Future determination of Oscillation parameters

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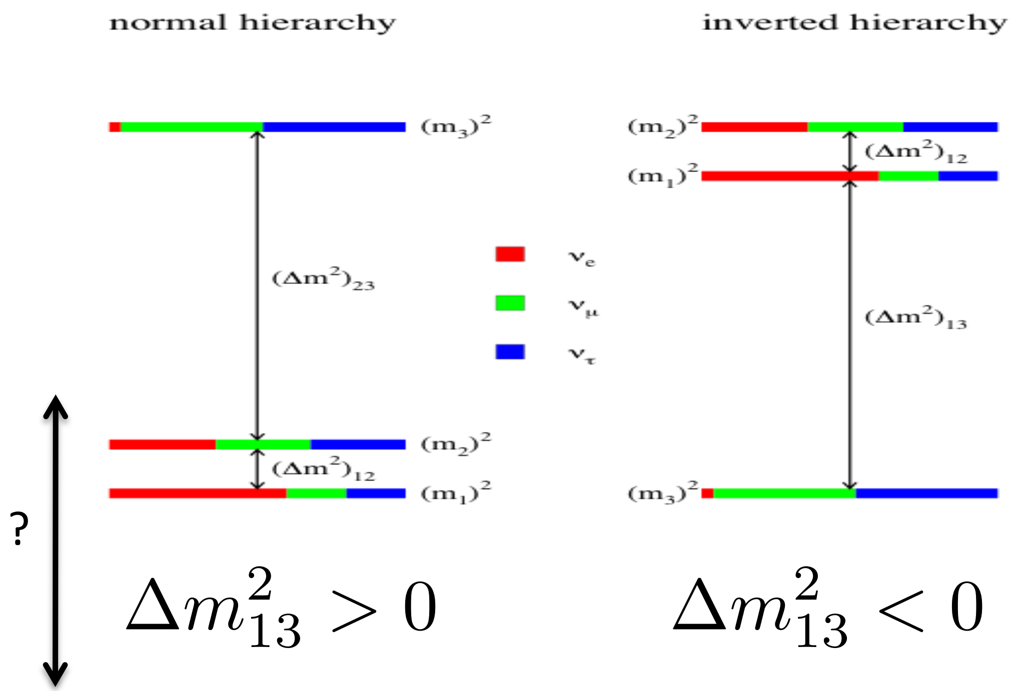
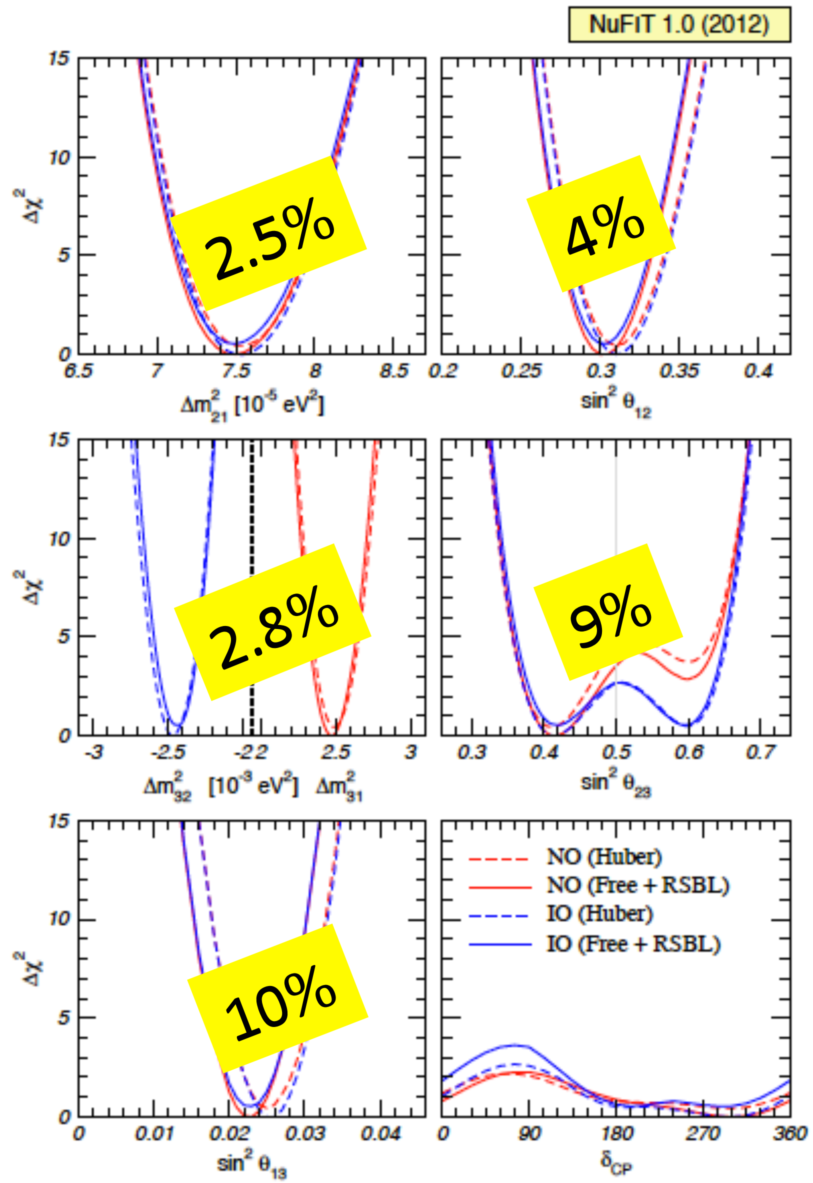
SM+3 massive neutrinos

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



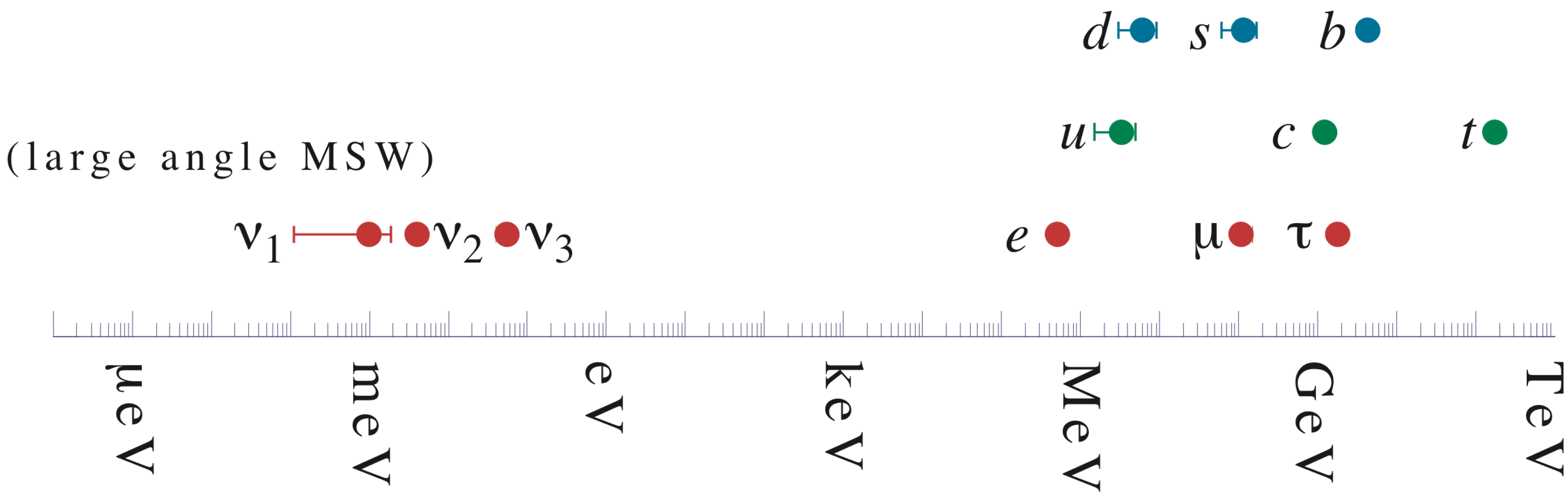
$\Delta m^2_{13} > 0$ $\Delta m^2_{13} < 0$



Gonzalez-Garcia et al 1209.3023

Why are neutrinos so much lighter ?

Neutral vs charged hierarchy ?



m_f

Why so different mixing ?

CKM

$$|V|_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

PMNS

3σ

$$|U| = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0,178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}$$

Gonzalez-Garcia, et al 1209.3023

A new physics scale

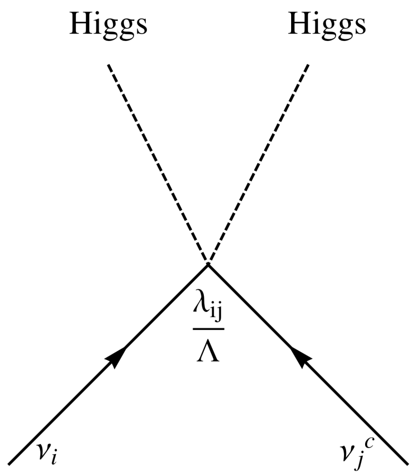
Neutrinos have tiny masses <-> a new physics scale

$$-\mathcal{L}_{\mathrm{Majorana}} = \bar{\nu}_L m_\nu \nu_L^c + h.c. \;\leftrightarrow\; \bar{L}\tilde{\Phi}\;\alpha\;\tilde{\Phi}L^c + h.c.$$

Weinberg

$$[\alpha] = -1$$

$$m_\nu \sim \lambda \frac{v^2}{\Lambda}$$



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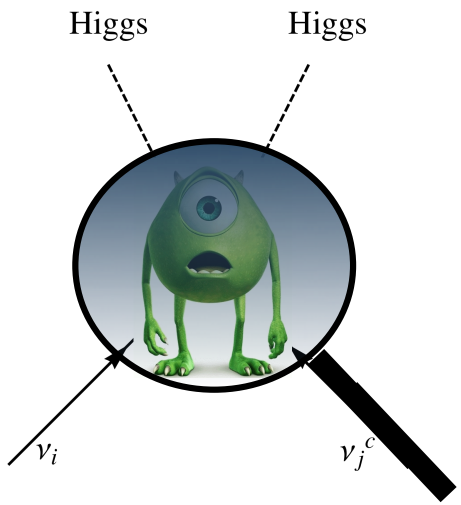
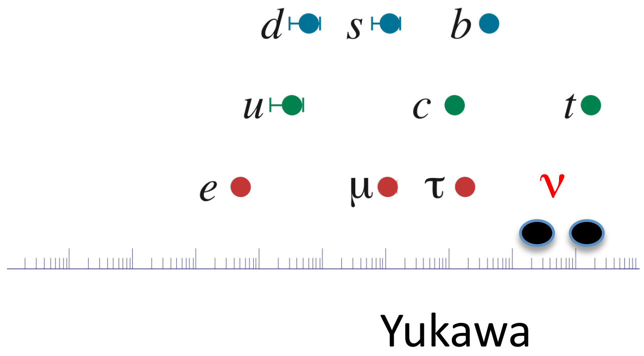
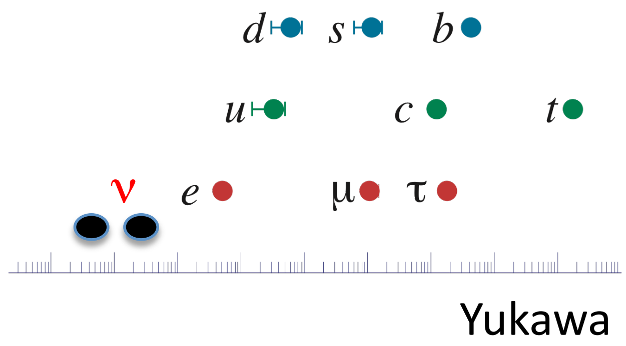


Charged/neutral hierarchy in seesaw (I)

$\Lambda \lesssim$ GUT

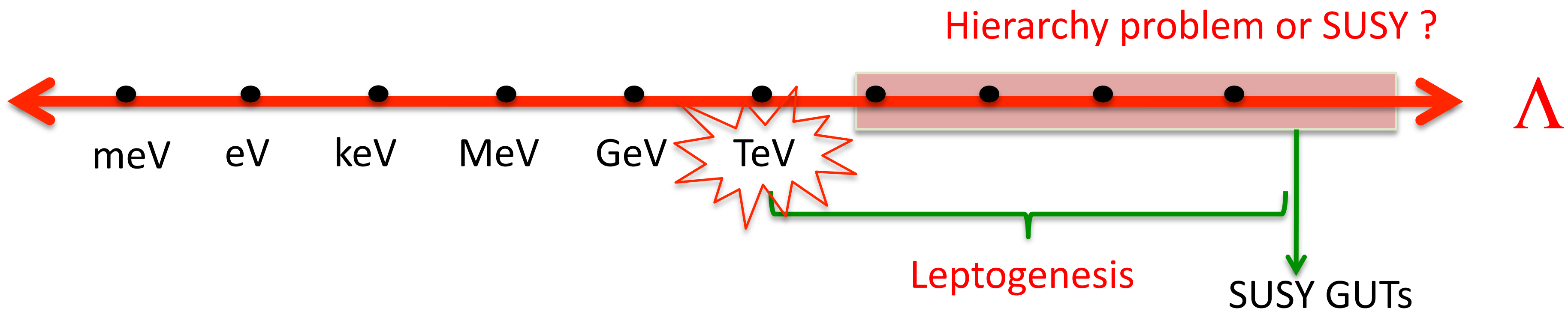


Λ = TeV



Minkowski; Gell-Mann, Ramond Slansky; Yanagida, Glashow…

Pinning down the New physics scale



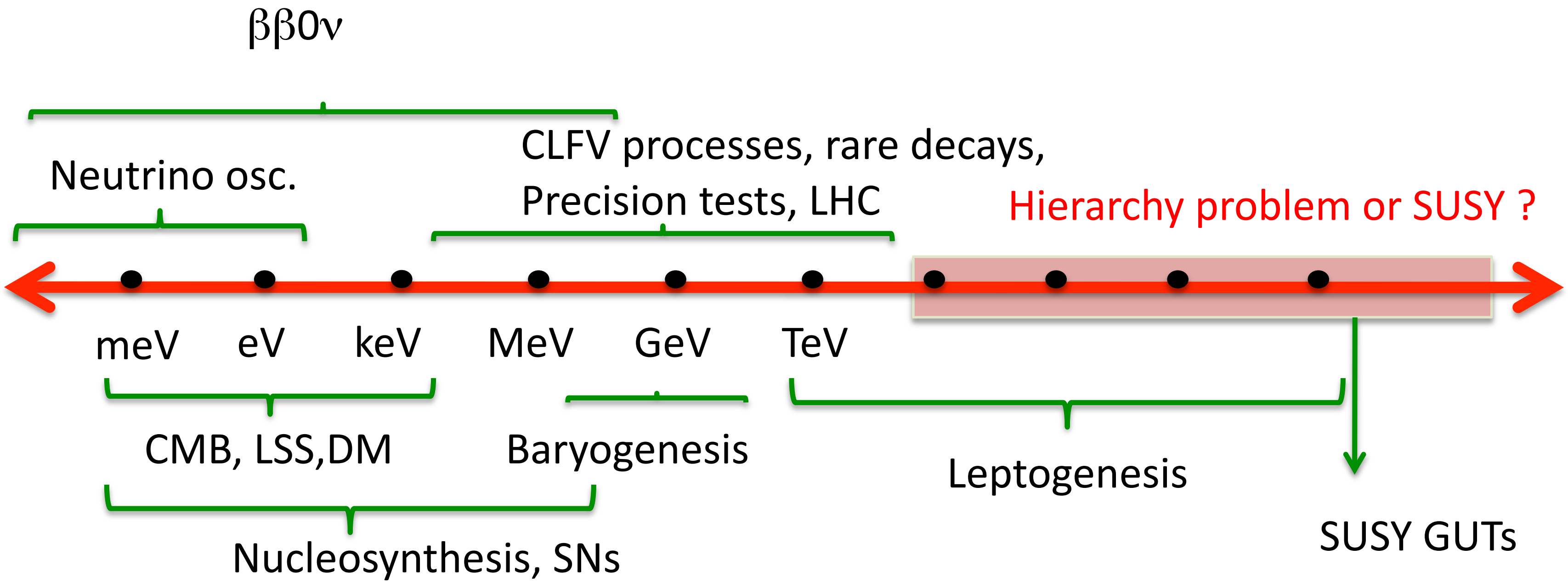
Robust predictions of high (and not so high) scale seesaw models:

there is neutrinoless double beta decay at some level (Λ > 100MeV)

a matter-antimatter asymmetry if there is CP violation in the lepton sector !

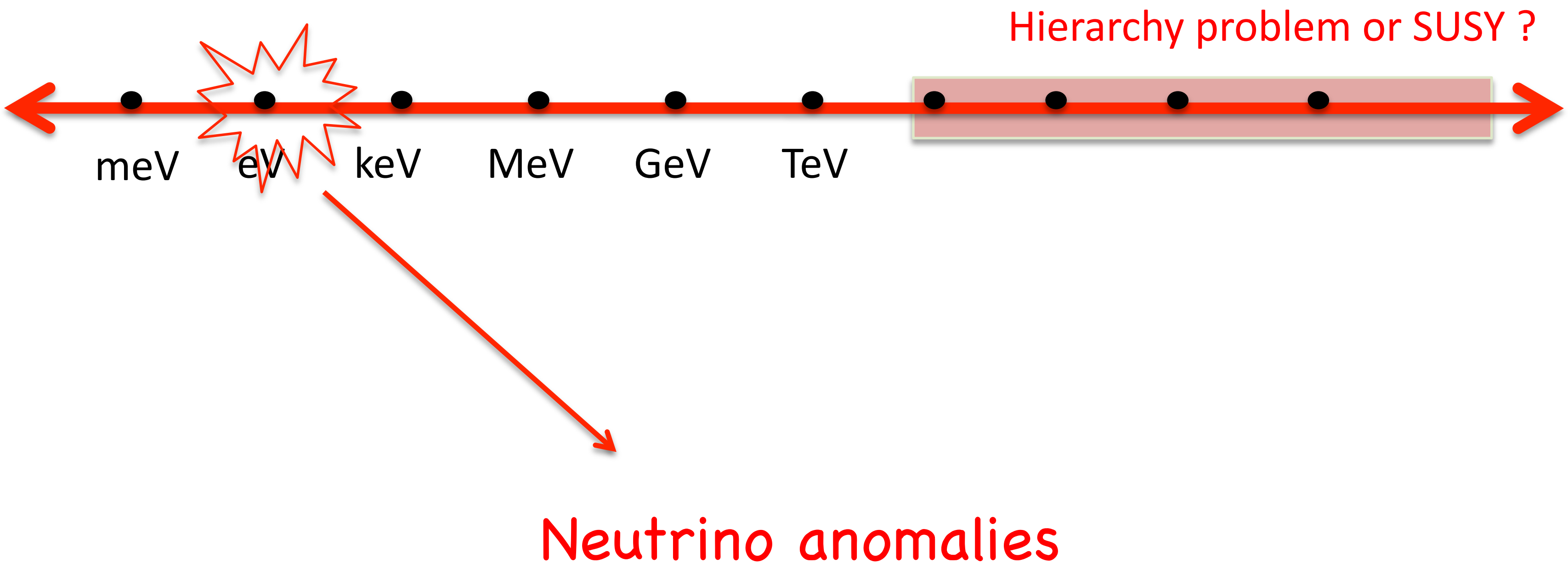
there are other states out there at scale Λ !

Pinning down the New physics scale



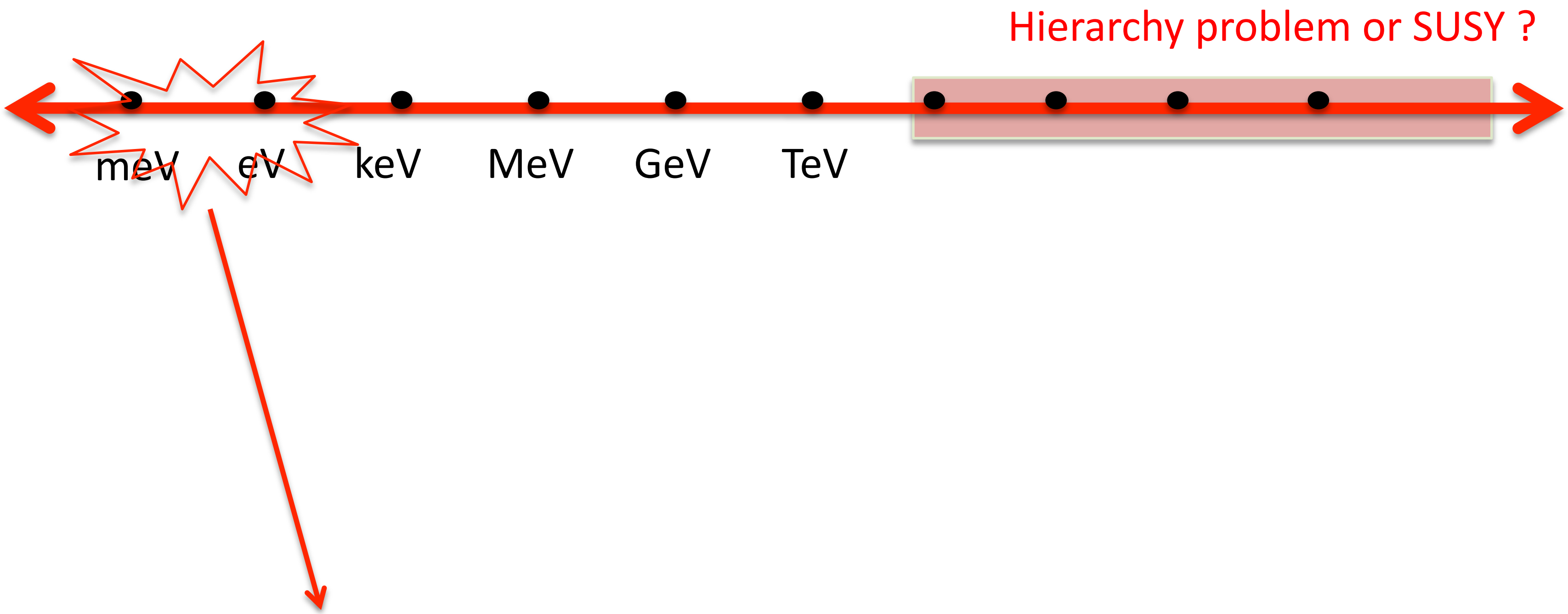
Light Sterile Neutrinos White Paper, Abazajian et al arXiv: 1204.5379 and refs. therein

Pinning down the New physics scale



Langacker's talk

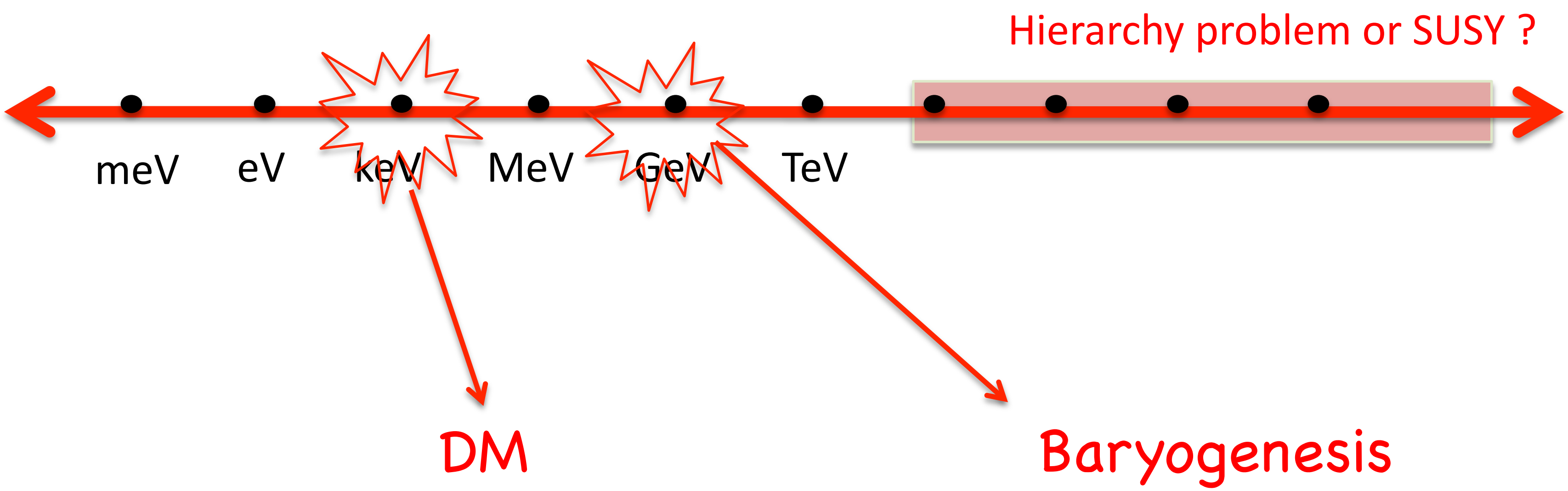
Pinning down the New physics scale



Cosmo anomalies ?

Wong's talk

Pinning down the New physics scale



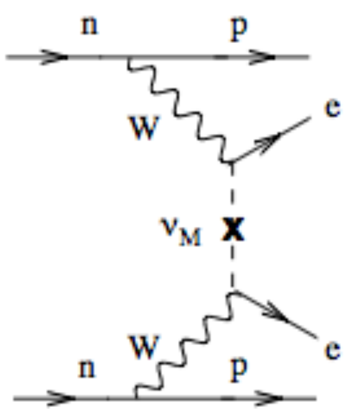
Ruchayiskiy's & Lindner's talk

Even though there are typically more parameters than those in the neutrino mass, there are correlations…

Knowing as much as we can about what we can measure will make easier to search for and interpret the unexpected

Majorana nature: ββ0ν

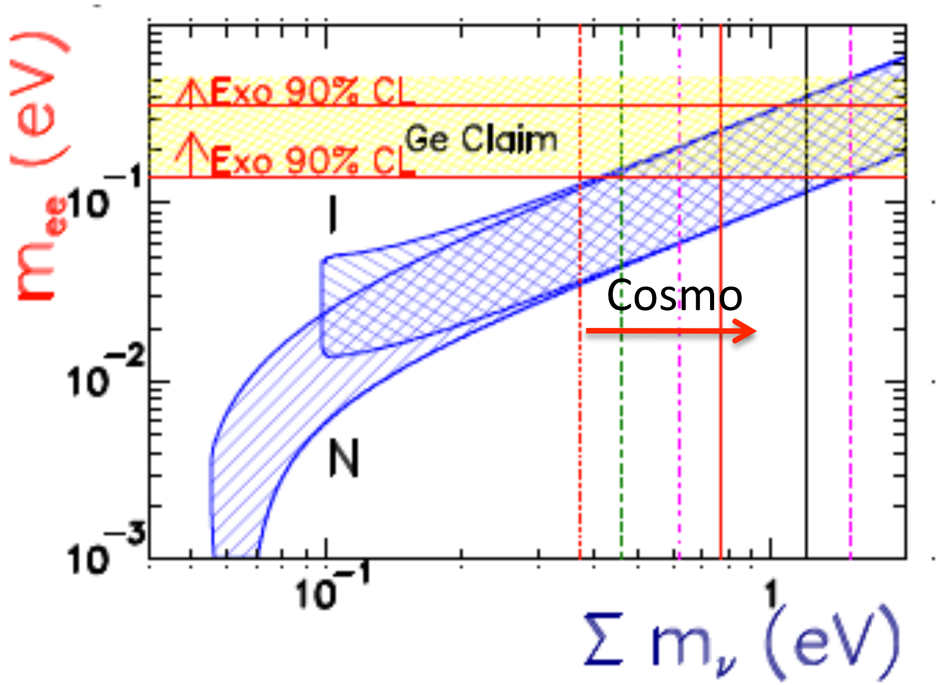
Plethora of experiments with different techniques/systematics: EXO, KAMLAND-ZEN, GERDA, CUORE, NEXT, SuperNEMO, LUCIFER…



$$m_{\beta\beta} \equiv |m_{ee}|$$

$$\Sigma \equiv \sum_i m_i$$

If Λ > 100MeV



Update Gonzalez-Garcia et al, 2012

Leptonic CP violation (in vacuum)

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

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

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

θ_{13} measurement

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

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

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

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

Golden Channel in matter

In matter:

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

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

$$+\tilde{J}\,\frac{\Delta_{12}}{A}\,\sin(\frac{AL}{2})\,\frac{\Delta_{13}}{B_\pm}\,\sin\left(\frac{B_\pm L}{2}\right)\,\cos\left(\pm\delta - \frac{\Delta_{13}\,L}{2}\right)$$

$$\tilde{J} \equiv c_{13}\ \sin 2\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23} \qquad B_\pm \equiv \sqrt{2}G_F n_e \pm \Delta_{13}$$

Cervera et al, hep-ph/0002108

Golden Channel in matter

Octant dependence

Hierarchy dependence

In matter:

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

$\tilde{J} \equiv c_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$ $\quad B_\pm \equiv \sqrt{2} G_F n_e \pm \Delta_{13}$

Cervera et al, hep-ph/0002108

Parameter degeneracies (eg. neutrino hierarchy, octant) compromise δ sensitivity

Burguet et al, hep-ph/0103258
Minakata, Nunokawa hep-ph/0108085
Barger, Marfatia, Whisnant hep-ph/0112119

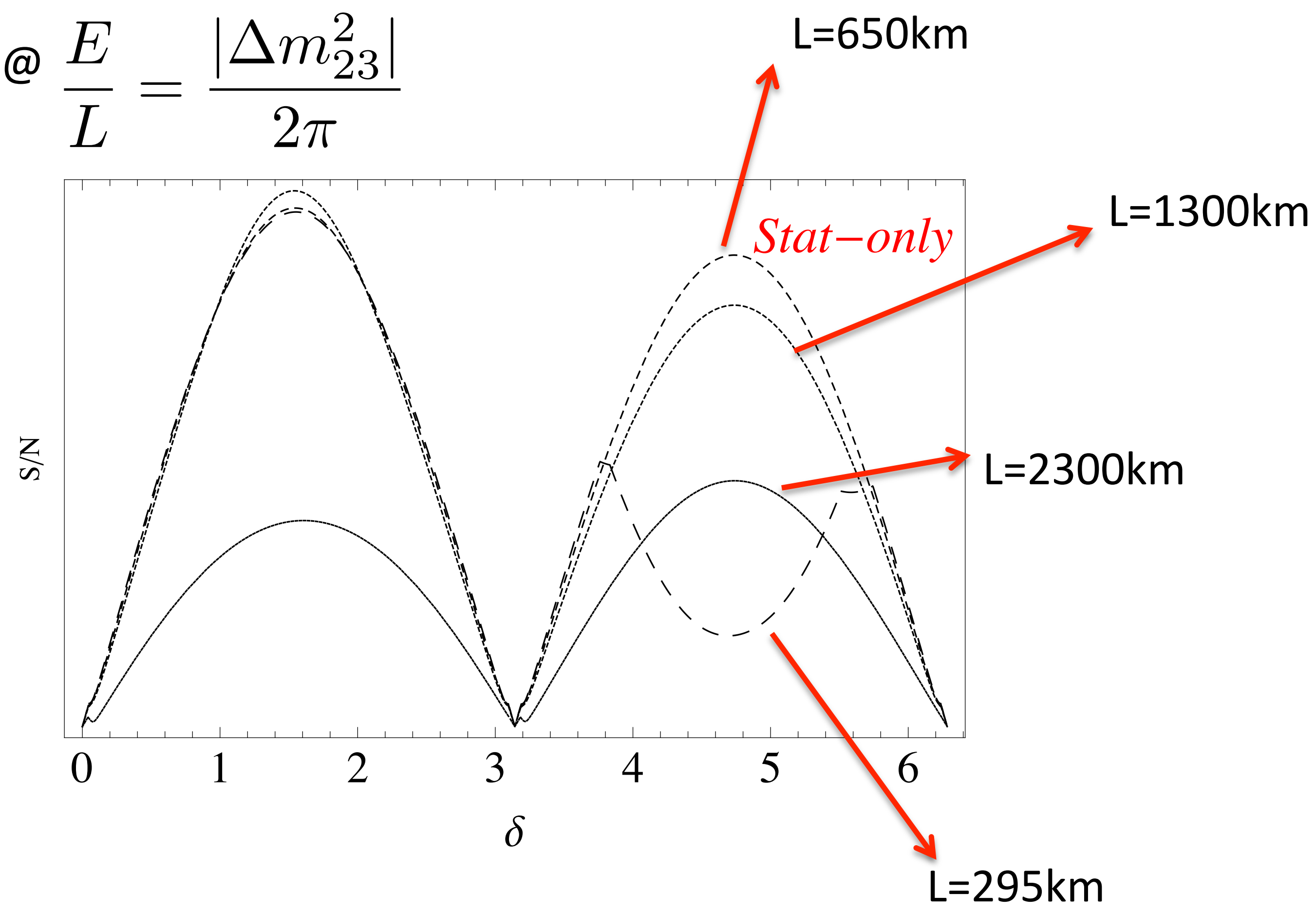
Optimization E, L

$$N_{events}(E, L) = \Phi(E, L) \otimes \sigma(E) \otimes P_{osc}(E, L)$$
$$= \frac{E^\alpha}{L^2} \times E^\beta \times P(E, L)$$

Ignoring the hierarchy degeneracy: Signal/Noise ($\delta \neq 0$, $\delta \neq \pi$) maximizes at

$$\frac{E}{L} = \frac{|\Delta m^2_{23}|}{2\pi}$$

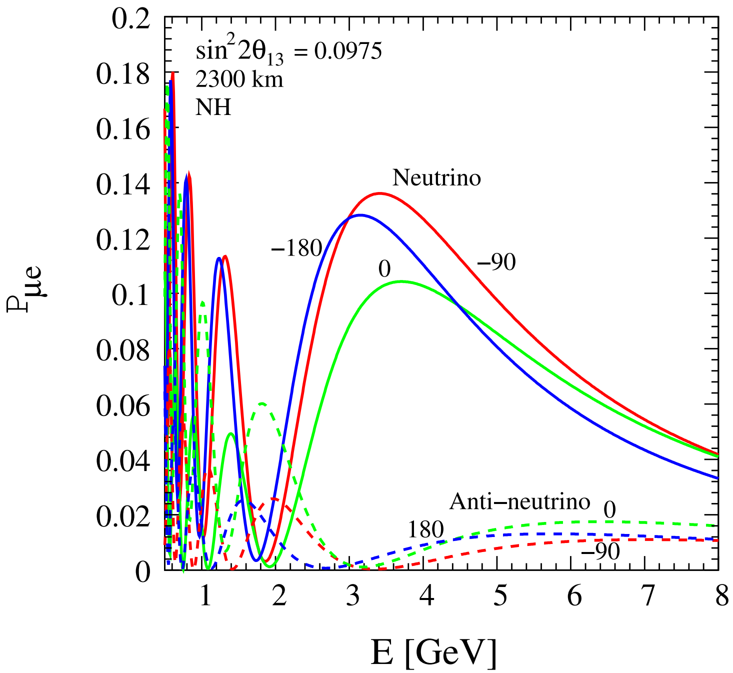
$$@\ \frac{E}{L} = \frac{|\Delta m^2_{23}|}{2\pi}$$

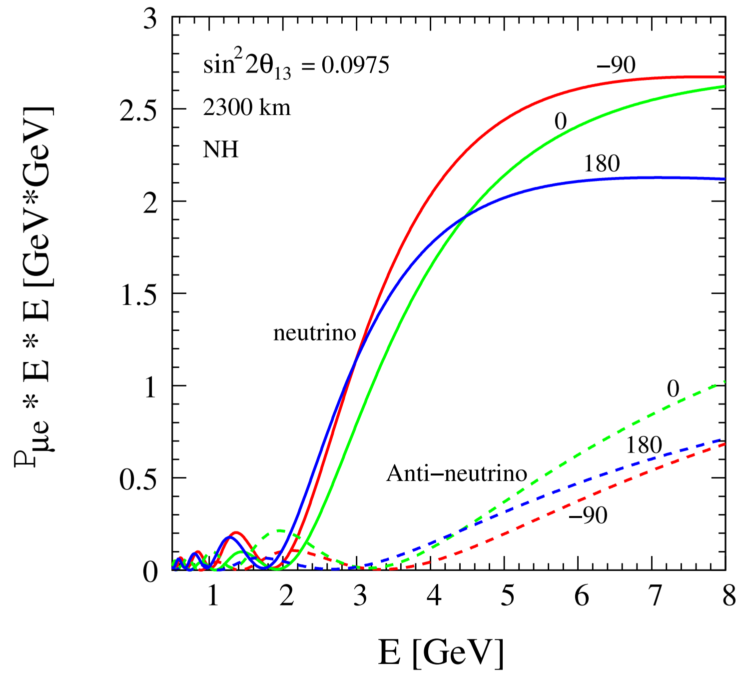


Naive scaling of S/N assuming statistical errors dominate ...
But systematics could change this conclusion…

To maximize sensitivity to CP violation don't go too far

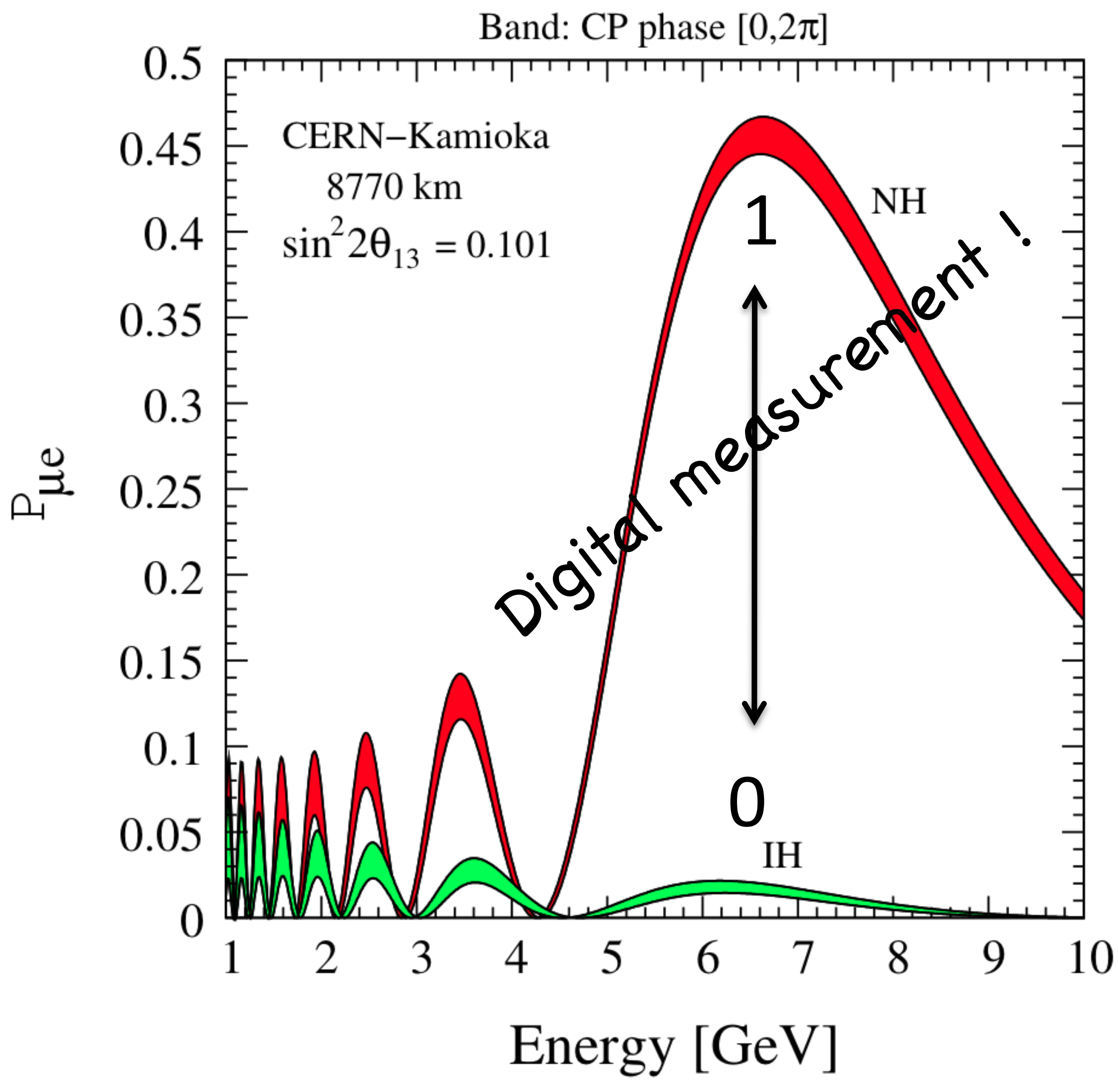
Large matter effect regime





Either neutrino/antineutrino (depending on the hierarchy) strongly suppressed

Hierarchy through MSW



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

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

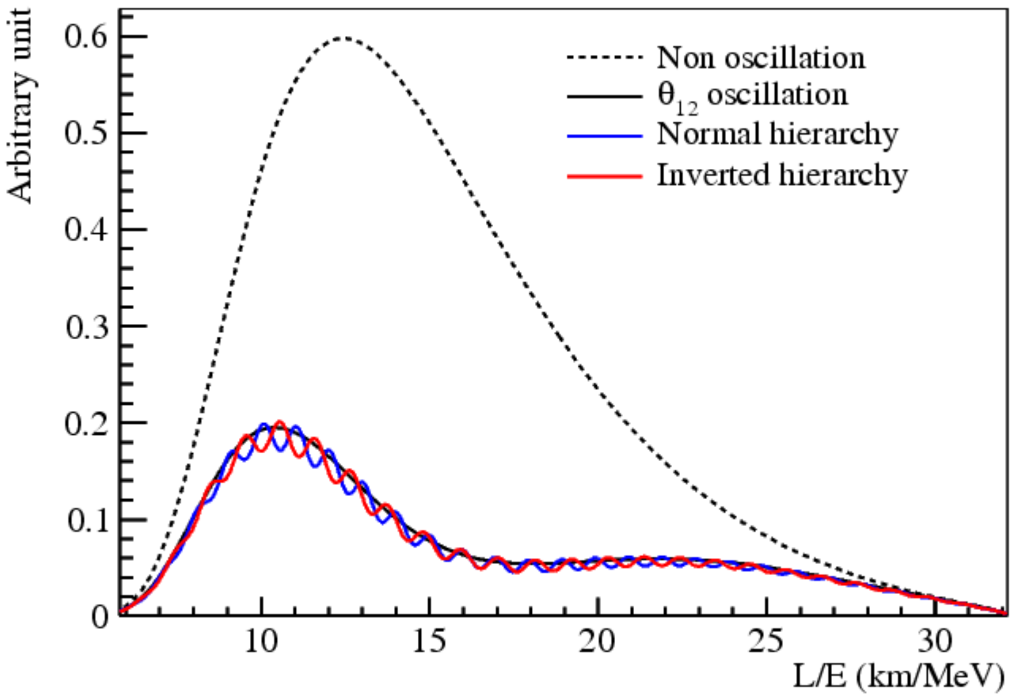
Spectacular MSW effect at O(6GeV) and very long baselines: no need for spectral info nor two channels

Mikheev, Smirnov;Wolfenstein

Hierarchy from reactor ν's

$$P_{\nu_e\nu_e} = 1 - c_{13}^2 \sin^2 2\theta_{12} \sin^2 \Delta_{21} - 2 s_{13}^2 c_{13}^2 \left(1 - \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}} \cos(2\Delta_{32} \pm \phi)\right)$$

$$\sin\phi = \frac{c_{12}^2 \sin 2\Delta_{21}}{\sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}}} \qquad \phi \simeq 0.12 \times 10^{-3} eV^2 \qquad \pm \mathrm{NH(IH)}$$



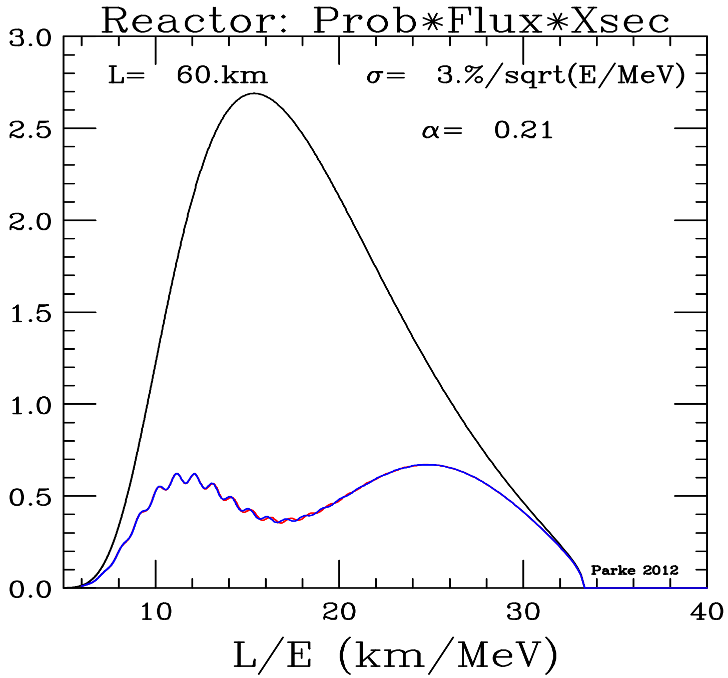
Petcov, Piai hep-ph/0112074; Choubey, hep-ph/et al 0306017;
Learned et al hep-ph/0612022

Hierarchy in reactors

Extremely challenging: 20kton, 2-3% energy resolution, <1% linearity in energy scale, error on $|\Delta m^2_{23}|$ << $\phi \simeq 0.12 \times 10^{-3} eV^2$

Qian, Dwyer, McKeown, Vogel, Wang, Zhang 1208.1551

With present error on $|\Delta m^2_{23}|$



Parke

Hierarchy from atmospherics:the hard way...

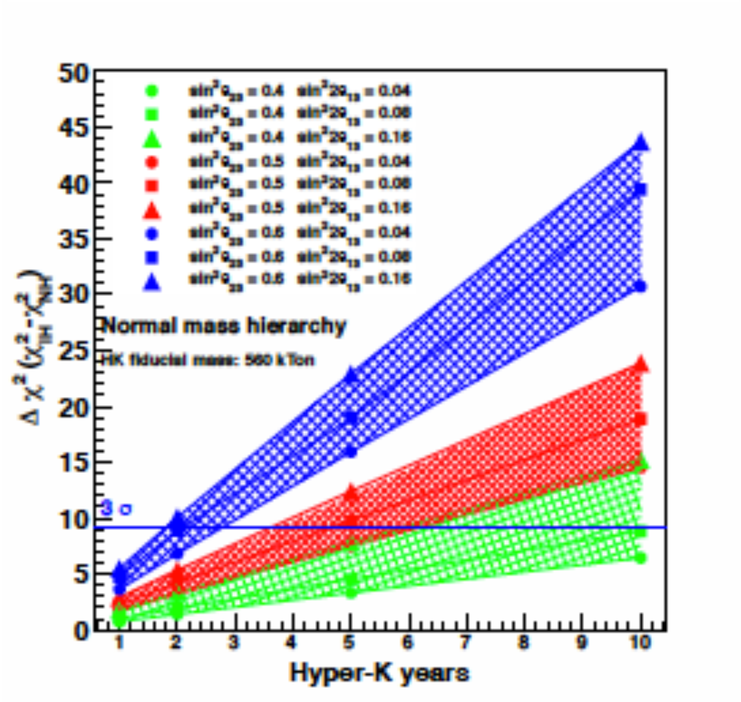
$$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$$

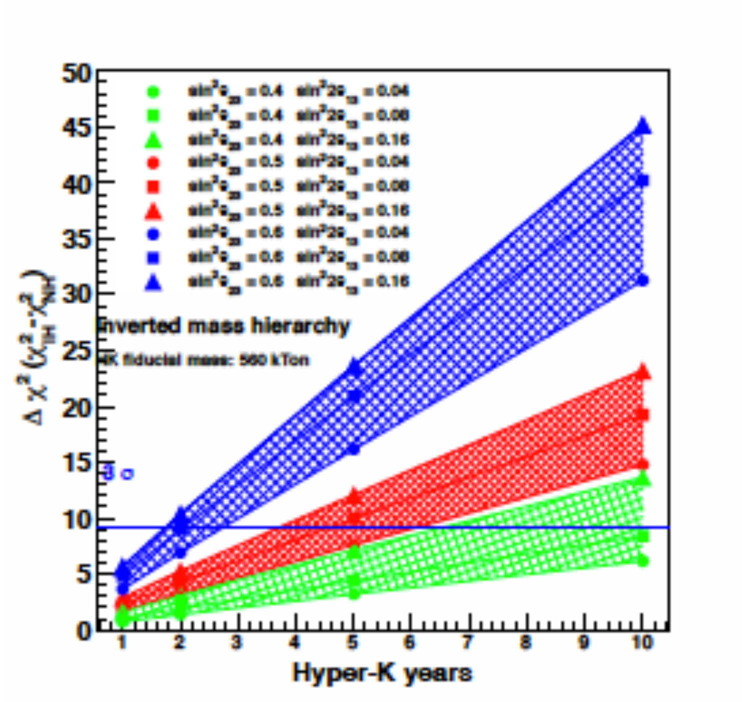
Hierarchy in atmospherics

Atmospheric data contain the golden signal but hard to dig…

Go Bigger with water

HyperK: 560kton





HK LOI

3σ in 2y-10y of HK

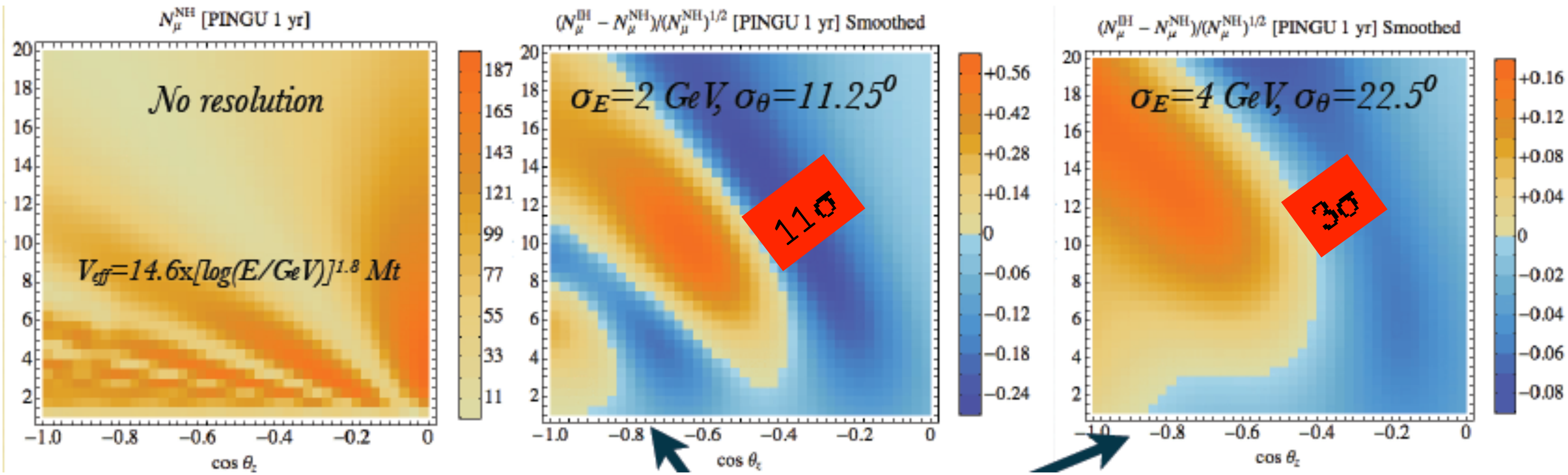
Hierarchy in atmospherics

Atmospheric data contain this golden signal but hard to dig...

Go much bigger in ice

PINGU @ Icecube

$$V_{eff} = 14.6\ log[E/GeV]^{1.8} Mton$$



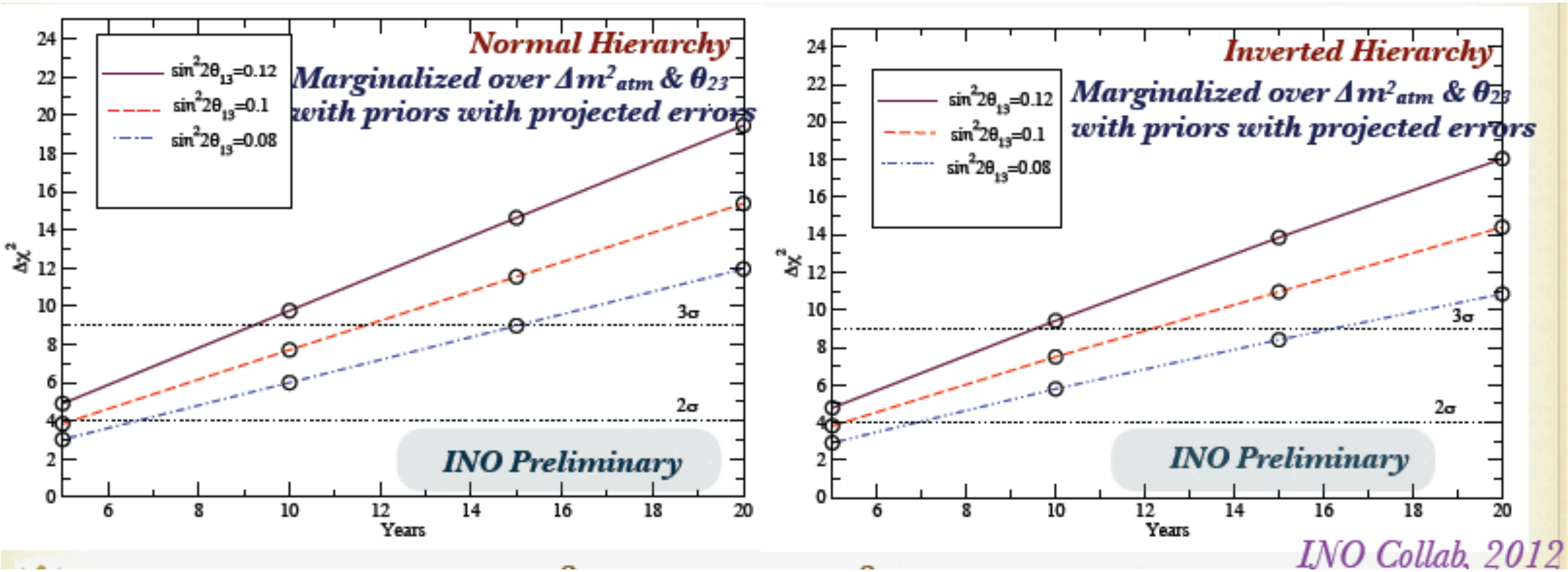
Ahkmedov, Razzaque, Smirnov 1206.7071

Hierarchy in atmospherics

Atmospheric data contain this golden signal but hard to dig...

Measure μ charge and better energy resolution GeV range

INO: 50kton Magnetized Iron

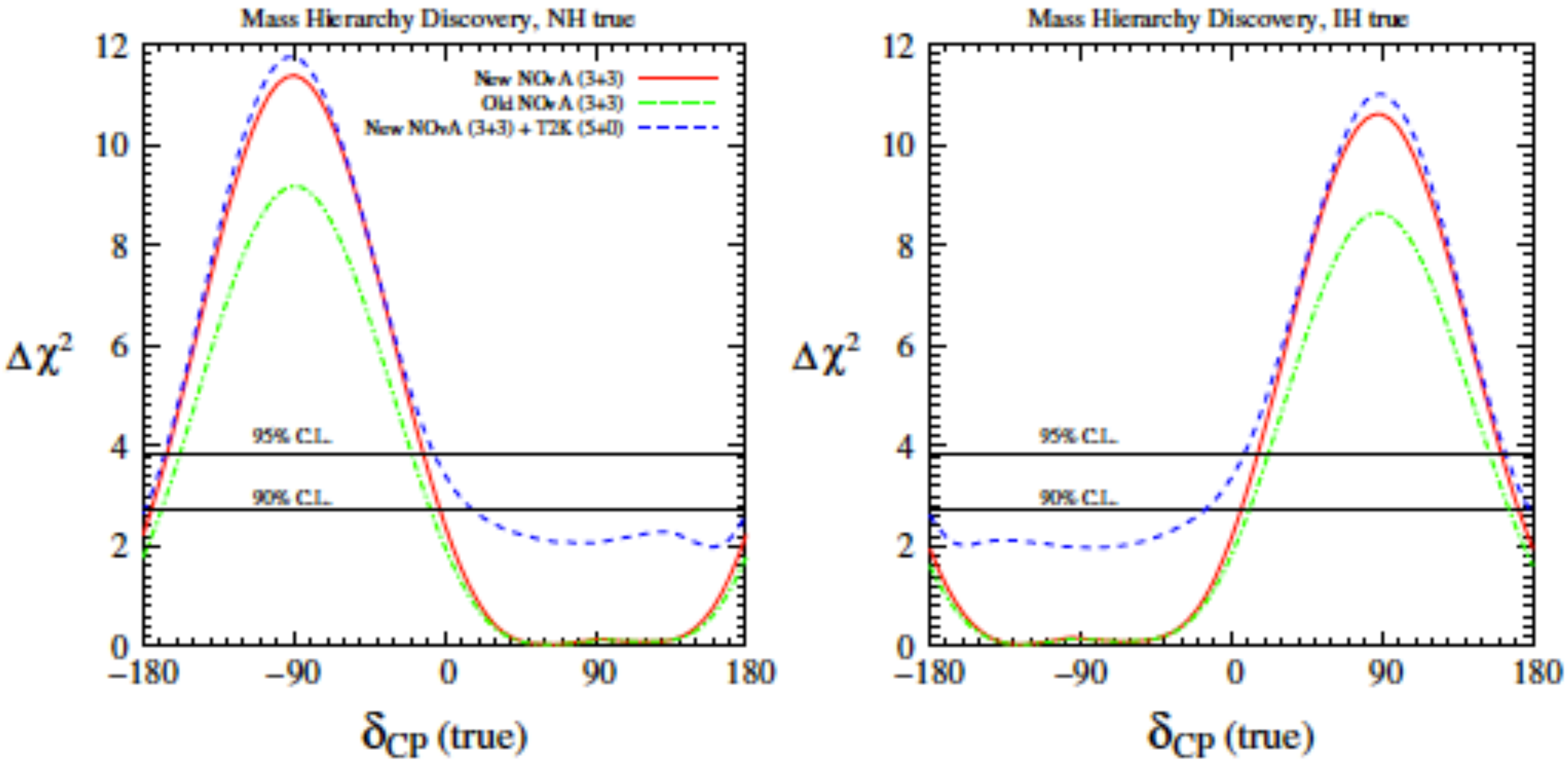


3σ in 12 y

Hierarchy from accelerator neutrinos:
the easy way...

First LBL experiments in < 10y : T2K, NOVA

T2K L=300 km
NOVA L=800km

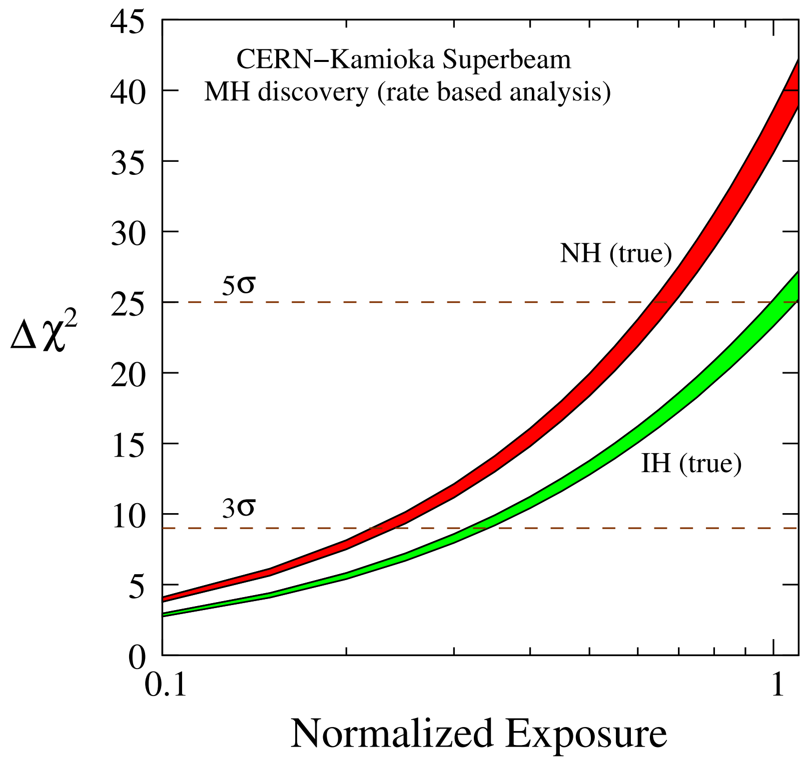


Agarwalla et al 1208.3644

With a new conventional beam (only ν) even with existing detectors, but shooting down !

One example: counting e-events at SuperK

4.5y of LBNO beam



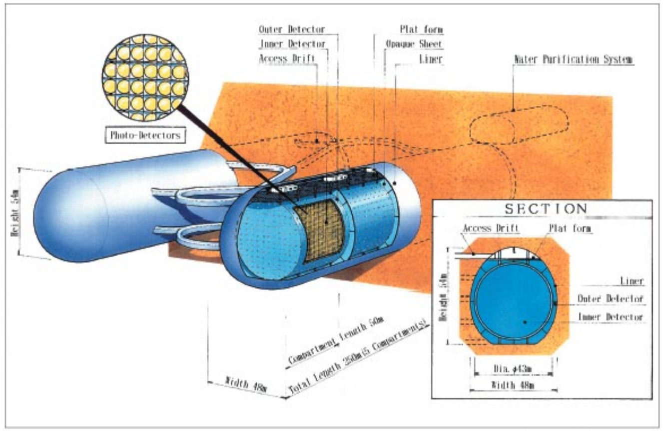
Agarwalla, PH 1204.4217

Hierarchy + CP in one go: a compromise...

Three concrete LBL proposals (to be ready in 10y) in the European Strategy Meeting

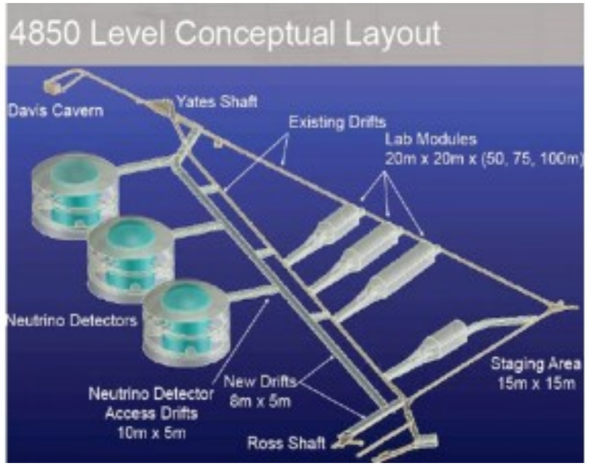
$p \rightarrow \text{Target} \rightarrow K,\pi \;\; \nu_\mu, \% \; \nu_e$

HyperK (Japan)



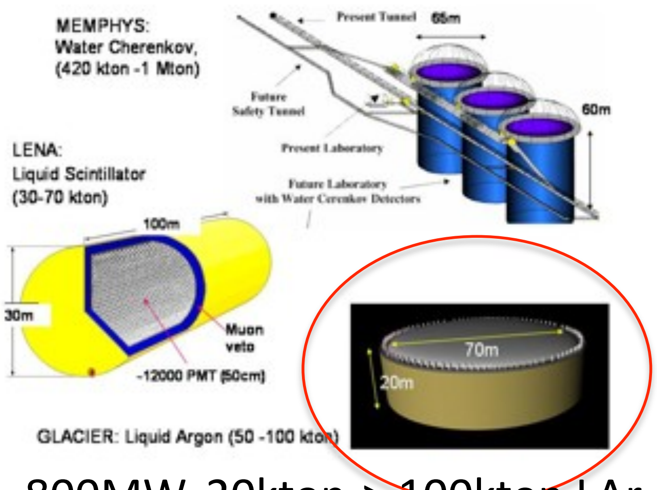
750MW, 560kton WC, Tokai-Kamioka (295km)

LBNE (USA)



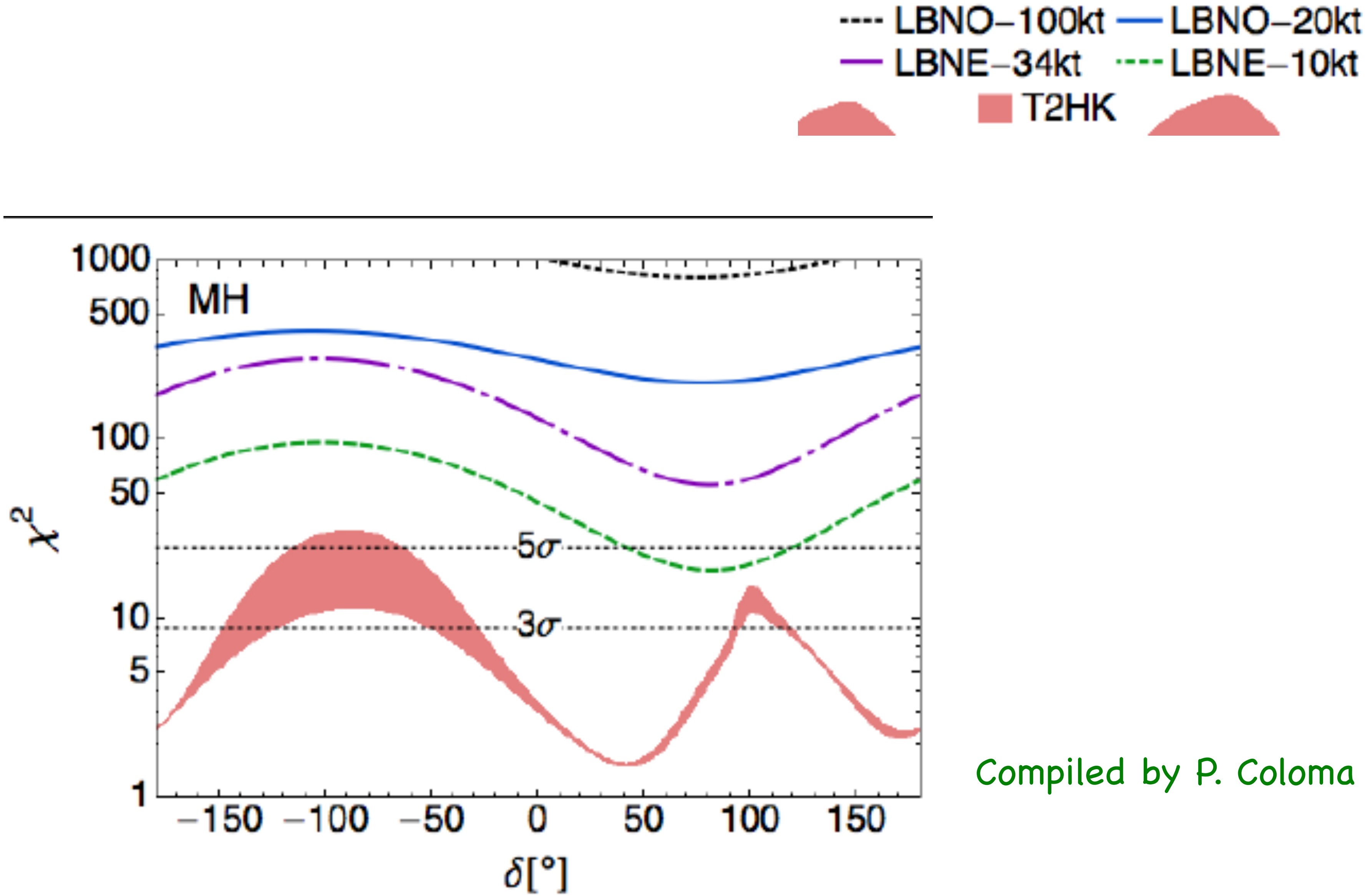
800MW, 10kton-> 35kton LAr, Fermilab-Homestake(1300km)

LBNO (Europe)



800MW, 20kton-> 100kton LAr, CERN-Pyhäsalmi (2300km)

In 20 years from now with conventional beams…

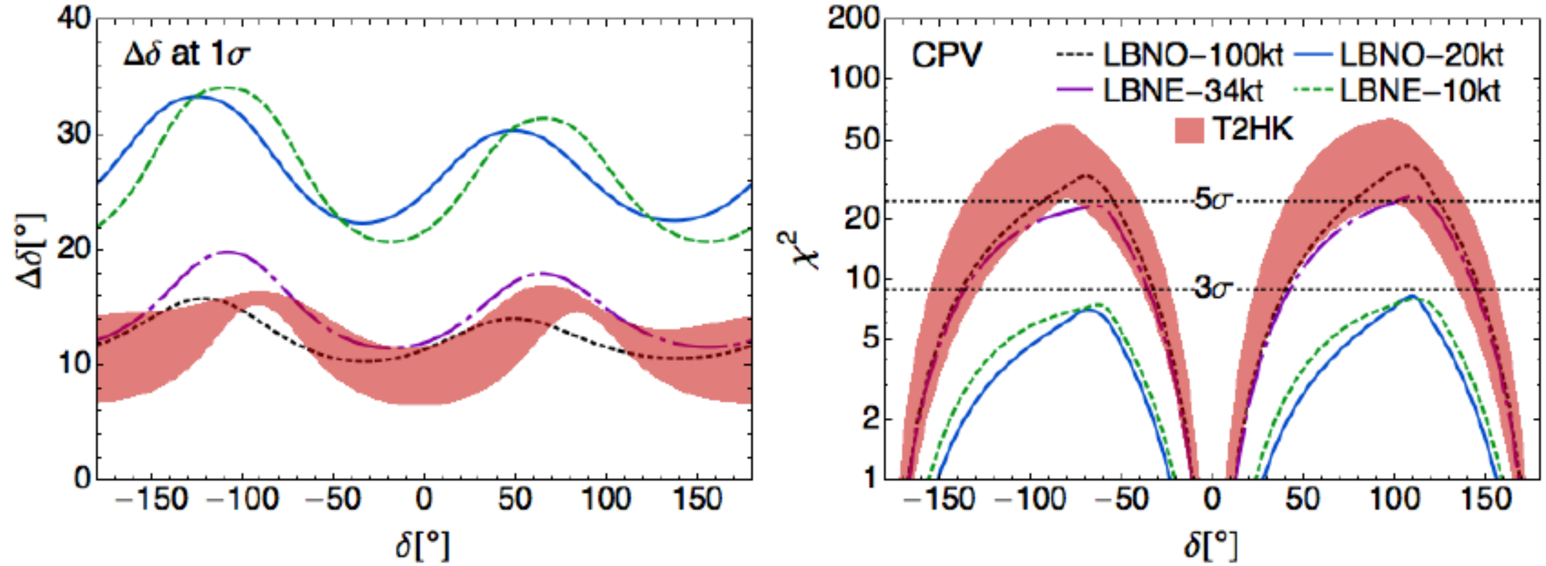


Compiled by P. Coloma

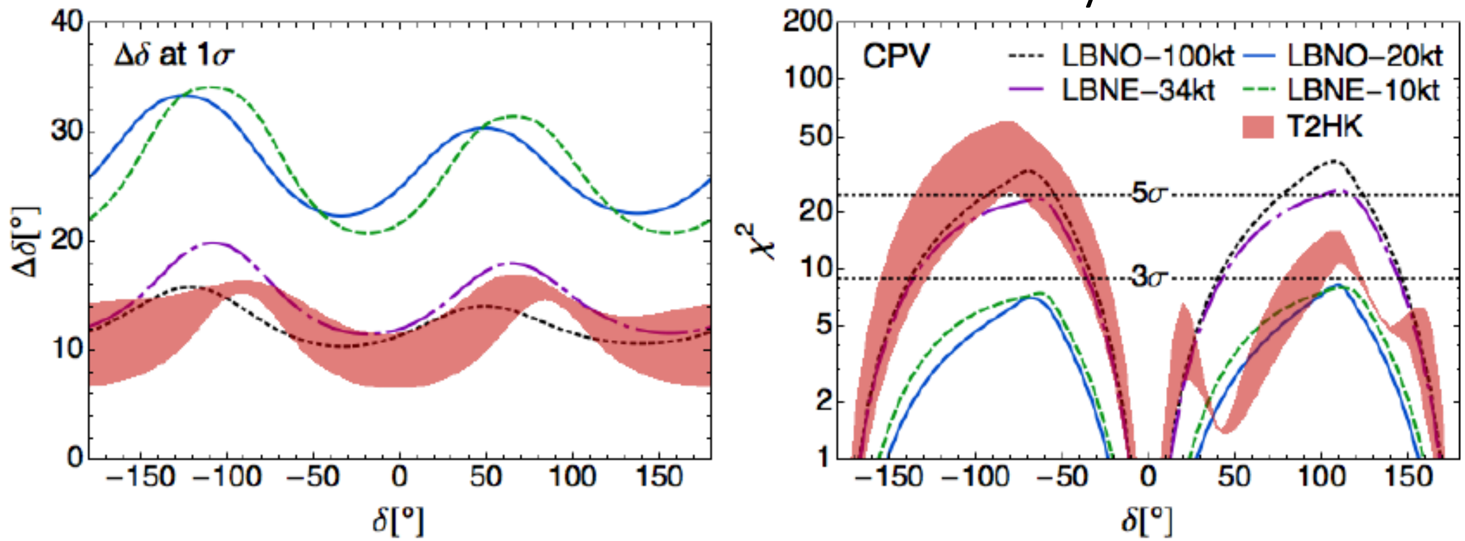
O(10kton) LAr can do the job easily

In 20 years from now with conventional beams…

Hierarchy known

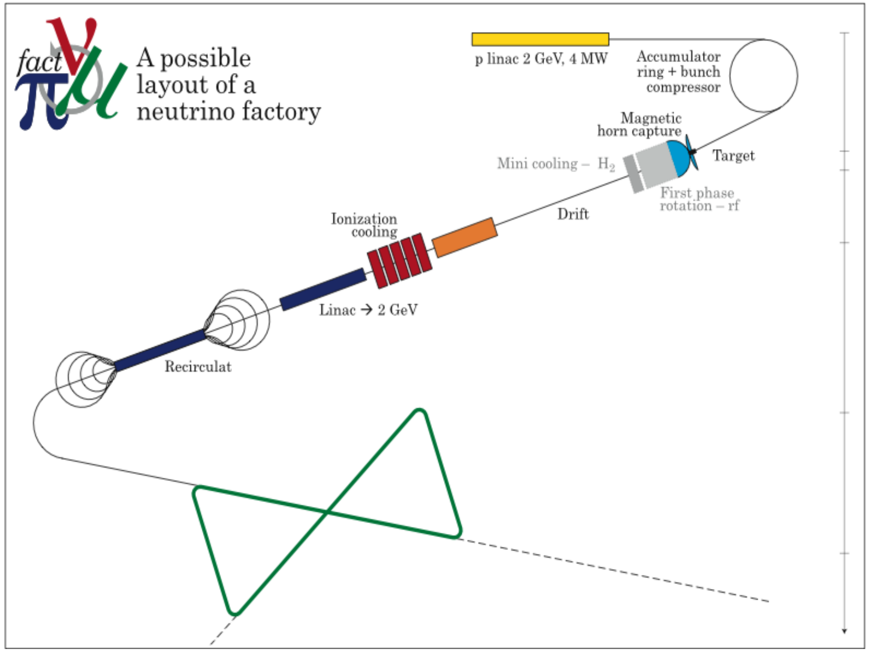


Hierarchy not known



Systematics as in Coloma, Huber, Kopp, Winter to appear

Neutrino factory



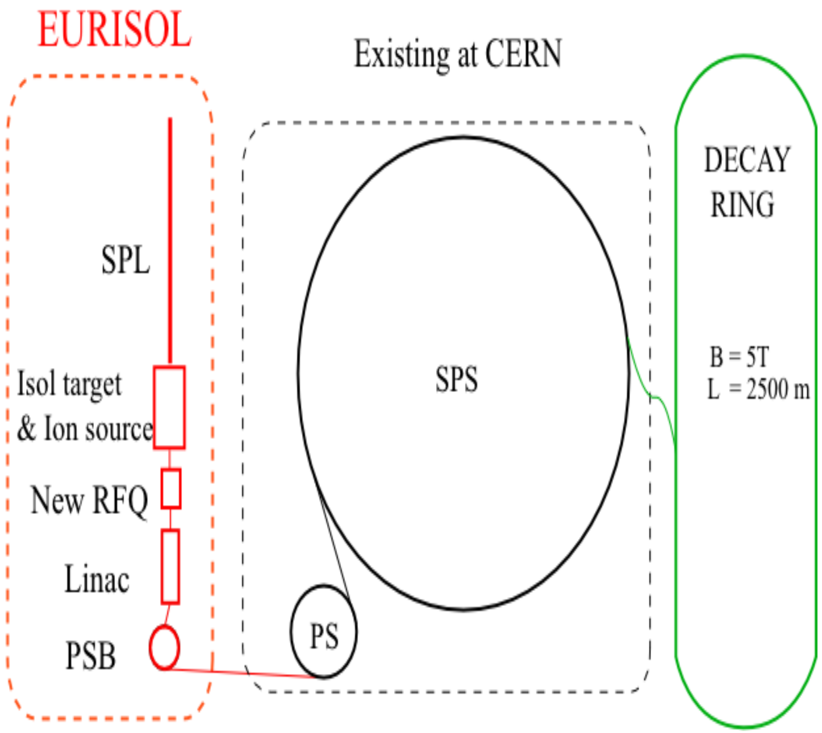
From μ decays

$$\mu^- \rightarrow e^- \quad \nu_\mu \quad \bar{\nu}_e\,;$$

$$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$$

$$\nu_\mu \rightarrow \nu_\mu \rightarrow \mu^-$$

β beam

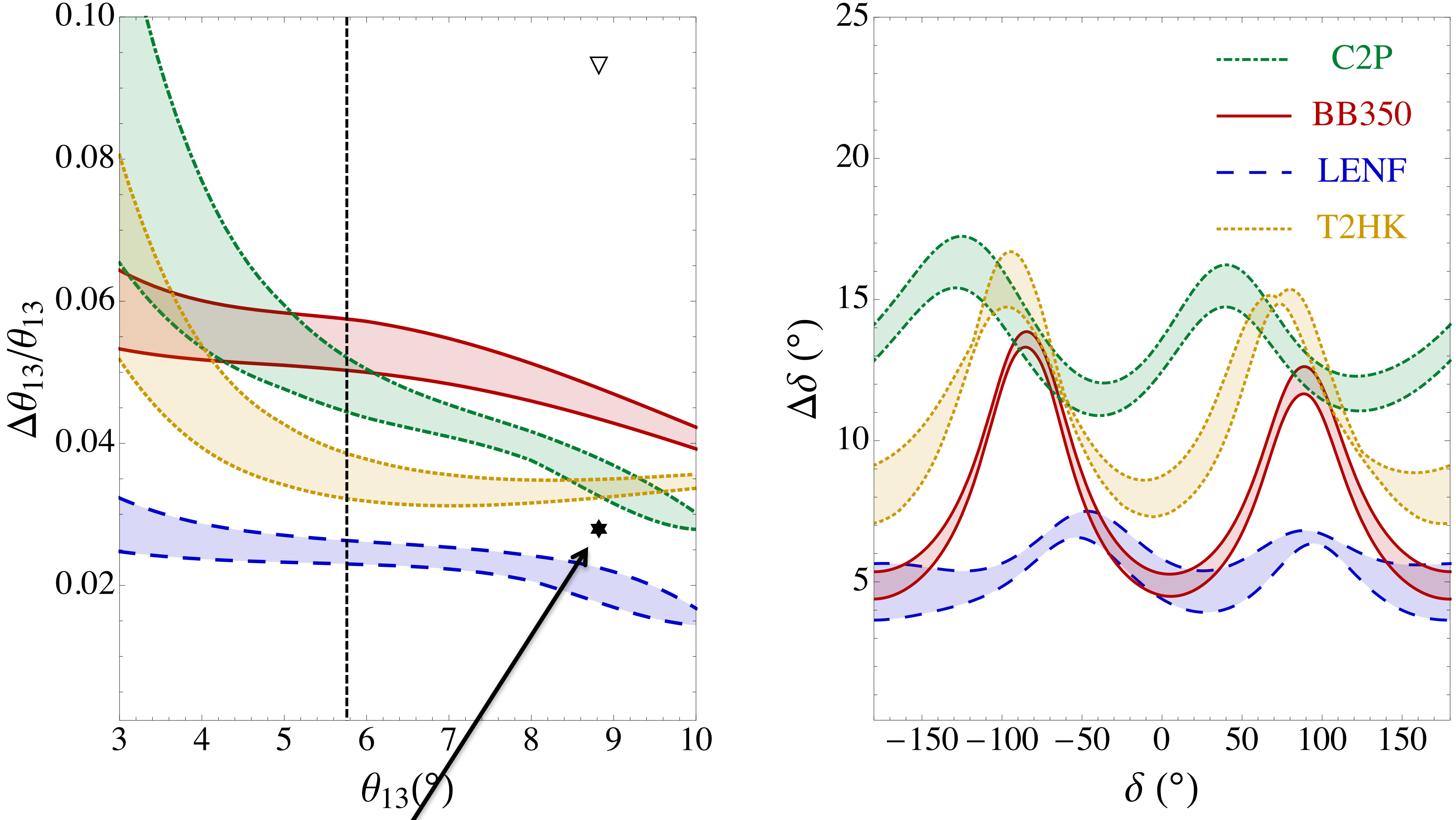


From radioactive ions

$$^{6}He^{++} \rightarrow ^{6}_{3} Li^{+++}\ e^- \qquad \bar{\nu}_e$$

$$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$$

With better beams in XX years…



Daya Bay syst only!

Coloma, Donini, Fernandez-Martinez, PH 1203.5651

What about the other parameters ?

	Current	Daya Bay II
Δm^2_{12}	3%	< 1%
Δm^2_{23}	5%	< 1%
$\sin^2\theta_{12}$	6%	< 1%
$\mathrm{Sin}^2\theta_{23}$	20%	-
$\sin^2\theta_{13}$	14% ➔ 4%	-

Wang at Nufact12

$\mathrm{Sin}^2\theta_{23}$ < 3% at HK ?

CKM

$$|V|_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

PMNS: in 20-30y from now...

$$U_{PMNS}(\delta = 90 \pm 5^\circ) = \begin{pmatrix} 0.827 \pm 0.002 & 0.541 \pm 0.003 & 0.152 \pm 0.003 \\ 0.432 \pm 0.013 & 0.650 \pm 0.013 & 0.625 \pm 0.010 \\ 0.360 \pm 0.012 & 0.533 \pm 0.015 & 0.766 \pm 0.008 \end{pmatrix}$$

CKM

$$|V|_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

PMNS: in 20-30y from now...

$$U_{\alpha i} = \begin{pmatrix} 0.820 \pm 0.002 & 0.520 \pm 0.003 & 0.150 \pm 0.003 & 0.15 \pm 0.003 & 0.13 \pm 0.003 \\ 0.320 \pm 0.013 & 0.720 \pm 0.013 & 0.590 \pm 0.010 & 0.110 \pm 0.010 & 0.130 \pm 0.010 \\ 0.470 \pm 0.012 & 0.420 \pm 0.015 & 0.640 \pm 0.008 & 0.330 \pm 0.01 & 0.280 \pm 0.010 \end{pmatrix}$$

CKM

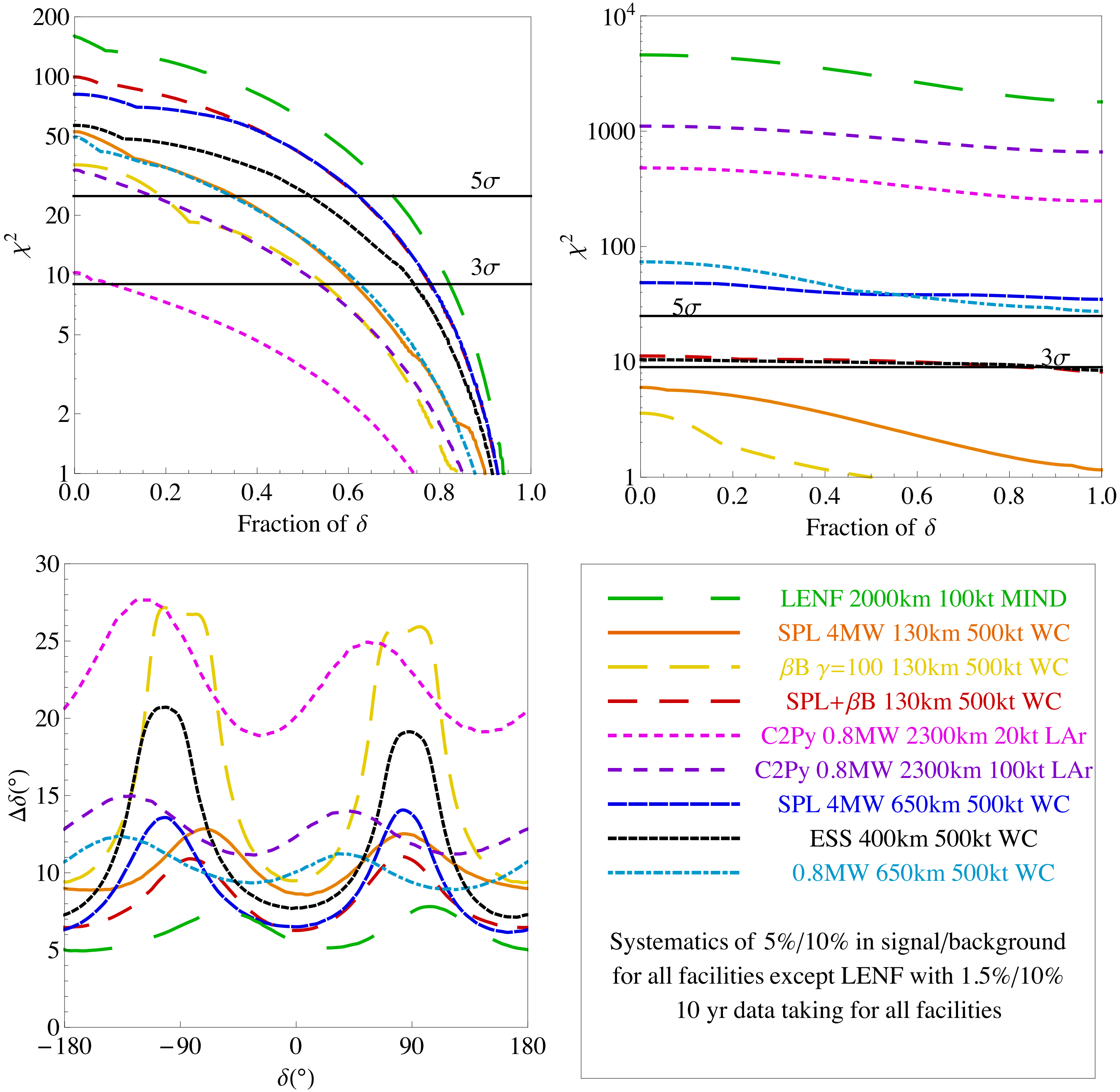
$$|V|_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm \ldots \ldots 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (4 \ldots) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & \ldots 146^{+0.000021}_{-0.000046} \end{pmatrix}$$

PMNS: in 20-30y fro… …

$$U_{PMNS}(\delta = 9 \ldots) = \begin{pmatrix} 0.827 \pm 0.002 & 0.541 \pm 0.003 & 0.152 \pm 0.003 \\ 0.432 \pm 0.013 & 0.650 \pm 0.013 & 0.625 \pm 0.010 \\ 0.360 \pm 0.012 & 0.533 \pm 0.015 & 0.766 \pm 0.008 \end{pmatrix}$$

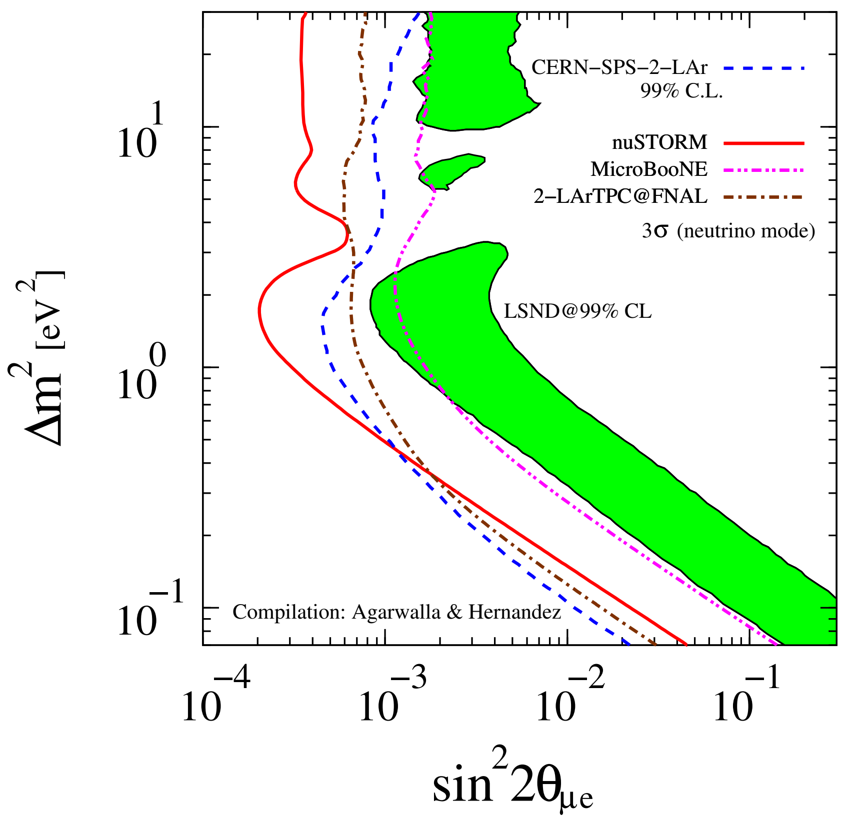
Will this error be matched by theoretical error ??

Backup



Fernandez-Martinez

Testing neutrino anomalies (in few y)



1) Conventional beams with near detector and better capabilities (LAr): MicroBooNe (Fermilab), ICARUS-Nessie (CERN) ($\nu_\mu \rightarrow \nu_e$) or nuSTORM ($\nu_e \rightarrow \nu_\mu$)
2) Reactors: near detector fluxes vs theoretical flux predictions
3) Atmospheric: SuperK, Icecube & LBL ….
4) Borexino …