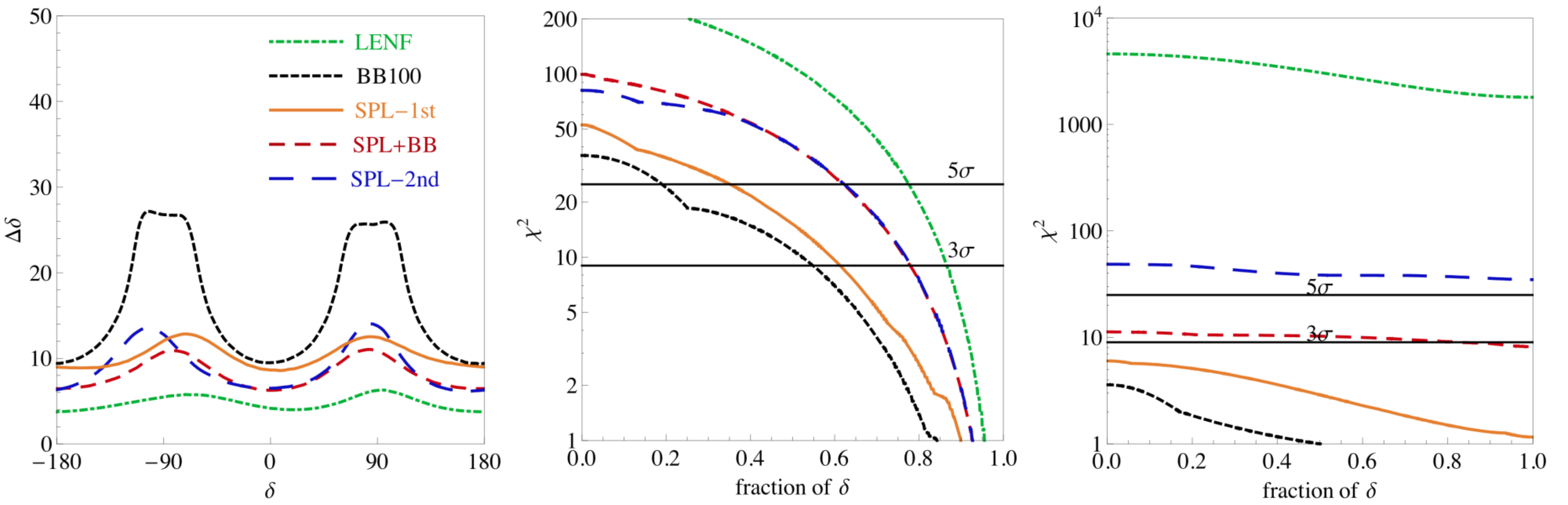
EURONU contenders



Courtesy of E. Fernandez-Martinez

Nufact systematic errors: signal 1% (Nufact), 5% (rest)
background 10% all

EURONU contenders



Courtesy of E. Fernandez-Martinez

Official systematic errors: signal 1% (Nufact), 5% (rest)
background 10% all

Physicswise: 1) Nufact absolute winner 2) SPL very good for CP (better at ~700km 3) BB-100 precision limited 4) SB+BB synergetic

Fluxes (WP2-WP4), detector parameters and detector systematics (migration matrices from WP5) will be updated with the final EURONU results for final report

Nufact: Flux: 10 GeV, L=2000km, 5 $10^{20}\mu^{+}$ & 5 $10^{20}\mu^{-}$

Detector: MIND 100kton

MMs courtesy of WG5

Other systematics: 1.4% (signal), 20% (bckgnd)

Betabeam: Flux: γ=100, L=130km, He/Ne 2.9/1.1 10^{18}/y

SPL: Flux: courtesy of WP2

Detector MEMPHYS

MMs courtersy of WP5

Other systematics: 5% ??, 20% ??

EURONU in broader context

• What if hierarchy measured before ? Atmospheric, T2K+NOVA+IN0

SB optimal L < 1000km (vacuum regime)

• How many ultimate facilities in the world ?

At least 2, probably best if they are more complementary (different systematics, different channels, different E, L):

two SB optimized for MH and CP separately ?, SB+Nufact, SB+BB….Similar timescales is mandatory!

•How many Mton WC/O(10kton)LAr there can be realistically in the world ?

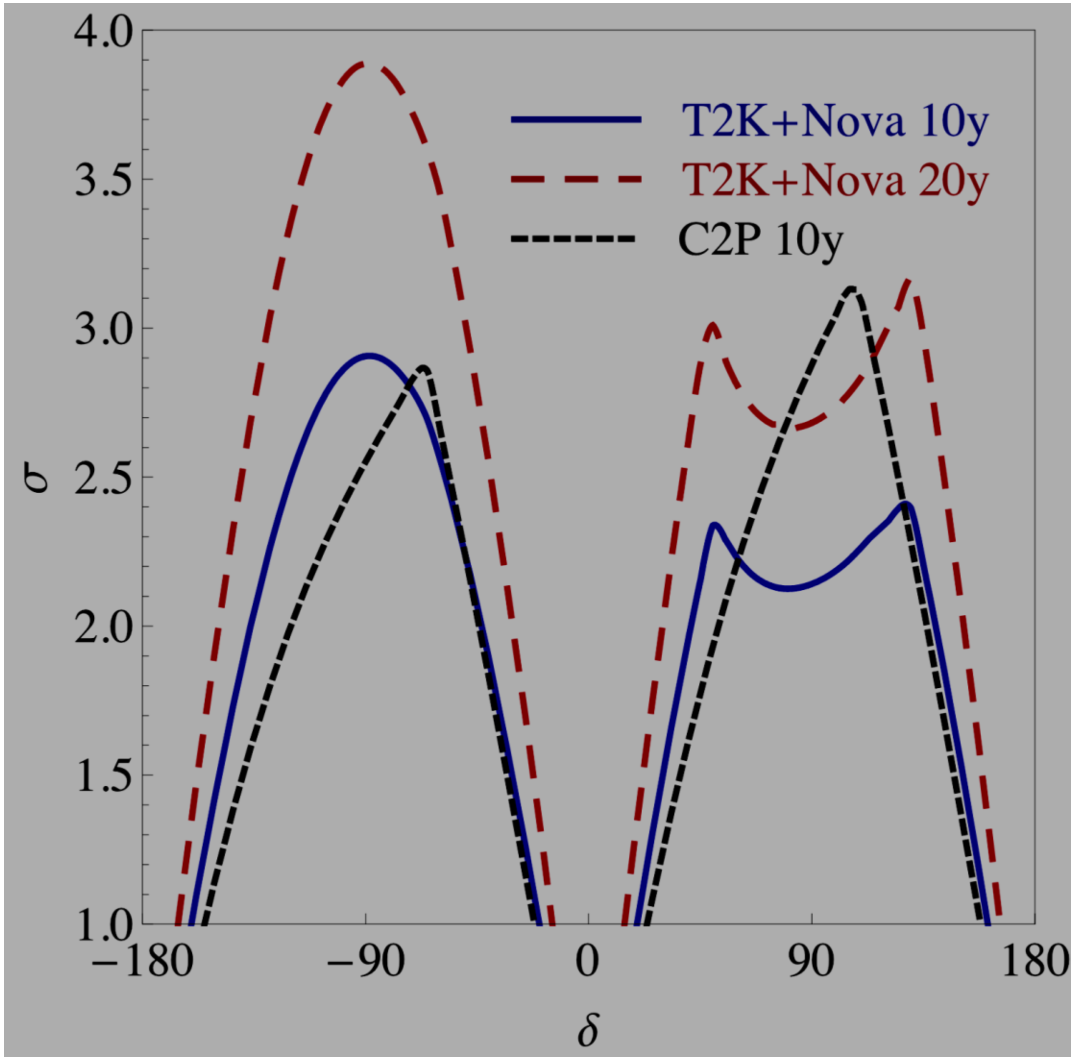
SPL/BB vs HyperK   C2P vs LBNE

Downgrading (the sign of our times)

Often comparisons are made and only then downgradings applied…

but they can change the comparisons !

One example: C2P (0.8MW, 20kton) vs T2K+NOVA



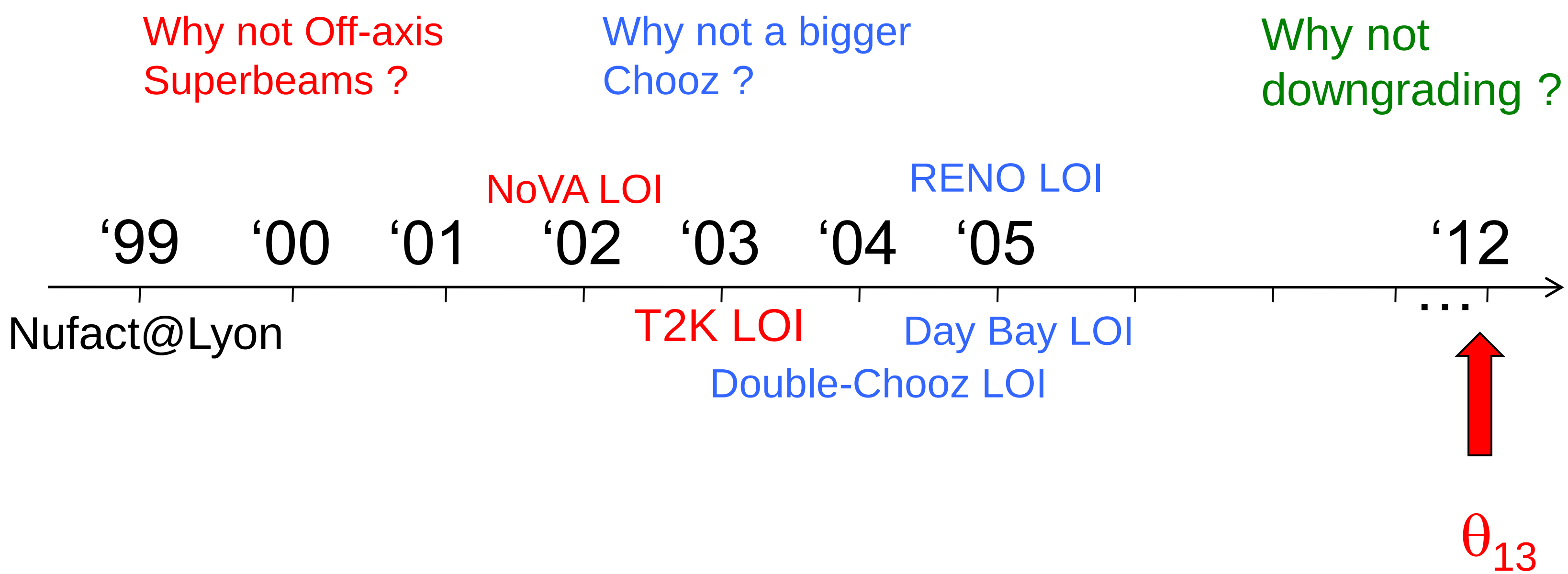
Courtesy of E. Fernandez-Martinez

Downgrading (the sign of our times)

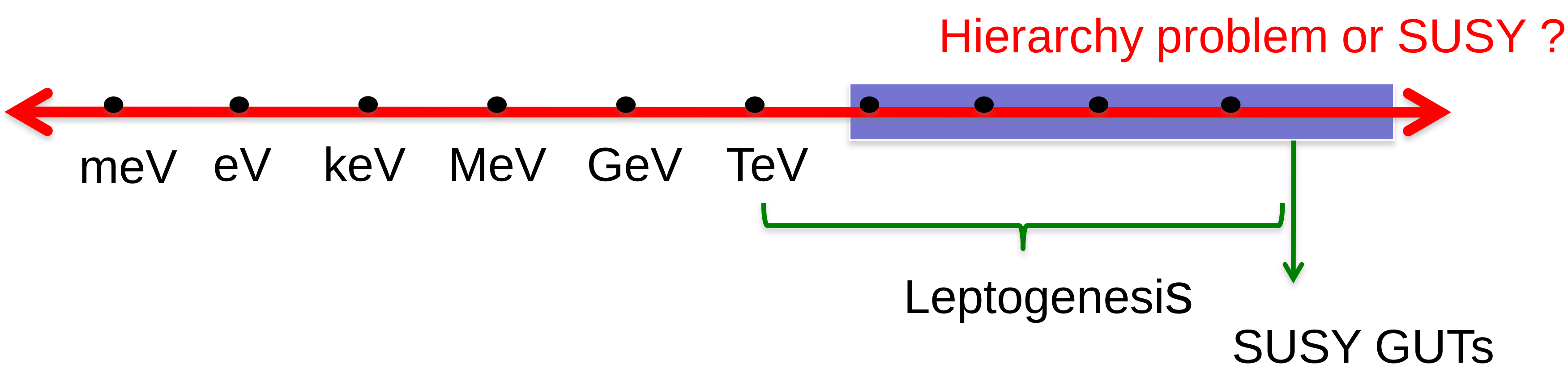
Could be dangerous if not in the context of

- a sensible staging where there are competitive physics output in each step
- each step does not delay the main goal (as long as remains a goal)

The art of the do-able



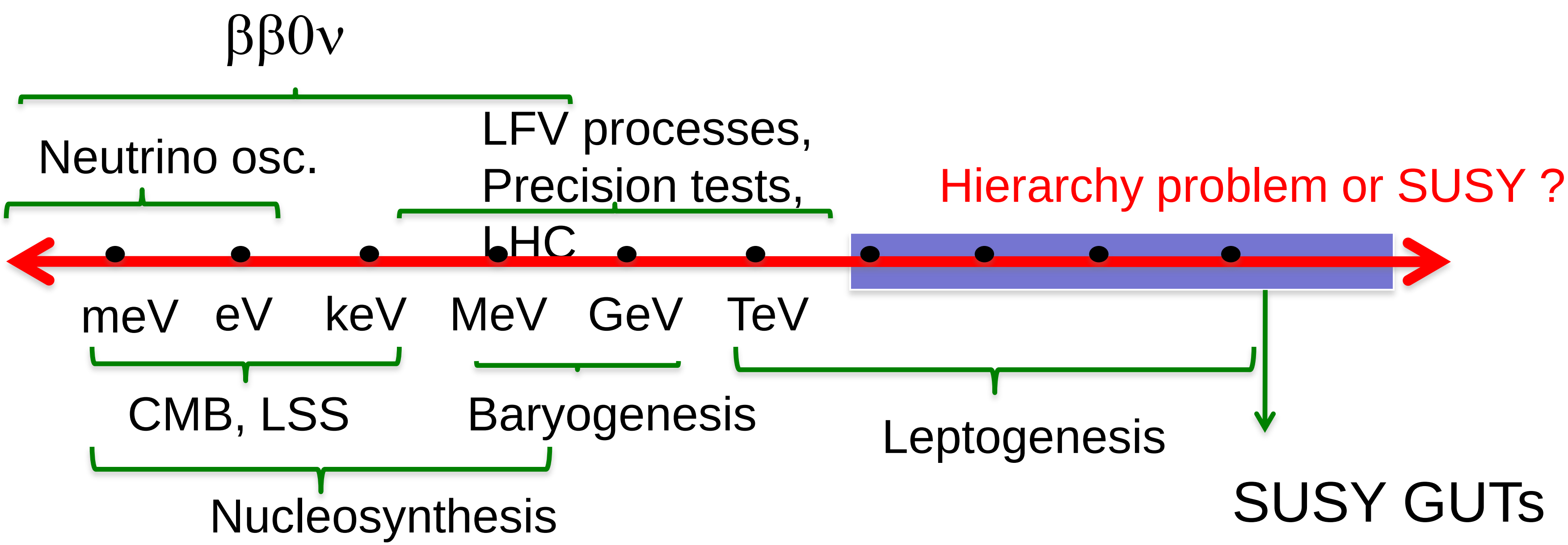
The New physics scale could be anywhere



Example: SM+ sterile Weyl fermions (Dirac neutrinos, See-saw I)

$$\mathcal{L} = \mathcal{L}_{SM} - \sum_{i=1}^{n_R} \bar{l}_L^{\alpha} Y^{\alpha i} \tilde{\Phi} \nu_R^i - \sum_{i,j=1}^{n_R} \frac{1}{2} \bar{\nu}_R^{ic} M_N^{ij} \nu_R^j + h.c.$$

Pinning down the New physics scale

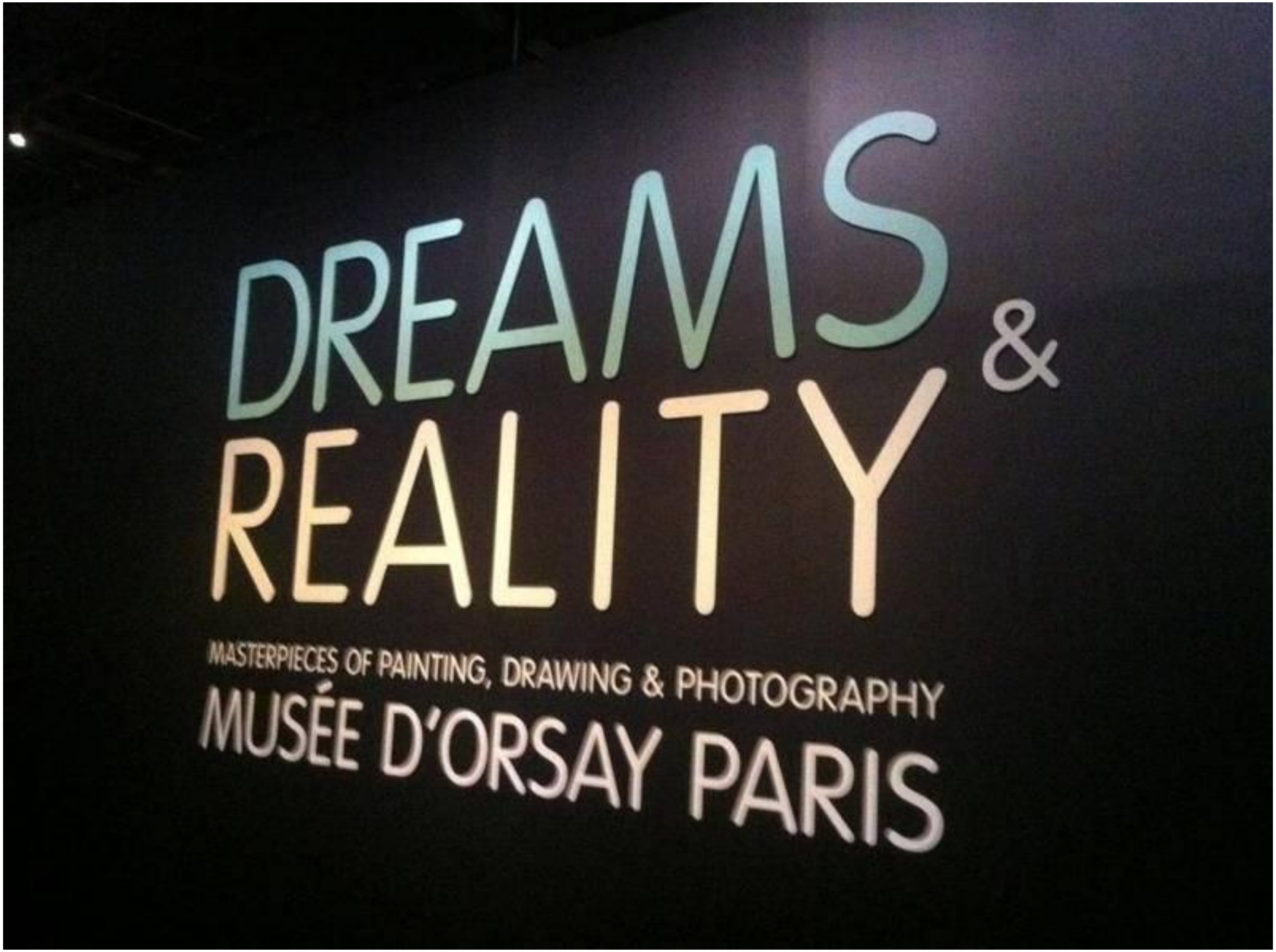


- The physics case for a neutrino factory or ultimate SB and/or BB is beyond question: which can get there first ?

- Large θ_{13}: no-loss game

- Staging important for such long term project, but must be well planned

- A decision on an ultimate facility must take into account Other existing proposals (Jparc-HK, LBNE) in terms of timescale, Competitiveness, complementarity…


DREAMS
&
REALITY
MASTERPIECES OF PAINTING, DRAWING & PHOTOGRAPHY
MUSÉE D'ORSAY PARIS