CP Violation in the Neutrino Sector

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Some Prehistory and History of Flavor Mixing

- 1930: Invention of the Neutrino by Pauli
- 1933: Theory of Beta Decay,:Fermi (almost correct except needing a factor of $(1 + \gamma_5)/2$)
- 1946: Sakata, invented muon and muon-neutrino (along with the decay scheme $\pi \to \mu \to e$) to resolve the confusion in cosmic rays about pions, confirmed by cosmic ray data, esp by Powell et al.
- 1948: Universality of couplings in all 4-Fermi interactions noted: β-decay, μ-decay, and μ-capture: Klein, Puppi, Tiomno-Wheeler and Lee-Rosenbluth-Yang.

1947 onwards: Discovery of strange particles, Λ-hyperons, Kaons etc….

1953-6: Gell-Mann-Nishijima: strangeness; Gell-Mann-Pais: K^0-$\overline{K}^0$ mixing, strangeness oscillations etc

1956-7: Discovery of Parity Violation, Lee-Yang, confirmed by Ambler-Wu et al., Lederman et al.

1957: Universal V-A Interaction: Sudarshan-Marshak, Feynman-Gell-Mann: $H_w = J^\dagger J$ with

$J\,(V\text{-}A) = \bar{p}\,n + \bar{e}\nu + \bar{\mu}\nu + \bar{p}\,\Lambda$…..

1958-59: Data show that Λ-β-decay much weaker than neutron β-decay leading to…..

1960: Gell-Mann-Levy proposal of modified universality: hadronic weak current with the form: $J = (\bar{p}\,n + \varepsilon\bar{p}\,\Lambda)/(1 + \varepsilon^2)^{1/2}$

$= \cos\theta\ \bar{p}n + \sin\theta\ \bar{p}\Lambda$

1962: Important step taken by Maki,Nakagawa, Sakata- they proposed similar mixing present in leptonic sector and further that

Neutrino flavor states are mixtures of mass eigenstates :

$$\nu_e = \cos\theta\, \nu_1 + \sin\theta\, \nu_2$$
$$\nu_\mu = - \sin\theta\, \nu_1 + \cos\theta\, \nu_2$$

They also discussed neutrino mixing and oscillations, estimating oscillation times in terms of δm^2 and L/E.

1969: Similar analysis carried out by Gribov and Pontecorvo

- 1963: Cabibbo analysed succesfully the semileptonic decays of all hyperons(Λ, Σ, and Ξ) using the angle θ, with octet assignment for both the current and the baryons under Gell-Mann's flavor SU(3).
- 1973: Kobayashi and Maskawa propose several ways to include CP Non-conservation in "Standard Model", including adding a third family.
- 1975-6: The K-M idea analysed and showed to be viable by Sugawara-SP, by Maiani and by Ellis-Gaillard-Nanopoulos.
- 1975: Discovery of Tau Lepton by Perl et al at SPEAR
- 1977: Analysis of a weak current with three lepton families, including a mixing between three neutrinos with a **complex**(hence CPV) unitary 3X3 matrix: Sugawara, SP, BWLee and Shrock,; Fritzsch
- 2000: Confirmation of the K-M scheme for CPV by observations in B decays by BELLE and BABAR as suggested by Bigi and Sanda(1981)

1978-80: Simple Phenomenology of CPV in ν-osc. worked out:
Cabibbo; Barger-Philips-Whisnant; S.P.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

CPV Tests:

$$P_{\alpha\beta}(t) \neq P_{\bar{\alpha}\bar{\beta}}(t)$$

T INV: $$P_{\alpha\beta}(t) \neq P_{\beta\alpha}(t)$$

CPT INV $\Rightarrow$ $$P_{\alpha\beta}(t) = P_{\bar{\beta}\bar{\alpha}}(t)$$

In Detail:

$$\Delta_{\mu e} = P_{\mu e}(L/E) - P_{\bar{\mu}\bar{e}}(L/E)$$

$$= 4\, J_{PMNS} \sin\Delta_{12} \sin\Delta_{23} \sin\Delta_{31}$$

$$J_{PMNS} = \mathrm{Im}\left(U_{\mu 2}^{*} U_{e2} U_{\mu 3} U_{e3}^{*}\right)$$

$$= s_{12} s_{13}^{2} c_{23} c_{23} \sin\delta$$

$$\sim 10^{-2} \sin\delta$$

$$J_{CKM} \sim 3 \cdot 10^{-5}$$

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - s_{12}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{23}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\times V_M$$

$$V_M = V_{Majorana} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

α_i = Majorana phases

not observable

in oscillations

Current Fits:

$$\delta m^2_{12} \sim 7.5 \cdot 10^{-5}\ eV^2$$

$$\delta m^2_{31} \sim 2.5 \cdot 10^{-3}\ eV^2$$

$m_2 > m_1$ (from MSW + Solar)

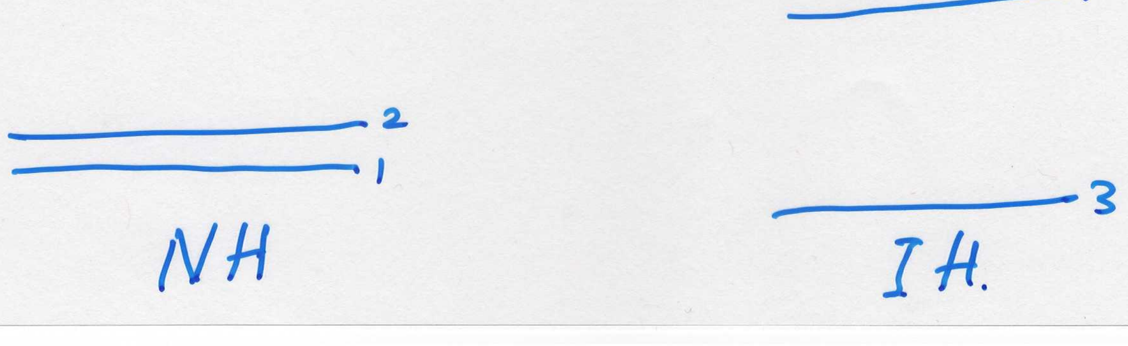
$$s^2_{12} \sim 0.3$$

$$s^2_{23} \sim 0.42$$

$$s^2_{13} \sim 0.024$$

Some preferance for $\cos\delta < 0$

mass ordering



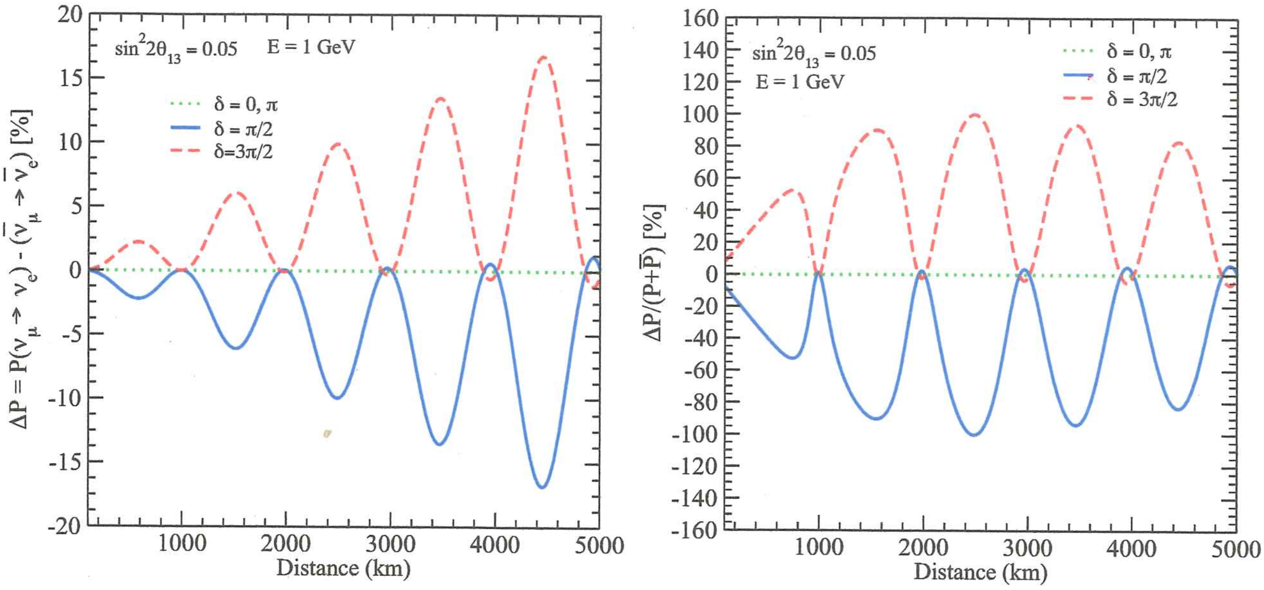


Figure 22: Examples of $\Delta P_{\nu\bar{\nu}} \equiv P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$ (left panel) and the asymmetry $\Delta P/[P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)]$ (right panel) in vacuum as a function of distance for fixed value of energy, $E = 1$ GeV and $\sin^2 2\theta_{13} = 0.05$. in vacuum.

CPV without $\bar{\nu}$ beams:

$$P_{e\mu}(t) = A + B\cos\alpha t + C\sin\alpha t$$

presence of both $B \neq 0, C \neq 0$

$\Rightarrow$ CPV.

Complication due to matter effects.
Most beams travel thru earth.
Matter NOT CP invariant.
But matter & CPV behave:

$$A_{CP} \propto f(L/E)$$

$$A_{matter} \propto f(L \cdot E).$$

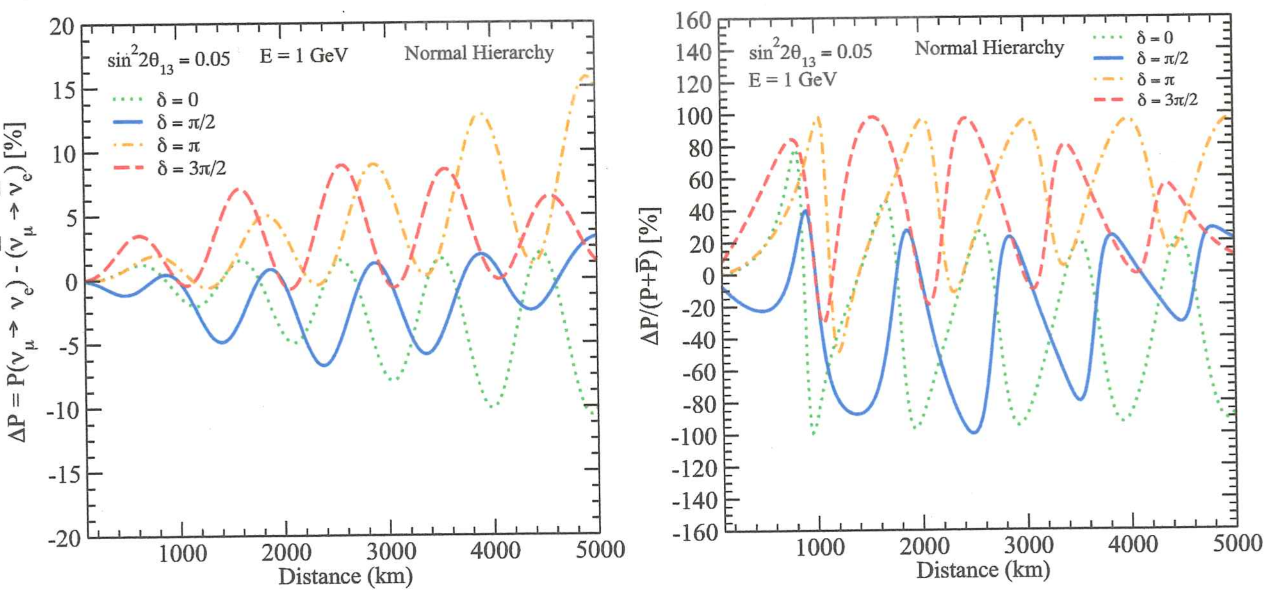


Figure 24: Examples of $\Delta P \equiv P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)$ (left panel) and the asymmetry $\Delta P/[P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)]$ (right panel) in matter as a function of distance for fixed value of energy, $E = 1$ GeV and $\sin^2 2\theta_{13} = 0.05$. For simplicity, we assume a constant electron number density $N_e = 1.5$ mol/cc.

5. CP violation?

Is $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$? (intrinsic)

$$\Delta P \propto \left(\frac{\delta m_s^2}{\delta m_a^2}\right) \sin\delta \sin^2 2\theta_x$$

- δ measurement depends on θ_x
- Both δm_s^2 and δm_a^2 oscillations must contribute
- Must distinguish intrinsic CP-violation from fake CP-violation due to matter effects

CPV in presence of matter:

$$\Delta P_{\mu e} = P_{\mu e} - P_{\bar{\mu}\bar{e}}$$

$$\simeq 2xyg\,\Delta f \cos\delta \cos\Delta$$

$$- 2xyg \sin\delta \sin\Delta\,(f + \bar{f})$$

where

$$\Delta = \delta m^2_{31} L/4E$$

$$\bar{A} = (A/\delta m^2_{31})$$

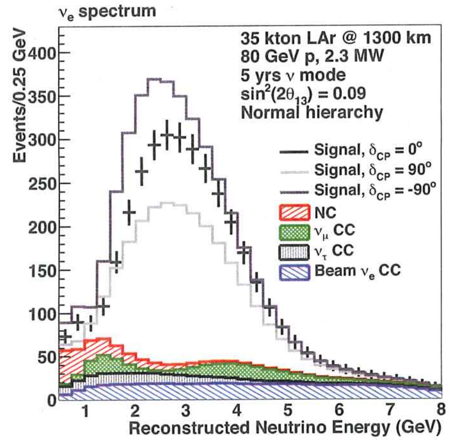
$$\alpha = \delta m^2_{21}/\delta m^2_{31}$$

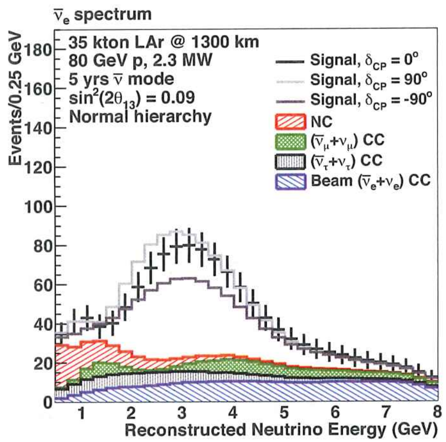
$$x = \sin\theta_{23} \sin 2\theta_{13}$$

$$y = \alpha \cos\theta_{23} \sin 2\theta_{13}$$

$$f, \bar{f} = \sin(1 \pm \bar{A})\Delta/(1 \mp \bar{A})$$

$$g = \sin\bar{A}\Delta/\bar{A}$$





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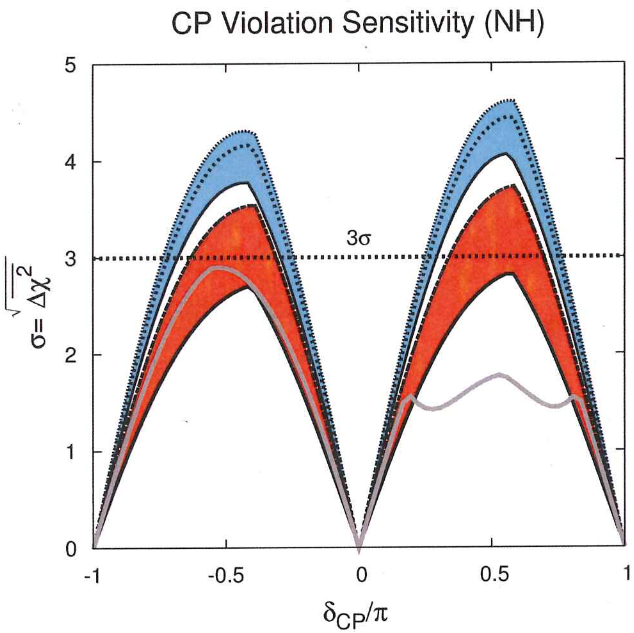
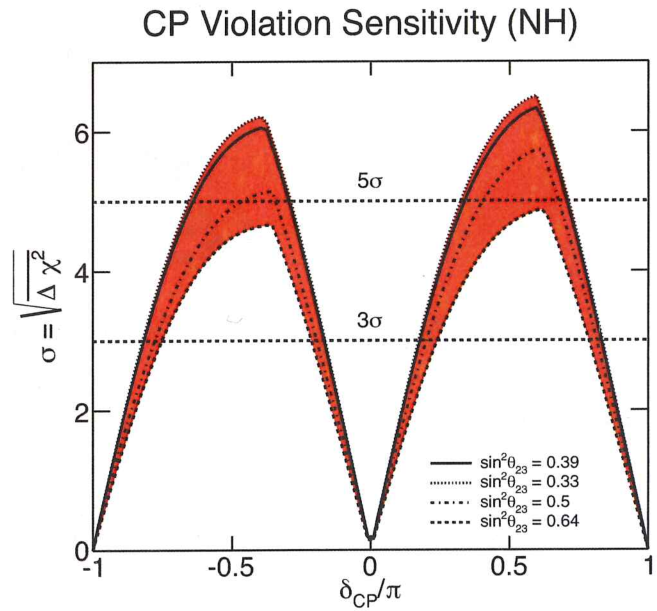
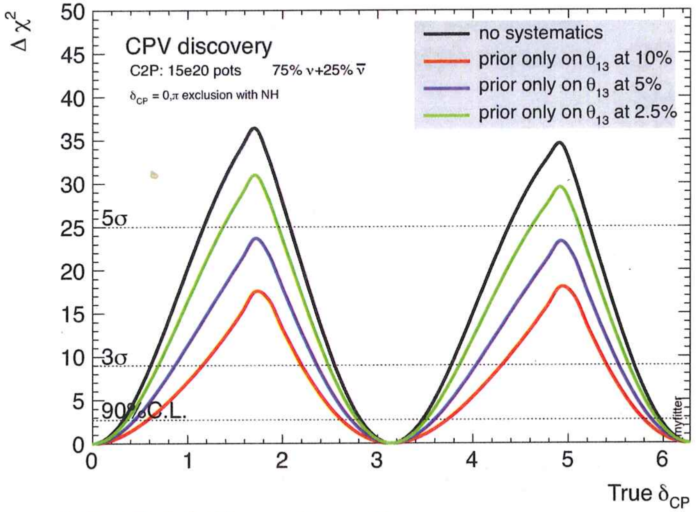


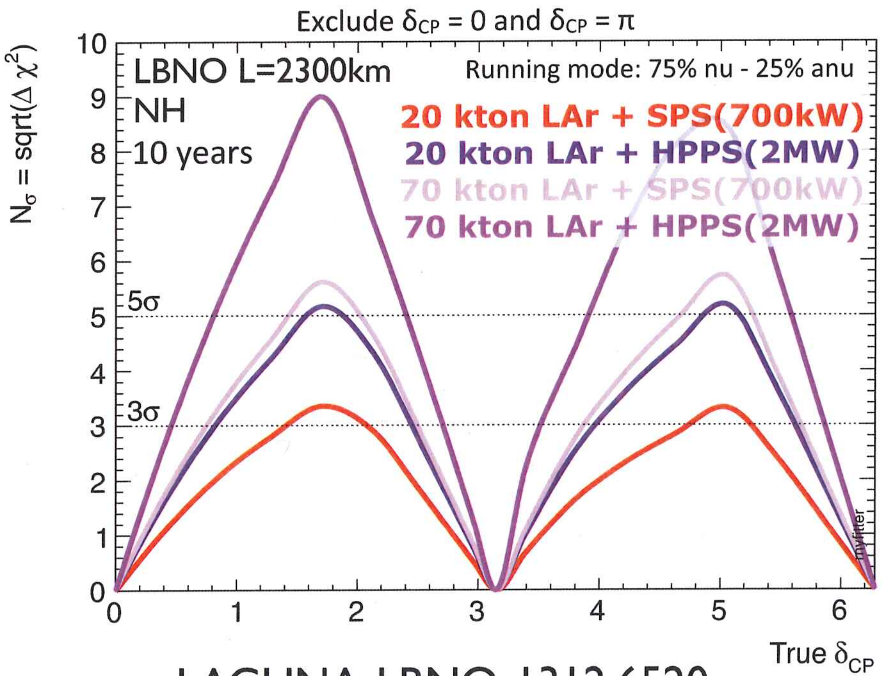
LBNE Coll., 1307.7335

LBNE-34kton



LBNO





LAGUNA-LBNO, 1312.6520

See T. Patzak's, R. Wilson's talk

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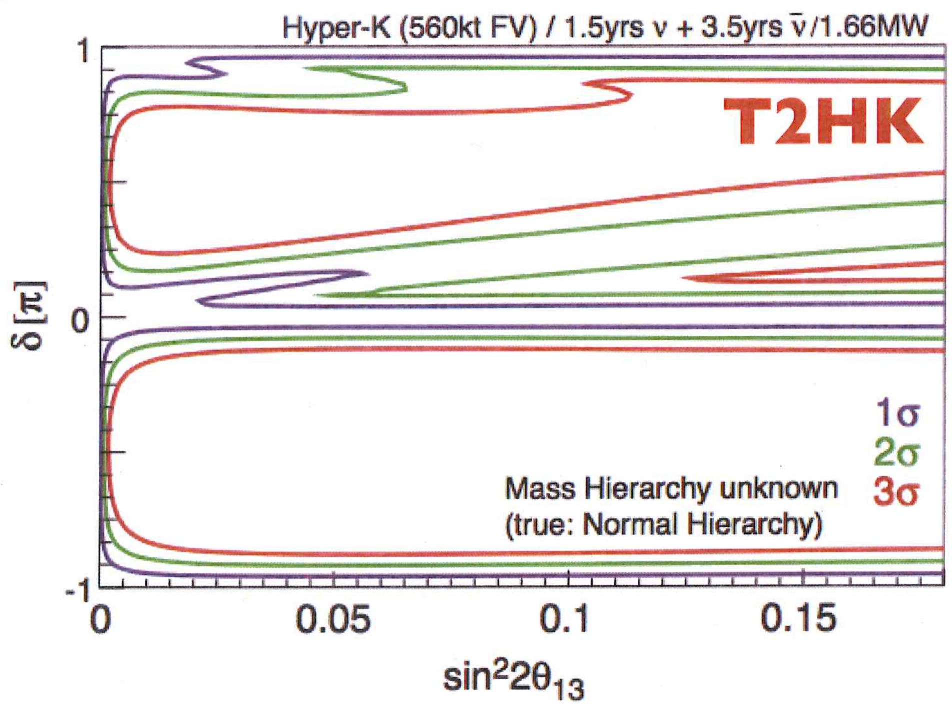
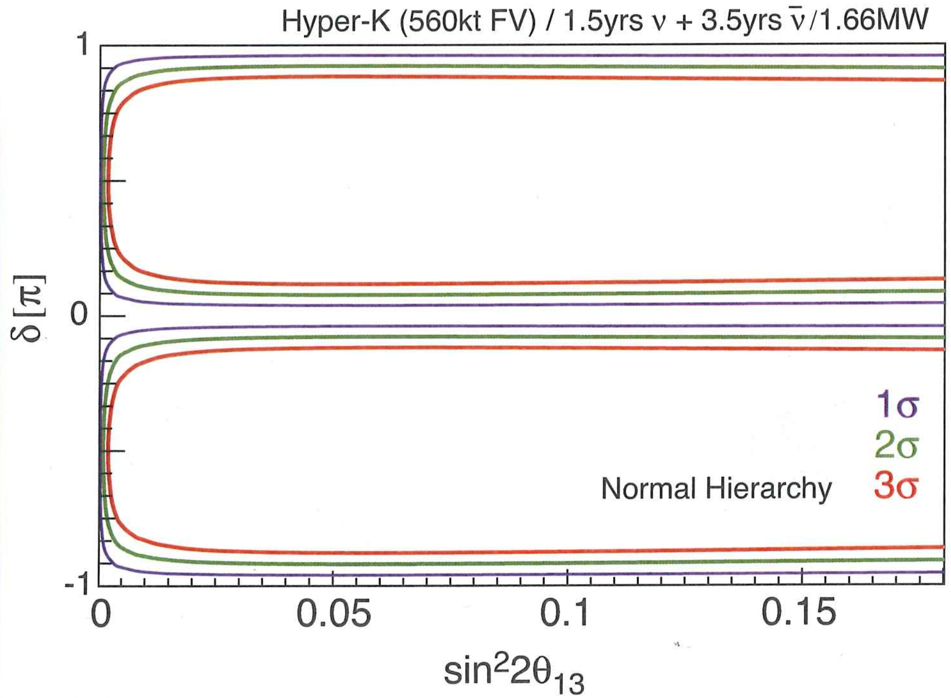
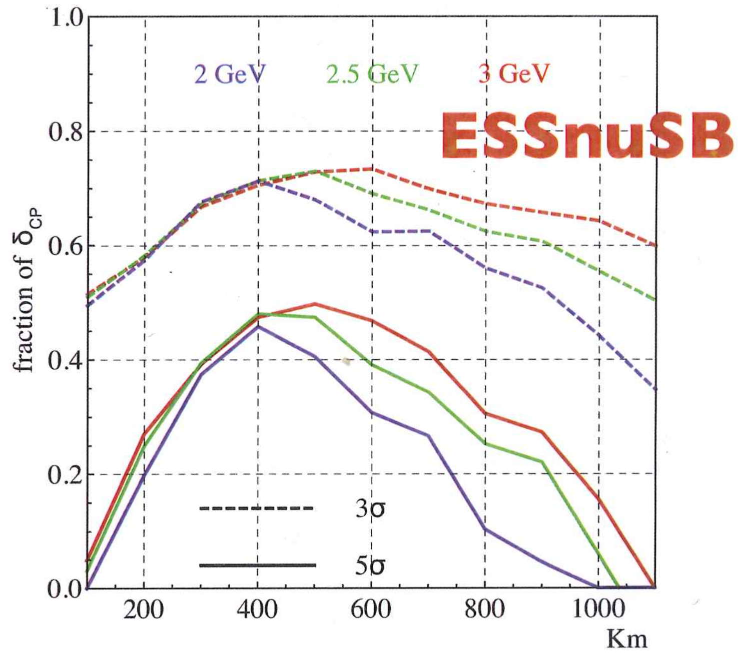




T2HK LoI, Abe et al., 1109.3262 See Y. Hayato's talk



ESSnuSB, 1309.7022

T2HK:

The knowledge of the mass ordering is crucial (CPV-mass ordering degeneracy)

ESSnuSB:

Use the information at low energy.

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Can Majorana CPV Phase be measured in Neutrinoless Double Beta Decay?

- $$M_{ee} = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i\alpha_1} + |U_{e3}|^2 m_3 e^{i\alpha_2} \right|$$

  $\{ \lessapprox 0.2\ \text{eV} \text{ (factor of 2)}. \}$.

- $$m_e = \sum_i |U_{ei}|^2 m_i$$ (katrin $\longrightarrow$ 0.3 eV).

- $$\Sigma = \sum_i m_i \sim 0.26\,\text{eV (PLANCK)}.$$

In approx. $\begin{cases} \delta m^2_{12} \ll \delta m^2_{13} \\ \sin\theta_{13} \ll 1 \end{cases}$

$$\rightarrow \quad \cos\alpha_1 \cong 1 - \frac{2}{\sin^2\theta_{12}}\left(1 - \frac{M_{ee}^2}{m_e^2}\right)$$

so in principle, YES — BUT

No Go Theorem: Barger et al. (2002)

With conservative errors all values of α, allowed!

Esp. NME!

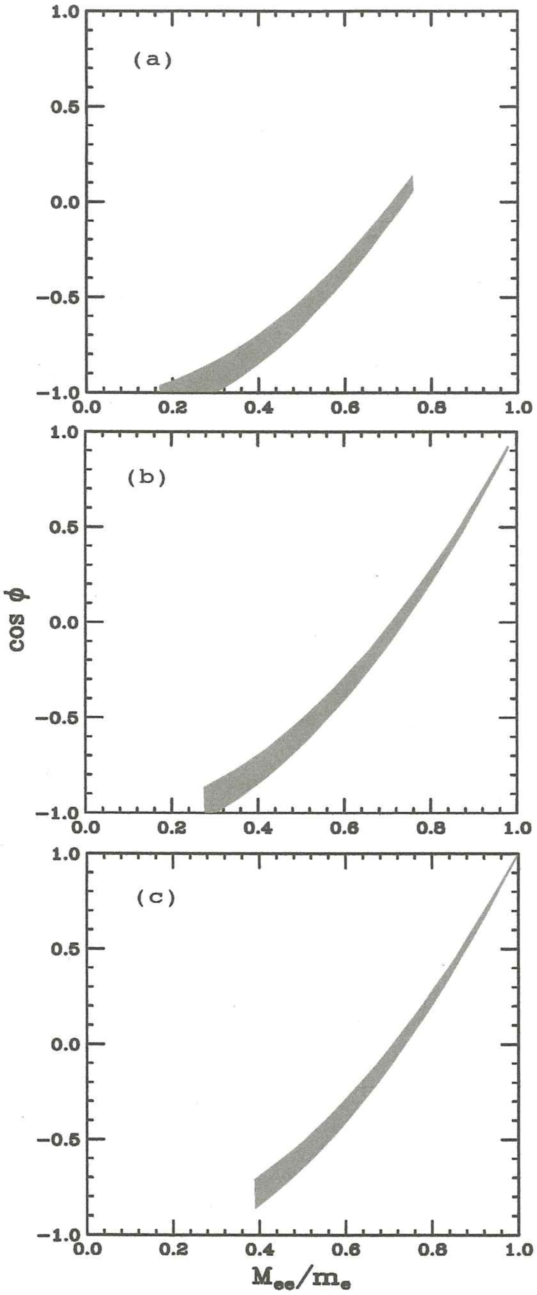
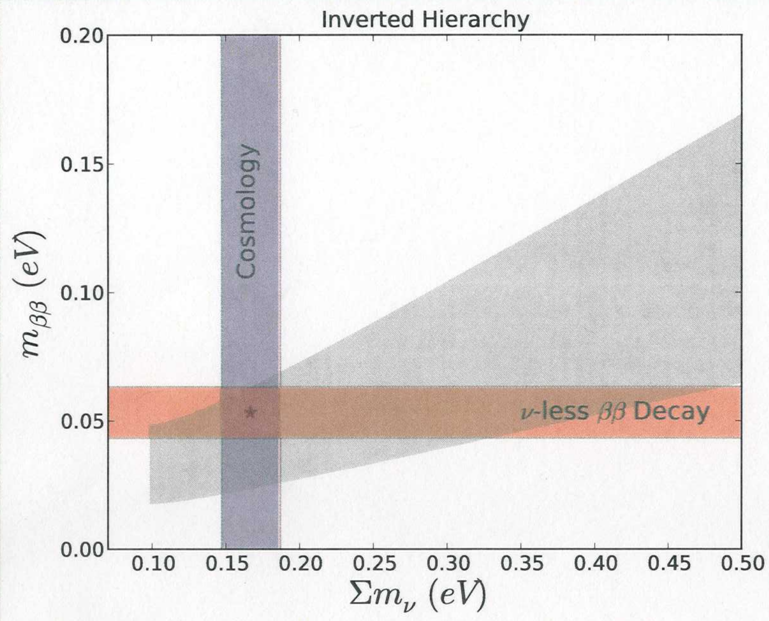


Figure 1: "1σ" bands in the M_{ee}/m_e–$\cos\phi$ plane for three possible measurements assuming the normal hierarchy: (a) $\Sigma = 0.24 \pm 0.04$ eV, $M_{ee} = 0.03(1 \pm 0.5)$ eV with the central value of $M_{ee}/m_e = 0.4$, (b) $\Sigma = 0.51 \pm 0.04$ eV, $M_{ee} = 0.10(1 \pm 0.5)$ eV with the central value of $M_{ee}/m_e = 0.6$, (c) $\Sigma = 1.12 \pm 0.04$ eV, $M_{ee} = 0.30(1 \pm 0.5)$ eV with the central value of $M_{ee}/m_e = 0.8$. Results are shown for the best possible solar amplitude (allowed by present solar data at 3σ) for the detection of CP violation, $\sin^2 2\theta = 0.95 \pm 0.04$. Δ is fixed at 3×10^{-3} eV^2.

An optimistic View!!

Measuring a Majorana phase using Neutrinoless Double Beta Decay and Cosmology



$$m_{\beta\beta}^{\text{inv}} \simeq c_{13}^2 \Big[(m_1 c_{12}^2)^2 + (m_2 s_{12}^2)^2 + 2\cos(2\lambda_2)(m_1 c_{12}^2)(m_2 s_{12}^2) \Big]^{1/2}.$$

Assumed sensitivities: $\Delta_\beta = 10$ meV and $\Delta_S = 20$ meV.

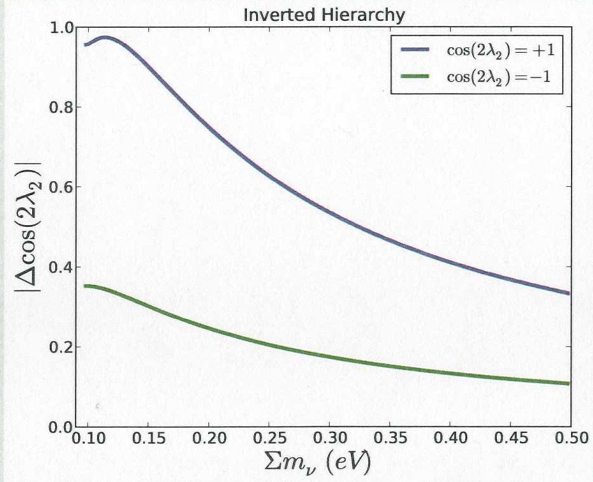


FIG. 2: Projected one-sigma constraint on the cosine of the Majorana phase from combined cosmic survey and neutrinoless double beta decay experiments. These constraints are relevant if the mass hierarchy is determined to be inverted.

S. Dodelson and JL, arXiv:1403.5173, and many previous works

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CPV and the Baryon asymmetry

There is evidence of the baryon asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.14 \pm 0.08) \times 10^{-10}$$

Planck, 1303.5076

In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:

Neutrinoless double beta decay

- B (or L) violation;

LBL

- C, CP violation;

Expansion of the Universe

- departure from thermal equilibrium.

Leptogenesis in models at the origin of neutrino masses

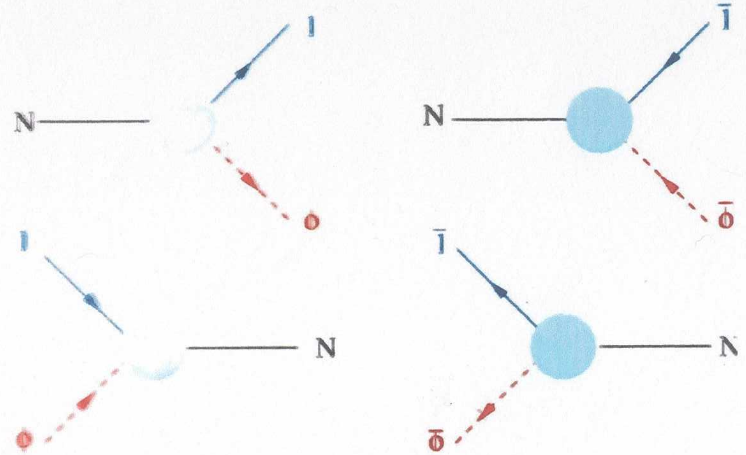
LEPTOGENESIS

Fukugita, Yanagida, 1985

.sea-saw mechanism for neutrino mass generation

$$m_\nu \approx \frac{m^2}{M}, \quad M \sim 10^{15}\,GeV$$

- $\Delta L=1$ processes: decays and inverse decays of a heavy Majorana neutrino ($N^c = N$)



CP violation ε in Majorana neutrino decays

$$\Gamma(N \to l\phi) = \frac{1}{2}(1+\varepsilon)\Gamma,$$

$$\Gamma(N \to \bar{l}\bar{\phi}) = \frac{1}{2}(1-\varepsilon)\Gamma$$

- **Because** of $\varepsilon > 0$ (which is generated by interference of tree level and one loop decays) there is a net lepton production in Majorana neutrino (N) decays.

Leptogenesis

- At T>M, the right-handed neutrinos N are in equilibrium thanks to the processes which produce and destroy them:

$$N \leftrightarrow \ell H$$

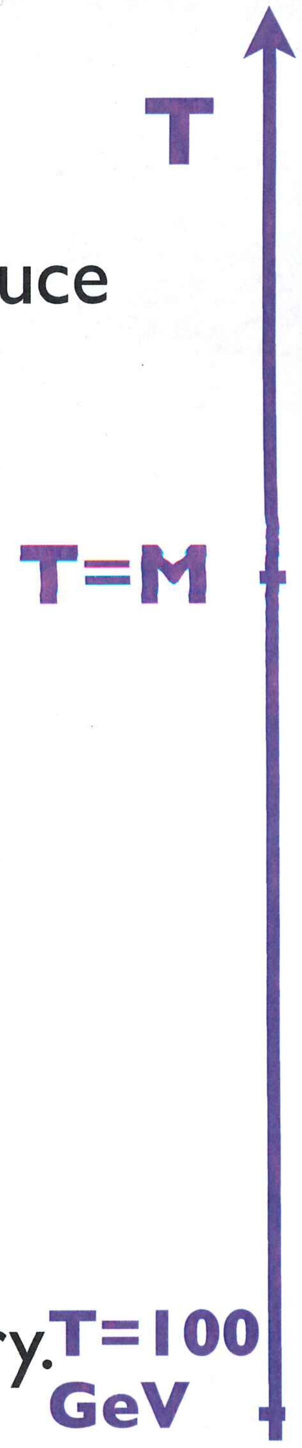
- When T<M, N drops out of equilibrium

$$N \to \ell H \qquad\qquad N \to \ell^c H^c$$

- A lepton asymmetry can be generated if

$$\Gamma(N \to \ell H) \neq \Gamma(N \to \ell^c H^c)$$

- Sphalerons convert it into a baryon asymmetry.



 Fukugita, Yanagida, PLB 174; Covi, Roulet, Vissani; Buchmuller, Plumacher; Abada et al., ...

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Although the SM Sphaleron mechanism cannot generate enuf baryon asymmetry, it is very efficient in washing out an asymmetry generated earlier by other means such as GUTs.

After the lepton asymmetry and a net lepton number L_i has been created at some high scale, as the universe cools and temperature drops to the electroweak scale, the sphaleron converts the lepton symmetry into baryon asymmetry. As B-L is conserved, one expects the final $B_f = -L_i/2$ and $L_f = L_i/2$. the actual detailed calculation gives B_f closer to $-L_i/3$.

the magnitude of its baryon asymmetry.) It is easy to see why these conditions are necessary. The need for B (baryon) violation is obvious. Let's consider some examples of B violation.

2.1. B violation

In the standard model, B is violated by the triangle anomaly, which spoils conservation of the left-handed baryon + lepton current,

$$\partial_\mu J^\mu_{B_L+L_L} = \frac{3g^2}{32\pi^2}\epsilon_{\alpha\beta\gamma\delta}\overset{\mathrm{tr}}{W_a^{\alpha\beta}} W_a^{\gamma\delta} \tag{2.1}$$

where $W_a^{\alpha\beta}$ is the **SU(2)** field s ength. As we will discuss in more detail in section 4, this leads to the **nonperturbative** sphaleron process pictured in fig. 4. It involves 9 left-handed **(SU(2)** doublet) quarks, 3 from each generation, and 3 left-handed leptons, one from each generation. It violates B and L by 3 units each,

$$\Delta B = \Delta L = \pm 3 \tag{2.2}$$

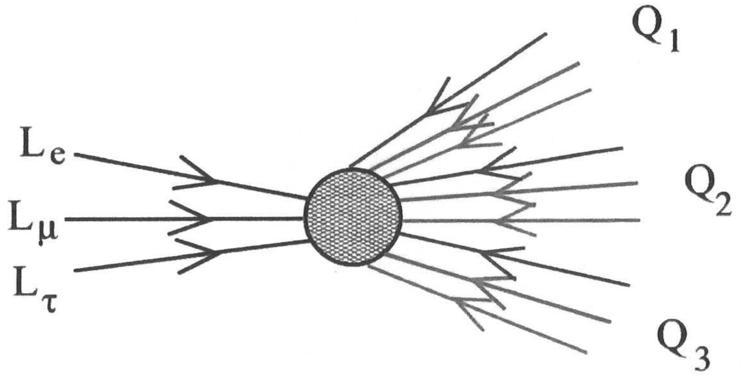


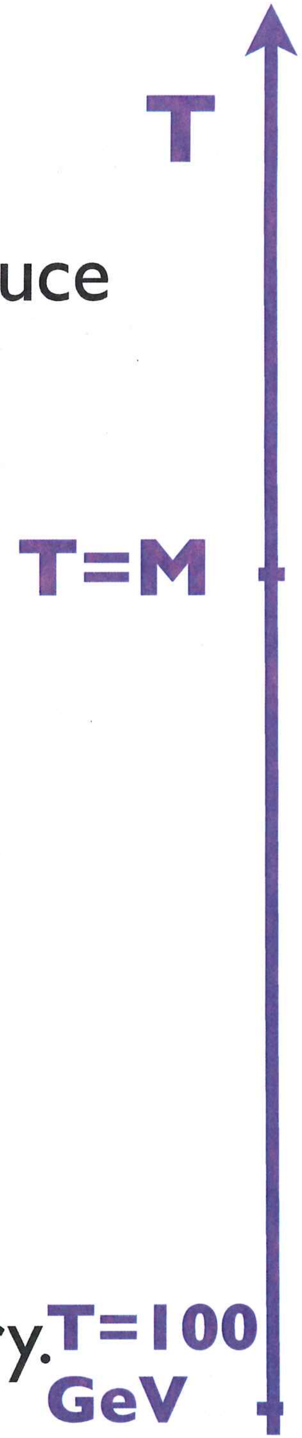
Fig. 4. The sphaleron.

In grand unified theories, like **SU(5),** there are heavy gauge bosons X^μ and heavy Higgs bosons Y with couplings to quarks and leptons of the form

$$Xqq, \quad X\bar{q}\bar{l} \tag{2.3}$$

and similarly for Y. The simultaneous existence of these two interactions imply that there is no consistent assignment of baryon number to X^μ. Hence B is violated.

Leptogenesis



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Fukugita, Yanagida, PLB 174; Covi, Roulet, Vissani; Buchmuller, Plumacher; Abada et al., ...

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In order to compute the baryon asymmetry:

1. evaluate the CP-asymmetry

$$\epsilon \equiv \frac{\Gamma(N \to \ell H) - \Gamma(N^c \to \ell^c H^c)}{\Gamma(N \to \ell H) + \Gamma(N^c \to \ell^c H^c)}$$

2. solve the Boltzmann equations to take into account the wash-out of the asymmetry

$$Y_L = k\epsilon$$

3. convert the lepton asymmetry into the baryon one

$$\boxed{Y_B = \frac{k}{g^*} c_s \epsilon \sim 10^{-3} - 10^{-4} \epsilon}$$

For $T < 10^{12}$ GeV, flavour effects are important.

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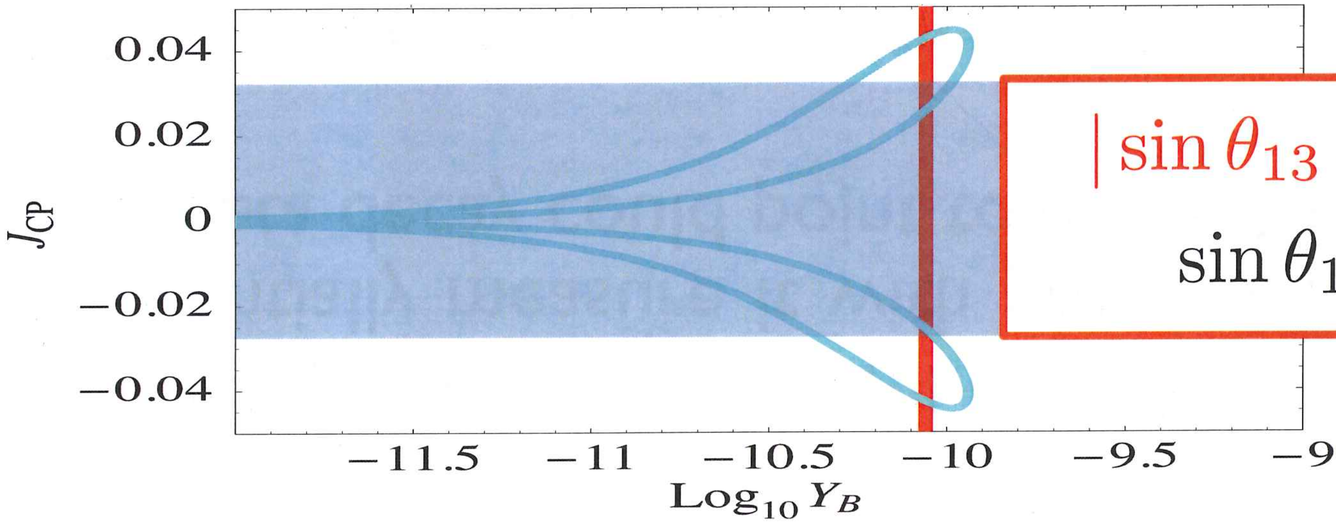
Does observing low energy CPV imply a baryon asymmetry?

It has been shown that, thanks to flavour effects, the low energy phases enter directly the baryon asymmetry.

Example in see-saw type I, with NH (m1<< m2 <<m3), M1<M2<M3, M1~5 10^11 GeV:

$$\epsilon_\tau \propto M_1 f(R_{ij}) \left[c_{23} s_{23} c_{12} \sin\frac{\alpha_{32}}{2} - c_{23}^2 s_{12} s_{13} \sin(\delta - \frac{\alpha_{32}}{2}) \right]$$



$$|\sin\theta_{13} \sin\delta| > 0.11$$

$$\sin\theta_{13}|_{\exp} \simeq 0.15$$

SP, Petcov, Riotto, PRD75 and NPB774

Large theta13 implies that delta can give an important (even dominant) contribution to the baryon asymmetry. Large CPV is needed and a NH spectrum.

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Predicting neutrino CP violation

$$V_\nu = \begin{pmatrix} 2c/\sqrt{6} & 1/\sqrt{3} & 2s/\sqrt{6} \\ -c/\sqrt{6}+is/\sqrt{2} & 1/\sqrt{3} & -s/\sqrt{6}-ic/\sqrt{2} \\ -c/\sqrt{6}+is/\sqrt{2} & 1/\sqrt{3} & -s/\sqrt{6}+ic/\sqrt{2} \end{pmatrix}$$

$c = \cos\theta, \ s = \sin\theta$

$$\Downarrow$$

$\sin^2\theta_{13} = \frac{2}{3}\sin^2\theta, \ \sin^2\theta_{12} = \frac{1}{2+\cos 2\theta}, \ \sin^2\theta_{23} = \frac{1}{2}$

$|\sin\delta_{CP}| = 1, \quad \sin\alpha_{21} = \sin\alpha_{31} = 0$

$$\delta_{CP} = \pm\pi/2$$

(These values need to be renormalised).

The predicton of CP phase depends on the respected Generators of FLASY and CP symmetry. Typically, it is simple value, 0, π, $\pm\pi/2$.

Talk by M. Tanimoto

We are a long way from here.

CONCLUSIONS / OUTLOOK

- Some hints that $\delta \neq 0$
  (but no CPV seen).
- Future LBL experiments will
  hunt for CPV
  in neutrino oscillations
- Ongoing search for ν-less
  $\beta\beta$ decay $\longrightarrow$

  . if observed
  . & if δ observed $\Big\} \Longrightarrow$

offer support for idea of
Leptogenesis . . . -

- This is a long term program

For more details & references

see:

Talk by Silvia Pascoli

at 2/2014 at:

https://indico.fnal.gov/getfile.py/access?contribid = 8022